Analysis of Data from LIGO and GEO

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Outline of this talk

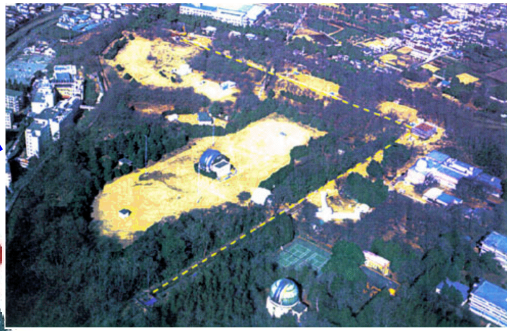
- The instruments
- Overview of S1 and S2 runs
- *Preliminary* Analysis results from S1 run:
  - Binary Coalescence
  - Pulsars and CW Sources
  - Stochastic Background
  - Unmodeled Burst Sources
- Lessons learned
- Plans for S2 and beyond

LIGO

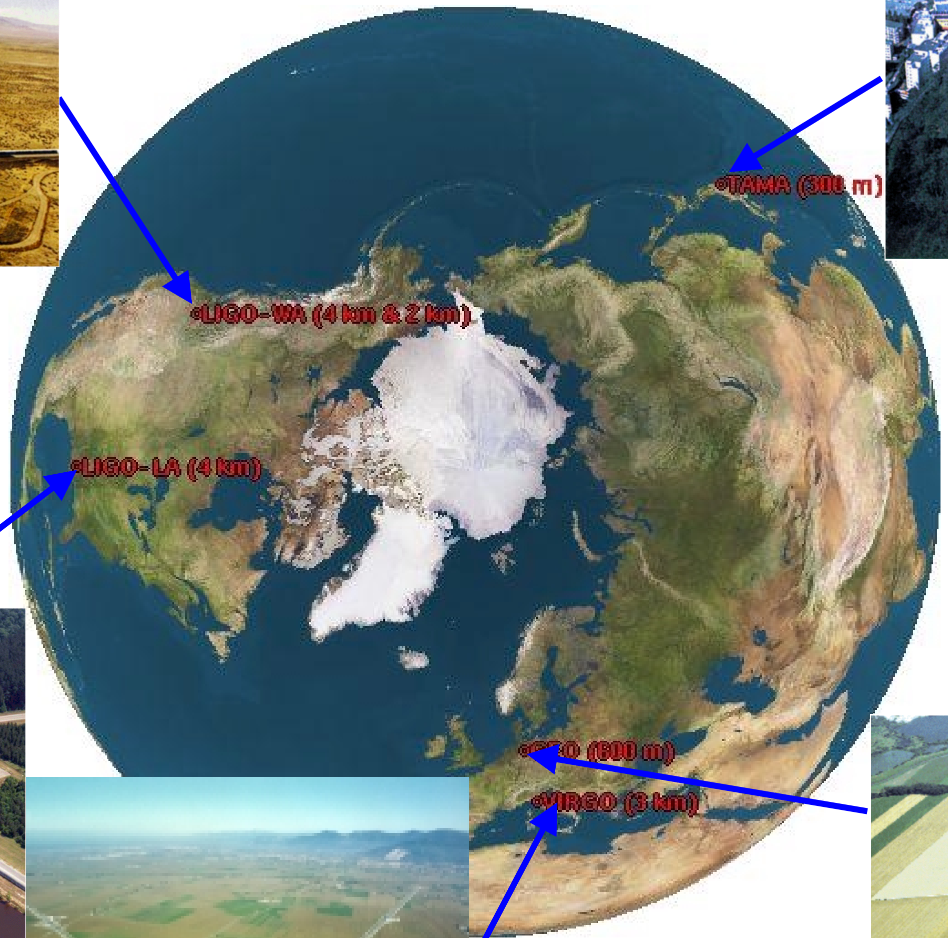
Gravitational Wave Interferometers Worldwide

GEO 600

LIGO Hanford WA (4km & 2km)



TAMA (300m)



AIGO

LIGO Livingston LA (4km)

GEO (600m)

VIRGO (3km)

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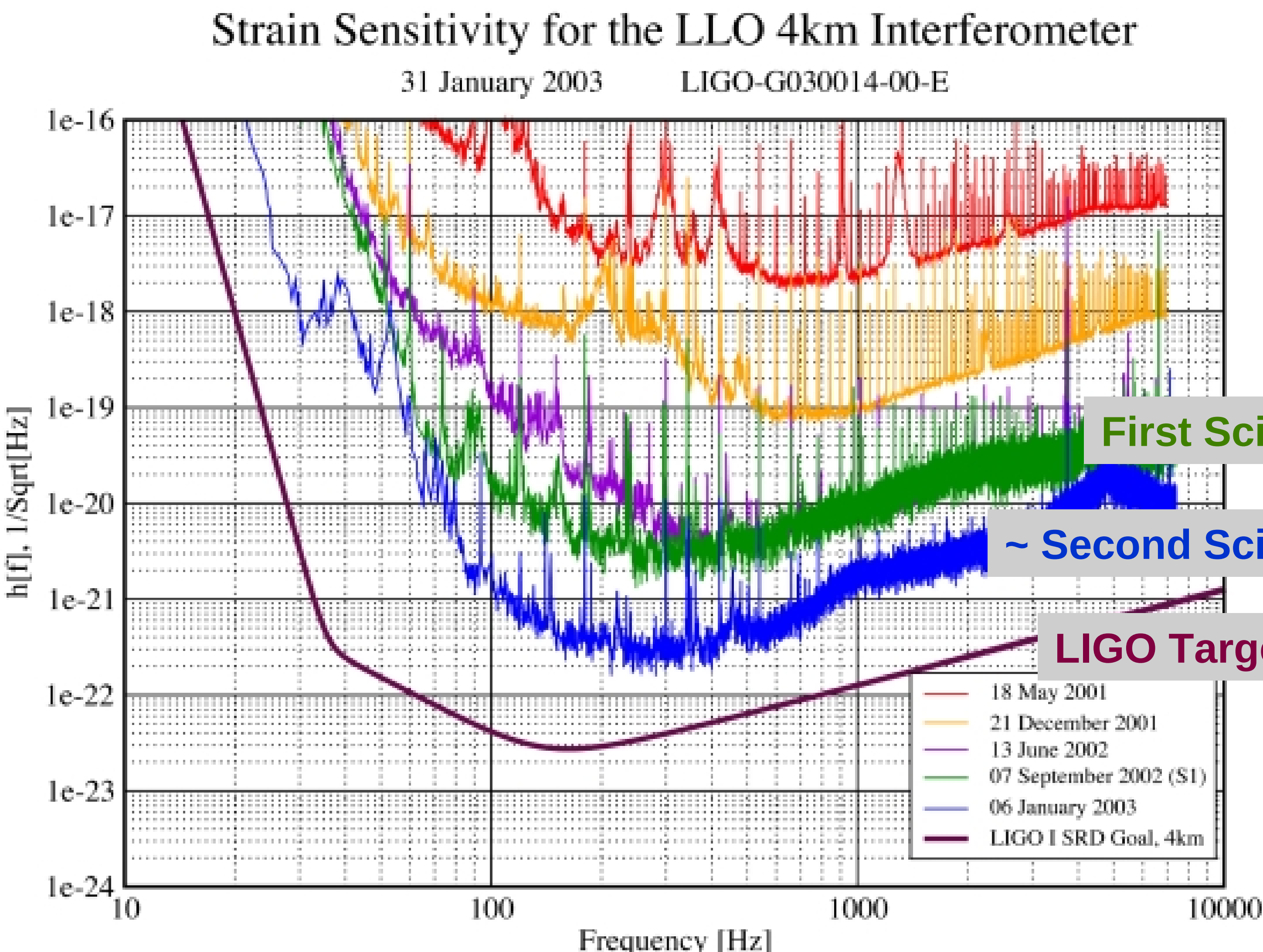
Sensitivity Improvements



First Science Run S1

~ Second Science Run S2

LIGO Target Sensitivity

Sensitivity in S1

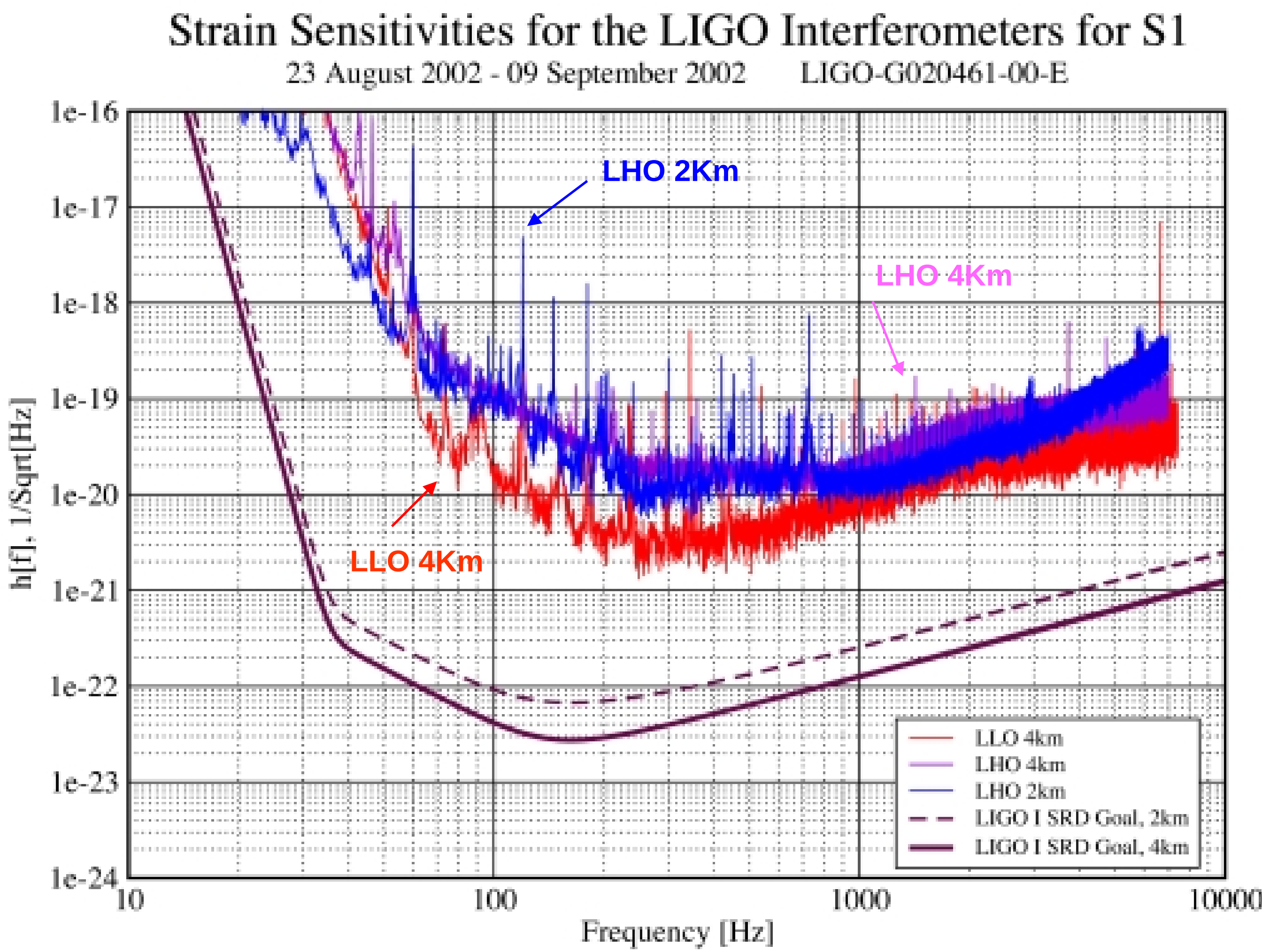
LIGO S1 Run

"First Upper Limit Run"

- **23 Aug–9 Sept 2002**
- **17 days**
- **All IFOs in power recycling config**

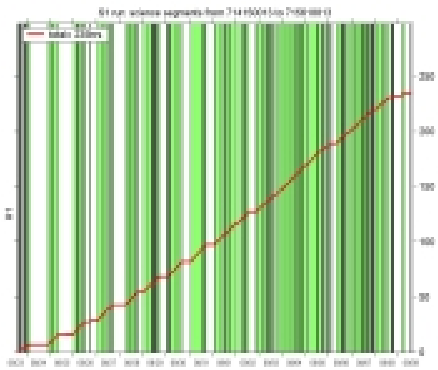
GEO in S1 RUN

Ran simultaneously In power recycling Lesser sensitivity

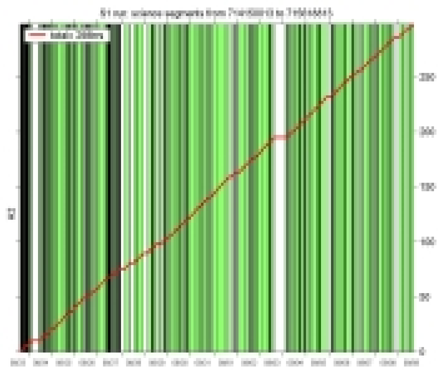


Lock Summary from S1

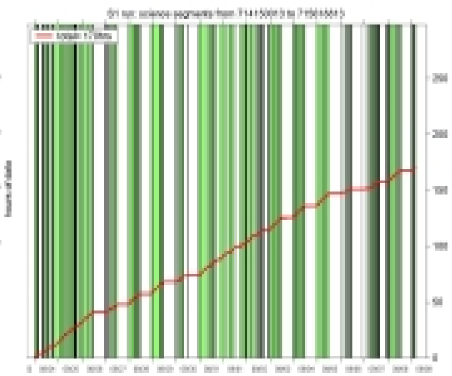
H1: 235 hrs



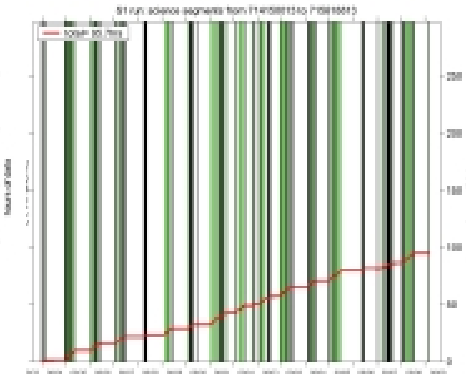
H2: 298 hrs



L1: 170 hrs



3X: 95.7 hrs



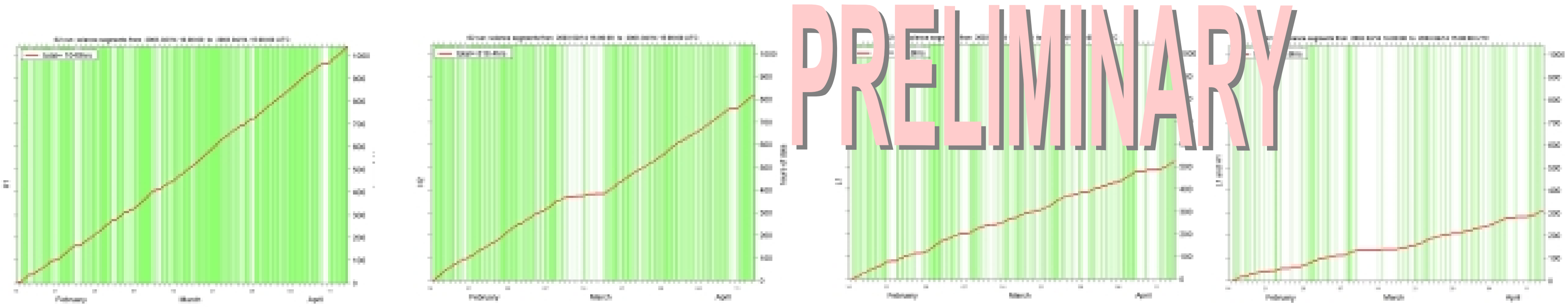
Red lines: integrated up time **Green bands (w/ black borders): epochs of lock**

- **August 23 – September 9, 2002: 408 hrs (17 days).**
  - **H1 (4km): duty cycle 57.6% ; Total Locked time: 235 hrs**
  - **H2 (2km): duty cycle 73.1% ; Total Locked time: 298 hrs**
  - **L1 (4km): duty cycle 41.7% ; Total Locked time: 170 hrs**
- **Double coincidences:**
  - **L1 && H1 : duty cycle 28.4%; Total coincident time: 116 hrs**
  - **L1 && H2 : duty cycle 32.1%; Total coincident time: 131 hrs**
  - **H1 && H2 : duty cycle 46.1%; Total coincident time: 188 hrs**

- **Triple Coincidence: L1, H1, and H2 : duty cycle 23.4% ; total 95.7 hours**

Preliminary S2 Summary

H1: 1040 hrs   H2: 818 hrs   L1: 523 hrs   3X: 312 hrs



Red lines: integrated up time   Green bands: epochs of lock

- February 14 – April 14, 2003: 1415 hrs (59 days - 1 hour).
  - H1 (4km): duty cycle 73.5% ; Total Locked time: 1040 hrs
  - H2 (2km): duty cycle 57.8% ; Total Locked time: 818 hrs
  - L1 (4km): duty cycle 37.0% ; Total Locked time: 523 hrs
- Double coincidences:
  - L1 && H1 : duty cycle 30.5%; Total coincident time: 431 hrs
  - L1 && H2 : duty cycle 24.8%; Total coincident time: 351 hrs
  - H1 && H2 : duty cycle 49.4%; Total coincident time: 699 hrs

- **Triple Coincidence: L1, H1, and H2 : duty cycle 22% ; total 312 hours**

Issues in Data Analysis

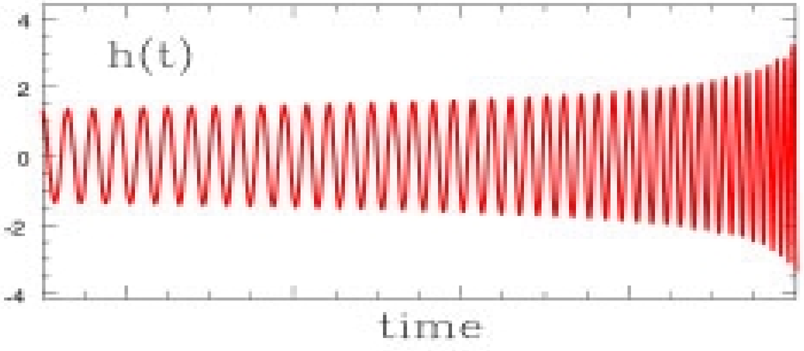
- **Interferometric data:** continuous time series (16KHz) of anti-symmetric port measures the strain of a gravitational wave.
- Additional **auxiliary** channels report on servo systems and instruments' environment. How should we use these?
- Instrument **calibration** at the 10% level:
  - » Response tracking: continuous fixed sinusoidals.
  - » Transfer function mapping: complete sweep sine calibration.
  - » Experimental "autocalibration system" tested in S1, implemented in S2.
- Several data analysis options: LDAS, DMT, grid-based (Condor)
- Analysis **emphasis**:
  - » Establish **methodology**, since **no** sources are expected.
  - » End-to-end **check and validation** via software and hardware **injections** mimicking passage of a gravitational wave.

LSC Data Analysis Organization

- LSC data analysis is currently organized in four working groups:
  - » Binary inspiral (Patrick Brady, Gabriella Gonzalez)
  - » Pulsars/CW (Marialessandra Papa, Mike Landry)
  - » Stochastic BG (Joe Romano, Peter Fritschel)
  - » Burst (Erik Katsavounidis, Stan Whitcomb)
- LSC LIGO-I author list has ~300 individuals and ~30 institutions from the USA, Europe, and Asia

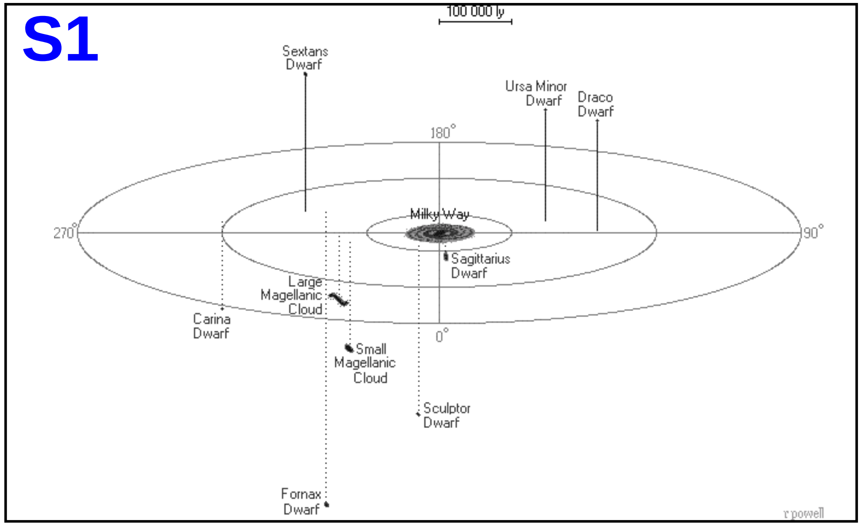
Search for Inspirals

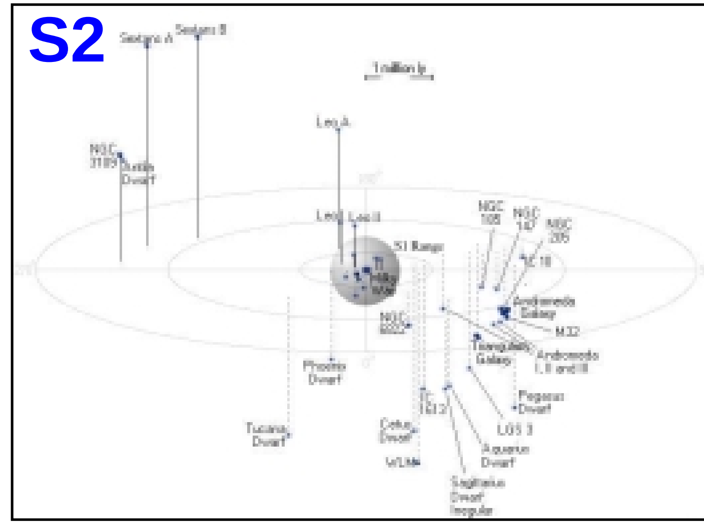
- **Sources:** orbital-decaying **compact binaries: neutron star** known to exist and emitting gravitational waves (Hulse&Taylor).
- **Analysis goals:** determine an **upper limit** on the **rate** of **binary neutron star** inspirals in the universe.
  - » S1 range included Milky Way (our Galaxy) and LMC and SMC
  - » S2 range includes Andromeda
  - » For setting upper limits, must have (and use!) source distribution model
  - » Search for black hole binaries and MACHOs will be pursued in the future
- **Search method:** system can be **modeled**, waveform is calculable:
  - » use optimal **matched filtering**: correlate detector's output with template waveform

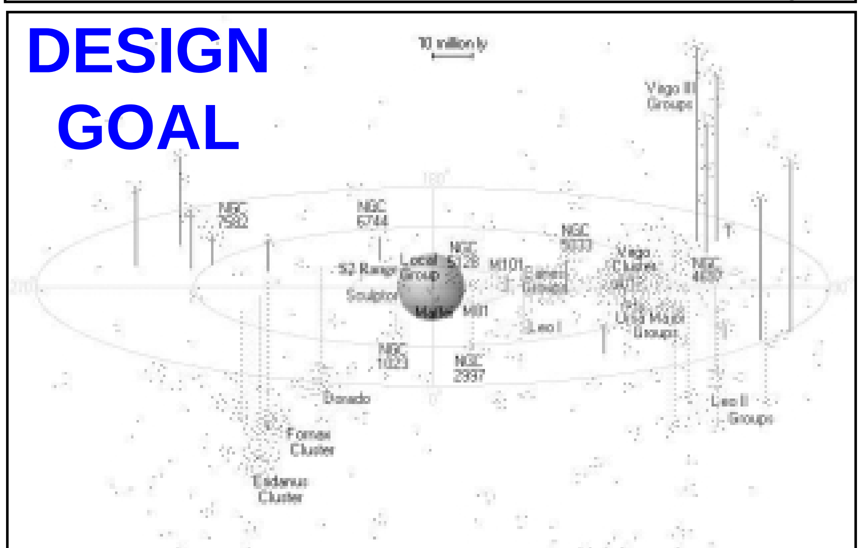


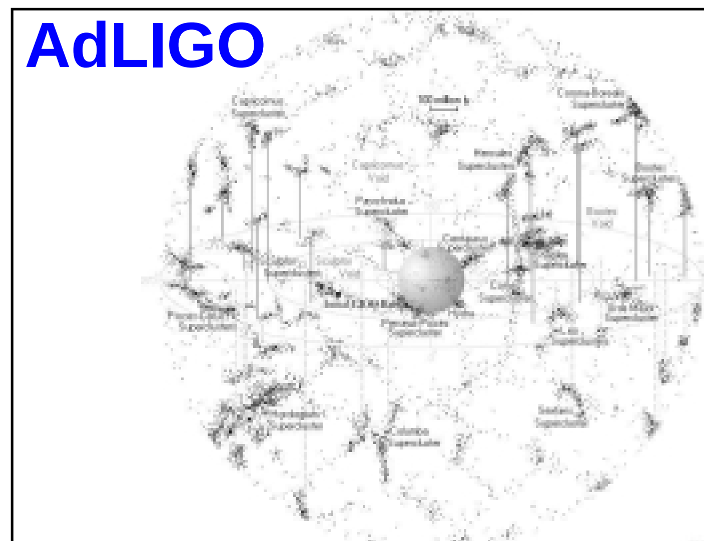
LIGO

Range for Binary NS









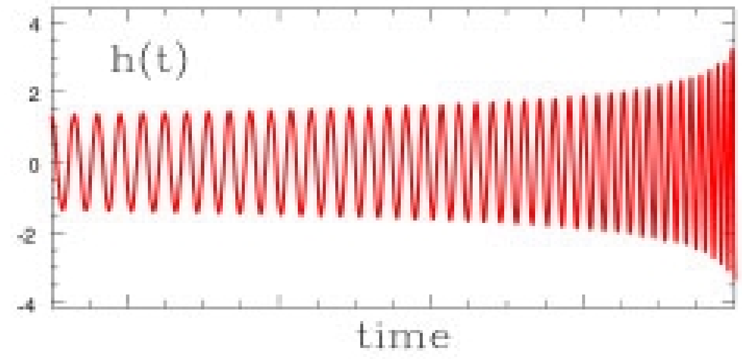
Images: R. Powell

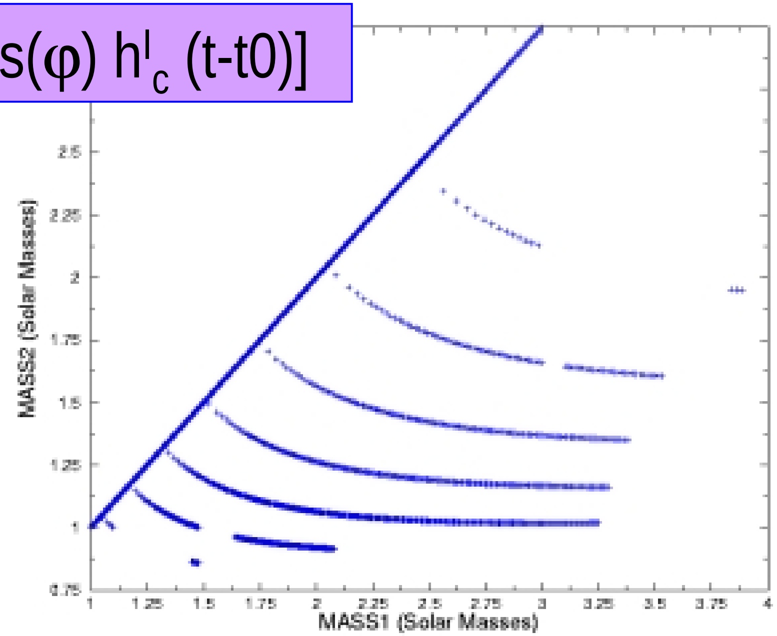
Inspiral Template Bank

- Use template based matched filtering algorithm
- Template waveforms for non-spinning binaries
  - » 2.0 post-Newtonian approx.

$$s(t) = (1\mathrm{Mpc}/D) \times [\, \sin(\varphi)\, h^{I}_{s}(t-t0) + \cos(\varphi)\, h^{I}_{c}(t-t0)]$$

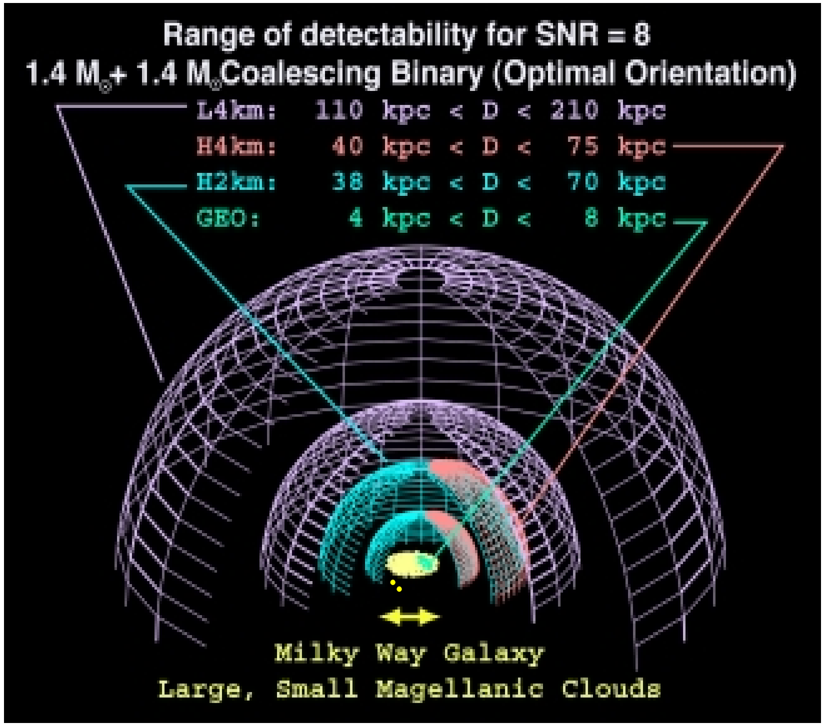
- D: effective distance; φ : phase
- Discrete set of templates labeled by I=(m1, m2)
  - » 1.0 Msun < m1, m2 < 3.0 Msun
  - » 2110 templates
  - » At most δ = 3% loss in SNR ρ





S1 Sensitivity to Inspirals

- 1-3M_{sun} **neutron star** search
  - » Second-order post-Newtonian template waveforms for **non-spinning** binaries
  - » Discrete set of 2110 templates designed for at most 3% loss in SNR
- **Range** of detectability of a 2x1.4 M_{sun} optimally oriented inspiral at SNR = 8
  - » **L1:** 110 kpc < D < 210 kpc
  - » **H1:** 40 kpc < D < 75 kpc
  - » **H2:** 38 kpc < D < 70 kpc
- Sensitive to inspirals in
  - » **Milky Way, LMC & SMC**
- **Playground** data set (10% real data) used to set thresholds, choose vetos for upper limit work



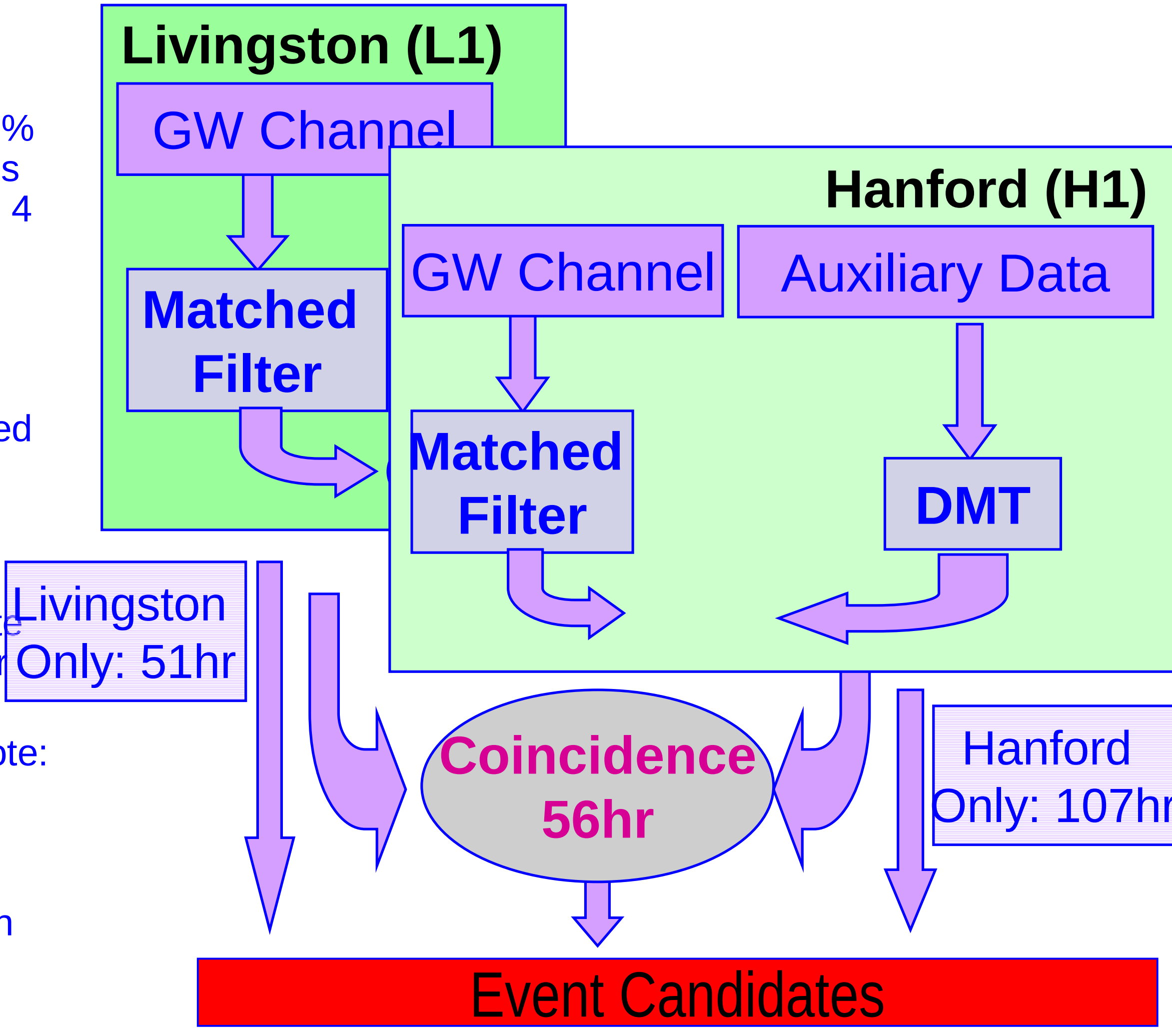
PRELIMINARY

Computational Engine

- Search run online at sites
- Offline at Medusa cluster (UWM)
  - » 296-node cluster
  - » Single CPU nodes: 1 GHZ P3
  - » 512 MB memory/node
  - » Mixture of 100 Mb/s and Gb/s networking
  - » Foundry Networks Fastiron III central switch (private subnet)
  - » Each node has 80 + 120 GB disk. Total spinning disk storage for data: 58 TB
  - » UPS systems for nodes, masters, and switch
  - » 54 kVA of power (use 23-31 kVA)
  - » 50 kVA of air conditioning
  - » Room full of undergraduate students!

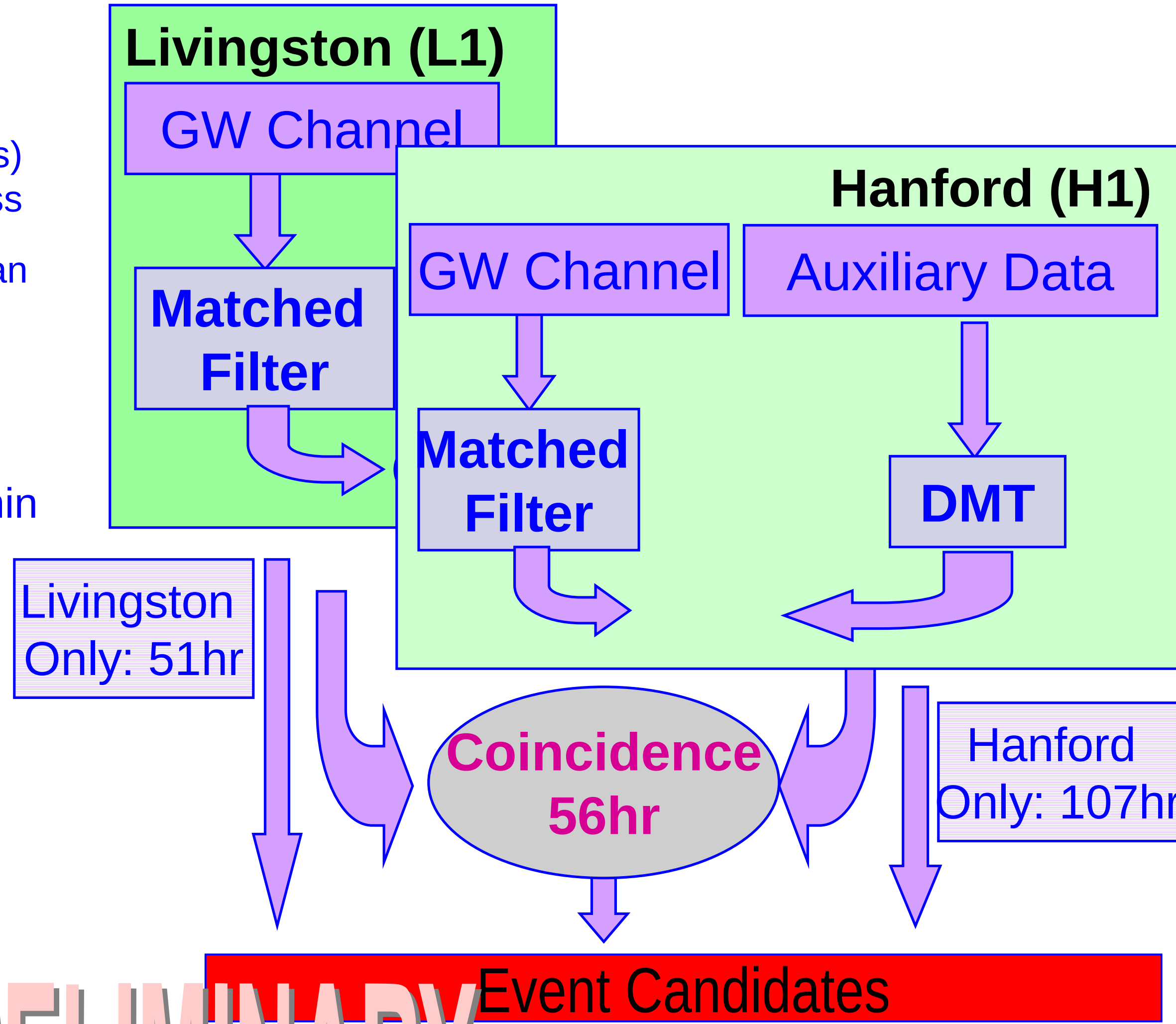
Inspiral Search Pipeline

- Auxiliary data triggers vetos eliminate noisy data
  - Cut 7.7% (13 hours) L1 and 18.5% (43 hours) of H1 based on excess power in gravity-wave channel in 4 freq bands (Epoch veto)
  - Used H1 reflected port (avg arm length, servos freq) glitches at 4/hour to veto 1 sec windows
  - 17 hours H1 & 8 hours L1 dropped (missing/uncertain calibration)
- Matched filter trigger:
  - » **Threshold on ρ=SNR>6.5**, and compute χ^2 : small values indicate that SNR accumulates in manner consistent with an inspiral signal.
  - » **Threshold on χ^2** <5(8+δ ^{2} ρ^2) (note: 14 DOF) record trigger
  - » Use coincidence only if both instruments operating & event strong enough to be seen in each



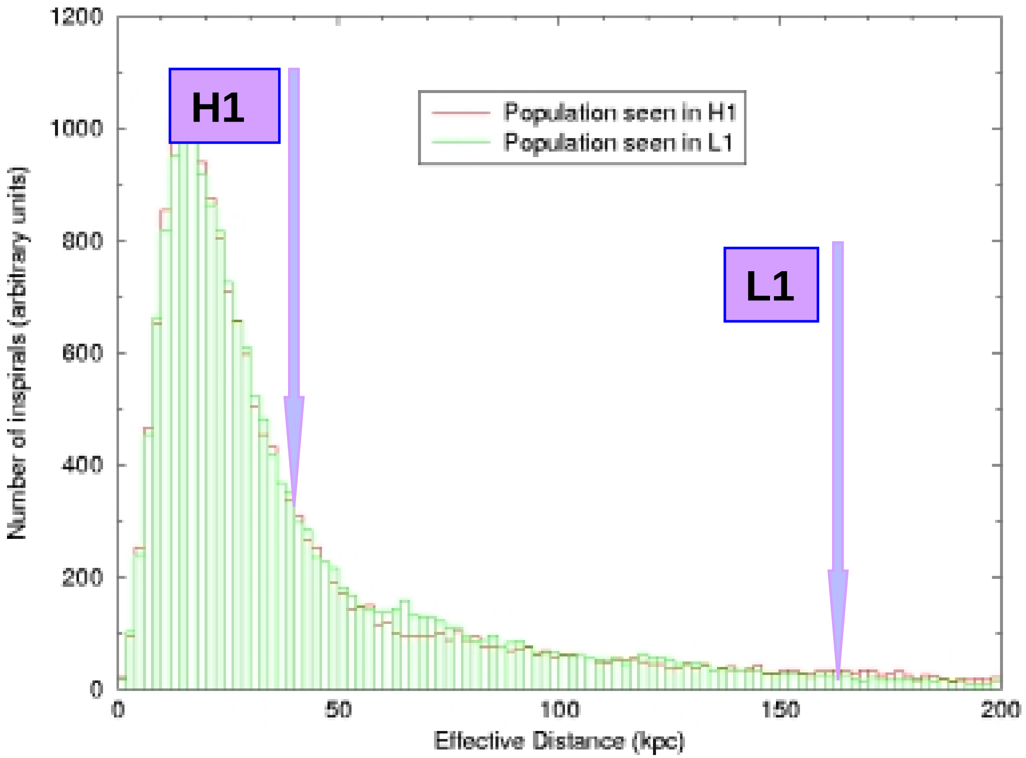
Inspiral Search Pipeline

- Event Candidates
  - » (H1, L1 clean):
    - – Coincident in time (±10 ms)
    - – Mass (fractional chirp mass difference < 1%) , and distance when H1, L1 clean
    - – **NO events found!**
  - » Only H1 or L1 operating:
    - – Single IFO trigger
    - – Largest SNR=15.9
  - » Triggers are **clustered** within empty 16s windows
- Use **Monte Carlo** simulations to calculate efficiency of the analysis
  - » Model of sources in the Milky Way, LMC, SMC
  - » 5071 simulated signals injected
  - » 520 found in coincidence data
  - » Approximately half of remainder found at SNR>15.9



PRELIMINARY

Population Monte Carlo



- Population includes Milky Way, LMC and SMC
- Neutron star masses in range 1-3 Msun
- LMC and SMC contribute ~13% of Milky Way
- Efficiency is fraction of the population detectable by the pipeline (above largest SNR event seen)
- Fake signals injected into data stream to determine efficiency

Inspiral Search Results

- Upper limit on binary neutron star coalescence rate
- Use all triggers from Hanford and Livingston: 214 hours
  - » Cannot accurately assess **background** (be conservative, **assume zero**)
  - » Use **maximum signal-to-noise ratio** statistic to establish the rate limit.
  - » Monte Carlo simulation **efficiency** = 0.51
  - » 90% confidence limit = **2.3/ (efficiency * time)**
  - » Express the rate as a rate per **Milky-Way Equivalent Galaxies** (MWEG)
  - » R < 2.3 / (0.51 x 214 hr) = 164 /yr/(MWEG) [note factor of 1.13 for MWEG units!]

R < 164/yr/(MWEG)

- Previous observational limits
  - » Japanese TAMA → R < 30,000 / yr / MWEG
  - » Caltech 40m → R < 4,000 / yr / MWEG
- Theoretical prediction
  - » R < 2×10^{-5} / yr / MWEG

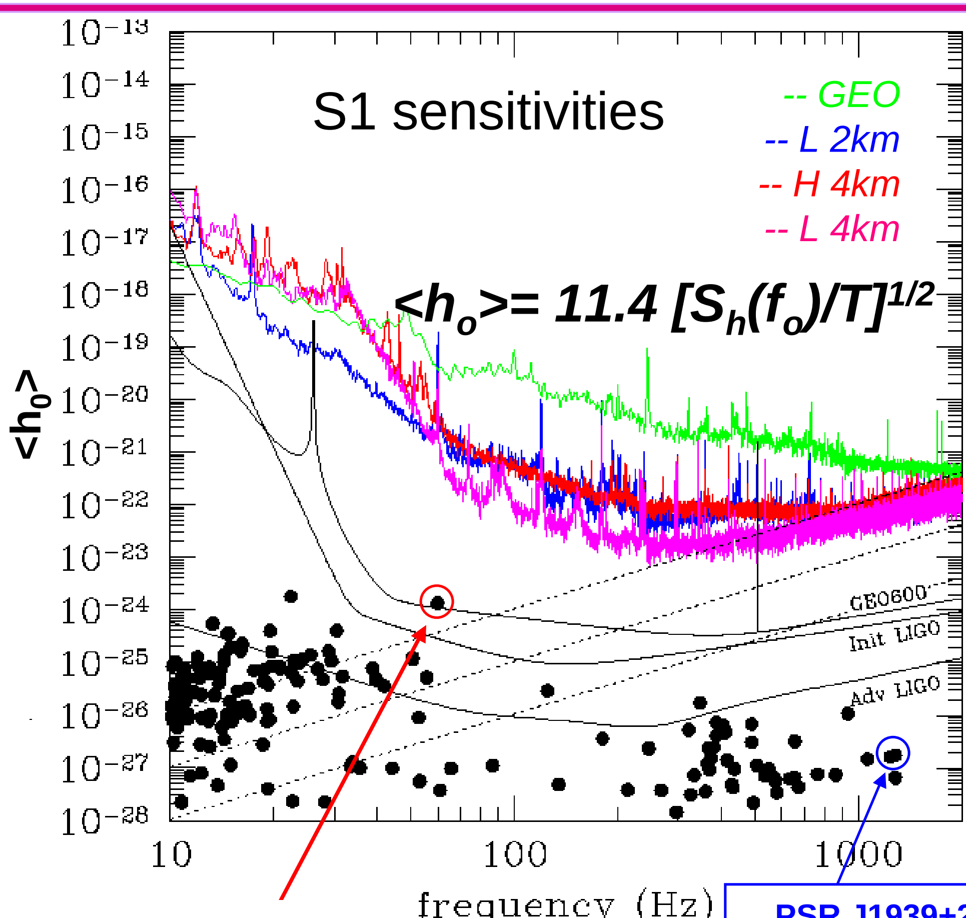
PRELIMINARY

Search for Continuous Waves

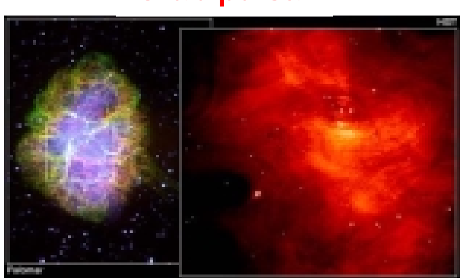
- **Sources: known rotating neutron stars** emitting gravitational waves due to small deviations from a perfectly axi-symmetric shape (small ellipticity).
- **Analysis goals:** given the position, frequency and spin-down parameter of a known pulsar establish **an upper limit on the amplitude** of its continuous wave emission.
- **Achievable sensitivities:** power spectral densities and observation time of the instruments determine the detectability level (1% false alarm, 10% false dismissal) of a continuous wave amplitude:

$$\langle h_0 \rangle = 11.4 \sqrt{S_h(f) / T_{obs}}$$

Expectations for Continuous Waves



Crab pulsar



PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
$\dot{P}$ = 1.0511 10^{-19} s/s
D = 3.6 kpc

- **Detectable amplitudes** with a 1% false alarm rate and 10% false dismissal rate by the IFOs during S1 (colored curves) and at design sensitivities (black curves)
- **Limits** of detectability for rotating NS with equatorial ellipticity $\varepsilon = \delta I/I_{zz}$: 10^{-3} , 10^{-4} , 10^{-5} @ 8.5 kpc
- **Upper limits** on $\langle h_o \rangle$ from spin-down measurements of known radio pulsars (filled circles)
- Design curves for 17 days; S1 curves for actual observation times.

S1: NO DETECTION EXPECTED

Algorithms for CW Search

- **Parameters** in detection:
  - »**Frequency** of source in Solar System Barycenter (SSB)
  - »**Rate of change of frequency** in SSB
  - »**Sky coordinates** (α, δ) of source
  - »**Amplitude** h_0
  - »**Orientation** ι
  - »**Phase, Polarization** φ, ψ
- Essential elements of detection code/algorithm
  - »**Conversion of time from SSB to detector time** (LALBarycenter) due to Earth's motion around sun, spin, motions of planets & moon, etc.
  - »**Amplitude modulation** due to the detector's antenna pattern.
- Search for **known pulsars** dramatically reduces the parameter space, and makes it computationally feasible**.**
- **Two** search **methods** used:
  - »**Frequency-domain** based (optimal for detection).
  - »**Time-domain** based (optimal for setting Bayesian upper limits).

Frequency domain CW method

- Input data: Short Fourier Transforms (SFT) of time series (60s time baseline)

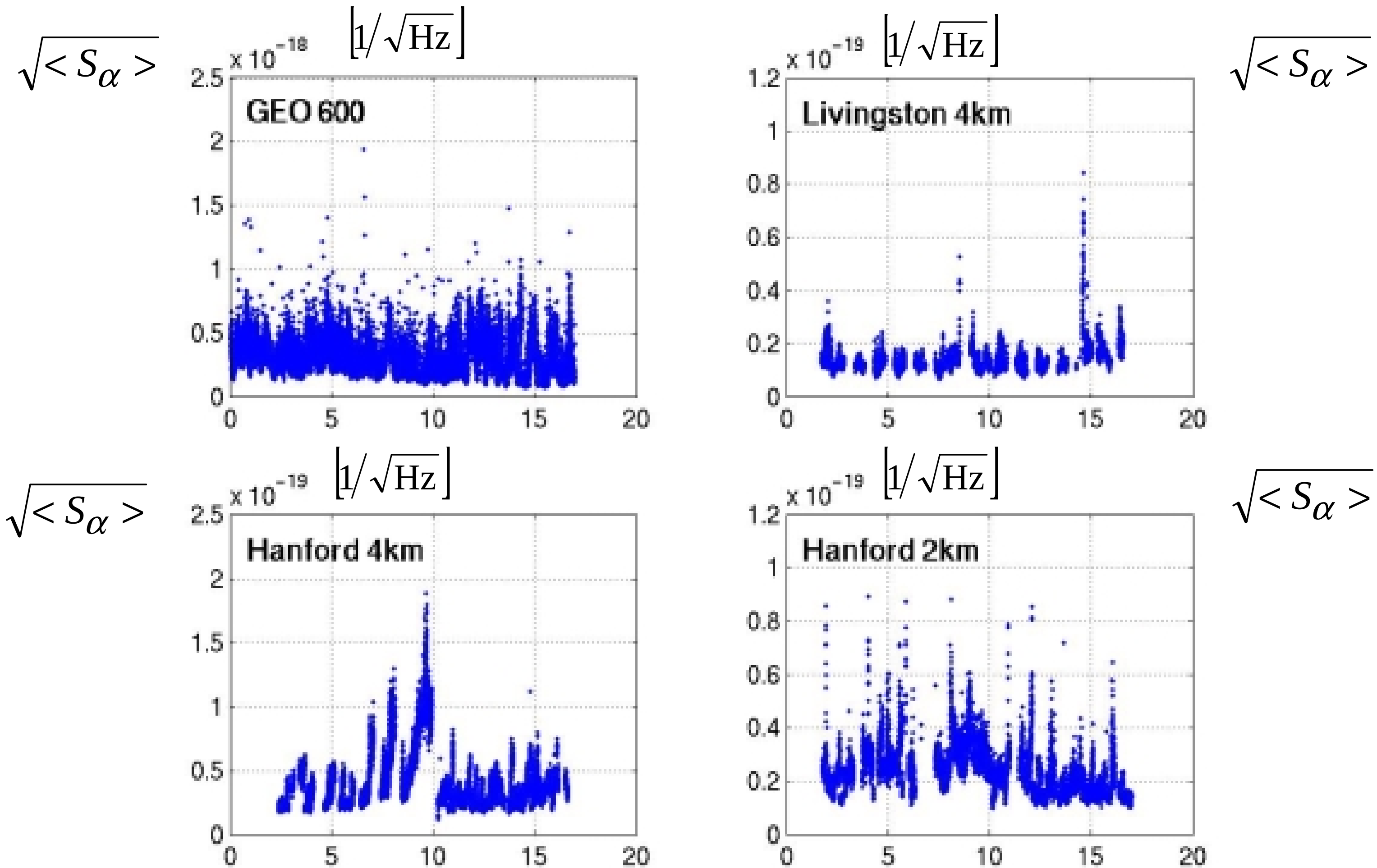
- Dirichlet Kernel used to combine data from different SFTs; efficiently implements matched filtering

- Detection statistic: **F =** likelihood ratio maximized over unknown parameters (initial phase, polarization, inclination of rotation axis)

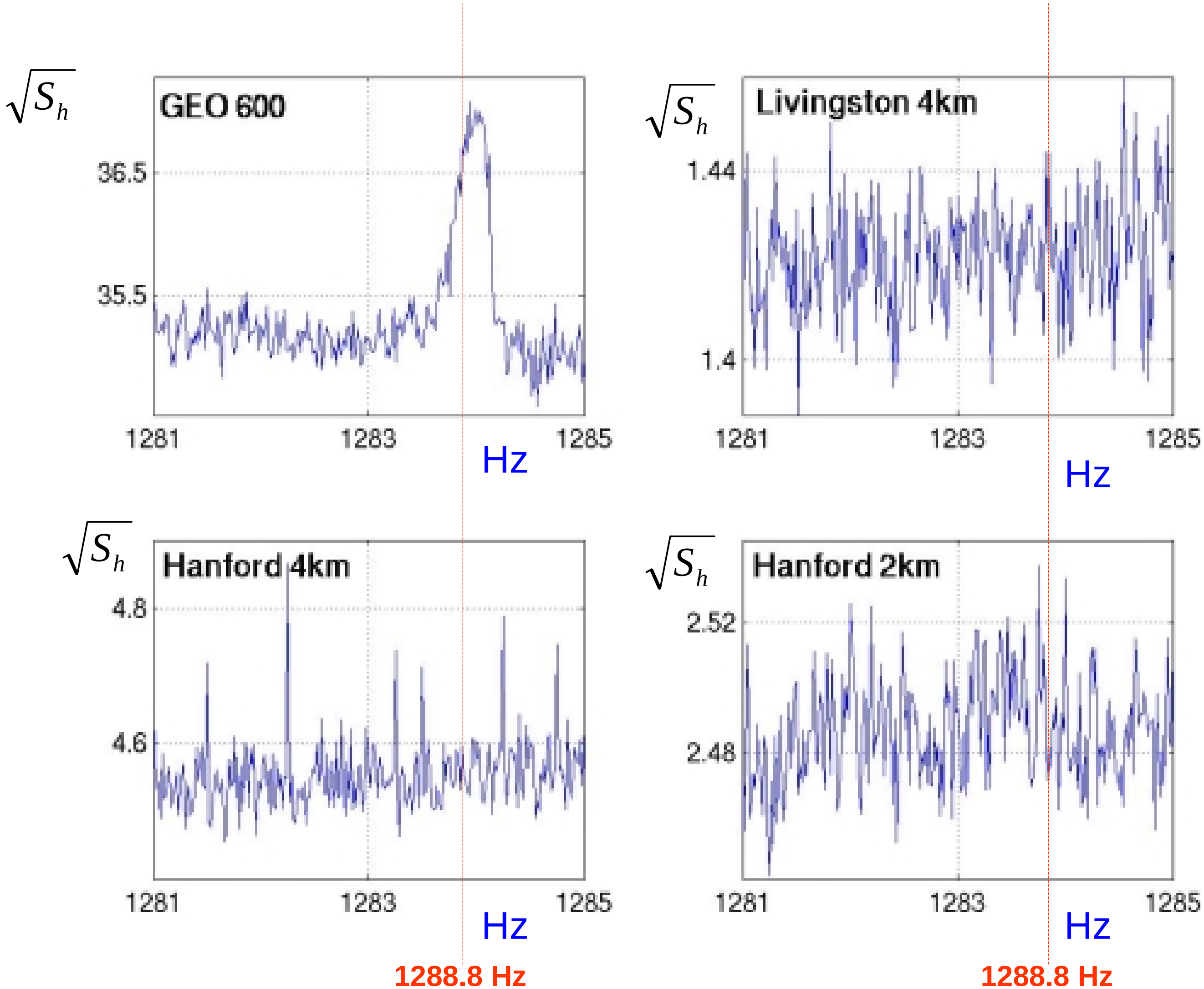
- Use signal injection Monte Carlos to measure Probability Distribution Function (PDF) of F

- Use frequentist approach to derive upper limit (extensive simulations to determine detection efficiency using two ~ 300 CPU clusters: Merlin @ AEI, Medusa @ UWM)

The data: time behaviour
(4 Hz band around 1283 Hz)

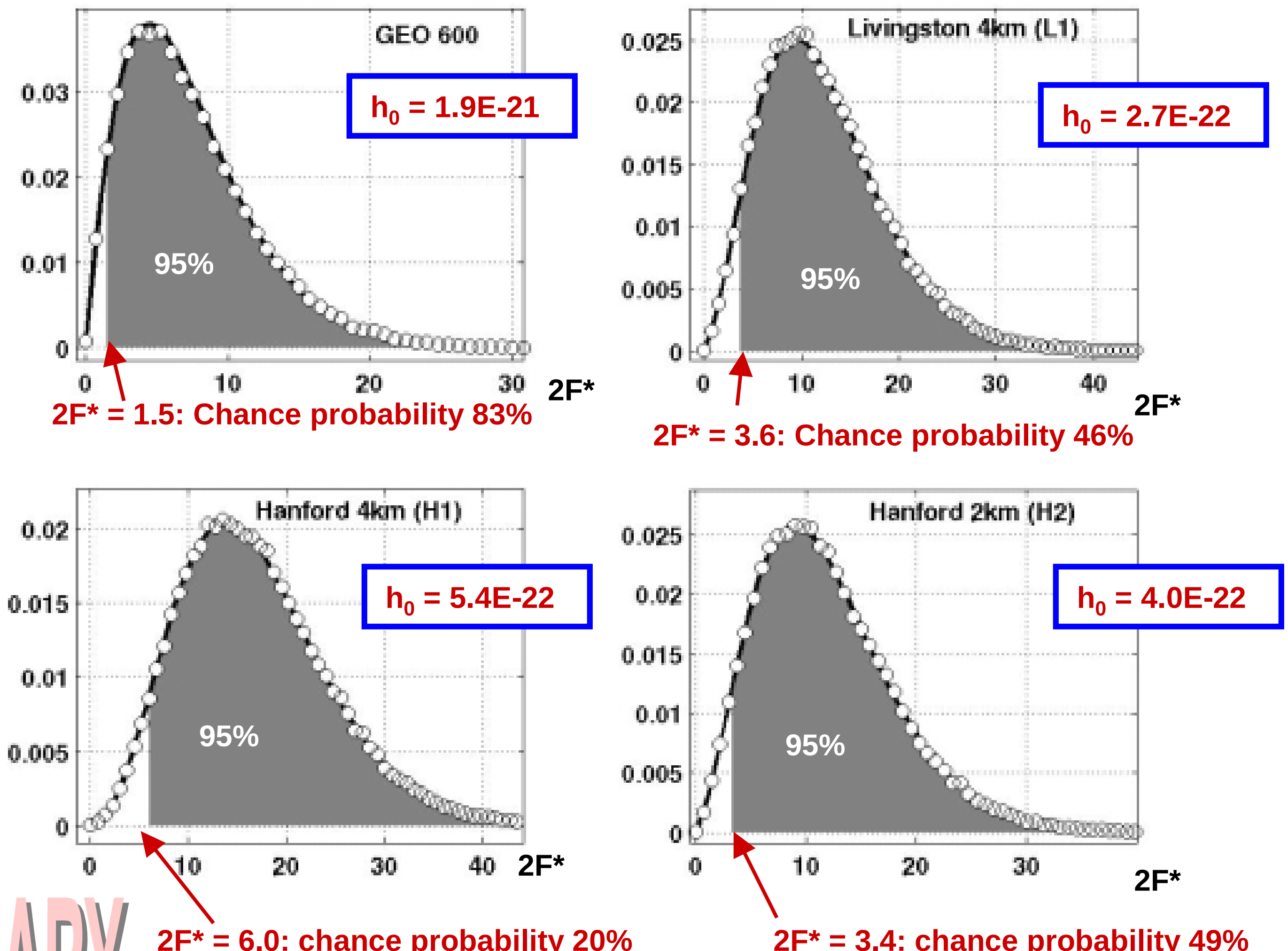


CW search: The data in frequency



LIGO CW: Measured PDFs for the F statistic with nearby fake injected signals

Note: **hundreds of thousands** of injections were needed to get such nice clean statistics!

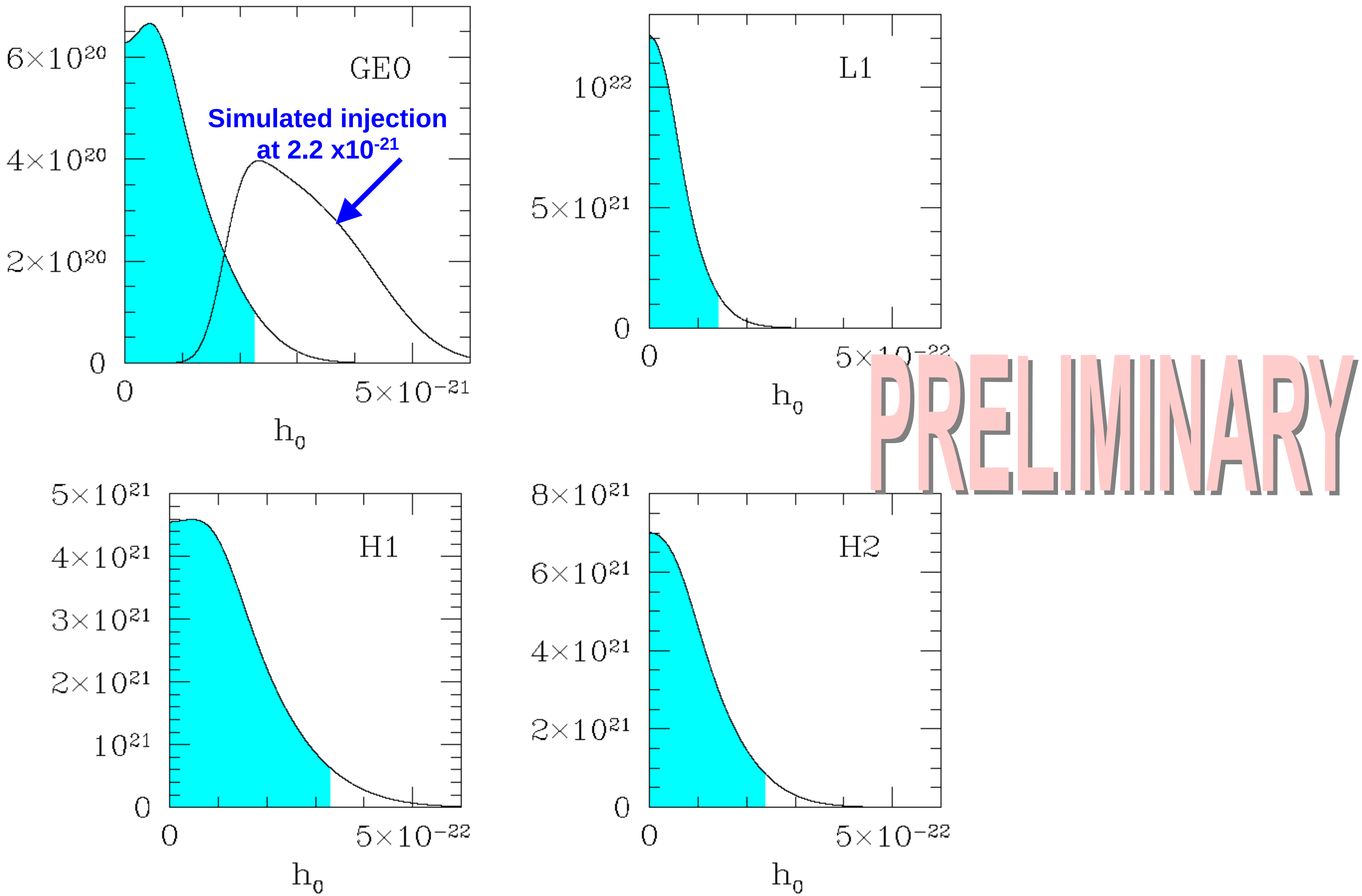


PRELIMINARY

CW search: time domain method

- Two stages of heterodyning to reduce and filter data:
  - » First with a 4 Hz bandwidth (8 samples/second)
  - » Second with a 1/120 Hz bandwidth (1 sample/minute)
- Noise estimated in 60-sec intervals. Data Gaussian
- Use time-domain model for signal
  - » function of unknown source parameters h_0, ι, φ, ψ
- Compute $\chi^2(h_0, \iota, \varphi, \psi)$. Since data Gaussian, exponential of this is simply related to probability and likelihood function.
- Naturally Bayesian approach: results are expressed in terms of a posterior PDF for h_0 , marginalizing with respect to the unknown parameters ι, φ, ψ.

Posterior PDFs for CW time-domain analyses



Results of Search for CW

- **No evidence** of continuous wave emission from **PSR J1939+2134**.
- Summary of **95% upper limits** on h:

IFO	Frequentist FDS	Bayesian TDS
GEO	$(1.9\pm0.1)\times10^{-21}$	$(2.2\pm0.1)\times10^{-21}$
LLO	$(2.7\pm0.3)\times10^{-22}$	$(1.4\pm0.1)\times10^{-22}$
LHO-2K	$(5.4\pm0.6)\times10^{-22}$	$(3.3\pm0.3)\times10^{-22}$
LHO-4K	$(4.0\pm0.5)\times10^{-22}$	$(2.4\pm0.2)\times10^{-22}$

PRELIMINARY

- $h_o<1.4\times10^{-22}$ constrains **ellipticity < 2.7×10^{-4}** ($M=1.4M_{sun}$, r=10km, R=3.6kpc)
- Previous results for PSR J1939+2134: **$h_o < 10^{-20}$** (Glasgow, Hough et al., 1983), **$h_o < 3.1(1.5)\times10^{-17}$** (Caltech, Hereld, 1983).

Stochastic Radiation

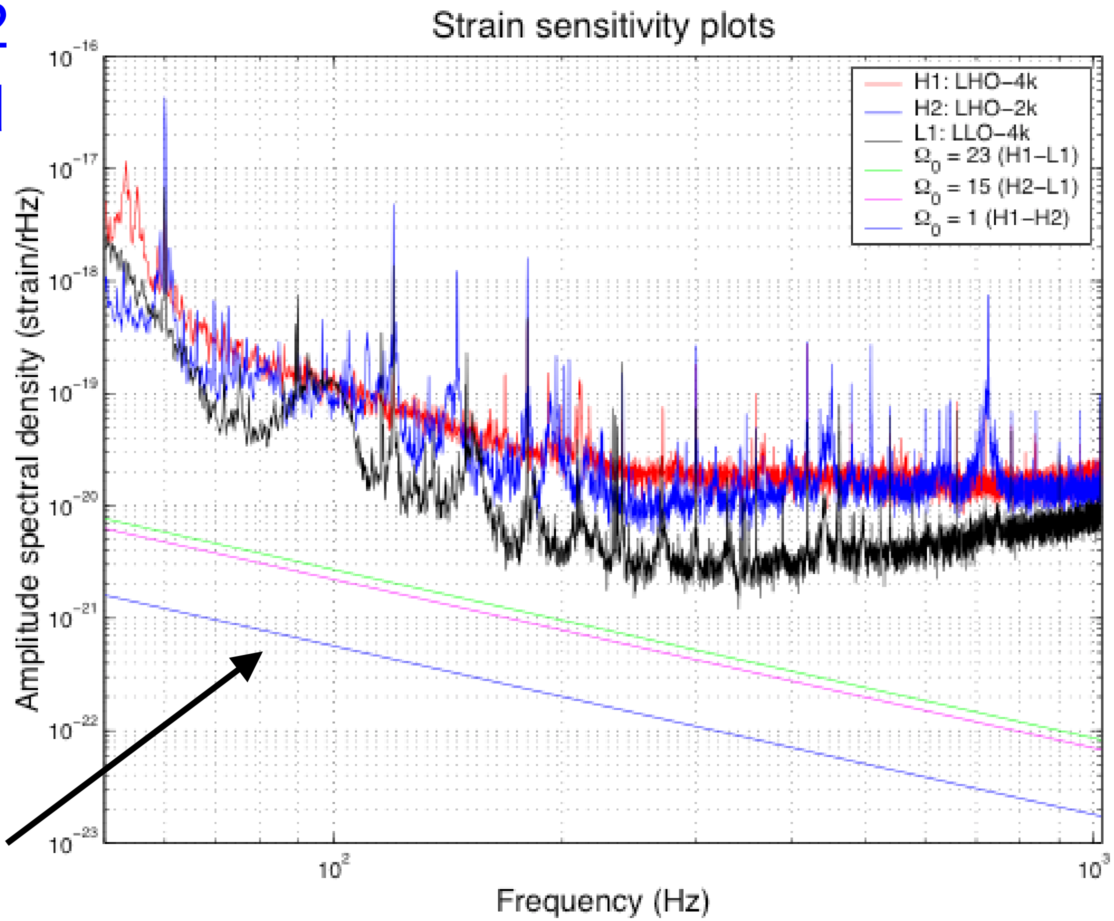
- **Sources (early universe, or contemporary)**
  - » Random stochastic: many independent weak unresolved sources emitting gravitational waves incoherently
  - » Expected: isotropic, unpolarized, stationary and Gaussian
  - » Described by frequency spectrum $\Omega_{GW}(f)$
  - » Almost certainly *NOT* a thermal spectrum
- **Analysis goals:** constrain $\Omega_{GW}(f)$

$$\int_0^\infty (1/f)\,\Omega_{GW}(f)\,df = \frac{\rho_{GW}}{\rho_{critical}}$$

- **Search Method**: cross-correlate detector outputs, look for "common" noise signal.

Stochastic Search Method

- Optimally filtered **cross-correlation** of detector pairs: L1-H1, L1-H2 and H1-H2
- Detector **separation** and **orientation** reduces correlations at high frequencies ($\lambda_{GW} \geq$ 2xBaseLine): **overlap reduction function**
  - » H1-H2 best suited (but correlated environmental noise)
  - » L1-H1(H2) significant <50Hz
- Achievable **sensitivities to Ω** by detector pairs in **S1**



Results of Stochastic Search

PRELIMINARY

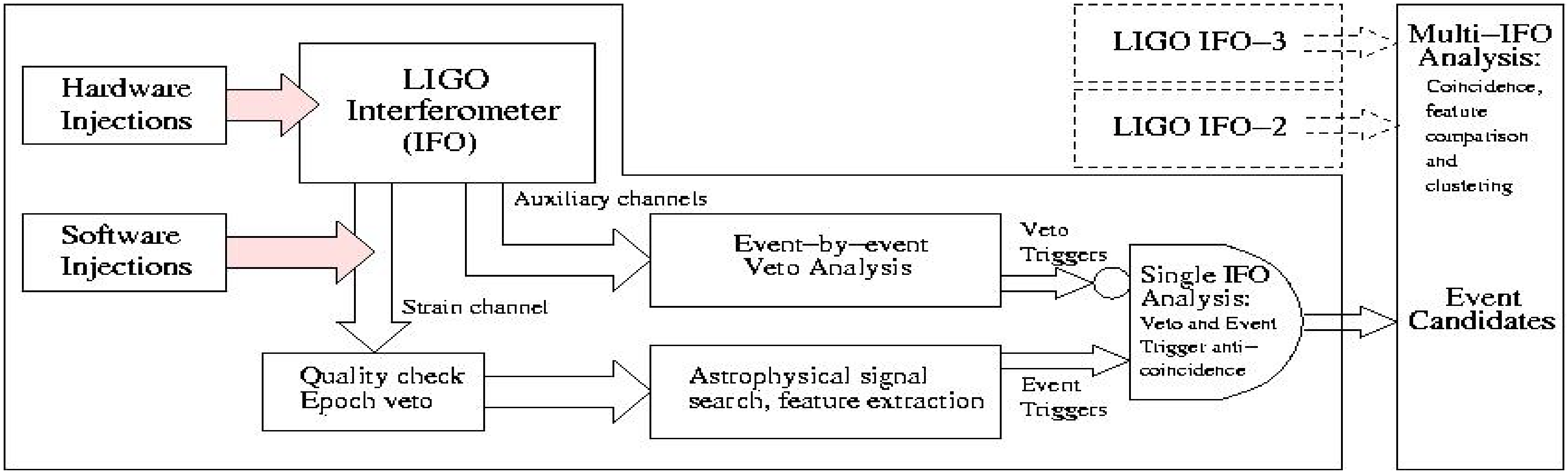
Interferometer Pair	90% CL Upper Limit	T_{obs}
LHO 4km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 55±11	64 hrs
LHO 2km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 23±4.6	51.3 hrs

- Non-negligible LHO 4km-2km (H1-H2) cross correlation: show to be instrumental (corresponds to $\Omega_{GW} < 0$)
- Previous best direct observational GW upper limits:
  - » Garching-Glasgow interferometers : $\Omega_{GW}(f) < 3\times10^5$
  - » EXPLORER-NAUTILUS (cryogenic bars): $\Omega_{GW}(907Hz) < 60$

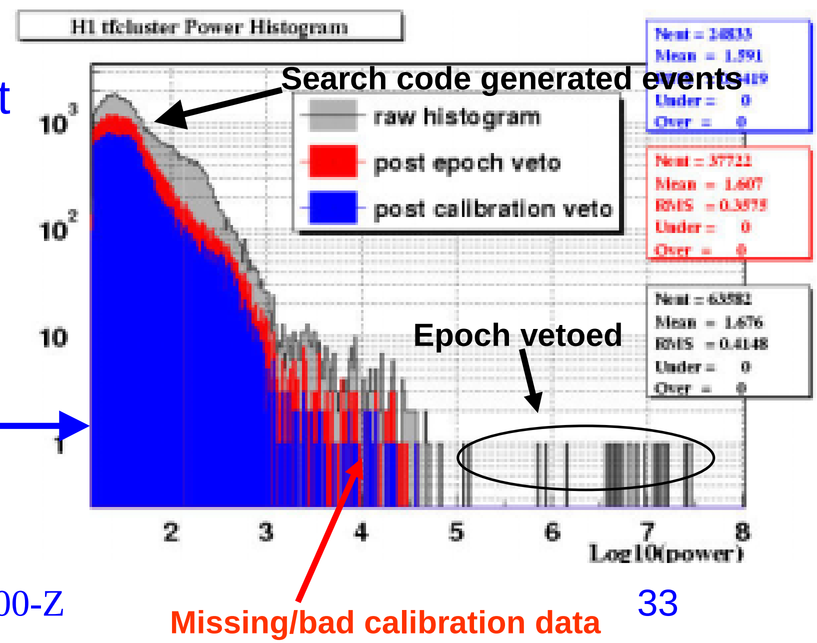
Search for GW Bursts

- **Sources:** **known** and **unknown phenomena** emitting short transients of gravitational radiation of **unknown waveform** (supernovae, black hole mergers).
- **Analysis goals:** **broad** frequency **band** search to (a) establish a **bound on their rate** at the instruments, (b) interpret bound in terms of a source and population model on a **rate vs. strength** exclusion plot.
- **Search methods:**
  - » **Time domain** algorithm ("SLOPE"): identifies rapid increase in amplitude of a filtered time series (threshold on 'slope').
  - » **Time-Frequency domain** algorithm ("TFCLUSTERS"): identifies regions in the time-frequency plane with excess power (threshold on pixel power and cluster size).

Bursts Search Pipeline

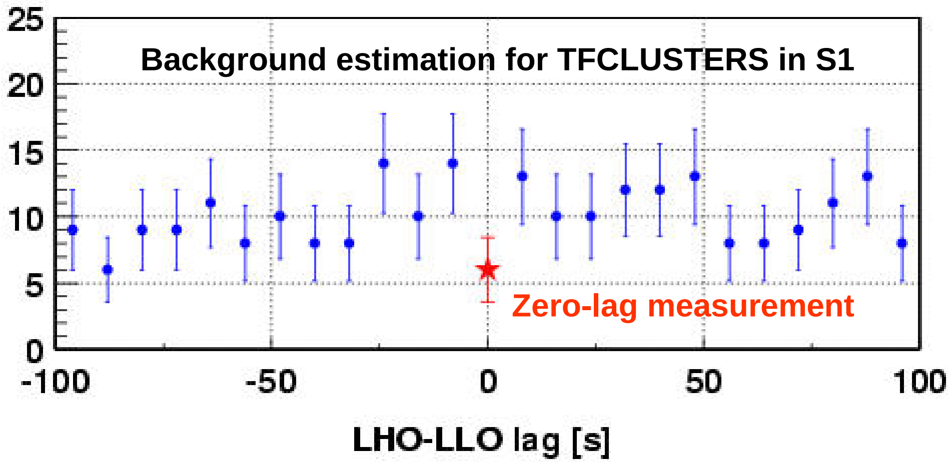


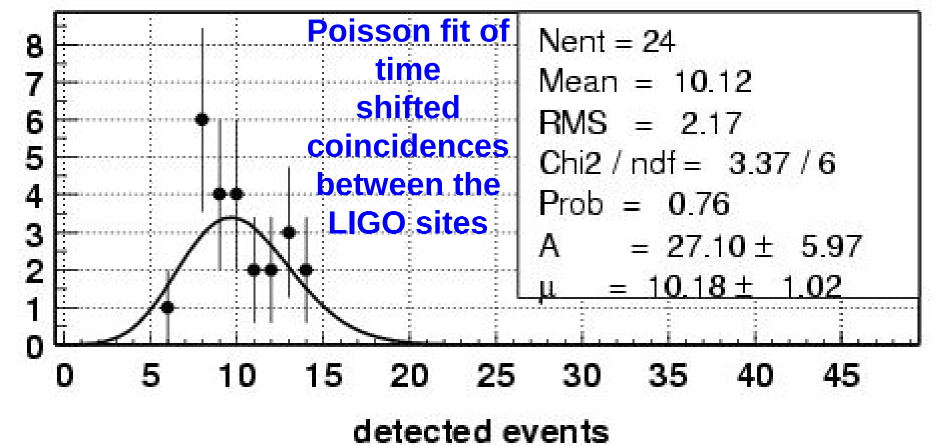
- basic assumption: **multi-interferometer response** consistent with a plane wave-front incident on network of detectors.
- **design the capability to veto** data epochs and events based on quality criteria and auxiliary channels.
- essential: use **temporal coincidence (±500ms)** of the 3 interferometer's 'best candidates'
- **correlate frequency** features of candidates (T/F domain analysis) overlap or <80 Hz apart.



LIGO Upper Limit on Burst Rate

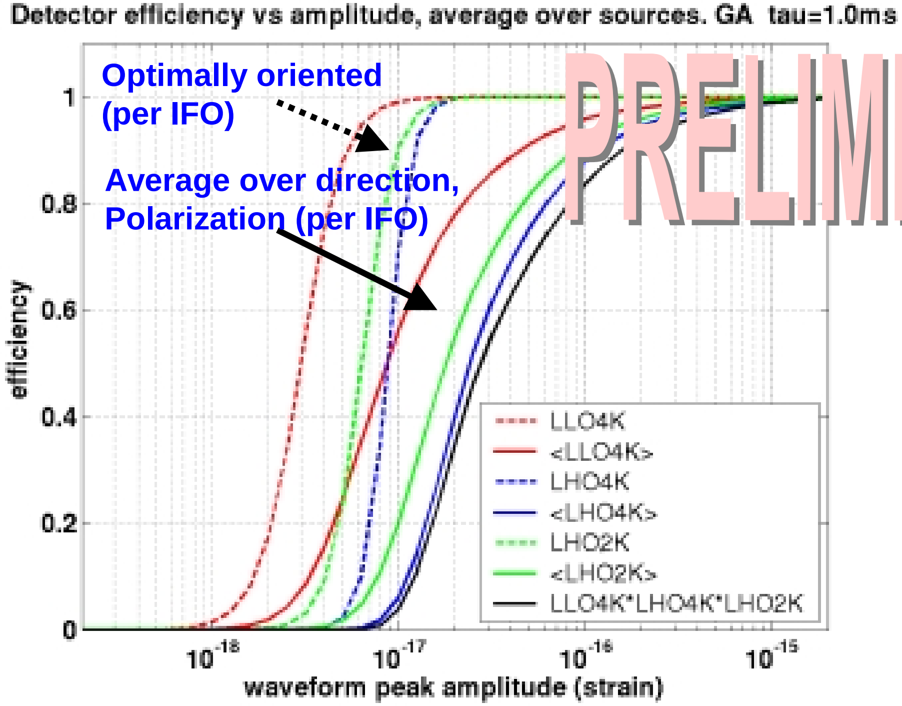
- **End result** of analysis pipeline: **number of triple coincidence events.**
- Use **time-shift** experiments to establish number of **background events.**
- Use **Feldman-Cousins** to set **90%** confidence upper limits on rate of foreground events:
  - » TFCLUSTERS: < **1.6** events/day
  - » SLOPE: < **5.6** events/day
- No Calibration data used up to this point

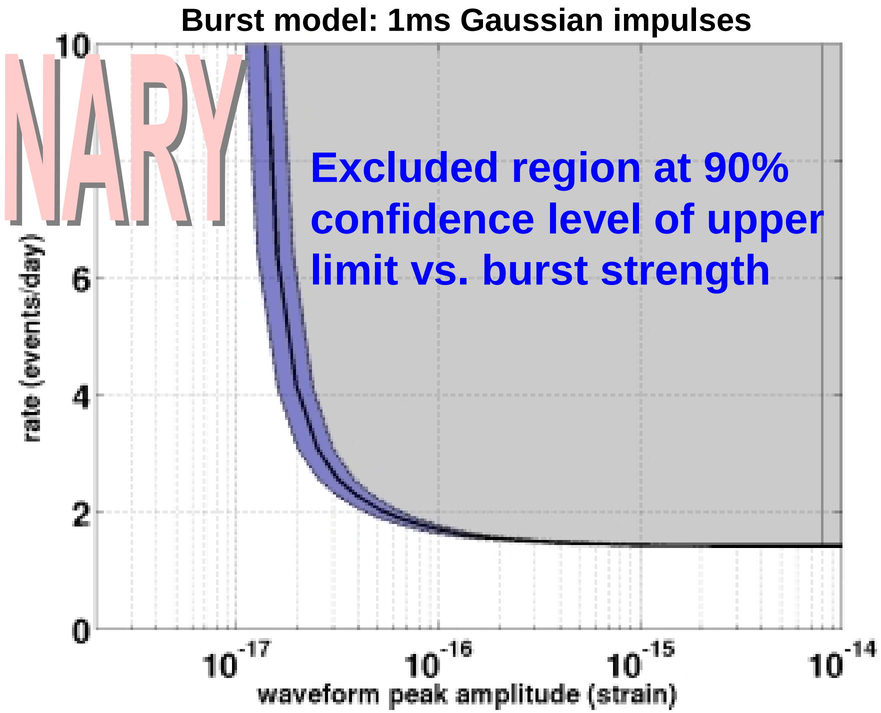




PRELIMINARY

Rate vs. Strength Plots for a Burst Model





- Determine **detection efficiency** of the end-to-end analysis pipeline via **signal injection** of various morphologies.
- Assume a **population** of such sources **uniformly** distributed on a sphere around us: establish upper limit on **rate** of bursts as a function of their **strength.**

Burst Search Results and the Future

- Search and raw results **sensitive** to a wide variety of waveform morphologies and **broad frequency features** (as long as signal has significant strain amplitude in LIGO's frequency band).
- Strain upper limit (assuming a burst model of 1ms Gaussian pulses) at **1.6** events/day rising up as the detection efficiency reduces (50% efficiency point is at **h~3x10^{-17}**).
- In the near future:
  - » Use multiple-interferometer information on **amplitude** of putative signal and **correlation** statistic of their raw time-series.
  - » Improve **time-resolution** of event trigger generators.
  - » Pursue rigorously an **externally triggered** (by GRB's, neutrinos) search for bursts (excercised during S1).

PRELIMINARY

Lessons Learned (the hard way)

- Monitor DAQ timing with multiple redundant methods.
- Have (at least!) two idependent calibration methods and (if possible) teams. Provide calibration data as fast as possible.
- Maintain a “table” of systematic errors through the calibration chain.
- Keep data on spinning disks whenever possible.
- Verify raw data compliance (on a continual basis) with FRAME standards.
- Inject fake hardware and software signals for *all* analysis pipelines.
- Provide tools for Monte-Carlo injection of fake software signals.
- Simplify path from raw data to analysis results as much as possible.
- Use grid-based tools for user authentication, login, data transfer.
- Maintain analysis codes in CVS (version control system) archive

LIGO/GEO Science Has Started

- LIGO has started taking data
- LIGO had its **first science run** ("S1") almost a year ago
  - » Collaboration has carried out **first analysis** looking for:
    - ✓ Bursts
    - ✓ Compact binary coalescences
    - ✓ Stochastic background
    - ✓ Periodic sources
- **Second science run** ("S2") from 14 February to 14 April 2003:
  - » Sensitivity is ~10x better than S1
  - » Duration is ~ 4x longer
    - – Bursts: rate limits: 4X lower rate & 10X lower strain limit
    - – Inspirals: reach will exceed 1Mpc -- includes M31 (Andromeda)
    - – Stochastic background: limits on Ω_{GW} should be $< 10^{-2}$
    - – Periodic sources: limits on h_{max} ~ few x 10^{-23} (ε ~ few x 10^{-6} @ 3.6 kpc)
- Ground based interferometers are **collaborating internationally**:
  - » LIGO and GEO (UK/Germany) during S1
  - » LIGO and TAMA (Japan) during S2
  - » LIGO and GEO during S3