LOOC-UP: Seeking Optical Counterparts to Gravitational-Wave Signal Candidates

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MOTIVATION

The general theory of relativity predicts that gravitational waves – perturbations in the geometry of spacetime – are emitted when massive objects change their shape or orientation rapidly, and propagate outward at the speed of light. Large gravitational-wave (GW) detectors are now listening for the signatures of energetic astrophysical events: mergers of neutron stars and black holes, core collapse of massive stars, quasinormal modes of disturbed neutron stars, cosmic string cusps, and more.

Many plausible GW sources release **a lot** of energy, some of which is likely to appear as electromagnetic emission. Specific models have been proposed for many progenitors. In some cases these electromagnetic transients may be detected in the course of regular surveys as gamma-ray bursts (GRBs), soft gamma repeater (SGR) flares, or supernovae. LIGO and Virgo are already carrying out "externally triggered" searches for GW signals associated with those reported events. However, some relatively nearby events may be missed by these surveys, e.g. due to the beaming of gamma-ray emissions or being out of view at the time of the event.

PROJECT GOALS

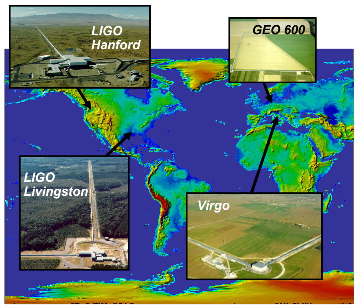
Capture a transient optical counterpart (if possible) in order to:

► **Confirm the candidate as a real astrophysical event**, even if the GW signal is too weak to stand out clearly from the background on its own

► **Obtain additional information about the source** such as host galaxy, relative timing and strength of GW and optical emissions

STRATEGY

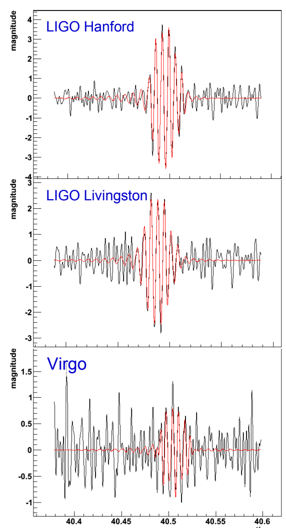
1. Identify GW event candidates ASAP



The LIGO and Virgo detectors are the largest and most sensitive gravitational-wave detectors to date. They utilize sophisticated laser interferometers with "arms" up to 4 km long which are capable of measuring length *changes*, induced by a passing gravitational wave, as small as ~1 part in 10^{21}. These quadrupole antennas **respond to GW signals arriving from almost anywhere in the sky**. (GEO 600, somewhat smaller and less sensitive, is currently offline for upgrading.)

As data is collected, it is calibrated in near-real time and immediately transferred to multiple data centers. **The data is then analyzed *coherently* to search for GW "burst" signals** using two algorithms: Coherent WaveBurst and Omega Pipeline. Each of these looks for consistent signals appearing in all detectors, taking into account the different polarization responses and relative time delays. These algorithms have good efficiency for arbitrary burst signals in the LIGO/Virgo frequency band, complement-ing matched-filter searches for binary inspirals and other well-modeled signals.

The significance of an event candidate is evaluated by comparing its strength to the distribution of "background" from detector noise fluctuations, estimated by analyzing time-shifted data streams. Candidates above certain thresholds are passed along for further processing. These **thresholds are set low in order to accept weak GW signals**.



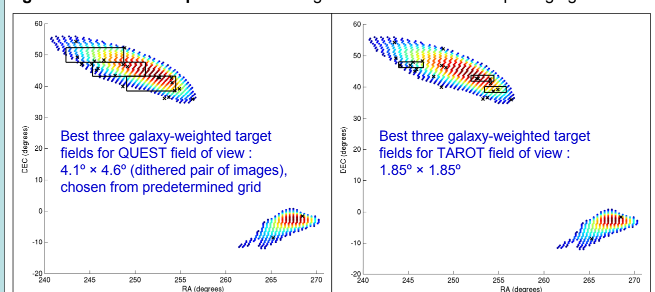
Above: A simulated signal injected coherently into the LIGO and Virgo detectors and recovered by Coherent WaveBurst. The black traces are the time-series data from each detector, whitened and bandpassed to selected the most sensitive frequency range, 64–2048 Hz. The red traces are the recovered waveforms in each detector corresponding to the inferred plane-wave GW signal.

2. Determine apparent arrival direction

Coherent event reconstruction allows for a general signal in the two GW polari-zation states expected from general relativity. Due to their different orientations, each detector responds to a different linear combination. If the arrival direction were known and there were no noise, then two detectors would be sufficient to fully reconstruct an arbitrary signal. Having *three* (or more) detectors over-determines the solution and allows all arrival directions to be considered, with a consistency test indicating **which arrival directions are most consistent with the model of a coherent signal plus normal detector noise.**

Studies show that Coherent WaveBurst and Omega Pipeline can localize very strong GW signals to about one square degree. However, the weaker signals near the threshold of detectability typically have position uncertainties of tens of square degrees, and often there are multiple disconnected patches on the sky. This fact motivates using **telescopes with wide fields of view** (FOVs) to follow up GW event candidates.

At current sensitivity levels, the GW detectors are limited to relatively nearby sources. For instance, a stellar-mass black hole / neutron star binary inspiral can be detected out to a maximum distance of ~50 Mpc. Therefore, we **target galaxies within 50 Mpc** when selecting coordinates for follow-up imaging.



Above: Coherent WaveBurst probability maps (indicated by colored dots) for different arrival directions considered for a selected GW event candidate. Black crosses indicate locations of known galaxies within 50 Mpc. Rectangles indicate telescope fields chosen to maximize chance of catching the optical transient (assuming there is one coming from a galaxy) for three pointings of the QUEST (left) and TAROT (right) cameras.

Elapsed time from arrival of GW signal: 5–10 minutes

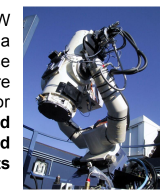
3. Obtain prompt optical images

At the current sensitivity level, few (if any) of the event candidates are expected to be real GW signals. Nevertheless, the great value of the "extra" optical image data in case of a discovery justifies the effort.

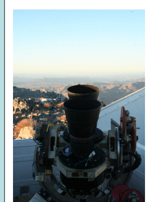
Even if an apparent optical counterpart is found, any promising GW event candidate will be subject to intense scrutiny to judge whether it constitutes a detection. Therefore, the current mode of operation is to work with **selected rapid-response telescope partners** by special arrangement. Public alerts will presumably begin in the Advanced LIGO / Advanced Virgo era when GW signals will be detected regularly.

A program called LUMIN receives notifications of GW event candidates and evaluates their significance. If a candidate is strong enough that the effective false alarm rate is less than one per day, text messages are sent to LSC/Virgo team members to check the data for problems. **If the data is clean and the candidate position localized reasonably well, imaging requests are sent to the telescopes.**

Elapsed time: 15–30 minutes



TAROT (scopes in France and Chile)



Pi of the Sky (Chile, 20×20° FOV)

Images will be analyzed to check for transients by comparing with reference images taken earlier or later. In principle, if an optical transient can be identified quickly, then larger-aperture telescopes with various instruments could be brought to bear.

Challenges

► **Unknown time scale** for optical signal – we aim at scales ranging from tens of minutes (like X-ray and optical afterglows seen for some GRBs) to hours or a few days (like supernovae)

► **Rapid action needed** to analyze data, evaluate GW candidates, and trigger telescope observations

► **Accidental coincidences with optical transients** are likely if one looks deeply enough, but we will focus on relatively bright transients since a detectable GW source is probably fairly nearby

PROJECT STATUS

LIGO and Virgo are currently in the middle of the S6/VSR2 science run, taking data while also testing new detector technologies.

The LOOC-UP project was implemented and tested in 2009 and began sending triggers on December 17. Initial telescope partners are TAROT, QUEST, and Pi of the Sky. A closely related project has lined up Swift target-of-opportunity observing slots. A few more telescopes may be added later in 2010, along with a near-real-time search pipeline focused on compact binary inspirals.

This is a relatively modest start for near-real-time multimessenger astrophysics with gravitational waves. **A major goal of the present effort is to gain experience in preparation for the Advanced LIGO / Virgo era**, on track to begin in 2014 or 2015.

MORE INFO

J. S. Bloom et al., "Coordinated Science in the Gravitational and Electromagnetic Skies", arXiv:0902.1527 (2009)

J. Kanner et al., "LOOC UP: locating and observing optical counterparts to gravitational wave bursts", *Classical and Quantum Gravity* **25**, 184034 (2008)

C. W. Stubbs, "Linking optical and infrared observations with gravitational wave sources through transient variability", *Classical and Quantum Gravity* **25**, 184034 (2008)

J. Sylvestre, "Prospects for the detection of electromagnetic counterparts to gravitational wave events", *ApJ* **591**, 1152 (2003)

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