First LIGO/GEO Upper Limits on Pulsar Gravitational Emissions

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For the Pulsar Upper Limits Working Group
of the LIGO Scientific Collaboration

CaJAGWR Seminar
April 15, 2003

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- 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
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GWs from pulsars

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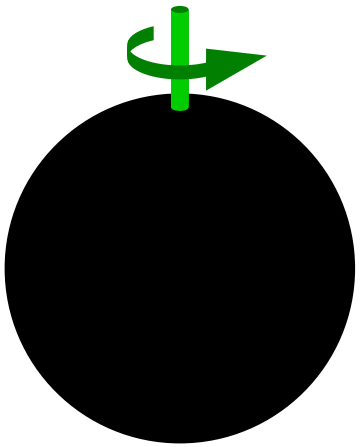

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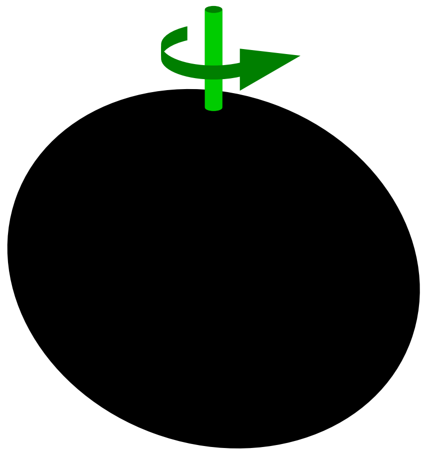

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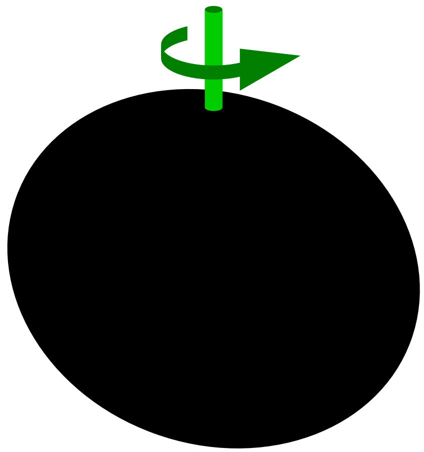

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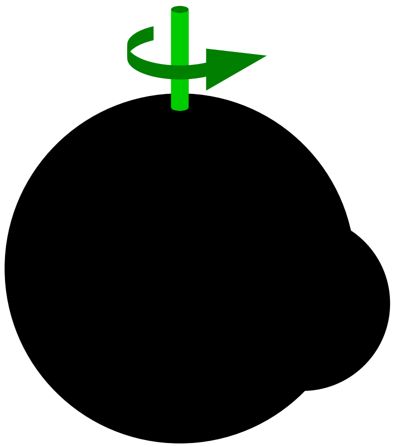

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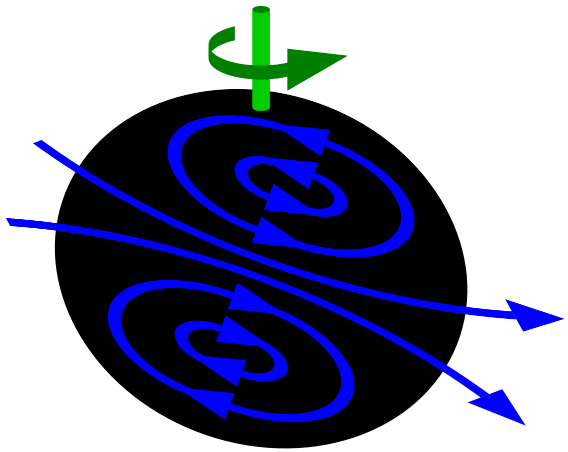

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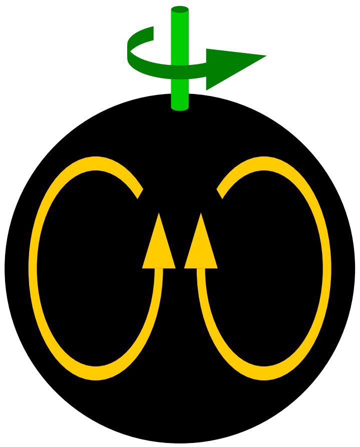

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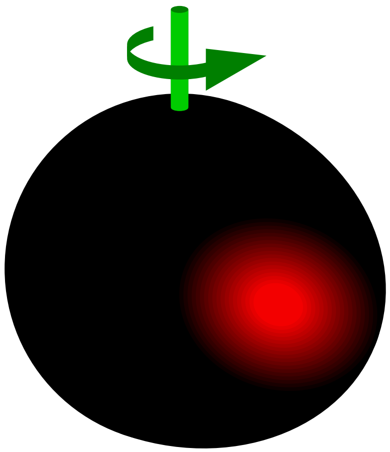

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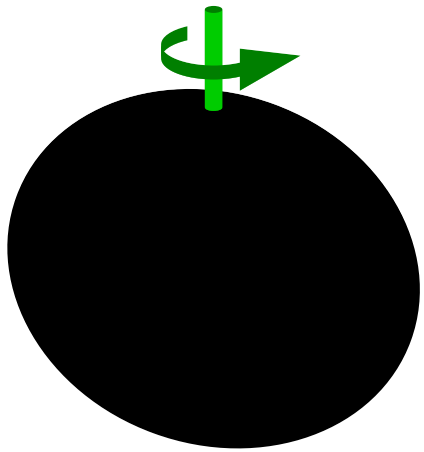

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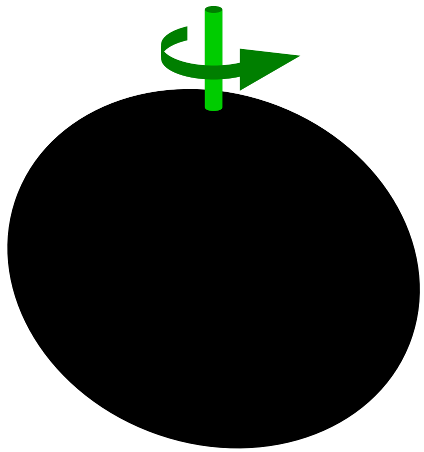

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- ⋆ Emit primarily at GW frequency = $2\times$spin frequency

GWs from pulsars

- Intrinsic amplitude:

$$h_0 = \frac{4\pi^2 G}{c^4} \times \frac{I f_{\rm gw}^2}{r}$$

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

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

$\vec{a}$:
- h_0 = intrinsic amplitude (above)
- ψ = polarization angle
- ι = inclination angle
- ϕ_0 = phase offset

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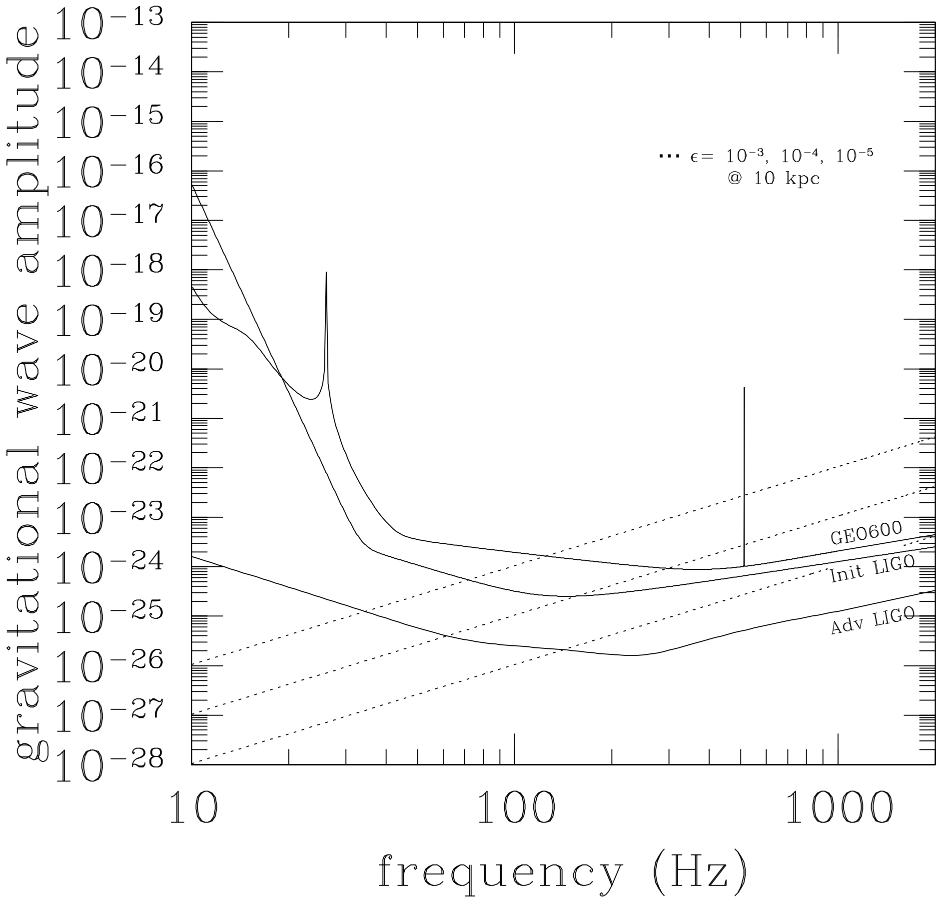

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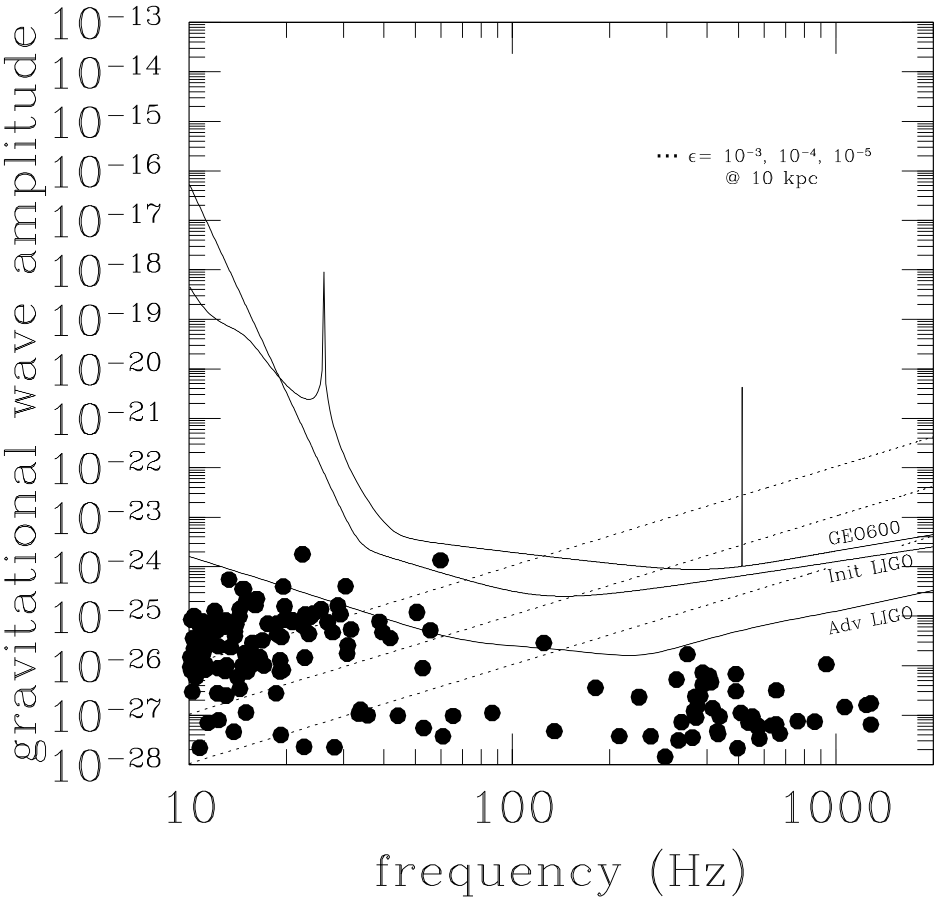

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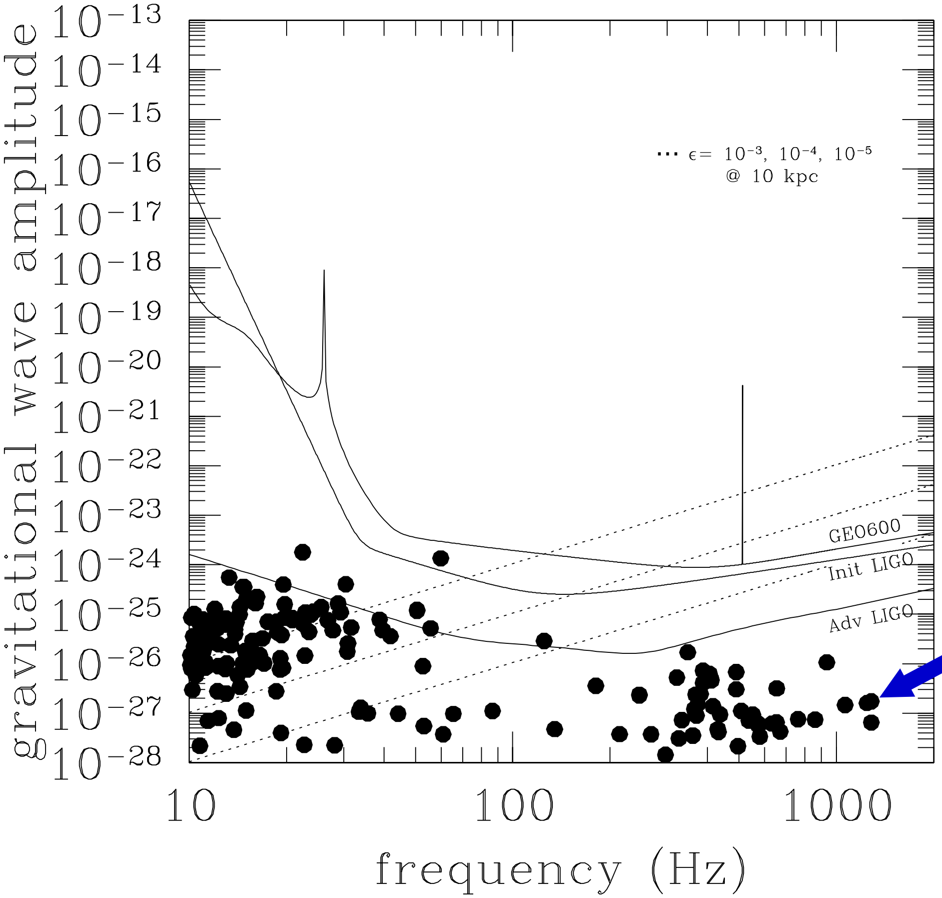

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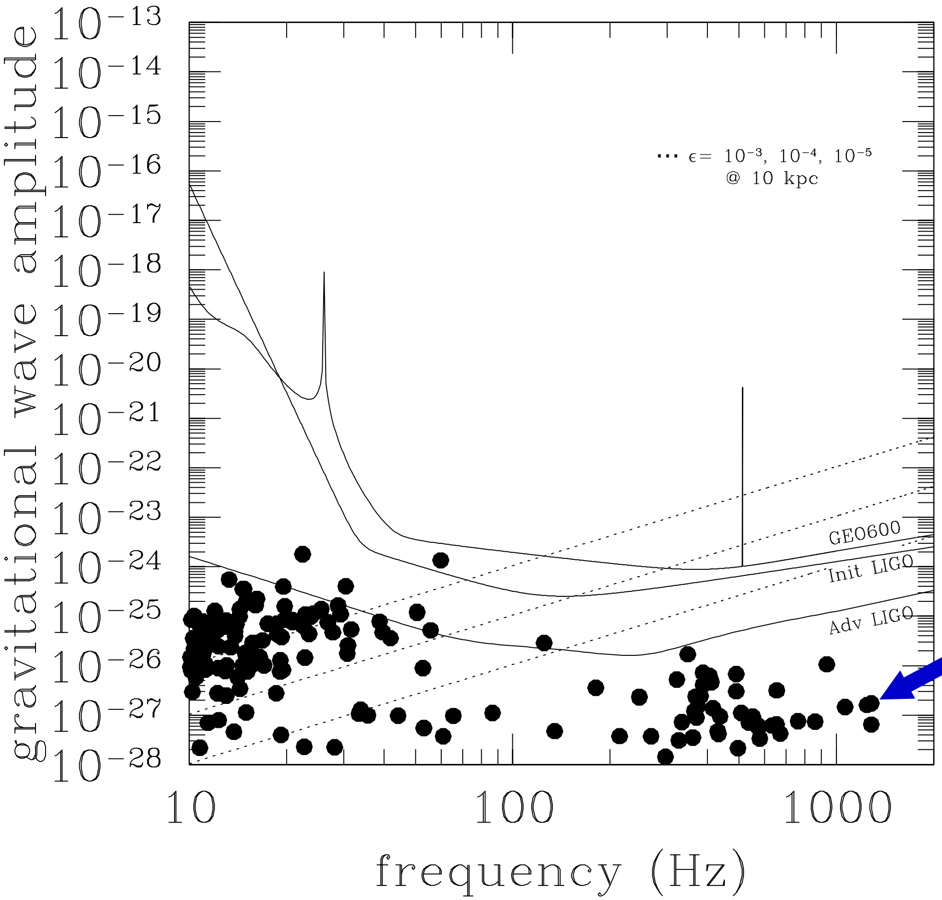

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$\Rightarrow$ No detection expected!

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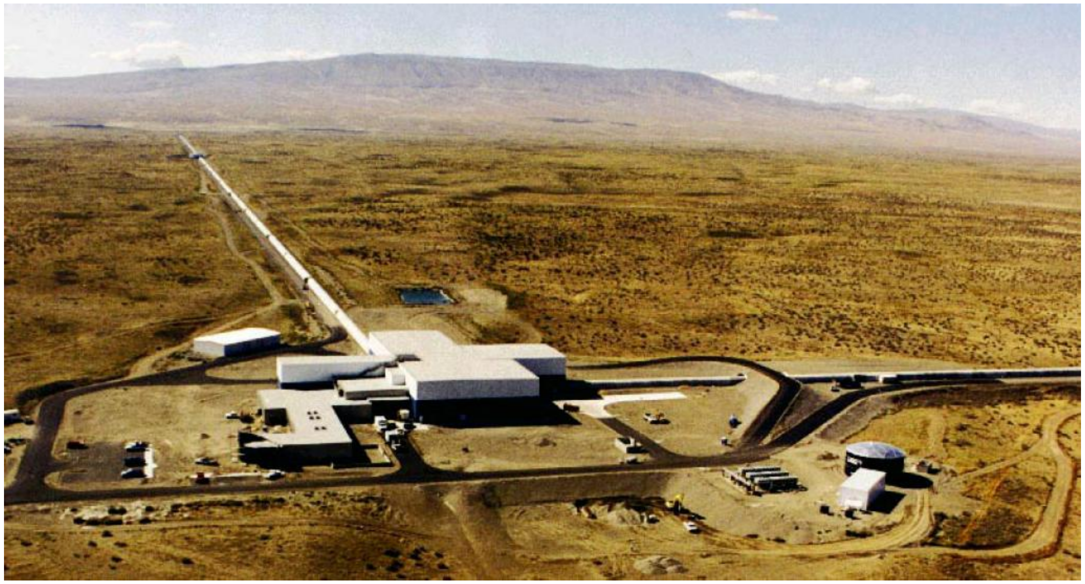

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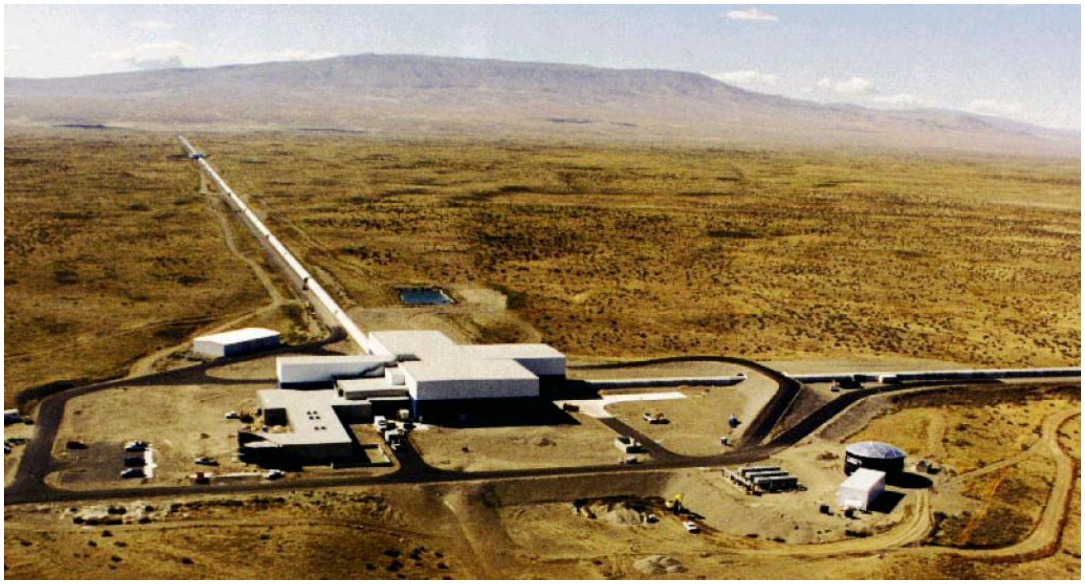

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    duty cycle 98.5%! total locked time: 396 hours

LIGO and GEO during S1

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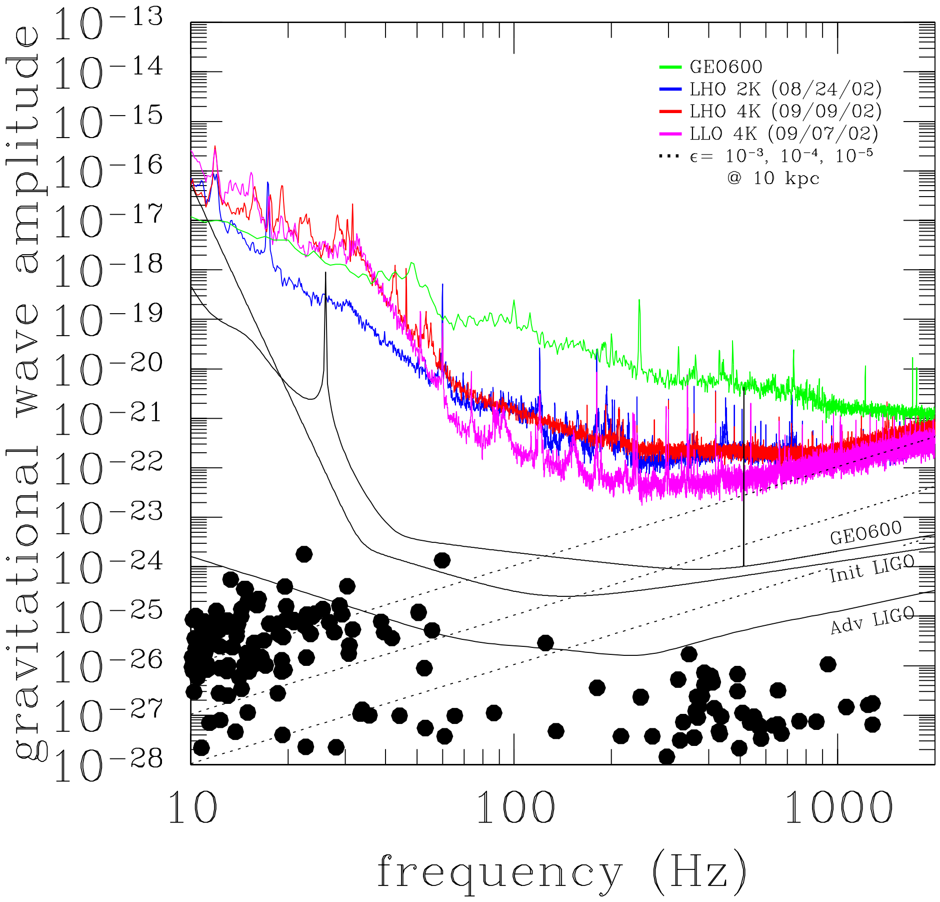

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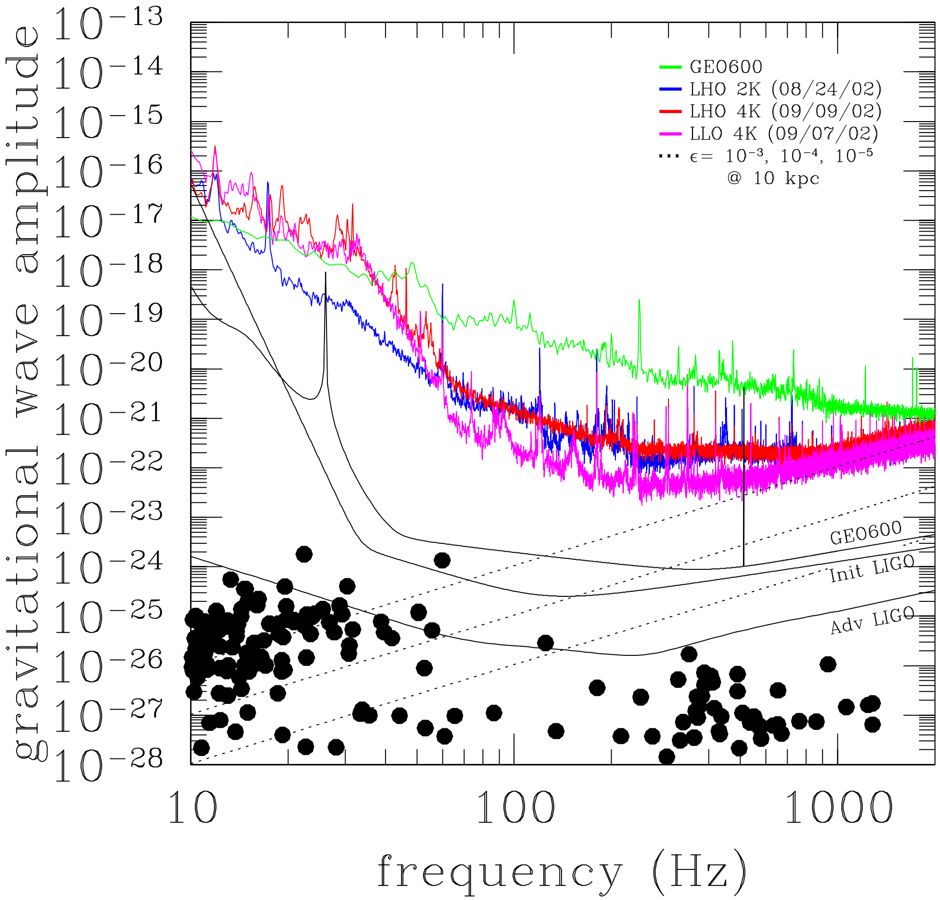

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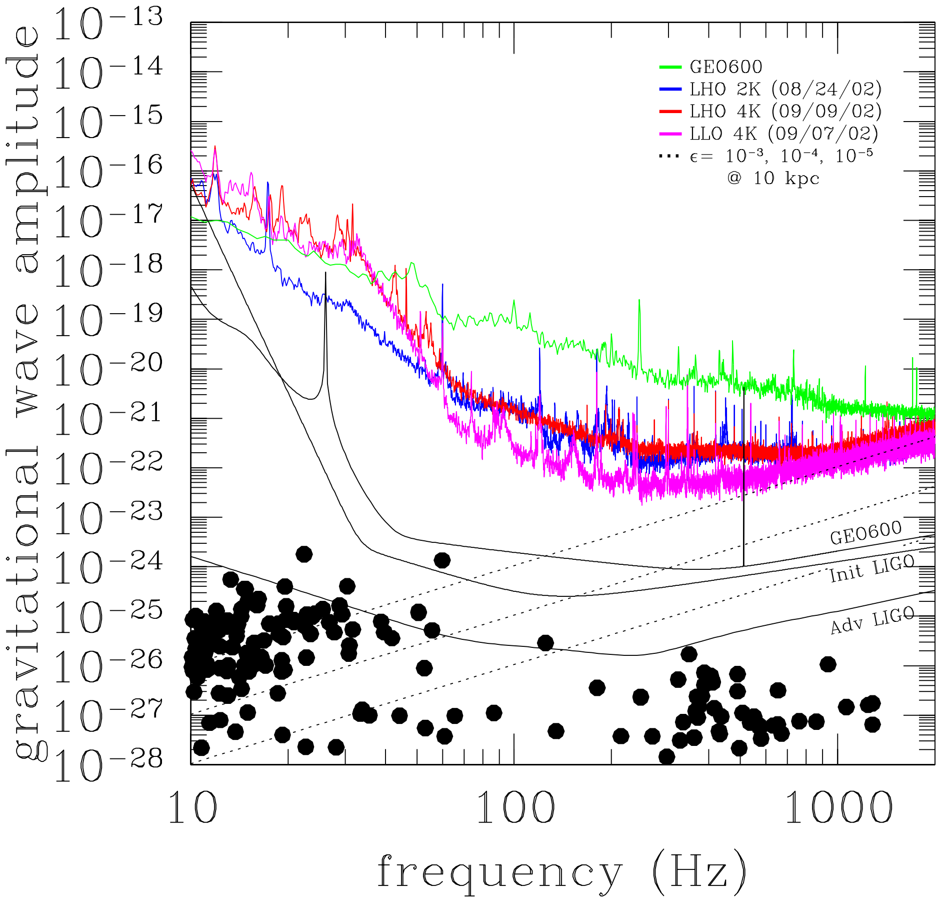

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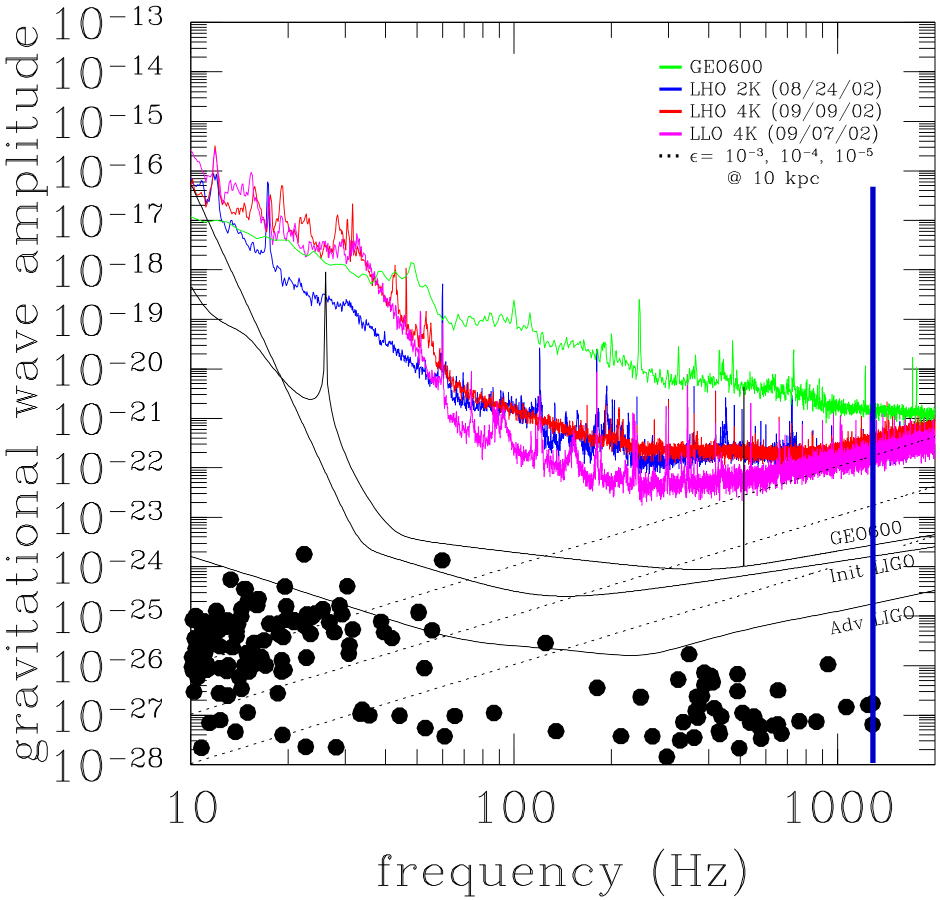

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⇒ Comparable sensitivity at frequency of interest!

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- 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.

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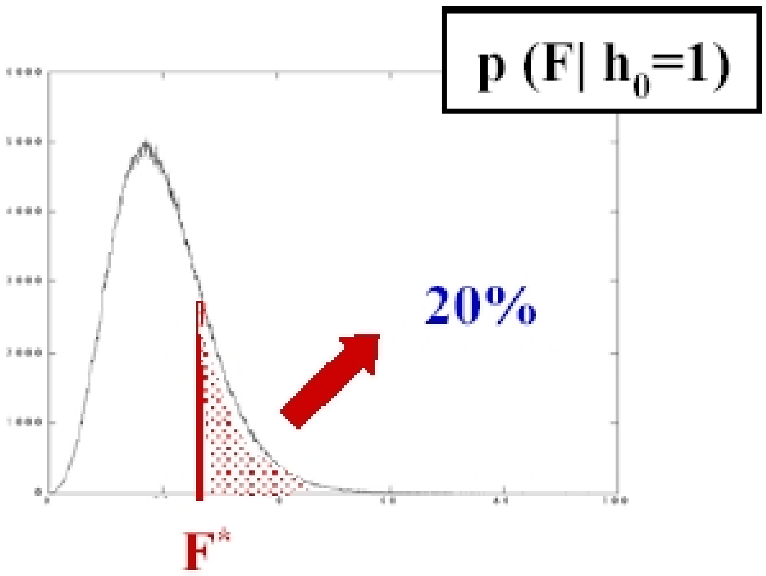

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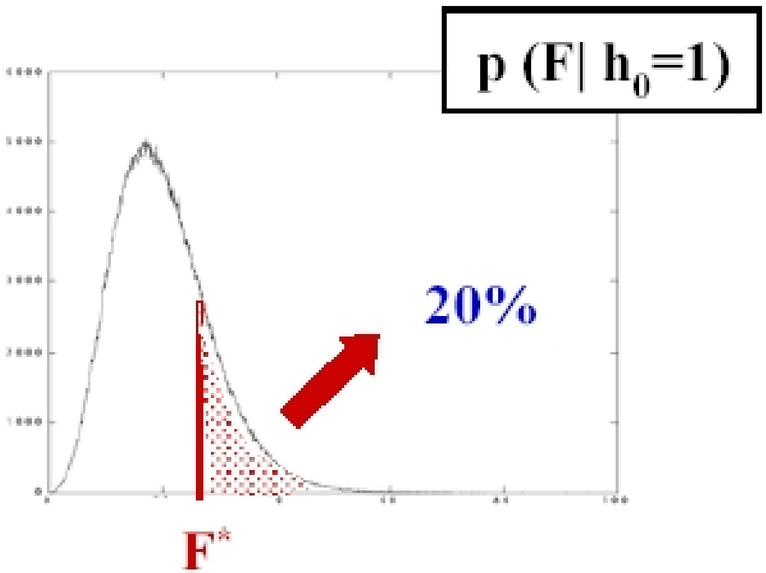

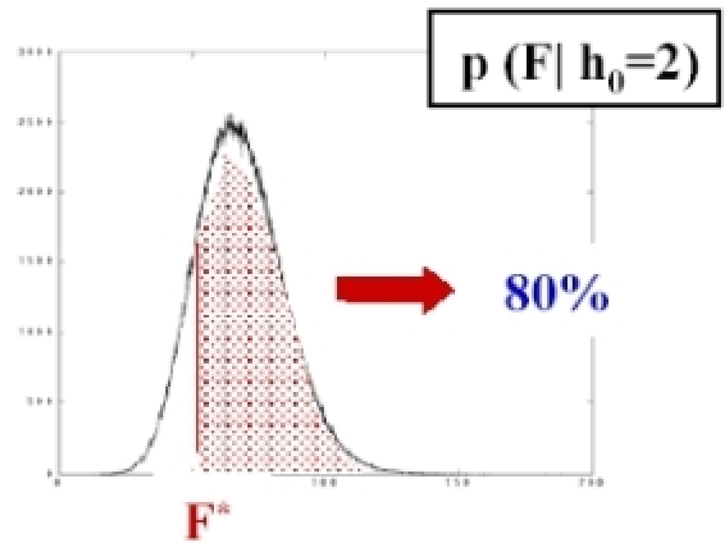

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- Extra detail: When computing $p(\mathcal{F}|h_0)$ via Monte-Carlo, inject signals with *worst possible* orientation ψ, ι. This gives a *conservative* upper limit.

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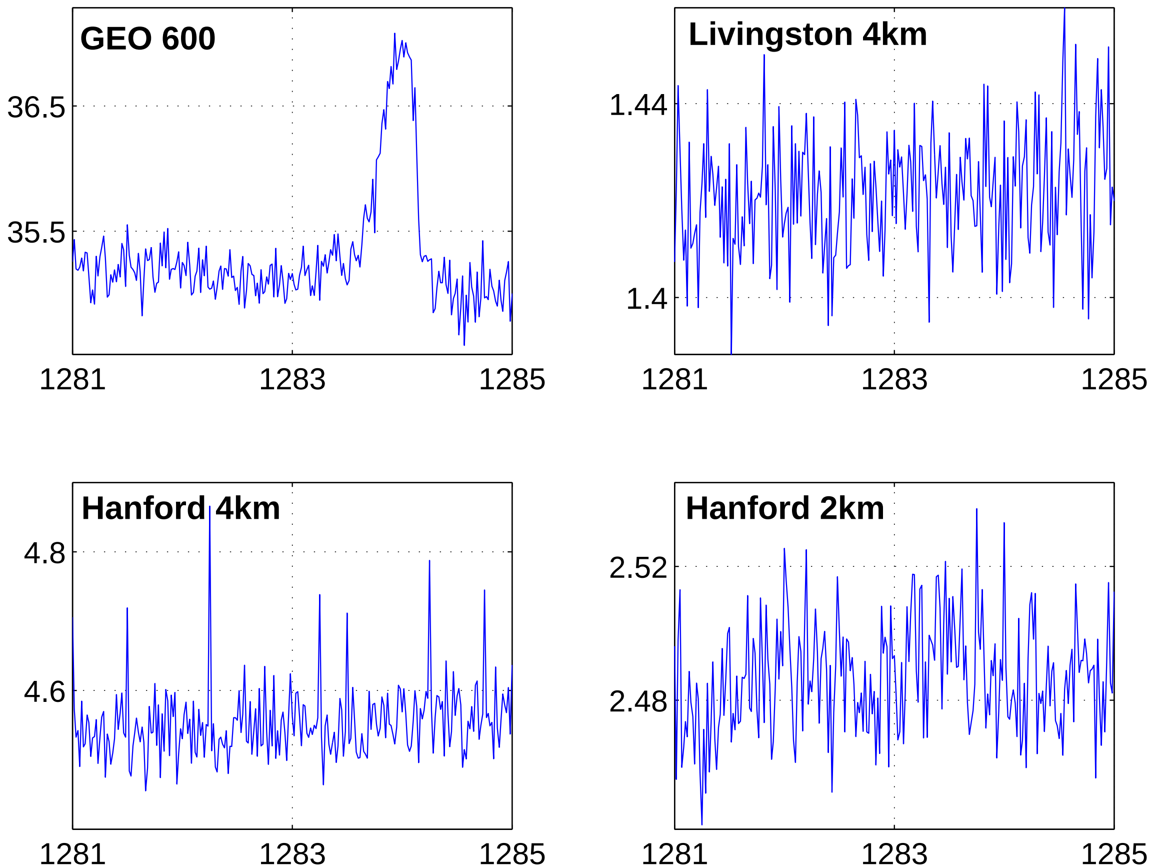
The raw data: $\sqrt{S_h}$ $(10^{-20}\mathrm{Hz}^{-1/2})$ versus frequency in Hz.



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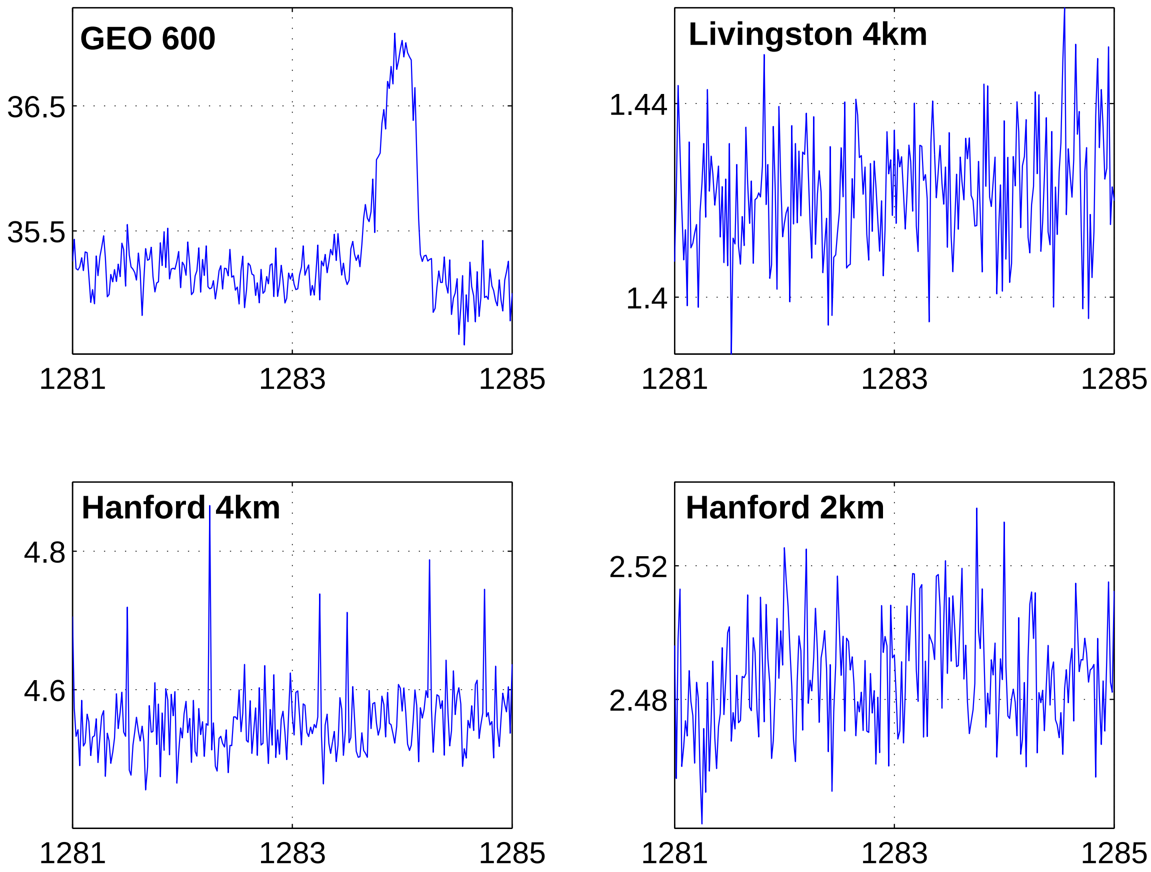

- Note spectral disturbance in GEO600

Frequency-domain analysis

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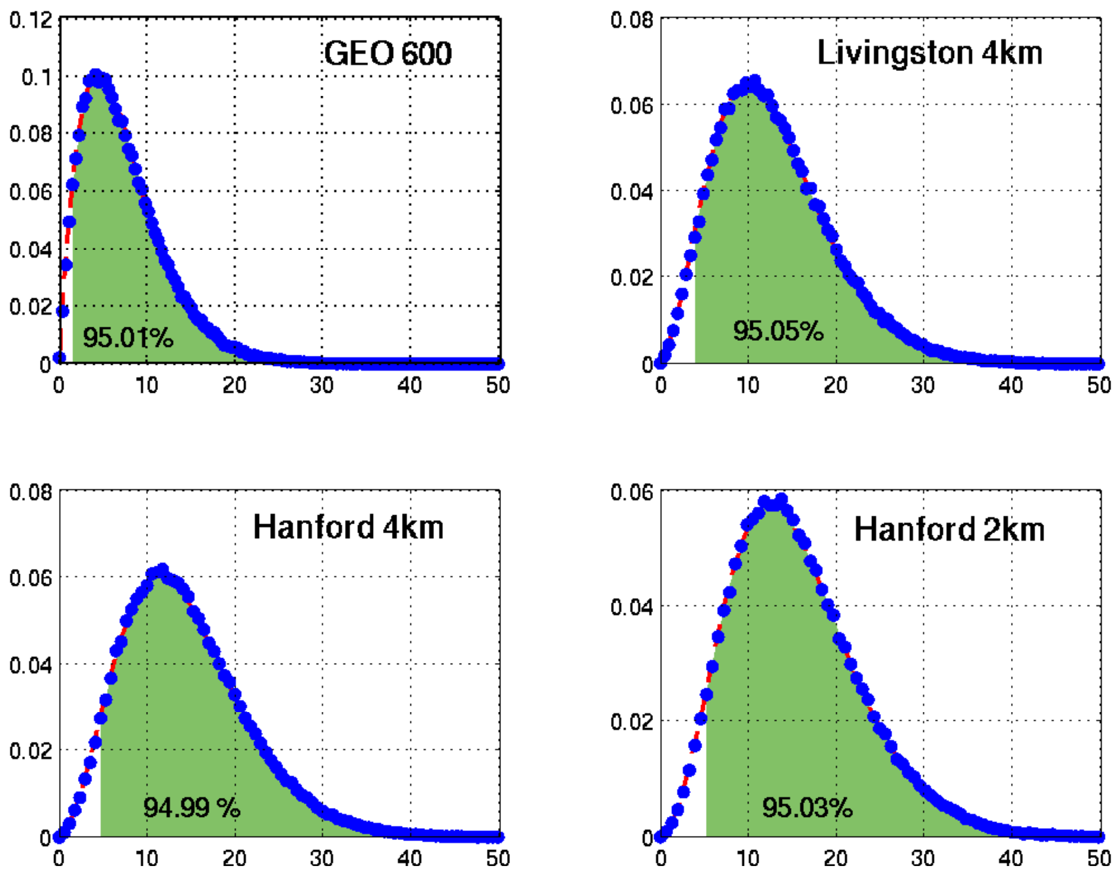

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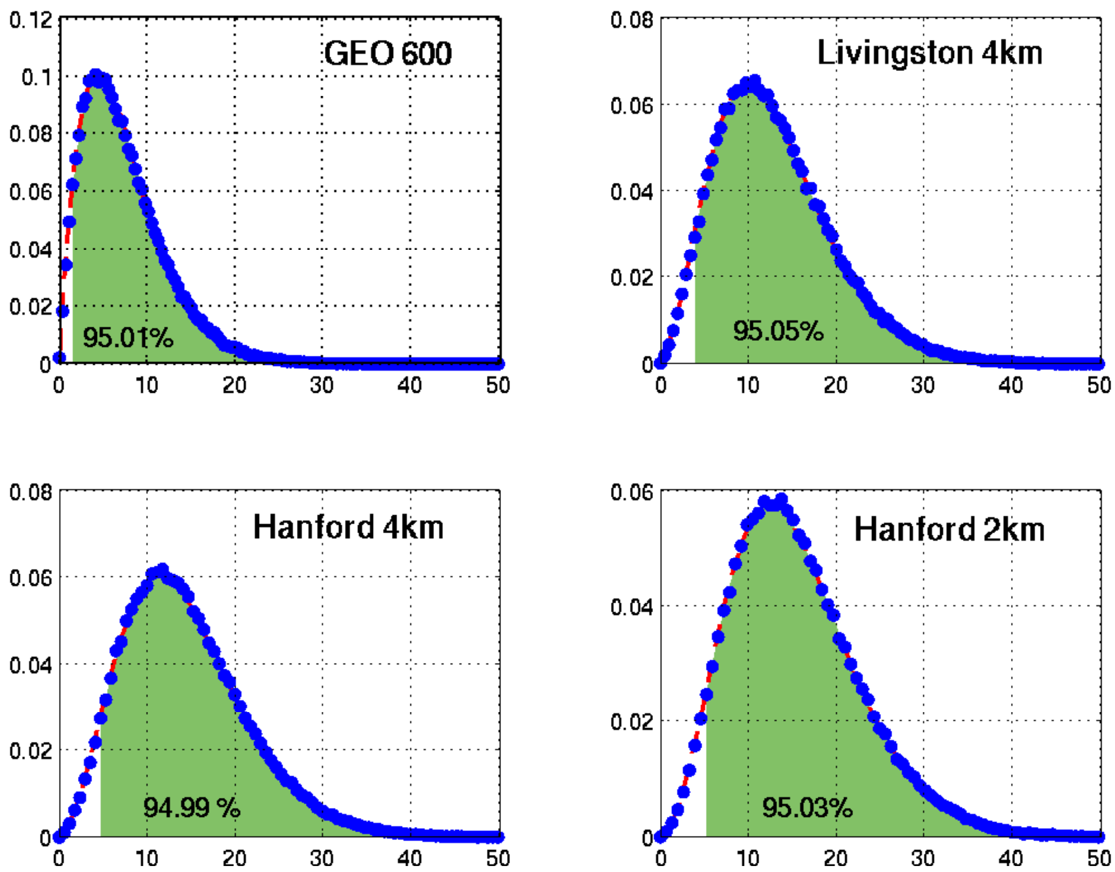

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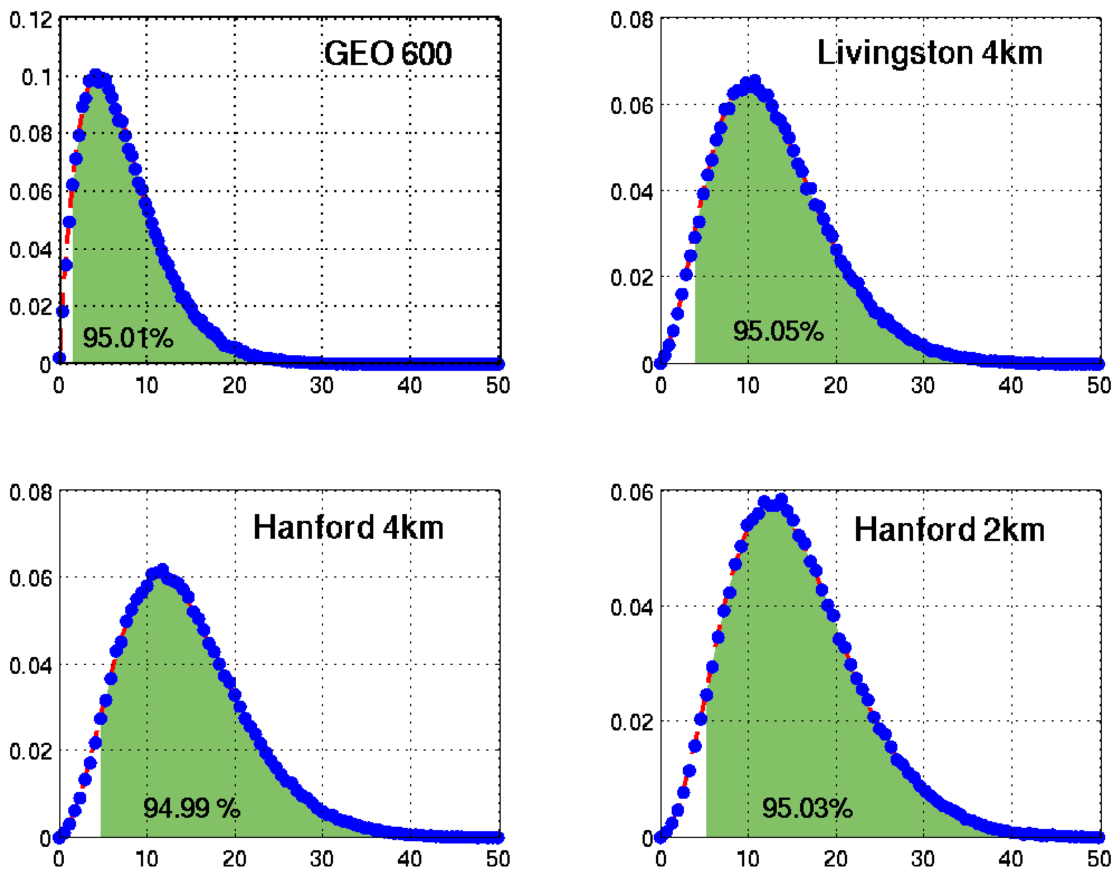

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- 95% upper limits:

	$2\mathcal{F}^*$	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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- 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

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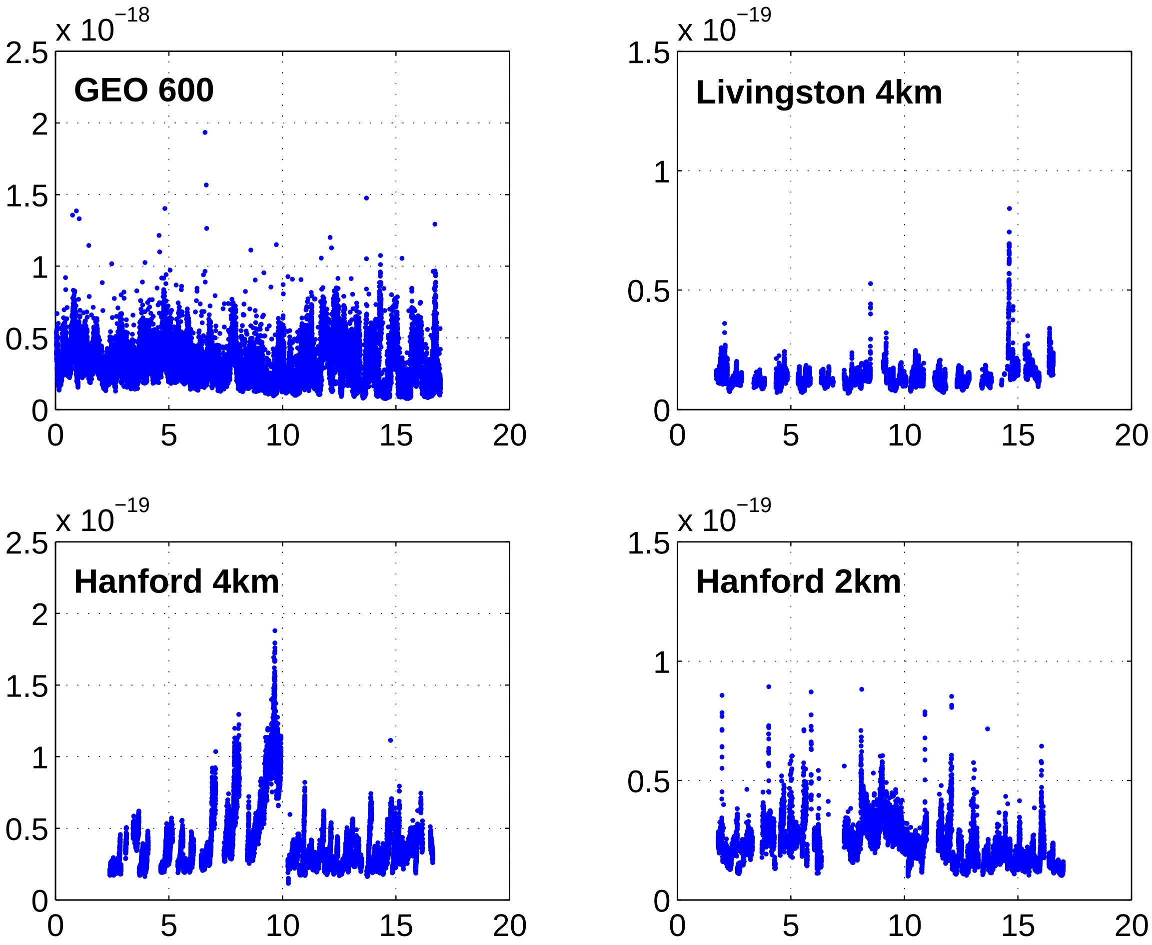
- 95% confidence upper limit h_{95} defined by:

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

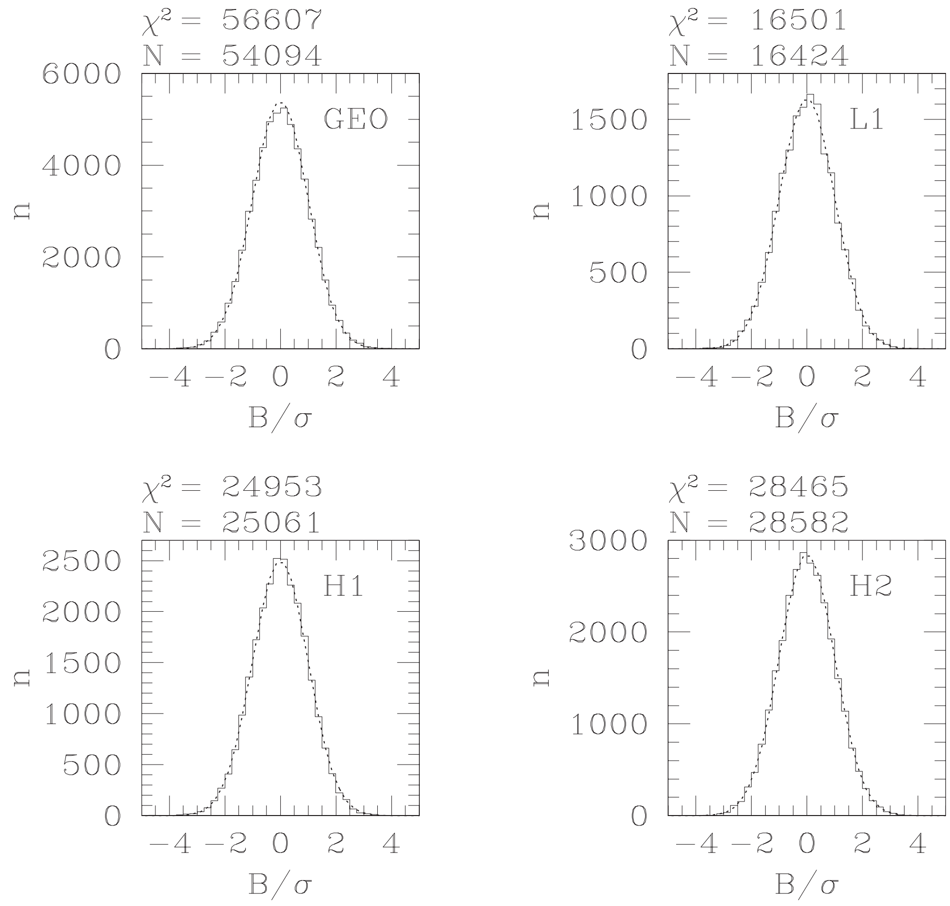
Time-domain analysis

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



Time-domain analysis

Gaussianity of resampled data B_k:



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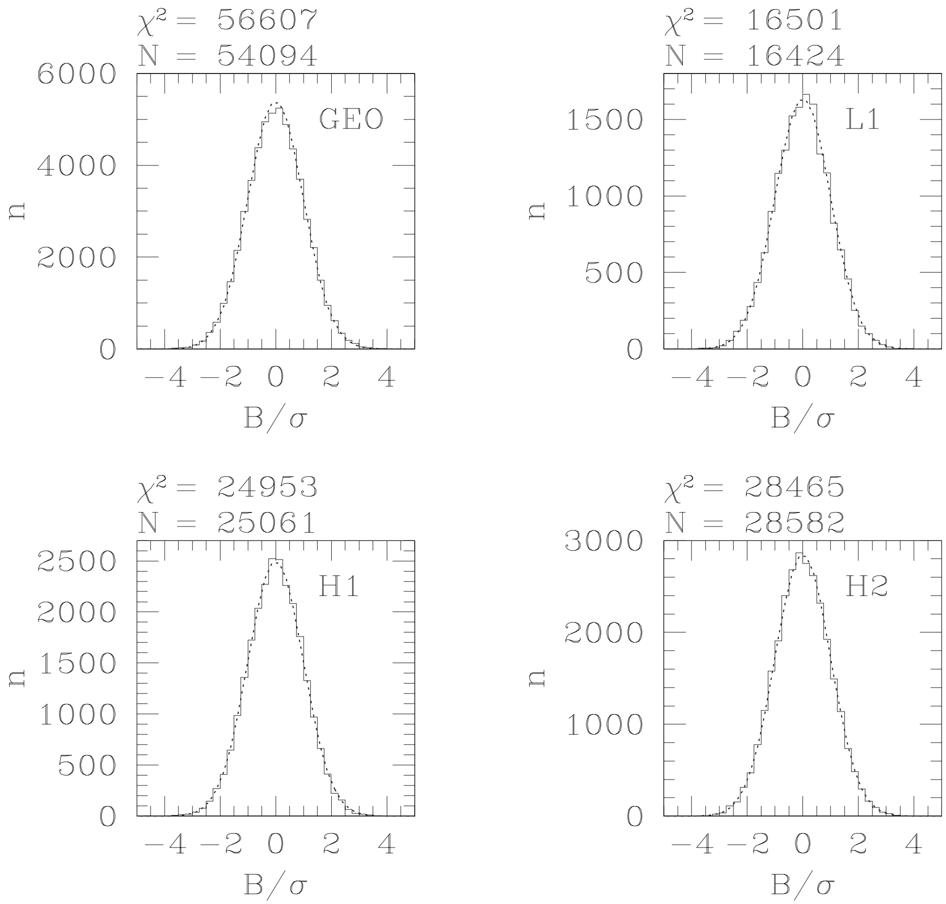

- GEO is not in fact consistent with Gaussian distribution.

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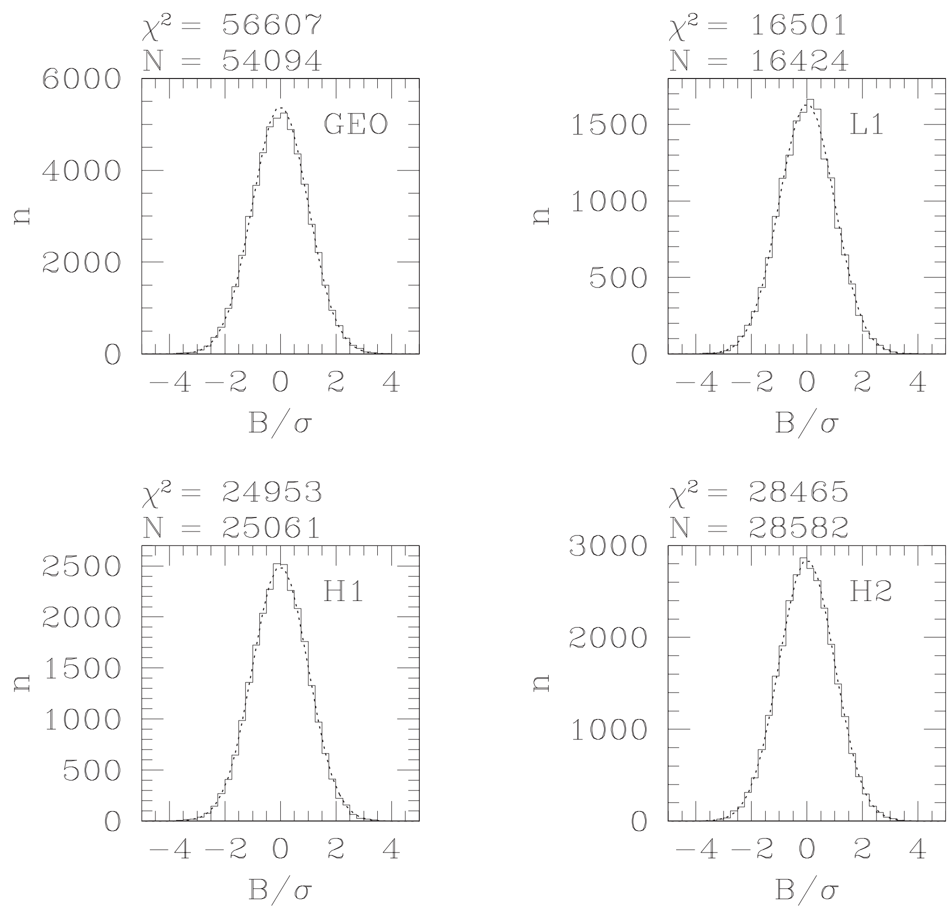

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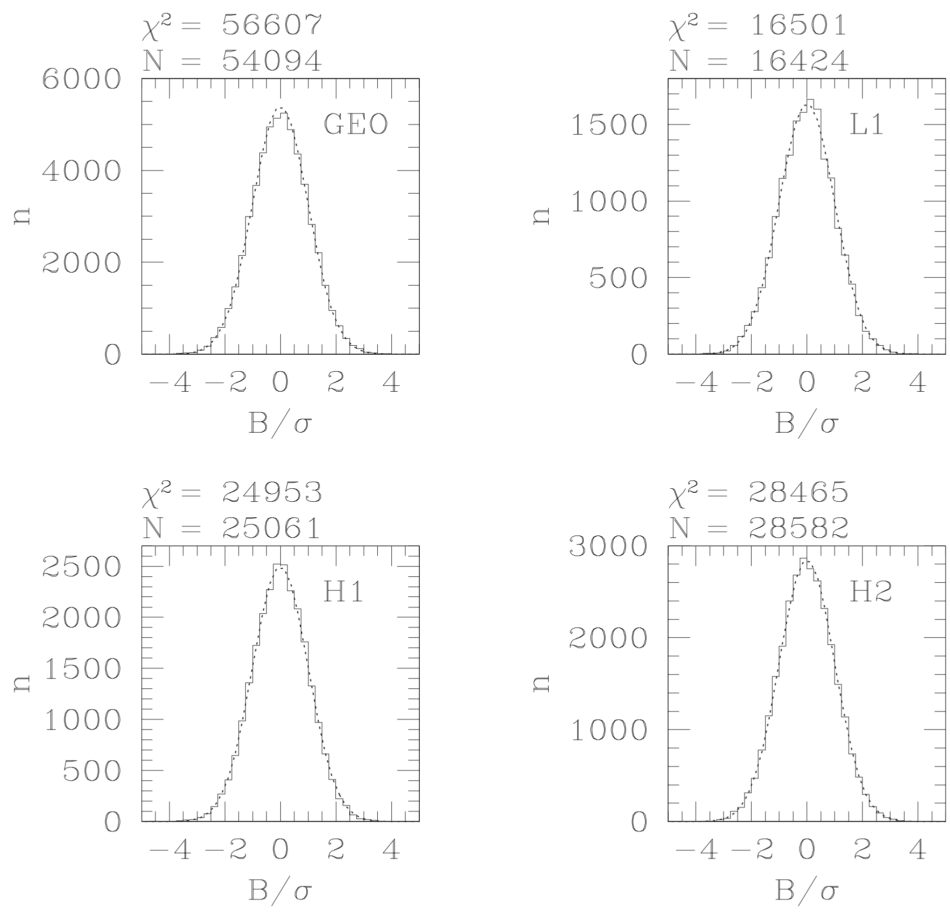

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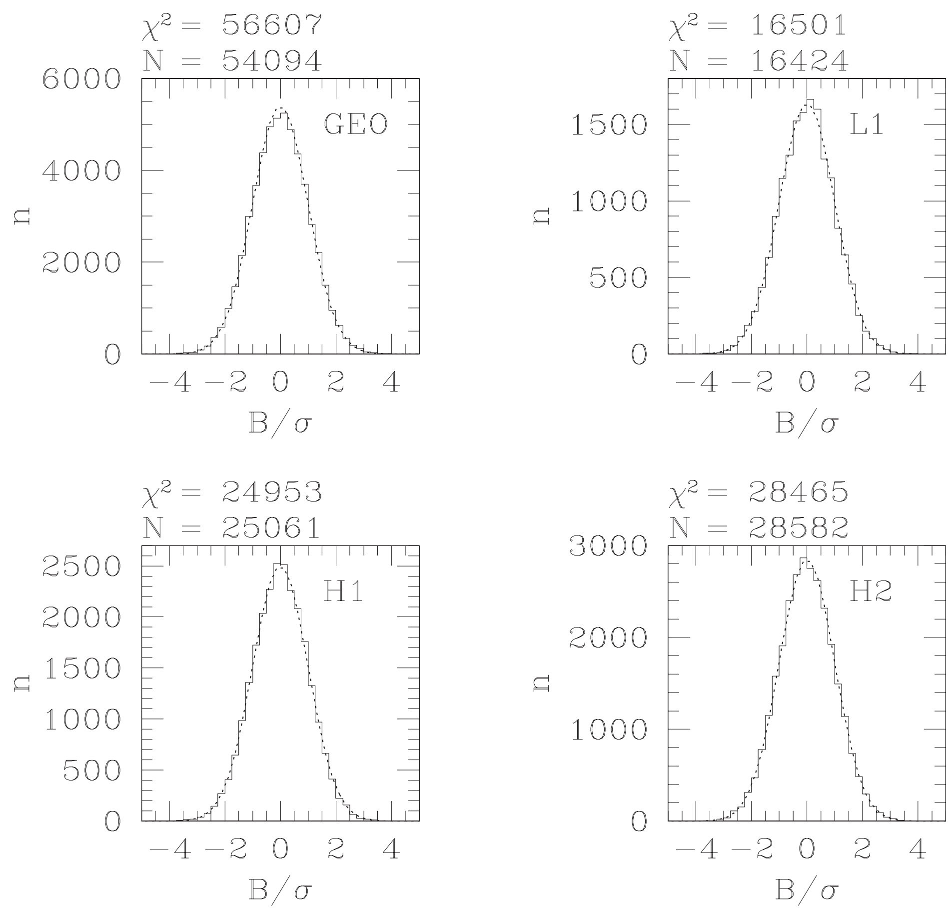

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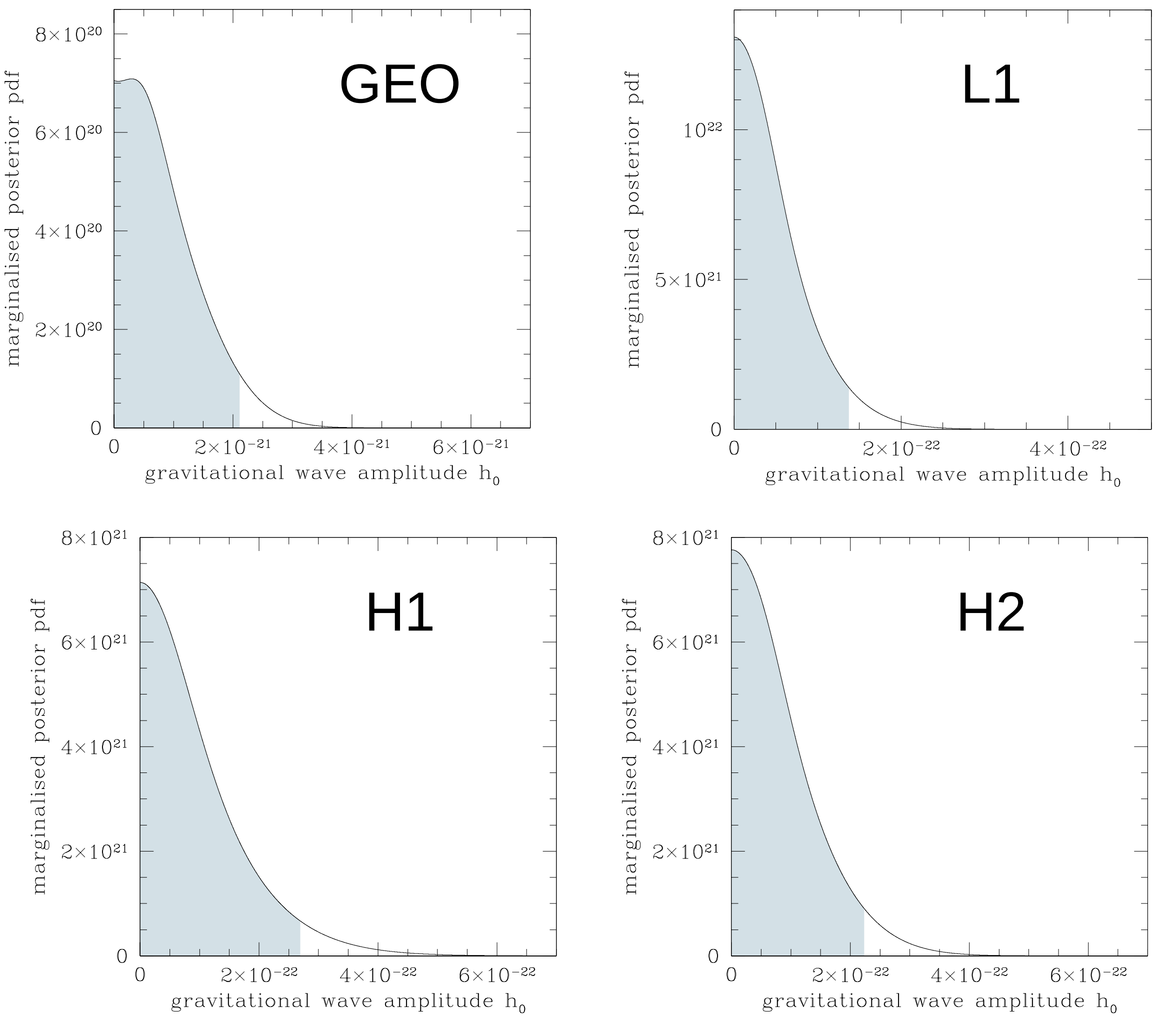
- LIGO detectors are consistent with Gaussian distribution.

Time-domain analysis

Posterior probability distributions:



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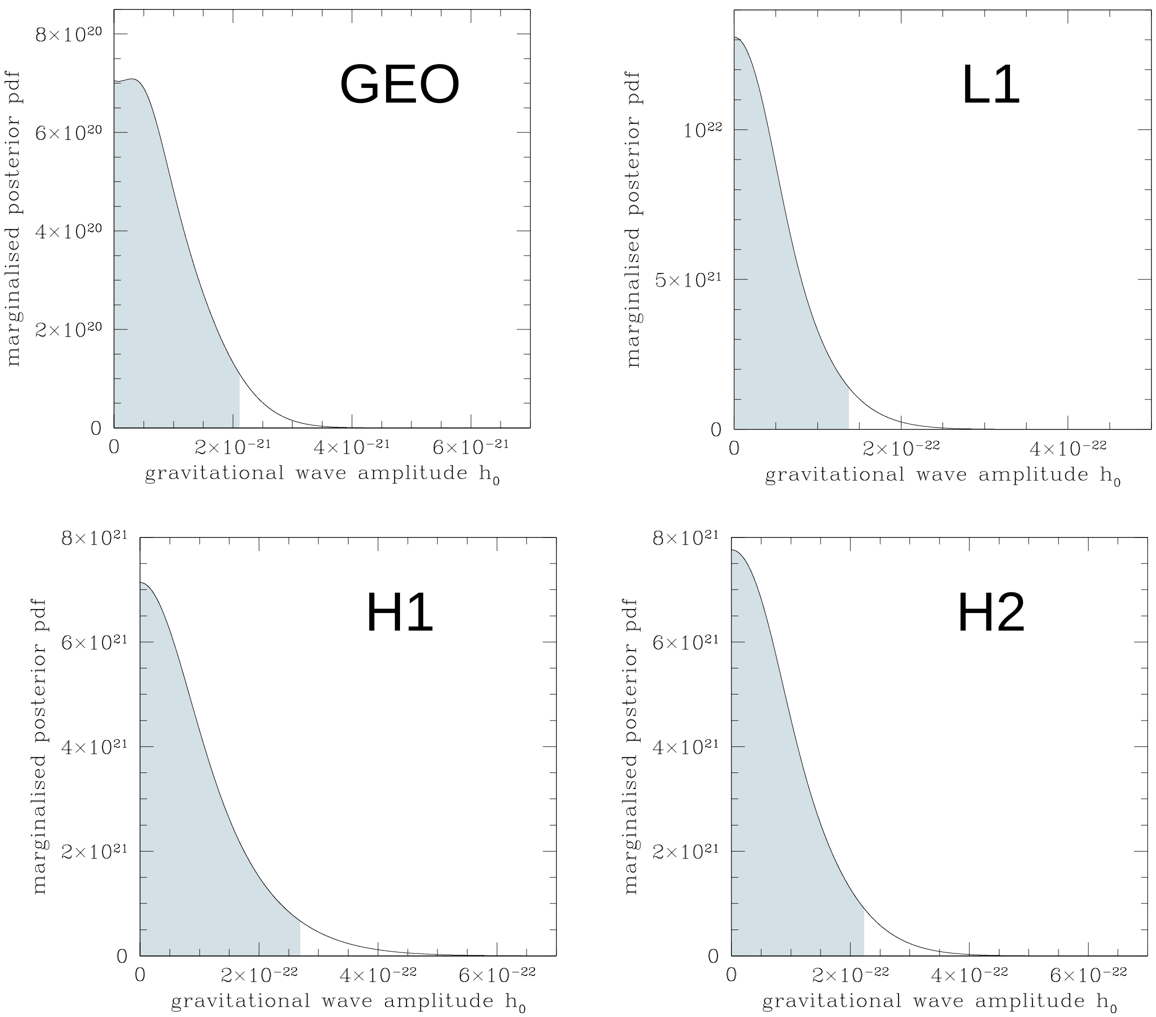

- 95% upper limits:

GEO	2.1×10^{-21}
L1	1.4×10^{-22}
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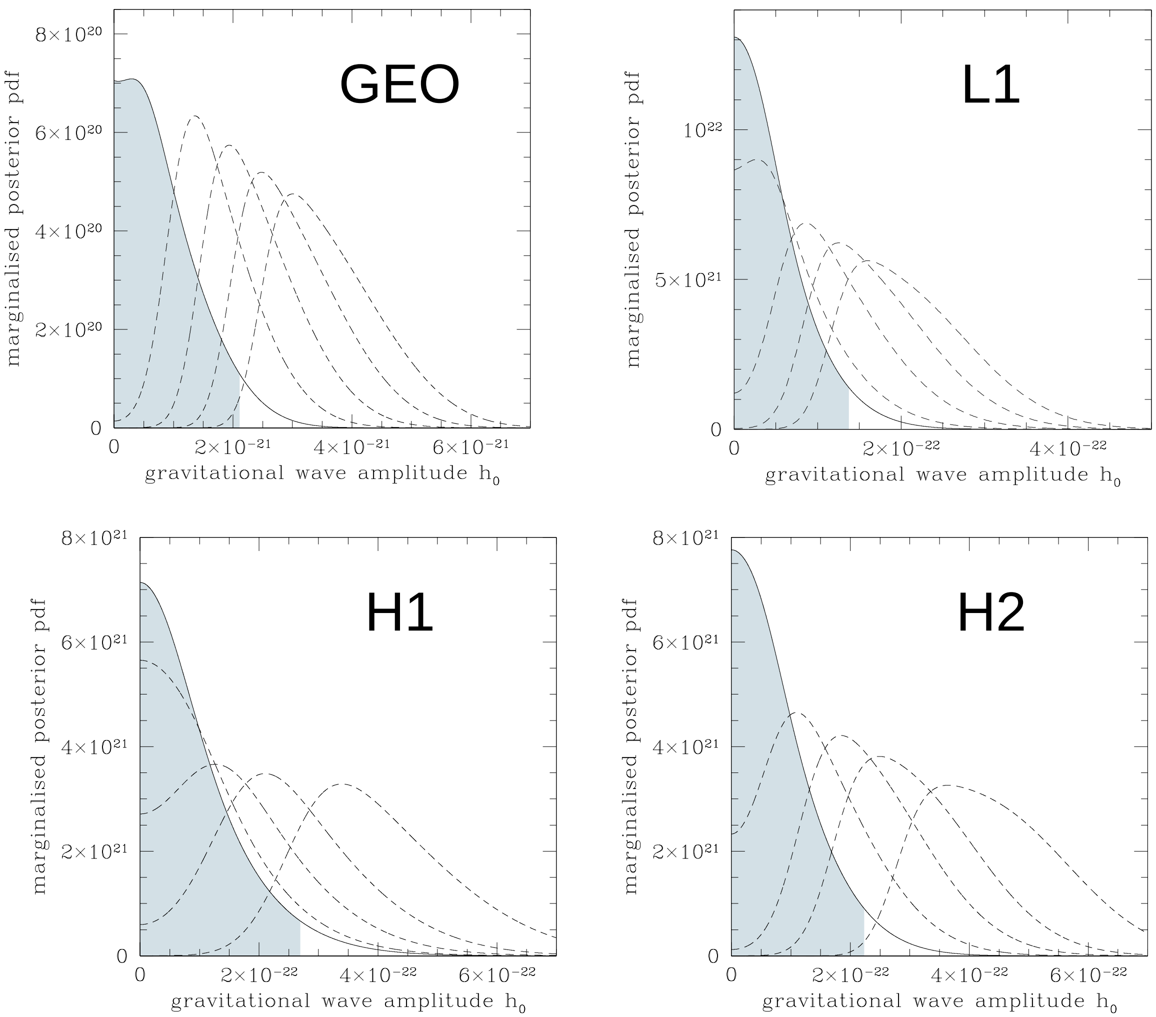

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- Can inject simulated signal to see how PDF changes.

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- Can also compute joint probability distribution:

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

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- Marginalizing gives:

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

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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

Comparison of results

	Frequentist UL h^*_{95}	Bayesian UL h_{95}
GEO	1.9×10^{-21}	2.1×10^{-21}
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- PSR J1939+2134 is at 3.6 kpc

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

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- Discrepancy largely due to *worst-case* (conservative) orientation chosen for frequentist approach.

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- Indirect observational UL is 2×10^{-27} based on spindown rate.

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Future searches

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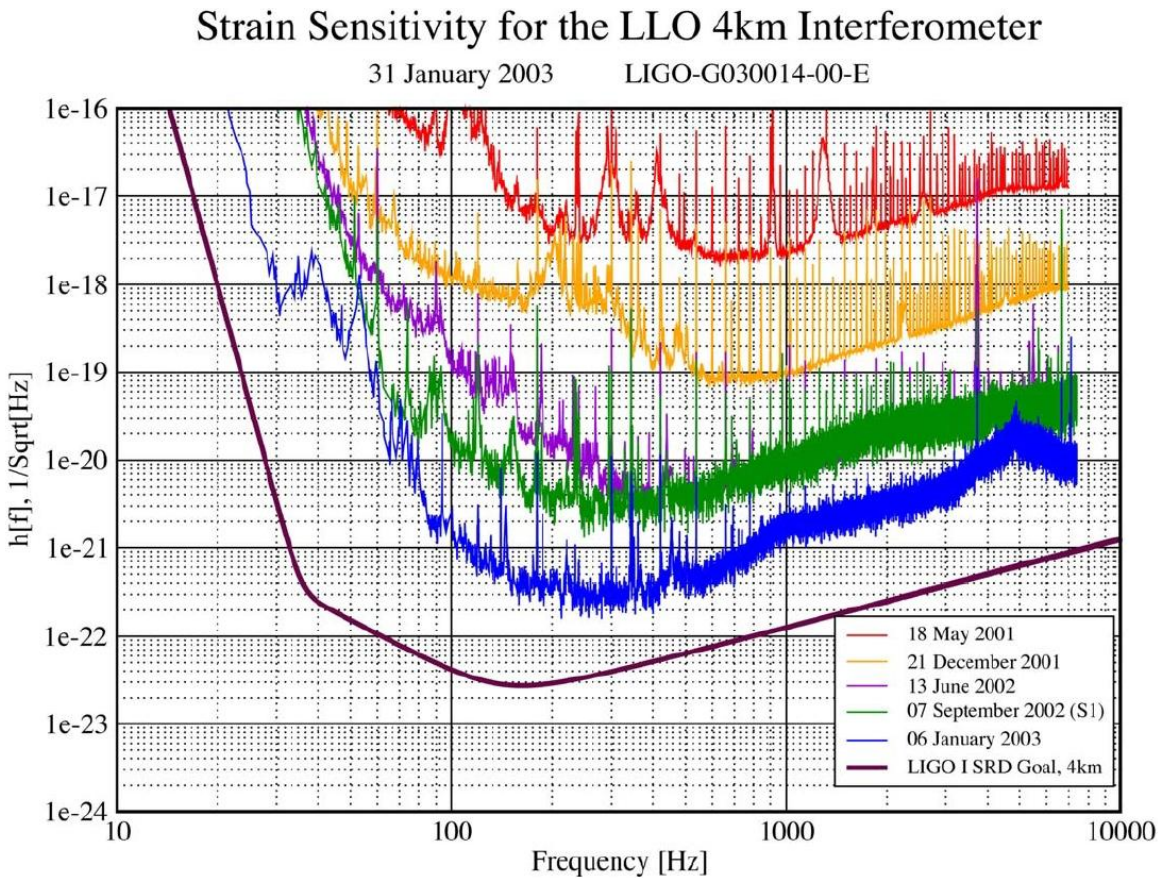

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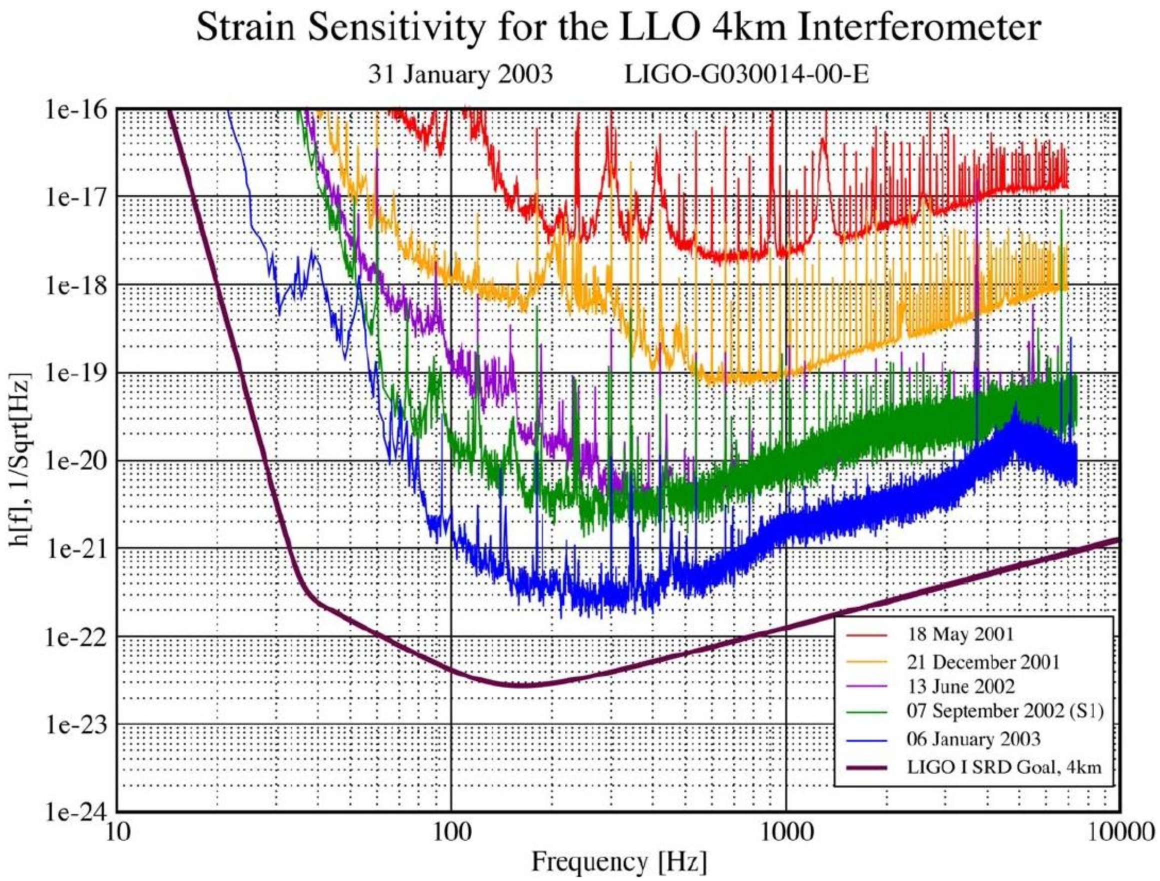

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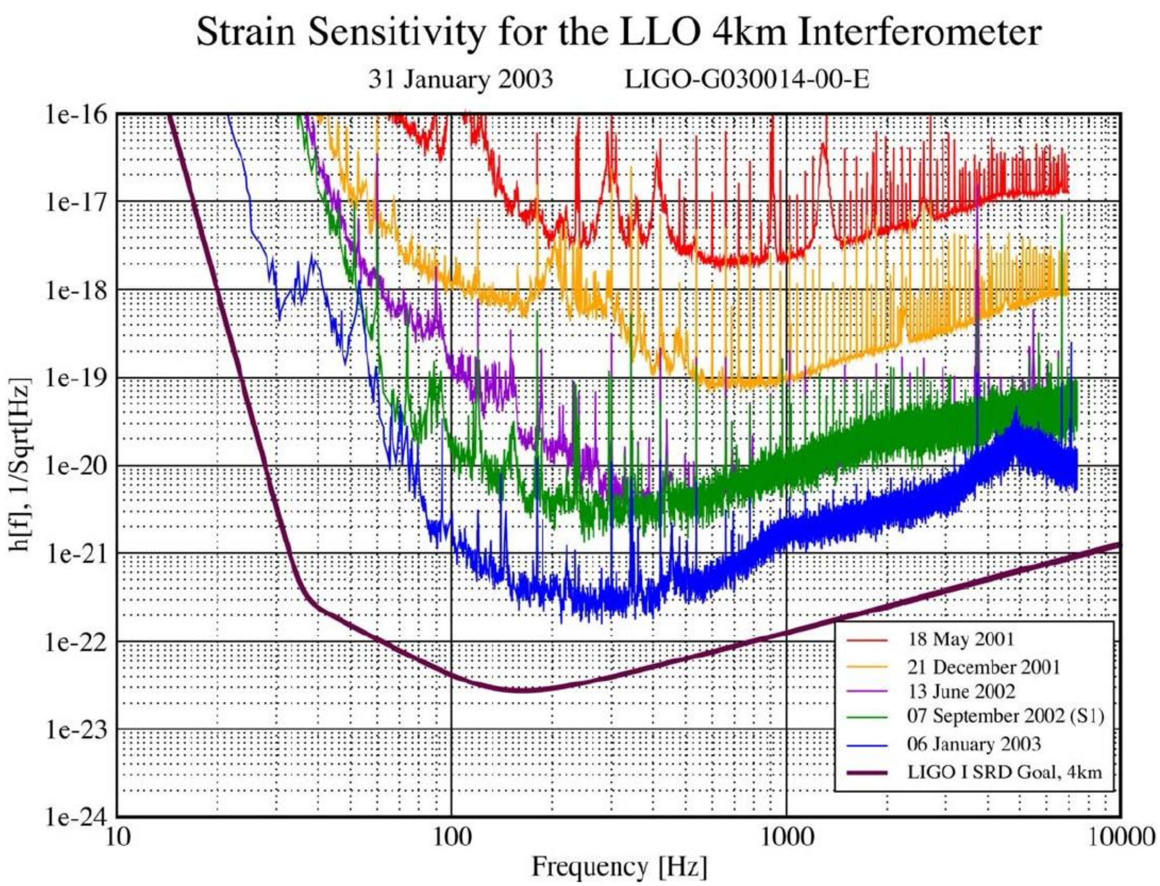

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- We want to start in on new data as soon as possible.

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- As instruments continue to improve, we may make actual *detections* of gravitational emissions!