First LIGO/GEO Upper Limits on Pulsar Gravitational Emissions

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CaJAGWR Seminar
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Executive summary

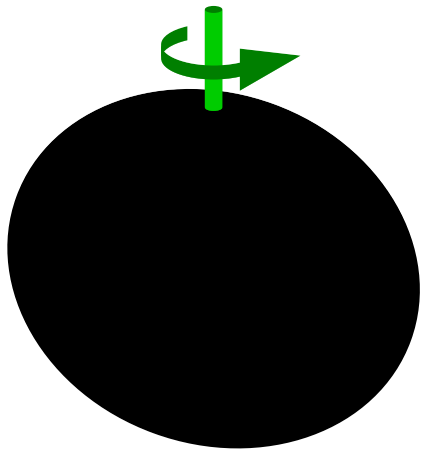
- S1 science run took 3 weeks of data (Aug. 23 – Sep. 9, 2003) on 4 detectors (LIGO L1, H1, H2, and GEO600).
- Data analyzed for signal from PSR J1939+2134, using two methods:
  - ⋆ Frequency-domain frequentist analysis $\Rightarrow h_0 < (2.8 \pm 0.3) \times 10^{-22}$
  - ⋆ Time-domain Bayesian analysis $\Rightarrow h_0 < (1.0 \pm 0.1) \times 10^{-22}$
- Upper limits were set in each case
- For this pulsar, $h_0 < 1.0 \times 10^{-22}$ corresponds to ellipticity ratio (non-axisymmetry) $\epsilon < 7.5 \times 10^{-5}$.

Outline

I. Gravitational waves from pulsars
II. LIGO and GEO during S1
III. Frequency-domain analysis method
IV. Time-domain analysis method
V. Comparison of results
VI. Future searches

GWs from pulsars

- Pulsars = spinning neutron stars
- Emit gravitational waves if they are *non-axisymmetric*
- Possible mechanisms:



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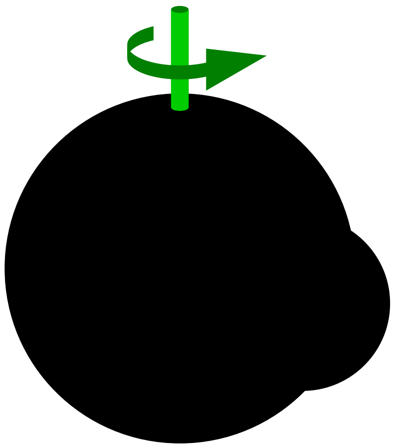

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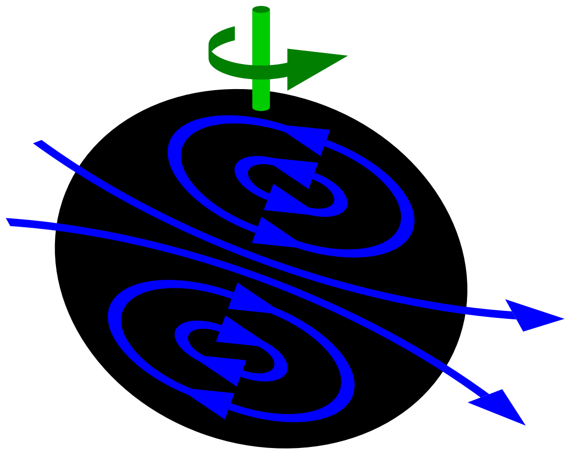

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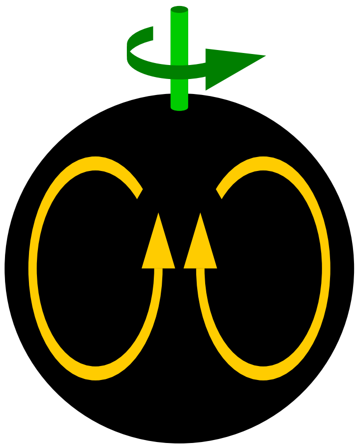

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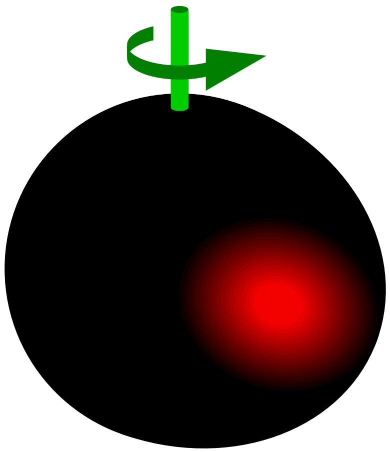

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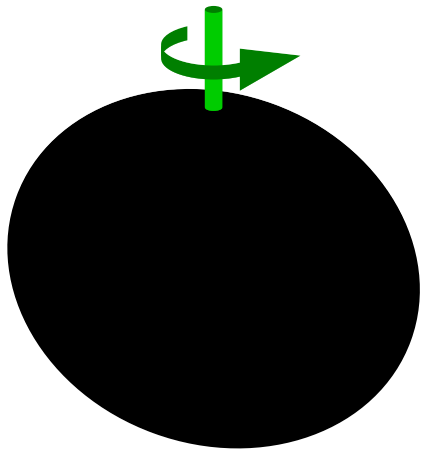


$\Rightarrow$ Most likely for known pulsars

- ⋆ Emit primarily at GW frequency = $2\times$spin frequency

GWs from pulsars

- Intrinsic amplitude:

$$h_0 = (1.06\times 10^{-23}) \left(\frac{I}{10^{45}\mathrm{g\,cm}^2}\right) \left(\frac{1\,\mathrm{kpc}}{r}\right) \left(\frac{f_{\mathrm{gw}}}{1\,\mathrm{kHz}}\right)^2 \left(\frac{\epsilon}{10^{-5}}\right)$$

- Signal in detector is:

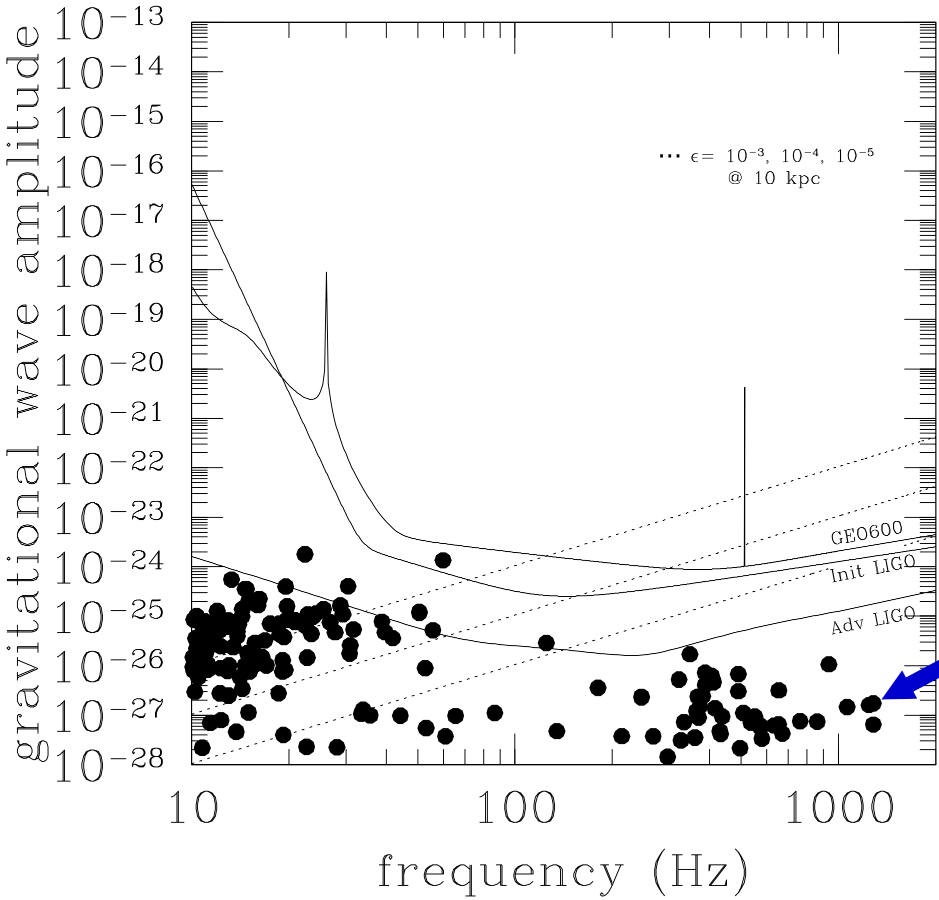
$$h(t) = h_0 \left\{ F_+(t,\psi)\frac{1+\cos^2\iota}{2}\cos[\Phi(t)+\phi_0] + F_\times(t,\psi)\cos\iota\sin[\Phi(t)+\phi_0] \right\}$$

$F_+,\ F_\times$ = polarization beam patterns (known)
Φ = observed rotation phase (known)

h_0 = intrinsic amplitude (above)
ψ = polarization angle
ι = inclination angle
ϕ_0 = phase offset

GWs from pulsars

- At a 1% false alarm threshold, required amplitude for 10% false dismissal is:



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

- 3 week integration
- Known pulsars shown
- PSR J1939+2134
  $f_{\rm gw} = 1283.86$Hz

$\Rightarrow$ No detection expected!

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LIGO and GEO during S1

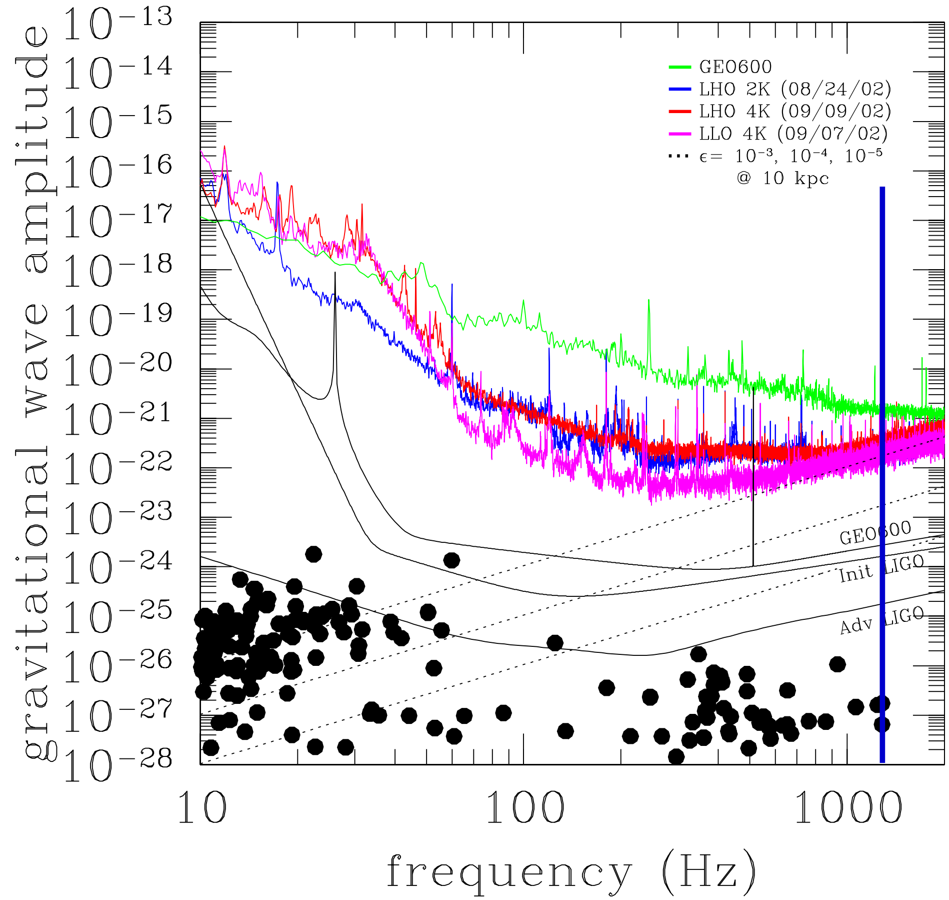
- First LIGO/GEO science run (S1): August 23 – September 9, 2002
  17 days = 408 hours

- Total of four interferometers participating:

  - ⋆ LIGO Livingston L1 (4 km):
    duty cycle 41.7%, total locked time: 170 hours
  - ⋆ LIGO Hanford H1 (4 km):
    duty cycle 57.6%, total locked time: 235 hours
  - ⋆ LIGO Hanford H2 (2 km):
    duty cycle 73.1%, total locked time: 298 hours
  - ⋆ GEO (600 m):
    duty cycle 98.5%! total locked time: 396 hours

LIGO and GEO during S1

Instrumental sensitivity:



- Coincidence not important, only total uptime
- Shorter instruments had higher uptime

⇒ Comparable sensitivity at frequency of interest!

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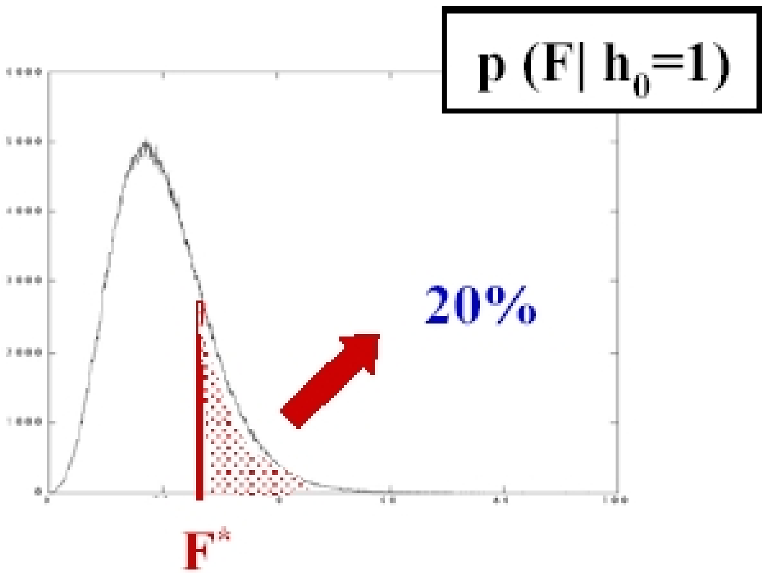
Frequency-domain analysis

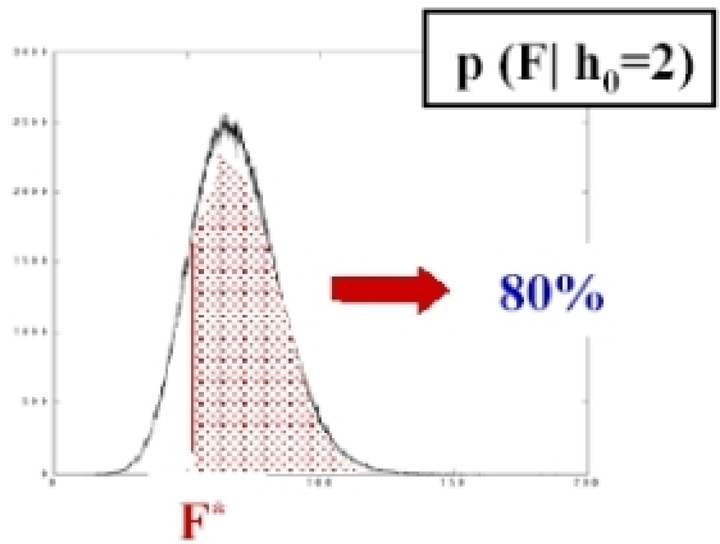
- $\mathcal{F}$-statistic is a quadrature sum of 4 linear filters.
- In Gaussian noise, it is a *maximum likelihood* estimator of signal amplitude, implicitly maximized over ϕ_0, ψ, and $\cos\iota$.
  - $2\mathcal{F}$ follows a χ^2 distribution with 4 degrees of freedom and non-centrality parameter $\lambda \propto \int h(t)^2 dt$.
- In generic noise, compute $p(\mathcal{F}|\vec{a})$ using Monte-Carlo injections of simulated signals.
- Originally developed for pulsar *searches*: code exists to compute $\mathcal{F}$ simultaneously over broad frequency ranges.

Frequency-domain analysis

- *Frequentist* approach: Determine the value $\mathcal{F}^*$ of the statistic for our source from our data.

- Determine $p(\mathcal{F}|h_0)$ for a range of h_0.





Frequency-domain analysis

- *Frequentist* approach: Determine the value $\mathcal{F}^*$ of the statistic for our source from our data.

- Determine $p(\mathcal{F}|h_0)$ for a range of h_0.

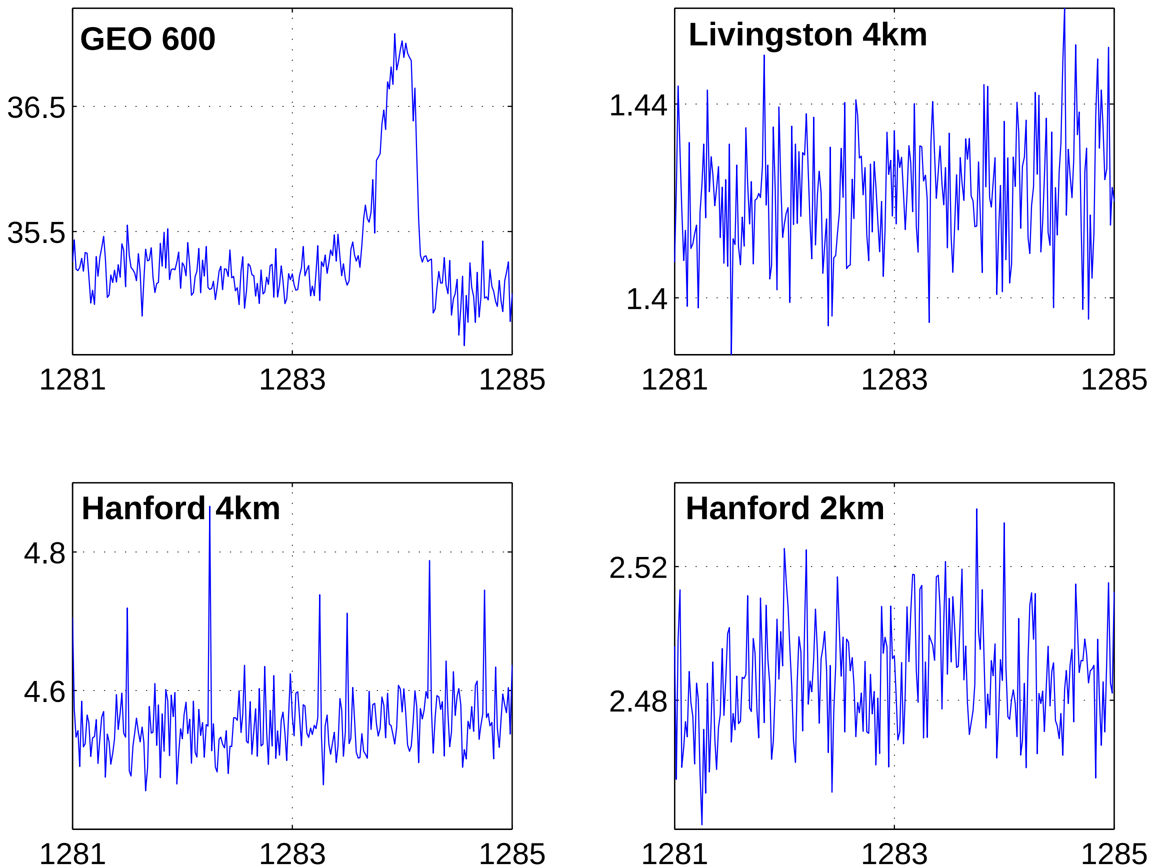
- 95% frequentist upper limit h^*_{95} is the value such that, for repeated trials with a signal $h_0 > h^*_{95}$, we would obtain $\mathcal{F} > \mathcal{F}^*$ more than 95% of the time:

$$0.95 = \int_{\mathcal{F}^*}^{\infty} p(\mathcal{F}|h_0 = h^*_{95})\, d\mathcal{F}$$

- Extra detail: When computing $p(\mathcal{F}|h_0)$ via Monte-Carlo, inject signals with *worst possible* orientation ψ, ι. This gives a *conservative* upper limit.

Frequency-domain analysis

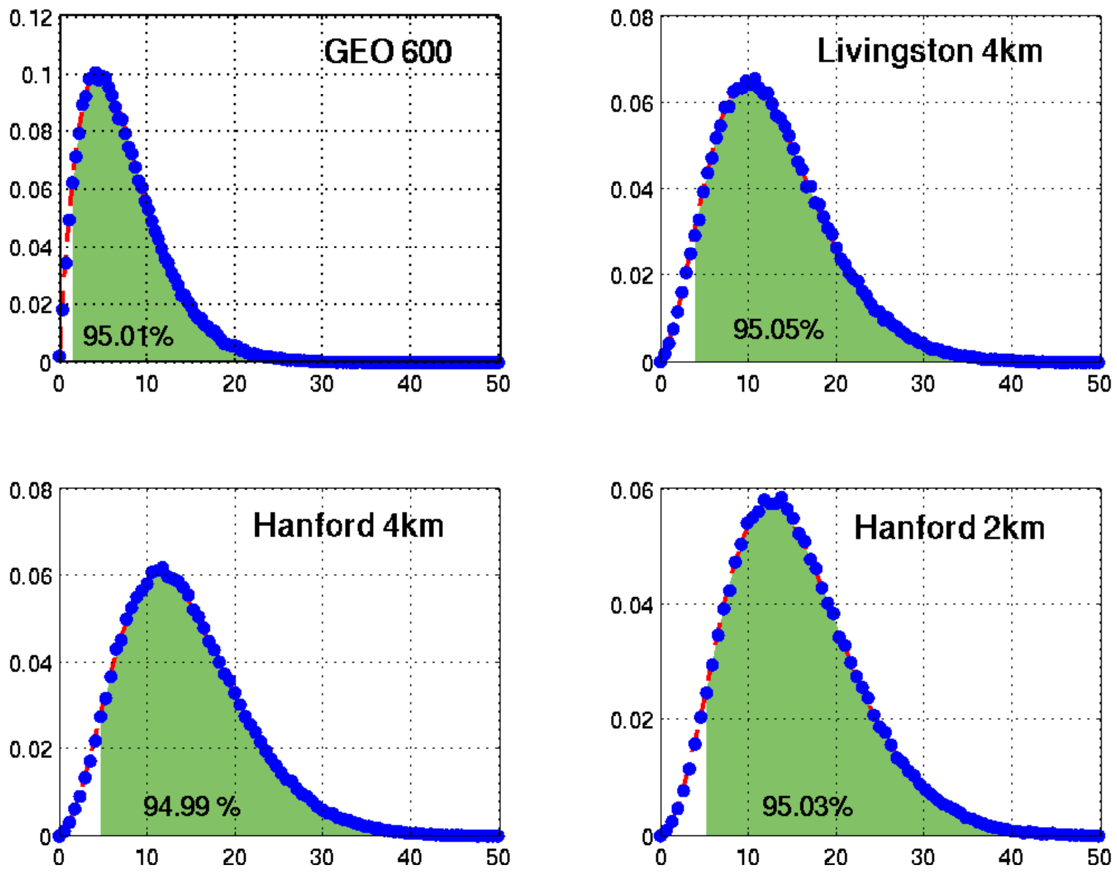
The raw data: $\sqrt{S_h}$ $(10^{-20}\mathrm{Hz}^{-1/2})$ versus frequency in Hz.



- Note spectral disturbance in GEO600

Frequency-domain analysis

Probability distributions:



- All except GEO600 are consistent with Gaussian statistics (Kolmogorov-Smirnov test)

- 95% upper limits:

	$2\mathcal{F}^*$	h_{95}^*
GEO	1.5	1.9×10^{-21}
L1	3.9	2.8×10^{-22}
H1	4.7	6.4×10^{-22}
H2	5.2	4.7×10^{-22}

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Time-domain analysis

- Signal is *heterodyned* by (known) instantaneous frequency of J1939+2134
  - ⋆ Reduces pulsar signal to DC
  - ⋆ Removes Doppler modulation from signal

- Resampled at 1/minute, and noise estimated for each minute

$\Rightarrow$ data $B_k \pm \sigma_k$ every minute.

- Data are then fit to a signal model:

$$y(t;\vec{a}) = \frac{1}{4}h_0 e^{2i\phi_0}\left[F_+(t,\psi)(1+\cos^2\iota) - 2F_\times(t,\psi)\cos\iota\right]$$

where $\vec{a} = (h_0, \phi_0, \psi, \cos\iota)$ are unknown parameters.

Time-domain analysis

- *Bayesian* approach: Compute joint probability distribution over all of $\vec{a}$, using *uniform* priors on h_0, ϕ_0, ψ, $\cos\iota$:

$$\underset{\text{posterior}}{\underset{\uparrow}{p(\vec{a}|\{B_k\})}} \quad \propto \quad \underset{\text{prior}}{\underset{\uparrow}{p(\vec{a})}} \quad \cdot \quad \underset{\text{likelihood}}{\underset{\uparrow}{p(\{B_k\}|\vec{a})}}$$

In Gaussian noise, likelihood $\propto e^{-\chi^2/2}$, where $\chi^2(\vec{a}) = \sum_k \left|\frac{B_k - y(t_k;\vec{a})}{\sigma_k}\right|^2$

- To get probability distribution on h_0, *marginalize* over other parameters:

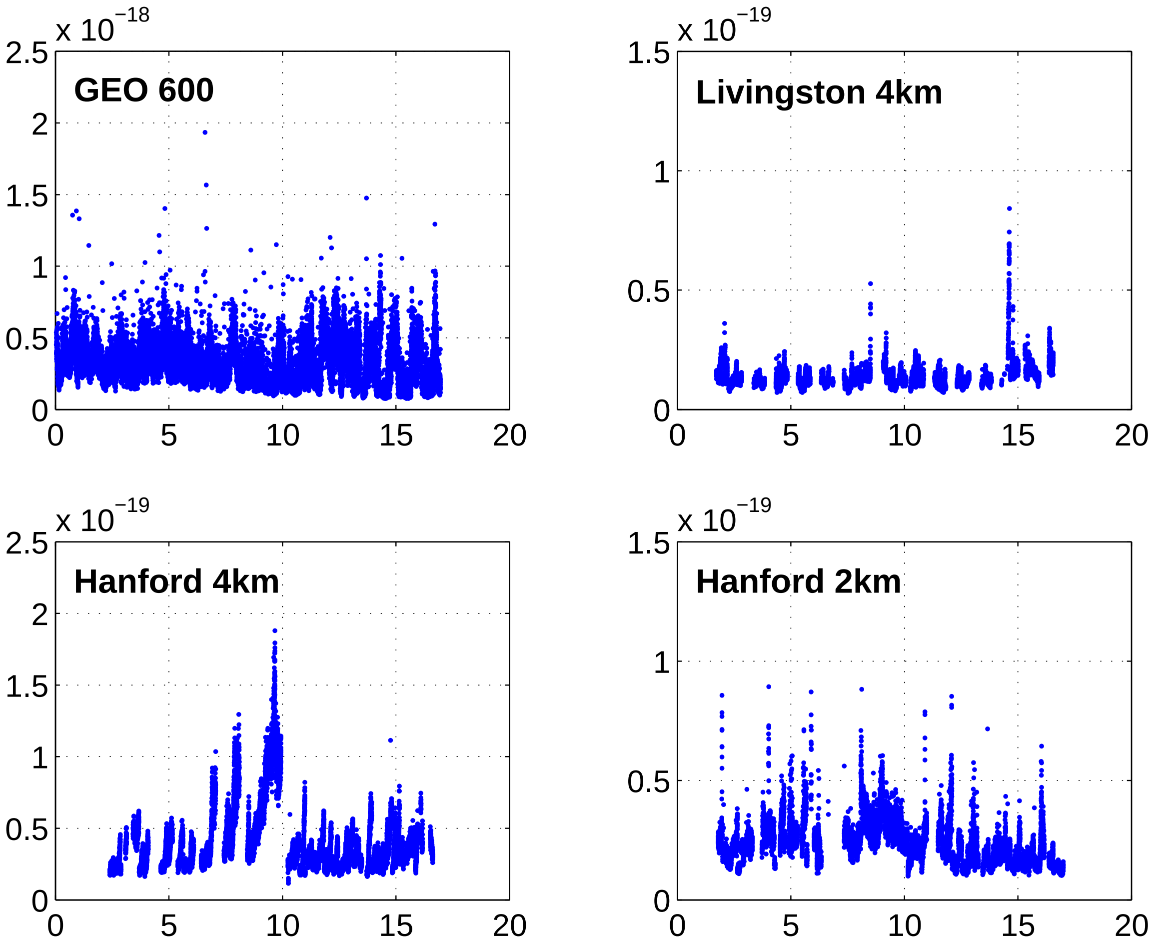
$$p(h_0|\{B_k\}) \propto \int d\phi_0 \int d\psi \int d\cos\iota \;\; e^{-\chi^2/2}$$

- 95% confidence upper limit h_{95} defined by:

$$0.95 = \int_0^{h_{95}} dh_0 \;\; p(h_0|\{B_k\})$$

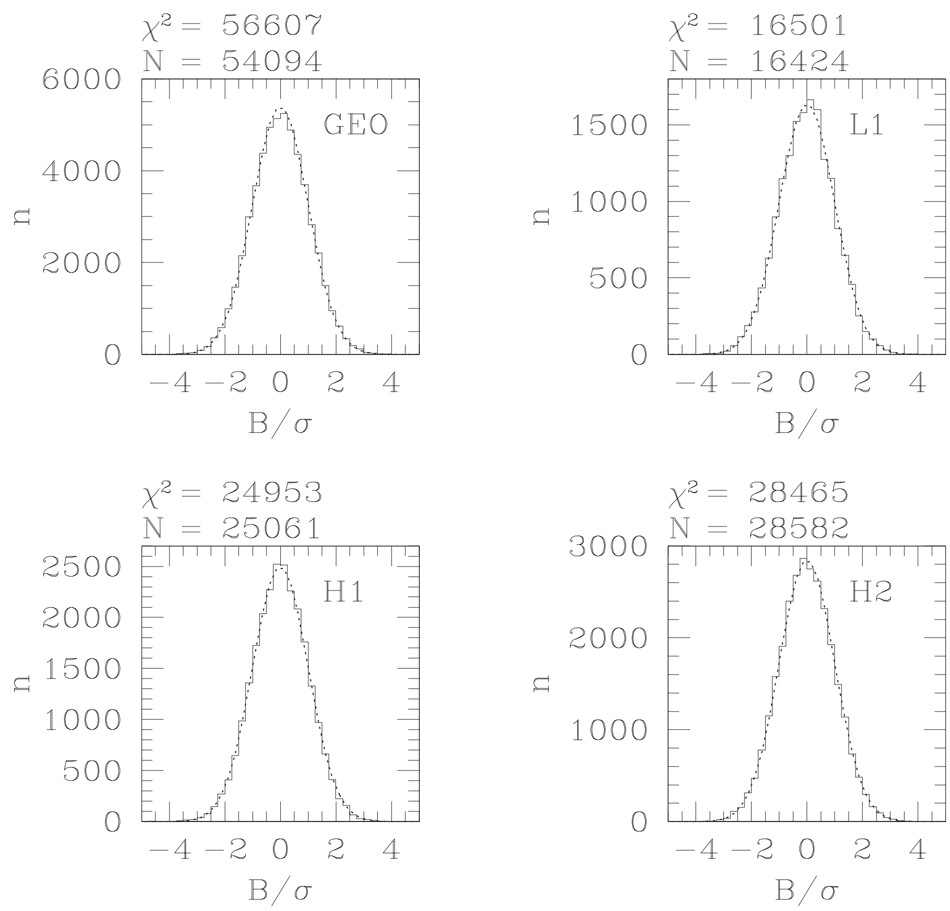
Time-domain analysis

The raw data: $\sqrt{S_h}$ $(\mathrm{Hz}^{-1/2})$ versus time in days



Time-domain analysis

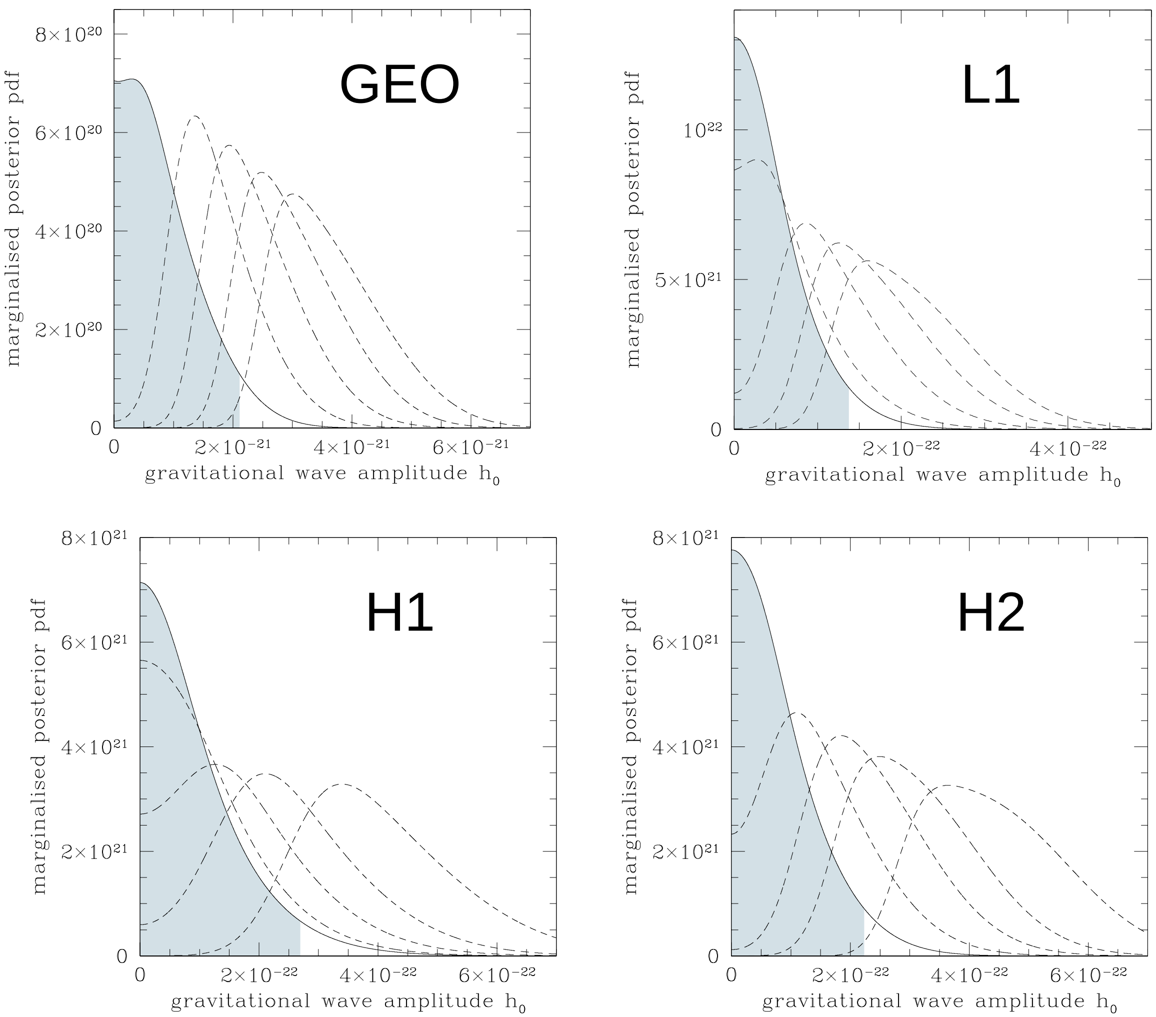
Gaussianity of resampled data B_k:



- GEO is not in fact consistent with Gaussian distribution.
  - ⋆ Spectral disturbance near this frequency
  - ⋆ Might raise our upper limit by about $\times 1.5$
- LIGO detectors are consistent with Gaussian distribution.

Time-domain analysis

Posterior probability distributions:



- 95% upper limits:

GEO	2.1×10^{-21}
L1	1.4×10^{-22}
H1	2.7×10^{-22}
H2	2.2×10^{-22}

- Can inject simulated signal to see how PDF changes.

Time-domain analysis

- Can also compute joint probability distribution:

$$p(\vec{a}|\text{all data}) = p(\vec{a}|\text{GEO}) \cdot p(\vec{a}|\text{L1}) \cdot p(\vec{a}|\text{H1}) \cdot p(\vec{a}|\text{H2})$$

- Marginalizing gives:

$$h_{95} = 1.0 \times 10^{-22}$$

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Comparison of results

	Frequentist UL h^*_{95}	Bayesian UL h_{95}
GEO	1.9×10^{-21}	2.1×10^{-21}
H1	6.4×10^{-22}	2.7×10^{-22}
H2	4.7×10^{-22}	2.2×10^{-22}
L1	2.8×10^{-22}	1.4×10^{-22}
Joint	–	1.0×10^{-22}

- PSR J1939+2134 is at 3.6 kpc

$\Rightarrow$ ellipticity $\epsilon \leq 7.5 \times 10^{-5}$

Comparison of results

- Bayesian and frequentist analyses answer *two different questions:*
  - ⋆ Bayesian: Given our model and priors, for what value h_{95} are we 95% sure that the true h_0 lies below this level?

    $\Rightarrow$ Threshold on $p(h_0|\text{data, priors})$
  - ⋆ Frequentist: Given the measured value of $\mathcal{F}^*$, for what value h_{95}^* would a signal with $h_0 > h_{95}^*$ yield $\mathcal{F} > \mathcal{F}^*$ 95% of the time?

    $\Rightarrow$ Threshold on $p(\text{data}|h_0, \text{orientation})$
- It is therefore not surprising that the values h_{95} and h_{95}^* do not in general agree.
- Discrepancy largely due to *worst-case* (conservative) orientation chosen for frequentist approach.

Comparison of results

Other experimental results:

- Best UL on continuous signals is from a bar detector: 2.9×10^{-24} around 921.3 Hz from Galactic centre
  - ⋆ but no known pulsar at that frequency/location.
- Best previous UL on PSR J1939+2134 is 1×10^{-20} (using a divided bar).
- Indirect observational UL is 2×10^{-27} based on spindown rate.

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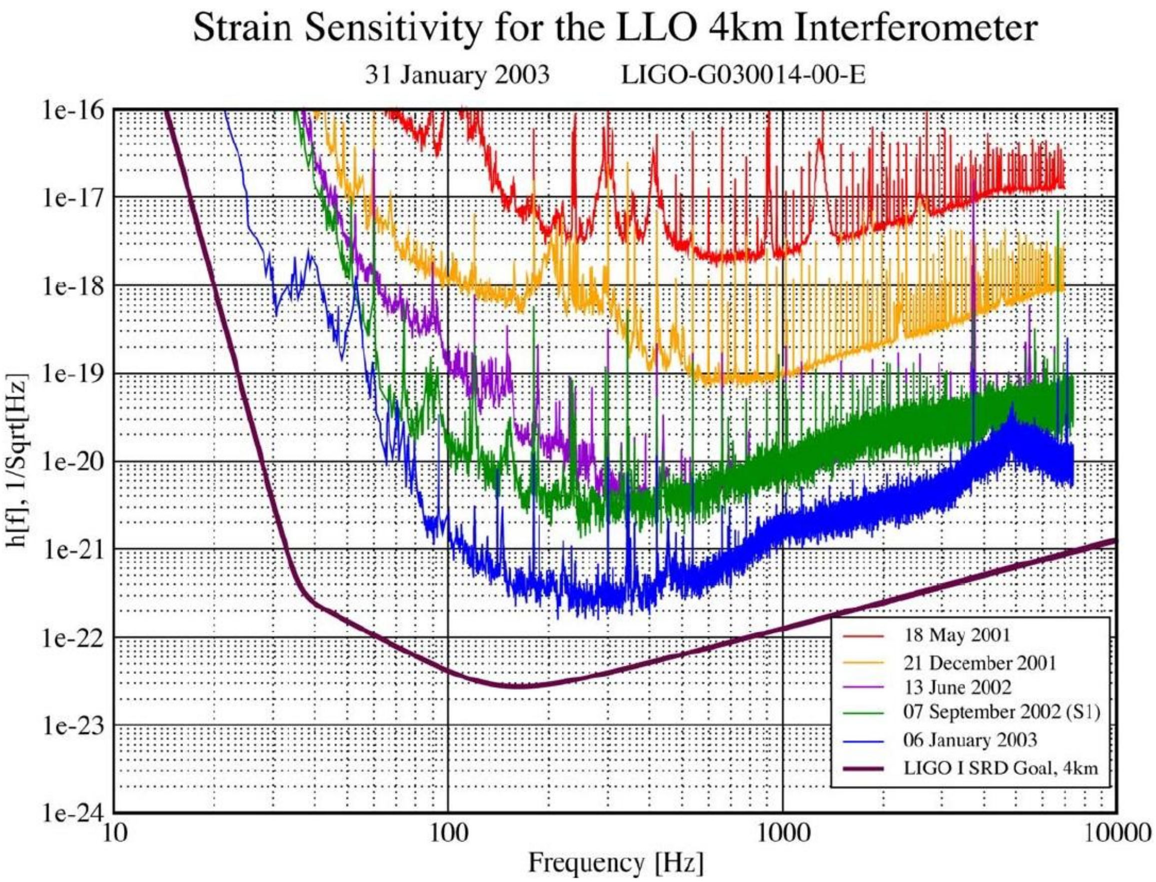
Future searches

Second science run (S2) has just completed.



- Order of magnitude improvement in sensitivity!
- We want to start in on new data as soon as possible.

Future searches

- Targeted searches on all known pulsars.
- Directed searches on known systems with unknown phase evolution (e.g. xray binaries).
- Broad-band wide-area searches.
  $\Rightarrow$ Set upper limits on *unknown* sources.
- As instruments continue to improve, we may make actual *detections* of gravitational emissions!