Results from the LIGO Science Runs

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for the LIGO Scientific Collaboration

Aspen Winter Conference on

Gravitational Waves and their Detection

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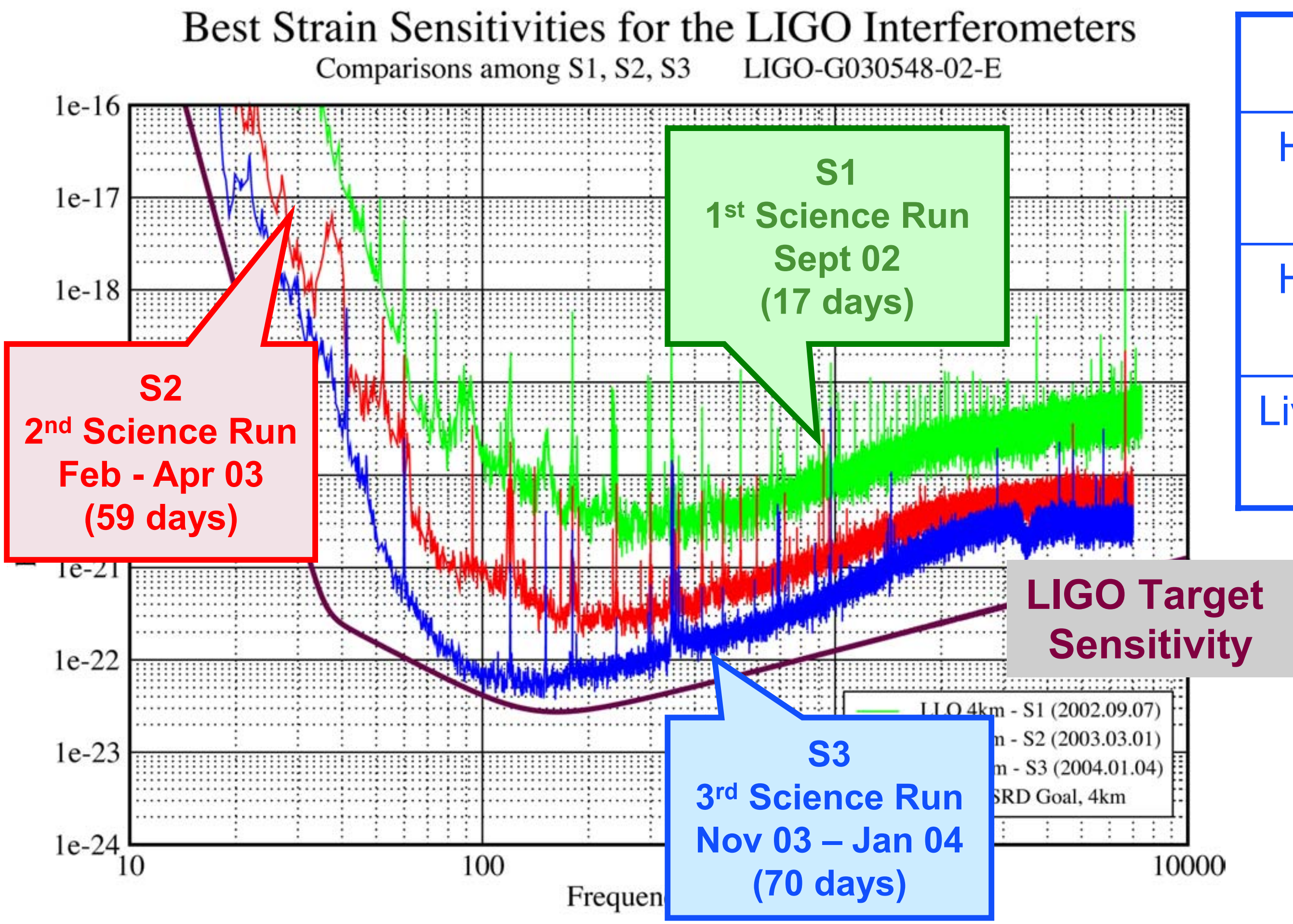
LIGO Science Runs

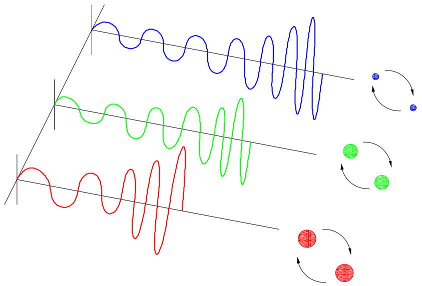


S3 Duty Cycle	
Hanford 4km	69%
Hanford 2km	63%
Livingston 4 km	22%*

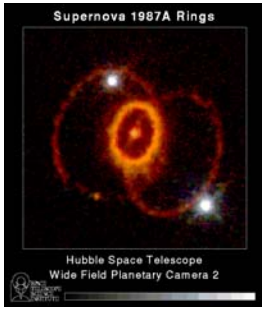
*Limited by high ground noise—upgrade currently underway

Astrophysical Searches with LIGO Data

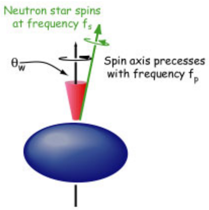
- Compact binary inspiral: *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms
  - » search technique: matched templates



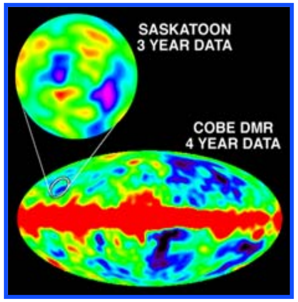
- Supernovae / GRBs: *"bursts"*
  - » burst signals in coincidence with signals in electromagnetic radiation
  - » prompt alarm (~ one hour) with neutrino detectors



- Pulsars in our galaxy: *"periodic"*
  - » search for observed neutron stars (frequency, doppler shift)
  - » all sky search (computing challenge)
  - » r-modes

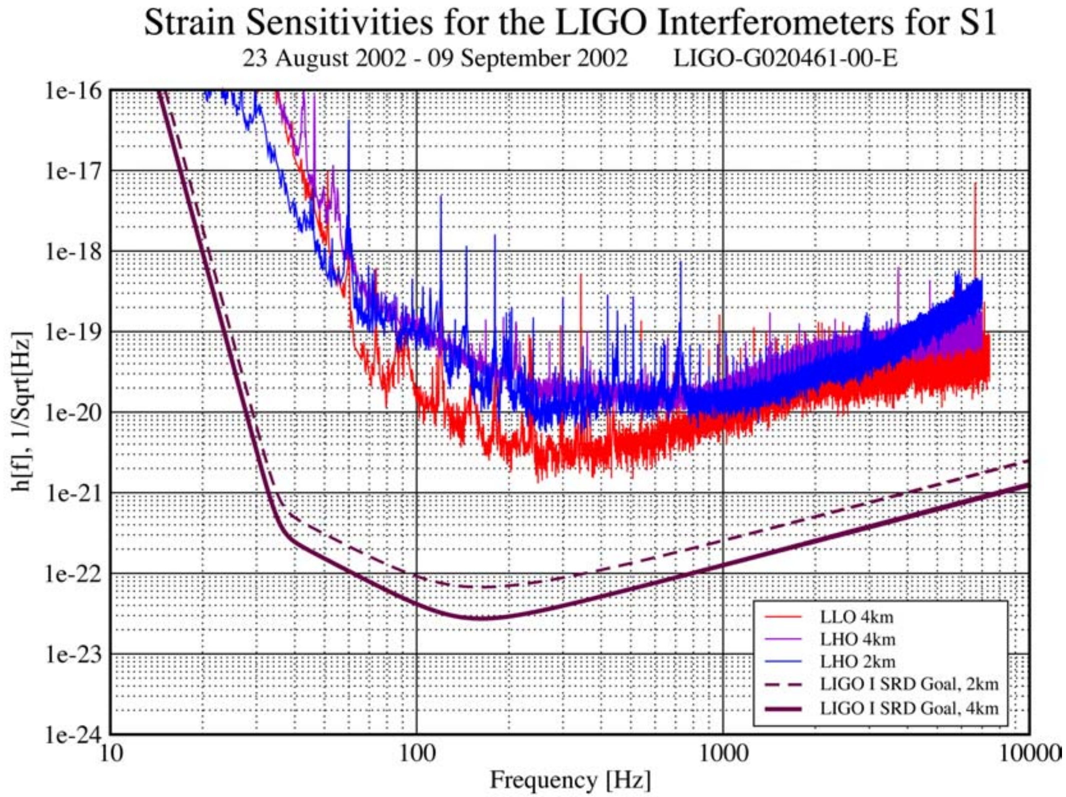


- Cosmological Signals *"stochastic background"*



First Science Run (S1)

- August 23 - September 9 (~400 hours)
- Three LIGO interferometers, plus GEO (Europe) and TAMA (Japan)
- Hardware reliability good for this stage in the commissioning
  - » Longest locked section for individual interferometer: 21 hrs



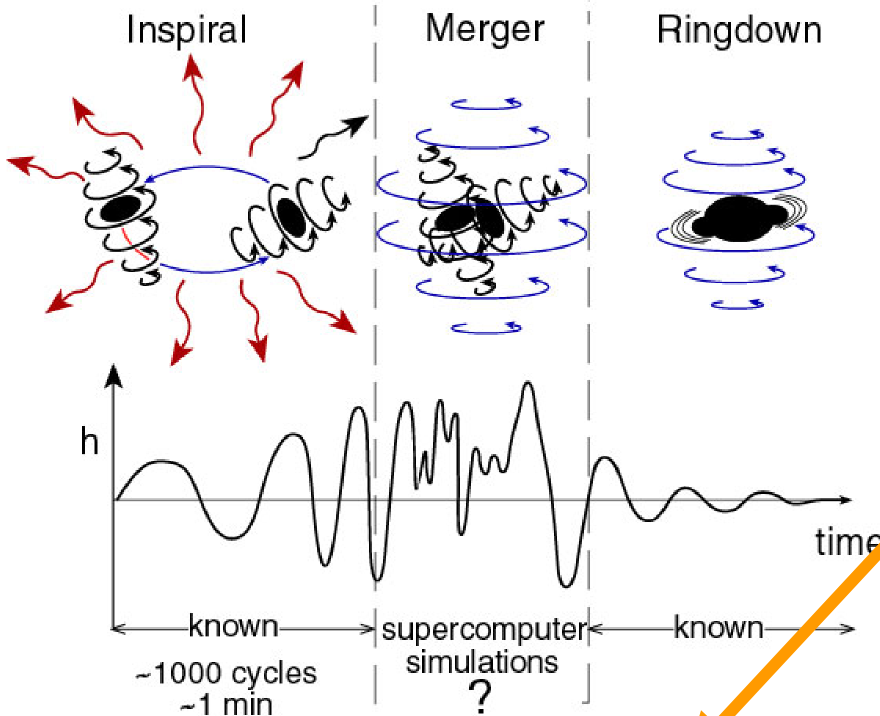
	LLO-4K	LHO-4K	LHO-2K	3x Coinc.
Duty cycle	42%	58%	73%	24%

S1 Papers

Papers by the LIGO Science Collaboration (~370 authors, 40 institutions):

- "*Detector Description and Performance for the First Coincident Observations between LIGO and GEO*", Nucl. Inst. Meth A, **517**, 154-179 (2004)
- "*Setting upper limits on the strength of periodic gravitational waves using the first science data from the GEO600 and LIGO detectors*" gr-qc/0308050, accepted for publication in PRD
- "*Analysis of LIGO data for gravitational waves from binary neutron stars*", gr-qc/0308069**,** being reviewed by PRD
- "*First upper limits from LIGO on gravitational wave bursts*", gr-qc/0312056**,** accepted for publication in PRD
- "*Analysis of First LIGO Science Data for Stochastic Gravitational Waves*", gr-qc/0312088**,** being reviewed by PRD

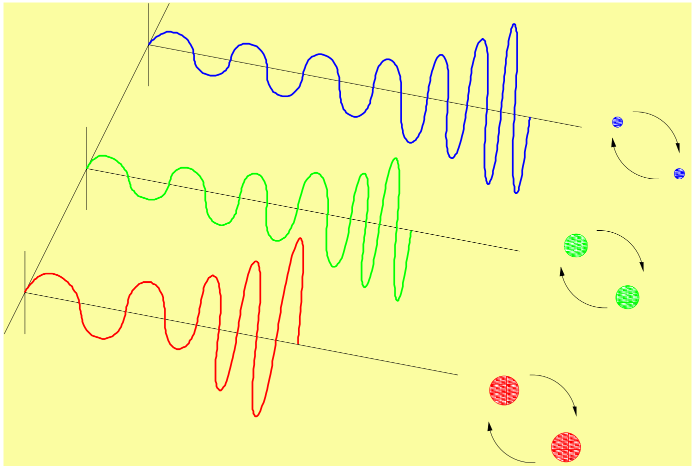
Compact Binary Coalescence



» Search: *matched templates*

» Neutron Star – Neutron Star
  – **waveforms are well described**

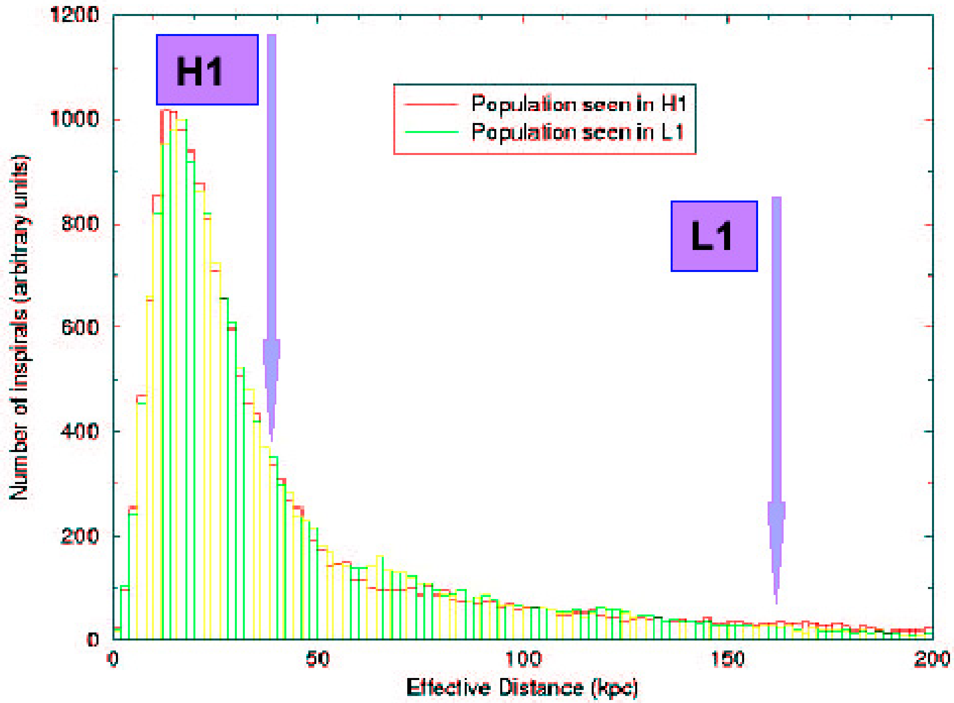
» Black Hole – Black Hole
  – **need better waveforms**



- Discrete set of templates labeled by (m1, m2)
  - » 1.0 Msun < m1, m2 < 3.0 Msun
  - » ~ 2000 templates
  - » At most 3% loss in SNR

LIGO

Results of S1 Inspiral Search



Simulated Galactic Population

- Population includes Milky Way, LMC and SMC
- LMC and SMC contribute ~12% of Milky Way

LIGO S1 Upper Limit

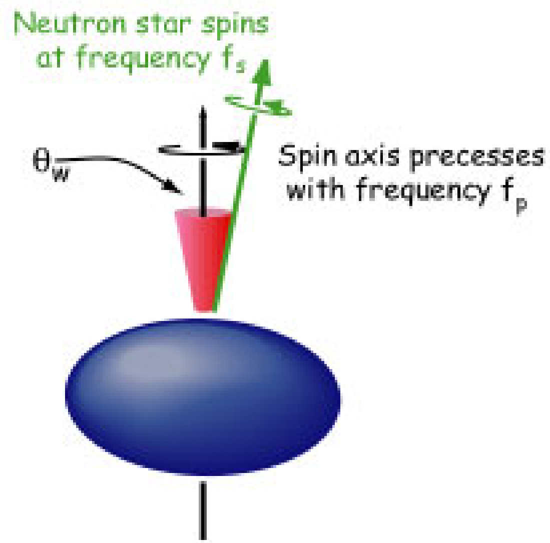
R < 170 / yr / MWEG

Best guess: Initial LIGO Rate = 1 per (5-250) years

Detectable Range for S2/S3 data includes Andromeda!

Periodic Sources

- Pulsars in our galaxy:
  - » search for observed neutron stars
  - » all sky search (computing challenge)
  - » r-modes

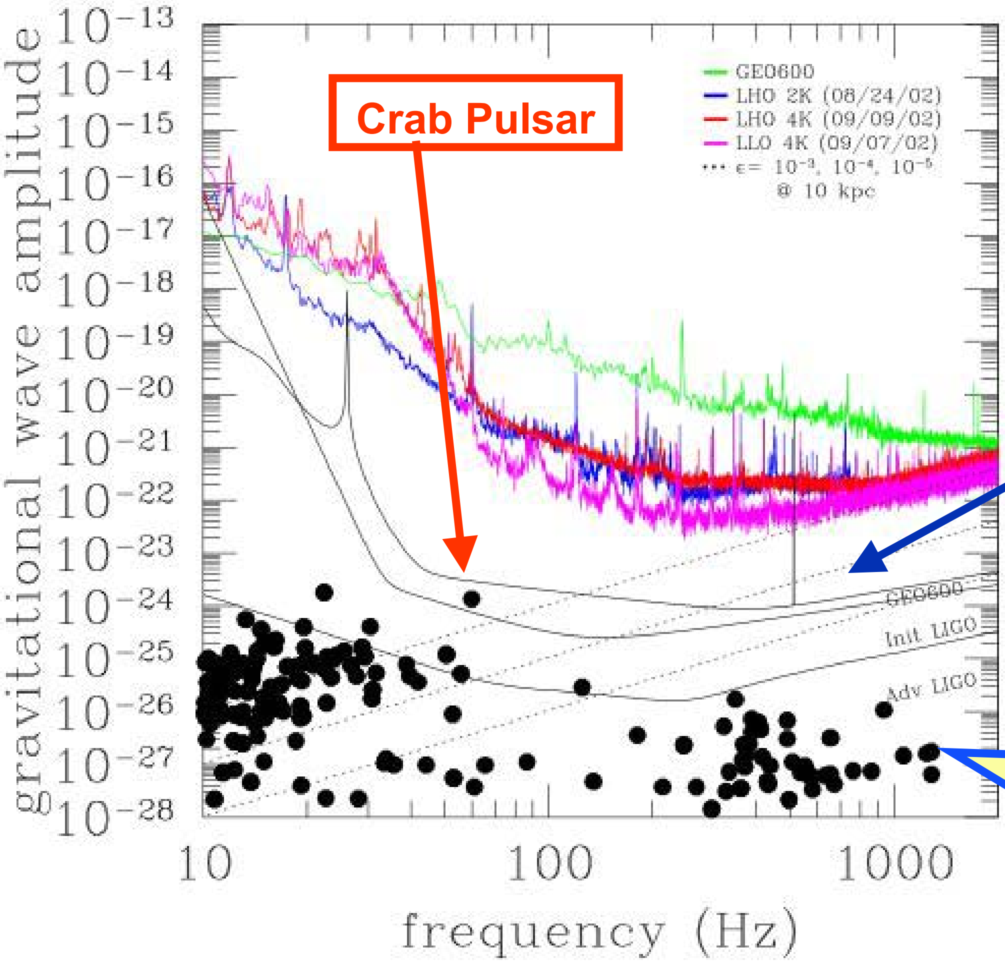


- **Frequency modulation of signal due to Earth's motion**
- **Amplitude modulation due to the detector's antenna pattern.**

Directed Search in S1

NO DETECTION EXPECTED

at present sensitivities



Predicted signal for rotating neutron star with equatorial ellipticity $\varepsilon = \delta I/I$: 10^{-3} , 10^{-4} , 10^{-5} @ 8.5 kpc.

PSR J1939+2134

1283.86 Hz

Two Search Methods

Frequency domain

- Best suited for large parameter space searches
- Maximum likelihood detection method + frequentist approach

Time domain

- Best suited to target known objects, even if phase evolution is complicated
- Bayesian approach

First science run --- use both pipelines for the same search for cross-checking and validation

Results: PSR J1939+2134

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

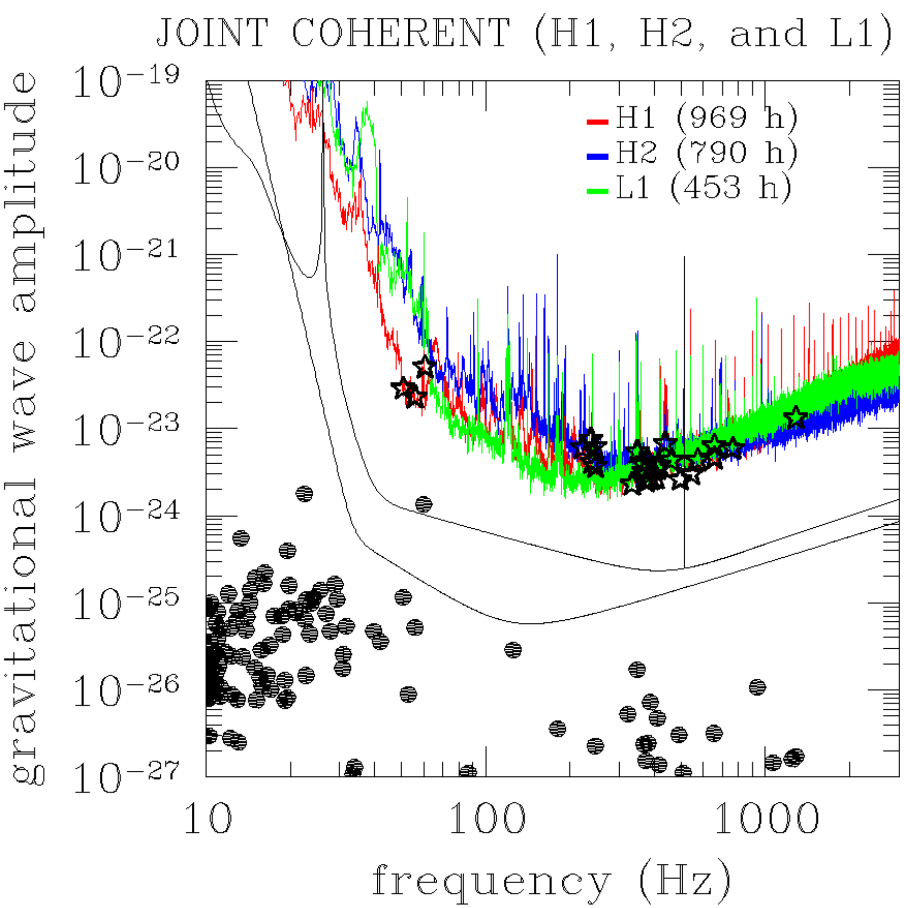
IFO	Frequentist FDS	Bayesian TDS
GEO	$(1.9\pm0.1) \times 10^{-21}$	$(2.1 \pm0.1) \times 10^{-21}$
LLO	$(2.7\pm0.3) \times 10^{-22}$	$(1.4 \pm0.1) \times 10^{-22}$
LHO-2K	$(4.0\pm0.5) \times 10^{-22}$	$(2.3 \pm0.2) \times 10^{-22}$
LHO-4K	$(5.4\pm0.6) \times 10^{-22}$	$(3.3 \pm0.3) \times 10^{-22}$

- **Best previous results for PSR J1939+2134:**

$h_o < 10^{-20}$ (Glasgow, Hough et al., 1983)

S2 Upper Limits

Note: Preliminary !



☆ 95% upper limits

- Performed joint coherent analysis for 28 pulsars using data from all IFOs
- Most stringent UL is for pulsar J1629-6902 (~333 Hz) where 95% confident that $h_0 < 2.3 \times 10^{-24}$
- 95% upper limit for Crab pulsar (~ 60 Hz) is $h_0 < 5.1 \times 10^{-23}$
- 95% upper limit for J1939+2134 (~ 1284 Hz) is $h_0 < 1.3 \times 10^{-23}$

Upper Limits on Ellipticity

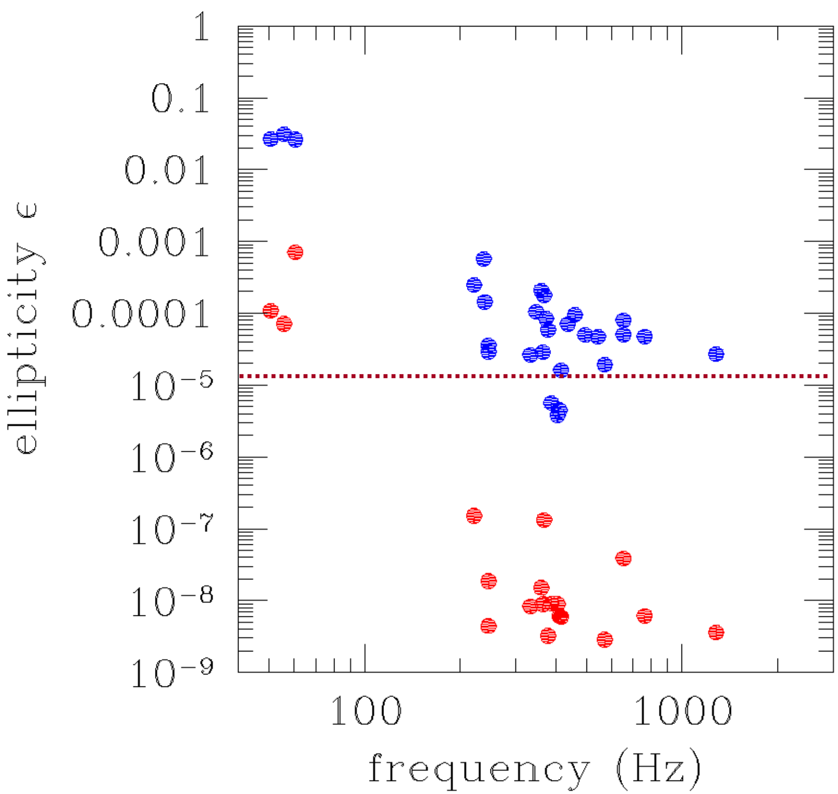
Note: Preliminary !

Equatorial ellipticity:

$$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

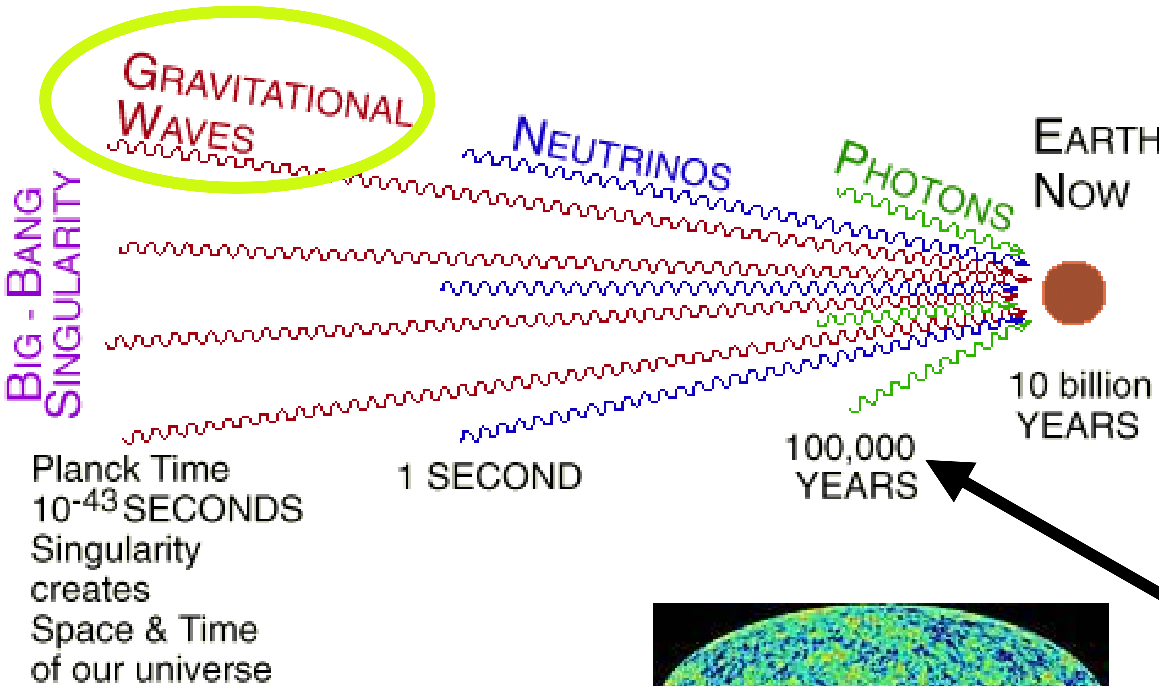
Pulsars J0030+0451 (230 pc), J2124-3358 (250 pc), and J1024-0719 (350 pc) are the nearest three pulsars in the set and their equatorial ellipticities are all constrained to less than 10^{-5}.

- S2 upper limits
- Spin-down based upper limits

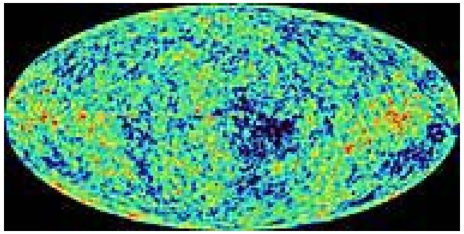


Early Universe
stochastic background

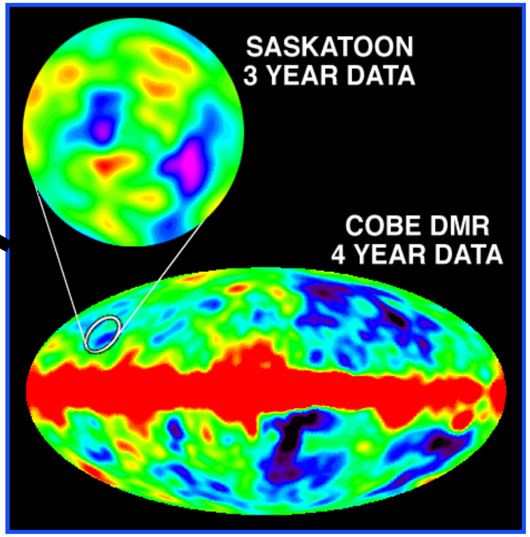
'Murmurs' from the Big Bang



Cosmic Microwave background



WMAP 2003

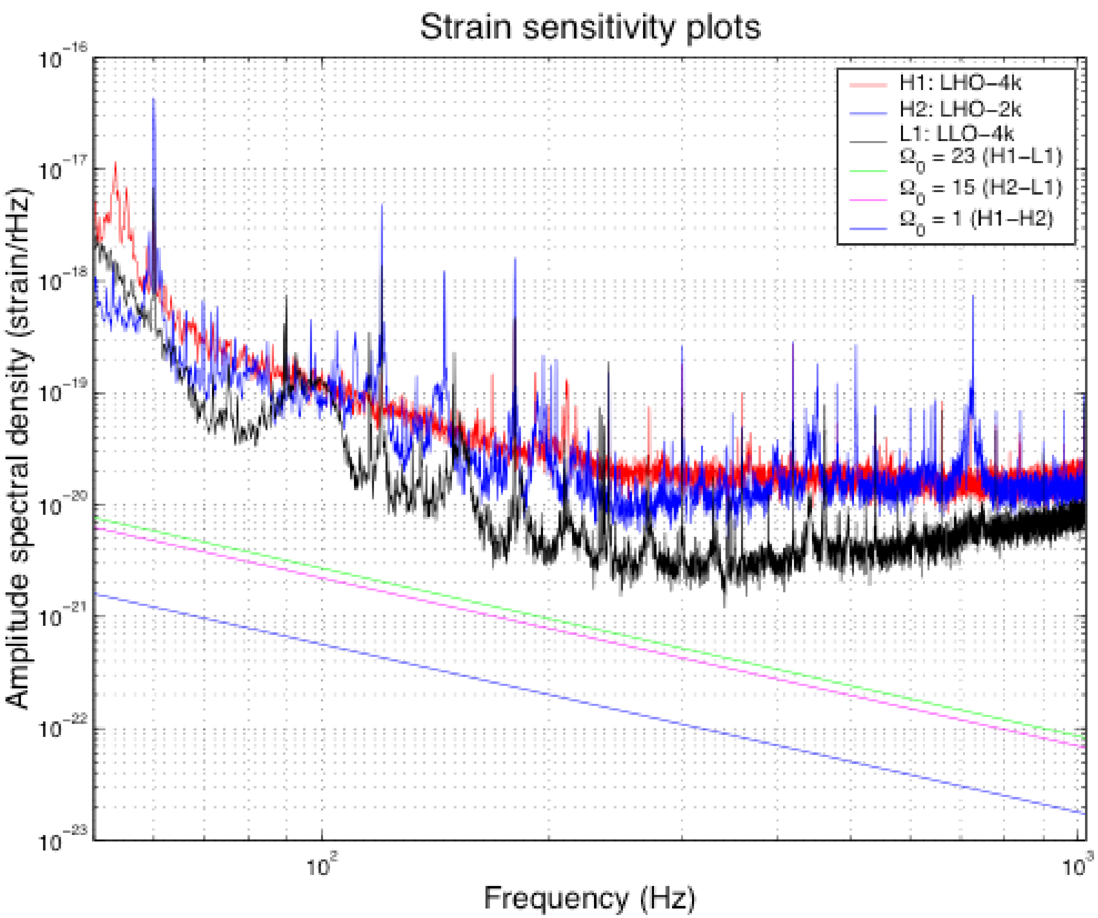


Stochastic Background

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

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

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

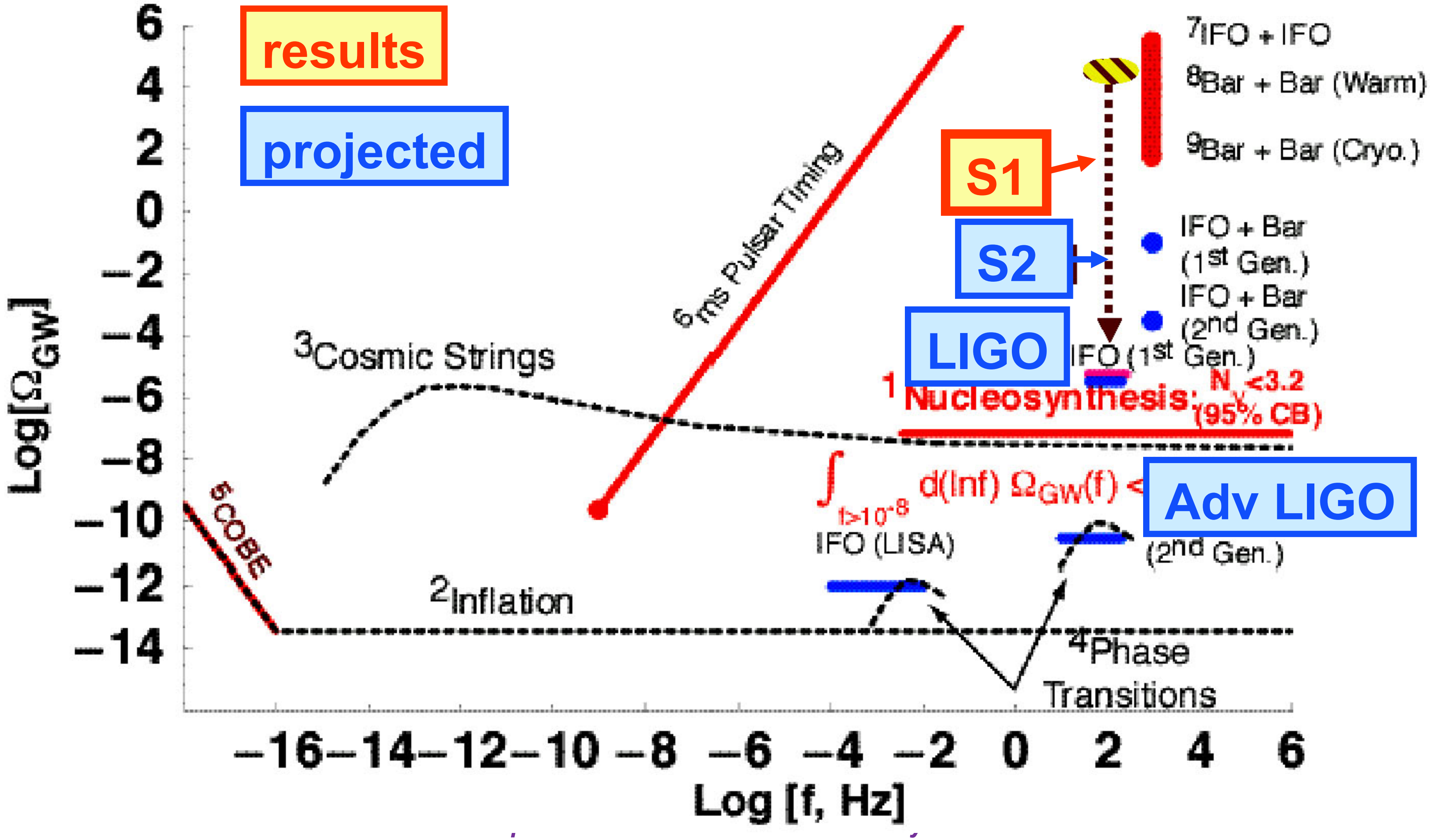


Upper Limit from Stochastic Search

Interferometer Pair	90% CL Upper Limit	T_{obs}
LHO 4km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 55	64 hrs
LHO 2km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 23	51.25 hrs

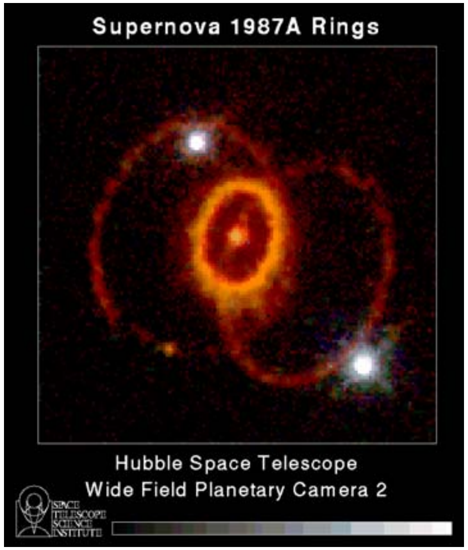
- Non-negligible LHO 4km-2km (H1-H2) instrumental cross-correlation; changes to the interferometer made to reduce coupling for S3
- Previous best upper limits:
  - » *Measured:* Garching-Glasgow interferometers : $\Omega_{GW}(f) < 3\times 10^{5}$
  - » *Measured*: EXPLORER-NAUTILUS (cryogenic bars): $\Omega_{GW}(907Hz) < 60$

Stochastic Background
sensitivities and theory



Burst Sources

- **Known sources -- Supernovae & GRBs**
  » **Coincidence with observed electromagnetic observations.**
    » **No close supernovae occurred during the first science run**
    » **Second science run – very bright and close GRB030329**



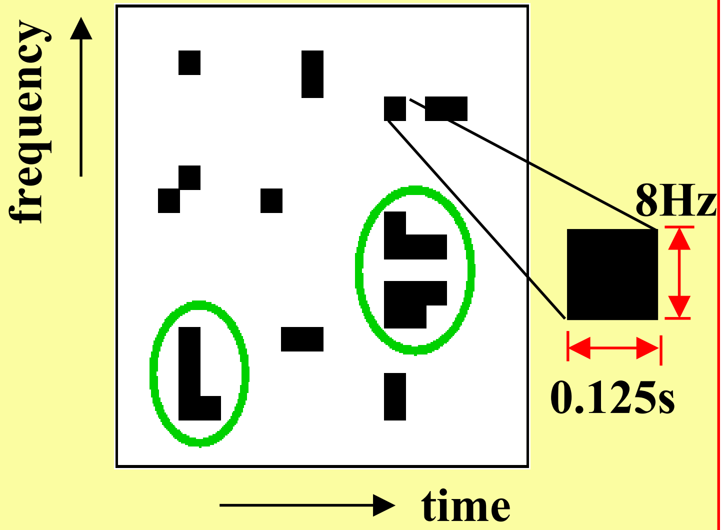
- **Unknown phenomena**
  » **Emission of short transients of gravitational radiation of unknown waveform (e.g. black hole mergers).**

‘Unmodelled’ Burst Search

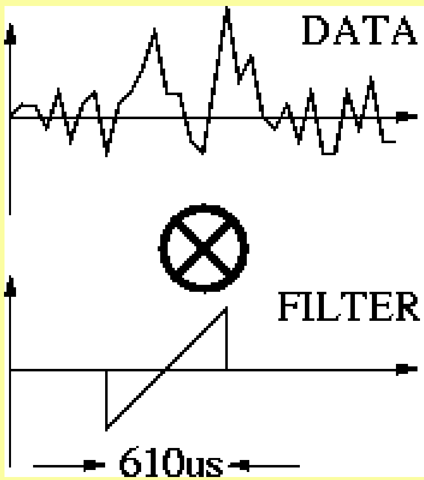
GOAL search for waveforms from sources for which we cannot currently make an accurate prediction of the waveform shape.

METHODS ‘Raw Data’ → Time-domain high pass filter

Time-Frequency Plane Search
‘TFCLUSTERS’

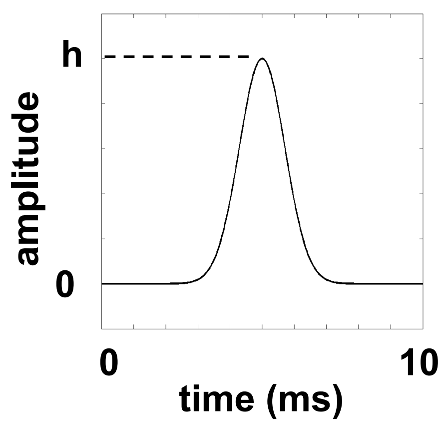


Pure Time-Domain Search
‘SLOPE’

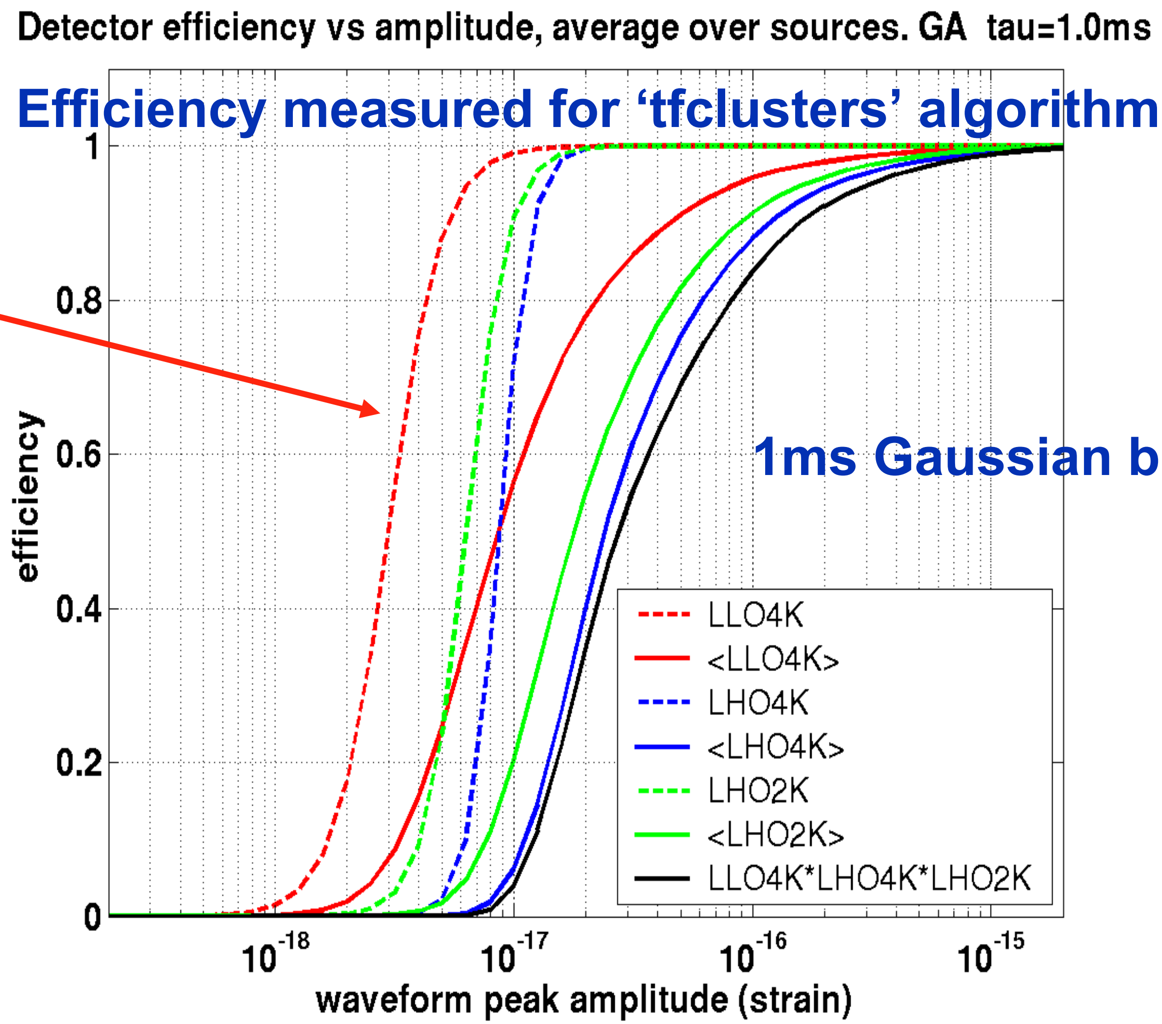


Determination of Efficiency

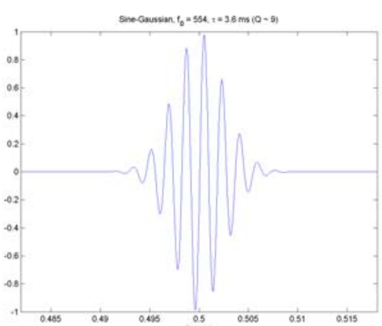
To measure our efficiency, we must assume waveforms



Efficiency measured for 'tfclusters' algorithm

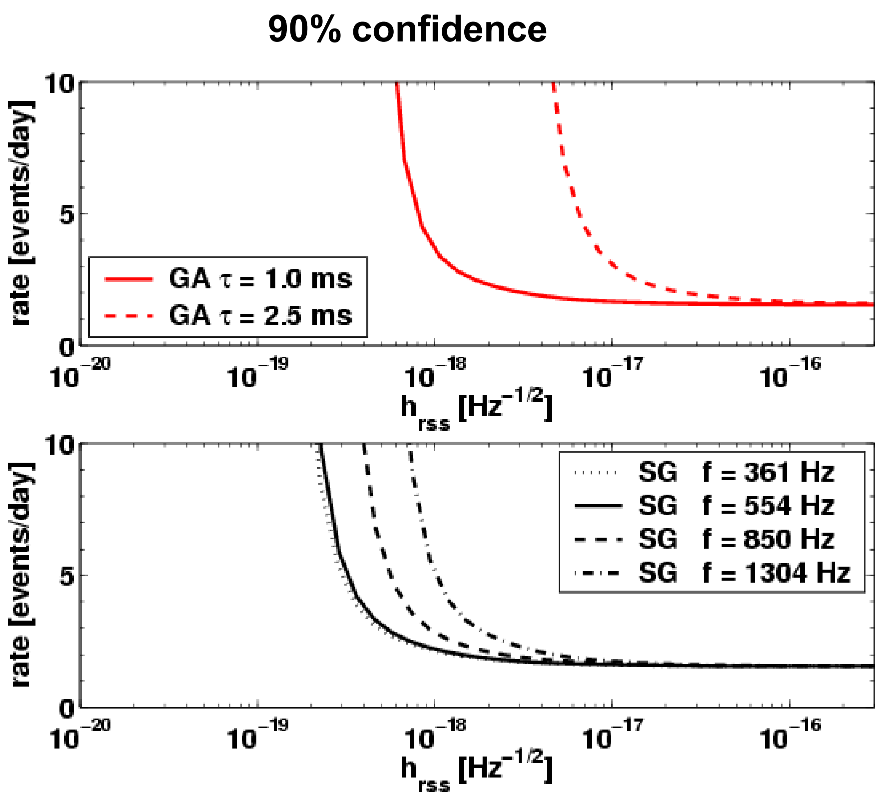


1ms Gaussian burst



Upper Limit

Result is derived using 'TFCLUSTERS' algorithm



Upper limit in *strain* compared to earlier (cryogenic bar) results:

- **IGEC 2001 combined bar upper limit: < 2 events per yr having h(f)=1x10^{-20} per Hz of burst bandwidth. For a 1kHz bandwidth, h_{rss}=3x10^{-19} Hz$^{-1/2}$**
- **Astone *et al.* (2002) report a possible excess at strain level of h_{rss} ~ 1x10^{-19} Hz$^{-1/2}$**

Signal region and GRB030329 trigger

Both Hanford detectors operating for GRB030329

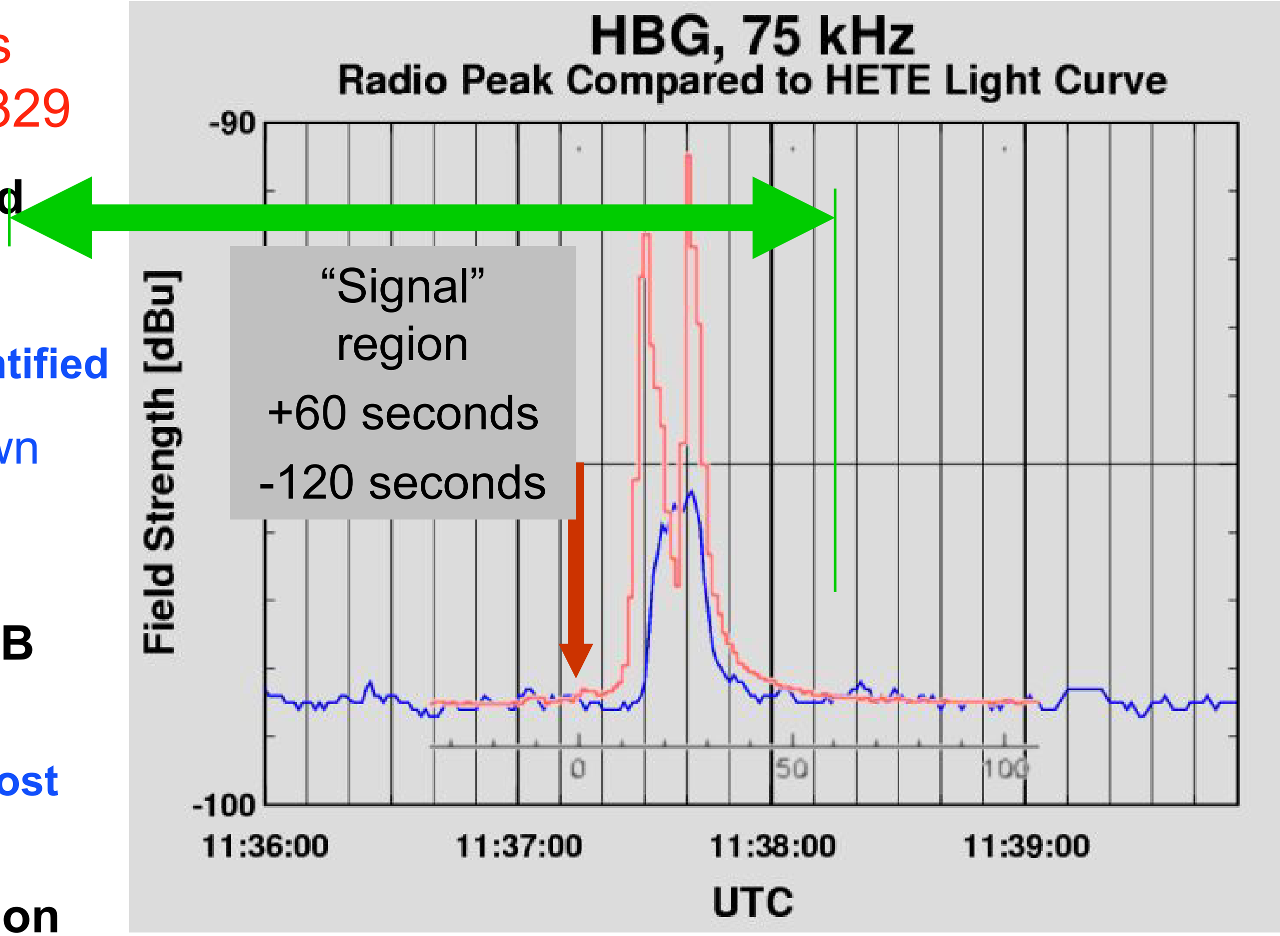
Optical counterpart located

- Known direction
- **LIGO antenna factor identified**
- Source distance is known
  z=0.1685 (d~800Mpc)

Relative delay between gravitational wave and GRB predicted to be small

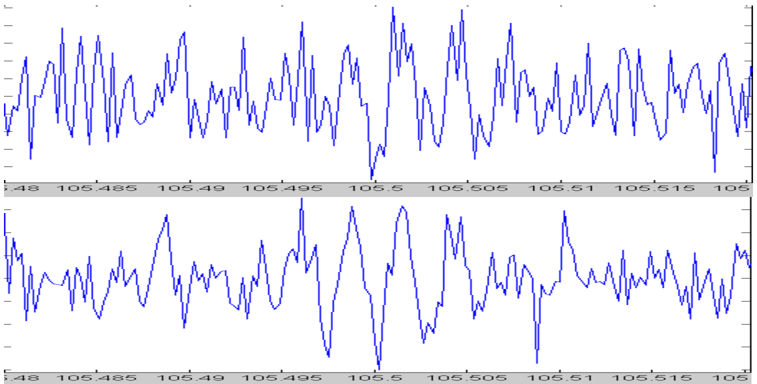
- **Signal region to cover most predictions**

Unknown waveform/duration



http://www.mpe.mpg.de/~jcg/grb030329.html

Correlation Analysis



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

$$s_2(t) = h(t - t_2) + n_2(t)$$

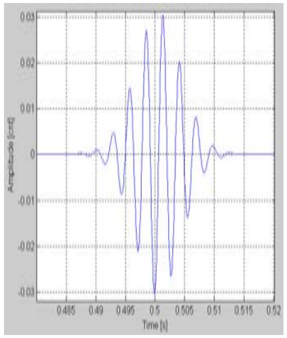
$$C(t, t_w, t_{off}) = \int_{t - t_w/2}^{t + t_w/2} s_1(t')s_2(t' + t_{off})dt'$$

$$\approx \int_{t_w} h^2(t)dt + \int_{t_w} n_1(t)n_2(t)dt$$

h_{rss}^2

< > = 0

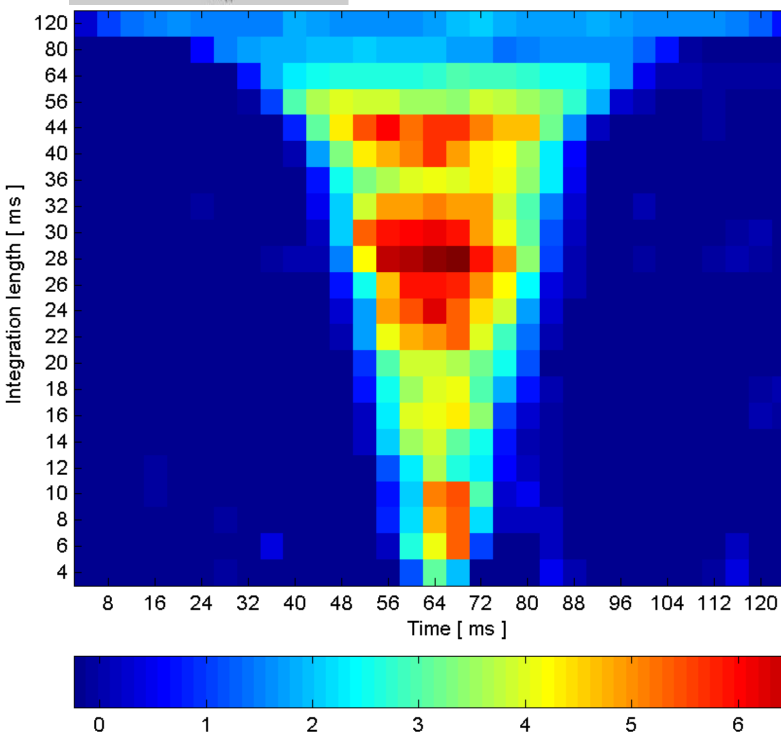
Event Identification - Simulated Signals

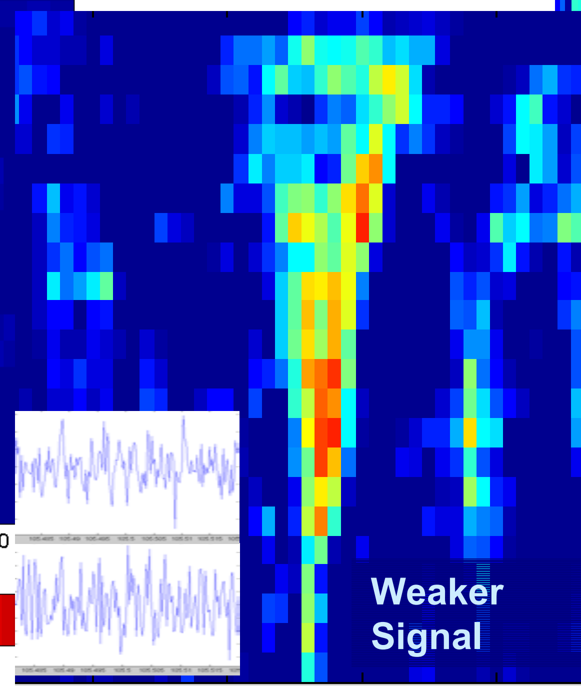


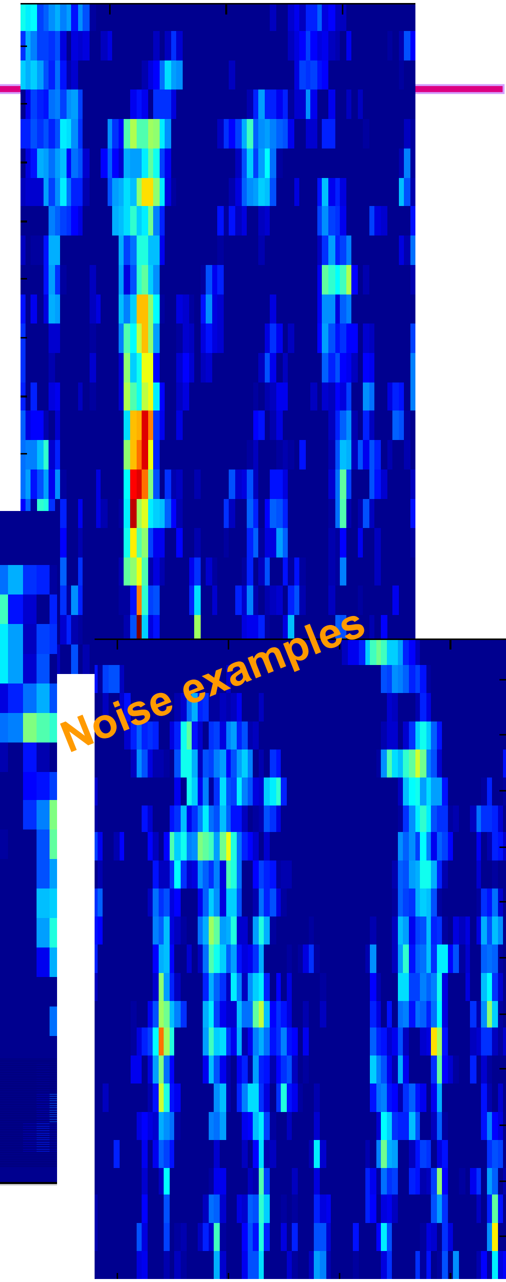
Color coding: “Number of variances above mean”

<u>Event strength</u> [ES] calculation:

Average value of the “optimal” pixels

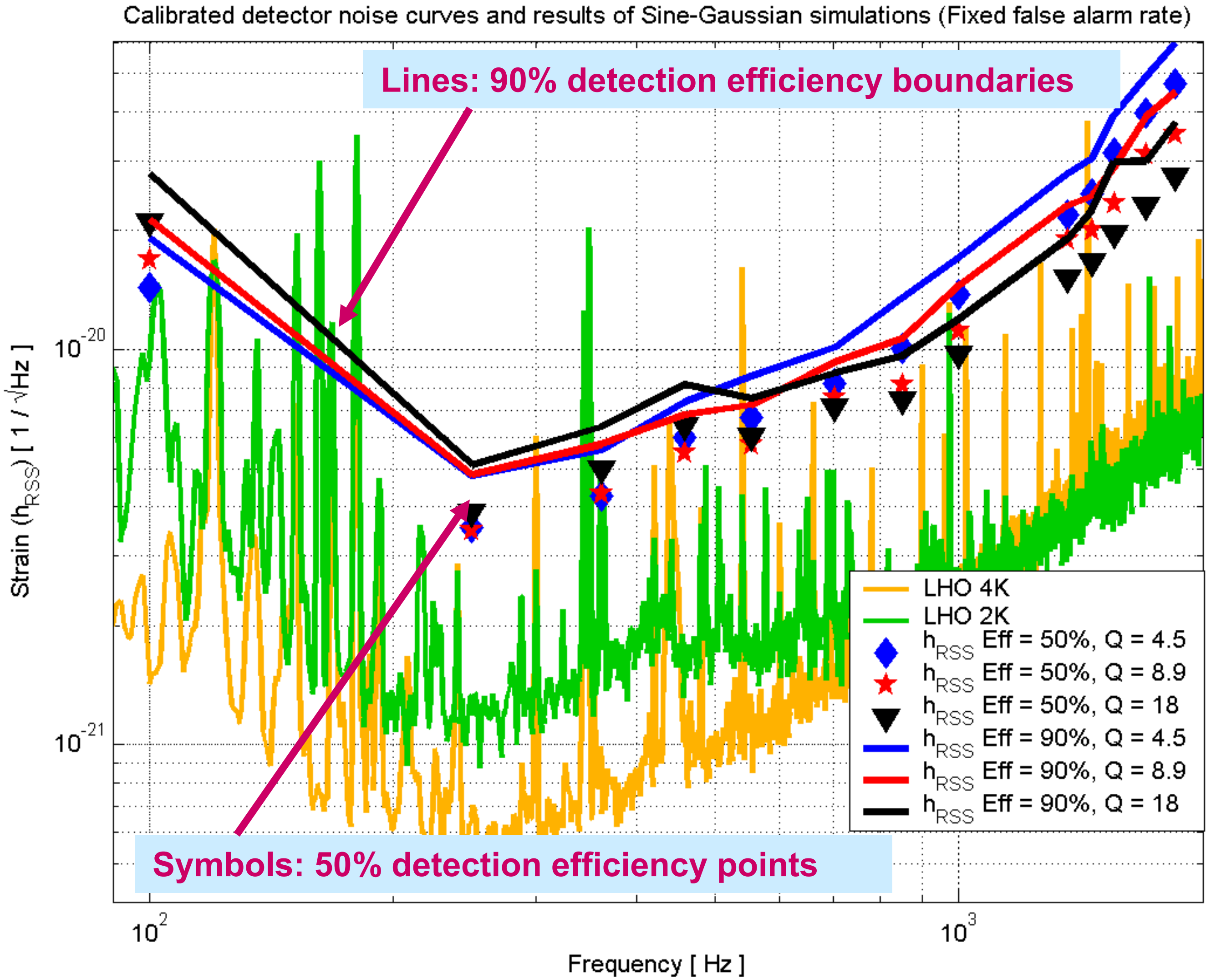






Detection Efficiency at Fixed False Alarm Rate

Note: Preliminary !

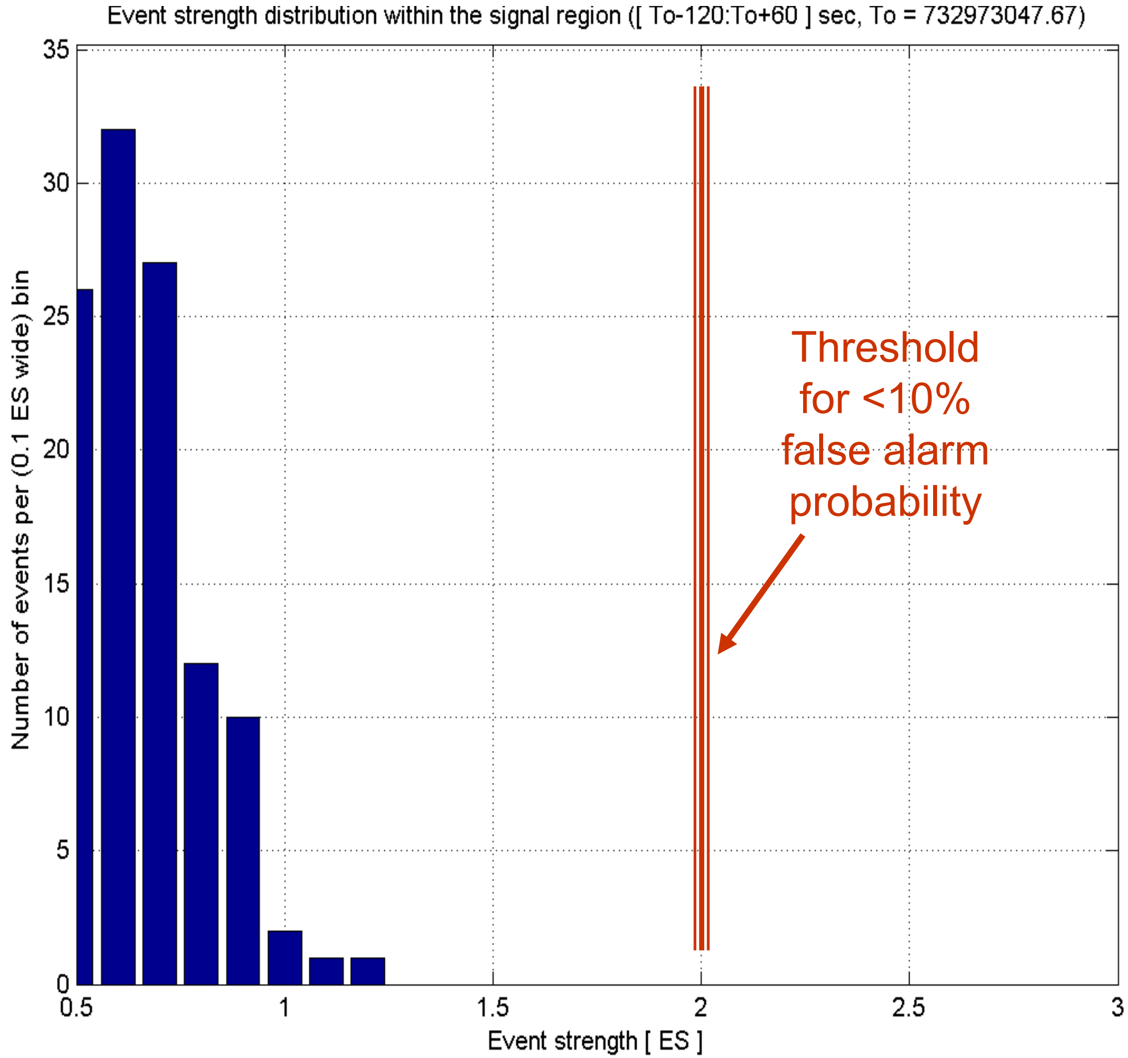


- Calibration known within ~10%
- Detection efficiencies obtained for threshold corresponding to ~4 x 10^{-4} Hz false alarm rate (<10% probability of noise event in 180 sec)
- H1/H2 noise curves reflect levels around GRB030329

Events Within the Signal Region

Note: Preliminary !

- **The signal region seems to be "relatively quiet" when compared to the neighboring regions**
- **No event was detected with strength above the pre-determined threshold**
- **It is an upper limit result**



Observed Limit on h_{rss} Relates to GW Energy

$$P_{GW} \propto \left| \frac{dh(t)}{dt} \right|^2$$

For an observation (or limit) made at a luminosity distance *d* from a source

$$E_{GW} = \left(\frac{2\pi^2 c^3}{G} \right) d^2 \int_0^\infty f^2 \left| \tilde{h}(f) \right|^2 df$$

$$\approx \left(\frac{2\pi^2 c^3}{G} \right) d^2 f_c^2 \int_0^\infty \left| \tilde{h}(f) \right|^2 df$$

h_{rss}^2

Example: Estimating E_{GW} for GRB030329

Note: Preliminary !

H1-H2 only

Antenna attenuation factor ~0.37 (assuming optimal polarization)

$z = 0.1685 \Rightarrow d \approx 800\text{Mpc}$

For narrowband GWs near minimum of noise curve (simulated with Q≈9 250 Hz sine-Gaussian), obtain 90% efficiency

$$h_{RSS} \lesssim 5 \times 10^{-21} \, [1/\sqrt{\text{Hz}}]$$

$$\Rightarrow E_{GW} \lesssim 125\ M_{\odot}\ (1 / 0.37) \approx 340\ M_{\odot}$$

Prospects for Future Searches

- Sensitivity (depending on frequency)
  h_{RSS} < few x 10^{-21} [$1/\sqrt{Hz}$]
  - » Current limit of some hundreds of $M_{\odot}$ in GWs
  - » Detector improvement: both detectors, factor of 10 – 30 (in h_{rss}) between S2 and final sensitivity (depending on frequency…)
    $\Rightarrow$ improvement of 100 – 300 in E_{GW}
  - » Beaming factor: estimate for every GRB detected, 100 to 500 "missed" -- reasonable for one year of observation might give 10 times closer event (cf. SN1998bw at ~ 40 Mpc)
    $\Rightarrow$ another factor of 100 in E_{GW}
  - » More detectors, better location in antenna pattern, better discrimination against noise events…
  - » Realistic chance to set a sub-solar mass limit in the near future

Summary

- First results are in!
- Joint searches performed with GEO, TAMA
  - » Soon AURIGA, Virgo
- Developing data analysis capability
- Prospects for interesting results over the next few years good