Searches for gravitational waves by the LIGO Scientific Collaboration

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Outline

- The LIGO Scientific Collaboration
- Why look for gravitational waves?
- What kinds of waves do we look for?
- What have we seen (or not) so far?
- Why are we optimistic?

LIGO

LIGO Scientific Collaboration

LSC

NSF

UTB TSC

SOUTHEASTERN LOUISIANA UNIVERSITY

LOYOLA UNIVERSITY NEW ORLEANS

California State University DOMINGUEZ HILLS

LELAND STANFORD JUNIOR UNIVERSITY ORGANIZED 1891

NORTHWESTERN UNIVERSITY

GEO 600

LSU

Universitat de les Illes Balears

SOUTHERN UNIVERSITY Agricultural & Mechanical College

HOBART COLLEGE

WILLIAM SMITH COLLEGE

THE UNIVERSITY OF ADELAIDE AUSTRALIA

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

UNIVERSITY OF FLORIDA

NAOJ 国立天文台

UNIVERSITY of WISCONSIN UWMILWAUKEE

SIGILL COLL CARLETON NORTHFIELD MINN AD 1866

CORNELL UNIVERSITY

THE UNIVERSITY OF BIRMINGHAM

SKC

IGR

SYRACUSE UNIVERSITY FOUNDED AD 1870

SUOS CULTORES SCIENTIA CORONAT

Universität Hannover

WASHINGTON STATE UNIVERSITY

CARDIFF UNIVERSITY

THE UNIVERSITY OF WESTERN AUSTRALIA

MICHIGAN

The Physics of the Universe PPARC

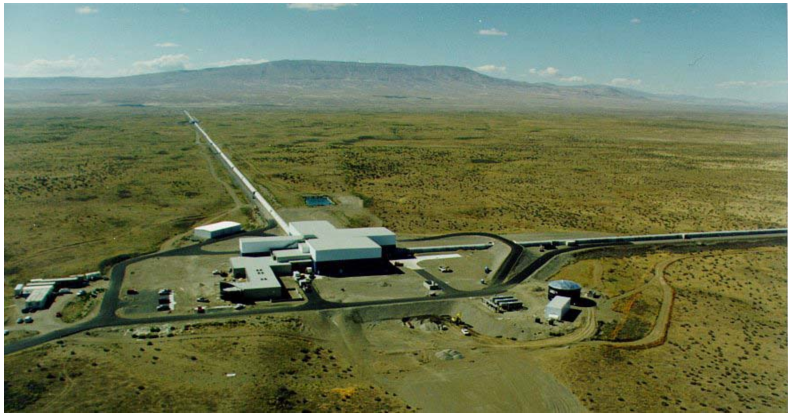
PAH

PENNSTATE 1855

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

UNIVERSITY of GLASGOW

LIGO and GEO



Four interferometers contribute data to LSC analyses:

- 4 km and 2 km interferometers at LIGO Hanford Observatory

- 4 km interferometer at LIGO Livingston Observatory

- GEO600

N.B.: No GEO data available for S2, but back on air for S3.

How a gravitational wave affects a set of test masses

- Transverse

  No effect along direction of propagation

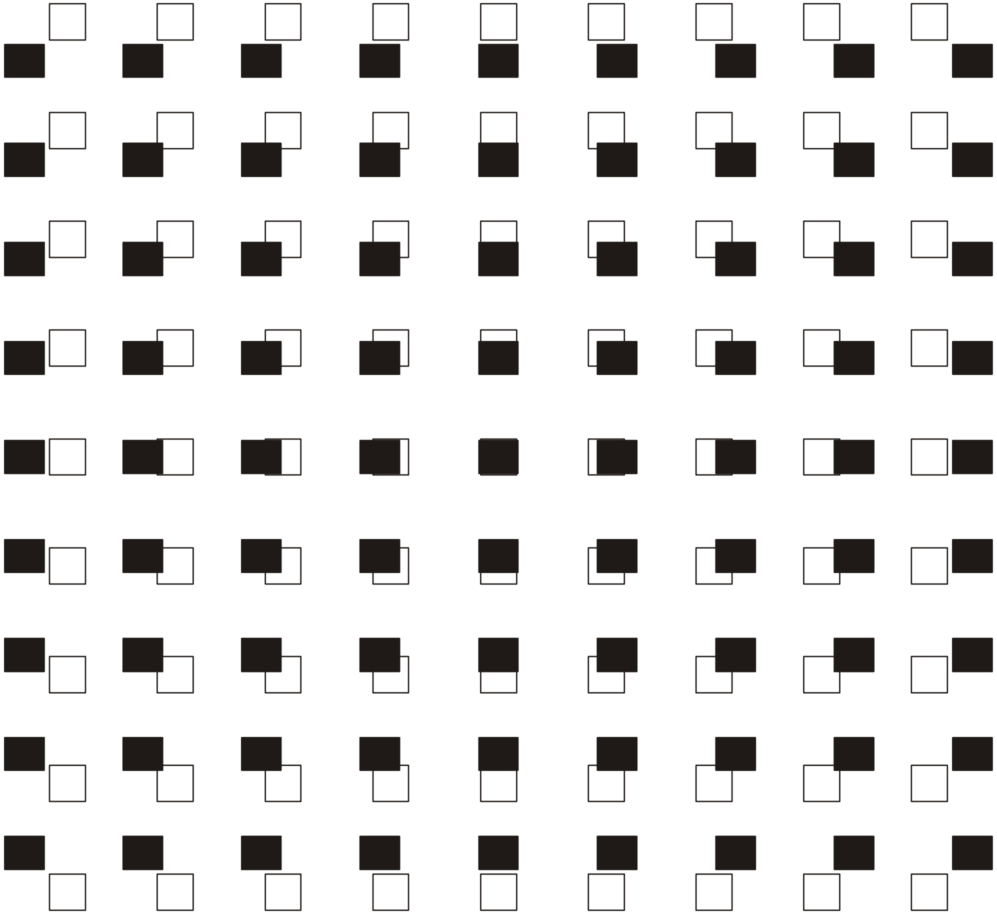
- Quadrupolar

  Opposite effects along *x* and *y* directions

- Strain

  Larger effect on longer separations

$$h \equiv 2\frac{\Delta L}{L}$$



LIGO-G040449-00-Z

Gravitational waveform lets you read out source dynamics

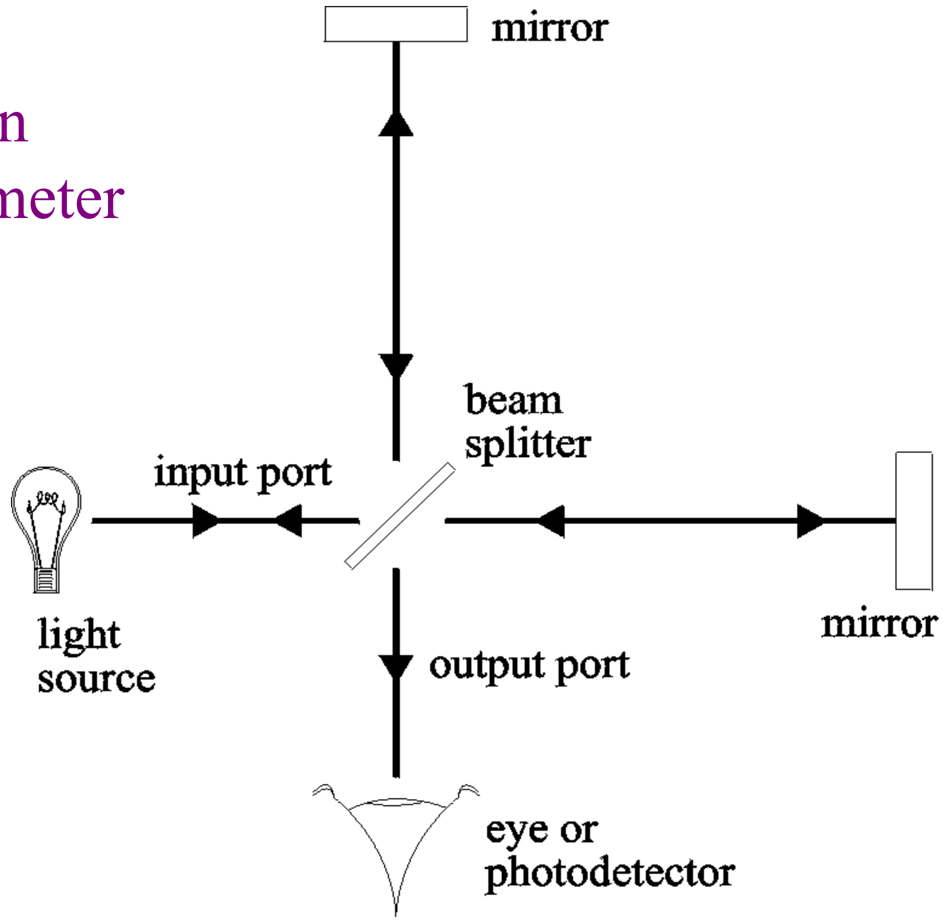
The evolution of the mass distribution can be read out from the gravitational waveform:

$$h(t) = \frac{1}{r}\frac{2G}{c^4}\ddot{I}(t)$$

Coherent relativistic motion of large masses can be directly observed.

Sense the motions of free masses with an interferometer

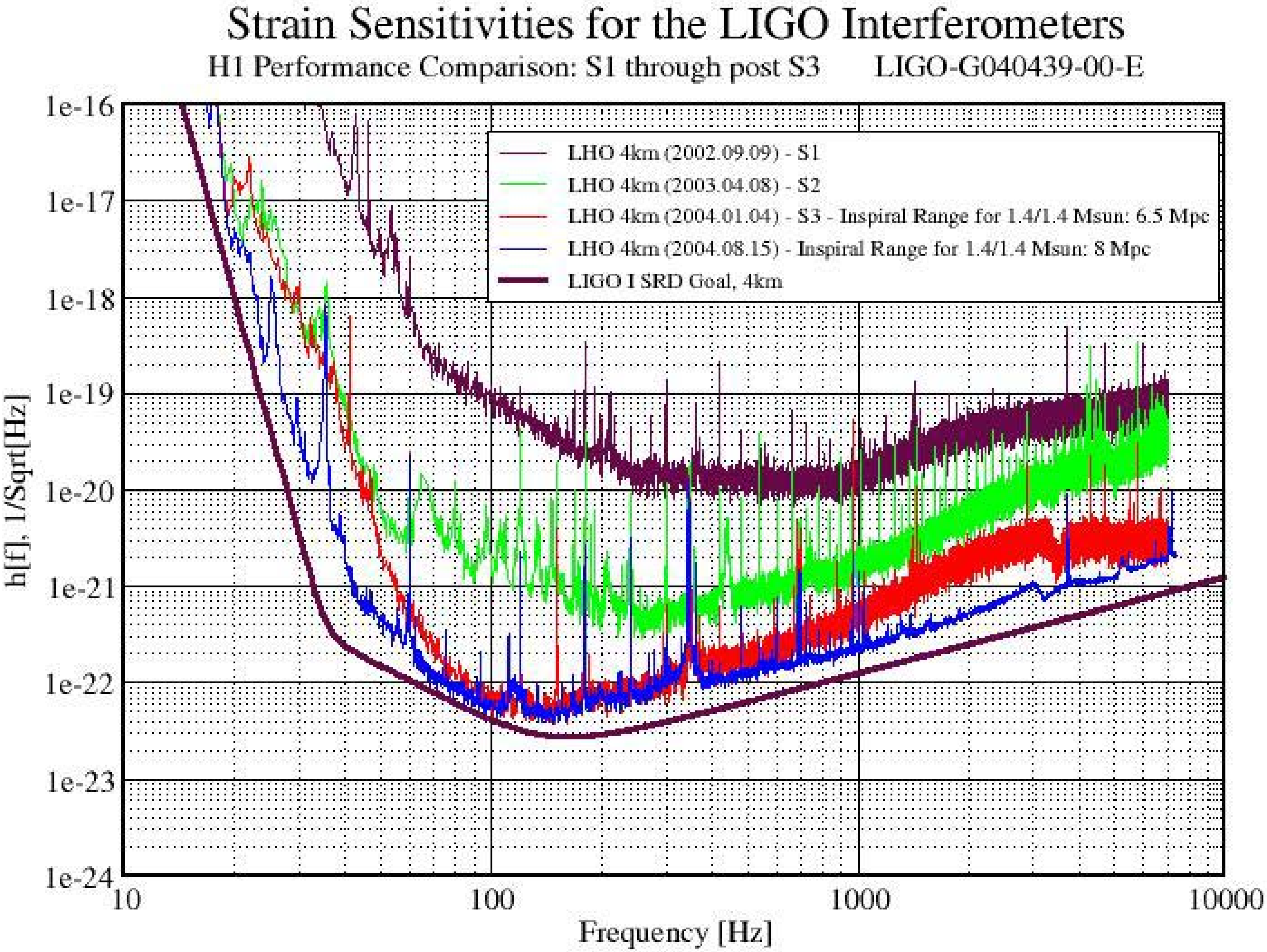
Michelson interferometer



Science Goals

- Physics
  - Direct verification of the most “relativistic” prediction of general relativity
  - Detailed tests of properties of grav waves: speed, strength, polarization, …
  - Probe of strong-field gravity – black holes
  - Early universe physics
- Astronomy and astrophysics
  - Abundance & properties of supernovae, neutron star binaries, black holes
  - Tests of gamma-ray burst models
  - Neutron star equation of state
  - *A new window on the universe*

Sensitivity



Data Runs

We have carried out three Science Runns (S1--S3) interspersed with commissioning.

S1 run:

17 days (August / September 2002)

Four detectors operating: LIGO (L1, H1, H2) and GEO600

Triple-LIGO-coincidence (96 hours)

Four S1 astrophysical searches published (*Phys. Rev. D* 69, 2004):

- **Inspiraling neutron stars 122001**
- **Bursts 102001**
- **Known pulsar (J1939+2134) with GEO 082004**
- **Stochastic background 122004**

Data Runs

S2 run:

59 days (February—April 2003)

Four interferometers operating: LIGO (L1, H1, H2) and TAMA300 plus Allegro bar detector at LSU

Triple-LIGO-coincidence (318 hours)

Many S2 searches are under way
– some preliminary results in this talk

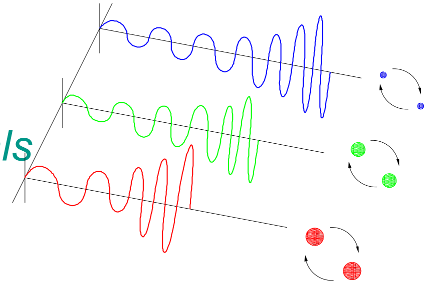
S3 run:

70 days (October 2003 – January 2004) – Analysis ramping up…

We search for four classes of signals

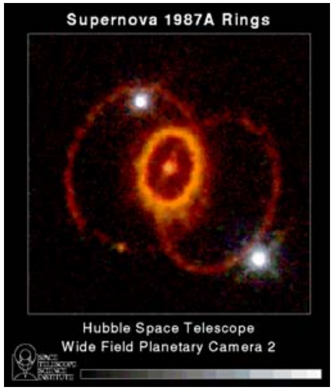
- Chirps

  “sweeping sinusoids” from compact binary inspirals



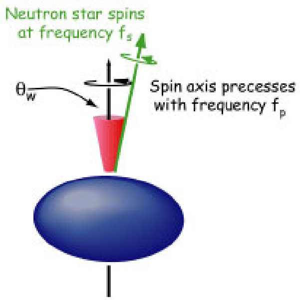
- Bursts

  transients, usually without good waveform models



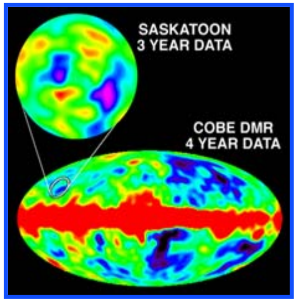
- Periodic, or “CW”

  from pulsars in our galaxy



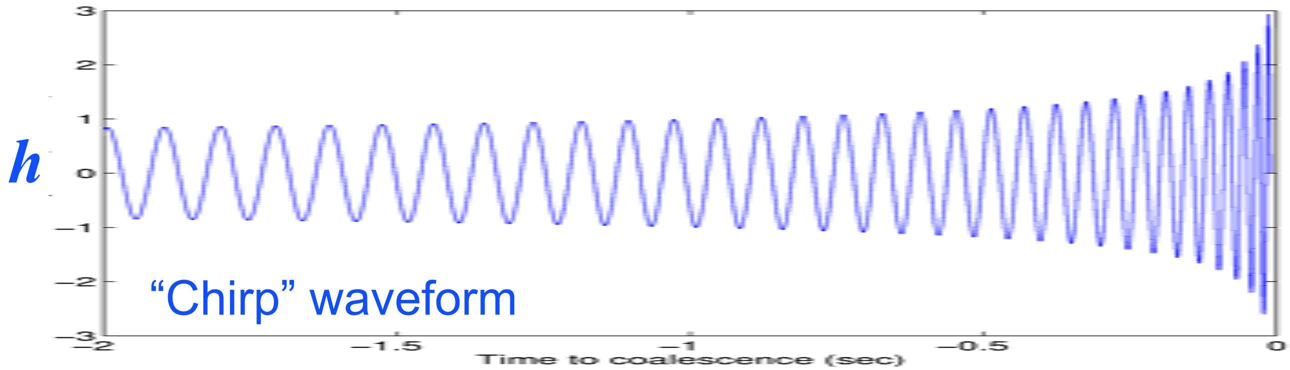
- Stochastic background

  cosmological background, or superposition of other signals



Inspiral Gravitational Waves

Compact-object binary systems lose energy due to gravitational waves. Waveform traces history.



In LIGO frequency band (40–2000 Hz) for a short time just before merging:
anywhere from a few minutes to <<1 second, depending on mass.

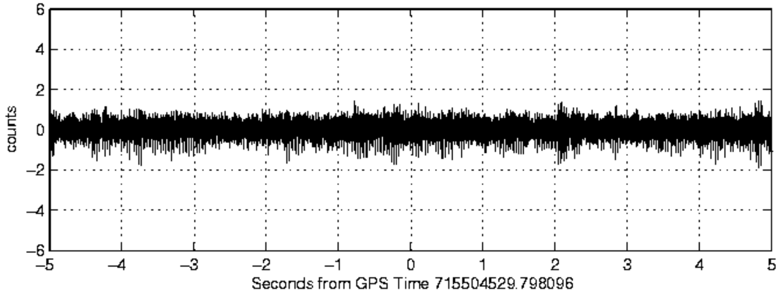
Waveform is known accurately for objects up to ~3 $M_\odot$

“Post-Newtonian expansion” in powers of (Gm/rc^2) is adequate

➔ Use *matched filtering.*

Matched filtering

GW Channel
+ simulated inspiral



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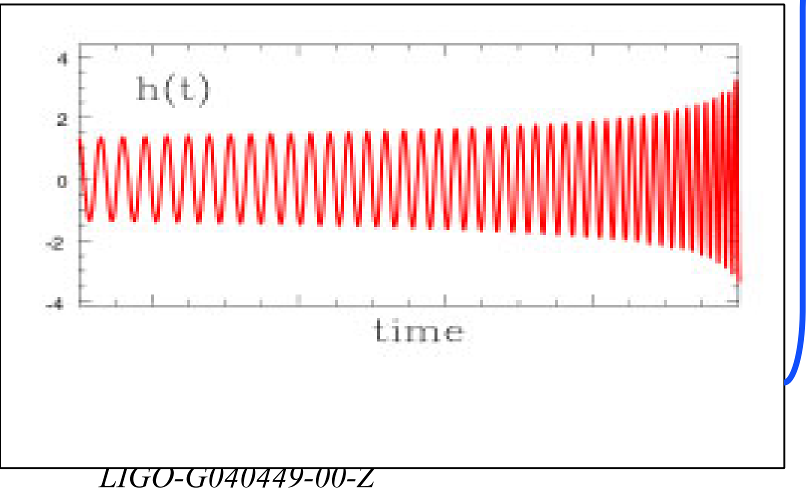
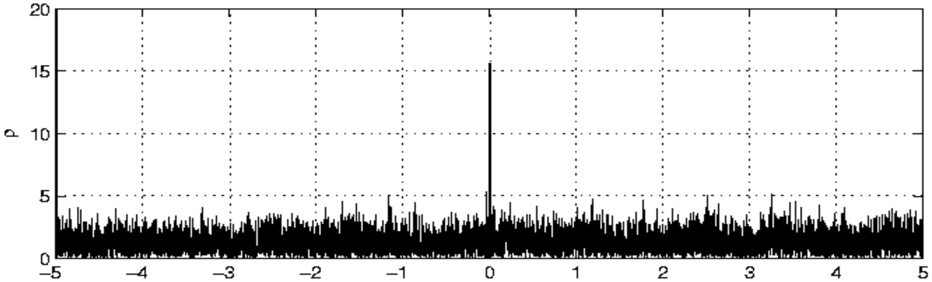


SNR



Coalescence Time

Cross-correlation for matched filtering

$$s_1(t) = h(t - t_1) + n_1(t)$$

$$h_{known}(t - t_2)$$

$$C(t, t_w, t_{off}) = \int_{t - t_w/2}^{t + t_w/2} s_1(t') h_{known}(t' + t_{off})\, dt'$$

$$\Rightarrow \int_{t_w} h^2(t)\, dt + \text{filtered noise}$$

Inspiral searches

First search is for neutron star binaries.

- These are known astrophysical objects. Rates determined from astronomical observations.
- LIGO-I at design sensitivity has a chance to see them. Advanced LIGO should see many.
- *Need a large number of matched templates, given range of possible masses of the two stars.*

We are also searching for

- Lower mass binaries ("MACHOs"), and
- Higher mass binaries (binary black holes).
    - Relativistic effects are more complicated at higher mass, and spin is a big complication.
    - Nevertheless, template families (for both non-spinning and spinning cases) have been developed for this search.
    - *Can see these sources far away.*

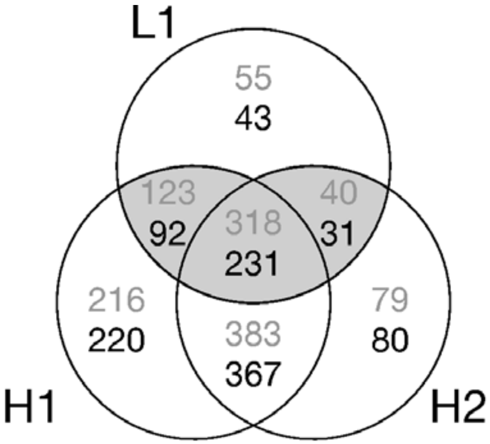
S1 Binary Neutron Star Search Results

- B. Abbott et. al. ‘Analysis of LIGO Data for Gravitational Waves from Binary Neutron Stars’
  - gr-qc/0308069, PRD **69** 122001 (2004)
- Searched total of 236 hours of LIGO data
  - Used LHO 4k and LLO 4k single IFO and double coincident data
- Average distance at which an optimal 2 x 1.4 M_{sun} binary gives signal-to-noise ratio $\rho = 8$
  - LLO 4k: 176 kpc
  - LHO 4k: 46 kpc
- No double coincident inspiral signals were found
- Loudest event found at $\rho = 15.9$ in LLO 4k
  - Not an inspiral signal: due to a photodiode saturation in the interferometer

S1 Upper Limit:
$R_{90\%} < 1.7 \times 10^2$
per year per MWEG

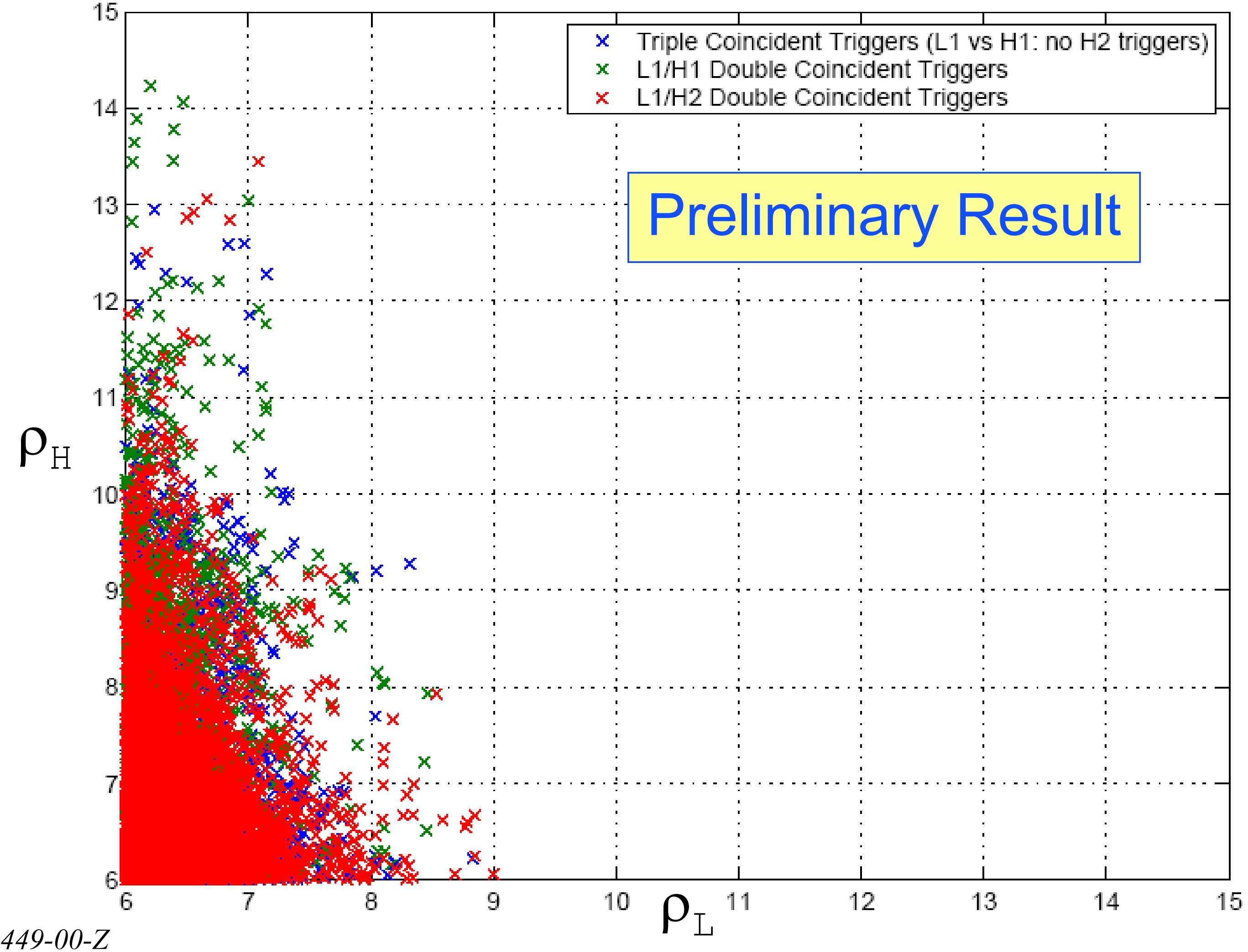
S2 Binary Neutron Star Inspiral Search

- Average distance at which an optimally oriented 2 x 1.4 M_{sun} neutron star binary gives r = 8:
  - LLO 4k: 1.8 Mpc reaches M31, M33, M32, M110
  - LHO 4k: 0.9 Mpc just reaches M31
  - LHO 2k: 0.6 Mpc
- Recorded over 1200 hours of data
  - Did not use single IFO or H1/H2 only data
  - Applied "data quality" cuts
  - Applied auxiliary channel "vetoes"
- Used 355 hours of data in search

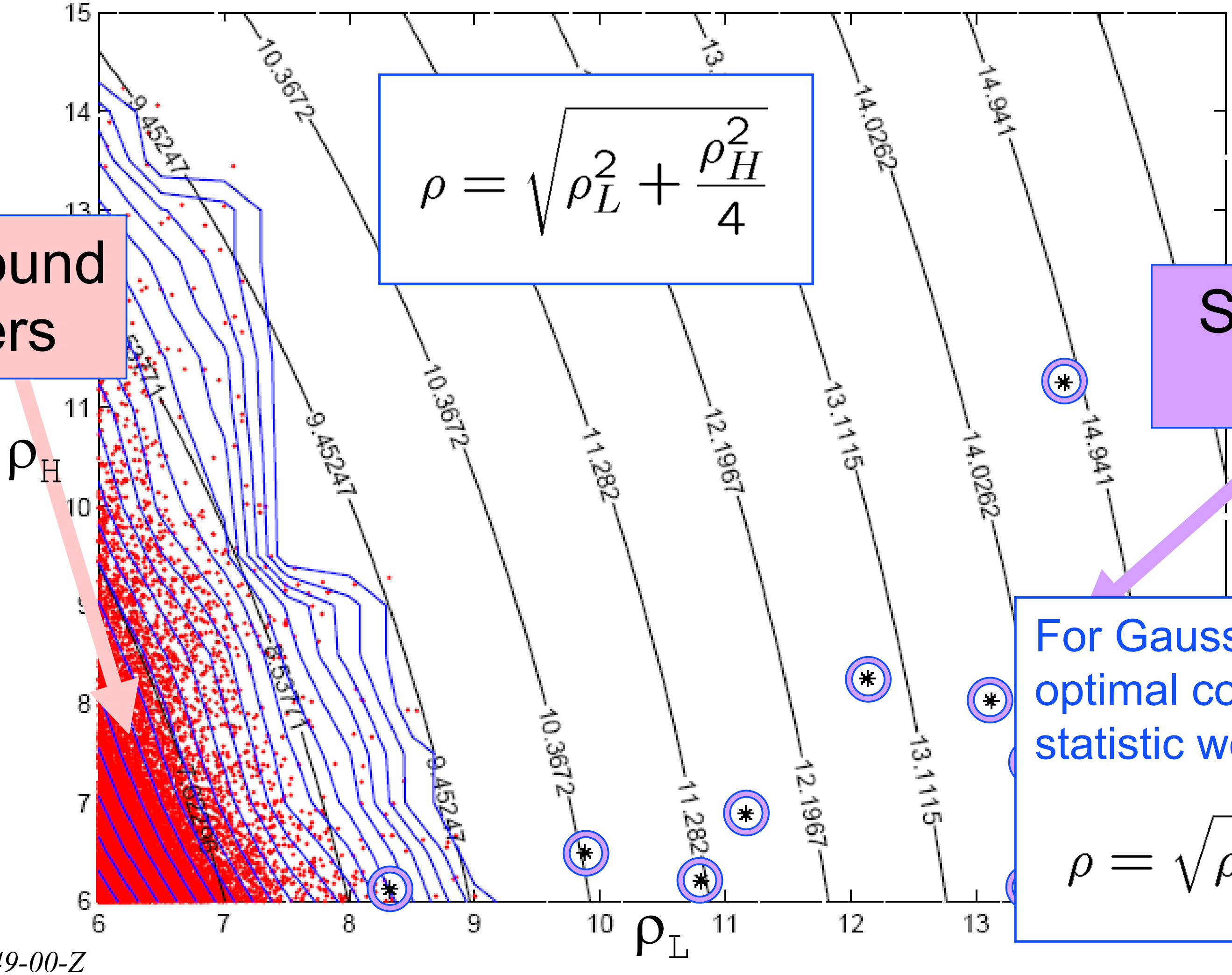


- Required triggers to be coincident in time and mass from at least two detectors

S2 Background Estimation Using Time Slides



S2 Empirical Coherent Statistic



$$\rho = \sqrt{\rho_L^2 + \frac{\rho_H^2}{4}}$$

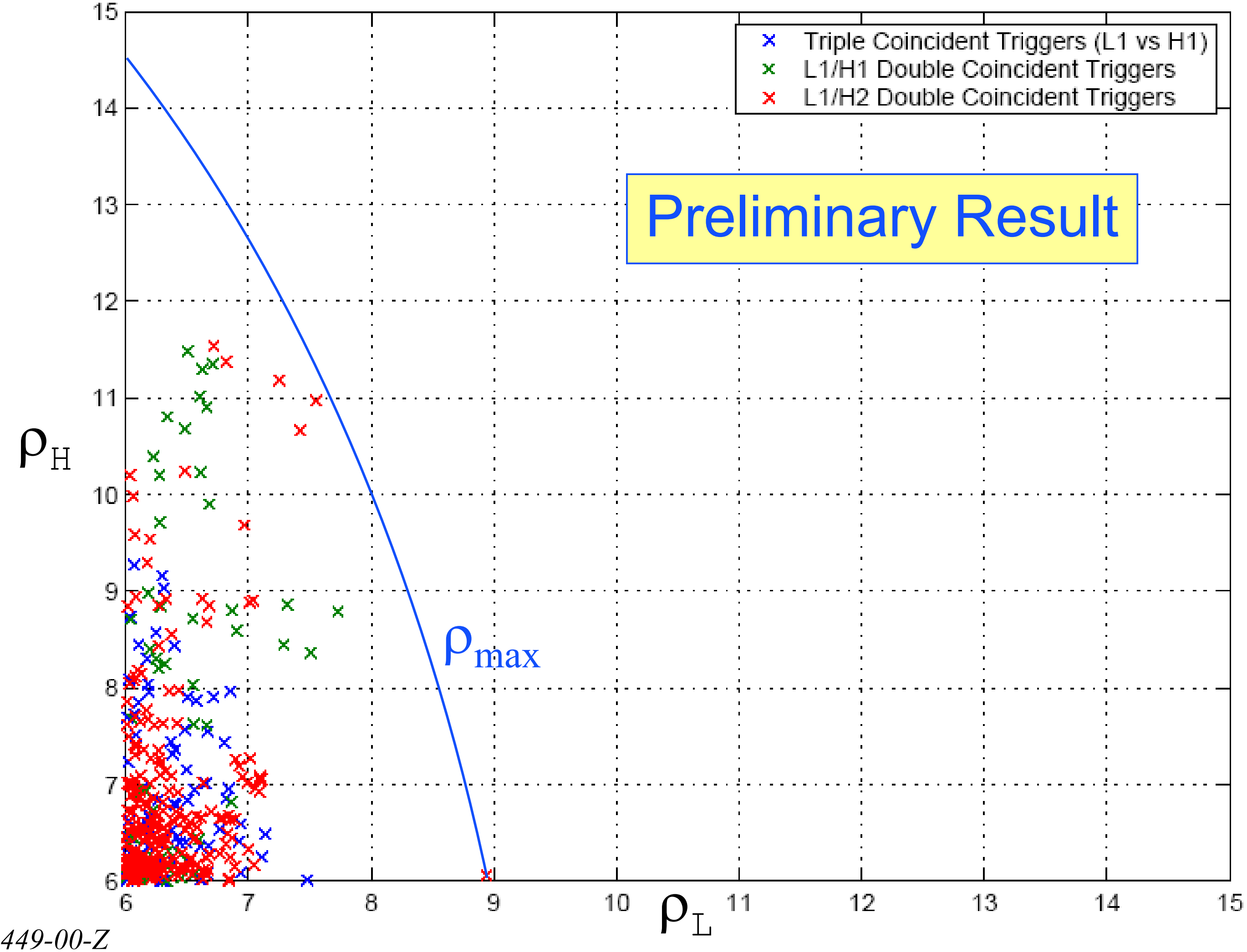
Background Triggers

Simulated Signals

For Gaussian noise, optimal coherent statistic would be

$$\rho = \sqrt{\rho_L^2 + \rho_H^2}$$

Preliminary S2 Triggers Observed



S2 Rate Upper Limit

- Use loudest event to determine rate
  - » No event candidates (real or background) were observed with $\rho > \rho_{\max}$
  - » Measure detection efficiency at $\rho_{\max}$ using Monte Carlo simulation:

N_G = Number of Milky Way Equivalent Galaxies to which we are sensitive at $\rho > \rho_{\max}$

  - » Can take background into account:

P_b = Probability of all background events having $\rho < \rho_{\max}$

- Obtain a one-sided frequentist confidence interval:

$$R_{90\%} = \frac{2.303 + \ln P_b}{T_{\mathrm{obs}}\ N_G}$$

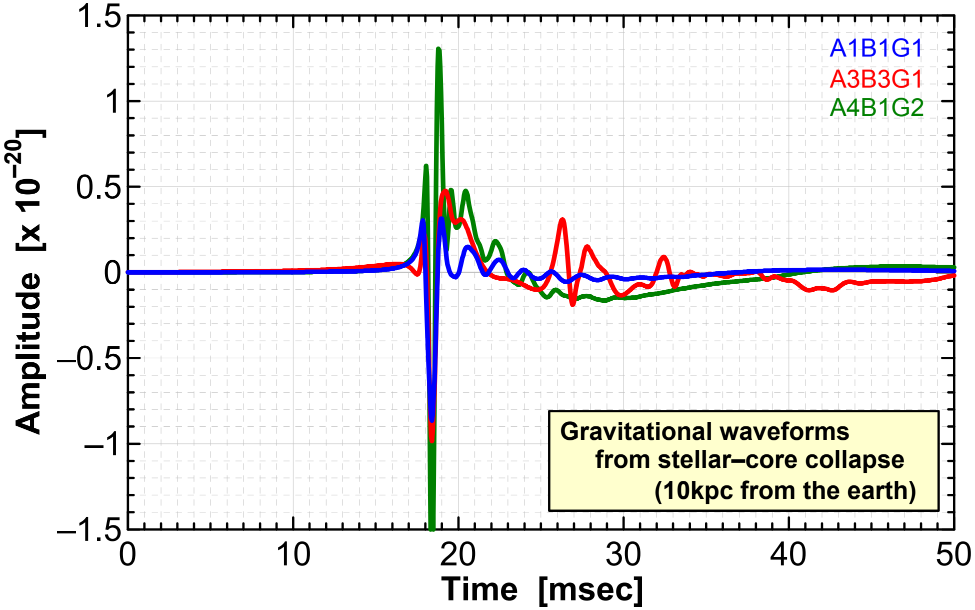
Preliminary
S2 Binary Neutron Star Result

- Observation time (T_{obs}) : 355 hours
- Conservative lower bound on N_{G} = 1.14
  - » Take the “worst case” for all systematic uncertainties to obtain this value
- Omit background correction term, $\ln P_b$
  - » Obtain conservative upper limit (Brady, Creighton, Wiseman gr-qc/0405044)
- Conservative upper limit:

Preliminary S2 Upper Limit:
$R_{90\%} < 50$
per year per MWEG

Burst Analysis

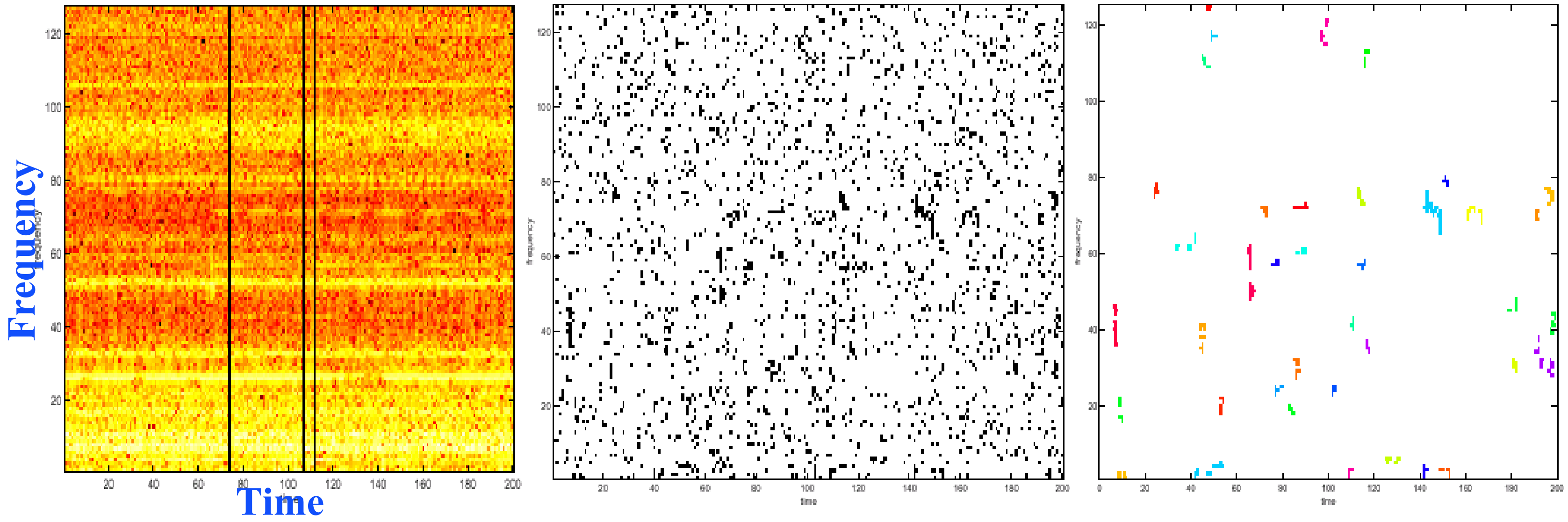
- Catastrophic events involving solar-mass compact objects can produce transient "bursts" of gravitational radiation in the LIGO frequency band:
  - core-collapse supernovae
  - merging, perturbed, or accreting black holes
  - gamma-ray burst engines
  - cosmic strings
  - others?
- Precise nature of gravitational-wave burst (GWB) signals typically unknown or poorly modeled.
  - Can't base such a broad search on having precise waveforms.
  - Search for generic GWBs of duration ~1ms-1s, frequency ~100-4000Hz.



possible supernova waveforms T. Zwerger & E. Muller, Astron. Astrophys. *320* 209 (1997)

Burst search example: Time-frequency methods

One way to search for bursts is by looking for transients in the *time-frequency plane*. Here, we illustrate the TFCLUSTERS algorithm.



- Compute t-f spectrogram, in short-duration time bins.
- Threshold on power in a pixel; search for clusters of pixels.
- Find coincident clusters in outputs of all interferometers.

Burst detection methods

LSC Burst group has used several variations on time-frequency methods.

Also,

- » Time-domain search for statistical *change points*
- » Simple time-domain filtering
- » Matched filtering for special cases where waveform is known
  - – Black hole “ringdowns”
  - – New search for cosmic string cusp and kink events.

Test the list of coincident event candidates for *coherence* between signals from three LIGO interferometers.

Coherence test is also the basis of a search for signals associated with times of gamma-ray bursts or other astrophysical events (“triggered search”.)

Time-domain burst search: BlockNormal

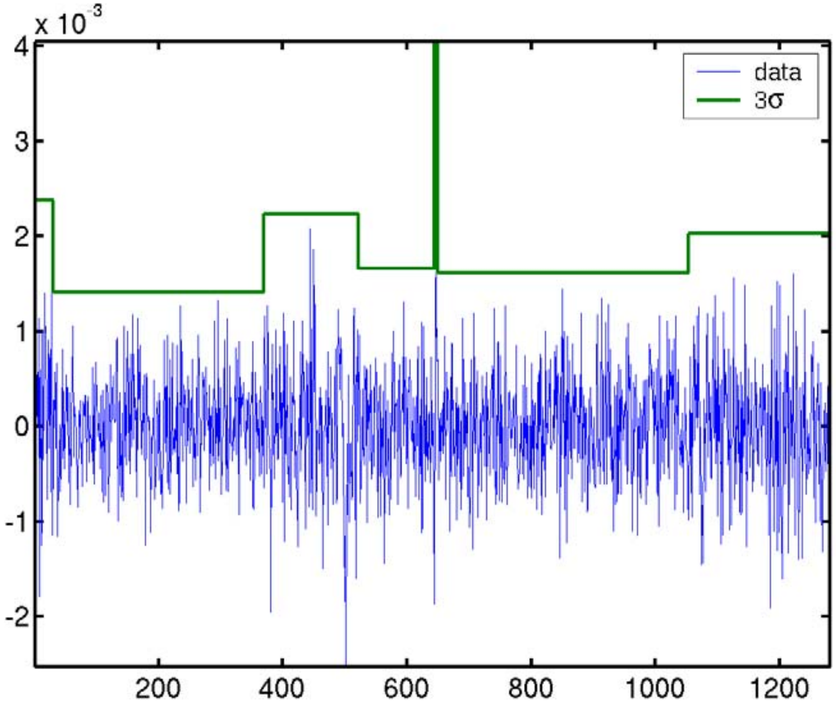
- Filter data into band-limited time series.
- Note *change points*, dividing time series into *blocks:*
  - Character of data changes between blocks.
  - Character of data within a block is roughly constant.
- Select unusual blocks: *events*.
- Collect adjacent events into a *cluster*.
- Look for coincident clusters to generate *triggers*.

Blocks in BlockNormal

Blocks characterized by:

- Start and end times
- Mean
- Variance

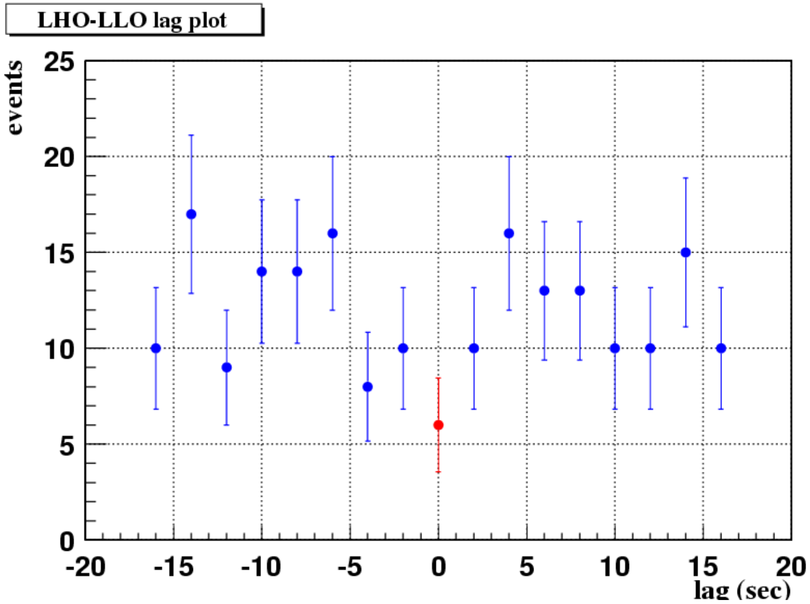
Events defined by noting blocks that differ significantly in mean or variance compared to typical epoch.



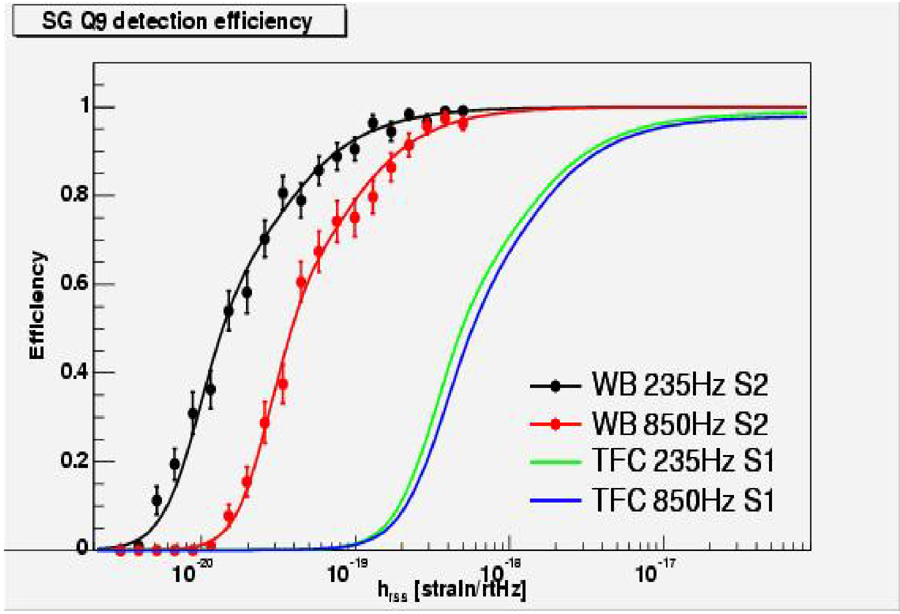
Coincidences, random coincidences, and efficiency

True coincidences at zero lag, and estimate of random coincidences from non-physical time lags.

Determination of search efficiency from artificial addition (in software) of trial signals to data.



S1



Comparison of S1 and S2

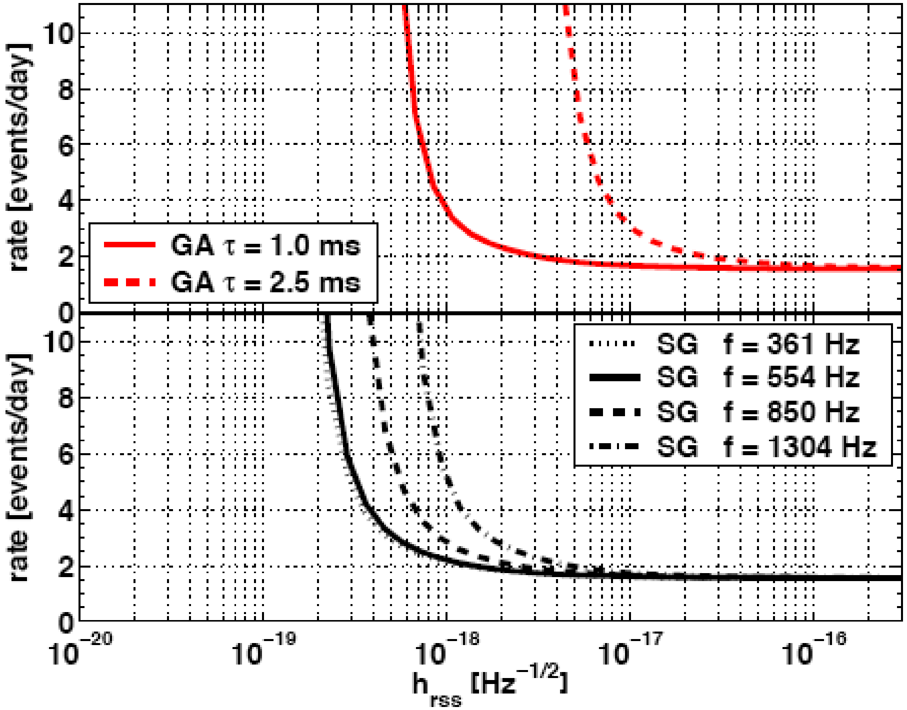
S1 Burst Search Results

Use Feldman-Cousins to set confidence upper limits on rate of foreground events:

- TFCLUSTERS: <1.6 events/day

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

Obtain rate vs. strength exclusion plots



Burst model: Gaussian/Sine gaussian pulses