Searching for periodic gravitational waves with LIGO: S2 and beyond

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LIGO Scientific Collaboration

LIGO Seminar
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LIGO-G040035-00-K

Summary

- S1 data run took 17 days of data (Aug 23 – Sept 9, 2002) on 4 detectors (GEO600, LIGO H1, H2, and L1)
  - Upper limit set for GWs from J1939+2134 using two separate methods:
    - Frequency-domain analysis
    - Time-domain Bayesian analysis: $h_0 < 1.4 \times 10^{-22}$
  - Preprint available as gr-qc/0308050; Accepted by PRD.

- End-to-end validation of analysis method completed during S2 by injecting fake pulsars signals directly into LIGO IFOs

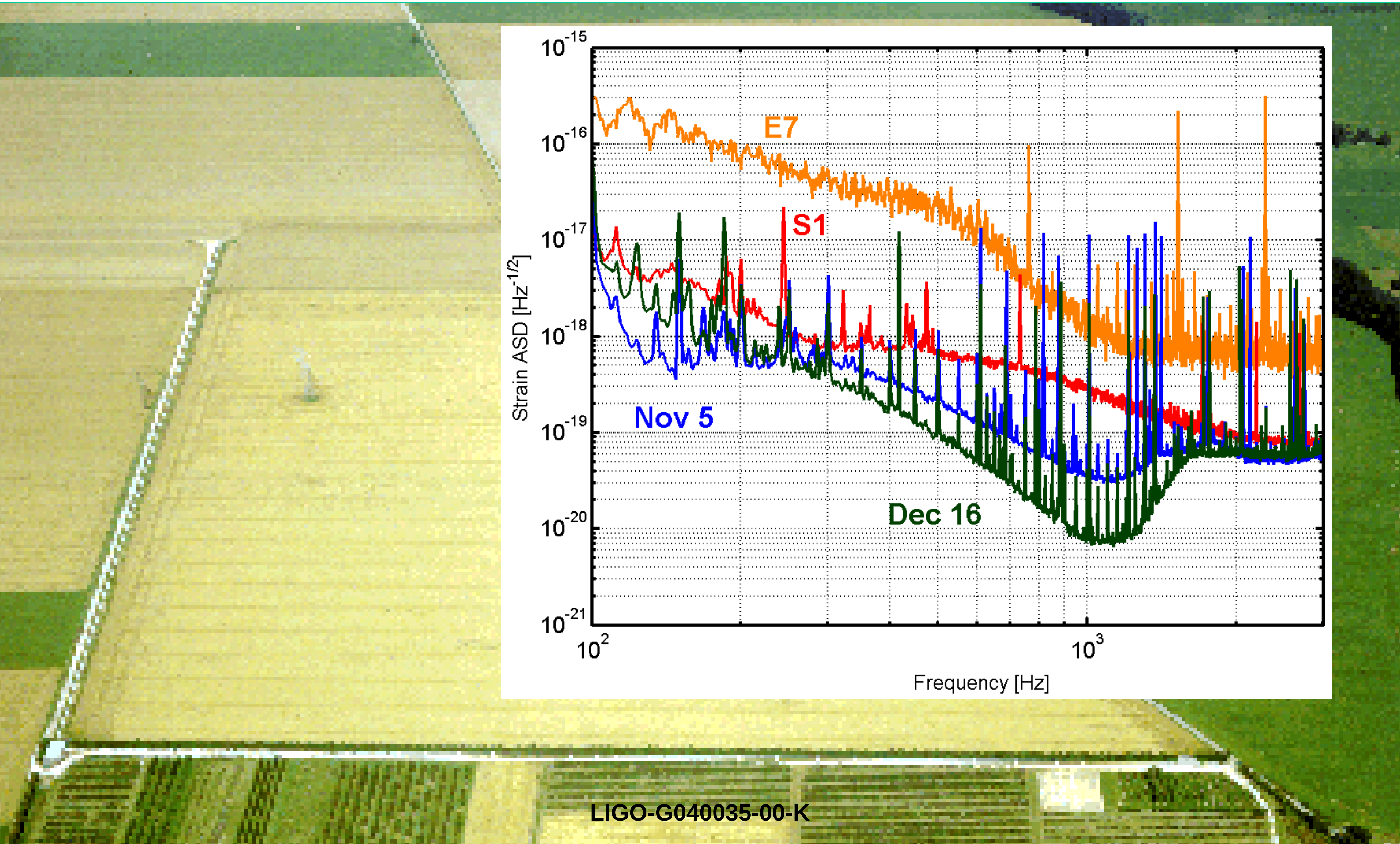
- S2 data run took 2 months of data (Feb 14 – Apr 14, 2003)
  - Upper limits set for GWs from 28 known isolated pulsars
  - Special treatment for Crab pulsar to take into account timing noise
  - All-sky searches are in progress

- With S3 we should be able to set astrophysically interesting upper limits for a few pulsars

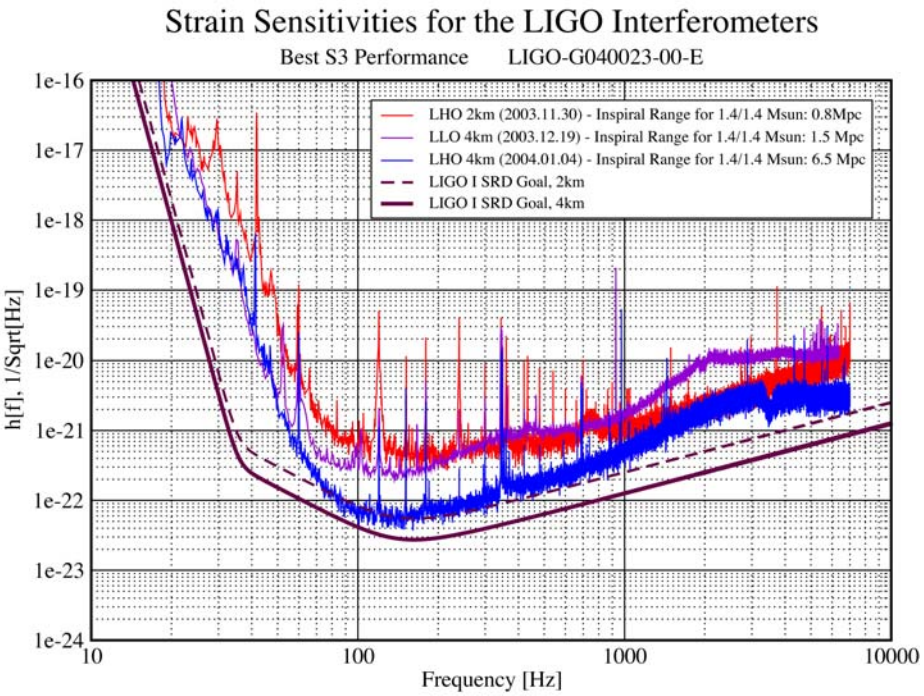
Outline of talk

1. Status of GEO 600 and LIGO
2. Nature of gravitational wave signal from pulsars
3. Review of Bayesian time domain analysis
4. Validation using hardware injections in LIGO
5. Preliminary results using LIGO S2 data
6. Plans for the future

GEO 600

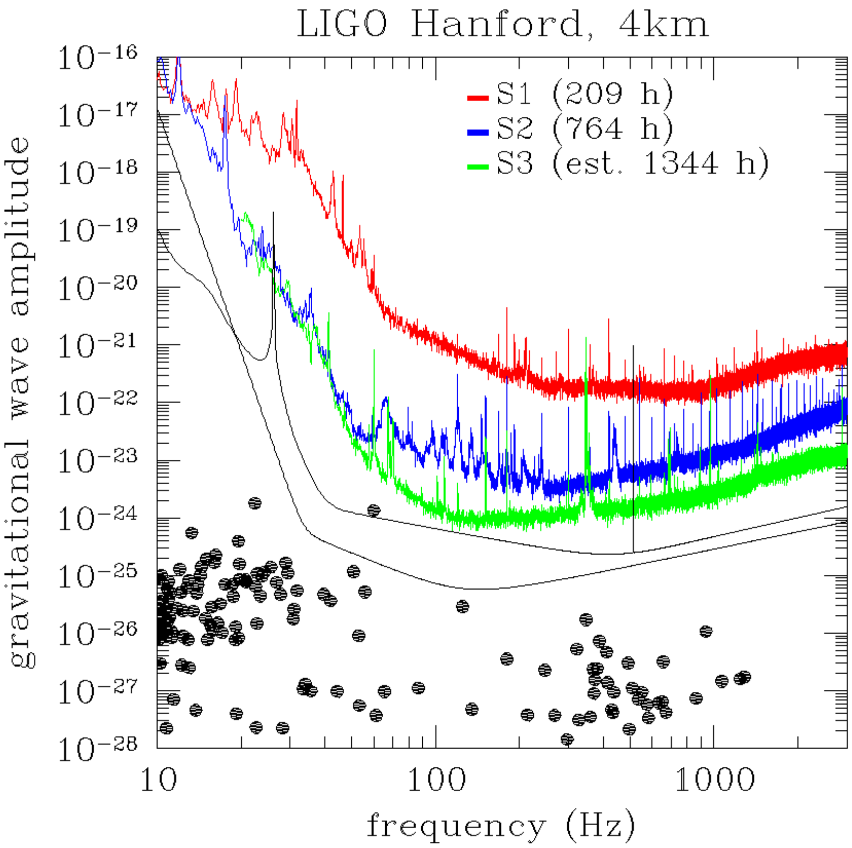

10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^-21
Strain ASD [Hz^-1/2]
10^2
10^3
Frequency [Hz]
E7
S1
Nov 5
Dec 16

LIGO



Strain Sensitivities for the LIGO Interferometers

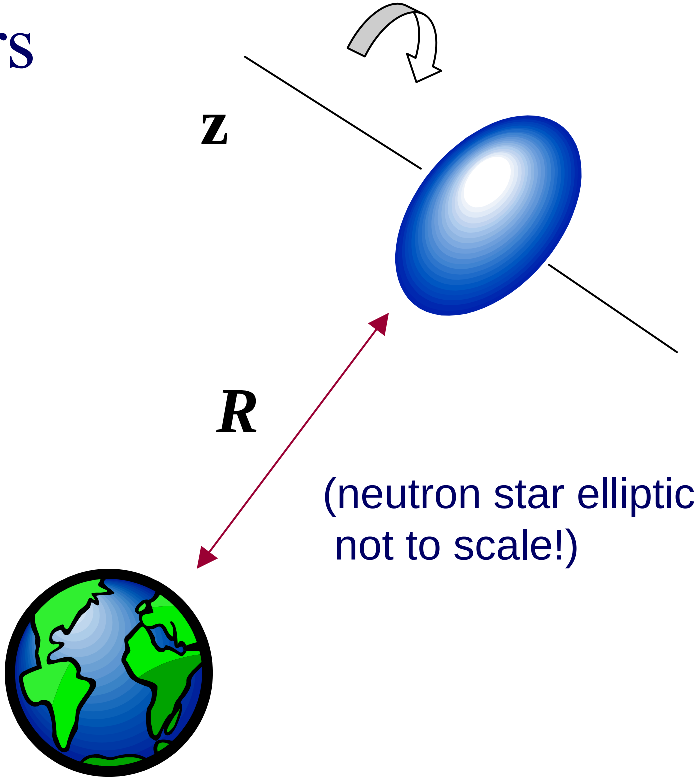
Best S3 Performance LIGO-G040023-00-E



LIGO Hanford, 4km

GWs from asymmetric pulsar

- Spherically symmetric neutron stars will not emit gravitational waves
- Ellipticity, ε, measures asymmetry in triaxially shaped pulsar.



(neutron star ellipticity not to scale!)

Equatorial ellipticity:

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

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz} f_0^{\,2}}{R} \varepsilon$$

equatorial ellipticity

Nature of gravitational wave signal

- The GW signal from a triaxial neutron star can be modelled as

$$h(t)=\frac{1}{2}F_{+}(t)h_{0}\left(1+\cos^{2}\iota\right)\cos\Phi(t)-F_{\times}(t)h_{0}\left(\cos\iota\right)\sin\Phi(t)$$

  - ➢ Simply Doppler modulated sinusoidal signal (at twice the pulsar rotation rate) with an envelope that reflects the antenna pattern of the interferometers.

- The unknown parameters are
  - h_0 - amplitude of the gravitational wave signal
  - ψ - polarization angle of signal; embedded in $F_{x,+}$
  - ι - inclination angle of the pulsar wrt line of sight
  - ϕ_0 - initial phase of pulsar $\Phi(0)$

Time domain method

- For known pulsars the phase evolution can be removed by heterodyning to dc.
  - Heterodyne (multiply by $e^{-i\,\Phi(t)}$) calibrated time domain data from detectors.
  - This process reduces a potential GW signal h(t) to a slow varying complex signal y(t) which reflects the beam pattern of the interferometer.
  - By means of averaging and filtering, we calculate an estimate of this signal y(t) every 40 minutes (changeable) which we call B_k.
- The B_k's are our data which we compare with the model

$$y(t) = \frac{1}{4} F_+(t) h_0 \left(1 + \cos^2 \iota\right) e^{i2\phi_0} - \frac{i}{2} F_\times(t) h_0 \left(\cos \iota\right) e^{i2\phi_0}$$

- Details to appear in Dupuis and Woan (2004).

Bayesian analysis

A Bayesian approach is used to determine the joint posterior distribution of the probability of the unknown parameters via the likelihood:

model

$$p(\{B_k\}|\vec{a}) \propto \exp\left[-\sum_k \frac{\left|B_k - y(t_k;\vec{a})\right|^2}{2\sigma_k^2}\right] = \exp\left[-\chi^2/2\right]$$

B_k's are processed data

noise estimate

$$p(\vec{a}\,|\,\{B_k\}) \propto p(\vec{a})\,p(\{B_k\}|\vec{a})$$

posterior

prior

likelihood

Bayesian upper limits

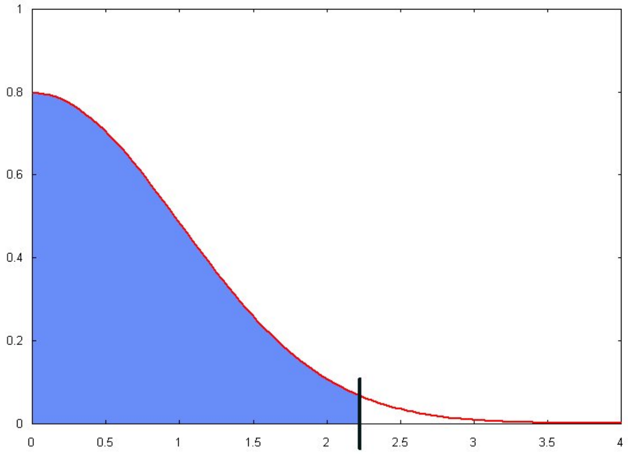
- Marginalize over the nuisance parameters ($\cos\iota$, φ_0, ψ) to leave the posterior distribution for the probability of h_0 given the data.

$$p(h_0 \mid \{B_k\}) \propto \iiint \mathrm{p}(\varphi_0)\mathrm{p}(\psi)\mathrm{p}(\cos\iota)e^{-\chi^2/2}\,\mathrm{d}\varphi_0\,\mathrm{d}\psi\,\mathrm{d}\cos\iota$$

- We define the 95% upper limit by a value h_{95} satisfying

$$0.95 = \int_0^{h_{95}} p(h_0 \mid \{B_k\})\,\mathrm{d}h_0$$

- Such an upper limit can be defined even when signal is present.

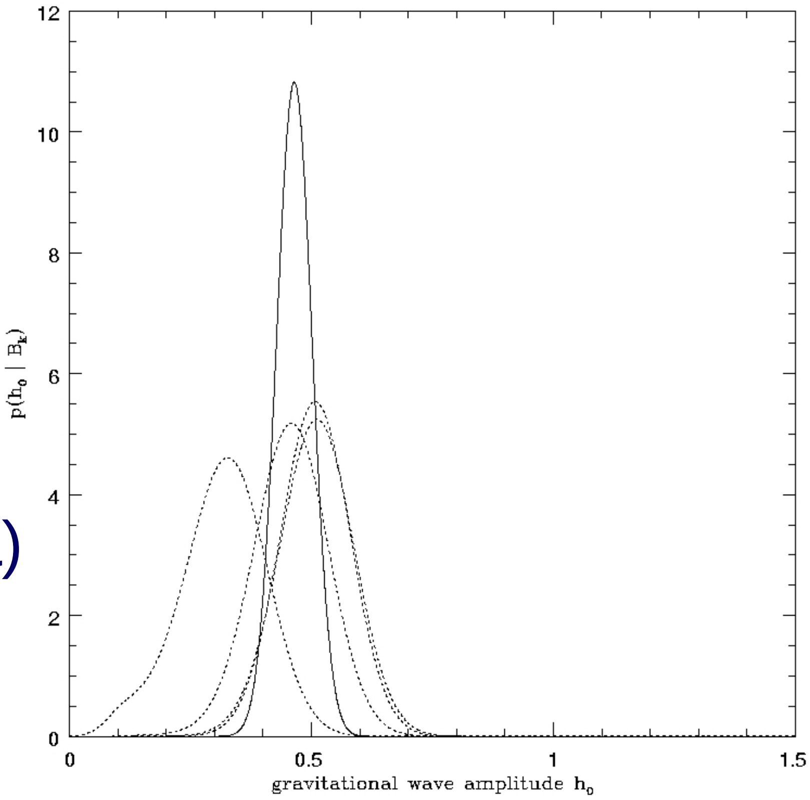


Coherent multi-detector analysis

The combined posterior distribution from all the available interferometers comes naturally out of a Bayesian analysis, and for independent observations is simply the product of the contributing probability distributions:

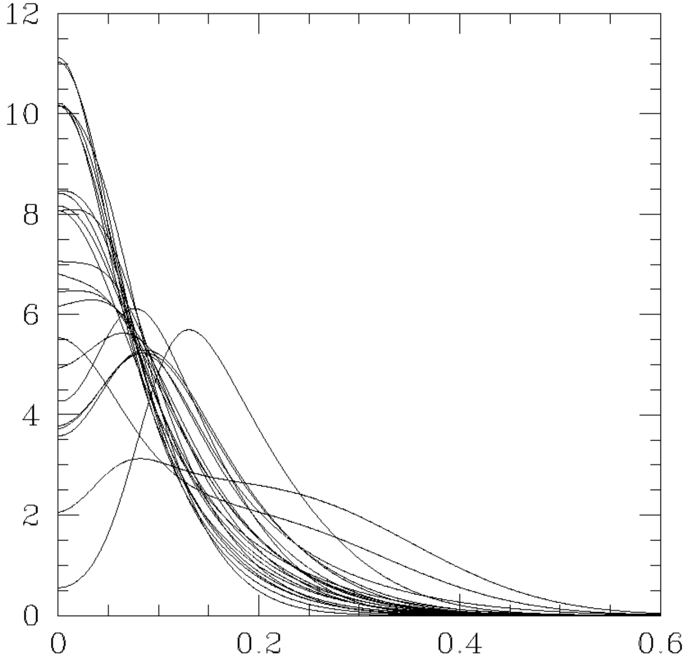
$$p(\mathbf{a}|\text{all data}) \propto$$

$$p(\text{GEO}|\mathbf{a})\, p(\text{L1}|\mathbf{a})\, p(\text{H1}|\mathbf{a})\, p(\text{H2}|\mathbf{a})\, p(\mathbf{a})$$

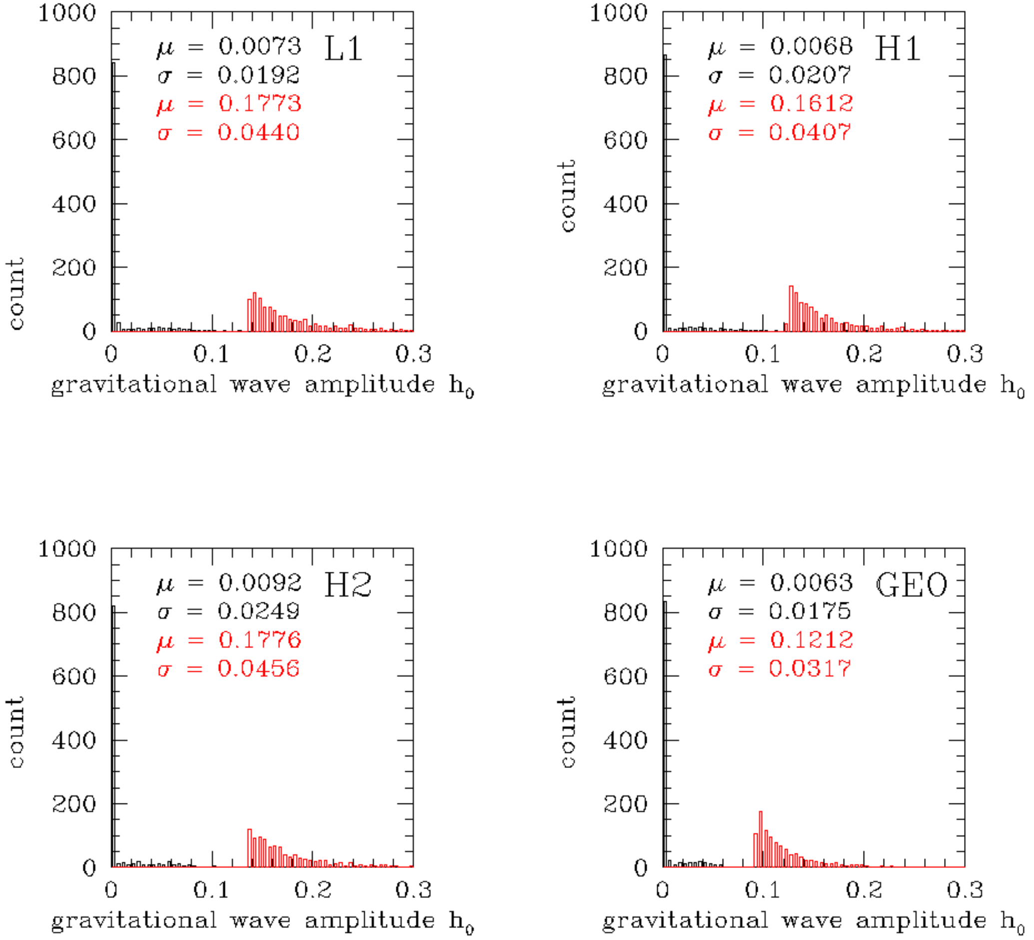


Repeated experiments (no signal)

$p(h_0 \mid \text{data})$ vs h_0



1000 simulations with Gaussian noise for each IFO using S1 time stamps
– black bins represent the location of the peak
– red bins the location of h95



S2 Pulsar Injection Parameters

- Signal is sum of two different pulsars, **P1** and **P2**

P1: Constant Intrinsic Frequency

Sky position: **0.3766960246** latitude (radians)
5.1471621319 longitude (radians)

Signal parameters are defined at SSB GPS time **733967667.026112310** which corresponds to a wavefront passing:

LHO at GPS time **733967713.000000000**

LLO at GPS time **733967713.007730720**

In the SSB the signal is defined by

f = 1279.123456789012 Hz

fdot = 0

phi = 0

A+ = 1.0 x $\mathbf{10^{-21}}$

Ax = 0 [equivalent to iota=pi/2]

P2: Spinning Down

Sky position: **1.23456789012345** latitude (radians)
2.345678901234567890 longitude (radians)

Signal parameters are defined at SSB GPS time: SSB **733967751.522490380**, which corresponds to a wavefront passing:

LHO at GPS time **733967713.000000000**

LLO at GPS time **733967713.001640320**

In the SSB at that moment the signal is defined by

f=1288.901234567890123

fdot = -$\mathbf{10^{-8}}$ **[phase=2 pi (f dt+1/2 fdot dt^2+...)]**

phi = 0

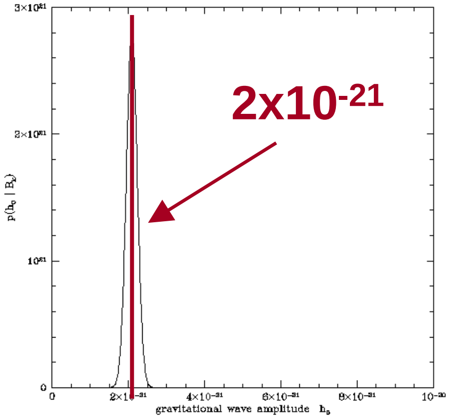
A+ = 1.0 x $\mathbf{10^{-21}}$

Ax = 0 [equivalent to iota=pi/2]

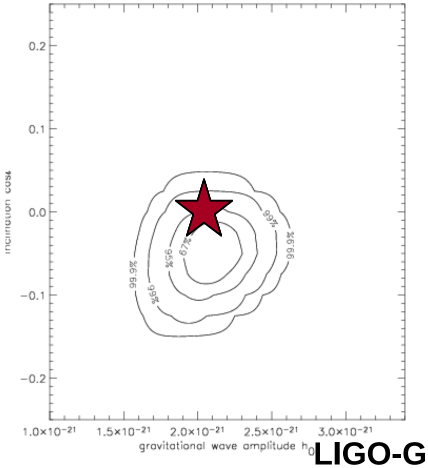
End-to-end validation

- Two simulated pulsars were injected in the LIGO interferometers for a period of ~ 12 hours during S2.
- All the parameters of the injected signals were successfully inferred from the data.
- For example, the plots below show parameter estimation for Signal 1 that was injected into LIGO Hanford 4k.

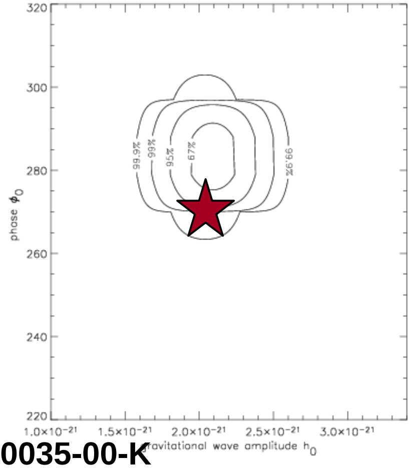
$p(h_0| B_k)$



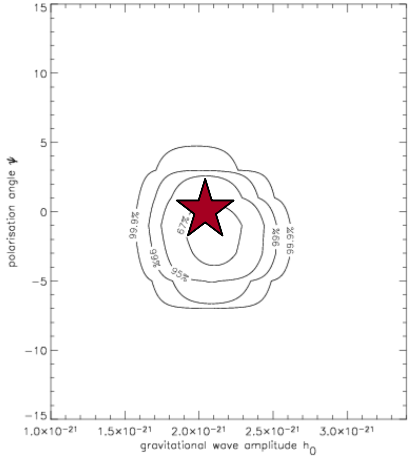
$p(h_0,\cos\iota \mid B_k)$



$p(h_0,\phi_0 \mid B_k)$



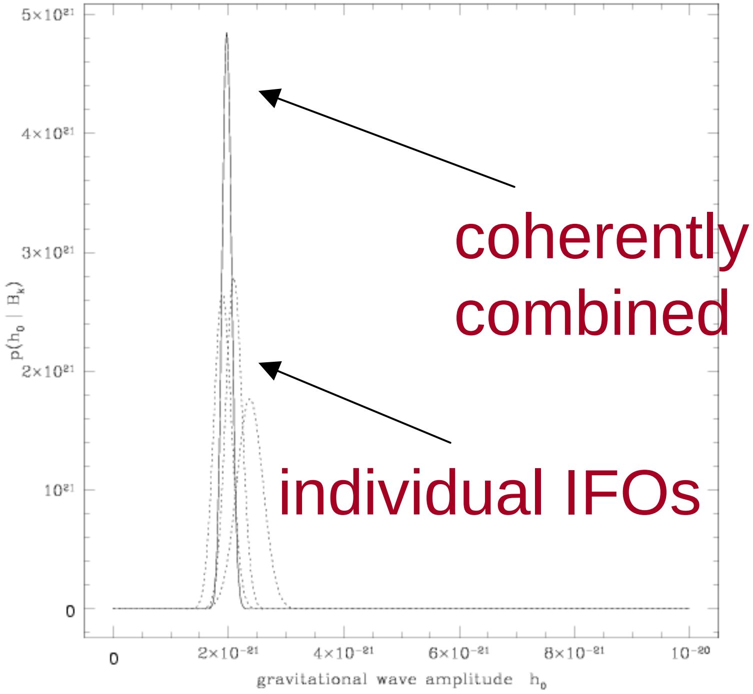
$p(h_0,\psi \mid B_k)$



Coherent multi-detector analysis

- A coherent analysis of the injected signals using data from all sites showed that phase was consistent between sites

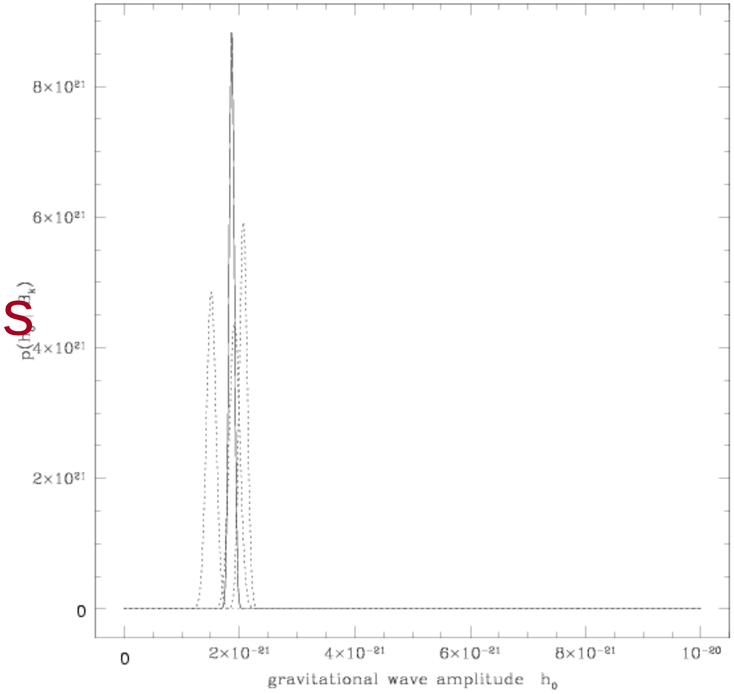
Signal 1



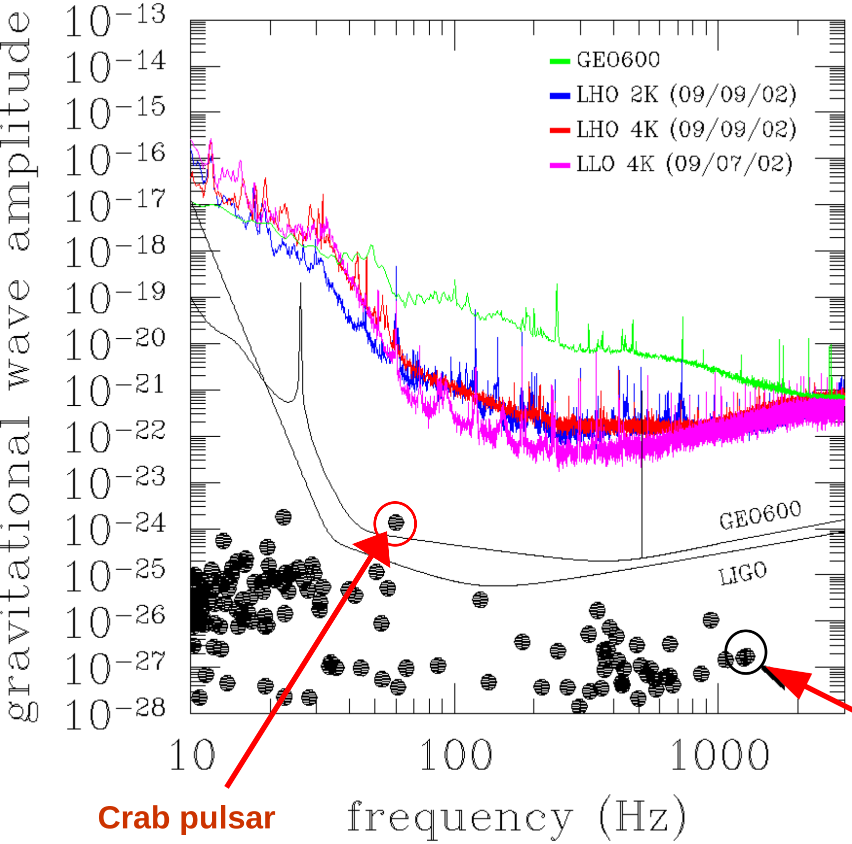
coherently combined IFOs

individual IFOs

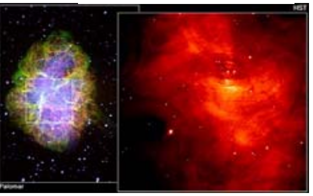
Signal 2



First science run (S1)



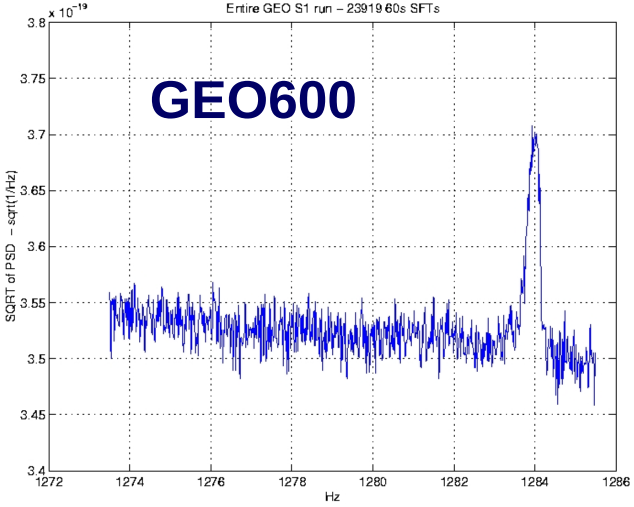
Crab pulsar

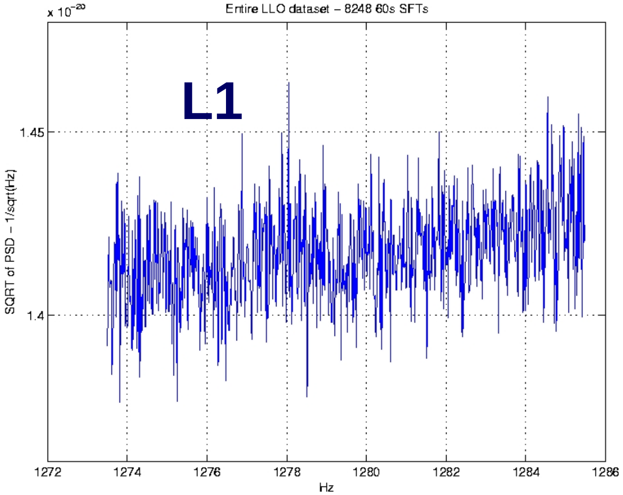


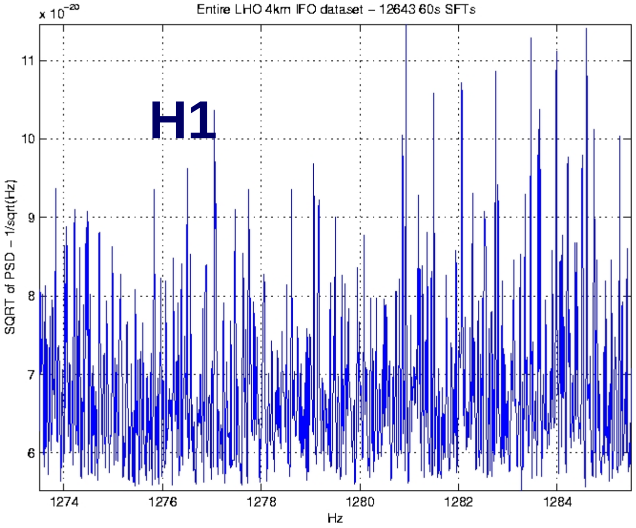
PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
Pd = 1.0519 10^{-19} s/s
D = 3.6 kpc

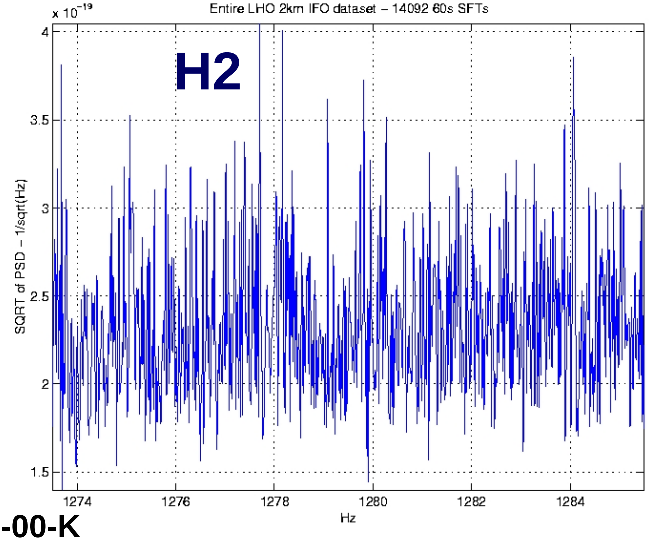
- 23 Aug – 9 Sept 2002
- Previously published UL on emission from PSR1939+2134: $h_0 < 10^{-20}$ (Glasgow, 1983)

S1 data near 1284 Hz

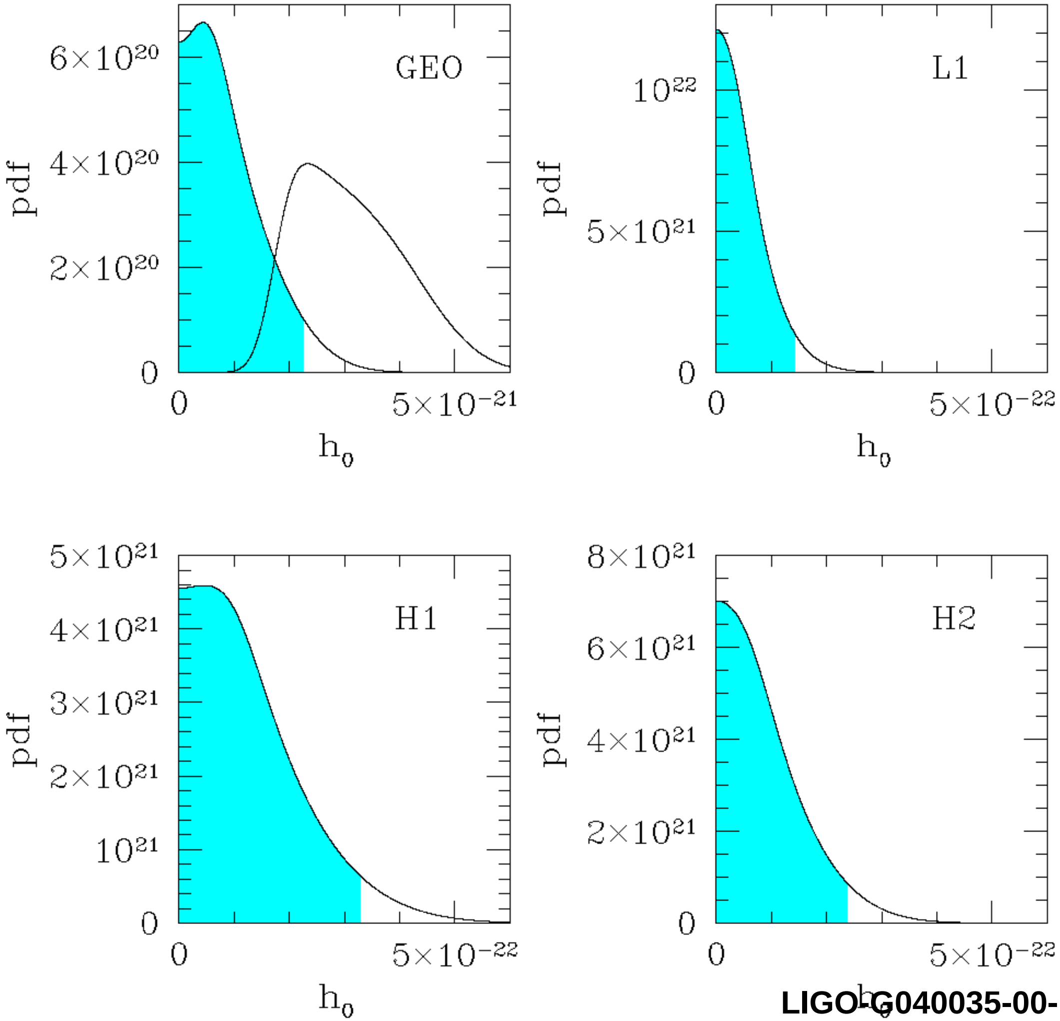








Results from S1 data



- **GEO – 451 hours – 95.7%**
- **$h_0^{95\%} < 2.2\times10^{-21}$**
- **dotted line represents signal injected at 2×10^{-21}**

- **L1 – 137 hours – 35.6%**
- **$h_0^{95\%} < 1.4\times10^{-22}$**

- **H1 – 209 hours – 54.4%**
- **$h_0^{95\%} < 3.3\times10^{-22}$**

- **H2 – 238 hours – 62.0%**
- **$h_0^{95\%} < 2.4\times10^{-22}$**

S2 known pulsar analysis

- Analyzed 28 known isolated pulsars with $2f_{rot} > 50$ Hz.
  - Another 10 isolated pulsars are known with $2f_{rot} > 50$ Hz but the uncertainty in their spin parameters is sufficient to warrant a search over frequency.
- Crab pulsar heterodyned to take timing noise into account.
- Total observation time:
  - 969 hours for H1 (Hanford, 4km)
  - 790 hours for H2 (Hanford, 2km)
  - 453 hours for L1 (Livingston, 4km)

B0021-72C
B0021-72D
B0021-72F
B0021-72G
B0021-72L
B0021-72M
B0021-72N

B0531+21 (Crab)
B1516+02A
B1820-30A
B1821-24
B1937+21 (S1)
B1951+32
B0030+0451

J0711-6830
J1024-0719
J1629-6902
J1721-2457
J1730-2304
J1744-1134
J1748-2446C

J1910-5959B
J1910-5959C
J1910-5959D
J1910-5959E
J1913+1011
J2124-3358
J2322+2057

Example: Pulsar J0030+0451 H1 (Hanford 4km)

J0030+0451

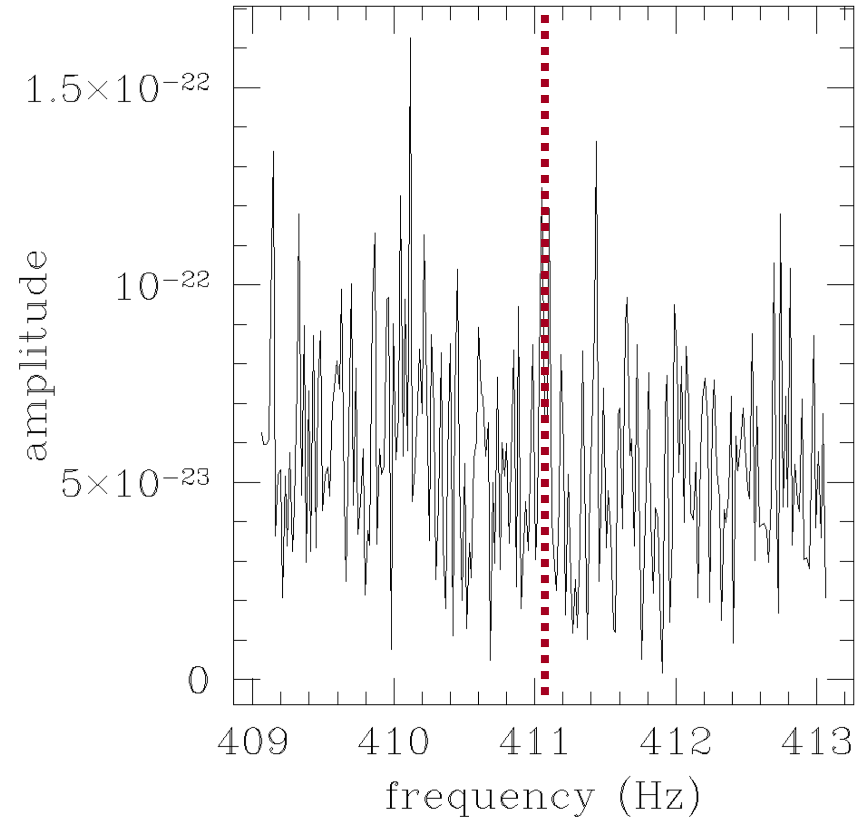
$f_{GW} \approx 411.1\text{Hz}$

$df_{GW} / dt \approx -8.4 \times 10^{-16}$ Hz/s

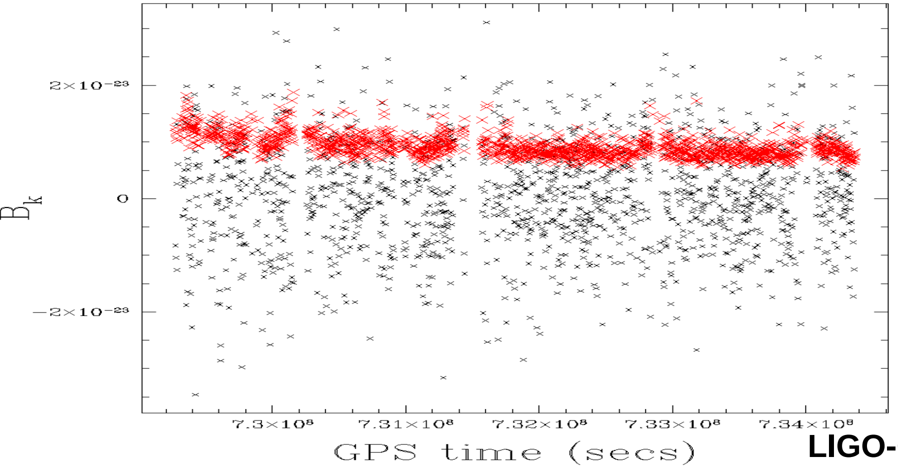
RA = 00:30:27.432

DEC = +04:51:39.7

FFT of 4 Hz band centered on f_{GW}

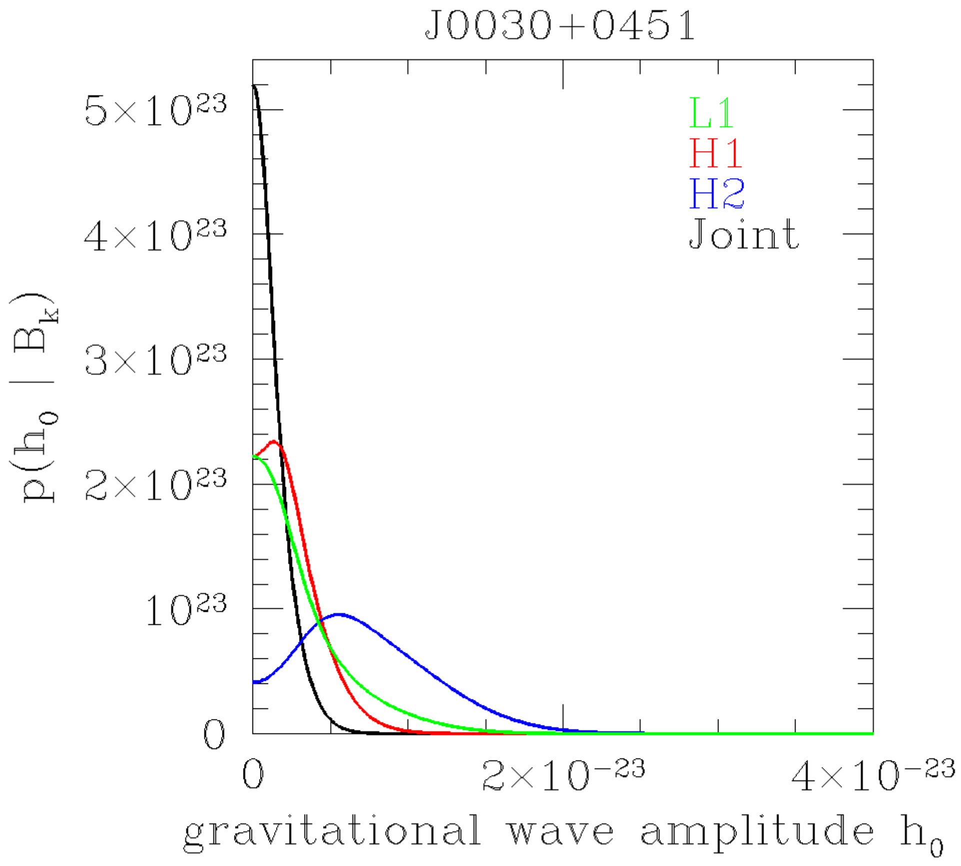


B_k vs time; σ_k vs time



Pulsar J0030+0451 (cont'd)

- This is the closest pulsar in our set at a distance of 230 pc.
- 95% upper limits from individual IFOs for this pulsar are:
  - L1: $h_0 < 9.6 \times 10^{-24}$
  - H1: $h_0 < 6.1 \times 10^{-24}$
  - H2: $h_0 < 1.5 \times 10^{-23}$
- 95% upper limit from coherent multi-detector analysis is:
  - $h_0 < 3.5 \times 10^{-24}$



Noise estimation

$$\chi^2 = \sum_{k=1}^{M} \frac{\left|B_k - y(t_k;\vec{a})\right|^2}{\sigma_k^2}$$

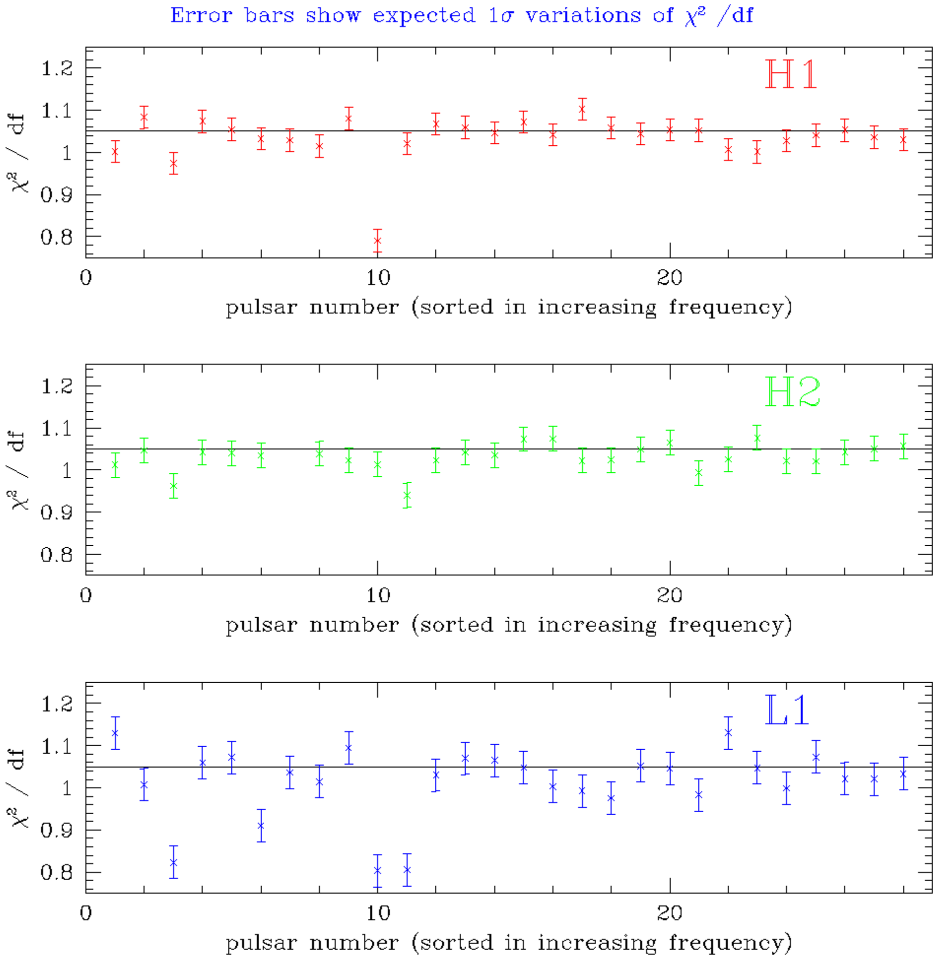
M = total number of B_k's (which are complex and estimated every 40 minutes).

If we are properly modeling the noise, we would expect (from Student's t-distribution)

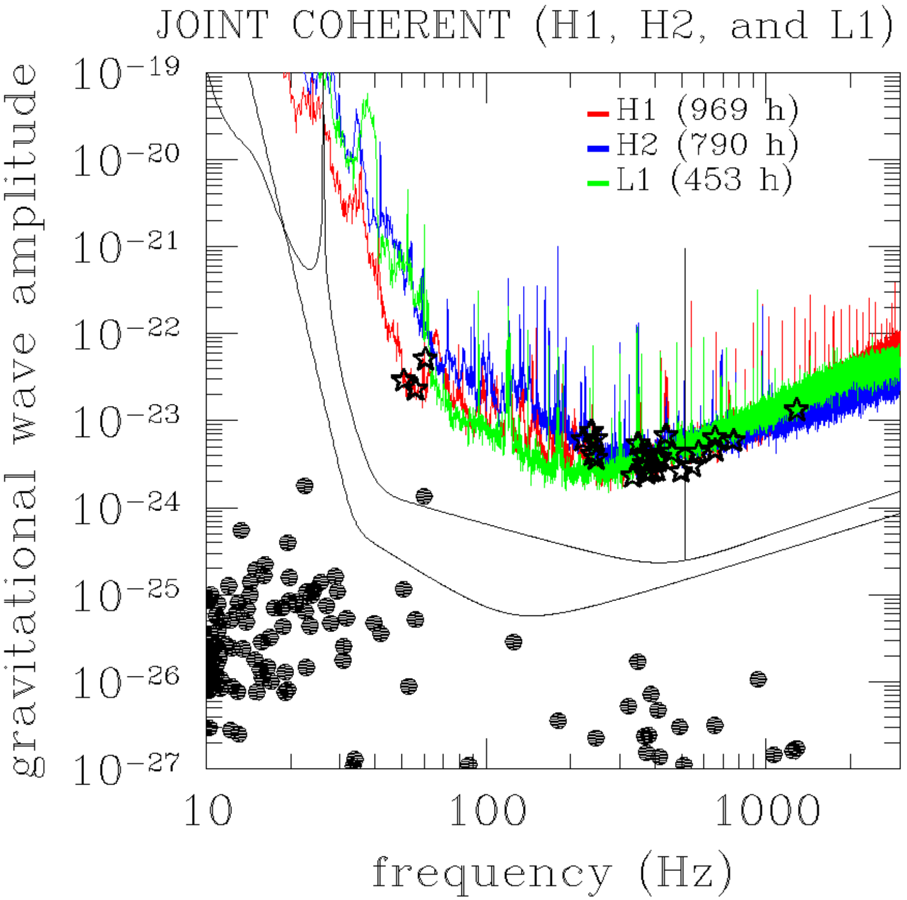
$$<\chi^2/(2M)> = \frac{n-1}{n-3} \approx 1.05$$

$$\mathrm{var}[\chi^2/(2M)] = \left(\frac{n-1}{n-3}\right)^2 \frac{2}{M}$$

where n = 40 (n is the number of data points used to estimate σ_k).



Multi-detector upper limits



☆ 95% upper limits (preliminary)

- 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 $h_0 < 2.3\text{x}10^{-24}$.
- 95% upper limit for Crab pulsar (~ 60 Hz) is $h_0 < 5.1 \text{ x } 10^{-23}$.
- 95% upper limit for J1939+2134 (~ 1284 Hz) is $h_0 < 1.3 \text{ x } 10^{-23}$.

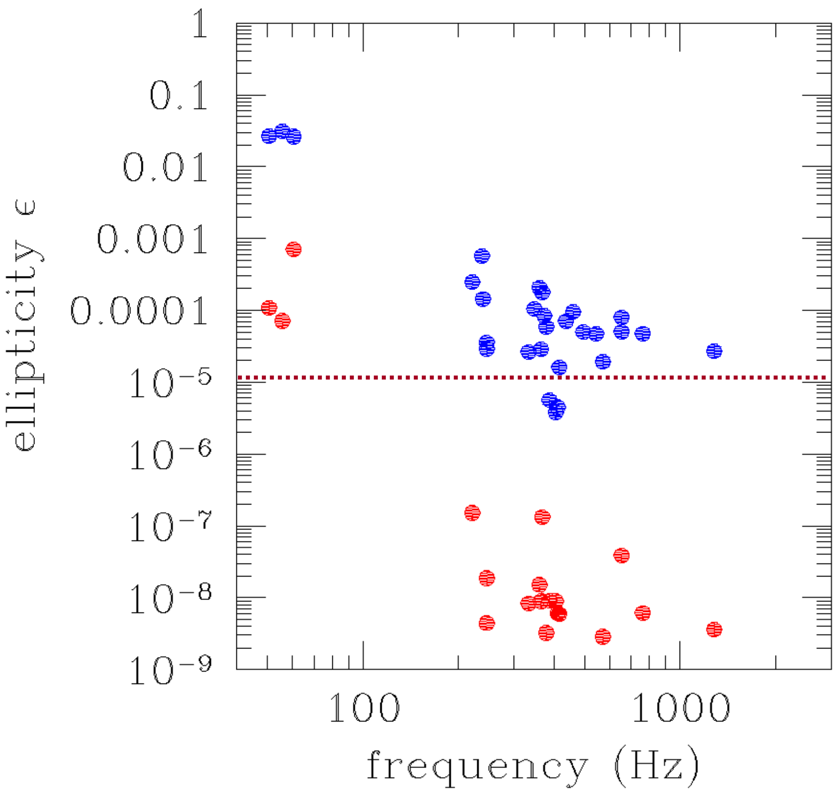
Upper limits on ellipticity

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}.

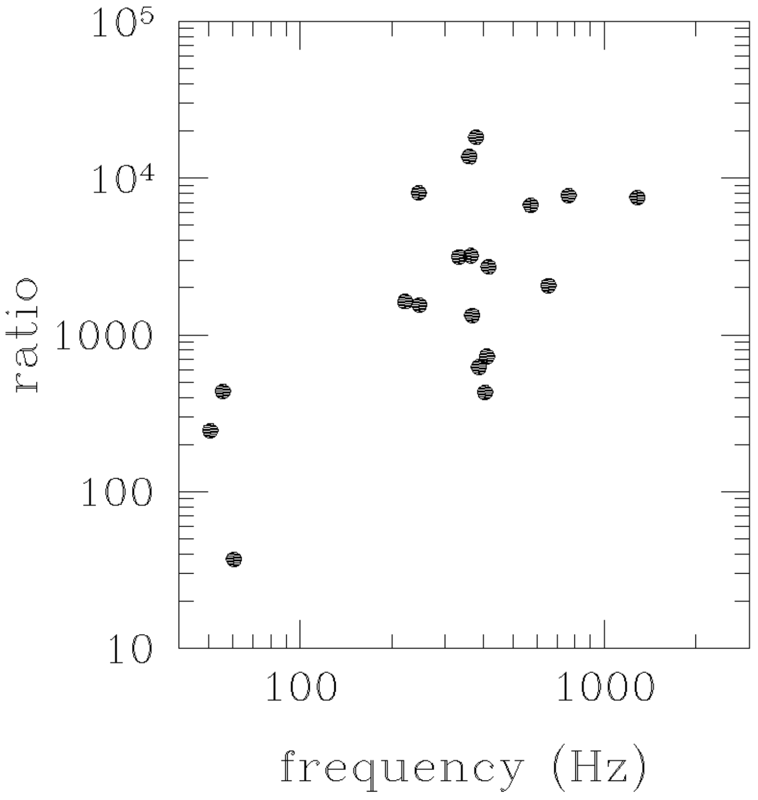
- ● S2 upper limits
- ● Spin-down based upper limits



Approaching spin-down upper limits

- For Crab pulsar (B0531+21) we were still a factor of ~35 above the spin-down upper limit in S2.
- Hope to reach spin-down based upper limit in S3!
- Note that not all pulsars analysed are constrained due to spin-down rates; some actually appear to be spinning-up (associated with accelerations in globular cluster).

Ratio of S2 upper limits to spin-down based upper limits



Plans for the future

- Look for signals from all known pulsars which can be described with one template (the majority) including those in binary systems.
- Use Markov Chain Monte Carlo approach to extend the parameter space (frequency, spin-down). Search for signals from SN87A, Cas A, …
- All sky searches are underway using S2 data.
- Einstein@home