LIGO SCIENTIFIC COLLABORATION
VIRGO COLLABORATION

Document Type **LIGO–T1300540** **V**

The LSC-Virgo white paper on gravitational wave data analysis
Science goals, status and plans, priorities
(2013-2014 edition)

The LSC-Virgo Data Analysis Working Groups, the Data Analysis Software Working Group, the Detector Characterization Working Group and the Computing Committee

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Processed with LaTeX on 2013/06/26

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1 Foreword by the DAC Chairs

As for the previous editions, the data analysis white paper annually describes the goals, status, and plans of the data analysis teams in the LSC and Virgo. The document is revised and updated every year in the summer, and finalized by early fall. This is the document for 2013-2014. It is intended to facilitate:

- the understanding of the science that we are doing
- the identification of "holes" in our science plan and of tasks that demand more manpower
- the prioritization of our objectives
- the identification of areas when manpower should be shifted to and/or removed from
- the exploitation of synergies among the work carried out in different search groups
- an harmonious exploitation of common resources

Since the understanding of artifacts in our data is an essential part of the analysis work (allowing us to reduce the false alarm rate and increase our confidence that we have the tools to reliably interpret the output of the detector), we begin with a section on Detector Characterization. 'Detector characterization' is a term that indicates a variety of activities at the boundary between the detector and the data analysis. These activities are aimed at supporting the experimental effort by understanding the detector sensitivity performance to various types of signals and spotting critical artifacts that degrade it. They are also aimed at supporting the data analysis efforts by providing lists of "safe" vetoes for times/frequencies and for triggers produced by the search pipelines which can be correlated with malfunctioning of known origin in the instrument and hence that can be discarded as not being of astrophysical origin. This section also includes information on the calibration procedures and expected calibration accuracy in the upcoming runs.

Since data analysis work both drives and is constrained by the computing environment and facilities where it develops, the last section of this document describes the development and maintenance of software tools and the management of software and computing resources.

The data analysis activities are organized in four groups which, broadly speaking, map into four different search approaches, depending on the different signals: compact binary coalescence signals, burst signals, continuous wave signals and stochastic backgrounds. This classification is historical in origin and as the searches that we carry out evolve, becoming more ambitious and broader, the boundaries between the different signals and the boundaries between the different search techniques become somewhat blurred and this distinction is only indicative.

The continuous waves (CW) and stochastic background searches are different with respect to the burst and CBC searches in that weeks to months of data have to accumulated before a meaningful search can be performed: the sensitivity scales with the inverse of the noise level (in sqr Hz) and with the square root of the effective length of the data used, counting all detectors separately. Hence these searches are going to be largely offline and do not require the development of the close-to-real-time trigger releases that are so crucial to transient signal searches. EM-follow-up observations of the sources of a continuous wave signal would surely take place if we detected a CW signal. However for a standard CW signal such follow-up study is likely not going to prove so crucial for enhancing the detection confidence, and could likely be carried asyncrounously with respect to the GW observation. So for this year EM follow-ups are still not going to be a focus area for the non-transient signals searches.

In the past year the CBC and burst groups have worked in teams that take responsibility for broad scientific topics. While the four search groups continue to maintain overall control and responsibility, we expect that the new teams will play a significant role in a healthy cross-group dialogue and promotion of good science. Any search carried out within either the CBC or burst group should also be discussed within the relevant team to ensure that it is tuned optimally with respect to the broader scientific context and/or more searches connected to similar scientific questions are considered jointly and planned in the same paper, when it makes sense. The burst group has identified 8 science focus areas: all-sky all-times searches, GRB triggered searches, joint gw-high energy neutrino searches, supernovae triggered searches, GWs as probes of neutron star physics, other EM counterparts and follow-up observations, binary black hole searches and finally signals from non standard sources. The CBC group has identified the science focus areas based on the binary components masses: neutron star-neutron star binaries, neutron star - black hole binaries, stellar mass black hole binaries and intermediate mass black hole binaries.

These science focus areas map directly on the searches and observational papers that we want to write. In practice, in order to support such goals all groups need to develop specific capabilities and tools. Examples of such capabilities and tools, common to both burst and CBC searches, are good data-quality information, reliable event significance assessment and parameter and rate estimation. Additionally the CBC group requires accurate waveforms. Close to real-time trigger generation capabilities are also among the science goals for all transient searches and these require a non trivial data management infrastructure and streamlined analysis pipelines down to the very final significance assessment steps. The development of such capabilities and the testing and qualification of our searches in turn requires that we can carry out large scale simulations of our searches including fake signal injections. All these tools need to work coherently to contribute to the main focus goals.

A certain amount of independent and somewhat unfocused research is of course important since breakthroughs often emerge unexpectedly from investigations. Surely the most difficult task for the chairs of the search groups is to strike the right balance between focus/goal - driven research and scientific liveliness and freedom of research in the Collaboration.

The LSC and Virgo will not release information on interesting GW triggers to the broad scientific community before the first few (4) GW detections. As a consequence the LVC have the responsibility to set up a follow-up program governed by MOUs with appropriate EM facilities to do this. Participation to this program will be open to any scientist who can fruitfully contribute and the process has begun with a call for letters of interest in this effort (https://www.lsc-group.phys.uwm.edu/webcommphp/science/GWEMalerts.php).

In order to further focus the work on the scientific deliverables (papers) in the advanced detector era, the search groups have been asked to identify and describe such deliverables, and describe what we still need to put in place in order to achieve such goals. Each search (scientific deliverable) should have its own document and all these documents are available at https://wiki.ligo.org/DAC/APT. There is a part in these documents that should be updated every six months: it is the one that tracks progress through a set of milestones. Every proposal is read by the DAC chairs and by at least two group chairs (excluding chairs of the group where most of the effort happens), who provide feedback and suggest changes aimed at clarifying things. We imagine that these proposals will be part of this white paper, and will be the place where the reader will see, in practice, how the various efforts come together.

2 Characterization of the Detectors and Their Data

A thorough characterization of the LIGO, Virgo, and GEO600 detectors and their data is a critical requirement for making confident detections in the coming years. This includes the identification and reduction of (stationary, non-stationary, transient and periodic) noise coupling into the detector outputs, accurate and stable calibration and timing, and careful monitoring of the interferometer state.

In the years 2013-2014 the Advanced LIGO instruments will be transitioning from installation and testing of the first subsystems, to integration and operation of more complete systems such as the half-interferometer and dual-recycled Michelson Interferometer [2]. The Virgo collaboration will continue its installation of Advanced Virgo. During this period GEO600 will be the only operational interferometric gravitational-wave detector. It will provide single-detector astrowatch coverage while undergoing incremental upgrades in the GEO-HF program. Meanwhile nearly all gravitational-wave searches on data sets from the initial detectors will be completed.

This will be a particularly important era for detector characterization. Noise transients, upconversion, spectral features and lines had important negative impacts on searches for gravitational waves with the initial detectors. A collaboration-wide effort in detector characterization is required to ensure that these disturbances are mitigated in the advanced detectors to allow and hasten the first detections. Detector characterization efforts should be prioritized on work that directly i) improves the sensitivity, calibration, or performance of the detectors or ii) improves the sensitivity or false alarm rate for LSC-Virgo gravitational-wave searches.

In many ways it makes sense to coordinate detector characterization efforts and share experience between LIGO, Virgo and GEO600. We describe in Subsection 2.1 the LSC-Virgo-wide priorities for the characterization of the detectors and data. However these detectors also have important differences in topologies and technologies and are at different stages of their installation schedules, so they require detector-specific planning. The detector characterization efforts specific to the LIGO, Virgo, and GEO600 are described separately in Subsections 2.2, 2.3, and 2.4, respectively.

2.1 LSC-Virgo-wide detector characterization priorities

The LSC and Virgo detector characterization groups have the following overall priorities for 2012-2013.

- **Characterize Advanced LIGO, Advanced Virgo, and GEO-HF subsystems as they come online.** In the past much of our characterization has been done by looking at artefacts in the detector outputs and trying to reconstruct their cause from the thousands of interferometer channels. Characterizing the systems during their construction gives us the unique opportunity to identify and fix issues with glitch and noise performance, channel signal fidelity and robustness, etc., and maximize our knowledge of the systems at an early stage and in simpler pieces. This will serve a dual role of training a wider pool of scientists who are familiar with the instruments. Both should lead to better understood and more sensitive detectors and expedite detections. However it should be noted that the actual coupling of noise to the detector output signals can only be investigated once the interferometers are assembled and the first locks have been achieved.

- **Improve upon the physical environmental monitoring (PEM) systems from the initial detectors.** The PEM systems are critical for identifying and removing noise couplings as well as following up detections, e.g. by ruling out external causes for putative signals. This includes instrumenting the sites with sensitive devices placed in key locations, calibrating the output of all sensors into physical units, evaluating the levels with which external disturbances couple into the detectors and their subsystems, and thorough documentation.

- **Strengthen the relationship between detector/commissioning scientists and detector characterization scientists.** It is important to have a strong relationship and effective communication between the instrumentalists/commissioners and the detector characterization groups in order to identify and quickly resolve data quality issues and expedite the time required to achieve high quality data. This can be achieved through cooperation on noise investigations, engineering runs, glitch shifts, and regular communication in both directions about issues with data quality and artefacts that are observed. This can also be improved by more direct involvement by commissioners in the detector characterization groups.

- **Develop and implement the infrastructure needed to ensure high data quality in low latency.** Low-latency and accurate knowledge of calibration, detector state, data quality flags, vetoes, timing, etc., will allow us to better assess the data quality of the advanced detectors and will enhance the science that can be done with low-latency searches by improving false-alarm rates and confidence.

- **Provide data quality support for all ongoing collaboration gravitational-wave searches.** In 2013-2014 we expect a small number of searches to continue on the collected S6/VSR2,3,4 data sets. We will work to ensure that these have accurately calibrated, well-understood, and high quality data.

- **Press for a breakthrough in glitch reduction/veto techniques.** Searches for short duration and/or unmodelled gravitational-wave signals with the initial detectors were limited by a background of transient noise glitches present in the instrumental outputs. A breakthrough is needed to ensure that the sensitivity of these searches will be limited by the stationary noise of the detectors in the advanced detector era. To identify more effective techniques we will reuse the S6/VSR2,3,4 data sets to test diverse inputs and more advanced algorithms. Our goal is significantly higher efficiency (>90% after current category 3 data quality) for low additional deadtime (≈10%).

- **Document the detector characterization work that had an impact on initial detectors and searches.** This includes contributing to analysis papers, completing an overview detector characterization paper for LIGO S6, and GEO S6 (following the lead of the Virgo VRS2,3 paper [38]), and completing papers describing methods that had an impact on detector/search sensitivity. This documentation should help us better assess the work that has been done and identify areas to improve for the advanced detector era.

- **Develop/implement improved detector characterization tools, techniques, and figures of merit.** A number of tools that were successful during the initial detector era can be improved upon. This includes continued work on the GEO, LIGO, Virgo collaborative summary pages, veto algorithms such as hveto, use-percentage veto and bilinear-coupling veto, figures of merit that give a truer indication of the range of the instruments taking into account non stationary and non Gaussian behavior, systems to record vital information about channels and their status, data viewing tools, and spectral features, coherence, and line monitors. Many of these improved tools can be deployed at GEO600 to test how they work on an operational detector and to interact with commissioning.

- **Transfer characterization knowledge and experience into automated tools and machine learning approaches.** A long-time goal of detector characterization is to take more of what we have learned and encode it in automated tools.

- **Validate and test new tools, and data, prior to using them in production mode.** The development of new tools is important for achieving the goals of detector characterization. To make the most efficient use of these tools they should be demonstrated to work effectively on test data sets. For example, glitch identification tools should be shown to effectively identify and accurately parameterize known or injected glitches, data quality and veto flags should be shown to have a significant beneficial effect on data with known artefacts, etc.

2.2 LIGO Detector Characterization

2.2.1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is an NSF-funded project with the mission of directly detecting gravitational waves from astrophysical sources. LIGO has completed six periods of scientific running, S1-S6, over the past decade, amassing several years of coincident observation with its detectors at design sensitivity, and often in coincidence with its international partners GEO600 and Virgo. LIGO is in the midst of a major upgrade, called Advanced LIGO, that will increase the strain sensitivity of each interferometer by more than a factor of 10 and the volume of the universe observable by gravitational waves by a factor of 1000. Advanced LIGO is expected to make the first gravitational-wave detections and begin an era of gravitational-wave astronomy.

The LSC detector characterization group [1] directly supports LIGO's mission because a thorough characterization of the detectors is required to confidently detect gravitational waves. Gravitational-wave searches require accurately calibrated data with precise timing. The collaboration's ability to make detections and the level at which upper limits for gravitational-wave emission are set depend critically on detector performance characteristics, such as the overall level of the noise-limited detector spectrum, the probability distribution of transients in the detector output, the degree to which the noise components are stationary, and lines and features that are present in the data. Detector characterization is also an important aid to the commissioning process. Characterization efforts identify issues and provide clues to commissioners, who use these to improve the instruments.

Detector characterization is carried out by a variety of scientists focused on different problems. Commissioners operate at the cutting edge of detector characterization, modifying the detector systems to increase their performance in terms of noise, lines, and robustness. Their investigations may focus on interferometer-based detector characterization, such as investigation of noise sources, lines and features, and environmental disturbances. Members of the analysis groups also make important contributions to detector characterization. They often direct their efforts toward impediments to astrophysical searches, such as coherent or accidentally coincident glitches that pollute compact binary and burst searches, features that could blind searches for periodic or stochastic background sources, or wandering line features that could mimic a pulsar.

During intense commissioning, it is difficult to evaluate the long-term performance of the instruments. Science and engineering runs serve as testing grounds for interferometer stability and for rapid communication between commissioning, detector characterization, and data analysis groups. As experience has accumulated, tools to evaluate the search backgrounds and instrument stability have improved and the latency of diagnostic feedback about the noise and transient behavior of the instrument has decreased greatly.

However, even after years of commissioning and detector characterization the data recorded for scientific analysis contains unforeseen artefacts that decrease the sensitivity of or even blind some searches if left unchecked. For that reason, the detector characterization group has a strong effort to identify and remove non-astrophysical artifacts from the recorded data. For transient searches this is done using data quality flags and vetoes. For periodic and stochastic searches, times and/or specific frequency ranges are identified and removed from the analyses. These efforts have led to improved upper limits in the searches performed to date.

As new artefacts are found, new characterization methods are developed. If the artefacts persist, the group works to automate the relevant methods for more rapid detection of problems. For initial LIGO, the online monitoring systems included the Data Monitoring Tool (DMT)[4] with a number of targeted monitors, the controls system software (EPICS)[5], and search-oriented monitors such as the trigger generators Omega [6] and KleineWelle [7] for the burst search, and daily iHope [9] for CBC search, as well as a variety of customized tools written in e.g., python, C++, and Matlab. It also included a human element, namely the attentiveness and active data exploration by interferometer operators and scientific monitors (scimons). For the advanced detector era, we plan to build upon this experience, automating and adding straightforward improvements to what worked, and developing new strategies to address issues that were encountered.

The LSC Detector Characterization community has a broad membership, including full-time commissioners, full-time data analysts, and many in between.The DetChar working group concentrated most of its effort in the initial detector era on providing characterization tools and monitors and on providing characterization (most directly data quality flags and vetoes, and diagnostic information) of interferometer data in science runs for astrophysical analysis. Every search working group has active DetChar members, and information flows in both directions, to mutual benefit. *The Det Char group has few members exclusively or even mostly dedicated to the group. This brings a beneficial diversity of ideas, but reduces efficiency with respect to full-time members. A goal of our group is to recruit more members that commit a substantial amount of their time to the group. The current LSC-Virgo MOU includes a less-restrictive publication policy for detector characterization work that supports this goal by allowing short author list publications on limited sets of interferometer data.*

In the following subsections, we describe the requirements on detector characterization for our collaboration to achieve its scientific goals during the advanced detector era (2.2.2), the LIGO-specific priorities for detector characterization (2.2.3), status and plans for data run support (2.2.4), commissioning support (2.2.5), and software infrastructure (2.2.6), as well as the activities and priorities of the different working groups, noise transients (2.2.7), spectral features (2.2.8), calibration (2.2.9) and timing (2.2.10).

2.2.2 Overview Requirements to Achieve aLIGO Science

Advanced LIGO is expected to begin scientific data collection in 2015 and perform observations of increasing sensitivity and duration in the years that follow [3]. The overarching goal of the LIGO detector characterization group over the next few years is to ensure that Advanced LIGO data is of high enough quality and accurately calibrated to maximize the scientific information that can be extracted from the first Advanced LIGO observations - especially gravitational-wave detections. The following requirements for detector characterization in the advanced detector era are driven by the science requirements of the search groups described in further sections of this whitepaper. Here we present the requirements but do not get into the specifics of how they will be addressed until Subsection 2.2.3.

1. **Provide accurate calibration, timing, and state information for the gravitational-wave channels.** It is imperative for confident detections and deep searches that the gravitational-wave channels for Advanced LIGO are accurately calibrated into physical units (strain) and have precise timing, and that the state of the detectors is accurately recorded (e.g. to signal what data should be analyzed and the expected quality of that data).

2. **Remove egregious data quality problems in the detectors.** Neutron star binary coalescence signals are the most likely source to be detected by Advanced LIGO. Owing to their minutes-long waveforms, binary neutron star (BNS) searches are expected to be relatively robust against short and quiet noise transients. However, loud transients or dramatic non-stationarity could complicate or blind a potential detection. To maximize detections, BNS searches require that egregious data quality problems are identified and removed in the detectors.

3. **Provide a well-understood and documented physical environmental monitoring system.** Among the most important requirements for both improving the detectors and following up potential signals

is a well-monitored and understood physical environment at the detector sites. Only a suite of well understood environmental monitors will allow us to say with confidence that potential coincident signals did not arise from anthopogenic, terrestrial, atmospheric, etc, external effects.

4. **Remove the majority of short duration transients in the detector outputs.** The initial LIGO detectors exhibited a high rate of non-Gaussian noise transients (glitches). These acted to increase the background in (and therefore decrease the sensitivity of) searches for shorter duration, less well modeled waveforms such as burst sources, and higher mass CBC systems (BHBH and NSBH). In addition, noise transients may effect parameter estimation for BNS detections. If Advanced LIGO has a similar glitch rate, these searches will require a significant reduction (possibly $> 90\%$ of single-detector noise transients above SNR 8). The best way to achieve this is through mitigating noise sources in the detector, which can be achieved through early characterization and closely working with commissioners. However, improved data quality products such as flags and vetoes will also be required.

5. **Remove lines or spectral features that limit continuous-wave and stochastic background searches.** For continuous waves and stochastic searches the detector characterization group should identify and help remove lines or spectral features, prioritizing those that are coherent in the instruments and/or occur at frequencies targeted by the searches.

6. **Provide high data quality with low latency.** Providing this information is necessary to carry out sensitive low-latency searches, including searches with electromagnetic followup. High data quality includes accurate calibration, timing, and information about the interferometer state, as well as the automatic removal of as many data artefacts as possible.

2.2.3 Priorities for LIGO Detector Characterization

In this section we set priorities for detector characterization during the upcoming year by choosing activities that will ensure that the requirements listed above will be met by the first aLIGO science run in 2015.

1. **Characterize the Advanced LIGO subsystems as they are brought online.** [*Supports requirements 2,3,5 above.*] We will investigate the data quality of Advanced LIGO subsystems as they are deployed. Each subsystem will have a detector characterization “lead" responsible for coordinating investigations for that subsystem. Investigations will include,
    - Documenting information about auxiliary channels, such as their name, meaning, sample rate, dates of recording, physical location, and calibration function and units.
    - Checking the fidelity of the recorded signals. For example, that each channel is recorded above ADC noise over its useful frequency range, and that the signals do not saturate during nominal operation.
    - Recording accurate and authoritative information about the state of each subsystem and of the entire interferometer.
    - Identifying artefacts (glitches, lines, features) in the key channels for each subsystem, and helping to find their exact origins and reduce them.
    - Contributing to the “noise budget" (a tool for understanding of the various noise contributions) for each subsystem.
    - Performing deeper and more specific investigations on the subsystems such as those listed in Section 2.2.5.

This work is aimed at identifying and fixing problems early - which is preferable to waiting for the first locks of the full interferometers in ca. 2014 and then trying to sort the myriad of artefacts present in the detector output back to their individual sources. This "ground up" approach is, we believe, an improvement over the "top down" approach that was typically used in Initial LIGO. It allows each subsystem to be carefully studied and "checked off" as well-behaved and understood during commissioning, which should result in a much cleaner output once the complete detectors are made operational. It will also train a larger number of detector characterization group members who are familiar with the individual subsystems. It should be noted however, that many data quality issues, such as complicated noise couplings, will only become apparent when the full interferometers are operating so we expect characterization in the later phases of commissioning and running (2014 and beyond) to also be very important.

2. **Upgrade the LIGO Physical Environmental Monitoring Systems for Advanced LIGO** [*Primarily supports requirement 2, but supports all goals above.*] The LIGO PEM system must be taken apart for aLIGO installation, affording an opportunity for redistribution of the sensors, system upgrades, and channel renaming based on lessons learned in initial LIGO. In addition, changes associated with Advanced LIGO will require redeployment of sensors to new coupling sites, installation of new sensors in new rooms and on new vacuum chambers, as well as redeployment of sensors made redundant by seismic sensors in the active isolation system. Plans for this PEM upgrade are laid out in the aLIGO PEM Upgrade document [8]. Associated with the upgrade are a number of hardware and software projects for LVC members, detailed in the upgrade document and listed here.

   Hardware

   - power meters for roof radio monitors
   - RF monitors at the main modulation frequencies for inside the LVEA
   - an RF spectrum monitoring system that sweeps from a few kHz to a couple of GHz
   - 1 Hz to 10,000 Hz RF monitor
   - an electrostatic field monitor
   - several coil magnetometers
   - a sky observation system
   - an upgraded cosmic-ray detection system
   - infrasound monitors

   Software

   - updated dead channel monitor
   - channel snapshots
   - statistical channel monitor
   - channel location and calibration web page
   - direction to source finder using propagation delays
   - code to search for "pulsars" in selected auxiliary channels using modified all-sky and/or specific pulsar search code
   - modified stochastic code to search for signal between aux channels
   - significance figure of merit for Carleton DARM-aux coherence line monitor
   - 1Hz (and other) comb monitor

3. **Participate actively in the Advanced LIGO engineering runs.** [*Supports all requirements above.*] In the upcoming years the LIGO Scientific Collaboration plans to have a series of engineering runs to test important software infrastructure, establish procedures for software release/maintenance during aLIGO, perform detector characterization early using real subsystem data, and measure progress of the analysis groups toward key science goals. The duration of these runs and the role played by the real interferometer data is expected to increase steadily from 2012 through 2014. In the detector characterization group we will work toward having key investigations completed and critical software (calibration, timing, state, data quality monitoring, etc.) implemented and tested in these engineering runs. We expect these periods will provide excellent opportunities to observe the longer term stability of the interferometer and its subsystems than is often possible during heavy commissioning.

4. **Develop improved methods to uncover the causes of and veto noise transients.** [*Supports requirement 2,4,5 above.*] During S6 we had some success using burst and CBC search algorithms [7] to parameterize glitches in the detector outputs and a large number of auxiliary channels and then using automated tools such as UPV [12] and hveto [11] to generate "veto" segments based on statistical correlation. To achieve requirement 5 above we will need to improve upon the performance of these algorithms. Promising avenues of research that should be followed are:

    - Improved glitch parameterization that works well over a broad parameter space in frequency, duration, and SNR, and runs on the detector strain channels and all high-sample-rate auxiliary channels.
    - Investigations of the utility of other physical inputs (than glitch parameters) as an indicator of glitches in the detector output. For example mean values or RMS of slow auxiliary channels (e.g. alignment).
    - Extending veto techniques by straightforward refinement, or using methods such as multivariate classifiers, bilinear coupling indicators, etc.
    - Data mining techniques that identify connections between times subject to glitches and the values of a wide array of control and monitoring signals. This will allow the exploration of the possibility that saturation of error signals in control systems causes extra sensitivity to environmental disturbances, as well as other mechanisms that can cause time-varying couplings between control channels and the gravitational wave output.

    Further discussion of this goal is in Section 2.2.7.

5. **Validate and test new tools and data prior to using them in production mode.** The development of new tools is important for achieving the goals of detector characterization. To make the most efficient use of these tools they should be demonstrated to work effectively on test data sets before being used broadly by the collaboration. Two key examples are, i) glitch parameterization tools should be shown to effectively identify and accurately parameterize known or injected glitches and ii) data quality flags and veto segments should be shown to have a significant beneficial effect on data sets containing known artefacts.

6. **Provide data quality support to search groups for remaining S6 analyses and engineering run analysis.** It is important that the detector characterization group provide support for data quality issues in all remaining Initial LIGO analyses, and support analyses that are performed on the Advanced LIGO engineering runs.

7. **Continue to document the detector characterization work that has had an impact on the LIGO detectors and searches.** This includes contributing to S6/VSR2,3 analysis papers, writing an overview

detector characterization paper for LIGO S6, documenting the PEM system, and completing papers describing methods had an impact on iLIGO or early aLIGO data.

8. **Characterize and reduce low-level correlated noise.** [*Supports requirement 5 above.*] This includes studies to answer the question, is there any correlated noise hidden below the uncorrelated noise curve that could affect stochastic searches? An important example of such a noise source are Schumann resonances (described in more detail in Section 6), electromagnetic resonances of the cavity formed between the Earth's surface and the ionosphere that are excited globally by lightning strikes.

2.2.4 Data Run Support

For most of the engineering runs and all of the science runs, LSC policy has been to staff the control rooms around the clock with one LIGO Lab operator and at least one LSC scientific monitor per observatory. The scientific monitors are responsible for monitoring the quality of the data, carrying out investigations, and making decisions on when to take science data *vs.* when to make adjustments / repairs, in consultation with the operator on duty and the local run coordinator, when appropriate.

The LSC is currently in the process of critically evaluating the performance of the scientific monitoring system and is develop a proposed plan to be tested in upcoming engineering runs and implemented in the Advanced LIGO science runs [13]. Two key goals that are emerging for this program are, i) to help increase the scientific output of the LIGO detectors, characterized by the product of searched volume and time, particularly by maximizing the amount of observing time available to searches by running as often as possible (as other astronomical observatories do) and ii) to form a bridge between the LIGO sites and the broader LSC to maximize the astrophysical potential of the LIGO detectors.

Besides human resources, working together with the search groups and the commissioning group to identify and display key figures of merit and developing and tailoring daily summary pages of the observatory data will also be key support to data runs - helping to quickly identify issues and inform data run decisions.

Another important aspect of data run support is injection of simulated astrophysical signals into the detector hardware to validate data analysis pipelines with high confidence. LIGO Laboratory and LSC scientists have provided the human resources to set up the injection infrastructure and carry out the injections. We will use the experience with initial LIGO, including the results of “blind" injection exercise, to plan for future runs.

Although there will be no science runs in the upcoming year, there will be engineering runs. We will use these periods to test data monitoring systems and interactions with the searches, and to gain an early understanding of the artefacts in each of the subsystems. This will require a close communication between commissioning teams and detector characterization groups, a relationship we would like to foster.

2.2.5 Commissioning Support

Heavy commissioning of Advanced LIGO is expected to begin and continue over the next several years. This commissioning is the primary way for the completed Advanced LIGO detectors to improve in astrophysical sensitivity and robustness over time. The detector characterization group needs to work more closely with the commissioning team over the next few years. Below are two main areas for joint work between characterization and commissioning groups.

Detector Commissioning and Characterization Projects Commissioners have spelled out a list of high priority projects that should be done by LSC detector characterization folks over the coming year. An abbreviated list of projects is below, and the full list is available on the DetChar wiki pages [14]. These projects are aimed at using the resources in the detector characterization group to solve a problem with LIGO that might not get solved otherwise due to limited human resources in the commissioning group.

- Set up daily summary pages that display the key figures of merit of the instrument and are iterated with commissioners.
- Measure suspension crackle noise by demodulating strain energy at bounce/roll frequencies.
- Create a monitor for mechanical modes of the optics or suspensions that can be excited and saturate some of the electronics, corrupting data.
- Create an early warning system for laser death and understand what the timescales involved are.
- Help identify the reasons for losses of interferometer control (lock). This will help improve stability and give longer locked periods for analysis.
- Track the test mass scattering and absorption to check whether the optics or their cleanliness are degrading over time.
- Create an estimator of the test mass thermal state to improve the accuracy of the thermal compensation system and reduce the down time caused by warming up after lock acquisition.
- Create an early warning system for trains, earthquakes, and traffic to trigger changes in the control state of the interferometer that will be more likely to ride out these disturbances, decreasing down time.
- Investigate the anomalously high coupling of acoustic noise to hardware in the vacuum chamber that houses the output modecleaner.

Subsystem characterization Characterization of the Advanced LIGO subsystems is Priority 1 from Section 2.2.3 because we think this will help us identify issues (such as with glitches, noise lines and robustness) early so that they can be fixed and will lead to a deeper understanding of the detector systems among the detector characterization group leading to better characterization and cleaner data. Strengthening the relationship between the detector characterization and commissioning teams is very important for these goals.

To foster this, we have set up an organizational scheme based around a “Subsystem Matrix” [15] that lists each subsystem (for example, the Pre-Stabilized Laser, Seismic Isolation, Data Acquisition System) as horizontal rows, with vertical columns for the projects/tasks that should be accomplished for each (for example, documenting the meaning of channels, monitoring their transient behavior, and checking signal fidelity). One person, a lead/liaison is assigned to each subsytem, as the primary person of contact from detector characterization, responsible for communicating with the commissioning experts for that subystem and organizing and reporting on the characterization work. In addition, there are lead/liaisons for the projects, who help define and are the primary contact for the work that should be done to complete that project.

2.2.6 Software Infrastructure

Over the years, many tools have been developed for on- and off-line monitoring of detector status and data quality. Many of these software tools (EPICS[5], DTT[10] and DataViewer) are used interactively in the Observatories’ control rooms by operators, commissioners and scientific monitors, and have proved to be essential to operations and commissioning. These tools were developed by the LIGO Laboratory, and we expect these tools to be maintained, and improved when appropriate, for Advanced LIGO operations.

The Data Monitoring Tools system, or DMT[10], is used as a background-process environment for continuous monitoring. The DMT system provided many critical functions in S6, including the online production of calibrated strain files that are were used for low-latency analyses, online production of data quality information that was used for selecting appropriate data to run on and vetoing noise transients in those analyses, and continuous graphical monitoring of the data and the environment displayed in the control room. Although programs used by the DMT system were written by scientists in many different institutions, the maintenance of the infrastructure is done by the LIGO Laboratory.

Data quality monitoring involves reviewing the results produced by monitors such as those run in DMT, veto selection programs such as hveto [11] and UPV [12], noise transient monitoring, coherence and line monitoring, results of data analysis such as search background, and other scripts running in the LIGO Data Grid clusters at the Observatories. This review is done continuously during science runs by scientific monitors at a basic level, and periodically at a deeper level by members of the Glitch and Spectral features subgroups. These investigations result in the diagnosis, identification, and sometimes fixing of artefacts in the gravitational wave channel, which reduce the background for the searches of astrophysical signals in the data. For Advanced LIGO we are working to bring all of these types of monitors together on a single easily digestible page (with many sub-pages) for each detector, called a LIGO summary page (with GEO and Virgo pages available from the same system).

The DetChar group compiles information from its investigations to create a repository of data quality (DQ) information for each run. The information is used to form time intervals which are flagged with data quality flags, which are incorporated into a database (which also has the information on which times are in nominal science mode). The database can be queried by the astrophysical search programs, as well as by members of the group diagnosing problems in the data. The database infrastructure was first used in S5, and was significantly revamped for S6 by the LSC Software Working group (7). This resulted in a reliable system where flags are introduced online by well tested DMT monitoring programs, and offline by the DetChar group and by scimons. For aLIGO we plan to move monitoring of critical state information of the interferometers and their subsystems to the front-end systems. This will enable the production of low-latency and authoritative state information that can be used automatically by searches, and downstream monitors.

For detector characterization it is important that collaboration members have easy and reliable access to the LIGO data, including the gravitational wave channels and the many auxiliary channels (and their archived trends). For most of the initial LIGO era access to LIGO data from outside the observatory control rooms required signficant effort - and this was an impediment to engaging more collaboration members in detector characterization. This situation was greatly improved in 2010 with the LIGO Laboratory's development of a secure network data server, NDS2. This system now reliably serves raw, archived, and trend data, and is robust enough for use by the entire collaboration. However, because Advanced LIGO is significantly more complex than initial LIGO, it will have many more channels, and in the era leading to first detections demand for served data will be greater. It is critical for detector characterization work in aLIGO that NDS2 be supported to reliably serve all raw, archived and trend data available on frames to a large number of users.

For Advanced LIGO we also require data viewing and signal processing tools to read the data served by NDS2 and make a variety of plots or results ranging from quick looks at timeseries and spectra to more complex analyses. The tools currently under active use and development are the Matlab-based graphical user interface LIGO Data Viewer, ligoDV [17], a script-based Matlab interface, mDV [18], and a python interface to the NDS server, pynds. Starting in 2011 a new web-based data viewer, ligoDV-web (`ldvw.ligo.caltech.edu`), was developed. This service has made it possible to access LIGO data through a web browser on your desktop, laptop, tablet or smartphone, and only requires users to have a valid ligo.org username and password for authentication.

Despite the critical importance of Detector Characterization, there are only two collaboration members with near full time dedication to detector characterization software (one dedicated to NDS2 and DMT, and another dedicated to ligoDV and ligoDV-web), and only a few other members partially dedicated to developing and maintaining software tools. To thoroughly characterize the more complex Advanced LIGO detectors and enable the first detections, the detector characterization group requires a more robust software infrastructure and human resources to support it.

Software priorities This section describes priorities for detector characterization software work over the next few years. In general we want to build on the successful software infrastructure from S6 and expand it to meet the demands of searches in the Advanced detector era. These activities will be coordinated with the Software Working Group, as described in Section 7.

1. Implement and test glitch parametrization software that can run online and continuously on the detector output and auxiliary channels and generates output that is improved (in sensitivity, particularly at low frequencies, SNR and frequency accuracy) with respect to the triggers that were produced in S6. Prepare to process hundreds of fast channels per detector from 1Hz to 6kHz. In order to make this information easily accessible by other characterization tools, adopt the common trigger handling format defined in T1300468 [16] for the upcoming engineering runs.

2. Implement a LIGO daily report webpage monitoring system inspired by the GEO summary pages.

3. Develop and implement Online Detector Characterization (ODC) channels to be deployed in the aLIGO front-end systems that will monitor key aspects of the interferometers and their subsystems and provide critical and authoritative information about the interferometer state.

4. Continue development of new and improved Channel Information System (CIS) `cis.ligo.org` containing channel names, sample frequencies, editable descriptions, links to appropriate subsystem models, and other information.

5. Automate and improve upon current data quality flag and veto segment performance validation tools. For Advanced LIGO these should be capable of running daily (and on longer timescales) for all data quality and vetoes and report individual and cumulative efficiency, deadtime, used percentage and safety with respect to hardware signal injections.

6. Improve the current dead channel monitor with a lower false alarm, integrated reporting, and more direct ties to the segment database. The LIGO detector uses thousands of auxiliary channels to validate instrumental behavior and to reveal environmental or instrumental disturbances coupled to the gravitational-wave (GW) strain channel. This information is invaluable for identifying excess detector noise and to help reduce false candidate events in gravitational-wave searches. However, the associated sensors can become faulty or disconnected. Hence, commissioners require having a diagnostic tool for monitoring auxiliary channels. The utilities should include locating a malfunctioning channel, graphic information of channel's time series and spectral data, and spectral change. In addition, since the GW strain channel can be affected by various band-limited environmental disturbances of non-astrophysical origin, a monitoring tool providing band-wise information is required. The detector characterization group will fully develop and test such a tool during the next year.

7. Produce software to monitor the first subsystems of Advanced LIGO that will form the foundation for data quality flags in the first runs.

8. Continue development of the LIGO segment database to increase input and output speed, robustness and to improved user interface tools.

9. Develop a new trigger database appropriate for the storage of short-duration veto information. This should be able to store parameters such as central time, duration, central frequency and SNR.
10. Continue development of NDS2, and data access/viewer/processing tools such as ligoDV, ligoDV-Web, pynds, to ensure easy and reliable access to LIGO data and standard signal processing techniques for detector characterization.
11. Continue refinement of veto production algorithms and test these improvements on aLIGO subsystem data.
12. Migrate data quality and veto flags that proved useful in S6 and are likely to be useful in Advanced LIGO to on-line production.
13. Maintain appropriate reduced data sets for Advanced LIGO to be used for detector characterization and for data analysis. This includes data from engineering runs.

2.2.7 Noise Transients

The largest detector characterization subgroup, the Glitch Group[19], carries out studies of interferometer noise transients, or “glitches”. Composed of experimentalists and analysts, the working group has broad expertise, and its work is closely coupled to the burst and CBC searches.

The goals of the Glitch Working Group are:

- To identify the times of brief transients in the data taken during engineering and science runs that will affect the astrophysical searches.
- To investigate the causes of these transients using information from auxiliary instrumental and environmental channels and other information such as logbook entries.
- To work with commissioners and experimentalists to confirm the suspected causes of transients and attempt to mitigate them by changes to the instrument.
- To produce data quality flags or other information that can be used by the astrophysical searches to reduce the effect of any transients that are impossible or impractical to mitigate.
- To provide information to experimentalists and builders of future detectors to achieve interferometer noise that is stationary and Gaussian.

In the years before the first advanced-era science runs, there will be short engineering runs dedicated to studying the data quality of the different Advanced LIGO subsystems as they are installed. This activity began in 2012 with the pre-stabilized laser, which was characterized during Engineering Run 3. Future runs will involve the input mode cleaner, suspensions, seismic isolation, and the Dual-Recycled Michelson Interferometer test at L1. We expect, with the LIGO Laboratory’s help, to take full advantage of the possibility to exercise data monitoring tools, as well as get an early understanding of the artefacts in each of the building blocks of the very complex gravitational wave detectors.

The priorities for the coming year are:

- Participate in commissioning of the aLIGO subsystems. Identify glitches in subsystem channels that would/will affect the interferometer in future science runs, with special focus on rare glitches.
- Participate in engineering runs, including staffing glitch shifts during times designated for intensive characterization of the instrument. When instrumental data is used as a fake gravitational wave channel, provide data quality information for the astrophysical searches on the fake data.

- Automate production of graphical visualization of the data products needed for evaluating data quality and identifying transients. Work with commissioners to configure these plots so that the most important channels and information are emphasized. The automated plots should be useful to commissioners and also the primary tools used for glitch shifts.
- Run burst-like searches on many auxiliary instrumental and environmental channels in real time. Improve these searches, their tuning, and their interoperability with data quality tools to provide the most useful information to glitch hunters.
- Devise improved ways to diagnose problems arising from data acquisition, data sampling and/or imperfect timing in digital control systems.
- Tune and improve currently existing code, and develop new approaches, for finding and diagnosing data quality problems. Test this on S6 data as well as the new data that is coming in.

One of the goals above is to carry out glitch shifts during the engineering runs, similar to the way that glitch shifts were carried out in S6. In that case, a wiki page of useful plots was generated automatically. For each detector site and week of data, a person was assigned to review this page and the electronic logs for data quality / glitch issues and to report on them to the glitch call. Going forward, we would like use the daily summary pages to provide the automated plots which are used for the glitch shifts. The glitch shifts are not anticipated to be run regularly at first, but to occur opportunistically when commissioners request particular concentration on a subsystem or when there is a period of especially interesting data, or running that is relatively undisturbed by configuration changes, during the engineering runs.

Two month test

Glitch identification challenge

The first and foremost goal for the advanced detector eta is to enable the astrophysical searches to make confident detections. This requires a deep cleaning of the background by understanding nearly all of the glitches that are of concern to the astrophysical searches, and either mitigating them or creating data quality flags that identify them with good accuracy. There are a number of sub-goals that will facilite requires better ways to analyze the auxiliary channels that provide information about the state of the instrument and the environment, since it is this information that predicts the occurence of glitches.

2.2.8 Spectral Features

Another working group of the LSC Detector Characterization group is charged with investigating spectral features of the gravitational wave spectral noise density, which is especially important for the searches of gravitational waves from rotating stars and stochastic background. Many of the spectral features are due to environmental disturbances, including seismic activity, high wind, acoustic noise, and electromagnetic interference. Some sources are natural, but many are also anthropogenic, including sources from observatory infrastructure, e.g., nearby motors and HVAC systems. A wide variety of environmental channels have been commissioned and are monitored in initial, enhanced and advanced LIGO, but unusual artefacts typically require detailed on-site investigations and eventually mitigation, work carried out by scientists from the observatories and from LSC institutions, as part of commissioning. Acoustic mitigation has played an especially critical role in lowering interferometer noise floors[23]. The retrofitting of LLO vacuum chambers with feed-forward, hydraulic pre-actuators led to dramatic improvement in L1 duty cycle, allowing the interferometer to ride out the passage of trains without lock loss. Nonetheless, significant increase in gravitational wave channel noise is seen during such a passage and in general during high seismic noise times, due to not very well understood upconversion of the noise into the gravitational wave band (40Hz-6kHz). Environmental disturbances may also, of course, be manifested through linear couplings to the interferometer as direct glitches or lines, for sources with characteristic frequencies in the LIGO band of sensitivity. There have been extensive studies during S5 and S6 to understand better the sources of steady-state environmental couplings, particularly lines; these studies are now extending to advanced LIGO subsystems.

The list of high priority activities related to characterizing spectral features in 2012-2013 are::

- Continue to analyze and investigate noise lines affecting data quality in S6 data, including summarizing frequency line issues in S6 for a data quality paper.
- *Noise budget for subsystems*: Measure the environment about advanced LIGO subsystems to identify periodic signals so as to develop a catalog of potential noise lines that could enter these sub-systems. Conduct noise injection tests to measure the transfer function of different environmental noise sources.
- *List of lines and line monitors in subsystems*: Apply the existing noise line finding tools in order to characterize the noise environment of advanced LIGO sub-systems. Use seismometers, accelerometers, microphones, magnetometers, voltage line monitors and other devices to map out noise, and how it couples into advanced LIGO subsystems. Use existing line finding tools, such as Fscan (a pulsar search code, applied to auxiliary channels), coherence (which calculates the coherence between the gravity wave channel and auxiliary channels), and NoEMI (Noise Event Miner, developed at Virgo).
- *Investigate coherence of environmental channels with the different subsystems*: Use the coherence tool to monitor the coherence between various signals. The Stochastic Transient Analysis Multi-detector Pipeline (STAMP) also allows for the long-term monitoring of the coherence between different channel pairs. These tools will be used to monitor noise signals in subsystems, producing an executive summary for each system. There will also be a need to study non-linear frequency up-conversion of noise; STAMP, as well as bicoherence code, will be used to study up-conversion of noise in subsystems.

As various advanced LIGO subsystems come on-line the software for spectral line identifications and interchannel correlations can be applied; this will serve as a means to identify noise in the subsystems, and prepare the routines for application on advanced LIGO h(t) data when it becomes available.

2.2.9 Calibration

For the LIGO interferometers, *calibration* involves converting data streams from channels that monitor the feedback control loop that maintains the differential arm length into a derived time series that represents the inferred differential arm length variations, h(t), which is normalized to the average arm length, approximately 4000m. h(t) is referred to as *interferometer strain* or just *strain*. The analog and digital filters used in h(t) production are first produced in the frequency domain by the calibration and commissioning team.

Calibration of the LIGO interferometers is a task critical to the success of the data analysis algorithms, and the confidence associated with their results. As such, the LSC created in its bylaws a Calibration Committee, separate from the Detector Characterization group, although there are still many common members and activities. The goal of the Calibration Committee is to provide calibrated h(t) with sufficiently small uncertainities in amplitude, phase, and timing. The current tentative goal is to have maximum calibration errors of roughly 10 percent in amplitude, a few degrees in phase, and about 10 microsecond in timing.

Calibration of a detector is a complex task that involves instrumental hardware measurements, detector modeling, computer programs, and extensive validation and review. The time domain calibrated data is the main data product, and its generation is sufficiently complex that it needs a dedicated team for calibration and another one for review. The Calibration Committee is therefore co-chaired by a time-domain chair and an experimental chair, and includes LIGO Laboratory and other LSC scientists. It works along with a dedicated Calibration Review Committee which provides advice and vetting of this work. The Calibration Committee's results are posted and documented on a web page[31] available to the LSC, and as with previous science runs, will continue to be recorded in the electronic logs, software repositories, and LIGO documents[32].

The scope of the calibration itself was expanded during and after the S5 run to include the timing of the LIGO data. If the interferometer model used for calibration is incorrect, it could skew the timing of LIGO data even if the clock system is working perfectly. See 2.2.10.

Estimation and reduction of the errors in the calibration data products will be a major effort in aLIGO. Towards that end multiple methods of calibration will be used, including a method using auxiliary laser pressure actuation ("photon calibrator")[30] and a method using interferometer laser frequency modulation[33], both of which were used in initial LIGO science runs. Work on the aLIGO photon calibrator subsystem design, fabrication, installation, and commissioning is ongoing, dealing with subtle performance issues, such as the elastic deformation of the test masses resulting from radiation pressure from the photon calibrator beams and forces from electrostatic actuators.

Production and analysis of the time-dependent calibration coefficients is an essential tool for calibration validations. They can be used to estimate the systematic and statistical uncertainties of the calibration as well as the time offset changes. These studies will be continued in the future. Development of on-line tools to monitor the time-dependent calibration factors, and more generally h(t) data quality, is essential.

The Calibration Committee's membership has been augmented in recent years by graduate students and scientists alike from several LSC institutions. Each site will have a dedicated LIGO lab person responsible for the calibration, but the Calibration Committee expects additional manpower of about 3 people per site, on time scales of 6-8 weeks per year, to be necessary to get calibration out and vetted in a timely manner around science runs. This manpower would be in addition to those working on the calibration software pipelines and those maintaining close communication with various aLIGO subsystem groups. This work provides students valuable instrumental training. It would be highly desirable to sustain this broad participation.

In anticipation of the aLIGO science runs we will be creating and maintaining communication channels between aLIGO and other projects' calibration teams and reviewers. In collaboration with Virgo and GEO, the calibration team will also work on improving h(t) generation techniques, and the development of preprocessed h(t) products such as whitened, cleaned, and coherent data streams. Also important is an exchange of ideas about the review process.

The work of the calibration team is currently focused on preparations for the advanced detector era. New independent techniques are being developed to produce h(t) data with second and sub-second latencies (during S6 the latency was 1 minute). These techniques include moving the generation of h(t) to the front end of the interferometer (CDS) and a gstreamer-based algorithm. In addition, online tools to monitor the quality of the data produced on the fly, and the development of pre-processed h(t) products (e.g. whitened, cleaned, and coherent data streams) are being developed.

The front end calibration effort is intended to develop the necessary code to perform time domain calibration on the CDS computers that directly runs the interferometer. This code would be directly embedded in the controls code. This method has the advantage of providing the lowest latency possible as it works directly with the data before it is sent on to be recorded, and can thus be included directly in the recorded frame data. Initially the plan is utilize this capability purely to help the commissioners in the control room as opposed to providing final calibration. However, as it evolves and if it proves to be accurate and robust enough, the final calibration could be moved over from the more traditional calibration methods to utilizing this scheme.

The calibration team is developing a low-latency (sub-second latency) gstreamer-based pipeline for time domain calibration in aLIGO. This will be a robust pipeline with both frame file and shared memory I/O capabilities, thus allowing for the same pipeline to run for both online and offline calibration. The online infrastructure required for the aLIGO gstreamer-based calibration pipeline is under development and was successfully tested during aLIGO's third engineering run. The offline infrastructure for the pipeline is also currently under development and was successfully tested during offline data reproduction after the third engineering run. The calibration team is continuing to develop both the infrastructure required for and the inner-workings of the low-latency aLIGO time domain calibration pipeline, and it will be further tested during the upcoming fourth engineering run and future engineering runs.

2.2.10 Timing

Traceable and closely monitored timing performance of the GW detectors is mission critical for reliable interferometer operation, astrophysical data analysis, and discoveries. For example, (a) timing jitter of digitization of the GW signal could directly contribute to the noise level degrading the astrophysical reach of the LIGO interferometers, (b) coincident and coherent observation using the network of GW detectors is only possible if the absolute timing of the data streams agree within a high degree of accuracy, (c) a network of interferometric GW detectors can only recover both the polarization and sky direction information for a detected event if the absolute timing of their data-streams are known, and (d) multimessenger astronomy with external observatories also require traceable and accurate absolute timing.

The Timing Stability Working Group (TSWG) includes scientists from both the LSC and the LIGO Laboratory. The group shall be responsible for (a.) the availability and diagnostics of timing information and signals provided for various subsystems (e.g., LSC, OMC, etc.), (b.) measuring and documenting the timing performance of mission critical digital subsystems such as LSC and OMC DAQs, (c.) in close collaboration with the Calibration team (also see 2.2.9), the end to end timing and phase calibration measurements of the detectors (e.g., through the photon calibrator[27], characterization of analog modules, etc.), and (d.) the documented review and certification of the physical/software implementation and verification of the availability of precise documentation of timing related parts of mission critical subsystems. While it is quite likely that issues with the timing performance of subsystems are discovered by the timing team, it is the responsibility of the subsystems to address the problem; the timing team is responsible only for the certification that the issue was indeed eliminated.

The construction, testing and diagnostics tasks have already provided fertile ground for undergraduate and graduate student research involvement and diversity in the program is strongly encouraged for the future.

The next challenge in timing diagnostic is long term. Several projects will be executed in preparation of the advanced detector era, such as:

- Further develop and test injection techniques to determine accurate timing through direct test mass excitations
- Augment and expand the capabilities of data monitoring tools related to timing and phase calibration
- Enhance the availability of timing diagnostics capabilities provided for various subsystems
- Measure and document the timing performance of mission critical digital subsystems
- Measure and document the end to end timing and phase calibration measurements of the detectors (e.g., through the photon calibrator, characterization of analog modules, etc.)
- Review and certify the physical/software implementation and verify of the availability of precise documentation of timing related parts of mission critical subsystems

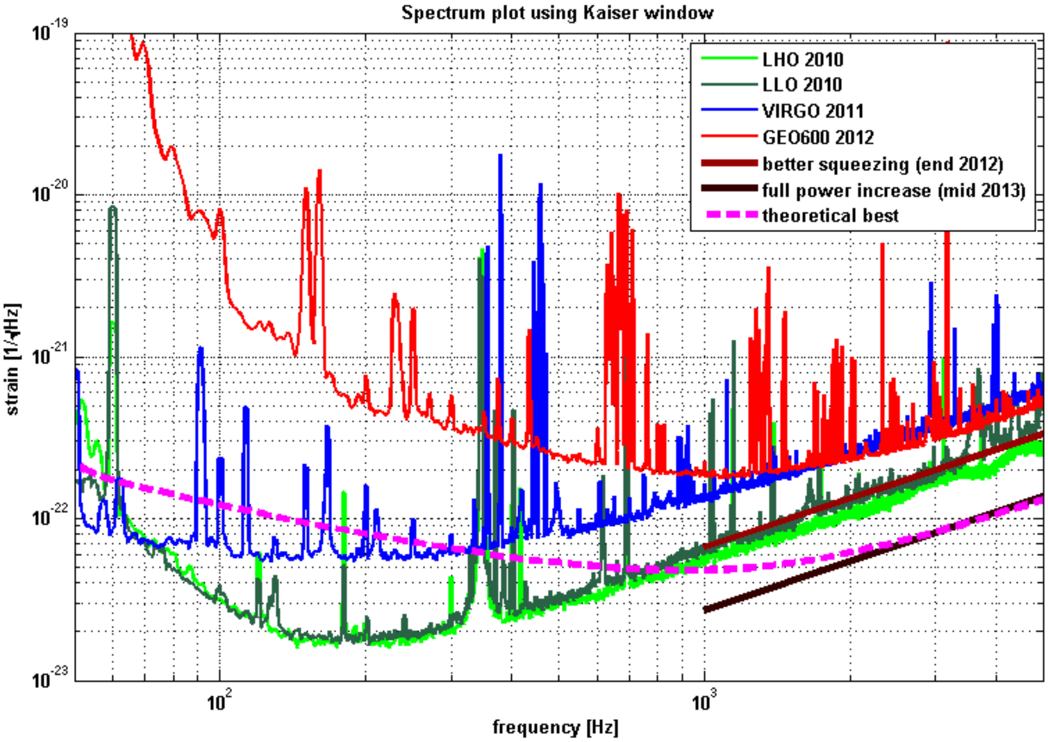


Figure 1: Recent interferometer sensitivities and GEO 600 projections. The improvements to the high-frequency sensitivity due to better squeezing and the power increase scheduled over the next year are depicted by the brown and dark brown guidelines showing only the rising part of the shot noise curve. A more accurate shot noise curve after the two upgrades, combined with the predicted level of thermal noise then results in the "theoretical best" curve.

2.3 GEO Detector Characterization

2.3.1 Introduction

GEO 600 is currently the only operating laser interferometer gravitational wave observatory in the world. Foreseeing this period of single interferometer operation, an upgrade program called GEO-HF was begun in 2008 [34]. This upgrade was designed in an incremental fashion such that the majority of the time can be operated in an astrowatch mode where the interferometer is set to low noise operation for nights and weekends. Figure 1 shows the results of the first phases of this upgrade program along with some projections for the future stages. In the coming years there will be a handful of multi-week long interruptions of astrowatch to carry out installations; otherwise most of the commissioning work will be carried out using short, daytime interruptions. Even when heavy commissioning is occurring, and the interferometer is operating smoothly, we are able to achieve a 70% duty cycle for astrowatch observations.

Aside from this astrowatch role, GEO 600 plays a special role in the gravitational wave research community because of the regime in which its sensitivity lies. Figure 1 shows that GEO 600 now has comparable high-frequency sensitivity to what Virgo achieved in its last science run and will soon be comparable and surpass the last sensitivities of both LIGO detectors in this regime. This sensitivity warrants round the clock operation, when the interferometer is not being used for commissioning purposes, as well as maintenance of this sensitivity to enable possible serendipitous detection of rare, loud events. However, the sensitivity to compact object binary coalescences is approximately an order of magnitude worse than what the LIGO and Virgo interferometers obtained for over two years of science operation. For this type of event, there is no chance of improving the upper limits to the population densities already set by the few-kilometer-scale interferometers. For this reason a balance is struck between data taking in astrowatch mode and carefully scheduled commissioning to improve detector sensitivity. This also provides a degree of flexibility for prototyping new techniques that is not enjoyed at the larger interferometers. Combined with the observational potential which results in the maintenance of the sensitivity, this accessibility gives GEO 600 a special niche in the gravitational wave research community. Taking this viewpoint *GEO 600 can be seen to be the sum of a working detector and a prototype of an observatory.* This brings the advantage of allowing tests of stability and long term implementation of prototyped techniques which cannot be investigated at smaller prototype interferometers where the duration of any given experimental setup is comparatively short.

The primary goal of the GEO detector characterization group is to utilize and maintain the easy access observatory nature of GEO 600 for characterization purposes. This goal has two main facets. The first is to aid in the commissioning process to improve the sensitivity of astrophysical searches carried out using GEO 600 data. The second is to provide implementation support for and/or develop advanced characterization techniques that require an operating interferometer. The rest of this section describes a few directions which the group is taking to achieve this goal.

2.3.2 Commissioning Tools

Currently the commissioning at GEO 600 is focused on improving both the high-frequency (above 1 kHz) and mid-frequency (between 100 Hz and 1 kHz) sensitivity. In parallel to the effort to lower the stationary noise floor of the interferometer, there is work devoted to reducing the number of loud transient signals in the detector output. All these lines of work naturally have positive consequences for GEO 600's observational potential. One of the aims of the GEO detector characterization group is to aid this commissioning process by providing views on many aspects of the interferometer through both established and novel means.

For example, the signal output of the GEO 600 interferometer contains an element of unexplained noise. Figure 2 is a recent noise budget that shows the discrepancy in the few hundreds of Hz band. Recently the work to search for this noise component has been started again. Two important pieces of information are known about a noise source in this frequency range. The first is that it has a dependency on the amount of power sent to the interferometer. The second is that this power dependent component is very non-stationary.

The non-stationarity of the noise component described above makes it very difficult to characterize via conventional means like calculating power spectra. Listening to the detector output is always a powerful tool but difficult to quantify and distinguish subtle changes. One of the current objectives of the GEO detector characterization team is to develop methods which are able to better characterize this non-stationary noise component. An example of this work is an effort to utilize data analysis pipelines such as Omega [35] and GSTLAL excess power [36] to display noise properties instead of triggers.

Projects such as this one can be described as data analysis for commissioning purposes. It is the commissioning that generates the questions which drive these analyzes. If these analyzes are successful then we will come full circle and they will start to drive the direction that the commissioning work takes. For the case of the mid-frequency noise investigations, the work of the characterization group at GEO 600 has already led to opening a new program of searching for scattered light in the interferometer. These types of projects makes up the bulk of the GEO detector characterization activities.

2.3.3 Interferometer Overview Monitoring

Another area of GEO detector characterization, which can also be seen as a type of commissioning tool, is that of interferometer overview monitoring. This consists of providing wide overviews of many different

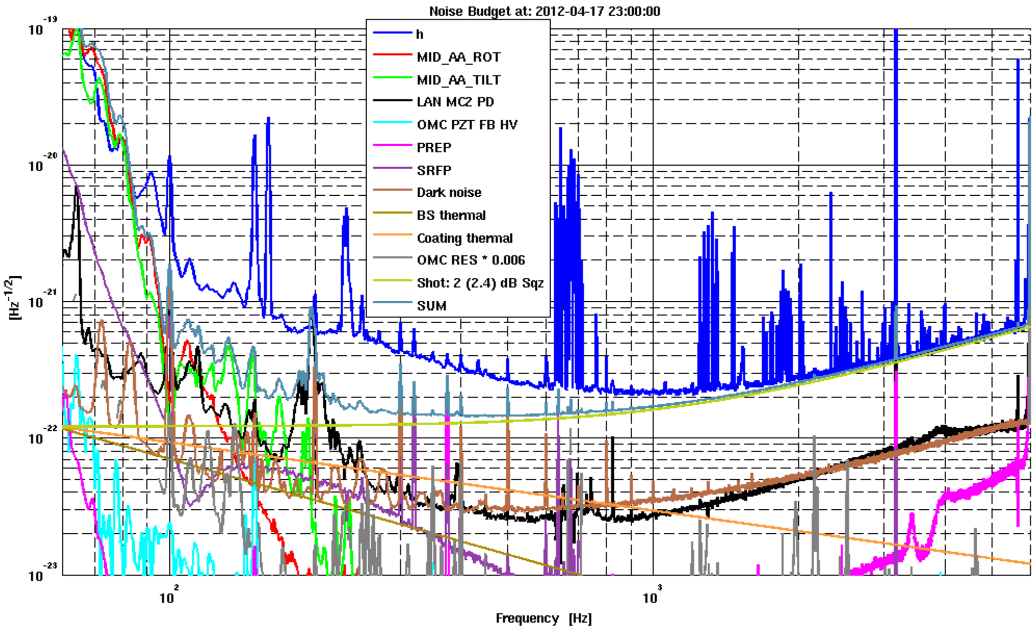


Figure 2: Recent noise budget for GEO 600. The blue curve shows a recent sensitivity curve. The gray-blue curve labeled "SUM" is the incoherent sum of all the noise contributions shown below it. We see that in the region from 85 Hz to 950 Hz the predicted sensitivity does not match the actual sensitivity.

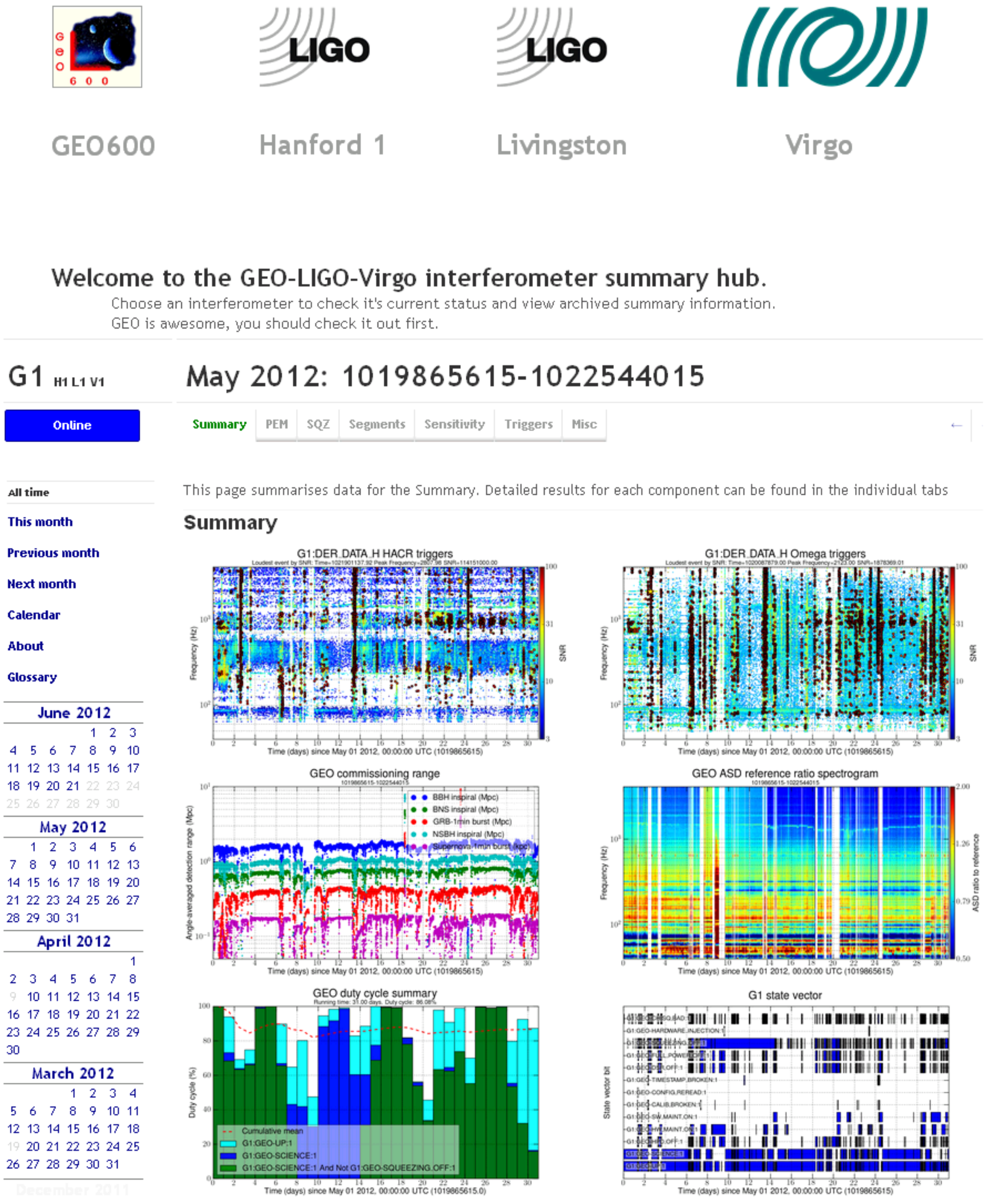
aspects of a running interferometer. These overview monitors are run constantly and save their history in an organized fashion that is easy to browse, normally as web pages. The first instances of such overview monitors were developed at the Virgo and GEO 600 interferometers. Recently, within the GEO detector characterization group a new implementation of these pages have been developed which makes it easy to generate these pages for all the different interferometers with a unified look and feel. Figure 3 shows two example pages from this work [37].

For these universal summary pages there are a few active areas of advancement. Since the universal pages are new, we are still thinking of ways to improve their organization. However, a larger area of expansion is in the content of the pages. As we grow in our understanding of how best to monitor gravitational wave interferometric detectors, these overview pages should evolve. The GEO detector characterization group will continue to improve the universal summary pages. This includes both the organization of the pages and exploring novel ways for monitoring that can then be added as content to these pages.

2.3.4 Advanced Techniques

The last category for work within GEO detector characterization is to investigate advanced characterization techniques. Since we are currently the only operating interferometer we would like to support the development of techniques that require such an environment.

We can again illuminate this type of characterization work by describing an example from ongoing work within the group. Recently we have been developing a new type of line monitor which follows both the amplitude and phase of a given line. This tool then can be used to generate a "noise-free" instance of the line. It is also very fast and can measure the line parameters in real-time. Because of this tool's real-time



Welcome to the GEO-LIGO-Virgo interferometer summary hub.

Choose an interferometer to check it's current status and view archived summary information.

GEO is awesome, you should check it out first.

This page summarises data for the Summary. Detailed results for each component can be found in the individual tabs

Figure 3: Interferometer summary pages. The very top section shows the hub which branches out to individual interferometers. It is shown here to emphasize the new feature of the code which is that it can be used to easily generate summary pages for any interferometer. Just below is an example of part of a monthly summary page from GEO 600.

capabilities we are planning to use this tool in the control scheme of GEO 600. Possible usages range from feed-forward control to subtract power line harmonic coupling to mirror motion, to adaptive feedback loop shapes which either enhance or subtract lines.

For techniques such as this which can benefit from demonstration on an operating interferometer, the GEO detector characterization team can provide some implementation and development support depending on how well it fits the aims of GEO 600's role in the community. Although the tool used in this example was developed by a part of the GEO detector characterization group, this does not have to be the case. We invite people with ideas to discuss them with us!

2.3.5 Summary

Another way to state the primary goal of the GEO detector characterization group is that it is to aid and contribute to the goals of the GEO 600 operation as a whole. As mentioned earlier, the GEO 600 overarching goals are two-fold. In one direction this is to make use of the advanced detector installation and commissioning time for serendipitous discovery. The other objective is to contribute in some way to the advanced detector era. These objectives will remain central to GEO 600 into this era when the GEO 600 sensitivity is surpassed at all frequencies. We find that for both of these goals, the solution to achieving each one takes us down pathways of commissioning and characterization which are often times very much overlapping, interactive, and not easy to distinguish.

Indeed, when closely inspecting the examples given in this section, they can each be classified at the same time as contributing to both objectives as well as lying on both pathways. Taking the non-stationary noise characterization work as an example, it is a project that was driven by a commissioning problem but utilizes tools from the analysis/characterization community. Its success rests on the contribution of ideas from both points of view. In addition to the possibility of increasing the chances of serendipitous discovery by helping to increase the mid-frequency sensitivity of GEO 600, this project will also contribute to characterization in the advanced era.

All the examples mentioned here and most of the work within the GEO detector characterization group share this very intertwined nature. It is our goal to bring the resources of the analysis community to the instrument, and thus balance observational sensitivity, as well as insight into future commissioning advances, as in no other place in the world.

2.4 Virgo Detector Characterization

2.4.1 Introduction

The search for gravitational signals requires a careful monitoring of the detector's response and the mitigation of the main sources of noise, both internal and due to the environment. In Virgo, the detector characterization relies upon a robust data acquisition system (DAQ) that has been designed to collect all data from Virgo sub-systems (including all probes that monitor the detector environment) and to provide data access to various processes/actors with minimal latency (down to few seconds for data viewer dataDisplay for example). The DAQ system was also thought to generate monitoring information about each sub-system. In Virgo, detector characterization is carried out by different actors involved in different groups that are highly interconnected:

- the commissioning group which has a dedicated team of people who track down any sources of noise that couple with the dark fringe (GW channel),
- the calibration team which measures and checks that control loops are well modelised and monitored to maintain the calibration and timing accuracy to an acceptable level for GW searches,
- and the Virgo data quality (VDQ) and Noise groups which study the quality of the data to provide useful information and vetoes to the data analysis groups and useful feedback and investigation tools to the commissioning team for noise mitigation.

To accomplish the Virgo detector characterization tasks, different processing algorithms and tools have been developed over the last years and most of them have been exercised during the past science runs (VSR1-VSR4). In addition, new tools are currently worked out, focusing mainly on providing help and hints for commissioning and noise investigation. These tools are described in section 2.4.2 and all of them are foreseen to be used for Advanced Virgo. In section 2.4.3, the plans of the different actors for Advanced Virgo are presented. Most of the results obtained during VSR1, VSR2 and VSR3 science runs are summarized in [38], while more details about Virgo detector characterization for Advanced Virgo can be found in the Virgo Data Analysis Report [39] and in the VDQ and noise groups strategy documents [40][41].

2.4.2 Detector monitoring, detector characterization tools and online processing

Since many years, several diagnostics tools have been developed to provide information to Virgo commissioners, people on shift and detector characterization experts. Most of these tools acquire data from the Virgo DAQ system (either from files written on disk or from shared memories), and generate results and web pages with latency that varies from few seconds up to few days, depending on the necessity to accumulate enough statistics and/or the necessity of a very prompt information. Most of the information generated during the four Virgo scientific runs has been archived in databases or in plain files stored on disk. Command line tools have been developed to help the Scimons (scientists on shift in control room) to get more rapidly and easily the needed information. An online vetoes production has been also developed to help fast follow-up decision for candidates selected by low-latency data analysis pipelines and to improve the significance of events found by offline analyses [42]. For Advanced Virgo, a reorganization and several improvements of those tools are planned, as explained in the following.

1. **Detector Monitoring System (DMS):** since the beginning of the Virgo interferometer's commissioning, several online detector monitoring algorithms have been implemented. The aim of such algorithms is to provide information (mainly as quality flags) used to set alarms in control room and to monitor various parts of the interferometer and each software process involved in the DAQ or interferometer's controls [43][44]. Technically, the detector monitoring implementation uses the same software tools as the DAQ system. All the detector monitoring algorithms use the same input and output software interface [45] and the same configuration syntax [46]. Moreover, the quality tests done within each detector monitoring algorithm can depend on the interferometer's locking state provided by the automation system. The quality flags generated by those algorithms are used to create a summary quality flag representing the general detector's quality. In addition, each algorithm generates an xml file containing the flags values used to build red and green flags to inform operators in control room about the interferometer's behavior:
   https://pub3.ego-gw.it/itf/qcmoni/V5/index.php

   For Advanced Virgo, the DMS is going to be upgraded to simplify the generation of quality flags, to better interface with data analysis and to provide in control room easy tools for alarms and detailed monitoring. A requirements document has been started and the upgrade of the DMS tool will be discussed and coded over the year 2013. One of the upgrade aim is to provide additional online data quality flags made with the information coming from the DMS.

2. **Channels Database:** a mySQL database is automatically and periodically updated by a dedicated online process to store information about each data channel available from the DAQ. A web interface has been developped to allow any user to fill a description field associated to each channel. A command line is available to get rapidly and easily the information on any channel. More details and documentation are available in
   https://wwwcascina.virgo.infn.it/DataAnalysis/chDBdoc

   For Advanced Virgo, we will look at the possible improvements of this database, for what concerns the information stored as well as for the users accessibility to the channels description and history.

3. **MonitoringWeb:** a tool based on web display, VEGA scripts [47] and bash scripts has been set up some years ago to generate periodically updated web pages. It has been upgraded in 2010 to provide

more features, a standardization of the scripts and an automatic daily archive of the information. This monitoring tool provides, in a set of web pages, the status of each detector's subsystem but also the status of the DAQ, online processing and online GW searches [48]. It includes also a set of plots showing the noise budget of the detector and a set of spectrograms computed over week, day and hour scales [49] in order to monitor the spectral behavior of several interesting signals. Archives and current pages are available in
https://wwwcascina.virgo.infn.it/MonitoringWeb.
Some noise monitoring web pages are generated with dedicated scripts that make plots from information stored directly in mySQL databases:
https://wwwcascina.virgo.infn.it/MonitoringWeb/Noise.

For the ER3 run, a MonitoringWeb page about the data transfer and the online Data Quality vector has been added.

For Advanced Virgo, it is foreseen to add a summary page providing the main figures of merits (horizon, glitch rate, etc...) and an automatic GW event summary page built for each GW event and providing the main information about the detector, its environment, the data quality information and the noise condition. We plan also to add monitoring pages for hardware injections, data storage and defective probes.

4. **Noise budget:** this tool, using model or measured transfer functions, produces information and plots, periodically updated, which summarize various noises contributions to the sensitivity curve:
https://wwwcascina.virgo.infn.it/MonitoringWeb/NoiseBudget

   Current implementation allows daily archives as well as the possibility to follow the noise budget evolution on a short time scale of a few minutes. For Advanced Virgo, this specific page of MonitoringWeb will be adapted to the noises of the new detector and will be improved in its short time scale display.

5. **Data visualization:** since the beginning of the Virgo interferometer's commissioning, dataDisplay [50] provides an easy way to display data online or offline. It allows to follow with a few seconds latency in control room the changes made on the interferometer or to do some trivial data processing (FFT, histograms, band pass filtering, ...). This tool allows also to combine signals and to do several types of plots on them: time plots, spectra, coherence, transfer functions, 1D or 2D distributions, time-frequency plots, etc...

   For Advanced Virgo, mostly during the year 2013, the dataDisplay will be largely upgraded to improve its speed, to cleanup its code and to allow more signal processing features.

6. **Calibration and h-reconstruction:** the calibration of the Virgo interferometer is necessary in order to perform precise data analysis. The "standard" calibration had been automated and extended to have some redundant measurements during the first science run, in 2007. It includes measurement of the absolute time of the Virgo data, measurement of the transfer function of the dark fringe photodiode readout electronics, measurement of the mirror and marionette actuation transfer functions and monitoring of the finesse of the arm cavities. The calibration methods [51] developed for Virgo have been automatized as much as possible.

   The calibration output are then used in the frequency-domain calibration to provide the Virgo sensitivity curve, and in the time-domain calibration to provide the h(t) strain digital time series.

   The last calibration campaign to prepare VSR4, and the calibration monitoring during the run, have shown that the actuation responses have been stable at the level of the percent during a one-year period, from June 1010 to September 2011 [52].

An independent method (photon calibration), developed to calibrate the mirror actuation gain, uses the radiation pressure of a secondary laser to push on the input mirrors and is in operation since 2007. It is used to determine the sign of h(t), defined as the sign of L_x-L_y where L_x and L_y are the lengths of the north and west arm cavities. Improvements on the calibration of this system have been performed [**?**] in 2010 and 2011. Moreover, the measurements allowed to draw a mechanical model of the mirror internal modes excited by the setup and to describe it up to 6 kHz. The data has then been used to validate the $h(t)$ reconstructed signal and its uncertainties within better than $\sim 7\%$ in amplitude and 10 μs in timing, in the range 10 Hz to 6 kHz during VSR4.

More information and the calibration and reconstruction notes can be found at:
https://workarea.ego-gw.it/ego2/virgo/data-analysis/calibration-reconstruction

7. **Hardware injections:** in order to perform coherent hardware injections simulating gravitational wave signals in the LIGO-Virgo detectors network, a system has been setup in 2009, based on the GPS time and using the calibration of the timing system. It was successfully used during VSR2, VSR3 and VSR4 for hardware and blind injections of gravitational-wave like signals. It should be possible to keep the same architecture for Advanced Virgo.

8. **Transient triggers generation:** Different algorithms are generating triggers with a low latency (less than a minute) and web pages are generated automatically in the MonitoringWeb system.

   Kleine Welle (KW): this algorithm is a computational method that finds transients in a time series by applying dyadic wavelet transforms (Haar basis) to look for excess energy regions in timescale decompositions [54]. Pre-processed whitened data is passed to the dyadic wavelet transform, then a threshold is applied on the energy of individual pixels. This step identifies the statistical outliers. The nearby pixels are clustered on the time-frequency plane and the significance is determined from their known distribution. Kleine Welle is the only transient finder algorithm able to process all auxiliary channels (more than 800 channels) on a few nodes accessing data available in shared memories of the DAQ. Nevertheless, it provides a frequency information not sufficiently reliable and might thus be replaced by the Omicron tool for Advanced Virgo.

   Omega and Omicron tools: a very useful tool for glitches investigations and glitchiness monitoring is the Omega burst search algorithm running online (Omega-online). Omega-online reads data from disk with a latency of few minutes. A web interface provides figures of merit using the omega triggers stored in ASCII files. Those various results and time-frequency plots are available at
   https://wwwcascina.virgo.infn.it/MonitoringWeb/Bursts.
   For significant triggers, an other process, Omega-scan, runs over several auxiliary channels and provides interesting information about possible origin of the trigger. Omega-scan results of all loud triggers are available in a centralized web page for further human investigation. Omega-online and Omega-scans are tools developed by LIGO and that we adapted to the Virgo needs.

   For Advanced Virgo an improved version of Omega, called Omicron, is developed in Virgo. Omicron has been processed on the full set of data of the VSR2 run and showed to be about 10 times faster than Omega and able to read hundred of auxiliary channels and providing triggers more reliable than KW. It provided vetoes which showed to be more efficient than those used for VSR2 and we expect it to allow also to investigate rapidly on loud glitches. First tests have shown that about 60 computing cores will be needed to run online over about 600 channels.

MBTA: MBTA is a Compact Binary Coalescence (CBC) search algorithm running online on LIGO and Virgo data. It is based on matched-filtering technics applied on separate frequency bands, the results being recombined coherently. In addition to providing GW event candidates, this algorithm provides Virgo triggers helpful to monitor in real time the glitches most similar to a CBC GW signal, to check the efficiency of data quality vetoes against such glitches and to categorize the DQ vetoes for CBC offline analyses. A MonitoringWeb page is dedicated to the results of MBTA:
https://wwwcascina.virgo.infn.it/MonitoringWeb/Inspirals

WDF: the Wavelet Detection Filter looks for transient signals in a wavelet based map. The input data pass trough a whitening filter [63]. A wavelet transform is applied to the whitened data and a set of wavelet coefficient are selected following a thresholding criteria with respect to the noise background. The highest values for wavelet coefficients are supposed to be linked to the transient signal. The result is built summing all the squared coefficients and dividing this value by the noise RMS. In principle, this is proportional to the SNR of the transient signal. After a selection using a fixed threshold the events are clusterized in time. The filter gives indication also on the frequency content of the trigger (frequency and time information is provided by the maximum value of wavelet coefficient). The online report is given at:
https://pub3.virgo.infn.it/MonitoringWeb/Noise/html/index.php?callContent=10
The last hour five loudest events are automatically analyzed to check their features in time and time-frequency domains, using a set of auxiliary channels:
https://pub3.virgo.infn.it/MonitoringWeb/Noise/html/index.php?callContent=34 WDF is linked to online DAQ chain and can be run offline with better parameters estimation procedures.

9. **Glitches identification:** this work is done mainly by using transient search algorithms like Omega-online or KleineWelle. The Omega-scan tool is also heavily used to find hints of coincident glitches in auxiliary channels. During runs, glitch shifts are organized. A list of loudest triggers found by online GW analyses and not DQ flagged is established and studied to identify glitch families. Such glitch shifts give also the opportunity to strengthen the relationship with the commissioning team. Logbook information is also used to define, offline, some DQ segments that flag bad quality data periods and/or to understand various noise increases. A web interface has been set up to allow Scimons to create DQ segments for any event that could affect the data quality. Investigation on glitches origin and on the noise coupling path are done in collaboration with the commissioning team. We especially investigate the possible correlation between the GW channel and all the auxiliary channels.

   For Advanced Virgo, some automatic glitch classification tool may help to accelerate the investigations. Already some tools that uses Omicron triggers (Omiscan, DQperf, UPV) and based on the home-made GWOLLUM library allow to provide interesting information to glitch hunters. Those tools are exercized on previous runs data, on Virgo and LIGO ER3 data or on the current Virgo Environment Monitoring data. For Advanced Virgo, we plan also to improve the organization of the glitch shifts and to include more tools providing automatized information for fast checks.

10. **KW-based vetoes:** KleineWelle (KW) transient search algorithm is useful to seek for statistically significant coupling between glitches in the dark fringe and any auxiliary channels. For this investigation veto algorithms UPV (Use Percentage Veto) and hVeto (hierarchical Veto) are run on each of the KW trigger lists over a daily period or a weekly period. They select and rank the channels that show a statistically significant excess of glitches in coincidence with the dark fringe glitches. Usually only triggers that pass all online DQ vetoes are considered in this study. When feasible and when the coupling between the dark fringe and a channel is persistent, a DQ flag based on this particular auxiliary channel is created. For all the other selected channels, KW-based veto segments are generated and used in the burst and CBC searches. More details are available in

https://wwwcascina.virgo.infn.it/DataAnalysis/KW/Veto/

11. **Excavator:** Excavator is a tool recently developed in Virgo to look at possible correlation between Omicron triggers (or any other pipeline triggers) and the amplitude of signals in all auxiliary channels. This tools has been exercized on several set of data (LIGO, GEO, Virgo) and showed to be useful either to select interesting auxiliary channels to investigate noise paths and origin or to set up efficient vetoes against families of glitches. More details can be found in
https://wwwcascina.virgo.infn.it/DataAnalysis/Excavator

12. **Data quality and veto generation:** using the same basic libraries as the DAQ system, a set of DQ monitors generates online DQ flags collected by a specific process (SegOnline) which produces DQ segments. Thos DQ segments are stored in a database (VDB) and, in parallel, are transfered to the LIGO database (segdb). Additional flags are produced offline and a reprocessing of the online DQ flags is done whenever needed. Offline and online production include several cross-checks to validate the DQ segment lists for each search group. On a weekly basis, we study the effect of the DQ vetoes on the triggers produced by the online burst and CBC GW searches. Statistical information such as efficiency, use percentage and dead-time of each DQ flag is computed online every week. In collaboration with the burst and CBC groups, each DQ flag is assigned a category which tells how the DQ flag should be applied by the GW search pipelines.

    The online DQ flags are permanently monitored in
    https://wwwcascina.virgo.infn.it/MonitoringWeb/DQ
    and the various reprocessings results are available from
    https://wwwcascina.virgo.infn.it/DataAnalysis/DQ

13. **Vetoes safety:** we validate the safety property of all the DQ flags and KW-based vetoes using loud hardware injections. The probability that a veto does not suppress any genuine GW event is computed considering the totality of the data since the start of a run. Different thresholds applied on this probability allow to detect when a veto becomes unsafe. In addition various tools are provided to monitor the data quality flags and to help glitch investigations. More details are available in
https://wwwcascina.virgo.infn.it/MonitoringWeb/DQ/safety

14. **Spectral lines identification:** NoEMi (Noise Event Miner) framework is looking for frequency lines in the dark fringe, h(t) and a subset of the auxiliary channels. It implements some of the algorithms developed for the CW search to extract, with a maximal one day latency, the peaks (Frequency Events or EVF) in a frequency spectrum. From the persistence distributions of the peak maps, NoEMi identifies the noise lines and looks for coincidence between channels. The lines are compared with those already extracted in the previous iterations, in order to track the non-stationary lines (lines whose frequency changes with time). NoEMi produces every day a set of summary plots of the peak maps and a list of identified lines published on the Virgo monitoring pages [55]. The tool raises an alarm if noise lines are found close to the Doppler band of some known pulsars. The peak maps and line parameters are stored into a MySQL database and can be accessed through a web user interface [56], which allows data filtering, plotting and addition of user-defined meta-data.

    There are currently two instances of NoEMi running on Virgo data: a "low resolution, fast update" one, with a 10 mHz frequency resolution, which updates the lines database every 2 hours, and a "high resolution, slow update" one with a 1 mHz frequency resolution and an update once a day.

15. **Coherence:** the coherence between dark fringe channel and all auxiliary channels is computed on 5 minutes chunks of data, decimated to 1 kHz (using a 8th order Butter-worth filter). A web page with two tables is generated. The first table is a list of all channels analyzed: each entry in the table is a

link to a plot of the corresponding coherence. The second table shows for each frequency bin a list of the 10 channels which gave the largest coherence. Results are in
https://pub3.virgo.infn.it/MonitoringWeb/Noise/html/index.php?callContent=407

For Advanced Virgo the coherence results will be archived in a database to allow queries and plots production on older data set. Coherence monitor will also be used jointly with NoEMi to better identify the source of noise for spectral peaks.

16. **Non stationarity:**

    NonStatMoni: This online monitor computes RMS over various frequency bands of the dark fringe signal. Such RMS value is a time domain signal whose spectrum at low frequency gives indication of the slow evolution of the dark fringe in different frequency bands. Its results are stored in the trend data and available through the Noise monitoring web pages.

    BRMSMoni: it computes for a set of channels, the RMS over a set of frequency bands. In addition, it can compute the amplitude of a spectral line at a given frequency. Its results are stored in the trend data and can be used to determine the level of noise in a control loop (looking for instance at the 1111Hz line injected in the laser frequency control loop) or to follow the level and type of seismic activities on the site:
    https://wwwcascina.virgo.infn.it/MonitoringWeb/Environment

17. **Non linear coupling investigation:** the “Regression” project aims at measuring the linear couplings and some classes of non-linear ones among a primary "target" channel (e.g. h(t) or dark fringe) and a set of auxiliary channels (environmental or instrumental channels). This information can then be used for commissioning and noise hunting activities, as well as for cleaning non Gaussian noises from h(t) by numerical subtraction of the measured correlation with the auxiliary channels.

    We are developing and testing two different procedures:

    - a procedure based on a forward-regression orthogonal estimator applied to non-linear system identification to subtract environmental noise to the dark fringe output. A Volterra series expansion is employed and the model results linear in the parameter. In this way, the identication algorithm can be the same as in the linear case, and orthogonal least squares method can be used. The identification accuracy is improved by filtering the error in a specified frequency region. A good point of the method, developed by S.A Billings et al., is that a ranking of the auxiliary channel significativity can be given.

    - a procedure based on a coherent analysis of the target and auxiliary channels. It consists in a linear regression or Wiener-Kolmogorov filter which predicts the target channel part correlated to auxiliary channels. Considering as input the mixing of more auxiliary channels, it is possible also to characterize bilinear (or higher order) couplings to the target channel, for instance up-conversion of low frequency noise to side-bands of strong spectral lines. The algorithm is based on a chi-square minimization to find the optimal prediction, whose last step selects the most relevant auxiliary channels for the prediction by applying a regulator to the ranked list to avoid increasing prediction noise due to un-useful auxiliary channels.

18. **Databases:**

    Segments database (VDB / DQSEGDB): this tool, based on a mySQL v5 server, allows to archive all the DQ segments generated in Virgo and to keep trace of any change. It also contains all basic segments, such as the Science mode and hardware injection periods, as well as the Scimon information generated by shifters. VDB provides useful facilities to perform requests and logical operations on DQ segments lists, by anyone in LIGO, GEO and Virgo.

A command line tool and a web interface have been developed to allow users to query and combine together DQ segments archived into the database. In particular a dedicated section about data quality and science mode segments list has been developed, with several features like showing each single DQ list with its properties or combine together several segments lists by using user defined logical expressions.

For Advanced Virgo, a large upgrade of VDB is currently under way. It includes a strong cleanup of the database content and the development of DQSEGDB, a LIGO-Virgo common database dedicated to Data Quality segments and aimed to replace Virgo and LIGO databases VDB and segdb. Three documents describing the user requirements, the API specifications and the database structure are under finalization and the development of the database and of the user interfaces will be done during this year 2013. >From first tests, we expect DQSEGDB to improve access speed, reliability and error tracking possibilities with respect to VDB and segdb.

Lines database (LinesDB): lines identified by NoEMi are stored in a mySQL database which can be accessed through a web interface. The database is updated in real time by NoEMi and is filled offline with user-defined information (type of instrument used in the measurement, general information on the line and its noise source, etc...) once the source of the disturbance is understood. The identification of the noise lines found in VSR2-VSR4 data started just after the end of VSR4. Out of the O(1000) lines found in each run, 90% have already been identified and less than 100 lines still require investigation. The lists of identified lines are used to veto fake candidates in the stochastic and CW searches.

Triggers databases: Some of the transient search algorithms (for instance WDF) stores triggers in mySQL databases. This allows to archive triggers in a well controlled way and to provide a standard interface to access to those triggers.

2.4.3 Advanced Virgo plans

Virgo science runs have demonstrated the importance of time periods at the frontier between commissioning and science run:
- noise hunting campaigns before data taking starts (for instance mitigation of seismic and acoustic sources of noise, that can generate spurious signals mostly by modulating the position of elements that scatter light inside the interferometer cavities),
- a pre-run period for online vetoes tuning,
- a commissioning time dedicated to the careful calibration of the instrument.

The organization of those time periods will be also a mandatory item of the detector characterization plans. Before we reach these after-commissioning time periods, the reduction of the environmental noise for Advanced Virgo is mandatory to reach the Advanced Virgo target sensitivity. This goes along with an upgrade of the monitoring sensors. In parallel to this effort, an upgrade of the calibration methods and of the injection tools may be needed. Finally, the detector characterization groups (VDQ and Noise groups) are defining the upgrades of the monitoring tools and developing new ideas to better identify the limiting sources of noise and to suppress their effects in GW searches. All those projects and the strategy adopted are briefly described below.

1. **Data quality monitoring and glitch shifts**

   Several tools that monitor the detector are in place and already fully integrated in the DAQ system. Improvements are foreseen yet, especially to better handle the flow of data quality information which is generated during science runs and to provide useful (fast and reliable) inputs to GW searches. Most of the foreseen improvements have been mentioned for each tool described in section 2.4.2.

Our main aim is to provide fast and easy to use tools to help any noise investigation on each Advanced Virgo sub-system as soon as it is ready and to help noise paths investigations as soon as commissioning starts. The goal is to detect and reduce any glitch sources during the commissioning period instead of developing hundred of quality flags to veto the remaining glitches during the Advanced Virgo scientific runs. The organization of the glitch shifts and the interactions with Scimons and commissioning team will be also one of the main items we plan to improve for Advanced Virgo.

2. **Calibration, h-reconstruction and injections**

   The calibration methods developed and automatized for Virgo will be still valid for Advanced Virgo calibration. Simulations of Advanced Virgo data in the condition used to measure the mirror actuation (the so-called free swinging Michelson configuration) have been done in order to estimate the expected powers on the photodiodes used for calibration and the sensitivity of the calibration measurements [57].

   The Virgo calibration is presently using the same actuators as those used to control the interferometer. The possibility of using an external actuator (the photon calibrator) to produce the excitation signal is under evaluation for Advanced Virgo. Plans to improve the photon calibration setup for Advanced Virgo have been described in the section 14.6 of the Advanced Virgo Technical Design Report [58]. In particular, two photon calibrators will be installed at the end stations of Advanced Virgo and will be used as an independent cross-check of the calibration.

   The current h-reconstruction method is expected to work for the first steps of Advanced Virgo, without signal recycling cavity. Studies are then needed to update it to the interferometer with the signal recycling.

   The architecture used to generate coherent hardware injections in the LIGO-Virgo network should be kept for the injections in Advanced Virgo.

3. **Environmental noise**

   Environmental noise coupling to the Virgo interferometer has been a primary issue along the detector commissioning and during all science runs. Eventually, residual noise had impact on GW signal searches. Based on this experience, Advanced Virgo detector design adopts strategies to reduce coupling and mitigate sources of environmental noise. We also foresee to upgrade and improve the environmental noise monitoring sensors network. We briefly describe below the environmental noise mitigation strategies and monitoring sensors upgrade.

   Noise mitigation strategies:

   Our goal in Advanced Virgo is to reduce environmental noise in the GW channel below the design sensitivity by at least a factor 10. To achieve this ambitious goal, we plan to work both on reducing the coupling of the disturbance to the interferometer and reducing the emitted noise and limiting noise transmission paths. Detector design strategies to reduce environmental noise coupling briefly consist in:

   - Reducing vibration noise coupling by:
     - minimizing beam paths in air and through ground connected optics, thus adopting in-vacuum suspended optical benches and replacing Brewster windows with cryogenic vacuum traps;
     - implementing an optimized in-vacuum suspended baffles system to absorb stray light from core optics;

  - minimizing diffused light at injection and detection ports, by adopting for example low diffusing optical components;
  - accurately designing new components (one example: new cryo-traps design will minimize re-coupling of vibrations from liquid Nitrogen bubbling).
- Reducing electromagnetic noise coupling by:
  - adopting lower strength magnet actuators on core optics (to couple less environmental magnetic fields);
  - assuring negligible EM coupling at new project components like Ring Heater thermal compensation device and new sensitive electronics.

On the other hand, strategies are defined to create a quieter environment at critical locations. We have defined more stringent seismic and acoustic noise requirements for the injection (INJ) lab (which will host in-air benches), the detection (DET) lab and experimental halls.

The planned actions are:

- to improve INJ and DET lab acoustic isolation, as well as labs air cleanliness quality by adopting dedicated clean room low noise HVAC systems;
- to relocate and/or silence more offending sources: for example vacuum scroll pumps will be confined in acoustically isolated rooms and seismically isolated;
- for electronics racks which cannot be segregated, but need, for operation reasons, to remain in the experimental halls, to reduce acoustic emission from cooling fans (which is the major noise source), to reduce fans number by optimizing heat dissipation, and to seismically isolate racks;
- to move most offending power transformers at some distance to minimize stray magnetic fields in the experimental areas close to the core optics. To this end, a DC distribution system will be implemented to serve at least part of the electronics. In addition, care will be taken to adopt power supplies with low stray field emission, i.e. implementing toroidal shaped transformers type.
- to reduce impact of stray magnetic fields from power cables by carefully designing new cable paths in order to keep them as far as possible from the payloads, and possibly adopt new power cables of twisted type.

Monitoring sensors upgrades:

The upgrade for Advanced Virgo will require also an improvement of the environmental monitoring network, following two major requests: on one hand a larger number of sensors are required due to the higher complexity of the interferometer, on the other hand the higher sensitivity of the antenna will require a more severe rejection of the environmental noise that implies a general improvement of the sensitivity of the monitoring network.

The first request mainly comes from the installation of the Signal Recycling tower, an improved monitoring of optical links, and an improved monitoring of electric power lines and infrastructure devices. The SR tower, as all other towers, will be equipped with a set of temperature probes for the suspension monitoring and accelerometers to monitor the tower vibration in the medium frequency. While suspended and in vacuum benches are not an issue for environmental seismic and acoustic noise, we foresee an accurate low and medium frequency seismic monitoring of parts which are potential diffused light recoupling location. These are the new optical links and cryotraps. All External benches will be equipped (similarly to Virgo) with acoustic and seismic probes. Each experimental building will be monitored with one microphone, one tri-axial low frequency velocimeters (like Guralp 40T) one infra-sound microphone, three low noise magnetometers, voltage and current probes and one RF antenna. The RF antenna monitor will be improved so to individually monitor each 10kHz band above and below each of the 3 AdV modulation frequency. Virgo infrastructure counts a number of devices (e.g. water chillers, air compressors) which follow on/off cycles driving high currents at the start-up. They are potential sources of noise transients. In addition to mitigating them, we plan to monitor their on/off status by adding simple current probes in the fast monitoring system. Similar probes will be used to monitor electric power currents to critical electronic equipments (suspension control racks, injection and detection electronics).

The second request implies the adoption of more sensitive probes, whenever possible, or the use of less noisy conditioning electronics to optimize the probe response to the environmental noise. For most sensors, in particular for episensors, PZT accelerometers and microphones, an improvement of the sensitivity can be easily obtained by increasing the output gain, if the standard environmental noise level allows this operation without saturating the electronic. This should be possible if all the foreseen actions, required for the noise mitigation, are effective.

More details can be found in
https://wwwcascina.virgo.infn.it/EnvMon

4. **Data quality for GW searches**

For Advanced Virgo, we do not plan to do large upgrades of the software architecture used to generate online DQ flags or KW-based vetoes. The main improvements will concern glitch investigations and new vetoes developments. We focus currently the development on the Omicron trigger generator, the development of the data quality segment database DQSEGDB and the various tools used to monitor glitches or to estimate vetoes performances and categorization. As previously explained, we will focus on the use of Omicron triggers to provide useful tools or information to commissioners and on the involvement of the VDQ group in the commissioning activity. For instance, the upgrade of the environment monitoring, defining characteristics and location of all the probes useful for the detection of glitch sources or for the development of efficient vetoes.

Also, tools for investigating on noise non linear coupling are under development and could help us to determine which set of auxiliary channels should be used to veto glitches or to mitigate the associated noise source. Related to this development, short time scale non-stationary lines are considered also as one of the main sources of glitches to be investigated and for which tools should be developed.

We also plan to improve the identification of glitch families to determine which are the main glitch characteristics to be combined to give a weight to GW triggers instead of vetoing time period as we do now. Being able to replace the vetoes categorization by such a number or more globally by a veto performance indicator would simplify the use of vetoes in data analyses. A reflexion in this direction has been started within the GWOLLUM project linked with the Omicron trigger generator.

To compute the safety probability, we assume currently that hardware injections and veto segments are randomly distributed in time. This is not the case for hardware injections (done each 5 seconds in a series of 10) and not always the case for the veto segments. Thus, the veto safety assessment has also to be improved.

We will need also to define which information is mandatory to be used by online analyses when producing GW events or by scientist on shift when deciding about GW event candidate to be sent for follow-ups by satellites and telescopes. The production of online DQ flags is mainly motivated by our ability to select good candidates for such low latency analyses and follow-up. This reflexion is linked to the glitch classification and the use of a statistical estimator weight on triggers to replace vetoes categorization, but this is a longer term priority.

A document describing the VDQ strategy for the coming years has been released. This document lists the current tools available and their foreseen improvements. It describes also the current projects, the needs and requirements for various aspects of the glitch investigations, online vetoes production, monitoring tools and commissioning help. This document will be subject to discussions and comments and will be updated accordingly once a year. It is accompanied by a web page listing the various tools and projects linked to detector characterization activities, to be also updated periodically:
https://wwwcascina.virgo.infn.it/DataAnalysis/DQ/dqtools.html

The Noise group is also defining in a document its strategy for Advanced Virgo. In addition to the upgrades of the NoEMi tool and the Lines database, the NMAPI [59] framework, which provides web interfaces to databases, will be upgraded. More precisely here is a list of on going projects in the noise group for Advanced Virgo:

- Centralised DataBase: we plan to have a centralised database to store and retrieve all Noise monitor results having a transparent access via a web interface. The aim is to increase the interoperability and communication between applications within this environment and NMAPI via the use of the Connections Database (CDB) [62].
- Upgrade NMAPI to D-NMAPI: we started the upgrade of NMAPI to a distributed version of the application (Distributed NMAPI) which will distribute the computational work on different computing nodes improving the performance of NMAPI. We are doing tests relying on a job distribution using condor, and we are integrating in NMAPI an interface to launch condor scripts and monitor the results.
- Non-linear coupling identification: new algorithms for detector characterization have been proposed that focus on the identification of non linear coupling of noise sources with the dark fringe. We started the integration of these algorithms into NMAPI [60, 61].
- Glitch characterization: the aim is to produce a catalogue of transient noise event waveforms (using cWB or WDF pipeline) and archive them in a Database. We started some tests on VSR4 data and the work is on-going.

Data analysis groups are common between LSC and Virgo, but detector characterization deals mainly with the specificities of each detector and its environment. Nevertheless exchange of knowledge and use of common tools like Omega-online, KW, UPV, hVeto were fruitful and we plan to intensify such relationship for the preparation of advanced detectors era. The LIGO Engineering Runs are part of our development plans. They will especially be helpful to test any new developments related to data quality, data tranfer or low latency CBC search (MBTA) and online processing before real data are generated by the commissioning of Advanced Virgo.

3 Searches for signals from compact binary coalescence

3.1 Priorities for the Compact Binary Coalescence Group

The inspiral and merger of a compact binary system generates gravitational waves which sweep upward in frequency and amplitude through the sensitive band of the Earth-based detectors [183]. The detection of gravitational waves from these astrophysical sources will provide a great deal of information about strong field gravity, dense matter, and the populations of neutron stars and black holes in the Universe. The scientific program of the LSC/Virgo Compact Binary Coalescence (CBC) Group is designed to identify GW signals from compact binary sources in the detector data, estimate the waveform parameters with confidence in the correctness and validity of the results, and use these signals for the study of gravity and the astrophysics of the sources [183]. The LSC charter states that the mission of the LSC is

> to detect gravitational waves, use them to explore the fundamental physics of gravity, and develop gravitational wave observations as a tool of astronomical discovery. The LSC works toward this goal through research on, and development of techniques for, gravitational wave detection; and the development, commissioning and exploitation of gravitational wave detectors.

We prioritize CBC tasks both in view of this mission statement and in terms of their chronological importance in the advanced detector era. Accordingly, *highest priority* is given to the ability to detect CBC sources with the LIGO and Virgo detectors that are believed to have the largest event rates, followed by science with the first detections (“high priority"), and finally the detection of sources which in the current astrophysical paradigm may have a low rate within the detectors’ volume reach, but whose discovery would nevertheless be of great astrophysical importance (“priority").

1. **Highest priority**

   The detection of gravitational waves from compact binary coalescence using the LIGO and Virgo detectors is the main goal of the CBC group. Highest-priority sources are binary neutron stars, stellar mass binary black holes, neutron star–stellar mass black hole binaries, and the detection of gravitational waves from compact binaries in coincidence with an externally triggered short-hard gamma ray burst. The CBC group must be ready to measure the masses and spins of sources on first detection, to provide rate estimates for detected sources, and to provide rapid significance measurements of externally triggered gamma-ray burst events.

   Achieving these goals requires LSC/Virgo scientists in the CBC group to prioritize: data quality, search pipeline development, rates and significance measurement, waveform development, and parameter estimation for detected sources.

2. **High priorities**

   Once CBC sources have been detected, a significant amount of astrophysics can be extracted from the observed gravitational waves. Preparing to extract this information accurately is a high priority for the CBC group. This includes: precise measurement of masses and spins for population studies; determination of the neutron star equation of state; tests of the genuinely strong-field dynamics of spacetime, a regime which can only be probed with direct GW detection; cosmological studies without the need for a cosmic distance ladder; and accurate measurement of coalescences rates for CBC sources.

   Although a coincident electromagnetic counterpart is not required to detect gravitational waves from compact binary coalescence, the coincident detection of an electromagnetic counterpart with a CBC event would add significant astrophysical information to our discoveries. Preparing for detections of EM counterparts to GW events is a high priority for the CBC group. This includes: development of low latency analysis data quality, pipelines, low-latency significance estimation, sky localization for CBC sources, and preparations for joint GW/EM observations in the advanced detector era.

3. **Priorities**

   Priorities include expanding the CBC search to binary black holes beyond stellar mass (e.g. intermediate mass ratio inspirals, massive binary black holes, eccentric binaries), which will necessitate the development of new data analysis algorithms and the implementation of associated template waveforms in the LIGO Algorithm Library.

This part of the white paper lays out the goals of the CBC group. We begin in Section 3.2 with an outline of the various sources that will be targeted in the advanced detector era. Next, we discuss the two remaining searches to be completed on the S6/VSR2-3 data set in Section 3.3. Then, in Section 3.4 we provide a brief overview of the analysis techniques and strategies that have been developed to detect our sources and use them as a tools of astronomical discovery.

3.2 Binary Coalescence Sources

We have split the parameter space of compact binary coalescence sources into five regions for the purpose of this white paper. These are

- Binary Neutron Stars (BNS)
- Neutron Star–Black Hole Binaries (NSBH)
- Stellar mass Black hole–Black hole binaries (BBH)
- Intermediate mass Black hole binaries (IMBBH)
- Gravitational wave counterparts to gamma-ray bursts (GRBs)

There are significant overlaps in the IMBBH and GRB analyses between the CBC and burst sections. The IMBBH sources and science are described below, while the GRB analysis is described in the burst section of the white paper.

3.2.1 Neutron star–neutron star binaries

The coalescence of binary neutron stars (BNS) is the most promising source of gravitational waves for Advanced LIGO (aLIGO) and Advanced Virgo (AdV). Radio observations of double neutron star systems containing pulsars suggest a significant coalescence rate in the volume of the universe accessible to the advanced detector network. The BNS gravitational waveform is well modeled in the sensitive frequency band of the advanced detectors (10—2000 Hz), allowing the use of optimal filtering for detection. A BNS will likely be the first gravitational-wave source observed by the advanced detectors and the first direct detction of gravitational waves. The detection of even a few BNS signals would greatly constrain the very broad uncertainties in the rate of BNS coalescence, thereby constraining the possible formation channels. Measuring the mass and spin distributions of BNS will inform stellar evolution, nuclear physics, and supernova physics. The presence of matter in the merger may give rise to detectable EM counterparts, including GRBs, orphan afterglows and kilonovae. BNS will provide a laboratory for measurement of the equation of state of neutron stars and for testing General Relativity in the post-Newtonian approximation. BNS searches are crucial to the science potential of the LIGO–Virgo detector network.

Population synthesis models, constrained by radio observations of double neutron star systems in the Milky Way, provide an estimate of the BNS merger rate of 0.01—$10\,\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$. This gives a BNS detection rate of 0.4—1000 per year for an Advanced LIGO detector at design sensitivity [7]. Early science runs in 2015, taking 3 months of data at a range of 60 ± 20 Mpc in Advanced LIGO and 20 Mpc in Advanced Virgo, could detect a BNS merger if the rates are near the upper end of the expected range [4]. The detection of three BNS sources would greatly reduce the uncertainty in the coalescence rate to a fractional error of $\pm 58\%$, assuming a Poisson event rate.

The masses of known neutron stars are conservatively measured to be in the range 0.7—$2.7\mathrm{M}_{\odot}$, with a mean mass of $\sim 1.4\mathrm{M}_{\odot}$ [112]. Neutron stars in binary systems with another neutron star may have a tighter mass distribution than the general population. A distribution of $1.35 \pm 0.14\,\mathrm{M}_{\odot}$ has been suggested in [112], whereas [115] finds an error-weighted mean of 1.402. Observations of galactic BNS systems also suggest that BNS systems are formed from electron-capture collapse of O-Ne-Mg cores for both components in the binary, implying that both have the same mass distribution [160, 185]. We will search for BNS with component masses between 1 and $3\mathrm{M}_{\odot}$ to ensure that the plausible mass range is covered.

BNS waveforms are well modeled by post-Newtonian theory in this mass range [62], with waveforms computed at seventh order beyond the leading-order orbital phase [49] for non-spinning binaries. Some known "recycled" binary pulsars have spins large enough to significantly affect the inspiral waveform, with the largest example in J0737-3039 of $44\,\mathrm{Hz}$, corresponding to a dimensionless spin of $J/m^2 = 0.04$ [124]. A search for spins up to these magnitudes can be analyzed with non-spinning template banks with negligible loss in efficiency [55]. A search for higher spin systems (neutron star spins up to $J/m^2 \simeq 0.4$ are possible [100]) requires the use of waveforms and template banks that capture the effect of spin [110, 111, 55]. Measurement of the physical properties of detected systems will be performed using parameter estimation techinques [15].

We have demonstrated that it is possible to claim the detection of a binary coalescence signal observed in two detectors without an electromagnetic counterpart [14]. However, there are several plausible electromagnetic counterparts to BNS mergers [135]. The detection and confident association of an EM counterpart to a BNS will allow a deeper study of compact object astrophysics than gravitational waves alone. The anticipated sky localization capabilities of the early advanced-detector network may only constrain the sky location of a BNS source to an area hundreds or thousands of square degrees, even if a confident detection can be made with gravitational waves. Despite these limitations, online pipelines [39, 70, 71] will provide rapid-alert triggers for EM follow-up during early runs in case a significant localizable event is observed, and to train for better localization accuracy as sensitivity improves. Detection of a coincident BNS signal coincident with a gamma-ray burst event is a significant science goal, as described in the GRB section of this white paper.

During the initial-detector era we developed algorithms for searching for BNS signals in a network of detectors [37, 30, 29, 167, 166], culminating with the *ihope* pipeline [36] used in the latter runs. Search results were published in a series of papers: S1 [16], S2 [17], S3 and S4 [20], S5–VSR1 [23, 24, 9] and S6–VSR2/3 [14]. No detections were made, and an upper limits of $R_{90\%} \leq 130\,\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$ was placed on the rate of binary neutron star coalescence. Historically, the BNS search has been performed in conjunction with CBC searches for neutron star–black hole (NSBH) and stellar-mass binary black hole (BBH) signals. We will continue to pursue a common searches for these sources where a joint search is appropriate, but will revise this as demanded by the physics of NSBH and BBH searches (particularly spin and BH merger physics).

The detection of BNS signals is a primary task of the advanced detectors. Direct detection of BNS systems will allow us to use gravitational-wave observations to probe the astrophysics of compact objects and the genuinely strong-field dynamics of spacetime [121, 122]. We will search all available science data with two or more detectors operating in coincidence.

Science of the first detections

Advanced detector observations of BNS coalescence will give us access to information previously unobtainable with electromagnetic astronomy. Using only the first few detections, we can place constraints on the astrophysical event rates, which in turn inform estimates of the population of binary neutron stars and their formation processes [128]. The coincident detection of a BNS signal with a GRB event could confirm BNS mergers as a progenitor of short GRBs if.

Science in the regular detection era

Once the advanced detectors have accumulated tens of confirmed signals, we will have enough information to begin to probe the statistical distribution of BNS systems. Of special interest are the mass and spin distributions, which can further constrain modes of production of BNS systems, in addition to the more accurate rate determination. The measurement of inclination angles coupled with electromagnetic observations will provide vastly improved constraints on the electromagnetic beaming angle of short GRBs [159]. We should be able to detect, or at least limit the tidal deformability of the neutron stars involved, yielding insights into the internal structure and equation of state of neutron stars, and possibly observe their tidal disruption prior to merger. Likewise, detection or constraint of deviations from general relativity in the dynamical regime will become possible, which could help to eliminate alternative theories of gravity. Determining the mass and equation of state will consequently allow the radius of the neutron star to be determined.

The GWs from compact object mergers have an absolute amplitude at the source that is known from first principles, and comparison with the amplitude measured at the antenna as well as with red shifts of possible host galaxies gives a set of possible Hubble parameters; repeated observations provide iterative refinement of the value of the Hubble parameter.

Goals Prior to First Detections

Population synthesis models, constrained by radio observations of double neutron star systems in the Milky Way, provide an estimate of the BNS merger rate of 0.01—$10\,\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$. This gives a BNS detection rate of 0.4—1000 per year for an Advanced LIGO detector at design sensitivity [7]. Early science runs in 2015, taking 3 months of data at a range of 60 ± 20 Mpc in Advanced LIGO and 20 Mpc in Advanced Virgo, could detect a BNS merger if the rates are near the upper end of the expected range [4]. The detection of three BNS sources would greatly reduce the uncertainty in the coalescence rate to a fractional error of $\pm 58\%$, assuming a Poisson event rate.

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Projects For Early Detection Era

This is work whose products will become necessary in or be completed in the era of the first few detections.

- What have we learned about the astrophysical rate of BNS? (*Rates*)
- Are GWs the progenitor of short GRBs? (*GRB*)
- What data products are to be released upon detection?
- Can we see evidence of tidal effects in the inspiral phase, to what level of accuracy? (*waveforms, PE, testingGR*)
- Can we see evidence of tidal disruption at high frequencies (> 400Hz)? In what systems? (*waveforms, PE, testingGR*)

Projects For Regular Detection Era

A list of topics for investigation. This is work whose products will become necessary in or be completed in the era of regular detections.

- Develop an event database for astrophysics.
- What is the astrophysical rate of BNS? (*Rates*)
- Can we constrain the equation of state of NS?
- How can we estimate background in the presence of multiple signals? (*Rates*)

- Can we see evidence of deviations from post-Newtonian expansion in the inspiral phase? (*testingGR*)
- What alternative theories of gravity can we constrain? (*testingGR*)
- What cosmology can we perform? (*Rates,testingGR*)
- What is the neutron star mass function? (*Rates*)

Publication plan

We will submit a paper with the results of the BNS search for publication after each science run, or at times when there is a clear break in detector running. In the event of extended science runs prior to detection with no easily identified break in running, we will publish updated results papers every time the rate limit is improved by an order of magnitude over previous results. In the past, we have published non-detection papers of BNS searches together with the results from neutron star–black hole and (stellar mass) black hole binaries. We will continue to do so. We will publish results of dedicated GRB searches separately.

S7 publication plans

There is the possibility of a BNS detection during a three month S7 run with a BNS range $\sim 60 \pm 20$ Mpc. With no detection, the rate limit would still improve by an order of magnitude, thereby warranting publication.

Confident detection In the case of a clear detection, the CBC group will aim to submit a paper for publication within 3 months of making the initial detection, allowing time for a full LVC meeting to take place. Based on past experience with the S6 blind injection, this time-line will only be achievable if detector characterization efforts are well coupled to both the commissioning and analysis teams *before and during the run,* the effects of calibration uncertainties are understood, a sufficiently accurate and correct calibration is available, and the analysis pipelines (detection, rate measurement, and parameter estimation) are tested, compared, and reviewed prior to the start of the run. LIGO-P1000146-v16 provides a good model for what we expect from a first detection paper, including calculation of the event significance and estimation of the event parameters. Subsequent LSC-Virgo papers will provide more details about the event.

No detections If no detection candidates are found, the CBC group will submit a paper covering the updated rate estimates for the BNS, NSBH and BBH searches within 3 months of the end of the science run.

Marginal detections If significant but not outstanding detection candidates are found, then the CBC group will submit a full analysis paper of the entire run within 6 months of its end, including details of any marginal candidates. Additional time is allowed to deal with issues that may arise with marginal detection candidates which we have no experience of with previous searches or blind injections.

Beyond S7 plan

No detections The current run plan gives about an order of magnitude increase in search sensitivity in each run. Thus, if there is no detection, we will release a joint upper limit paper.

Multiple signals As the sensitivity of the detectors improves, we will expect to make multiple observations in a single science run. After the first detections, we do not foresee publishing a separate paper with each new signal, but will instead publish results at the end of short science runs ($<$ 6 months), or at predetermined intervals throughout the run.

3.2.2 Neutron star–black hole binaries

Neutron-star, black-hole (NSBH) systems are thought to be efficiently formed in one of two ways, either through the the stellar evolution of field binaries, or through dynamical capture of a neutron star by a black hole. Though no NSBH systems are known to exist, both mechanisms are known to be efficient at forming comparable binaries [94, 171, 117, 43]. Rates for the occurance of, and even the existence of, these systems are unknown, although they are estimated to be 0.03 Mpc^{-3} yr^{-1} from population synthesis of field binaries [8]. Current dynamical simulations of globular clusters predict nearly no NS-BH mergers [82], however new formation channels have been proposed that might allow higher rates [116]. The rate of short GRBs has also been estimated as > 0.01 Mpc^{-3} yr^{-1} from observations [140, 158], however it is not known what fraction of short GRBs will be NSBH mergers as opposed to BNS mergers.

The mass distribution of NSBH systems is not well known as no systems have been observed. However, it is possible to place estimates on the mass ranges by looking at other observed systems. From mass measurements of over 50 pulsars, it can be observed that, in general, the mass of the pulsar is very consistent with a value of $1.35 M\odot$ [128, 112]. However a few pulsars have been observed with larger masses, up to $2.74 \pm 0.22 M\odot$ [128], although the mass distribution for NSs is tighter for those in binaries with other NSs [112], which would presumably apply to NSs in binaries with stellar mass BHs. BH masses can be estimated through observation of ∼20 x-ray binaries where it has been possible to measure the black hole's mass. Their masses vary between ∼4 and ∼20 solar masses, however this may not be reflective of the mass distribution for NSBH systems [128]. We should prioritize these ranges of NS and BH masses in our searches, however it may be possible for NSBH systems outside of these expected mass ranges to exist and it is important to remember this when implementing NSBH searches in the advanced detector era.

The spin distribution of black holes in NSBH systems is not well known, some black holes observed in x-ray binaries have very large dimensionless spins (>0.7), while others could have much lower spins (∼0.1) [131, 128]. At birth the spin period of a neutron star is believed to be in the range of 10 to 140 ms, which corresponds to dimensionless spins ≤0.04 [128], depending on the equation of state (EOS) of the NS. However, these natal spin periods are expected to die off significantly in the long time between the formation of the neutron star and the merger of the two objects. It is possible for neutron stars to be spun up to much higher spins that will persist until merger [100], for example a ∼1 ms pulsar has a dimensionless spin of 0.4. However it is unlikely for a field NSBH system to be spun up by accretion as the BH would form first.

Searches for these objects have so far have been done during S5/VSR1 and S6/VSR2-3 within the context of the non-spinning, low mass CBC search [23, 24, 9, 14]. However, as aLIGO and aVirgo will be sensitive to lower frequencies [97, 1], it may be more important to include the effects of spin for these objects [25, 56].

Numerical relativity simulations of these systems have been performed [88, 165] and show that certain combinations of mass, spin, and NS equation of state (EOS) parameters can cause the neutron star to tidally disrupt before coalescence. Therefore these systems could power the central engines of short GRBs or produce other types of prompt or delayed EM counterparts.

Science of the first detections

With the first observation of GWs from the merger of a NSBH system, we may be able to provide the first direct evidence for the existence of NSBH binary systems. To do so, we will need to be able to confidently distinguish the purported NSBH GW signal from a BBH, or even BNS, GW signal. This will require us to investigate how confidently we could make such a statement, either through the use of only GW information (including information extracted from including higher harmonics [34] or precession effects), or from the identification of an EM counterpart.

Science of order 10 detections

Once detections of NSBH GW signals are routine, there are more scientific questions we can hope to answer. One of the first pieces of information we will have access to is the observed rate of NSBH coalescences. We will also directly have access to a measurement of the mass and the spin distribution of both the BH and NS.

Extracted information will allow us to probe different formation models by investigating how well the predicted distributions agree with the theoretical distributions. From this we may be able to determine if the majority of NSBH systems form as field binaries or through dynamical capture. This may also be possible from measurements of the eccentricity of the binary as it enters the sensitive band of the detectors. Conventional models from globular clster interactions lead to binaries with wide separations [94], which would circularize before entering the detectors' sensitive bands [157, 156]. However exceptional mechanisms that allow relativistic capture may lead to measurable eccentricities in the sensitive band of the detector. This analysis would require the development of waveforms that accurately model the eccentric binary evolution [57].

The observation of the spin distribution of the BH would provide information about two aspects of the formation of the NS for field binary NSBH systems. The alignment of the BH spin with the orbital angular momentum would tell you about the size of the kick imparted on the compact objects during their formation [109, 101, 35, 96, 89, 108, 193]. Whereas the size of the spin of the BH would provide information on the amount of accretion the BH experienced [131].

As with BNS systems, finite size effects may become measurable with collections of observations. This would aid in making a statistical NS radius and EOS measurement [155, 130]. Investigation is needed to understand if this kind of study is easier with NSBH signals than with BNS signals, NSBH systems will merge at lower frequencies, and thus these finite size effects may be easier to observe with NSBH mergers.

The identification of an electromagnetic counterpart could provide several insights. The estimated parameters from many of these systems, along with EM counterparts or lack-there-of, would allow us to test the predictions of numerical relativity for which configurations of the BH mass, spin, and NS EOS produce accretion disks that power short GRBs [88, 165]. Additionally, galaxy host identification of EM counterparts can allow us to better constrain their formation process, as with (the possibly identical) short GRB events [44]. For example for short GRBs, host galaxy information has been used to constrain their typical age; host galaxies also let us constrain the size of the kicks imparted on the binary from SN [35, 101].

In the absence of a detection of NSBH GW signals, we could place scientifically interesting constraints on the rate of NSBH coalescences. The absence of NS-BH detections will also constraint the fraction of short GRBs powered by NS-BH mergers.

Technical issues

In addition to solifidying the scientific statements we could make, there are many technical challenges that will need to be overcome associated with various stages of searching for NSBH GW signals. The open questions that need to be addressed for NSBH searches are as follows: *Input required as indicated*

- What parameter space should we search?
  - Should we restrict to the "estimated" masses above or broaden our search windows?
  - How much does the NSBH parameter space overlap that of other sources?
  - Should we search the full range of spins mentioned above? Is it okay to neglect NS spin?
- What waveforms should we use?
  - How accurate are the waveforms? (*Waveforms*)
    - NSBH waveform are very different between approximants, especially in the high mass ratio limit. We need to investigate and quantify by how much?
    - When waveforms do vary which one should we trust/use?

    - Can we compare with numerical relativity waveforms? Are such waveforms available over the full NSBH parameter space.
    - Are time-domain waveform implementations stable when integrated for long times? At what sampling frequencies is this true?
  - Should we use spinning/precessing filters? (*Searches*)
    - How sensitive at fixed FAR are our search pipelines to NSBH signals if non-spinning template waveforms are used?
    - How sensitive at fixed FAR are our search pipelines to NSBH signals if aligned-spin template waveforms are used?
    - Can an efficient precessing NSBH pipeline be deployed? (e.g., physical template family [152])
    - How do these search strategies compare fixed FAR and computational cost?
  - How fast are the waveforms? (*Waveforms, PE*)
    - For parameter estimation we will want the waveform generation to be faster than the filtering done with them.

- How do we search? (*Searches*)
  - What priors do we use on these searches? (BH and NS masses and spins)
  - Can these waveforms be compressed to reduce computational cost [70, 69, 71, 87, 99]?
  - At fixed computational cost, at fixed FAR, is it better to do a coincident or a coherent search?
  - How will this change between low-latency and offline searches?

- How accurately can we estimate parameters? (*Waveforms, PE*)
  - Sky localization:
    - How accurate can we be after 3 hrs, 6 hrs, 1 day, and 7 days?
    - How does ignoring spin affect sky localization?
  - Mass estimation:
    - Do precessional effects help?
    - (How quickly) Can we can we distinguish between NSBH and BBH signals?
    - How well can we measure the spin magnitudes/orientations of the BH and the NS.

- Event significance and rate estimation (*Rates*)
  - To confidently claim a NSBH detection we will be required to confidently estimate very low false alarm rates. This is not an NSBH specific problem though and is likely a more pressing issue for BNS searches, where the first detection is most likely to be made.
  - To be able to place reliable limits on NSBH merger rates we will require large-scale simulation campaigns to evaluate the search sensitivity. Given the potentially very large cost of performing a NSBH search, it is vital to be able to do this efficiently.

- DetChar and DQ requirements: (*DQ, searches*)
  - How important are phase and amplitude calibration for determining masses, spins, and sky locations?
  - What types of glitches would NSBH filters be susceptible to?

3.2.3 Stellar mass black hole–black hole binaries

The main feature of this source is the large space of possible intrinsic parameter values (component masses and spins) due to wide uncertainties in current astrophysical knowledge. This presents challenges in carrying out and optimizing our searches and interpreting their results; but also opportunities to extract significant new information about the sources, well beyond that provided by EM observations, and to distinguish between astrophysical models of stellar collapse and binary evolution.

There are no known stellar-mass binary black holes; their existence is predicted from population syntheses of field populations, and through dynamical modeling of dense stellar clusters. For massive field progenitors, the common envelope and mass-transfer phases which are required in order to produce BBH merging within a Hubble time [142, 41] may lead to strong correlations between the properties (spins and masses) of the components of field binary black holes. Binary black holes may also be formed dynamically, either in dense globular clusters [82, 83, 145] or galactic nuclei. The components of such binaries have generally evolved in isolation, thus the component properties may be largely independent of each other and of the orbital parameters. Binaries formed near galactic nuclei may also have significant orbital eccentricity [144].

The mass distribution of Galactic stellar mass BH has been estimated in [84, 148, 133]. X-ray observations constrain the mass of a few BH to lie in the range $5 \leq M_\bullet/\mathrm{M}_\odot \leq 20$, which has been confirmed with dynamical mass measurements for 16 black holes. An apparent lack of BH masses in the range 3–5 $\mathrm{M}_\odot$ [84] (though, see [114]) has been ascribed to the supernova explosion mechanism [40, 91].

The most massive observed stellar mass black holes are found in extragalactic high-mass X-ray binaries, IC10 X-1 and NGC300 X-1, both with BH masses in the $20 - 30\,\mathrm{M}_\odot$ range and with Wolf-Rayet star companions [176, 74]. These systems are likely to be field stars that formed in low-metallicity environments. Population synthesis based on recent stellar wind models allows for isolated black hole masses up to $\sim 80\,\mathrm{M}_\odot$ [91, 42], though common envelope binary evolution [81] can have a strong influence, reducing the maximum expected component mass, at low metallicity, to $\sim 60\,\mathrm{M}_\odot$ and total mass to $\lesssim 100\,\mathrm{M}_\odot$ [80]. There is no direct observational limit on BBH mass ratios; for a minimum mass of $3\,\mathrm{M}_\odot$ we have $1 < q \lesssim 25$. Current models of isolated binary evolution favor $q \lesssim 4$ [80], though future studies may lead to the re-assessment of such priors.

X-ray observations of the spins of accreting black holes in binary systems, while technically challenging, indicate a fairly uniform distribution over the entire range $0 \leq a \equiv S/m^2 \leq 1$ [137, 175, 132, 123, 93, 76, 118]. Indications that spin-orbit misalignment in field binaries may be small come from observations of the microquasar XTE J1550-564 [178], and population synthesis models of Fragos et al. [89].

The estimated rates of BBH coalescence have large uncertainties: current estimates are between 1×10^{-4} and $0.3\,\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$, with a best estimate of $0.005\,\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$, for systems consisting of two $10\,\mathrm{M}_\odot$ black holes [7]. Observations from initial LIGO and Virgo have placed an upper limit about a factor of 4 larger than the "high" rate estimate [14].

Science of the first detections

The first detection from this source would prove the existence of a previously unobserved type of binary and constitute a major discovery. Given the large parameter space, the first few confident detections could begin to distinguish between astrophysical models of compact object populations. At least one intrinsic source parameter will be well measured (chirp mass, in the low-mass limit); depending on the measured values, nonzero rates could be estimated to within a factor of a few, while upper limits in regions of parameter space where *no* detections are made would be significantly improved, potentially ruling out classes of model or allowing us to tune the parameters of population synthesis models [147]. If one of the first few detections has moderately high SNR, we may find strong evidence for at least one spinning component, independently establishing the existence of black hole spin in GR.

Science of order(10) detections

With several detections we begin to establish an observational distribution over chirp mass, and, possibly, spin or mass ratio, further constraining models of BBH populations [58]. Some of the louder signals could give indications for or against precessing component spins, and/or allow component masses to be well estimated, allowing us to test competing models of binary formation, and possibly test the hypothesis of a "mass gap" [91] between neutron stars and low-mass BH. Rare signals could also be seen outside the main mass distribution. As the mass distribution carries information about most input physics, even the approximate answer provided by order(10) detections will allow us to rule out many alternatives [129, 146], allowing inferences on the environments (metallicity) of star formation and stellar winds, on mechanisms of stellar collapse and binary evolution (supernova kicks, mass transfer episodes) and possibly on kicks from BBH mergers for dynamically formed binaries.

A more speculative aim is to test the validity of our waveform models based on PN expansion, numerical relativity in the strong-field regime and BH perturbation theory. Establishing a deviation from the predictions of GR, for example the Kerr description of BH, would be a major discovery, though requiring many technical challenges to be brought under control.

Overall search issues and strategy

Given the very large parameter space of signals, the BBH search will naturally tend to split into several parameter regions, and possibly into independently-tuned pipelines using different filter waveforms and methods. We then need to determine in which regions different searches or pipelines are more efficient, considering also false alarm rates (FARs), and use this information to plan the search as a whole.

As in present searches, we may calculate separate FAR estimates for each parameter region or pipeline. This can lead to a trials factor problem where false alarms from templates corresponding to a-priori less favoured signals, for example at high mass ratio, penalize the significance of likely first detections. We will study strategies for ranking candidates in order to improve the prospects of first detection, given weak astrophysical priors, while not excluding the possibility of finding unexpected signals.

After the first few detections, the scientific focus is likely to shift to making astrophysical deductions on rates and parameters from a broad range of searches. Bayesian inference will find a natural application in combining information from several pipelines with varying efficiencies over parameter space. The overall search plan in this era is likely to be constrained by computational cost, for instance in measuring the search efficiencies over the parameter space, or in accurately determining the parameters of spinning signals.

Waveforms and search algorithms (*Waveforms, Searches*)

The main goal here is appropriate choice and placement of templates over the parameter space. Where should the boundary between using inspiral-only templates and IMR templates be, given the differences in search sensitivity and computational cost? Should we search with templates including the effects of spin or higher signal harmonics? How should templates be placed in higher-dimensional parameter space, or when the metric may not be analytically computable? An alternative to current geometrical placement methods is the "stochastic" template bank [98]: a near-term goal is to further develop this method and evaluate its possible benefits.

Aligned-spin waveforms / searches : Recently, IMR waveforms for aligned-spin systems have been developed [172, 180], and the metric for aligned-spin inspiral signals has been calculated [55]. Further work is required to implement aligned-spin search pipelines: outstanding questions include IMR template placement, choice of waveform model over parameter space, and comparisons with the non-spinning search.

Precessing waveforms / searches : Precession effects from mis-aligned spins may be common for BBH [107, 145]. Detecting precessing systems involves several challenges. Past attempts at searching for precessing inspiral signals involved a large increase in the number of template degrees of freedom, leading to higher FARs [184, 59], though some highly precessing signals may gain enough SNR to offset this increase.

Future studies should develop improved methods to describe [56] and search for precessing signals, and quantify the potential benefits from an optimized precessing search.

The current phenomenological precessing IMR waveform family [163] is only tuned on a very small region of the parameter space: significant work is needed to develop more generally valid models, intersecting with efforts in numerical relativity and analytical relativity (NRAR) to simulate and describe precessing systems. Such developments are important to fully realize the potential of parameter estimation on BBH.

Waveforms including higher harmonics : EOBNR waveforms for non-spinning systems incorporating modes other than $l = 2, m = 2$ have recently been developed [150]. Higher harmonics are expected to play a significant role for asymmetric systems ($q \gg 1$), though such sources are not favoured by current models of binary evolution. Ongoing studies should determine how well existing dominant-mode templates fit these more realistic waveforms, and over what parts of parameter space they could influence detection prospects.

Systems with orbital eccentricity : While most BBH are expected to have negligible eccentricity in the detector's sensitive frequency band, some coalescences occuring in high-density environments may retain significant eccentricity [144]. For these systems we may study whether a templated search can be effectively carried out [57, 72] or an unmodelled search is preferable.

Data Quality (*DQ*)

The wide range of BBH waveforms (ranging from minutes to fractions of a second in duration) presents severe challenges in understanding and mitigating the effects of non-Gaussian transients in data. Future studies will model such transients, quantify their effects on the BBH templates, and develop methods to better use data quality information in BBH searches, either by category vetoes or by modifying the ranking of triggers to account for the likely "glitchiness" of data.

Event significance and rate estimation (*Rates*)

To make confident first detections it will be necessary to reliably estimate very small FARs; several methods for improving the precision of background estimation are under current investigation. Signal-background discrimination is a significant challenge for BBH due to the strongly-varying response of templates over the parameter space to detector artefacts. Multivariate classifiers have been investigated for this task: it remains an open question how best to make use of such techniques.

BBH searches may have significant overlaps with NSBH or unmodelled burst searches, as well as within the BBH parameter space itself, thus a strategy is needed (*e.g.* [47]) to evaluate the significance of candidates for which several pipelines may be sensitive.

To infer astrophysical rates over the BBH parameter space and determine the implications for astrophysical models, we require accurate measures of search sensitivity. Priorities here include improving computational efficiency when simulating large numbers of signals, and developing more powerful methods to draw astrophysical inferences from the results of our searches.

Estimation of source parameters (*PE*)

The information gained from accurate estimates of source parameters will be crucial to answer astrophysical questions. If we are able to measure BBH component masses, the possible "mass gap" between $3 - 5\,\mathrm{M}_{\odot}$ can be investigated. Distingishing between precessing *vs.* spin-aligned BBH will also have strong astrophysical implications. Studies are in progress to determine the expected accuracy of such measurements in the Advanced era, and point to areas where further development is needed.

Testing strong-field dynamics of GR (*testingGR*)

Uncovering deviations from predicted GR waveforms with BBH signals is an exciting possibility, but presents many challenges due to systematic uncertainties in waveform models, the large parameter space of possible GR signals, and instrumental noise artefacts. Studies have been carried out [120], and more are needed, to determine what statements can be made in the Advanced detector era.

3.2.4 Intermediate mass black hole binaries

Gravitational-wave sources:

Intermediate-mass black holes (IMBHs) with a mass between ~ 100 and $\sim 10^4$ solar masses occupy the mass range between stellar-mass and massive black holes (see [138] for a detailed review). There is growing but still ambiguous evidence for IMBH existence, including observations of ultra-luminous X-ray binaries (e.g., [85]). A number of formation mechanisms have been proposed, which may lead to the existence of IMBHs of a few hundred solar masses in globular clusters. Such IMBHs are likely to form binaries which can be hardened through dynamical interactions to the point of merging through gravitational-wave radiation reaction. If IMBHs in this mass range are generic, then Advanced LIGO and Virgo can detect gravitational waves from their coalescence [7]. Compact binary mergers involving IMBHs can be divided into two categories:

(i) *Mergers of IMBH binaries.* Two intermediate-mass black holes can merge either if two are born in the same cluster [90], or if their globular-cluster hosts merge [31]. Another potential source is the merger of two lighter seeds of massive black holes [92], though these are likely to occur at too high a redshift to be detectable by advanced detectors. The rate of IMBH binary (IMBHB) mergers is not well understood, largely because of the uncertainty in the occupation number of IMBHs in globular clusters; [90] predict up to one detection per year by advanced detectors. An approximate upper limit can be obtained by assuming that no globular cluster should have more than $O(1)$ such IMBHB mergers; a space density of ~ 1 globular cluster per Mpc^3 with a typical age of 10 Gyr yields up to one detection per year for the high-sensitivity version of the early aLIGO noise spectrum. Typical spins and eccentricities are uncertain. Given the IMBH mass range and the low-frequency noise spectrum of advanced detectors, gravitational waves where the inspiral portion of the IMBHB waveform are likely to be below the low-frequency sensitivity cutoff, with the detectable signal is dominated by the short merger and ringdown phases [153].

(ii) *Intermediate-mass-ratio inspirals.* If an IMBH exists in an environment where it is surrounded by neutron stars and stellar-mass black holes, such as a globular cluster, intermediate-mass-ratio inspirals (IMRIs) of compact objects into IMBHs become likely sources of gravitational waves [54]. Advanced LIGO and Virgo could detect tens of such events per year [126]. The dominant capture mechanism is likely to involve gradual binary hardening via three-body interactions, meaning that the binary eccentricity will be very low in the GW detector band [126]. Spins of IMBHs that grow primarily through such minor mergers should not exceed ~ 0.3 [125]. For systems with very asymmetric mass ratios, the power emitted during the merger and ringdown portions of the waveform will be suppressed, so the late inspiral may dominate the signal-to-noise ratio.

Waveforms:

For IMBHBs, accurate waveform including merger and ringdown are critical. Several waveform families already exist, such as PhenomIMRB & EOBNR (see Section 3.4.2) but more waveform accuracy studies are needed specifically for waveforms covering the IMBHB parameter space.

Accurate waveforms for IMRIs are particularly difficult, because the PN approximation is expected to fail for binaries that spend so many cycles close to the ISCO, while the IMRI mass ratio is not extreme enough for the mass-ratio expansion to be accurate [127]. EOBNR waveforms may be accurate in this regime; other approaches include hybrid waveform families [102]. Waveform accuracy studies are made difficult by the absence of accurate numerical-relativity waveforms at IMRI mass ratios, although there have been promising recent advances in numerical simulations of IMRIs [139]. Nonetheless, good overlaps between the hybrid waveforms and inspiral-only EOBNR waveforms indicate that existing waveforms may allow an IMRI search without extreme loss of sensitivity [**?**].

In the future, waveforms including precessing spins, inspiral-merger-ringdown phases, higher harmonics, and possibly eccentricity will be highly desirable for the development of searches and interpretation of search results.

Detection and parameter estimation:

The following are some of the special challenges presented by the detection and parameter estimation of binaries involving IMBHs, and the available avenues of addressing them:

- The low frequency of sources involving IMBHs places a greater emphasis on low-frequency detector performance. (*DQ, Searches*)
- The short signal duration of IMBHB sources, and the possible semblance of IMRIs to instrumental artifacts, lead to stringent data quality requirements (see Section 3.4.1). (*DQ, Searches*)
- Can template-bank-based inspiral-merger-ringdown searches [11] be extended to higher masses? (*Searches, Waveforms*)
- The parameter space spanned by the IMBHB sources can be also explored with (coherent) burst searches (see Section 4.4.7), which do not rely on accurate GW waveforms.
- The relative sensitivity and utility of ringdown-only searches (e.g., [22]) requires further study. (*Searches*)
- Is a dedicated search necessary for IMRIs?
- The accuracy of parameter inference, including mass and spin measurements, needs to be explored in this mass range (see Section 3.4.8). This includes challenges with parameter estimation when using templates with potentially significant systematic uncertainties (for IMRIs) and technical developments necessary to run parameter-estimation tools on triggers provided by burst searches. NINJA-style studies can lead to improved confidence in the ability to accurately infer IMBHB parameters. (*PE, Waveforms*)

IMBH Science:

A single detection of a $100+\ M_{\odot}$ system could provide the first unambiguous confirmation of the existence of IMBHs. This alone would be a major discovery.

Further detections could allow us to investigate the prevalence of IMBHs in globular clusters and cluster dynamics.

IMBHs could provide particularly exciting ways of testing general relativity (see Section 3.4.9). For example, independent measurements of the IMBH mass quadrupole moment from IMRI gravitational waves would probe the IMBH spacetime structure [54, 168]. Ringdown studies of IMBHs could similarly test whether IMBHs are really Kerr black holes [104].

3.3 Searches for Binary Coalescences in the S1-6 and VSR1-4 data

The CBC group has now completed searches for binary coalescence with total mass between $2\mathrm{M}_{\odot}$ and $25\mathrm{M}_{\odot}$ (including binary neutron stars with component mass as low as $1\mathrm{M}_{\odot}$ using its flagship *ihope* pipeline and all Initial LIGO/Virgo data. The results have been published in a series of papers: S1 [16], S2 [17], S3 and S4, [20], S5+VSR1 [23, 24, 9] and S6+VSR2/3 [14]. No detections were made, but a 90% confidence upper limit on the rate of binary neutron star coalescence of $1.3 \times 10^{2}\mathrm{Mpc}^{-3}\mathrm{Myr}^{-1}$ was determined using this data.

A low-latency search was performed in addition to the *ihope*-based search using the triple-coincident data from S6/VSR3. Using the *MBTA* pipeline a latency of around three minutes from data recording to sky localisation was achieved, and the resulting triggers were sent for electromagnetic followup by several telescopes [105].

A number of additional searches have been performed for: binary black hole systems in S2 [18]; spinning black hole and neutron star binaries in S3 [21]; the ringdown of black holes formed after coalescence of binary systems, in S4 data [22], binary black hole systems in S5 data [11].

Finally, we have conducted searches for gravitational waves associated to short gamma ray bursts in S5-VSR1 [10], S6-VSR2/3 [53] as well as for two GRBs whose localizations overlapped nearby galaxies: 051103 [13] and 070201 [19].

There are two remaining CBC searches for gravitational waves using the data taken by the initial LIGO and Virgo detectors that we describe briefly below.

3.3.1 Search at times of IPN GRBs

The preferred progenitor scenario for short-hard gamma ray bursts (GRBs), is the merger of a neutron star or black hole-neutron star binary system. This motivates a search for gravitational waves using LIGO S6 and Virgo VSR2/3 data for CBC signals associated with GRB events. Searches for GRBs identified by Swift and Fermi have been completed on the S5-6 and VSR1-3 data. The interplanetary network (IPN) is also able to detect and localize GRBs, manual followup is required to analyze the IPN data to compute a sky localization. A list of IPN GRBs detected during S5-6 and VSR1-3 has been produced and a CBC search for gravitational waves associated to the short IPN GRBs is well underway.

3.3.2 Ringdown search

For high mass binary coalescences ($M \gtrsim 100 M_{\odot}$) , the majority of the power received by the LIGO and Virgo detectors will be from the ringdown part of the coalescence. Therefore, the search for coalescencing binary systems can be done looking for the final ringdown which has a known and simple waveform (a damped sinusoid), whose parameters (frequency and damping time) can be related to the final black hole mass and spin. The uncertainty in the theoretical predictions for how the inspiral, merger and ringdown phases couple into a single waveform governed by a single set of source parameters (masses and spins) leads us to pursue such a ringdown-only search. In addition to binary coalescence, other mechanisms for strongly perturbing an astrophysical black hole can also result in an observable ringdown.

This search is being run on the S5/VSR1 (H1,H2,L1) and S6/VSR2-3 (H1,L1,V1) data using an improved and re-tuned analysis. The analysis is nearing completion and a results paper is in preparation.

3.4 Analysis techniques and strategies

Here, we outline the major parts of the analysis that is required to identify gravitational wave signals from CBC in the detector data as well as to characterize the signal and extract the relevant gravitational and astro-physics.

3.4.1 Data quality

The method of matched filtering upon which the CBC searches are based is optimal in the case of stationary Gaussian noise. However, the noise of the real detectors deviates in several ways from this simple model. The noise power spectra of the detectors changes over minute and hour timescales. Also, there are a large number of glitches in the data, which are non-Gaussian transients typically on sub-second time scales. These deviations from Gaussian noise can have important negative impacts on CBC search sensitivity, background characteristics, and parameter estimation.

The Detector Characterization group is responsible for understanding these non-ideal characteristics of the detector and working together with the CBC group and the detector groups to minimize their impact on

CBC searches. For example, the Glitch sub-group produces flags which predict the occurrences of glitches in the data. The CBC Data Quality group is responsible for studying:

What kind of data quality issues are the advanced detectors likely to have? How do each of these data quality issues affect each of the CBC searches? The length of the templates is probably the primary determining factor in what data quality issues a search needs to worry about. The binary neutron star search is likely to be most affected by non-stationarity like slow changes in the PSD over time, and non-stationary lines. Binaries containing black holes have shorter templates which will be more affected by glitches. All searches should also have a way of cutting out very loud glitches from the data so they don't corrupt the PSD or the filters. Software must also be developed to simulate expected and observed types of data quality issues, so that we can better understand how searches and parameter estimation are effected by glitch classes. And recolored S6 and VSR2-3-4 data as well as engineering run data also provide excellent tests of our understanding of how realistic data affects the search.

Find the best way to incorporate DQ information into the search, using vetoes or incorporating the information into the likelihood ranking. Data quality information should be incorporated in a more sophisticated way than just putting integer second vetoes around the glitch. We need a good map from the glitch characteristics (its frequency, Q, and amplitude) to the time and SNR of the inspiral triggers it will cause. The same goes for non-stationarity, or long-lived rumbliness. We should have both some improvements on the traditional veto method, and some developments of folding in the DQ information to the ranking statistic or feeding it into a classifier.

Improve signal-based vetoes based on likely behaviors of the instrument. In Gaussian noise and in a single detector, the SNR is the optimal statistic. Searches in real data require signal-based vetoes, but which of these vetoes are used and how they are tuned depends entirely on how the noise deviates from Gaussian. We must evaluate our various chi-squared and other signal-based tests and optimizing their tuning, and come up with other signal-based vetoes as well. Another ability that should be developed is to matched filter for known glitch classes, so we can ask "does this look more like an inspiral, or more like this known type of glitch". This would most likely only be a last resort if there were a significant type of glitch that could not be eliminated by any other type of method.

Develop measures of the effect of data quality issues on the search sensitivity (and the improvement when vetoes are applied). The most important thing is testing. We need to rigorously evaluate how well our search is doing. Then we use that to tune our use of data quality information - whichever way makes the search most sensitive is the way that we use. This interacts with efforts to improve background estimation. It's easy to miss things that hurt you at the 1/1000 year level if you've only got background out to the 1/100 weeks level. We also should try to know what things in the single-detector background are going to hurt the full search. This information must be fed back to the detector characterization group for investigation and mitigation.

High-priority goals for the next year

- Continue to participate in Engineering Runs using recolored data from advanced detector subsystems (or from previous science runs). Identify issues in this data that affect the CBC searches. Use this information to improve the search for simulated signals in this data and to make confident detections of these simulated signals.

- Develop an understanding of how glitches or non-stationarity affect CBC searches in advanced detector noise. Compare these expectations to examples seen in the Engineering Runs or Mock Data Challenges.

- Continue to develop software to simulate data with simplified models of data quality issues. Examples are non-stationary PSDs, jitter lines and lines with sidebands, scattered light, and simple (or observed) glitch models.

- Prototype tools to rigorously evaluate the sensitivity of the search in real data.
- Continue to develop and test methods to remove very loud glitches in the data so that they have no effect on the power spectrum estimation or matched filtering. Investigate whether detection confidence can be improved by cleaning glitches from the data to prove that these glitches did not cause a particular CBC trigger, as was done with a candidate in ER3.

Goals for the advanced detector era

- Understand in detail how all important types of glitches and data quality issues affect the search.
- Given an event or detection candidate in imperfect data, be able to very confidently determine whether it was caused by a data quality issue. It should be possible to detect even in data with glitches if we can prove that these glitches could not have caused the trigger.
- Develop the ability to use low-latency data quality information in the online search.
- Optimally use data quality information in ranking event candidates rather than using on/off integer second vetoes. This will most likely involve likelihood or multivariate classifier methods.
- Have simple-to-use software that rigorously evaluates the sensitivity of the search in imperfect data, with and without data quality information applied. This will make it very simple to determine whether some new data quality flag, method, or tuning of the search is an improvement.
- Achieve a much better cleaning of the search background, and approach as closely as possible the Gaussian limit.

3.4.2 Gravitational waveforms emitted during binary coalescence

Gravitational waves emitted from compact binaries with total mass $\sim 1 - 10^3\, M_\odot$ are considered prime detection candidates and could potentially yield the most information about their sources and the underlying laws of gravity, as accurate waveform models are available. These waveforms can be used as templates for a matched filtering search which can extract weak signals buried in noise. The waveforms are also used in injection studies, which are important for assessing detection efficiency and estimating the false alarm rate of candidate events. Lastly, after detections are made, the waveforms will be used within Bayesian inference pipelines, which will measure the probability distribution for source parameters such as the masses, spins and sky location, see sec. 3.4.8, as well as possibly fundamental gravity parameters, see sec. 3.4.9.

Waveforms calculated within the post-Newtonian (PN) framework are thought to provide accurate representations of the adiabatic inspiral when the two bodies are relatively widely separated [50, 62]. Numerical relativity has achieved simulations which cover the late portion of the inspiral, the merger of the two bodies, and the ringdown as the merged body settles into a final steady state, with excellent agreement among different groups and independent codes [161, 38, 66, 162, 103, 95].

The final ringdown phase can also be described by black hole perturbation theory [46]. Analytic waveform models have been developed which combine insights from post-Newtonian theory, numerical relativity and black hole perturbation theory to describe the entire inspiral-merger-ringdown (IMR) evolution: these include the Effective-One-Body (EOB) framework [60, 61, 63, 64, 75, 151, 150, 180] as well as phenomenological or hybrid approaches [27, 28, 172, 163].

Waveform development remains a very active area of research, as analytic waveform models are frequently improved through the inclusion of new and better descriptions of physical effects such as spin couplings and precession, higher harmonics of the orbital frequency, tidal deformability of neutron stars in binaries, memory effects, eccentricity as well as non General Relativity effects.

Furthermore, numerical simulations have until recently focused mostly on non-spinning or spin-aligned binaries of comparable component masses [149]. However, these simulations are being pushed to more difficult cases of extreme mass ratios, large spin magnitudes and generic, precessing spin configurations. As more simulations are performed, analytic IMR models are re-calibrated so as to have the best possible agreement with all of the available simulations.

The continued development of new and improved waveform models is an important goal for the CBC working group, also in collaboration with numerical and analytical relativists. More accurate waveform models will increase the chances of detection and improve the quality of science that can be done with those detections. The development of many waveform models will also allow us to gauge systematic errors by examining the differences between models.

A wide range of waveform families have been implemented within the LALSimulation library of LAL. Any of the waveforms can be accessed through a common interface for use as search templates, injected signals, or within Bayesian inference pipelines. Users can easily try several different waveform families and control the order to which spin, tidal, phase and amplitude corrections are included to assess their importance and find the most appropriate waveforms for their needs. A key goal for the next year will be a full code review of the waveform routines in LALSimulation. This will include verifying the codes are bug-free and implement what was intended in the literature, checking that the waveforms are self-consistent and respect any symmetries they possess, and checking that a model is consistent with other related waveform families. A longer term goal is to add more flexibility in the tables specifying waveform parameters, to let new waveform approximants and physical effects be introduced smoothly in the pipeline.

High-priority goals for the next year

- Perform a full code review of the waveform routines within the LALSimulation library. Review goals should include quantitative comparisons among different waveforms in overlapping regions of validity.
- Implement tools for transforming a collection of spin-weighted spherical harmonic modes, finding “preferred” or co-rotating frames of precessing binaries and performing related data analysis calculations.
- Comprehensively assess the faithfulness and effectualness of existing IMR models using newly available NR simulations.
- Develop new waveform families:
    1. Implement and test frequency-domain, precessing waveform models.
    2. Implement a new spin-dominated waveform model for extreme mass ratio, spinning binaries and compare to other spinning waveform models.
    3. Implement a spinning, precessing EOB model (SEOBNRv2).
    4. Implement a frequency-domain, aligned spin EOB model.
    5. Implement additional PN inspiral-only, precessing waveform families (SpinTaylorT1, Hamiltonian-based models).
- Improve upon existing waveform families:
    1. Compute higher PN order spin effects and include them in waveform models.

2. Enable higher harmonics for the widely-used TaylorF2 model.
3. Improve the SEOBNRv1 model by calibrating it across the full spin range and including higher harmonics.
4. Speed up all existing time-domain EOB models.

Goals for the advanced detector era

- Seek further waveform speedup, especially through use of GPUs.
- Include eccentric waveforms, memory terms and all possible physical effects not included in waveform models currently available in LAL.
- Modify tables currently used to store waveform parameters in order to allow more flexibility in parameter specifications.
- Work with the various source groups to determine the best available waveforms for each source.
- Perform studies to quantify the level of systematic bias from waveform uncertainties due to the inclusion or omission of higher harmonics of the orbital frequency, tidal effects, eccentricity and other physical effects.
- Waveforms may be also modified by the effects due to soft neutron star equations of state (which affect the waveform at frequency larger than 450Hz [179]). Inclusion of such effect requires some more analytical modeling.

3.4.3 “Streaming” analysis pipelines

Since 2008 the LSC has been preparing a stream-based CBC pipeline that aims to ultimately reduce the latency of compact binary searches down to $\lesssim 10$ seconds despite the challenges presented with longer duration signals in the advanced detector era. This will be a gradual process with the first advanced detector science runs likely having $\lesssim 1$ minute latency. Rapid searches for BNS and NSBH systems, combined with rapid detector characterization, source localization and candidate event alerts, will facilitate the LSC and Virgo’s role as a member of the broader transient astronomy community and will hopefully enable the association of transient GW events with transient electromagnetic events. It also serves to provide rapid feedback to the GW community regardless of EM counterparts.

The project that aims to achieve this goal is known as GstLAL, which is a library that relies on the open source signal processing / multimedia library Gstreamer and the gravitational wave analyis library LAL. Gstreamer provides the infrastructure to quickly create and deploy stream-based analysis work flows that handle processing GW detector data with near real-time performance. LAL provides the waveform generation codes, simulation engine, and many other tools that have been developed by the LSC and Virgo. In addition to creating a software library, a substantial amount of new algorithm development was necessary to enable this project [70, 71, 69, 68].

In addition to the low latency CBC search that GstLAL provides, the project also maintains an “off line" pipeline that allows one to analyze older data efficiently using the same tools developed for the low latency analysis.

Our main goal over the next year is to continue testing several advanced detector observing scenarios through engineering runs and participation MDCs. This process will culminate in a full review of the analysis pipeline.

Engineering runs are designed to ramp up critical analysis systems as Advanced LIGO and Virgo are being constructed and commissioned. The GstLAL CBC search participated in the first advanced detector engineering run and will continue to participate in biannual engineering runs for the foreseeable future. The GstLAL CBC search development will continue towards the goal of meeting the science metrics established by the CBC group for low latency analysis. In addition, GstLAL CBC searches will participate in Mock Data Challenges (MDCs) to validate that the analysis is capable of obtaining the expected sensitivity to compact binary sources across all relevant parameter spaces required for the detection of gravitational waves using simulated data from various proposed advanced detector noise curves [**?**].

High-priority goals leading up to 2015

- Continue testing long filters (15 Hz = $\sim$ 10 min for 1,1 $M_{\odot}$; 10 Hz = $\sim$ 30 min for 1,1 $M_{\odot}$) and large template banks brought on by increased low frequency sensitivity.
- Provide search latencies that are no worse than S6 ($\leq$ 2 min) despite the increase in filter length.
- Provide a filter length independent search latency so that filters which are 30 min long have results at the same time as filters that are 1 min long.
- Online detection level false alarm probability estimation with 5 sigma confidence capability at the time the event is reported.
- Deal with data drop outs, data corruption and data glitches that are inherent in a low latency analysis.
- Report events greater than some significance threshold to gracedb reliably so that the astronomical alert system can take over.
- Verify triggers are sufficient for parameter estimation and sky localization follow up.
- Sub-solar-mass search - The GstLAL CBC effort will prepare to analyze S5 and S6 data for compact binaries with component masses less than 1 solar mass pending successful review of a search proposal and analysis plan. This is a yet unsearched dataset for such systems and also offers a unique opportunity to test advanced detector algorithms and technology due to the similarities to an advanced detector neutron star search (i.e. long waveforms and large template numbers).
- Intermediate-mass-black-hole (IMBH) search: The gstlal CBC pipeline will participate in a joint analysis of IMBH sources with the burst group.

Goals for the advanced detector era

- Expand the signal parameter space to include the effects of spin, merger, ring down and any other effects that are critical for detection of CBC signals as source modeling improves
- Further reduce the latency associated with CBC searches and integrate full, global GW detector network as instruments come online.

3.4.4 Multi-Band pipelines

The Multi-Band Template Analysis (MBTA) is a low-latency implementation of the standard matched filter that is commonly used to search for CBC signals. It divides the matched filter across two frequency bands (or more). Thus the phase of the signal is tracked over fewer cycles, meaning sparser template banks are needed in each frequency band, and a reduced sampling rate can be used for the lower frequency band, reducing the computational cost of the FFTs involved in the filtering. The full band SNR is computed by coherently combining the matched filtering outputs from the two frequency bands.

MBTA was used during S6/VSR3 to perform an online CBC search as part of the EM follow-up program. It delivered triggers with a latency of a few minutes, the most significant of which leading to alerts being issued.

The developments and investigations needed to upgrade the MBTA pipeline and search in view of the advanced detector era are briefly described below.

- Technical improvements
  - Simplify the software installation procedure.
  - Improve the robustness of the pipeline and its error reporting.
  - Investigate the possibility to use multithreading, which would leverage the increased number of cores per machine expected in the future, and would make it easier to balance the load between processes.
  - Upgrade the pipeline to work with four detectors (or more).
- Improving the latency

  As templates get longer with the increased bandwidth expected in advanced detectors, some actions are needed to keep the latency low. A trade-off can be found between computing efficiency and latency by adusting some configuration parameters:
  - Reduce the size of the FFT in each of the frequency bands
  - Increase the overlap between successive FFTs
  - Increase the number of frequency bands
- Optimizing the sensitivity

  Several possibilities need to be explored.
  - In case of detectors with different sensitivities, the observed volume may be optimized by adjusting the various single detector thresholds, possibly in an adaptive way.
  - It should also be possible to increase the efficiency by implementing a low threshold search hierarchically, triggered by the observation of a loud trigger in at least one detector.
  - The possibility to implement an additional step based on a coherent search across detectors should also be investigated.
  - The search configuration needs to be optimized as a function of the detectors noise spectra. Especially, there is a trade-off to be found to choose the low frequency bound ot the search - lowering if allows to increase the SNR but also requires a denser template bank, thus increasing the probability of a false alarm. One can also consider configuring the search with an extra frequency band at very low frequency, used in a hierarchical way to add to the SNR of a trigger detected in the other frequency bands.

  - The consistency tests - the chi2 cut at the single detector level and the mass cut at the coincidence step - need to be tuned and optimized for the sensitivities and glitchiness of the advanced detectors.
  - The trigger clustering step needs to be optimized to avoid trigger "pile-up" when the trigger rate increases (due to the larger template bank and/or detector glitchiness).
  - Investigations are needed to understand if the sensitivity to sources with significan spin can be improved by using spinning templates.

- Assessing the parameter estimation capabilities of the pipeline

  It is important to understand how close one can get to the instrinsic timing accuracy of the detectors - depending on their bandwidth - since timing accuracy translates into sky localization ability.

  The question of spin also needs to be looked at from this perspective. Adding a second search step with spinning templates might be worthwhile to pass on more accurate timing information to the sky localization software.

3.4.5 FFT based pipelines

Offline analysis in the CBC relies heavily on the *ihope* pipeline. This pipeline [36] performs matched filtering of data in the frequency domain, relying on the fast Fourier transform (FFT), and it and its predecessors have been widely used in several published or forthcoming CBC analyses setting upper limits in both blind searches and triggered searches [9, 11, 14, 23, 24, 10, 6].

As the advanced detector era approaches, this pipeline must be maintained and developed to accommodate longer templates and larger template banks necessitated by the improved detector noise profile, as well as continue to support a variety of different waveform families as appropriate for different potential sources. In each of these cases, it must provide a sensitive search with an accurate characterization of candidate event significance.

To deal with these new challenges, several different strategies are being employed or developed:

- Larger template banks, with each template significantly longer, will be necessary for binary neutron stars in the advanced detector era. As this will increase the computational cost of such searches, the computational power of graphical processing units (GPU) is being investigated for use in such searches, as well as an investigation of how the changing the low-frequency cutoff (and hence the template length) affects the recovered signal-to-noise ratio, to determine how much longer templates should be.

- The current pipeline looks for coincidence between detectors of at least two events above threshold. When such a coincidence is found, candidate triggers are followed up with a second stage of the search that employs a variety of signal consistency tests to winnow the candidate triggers to a set that is quasi-Gaussian and can be evaluated for statistical significance. Though computationally cheaper than some alternatives, this approach can complicate event significance estimation. So alternate pipelines being developed are:

  - Single-stage pipelines that apply signal consistency vetoes to all triggers.
  - The use of exact mass coincidence between detectors, rather than the ellipsoidal algorithm currently used (and which in particular would need to be extended to higher-dimensional parameter spaces when spin-effects of sources must be considered).

  - Coherent pipelines have proven more sensitive in triggered searches [10, 6] and are also being explored for all-sky searches. As a naive implementation is computationally very expensive, alternatives in both the formulation of the search as well as the possible speedup such a search might receive when implemented on a GPU are both being investigated.

- Experience with the S6 science run has shown that more robust PSD estimation and automatic excision of glitches could be beneficial, and strategies for doing so are under investigation.

- Finally, in order to rapidly turn-around any particular candidate event, it will be important to automate extended background estimation.

Several of the developments above require alternate choices to those presently made in the ihope pipeline, and the integration of new software into that pipeline. Taken together with the need to investigate alternative event significance and rate estimation techniques (section 3.4.7) and possibly filter against other templates (section 3.4.2) these plans all necessitate effort to ensure that our pipeline becomes more flexible, so that the different software components may be assembled as needed by scientific goals. To that end, many of the near term projects described below are focused on improving that flexibility. In addition, rapid and whenever possible automatic background estimation will be essential for ensuring that the FFT-based pipelines can deliver detection results quickly enough to allow the publication turnaround specified for a detection.

Timeline of Development for the Advanced-Detector Era

Current Status The current state of the pipeline, emphasizing new developments in the past year, is:

- The ihope pipeline in essentially the same form as used for S5, S6 and VSR2/3 analyses should be capable of delivering detections in the first science run of the advanced-detector era. It is currently being run on part of the first Mock Data Challenge set to establish a reference for comparison for future pipeline developments.
- By running the coherent search in single-detector mode, recent modifications to the coherent search allow the analysis of segments of up to 480 seconds in length. This pipeline is being run on the MDC set for comparison.
- The pipeline now has the ability to use multiple criteria for matching injections to events.
- A single-stage, exact-match coincidence pipeline has been implemented and compared against the two-stage, ellipsoidal match pipeline, showing some improvement in sensitivity.
- GPU capable toolkits, both PyCBC and GWTools, have reasonable coverage of features and are now being assembled into toolkits to run on the MDC sets.

Plan for 2015 In S6-VSR2/3 the ihope pipeline demonstrated the ability to make a detection. It is critical that this ability is maintained at all time, whilst also enhancing the analysis to address the challenges of the advanced detectors. The main critical tasks for the 2015 time-frame are to automate background estimation and other tasks that were performed manually for the "big dog" to ensure that rapid turnaround of detection candidates is possible. Nevertheless, we also expect to continue development of features that will be essential for the mid to late advanced-detector era, as these will require time to validate and review. Should sensitivity improvements through such changes be demonstrated and reviewed we will integrate these into the pipeline even in S7. High priority goals for confident, rapid detection of one or more inspiral signals in S7 include:

- Automate the extended background estimation used for the S6 blind injection challenge.
- Continue, in ER4 and beyond, to validate and as necessary fix or improve, daily ihope runs for data quality purposes.

- Enable the filtering of longer templates. There are straightforward changes to data segmentation that can significantly increase the length of templates that can be filtered, and these have already been implemented in the coherent analysis. These changes will be implemented in the ihope search. It is likely that the most straightforward way to do this will be to replace the inspiral.c executable with the coherent analysis running in single detector mode. This will also make the bank and auto vetoes used in the coherent analysis available within ihope.
- Templates incorporating (aligned) component spins can be generated and used within the search. We will identify the regions of parameter space where spinning templates are beneficial and work towards implementing a spinning search over those parts of the parameter space.
- Complete investigations of single stage versus two stage, elliptical versus exact match and static versus dynamic template banks in the pipeline and converge on preferred choices in the ihope analysis.

Plan for the mid to late advanced-detector era Many of the tasks below remain high-priority goals for the coming year as well, both because of the lead time that will be required to test and review them, and because potential sensitivity or computational improvements will be helpful in S7 even if the existing ihope pipeline is fully capable of meeting our detection needs. For both computational and sensitivity improvements, the internal benchmark of the FFT pipeline group will be running on the MDC sets and comparing to ihope; we also expect the most sensitive variants of these pipelines for a given search to be compared against other pipelines (sections **??**).

- Development of an all-sky coherent search pipeline.
- In cooperation with the rates and significance group (section 3.4.7), investigate and deploy alternative background-estimation techniques.
- Development of GPU based pipeline using the PyCBC and GWTools toolkits. High priority on using these to cover the extended template banks and longer waveforms needed for advanced-detector BNS searches in a computationally efficient manner.
- In cooperation with new developments from the waveform group (section 3.4.2), implement pipelines for both aligned-spin and possibly precessing spin. There should be GPU-capable versions of these searches.

GWTools:
GWTools - the C++/OpenC based Gravitational Wave data analysisToolkit - is an algorithm library aimed to bring the immense computing power of emerging many-core architectures - such as GPUs, APUs and many-core CPUs - to the service of gravitational wave research. GWTools is a general algorithm library intended to provide modular building blocks for various application targeting the computationally challenging components of GW data analysis pipelines.

Current status: One of the primary goal of the project is the provide an executable to be used as a replacement of lalapps_inspiral in the standard iHope pipeline which results c.c. 2 orders of magnitude decrease of computational time. The first prototype of the executable has been developed, currently measure typical speed-up factors for a spinless BNS system with chi2 veto included is around x40-x50. The executable processes the standard template bank xml file and produces an iHope pipeline compatible xml output (trigger list) which can be processed further by the rest of the pipeline.

Future plans regarding computing (2013): Starting more serious profiling and reaching the designed speed-up factor.

Future plans for physics (2013-14): Perform various restricted parameter space analysis which are challenging for the GPU-less pipeline but doable with GPUs. Perform a search for aligned-spin BNS. Start developing an analysis for coherent searches.

Future plans (2014-15): Implement more sophisticated waveforms and search algorithms, extend the capabilities and its inter-operation with other GW softwares in use. Application for low latency pipelines.

3.4.6 Electromagnetic followup of gravitational wave events

Compact binary mergers involving at least one neutron star (cf. Sections 3.2.1 & 3.2.2) are (1) expected to produce electromagnetic (EM) radiation at a variety of wavelengths and timescales [135, 136, 141] and (2) thought to be the progenitors of some short γ-ray bursts [51, 45, 190, 44, 140]. As such, they are the most promising sources for joint EM+GW observations and a key science goal for the LVC.

In S6/VSR2,3 the LVC performed its first low-latency search for joint EM+GW radiation [12]. The search focused on triply coincident triggers generated by the MBTA pipeline (cf. Section 3.4.4). These triggers were then passed to GraCEDb, where an automated process applied data quality vetoes and performed sky localization, at this point having incurred a total latency of about 3 minutes. From there, surviving triggers were then passed on via the LVAlert protocol to the LUMIN and GEM [182] processes where tilings were produced and view times were determined for each partnering telescope. In the end a single trigger with a false alarm rate of $\sim$once every six days was sent out for imaging.

Moving forward there will be two modes of participation in the EM Followup program: A “contributed" mode for astronomy partners who wish to carry out the necessary observations and spectral/multi-wavelength followups themselves and a “coordinated” mode for astronomy partners who wish to pool their observing resources for better sky and spectral coverage. An open call for letters of intent will be sent out in the summer of 2013 and a meeting of respondees will take place in the fall.

In the next year our goals include streamlining the various EM Followup tasks and integrating them into a working version of the pipeline that will be on-line in the advanced detector era. In addition, we will define clearly the information to be shared with observing parters, e.g. the form and contents of alerts. At the same time, as observing partners are identified, we will work with them to ensure we have the pieces in place to allow for successful observation of EM counterparts and timely publication of the results.

High-priority goals for the next year

- Clearly define roles and responsibilities for both “contributed” and “coordinated” modes of participation.
- Produce technical documents describing (1) the format and contents of LVC skymaps and (2) the information contained in the alerts to be sent out to observing partners (e.g. VOEvents).
- Put in place a prototype of the event selection tool that will take the place of LUMIN and GEM. It is expected to run during the engineering runs.
- Begin work on bulletin board for interacting with “coordinated” observing partners to keep track of observations (where and when) and results. This work will evolve in collaboration with observing partners.
- Continue exploring improvements to sky localization latency and accuracy.
- Investigate a “tiered" approach to parameter estimation (particularly sky localization): Provide initial skymap and parameters from the matched filter output with a latency of $\sim$minutes and provide updates as the dedicated parameter estimation codes converge.

- Work to provide low-latency constraints on parameters parameters in addition to sky location using developments in low-latency MCMC methods (e.g. distance, masses, spins, etc.).
- Work to improve the use of galaxy catalogs as priors and jump proposals (for MCMC).

Goals for the advanced detector era

- Assess the errors in sky localization introduced by using non-spinning templates for spinning systems.
- Maintain and update GraCEDb and LVAlert to provide a clearinghouse for all relevant GW trigger information, including that from electromagnetic observatories, neutrino detectors, etc.
- Determine which potential electromagnetic counterparts are most promising given the latencies of trigger generation and sky localization as well as the expected rate of serendipitous EM transients.
- Provide an interpretation of the significance of joint EM+GW observations. Investigate incorporating these results into those from the offline pipelines.

3.4.7 Event significance and rate estimation

The confidence with which a CBC trigger is believed to be due to a true GW signal is determined through estimation of the background of events due to detector noise (the false alarm rate, FAR) and measurement of the efficiency of the analysis pipeline to simulated signals in detector noise. In addition to the determination of the statistical significance of individual GW candidate events, the ensemble of events output from a CBC pipeline are used to infer the properties of the underlying astrophysical population of sources, primarily the event rates of different source classes. The current state for the ihope pipeline can be summarised as:

- The FAR is estimated using 100 time-slides over a $\sim$6-week analysis time. This enables us to achieve values down to $\sim 0.2\,\mathrm{year}^{-1}$.
- Extending time-slides to $\mathcal{O}(10^6)$ slides over $\sim$4 months of data (performed for the blind injection challenge with a new coincidence code) enabled the accuracy of FAR estimation to be improved to $\sim 10^{-4}\,\mathrm{year}^{-1}$.
- Detection efficiencies are estimated with injection runs made uniformly over distance, using information from one “loudest event” per analysis. This has been deemed adequate to set upper limits with a few$\times 10\%$ systematic uncertainty (comparable to calibration errors).
- Signal-background separation based on ad-hoc tuning to background and injection triggers have been found to be both time and effort-consuming.

Ongoing studies and developments fall under headings as follows: background estimation for confident detection; astrophysical rate estimation; and event ranking methods to better separate signal from background.

Background estimation

- A new coincidence code is being integrated into the ihope framework for a single-stage pipeline, enabling more than the current limit of $\sim 10^4$ time-slides to be routinely carried out.
- The use of continuous time shifts (all possible coincidences) for background estimation. This technique estimates FARs to a level that would require millions of time-slides but with a much lower computational cost. Issues to address include accounting for non-independence of trials across parameter space and time, and determining the best method for combining single-template FAR distributions.

- Time-slide-less methods for FAR estimation. These are based on separately estimating the total rate of coincidences, and the fraction of events louder than a given candidate. This has been implemented for gstlal based online and offline CBC pipelines [67] and a similar approach using all possible trigger pairs within a range of parameter space is under development for ihope/fft triggers.
- A detailed comparison of several different FAR estimation methods for the 2-detector case, using a month of S5 data with fake signals [79].
- Calculating the combined significance of more than one candidate event, in the case of several possible GW signals.

Rate estimation

- The potential systematic uncertainties of the loudest-event statistic due to finite statistics. This involves the improvement of the "Lambda" [52, 48] calculation including quantifying its uncertainty (this relates strongly to improved FAR and efficiency estimates).
- The application, improvement, and possible replacement of the loudest-event statistic in the detection era. This includes the combination of results from many disjoint analysis times and over many distinct classes of source (*e.g.* mass bins). Ongoing investigations into statistical bias in rate estimation schemes and the replacement of the loudest-event statistic with a more general approach utilising all loud triggers.
- Improving computational efficiency and accuracy of the estimated sensitive volume by optimizing injection placement. This is done whilst balancing the cost with limiting effects such as noise non-stationarity, calibration and inaccuracy of prior astrophysical parameter distributions.
- Quantifying selection biases for pipelines, from both model assumptions and pipeline implementation factors. This includes modeling injection results with analytic and phenomenological expressions.

Automated methods/trigger ranking

- Multivariate statistical classifiers (MVSCs) can improve the separation of signal from background in multi-dimensional spaces, for instance the parameter space of CBC triggers. A specific multivariate classifier known as a random forest of bagged decision trees was developed for use in the S6 high-mass search. Several technical issues were identified and addressed, but not before the S6 highmass search was completed. The technique is now being applied for the S5 and S6 ringdown searches and can be further developed for Advanced-era searches. MVSCs can also be used to incorporate DQ information into search results (see section 3.4.1).
- Another approach for ranking triggers in high-dimensional parameter spaces is to approximate the N-dimensional likelihood distribution with lower-dimensional distributions: the "likeliness" code includes all (relevant) combinations of 2-dimensional slices. This approach could help extend the likelihood estimation used in gstlal [67] by allowing individual dimensions to be used repeatedly. `lalapps_likeliness` could also be incorporated into ihope's "pipedown" post-processing.

3.4.8 Accurate estimation of source parameters

In past few years the CBC group has been developing tools of increasing complexity to carry out Bayesian inference – model selection and parameter estimation – of the detection candidates. Being able to accurately estimate the parameters of coalescing binary systems – masses, spins, distance, location in the sky, etc – and to compare alternative hypotheses, are essential elements for studies in astrophysics, cosmology and fundamental physics that are enabled by GW observations.

Over the last year a major milestone has been completed: the paper reporting the status of parameter estimation and model selection at the end of S6/VSR2-3, including the blind injection challenge [5], has been submitted to PRD. As part of this work, the review of the code-base – the LALInference library – has been completed. In the coming period the emphasis will be to enhance the functionalities of the library, and to deliver and validate the components that are required for the search analyses that are planned with the start of operation of aLIGO. At this stage, it is still essential that a suite of stochastic sampling methods – specifically, Markov-chain Monte-Carlo (MCMC) methods [169, 170, 186, 187, 164, 191] and Nested Sampling [177, 86, 486] – continue to be pursued in order to validate the algorithms and pipelines, explore trade-offs in terms of efficiency and accuracy while we prepare for the science runs with advanced detectors.

High-priority goals for the next year

- As part of the technical work to validate the algorithms and codes, a review of the code changes of the last period will be completed, and the technical document describing the LALInference library will we turned into a paper for future reference
- The BNS search requires work in a number of areas, which are listed below:
  - Use of long-duration templates required by the lower frequency cut-off of aLIGO/aVirgo, and efficiency studies (BNS-PE.1);
  - Tracking of the relevant waveform developments (BSN-PE.3/WAVE 3-5);
  - Maintaining the automatic pipeline and support GraceDb interface (BSN-PE.5);
  - Studies of the effect of glitches likely to overlap long-duration signals (BNS-PE.6) – this work will be carried out on ER's and MDC's – as well as new methods to include non-gaussian features into followup analysis, see *e.g.* LIGO-P1300066;
  - Support and infrastructure for strong field group (BNS-PE.7)
- In the area of sky localisation, it is important to compare Bayesian codes with BAYESTAR, establish the relative strengths/weakness of the two approaches, and investigate how the full Bayesian analysis could provide sky localisation information on shorter time-scales, *e.g.* by running a Bayesian follow-up on triggers for which the mass (and other intrinsic) parameters have been fixed to the values returned by the detection template, and therefore reduce the total parameter space to sample.
- As the Engineering Run and Mock Data Challenge efforts continue, we will include the Bayesian follow-up stage to ensure readiness for the first science run.
- Some work has already been done to explore whether one can use the Bayes factor as a figure of merit to establish confidence in detection candidates, see *e.g.* [413]. Further investigations in this area are ongoing, using archived S6 timeslide data.
- The results of Bayesian inference depend both on the likelihood function *and* the priors used in the analysis. Work is needed to investigate suitable priors to use in the analysis and the effects of difference choices on the result (BNS-PE4).
- Model uncertainties, related to waveform, calibration and noise modelling can affect and bias the results of a model selection and/or parameter estimation analysis. Work is needed to address, in general terms, these effects *and* to deal with model uncertainties into the Bayesian analysis.

- Several generic infrastructure improvements are needed, in particular for post-processing tools, and standard testing and validation tools of new software committed to the repository.

Goals for the advanced detector era

Several further improvements are essential, and some of them are already actively pursued, to fully exploit the initial data sets from advanced LIGO, and they are included below:

- Bayesian analyses remain computationally expensive. Work is needed to speed-up the analysis using more efficient waveform and/or likelihood computations. These include, but are not restricted to SVD, selective sampling, dedicated implementations on GPUs, and more generally algorithms efficiency improvements.
- New waveform approximants are being developed, in particular in the context of "high-mass" black holes (see *e.g.* the NINJA-related work), NS-BH binaries (spin effects are particularly important), matter-induced effects (such as tidal effects for BNS). It is essential that the Bayesian analyses can take full advantage of these waveform developments, and the implication for science exploitation are properly evaluated.
- Bayes' factors are one of the output of a Bayesian analysis, but limited work has been done so far to establish to what extent it can be used in real data to distinguish between competitive models. Work is needed to make progress on this front.
- The ability to reconstruct broader information about the astrophysics of sources and their populations, formation rates, binary formation channels, depends directly on the quality of parameter estimation, and of course the underlying binary population(s). Investigations are needed in order to address the issue of providing quantitative statements on broader astrophysical questions starting from a collection of detected sources.
- In addition to an EM-triggered search of LIGO data it is also possible to follow up triggers by looking in archived data from GRB missions. As proof of concept study we will use sky location and distance information from parameter estimation to run a targeted followup of S6 CBC events searching for sub-threshold high-energy electromagnetic counterparts to NS/NS and NS/BH mergers in Fermi GBM and RXTE ASM data.

3.4.9 Investigating the strong field dynamics of gravity

The most stringent tests of the dynamics of general relativity (GR) to date are set by measurements of the orbital parameters of the binary pulsar system PSR J0737-3039 [65, 113]. The *compactness* $GM/(c^2R) \simeq 4.4 \times 10^{-6}$, with M the total mass, R the orbital separation, and the typical orbital velocity $v/c \simeq 10^{-3}$ of this system, place it in the relatively weak-field regime. By contrast, for an inspiralling binary at the last stable orbit, the compactness is $1/6$ and the velocity is $1/\sqrt{6}$ in units of c. Therefore, the emission of gravitational waves during the coalescence of compact binary systems is, in the foreseeable future, the only phenomenon allowing empirical access to the full dynamics of GR. This characteristic allows for unprecedented tests of the non-linearity of GR [192] and, for systems involving at least one neutron star, measurements of the behavior of matter in some of the most extreme situations. The LIGO/Virgo collaboration has recently started investigating these things.

Detecting deviations from general relativity during the inspiral phase

Binary neutron star systems A first effort to detect deviations from GR has recently been started by the LIGO/Virgo collaboration; a full pipeline – named TIGER – focusing on binary neutron star (BNS) systems is well into development and indications about the accuracy of GR tests are already available. BNS were chosen as, in these systems, higher harmonics, spin interactions and precession are believed to be relatively unimportant, although finite size effects do become important late in the inspiral. This allows the use of frequency domain templates in the analysis. As for the "standard" detection methods, TIGER requires the estimation of a *background* for the detection statistics (the Bayesian *odds ratio* in the case of TIGER). The background is computed by running the pipeline over many GR signals. The distribution of odds ratios defines the efficiency, for a given false alarm probability, of the detection of departures from GR. A series of tests in simulated gaussian noise show that, with the current setup, a wide variety of deviations from GR can be detected [119, 120]. With as few as 15 detections, deviations of $\sim 10\%$ in the 1.5PN coefficient – the "tail" term – are picked unambiguously even when spins are considered. The same holds for deviation of $\sim 20\%$ in the 2PN coefficient. These PN orders are, to date, still uncharted territory. If no deviations are detected, however, TIGER can constrain PN coefficients to $\sim 1\%$ [119]. Furthermore, the robustness of the background calculation against differences in waveform approximants, instrumental calibration errors, precessing spins were demonstrated as well as the effectiveness of TIGER even when the template waveforms are truncated at 400Hz to avoid contamination by unknown matter effects. Note that rather generic deviations from GR can be detected, not just violations in one or more of the PN coefficients [119, 120]. An as yet unsolved problem is how to pinpoint the precise nature of a GR violation if one is found. Here the waveform parameterization of the so-called parameterized post-Einsteinian (ppE) may be of help [194].

Binary black hole systems Being a pure space-time process with an extremely rich dynamics, the coalescence of binary black holes (BBH) is the ideal setting to perform tests of GR. However, for BBH, higher harmonics, spin interactions and precession are very important and, for a reliable test, they must be included in the analysis. Since no waveform model encompassing all the aforementioned effects is yet mature or fast enough, exploratory investigations relied on phenomenological models [26] considering only aligned spins. For these systems, preliminary studies indicate that deviations $\sim 1\%$ in any of the known PN coefficient can be detected.

High priorities for next year

- Keep TIGER development up to date with the parameter estimation effort (LALinference).
- TIGER will be tested in recolored real noise in the context of the MDCs.
- The existing pipeline will be adapted to make use of Virgo computational resources.

Longer term goals

- Tests of GR using systems containing black holes require waveforms that include all the known dynamical effects of GR. Current testing capabilities are limited by the availability of accurate and sufficiently fast inspiral-merger-ringdown waveforms including fully precessing spins. Furthermore, since the bottleneck of TIGER is the computation of the background over $O(10^5)$ simulated events, the waveform models and the parameter estimation infrastructure will necessarily have to be fast.
- A large class of alternative theories of gravity predicts the existence of additional GW polarisations [192]. With the exception of few efforts within the LSC, the detector response to these polarizations is not taken yet into account within current pipelines, but dedicated functions are already available. The

detection of alternative polarization states would immediately rule out GR as the theory of gravity. However, waveforms that produce such additional states are not yet available and will have to be implemented.

- Ringdown signals from massive systems can also be used to test the no-hair theorem and the nature of the remnant metric, e.g. [104]. A concrete testing infrastructure similar to TIGER will be implemented.

Constraints on alternative theories Several modifications to GR waveforms during the inspiral stage have been worked out, see Table I in [73] for a list. For many theories, interesting bounds on non-GR parameters can be set by Advanced LIGO/Virgo. Fisher Information Matrix based studies suggest that interesting bounds can be put on the dipolar radiation [32] and on the mass of the graviton [33]. For simplistic massive graviton models, Bayesian studies also suggest that current limits based on Solar System observations can be improved using GW observations[78, 73]. Subsequently, efforts towards understanding the constraints on their additional parameters are needed. To achieve this, the development of theory-specific waveforms is necessary. Selected alternative gravity waveforms - the ones corresponding to "massive gravity" theories - are ready to use and more will be added as they become available.

Long term goals

- Development of GW waveforms for alternative theories and full integration within the parameter estimation framework.
- Analyses of GR signals both in Gaussian noise and real-like noise and assessment of expected sensitivity to non-GR parameters.
- Determination of biases introduced in the parameter estimation process when non-GR signals are analysed using GR templates.

Measuring the equation of state of neutron stars During the coalescence of BNS systems, finite size effects become important at orbital frequencies ≥ 400Hz. The exact shape of the tidally distorted GW signal depends on the details of the equation of state (EOS) of the neutron stars. Preliminary studies based on Bayesian model selection techniques and frequency domain templates indicate that Advanced LIGO/Virgo will be able to detect the signature of matter effects and discriminate among soft, medium and hard EOS with $O(10)$ BNS signals.

High priority for next year

- Preliminary studies involving non-spinning, frequency domain templates will be extended to utilize fully precessing time domain waveforms including also the contribution of the so-called "quadrupole-monopole" term.
- A variety of classes of equations of state will be coded.
- For the case of NSBH, phenomenological waveforms will be developed which have a close match to numerical waveforms that include matter effects.

Long term goal

- Two data analysis pipelines will be developed, one performing Bayesian model selection between a number of predicted EOS, the other directly estimating EOS parameters assuming *e.g.* a polytropic EOS.

Measurement of the Hubble constant The determination of the Hubble parameter H_0 is still one of the most critical issues in cosmology, with repercussions on a wide range of fields in physics ranging from the determination of the abundances of light elements in the early Universe, the content of weakly interacting particles, and the nature of dark energy. The exact value of the expansion rate at the current epoch is still a matter of debate. Its current accepted value lies in the range $60 - 75$ km s^{-1} Mpc^{-1}; see e.g. [106]. The ingredients required for the measurement of the cosmological parameters are a *luminosity distance* and the corresponding *redshift*. Canonical measurements of the Hubble constant – and any other cosmological parameter – require the determination of the so-called *cosmic distance scale ladder*. By contrast, GW give a direct measurement of the luminosity distance [173], thus completely bypassing the need for distance calibrations. However, GW provide no information about the redshift of a source (but see [134]). Many different methods have been proposed to obviate to this deficiency:

- If short-hard Gamma-ray Bursts (GRBs) are the result of the coalescence of binary systems containing at least a NS, the simultaneous observation of a GRB and a GW could provide the redshift of the source. With this method H_0 can be measured to $\sim 13\%$ with 4 events and to $\sim 5\%$ with 15 events [143].
- If one knows (or estimates) the mass function of neutron stars, it provides one with a statistical measurement of the redshift. Using this method, H_0 should be measured to $\pm 10\%$ using ~ 100 observations of BNS systems [181]. This method amounts to a modification to the prior probability distribution for the mass parameters during the parameter estimation process.
- The measurement of the extrinsic parameters of a GW event provides a 3-dimensional error box in the sky. By cross-correlating with a galaxy catalogue, one can obtain a statistical measurement of the redshift of the source. In this case H_0 can be estimated to $\sim 5\%$ after 25 observations [174, 77]. This method requires use of the redshifts and sky positions of known galaxies as prior distributions during the parameter estimation process.

High priorities for next year

- Implementation of the necessary infrastructure for the use of redshifts and sky positions of known galaxies as prior distributions within the parameter estimation framework.
- Implementation of dedicated code for a “cosmological” follow-up of events analysed by the parameter estimation group.

3.5 Road map to the Advanced Detector Era

In preparing for the advanced detector era it is necessary to validate analysis techniques and to integrate and test analysis infrastructure. To achieve these goals the CBC group will participate in engineering runs and mock data challenges leading up to the first advanced detector science run. Engineering runs will be used to test data and metadata replication and storage from each of the observatories as well as to test all services that support both online and offline analysis. Additionally, both online and offline CBC analyses will run during these periods simulating a science run while providing feedback to detector commissioners regarding data quality. Mock data challenges have a narrower scope, which is to test CBC pipelines and analysis techniques for regression and to aid in the systematic development of new and improved technologies to detect and estimate the parameters of compact binary mergers.

3.5.1 Engineering runs

A series of engineering runs utilizing data from anticipated sensitivity as well as detector subsystems under commissioning have been carried out and several more are planned in the lead up to the first science runs of the advanced detectors. The main goals of these runs are:

- Aid in commissioning and detector characterization of the instrument as a whole
- Assist in commissioning of upgraded detector subsystems as they become available.
- Commission searches to be ready for the first science runs.
- Test the ability of the collaboration to detect GW sources in low latency.
- Establish a strong communication channel between low latency gravitational-wave analyses and electromagnetic instruments for fast follow-up of candidates.
- Develop data analysis computing and services.

Engineering Run 1 The initial advanced detector engineering run took place between January 18, 2012 and February 15, 2012. Since no full detector subsystems were available at the time, mock noise was used to simulate the two (then anticipated) Hanford detectors, the Livingston detector, and the Virgo detector. This mock noise used colored Gaussian noise derived from the high power, zero detuned advanced LIGO configuration sensitivity, and the corresponding projected advanced Virgo sensitivity. Injected signals included a blind population of double neutron star binaries and black hole neutron star binaries produced within predicted realistic event rates [126].

The gstlal CBC pipeline (see section 3.4.3) participated in ER1, utilizing the low latency network to distribute the analysis over several computing nodes. Several inferences about the presence of gravitational waves from the injected source populations were made to high confidence. The Multi-Band Template Analysis (MBTA) pipeline (see section 3.4.4) was also run online during this period, and established detection level confidence in several events, including blind injections.

Engineering Run 2 The second advanced detector engineering run took place between July 11, 2012 and August 8, 2012. Injected source populations were similar[154] to ER1, but also included higher mass signals such as black hole binaries. Both the MBTA and gstlal-based pipelines analyzed this data in near real time, reporting significant triggers with a latency of a few minutes or less.

The primary goal of this run was to drive closer coupling of data analysis to the instruments as they are constructed and commissioned as well as better understanding the impact of non-stationary and non-Gaussian data. The first tests of recoloring an advLIGO subsystem (the pre-stabilized laser) to the 2018 reference advanced LIGO sensitivity were successfully performed during this run. This recolored data was distributed in low latency as a surrogate for actual detector data and was the product analyzed by GW searches. Using this data, the offline “daily ihope” detector characterization tool as well as the full ihope-based analysis (see section 3.4.5) was successfully performed offline after the run.

Engineering Run 3 The third advanced detector engineering run took place between January 20, 2013 and February 25, 2013. Injected source populations were nearly identical to ER2. In addition, a set of GRB notifications associated with the GW injection population were produced and distributed, and the resulting event cross-correlation was developed and automated (see section 3.4.6). Both MBTA and gstlal-based pipelines analyzed this data online, and the ihope pipeline was run offline.

The data generation process was refined to use the gstlal infrastructure to recolor the same channel as in ER2. This pipeline was developed to serve as a placeholder for the anticipated online calibration pipeline in the advanced science runs. Using the recolored data, several issues arising from detector construction and data ingestion were identified by both the gstlal and ihope pipelines. Coordination of data quality activities and feedback was accomplished through the DQ group (see section 3.4.1).

Future Engineering Runs Engineering runs are scheduled to take place roughly every six months until the first advanced observational run. Two upcoming tests involving the instruments will exercise several of the advanced instrument subsystems. The fourth engineering run is scheduled to be possibly concurrent with the half-interferometer (HIFO) test at Hanford and the dual-recycled Michaelson interferometer (DRMI) test at Livingston. These tests will provide valuable opportunities for participation by the DQ and science subgroups to interact with the instruments as we expect them to operate during the advanced runs.

Engineering Run 4 Data generation and distribution is expected to develop incrementally in a very similar way to ER3. One possible difference that Livingston's recolored data may be derived from a subsystem which is further along the optical path. In this case, the input mode cleaner is being investigated as a potential target. Also, the injection population to be injected will no longer include NSBH and IMBH source types.

In addition, several infrastructure and data fidelity / archiving tasks have been identified to verify and enhance the data analysis tasks which are already being performed. These include verification of the data from its initial transfer at the front end, verification of segments generated from the instrument data, verification of the recolored data from the targeted subsystem channel, and verification on the match between the data distributed to online analyses and archived data.

3.5.2 Mock Data Challenges

The CBC group will conduct mock data challenges (MDC) to test pipeline development for regression and establish readiness for the advanced detector era by quantifying the sensitivity and performance of analysis through various metrics. This procedure will also serve as a paradigm for review of analysis techniques and software. Our plan is presented in the following outline:

S6/VSR2,3 analysis regression tests:

- Establish that previous results are reproducible through explicit reanalysis of existing data.

Provide a benchmark sensitivity metric to serve as a reference for future investigations:

- Compute effective volume and analysis live time (VT) at false alarm rates spanning the relevant interval of 1/analysis (the expected loudest event from noise) – $\sim$1/1000 years (detection level).
- Establish "expected" sensitivity to serve as an absolute reference.

Produce references for small numbers of "detection candidates" for rates and significance studies:

- Study software injections added directly into the data prior to analysis with an astrophysically plausible distribution.

- These injections should impact searches exactly as if they were real candidate events.

Compare proposed enhancements:

- Compare different pipelines and enhancements through extensive simulation campaigns consisting of large, identical software injection sets in order to understand how various techniques can help us to directly detect gravitational waves and best use gravitational wave observatories as a tool for astronomical discoveries.
- Show improvement over our benchmark VT curves or other performance metric improvements at similar VT levels.
- Followup negative changes with regard to detectable simulated signals even if other metrics (such as relative VT) are improved.

Subsequent investigations:

- Establish detection readiness
  - Test significance estimation for all searches to the required level.
  - Test our ability to handle multiple detections and the statistical detection of a population.
- Understand the impact of data quality vetoes and signal consistency tests
  - Establish whether traditional veto categorization is the best way to proceed for the advanced detector era.
  - Establish which signal consistency tests are most powerful and determine how to incorporate them into the searches.
- Carefully assess sensitivity across parameter space
  - Highlight regions of parameter space where sensitivity is inadequate (e.g. spin-aligned and precessing spin sources).
- Perform large scale parameter estimation tests
  - Conduct large scale parameter estimation runs over the full parameter space to establish the accuracy and precision of parameter estimation techniques.
- Determine how we will publish and present results
  - Decide how to combine online, offline and parameter estimation analyses to report on detection candidates.

4 Searches for general burst signals

The mission of the LSC-Virgo Burst Analysis Working Group, also known as the *Burst Group*, is a broad search for short duration gravitational wave (GW) transients, or *bursts*. A variety of astrophysical sources are expected to produce such signals, as summarized in Sect. 4.1. Sophisticated models are available for certain sources, but in most cases the amplitude and waveform of the GW signal are highly uncertain; for this reason, a burst source requires robust detection methods. While initially the Burst Group focused on signals much shorter than 1 second, with little or no assumption about their morphology [195], it is now also pursuing longer signals and the incorporation of available signal waveform knowledge, to seek specific targets in addition to unknown phenomena and mechanisms of emission and propagation. Section §4.2 summarizes recent GW burst search results, while §4.3 describes the methods used in our searches.

In §4.4 we describe the Burst Group scientific goals and plans over the next 2 years, as we prepare for the advanced detector era, including a discussion of top priorities and a timeline of our preparations. While this document includes all ongoing or planned burst analyses and investigations, the Burst Group remains open to new, scientifically motivated activities that will support its goals for the Advanced LIGO/Virgo era.

In some cases, an overlap in astrophysical targets and methods exists with other LSC-Virgo analysis groups. Such cases include short-duration gamma-ray bursts and the merger and ringdown of binary compact objects, which are pursued by both the Burst and CBC (§3) Groups. Longer duration transients ($\sim$minutes or longer) may also be pursued using methods developed by the Stochastic (§6) and Continuous Waves (§5) Groups. The Burst Group will coordinate with other analysis groups in areas of common interest, to ensure the best possible scientific results.

4.1 Gravitational-wave Burst Sources & Science

The Burst Group targets a broad range of astrophysical systems and phenomena that potentially emit GW transients. The primary goal of searches with the initial LIGO, GEO and Virgo detectors was to make a first detection, but along the way new observational constraints with astrophysical relevance have been established on the GW emission from targeted sources.

The list of potential burst sources does not change from the initial to the advanced detector era. However, due to the ~ 10 times greater distance reach and ~ 100 times greater energy sensitivity of advanced detectors, the chance of detection and the potential for the extraction of interesting fundamental physics and astrophysics will increase. GW burst data analysis strategies in the advanced detector era will need to take into account more information from astrophysical source models, which in turn requires higher-fidelity theoretical and computational modeling. We must actively encourage the modeling community to develop improved models for use in advanced detector searches, with a theoretical understanding *for each source* of the mapping between signal characteristics (e.g., frequency content, time-frequency behavior) and physics parameters. This includes the knowledge of potential degeneracies that may be broken by complementary information from electromagnetic (EM) or neutrino observations, which make multi-messenger theory and observations a necessity.

Searches for GW bursts in the advanced detector era will be a combination of untriggered, all-sky searches and externally triggered localized searches. Untriggered, all-sky searches (§4.4.1) have the greatest potential of finding electromagnetically dark sources (§4.1.4); they may discover unexpected sources (§4.1.8), and they also provide triggers for follow-up studies of candidate events with EM observations (§4.4.6). Externally triggered searches will have electromagnetic and/or neutrino counterpart observations. In both cases, strategies are required for the extraction of physics at the post-detection stage combining EM, neutrino, and GW information. Hence, it will be important to continue to work with our external partners and to seamlessly extend collaborations from trigger exchange up to full data sharing and joint analysis, wherever it facilitates better scientific output.

While we can expect to learn more astrophysics about known sources (even non-detections, translated into improved limits, will have important consequences for astrophysics) and potentially constrain aspects of fundamental physics (e.g., the nuclear equation of state), we must be ready for the unexpected. This may be a detected signal from a known source (e.g, with an EM or neutrino counterpart) that is completely different from model predictions, or a high-significance event that is detected with unexpected characteristics and with no EM or neutrino counterpart. We must be ready to handle both scenarios.

In the following, we discuss key burst sources that are likely to be focal points of data analysis efforts in the advanced detector era and briefly discuss the corresponding science opportunities.

4.1.1 Gamma-Ray Bursts

Gamma-ray bursts (GRB) are intense flashes of gamma rays that are observed approximately once per day, isotropically distributed across the sky. GRBs are divided into two classes by their duration and their spectrum [196, 197]. Long GRBs ($\gtrsim 2\,\mathrm{s}$) are associated with star-forming galaxies of redshifts of $z \lesssim 9$ and core-collapse supernovae [198, 199, 200, 201]. Short GRBs ($\lesssim 2\,\mathrm{s}$) have been observed from distant galaxies of different types. Most short GRBs are believed to be due to the merger of neutron star (NS-NS) or neutron star – black hole (NS-BH) binaries [202, 203], while a few percent may be due to extragalactic SGRs [204, 205].

Short GRBs: NS-BH, NS-NS Coalescence and Postmerger Evolution

Post-Newtonian theory predicts a distinctive GW chirp signal from the inspiral stage of NS-NS or NS-BH coalescence, so that the detection of such a signal associated with a short GRB would provide "smoking gun" evidence for the binary nature of the GRB progenitor. Recent analytic and computational work suggests that constraints on the nuclear equation of state (EOS) are possible by matched filtering of advanced detector data from the intermediate to late inspiral of NS-NS and NS-BH binaries [206].

Interesting science potential is not restricted to the inspiral phase. In the NS-NS case, the merger signal as well as the GW emitted in the postmerger evolution reveal the mass and spin of the system, whether black hole formation is prompt or delayed, and may also place constraints on magneto-hydrodynamic (MHD) spin-down and the nuclear EOS. The postmerger signal (which cannot be templated) may also provide information on whether a short GRB is powered by a millisecond hypermassive neutron star or by a black hole – accretion disk system. However, most of the postmerger GW emission will occur at frequencies of $1-4\,\mathrm{kHz}$. With an expected energy emission of up to $\sim 10^{-3}-10^{-2}\,M_{\odot}c^2$, these signals will most likely be detectable only for nearby events ($D \lesssim$ few $\times$ $10\,\mathrm{Mpc}$). It will therefore be worthwhile to perform a targeted search on the postmerger evolution for the most nearby events.

The majority of nearby NS-NS/NS-BH coalescence events are likely to be gamma-weak or silent due to the expected beaming of the prompt emission, but more isotropically emitted precursors or afterglows (e.g., [207, 208, 209, 210, 211, 212, 213]) are expected in bands from radio to X-ray. Discovering the EM counterpart of a NS-NS/NS-BH merger will be a major breakthrough. Joint EM-GW observations of short GRBs in the advanced detector era have great science potential and will provide answers to many open astrophysics questions connected to short GRBs and binary mergers (e.g., [214, 203, 202]).

Long GRBs and Engine-Driven Supernovae

The nature of the long GRB central engine is one of the major unsolved problems in relativistic astrophysics. There is overwhelming evidence from EM observations that long GRBs are related to massive star death and core-collapse supernovae [215] (see also §4.1.2), but the precise nature of this relationship is unclear. Central engine scenarios either involve a very rapidly spinning magnetar with millisecond period, or a stellar-mass black hole with an accretion disk. Relativistic GRB outflows may be powered by neutrino pair annihilation in polar regions or extraction of spin and/or accretion energy via MHD processes, or a combination of these.

The early GW and neutrino signals expected from a long GRB will be similar to those of a rapidly spinning core-collapse supernova before explosion [216]. Hence, long GRBs should be approached with similar modeling input as supernova searches. During the GRB stage, GW emission may come from accretion disk instabilities, such as clumping and fragmentation [217, 218, 219], or non-axisymmetric magnetar deformation [220, 217]. The most extreme of these models predict emitted energies in GW of order $0.1\,M_{\odot}c^2$ which advanced detectors may be able to constrain to many tens to hundreds of Mpc, depending on the frequency of the GW emission [221]. For nearby GRBs ($D \lesssim$ few Mpc), engine scenarios may be constrainable, but much more theoretical modeling will be necessary to establish signal shapes characteristic of particular central engine models.

An interesting class of objects between long GRBs and regular core-collapse supernovae are hyper-energetic type-Ib/c supernova explosions that do not produce an observed GRB, but exhibit late time energy input into the ejecta by a central engine seen in radio observations (e.g., [222, 215]). Engine-driven supernovae occur considerably more frequently in the local universe than long GRBs and may be extreme core collapse events with plausibly strong GW emission. An engine-driven supernova within a few tens of Mpc would be an interesting science target for advanced detectors.

Current and future searches for long GRBs rely on external triggering by the prompt gamma emission observed by satellites. As in the case of short GRBs, joint EM-GW observations may help answer pressing questions regarding the central engine and progenitors of long GRBs.

Additional long GRB science opportunities are in joint searches for GW and high-energy neutrinos (HENs) from GRBs. HENs are expected to be generated by interactions of accelerated protons in relativistic shocks in GRBs [223, 224, 225, 226, 227, 228, 229, 230, 231, 232, 233] and may be observable by HEN detectors. Of particular interest to joint GW+HEN searches are so-called *choked* GRBs (e.g., [234, 227]). These EM weak/silent systems may arise if the central engine turns off before the jet can escape from the star. In this case the jet stalls (*chokes*). While no gamma ray emission can be observed from such systems, HENs generated in the jet earlier on can escape if the envelope is not too thick [235]. Afterglow X-ray/optical radiation are also potentially observable. An important component in probing the structure of such joint GW+HEN sources is the connection between the time-of-arrival of GW and HEN signals [236].

Low luminosity GRBs [237, 238, 199, 239, 240, 241, 242, 243] have sub-energetic gamma ray emission and form a sub-class of long GRBs. While they are more difficult to detect via gamma-ray observations, they are more populous than conventional GRBs [240, 242]. Due to the higher event rate, the overall GW and neutrino flux from these sources may be comparable or even surpass that of conventional GRBs [244, 245, 246].

Other phenomena expected to produce simultaneous HENs and GWs include short-hard GRBs [223], core-collapse supernovae [229], and soft gamma-repeaters [247, 248, 249].

4.1.2 Core-Collapse Supernovae and Accretion Induced Collapse

Massive star collapse does not immediately lead to a supernova explosion. Within half a second of collapse, the inner stellar core reaches nuclear density. There the nuclear EOS stiffens, leading to a rebound of the inner core (*core bounce*) into the still-infalling outer core material. This results in the formation of the supernova shock that initially moves out quickly in mass and radius, but soon is decelerated, then stalls due to the dissociation of heavy nuclei and neutrino losses. The shock must be revived by the core-collapse supernova mechanism, but how precisely this occurs is currently uncertain [250]. It has been argued [251, 252] that GW from a galactic core-collapse supernova could help constrain the mechanism.

Core-collapse supernovae, no matter how precisely they explode, are expected to involve a wealth of processes leading to the emission of GW [216]. Based on all-sky search results from the initial detectors [253, 254], advanced detectors can be expected to detect core-collapse supernovae emitting $10^{-10} - 10^{-9}\,M_{\odot}c^2$ ($10^{-8} - 10^{-7}\,M_{\odot}c^2$) at $100\,\mathrm{Hz}$ ($1000\,\mathrm{Hz}$) throughout the galaxy. This is well within what is predicted by current simulations (see, e.g., [216, 255] for reviews). More optimistic predictions based on analytic models suggest GW energies of up to $\sim 0.1\,M_{\odot}c^2$ [217]. Advanced detectors are likely to be able to constrain these models out to tens of Mpc. Improved modeling, in particular full 3D models that provide signal predictions for both polarizations, will be necessary to fully exploit the improved sensitivity that advanced detectors will offer.

The rate of nearby core-collapse supernovae is known only to a factor of about two. Galactic events are expected once or twice per century and the rate for the entire local group, including Andromeda, is roughly two to four per century [256, 257]. The rate increases dramatically at a $3 - 5\,\mathrm{Mpc}$ where star forming galaxies produce $\sim$0.5 core-collapse supernova per year [233, 258]. Within $10\,\mathrm{Mpc}$ the core-collapse supernova rate is about $1/\,\mathrm{year}$. While the expected event rate is moderate, the physics that may be learned from a detection of GW from a core-collapse supernova goes far beyond constraining emission and explosion mechanisms. Supernovae are cosmic laboratories for high-energy-density gravitational, plasma, nuclear, and particle physics. In particular, it may be possible to extract information on the nuclear EOS directly from GW observations [259]. Combining information carried by neutrinos with that carried by GW may allow more robust parameter estimation and physics extraction, but the details of how these data can be combined are unknown and must be worked out.

Current constraints on core-collapse supernova GW emission come from all-sky blind burst BLAH searches [253, 254]. Sensitivity improvements by factors of order unity can be expected from a targeted all-sky search using information from models and, in particular, from a search that uses EM triggers for extragalactic supernovae. Such searches are in development, with emphasis on finding ways to handle the large uncertainties on the time of core collapse and onset and end of GW emission inherent to an EM triggered search.

Low-energy neutrinos are emitted copiously in core collapse, and such triggers will provide much better timing than EM triggers (e.g., [260]). Current initiatives to collaborate with neutrino observatories will need to be intensified in the advanced detector era. Triggering by neutrinos will be trivial for any Milky Way or Magellanic cloud event. More distant events in galaxies of the local group (e.g., in Andromeda) will lead to only very few events in current and near-future neutrino detectors [261, 262] and a joint GW-neutrino search for sub-threshold triggers may increase the detection efficiency by up to a factor of two [263].

An interesting challenge to be ready for is the detection of GW and neutrinos from a galactic core collapse event with no EM counterpart. This could be either an *unnova*, i.e. an event that leads to a weak explosion or no explosion at all [264] and in which a black hole is formed after $\sim 1-2\,\mathrm{s}$ of GW and neutrino emission, or it could be a EM-obscured supernova. Unnovae or obscured supernova may make up $\sim$50% of all core collapse events [265].

Accretion-Induced Collapse (AIC) of Massive White Dwarfs

AIC occurs when a white dwarf (WD) is pushed over its Chandrasekhar mass limit and its conditions of central density, temperature, and composition favor collapse rather than thermonuclear explosion. AIC may occur in binary WD merger events or by accretion from a companion star. Their occurrence rate is probably multiple orders of magnitude smaller than that of regular core collapse (e.g., [266]). AIC will proceed like a normal core-collapse event, but unlike ordinary massive stars, AIC progenitors are quite likely rapidly spinning. Hence, AIC is likely to give a strong GW signal from core bounce. In addition, postbounce long-lasting nonaxisymmetric rotational instabilities are plausible [266, 217].

AIC are expected to lead to EM-subluminous supernova explosions and we may be faced with a strong GW and neutrino signal with a weak EM counterpart. Being able to differentiate the AIC case from the black-hole forming regular core-collapse case will be important.

4.1.3 Neutron Stars

Isolated neutron stars may be sources of detectable GW bursts via a number of processes. Broadly speaking, currently known GW emission mechanisms lead either to subsecond, kiloHertz frequency bursts, such as those from f-mode oscillations, or longer duration, lower frequency signals like those which might be expected from r-mode excitation. Both classes of signal may be emitted in a variety of astrophysical phenomena, including soft gamma repeater flares, pulsar glitches and in the aftermath of binary neutron star coalescence.

Short Duration Transients

It is expected that phenomena in neutron stars which exhibit a sudden localized energy release could excite non-radial pulsational oscillation modes. The f-mode is of particular interest since the radiation reaction timescale is significantly shorter than other dissipative timescales; hence, the f-mode is the most efficient source of GW in oscillating neutron stars. The frequency and decay time of the f-mode are determined by the neutron star's mean density and compactness (M/R), respectively, making their detection and measurement a potential probe of the neutron star equation of state. The GW signature of the f-mode is generally assumed to take the form of a decaying sinusoid whose frequency lies somewhere in the range $1-3\,\mathrm{kHz}$ with damping times $\sim\mathcal{O}(100)\,\mathrm{ms}$. The existing burst analysis pipelines should be sensitive to f-mode signals, provided the search is extended up to sufficiently high frequencies.

Long Duration Transients

In addition to the rapidly damped subsecond burst signal it is possible that some violent event may excite the neutron star r-mode or that some GW-emitting instability may develop.

The r-modes are a type of inertial mode (oscillation modes restored by the Coriolis force) and have frequencies proportional to the star's angular velocity, placing them around tens of Hz for most putative sources. They are considered relatively more efficient GW-emitters compared to other inertial modes [267]. As in the case of the f-mode, a ring-down morphology is assumed in the absence of any precise modelling of the GW signal. The timescales associated with r-mode emission is dominated by damping from the viscous boundary layer between the outer crust of the neutron star and its fluid core. According to the model proposed by Levin and Ushomirsky [268], the expected time constants are of order 10^5 seconds or shorter for neutron stars in the frequency band of terrestrial GW detectors. This analysis is being developed in collaboration with the Continuous Wave working group (§5).

Oscillations excited in the neutron star by, e.g., magnetar flaring may develop into GW-emitting rotational instabilities. Instabilities can be broadly divided into two classes: dynamical and secular, with dynamical instabilities being of most interest as transient sources. The most commonly considered dynamical instability is the bar-mode instability associated with the star's fundamental (f) mode, which sets in once the ratio of kinetic energy to gravitational binding energy exceeds some threshold. The instability then causes the f-mode to grow and deform the star into a rotating bar-like structure; ideal for GW emission and resulting in a quasi-periodic signal at twice the rotation frequency of the unstable neutron star. The lifetime of the bar-mode depends on dissipative processes and may survive for $\mathcal{O}$(seconds). Given that the dynamical instability requires a high rotation rate and differential rotation, it is likely that such signals, if they exist at all, should only be expected in newly formed proto-neutron stars following supernovae and in surviving post-merger objects following binary neutron star coalescence.

Excitation Mechanisms & Target Sources

We conclude this section with a brief review of astrophysical phenomena that may plausibly give rise to some, or all, of the emission scenarios listed above.

Magnetar Flares: Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) emit short-duration X-ray and gamma-ray bursts at irregular intervals, and (rarely) giant gamma-ray flares with luminosities up to $10^{47}\,\mathrm{erg/s}$ [269]. SGRs/AXPs are most likely strongly magnetized neutron stars (magnetars) that experience recurring dynamical events in their crust or magnetosphere, which lead to the observed outbursts, though the details of the outburst mechanism remain to be understood. If magnetar outbursts/giant flares are due to magnetic-stress induced crust quakes (e.g., [270, 271]) and if crust and core are efficiently coupled in magnetars, SGRs/AXPs will emit GW via the excitation of the magnetar's non-radial oscillation modes [272, 273, 274, 275, 276, 277, 278, 279].

The pulsating X-ray tail of SGR1806$-$20 also revealed the presence of quasi-periodic oscillations (QPOs) [280, 281, 282] that were plausibly attributed to seismic modes of the neutron star, thus suggesting associated GW emission [283, 284].

Together with glitching pulsars, bursting magnetars are the closest known potential sources of GW. A network of advanced detectors will probe the energetics of galactic magnetar outbursts several orders of magnitude below the typical electromagnetic energy output of giant SGR flares, constraining an unexplored and interesting region [285, 276, 286, 277, 278, 272].

Pulsar Glitches: Radio, X-ray and gamma-ray pulsars exhibit occassional sudden changes, or *glitches*, in their rotation rate. These glitches may be due to starquakes where the equilibrium configuration of the solid crust of the neutron star deforms as the pulsar spins down. Alternatively, it may be that the interior can be modeled as consisting of a superfluid core rotating more or less independently of a solid crust which experiences an electromagnetic torque due to the star's magnetic field interacting with its environment. It has been suggested by eg. [287], that once this differential rotation reaches a critical value, a dramatic un-pinning of superfluid vortices occurs, coupling the rapidly rotating superfluid to the more slowly rotating crust, causing the observed temporary spin-up. It is possible that the neutron star r- and f-modes will be excited by both mechanisms. Pulsar glitches, however, are not enormously energetic events. The most optimistic (naive) estimate of the energy involved in the glitch is $\sim 10^{42}$ erg. It is not thought likely that this much energy will be emitted as GW but, given the lack of complete understanding of glitch mechanisms, observational constraints which probe energy regimes comparable to or below thish may help constrain future glitch modeling.

Type 1a X-ray Bursts In Accreting Milisecond Pulsars: Low-mass X-ray binary systems are comprised of a neutron star accreting matter from a low-mass companion star. The accretion process leads to spin-up of the neutron star, resulting in a milisecond pulsar (MSP). Accreting MSPs spend most of their time in a quiescent phase with X-ray luminosities $\mathcal{O}(10^{31}\text{-}10^{33})\,\mathrm{erg\,s^{-1}}$, occassionally showing X-ray outbursts with luminosities varying between $\mathcal{O}(10^{39}\text{-}10^{42})\,\mathrm{erg\,s^{-1}}$. These outbursts are interpretated as the thermonuclear ignition and burning of accreted material on the surface of the neutron star, plausibly leading the the excitation of f- and/or r-modes. MSPs present a particularly attractive source of r-mode emission since the rotation frequencies of several known sources result in r-mode frequencies directly in the most sensitive band of aLIGO.

Post-merger Remnants (Hypermassive Neutron Stars) The end-state of binary neutron star coalescence is determined by the neutron star equation of state and the binary parameters. Recent simulations suggest that the favored outcome is a metastable hypermassive neutron star (HMNS), rather than prompt collapse to a black hole [288, 289, 290] (A review of the state of the art of binary neutron star merger simulations may be found in [291]). If such an object is formed, it will exhibit transient deformations and undergo non-axisymmetric oscillations, leading to a short (1-100 ms), high frequency (1.5-4 kHz) burst of GW and possibly develop a bar-mode instability. The mere detection of a GW signal in this frequency range, following binary neutron star coalescence, would confirm the formation of a HMNS and provide an unambiguous distinction between a binary neutron star merger and neutron star-black hole merger. Futhermore, accurate measurement of the frequency content, in particular the dominant post-merger frequency and, ideally, the sub-dominant modes, may lead to constraints on the neutron star equation of state to complement and rival those offered by measuring tidal distortion effects during the late inspiral [292, 293]. With an expected energy emission of up to $10^{-3} - 10^{-2}\, M_{\odot}c^2$, these signals will most likely be detectable only for nearby ($D \lesssim \mathrm{few}\ \times\ 20\,\mathrm{Mpc}$) events. However, the science possible with this source, together with the associated detection of the inspiral signal, make this a strong target of opportunity.

4.1.4 Mergers of Black Hole Binary Systems

The coalescence of binary compact objects consisting of neutron stars (NS) and/or black holes (BH) are the most promising sources for detection by LIGO and Virgo. Sources consisting of binary black holes (BBH) and intermediate mass black hole binaries (IMBBHB) are discussed in details in the CBC sections of this white paper (§3.2.3 and §3.2.4). and they are a subject of the Burst Group research as well (§4.4.7).

Current approaches to the detection of GWs from binary black holes expect the binary to have a circular orbit by the time it enters the frequency band of ground-based detectors. However, black hole binaries may form through various scenarios, for example, by dynamical interactions in galactic nuclei containing a supermassive black hole (SMBH), or in globular clusters [294]. If stellar-mass or intermediate-mass black holes form a dense population around SMBHs, the probability of close encounters of two black holes could be high [295]. Such encounters may lead to the formation of binary black hole systems. The initial eccentricity e of such binary system is likely to be close to unity and remain large all the way to the merger. The merger may happen within hours, and such short lived systems are expected to have a unique GW signature: a series of short bursts. There are no accurate eccentric binary black hole waveforms with $e > 0.05$ available at this time and the burst searches may be the only way to detect and study binary sources with high eccentricity.

The advanced detectors will provide an exciting opportunity for the first detection and study of GW signals from BBH mergers, with sensitive ranges of up to several Gpc for some systems. The expected detection rates [296] vary dramatically between 1 and a few thousand BBH mergers per year, with possibly ~30 events/year for lighter BBH systems (total mass $< 100M_{\odot}$) and $\sim$1 event/year for heavier IMBBH systems (total mass $> 100M_{\odot}$). Observations of BBH and IMBBH binaries in a wide parameter space and measurements of their parameters will have important consequences for theories of the formation and growth of supermassive black holes and the dynamics and evolution of globular clusters [297].

4.1.5 Cosmic (Super-)String Cusps and Kinks

Cosmic strings are one-dimensional topological defects that may have formed during one of the early symmetry-breaking phase transitions in the universe [298]. Superstrings are the supposed basic constituents of matter in fundamental string theory or M-theory, which is at present the leading contender for a unified theory of all fundamental interactions including gravity. Both cosmic strings and superstrings are still purely hypothetical objects. There is no direct observational evidence for their existence even though they may produce a variety of astrophysical signatures. One of the most promising ways of detecting the presence of cosmic strings and superstrings is via their GW emission. This is the primary mechanism of energy loss from strings, so strings are believed to contribute significantly to the cosmological GW background.

An important role in the emission of GWs is played by the presence of cusp features on strings resulting from an oscillating loop. At such points the string reaches the speed of light for a brief moment and a burst of GWs is emitted, with strong beaming in the direction of the string's motion. This yields a characteristic GW signature which depends on the reconnection probability, the size of the loop, and the string tension $G\mu$ [299, 300, 301]. This last parameter is crucial to characterize a string network and its evolution. The best current constraint is given by the CMB observations of WMAP: $G\mu < 2.1 \times 10^{-7}$ (68% C.L.) [302].

The GW waveform is well-modeled by a power law in frequency ($\sim f^{-4/3}$) with a frequency cutoff given by the angle between the cusp feature and the line of sight. This allows a templated search with a better efficiency than the standard all-sky burst search.

A second type of GW signal is expected from cosmic strings, originating from a string kink produced after the reconnection of two string segments. As for cusps, the kink signal obeys a power law in frequency ($\sim f^{-5/3}$) but with a smaller strain amplitude, which disfavors detection. However, recent studies (e.g., [303]) show this might be compensated for by a higher production rate. A kink search would be a straightforward extension of the current LIGO-Virgo analysis.

4.1.6 Exotic Theories of Gravity and Matter

Although General Relativity has withstood all tests at the post-Newtonian level so far, the direct detection of gravitational waves will provide an opportunity to probe the regime of validity of alternative theories of gravity [304, 305, 306]. An evidence of such alternative theories could, in turn, provide clue to outstanding problems in astrophysics, such as dark energy and dark matter, and help reconcile gravity and quantum mechanics [307].

Alternative theories of gravity may result in a difference between the speed of light and the speed of propagation of gravitational waves [308]. Coordinated electromagnetic and gravitational wave searches could place constraints on the propagation speed of gravitational waves.

Alternative metric theories of gravity also predict extra polarization states, in addition to the *plus* and *cross* polarization modes of Einstein gravity. Indeed, every other known viable metric theory of gravity predicts more than two polarization states [309], and the most general gravitational wave can have up to six polarization states [304, 305]. For instance, Brans-Dicke theory and other scalar-tensor theories predict an additional scalar transverse polarization state. This will have an impact on multi-detector coherent gravitational wave searches, as the linear combination of data streams that maximizes the gravitational wave content depends on the number and type of additional polarization states. If the direction of the gravitational wave is known in advance, then it is possible to establish which polarization states are present in a signal, provided there are at least as many detector data streams as polarization modes [305]. This is the case for externally triggered searches, and for searches where the gravitational wave triggers have sufficiently large signal-to-noise to establish the sky location with triangulation. For all-sky searches new techniques need to be developed to separate out the expanded set of polarization states. On the other hand, if the scalar mode is the dominant component of the signal, as might arise from stellar core collapse to a proto-neutron star and/or the birth of a black hole, then a search for *only* the scalar mode is interesting, and can be implemented effectively even with only two or three detectors.

Evidence for the the existence of extra polarization states would be fatal for General Relativity. A non-detection, however, may not rule out alternative theories of gravity because the strength of the extra polarization states depends on the source and emission mechanism. The emission mechanism can also be different in alternative theories of gravity. In particular, different multipole moments (such as the dipole) contribute to the radiation.

4.1.7 Bursts with memory

The possibility for a gravitational-wave burst to settle in a non-zero strain has been identified in the mid-1970's [310]. Such a DC effect in gravitational-wave radiation, a *memory*, may provide a distinct companion to the transient part of the radiation from several astrophysical systems. This includes bursts from core-collapse supernovae [216] as well as merging binary systems [311, 312]. This effectively zero-frequency strain signal presents challenges in detecting it with ground-based interferometers due to low frequency seismic noise.

4.1.8 Unknown Unknowns

Blind burst searches allowing for any kind of time-frequency signal content remain the only way to identify unknown and unexpected signatures that do not have EM/neutrino counterparts. The dramatic increase of the volumetric reach of advanced detectors will increase the possibility of discovering an unexpected event, and will require a strategy and/or a protocol to communicate such discoveries to the theory community.

4.2 Recent Observational Results

The following LSC-Virgo Burst Group papers have appeared in journals in the past year:

S6/VSR2+3 SWIFT followup [313]: The feasibility of rapid multi-wavelength follow-ups of GW burst candidates is demonstrated in this analysis of two candidate GW events recorded in S6/VSR2+3, whose reconstructed sky locations were observed by the *Swift* observatory. *Swift*'s observations yielded no evidence for an electromagnetic signal associated with either event.

S6/VSR2+3 GRB [314] (joint with CBC)**:** We searched for GW transients associated with 155 GRBs detected by satellite-based gamma-ray experiments during S6/VSR2+3 [315, 316, 317]. No candidate events were found, and distance exclusion limits were set on both generic GW bursts and also binary progenitors.

S5/VSR1 GW+HEN Antares [318]: We searched for GW bursts coincident with high-energy neutrino candidates collected by the ANTARES neutrino telescope from January to September 2007. No significant coincident events were observed, and we place limits on the density of joint high-energy neutrino and GW emission in the local universe.

The following LSC-Virgo Burst Group paper has been published to arXiv:

Commissioning and Observing Scenarios [319] (joint with CBC)**:** This paper discusses prospects for the detection and localization of GW transients (both bursts and inspirals) by the Advanced LIGO and Advanced Virgo observatories. It also discusses a plausible scenario for the commissioning of the detectors.

4.3 Methods Used in Burst Searches

This section describes how the Burst Group searches for GW transient signals without knowing their form, select good-quality data, evaluate the background rate of false triggers from detector noise fluctuations, and estimate the sensitivity of its searches.

4.3.1 Signal Extraction

Despite rapid progress in relativistic astrophysics, there is still significant uncertainty in the predicted waveforms for most GW burst sources described in §4.1. Therefore, the Burst Group implements a variety of methods to find transients in the data that are inconsistent with the baseline noise, and rely heavily on coincidence between multiple detectors to discriminate between GWs and noise fluctuations. A *search pipeline* generally consists of one or more signal processing algorithms, post-processing tools and diagnostics criteria. The analysis pipeline produces a set of *triggers* which, if they pass all significance tests and consistency checks, are considered to be candidate GW burst events.

In a few special cases when an accurate signal model is available, such as for cosmic string cusps or neutron star or black hole ringdowns, a search can be done using matched filtering with a bank of templates.

Otherwise, GW bursts can be identified in the detector output data as excess-power localized events in the time-frequency (TF) domain. To obtain a TF representation of data a number of transformations are used, including windowed Fourier transforms, discrete wavelet decompositions (Symlets, Meyer wavelets) [320] and continuous wavelet transforms (Q-transform) [321]. These transformations are actively used in the burst search algorithms. At the same time, the Burst Group is open to other promising approaches such as the Hibert-Huang Transform (HHT) adaptive time-frequency decomposition [322], and the fast Wilson-Daubechies transform [?]. A few other methods which do not start with a TF representation have been implemented in past burst searches, including a change-point analysis of bandpassed data [323] and a cross-correlation analysis using pairs of detectors [324].

Access to detector networks is especially important for the detection of GW bursts, as the identification of a consistent signal in multiple instruments increases the significance of a candidate event and distinguishes it from instrumental and environmental artifacts. Also, data from multiple detectors allow to reconstruct the two GW polarizations and determine the direction to the source. For these reasons, the Burst Group has developed multi-detector search algorithms which can be classified as *incoherent* or *coherent*. Incoherent algorithms [323, 321, 325, 326] identify excess-power events in individual detectors; a time coincidence is then required between events in different detectors. This is particularly useful for detector characterization and the study of enviromental and instrumental artifacts (§4.3.2). Coherent algorithms are based either on cross-correlating pairs of detectors [327, 328, 329] or on a more general coherent network analysis approach [330, 315]. In these methods, a statistic is built as a coherent sum over the detector responses, which, in general, yields better sensitivity, at the same false alarm rate, than individual detector statistics.

Several coherent approaches have already been adopted in past analyses, including a constrained likelihood method for untriggered searches [331, 330, 332] and a likelihood method for triggered searches [315]. In preparation for the analysis of advanced detector data, these methods are being upgraded and tested both on initial detector data and engineering runs. The Burst Group is also exploring a Bayesian formulation of a coherent network analysis [333], already used in the analysis of initial detector data [334], and on maximum entropy methods [335]. In addition, the Burst Group is investigating dedicated coherent algorithms which may use partial information about burst sources and incomplete source models, for targeted searches that address the science goals described in §4.4.

The prompt detection of GW signals and estimation of source coordinates enables coincident observations with other astronomical instruments, which can significantly increase the confidence of detection [336]. Such measurements may not only aid the first detection of GWs but also they will give us fundamentally new information about the sources and their distribution. The Burst Group has made significant progress in the development of source localization methods, which were extensively tested during the Position Reconstruction Challenge and used during the S6-VSR2/3 run [182]. The source localization problem will remain a high priority of the Burst Group in preparation for advanced detector network. LIGO, Virgo and other ground-based GW detectors have a linear response to the GW strain at the detector sites. The inferred GW strain at each detector site thus amounts to the greatest information that GW detector observations can provide for the purpose of astrophysical interpretation. Even in the absence of an electromagnetic counterpart an inferred waveform can provide basic information about a source and its dynamics. With an electromagnetic counterpart the accessible physics and astrophysics expands exponentially. Waveform inference is thus a basic desideratum of GW detection and the pursuit of robust and reliable reconstruction algorithms that provide the collaboration this capability is one of the Burst Group priorities (see also §4.3.6).

The Burst Group strategy in the advanced detector era is to support both an incoherent pipeline, with a coherent network follow-up, and a coherent network analysis pipeline. Future needs for hardware computing infrastructure will need to be evaluated during the transition years. The Burst group will benefit from an effort to make the software user-friendly for all group members, with search codes packaged as common tools for all to run and configure for customized analyses, with reduced overhead for learning how to use the code, and a standardized output from all pipelines. The development of new software will be coordinated with DASWG; the group encourages making best possible use of existing and validated code. We remain open to better ways to do things but aim to avoid unnecessary duplication of effort, maximize efficiency, recognize practical development of new tools.

4.3.2 Detector Characterization

Data quality plays a key role in burst searches, where the false alarm rate is dominated by noise transients, or *glitches*, which can happen with similar morphology in multiple detectors and pass the coherence tests developed for the identification of GW candidates. Glitches represent the ultimate limit to the sensitivity of the burst search and to the confidence in a possible detection.

In a coordinated effort of Burst and CBC Group members, the LSC Detector Characterization team (DetChar) and the Virgo Data Quality Group (VDQ) study the correlation of the rate and strength of single detector transients to trends and transients in the sensing and control systems that maintain the interferometers in their operating condition, as well as monitors of the physical environment in which the interferometers sit: vibration, sound, magnetic and electric fields, power line voltages, and others. These studies have led to the identification of times likely to be contaminated by non-GW effects, which the Burst Group uses to veto event candidates found by the GW channel analyses. Based on their duration and character, we distinguish between *data quality* vetoes and *event-by-event* vetoes [337, 338].

Data Quality (DQ) vetoes are long time intervals, typically several seconds, during which auxiliary signals indicate that an interferometer was out of its proper operating condition. The vetoes are constructed from DQ flags identified by DetChar and VDQ groups. Different flags have different correlation with transients in the GW channel, thus we developed a categorization system for DQ flags to be used as vetoes:

- Category 1 vetoes define which data can be safely analyzed by the search algorithms; they remove features that could affect the power spectrum.
- Category 2 vetoes define the *full* data set, where to search for detection candidates. They remove times when the detector is unambiguously misbehaving with a well-understood physical coupling. They introduce a small dead time (a few percent) and have high efficiency for removing single-detector outliers.
- Category 3 vetoes define the *clean* data set to be used to set an upper limit in the case of no detection. They identify times with an excess of single-detector triggers in the GW channel, but the correlation is not unambiguous and they may introduce up to 10% dead time. If a detection candidate is found at these times, this flag is taken into account in the event followup, as described in §4.3.7.
- Category 4 flags specifically tag the times where hardware injections were performed. In most searches they are to be used as Category 1 vetoes since they might affect the PSD computation.
- Category 5 data quality are advisory flags: there is no obvious correlation with single detector transients, but they are known detector or environmental features.

This classification is based on single-detector triggers [339, 334]; once the tuning is complete, their effectiveness is tested on coherent network candidates.

Event-by-event vetoes are short intervals, typically 100 ms or shorter, that mark individual transients in an interferometer's output with a coincident transient in one or more diagnostic signal. They are identified with extensive statistical studies of coincidence between single detector triggers in auxiliary channels and event candidates, with a software package which considers many possible veto conditions in a hierarchical classification process. The vetoes are ranked on the basis of the significance of their correlation with GW triggers, and their significance is re-evaluated in subsequent iterations, after each condition is applied. Their safety is tested against hardware injections [340]. In the past year we completed studies of machine-learning algorithms and multivariate classifiers in event-by-event veto definition, combining information from glitches in multiple detector channels [341]. Their performance is comparable with traditional hierarchical methods [342].

While there is overlap in personnel and activities between the Detector Characterization group and the Burst Group, the Burst Group is responsible for applying DQ flags and vetoes to and identifying which artifacts are creating the greatest problems in burst analyses. Preparations for the advanced detector era are building upon the techniques and definitions developed in past science runs, with the currently existing approaches serving as a baseline which will be improved for future runs. Any target-of-opportunity externally triggered analyses using GEO astrowatch data currently being collected will be supported by the detector characterization activities and employ these basic strategies as well.

Despite the intense detector characterization effort in previous science runs, the burst search sensitivity in initial detector data was dominated by glitches. As we prepare for the advanced detector era, new, the development and implementation of new sophisticated techniques is needed for an effective mitigation of non-Gaussian noise transients, with a target of at least 90% cleaning of single detector triggers in future runs. Close collaboration between the Detector Characterization group, VDQ Group, Burst and CBC analysis groups, and the instrumental commissioners will be critical in meeting these objectives.

Online analysis will remain an area of focus in the advanced detector era, partially in order to enable rapid feedback to commisioners. In the previous science runs, the Burst Group collaborated with the Detector Characterization group and the VDQ group for a prompt and documented definition of DQ flags and veto criteria to enable online analysis. Single-interferometer triggers were produced online and time-frequency plots, as well as histograms and correlograms, were available with a latency of 2-3 minutes.

Burst online trigger generators are very important for characterizing non-Gaussianity or glitches in auxiliary channels. These are very important for DetChar studies and the development of vetoes. The Burst Group is currently developing trigger generators that are both capable of running on many auxiliary channels and providing good time-frequency characterization of the triggers. Over the next year, these new methods will be validated with tests and injections of simulated signals, and tuned to provide the most useful information to DetChar while not producing an overload of triggers. As data from advanced detector subsystems continue to become available, engineering runs will be increasingly useful as testbeds for detector characterization techniques, as well as gaining an understanding of the subsystems themselves.

4.3.3 Background Estimation

The key to a burst search is discrimination between GW signals and *false alarms*, or background noise fluctuations which pass the analysis selection criteria. The False Alarm Rate (FAR) or, alternatively, the False Alarm Probability (FAP) for the observation time, depends on the detector noise properties and on the full set of analysis selection criteria. The FAR is typically estimated with an *off-source* resampling of the observation data, equivalent to switching off any GW signals.

In a network of detectors with independent noise, the off-source resampling is performed by *time shifting* the data of detectors relative to each other by more than the maximum light travel time between the sites. This voids the coincidence conditions for any GW signal which may be present in the data and provides a reliable estimate of the accidental background if the noise properties vary over time scales longer than the time shifts. This procedure is repeated many times with different time shifts, so that each resample can be considered independent from the others. The sum of the resampled observation times should exceed the inverse of the target FAR by at least a factor of a few. If there is a known trigger time for the possible GW, the background estimation can take advantage of it by defining off-source samples within a single detector.

The significance of event candidates found in the *on-source* (unshifted) analysis can be evaluated by comparison with the distribution of the accidental background, typically quantified with statistics that describe the strength or quality of the signal. For an objective assessment of the FAR, we adopt a *blind* statistical procedure, where we use the off-source data, without examining the on-source data, to tune the procedures to compute the test statistics and their thresholds. Once the on-source has been disclosed, a second set of independent off-source resampling can be drawn to re-evaluate the false alarm rate. This avoids possible biases from over-fitting to the first off-source sample.

This method has a few caveats. The time shift analysis cannot discriminate between GW signals, other foreground signals or correlated noise sources at different detectors. Moreover, if accidental events are not consistent with a Poisson point process, it is not obvious how to evaluate the uncertainty of the empirical off-source distribution, which propagates into the FAR uncertainty. Another problem with the time-shift method occurs if strong signal events in the detectors produce accidental coincident events in off-source resamples and induce a positive bias on the FAR estimates. This effect is mitigated in coherent network analyses: the stringent consistency checks between detector responses makes them more robust against this bias than incoherent analyses. Up to this point we have seen no evidence that signal injections in the data can affect the result of coherent burst searches.

4.3.4 Simulations

The Burst Group uses software signal injections in the data to tune its analyses, assess their *detection efficiency*, once all selection criteria are fixed, and interpret the results against different signal models. In the analysis of initial LIGO-Virgo data, simulated signals were added to the data at pseudo-random times, spanning the expected range of signal properties (frequency, duration, etc.), but without attempting to exhaust all plausible signals, as the robustness of the signal extraction methods allows to extrapolate to other signals.

The detection efficiency is evaluated as a function of waveform and amplitude, averaged over random sky positions, for all-sky burst searches, or at the fixed sky position of an astrophysical event which triggered the search. Results are also interpreted using models of galactic and extragalactic mass distributions. The standard set of simulated waveforms has been expanded over time, to improve the astrophysical interpretation, e.g. including elliptically polarized signal models and random distribution of the inclination angle of the source with respect to the line of sight.

Systematic effects of calibration uncertainties on the detection efficiency are estimated with injections of signals with suitably mis-calibrated amplitude and phase (or time). These tests can be performed on subsets of the observation time to limit the computational load, since typically a few-days subset is representative enough of the detection efficiency through a data run.

While the basic simulation machinery used in the analysis of initial LIGO-Virgo data is well-established, exploratory work is being done for a more flexible simulation mechanism in the advanced detector era. Also, work is in progress to expand the set of waveforms and include modeled or astrophysically motivated signals.

4.3.5 Hardware Signal Injections

We inject simulated signals into the interferometer hardware from time to time as an end-to-end test of the detector, data acquisition system and data analysis pipelines. By comparing the reconstructed signal against the injected one, we check the detector calibration. Hardware signal injections are also useful for establishing the safety of vetoes, i.e. testing the limits on the cross-coupling of loud GW signals into auxiliary data channels that might be used to define vetoes. The signal generation paradigm is currently being re-implemented for the advanced detectors and exercised in the periodic engineering runs.

4.3.6 Burst Parameter Estimation

The detection of a GW burst will present the astrophysics community with a wonderful mystery to solve: What produced the signal? Answering this question will require an assessment of the degree of confidence that one process or another was at work, and learning as much as possible about the underlying dynamics of the system from the gravitational wave data.

The process of characterizing GW signals for modeled systems such as binary black hole mergers is fairly straightforward and well understood (see for instance [343]). Physical parameters such as the mass and spin of the component black holes affect the waveforms in a known way, and by comparing the parameterized waveforms to the data it is possible to develop posterior probability distributions for the model parameters. The problem of parameter estimation for a general burst signal is more difficult. At first sight the question may seem ill-posed since the signal extraction and search techniques generally do not use physically parameterized models. For example, the output of a burst search may be a list of best-fit wavelet amplitudes for the reconstructed signal, from which it is possible to derive physical quantities such as the duration, rise and decay times, peak frequency, frequency band containing 90% of the power, etc.. The choice of physical quantities is flexible, and can be tailored to address particular astrophysical questions. In addition to characterizing the time-frequency and energy content of the signal, the coherent network techniques adopted by the Burst Group allow to estimate the source sky location and reconstruct the waveform with its polarization, as discussed in §4.3.1.

The goal of burst parameter estimation is to go beyond finding best fit point estimates for the quantities that characterize a signal, and to produce posterior probability distributions for the parameters. It is only when the spread in the parameter estimates are available that it becomes possible to meaningfully compare the predictions of different astrophysical models. This is a high priority item for the Burst Group in the advanced detector era. So far only preliminary studies have been conducted with techniques described in this sections, incorporated in the science team activities described in §4.4.

Examples of ongoing burst parameter estimation efforts include Bayesian techniques where wavelets are used to model both the network-coherent GW signals and instrument glitches [344], producing full posterior distributions for the signals and glitches and incorporating Bayesian model selection, which provide odds ratios for the detection and non-detection hypotheses. An additional benefit of using Bayesian inference in the analysis is that it is easy to incorporate priors, including strong priors on the signal morphology that can be used in targeted searches. For instance, there are ongoing efforts to incorporate information from numerical simulations of core collapse supernovae and the resulting gravitational waveform catalogues, using a Principal Component analysis and Markov Chain Montecarlo based reconstruction [259] or Nested Sampling. This type of Bayesian inference for parameter estimation and waveform reconstruction in targeted searches will be pursued as waveform catalogues become available, with coordination to take place within the science teams.

4.3.7 Be Prepared to Detect a GW Signal with Confidence

Establishing high confidence in the detection of a GW transient remains the most challenging problem for the Burst Group in the Advanced Detector era. Burst searches are not tied to a specific source model, and therefore they are more affected by non-stationary noise than templated searches. In the analysis of data from the initial generation of GW interferometers, the Burst Group has adopted several tests to assess whether a candidate event should be considered a GW detection, including consistency tests among coincident signals from different interferometers, extensive detector characterization studies, to exclude instrumental and environmental transients, and background studies to establish the significance of observed candidate events. There have been significant improvements in the burst algorithms during the analysis of initial LIGO/Virgo data, and yet, they are not sufficient for a confident detection of expected GW signals. During the data runs of initial detectors there were two blind burst injections, which have been promptly discovered and reconstructed by the burst algorithms. However, due to excessive non-stationary background noise the burst search could not identify these events as GW signals with high confidence.

In preparation for the analysis of data from advanced detectors, and to solve the problem of non-stationary background noise, the Burst Group has identified several directions of research aiming a confident detection of low rate GW transients.

Coherent network analysis: this approach has proven very effective in searches of initial data; further development is in progress, to fully exploit the potential of advanced detector networks.

Inclusion of models into burst searches: folding non-perfect models in the analysis can help divide assorted un-modeled events into wide weakly-modeled classes with significantly reduced background. For example, the classification of burst triggers into different polarization states has been already adopted in the analysis of initial detector data; other models targeting particular classes of burst signals can be similarly implemented in the analysis. However, weakly-modeled algorithms are quite computationally intensive and require robust source models and a close collaboration with the wider astrophysical community.

Improved statistical analysis is required to combine different runs and searches in order to establish a significance of observed candidate events. For example, during the S6/VSR2+3 burst analysis there were 4 different time epochs and four different network configurations with significantly different rates of background events, for a total of 16 analysis configuration. All these configurations need to be combined in a single measurement with a clear statement of statistical significance of the candidate events. Such statistical approaches based on likelihood, false alarm density, and other methods are under development in the Burst and CBC groups and need to be tested, but there is room and need for other, more advanced statistical algorithms.

Advanced background studies are needed to better understand the low rate non-stationary tails in the background rate distributions. Burst searches can measure false alarm probability at the per thousand scale, by performing thousands of time lags. However this is often not sufficient in case of strong candidates, and new technical approaches are being developed to investigate the false alarm probability range down to a part per million.

Detector characterization studies is one of the most important activities in the Burst Group. Burst Group members actively participate in detector characterization studies (as part of the LSC Detector Characterization group) and the burst algorithms are used for identification of data quality flags and vetoes. During the analysis of initial detector data, the burst group also developed a *detection checklist* - a follow-up procedure for candidate events. We will continue to work with members of other LSC working groups to improve the identification of spurious events in the detectors. New approaches to detector characterization are needed to make a breakthrough in this area and to dramatically improve the efficiency of the data quality selection cuts and vetoes. One such approach is based on the estimation by regression methods of linear and non-linear couplings between the gravitational wave channel and the hundreds of auxiliary channels monitoring environment or instrument operation. This approach recently demonstrated the capability of cleaning the gravitationa wave channel from some classes of noise lines and related side bands due to up-conversion noise. Investigations on the performances of this tool are ongoing, aiming at the suppression of non gaussian excess noise.

Best use of the initial detectors data set: We do not need to wait for advanced detector data to improve and test advanced analysis algorithms, new statistical procedures and novel data quality methods which are required for a confident detection of burst GW signals. All this work can be done on the existing data set, before a data from advanced detectors is collected. Detection challenges and tests of confident detection approaches can be performed using previous data sets (recolored to match the spectral sensitivity of advanced detectors) as well as a part of the software engineering run plan.

Efficient use of trigger event properties and source distribution: Beyond perfecting our GW search methods, it is also crucial to understand and incorporate information from other messengers in the analysis. The anticipated source distribution based on the available galaxy catalogs is a good example where we can significantly enhance our sensitivity by weighting results with the probability distribution of potential sources. For external triggers, trigger properties beyond source direction (e.g. source distance for GRBs or neutrino energy for HEN searches) can be an important addition to the information used in the analyses.

4.4 Science Goals

The Burst Group's mission goal is to detect GW transients and use them to decode new information on population and emission mechanism of astrophysical objects, as well as to test theories of gravity. We aim to extract a broad range of observational results from early data from the advanced GW detector network, building on our online and offline analysis experience and infrastructure developed for the initial detectors. The analysis for S6/VSR2+3 *first science targets* is complete, and while a few remaining searches from S6/VSR2+3 are still under review, the focus of the group is on preparations for the advanced detector era.

Although burst search algorithms are designed to detect a wide range of signals, their tuning and interpretation benefits from considering how they perform for plausible astrophysical signals. Therefore, the group's science program involves an active collaboration with the theoretical astrophysics, source modeling and numerical relativity communities. Many of the gravitational-wave sources introduced in §4.1 should be observable in more traditional channels, from Earth-based astronomical data, through sensitive GRB/X-ray satellite detections, to neutrino signals. Knowledge of the time and/or sky position of the astrophysical event producing a GW burst increases the sensitivity of a triggered burst search compared to an untriggered, all-sky search, and the association with a known astrophysical event may be critical in establishing our confidence in a GW burst detection. Perhaps most importantly, joint studies of complementary data enable scientific insight that cannot be accessed through gravitational waves or other messengers alone. Therefore, in addition to searches using only the GW data, a significant part of the Burst Group's science program involves connecting with other observations and working closely with the astronomy and astrophysics communities. The Burst Group is preparing to perform rigorous and sensitive analyses from the very beginning of the advanced detector era, with a commitment to deliver, as **first science targets**:

1. an all-sky statement on GW bursts: upper limits if there is no detection, a rare-event detection significance if we have one candidate, or population studies if we have several detections;
2. prompt burst analysis and trigger production, for the electromagnetic followup of GW transients;
3. prompt reports on interesting astrophysical triggers, such as GRBs, SGRs, and supernovae.

For this, the group is now pursuing the necessary ingredients: data access, data quality, simulations, interpretation and statistics, and improved background estimation, as detailed in §4.3.

The Burst Group activity is distributed across eight science teams:

- **All Sky – All Time:** the most general search for GW transients, which is also starting point for certain targeted source analyses;
- **Gamma-Ray Bursts (GRB):** GWs associated with gamma-ray burst triggers;
- **High Energy Neutrinos (HEN):** GWs coincident with high energy neutrino events;
- **Supernova (SN):** GW searches triggered by optical or low-energy (MeV) neutrino observations;
- **Neutron Star Physics (NS):** GWs from isolated neutron stars, including searches triggered by SGRs and pulsar glitches;
- **Other Electromagnetic Counterparts (EM):** GWs associated with X-ray, UV, optical, radio counterparts, using searches triggered by EM events other than the specific sources mentioned above, or else triggered by GW events and followed up with EM observations;
- **Binary Black Holes (BBH):** searches for GWs from intermediate mass and eccentric BBH systems, with close ties with the CBC group;
- **Exotica:** Alternative theories theories of gravity, cosmological defects (cosmic strings), bursts with memory.

This organization is centered on science targets and sources, rather than analysis techniques. Although the ultimate decision on the science goals belongs to the full Burst Group, each team is charged with formulating the science case for its analysis, proposing the methods and defining a coherent publication strategy. Each team is responsible to lay out a timeline with readiness milestones, using the engineering runs schedule to plan on testing, review accomplishments and report to the whole Burst Group.

New searches or teams will be embraced by the group only once they have proven their potential with astrophysical motivation and a viable implementation plan. The team should consider the likely signals; what astrophysical interpretation(s) should be pursued for a non-detection or for a detection; the suitability of existing analysis tools and techniques; what specific improvements need to be made; and what new tools or techniques (if any) need to be developed. Simulations and astrophysical input will help decide whether a specific source requires a targeted analysis or a different tuning and interpretation of the standard all-sky and externally triggered searches.

4.4.1 [ALL-SKY] Search as Broadly as Possible for Gravitational Wave Bursts

There is strong astrophysical motivation to search for burst-like GW signals with ground-based laser interferometers [345]. The emphasis has historically been on astrophysical systems for which the resulting burst waveforms are either poorly modeled or unknown, including, but not limited to, the merger phase of binary coalescence and core-collapse supernovae. In recent years numerical relativity calculations have offered significant information on the waveform accompanying binary mergers [346], as well as new information on the features of signals accompanying core-collapse [216, 347]. Burst sources with well-modeled waveforms include emission from neutron star ringdowns following a pulsar glitch, black hole ringdowns or cosmic string cusps (§4.1.3, §4.1.5). Typical predicted signals last from less than a millisecond to a second, with signal power in the sensitivity band of advanced detectors, i.e. from 20 Hz up to a few kHz. Various models of GW emission from core-collapse supernovae [216] and gamma-ray burst progenitors [348] may result in signals lasting up to several seconds and minutes. Given this broad spectrum of sources and signal morphologies, their uncertainties and the possibility of unanticipated sources, the burst search follows an eyes-wide-open approach for the detection of the widest range of signals.

Our approach relies on minimal assumptions about the signal morphology. The search analyzes as much of the available data as possible from times when two or more detectors are running well, and no assumption is made on sky location or GW burst source. This untriggered burst search is often referred to as *all-times, all-sky*, or simply *all-sky*. The search is tuned in such a way that a very low number ($\ll 1$) of background events is expected over the duration of the observation. Foreground events resulting from this analysis are detection candidates for which further and exhaustive investigation is performed (§4.3.7). The immediate result of this search is a statement on the time, strength, statistical confidence in terms of false alarm rate, reconstructed source location and GW burst waveform.

An astrophysical interpretation of the results can be formulated for specific source models, by estimating the distance to which a signal could be detected. In the case of null results, we plan to provide rate density limits for standard-candle sources (upper limits to the rate per unit volume) and limits on source population models folded with galaxy catalogs (when applicable). In the case of detection candidates we are committed to improving on accidental background rejection, on robust parameter estimation tools for generic bursts, on classification of GW candidates into pre-determined signal classes, and on extracting science through multi-messenger observations (see the following sections).

The all-sky search on first-generation LIGO-Virgo data is now complete [254]. The activity is now focused on the upgrade of the main coherent network analysis pipeline[1], both for the off-line and the low-latency versions, which are expected to reach maturity in the next year. A short-term science goal for the all-sky main pipeline is to **re-analyse the S5-6/VSR1-3 data sets** with an extended set of simulated signals that comprehensively covers most known astrophysical models, including supernovae, ringdowns, cosmic strings, and inspirals, as well as realistic signal parameter distributions: source inclination, signal polarization, location according to the galaxy distribution in the local universe. This re-analysis will produce a sound astrophysical interpretations of the GW burst limits from first-generation detector data. At the same time, it will serve as a powerful test of our upgraded pipelines and a statement of the potential of GW burst searches in the advanced detector era.

In addition to the search for short-duration bursts, the group is **expanding analysis coverage to signals that last up to several seconds or minutes**, with tailored modification to existing all-sky algorithms or new cross-correlation techniques. Some of these efforts are pursued jointly with the Stochastic Group (§6). The first milestone for these new methods will be to demonstrate their performances on a significant fraction of the previous observation time.

The Burst Group has a goal of fielding two independent all-sky pipelines, as was the case in S6/VSR2,3. The development of a second pipeline recently started, based on single detector pipelines, which are also used in detector characterization and veto studies (§4.3.2) and network data analysis modules of (primarily) existing methods. The second pipeline will provide an independent approach to the burst search, an opportunity for cross-checking, reviewing and final vetting of results. The S5-6/VSR1-4 data and the Engineering Runs will be vital for testing and validating our pipelines. In particular, we plan to use a subset of past data recolored to match advanced detectors' sensitivities to set up an all-sky search challenge, including also goals related to signal reconstruction or parameter estimation.

Historically, many pieces of burst analysis infrastructure and techniques were first developed in the all-sky search, and later applied in other more specialized searches. We expect this pattern to continue. In particular, we intend to **investigate the feasibility of reusing all-sky event data for specialized searches**, for instance triggered searches or searches for specific source classes as Binary Black Holes mergers, §4.4.7. This approach optimizes efforts and allows the specialized searches to take advantage of the low-latency nature of the all-sky search. Moreover, the all-sky search performances of the main pipeline will be considered as standard benchmark for all other burst searches.

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[1] coherentWaveBurst 2G

4.4.2 [GRB] Look for GW Transients Associated with Gamma-Ray Bursts

Note: This science team encompasses GRB searches in both the Burst and CBC Groups.

LIGO and Virgo have a long history of searching for GWs associated with GRBs [349, 350, 351, 352, 328, 316, 353, 354, 314]. In the early advanced detector era, the detection of a GRB-GW event would provide compelling support for the associated GW signal. And, as discussed in §4.1, the GW signals would provide valuable insights into GRB progenitor models. Eventually, GRB-GW observations may provide important connections to cosmology (§3.4.9).

The search strategy is based on looking for a GW signal coincident in time and sky direction with the external GRB trigger. The burst search algorithm is applied to both long and short GRBs. The current search pipeline [315] is based on a coherent network algorithm designed to be sensitive to generic or weakly modeled gravitational wave transients. The CBC analysis focuses primarily on short GRBs. It is a coherent matched-filter search (see [314] and §3.4.5) for low-mass binary inspirals, which are a likely progenitor of this GRB class. The burst analysis is complementary to the CBC search, providing the ability to detect or constrain any gravitational wave emission that does not match the inspiral waveform. Even non-detections can be significant; for example, the analyses of GRB 070201 [350] and GRB 051103 [354] supported the hypothesis that the event progenitors were not compact binary mergers in the target galaxies, and were more likely to be SGR giant flares.

GRB triggers are collected primarily from the GRB Coordinate Network (GCN, [**?**]), and from the Third Interplanetary Network (IPN, [355]). While GCN notices are distributed in real time, the localization of IPN GRBs requires manual effort by IPN scientists and therefore these triggers are obtained via collaboration with the IPN with a time lag of months to years. As a result, GCN and IPN GRBs have been analysed separately. The analysis of all GCN GRBs during S6/VSR2-3 has been completed [356]. Near- term goals are to **complete the ongoing analyses of IPN GRBs from S5/VSR1 and S6/VSR2-3, and GCN GRBs from Astrowatch periods**. Ongoing collaboration between LIGO/Virgo and the IPN should streamline IPN trigger generation in the advanced detector era, assuming continuing operation of the IPN network and support of operations.

Additional GRB triggers are generated by analysis of data from the *Swift* satellite for candidate GRBs which are below the nominal *Swift* trigger threshold. Since GW signal strength does not necessarily follow GRB luminosity, such a search is worthwhile, as relatively nearby GRBs may be included in this sample. Indeed, this sample could be enriched in a suspected local population of low luminosity GRBs [357, 358]. **Completing the ongoing analysis of sub-threshold *Swift* triggers** is another near-term goal of the GRB team.

The current plan is to publish a paper containing all the S5-S6 GRBs and to perform a complete exclusion analysis with all the statistic available.

In addition to an EM-triggered search of LIGO data it is also possible to follow up S6 triggers by looking in archived data from GRB missions. We will use sky location and distance information from parameter estimation to run a targeted followup of S6 CBC events searching for sub-threshold high-energy electromagnetic counterparts to NS/NS and NS/BH mergers in Fermi GBM and RXTE ASM data.

A specific burst analysis has started and will be concluded within the year on GRB analysis using long (10 – 1000 s) GW signals [359, 360, 361, 362, 363]. This analysis is based on the STAMP pipeline developed within the stochastic group. At present the analysis focuses on the S5 data because of the small error window provided by the associated Swift GRBs.

In addition to the search for signals from individual GRBs, one can search collectively over a population of GRB triggers, to infer properties of the population of astrophysical sources as a whole rather than any one member [364]. This strategy has been successfully used to improve upper limits on GW emission from GRBs [328].

In looking ahead to the advanced detector era, a few issues stand out. Most fundamentally, there must be operating GRB satellites. Since current missions will be at or past their anticipated lifespan as Advanced LIGO/Virgo approach their best sensitivities, this is far from assured. One a first step for the GRB analysis is the bookkeeping and the vetting of our external triggers to always use up-to-date information and be sure we will not miss any astrophysical interesting GRB like GRB070201. This activity has recently started in the group and will be push forward as we want to include not only alerts but also catalogues to crosscheck all astrophysical knowledge on the event. In parallel, contact have been taken with the Fermi LAT and GBM teams to create a common working group to determine the type of information needed from their side and also to work on coupling gamma and GW sky maps to provide an improved GRB localization on the sky. Another issue is the handling of GRB trigger data. Ideally, it should be treated in a manner which is fully coordinated and compatible with other astrophysical observers. The collaborations should **prepare for low-latency GRB-triggered searches**, with a goal to be ready to provide GW observational information which can be included in a public GRB trigger notice with a latency sufficiently short so as to be relevant to follow-up observers. Options for the low-latency searches include either the launching of dedicated algorithms which make use of the known GRB time and location, or to simply compare GRB triggers with lists of GW triggers resulting from all-sky, all-time pipelines. The infrastructure for the latter is already in place based on graceDB. When a GRB alert is registered in the database, an automatic coincidence scan is done on the all-sky trigger list saved in the database. This will be completely tested during the next ERs. The infrastructure from graceDB permits the capability to automatically start jobs on the clusters and thus to automatically start the full GRB analysis. Refinements of existing pipelines are foreseen. Specifically, for the CBC case the searches will need to incorporate longer templates and, due to GRB beaming, may specialize to face-on CBC orientations.

4.4.3 [HEN] High-Energy Neutrino Multimessenger Analyses

Many of the most violent and interesting phenomena producing GW transients are also thought to be sources of high energy neutrinos (HENs) [365, 366, 367, 368, 369, 370, 318]. These non-thermal, GeV-PeV neutrinos neutrinos are thought be produced in relativistic outflows driven by central engines also responsible for GW emission [371, 372, 373, 374, 375, 376, 377, 378]. Both long and short gamma ray bursts (GRBs), core-collapse supernovae with fast rotating cores, and highly magnetized neutron stars (magnetars) are thought to produce GWs and HENs that may be detectable out to relevant distances [370].

There are multiple scientific benefits of simultaneously observing GWs and high energy neutrinos from a common source:

- **High-confidence detection** – Both GWs and neutrinos are weakly interacting messengers, and so far there has been no confirmed detection of either sources of cosmic origin. The combined information from GW and HEN observatories can greatly enhance our confidence in a joint detection [365, 366, 367, 368, 369, 370, 318, 379]. In particular, a comparison [369] of joint GW+HEN searches using advanced GW detectors and the completed km^3 IceCube detector to the reach of independent searches using the same detectors concluded that, while the main advantage of joint searches is increased sensitivity for the actual detection of sources, joint searches will provide better constraints than independent observations if, upon non-detection they result in an increased exclusion distance by at least a factor $\sim f_b^{1/3}$ compared to independent searches, where f_b is the neutrino beaming angle. This study derived the first observational constraints on common GW-HEN sources using initial LIGO, Virgo, and IceCube data, and also projected population constraints from joint searches with advanced GW and HEN detectors.

- **New probe of the depths of violent astrophysical phenomena** – GWs and HENs both carry information from the depth of their source that is, to a large extent, complementary to the information carried by electromagnetic radiation. While the GW signature of cosmic events is characteristic of the dynamics of their central engine , a HEN flux is reflective of the presence of hadrons in the relativistic outflow generated and driven by the central engine. Detecting both messengers from a common source would provide the unique opportunity to develop and fine tune our understanding of the connection between the central engine, their surrounding, and the nature of the outflows. For example, it has recently been demonstrated [235] that the energy-dependence of the onset time of neutrino emission in advancing relativistic jets can be used to extract information about the supernova/gamma-ray burst progenitor structure. Together with observed GWs, this would provide information on the inner density of the progenitor beneath the shock region ($\sim 10^{10}$ cm for mildly relativistic jets). In favorable conditions, very few neutrinos, in coincidence with a GW signal, would be sufficient to provide important information, and/or to differentiate between progenitor types.

- **Prospect of common sources dark in gamma rays** – The emission of HENs is tightly connected to the presence of high energy photons (gamma rays) in the outflow. There are specific cases where the source optical thickness is large and prevents the gamma-rays to escape from the source. One of the most interesting prospects of joint GW - high energy neutrino searches are common sources that are dark in gamma rays. One of the prominent such sources are choked GRBs [373, 380, 381] or low-luminosity GRBs [237, 238, 199, 239, 240, 241, 242, 243]. These sources are difficult to detect with electromagnetic observatories, and hence provide an exciting opportunity to joint GW - HEN searches that can discover them and/or constrain their population [368, 369, 379]. Further, it is plausible that previously unanticipated sources or mechanisms can be discovered and studied with joint searches.

Currently operating HEN observatories include IceCube [382], a cubic-kilometer detector at the South Pole, and ANTARES [383] in the Mediterranean sea. ANTARES is proposed to be upgraded to cubic-kilometer detector (called KM3NeT) in the coming years [384]. A third HEN detector is operating in lake Baikal and has been proposed to be upgraded [385].

There have been coincident data taking periods between initial GW and HEN detectors in the last few years, providing datasets that have already been used to derive population constraints on joint sources [369]. This includes the first coincident search for GWs and HENs, using the S5/VSR1 data and the partial ANTARES detector in its 5-string configuration. The analysis uses the directional distribution and the time of arrival of HENs to trigger a GW follow-up analysis, similar to the analysis used for GW follow-up searches of GRBs. This analysis has been completed and published [318].

Near-term goals for the HEN team include **analysis of the joint S5/VSR1 and IceCube data**. The baseline analysis [386, 379] takes into account the significance of the GW and HEN signals, calculated based on the excess energy in the GW datastream (see e.g. [387]) and the reconstructed neutrino energy and neutrino flux (i.e. number of coincident neutrinos). The analysis also takes into account the directional probability distributions of the GW and HEN signals, as well as the *a priori* source distribution using the observed distribution of blue luminosity in the universe[2]. A parallel search is performed where the blue-luminosity distribution is ignored in order to search for sources not connected to blue luminosity, e.g. galactic sources. The joint search will use the coincidence time window derived in [368]. It will consider individual signal candidates, as well as an ensemble of weak, sub-threshold signals that could not be detected individually. In the case of no detection, results will be used to obtain upper limit estimates of multimessenger GW+HEN sources.

The joint **analysis of ANTARES 12-line and LIGO-Virgo S6-VSR2/3 data** approaches completion. A layer of improvement to the baseline analysis has been developedand applied to this data set [388]. It consists of a modification of the GW event generation algorithm which allows the full use of all GW data (currently restricted periods when three GW detectors are operating).

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[2] I.e. the analysis assumes that the source distribution follows the blue-luminosity distribution of galaxies.

Another exciting future direction is to **search high energy neutrinos in coincidence with longer GW transients**, lasting from seconds to weeks. Such GW transients may be emitted, e.g., by collapsars, some of which may produce long GRBs. For long GRBs the central engine is active for at least the duration of the prompt gamma-ray emission [368]. GW emission can be even longer, e.g., due to a rotationally unstable protoneutron star remaining after core-collapse [389]. A specific GW search pipeline, called STAMP, has been developed to search for such second-week-long transient GW events with no prior assumption on GW frequency and temporal evolution [390]. The possibility of a joint GW-high energy neutrino search using the STAMP pipeline and neutrino data from the partially completed IceCube is under investigation.

The advanced detector era holds the exciting promise of the detection of gravitational waves and high energy neutrinos. The expected sensitivity of multimessenger searches was recently surveyed by Bartos *et al.* [369]. Bartos *et al.* derived the first observational constraints on common sources of GWs and high energy neutrinos with initial LIGO and Virgo GW data (S5/VSR1 science runs), and neutrino data from the partially completed IceCube detector with 40 strings. They used these results to calculate projected constraints for common GW-neutrino sources obtainable with advanced LIGO-Virgo and the full IceCube detector with 86 strings. They also compared the estimated reach of joint GW+HEN searches using advanced GW detectors and the completed km^3 IceCube detector to the reach of independent searches using the same detectors. Studies indicate that multimessenger searches with advanced detectors will be able to probe some of the most interesting parameter space for GRBs, including choked GRBs [369]. The search algorithms developed for current detectors will also be applicable in the advanced detector era. For example, the baseline GW+HEN LIGO-Virgo-IceCube analysis method [386, 379] can readily incorporate multiple coincident neutrinos in the analysis, a tool that will be crucial given the highly increased neutrino frequency expected from, e.g., the full IceCube detector.

Advanced searches will also be able to build on some of the search parameters developed for earlier searches. For example, the maximum time difference between the arrivals of the observed GW trigger and HEN events [368], one of the key parameters of the joint GW+HEN search algorithm, will be usable for advanced searches as well. Here, a too small time window might exclude some potential sources, while a too large time window would unnecessarily increase the false alarm rate and the computational cost.

Low-latency joint GW+HEN searches will constitute an interesting new direction for the advanced detector era. Both GW and HEN detectors and their implemented event reconstruction algorithms will be able to provide low latency events that in turn can be used in low-latency joint searches. As both GWs and HENs can arrive prior to the onset of electromagnetic emission from sources such as GRBs, joint GW+HEN events may be primary targets for electomagnetic follow-up searches.

In short, GW+HEN observational results have already proved to produce exciting scientific results [369, 318], while the projected constraints [369] and expectations (e.g., [235]) suggest that multimessenger GW+HEN searches will be a fruitful direction of research during the advanced detector era.

4.4.4 [SN] Supernovae as Astrophysical Triggers

Core-collapse supernovae are interesting candidates as gravitational-wave sources and can be studied in conjunction with both neutrino and optical messengers (§4.1). The theoretically expected GW signal is most likely very weak (e.g., [216, 255, 347]), but a galactic core-collapse supernova would be detectable even in pessimistic models. Extreme emission scenarios can be constrained with advanced LIGO out to a few few Mpc.

Most optical triggers carry the burden of a large uncertainty on the derived event time (order of several hours or more), making the GW data analysis task challenging due to large backgrounds and varying detector duty cycles. Well-known sky locations are a significant aid to the analysis. **A near-term goal is**

completion of the optical supernova search in data taken by the initial detectors, which is underway, now at the review stage, and might be able to constrain the most extreme core collapse models for extragalactic S5/A5/S6 supernovae. The enhanced reach of advanced detectors will be able to constrain a more significant swath of the model space.

Supernova triggers from detectors sensitive to low energy (up to tens of MeV) neutrinos can be used in GW searches as well. For example, a core-collapse supernova near the galactic center is expected to produce a large flux of ~ 8000 detected neutrinos in the Super-Kamiokande detector [262] with a pointing accuracy of 4°. Unlike photons, which can take up to a $\sim$day to break out, neutrino bursts and gravitational waves mark the moment of core collapse, and are expected to be coincident in time to $\lesssim 1$ s (most likely, GW and neutrino emission will set in within milliseconds of each other [216, 391]). The expected strong neutrino signal for a galactic core-collapse supernova would provide excellent timing and good pointing, thus allowing an improved sensitivity gravitational-wave burst search, similar to that employed for GRBs. For extragalactic supernovae, the neutrino signature would in general provide timing but not pointing. At the distance of Andromeda, the expected flux of detected neutrinos in Super-Kamiokande would fall off to $\mathcal{O}(1)$. In this case, joint neutrino-GW time-coincident searches would substantially increase detection probability and decrease the false-alarm rate.

A proposed joint search for GWs and low-energy neutrinos from core-collapse supernovae on archival (and future) data has been positively reviewed by the LSC and Virgo. We are presently at the stage of drafting MoUs with neutrino collaborations. These will include, initially, Borexino, LVD, and IceCube. The Super-Kamiokande collaboration is not intending to be part of this effort at this time.

In the case of a supernova GW detection, likely from a Milky-Way or Large/Small-Magellanic-Cloud core-collapse supernova accompanied by a neutrino signal, the urgent question will be “what can the signal teach us about the physics underlying core collapse and the explosion mechanism?” This question is best approached with model selection and parameter estimation algorithms. We are developing the Supernova Model Evidence Extraction, a Bayesian pipeline, for this purpose [252]. **A near term goal is to prepare and characterize SMEE for the realistic aLIGO detection scenario of gravitational-waves from the next nearby supernova. A further goal is to incorporate a basic ability to identify supernova-like signal into a broader low-latency burst parameter estimation pipeline.**

4.4.5 [NS] GWs as probes of Neutron Star Physics

Isolated neutron stars in our galaxy may be sources of detectable GW burst via a number of processes, as discussed in §4.1.3. Searches for GWs from these systems are carried out in coordination with the Stochastic (§6) and Continuous Waves (§5) Groups as appropriate.

Triggers from Magnetars

Current externally triggered searches look for GWs associated with bursts from magnetar candidates – soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) – following two distinct search strategies. The first strategy looks for GW emission associated with the prompt gamma-ray burst from individual magnetar bursts and giant flares. An emphasis is placed on GW emission from the damping of f-modes in the magnetar which may be excited in the burst, but the entire detector band is searched up to 3 kHz. This strategy has been used to analyze over 1400 electromagnetic SGR and AXP triggers, including the 2004 giant flare [329, 285]. The second strategy looks for the collective signature of weak GW bursts from repeated flares from a single SGR source, stacking the GW data to dig deeper into the noise at the expense of additional but plausible model dependence. This strategy was used to analyze the 2006 SGR 1900+14 storm [392].

Triggered r-mode Searches

Investigations into excitations of pulsars (post-glitch) and accreting millisecond pulsars (post-flare) have shown that gravitational waves emitted at r-mode frequencies are a potential source for second and third generation gravitational wave detectors.

A search strategy has been formulated with members of the Continuous Waves working group to search for these long-lasting transient signals. Trial runs on simulated data have shown the search strategy capable of identifying the presence of long transient signals at strengths estimated by previous feasibility studies. The next step is to perform a comprehensive characterisation of the search using both simulated data and data acquired by interferometers. Efforts will also be made to translate the outputs from search codes into astrophysically interesting constraints on the source parameters.

Burst Followups of Binary Neutron Star Inspirals

One of the most likely detection scenarios and probably one of the most frequent, is the signal from binary neutron star coalescence. Although the merger/post-merger signal may only be detectable to $\mathcal{O}(10)$ Mpc, yielding rather low detection rates (~ 1 per century), the opportunity for increased detection confidence by association with the inspiral signal and possible EM counterpart, make searching for the HMNS signal a potential source of high-profile burst science.

Investigations are underway to develop a search strategy using traditional burst detection pipelines and newly developed Bayesian parameter estimation methods with general applicability to other neutron star sources, such as f-modes and bar-mode instabilities.

Triggers from the low mass X-ray binary (LMXB) Sco X-1

The Rossi X-ray Timing Explorer (RXTE) mission was been extended to the end of 2010 and observations overlapped with the S6/VSR2/VSR3 run. Multi-messenger observations of Sco X-1 allow us the opportunity to search for correlations between the X-ray and potential GW emission. An exploratory cross-correlation analysis between RXTE and LIGO has been performed using S5 coincidence data. In addition to this ongoing analysis a second approach is under way where both RXTE and LIGO-VIRGO time-series data are analyzed to generate trigger lists using existing search pipelines developed for gravitational-wave burst detection. LIGO-VIRGO data is analyzed by a coherent network analysis pipeline and RXTE data by a single detector pipeline based on the excess power method. Masking the sky around Sco X-1 using a coincidence analysis can improve the detection confidence, and therefore enable us to set upper limits on GWs correlated with astrophysical events encoded in RXTE data.

4.4.6 [EM] Other Electromagnetic Counterparts and Follow-up Observations

The previous subsections described several scenarios in which astrophysical systems are expected to emit electromagnetic (EM) radiation along with GW bursts, and the substantial benefits of joint observations. Here, we consider other EM counterparts where the nature of the source is unclear, and/or where the EM signature is present but was not initially detected by surveys.

Radio burst triggered GW searches

Bursts of radio waves have been detected by various radio telescopes, but their origin remains mysterious. Some, such as the remarkable “Lorimer Burst” [393], are suspected to have a terrestrial origin [394], but not *all* observed bursts can be discarded in that way. Since energetic events which produce detectable GWs are likely to feed some of the released energy into EM emission, radio transient counterparts are quite possible. The radio transient either could be short and prompt, or else an afterglow rising and peaking days, weeks or months later (depending on radio frequency band). A short transient would result from coherent emission, e.g. from some plasma excitation, while a radio afterglow could be synchrotron emission from an expanding jet or fireball.

Prompt radio bursts are natural candidates for joint analysis with GW data, especially because there are theoretical models in which various mechanisms give rise to a prompt pulse of radio emission from some putative gravitational wave sources, e.g. compact binary coalescence scenarios or cosmic string cusps [395]. Therefore, the Burst Group science program includes GW burst searches targeting the times and sky locations of reported radio bursts recorded by radio telescopes such as Green Bank [396], Arecibo, LWA, and potentially others.

An interesting aspect of follow-up of radio triggers is that for each event we will have the dispersion measure. This will provide an independent measure of the distance, allowing us to better predict when the gravitational wave should have arrived at our detectors and also to estimate the absolute gravitational-wave luminosity of a detected event.

Tasks for this area include:

- Identify interesting radio transients, taking into account whether they appear to be truly astrophysical
- Consider the detectability of possible GW sources that could have produced the radio transients
- Develop search techniques with appropriate coherent/coincident analysis conditions
- Complete searches
- Consider what conclusions can be drawn from positive and negative search results
- Formulate a good plan for joint radio-GW searches in the advanced detector era

EM follow-ups of GW event candidates

Telescopes cannot cover the whole sky at all times with good sensitivity. Current EM survey projects typically have lengthy cadence times, or are considerably less sensitive than their more directed counterparts [397]; therefore it is quite possible that the EM signature from an interesting event will be missed because no telescope of an appropriate type is looking in the right direction at the right time. The GW detector network, on the other hand, is effectively an all-sky monitor for highly energetic astrophysical events. Thus there is a strong motivation to point optical, X-ray and/or radio telescopes in response to potential GW triggers and thereby attempt to catch an associated transient EM signal which would otherwise be missed.

For example, because the gamma rays from GRBs are believed to be beamed (and because even the Fermi Gamma-ray Burst Monitor covers only half the sky), there may be short-lived "orphan afterglows" from nearby GRB progenitors which are going undetected [203]. Other possible sources of joint EM/GW emission include decaying neutron star matter ejected during merger [398, 399, 212, 400] and supernovas [217]. Some more details on these sources and their expected observational signatures can be found in [401, 397]. If such an event is detected by the network of GW interferometers, then the reconstructed sky position can in principle be used to point one or more telescopes and catch the afterglow before it fades away.

Like externally triggered GW searches, GW-triggered EM follow-up observations can be beneficial in two ways. First, they would help establish the event as astrophysical in nature, effectively increasing the reach of the interferometer network in the case of a low-signal-to-noise-ratio event that might not otherwise stand out from the background. Additionally, having an associated EM signal increases the astrophysical information that can be mined from a GW event [402, 403, 404]. Note that both prompt and delayed follow-up observations, as well as simply checking against lists of transients identified by other surveys, are appropriate to catch different possible light curves.

Scientific prospects for EM follow-up observations with specific observing strategies have been studied over the past several years [401, 405, 406, 407], and a first complete EM follow-up projected was implemented and carried out during the S6/VSR2-3 science run [408]. For the Advanced Detector era, we will again search for burst signals with low latency as the data is collected (complementing the low-latency CBC search effort, see §3.4.6). Burst candidates identified in the data will be inserted into the GraceDB database, with reconstructed sky maps. Significant events will be selected and packaged for alerts to participating observing partners, enlisted through the LSC-Virgo partnership protocols that are currently being worked out.

Tasks for this area include:

- Complete review of S6/VSR2+3 image analysis paper, and publish it
- Validate low-latency trigger generation with new version of coherent WaveBurst
- Run both unconstrained and polarization-constrained versions of coherent WaveBurst
- Consider whether to also run a second low-latency burst search pipeline trigger generation
- Make sure there are useful diagnostics for proper operation
- Evaluate latency and robustness to gaps, glitches, etc.
- Evaluate and apply low-latency data quality and veto cuts
- Set up background estimation procedures
- Validate and document standard (HEALPix) format for sky maps
- Consider how to make best use of galaxy catalog information
- Check correctness of sky maps at advertised probability level
- Assess position reconstruction error regions for different signal types and amplitudes, and with different networks of detectors, including two-detector networks
- Quantify effects of calibration uncertainties
- Develop and test event selection tools(s)
- Intelligently merge events found by more than one pipeline
- Package event information to send with alert
- Establish/test standard communication protocol with observers
- Define roles and responsibilities for both “contributed” and “coordinated” modes of participation.
- Develop and improve methods for joint analysis with X-ray, radio, etc.
- Prepare for timely publication of results

Search for EM counterparts in archival data

In addition to the rapid-response EM followup mentioned above, there is also a wealth of all-sky high-energy photon survey data which can be searched offline for EM counterparts to GW events. Joint search pipelines are currently being run and refined to search specifically for S6/VSR2+3 GW-triggered EM counterparts in Fermi GBM (20 keV−40 MeV) and RXTE ASM (1−10 keV) archival data. This is done in coordination with scientists from both missions. The search targets prompt gamma-ray emission from GBM which may be below threshold for public reporting to the GCN, as well as x-ray afterglow signals in the ASM.

4.4.7 [BBH] Explore Binary Black Holes in a Wide Parameter Space

Burst searches are usually un-modeled or weakly modeled to be open to the broad spectrum of sources discussed in §4.1. In particular, they can be sensitive to a wider class of CBC sources (§4.1.4) than dedicated inspiral template searches (§3). The burst approach is robust against possible discrepancies between theory and nature, albeit at the cost of reduced search sensitivity and increased false alarm rates.

The goal of the burst BBH searches is to explore as wide as possible the parameter space of BBH sources which may not be accessible by the CBC matched-filtering searches due to the lack of complete or accurate template banks. In principle, the existing all-sky pipelines can be used for such searches. However, for specific source signatures a better reach can be achieved by introduce a weak-model constraint that allows to better suppress the false alarm rate, but still preserves the robustness of un-modeled burst search. For instance, we conducted a dedicated search for intermediate mass BBH (100–400$M_\odot$) on the initial LIGO and Virgo data, by enforcing an elliptical polarization constraint [409].

In preparation for the first detection of BBH sources in a wide range of BBH parameters with arbitrary spin configurations and possible high eccentricities, the burst BBH working group identifies the following science targets, pursued in collaboration with the other working groups.

Detection with confidence. Most of anticipated BBH signals are expected to have relatively short duration (few seconds or less) and can be easily confused with the instrumental/environmental artifacts (glitches). Identification and rejection of such false events is a serious challenge in the burst analysis. Therefore, advances in the detector characterization (§2.2,2.3,2.4) and data regression are critical for the burst BBH searches. To improve the BBH detection efficiency and reduce false alarm rate, the BBH searches employ model constraints. The group will improve existing constraints on the GW polarization states and develop new robust BBH constraints based on the time-frequency pattern recognition. A special concern is a production of large background samples (by at lest a factor of 10 compared to the S5/S6 burst analysis) and better estimation of the false alarm rates, Background production is very CPU intensive and require the development of efficient analysis algorithms.

Development and validation of astrophysical waveforms. An ongoing collaborative effort with the CBC group is studying the use of the full coalescence BBH waveforms, including the inspiral, merger, and ringdown phases. The same set of phenomenological and EOBNR waveforms [27, 63, 410, 411] is being analyzed by burst search methods, inspiral and ring-down matched filtering to compare their detactability across the BBH parameter space. We will also pursue the development of the faithful BBH waveforms (with high spin and eccentricity [412, 295]) covering the BBH parameter space as wide as possible. Studies of such waveforms will help to devise new detection techniques and provide important guidance for the interpretation of search results. The astrophysical BBH waveforms will be used to quantify the reach of the BBH searches and in the parameter estimation studies.

Coordinate reconstruction. Sky localization is a challenging problem for the BBH analysis, particularly for sources with high masses. Such BBH sources are expected to produce a signal at low frequency where the triangulation capabilities of detector networks are affected by the diffraction limit: (λ/d 1, where λ is the GW wavelength and d is the network base length. For these reasons it is important to develop coherent network reconstruction algorithms which use advantage of the antenna polarization coverage. The burst BBH working group concentrates on the un-modeled (robust) sky localization in close coordination with the CBC group (§3) and the astrophysical follow up effort (§4.4.6).

Waveform reconstruction and source parameter estimation. In preparation for a detection, the working groups need to improve parameter estimation techniques (as discussed in §4.3.6). One of the main priorities of the BBH working group is a weakly-modeled reconstruction of the BBH waveforms, Such analysis can identify the polarization state of the BBH system and determine such source parameters as the binary inclination angle and eccentricity. The reconstructed waveforms can be compared to known models for extraction of other source parameters (component masses, etc.). Progress towards waveform reconstruction has already been made via coherent techniques, but more progress is needed to compare a candidate to waveform parameters. Bayesian [413] and MCMC [414] techniques are currently being explored by the CBC Group as well as members of the Burst Group. We are open to exploration of new techniques which may prove useful for reconstruction of BBH waveforms.

4.4.8 [EXOTICA] Beyond Standard Theories and Sources

A prototype analysis looking for cosmic (super)string signatures has been performed on S4 data [415]. The near term goals include the completion of the S5/6-VSR1/2/3 analysis, its review and publication. A paper draft of the publication has been circulated to the Burst group in early 2013. The review of the publication and of the analysis as a whole is well under way. If no detection is made, it is expected to set upper limits on $G\mu$ about 3 times more stringent than the current CMB constraints and for intermediate values of the cosmic string loop size parameter ε. A factor of 10 or more may be expected from searches in the advanced detector era, especially since signals from string cusps are strongest at low frequencies where the sensitivity improvement is expected to be the greatest.

Search strategies for alternative theories of gravity have already started being investigated within the Burst Group. In the past year, the existing all-sky search infrastructure was modified in order to study the detectability of scalar signals. A similar approach for a supernovae-triggered search for scalar bursts using a modified version of the pipeline normally used in the GRB triggered searches was also implemented. Completion of these detectability studies may lead to short-author-list papers in the near future.

A search for bursts with memory may complement searches for generic bursts or from binary systems. A formal proposal for a development project/search for such signatures was presented to the Burst Group in September 2012. We have identified the potential sources, including predicted energy and strain scales associated with them. In terms of implementing a prototypical search, we still plan to adopt existing general burst-search methods as well templated search methods like the one used in the search for cosmic (super)strings in order to look for memory in our data. This includes adding functionality within LAL for generation of such signal morphologies. The emphasis will mainly be for the advanced detector era, but any significant progress until then in terms of methods and proof-of-concept work using data already in hand may lead to publication.

5 Searches for continuous-wave signals

UPDATED

Rapidly rotating neutron stars are the most promising sources of continuous-wave (CW) gravitational signals in the LIGO and Virgo frequency band.[3] These stars are expected to emit gravitational radiation through a variety of mechanisms, including elastic deformations [420, 421, 423], magnetic deformations [422, 426], unstable r-mode oscillations [424, 420, 425], and free precession [430], all of which operate differently in accreting and non-accreting stars. We present a review of these emission mechanisms in [419]. Indirect upper limits on gravitational wave emission inferred from photon astronomy are more optimistic for non-accreting stars, but according to present theories accreting neutron stars are more likely to be emitting at or near the indirect limits.

The sources for which we search fall into four broad categories: non-accreting known pulsars for which timing data is available, non-accreting known stars without timing data, unknown isolated stars, and accreting stars in known binary or stars in unknown binary systems. For each type of source, we know or can infer properties of the source population; and for particular stars, there are indirect upper limits on gravitational wave emission which LIGO or Virgo must beat in order to claim a novel result. From our point of view, each type of object presents a distinct data analysis challenge which is directly constrained by more conventional astronomical observations. In particular, as most of our searches are computationally limited, their sensitivities are directly dependent on the constraints that come from conventional astronomy. As a result of our computational limitations we support a variety of search codes, each optimised for a different portion of parameter space. Where possible these code share common libraries and are cross-checked on fake signals injected into the detectors.

The breadth of investigation is fundamental to our search method. Given the large uncertainties in neutron star demographics (only $\sim$2000 of 10^8-10^9 neutron stars in the galaxy have been detected), evolution, and structure, we cannot confidently predict which type of source will provide our first continuous-wave discovery. Prudence demands an eyes-wide-open approach and enough flexibility to exploit unexpected waveform models. That said, however, we do adhere to certain priorities in allocating resources (scientists and computers) to different searches. Specifically, we place the highest priority on targeted searches for known pulsars (especially those for which the spin-down limit is achievable – see below) and on all-sky searches for unknown isolated pulsars.

The merging of LSC and Virgo CW efforts has revealed strong and well-developed programmes from both groups. An ongoing task is to combine these effectively, maximising both the return on time already invested in developing codes and the science delivered by new joint ventures. Our state right now is one of transition, where we are evaluating the scientific justification and available manpower for these searches, while balancing the importance of redundancy against current resources.

An important new element in this evaluation is the recent creation of simulated data with several thousand software injections for pulsars at randomly chosen sky locations and with frequencies and frequency derivatives spanning our search ranges (see section 5.7.1). These standardized data sets should enable us to compare with more statistical precision and more systematically the sensitivity and robustness of the various pipelines in detecting pulsars in blind searches or in reconstructing source parameters in targeted searches. A mock data challenge based on these injections was launched in fall 2012, with stage-1 results reported in December 2012. Stage-2 reports will be due July 31, 2013, with stages 3 and 4 (blind injections) concluding in December 2013 and June 2014. The outcomes of these comparisons are expected to lead to the abandonment (or at least de-prioritization) of some search pipelines.

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[3] We use the term "neutron star" broadly, keeping in mind that some such stars may contain quark matter or other exotica.

5.1 Non-accreting pulsars

UPDATED

We include in this source type all objects for which pulsations are observed in radio, X-ray, or other electromagnetic radiation, with the exception of accreting millisecond pulsars. Photon astronomy can tell us precisely the sky positions, frequencies, and frequency changes of these objects, meaning that our analyses need search only a small parameter space and are not computationally limited (see section 5.1.1 below). Photon astronomy also sets an upper limit on the gravitational wave strain we could see from a known pulsar, assuming that all of the observed spin-down is due to gravitational waves. In terms of the distance D, gravitational wave frequency $f_{\rm gw}$ and its time derivative $\dot{f}_{\rm gw}$, this indirect limit is [419]

$$h_{\rm IL} = 8.1 \times 10^{-25} \left(\frac{1\,{\rm kpc}}{D}\right) \left(\frac{-\dot{f}_{\rm gw}}{10^{-10}\,{\rm Hz/s}} \frac{100\,{\rm Hz}}{f_{\rm gw}}\right)^{1/2} \left(\frac{I}{10^{38}{\rm kgm}^2}\right)^{1/2} . \tag{1}$$

Here I is the star's moment of inertia, as estimated by theory but not directly observed, and could be higher than the fiducial value by a factor of up to 3. For most pulsars the distance D is determined by combining their observed radio dispersion measure with a model of the galactic HII distribution and is uncertain to at least 20%. Analysis of the LIGO full S5 data and the Virgo VSR2 data has beaten this indirect "spin-down limit" by a factor of 7 for the Crab pulsar (59.45 Hz) and by $\sim$40% for the Vela pulsar (22.38 Hz). Other pulsars for which the spin-down limit may be reached in S6/VSR2/VSR4 include PSRs J0205+6449 (30.45 Hz), J1833-1034 (32.33 Hz), J1813-1749 (44.74 Hz), J1913+1011 (50.59 Hz), J1952+3252 (55.69 Hz), J0737−3039A (88.11 Hz) and J0537−6910 (123.95 Hz) [427].

The discussion above assumes gravitational wave emission from a triaxial neutron star, with the electromagnetic and gravitational wave components rotating as one unit. The astrophysical return from detecting such emission would be the first ever measurement of the difference between the two (equatorial) components of the inertia tensor. This in turn would give important information on the strength and strain profile of the solid phase of the star (the crust, or possibly a solid core) and/or information on the nature of the internal magnetic field.

While this form of gravitational wave emission is the simplest and most plausible, it is by no means the only possible wave generation mechanism. Other emission mechanisms include free precession, excited modes of oscillation of the fluid, and the spin-down of a multi-component star. The astrophysical returns from detection of such wave generation could be considerable, potentially giving information on asymmetries in the inertia tensor, the viscosity of the fluid, and the internal structure of the star. However, the observational challenge is correspondingly greater, as the gravitational wave emission no longer occurs at twice the spin frequency. This means that searches for such waves require careful thought in order to pick out a range of parameter space (i.e., the wave frequency and its time derivatives) that is both astrophysically reasonable and computationally feasible to search over. As described below (5.1.2), such a search has already been carried out for the Crab pulsar, concentrating on a small patch of parameter space centred on (twice) the observed spin frequency. Clearly, a more comprehensive search over an enlarged parameter space and for more pulsars is needed to fully exploit the science potential of targeted searches.

Targeted searches are those for gravitational wave emission from pulsars of known position, rotation frequency, spin-down rate, and binary orbital parameters where necessary. This additional information greatly reduces the size of the parameter space over which we must search, and allows us to perform a fully coherent search for signals over all the available data. Timing accuracy is sufficient to maintain coherence both during and between science runs, and the relative phasing of the interferometers is also sufficiently well determined for us to be able to combine data from all runs and all detectors coherently, resulting in the lowest signal sensitivities achievable by LIGO and Virgo.

Three different pipelines are in current use for targeted searches: 1) a time-domain Bayesian method used in previous LIGO searches; 2) a new Fourier-domain method with Wiener filtering and deconvolution of amplitude modulation; and 3) a new matched filter method based on the $\mathcal{F}$-statistic and (new) G-statistic. These three methods are described below.

5.1.1 Time domain Bayesian method

UPDATED

The time-domain Bayesian method has been applied successfully to data from the first five LSC science runs [416, 417, 436, 434, 435] and to the Virgo VSR2 run. It has also been used for searches in S6 VSR3 and VSR4 data with a paper currently in an advanced stage of production. A detailed discussion of the method can be found in [433], with the implementation of the inclusion of binary system parameters in [437].

The method is designed to carry out robust signal extraction and optimal parameter estimation, rather than perform well in a large parameter space search. Its primary purposes are

- to perform searches for signals from known pulsars,
- to perform followups on triggers from all-sky searches and
- to determine the astrophysical parameters of these candidate sources.

The current method comprises a heterodyne and filtering stage to extract interferometer data in a tracked 1/60 Hz band centered on the expected gravitational wave signal, followed by a Bayesian parameter estimation stage. This second stage delivers an upper limit to the strain amplitude of any signal and an estimation of the signal's parameters, should one be detected, in the form of marginal posterior probability distributions for the signal parameters. The method has successfully determined the parameters of the injected signals in all our science runs. The most computationally intensive part of the search is the heterodyning and down-sampling of the raw data. Currently this takes about 25 min per pulsar per detector per day of data.

We are currently investigating a new method of computing the tracked 1/60th Hz band by combining short (1-minute) Fourier transforms rather than by heterodyning the time series. This spectral interpolation method gives a very significant speed-up when processing multiple targets and will be employed as part of an all-sky search candidate follow-up campaign.

We have strong links with the radio groups at University of Manchester (Jodrell Bank), ATNF (Parkes), MPIfRA (Effelsberg), Nancay, Arecibo, HartRAO, Hobart and NRAO (Green Bank) who have generated timing solutions for our pulsar candidates over the LIGO and Virgo observing runs, and checked that no glitches have occurred in these pulsars. These collaborations have provided data for the S5 targeted searches and more recently have generated timing solutions for an even wider range of targets in S6/VSR2/3/4. We have collaborated with Frank Marshall (RXTE) and this has provided useful discussions and timing information for the young X-ray pulsar PSR J0537$-$6910, which is another pulsar for which we have closely approached the spin-down limit. However RXTE is no longer operational and there are no immediate plans for another X-ray timing satellite. We are also compiling timing data on new γ-ray pulsars discovered with the Fermi satellite.

Of the pulsars for which we have accurate timing, the Crab pulsar is both one of the youngest, and most rapidly spinning-down, candidate within our sensitivity range. The relatively large amount of intrinsic timing noise for this pulsar is tracked and corrected for within our search method [436, 437]. We have published the results of a search for gravitational waves from the Crab pulsar using data from the first nine months of S5 until the time that a large timing glitch was observed in the Crab pulsar [434] (also see §5.1.2.)

A follow-on search for 116 pulsars in the full S5 data set included the Crab and enabled us to beat the spin-down limit by a factor of 5.6 using uniform priors over the unknown parameters. Astrophysically motivated priors on the inclination and polarisation angles allowed us to further beat the spin-down limit by an extra factor of 1.3. This result has allowed us to constrain the amount of the pulsar spin-down power budget released by gravitational radiation to be less than about 2%.

Results from a search for the Vela pulsar in VSR2 data have been obtained for both uniform and restricted priors on its orientation. These results beat the spin-down limit for Vela and have been published [488], along with results from the other two targeted pipelines described below.

In 2013 we completed the search in full S6 and VSR2/VSR4 data sets for all accessible known pulsars with available precise timing and have set even lower limits on the gravitational luminosity of nearly all. This includes the Crab and Vela, which now lie at about 1% and 10% of spin-down luminosity on gravitational wave emission.

We have started a programme to search for known pulsars not only at the nominal $2f_{\rm rot}$ frequency, but also at $f_{\rm rot}$ (using the model described in [487]), and potentially in the vicinity of $(4/3)f_{\rm rot}$ for *r*-modes, as part of a broader effort to widen the parameter space in targeted searches. An upgrade to the current MCMC parameter estimation code has been implemented that makes use of the nested sampling algorithm [486]. In addition to providing marginal posterior probability distributions for signal parameters this will provide a signal vs. noise odds ratio that can be used as a detection statistic. The algorithm will also be more robust when applied to wider band searches. A methods publication describing and characterising the nested sampling algorithm, the odds ratio and its use for deriving limits simultaneously from $f_{\rm rot}$ and $2f_{\rm rot}$ searches is planned for the coming year.

In the ADE we plan to have the targeted code running in real time, either using the heterodyne or the spectral interpolation methods, and generating web pages of preliminary results quasi-autonomously. This will allow us to monitor the sensitivity of our searches in the relevant bands before we have the final timing solutions. Development work for this has already started and will continue this year.

5.1.2 Narrowband Searches for Known Pulsars

UPDATED

We know of several physical mechanisms that could cause the frequency of a neutron star's emitted gravitational waves to differ slightly from the typically assumed $2f_{\rm rot}$, with $f_{\rm rot}$ being the rotation frequency. Using estimates of the maximum frequency difference the $\mathcal{F}$-statistic search method has been used to searched a small frequency and frequency derivative parameter space for the Crab pulsar with nine months of data from the S5 run [434]. This search has also been performed on 28 days of S6 and VSR2 data.

The nested sampling parameter estimation code developed for the targeted known pulsar search can also be extended to search narrow frequency bands. We will compare both the $\mathcal{F}$-statistic search and the nested sampling approach to the searches. The $\mathcal{F}$-statistic search's template coverage will provide confidence that the entire parameter space is covered, whereas the nested sampling method naturally provides signal parameter estimates and upper limits. We will study these using the multi-source mock dataset that we have developed. This will allow some previously poorly timed pulsars to be including in the analysis.

In the longer term, these narrow-band search methods will be explored as a follow-up step to semi-coherent all-sky searches.

5.1.3 Signal Fourier 5 components method

UPDATED

The signal Fourier 5 components targeted search starts from the short FFT database (SFDB) which contain data after a time-domain cleaning which allows to efficiently remove short time domain disturbances[441]. Schematically, from the SFDB a small (fraction of Hertz) band is extracted and transformed in to the time domain, keeping the original sampling rate. Doppler, spin-down and Einstein effects are then corrected by means of a resampling procedure which, for a given search direction, makes the Doppler correction effective for all the frequencies and under-samples the data at a much lower rate (e.g. 1Hz). After these corrections, a further cleaning step is applied in order to remove outliers appearing in the small frequency band considered. At this point the data 5-vector is computed as well as the matched filters with the signal templates (1 matched filter if polarization parameters are known, 2 matched filters if they are unknown). The outputs of the matched filters are used to build a detection statistics. See [442] for more details. The corresponding p-value is then computed in order to establish how much the data are compatible with pure noise. If no significative evidence of a signal is obtained, an upper limit to the signal amplitude is determined. This method has been applied, together with the other two coherent pipelines, for the search of CW signals from the Vela pulsar in the VSR2 data [488] beating the spin-down limit by a factor of about 1.6.

Latest developments concerns the method extension to allow a coherent analysis of different datasets, coming from the same or different detectors [443] and upper limit computation now based on a mixed frequentist-bayesian method[444]. Both these upgrades has been fully reviewed.

We are finalizing the analysis of VSR2/VSR4/S6 data and have obtained new upper limits for Vela (VSR4), Crab (VSR2/VSR4/S6), improving over previous results, and for a few other pulsars for which ephemeris covering the observation period have been obtained: J0537+6910, J1813-1246, J1833-1034, J1913-1011, J1952+3252. For these targets the spin-down limit has not been beaten, at least assuming a standard value for the star moment of inertia, but we have approached it to within a factor less than about 4. The review of results is nearly finished. The paper describing this analysis is being written, together with the two other groups working on targeted searches, and a mature draft is expected within end of June 2013.

Next step will be the extension of the method to 1*f frequency and apply it to some potentially interesting targets, like the Crab. We are also working on a detailed statistical characterization of the 5-vector method and a full comparison with other coherent pipelines which will be described in a methodological paper to be ready by the end of 2013.

5.1.4 Narrow-band search with the signal Fourier 5 components method

UPDATED

Due to the use of a resampling procedure for Doppler correction, the 5-vector method described in the previous section can be also used for narrow-band searches. We are developing[4] a full method for such kind of search, which assumes a known source position and a a possible small mismatch between two times the EM frequency and the GW frequency. Tests with software and hardware injections have been done and preliminary upper limits for Crab and Vela have been obtained using Virgo SR4 data. A methodological paper will be written and we think method/software review could start after the summer.

5.1.5 Time domain matched-filter method using the $\mathcal{F}$ and G statistics

UPDATED

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[4] This is the work the student Roberto Serafinelli is doing for his thesis.

Assuming that other parameters of the gravitational wave signal, *i.e.*, the amplitude, the phase, polarization and inclination angles are unknown, matched filtering is realized by computing the $\mathcal{F}$-statistic [473]. If the computed value of the $\mathcal{F}$-statistic is not significant, we derive an upper limit on the gravitational wave signal. From current observations of the Vela nebula the polarization and inclination angles can be estimated to a very good accuracy [474]. We use this knowledge to improve our search. This required derivation of a new optimum statistic called the G-statistic. In our analysis we take into account non-Gaussianity and non-stationarity of the noise.

We can apply these methods to target various interesting known pulsars. In particular they have been applied to the analysis of VSR2 data for the Vela pulsar, for which the spin-down limit was beaten in VSR2. For this analysis we are using updated ephemeris data provided by radio-astronomers (Hobart & HartRAO) Another obvious target is the Crab pulsar, for which about 2.5 months of data would allow to go below the current upper limit at $2f_{\mathrm{rot}}$, at the Virgo design sensitivity. The search for emission at f_{rot} will be also performed.

The status of the search for Vela in VSR2 data was described at the 2010 GWDAW meeting [450]. Final results for VSR2 data beat the spin-down limit for Vela and have been published [488], along with results from the other two targeted pipelines described in Sections 5.1.2 and 5.1.3.

We have applied our pipeline to search for 7 known pulsars in VSR2/VSR4/S6 data sets. These pulsars include Crab and Vela pulsars for which the spin-down limit has been beaten and a few other pulsars for which ephemerides covering the observation period have been obtained: J0537+6910, J1813-1246, J1833-1034, J1913-1011, J1952+3252. For Vela pulsar we have improved our upper limit obtained from the analysis of VSR2 data and the spin down limit for Crab pulsar is also improved with respect to the previous searches. For the other pulsars the spin-down limit has not been beaten but was found to be within a factor of less than 4. This analysis is also done by using two other pipelines (see Sections 5.1.2 and 5.1.3). The review of results is nearly finished. The paper describing the analysis by all three pipelines is being written and a draft for circulation to the collaborations is expected by the end of June 2013.

We have also started to develop a targeted search at once the spin frequency assuming the model described in [487]. To detect the signal we calculate the sum of the F-statistics for once and twice the spin frequency (see [473]). To estimate astrophysically interesting parameters like the polarization angles of the wave we first estimate the 8 amplitudes associated with F-statistics at once and twice the spin frequencies and then we estimate the astrophysically interesting parameters by a least squares fit to the amplitudes. It was recently clarified by I.D. Jones that the number of independent parameters in the 8 amplitudes is 6 and not 7 as originally thought. We expect to publish method's paper in 2013 and perform the search in 2014.

5.2 Non-pulsing non-accreting neutron stars and favorable directions

UPDATED

This type includes point sources, such as central compact objects in supernova remnants, as well as highly localized regions, such as the innermost parsec of the galactic center. Photon astronomy can provide sky positions for these objects, but since no pulses are observed, the external measurements cannot provide us with frequencies or spin-down parameters. Since we must search over many frequencies and spin-down parameters, sky-survey positional errors (such as from ROSAT) are too large: we require arcminute accuracy or better to keep down the computational cost of a long integration time and thus a deep search. Although no f and $\dot{f}$ are observed for these objects, we can still define an indirect limit we need to beat. If we assume an object has spun down significantly from its original frequency and that this spin-down has been dominated by gravitational wave emission, we can rewrite Eq. (1) as

$$h_{\mathrm{IL}} = 2.3 \times 10^{-24} \left(\frac{1\,\mathrm{kpc}}{D}\right) \left(\frac{10^3\,\mathrm{yr}}{\tau_{\mathrm{sd}}}\right)^{1/2} \left(\frac{I}{10^{38}\,\mathrm{kg\,m^2}}\right)^{1/2} \tag{2}$$

in terms of the age a, which can be inferred in various ways.

Initial LIGO can beat this upper limit for several objects of this type, including the youngest – the object in supernova remnant Cas A ($\tau_{\mathrm{sd}} = 326\,\mathrm{yr}$, $h_{\mathrm{IL}} = 1.2 \times 10^{-24}$) – and the closest, Vela Junior ($D > 200\,\mathrm{pc}$, though the precise value is uncertain). Several more objects have indirect limits attainable with advanced LIGO, including the remnant of Supernova 1987A ($h_{\mathrm{IL}} = 3.2 \times 10^{-25}$). However this putative neutron star is only 25 years old and would require a search over a large parameter space including six or seven frequency derivatives. Searches over small sky areas (single "pixels") are computationally the same as searches for known point sources, and for several of these (such as the galactic center) even initial LIGO could beat indirect limits. We recently completed a search for Cassiopeia A [475] and have begun searching for other interesting locations on the sky, such as star-forming regions and globular clusters, as described below. We are collaborating with several photon astronomers on constructing more complete target lists of point sources and small areas, both for initial and advanced LIGO (see section 5.2.8).

The first search for a source with no timing (Cas A) used the $\mathcal{F}$-statistic code with a single integration of $\mathcal{O}(10)$ d. Our estimate of computational cost and sensitivity [476] shows that this is enough to start beating indirect upper limits on some sources. For young sources even such a short integration time requires up to the second frequency derivative; thus metric-based methods and code for tiling parameter space in multiple dimensions are important to reduce the computational cost. In the near future we will try hierarchical searches (see other searches below) which will require algorithm and code development to adapt to the needs of this search. We are also evaluating the potential of resampling methods to reduce not only the computational cost for a given search, but also the cost's scaling with integration time. This, combined with hierarchical methods, will allow us to search a significant fraction of the S5/S6 data sets (and future sets of comparable length) rather than $\mathcal{O}(10)$ d.

A similar but deeper search was carried out for Calvera, which is an X-ray source originally detected by ROSAT and confirmed with Swift and Chandra measurements. Until fall 2010 it had no detected optical or radio counterpart and was thought to be an isolated neutron star, possibly a millisecond pulsar beaming away from us, but relatively close – O(100 pc) away.

A fully coherent search using a barycentric resampling method based on interpolation in the time domain was carried out for Calvera over the 90-360 Hz band [478], assuming an age of O(10^6) years which severely restricts the spin-down range to be searched. Because the sky location was known, the search benefitted dramatically in reduced computational cost from the resampling step during preprocessing. Preliminary upper limits were obtained in summer 2010, but the subsequent observations of pulsations in X-rays [477] outside the sensitive LIGO band deterred pursuing publication. Nonetheless, the search served as a useful benchmark for directed, deep searches for old objects and as a proving ground for the barycentric resampling method.

5.2.1 Coherent directed searches

UPDATED

The coherent S5 search for Cas A [475] is being updated to S6 data and extended to supernova remnants G1.9+0.3, G18.9–1.1, G93.3+6.9, G189.1+3.0 (IC 443), G266.2–1.2 (Vela Junior, two searches), G291.0–0.1, and G347.3–0.5, for a total of nine searches and eight objects. These remnants, like Cas A, contain non-pulsing candidate neutron stars, except for G1.9+0.3 which has now taken Cas A's place as the youngest known supernova remnant in the galaxy and is small enough to be searched with one sky position. The update includes the SSE2 enhancements to floating-point instructions on Intel processors, resulting in nearly a factor 3 speed-up over the standard F-statistic code. All of the searches except G347.3–0.5 are done, no plausible signals have been found, preliminary upper limits have been set, and more careful post-processing including improved vetoes is underway. The sensitivities of these coherent searches, integrating over time spans from 5 days to several weeks of S6 data, beat the indirect limits on gravitational-wave emission over frequency bands of at least 100 Hz and in one case nearly 2 kHz. Post-processing (and the last search) should finish over summer 2013, with the observational results paper review starting by fall.

In addition, a search based on time domain resampling [478], following the template placement method of the Cas A search [475], is being carried out for isolated stars in globular cluster NGC 6544. The search pipeline is based on an Einstein@Home implementation of the resampling algorithm. Code development is being coordinated with the E@H team, to permit a common code base for a variety of future searches. Production running began in fall 2012, and preliminary upper limits from combined H1-L1 data have been obtained over the 200-560 Hz band to date. Systematic follow-up of outliers is under way.

5.2.2 Searches for sources near the galactic center

UPDATED

The galactic center is a location where one might expect to find a large number of unknown, young neutron stars. Standard electromagnetic observations have identified only a small fraction of all pulsars thought to be present near the galactic center. The dispersion and scattering of the signal by interstellar material between potential sources and the Earth significantly reduces the depth of such observations. A few hundred pulsars are expected to orbit Sgr A* within the inner few parsecs. Some of those objects could be promising sources of CW gravitational wave signals. Searching in the direction of the galactic center involves searching over a small sky region but over large frequency and spin-down ranges.

Most of the S5 data set has been scanned in an all-sky search using the `Einstein@Home` infrastructure. This search is meant to be more sensitive over a different region of parameter space – it searches a larger range of spin-downs and a narrower frequency band – and uses a larger data set.

A single sky template is used for this search with the coordinates of the galactic center (Sgr A*). The frequency band is 78-496 Hz. The range of spindowns is specified via $0 \leq -\dot{f} \leq \frac{f}{200\ \mathrm{ys}}$, where f is the gravitational wave frequency of a neutron star. The data searched is from S5, using only data from the H1 and L1 detectors. It is a semi-coherent search using 630 data segments of length 11.5 hours. No second order spin-down parameter is considered in the search.

The production run finished over two years ago. A chain of different post-processing steps has been applied to the results of the analysis, resulting in no statistically significant detection. 59 candidates can not be ruled out as gravitational wave signals having a second order spindown value. Upper limits have been derived for the target population and for a population that has second order spindown, taking into account these 59 candidates. The review of the search is completed.

At the March LSC meeting (2013) the results and a draft of the observational paper were presented. We expect to publish the paper this summer. Two follow-up projects are in the planning stage, both of them being connected to 59 candidates which can not be ruled out as gravitational wave signals having a second order spindown value. One is a coherent follow-up search including second order spindown, the other is a collaborative search (with Stephen Eikenberry) for coincident X-ray signals in RXTE data.

5.2.3 Supernova 1987A using the cross-correlation technique

UPDATED

As described elsewhere, the semi-coherent excess power methods are more robust than the fully coherent searches. This is because they demand phase coherence of the signal only over the coherent integration time, which is much shorter than the total observation duration. This reduction in the minimum coherence time has the added advantage of significantly reducing the computational cost. It is possible to reduce this coherence time even further by using cross-correlations between data from multiple detectors. In the case when we correlate coincident data from two detectors, the minimum coherence time is just the light travel time between the two detectors. In the general case, we can correlate data streams collected at arbitrary times from two distinct detectors, and also from the same detector at distinct times. The details of this method, which is a generalization of methods used previously in the stochastic "radiometer" search [499, 467], can be found in [461]. The main feature of this generalization is the presence of a free parameter, the minimum coherence time required of the signal, which can be tuned depending on the desired sensitivity, robustness and computational cost.

The starting point for this search is a set of SFTs of duration $T_{\rm sft}$ covering a total observation time $T_{\rm obs}$ followed by: i) a choice of the minimum coherence time $T_{\rm coh-min}$ which is used to create pairs of SFTs, ii) a computation of the cross-correlation statistic for each pair for a given set of pulsar parameters, and iii) calculating a weighted linear combination of the various cross-correlations, with the weights chosen to maximize the sensitivity exactly as in the PowerFlux or the weighted Hough searches. Many of the existing standard CW searches can be viewed as special cases of this scheme. The standard PowerFlux search corresponds to considering only self correlations of the SFTs, a full coherent search corresponds to considering all possible SFT pairs, and the hierarchical search is an intermediate case with $T_{\rm obs} \gg T_{\rm coh-min} \gg T_{\rm sft}$. This is however a computationally inefficient way of calculating the coherent statistic, for which it is better to use the existing $\mathcal{F}$-statistic, so we expect that the cross-correlation is useful only with $T_{\rm coh-min}$ either comparable or lesser than $T_{\rm sft}$.

One object to which this semi-coherent method can be applied in a directed search is a neutron star in the supernova remnant SN1987A [462]. In searching for such a young object, searching over frequency derivatives can be prohibitive because of the need to search over higher derivatives. It turns out that the search space can be narrowed by using a physical model for the frequency evolution: $\dot{nu} = Q_1\nu^5 + Q_2\nu^n$. The first term is the usual term due to gravitational wave emission while the second term represents all other effects (ideally, for electromagnetic braking, one would expect a braking index of $n = 3$, but in practice one observes a range $1 < n < 3$ for the $\sim$ 10 objects whose n can be measured by absolute pulse numbering). With this model, and using $T_{\rm coh-min} \approx 1$ hr, it turns out that the computational cost becomes manageable for astrophysically interesting parameter ranges, namely $B \lesssim 10^{11}$ G and $\epsilon \gtrsim 10^{-4}$, where B is the magnetic field strength and ϵ in the ellipticity [462].

A pipeline to perform a cross-correlation search for isolated neutron stars has been written and tested and undergone significant review. The pipeline has been calibrated via Monte-Carlo simulations for pure noise and injections, with and without averaging over the inclination and polarization angles, and with and without spin down. A partial search for SN 1987A over $\sim 30\%$ of the parameter space has been done with S5 data. In the coming year, the search will be completed on S5, S6 and/or VSR2-3 data, with an eye towards producing a publication before Advanced LIGO data begins to flow. Additionally, this pipeline is being reorganized to address some of the shortcomings of the original pipeline (e.g., the need to keep track of the detection statistic for every point in parameter space rather than using a "toplist" of the most significant points), and to allow a wider set of signal parameters, including orbital parameters for a neutron star in a binary system. (See Sec 5.4.2.) A rudimentary version of this pipeline should be in place by the end of summer 2013.

5.2.4 Semi-targeted search using stroboscopic resampling

UPDATED

In general, the correction of the Doppler effect due to Earth motion depends on the source sky direction and frequency. Since the parameters are often unknown, a large computational effort is required to correct for any possible direction and emission frequency. A correction technique independent of the frequency is used in a pipeline based on stroboscopic resampling. The antenna proper time is accelerated or slowed down by deleting or duplicating in a timely manner single samples of the digitized signal in order to keep the reference clock synchronized with the source clock, within an accuracy given by the inverse of the sampling frequency f_s (several kilohertz) [439]. The removal (or the duplication) of the samples takes place typically each few seconds. The list of samples to be removed or duplicated (named *mask*) is thus not huge and can be easily computed by simple geometrical consideration. As detailed in [439] the mask corresponding to a given direction is provided by the times when the antenna crosses one of the equi-phase parallel planes fixed in the space, perpendicular to the wave vector and each at a distance c/f_s from the next one. Each "crossing time" is computed by the scalar product of the antenna velocity and the wave direction (in practice by a few operations each second of data).

The maximum phase error due to the non-perfect synchronization is given by $2\pi f_0/f_s$ where f_0 is the signal expected frequency and f_s is the sampling one. As a reminder, a phase error around a few tenths of rad is small enough to guarantee that almost all the signal energy is recovered around the main frequency. It is thus important to resample the data working at the Virgo data acquisition frequency (20 kHz) in order to use the method effectively up to several hundred Hz. This frequency independence makes the method very appealing for sources where the direction is well fixed, but the emission frequency is uncertain (semi-targeted search). The pulsar spin-down is taken into account by properly shifting the equi-phase target plane during the acquisition time. As a consequence, a single mask requires specifying both the direction and the spin-down value of the source. The Einstein delay and the Shapiro effect can be also easily computed without any significant additional computational cost.

We have developed an analysis pipeline and are applying it to VSR2 data. The Earth ephemeris is computed by using the Roma 1 group PSS routine. In just a few minutes the ephemeris and Einstein delay data are computed and stored for the entire VSR2 period with a sampling time of a few seconds (enough to approximate Earth motion with enough accuracy).

Starting from the ephemeris, another routine computes the masks for a set of directions and spin-down values. The computation time was tested not to exceed a few 10^{-8} of the integration time, per each mask (i.e., per each direction and spin-down).

In parallel the antenna data, already cleaned from non-stationary events by usual PSS techniques, is pass-band filtered around the signal expected frequency. The bandwidth must be large enough to contain all the sidebands produced by Doppler and spin-down. Several tens of operations per sample are necessary in the data filtering. The final cost will be evaluated after implementation, but we expect to work with a computing time around 10^{-4} – 10^{-3} of the integration time.

During the signal decimation, different masks can be applied in parallel to the filter output (at signal sampling frequency). Very light buffers are produced at the downsampling frequency (inverse of the filter band) for FFT spectral analysis. Usual statistical analysis for peak identification will be adopted in the final step of the pipeline.

Since the Doppler correction (computation of masks and their parallel application in decimation of the filtered data) is negligible, the optimization strategy for the semi-targeted search is straightforward. We need only choose the width of the pass-band filter ("slice"). Indeed this choice determines the downsampling factor, thus the length of the buffers governing the FFT computation time. Finally we must multiply the time required for the previous operation (filtering and parallel FFTs) times the number of slices required to cover all of the interesting detection band. The optimization of the pass-band filter width, obtained minimizing the total computation time, depends on the analysis to be performed. Many tests have been performed on simulated data assuming different antenna orbits, spin-down values, sampling frequencies and source frequencies. In all cases, the expected phase-locking and peak reconstruction accuracy has been found. Similar tests have been performed injecting signals in the VSR1 data. All the results are described in Torre's graduation thesis [463], or (more in summary) in [464]. The resampling of the data requires less than 10^{-5} of the investigated time (for a single direction and spin-down on a few Hz band), that is negligible with respect to the time required to read the HF stream (of the order of 10^{-4}). A method to read the data and apply the resampling technique directly to the down-sampled data (making negligible the computing time for reading data) is in progress.

A methods paper was recently published in Phys. Rev. D [481].

The amplitude modulation will be taken into account using a matched filtering in the frequency domain, in a way similar to the one developed by the Rome group. We are currently implementing a full pipeline for this purpose, and testing it on hardware injections in VSR2 data.

After the validation of the pipeline we plan to apply it to the observation of the supernova remnant RX J0852.0-4622. There is a Ph. D. student dedicated to this (Oriella Torre), which should discuss her thesis during the current year (2013). We expect to be able to finalize the main steps of the activity (not including internal reviews) in time for this.

5.2.5 Semi-targeted searches for "transient CW signals"

UPDATED

This section concerns searches for gravitational wave signals longer than those traditionally considered by the Burst group, but shorter than those traditionally considered by the CW group. A code capable of performing such searches was developed by Giampanis & Prix. As an astrophysical application of this, the possibility of the excitation of r-modes in rotating neutron stars has been considered. Two different kind of sources have been identified:

- **Glitching pulsars** which are mainly young pulsars (although one millisecond pulsar has been observed to glitch).
- **Type I bursts** from accreting millisecond pulsars.

Some thought has already been given to the astrophysics of carrying out such searches, in terms of wave frequencies, durations and detectability. Given that the r-mode's frequency is known with a precision of $\sim 20\%$, searches will need to be carried out in a frequency band defined by this uncertainty. This means that for young pulsars like the Vela Pulsar ($f_{mode} \sim$ 15 Hz) a $f_{band} \sim$ 3 Hz is required, while for faster spinning stars like 4U 1608−522 ($f_{mode} \sim$ 825 Hz) a $f_{band} \sim$ 165 Hz is required.

Crucially, the signal decay timescales were estimated using an energy dissipation model that assumes the existence of a viscous boundary layer at the star's crust-core interface by [491]. This predicts that the emission from young glitching pulsars will last $\sim 10^2$ seconds, while emission from millisecond pulsars will last $\sim 10^4$ seconds, although both timescales are subject to some considerable uncertainty.

In the case of pulsar glitches, an assumption that $E_{\rm mode} = E_{\rm glitch}$ was made, and in a similar way, for the Type 1 Bursts $E_{\rm mode} = E_{\rm burst}$ was assumed, where $E_{\rm mode}$ is the energy deposited in the r-mode, $E_{\rm glitch}$

an estimate of the energy involved in a glitch, and $E_{\rm burst}$ an estimate of the electromagnetic luminosity of an X-ray burst. Using these simple estimates, it was found that, if the Levin and Ushomirsky dissipation model [491] is considered, the detection of gravitational waves associated with glitches in young pulsars is not plausible with 3rd generation gravitational waves detectors. On the other hand, glitching millisecond pulsars would be significantly easier to detect, although such glitches may be extremely rare. Type I X-ray bursts in accreting millisecond pulsars also seem to be of potential interest too.

To gain a more accurate picture of the feasibility of such searches, the transient gravitational waves search code [482] has been tested to recover signals with timescales in the order of $10^2 - 10^4$ s and signal-to-noise ratios ~ 10. Efforts are now focused on (i) Completing the extraction of injected transient signals from realistic data, (ii) The assembly of a methods paper, combining the astrophysical motivation with details of the search method, and (iii) Assessing what can be learnt regarding the source parameters in the event of a successful detection.

5.2.6 Directed search using $\mathcal{F}$-statistic

UPDATED

Another directed-search pipeline is under development, building upon already implemented all-sky search code that employs the $\mathcal{F}$-statistic method (Sect. 5.3.9). Novel usage of graphical processor unit (GPU) solutions, framework and dedicated libraries promise that a search for GWs from astrophysically motivated sources over a large frequency and frequency derivative will dramatically reduce computational costs, as well as allow for much greater flexibility in comparison to what is possible in all-sky searches. Additionally, the pipeline will serve as a testing ground for new theoretical methods of parameter space optimization and hardware/software implementation techniques.

5.2.7 Einstein@Home semi-coherent directed searches

UPDATED

We are currently launching a new class of searches on the Einstein@Home platform, targeting known or suspected compact objects that are well-localized on the sky, but have unknown rotation frequency and spindown. These "directed" semi-coherent searches on LIGO S6 data will focus on the list of astrophysical targets that was initially collected for fully-coherent directed searches (see Sec. 5.2.1 and Sec. 5.2.8). We aim for a near-optimal distribution of computing power, both over the different astrophysical targets, as well as in the choice of semi-coherent pipeline parameters (length and number of segment, template-bank mismatches). Semi-coherent directed searches are expected to be the most sensitive searches of this kind, and will beat the indirect spindown-limit for most of these targets over a wide frequency range of up to $\sim$1kHz. In practice we will start with a single directed search for Cas A, lasting for about 3 months, which is expected to launch in mid-June 2013. This will be followed by several searches over further targets, either individually or "bundled" into groups of targets. In total we expect to spend about 1–1.5 years of Einstein@Home computing time on these directed searches. Post-processing is planned to start while the searches are still ongoing in order to reduced transit time until publication of results, but detailed publication plans are yet to be decided.

5.2.8 Other targets

UPDATED

We are collaborating with several astronomers on constructing lists of interesting targets for further directed searches, i.e., targets where LIGO and Virgo can beat the indirect limits on gravitational-wave emission. Apart from Cas A there are of order ten candidate non-pulsing neutron stars with indirect limits on h_0 beatable with S5 or S6/VSR2 coherent and semi-coherent searches. There are also several small, young supernova remnants (such as SN 1987A) and pulsar wind nebulae where the neutron star is not seen. Other small sky regions (further discussed below) also can be targets of this type of search. Examples include regions of massive star formation such as the galactic center and massive young clusters containing magnetars such as Westerlund 1. Globular clusters are not likely to contain young neutron stars, but some old neutron stars are known to possess planets and debris disks. Frequent perturbations in the dense environment of a cluster core could trigger bombardment episodes, and a star with an impact-related deformation counts as rejuvenated for purposes of a gravitational-wave search. Considering interaction timescales, most of the best targets are nearby, dense clusters such as NGC 6544. However 47 Tuc's interaction timescale is short enough to make it an attractive target even though it is further away; and furthermore the first GLAST/Fermi results show considerable high-energy diffuse emission which is likely related to neutron star activity in the relatively recent past.

It is useful to maintain ties because X-ray and gamma-ray astronomers are beginning to find many point source neutron star candidates, and thus it is likely that the interesting target list for LIGO will expand substantially even before advanced LIGO. Examples include Fermi point sources and HESS TeV gamma-ray sources that are followed up with Chandra and XMM-Newton X-ray observations, yielding pulsar wind nebulae and sometimes the neutron stars themselves.

A paper describing an interesting list of targets in in preparation and will be submitted for publication this year. As the advanced detector era approaches, these studies will be extended.

5.3 All-sky searches for isolated neutron stars

UPDATED

These are objects which have not been previously identified at all, and thus we must search over various possible sky positions, frequencies, and frequency derivatives. They are believed to constitute the overwhelming majority of neutron stars in the Galaxy, but most of them are not believed to be good sources for LIGO or Virgo. It has been argued, based on the observed supernova rate and inferred population of neutron stars in the Galaxy, that the indirect limit on the strongest signal from this population is no more than

$$h_{\rm IL} = 4 \times 10^{-24} \left(\frac{30\,{\rm yr}}{\tau} \right)^{1/2}, \tag{3}$$

where τ is the mean time between supernovae in the Galaxy. The latest and most detailed derivation of this upper limit is given in [419]. Note, however, that a more recent simulation analysis finds significantly lower expectations that depend on the assumed source frequency and ellipticity [460].

It is useful here to briefly explain the computational challenge that must be overcome for these searches. The parameter space for blind searches for weak signals from unknown isolated neutron stars is very large. The number of templates N_p, required to cover the entire sky, a large frequency band, and a range of spin-down parameters and using data which spans a duration T, is roughly proportional to T^5. The computational cost therefore scales as $\sim T^6$. In fact, for any reasonable volume of parameter space, N_p becomes so large that using our existing coherent integration code and using the full computational power of our largest computational platform `Einstein@Home` running for a few months, it is not possible to consider values of T larger than a few days. Even if we were able to speed up our coherent demodulation algorithm by, say, a factor of 100, T would increase only by a factor of $100^{1/6} \approx 2.2$. On the other hand, we require T to be a few months to have a realistic chance of detection. The situation is, naturally, even more demanding for neutron stars in binary systems.

For this reason, different methods using a combination of coherent and semi-coherent techniques have been designed. The basic idea is to break up T into smaller segments which are analysed coherently, and to stitch together these segments using a semi-coherent technique. Outlier candidates are then followed up. The sophistication and automation of the follow-ups have improved in recent analyses and offer the promise of lowering detection thresholds significantly in some search pipelines.

Five all-sky pipelines are currently in use for carrying out all-sky searches: 1) a quick-look semi-coherent method known as PowerFlux using incoherent sums of strain spectral power from many 30-minute "Short Fourier Transforms" (SFTs), 2) a multi-interferometer Hough transform method starting from 30-minute SFTs, 3) a hierarchical algorithm using `Einstein@Home`, based on phase-preserving demodulation over many ∼day long intervals, followed by a semi-coherent step (see below), 4) a hierarchical method, developed in Virgo, based on the alternation of coherent and incoherent steps; and 5) an $\mathcal{F}$-statistic-based search also developed on Virgo data. It is likely that the use of one or more of these pipelines will be discontinued in the next 1-2 years, following the systematic comparisons using standardized simulated data sets, as described above.

In addition, two new methods are under development that offer greater robustness against uncertainty in the source model: 1) a “loosely coherent” method [455] using the PowerFlux infrastructure; and 2) a cross-correlation method [461] which provides a smooth bridge between semi-coherent and coherent methods, with the possibility of parameter tuning to improve sensitivity over semi-coherent methods while maintaining robustness.

5.3.1 PowerFlux method

UPDATED

For a monochromatic, constant-amplitude sinusoidal wave in Gaussian noise, summing the strain power from M short Fourier transforms improves the sensitivity (strain value for a fixed signal-to-noise ratio) by a factor $M^{1/4}$. In contrast, a coherent search based on a single Fourier transform over the entire M intervals gives a sensitivity that improves like $M^{1/2}$. One strong advantage of the semi-coherent methods is their robustness against unknown source phase disturbances, such as from frequency glitches due to starquakes.

The searches we must perform are more complicated than simple power sums. Frequency and amplitude modulations that depend on source direction are relatively large. The frequency modulations arise from the motion of the detectors with respect to the source, with components due to the Earth's rotation ($v/c \sim 10^{-6}$) and to its orbital motion ($v/c \sim 10^{-4}$). The amplitude modulation arises from the changing orientation of the interferometer arms with respect to the source direction as the Earth rotates. As a result, an all-sky search requires a set of finely spaced templates on the sky with varying corrections for these modulations. In general, the number of templates required for a given coverage efficiency scales like the square of the source frequency.

Over the last several years, we have explored three related methods for incoherent strain power summing: StackSlide [428], Hough [451, 418], and PowerFlux [452]. These methods take different approaches in summing strain power and in their statistical methods for setting limits, but their performances are quite similar. Because PowerFlux has been found to yield somewhat better efficiency than the other two methods for most frequency bands, it has been chosen as the quick-look semi-coherent algorithm used on data from the S5 and S6 science runs. An article based on applying all three methods to the S4 data was published in early 2008 [453] in Physical Review D.

In short, PowerFlux computes from many thousands of 30-minute SFTs an average strain power corrected for antenna pattern and with weighting based on detector noise and antenna pattern. Its signal estimator is direct excess strain power for an assumed source direction and polarization, using one circular polarization projection and four linear polarization projections. PowerFlux, like Hough or StackSlide, corrects explicitly for Doppler modulations of apparent source frequency due to the Earth's rotation and its orbital motion around the Solar System Barycenter. Source frequencies are searched with ∼0.56 mHz spacing and limits presented separately for 0.25 Hz bands.

A short publication based on an improved PowerFlux search over the first 8 months of S5 data was published in Physical Review Letters in early 2009 [454]. These results cover the frequency range 50-1000 Hz and negative spin-down as large as 5×10^{-9} Hz/s. The present PowerFlux program permits deeper searches for coincident candidates among multiple interferometers than in S4 and applies tighter coincidence requirements between candidates in the H1 and L1 interferometers, which allows setting lower SNR thresholds for followup of candidates.

A series of major improvements to computational efficiency were made to facilitate a PowerFlux run over the full S5 data while keeping memory requirements within the bounds of LIGO processors and keeping total computational time for the first-pass search within a half-year. A two-interferometer power sum was used, together with coincidence between H1 and L1, to push deeper into the noise than before.

In parallel, a "loosely coherent" follow-up was added directly to PowerFlux, one that allows for slow drifts or modulations in phase from one SFT epoch to the next [455]. It offers the possibility of a "controlled zoom" of interesting candidates and reduces the chances of missing a true signal because it doesn't quite fit the template for a long coherent search. Upper limits for the 50-800 Hz band based on a search of the full 2-year S5 data were produced, and outliers followed up with the new loose coherence step. These results were published in 2012 [457].

Preliminary S6 results have been obtained, with follow-up of outliers in progress. A large number of spectral artifacts seen in S6 data (associated with the output mode cleaner) make this follow-up more laborious than expected. A novel "universal" statistic [458] has been developed to cope with the large number of non-Gaussian S6 bands in both H1 and L1 data. Other recent improvements included a coherent IFO-sum option for each SFT to gain further SNR [459]. Publication of final S6 results is expected in the next few months.

5.3.2 Hough transform method

UPDATED

As in the PowerFlux method, the weighted Hough transform method (used already to analyze the S4 data [453]) takes into account the detector antenna pattern functions and the non-stationarities in the noise. This algorithm allows to combine data from different interferometers, to perform a multi-interferometer search.

For the analysis of the full S5 data, many new features have been included into the Hough search code, such as dynamical selection of data depending on SFT noise floors and sky-positions, splitting of sky patches with frequency dependent size, creation of a top list of candidates, internal follow-up using the full data, and a chi-square test [465] to reduce the number of candidates and consequently increase the sensitivity of the search.

Separate analyses of the first and second calendar years of S5 data have been carried out, and coincidence of outliers between years 1 and 2 has been imposed as a filter on outliers to be followed up. This has allowed to use a lower threshold compared to previous searches for candidate selection permitting deeper searchers. In particular, the search has improved to process outliers down to *significance* from 5.10 at 50 Hz to 6.13 at 1000 Hz. The previous search [453] rejected candidates with significance greater than 7 in the multi-interferometer search and of 6.6 using data from individual interferometers.

The search covered the frequency range $50-1000$ Hz and with the frequency's time derivative in the range -8.9×10^{-10} Hz/s to zero. Since no evidence for gravitational waves has been observed, we have derived upper limits on the intrinsic gravitational wave strain amplitude using a standard population-based method. The best upper limits correspond to 1.0×10^{-24} for the first year of S5 in the $158 - 158.25$ Hz band, and 8.9×10^{-25} for the second year in the $146.5 - 146.75$ Hz band. Full-S5 Hough results have been completed and presented to the collaboration. A publication is under preparation and it will be submitted for publication soon.

5.3.3 `Einstein@Home All-Sky Searches`

UPDATED

Overview: `Einstein@Home` is a public distributed-computing project in which users contribute the spare CPU cycles on their computers for gravitational wave searches. Thus far, it has been used in the all-sky wide parameter space searches for CW sources. It was launched in February 2005, and since then it has built up a user-base of over 200 000 active users; it currently delivers more than ~ 1 Pflops of continuous computing power. This is by far the largest computational platform available to the LSC and it is also one of the largest public distributed projects of its kind in the world. The project is targeted towards making a detection. So far it has analysed LIGO data from S3, S4, S5 and S6.

S5GC1 search: A significant improvement with respect to the Hough transform hierarchical search was claimed in [472] by exploiting global correlations in source parameter space. An engineering run (S5GCE) to test this improvement was completed in spring 2010, and a new production run (S5GC1) over the full S5 data has recently completed. A preliminary study of the sensitivity of this run shows that it is in fact less sensitive than the S5 run whose results were published in February 2013 (H.B. Eggenstein, P. Leaci and M.A. Papa). However this run covers a range of frequencies above 1190 Hz which were not searched before. The plan is to analyse the results from this band and publish a short report.

S6 Bucket search: A production run over the most sensitive S6 data (in the "bucket") begun in 2011, where the relatively low frequencies (50-450 Hz) permit searching with a longer coherence time (90 segments of 60 hours each) and up to spin-downs corresponding to an age of 600 years. The run completed, and a similar run was launched in 2012 which returns candidates ordered according to a different statistic from used in the first bucket search. In particular, the results are ranked according to a "line veto" statistic that, broadly speaking, decreases the significance of candidates with signal-inconsistent average multi versus single-IFO F-stat values (see 5.3.5). This run also completed, at the end of 2012. The systematic post processing of these runs has begun in 2013. Apart from an improved sensitivity and hence a publication of the results of this search, a comparison between the candidates of the different runs will allow us to characterise the performance of the different detection statistics that have been developed.

Data selection and run set-up procedures: The best exploitation of the limited computing resources for a given parameter space is an optimization problem that depends on the noise level of the data and on their gaps relative to all the usable detectors. Up to now each `Einstein@Home` run has required an ad hoc iterative study of the set-up parameters. The team is trying to quantify through figures of merit the relevant choice parameters and to set up automatic procedures to define run parameters. An additional factor that has entered the run-set up decisions up to now in different, and not always consistent ways, is the prior chance to make a detection as a function of parameter space. We would like to develop schemes that at least highlight the priors underlying the run set up choices.

Speed-up of the F statistic search: Incorporate the resampling-based code developed by Chris Messenger in the `Einstein@Home` hierarchical pipeline. Progress has been made in 2011-2012 on this. We foresee integrating the resampling technique in our mainstream searches but we are not sure that we will be able to achieve this during this year.

Signal-based veto procedures: A “Line Veto statistic” has been developed in order to discard spurious disturbances related to instrumental “line” artifacts from the top-list of returned candidates, which will improve the sensitivity of searches, as described in more detail in section 5.3.5. The S6 Bucket runs have used this for the first time and, as described above, the post processing of the results will allow to characterise the performance of this statistic and determine a solid tuning method for its free parameters.

Clustering of correlated candidates, detection tests over portions of the parameter space Based on the final results of ongoing post processing efforts, identification of correlated candidates will be studied and possibly incorporated in the hierarchical `Einstein@Home` pipeline allowing to save follow-up cycles. For the same purpose, i.e. identification of interesting regions in parameter space, we will also investigate the application of standard hypothesis testing methods, for example the Bayes ratio. We plan to address this in the context of the S6 bucket post processing. For directed searches a clustering scheme was designed and successfully used in the Galactic centre search.

re-write of GCT code In 2011-2012 the GCT search code routines were modified to allow the use of 2nd order spin-down to expand the population of sources that we can search for. Recent investigations in the context of setting up the S6 Einstein@Home directed searches have uncovered performance issues with the most current implementation that need to be understood. Probably a GCT scheme still makes sense for directed searches.

New all-sky hierarchical code The GCT scheme in its current implementation is not suited for all-sky searches over periods of a year or more. This is a major drawback and makes it compelling for us to develop an alternative. The Hough scheme does not appear to be a promising alternative for a few reasons : 1- already explicitly searching over first order spin down the memory requirements are too large for the Einstein@Home host machines 2 – second order spin down searches have not been implemented but memory requirements might become prohibitive 3 – the look-up tabs approach which is responsible for speed performance makes it hard to extend the method to perform a sum of Fstatistic values (stack-slide search rather than a zeros or ones sum).

Sensitivity estimates and comparisons We maintain and develop an analytical framework to estimate the sensitivity of the complex search procedures that the `Einstein@Home` performs as well as other searches, most notably the Powerflux search. Such framework successfully predicted the S5R5/R6 $h_0^{90\%}$ ULs.

Performance benchmarking We will use the reference MDC set of the CW group to characterise the performance of the Einstein@Home searches through the standard figures of merit used by the other CW group teams.

Automatic follow-up procedures: Based on the final results of ongoing optimization studies for a hierarchical search (see below), automatic follow-up procedures will be implemented in the `Einstein@Home` core code in the long term, ultimately permitting improved sensitivity (cf Sec. 5.3.4).

Support and maintenance: The `Einstein@Home` servers and project require continual maintenance in the form of software updates, message board interaction with users, publicity, maintenance of server hardware, maintenance, repair and extension of the BOINC libraries, bug tracking and elimination, etc.

Automatization of work-unit generator for different searches: Currently much work and specialized expertise is required in order to set up a new BOINC project, or even to prepare and launch a new run in an existing project such as `Einstein@Home`. Some of the key steps required are a "workunit generator" that needs to be implemented (coded in C++ against the BOINC library), together with a validator and an assimilator. The science application needs to be installed on the server, together with various setup steps required on the server in order to prepare the scheduler and the database. Work has now begun on a project to make this increasingly easier and more "user-friendly", allowing users to set up new runs or even whole projects "on the fly".

Relation to the "Grid":

BOINC is a general computing platform that is able to leverage huge computing power from a pool of heterogeneous computing resources in a fault-tolerant and robust way. In this it achieves an important goal that is also part of various "grid" initiatives. If one can create a flexible and simple interface, similar to that of condor, say, to this powerful infrastructure, one could leverage the massive pool of LSC computing clusters or other "grid" resources in a more transparent and flexible way than is currently possible.

5.3.4 Followup-searches to confirm or veto CW signal candidates

UPDATED

Better theoretical understanding and the development of software tools is required in order to deal efficiently with the follow-up of interesting candidates from incoherent search pipelines. A fully coherent follow-up method has been developed based on a non-grid based approach using a Mesh Adaptive Direct Search algorithm (NOMAD). A methods paper describing this follow-up procedure and its performance has been published. A follow-up pipeline has been implemented and applied to candidates from the S5R5 Einstein@Home search. A methods paper about the application of this follow-up procedure to the S5R5 Einstein@Home candidates is in preparation. An alternative coherent and completely deterministic procedure was used to follow up low significance candidates of the targeted Galactic centre search. Investigations along both lines will continue. The final goal is to move the coherent follow-up step onto the hosts participating in the Einstein@Home search. We will investigate the possible application of the follow-up method to candidates from searches for unknown binary systems.

5.3.5 Instrumental line-veto statistics for wide-parameter searches

UPDATED

One of the standard methods of CW data analysis is the multi-detector $\mathcal{F}$-statistic. In a typical search, the $\mathcal{F}$-statistic is computed over a range in frequency, spin-down and sky position, and the candidates with highest $\mathcal{F}$ values are kept for further analysis. However, this detection statistic is susceptible to a class of noise artifacts, strong monochromatic lines in a single detector. Conventionally, these artifacts are removed manually in post-processing. By assuming an extended noise model - standard Gaussian noise plus single-detector lines - we can use a Bayesian odds ratio to derive a generalized detection statistic, the line veto (LV-) statistic. In the absence of lines, it behaves similarly to the multi-detector $\mathcal{F}$-statistic, but it is much more robust against line artifacts, reducing the need for manual removal in post-processing.

As mentioned in section 5.3.3, for the S6LV1 run a simple version of the LV-statistic has been implemented directly on the Einstein@Home clients in order to improve the sensitivity of the search in disturbed bands. Namely, by avoiding saturation of the top-list of candidates by triggers from line artifacts, the detection threshold is effectively lowered and weaker candidates close to disturbances can be investigated. Joined post-processing of the S6Bucket (F-stat) and S6LV1 (LV-stat) runs will lead to a characterization of the sensitivity improvement on real data.

Furthermore, a simple adaptive tuning approach has been developed, estimating free parameters of the LV statistic from the data, which further improves detection power in real data. This approach will be used for the S6Bucket/LV1 post-processing as well as for the S6Directed run.

A methods paper about the general LV-statistic and the adaptive tuning approach is expected for publication during 2013. Further work will go into researching improved LV-statistics, using more complete line models and thereby further improving sensitivity in disturbed bands.

5.3.6 Identification of low signal signature areas of parameter space for wide-parameter searches

UPDATED

There are parameter space cells that present a low signal-specific-signature and are hence more prone to display high detection statistic values due to instrumental disturbances. We would like to develop a technique to weight this fact in the decision to follow-up candidates from these regions of parameter space.

5.3.7 Hierarchical Hough search

UPDATED

The All-Sky search, as already described in past WPs [440, 441, 445, 449] for unknown neutron stars, is carried out in the Rome group with the “Frequency Hough Transform method”, a transformation from the time/observed frequency plane to the source frequency/spin-down plane. A detailed method paper (following a previous one in which the basis of the method were outlined) is in preparation and will be finished by the end of 2013. We are now concentrating on the analysis of Virgo VSR2-VSR4 low frequency region, from 10 to 128 Hz, where the good Virgo sensitivity gives the opportunity to exploit a band never analyzed before for All-Sky searches, in particularly below 50-60 Hz. The review of the method and software is nearly finished. The analysis of VSR2 and VSR4 data has been completed, search sensitivity and upper limits computed in the band 10-128 Hz for each run separately. We have also run the search in the high frequency band, producing candidates in the range 128-1024 Hz.

Plans: We plan to rapidly complete the review, in particular discussing the upper limit results for the low frequency analysis. The writing of a result paper is just started and should be finished by Fall 2013. We also plan to run some semi-directed search, e.g. toward the Galactic center, with small spin-down age (e.g. 100 years).

5.3.8 Coincidences and Followup of hierarchical Hough candidates

UPDATED

In parallel to this, we are now developing the procedure to do coincidences among the candidates that we will find with VSR2 and VSR4 data. Coincidences allows to strongly reduce the false alarm probability. Coincidences are imposed on a parameter space of 4 parameters: frequency, spin-down and the two Sky coordinates. A first analysis of the candidates evidenced the severe reduction of the sensitivity due to the presence of frequency varying disturbances. So we developed a new time-frequency cleaning procedure that removes the varying frequency lines from the peak-maps. Furthermore we developed a procedure to identify and consolidate clusters of candidates that are reasonably due to a single "cause" (normally a disturbance). We are now working on the candidates produced with these procedures. Given the fact that the two runs are not parallel in time, of particular importance is the spin-down estimation (needed for the estimation of the source frequency). The follow-up procedure will be applied only on candidates that survive after the veto and the coincidences. We still have to design the details of the follow-up procedure. The time needed to follow-up candidates will clearly depend on how many candidates will survive and also on how much time we will need to study and fully understand the features of all the found candidates, to safely reject those due to noise.

5.3.9 $\mathcal{F}$-statistic all-sky search

UPDATED

Another analysis method currently used for all-sky searches is based on the $\mathcal{F}$-statistic [473]. It consists of a coherent stage over 2-day data segments, each covering a 1-Hz bandwidth and a follow up procedure of searching for coincidences among the candidates obtained in the coherent stage. We search the band from 100Hz to 1kHz, and we assume the minimal spin-down time of 1000 yr. We use a constrained optimal grid with minimal match MM = $\sqrt{3}/2$. The constraints are such that we need to resample the data only once for each sky position and such that we can use the FFT to calculate the F-statistic. Our guiding principle in the choice of a segment to analyze will be the quality of the data. The data for analysis is narrow-banded and cleaned using the procedures described in section 5.1.5. We set a threshold of 40 for twice the value of the $\mathcal{F}$-statistic above which we shall register the parameters of the candidates. Finally we search for coincidences among the candidates from different segments. We collaborate on the coincidence analysis with the LSC Einstein@Home team.

VSR1 production run is complete. 20419 narrowband data segments were coherently searched with the F-statistic and 4.21×10^{10} candidates were obtained. We have applied a vetoing procedure to the candidates. Firstly we have identified periodic interferences in the data, and then we have applied three vetoes to the candidates. Firstly we removed candidates in a narrow band around the identified lines, secondly we applied stationary line veto known from the Einstein@Home searches, and finally we removed candidates close to the poles in equatorial coordinates. As a result 3.19×10^{10} candidates remained. We have preliminary imposed upper limits on amplitude of gravitational wave for 1-Hz bands analyzed assuming normality of the noise. Our best upper limits reach 3.2×10^{-24}. We have developed a code to search for coincidences among the candidate. The code uses a flat metric to define coincidence cells, similar to that used in defining the grid in the parameter space. The code uses an efficient sorting algorithm developed by E@H team to search for coincidences. We have completed the follow-up procedure of our all-sky search by applying the code to search for coincidences in candidates from 20419 narrowband data segments of VSR1 data. No statistically significant coincidence was found. Currently we are completing the final stage of our analysis by determining the sensitivity of our search through software injections in the bands analyzed. The review of the analysis is well under way and a paper describing the all-sky search is expected to be submitted for publication later this year. In the longer term the search pipeline will be applied to the full VSR2 and VSR4 data, with improvements based on the global correlations code used in `Einstein@Home`.

5.3.10 Loosely coherent search

UPDATED

A new method called "loose coherence" is based on the notion of allowing slow drifts or modulations in phase from one SFT to the next, as described above for following up PowerFlux outliers. But, at least for small sky regions, the method can be applied from scratch in a dedicated pipeline to identify those outliers. A stand-alone program has been developed to permit "spotlight" searches for narrow regions in frequency, frequency derivative and sky location [456]. Production running began in fall 2012 for two spotlight directions in the galactic plane with overdensities of stars, associated with spiral arm spurs.

5.3.11 Cross-correlation search

UPDATED

The cross-correlation method has been described previously. Its present uses are as a directed search for known neutron stars, either isolated (Sec 5.2.3) or in binary systems (Sec 5.4.2). It could in principle also be used for an all-sky search complementing the existing semi-coherent searches, but such plans are in the future.

5.4 Accreting and unknown binary neutron stars

UPDATED

For this class of source the gravitational radiation is thought to be powered by ongoing or previous accretion onto the neutron star. In this scenario, first proposed by [431], the neutron star achieves an equilibrium state whereby the angular momentum fed to it through accretion is balanced with the angular momentum radiated away through gravitational waves. This argument and its history is summarized in [419]. The resulting indirect limit can be put in terms of X-ray flux F_x and spin frequency $f_{\rm rot}$ as

$$h_{\rm IL} = 5\times 10^{-27}\left(\frac{300\,{\rm Hz}}{f_{\rm rot}}\right)^{1/2}\left(\frac{F_x}{10^{-8}\,{\rm erg\,cm^{-2}\,s^{-1}}}\right)^{1/2}. \qquad (4)$$

At present we divide the known accreting neutron stars into two groups: the low-mass X-ray binaries (LMXBs) and the accreting millisecond X-ray pulsars (AMXPs). Sources from both groups consist of a neutron star in orbit around a lower mass companion object from which it is accreting matter. From a data analysis perspective the key difference is that for the majority of the ∼85 known LMXBs the spin frequency of the neutron star is unknown but thought to lie in the range ∼200 Hz – 1 kHz and for the 7 known AMXPs the spin frequency (equal to the pulsar frequency) is known to high accuracy. This difference makes searches for the LMXBs a far more challenging task that of the AMXPs. Note that there are 10 LMXBs for which type-I thermonuclear bursts are seen from which the spin frequency can be constrained to within ∼1 Hz.

Another important difference comes from the indirectly measured time-averaged accretion rates which are typically at, or within a factor of a few of, the Eddington limit for the LMXBs. The AMXPs exhibit accretion rates lower by a factor of 10 – 100 in comparison. This difference, according to Wagoner's arguments, makes the LMXBs likely to be stronger gravitational wave emitters than the AMXPs.

To date we have published a single coherent analysis on the accreting neutron star in the LMXB Sco X-1 using S2 data [419]. This was an exercise in wide multi-dimensional parameter space matched filtering and due to the rapid increase of search templates with observation time, the search was computationally limited to an observation time of only 6 h. Sco X-1, although the brightest X-ray source in the sky and consequently, also likely to also be the brightest continuous gravitational wave source, is typical of the LMXBs. As such it is clear that incoherent hierarchical search strategies need to be developed in order to maximise the search sensitivity, given the volume of parameter space we need to search and the computational resources. In this spirit, an incoherent search approach, based on the "radiometer" cross-correlation technique developed within the stochastic background group was applied to S4 data to set an upper-limit on radiation from Sco X-1 [499]. This result was recently updated with an S5 search, which also included a search in the directions of the galactic center and SN1987A [467]. A modification of the cross-correlation method to include information from the CW signal model, which allows cross-correlation of data from different times as well as different detectors, was proposed in [461]. This allows for a "tunable" semicoherent method where sensitivity can be increased by allowing the correlation of data further separated in time, at the expense of a greater needed resolution in parameter space. At present there is an ongoing study into the relative merits of each of the possible search strategies available within the LVC for targeting Sco X-1. A paper comparing and contrasting the methods, including the sideband, cross-correlation, twospect and radiometer searches is underway. We estimate that results will be available within a year and publication submission estimated towards the end of 2013.

Finally, we are exploring new methods to carry out an all-sky search for unknown neutron stars in binary systems. Because the unknown orbital parameters increase the parameter space enormously, it is expected that only relatively insensitive methods using short coherence times will be feasible.

5.4.1 Sideband search for known binary systems

UPDATED

The GWs from a continuously emitting source in a binary system will be received at a ground–based detector as a frequency and amplitude modulated signal. For known binary sources such as the low–mass X–ray binaries (LMXBs) we can remove the effects of the detector motion and maximize over the unknown amplitude modulation parameters through barycentric corrections and the use of the $\mathcal{F}$-statistic. The remaining time dependent frequency modulation, due to the binary Doppler motion of the source, allows us to decompose the signal into the infinite sum of frequency modulated sidebands. Under the conditions that the observation time is $\gtrsim 3$ orbital periods and that there is negligible drift in the intrinsic spin frequency of the source (i.e $\dot{\nu} \lesssim T^{-2}$ where T is the observation time) this sum is truncated leaving $M \sim 4\pi f_{\mathrm{gw}} a \sin i/c$ frequency resolvable sidebands where f_{gw} is the intrinsic GW frequency and $a \sin i/c$ is the orbital semi-major axis projected along the line of sight and normalised by the speed of light. Each of the sidebands is uniformly separated from the next by $1/P$ where P is the orbital period, and any orbital eccentricity acts only to redistribute power amongst existing sidebands.

By computing the $\mathcal{F}$-statistic for a given sky position and for a long enough observation time, a signal of adequate amplitude could be extracted by incoherently summing together the $\mathcal{F}$-statistic at each sideband frequency [468, 469]. This is equivalent to convolving the detection statistic frequency series with a "comb" of unit amplitude spikes separated in frequency by the inverse of the orbital period. The incoherent summing makes this a non-optimal strategy, but one that can have greater sensitivity to GW signals than a matched–filter approach because its observation length is not computationally limited. When using this approach, the parameter space resolution (and hence the number of search templates) is significantly reduced. It should also be noted that the sensitivity of this search to GWs scales with $T^{-1/2}$, as with a coherent search (and unlike other incoherent searches), however, the sensitivity also scales as $M^{-1/4}$ (M is the number of sidebands) and hence high frequency, large orbit sources will be harder to detect with this method.

Of the LMXBs it is those of unknown spin frequency to which this search is most suited. This includes the Z and atoll sources (rather than the accreting millisecond X-ray pulsars) which have known sky position, and for some, a reasonably well known orbital period. The remaining orbital parameters, semi-major axis, time of passage through the ascending node, eccentricity etc. are generally quite poorly known. This scenario suits this search, as the sensitivity is relatively insensitive to all orbital parameters except for the orbital period.

The search code and associated pipeline are complete and preliminary results have been obtained from a ten day stretch of S5 data. This data length has been chosen so that a monochromatic signal can be assumed for the duration observation time span. The expected sensitivity of this search will become astrophysically interesting (i.e., will start challenging accretion balance upper-limits) for advanced LIGO and specifically for the LMXB source Sco X-1.

A methods paper detailing the search is nearing the submission stage and will be circulated within the continuous waves group in mid-2013. The associated results paper is currently being drafted, while the review, which has progressed toward the final stages, is currently on hold due to a reduced FTE level.

5.4.2 Cross-correlation searches for known binary systems

UPDATED

The cross-correlation search described in section 5.2.3 can also be applied to a search for binary systems at known sky locations, such as Sco X-1. The parameter space is three-dimensional, consisting of the gravitational wave frequency and the two unknown binary orbital parameters (e.g., projected semimajor axis and binary orbital phase), so a semi-coherent cross-correlation search with a short coherence time should allow a search using a manageable number of templates. This search should allow the use of more data than in the fully-coherent short-time search done in [419], and a more sensitive search than the incoherent cross-correlation search done in [467]. A methods paper [492] is in preparation which describes the expected sensitivity and computational cost of this search, as well as some further enhancements to the cross-correlation method (e.g., a parameter space metric, and the effects of windowing and leakage [493]).

A reorganized version of the LAL/LALApps cross-correlation code is being written, as described in Sec 5.2.3. We will apply in a search for radiation from Sco X-1. This will initially be done as part of the Sco X-1 Mock Data Challenge, described in Sec 5.4.5, and subsequently performed on S6/VSR2 data, with an eye towards having the pipeline fully developed by the time advanced detectors come on line.

5.4.3 Polynomial search for unknown binary systems

UPDATED

As discussed above, searches for unknown binaries present formidable computing challenges. The orbital movement of the neutron star around the center of gravity of the binary system may induce large and rapidly changing frequency modulations of the gravitational wave. The frequency $f_{\rm ssb}$ detected in the solar system barycenter may be modeled as

$$f_{\rm ssb} = f_{\rm gw}\gamma\left(1 - \frac{\vec{v}\cdot\vec{n}}{c}\right) \tag{5}$$

with $f_{\rm gw}$ the frequency of the gravitational wave in the neutron-star rest frame, γ the Lorentz contraction factor, $\vec{v}$ the velocity of the neutron star with respect to the solar system barycenter, and $\vec{n}$ a unit vector in the direction of the source. Similarly, the change in frequency per unit time may be modeled by

$$\frac{df_{\rm ssb}}{dt} = f_{\rm gw}\gamma\left(1 - \frac{d\vec{v}}{dt}\cdot\frac{\vec{n}}{c}\right) + \frac{df_{\rm gw}}{dt}\gamma\left(1 - \frac{\vec{v}\cdot\vec{n}}{c}\right). \tag{6}$$

Assuming that the movement of the neutron star can be described adequately by Keplerian orbits, the phase of the gravitational wave depends on 6 extra parameters (e.g., the phase in the orbital, the orbital period, the mass of the accompanying star, the eccentricity, and the angles of the major and minor axes with respect to $\vec{n}$). For short orbital periods, the derivative of the detected frequency df/dt will be completely dominated by the Doppler shift. As an extreme example, for a neutron star orbiting an object with the same mass in a circular orbit with a period of 5000 s, $df_{\rm ssb}/dt$ may be as large as $0.002 \times f_{\rm gw}/s$.

In order to accommodate such large frequency shifts, a new search algorithm is being developed. An extension of the coherent search method with extra parameters to describe the orbital motion of the neutron star is not computationally feasible (for coherence times in the order of 1 h, the extra number of parameter values needed to cover all likely Keplerian orbits exceed a factor of 10^9). A hierarchical search method like the stack-slide or Hough transform methods as discussed in Ref. [428] is also not promising, since the short FFT database must have a time length below about 25 s in order to keep the strength of the gravitational wave in 1 bin. As an alternative, we propose to apply a set of filters that describe the phase of the gravitational wave as a third-order polynomial in time (and hence the frequency as a second-order polynomial in time). The presence of the gravitational wave may be detected by looking for the correlation of the data with these filters. The polynomial shape of the filters facilitates the analysis (a large reduction in filter parameters is obtained by relying on the fact that translating the polynomial filter in time or in frequency will give another polynomial filter in the same parameter set) and renders a complete scan over years of data computationally feasible. The filters should be coherent over the time that they are applied, implying that third-order derivatives of the frequency of the gravitational signal should be small. For binary systems with orbital periods of the order of 4000 s, the coherence time is limited to about 500 s for this reason. However, for such waves the frequency could spread over hundreds of frequency bins in a 500 s Fourier transform, hence the proposed set of filters should give a sizeable improvement over stack-slide or Hough-transform techniques that start from a short FFT base. Searches for binary systems with larger orbital periods may be applied with a larger coherence time.

If a correlation between a filter and the data exceed a threshold and constitutes a hit, then for the hit the frequency is known as a function of time. Therefore, hits between data stretches can be correlated easily. We are currently developing this analysis strategy and the algorithms. Analysis of the Virgo and LIGO data with this set of filters could set an upper limit on the existence of gravitational waves within a parameter range that is not currently covered by other analysis techniques, i.e., waves with frequency derivatives df/dt up to 2 mHz/s and d^2f/dt^2 up to 10^{-6} Hz/s^2.

For this search, the code has been implemented tested on simulated data with white noise. The results have been published in S. van der Putten's thesis [494]. The code can read processed detector output data as well as simulated data from both LIGO's (MakeFakeData) and Virgo's (SIESTA) software. Linear combinations of real and simulated data are also possible. This allows for testing under realistic noise conditions.

This year, a methods paper should be published and the software should be validated for analysis of Virgo and LIGO data. Polynomial Search also participates in the Sco X-1 pipeline comparison project discussed in section 5.4.5.

5.4.4 TwoSpect search for unknown binary systems

UPDATED

The TwoSpect search is a hierarchical method for detecting unknown continuous wave sources from binary systems. The goal of the TwoSpect search is to probe regions of the large parameter space of pulsars in binary systems without exhausting the existing computational resources available. It seems unlikely that the search will have the sensitivity to make a detection in S5 or S6/VSR2-3 data, but since accreting neutron stars in binary systems are the best candidates to have large ellipticities, carrying out a search is prudent.

The TwoSpect method relies on computing two successive power spectra of the calibrated strain data channel, hence the name TwoSpect. First, we take a power spectrum of the time series data, where the coherence time for the first power spectrum depends on the region of parameter space we wish to cover. For shorter-period binary systems, we use a shorter coherence time for each SFT. We make these choices to ensure the signal remains in one bin during most of each SFT interval. We then demodulate the SFTs based on the sky location, correcting for the Earth's daily and annual motions. The SFTs are noise- and antenna-pattern-weighted in the same manner as for the PowerFlux algorithm. The initial power spectra are mean-subtracted within search bands to ensure that the powers computed in the second-stage spectra are distributed as a χ^2 distribution with two degrees of freedom. The second spectra are taken over a long observation time, e.g., 1 year, for each bin in the first set of spectra. The resulting frequency- by-frequency plot is matched against templates which are either rough approximations of a CW signal from a binary system (less computations required) or a more detailed approximation (more computations required). This two-stage pipeline acts as a filter to find the best candidates for a deeper search. We also use a spectrum folding algorithm known as Incoherent Harmonic Summing (IHS) developed by the radio pulsar community. This algorithm can provide a threshold filter for deciding whether or not to carry out a template calculation for a putative set of source parameters.

The first production run on S6 and VSR2/3 data began in early spring 2012 and has been running on the LIGO computing clusters. Thus far, the search has achieved an unparalleled sensitivity to unknown spinning neutron stars in binary systems. Simultaneously, a detailed review of the computer code and associated scripts began in summer 2012. The review is ongoing, and the search will continue to higher frequencies during the course of the review process. The methods described in [483] are employed in the analysis.

In parallel, a study will be carried out in the coming year of optimizing the TwoSpect method for directed searches for known LMXBs and unknown binaries in globular clusters, for which elimination of the IHS step should be feasible and should improve sensitivity. One aspect of this study is a comparison in sensitivity and parameter estimation with other search methods in Scorpius X-1 style searches. We anticipate an article describing the results in late 2013 (see section 5.4.5).

5.4.5 Sco X-1 pipeline comparison

UPDATED

The low-mass X-ray binary Scorpius X-1 is potentially our most luminous source of continuous gravitational wave radiation. Within the continuous wave and stochastic groups there exist a number of search pipelines that are sensitive to this source. We have begun the process of comparing the characteristics and sensitivities of these pipelines with regards to Sco X-1 through the use of a mock-data-challenge. Those participating in the comparison project have been meeting regularly since the end of 2012 and the final version of the challenge data itself will be complete by mid-2013 with a tentative aim to compile and compare results ready for the September 2013 LVC meeting. A short author-list paper documenting the project and its findings will follow soon after.

5.5 Search for Non-Sinusoidal Periodic Waves

UPDATED

Our searches for continuous waves focus mainly on waveforms that are nearly sinusoidal, with smooth modulations in frequency and amplitude. But in the spirit of keeping eyes wide open, it is reasonable to look for other periodic gravitational waveforms, such as periodic pulses similar to the radio pulses that led to the original electromagnetic discovery of pulsars. In the Fourier domain these non-sinusoidal waveforms could contain many frequency harmonics, no one of which has sufficient power to be detectable in a conventional CW search.

A number of algorithms can be applied to detect such waveforms, including incoherent harmonic summing [484] and the Gregory-Loredo method [485]. We have begun to explore the use of the Gregory-Loredo method, which has been used previously in radio, X-ray and gamma ray astronomy to search for non-harmonic periodicity in time-series. It is designed to be efficient in detecting pulsating signals in sparse sampled data. We have studied the tradeoffs in detection efficiency vs. computational cost for non-sinusoidal pulses when applied to the high-duty-factor LIGO and Virgo data. We have applied a Fast Folding Algorithm to increase dramatically the speed of the Gregory-Loredo algorithm and in its current implementation the GL method has a computational complexity comparable with the traditional Fourier methods. The main elements of the pipeline have been tested separately and in an integrated algorithm (even if not completely optimized yet).

Because the method remains computationally intensive, it will likely be applied only in directed searches at interesting points on the sky, such as the galactic center and globular cluster cores, where high stellar density might lead to periodic transients. Realistic searches under these constraints are underway and they will be perfected in the next future. We are also testing the added computational cost and particularly the best approaches to this detection method to account for modulations due to the EarthâĂŹs motion (Doppler effect, antenna pattern). A reliable method to calculate upper limits for specific classes of non-sinusoidal pulsating signals has been developed and it will be tested for injected signals in real noise over integration periods up to one month.

It should be noted that the Gregory-Loredo method may also prove useful in detector characterization to identify periodic instrumental glitches or periodic non-stationarities. A DMT implementation of the search code could be applied straightforwardly for such glitch searching in online, real-time detector monitoring.

5.6 Sidereal periodicity studies

UPDATED

We found a sidereal periodicity in the VSR2 h-reconstructed power. Applying the same method of analysis to the LIGO antennas (with the S6 data) we also found the sidereal peak, but in this case it is accompanied with an anti-sidereal one.

Recently we have found that an artifact due to an annual periodicity can explain the sidereal and anti-sidereal doublet found in the two LIGO antennas. Anyway this artifact cannot explain the Virgo sidereal effect. A procedure to avoid the artifact has been developed, but it is not completely satisfactory. For more information see [490]. This activity is frozen until new (Virgo) data, at least 6 months long, will be available.

5.7 Support infrastructure

UPDATED

There is important infrastructure needed to support the various CW searches. New software injections will be an important element in evaluating the performance of search pipelines. Systematic detection and identification of instrumental or environmental spectral lines, particularly wandering lines, has been and will continue to be necessary to eliminate outliers in many searches. Other spectral artifacts with apparent sidereal behavior can also lead to outliers. In this section we describe ongoing and planned work to address these support needs.

5.7.1 Software injections

UPDATED

An important new element in evaluating search pipeline performance is the creation of simulated data with several thousand software injections for pulsars at randomly chosen sky locations and with frequencies and frequency derivatives spanning our search ranges. These standardized data sets should enable us to compare with more statistical precision and more systematically the sensitivity and robustness of the various pipelines in detecting pulsars in blind searches or in reconstructing source parameters in targeted searches. The outcomes of these comparisons might well lead to the abandonment (or at least de-prioritization) of some search pipelines.

We created 3 000 parameter files for artificial pulsars and generated signals from these over the period of S6. The signals have been added to a replica of the S6 frames and distributed to the LSC clusters. These reference software injections are being used to compare and contrast the performance of search pipelines in an ongoing, four-stage mock data challenge. Results from stage 1 of the MDC ($\sim$20 injections) were reported by a subset of targeted, directed and all-sky isolated-star pipelines in December 2012 and January 2013. A larger subset of pipelines plan to participate in stage 2 ($\sim$200 injections) to conclude in July 2013. Stage 3 will conclude in December 2013 ($\sim$1500 injections), and stage 4 will conclude in June 2014 ($\sim$1500 *blind* injections).

In preparation for the advanced detector era engineering runs are being performed to simulate detector data. In the first three engineering runs, ER1-3, two simulated pulsars were created and injected into the dataset. These have been successfully extracted using the known pulsar search method. Similar injections will also be performed in the successive engineering runs.

5.7.2 CW detector characterization

UPDATED

The CW Group has a strong interest in monitoring (and mitigating) instrumental spectral lines (see the detector characterization chapter) with low latency. In preparation for S6 the nascent “F-Scan” infrastructure developed during S5 for generating high-resolution spectrograms to detect wandering lines visually was automated and expanded to auxiliary channels and to Virgo channels. These spectrograms and data files proved invaluable in quickly spotting and tracking down instrumental lines in S6 data. The F-Scan output has also been mined for spectral coincidences between interferometers and between strain and auxiliary channels. Further improvements included dedicated F-scans for bands relevant to special pulsars, such as the Crab and Vela. An F-Scan version with further enhancements has been run on H1 and L1 PSL data, on H2 One Arm Test data in summer 2012, and is being run in 2013 on half-interferometer data at Hanford and Livingston.

In addition, the offline auxiliary-channel coherence studies used in following up on S4 and S5 pulsar candidate outliers have continued for S6/VSR2 analyses. Special attention has been given to narrow spectral bands around a half dozen known pulsars for which the spin-down limit may be accessible in S6/VSR2/VSR4 and to bands containing outliers coincident between H1 and L1. A new technique using spectral correlations is also under development.

On the Virgo side, a new infrastructure called NoEMi has been developed for identifying/mining stationary or slowly wandering spectral lines. It was run offline on VSR2 data, and in real-time on VSR3 and VSR4 data. During science runs NoEMi publishes daily summary pages, with plots and lists of the found noise lines, on the Virgo monitoring web pages. In particular, for the objectives of the CW targeted search, noise lines found at the same frequencies of the known pulsars are highlighted in the summary pages. More details on NoEMi can be found in [489].

Lines found by NoEMi are stored in a database which is made accessible via a web interface. The database allows to add user-defined information (metadata) to each identified line.

NoEMi will be used as the main noise line monitoring tool for the Advanced Virgo, LIGO and GEO detectors. NoEMi will run on the "local" computing centers (thus distributing the computing load and storage requirements) and send the formatted data to a centralised (cluster of) databases. As a preliminary test-bench of the upgraded framework, NoEMi was installed and run at Caltech on the full S6 LIGO data and then commissioned at Hanford to run daily on the H2 One Arm Test data in summer 2012. This infrastructure too is being run on the half-interferometer data at Hanford and Livingston in 2013.

Because of sidereal modulation of CW source amplitudes (as seen by the interferometers), it is good to be aware of instrumental or environmental effects that could lead to apparent sidereal artifacts. Ongoing investigations have indeed revealed apparent artifacts in both strain and auxiliary environmental channel. Further analysis will be carried out of the full S6/S6/VSR2/VSR4 data sets to quantify the effects of these artifacts on CW searches.

In addition, the Gregory Loredo method will be used in the coming year to investigate instrumental artifacts that lead to periodic transients, and spectral correlation methods (different from spectral coherence) will be used for studying environmental contamination of the strain channels.

6 Searches for stochastic backgrounds

6.1 Sources of Stochastic Gravitational-wave Background

The stochastic gravitational-wave background (SGWB) is formed from the superposition of many events or processes, which are too weak and/or too numerous to resolve individually, but which combine to produce a signal characterized by its ensemble properties. The prime objective of the Stochastic Group is to measure the SGWB.

The SGWB can arise from both cosmological and astrophysical sources. According to various cosmological scenarios, we are bathed in an SGWB glow generated in the first moments after the Big Bang. This SGWB can arise due the amplification of vacuum fluctuations following inflation, as well as from GW radiation produced in the final stages of inflation (for example in preheating models or models of axion inflation). Detection of this background would have a profound impact on our understanding of the evolution of the Universe, as it represents a unique window on the very early Universe and on the physical laws that apply at the highest energy scales, potentially up to the Grand Unified Theory scale 10^{16} GeV. Other models of cosmological GW background include phase transitions, cosmic (super)string models, and pre Big Bang models.

Astrophysical SGWBs, meanwhile, may have result from the superposition of a large number of unresolved sources since the beginning of stellar activity. Among the most promising models are mergers of compact binary neutron stars and/or black holes, instabilities in rotating neutron stars such as r-modes, bar-modes, or quasinormal modes, magnetars, and core collapse supernovae to neutron stars or black holes including hypothetical population-III stars. Detection of an astrophysical GW background would not only provide information about the physical properties of the respective astrophysical objects (such as compact binaries of neutron stars), complementing individual GW detections and electromagnetic observations of these objects such as gamma ray bursts, but it would also elucidate the evolution of these objects with redshift and trace the star formation history or the metallicity. Recent studies suggest that the astrophysical SGWB from compact binary coalescences may be detectable with Advanced LIGO-Virgo [502]. Characterizing the SGWB from compact binary coalescences is a major focus of the group as we prepare for the advanced detector era.

Using cross-correlation tools developed to search for the stochastic background, the group has expanded its scope. For example, we have utilized the stochastic radiometer (see below) to produce the current best upper limits on strain from Sco X-1, a nearby low-mass X-ray binary [500]. We are also investigating long-lived gravitational-wave transients with the Stochastic Transient Analysis Multi-detector Pipeline (STAMP). The unifying feature of current Stochastic Group analyses is that we use cross-correlation algorithms to study signals, which are long-lived and difficult or impossible to model in the time domain.

6.2 Stochastic Methodology

The stochastic search method has evolved from a search for an isotropic SGWB (see section 6.2.1). S5 LHO-LLO-VSR1 isotropic and directional analyses have been published, while S5 long transient analyses remain in progress. S6-VSR23 analyses are in progress and the S5 H1H2 analysis is in review. We are continuing to develop and extend the stochastic formalism, for example, to estimate the parameters of models of the SGWB.

6.2.1 Isotropic Search

A stochastic background of gravitational waves (GWs) is expected to arise as a superposition of a large number of unresolved sources, from different directions in the sky, and with different polarizations. It is usually described in terms of the logarithmic spectrum:

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\,\frac{d\rho_{\rm GW}}{d\ln f}\,, \tag{7}$$

where $\rho_{\rm GW}$ is the energy density of gravitational waves, ρ_c is the critical density of the Universe, and f is the frequency. The effect of a SGWB is to generate correlations in the outputs s_A, s_B of a pair of GW detectors, which can be described for an isotropic background in the Fourier domain by

$$\langle \widetilde{s}^{\,*}_A(f)\,\widetilde{s}_B(f')\rangle = \frac{1}{2}\delta(f-f')\,\gamma_{AB}(f)\,S_{\rm gw}(f) \tag{8}$$

where $\tilde{s}_A$ and $\tilde{s}_B$ are the Fourier transforms of the strain time-series of two interferometers ($A \neq B$).

The raw correlation depends on the (one-sided) power spectral density $S_{\rm gw}(f)$ the SGWB would generate in an interferometer (IFO) with perpendicular arms, as well as the observing geometry. The geometrical dependence manifests itself via the overlap reduction function [506, 507], which can be written as

$$\gamma_{AB}(f) = d_A^{ab}\,d_B^{cd}\,\frac{5}{4\pi}\iint d^2\Omega_{\hat{n}}\,P^{\rm TT}_{abcd}(\hat{n})\,e^{i2\pi f\hat{n}\cdot(\vec{r}_2-\vec{r}_1)/c} \tag{9}$$

where each IFO's geometry is described by a response tensor constructed from unit vectors $\hat{x}$ and $\hat{y}$ down the two arms

$$d^{ab} = \frac{1}{2}(\hat{x}^a\hat{x}^b - \hat{y}^a\hat{y}^b)\,, \tag{10}$$

$\vec{r}_{1,2}$ is the respective interferometer's location and $P^{\rm TT}_{abcd}(\hat{n})$ is a projector onto traceless symmetric tensors transverse to the unit vector $\hat{n}$ (see [508], p. 10).

We employ a cross-correlation method to search for the stochastic GW background, following [509]. In particular, we define the following cross-correlation estimator:

$$Y_{AB} = \int_{-\infty}^{+\infty} df \int_{-\infty}^{+\infty} df'\;\delta_T(f-f')\;\tilde{s}_A(f)^*\;\tilde{s}_B(f')\;\tilde{Q}_{AB}(f')\,, \tag{11}$$

where δ_T is a finite-time approximation to the Dirac delta function, and $\tilde{Q}_{AB}$ is a filter function. Assuming that the detector noise is Gaussian, stationary, uncorrelated between the two interferometers, and uncorrelated with and much larger than the GW signal, the variance of the estimator Y_{AB} is given by:

$$\sigma^2_{Y_{AB}} = \frac{T}{2}\int_0^{+\infty} df\;P_A(f)P_B(f)\mid\tilde{Q}(f)\mid^2\,, \tag{12}$$

where $P_i(f)$ are the one-sided power spectral densities (PSDs) of s_A and s_B, and T is the measurement time. Optimization of the signal-to-noise ratio leads to the following form of the optimal filter [509]:

$$\tilde{Q}_{AB}(f) = N_{AB}\,\frac{\gamma_{AB}(f)S_{GW}(f)}{P_A(f)P_B(f)}\;,\;\text{where } S_{GW}(f) = \frac{3H_0^2}{10\pi^2}\,\frac{\Omega_{GW}(f)}{f^3}\;. \tag{13}$$

$S_{GW}(f)$ is the strain power spectrum of the stochastic GW background to be searched. Assuming a power-law template spectrum with index α, $\Omega_{GW}(f) = \Omega_\alpha(f/f_{\rm ref})^\alpha$, the normalization constant N_{AB} is chosen such that $\langle Y_{AB}\rangle = \Omega_\alpha T$. Here $f_{\rm ref}$ is a reference frequency. The signal-to-noise ratio for a pair of interferometers for an ideal measurement of length T in stationary noise can be written as

$$\text{SNR} = \frac{3H_0^2}{10\pi^2}\left(2T\int_0^\infty df\gamma^2_{AB}(f)\frac{\Omega^2_{GW}}{f^6P_A(f)P_B(f)}\right)^{1/2} \tag{14}$$

where H_0 is the present value of the Hubble expansion rate. The largest contribution to this integral comes from the frequency region where $P_{A,B}$ is minimum, which is between 50Hz and 150Hz for initial LIGO.

In order to handle gaps in the data, data non-stationarity, and for purposes of computational feasibility, the data for an interferometer pair are divided into many intervals of equal duration (typically 1-3 minutes), and Y_I and σ_{Y_I} are calculated for each interval I. The loss in duty-cycle due to the finite interval size is of order 1 minute for each analyzable data segment (which is typically several hours). The data in each interval are decimated from 16384 Hz to 4096 Hz and high-passed filtered with a 40 Hz cut-off. They are also Hann-windowed to avoid spectral leakage from strong lines present in the data. Since Hann-windowing effectively reduces the interval length by 50%, the data intervals are overlapped by 50% to recover the original signal-to-noise ratio. The effects of windowing are taken into account as discussed in [511].

The PSDs for each interval (needed for the calculation of $Q_I(f)$ and of σ_{Y_I}) are calculated using the two neighboring intervals. This approach avoids a bias that would otherwise exist due to a non-zero covariance between the cross-power and the power spectra estimated from the same data. Furthermore, by comparing σ_I calculated using the neighboring intervals with σ'_I calculated using the interval I, we identify intervals containing large noise transients and reject them from the analysis. In addition to this stationarity cut, we impose some data-quality flags (such as 30-sec before lock-loss), a large-σ cut (rejecting particularly noisy time-periods), and we ignore frequency bins which are determined to contain instrumental correlations. The intervals that pass all the data-quality cuts are averaged with $1/\sigma_I^2$ as weights, yielding the final estimates of Y and σ_Y.

6.2.2 Directional Search

The analysis described above is designed to search for an isotropic SGWB. It is also possible to search for anisotropies in the GW background. One way to approach the problem is to define a sky-position dependent optimal filter. As discussed in [512], one can write:

$$Q(t,f,\hat{\Omega}) = N(t,\hat{\Omega}) \frac{\int d\hat{\Omega}' \, \gamma(t,f,\hat{\Omega}') \, A(\hat{\Omega},\hat{\Omega}') \, H(f)}{P_1(f) \, P_2(f)}, \tag{15}$$

where $A(\hat{\Omega},\hat{\Omega}')$ reflects the anisotropy in the GW spectrum across the sky. For point sources, one chooses $A(\hat{\Omega},\hat{\Omega}') = \delta^2(\hat{\Omega},\hat{\Omega}')$. Note, also, that the overlap reduction function γ is now dependent on the sky-position, as well as on the sidereal time t. Following the procedure analogous to the one outlined in the previous Section leads to an estimate of Y and σ_Y for every direction on the sky—i.e. a map of the GW background. However, this map is blurred by the antenna patterns of the interferometers. The problem of deconvolving the antenna pattern from this map is described in [500, 516]; (see more below).

Work is in progress to improve the sensitivity of directed searches. In particular, the group is working to improve the radiometer analysis of Sco X-1 (more below) by using information about the binary motion of Sco X-1 in order to search optimally sized overlapping frequency bins. The upgraded analysis will be benchmarked and compared with CW pipelines as part of a mock data challenge undertaken jointly with the CW group.

A second directional project aims to combine the narrowband radiometer with the all-sky search in order to facilitate an all-sky search for narrowband GW signals. Previously, we have carried out either broadband all-sky searches or narrowband targeted searches [499, 500] since it is computationally challenging to search over both sky location and frequency bins. This project is in the planning stages.

6.2.3 Mapping

The methods described in 6.2.1 and 6.2.2 are optimal under the assumption that the background is either isotropic or dominated by point sources, but neither addresses the question of estimating the actual spatial distribution of a stochastic background. A method that does this is described in this section.

The spatial distribution $\mathcal{P}(\hat{\Omega})$ of the strain power of stochastic background can be expanded with respect to any set of basis vectors on the sphere:

$$\mathcal{P}(\hat{\Omega}) = \mathcal{P}_\alpha \mathbf{e}_\alpha(\hat{\Omega})\,, \tag{16}$$

Defining $C(f,t)$ as the cross-power between the output of the two detectors,

$$C(f,t) = \frac{2}{\tau}\,\tilde{s}_1^*(f,t)\tilde{s}_2(f,t)\,, \tag{17}$$

one can show that its expectation value is given by

$$\langle C(f,t)\rangle = H(f)\gamma_\alpha(f,t)\mathcal{P}_\alpha\,, \tag{18}$$

with $H(f)$ the strain power spectrum of the stochastic background. The $\gamma_\alpha(f,t)$ are basis dependent geometric factors that can be pre-calculated and play the role of the overlap reduction function in the isotropic analysis. The covariance matrix of $C(f,t)$ is given by

$$\begin{aligned} N_{ft,t't'} &= \langle C_{ft} C^*_{f't'}\rangle - \langle C_{ft}\rangle\langle C^*_{f't'}\rangle \qquad (19)\\ &\approx \delta_{tt'}\delta(f-f')P_1(f,t)P_2(f,t), \qquad (20)\end{aligned}$$

with P_1 and P_2 the strain noise power spectra of the two detectors.

Assuming Gaussian noise, the likelihood for measuring a specific cross-power $C(f,t)$ is

$$\begin{aligned} p(C_{ft}|\mathcal{P}_\alpha) &\propto \exp\Bigg[-\frac{1}{2}((C^*_{ft} - \langle C^*_{ft}\rangle)N^{-1}_{ft,f't'} \\ &\qquad\qquad (C_{f't'} - \langle C_{f't'}\rangle)\Bigg] \qquad (21)\end{aligned}$$

where $\langle C_{ft}\rangle$ is given by 18 and repeated ft and $f't'$ indices are summed and integrated over—e.g., $\sum_t \int_{-\infty}^{\infty} df$..

Now one can ask for the $\mathcal{P}_\alpha$ that maximize this likelihood. They are given by

$$\hat{\mathcal{P}}_\alpha = (\Gamma^{-1})_{\alpha\beta}\, X_\beta \tag{22}$$

where

$$X_\beta = \sum_t \tau \int_{-\infty}^{\infty} df\, \gamma^*_\beta(f,t)\,\frac{H(f)}{P_1(f,t)P_2(f,t)}\,C(f,t)\,, \tag{23}$$

$$\Gamma_{\alpha\beta} = \sum_t \tau \int_{-\infty}^{\infty} df\, \gamma^*_\alpha(f,t)\,\frac{H^2(f)}{P_1(f,t)P_2(f,t)}\,\gamma_\beta(f,t)\,. \tag{24}$$

The matrix inversion in Eq.22 in practice requires a regularization scheme because the interferometer pair can be insensitive to particular background distributions. Note that if one restricts the basis set to either just an isotropic component or just a point source at a given location, one will get exactly the analysis described in 6.2.1 and 6.2.2 respectively.

While this algorithm in principle would work in any basis, a basis with a natural resolution cut-off will reduce the required number basis vectors and thus simplifies the required matrix inversion. One obvious such basis is formed by spherical harmonics, which is what we currently use to construct gravitational-wave sky maps.

6.2.4 Multi-baseline: LIGO/VIRGO joint search

As shown in [509, 507], the optimal method for combining more than two detectors is to make pairwise correlation measurements, and then combine these results in the same way measurements from different times are combined: average the point estimates Y with a relative weighting of σ^{-2}, or equivalently in the mapping formalism, sum up the X_β and the Fisher matrices $\Gamma_{\alpha\beta}$. As discussed in [510] the inclusion of the LIGO-Virgo pairs can enhance the sensitivity of the global GW detector network to an isotropic background of gravitational waves, particularly at frequencies above 200 Hz. The improvement in the low frequency range is small owing to the overlap reduction factor in Eq. (14). Furthermore, the addition of a third instrument with comparable live time and sensitivity improves both the resolution and sensitivity of the mapping algorithm, effectively simplifying the regularization problem mentioned in Section 6.2.3.

6.2.5 Mitigation of correlated noise

The isotropic search outlined above is usually applied to the non-collocated interferometers (such as the two 4-km interferometers at Hanford and Livingston), in order to minimize the instrumental correlations. However, the overlap reduction for this interferometer pair is significant above 50 Hz. Hence, the collocated pair of Hanford interferometers could potentially lead to a result $\sim 10\times$ more sensitive than the S5 isotropic stochastic result. (The advantage of co-located interferometers is expected to be less during the advanced detector era, since the overlap reduction function is relatively large at the low frequencies where the aLIGO interferometers are expected to be most sensitive.) However, co-located interferometers are also more susceptible to instrumental correlations. The Stochastic Group has developed two methods to handle this problem.

One approach relies on the coherence, defined as

$$\Gamma_{XY}(f) = \frac{|P_{XY}(f)|^2}{P_{XX}(f)P_{YY}(f)} \tag{25}$$

where P_{XY} is the cross-power spectrum between channels X and Y, and P_{XX} and P_{YY} are the two power spectra. As discussed in [514], it is possible to estimate the instrumental correlations between interferometers 1 and 2 by

$$\Gamma_{instr,12} \approx \ \mathrm{max}_i(\Gamma_{1Z_i} \times \Gamma_{2Z_i}) \tag{26}$$

where Z_i are the numerous environmental channels, including microphones, seismometers, accelerometers, power-line monitors etc. As discussed in [514], this method can be used to identify frequency bands in which the instrumental correlations between two interferometers are large. These bands could then be removed from the isotropic stochastic search. Moreover, the method can be used to estimate the residual contamination in the ”good” frequency bands.

The second approach relies on time-shifting one GW channel with respect to the other. Since the stochastic GW background is expected to be broadband, its coherence time is much shorter than ~1s, so the GW correlations between the two channels are expected to disappear at 1s time-shift. However, narrow-band features (of width $\sim$ 1 Hz) are expected to survive 1s time-shift. Hence, this method can also be used to identify narrow-banded instrumental correlations. The two methods agree well.

6.2.6 Searching for Long-Lasting Transients

The Stochastic Group has developed a pipeline called STAMP (Stochastic Transient Analysis Multi-detector Pipeline) for the study of long gravitational-wave transients lasting from $\sim 10\,\mathrm{s}$ to weeks. STAMP utilizes frequency-time (ft)-maps (spectrograms) of cross-power created from two or more spatially separated detectors (e.g., H1 and L1). It extends the principle behind the narrowband radiometer [499, 512, 513] in order to identify signals with finite durations and more complicated spectral content.

STAMP can call on a variety of pattern recognition algorithms in order to identify structure in ft-maps. Current analyses utilize a track search algorithm called *burstegard* favored for its speed and effectiveness, though, additional clustering algorithms may be used as well. STAMP searches can be externally triggered (e.g., using long GRB triggers) or all-sky (no external triggers).

Work is in progress to develop improved clustering algorithms for STAMP. Preliminary investigations of "seedless" clustering algorithms suggests that it may be possible to significantly improve STAMP's sensitivity to long GW signals. The group is working to investigate the feasibility of such improvements.

STAMP is also used for detector characterization purposes. Instead of cross-correlating two gravitational-wave channels, we cross-correlate one gravitational-wave channel with a physical environmental monitoring channel to look for noise that is coherent in the gravitational-wave channel. This "STAMP-PEM" technique has been used to investigate airplane/helicopter noise, chiller-pump "Crab" noise, and noise from lightning and thunder [517]. Work is ongoing to apply STAMP-PEM to aLIGO commissioning data in order to find correlations between PEM sensors and sensing channels (eventually DARM).

6.2.7 Stochastic Intermediate Data and Stochastic Folded Data

Since several searches rely on similar quantities (such as strain cross and power spectral densities of different interferometers), the group has produced Stochastic Intermediate Data (SID), stored in the frame format, and containing the commonly used quantities calculated for segments throughout the S5 run. More recently, the intermediate data has been stored in Matlab .mat files in order to speed up input/output time for STAMP searches. In addition to simplifying the standard stochastic searches, the SID frames also find use in detector characterization studies and in searches for GW transients on minute or hour time-scales. In particular, the SID frames combined with the new algorithms searching for long-lasting transients have led to a new S6 data quality flag identifying transients due to passing airplanes.

The filter functions used in any long-duration stochastic search have a symmetry—they have a period of one sidereal day. One can use this symmetry to "fold" cross-spectral data from each day on top of each frequency bin of each sidereal time segment. That way effectively one has to analyze one sidereal day long data, as compared to few hundreds to a thousand days of data over a science run, thus saving huge amount of computation time. In addition, the folded data is highly portable—the whole dataset can be loaded in a desktop computer's memory and can be stored in a DVD. A MATLAB based pipeline was developed to fold "Stochastic Intermediate Data (SID)" to one sidereal day, which was applied to fold the whole S5 data. All the existing and new long duration analyses can now be performed on the folded data. However, rigorous validation of the results has to be done before making the data available for different analyses, which the group proposes to do in the coming months.

6.2.8 Non-Gaussian Pipelines

Astrophysical sources of the SGWB tend to be non-Gaussian whereas cosmological sources tend to be Gaussian. Measuring the non-Gaussianity of the SGWB may therefore provide a tool for disentangling astrophysical and cosmological sources. It may also be possible to improve our search sensitivity by including information about the Gaussianity of the signal. The group is exploring the possibility of one or more non-Gaussian pipelines. A framework for measuring the Gaussianity of the SGWB using realistic (non-colocated) detectors has been proposed [524]. An independent approach, relying on the fourth-order Edgeworth expansion is under investigation. Future work will investigate the application of this technique (and possibly others) to the measurement of astrophysical SGWBs. This project will build on the mock data project described below.

6.3 Status of S5/S6 Searches

An upper limit on the stochastic gravitational-wave background of cosmological origin (published): The Stochastic Group finished the isotropic search with LHO-LLO interferometer pairs using the S5 data. The final results is a new 95% upper limit on the gravitational-wave energy density $\Omega_0 < 6.9 \times 10^{-6}$ for a frequency independent spectrum ($\alpha = 0$) in the band 41-169 Hz. This result is 10 times more sensitive than the previous upper limit based on S4 data [497], and it is more sensitive than the Big-Bang Nucleosynthesis bound and the Cosmic Microwave Background bound in the LIGO frequency band. The result was published in Nature [515], including the implications of the new result for the models of early-universe cosmology, for cosmic (super)string models and for pre-big-bang models.

Directional limits on persistent gravitational waves using LIGO S5 science data (published): The Stochastic Group has analyzed the S5 data set with both the radiometer and the Spherical Harmonics decomposition analysis described in sections 6.2.2 and 6.2.3. The results were published in Physical Review Letters [500]. The radiometer analysis produced maps of the GW sky 30 times (in strain power) more sensitive than those produced using the S4 data [499], as well as targeted narrow-band limits on GW radiation coming from Sco X-1 and the Galactic Center. It also confirmed the previously published isotropic result. The second directional analysis produced the first spherical-harmonic decomposition map of the gravitational-wave sky, similarly to what is done in the field of Cosmic Microwave Background. This method targeted complex source distributions on the sky, and has been summarized in a method paper published in Physical Review D [516]. The S6-VSR23 update may be part of a single paper with the isotropic result depending on whether there is sufficient new material to warrant separate papers.

Upper limits on a stochastic gravitational-wave background using LIGO and Virgo interferometers at $600 - 1000\,\mathrm{Hz}$ *(published):* The Stochastic Group also conducted a joint LIGO-VIRGO stochastic search, using the shared S5+VSR1 data (data acquired between May 18, 2007 and October 1, 2007). Although the LIGO-VIRGO interferometer pairs are less sensitive than the LIGO 4-km interferometer pair to the isotropic stochastic background at frequencies below 800 Hz, above 800 Hz the LIGO-VIRGO pairs are similar or even more sensitive than the LIGO-LIGO pairs. Moreover, the LIGO-VIRGO pairs have different zeroes in the overlap reduction function, which can improve the overall network sensitivity even at lower frequencies. This paper was published in Physical Review D [501].

Improved Upper Limits on the Stochastic Gravitational-Wave Background (in progress): The strain sensitivity of the LIGO 4-km interferometers (H1 and L1) is improved compared to S5, though, the coincidence time is limited by the relatively low duty cycle, especially early in the run. Virgo sensitivity, meanwhile, did not match the VSR1 levels around 100 Hz. Preliminary results suggest that the low-frequency $40 - 170\,\mathrm{Hz}$, $\Omega(f) \propto f^0$ limits are only marginally improved compared to the previous results from S5. However, we expect to achieve a factor of $\approx 3.5\times$ improvement for our high-frequency $600 - 1000\,\mathrm{Hz}$, $\Omega \propto f^3$ limits compared to the previous best.

Searching for stochastic gravitational waves using data from the two co-located LIGO Hanford interferometers (in review): The isotropic searches performed up to date have used non-collocated interferometer pairs because of the reduced chances of environmental correlations. The LHO interferometer pair, however, could potentially be $\sim 10\times$ more sensitive to stochastic GW background due to the more favorable overlap reduction function. However, the collocated interferometer pair also suffers from instrumental correlations, because the two interferometers share the same environment and the same sources of instrumental noise. The Stochastic Group developed two methods to estimate and suppress the instrumental correlations, as discussed above in more detail. The group has applied these methods to the S5 data, and the results indicate that the PEM-coherence and the time-shift approaches identify well the grossly contaminated frequency bands, which are then removed from the analysis. Moreover, the PEM-coherence approach can be used to estimate the residual contamination in the ”good” frequency bands. The co-located interferometer (H1H2) analysis was performed in two frequency bands: low-frequency (80-160 Hz) and high-frequency

(460-1000 Hz). The low-frequency band was found to contain residual correlated noise at a level that rendered the resulting upper limit noncompetitive. In the high-frequency band, however, we obtain an upper limit of $\Omega(f) < 9 \times 10^{-4} (f/900\,\mathrm{Hz})^3$, which represents a factor of $> 350\times$ improvement over the previous best limit. In addition to this important result, we expect the paper to serve as a useful reference for future analyses dealing with correlated noise.

A search for unmodeled long-lived gravitational wave transients from stellar collapse (in review). This first STAMP search uses S5 data to search for long-lived $\sim 10 - 1000\,\mathrm{s}$ GWs coincident with 50 long GRBs identified by the *Swift* satellite. The analysis explores models in which long-lived GW transients are produced following stellar collapse, for example, by the formation of accretion disk clumps. Since no GW candidates are observed, limits are placed on GW fluence and the distance to each GRB. The best 90% CL distance limits are $D > 33\,\mathrm{Mpc}$ assuming an energy budget of $E_{\mathrm{GW}} = 0.1 M_\odot$. For additional information, see the GRB section of the white paper.

An all-sky (untriggered) search for long-lived gravitational waves (in preparation). The STAMP All-Sky (STAMP-AS) analysis is an untriggered search looking for long duration $\sim 10 - 200\,\mathrm{s}$ burst-like signals. Possible astrophysical sources for such signals are accretion disk instabilities, instabilities in nascent neutron stars, eccentric black hole binary systems, and neutron stars quasi-periodic oscillations. To carry out this search, several enhancements have been made with respect to the original STAMP code such as a faster clustering algorithm allowing the code to look for a signal everywhere in the sky even without investigating every sky direction, and a more efficient way to cross-correlate data. A dedicated STAMP-AS pipeline is available. The goal is to analyze S5-S6 + VSR123 data set. We plan to estimate background using 100 time slides. Current work is focused on estimating the sensitivity of the STAMP-AS pipeline to the previously mentioned astrophysical sources.

Stochastic backgrounds with non standard polarizations with VIRGO and LIGO. General relativity predicts gravitational waves with two independent transverse polarizations. The purpose of this project is to search for a stochastic backgrounds associated with non standard polarizations. These are predicted generically by extended theories of gravitation. For an isotropic search, a minimal modification of the standard pipeline is required, namely the correct overlap reduction functions must be introduced. Preliminary investigations are underway to assess the possibility of an analysis with S5/VSR1 and S6/VSR2 data.

Several other projects are in an exploratory phase, including an improved analysis of Sco X-1 using S6+VSR23 data, a search for r-modes and other signals associated with isolated neutron stars, and a search for long-lived GWs coincident with high-energy neutrinos .

6.4 Stochastic Group's Plans for Advanced Detector Era

Advanced detectors are expected to have about $10\times$ better strain sensitivity than the initial interferometric detectors, as well as to extend the sensitive band from 40 Hz down to 10 Hz. Furthermore, the number of detectors operating in a worldwide network is expected to increase, eventually including sites LIGO-Hanford, LIGO-Livingston, Virgo, GEO-HF (at high frequencies), KAGRA (Japan), and potentially LIGO India. These significant strain sensitivity improvements and the increase in the number of available detector pairs that could be cross-correlated will enable real breakthroughs in Stochastic Group searches. In particular, advanced detectors may be able to detect the SGWB from compact binary coalescences [502]. We summarize below the scientific targets and the corresponding searches that the Stochastic Group plans to perform in the advanced detector era.

6.4.1 Modeling of the stochastic background

The Stochastic Group is developing a catalog of cosmological and astrophysical sources of the SGWB. While many SGWB models have been proposed in the literature, most of them have not been systematically studied in terms of their accessibility to future GW detectors. It is therefore critical and timely to perform a systematic study of these models and identify specific science questions in the framework of these models that could be addressed by the second-generation GW detector network. Furthermore, as the GW community is beginning to conceive the design of the third-generation detectors, it is also important to identify the SGWB science targets that could be pursued by these detectors, thereby influencing the design requirements for such detectors. This effort is closely linked with the development of the parameter estimation techniques and the mock data project (see below).

This effort has already yielded some very interesting results: for example, if one assumes realistic rates of coalescences of binary neutron stars and/or black holes (such rates would imply tens of individual coalescences observed per year by the second-generation detectors), then the GW background generated by summing signals from all binary coalescences in the Universe may also be detectable by the second-generation detectors [502]. In a separate study [504], our group have shown that a large part of the parameter space of the model for stochastic GW background due to magnetars is also accessible to the second-generation detectors. Consequently, a measurement of the stochastic GW background by second-generation detectors would constrain the ellipticity and the equation of state of these neutron stars in strong magnetic fields. Other studies have shown that similar constraints could be placed on models of cosmic (super)strings, pre-Big-Bang models, and polarized stochastic backgrounds from parity-violating inflation models [528].

6.4.2 Parameter estimation

Until recently, stochastic isotropic searches were limited to estimating the amplitude of the stochastic background (for a specific assumed spectral shape). The group has recently developed new techniques can be used to estimate additional model parameters [503]. Parameter estimation techniques can be used to constrain parameters in generic models (such as the power index in the power-law spectral form), or to constrain fundamental parameters in SGWB models, as identified in the systematic SGWB model studies. Current work on stochastic parameter estimation has focused on estimating the parameters of simple (two-parameter) models including generic power-law models and models of the SGWB from binary neutron stars and binary black holes [503]. In the case of an SGWB from compact binary coalescences, stochastic measurements can be combined with transient measurements (of individual coalescences) to gain more information about the source of an observed stochastic background [503].

Future work will explore a wider variety of models including those characterized by more than two parameters. Exploring the higher-dimensional likelihood functions may require the application of numerical integration tools such as nested sampling [505] and/or Markov Chain Monte Carlo. The group is exploring publicly available (open source) code for these calculations. Another focus of future work will be combining information from other sources (such as transient GW detections) in order to disentangle different sources of the SGWB.

6.4.3 Searches for Isotropic Stochastic Gravitational-Wave Background

Isotropic stochastic GW background will be one of the prime targets of the Stochastic Group in the advanced detector era. This is especially true since recent work has shown that the stochastic background from compact binary coalescences may be detectable by advanced LIGO [502]. The flagship search targeting this background will be the multi-baseline cross-correlation search, using non-collocated GW detectors. The improved detector strain sensitivities and the increased number of baselines will improve the sensitivity of the detector network to the level of $\Omega_{GW} \sim 10^{-9}$ or better. The code/pipeline for these searches already exists and has been applied to S4/S5 LIGO data [497, 498, 515]. Minor adjustments will be needed to apply it to advanced detector data such as extending the sensitive band down to 10 Hz and creating a new high-pass filter.

6.4.4 Searches for Anisotropic Stochastic Gravitational-Wave Background

Anisotropic stochastic searches have already been performed on S4 data [499] and S5 data [500]. This includes both the radiometer searches that target point sources, and the spherical-harmonic decomposition search which is capable of searching for complicated angular distributions. Both of these methods also produce the isotropic result as a limiting case, so could be combined with the isotropic search discussed above. The improved strain sensitivities of detectors, as well as the larger number of detector baselines, will lead to at least 100-fold improvement in the sensitivity to anisotropies in the stochastic GW background as compared to the S5 result [500]. Additional improvements are expected by extending the frequency band of the search down to 10 Hz. The increased number of detector baselines will also significantly improve the angular resolution of the search.

The radiometer search can be used to target specific point-like sources, as was done in the case of Sco-X1 and the galactic center with S4/S5 data. A study is in progress to determine which sources would be suitable targets for such searches (especially since the new band 10-40 Hz will be opened), as well as to understand the relative advantages and disadvantages as compared to Continuous-Waves searches.

Finally, we note that the current anisotropic searches average over the two GW polarizations. The algorithm could be extended to estimate the two polarization components. Depending on the available manpower, a detailed study could be made to add this functionality to the search code/pipeline and to quantify its performance using a series of signal simulations/injections.

6.4.5 Mock Data Project

In order to prepare for the advanced detector era, the Stochastic Group has created infrastructure for generating mock data (in *.gwf frame files) containing various SGWB signatures, such as from a population of BNS/BBH coalescences. The group is using this mock dataset to validate existing analysis tools and as a testbed to study new ones. For example, tests are underway to ascertain if there are any complications that might arise when we try to measure SGWB from CBCs, which is non-Gaussian. We plan to use this dataset to test new parameter estimation schemes and to benchmark new non-Gaussian pipelines. In this way, the mock data project will facilitate a number of other group projects.

In order to create a realistic mock dataset, we draw on the experience gained from our projects to model sources of the SGWB (see above). The current mock dataset, populated with compact binary coalescences, utilizes observations and population synthesis results (for example the evolutionary code StarTrack) to generate sources realistically distributed in the parameter space (mass, spin, merging time, orientation, sky position) but also in time and redshift, accounting for the star formation history of the universe. The mock data generation code [527, 526] based on the LAL library was first developed in the context of the Einstein Telescope and then extended to the network of advanced detectors. Future work may include the simulation of other sources of the SGWB, the inclusion of recolored (glitchy) noise, and the use of galaxy catalogs to model anisotropies in the SGWB.

6.4.6 Searches for Long-Duration Transients

The STAMP code suite (see above) has reached a mature stage. The first analysis targeting GRBs is nearing the end of review. The more computationally challenging STAMP all-sky analysis is underway and we hope to wrap it up during the 2013-2014 academic year. The improved sensitivity of aLIGO should allow us to probe long-duration transient models out to astrophysically interesting distances: $\approx 300\,\mathrm{Mpc}$ for extreme models emitting $E_{\mathrm{GW}} = 0.1 M_{\odot}$ of energy in GWs. Future work is expected to focus on improvements to the clustering algorithms in order to search for longer and weaker (more distant) signals.

6.4.7 Computation for stochastic searches

The Stochastic Group currently relies on Matlab for most analyses, and many users still use Matlab 2007a. As part of our preparation for Advanced LIGO, we have begun to test that our pipelines will continue to work with the most recent version (currently Matlab 2012a). Based on these tests, we believe Matlab will continue to suit our needs during the Advanced LIGO era. While we expect Matlab to play a central role in the near future for stochastic analyses, we are also investigating new directions. Some interest has been expressed in developing stochastic pipelines in C++ or python in order to facilitate potentially time-consuming calculations. It is likely that such work will be driven if necessary by computational needs.

6.4.8 Detector characterization for stochastic searches

The greatest detector characterization challenge facing the stochastic group in the advanced detector era is the possibility of correlated noise at widely separated detectors. Recent studies suggest that correlated noise from global Schumann resonances may occur at a level that is problematic for advanced detector SGWB analyses [525]. Correlated noise is problematic for SGWB analyses because it can bias our estimator for $\Omega(f)$.

The group has undertaken a multi-pronged approach to address correlated noise. First, we are working with instrumental experts and commissioners to determine if the coupling of magnetic fields to test mass motion can be reduced to a level that is acceptable for aLIGO SGWB analyses. Second, we are investigating the possibility of a Wiener filter subtraction scheme in order to measure and subtract correlated noise from Schumann resonances. As part of this effort, we are studying whether the efficacy of subtraction can be improved by relocating magnetometers to magnetically quiet locations. We are looking into the performance of different magnetometers. Various schemes and proposals are evaluated using a Monte Carlo model. Finally, we are working to develop frameworks in which we can make astrophysical statements in the presence of correlated noise. This last effort overlaps with recent developments in the S5 H1H2 analysis.

The stochastic group continues to investigate noise lines. The long integration time used in the stochastic analysis can reveal noise noise lines. Common noise lines at two sites can occur due to similar equipment in the laboratory, or common timing in the data acquisition systems. A strong line in on interferometer, along with a large random fluctuation in the other, can also produce a signal at a specific frequency in the stochastic search pipeline. In the advanced detector era the coherence between pairs interferometers' output will be calculated in real time. In this way noise lines that would affect the stochastic search (and by extension, also the CW search) can be identified during the science runs, and possibly even be addressed and fixed in the laboratory.

The STAMP pipeline has been demonstrated to be a good tool to search for long duration noise transients in interferometer data [517]. The STAMP pipeline will be applied to interferometer control signals and physical and environmental monitoring channels as aLIGO sub-systems come on-line. This noise search effort will be done in collaboration with the detector characterization group.

6.5 *Stochmon*: realtime monitor for stochastic searches

The group is developing a web-based monitoring tool called *stochmon*. The *stochmon* webpage will include a variety of standard diagnostic plots and metrics, which will give the group an idea of the sensitivity for stochastic searches achievable with the data collected so far (without unblinding the final results). It will also serve to alert the group to detector characterization problems such as coherent electronic lines and non-stationary noise. By providing this information in near real time, *stochmon* will facilitate rapid feedback to commissioners. It will help us to plan our publication strategy by showing when our sensitivity is projected to reach interesting levels. Finally, it will set the stage for real-time data analysis, helping the group to obtain final results shortly after the completion of a science run.

7 LSC Computing and Software

The LIGO instruments deliver about 1TB/day of data. Even with only about 1% of this data in the gravitational-wave strain channel (the rest consists of detector and environment monitoring information) LIGO data analysis is a formidable computing challenge. Binary inspiral, burst and stochastic searches can utilize many Tflops of computing power to analyze the data at the rate it is acquired. *LIGO's scientific pay-off is therefore bounded by the ability to perform computations on this data.*

The LSC has adopted commodity computer clusters as the solution that meets its computational needs most cost effectively. Compute centers are geographically distributed at several sites around the world; this approach has the advantage that it puts resources close to the university researchers who are analyzing the data. Grid middleware allows for relatively easy access to data and computing power. If local resources are inadequate or a poor match, a researcher can access additional resources on the grid.

The LSC also developed the Einstein@Home project to leverage an alternative distributed computing paradigm for its most formidable computing challenge, the search for gravitational waves from isolated pulsars. The pulsar analysis puts reduced demand on quick turn-around and has low data flow, but requires PFlops of computing power. The analysis engine that underlies Einstein@Home utilizes much of the standard LSC software infrastructure described below; BOINC [5] is used to distribute work to thousands of volunteered personal computers world-wide.

7.1 Current status

The LIGO Data Grid (LDG) is the combination of computational and data storage resources, grid computing middleware and LSC services which, together, create a coherent data analysis environment for gravitational-wave science. With resources located at LIGO Laboratory centers (Caltech, MIT, LHO and LLO) and LSC institutions (UWM, Syracuse, and 3 sites in the EU managed by the GEO-600 collaboration), the LDG is a true distributed facility.

The LIGO Data Grid currently offers the minimal services required on a fully functional data grid. The LDG continues to see growth in the number of users, higher demand for the resources, and construction of more sophisticated workflows. It is essential, therefore, to provide support of the LDG infrastructure, to provide user support and documentation, and to create the new services that gravitational-wave scientists will require. These services include: improved resource monitoring service and a resource brokering service to ensure that optimal use is made of LDG resources at all times; a metadata service to provide collation, distribution and access to the scientific results of searches; and a virtual organization management service to facilitate access control of LDG resources.

We anticipate evolution of the usage model as the community gains experience, so we are committed to a modular approach which allows us to remain light on our feet and to implement solutions which enable the best gravitational-wave science. A detailed description of the program of work on the LIGO Data Grid follows.

7.2 Activities in support of LDG Operations

1. **Hardware and Operating System Maintenance** The LDG clusters are all commodity clusters as this offers the most GFLOPs/dollar of capital investment. Using Linux requires an investment to track, and in some cases work around, this developing operating system. These are the traditional system-administration roles independent of grid activities.

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[5] `http://boinc.berkeley.edu`

2. **Grid Middleware Administration** Each local cluster must maintain an evolving set of middleware in as stable a fashion as possible. The primary means to do this is the LDG Server software, discussed below. This software is rapidly evolving and requires effort to configure, support and maintain, independent of the effort required to create and maintain the LDG Server package itself.

3. **Data Distribution and Storage** The LDG currently uses the commercial SAM-QFS mass storage software from Oracle, commodity storage in the compute nodes, Linux based RAID servers, and the LIGO Data Replicator (LDR) to store and distribute data. Input data is common to the majority of analysis pipelines, and so is distributed to all LDG centers in advance of job scheduling.

4. **Reduced Data and Calibrated Data Products** The Initial LIGO raw full-frame data files contain 13 to 15 thousand channels, including the gravitational-wave channel. For Advanced LIGO the number of channels is expected to increase by an order of magnitude. Within the LIGO Data Analysis Systems (LDAS) at the observatories, a Level 1 Reduced Data Set (RDS) is generated that contains on the order of 300 channels (some of which are downsampled) that are the most useful for analysis and detector characterization. The Level 1 RDS files are about 20% the size of the raw frames, facilitating their distributed storage on cluster disk space for rapid I/O and for transfer to downstream LDG clusters. An even smaller Level 3 RDS is generated that contains just the gravitational-wave channel and instrument status information. Within the RDS infrastructure, LDAS also generates calibrated strain data using code from the LSC Algorithm Library, which it distributes as a separate set of frames files that are used for most offline analyses.

5. **Certificate Authority and User Accounts** LIGO uses X.509 certificates for authentication of users on the LDG. Several international Grid Certificate Authorities (CAs) supply user certificates, including DOEGrids CA in the USA. The LSC provides a simplified script interface for DOEGrids CA users within LIGO. RA agents are required to verify certificate requests to the CA and then approve them. LDG user accounts are requested via a web interface; these are also verified, and approvals are sent to each LDG site where local admins add the accounts.

6. **LIGO Data Grid Client/Server Bundles** LSC staff leveraged experience and built upon the Virtual Data Toolkit (VDT) to create the LIGO Data Grid Client and Server packages. The server bundle enables LSC administrators to easily deploy standard grid services and middleware such as Globus GRAM and GridFTP across the LDG. The client bundle provides quick one-stop installation of all the software needed to gain access to the LDG resources by users in the LSC. Moreover, the LDG Client bundle provides scripts specific to the LDG to simplify certificate requests and other activities that users perform. Over the past year, the LSC has worked with the VDT team to migrate the LDG Client and Server to use native packaging for Linux platforms. The LSC now maintains these bundles in the LSCSOFT repositories for easy installation and configuration on the LDG. A Mac OS client suite is maintained in order to support the increasing number of scientists using this platform to access LDG resources. The LSC continues to collaborate with the VDT team to provide feedback on their software and distribution mechanisms.

7. **User Support** The LDG predominantly uses Condor for job queue management. As the analysis workflows for this new branch of astronomy are evolving rapidly, significant effort is required to work closely with the Condor development team to ensure efficient use of the LDG clusters. This feedback has been productive, with many timely bug fixes and feature enhancements being provided, however this requires significant effort from LDG administrators to isolate and troubleshoot issues that are particular to gravitational-wave data analysis. Compared with our High Energy Physics colleagues, the workflows that are being developed on the LDG are not yet as mature or stable, causing a significant

burden on cluster administrative staff. Since the LDG users are generally scientists and not grid experts, staff are required to offer performance tuning in terms of GFLOP/s, job scheduling efficiencies, memory utilization, file management, and general debugging support for intermittent job failures.

8. **LIGO VO Support for OSG** Provide primary support for OSG usage of LIGO VO resources, continue to fulfill the responsibilities of OSG point of contact, security contact, and support center for LIGO, and handle any issues that arise for OSG users, OSG administrators and the OSG Grid Operations Center (GOC) while using LIGO facilities; regular participation in OSG Operations, OSG Integration, and OSG Support Center telecons. Maintain and administer the Virtual Organization Membership Service (VOMS) and LIGO Accounts Management System (LAMS) used to track users with Grid certificates approved to use LIGO Data Grid resources.

7.3 Data Analysis Software Development Activities

A suite of software tools are supported, developed and released by the LSC for the purpose of analyzing data from gravitational-wave experiments. These data analysis software projects are developed under the umbrella of the *Data Analysis Software Working Groups* (DASWG). Many of these projects have evolved into full scale software projects which enable most of the large scale analysis efforts within the LSC, thus requiring substantial effort to maintain them. Moreover, the LSC and the international community of gravitational-wave astronomers have embraced the grid-computing model and its associated technologies placing further demands on the software tools developed by DASWG.

1. **Data Monitoring Tools** The Data Monitoring Toolbox or DMT is a C++ software environment designed for use in developing instrumental and data quality monitors. About 50 such monitor programs have already been developed by members of the LIGO Scientific Community. DMT monitors are run continuously while LIGO is in operation, and displays produced by these monitors are relied on to give the operators immediate quantitative feedback on the data quality and interferometer state. In addition to their on-line use, the monitors and the software infrastructure they are based on have many offline applications including detector characterization, data quality determination and gravitational wave analysis. To facilitate the use of the DMT environment and monitors offline, the majority of the DMT package has been ported to the LSC offline processing clusters. Porting and packaging the DMT for offline use will continue to be supported.

2. **GLUE** The Grid LSC User Environment (GLUE) provides workflow creation tools and metadata services, written in Python, which allow LSC scientists to efficiently use grid computing resources within and external to the LIGO Data Grid. Analysis of data from gravitational-wave detectors is a complicated process typically involving many steps: filtering of the data from each individual detector, moving trigger data to a central location to apply multiple instrument coincidence tests, investigating auxiliary channels, and coherent combination of data from all detectors in the network. The description of these complicated workflows requires a flexible and easy to use toolkit to construct a virtual representation of the workflow and then execute it on a single cluster, across the entire LIGO Data Grid, or on external compute resources such as the OSG. The GLUE pipeline module provides this facility and is used by numerous LSC-Virgo data-analysis pipelines. GLUE is integrated with Pegasus workflow planner, allowing scientists to better manage the workflows generated using the pipeline module. Direct generation of Condor workflows is also supported. GLUE also provides an extensive suite of metadata management tools. The ligolw module provides a toolkit for generating and manipulating LIGO light-weight XML documents (LIGOLW XML). These documents are used to store many data products, from detector data quality and metadata information to the scientific products of searches. GLUE also provides the server tools to manage the extensive detector state metadata

generated by the LIGO, Virgo and GEO detectors, as well as client tools used by LSC-Virco scientists to access these data.

3. **LSC Algorithm Library Suite** The LSC Algorithm Library Suite (LAL) is a collection of C language routine libraries that form the engine of the computationally-intensive data analysis programs. LALSuite routines are used in LAL Applications (collected in the LALApps package) which are programs that perform specific data analysis searches, and the LAL-Python interface (PyLAL) that provides access to LAL routines within the Python language. LALSuite contains (i) general purpose data analysis routines that provide common data analysis tools (e.g., routines to perform time-domain filtering, Fourier and spectral analysis, differential equation integrators), astrometric tools (e.g., routines for converting between sky coordinate systems and time systems), and gravitational-wave specific tools for signal simulation and data calibration; (ii) routines for reading and writing data in standard LIGO data formats; and (iii) implementations of search-specific gravitational data analysis algorithms. Enhancements are planned to improve the I/O routines to interface with LDR data catalogs directly and to leverage Grid tools to directly access data stored remotely. Also planned are significant improvements to the interface of the core analysis routines to make these routines easier to integrate into other software.

   C language applications for performing specific searches are contained in the LALApps package which is freely available under the GPL. This package provides a set of stand-alone programs that use LAL routines to perform specific pieces of a search pipeline. The programs can be strung together to form a data analysis workflow: a sequence of steps that transform the raw interferometer output into a set of candidate events. These applications continue to be enhanced and new ones developed.

   PyLAL is a Python module that includes extension modules that link against LAL, thereby making LAL routines available within the Python scripting environment. PyLAL thus provides a mechanism for rapid data analysis application development, for data exploration and graphing, and for performing quick follow-up analyses. As PyLAL matures, many more LAL routines will be incorporated so that significant aspects of the data analysis pipelines will be written in Python.

4. **MATLAB Applications** The MATLAB software suite is a commercial product which is widely used within the LIGO Scientific Collaboration (and the broader gravitational wave detection community beyond) for on-line and off-line data analysis, detector characterization, and operations. The MATLAB Applications package (MatApps) is a collection of gravitational-wave data analysis tools for use within the MATLAB environment that were written by the LSC members in support the analysis of LIGO, Virgo, and GEO data. This software is now maintained as part of the LSC MATLAB Applications (MatApps) project. Many of the contributions to MatApps are complete analysis tools developed by individual scientists and, as a result, there was considerable duplication within the repository. Recent initiatives seek to streamline the repository, better document its contents and share this knowledge with the MatApps community in order to minimize the duplication of efforts and increase ease of use. Streamlining has taken the form of migrating MatApps from a CVS to an SVN and flattening the repository structure for better intuitive use; this effort is ongoing. Improving the communication within MatApps includes the creation of a MatApps wiki, where users (including MatApps leadership) are continually developing the documentation content, and the creation of a MatApps discussion email list where users ask questions of the community at-large. A pilot newsletter has been issued and will be used in the future to communicate general information that may affect a user's interaction with MatApps (outages, new features in the latest MATLAB release, etc.). Better user support efforts are ongoing and include the creation of a dedicated RT tracking system for users to seek assistance with MatApps. Finally, MatApps intends to further reduce duplication of efforts by integrating more with other software projects within the LSC (e.g. LAL/LALApps, PyLAL, GLUE). Specifically, im-

provement to I/O routines can be made by interfacing with LDR and LDAS data catalogs. Through these streamlining and communication efforts, the collaboration will significantly increase the verifiability and maintainability of this analysis software, while simultaneously reducing the barrier to the development of analysis software by individual researchers, educators and students.

5. **LIGO Data Analysis Systems Software** The LIGO Data Analysis Systems (LDAS) includes an important software component which provides (among other things) a frame API for interacting and reducing gravitational-wave frame data, a diskcache API for tracking the location of tens of millions of files mounted on hundreds of filesystems, a job management service for running frame and diskcache API jobs, and the maintenance of a C++ library for interacting with frame data. LDAS RDS and calibrated strain data generation, the data finding service provided by GLUE, and the data replication publishing service provided within LDR are among the software components that use LDAS software services.

6. **Support and Release of Software** The LSC now releases a unified build of the LSCSoft bundle for use by the LSC and other gravitational-wave scientists. This release method will be enhanced to include better support of platforms other than the cluster operating systems selected by the CompComm and DASWG.

   A well defined LSCSoft Software Release Protocol [6] has been developed over the past two years and is currently in use. This protocol requires that inclusion of new or modification/updating of existing packages in the LSCSoft bundle must be approved first by the Software Change Control Board (SCCB). These packages are then built, by the repository maintainers, for the officially supported operating systems [*Scientific Linux 6.1 Debian 6.0 Squeeze and MacOS X Snow Leopard*].

   These packages [*rpm*'s for Scientific Linux, *deb*'s for Debian] are maintained in `YUM` [for Scientific Linux] and `APTITUDE` [for Debian] repositories at UWM. The external *MacPorts* repository is used for MacOS X. These comprise *Testing* and *Production* repositories. The Scientific Linux build process leverages modern virtualization technologies, i.e., a testbed of Virtual Machines at UWM [*Xen, VMWare, VirtualBox*] which are used for building & testing the built the software before publishing it to the testing repositories and announcing their availability to the DASWG email list. For the Debian packages, a similar process [but without using virtualization technologies] is carried out by the Debian Team at Hannover Univ., which also maintains a mirror of the UWM repository. Once the testing phase ends, and if no errors are found in the packages, they are moved to the production repositories upon approval by the SCCB. The corresponding announcement of the official release is then made to DASWG email list.

   The next step in this project is to deliver fully functional virtual-machine images to downstream users. Initially, virtual machines will include the full LSCSoft bundle and LDG client installed and configured to provide a fully integrated environment for analysis. It is further anticipated that users may wish to have custom configured virtual machines with selected software and applications installed. An interface will be developed to allow users to request such VMs which will be automatically built and delivered to them. In the long term, this approach will allow the LSC to maximally leverage Cloud Computing technologies and may provide a route to reduce the total cost of computing for gravitational-wave astronomy.

7.4 Intermediate-term development activities

The distributed LDG relies on a number of grid services to allow robust, efficient operations. A minimal subset are currently deployed on the LDG. The full set is outlined here along with estimated personnel

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[6] `https://www.lsc-group.phys.uwm.edu/daswg/wiki/SoftwareReleaseProtocol`

requirements to support, enhance and deploy them where appropriate.

1. **Problem Tracking and Support** Robust operation of the LDG requires detailed problem tracking to insure that services are maintained and that security issues are quickly and efficiently addressed. There is already web based problem tracking facilities. This service needs to be extended and integrated with the LDG monitoring services. Over the next year, the informal knowledge base that exists in mailing lists and sprinkled throughout web pages and wikis will be harvested to develop a powerful and extensible help system. Furthermore, problem reporting and tracking will be simplified.

2. **Authentication and Authorization** The LSC relies on the Grid Security Infrastructure (GSI) from the Globus toolkit to authenticate users. GSI authenticates using X.509 certificates, which are currently obtained from a number of nationally operated grid certificate authorities from countries in which LSC member institutions reside. User access is provided at each site via hand-maintained grid map files. Users access standard unix accounts which are provisioned by hand by administrators. This approach does not scale sufficiently for the LDG. The OSG is using the VOMS-GUMS-PRIMA model for this purpose. The LSC has deployed these tools to share resources with OSG, but needs to explore all technologies that meet the collaboration's needs.

   Within the next year, this model will change substantially. Using the centralized authentication and authorization infrastructure currently being developed in the LSC and LIGO lab, short-lived X.509 certificates and proxy certificates will be supplied by MyProxy backed by LIGO.ORG CAs. MyProxy will leverage the existing centralized authentication infrastructure (in particular the LIGO.ORG and LIGO-GUEST.ORG kerberos realms) to link these certificates to user's identity in the LIGO.ORG LDAP. This will allow the capability for fine-grained access control and for automatic and uniform account provisioning on the LDG. Over the next several years, LIGO will be seeking TAG-PMA accreditation for the LIGO CAs to allow LIGO users to seamlessly interact with other scientific grids such as OSG.

   These developments are part of a larger effort, known as the Auth Project, which is described in more detail in 7.5.

3. **Monitoring Services** While the current LDG infrastructure is working well, it lacks of a fully deployed monitoring/information system. Having easy access to current information about the health of the LDG would allow us to prevent problems and/or troubleshooting issues much more effectively. Moreover, having access to historical data about usage and health of the LDG would facilitate decision making when the time comes to enhance or adjust the LDG. It is clear that aLIGO will require a considerable growth in the current computational infrastructure that will benefit from a fully functional monitoring service.

   One type of information inherent to grid computing models describes the status of clusters, their processes, their services, the status of jobs on the cluster, and the status of connectivity between clusters. In order to maximize the throughput, users and job submitting agents need to have access to this information. The LDG currently uses Ganglia to obtain snapshots of the status of clusters at different locations and then reports them to a central Ganglia metadata server. Enhancing monitoring services by including new tools to collate the information collected and to provide a consolidated Grid friendly interface is an essential step to improve efficiency.

   A prototype information service, the LSC Grid Information Service (LSCGIS), has been deployed which uses standard cluster monitoring tools and scripts to gather the required information and then exposes it via a RESTFul web service. This LDG-customized project can be enhanced by integrating it together with more general tools such as *Nagios*, for a finer metadata gathering. While this information is currently used to prevent/fix problems, it is clear that it can also be used to feed information into analysis pipelines or workflows to make them aware of available infrastructure and to make them more intelligent. The prototype LSCGIS should will continue to be evolved to address all of these possibilities.

4. **LIGO Data Replicator** The LIGO Data Replicator (LDR) replicates bulk interferometer data files to LIGO Data Grid (LDG) computing sites, as well as the Virgo site in Cascina, Italy (CSC). LDR provides a metadata catalog for gravitational wave data files (typically with extensions .gwf and .sft) that in conjunction with other tools allows LIGO and Virgo scientists and their codes to discover data and other files within the LDG. Replication begins when data is *published* into the LDR network at a site. Publishing implies that relevant metadata about a file is entered into the local metadata catalog that is part of LDR and that a mapping from the logical filename (LFN) to an access path (typically a URL) or physical filename (PFN) is created in the local replica catalog (LRC). By the end of the LIGO S6 science run the LDR metadata catalog contained metadata information on more then 35 million files and each RLS replica catalog is expected to hold between 1 and 50 million mappings, depending on the data sets replicated to each site. Currently LDR is deployed at the LIGO Hanford observatory (LHO), LIGO Livingston observatory (LLO), Caltech (CIT), Massachusetts Institute of Technology (MIT), Syracuse University (SYR), University of Wisconsin-Milwaukee (UWM), Albert Einstein Institute Hannover (HAN), Cardiff University (CDF), and Birmingham University (BHM), as well as the Virgo site CSC. The CDF and BHM deployments leverage the "LDR as a service" model where only a GridFTP server is deployed at the site and the rest of the LDR logic and tools are hosted at UWM and provided as a service to the site. Investigations and testing continue to ensure scalability and performance meet the demands for the post enhanced LIGO era, especially since data from both the Virgo and GEO instruments will continue to be published, replicated, and discovered using LDR even as the LIGO instruments turn off after S6. Specific directions include tightly integrated web based monitoring to further ease the administrative burden, as well as migrating the LRC to a web services and more robust server platform.

5. **Data Quality and Segment Database** The lightweight database daemon (LDBD) provides a client and server framework for scientific meta-data services. LDBD is built on top of the existing LIGO authentication and authorization services, with a relational database back-end (DB2). This framework is designed to be extensible; the first application using it is the interferometer data quality service (Segment Database). Tools have been developed for low latency discovery and archival of Science and DQ segments for the S6 online and offline analysis. Two production servers at Caltech and a development server at Syracuse are currently providing critical metadata services for the LSC and Virgo collaborations.

   This S6 data-quality service is currently being enhanced to better meet the needs of online data-analyses and control-room work through a combination of improvements to the existing database infrastructure and the implementation of new, related data-quality services and APIs. In addition to scalability and reliability improvements, these will deliver metadata at lower latencies and higher rates, and enable the development of more powerful, integrated client tools. For example, core DQ flag generation is being moved to the Online Detector Characterization system (section 2.2.6) to avoid timing errors and enable offline data analyses to access critical data-quality information directly in frames. Additional (expensive or otherwise offline-generated) DQ flags will continue to be inserted into the SegDB from other sources. Specific improvements include simplifying and improving the performance of the Segment Database by allowing trigger metadata to be stored in a dedicated trigger database supporting sub-1Hz resolution and additional metadata. Critically, a consistent API between these data-quality services will facilitate the implementation of more powerful client tools that can access and synthesize information from the segment database, conlog, and trigger database.

6. **Event Database and Archival Project** The gravitational-wave candidate event database (GraCEDb) is a prototype system to organize candidate events from gravitational-wave searches and to provide an environment to record information about follow-ups. A simple client tool is provided in Glue to submit a candidate event to the database.

   An entity submits an event to Gracedb using the client tool in Glue or via the web interface. At the time of submission, the following things happen: 1) A unique ID is assigned to the candidate event. This UID is reported to the entity submitting the candidate event. The UID takes the form GXXXX, where XXXX is a number with a minimum of four digits. Extra digits will be used as needed. The UID is intended for internal use only. 2) The submitter, the search group, the search type that generated the event are recorded. 3) A web area is created to hold information about the candidate event and any follow-ups that are performed. These directories are accessible via web browsers and by logging into any of the submit machines at UWM, in particular hydra.phys.uwm.edu:/archive/gracedb/data/GXXXX. The general directories have the same permissions as /tmp in a Unix file system, so any LVC users can add content under that directory. The use of directories based on ligo.org usernames is encouraged to keep things organized. 4) A wiki page is created to allow easy entry of information about the candidate event. 5) An alert is published to the corresponding node in the LVAlert system; subscribers to that node receive the alert and initiate follow-ups. Alerts are also sent to the gracedb@ligo.org mailing list.

   As with the DQ and Segment Database, the database lacks robust monitoring and fail-over solutions. The production database is backed up, but no hot spare exists. An automated fail-over solution must be developed, along with replication of event information to redundant off-site systems. In the intermediate term, production-level support will be provided for the LSC and Virgo collaborations through the end of the S6 run and during the era that VSR3 and GEO-HF will be operating.

   LARS will be a collection of tools and services that provides archival storage for LIGO. A prototype has been delivered. The user tools are simple programs that are intended to allow LIGO scientists to catalog and share search results. Users may add descriptions and locations of search results to a simple database. This database may be queried by others to discover result locations. Individual results may be narrowed within a search by specifying a description in the result's LALCache. When found, query results may be listed or data may be presented to the user in a local directory, if sshfs is available. Work has started to leverage cli.globus.org services to provide transparent and efficient transport and distribution of data products by users. When implemented, we anticipate LARS will become an important tool for scientists.

7. **Multi-Site Scheduling and Brokering** The ability to plan, schedule, and monitor large workflows simultaneously across multiple LDG sites is becoming increasingly necessary in order to load balance across the computational resources distributed throughout the LDG and to support ever larger workflows which cannot easily or always be serviced within time constraints at a single LDG site. A number of intermediate-term development activities are focused on supporting LIGO data analysis workflows across multiple LDG sites as well as other "grid" sites external to LDG.

   One such activity focuses on leveraging the "Grid Universe" available with the Condor High Throughput Computing system and in particular "Condor-C", the Condor Grid type. Currently Condor manages most LDG computational resources (Linux clusters) at a site level. That is, each Linux cluster resource is its own Condor pool and jobs submitted to be run and managed at any single site only run within that same Condor pool. When properly configured, however, the jobs submitted at one site and into one Condor pool may migrate and be run and managed by a remote Condor pool, with the results and output being staged back to the original submission site as if the jobs had ran at the submitting site. An earlier attempt by Condor to support this type of migration of jobs was the Condor "flocking" mechanism. This newer approach known as Condor-C promises to scale better. LDG staff are evaluating Condor-C throughput and scaling behavior and providing feedback to the Condor team, as well as working to understand how best to abstract the details of Condor-C job submission and management away so that LDG users do not have to manage the details themselves.

While Condor-C provides the "plumbing" to allow jobs to flow between clusters, LSC-Virgo workflows must be written to take advantage of the transport mechanisms Condor-C provides. One approach to solving this problem is leverages the Pegasus workflow mapping engine. GLUE has the ability to output LSC-Virgo workflows in the abstract directed acyclic graphs (DAX) format (this is now the standard format used by CBC workflows). The Pegasus workflow planner can then be used to render these "abstract" workflows to "concrete" Condor DAGs. The actual management of the workflow is handled by Condor DAGMan. At present, Pegasus translates CBC workflows to Condor DAGs consisting of standard and vanilla Condor universe jobs targeted for a single LDG cluster. Pegasus provdes services such as bundling short running jobs into larger jobs and better management of input and output data products. LDG scientists are currently investigating Pegasus' ability to render workflows as Condor-C jobs which would allow execution across multiple LDG sites connected with Condor-C.

Pegasus can plan also plan workflows for execution across sites that do not run Condor pools as well as into sites that do run Condor pools. LDG staff are evaluating Pegasus and working to understand how to tune Pegasus to schedule LIGO workflows across non-LSC sites (such as the OSG) most efficiently.

Finally, the use of pilot servers to provide a simple interface for the users that want to submit jobs on the LDG, but have them run on other resources including those available to the Virgo collaboration. An existing test system will be duplicated and extended to provide efficient resource sharing across the LDG.

8. **Test and Build** To ensure the successful analysis of LIGO-Virgo data, it is increasing important to automate the validation of LIGO software and infrastructure. With continuous advancements in scientific analyses and computing technology, LIGO's software and computing infrastructure is growing in size and complexity. This trend is driving the need for more automated validation.

   As a result, automated build and test systems such as the NSF-sponsored Metronome framework can be of enormous benefit to LIGO. Such automated testing is also critical to the validation of changes to LDG system architecture, operating systems, and runtime environment. However, regression testing a distributed software stack is a computationally demanding task—an apparently harmless update of one component can cause subtle failures elsewhere in the system. And in the event of a critical security patch to one or more components, regression validation of the entire system absolutely must happen very quickly.

   Enabling an automated testing solution tailored to the needs of LIGO's distributed computing environment, will help ensure that changes to LIGO code or to LDG system architecture, operating systems, and runtime environment do not cause unexpected and undesirable changes to scientific results. Additional testing resources would also support testing the reproducibility of past results in the face of such changes. Automated test and build is essential to enable higher-quality software and prevent "bitrot" as LIGO scales past the capabilities of largely manual software and infrastructure validation processes.

9. **gstLAL** gstLAL in a software project to wrap the GW data analysis machinery of LALSuite in GStreamer "elements". GStreamer is a free C library that provides the infrastructure required to build complex realtime and non-realtime digital signal processing pipelines. GStreamer is primarily

intended to be used in multimedia applications for the desktop, but it is of high quality with many features and easily satisfies our own needs for data analysis pipelines.

Using gstLAL, a prototype application is being developed to search for the gravitational-waves from collisions of very low-mass primordial black holes. The PBH templates used by the search are up to 30 minutes long, and so the completion of this search will serve as a technology demonstrator for Advanced LIGO, proving that we have the software infrastructure required to handle the long templates in the flagship binary neutron star search. At present the PBH trigger generator program runs, but many problems remain to be solved before a full PBH search can be completed, for example how to perform background estimation with such long templates and how to practically construct banks of such long templates. These problems are outside the scope of gstLAL itself but the further development of gstLAL will be driven by their solution.

7.5 Preparing for the advanced detector era

Work on the requirements for the hardware, software and services needed for gravitational-wave astronomy in the Advanced Detector Era (ADE) has been ongoing for several years now. A number of discussions and presentations have allowed the CompComm and DASWG to build a task list and determine the approximate FTE count to meet the needs.

Towards the end of 2010, a proposal was prepared to support the continued operations of the LIGO Data Grid, including software support, enhancement, and release. In addition, in 2011 a plan was presented for a sequence of engineering runs to test this infrastructure.

Following a table of tasks and FTE requirements, this section gives a summary of the engineering run plans, followed by more details of the larger projects that will need to be completed in order to leverage the advanced detectors for maximal scientific productivity.

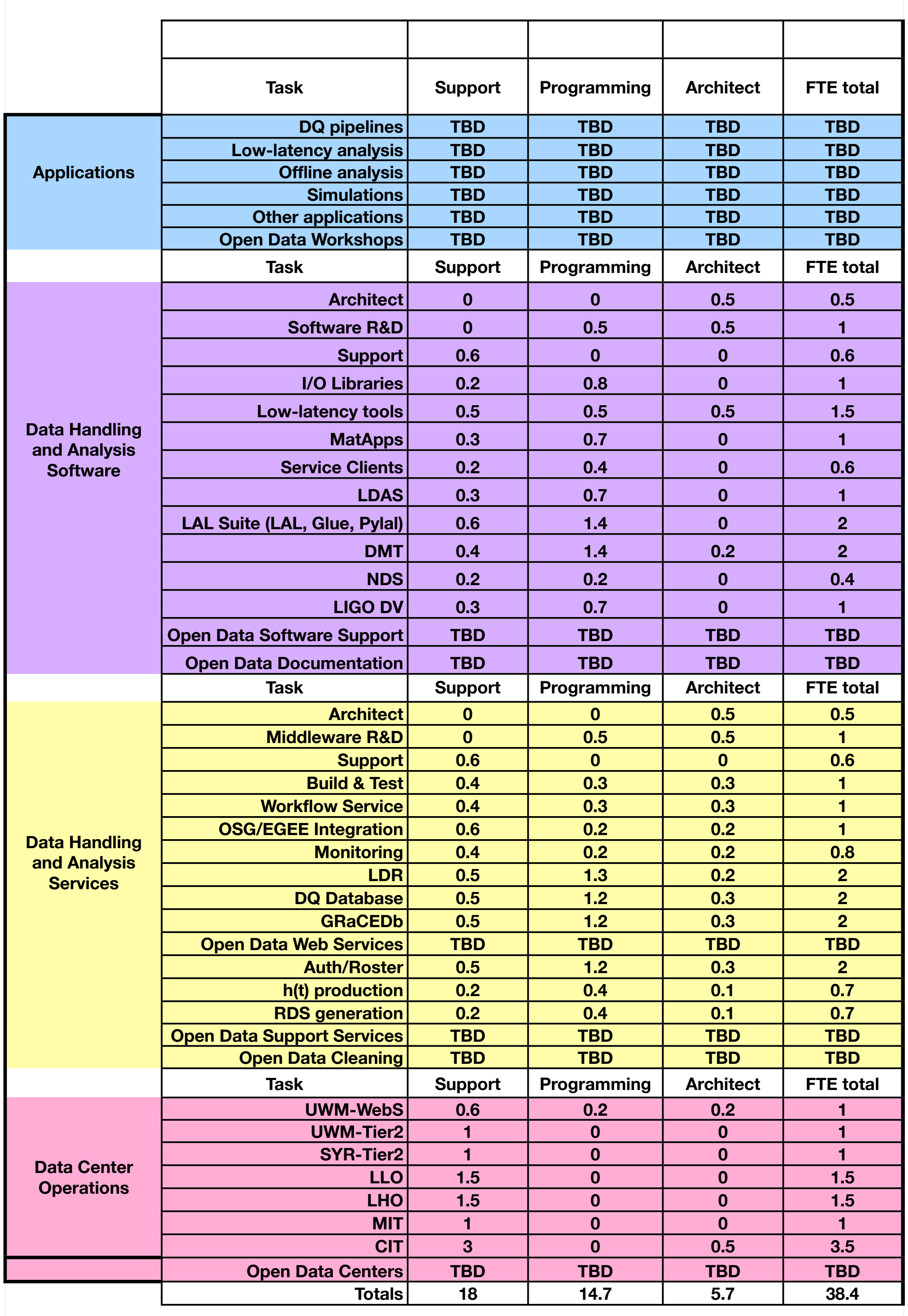
7.5.1 Engineering Runs

In 2011, a sequence of engineering runs was planned that would:

- Test important software and computing infrastructure.
- Establish run procedures for the Advanced Detector Era.
- Test detector characterization using real subsystem data.
- Measure progress on software for key science goals.

The runs were named and tentatively scheduled for dates within this time frame:

- ER1: January - February 2012. (Complete)
- ER2: July - August 2012. (Ongoing)
- ER3: January - February 2013.
- ER4: Coincident with advanced detectors coming online in 2013.
- ER5: Coincident with advanced detectors coming online in 2014.
- ER6: Coincident with advanced detectors coming online in 2014.



	Task	Support	Programming	Architect	FTE total
Applications	DQ pipelines	TBD	TBD	TBD	TBD
	Low-latency analysis	TBD	TBD	TBD	TBD
	Offline analysis	TBD	TBD	TBD	TBD
	Simulations	TBD	TBD	TBD	TBD
	Other applications	TBD	TBD	TBD	TBD
	Open Data Workshops	TBD	TBD	TBD	TBD
	Task	Support	Programming	Architect	FTE total
Data Handling and Analysis Software	Architect	0	0	0.5	0.5
	Software R&D	0	0.5	0.5	1
	Support	0.6	0	0	0.6
	I/O Libraries	0.2	0.8	0	1
	Low-latency tools	0.5	0.5	0.5	1.5
	MatApps	0.3	0.7	0	1
	Service Clients	0.2	0.4	0	0.6
	LDAS	0.3	0.7	0	1
	LAL Suite (LAL, Glue, Pylal)	0.6	1.4	0	2
	DMT	0.4	1.4	0.2	2
	NDS	0.2	0.2	0	0.4
	LIGO DV	0.3	0.7	0	1
	Open Data Software Support	TBD	TBD	TBD	TBD
	Open Data Documentation	TBD	TBD	TBD	TBD
	Task	Support	Programming	Architect	FTE total
Data Handling and Analysis Services	Architect	0	0	0.5	0.5
	Middleware R&D	0	0.5	0.5	1
	Support	0.6	0	0	0.6
	Build & Test	0.4	0.3	0.3	1
	Workflow Service	0.4	0.3	0.3	1
	OSG/EGEE Integration	0.6	0.2	0.2	1
	Monitoring	0.4	0.2	0.2	0.8
	LDR	0.5	1.3	0.2	2
	DQ Database	0.5	1.2	0.3	2
	GRaCEDb	0.5	1.2	0.3	2
	Open Data Web Services	TBD	TBD	TBD	TBD
	Auth/Roster	0.5	1.2	0.3	2
	h(t) production	0.2	0.4	0.1	0.7
	RDS generation	0.2	0.4	0.1	0.7
	Open Data Support Services	TBD	TBD	TBD	TBD
	Open Data Cleaning	TBD	TBD	TBD	TBD
	Task	Support	Programming	Architect	FTE total
Data Center Operations	UWM-WebS	0.6	0.2	0.2	1
	UWM-Tier2	1	0	0	1
	SYR-Tier2	1	0	0	1
	LLO	1.5	0	0	1.5
	LHO	1.5	0	0	1.5
	MIT	1	0	0	1
	CIT	3	0	0.5	3.5
	Open Data Centers	TBD	TBD	TBD	TBD
	Totals	18	14.7	5.7	38.4

Table 1: A list of tasks and FTE requirements for LIGO Data Grid operations and software/service design, development, release and support. The support activity includes administration, help desks, packaging, testing, release. The architect activity refers to high-level architecture development. Notice that the applications layer is considered separately from core operations and support activities. All open-data activities remain TBD until the plan is formulated and accepted.

This schedule is timed to allow groups to report on milestones/metrics at the following LIGO-Virgo meeting. The runs will also become longer and more integrated with interferometer data as the advanced detector subsystems come online. After the last run, the software infrastructure will be in place and have been tested to prepare for the first ADE science run.

As of the writing of this white paper, ER1 has been completed. It ran from January 18 to February 15 2012. The goals for ER1 were to deploy improved low-latency data transfer and access tools, test the mock-data-challenge signal generation infrastructure, establish science metrics for analyses, and test the DAQ at Livingston, and to encourage detector characterization on existing sub-system data there.

Both the low-latency transfer (LLD) and bulk transfer (LDR) networks were run. Simulated H1, H2, L1, and V1 data was generated using the noise curves for high power aLIGO and advanced Virgo. Burst injections were done at known times every $10,000$s, and blind compact binary signals were injected at about the best-guess astrophysical rate, uniformly distributed in space.

Low latency analysis was done by the cWB, gstlal-inspiral, and MBTA pipelines. A list of gravitational-wave (injection) candidates was prepared by gstlal-inspiral in advance of unblinding which reported three with 5-σ confidence. After the injections were unblinded on 15 March, performance reports were prepared for the three pipelines and it was shown that the gravitational-wave (injection) candidates identified by gstlal-inspiral were indeed blind injections.

The next engineering run, ER2 (scheduled for July 11 to August 8, 2012) is in progress at time of writing. Its goals are to deploy prototype h(t) system for LIGO, deploy prototype low-latency detector characterization environment at the LIGO sites, test connection to Transient Alert Network (GCN), harden existing services, and benchmark further searches.

There is also the goal (for ER2 or the next run) to recolor real subsystem data (e.g., from the PSL which currently is running for H1 and L1) to generated the fake mock-data-challenge-data. In this way, real detector characterization activities can be connected with the astrophysical searches of the data.

The proposal for ER3 is to run from January 23 to February 20, 2013. After this, the runs will hopefully coincide with the detectors coming on line. In this way, the engineering runs will begin to bring together the software and detectors in complete end-to-end tests in preparation for the first ADE science run.

7.5.2 Software

A list of critical software development areas follows below. Most of these are tied to existing DASWG projects. A number of efforts are under way to prototype GPU enabled analysis codes, to wrap existing libraries for use in python (and other languages), and to develop standalone software toolkits for data analysis. Over the next 12 months, the LSC will review these prototyping activities, establish formal software projects or merge with existing projects, and sunset activities that are duplicating existing capabilities.

1. **I/O Libraries** Because of the volume of data involved and the complexity of the algorithms we use to process it, searches for gravitational waves can quickly transform from problems of astrophysics and astronomy to problems of data management. Experience has taught us that the ease and speed with which data analysis challenges are solved is often closely related to the quality of the software libraries used to read and write data products, and so the selection of an I/O library is an important step in the development of a search for gravitational waves. Libraries with well-designed interfaces and robust bug-free internals allow us to spend more time doing science and less time solving I/O problems.

   Today, our searches rely on a combination of I/O libraries developed in-house and libraries maintained by third parties. Libraries developed in-house provide the benefit of being under our control — bugs that affect us are fixed when we need them to be, and we choose when to change software interfaces and file formats — but suffer by requiring people within the collaborations to do the design and maintenance work, people who often do not have a great deal of experience engineering and maintaining complex software projects and whose time is principally allocated to other tasks. Libraries developed externally, on the other hand, are often designed and maintained by people with greater software engineering experience, but sometimes see interface changes occur at times that are not convenient for us.

We have seen a trend within the collaboration to transition from in-house libraries to libraries developed externally. For example, much of our XML I/O now relies on professionally-maintained XML parsers like expat instead of the metaio library developed in-house. In the future, this trend should continue. Whenever a new I/O challenge presents itself every effort should be made to research existing solutions, and use them when possible. In particular, we foresee a growing need for the network transport of many different types of data including astronomical alerts, audio-frequency time-series data in both realtime and non-realtime, database queries and other kinds of remote procedure calls. An enormous variety of technologies has already been developed for solving problems of these types and more. It is important to use those existing solutions whenever possible to allow the expertise and time of their designers and maintainers to streamline our own work, and to help drive the development of those projects so that gravitational wave astronomy can contribute to technological progress in other areas as well.

2. **Low-latency tools** It is not yet clear whether or not a network of ground-based gravitational-wave antennas can be used to successfully provide alerts of transient events to non-GW observatories, there is a significant probability that useful alerts will continue to flow the other way for many years into the advanced detector era. However, one of the challenges facing the search for GWs from binary neutron star collisions in the advanced detector era is the length of the template waveforms required by the search and the number of them. Advanced LIGO BNS templates might be up to 30 minutes in length and be more than an order of magnitude more numerous than the 45 s long templates used by Initial LIGO. The increase in the BNS search's computational complexity indicates the need for a new approach to the problem of matched-filtering, in particular the desire is to develop techniques that allow data to be processed in small chunks *less* than the length of a single template. We have been addressing this need by developing a new software project named gstlal. See `http://www.lsc-group.uwm.edu/daswg/projects/gstlal.html`. Although the development of this technology is motivated by the need to reduce the memory requirements of the analysis pipeline, a side-effect of the effort has been the creation of a suite of data analysis software tools that allow the creation of pipelines in which the time delay between data going in and answer coming out is short.

   The data analysis machinery used by gstlal continues to reside within the lalsuite of libraries (see below). gstlal wraps the lalsuite machinery in GStreamer "elements". GStreamer is a free C library providing the infrastructure required to assemble digital signal processing pipelines, and although it is primarily used to implement multimedia recording and playback on desktop computers, the GStreamer library is of very high quality and easily satisfies all of our own needs for such a library. By using it, not only do we leverage the design experience of GStreamer's developers, but the bug fixes and feature enhancements we have provided back to the project can now be found in Nokia cell phones where GStreamer provides the multimedia playback software, making the gstlal project one of the few places where GW data analysis can be said to have provided industrially-relevant spin-off technology.

   A prototype application has been constructed using the tools provided by gstlal to search LIGO and Virgo data for GWs from compact object collisions. Because gstlal-based applications also have access to all the machinery of GStreamer, they are easily interfaced to network protocols, sound cards and multimedia file formats, and so in the future gstlal might be useful for outreach activities. For example, one could imagine writing software to demonstrate what GWs sound like, allow users to add simulated GWs to simulated detector data streams to hear how different detector configurations make it easier or harder to find different GWs, and so on.

3. **Low-latency data distribution (lldd)** Rapid analysis of data from the global gravitational-wave network requires aggregation of the gravitational-wave strain channels at a central processing location. The low-latency data distribution network is being developed to meet this need. A prototype system was developed, released, and deployed during the past year. It has been used during ER1 and ER2 to allow low-latency transient searches to deliver gravitational-wave triggers to a central database in under a minute after data acquisition. The same system will be used at the observatories to deliver raw interferometer data to the clusters for rapid detector characterization activities. Over the next 12 months, the `lldd` software package will be enhanced to provide improved monitoring and more robust data transfers. Performance results from ER2 will be used to prioritize the next development activities with the goal of a mature low-latency distribution network by the start of ER4.

4. **MatApps** With Advanced LIGO comes the prospect of the first direct detection of gravitational waves and the beginning of the field of gravitational wave astronomy. As a consequence, real-time data analysis will have increased importance as will rapid prototyping of code and visualization of results. While MATLAB is not the only choice users have to achieve these goals, MatApps intends to support this effort by building its infrastructure through coordination and communication with the MATLAB-using community. Coordination needs to be developed between MATLAB-rich repositories that exist outside of MatApps (e.g. LigoDV) to promote ease of code development and to reduce duplication of efforts. Communication is the foundation of user support in MatApps. While we will continue to address individual user questions and concerns, we want to develop the MatApps community to be a clearinghouse of best practices to achieve computational speed and ease of use. We also intend to communicate MATLAB knowledge through documentation. MATLAB is a powerful tool for use in the grid computing environment and we intend to promote its use in this way by keeping complete documentation in a centralized location and offering training to those who wish to gain experience. MathWorks, the author of MATLAB, often updates MATLAB several times a year and we intend to streamline our vetting of new versions and updating documentation about any issues or other considerations so that users may take advantage of the latest features. These new initiatives, combined with our ongoing efforts, will help scaffold the increased demand for data analysis results that Advanced LIGO will introduce.

5. **LAL Suite (LAL, Glue, Pylal)** The LAL Suite of tools has grown beyond its initial scope to include I/O libraries, time and frequency series analysis tools, and domain-specific functionality that enables scientists to access and analyze gravitational-wave data. The development model adopted during the first generation LIGO science runs was deliberately agile. It allowed the developers, largely the same group as the user base, to be remarkably fleet-footed. The LAL Suite user base continues to expand. Indeed, the software has been used by scientists involved in the LISA mock data challenge demonstrating the utility of the software beyond LIGO. It is timely, as advanced instrumentation is installed in the LIGO facilities, to rework and retool LAL Suite to meet the decade-long scientific campaign that lies ahead by providing LSC scientists as well as the wider community of gravitational-wave astronomers with a toolbox for performing gravitational wave data analysis and simulation.

   As LAL Suite developed organically without an imposed final design, the code is not as clean, or general, as it could be. Therefore one of the first steps in improving the sustainability of LAL Suite for the future is to ensure that it has a clean, and easy to understand API (Application Programming

Interface). Another effect of the organic development of LAL Suite is that there are numerous functions that are no longer used and that there are many functions that perform similar tasks. The code base will be simplified by unifying these similar functions, thereby decreasing the amount of code redundancy.

While having a clean code base will greatly improve the maintainability and sustainability of the code, another critical aspect is adequate documentation of the software. The LAL code has now been restructured, but unfortunately the documentation has not; therefore the documentation sectioning does follow the current structure of LAL Suite. The documentation will be unified and restructured to improve the clarity and usefulness.

LAL Suite was originally written using the C89 standard, as at the time the C99 standard had been approved but there where no shipping compilers that supported the standard to an acceptable level. This is no longer the case. C99 provides many improvements and features to the C language which will help in the maintenance of LAL Suite. The adoption of the C99 standard has already started in several minor, but key, areas: the first of which is the use of the C99 fixed-width integer datatypes. The C89 standard did not define the size of the integer datatypes, and therefore they are platform and compiler dependent. As LAL Suite is used on multiple platforms with different compilers, a way was needed to ensure that the integer datatypes were consistent across the different platforms. This led to custom code that determined the size of the various integer datatypes and made the appropriate typedefs. The C99 standard provides fixed width integer datatypes that are of the same size regardless of platform and compiler. Using these greatly simplifies the code base which leads to increased maintainability.

There are many functions in LAL that are very similar and only differ in the datatype on which they operate. This leads to a lot of similar code that needs to be maintained consistently so that errors are not introduced by updating one function and not another. Ways in which this duplicated code can be reduced will be investigated.

Another key feature that is provided by the C99 standard is support for complex numbers and complex arithmetic. Currently LAL defines is own complex datatype as a structure with two floating point fields. While this accomplishes the task of representing complex numbers, it complicates matters as helper functions need to be written to perform simple arithmetic. This greatly complicates the code base, and a transition to the built in complex type will alleviate a lot of problems. The C99 complex type is however not entirely a drop in replacement for the current LAL complex structure therefore, so an in depth study will be done in order to determine the optimal way to transition to the native C99 complex datatypes.

The ability to simulate the gravitational wave strain that would be produced from various types of astrophysical sources, e.g., coalescing compact binaries, continuous waves from distorted pulsars, random gravitational-wave noise from the early universe, is an important feature of the LAL libraries. However, the simulation software is currently integrated into individual searches, and is not exposed in a general, well documented, and easy-to-use API. This situation is unsatisfactory: one of the major functions that LAL Suite should perform is to provide the community with vetted software for gravitational waveform simulation. Therefore, one of the significant goals is to extract the routines that perform gravitational wave simulation from the individual search packages and combine them into a LALSimulation library. The routines will be re-implemented where necessary so that they have a common and useful interface. They will also be carefully documented community vetted so that their correctness is assured. This library will be the primary contribution of LAL Suite to the community of scientists outside of the LSC.

While it is important to have a clean and well-documented code base, it is also important that this code base is tested on a regular basis to ensure that the code works as expected, and that no code modifications lead to unexpected changes in behavior. One way towards achieving this is to implement unit tests which aim to isolate each part of the code and shows that each of these "units" behaves as expected. Ideally every function inside the LAL libraries should have a test associated with it, therefore individual functions can be regularly tested to ensure correct behavior. Unit tests best work when the library functions perform one simple task that can be easily tested; many of the core library functions are now being written to perform such single tasks, and are therefore amenable to effective unit testing. The unit tests will be developed for these routines within the existing testing environment. Testing of individual functions is a step in the right direction but to ensure that the code works as expected complete workflows need to be tested in addition to the unit tests. Therefore an investigation into a build and test systems, such as Metronome, will be made to determine how complete LAL Suite workflows can be tested on a regular basis.

Increasingly, programs are being writing in scripting languages, such as python, as these provide a quick and easy method to accomplish tasks. We are finding that we are frequently needing to access many of the LAL Suite functions within such scripting languages. To date, required functions have been manually wrapped by hand as needed, an approach which clearly will not scale and a task that will need to be done for each scripting language that needs access to these functions. SWIG (Simplified Wrapper and Interface Generator), is a tool that can be used to automate the generation of bindings and one of the main advantages is that once things are setup bindings for any supported language can be automatically created. It will therefore be investigated how SWIG can be used to automate generation of language bindings.

6. **DMT** With the upgrade of the Ligo Control and Data System (CDS) for Advanced LIGO the reference platform for the DMT will formally move from Solaris to Linux. In fact, because of the enormous offline computing power available from the Linux clusters, much of the recent DMT development has been tested on both Linux and Solaris insuring relatively simple porting to the new platform. Further development and rigorous testing will still be necessary for the online components, especially those involved in distributing online data to all the processes. Although at present, the plan is to leave the frame broadcasting mechanism much the same as for initial ligo, the opportunity to receive data more quickly by way of an direct connection to the CDS data network should be evaluated.

   Additional DMT software development will also be needed to monitor and characterize the new and more complex aLIGO interferometry.

   The use of the same operating system online and offline, provides the opportunity to unify the packaging and distribution of the online and offline DMT software. Already, much work has been done to unify the packaging of all software from the DMT/GDS package used by CDS DMT-online and DMT offline.

7. **NDS** The version 2 Network Data Server (NDS2) allows Ligo-Virgo collaboration members to access current and archived Ligo data remotely. The network protocol uses Kerberos to allow nearly transparent authentication by the Ligo-Virgo scientists while preventing access by unauthorized persons. Offline and online NDS2 servers are currently running at Caltech and LHO, respectively, with the offline server making all Ligo raw data acquired since the start of S5 available. The NDS2 client code has been interfaced to matlab, octave, python, C and C++. An example client application is the ligoDV viewer, described in the following section.

   This year the server and client have advanced considerably. The focus of recent development has been to:

- Improve server reliability: preventing hangups when requested data are temporarily not available or the server is swamped with requests.
- Improve error reporting and fail-over: Produce more meaningful error status returns and allow successful return of partial data if some channel is unavailable.
- Improve portability: Client interfaces have been added for several interpretive languages (matlab, octave and python) and building and packaging has been developed and tested on many platforms (centos, debian, solaris, Mac).

We expect that use of data from the NDS2 server will increase significantly in the future. NDS2 provides an exceptionally fast and convenient means to fetch data for real-time analysis. It may also provide a distribution mechanism for the proposed Open Data Initiative.

Future improvements will include ports to additional platforms (e.g. Windows) and improved dynamic data finding by the server.

8. **ligoDV** The LIGO Data Viewer (ligoDV) project `https://wiki.ligo.org/LDG/DASWG/LigoDV` is aimed at increasing the accessibility of LIGO data and standard data processing algorithms to all scientists within the LSC. It currently consists of two primary sub-projects, ligoDV and ligoDV-web, described below.

   The primary software tool in the project, ligoDV, is a Matlab-based graphical user interface that allows LSC members to connect to LIGO data servers, specifically the network data servers NDS and NDS2, and retrieve data. Furthermore it provides a platform for applying mathematical manipulations such as filters, Fourier transform, coherence, transfer functions and others to this data and finally exporting and/or plotting the results. The package is essentially operating system independent, since it consists of a collection of m-files that require only a graphics-capable Matlab installation and NDS2 client. Owing to the portability of the NDS client, ligoDV is also location independent allowing users to query data and do studies while at meetings or anywhere with an Internet connection. The ligoDV user-base has grown over the past few years and it is now used widely within the LSC. This in turn has aided detector characterization, commissioning and data analysis studies by lowering the hurdles required to access LIGO data.

   LigoDV has been in active development for most of the last year and a new version has been released with the following improvements.

   - Saving of configuration data specifying server, time intervals and channel selection.
   - Detailed documentation has been developed covering installation and usage. The program GUI now includes buttons that link to the appropriate section of the wiki.ligo.org describing how to use that function.
   - On line notification when a new version is available.
   - Improved error messages and pop-up error windows.
   - Improved filter module that allows viewing the combined response of several filters.
   - Minor changes to the user interface to streamline operation.

   In addition there have been a number of requests for enhancements to ligoDV.

   The following are the development priorities for ligoDV in the coming year.

   - Extend the configuration operations to include filter specification and plot products.

- Use the new SWIG/Java bindings to NDS2 to remove the need for Matlab/C interface to be compiled for each version of Matlab on each operating system. This also includes using a local database to cache channel lists for faster access.
- Continue expanding filtering options to add pole/zero specification and the ability to import Foton filter definitions.
- Add Omega-scan as a new plot product.
- Continue to refine the user interface with the goal being to simplify operation by disabling or hiding options not pertinent to the processes defined.
- Improve channel list handling to work with the millions of channels available in the aLIGO era.

The continued development of ligoDV will lead to a much improved tool. This will benefit the detector characterization and analysis work remaining for Enhanced LIGO. It will also be a central component of the Advanced LIGO detector characterization program that will be actively monitoring data during the establishment of the first Advanced LIGO subsystems (DetChar priority 1 in Section 2.2.3.

LigoDV-web is a new product in development `https://ldvw.ligo.caltech.edu`. As we saw more users of LigoDV, it became obvious that the our biggest impediment to expanding the user base is the cost/availability of Matlab and the installation of the NDS2 client on desktop systems that are not running a reference operating system. While there have been vast improvements in the portability of the NDS2 client it can still be a challenge to install. There will always be a significant fraction of the LSC that can benefit from a web-based client that has essentially no accessibility barriers to allow quick-look studies of the data.

LigoDV-web is a Java based thin-client model product that has no installation requirements except a modern browser with javascript enabled. It uses the NDS2 client to access data and will provide most of the products available in LigoDV. It is fully integrated with the ligo.org Shibboleth authentication so that LSC-Virgo users can gain access to the site using their logo.org credentials. It provides quick easy access to all available data (raw, online, RDS, trend) on most Internet appliances including smart phones, tablets and computers. Furthermore, the channel list retrieval, databasing, data retrieval, calculations, and plot generation are all done server-side such that users need only specify a plot, wait, and then see it appear in their browser - at which point it has also been archived and they can share it as a link with others.

The development priorities for LigoDV-web over the next year are as follows.

- Continue development of the infrastructure to improve robustness, speed and improve the user experience.
- Allow users to export data products such as spectra and time series in formats that are easily read into other code such as python or Matlab for further analysis.
- Prefiltering data to ameliorate frequency leakage for data with a very large dynamic range (such as strain data).
- New plot products such as histograms, coherence and transfer functions.
- Automatic updating plots of online data.
- Offline processing of requests that require too much time for browsers to wait.

7.5.3 Services

1. **Network Data Simulator** It will be important to continually test and assess the data analysis infrastructure for the advanced detector era as it is developed. A new project will be established to simulate the data streams from the network of gravitational-wave detectors and deliver it to analysts by the same means they can expect during future observing runs. This will allow users to develop their analysis tools with knowledge of the key infrastructure and an operational testbed against which to test. A key component of this project will be to run regular and long-lived mock data challenges of increasing complexity which will allow the collaborations to efficiently benchmark analysis codes against each other. This project will be initiated in the coming year. Details should be available by mid 2011.

2. **Monitoring** The main advantage of having a customized solution to provide LDG metadata is that it can be integrated, redesigned and reconfigured at will, with almost any other tools designed to gather information about complex infrastructures. The LSCGIS prototype can be integrated with less flexible tools such as Nagios, ReSS (Re_source Selection Service, used by OSG), BDII, Relational DataBases, etc., which can help to improve the information service. Implemented as a RESTFul Web Service, LSCGIS is flexible and scalable enough that it can even use web technologies such as Google Maps API, PHP dynamic server scripting, be displayed in Internet enabled cellphones, etc.

   Under the umbrella of this project several studies are being carried out to choose among the best Grid monitoring technologies and to integrate them in a customized monitoring environment for LDG. The **OSG ReSS** is particularly interesting since it can also be integrated with Condor-G, which could be useful once LDG transitions from a Data Grid towards a Computational Grid, with the aid of other Grid technologies.

   Also, studies about integration of Identity Management technologies (Kerberos, MyProxy, LIGO Auth Project, etc.) with Monitoring services are being considered. We are convinced that no a single solution will be enough to cover all the needs of a complex VO such as LSC/VIRGO and that the integration of several customized proposals will be the best approach to keep the computational infrastructure as flexible and scalable as possible. Besides, intelligent workflows will need of all the best available information gathering and customized solutions in order to retrieve useful and relevant LDG metadata and use it as input for the analysis pipelines.

3. **LIGO Data Replicator (LDR)** Initial and enhanced LIGO have clearly demonstrated the need for bulk replication of interferometer data sets to computing centers around the world during the advanced detector era. The growing development of “real time” or stream based analysis in addition to file based analysis does not diminish the need for robust replication of curated interferometer data sets to computing sites for efficient consumption by data analysts and their codes.

   The experience gained during the LIGO S6 science run with data replication provided as a service (“LDR as a service”) to the Cardiff University and Birmingham University groups demonstrated that the software as a service (SAS) model for bulk data replication in the advanced interferometer era is not only viable but preferred. Individual computing sites are simply not staffed at a level that allows deep knowledge at each local site of all the necessary details for robust and continuous replication of data. Instead, the LDR as a service model demonstrated the efficiency of requiring at a computing site only a standards-based interface to local site storage (usually GridFTP) and then locating the rest of the necessary logic and tooling at a centrally managed collaboration facility, where local experts can monitor and tune the replication network over time.

   Of course moving all of the LDR functionality except for the interface to local site storage to one physical facility carries the risk that the entire replication network could fail if that one central facility should be cut off from the internet or go down for whatever reason. In the advanced detector era, hence, LDR as a service must evolve so that it leverages the necessary tools and infrastructure to provide a high availability service with failover capabilities supported by a small but expertly staffed geographically distributed set of data centers.

The S6 and earlier science runs have also demonstrated that data discovery, as provided most recently by the server tool LDRDataFindServer and the client tool ligo_data_find, should be to some extent decoupled from bulk data replication. While the server tool needs to be able to consume state information from the replication service, it need not be tightly coupled to the replication service and should be capable of consuming information about the location of data files from many sources in a "pluggable" fashion, and then delivering that information via a variety of standardized interfaces and APIs to various data analysis tools and other services.

4. **GRaCEDb** The current Gracedb/Lumin system is excellent prototype service accepting a number of injected event streams (MBTAOnline, Omega, Ringdown etc) and a small number of event subscribers (ROTSE, LOFAR, QUEST, TAROT, SWIFT etc).

   As we move to the era of Data Challenges and eventually Advanced LIGO, the set of pipelines reporting events will change with time, with new pipelines, modifications to existing pipelines, and changes in personnel leading to "black-box" code. The LIGO event system should have a well-defined protocol for working with the pipelines that create event triggers, so that streams can be added and throttled in a well-defined way. On the other side, the set of subscribers to LIGO events will grow, and the upgraded system should streamline the process of adding subscribers and handling the individual requirements.

   The current event model is an "imperative", where LIGO software decides what each follow-up telescope should do. As the number of subscribers grows, this individual attention will become an undue burden on LIGO staff. Furthermore, we expect stiff competition for robotic follow-up facilities, as new, prolific event streams come on line (LOFAR, LSST, etc). It will become more difficult to get the best facilities if LIGO expects to take immediate, imperative control of the telescope. The new model will need to shift to *informational* rather than *imperative*, meaning the subscriber gets what LIGO has observed, and decides what to do. Thus the telescope scheduling code (much of Lumin) will be run and modified by the event subscriber rather than the event author.

   Past events are also important, for studies of correlation with other event streams. Already astronomical events are being collected into repositories (PTF, Galex, CRTS, SWIFT, etc), and interoperability of these archives will be needed for these important scientific studies. The International Virtual Observatory Alliance has already defined a standard event representation (VOEvent), and many authors and subscribers are exchanging these standard packets. The LIGO event distribution system would be well-positioned for the future by adopting VOEvent.

   Currently, Lumin delivers messages by a protocol customized for each subscriber, and as the number of subscribers grows, this will be more and more difficult. Therefore the event distribution from LIGO should adopt a standard transport protocol. Some requirements for this may include buffering and reliable delivery, strong security (preferably linked to the LIGO Auth system), integrity signatures, indication of presence and readiness, broadcast, multiple implementations, and widespread adoption.

   In addition to delivering LIGO observations to follow-up facilities (Gracedb and LoocUp), LIGO is acting as a follow-up facility for external triggers from other observatories. These two sides of the same coin could be unified by handling *all* relevant astronomical event streams in the same way, whether they are from LIGO or not.

5. **Rapid Event Distribution** As noted in section 3.3.6, the science return of LIGO will be greatly improved if GW detections are backed up with afterglow detection in electromagnetic bands, especially if the follow-up observations are undertaken as soon as possible after the detection.

Rapid event release is well elaborated by the NASA GCN system [532], which has been sending rapid, electronic notices of gamma-ray bursts, and other phenomena, for nearly 20 years. The GCN is now one of many providers of astronomical events, and LIGO will become such a supplier itself in the era of Open Data.

The VOEvent format [533] has become an international standard for reporting and rapid follow-up of astronomical transients. There will be LIGO services that allow publication of gravitational-wave events and receipt by subscribers within seconds. Subscribers may selectively subscribe to event feeds, query past events, and investigate possible event correlations (e.g., GRBs and neutrino events).

The effort here is to ensure that LIGO has the requisite tools to send information about candidate events from GraCEDb to partnering astronomers for follow up. The LSC will develop/deploy simple client tools that allow rapid distribution via TAN (formerly NASA GCN), SkyAlert, and other mechanisms as needed.

6. **Identity Management** Moving into the advanced detector era, the size of the gravitational wave community (which includes the LIGO Laboratory, the LIGO Scientific Collaboration (LSC), Virgo and other collaborators) will continue to grow. Having centralized identity management for members of the community will be essential for a satisfactory user experience, for effective resource administration and for computer security. LIGO Laboratory and the LSC have initiated a joint effort called the Auth (Authentication and Authorizations) Project to develop a unified identity management infrastructure to serve the needs of the community. The project is currently funded on grid operations funding from the Physics at the Information Frontier award **PHY-0600953**. It focuses on four areas - core infrastructure to collect and store user information and create credentials, web services, grid services and general computing and shell access.

   The core infrastructure includes a custom MySQL database with PHP user interface to collect and store user information, two Kerberos realms (LIGO.ORG and LIGO-GUEST.ORG) to provide single sign-on (SSO) authentication to community members and collaborators, an LDAP directory service to provide authorization information and a second to provide user directory information, and an Internet2 product called Grouper which allows creates easy and flexible organization of LDAP entries into groups with an ability to delegate group management. Group membership forms the basis for all subsequent authorization decisions (eg members of the LSC Computing Committee group can view and edit the minutes of the LSC Computing Committee meeting).

   Web services leverage Internet2's Shibboleth software for authentication and authorizations. This integrates with Kerberos to provide an SSO web solution with fine-grained authorization capabilities to LIGO and LSC web services. We currently provide our own Shibboleth Identity Provider (IdP) service because too few community members participate in InCommon (or other Shibboleth federations) to make using external IdPs feasible, but our plan is to start leveraging external IdPs as they become more ubiquitous. The use of Shibboleth is starting to spread throughout LSC web resources and should be generic in the advanced detector era.

   Grid services will leverage MyProxy, a product developed at NCSA, to provide transparent grid access to the community leveraging Kerberos authentication. MyProxy will issue short-lived X.509 certificates and proxy certificates underwritten by the LIGO.ORG Certificate Authorities (CAs). Distribution of Grid Map Files with the MyProxy generated user credentials will be handled by an in-house product. At present, the LIGO CAs are in operation, and detailed planning documents for the rest of the infrastructure have been written. In the advanced detector era, the grid services will be fully deployed and operational. Based on extensive discussions with the grid CA community, we expect the LIGO.ORG CAs to be accredited by TAGPMA by that time as well.

General computing and shell services will leverage kerberos via SSH or PAM for login. Account provisioning will be serviced by LDAP and NSSwitch, with LDAP transparent proxy overlays to augment the LSC managed information with site-specific information. This model, which is intended for major community compute centers but not individual community institution workstations and laptops, is currently deployed for LHO and LLO general computing.

As well as the four major areas, there are a number of other IdM related services that the Auth Project provides support and development for, including mailing lists, request tracking systems, version control systems, special needs environments such as LIGO control room CDS systems, and others. A more comprehensive description of the plans and activities is available at the project wiki (`https://www.lsc-group.phys.uwm.edu/twiki/bin/view/AuthProject/WebHome`).

7.6 LIGO Open Science Center (LOSC)

LIGO has a mandate from the NSF to broadly disseminate data products from the LIGO gravitational wave (GW) detectors, including the full calibrated strain data sets, to the wider community of scientists (amateur and professional) and students, as laid out in the LIGO Data Management Plan [529].

This plan identifies two phases of data release. In phase 1, the detectors are evolving towards design sensitivity and the understanding of instrumental artifacts is in its early stages; detections are expected to be rare. In this phase, data release to the wider research community makes the most sense for validated gravitational wave data surrounding confirmed discoveries, and important non-detections where detectable gravitational waves might plausibly have been expected. A small number of example data releases have already been made for an injected event [531] and a significant non-detection [530]. LIGO will continue to build these data releases, creating a catalog.

In phase 2, the performance of the detectors and the understanding of their noise characteristics will have grown, and detections are expected to be more frequent. During this phase the entire body of gravitational wave data, along with associated information about the data quality, will be released to the wider research community.

The LIGO Open Science Center (LOSC) is a project that aims to meet these goals by making LSC data products and documentation as accessible as possible to outside users. LSC members, especially new LSC members, will also benefit from this effort. The LOSC strives to make data products interoperable with other astronomical data systems, using standard formats and service profiles whenever possible. The list of data products curated by the LOSC will eventually include:

- Low-latency GW transient alerts generated by the detector network (See section 7.5.3)
- A database of time periods when gravitational wave detectors in the network are collecting science-quality data. These currently are stored (internal to the LSC) as “science segments”: GPS start-stop time pairs. These should be easily searchable and presentable in a variety of formats.
- Data products associated with LSC/Virgo observational and technical papers. The LSC and Virgo have already begun producing science summaries of every publication, along with downloadable data products for every figure and table in that publication (`http://www.ligo.org/science/outreach.php`). The LOSC will provide links to these pages.
- Detailed information about confirmed detections and important non-detections (e.g., associated with nearby GRBs). These will include short calibrated h(t) time series snippets associated with the event. Prototypes of this kind of data release have been prepared for the S6/VSR3 blind injection (`http://www.ligo.org/science/GW100916/`), and for the non-detection of a gamma-ray burst that appeared to originate nearby (`http://www.ligo.org/science/GRB051103`).

- Searchable catalogs of detected events (CBC or Burst transients, and CWs from spinning neutron stars), with the ability to select event categories or generate summaries (e.g., a histogram of network SNRs for CBC events).
- Bulk GW detector strain data “h(t)”. It should be noted that these data streams are mostly noise, but these are the data streams that are searched for signals. These data streams will be accompanied by essential auxiliary data; e.g., associated noise power spectral densities, data quality information (encoding times when the quality of the data is degraded and/or suspect), calibration information, etc.
- Data access and manipulation tools that are easy for outside users to employ. These may include: GUIs and automated scripts for data queries and downloading and basic scripts (MATLAB, Octave, Python) for reading in data, resampling, making time series plots, noise PSDs, time-frequency spectrograms, low-pass and band-pass filtering, and even simple glitch/burst finding.
- Documentation. The LOSC web portal will include links to web pages containing background on GW science and LIGO, education and public outreach (EPO) pages, etc. The web portal will also include unique documentation, tutorials, and webinars on the use of LIGO data.

The LOSC will implement a software infrastructure to make each of these data products and associated material easily accessible to users. Users’ first point of entry will be a web portal inspired by similar open data sites such as IPAC (`http://www.ipac.caltech.edu`), Hubble Space Telescope MAST (`http://archive.stsci.edu/`), LAMBDA CMB (`http://lambda.gsfc.nasa.gov/`), and NASA HEASARC (`http://heasarc.gsfc.nasa.gov/`).

The web portal should provide one-click access to all LOSC services. This will include the ability to discover available open data, access it, find metadata and documentation, and find toolkits to start using the data. In addition, it should allow machine-friendly access to LOSC data and services without the need to surf-and- click, such as command-line tools, web-services and/or a software library with an API.

Prototyping of open data releases will continue over the next 12 months. Several new staff will be hired to prototype the gravitational-wave object catalog(s), the web services framework for open data access, and the procedures for data curation. Goals for the next year include:

- Mount a LOSC web portal aimed at transient astronomers and numerical relativists. At first, this portal will have access restricted to the LSC and partners, such as the LIGO Astronomy and Astrophysics Advisory Panel (LAAAP).
- Mount a prototype catalog of mock detected GW transient events by exposing selected GraceDB resources.
- Construct prototypes of mock events (e.g., recovered Engineering Run data injections) containing information similar to what is available in Blind Injection open data page: `http://www.ligo.org/science/GW100916/`.
- Mount a prototype of a useful database of time periods when gravitational wave detectors in the network are collecting science-quality data.
- Begin development of data-intensive web services for accessing bulk data.
- Begin development of a data manipulation software toolkit for users.
- Begin development of LOSC-specific documentation.

- Work with the LSC to sponsor and participate in open data workshops with the global astronomical community. Report on LOSC development progress, provide hands-on data access and analysis tutorials, and gather and act on user feedback.
- Create a “LIGO Open Data User’s Group”.

Each of these goals is a major undertaking, and they will all evolve as we better understand the interests of the potential user community. In the short term, we aim for simple prototypes of each service or activity, in order to solicit feedback from users. All LIGO open data products will be produced by the LSC, and are expected to be useful to and used by the LSC. All open data products will be internally reviewed and validated by an LSC review committee composed of LIGO data experts, and externally reviewed by volunteers drawn from potential LIGO open data users, prior to public release.

8 Virgo computing and software

In 2012/2013 the work to write the Advanced Virgo computing model has begun, and a draft version 0.1 is available since April 2013 under the Virgo TDS system (VIR-0129A-13). It includes three out of 5 parts of the model, as detailed below. The official approval by the collaboration has not been asked yet, as the whole process will be done once the document will be ready in its 1.0 version, as foreseen by Octber 2013. The CM will guarantee a production and analysis system which gives an easy and robust access to data and resources, for both commissioning and analysis. The document is intended to be a living document, updated with well defined cycles. In fact, an “Implementation Plan” will then describe the technical solutions, as they are foreseen with the actual computing resources, together with plans for testing them. The Model is sustained by a “Management Plan”, which addresses the management procedures to make reality checks on it. As said, the Model is composed by five parts: Workflows, Data Model, Data Management Distribution and Access, Software description and Computing Facilities resource requirements. Software description and Computing Facilities resource requirements are the parts we are now writing.

The Computing Model for Advanced Virgo is being written taking advantage from the experience gained so far with the data taking and analysis from the first engineering runs to the latest Science runs VSR1-VSR4 (the last run ended in September 2011). It takes also into account the technological progresses of these years, from the original Virgo Plan, which is dated back to the year 2002, VIR-PLA-DIR-7000-122 The Computing Model reflects also needs and constraints arised from the LIGO/Virgo agreement with which we have been facing during the last years, and have finally been able to address in an organized way in this Computing Model.

To explore gravitational wave (GW) physics with the Advanced Virgo detector the Collaboration aims to define a Computing model that fully supports *accessing* and *analyzing* the data. In general analyses run on real LIGO-Virgo data, more rarely on simulated data. Therefore, the goal of the computing model is to define a production and analysis system able to guarantee an easy and robust access to data and resources. For this goal data distribution and data access are crucial points.

Advanced Virgo has a hierarchical model for data production and distribution: different kinds of data are produced by the detector and firstly stored at the EGO site in Cascina (“Tier-0”). Two copies of the data sets are stored to the national Computing Centres (CC), CNAF (Bologna) and CCIN2P3 (Lyon) (“Tier-1s”). A sub-set of LIGO data are also copied directly to our CCs (this is different from the procedure adopted for Virgo) and another sub-set is copied to Cascina for “low-latency” analysis, which have the need to produce fast results (see below). Some data, from CNAF and CCIN2P3, are also moved to “Tier-2s” (institutionals, managed by Virgo members), “Tier-3s”(institutionals, not managed by Virgo members), “Tier-4s” (users workstations).

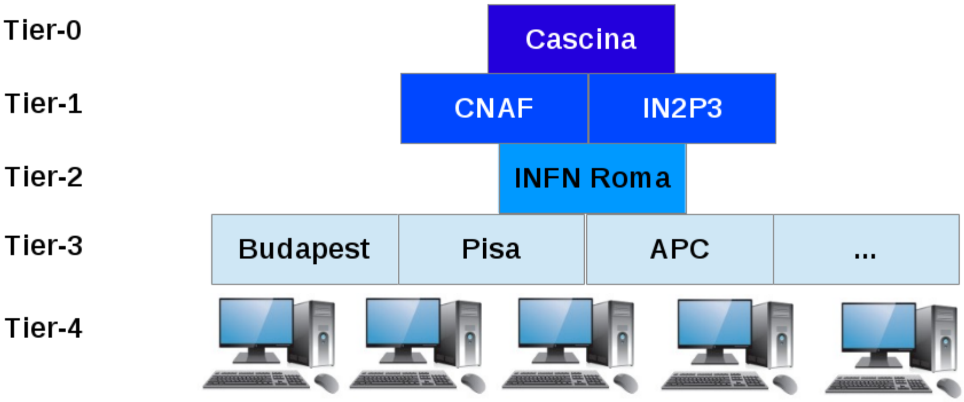


Figure 4: Virgo Computing Centers. Some analysis are carried on jointly with LIGO colleagues and thus also LIGO CCs are used, even if not shown here (we might consider them at the level of "Tier-3s").

The Cascina facility is dedicated during the runs to data production and to different detector characterization and commissioning analysis, which have the need to run "on-line" (with a very short latency, from seconds to minutes, to give rapid information on the quality of the data) or "in-time" (with a higher latency, even hours, but which again produce information on the quality of the data within a well defined time scale). The detector characterization analyses give support to both commissioning and science analysis. There is no permanent data storage in Cascina, and only data of a given time period (six months so far for Virgo, still to be defined for ADE) are stored there. The Scientific analyses are carried on at the Virgo Computing Centers (CNAF and CCIN2P3), with the only exception of "low-latency searches". And some analysis, due to the fact that we analyze data jointly with LIGO for many searches, are carried on in LIGO CCs. This as been detailed in the description of DA workflows. The AdV centres receive a copy of the data and provide storage resources for permanent data archiving. They must guarantee fast data access and computing resources for off-line analyses. Finally, they must provide the network links to the other Virgo computing resources.

The two CCs are integrated in the European GRID Initiative (EGI): for this reason we believe that pushing toward the adoption of the EGI products for ADE would be quite convenient. But the main constraint behond this is that we will always guarantee to users the possibility to work out of GRID, using local access to the data through "ffl" file lists, use of native batch systems and interactive when appropriate. Using EGI, we will take advantages of various tools and solutions already available and fully supported. To this goal, we have started working to implement a Data Transfer framework in the GRID environment, at least towards CNAF. In fact, some work is still needed to fulfill this scenario. For instance the data access interface used by Virgo at CCIN2P3 is based on XrootD; in order to be integrated in Grid it is necessary to install a specific layer between XrootD and the Grid Storage Resource Manager (SRM), and this has to be planned with the IN2P3 staff. We are going to exploit if this scenario will be possible or not.

We also aim to run most off-line science analyses in the GRID (any evolution of the GRID which might be working by ADE) framework. At the same time we need to guarantee that the developement, testing of new pipelines and the not computationally demanding analyses can be carried on outside the Grid environment, i.e. running interactive analysis or using local batch systems. This requires in particular the possibility to access subsets of data using "standard" technology, e.g. posix, scp, etc. To guarantee the accessibility of the data to a community of users as wide as possible we are thus investigating the implementation of a "user-friendly" Remote Data Access framework (based on a client-server communication protocol), which would be a layer between the users and the different underlying storage technologies. This framework would require the implementation of a "File Locator" database, which provides the information on the physical location of the data files and on the methods how to read them, and a database of the scientific metadata Clearly, this challenge (foreseen for the end of 2014) would take great advantage if the Tier-1 centers could adopt the same base technology.

Another hot topic is that as a consequence of the LIGO/Virgo agreement, the most of our Science analyses are carried on using both Virgo and LIGO data. Then in practice some analyses are performed in our Computing Centers and some others are carried on in ("LIGO Scientific Collaboration") LSC CCs. The latter are based on the "LSC Data-grid" (LDG) environment, whose workflows are not directly compatible with GRID workflows. It is therefore important, as we don't want to be in the position of not being able to run a particular analysis on our CCs (even only to repeat an analysis or to make additional tests), that the software we develop for our analyses should be independent of the used platform, or at least easily adaptable to different platforms.

This is a strong challenge, but we have shown it is possible. For instance, making use of the "Pegasus" workflow management system, we have already succeeded in executing the main CBC (Compact Binary Coalescence) search pipeline on both Virgo (at CNAF, in the EGI environment) and LIGO computing infrastructures.

We are also envisaging the possibility to run our pipelines in clusters using GPU technology. For this goal we started to translate part of our codes in the OpenCL language, which allows transparent execution on CPUs or GPUs.

A particular class of GW analysis are the so-called "low-latency" searches, which aim to provide fast alerts to the astronomical community in order to perform follow-up analyses of candidate GW signals. These searches require special solutions for both data transfer and computing workflow. The input data consist of the science data stream of the GW detector network (ADLIGO Hanford, ADLIGO Livingston and ADVirgo) and the data quality information. The produced output triggers are finally stored in a joint LIGO-Virgo database (GRACEDB is the one so far used) and sent to the astronomical community.

We foresee two different "low-latency" searches: the Multi Band Template Analysis (MBTA, a CBC pipeline) will run in Cascina; the Coherent Wave Burst (version 2) analysis (CWB-2G, a GW burst search pipeline) will run on one of the LIGO clusters.

The most important issues addressed by the Advanced Virgo computing model may be summarized as follows:

- guarantee adequate storage and computing resources at Cascina, for commissioning, detector characterization and low-latency searches;
- guarantee fast network links between Cascina and LIGO CCs for low-latency searches;
- guarantee reliable storage and computing resources for off-line analyses in the CCs (CNAF and CCIN2P3);
- push towards the use of geographically distributed resources (GRID), whenever appropriate;
- push towards a homogeneus model for Bulk Data Transfer (Virgo data from Cascina to CCs and LIGO data to CCs), Data Bookkeping and Data Access;

All the details are and will be described in the cited documents (model and implementation plan).

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