Observational Results from the LIGO Second Science Run

LIGO Hanford Observatory

LIGO Livingston Observatory

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For the LIGO Scientific Collaboration

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Gravitational Wave Searches in LIGO

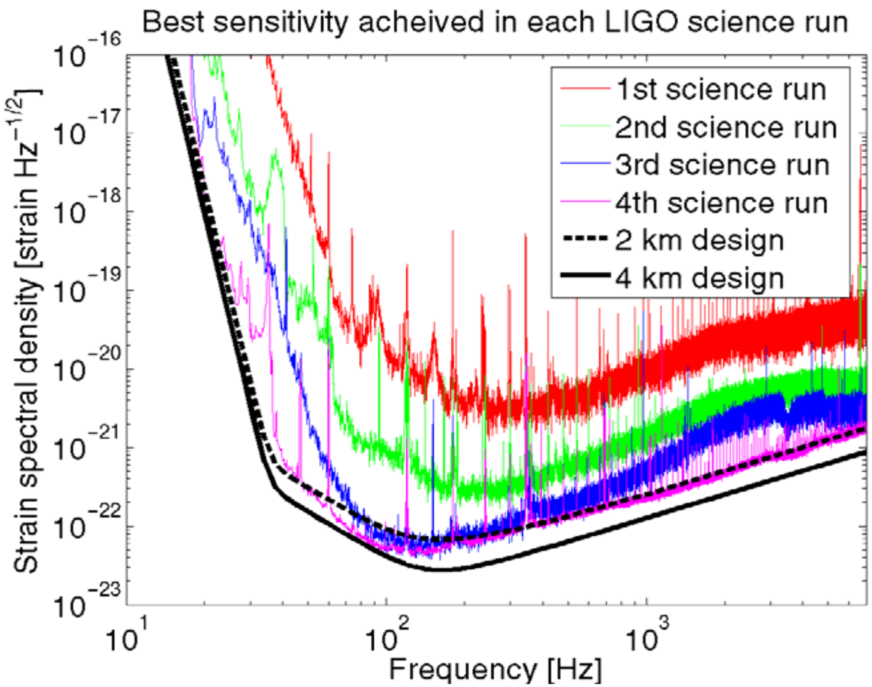
The previous talk described the Gravitational Wave Sources targeted by LIGO

1. Bursts: brief transient sources [e.g. from core-collapse supernovae]
2. Chirps [inspiraling binary systems]
3. Continuous sources [pulsars]
4. Stochastic sources [cosmogenic]

LIGO data: four science runs in 2002-2005, with increasing sensitivity and duty cycle

1. S1: published results
2. S2: published or soon to be submitted
3. S3: some in progress, some ready for submission
4. S4: several searches in live time. Results expected soon.

This talk:
search methods and current results

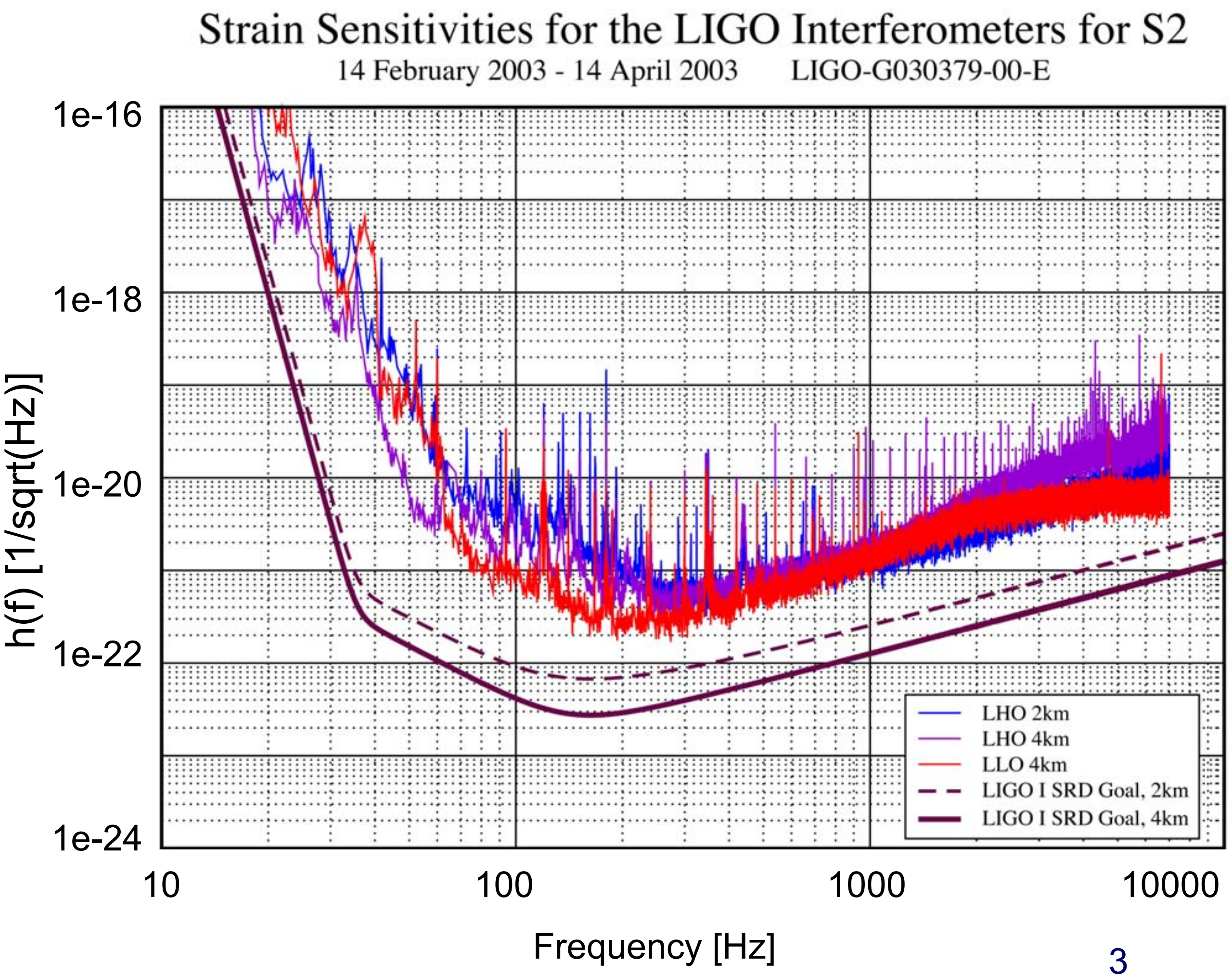


S2: Second Science Run

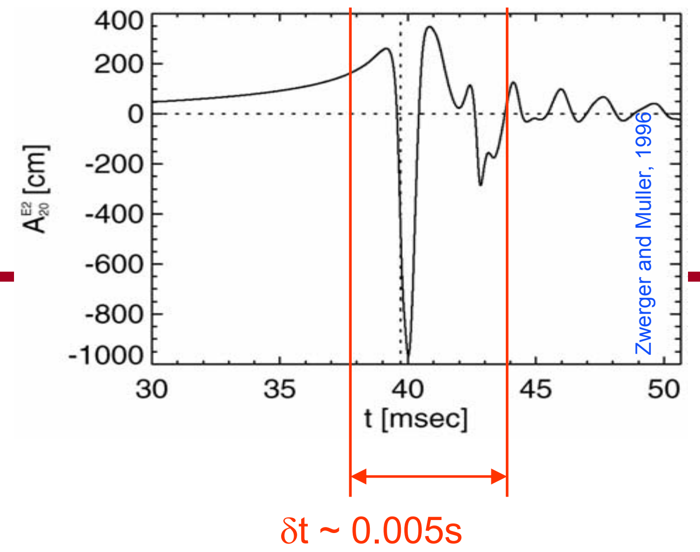
S2 improvements over S1:

~ 10 times more live time with three detectors

~ 10 times better sensitivity



Burst Search



Goal:

"wide-eye" search for un-modeled signals

minimal assumptions

open to unexpected sources and serendipity

Un-triggered Search

Broadband search (100-2000Hz) for short transients (few ms - 1 sec) of gravitational radiation of unknown waveform (e.g. supernovae, black hole mergers).

Method: *excess power* or *excess amplitude* techniques; coincidence between detectors

Results from first science run (S1): Phys. Rev. D 69 (2004) 102001

Externally Triggered Search -- Supernovae & Gamma Ray Bursts

Exploit coincidence with electromagnetic observations.

Waveforms still unknown, but time, direction potentially known.

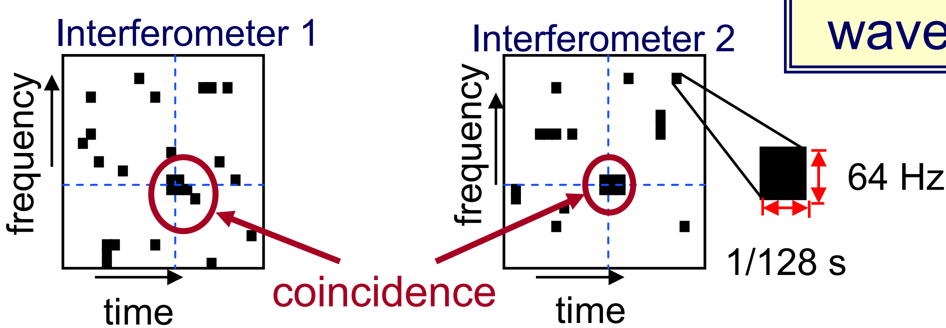
Method: interferometer-interferometer cross-correlation techniques.

No close supernovae/GRBs occurred during the first science run.

Second science run: we analyzed GRB030329. gr-qc/0501068 (Submitted to PRD)

S2 Untriggered Burst Search

Exploit coincidence in all three LIGO interferometers (H1, H2, L1)



⇓

Interferometer 1 events

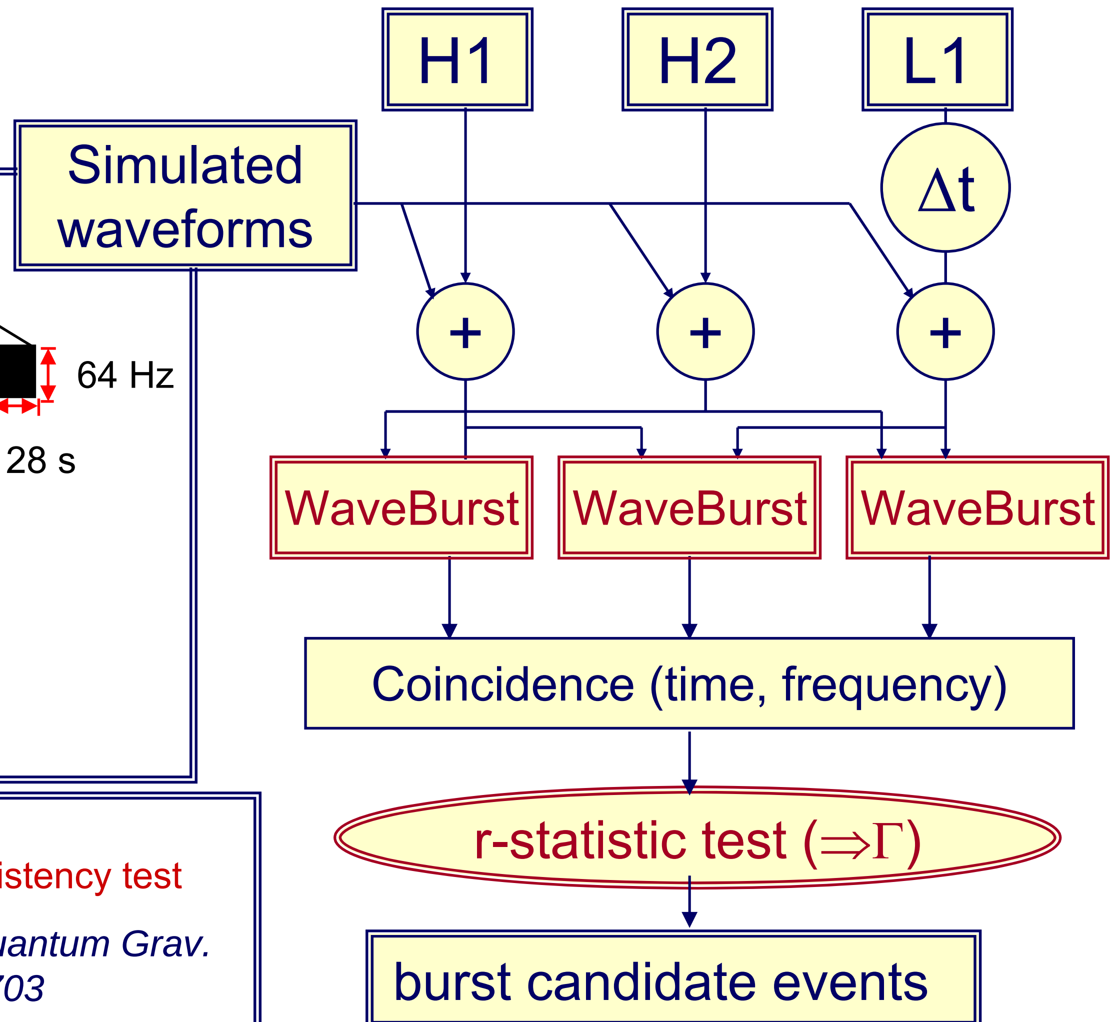
WaveBurst event trigger generator

Ref: Class. Quantum Grav. 21 (2004) S1819

$$r_k = \frac{\sum_i (x_i - \bar{x})(y_{i+k} - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_{i+k} - \bar{y})^2}}$$

r-statistic waveform consistency test

Ref: *Class. Quantum Grav. 21 S1695-S1703*



Upper Limit on Rate of Detectable Bursts (100-1100 Hz)

- The blind procedure gives one candidate with 0.05 estimated background
  - » Event immediately found to be correlated with airplane over-flight at Hanford.
  - » Acoustic noise detected in microphones and known couplings account for Hanford burst triggers (solved before the S3 run)

Introducing a post-facto acoustic veto

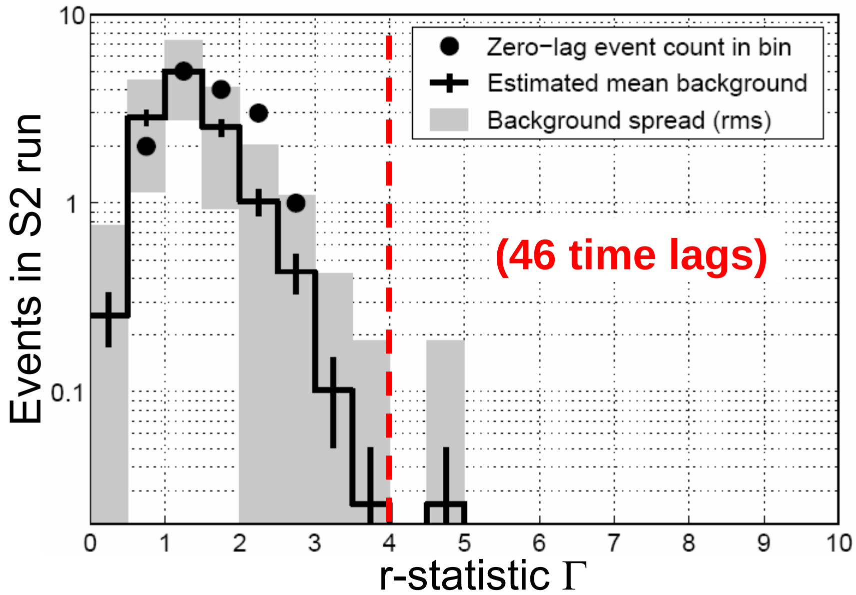
- » power in 62-100 Hz band in PSL table microphone

No surviving events in 10 live-days

Background estimate is 0.025

90% CL upper limit is 2.6 events

- » Account for modified coverage due to the introduction of a post-facto veto

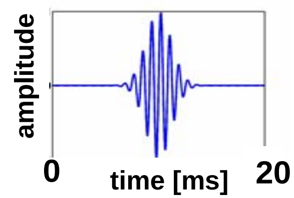


Rate upper limit = 0.26/day (1.6/day in S1)

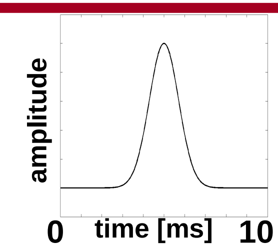
"Interpreted" Upper Limit

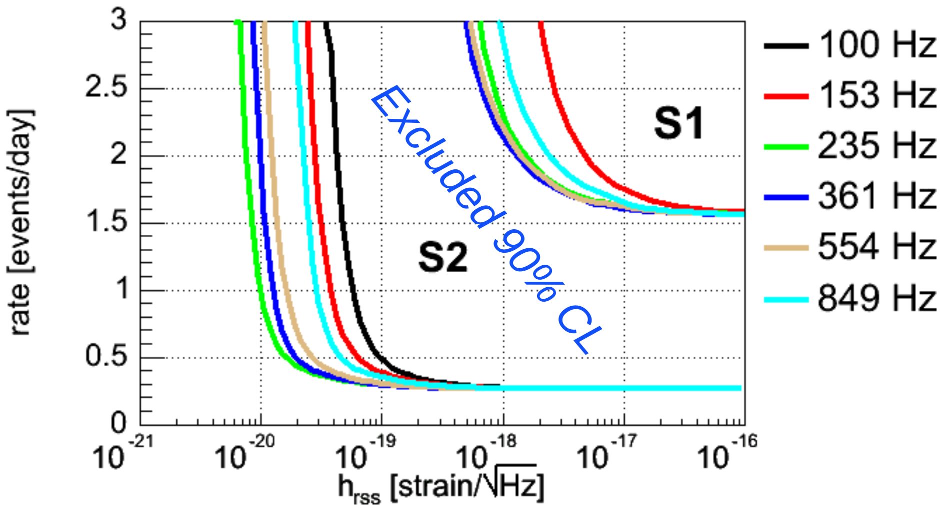
To measure our efficiency, we must pick a waveform!

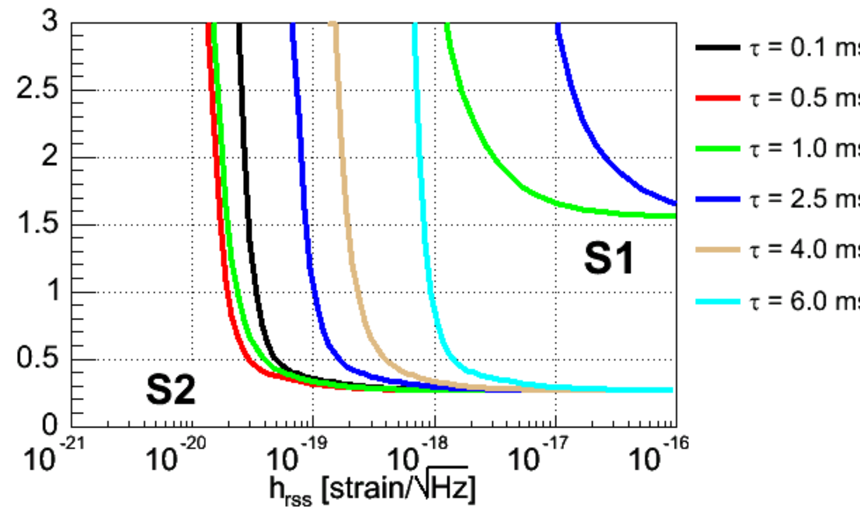
sine-Gaussians



Gaussians







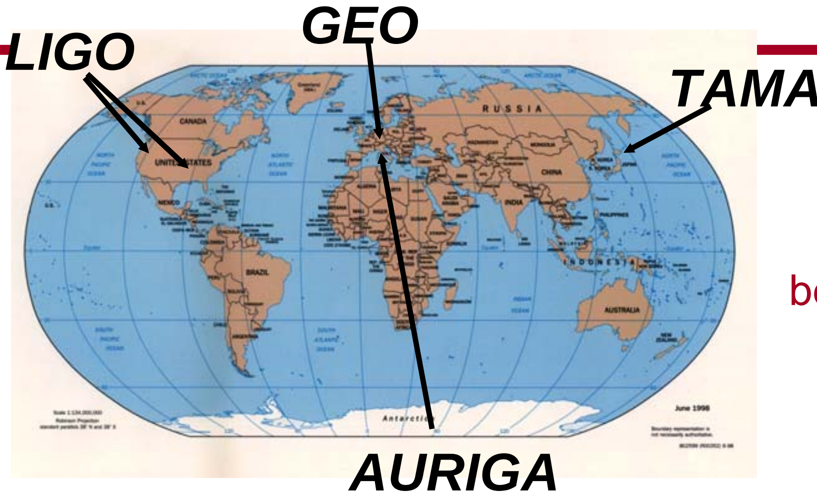
$$h_{rss} = \sqrt{\int |h(t)|^2 dt}$$

$$R(h_{rss}) = \frac{\eta}{\varepsilon(h_{rss}) \times T}$$

η=upper limit on event number
T=live time
$\varepsilon(h_{rss})$=efficiency vs strength

Exclusion curves account for 8% systematic calibration uncertainty and MonteCarlo statistical error

700-2000 Hz : Network Analysis



Ongoing joint analyses:

S2: TAMA (700-2000 Hz)

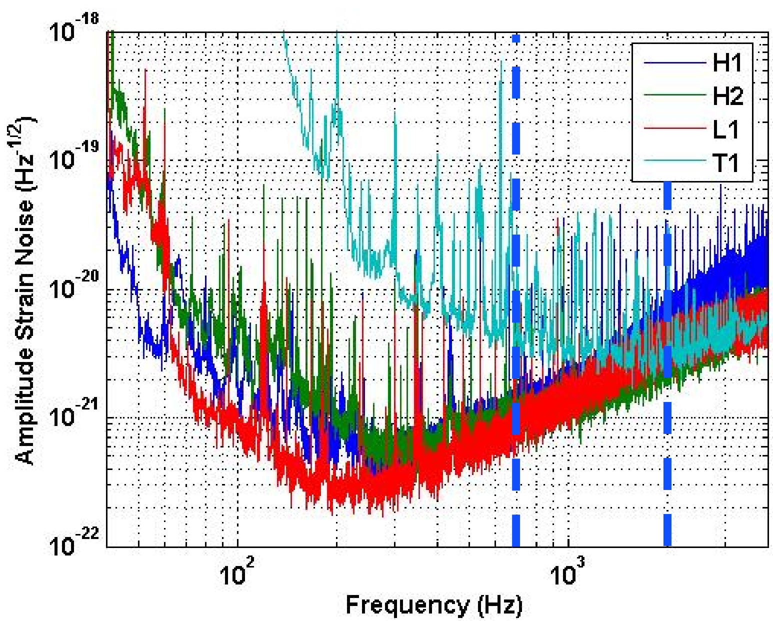
S3: GEO (700-2000 Hz) AURIGA (850-950 Hz)

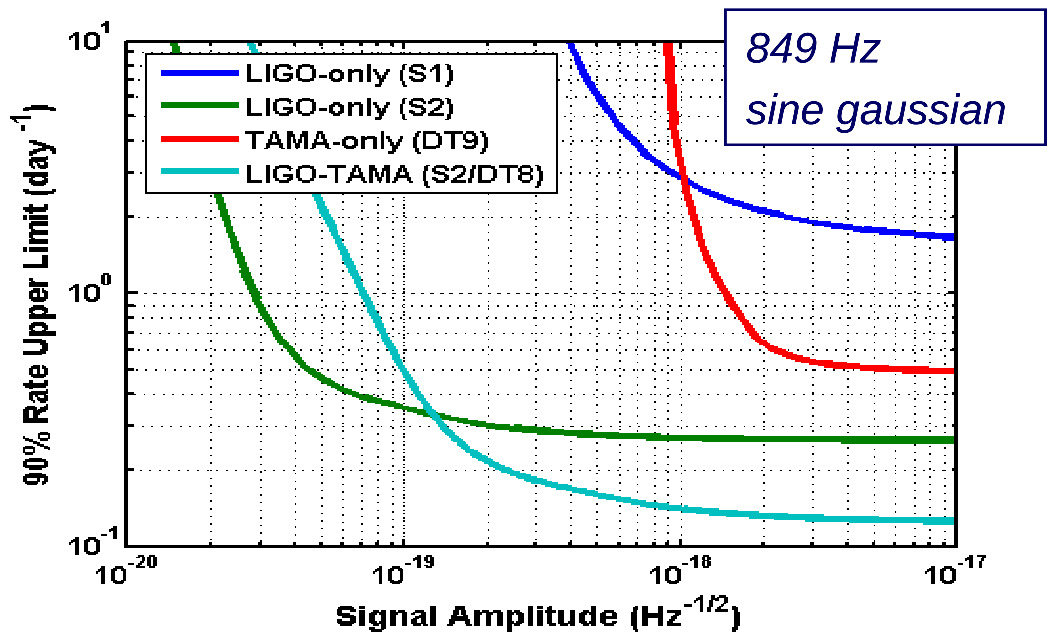
benefits and costs:

» Reduction of false alarm rate (4X)

» Increase in observation time (3X & 4X)

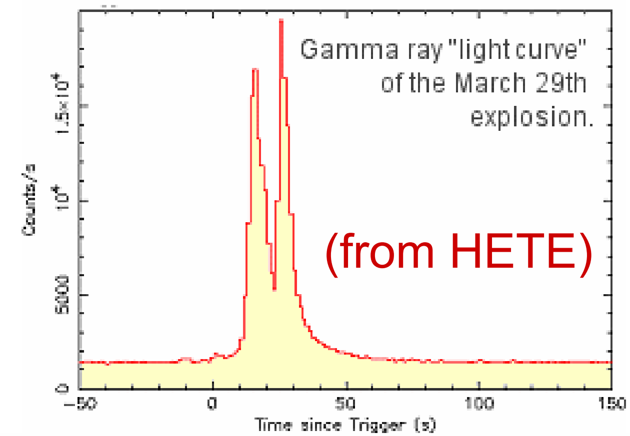
» Sensitivity restricted to common (high-frequency) band, limited by least sensitive detector

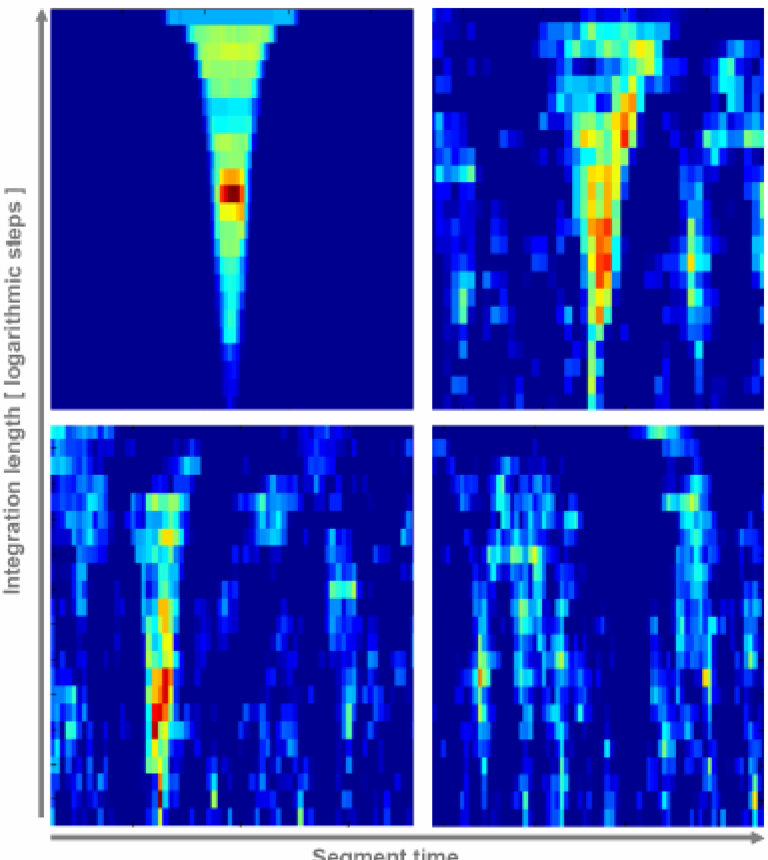


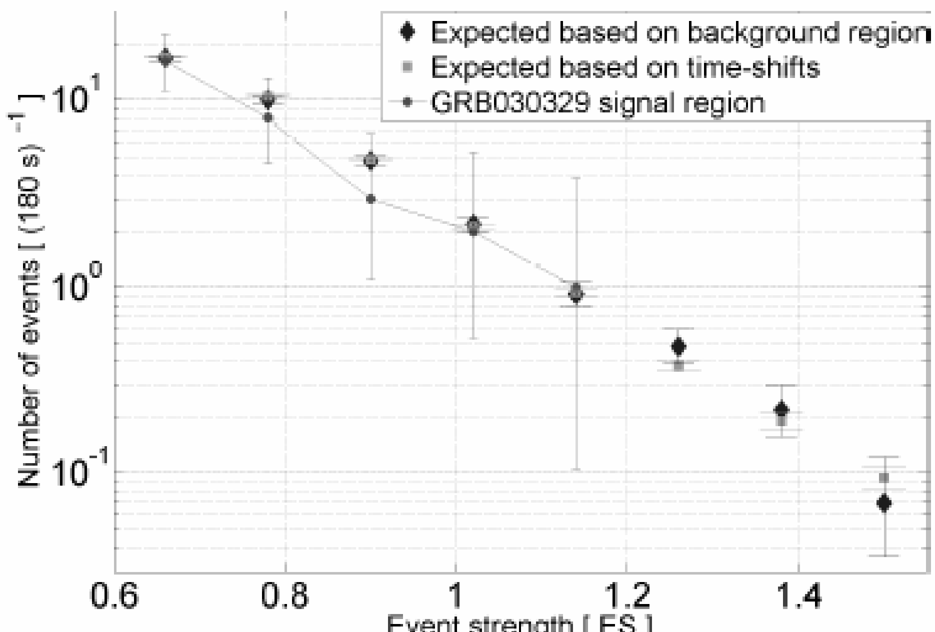


Externally triggered searches: GRB030329

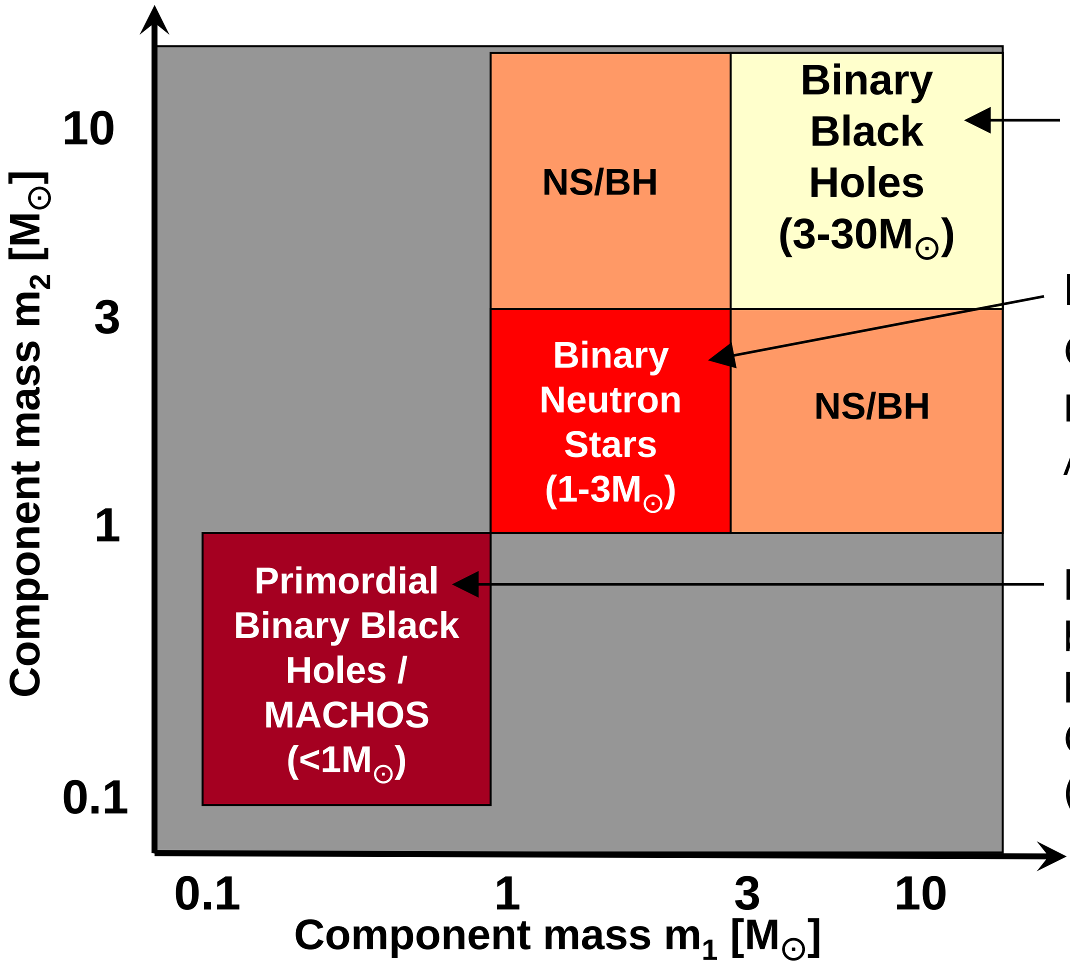
A supernova 800 Mpc away - H1, H2 in operation
A targeted search resulted in no detection
(none expected from 800 Mpc source)







Search for Inspiral Binary Systems



High mass systems: BBH
Predicted rate:???

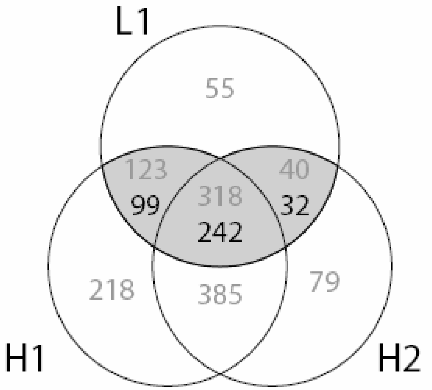
Intermediate mass systems: BNS
Galactic rate: ~80/Myr
Initial LIGO rate ~1/30yrs (>1/3yrs)
Advanced LIGO rate ~1/2days (>5/day)

Low mass systems: primordial black holes, MACHOS (galactic halo)
Galactic rate: < 8/kyr
(from microlensing observations)

Results from BNS search in the first science run (S1): Phys. Rev. D 69 (2004) 122001

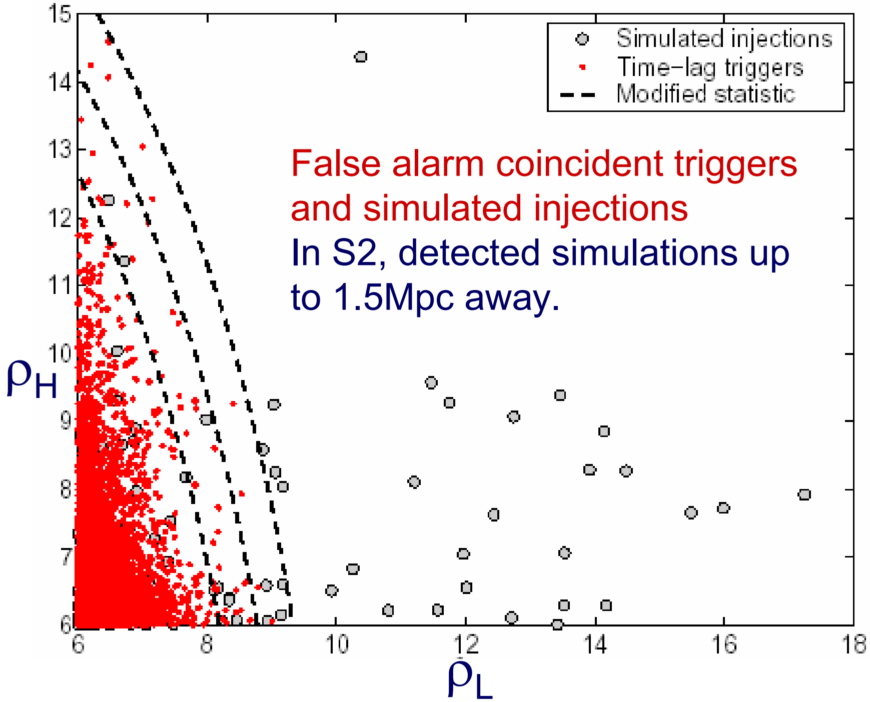
Analysis Method

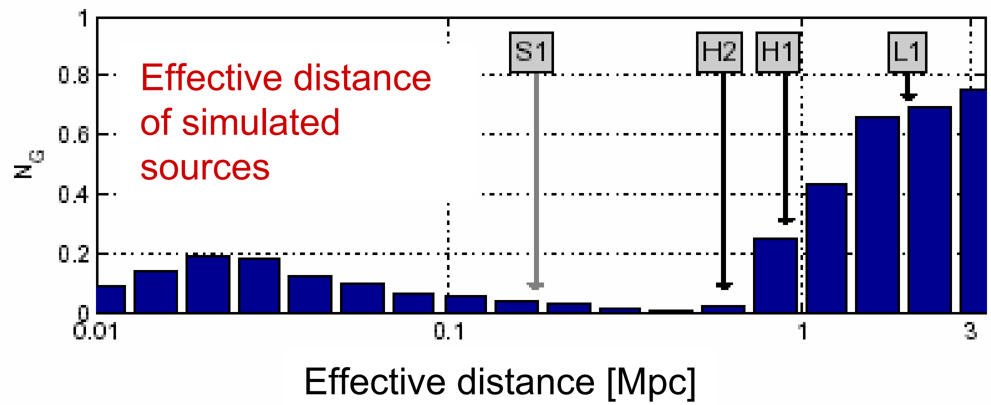
Compact binary systems, inspiraling phase:
"well" known waveforms (chirps), can use optimal filtering

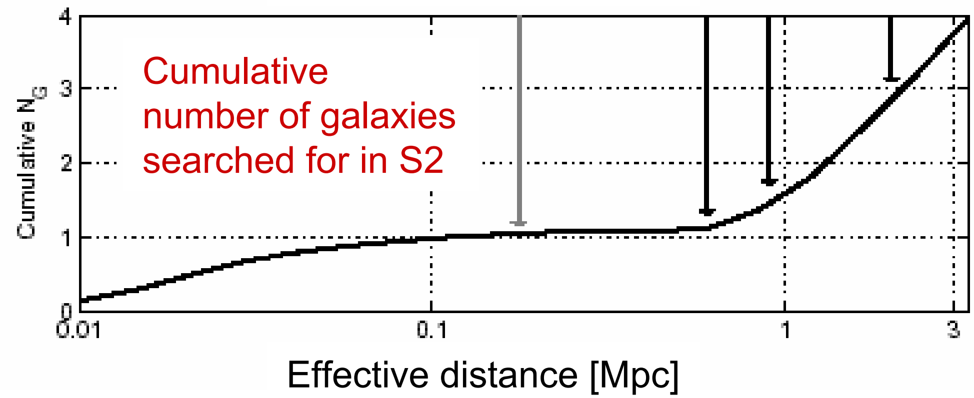


- Analyze data from each interferometer
  - » use a bank of 2nd order post-Newtonian templates (m_1, m_2)
  - » matched filter; threshold on signal-to-noise ratio (SNR)
  - » Apply waveform consistency veto: χ^2 test
- Require coincidence between Livingston and Hanford (time and mass)
- Combined signal-to-noise ratio: $\rho^2 = \rho_L^{\,2} + 0.25\, \rho_H^{\,2}$

Astrophysical Reach for Binary Neutron Star Sources





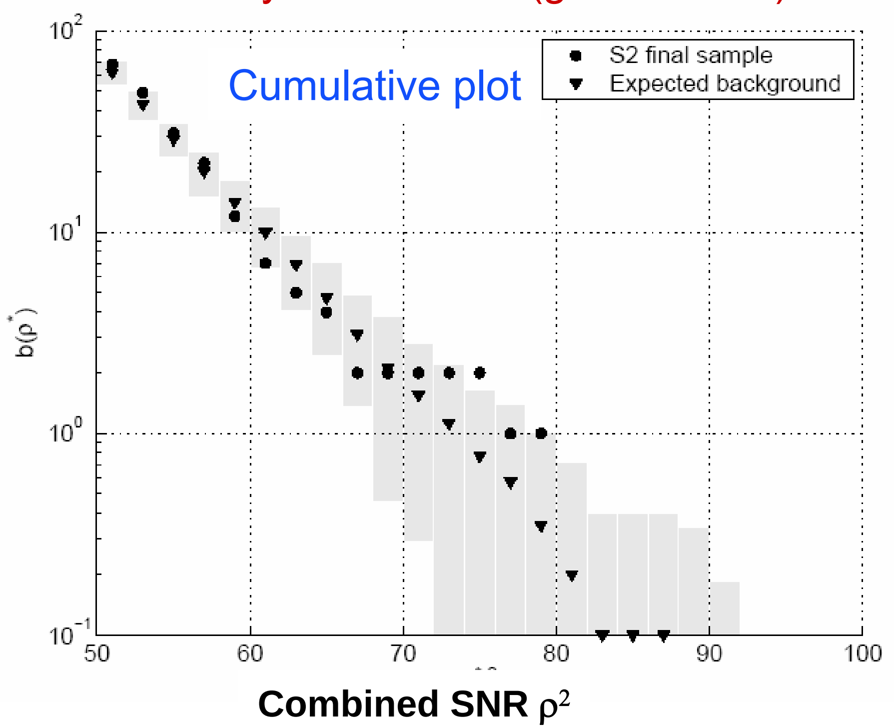


- S1: 176 kpc for L1, 46 kpc for H1
- S2: 1.8 Mpc for L1, 0.9 Mpc for H1
- S3: 2.2 Mpc for L1, 6.8 Mpc for H1
- S4: 14.1 Mpc for L1, 17.4 Mpc for H1

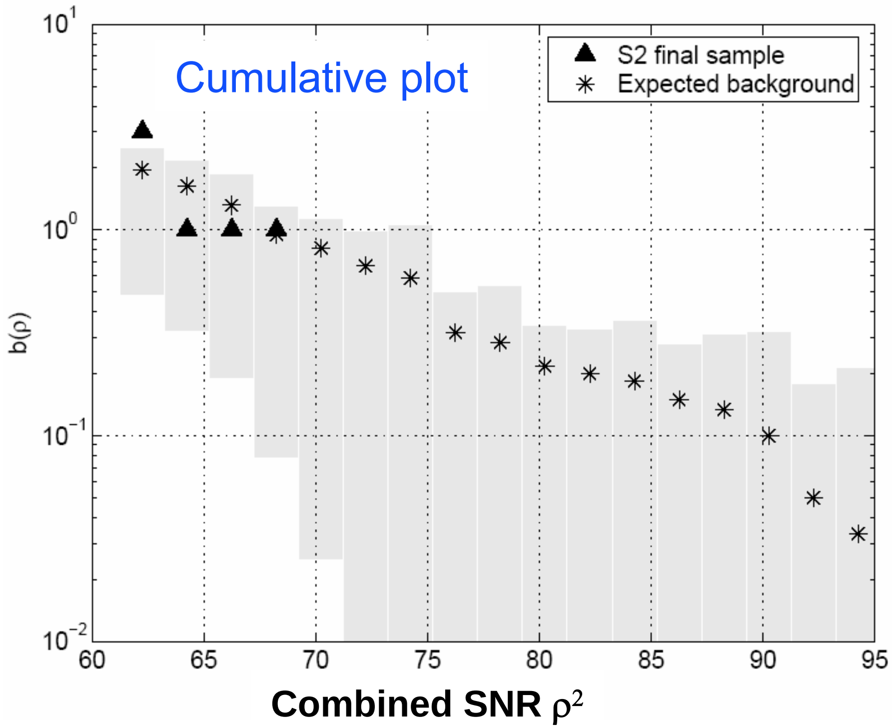
← Reach for a 1.4-1.4 M optimally oriented binary, at SNR threshold=8

S2 Inspiral Search Results

Neutron Stars binary systems:
R < 47 / year / MWEG (galactic rate)



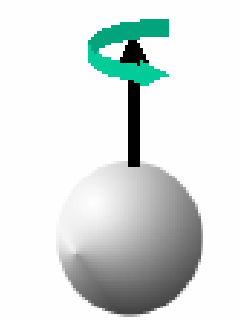
MACHO search:
R < 63 / year from the galactic halo



Black Hole binary systems search: in progress

Search for Periodic Sources

- First science run: looked at a single isolated pulsar (J1939+2134) using two different coherent searches. [*Phys. Rev. D 69 082004,2004*]
- Second and third science runs: pursuing several different approaches:



Rotating stars produce GWs if they have asymmetries

Coherent searches:

-Time-domain:
+ Targeted [gr-qc/0410007]
+ Markov Chain Monte Carlo

Searches over narrow parameter space

- Frequency-domain:
+ Isolated
+ Binary, Sco X-1

Searches over wide parameter space

Incoherent searches:

+ Hough transform
+ Stack-Slide
+ Powerflux

Excess power, wide parameter space searches

to be combined in a hierarchical scheme

einstein@home
http://einstein.phys.uwm.edu

S2 results for 28 targeted, known pulsars (f>25Hz)

to appear in PRL, 2005, gr-qc/04100007

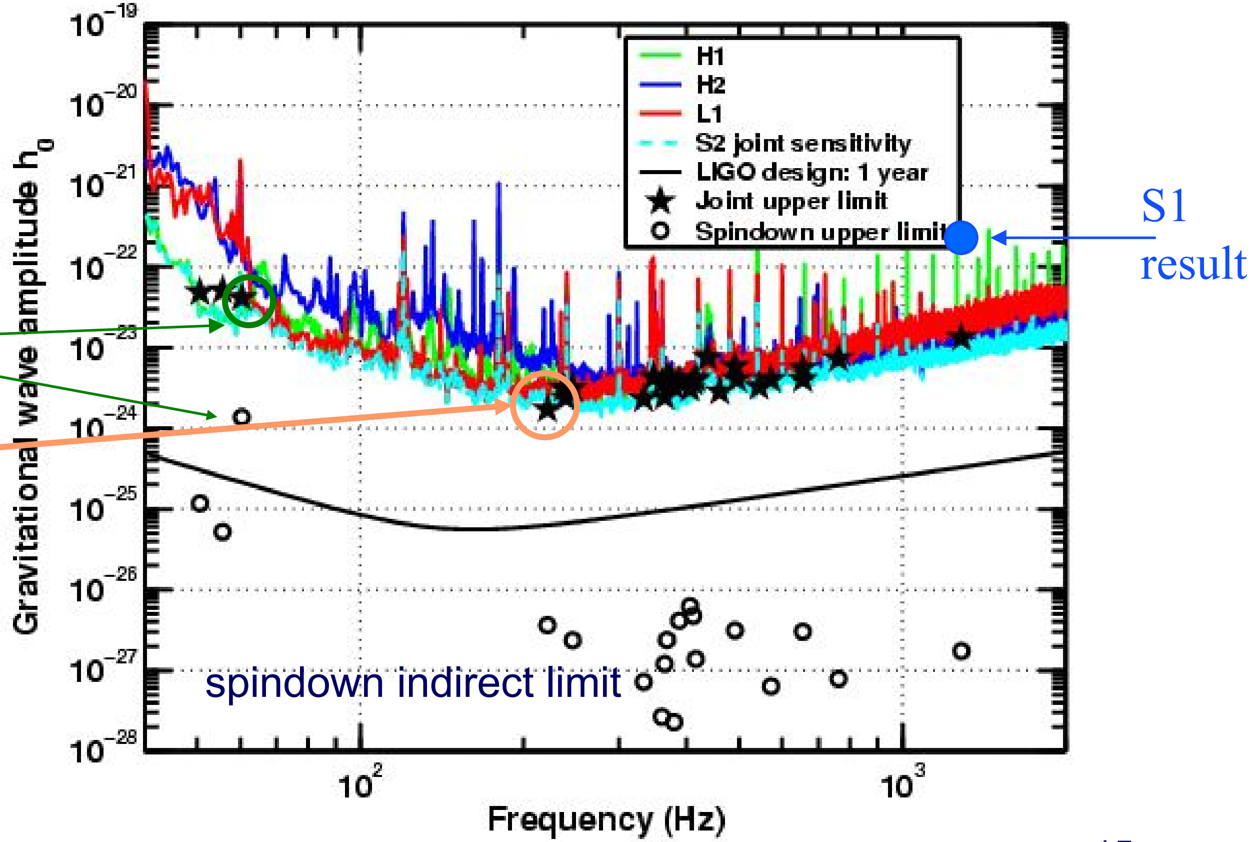
- No GW signal.
- First direct upper limit for 26 of 28 sources studied (95%CL)

sensitivity for actual observation time @1% false alarm, 10% false dismissal

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

Crab pulsar
$h_0 < 4.1 \times 10\text{-}23$

J1910-5959D
$h_0 < 1.7 \times 10^{-24}$



Equatorial ellipticity constraints as low as: $\varepsilon < 10^{-5}$

Stochastic Background

- Strength specified by *ratio of energy density in gravitational waves to total energy density* needed to close the universe:

$$\Omega_{GW}(f) = \frac{1}{\rho_{critical}} \frac{d\rho_{GW}}{d(\ln f)}$$

$$S_{\mathrm{gw}}(f) = \frac{3H_0^2}{10\pi^2} f^{-3}\Omega_{\mathrm{gw}}(f)$$

Strain power spectrum associated to Ω_{gw}

- Detect by *cross-correlating* output of two GW detectors:

$s_i(t) = h_i(t) + n_i(t)$

$$Y = \iint dt_1 dt_2\, s_1(t_1) Q(t_1 - t_2) s_2(t_2)$$

$$\tilde{Q}(f) \propto \frac{\gamma(f) S_{gw}(f)}{P_1(f) P_2(f)}$$

Limits on $\Omega_0 h_{100}^2$

Assuming $\Omega_{GW}(f)=\Omega_0$ (constant) and $h_{100} = H_0/(100\ km/sec/Mpc)$

LIGO run	H-L	H1-H2	Frequency Range	Observation Time
S1 PRD 69(2004)	< 23 +/- 4.6 (H2-L1)	Cross-correlated instrumental noise found	40-314 Hz	64 hours
S2 Preliminary	< 0.018 +0.007- 0.003 (H1-L1)	Cross-correlated instrumental noise found	50-300 Hz	387 hours
S3 In progress		Trying to account for instrumental noise in bounding Ω	50-250 Hz (H1-L1) 70-220 Hz (H1-H2)	350 hrs (H1-L1) 550 hrs (H1-H2)
S4 Starting Analysis				447 hrs (H1-L1) 510 hrs (H1-H2)

Initial LIGO (1 yr) : $\Omega_0 h_{100}^2 < 2 \times 10^{-6}$

Advanced LIGO (1 yr) : $\Omega_0 h_{100}^2 < 7 \times 10^{-10}$

Conclusions

- The LIGO Scientific Collaboration is busy in the analysis of LIGO data: many searches, no detections, observational upper limits.
- Many more results are coming out in the next few months.
  » The latest run, S4, had some searches and much diagnostics done in real time.
  » An "astrowatch" is in progress at times when detectors are in operation while not in "science runs".
  » S5 will start in the fall, and collect one-year integrated time. An on-line search is expected, as well as deeper, off-line searches. Stay tuned!

Extra slides

Comparison with the IGEC Burst Search

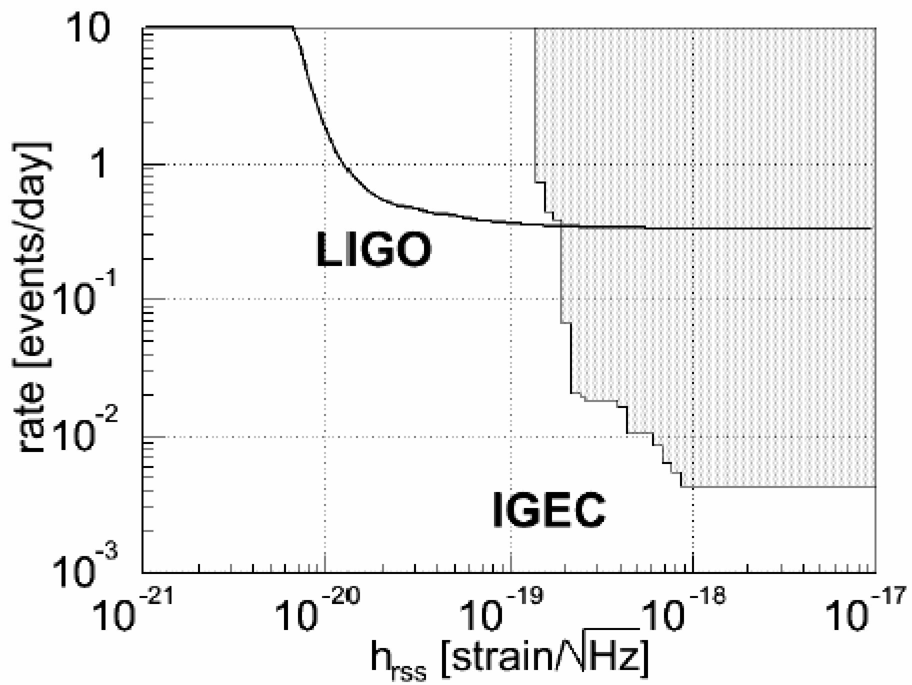


FIG. 14: Rate versus $h_{\rm rss}$ exclusion curves at the 95% confidence level for optimally oriented Gaussians of τ=0.1 ms. The solid curve displays the 95% confidence level measurement obtained by LIGO with this search. The IGEC exclusion region is shown shaded and it is adapted from Fig. 13 of [46]. If the comparison were performed using Q=8.9, 849 Hz sine-Gaussians, the LIGO and IGEC curves would move to smaller amplitudes by factors of 1.1 and ~3, respectively.

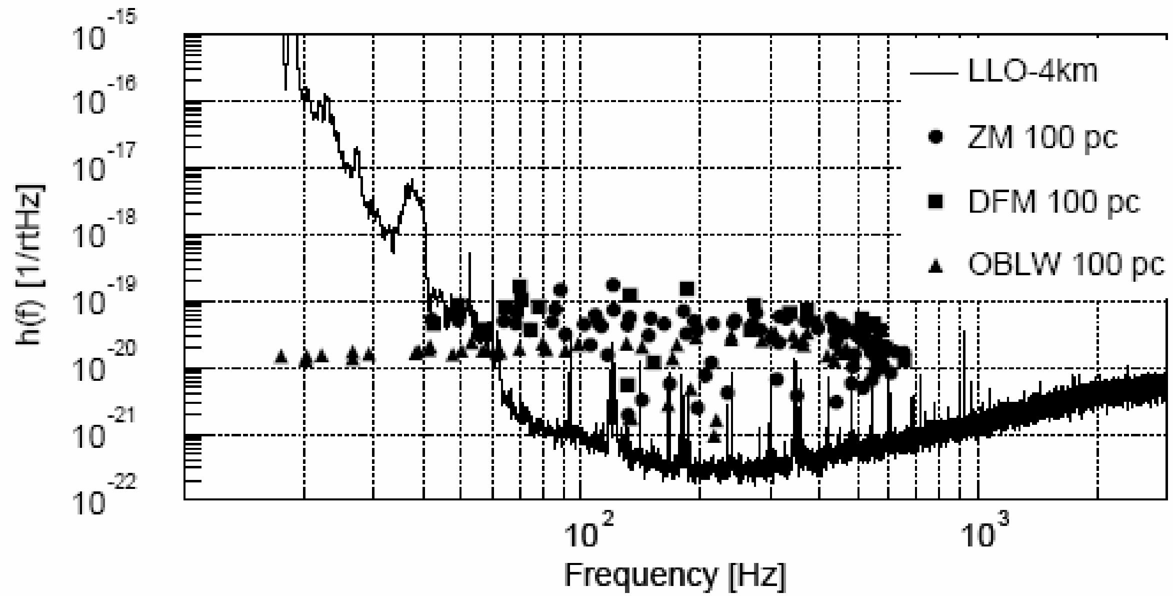
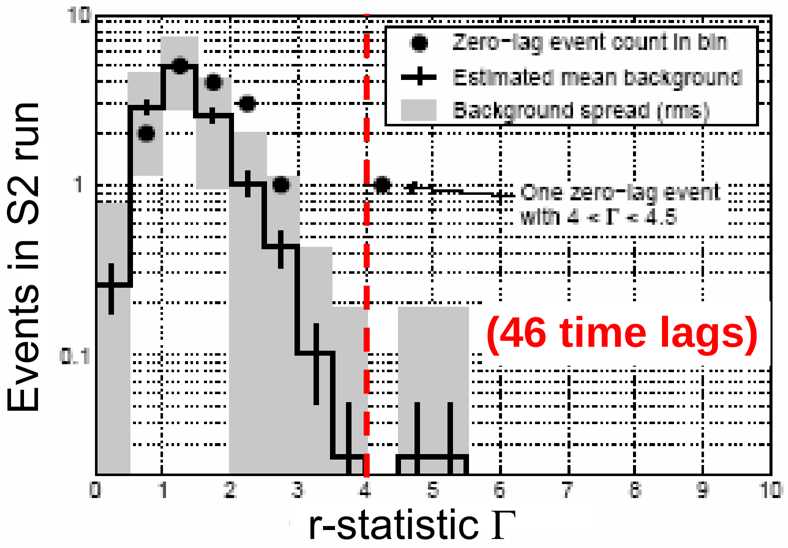


FIG. 13: Signal strength $h_{\rm rss}$ at the detectors versus central frequency for the 176 supernovae waveforms from the three models described in references [14–16]: the hydrodynamical model of ref. [14], labeled "ZM", the relativistic effects considered in ref. [15] and labeled "DFM", and finally the hydrodynamical model employing realistic nuclear equation of state of ref. [16], labeled "OBLW". In all cases, the supernova events are positioned in optimal orientation and polarization at 100 pc from the detectors. The strain sensitivity of the L1 detector during the S2 run is shown for comparison.

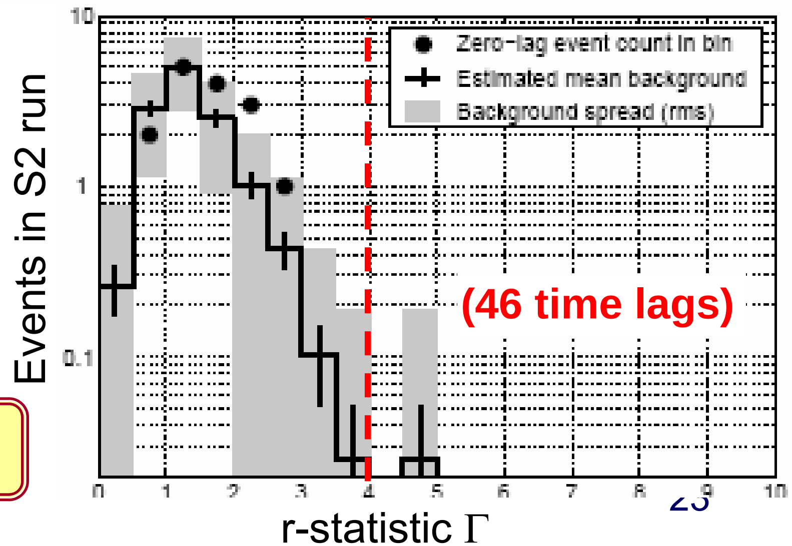
Upper Limit on Rate of Detectable Bursts (100-1100 Hz)

- The blind procedure gives one candidate
  - » Event immediately found to be correlated with airplane over-flight at Hanford.
  - » Acoustic noise detected in microphones and known couplings account for Hanford burst triggers (solved before the S3 run)
- Background estimate is 0.05



- Introducing a post-facto acoustic veto
  - » power in 62-100 Hz band in PSL table microphone
- Background estimate is 0.025
- 90% CL upper limit is 2.6 events
  - » Account for modified coverage due to introduction of post-facto veto

Rate upper limit = 0.26/day (1.6/day in S1)



Equatorial Ellipticity

- Results on h_0 can be interpreted as UL on equatorial ellipticity.
- Ellipticity scales with the difference in radii along x and y axes.

$$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}, \qquad \varepsilon = \frac{c^4}{4\pi^2 G} \cdot \frac{r}{f_{gw}^2} \cdot \frac{h_0}{I_{zz}}$$

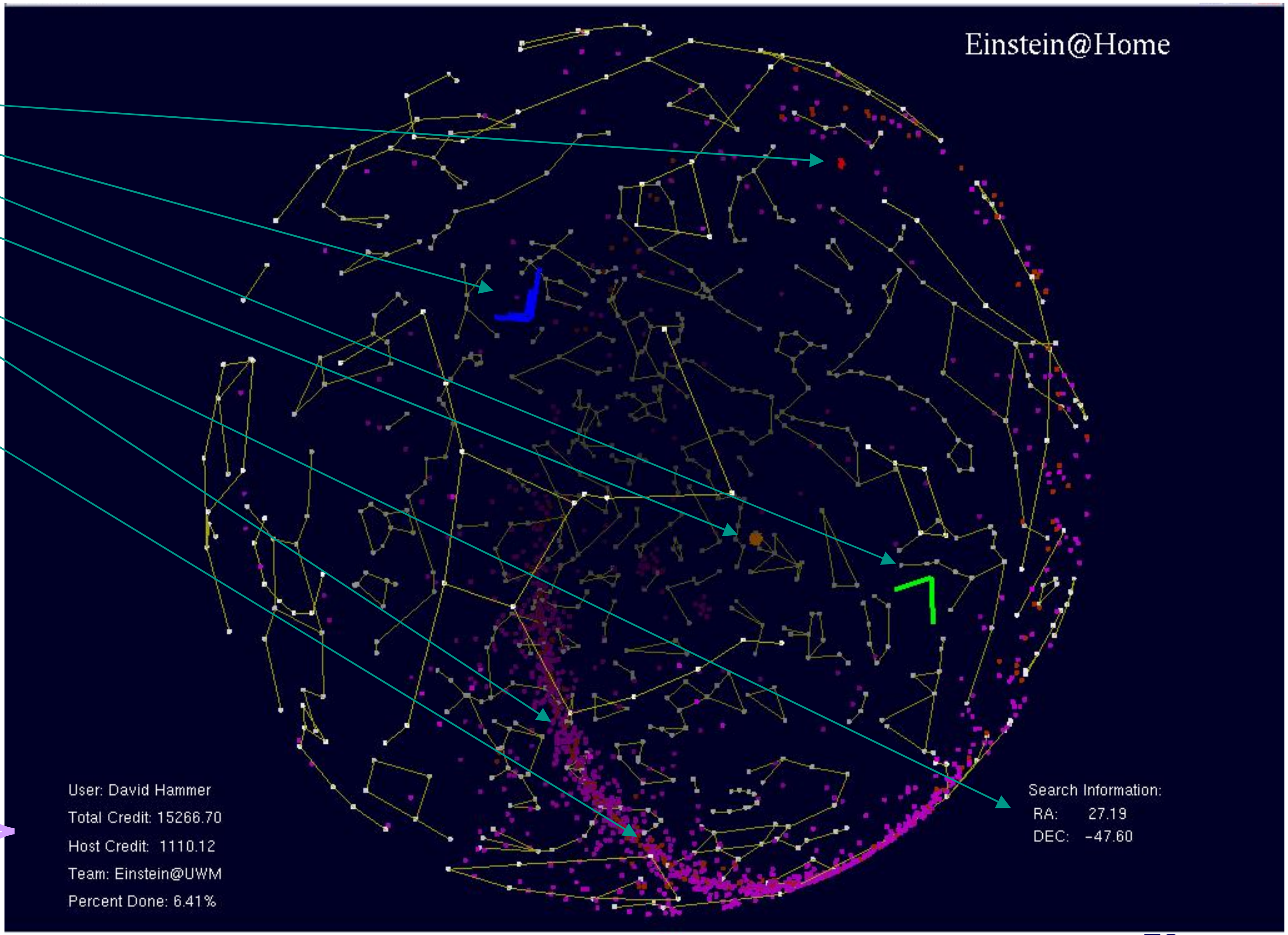
- Distance r to pulsar is known, I_{zz} is assumed to be typical, 10^{45} g cm^2.
- Pulsars J0030+0451 (230pc), J2124-3358 (250 pc), J1744-1134 (360 pc), and J1024-0719 (350 pc); the nearest four pulsars

$$\varepsilon < 10^{-5}$$

- Nine of the pulsars are actually spinning up, so this analysis is the first upper limit on the ellipticity for these objects.

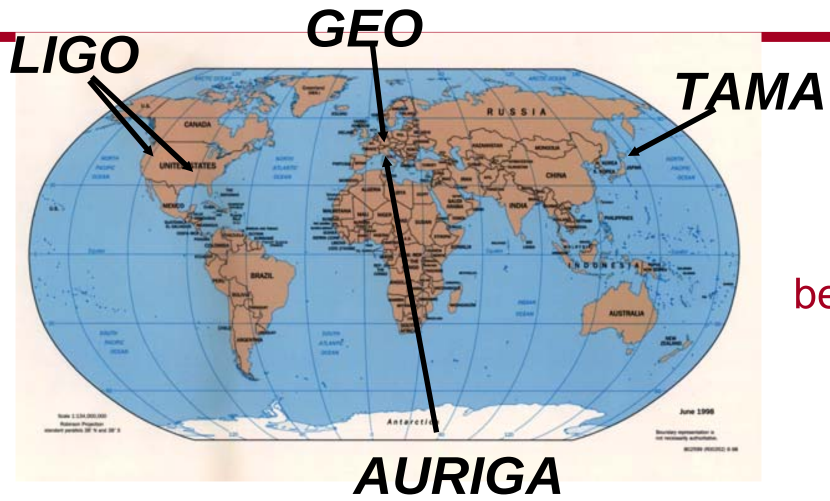
Einstein@home

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remenants



- User name
- User's total credits
- Machine's total credits
- Team name
- Current work % complete

700-2000 Hz : Collaborative Analysis



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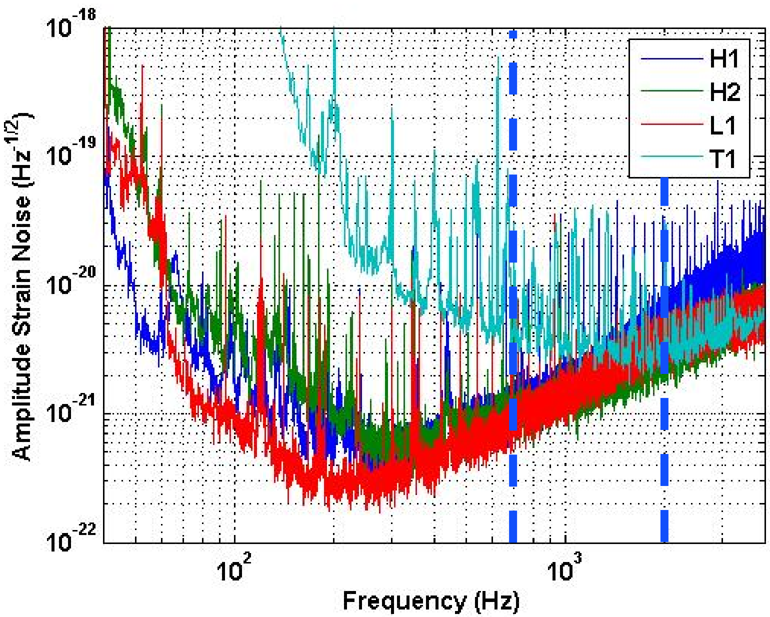
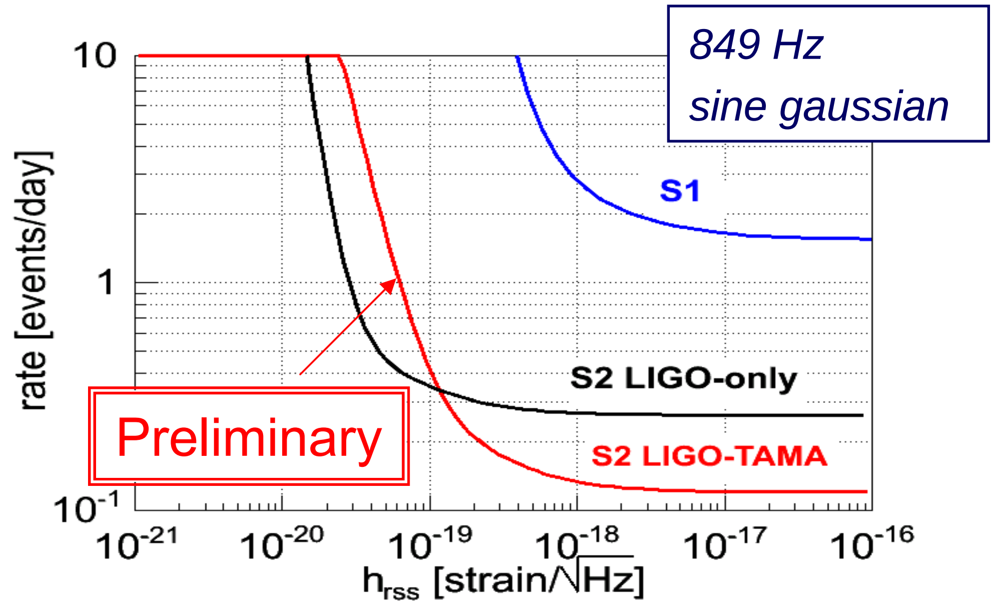




Characterization of a Stochastic Gravitational Wave Background

- **Assuming SGWB is isotropic, stationary, and Gaussian the strength is fully specified by the energy density in GWs**

$$\Omega_{gw}(f) = \frac{1}{\rho_{critical}} \frac{d\rho_{gw}}{d(\ln f)}$$

- **$\Omega_{gw}(f)$ in terms of the strain power spectrum, $S_{gw}(f)$:**

$$S_{\rm gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3}\Omega_{\rm gw}(f)$$

- **Strain amplitude scale:**

$$h(f) = S_{\rm gw}^{1/2}(f) = 5.6\times10^{-22}\, h_{100}\sqrt{\Omega_0}\left(\frac{100\rm Hz}{f}\right)^{3/2} {\rm Hz}^{1/2}$$

Data Analysis Strategy

- **Assume that detector noise $n_i(t)$ dominates the output, $P_i(f)$ - noise power spectrum**
- **Cross-correlate outputs from two interferometers $s_i(t) = h_i(t) + n_i(t)$**
- **Operator $\tilde{Q}(f)$ weights the cross-correlation to maximize the signal-to-noise ratio of the $\Omega_{gw}(f)$ measurement**
- **Overlap reduction function $\gamma(f)$ accounts for separation and angle between two detectors**

$$Y = \iint dt_1 dt_2 \; s_1(t_1) Q(t_1 - t_2) s_2(t_2)$$

$$\overline{Y} = \frac{T}{2} \int df \, \gamma(f) S_{gw}(f) \tilde{Q}(f)$$

$$\sigma_Y^2 \approx \frac{T}{4} \int df \, P_1(f) \left| \tilde{Q}(f) \right|^2 P_2(f)$$

$$\tilde{Q}(f) \propto \frac{\gamma(f) S_{gw}(f)}{P_1(f) P_2(f)}$$

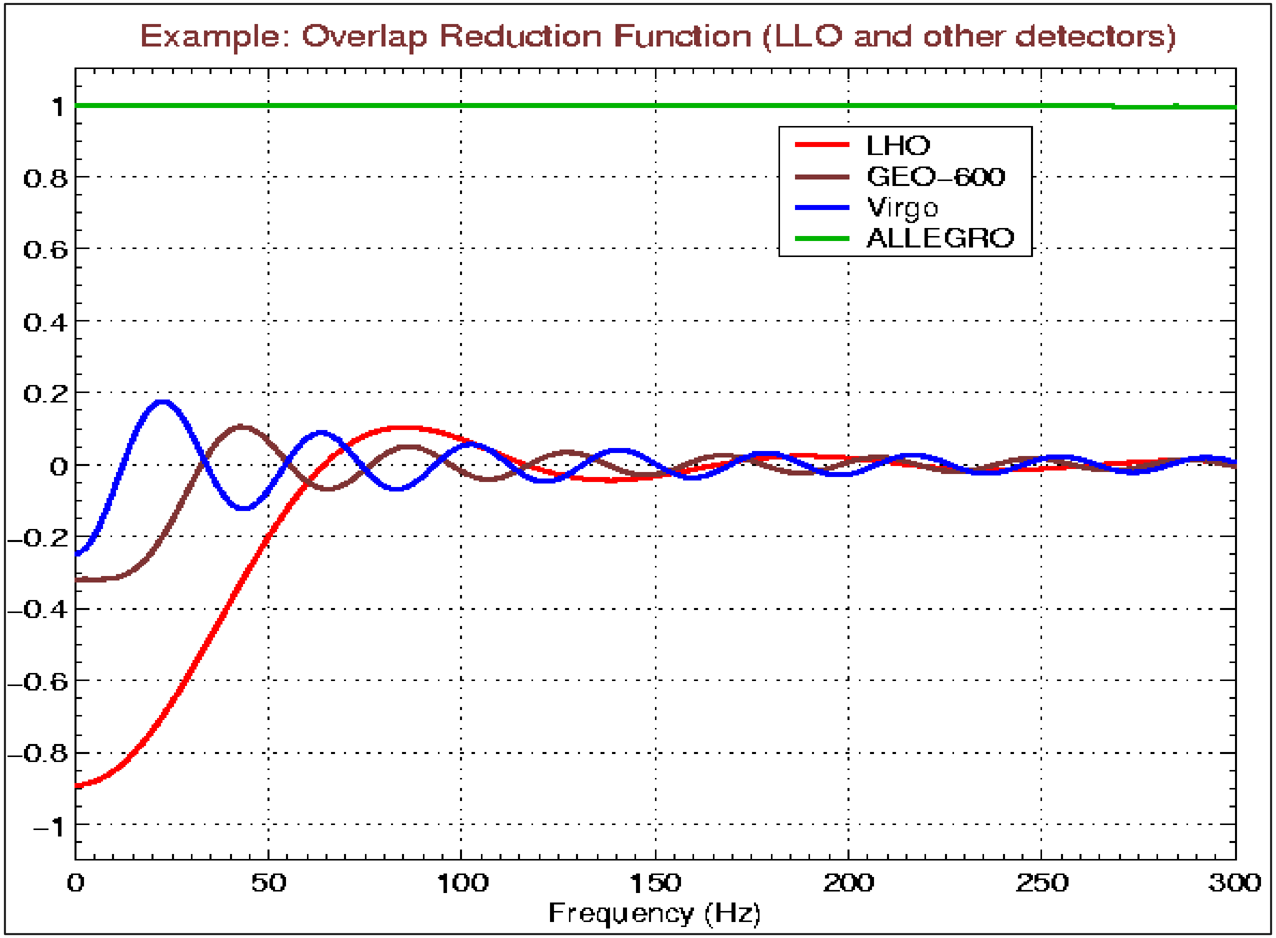
Signal

Noise

Allen, Romano, PRD59 (1999)

$S_{gw}(f) \propto 1/f^3$ for $\Omega_{gw}(f) = \Omega_0 =$ const

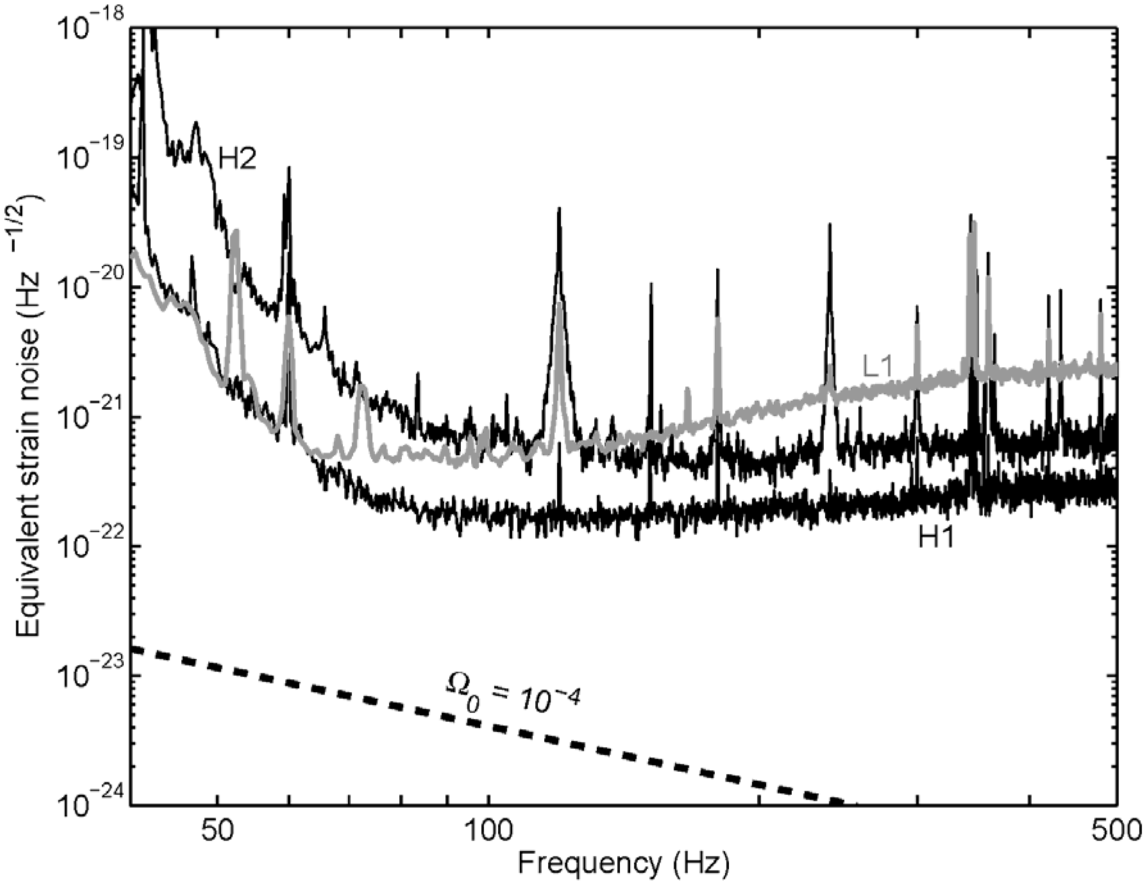
Overlap Reduction Functions Between L1 and Other Detectors



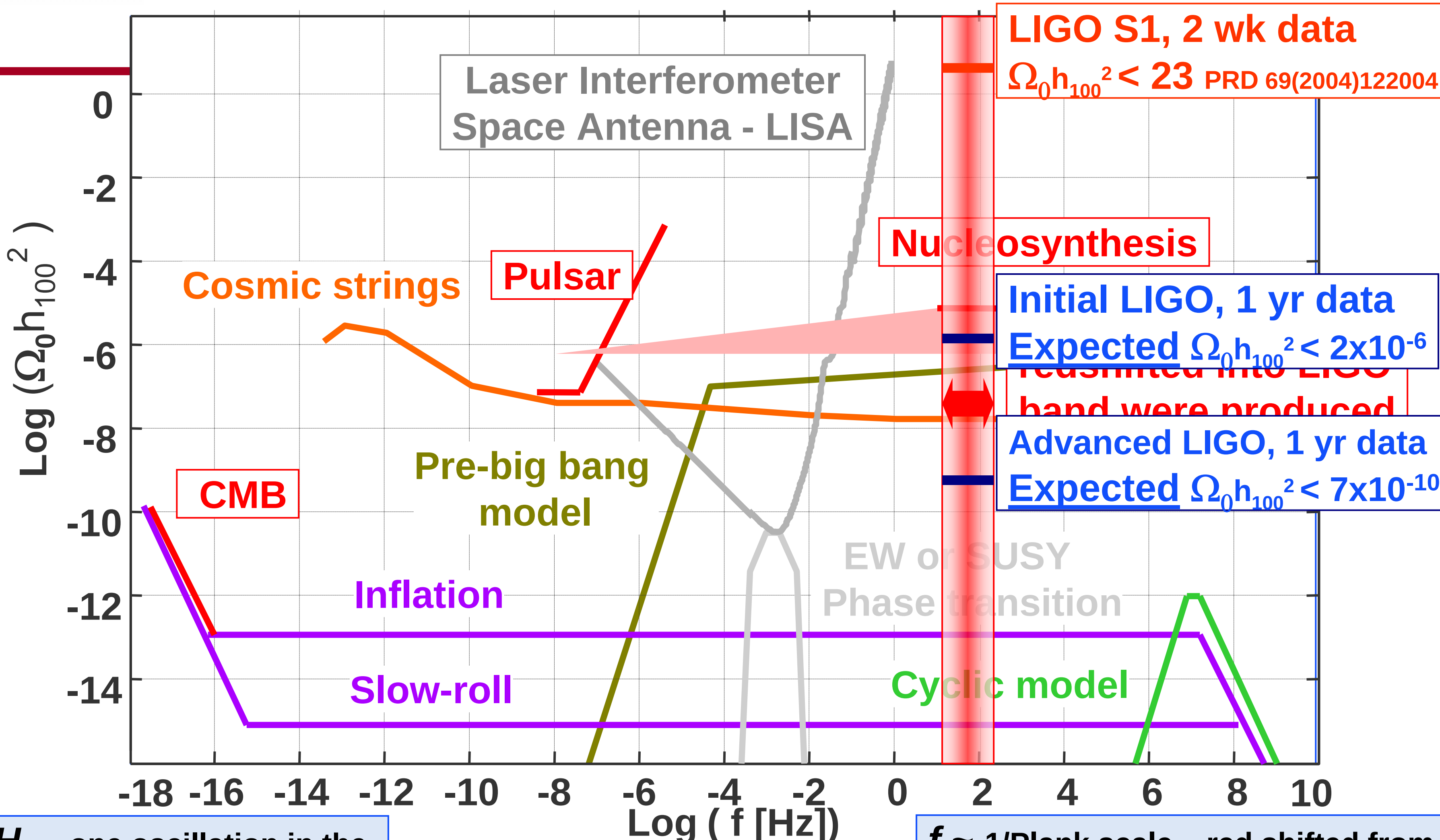
Flanagan, PRD48, 2389 (1993)

Strain Noise Spectral Density

$$h(f) = S_{\rm gw}^{1/2}(f) = 5.6\times10^{-22}\, h_{100}\sqrt{\Omega_0}\left(\frac{100\mathrm{Hz}}{f}\right)^{3/2}\mathrm{Hz}^{1/2}$$



LIGO Predictions and Experimental Limits



f ~ H_0 - one oscillation in the lifetime of the universe

f ~ 1/Plank scale – red shifted from the Plank era to the present time

LIGO Results

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S1 PRD 69(2004)	< 23 +/- 4.6 (H2-L1)	Cross-correlated instrumental noise found	40-314 Hz	64 hours
S2 Preliminary	< 0.018 +0.007- 0.003 (H1-L1)	Cross-correlated instrumental noise found	50-300 Hz	387 hours
S3 In progress		Trying to account for instrumental noise in bounding Ω	50-250 Hz (H1-L1) 70-220 Hz (H1-H2)	350 hrs (H1-L1) 550 hrs (H1-H2)
S4 Starting Analysis				447 hrs (H1-L1) 510 hrs (H1-H2)

Previous best upper limits:

» *Measured:* Garching-Glasgow interferometers : Ω_{GW} (f)<3x10^{5}

» *Measured*: EXPLORER-NAUTILUS (bars): Ω_{GW} (907Hz)<60

Initial LIGO (1 yr) : $\Omega_0 h_{100}^2 < 2 \times 10^{-6}$

Advanced LIGO (1 yr) : $\Omega_0 h_{100}^2 < 7 \times 10^{-10}$