Gravitational radiation from known radio pulsars using LIGO data

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Overview

- Four Science runs since 2002
  - **S1:** (8/23/02-9/9/02) targeted search for GW from J1939+2134 (B. Abbott *et al,* **PRD69:**082004,2004)
  - **S2:** (2/14/03-4/14/03) Search of 28 known isolated radio pulsars (**gr-qc/0410007** accepted by **PRL)**
  - **S3:** (10/31/03-1/9/04) Search is in progress on 110 pulsars with rotational frequencies>25 Hz.
  - **S4:** (2/22/05-3/23/05) Just finished taking data!
- Analysis for S1, S3 and S4 done, or in progress, in conjunction with **GEO**.
- Use of frequency domain and **time domain** techniques.

S2 Time Domain Analysis

- Targeted search of 28 pulsars with $f_{rot} > 25$ Hz.
- Expected GW signal is at $2f_{rot}$.
- 18 were timed before and after S2 by radio observations. 10 others used timing data from before S2.
- Includes **Crab**, and fastest known millisecond pulsar **J1939+2134** (f_{rot}=641.93 Hz).
- Signal is frequency modulated by Doppler shifts and amplitude modulated by the detector antenna response.

Source Model

- Expected signal has the form:

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

Source Model

- Expected signal has the form:

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

Strain antenna patterns of the detector to different polarizations. Bounded between -1 and 1.

Source Model

- Expected signal has the form:

$$h(t) = F_{+}(t;\psi)\boxed{h_0}\left(\frac{1+\cos^2\iota}{2}\right)\cos\Phi(t) - F_{\times}(t;\psi)h_0\cos\iota\sin\Phi(t)$$

Amplitude of the GW Signal

Source Model

- Expected signal has the form:

$$h(t) = F_+(t;\boxed{\psi})h_0\left(\frac{1+\cos^2\iota}{2}\right)\cos\Phi(t) - F_\times(t;\psi)h_0\cos\iota\sin\Phi(t)$$

Polarization angle of signal.

Source Model

- Expected signal has the form:

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

Angle of inclination of source
with respect to line of sight.

Source Model

- Expected signal has the form:

$$h\left(\mathrm{t}\right) = \mathrm{F}_{+}\left(\mathrm{t};\psi\right)\mathrm{h}_0\left(\frac{1+\cos^2\iota}{2}\right)\cos\Phi(t) - \mathrm{F}_{\times}\left(\mathrm{t};\psi\right)\mathrm{h}_0\cos\iota\sin\Phi(t)$$

Phase. Initial phase ϕ_0 is unknown

Source Model

- Expected signal has the form:

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

- Heterodyne at a frequency close to the expected frequency of the signal i.e. multiply by $e^{-i\phi(t)}$
- This reduces the potential GW signal h(t) to a slowly varying complex signal y(t), which reflects the beam pattern of the interferometer.

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

- **a** is a vector of the parameters h_0, ϕ_0, ψ, ι

Bayesian Analysis

- Heterodyned, filtered, averaged data for each minute, called B_k.
- These B_k's will be compared to our model of the expected signal.

model

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

processed data

noise estimate

$$\underbrace{p(\vec{a}\,|\{B_k\})}_{\text{posterior}} \propto \underbrace{p(\vec{a})}_{\text{prior}}\;\underbrace{p(\{B_k\}\,|\vec{a})}_{\text{likelihood}}$$

Bayesian Analysis

- Used a uniform prior for $\cos\iota$, ϕ_0, ψ and h_0 (>0).
- Uniform prior for h_0 chosen for simplicity, ease of comparison to other results.
- Marginalize with a Jeffreys prior over the constant but unknown noise level in each 30 min. segment.
- 95% Upper Limit is a value $\mathbf{h_{95}}$ satisfying:

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

S2 Analysis

- Analysis limited to continuous 30 minute segments of data, which covers 88% of S2 data.
- Observation times:
  - **H1(4 km):** 910 hours
  - **H2(2 km):** 691 hours
  - **L1(4 km):** 342 hours
- Bayesian analysis allows data from different interferometers to be easily combined:

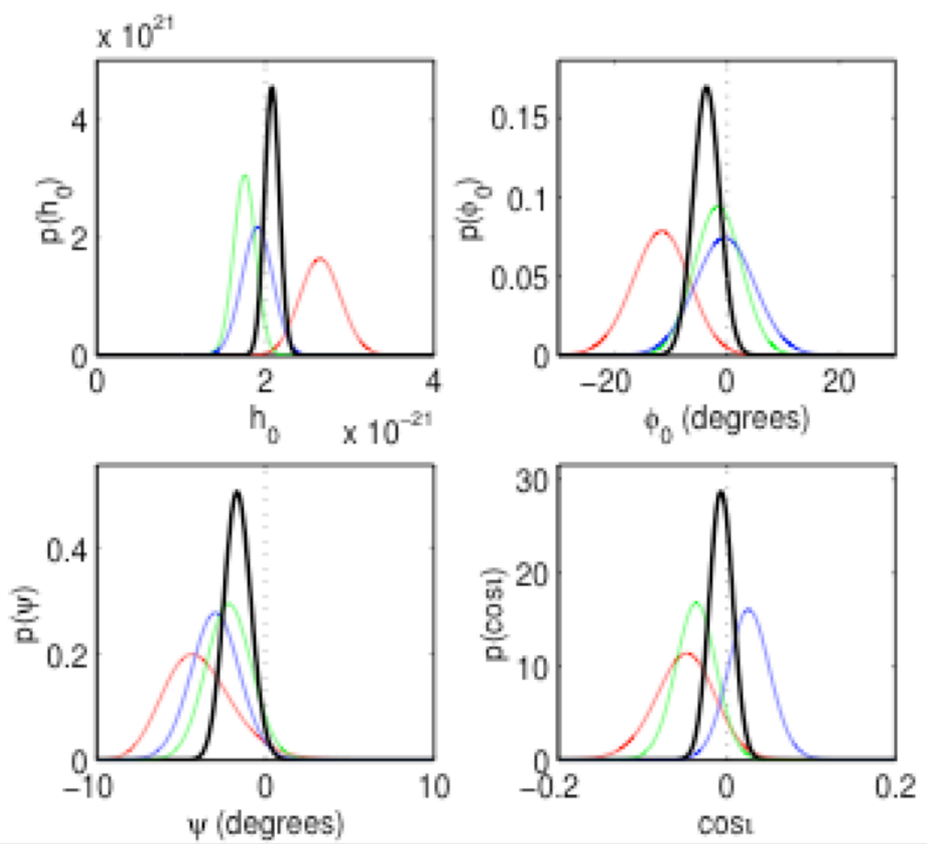
$$p(\mathbf{a}|\text{all data}) \propto p(\mathbf{a}) \times p(H1|\mathbf{a}) \times p(H2|\mathbf{a}) \times p(L1|\mathbf{a})$$

Validation using Injections

- Injected two artificial pulsar signals into all three interferometers for 12 hours.

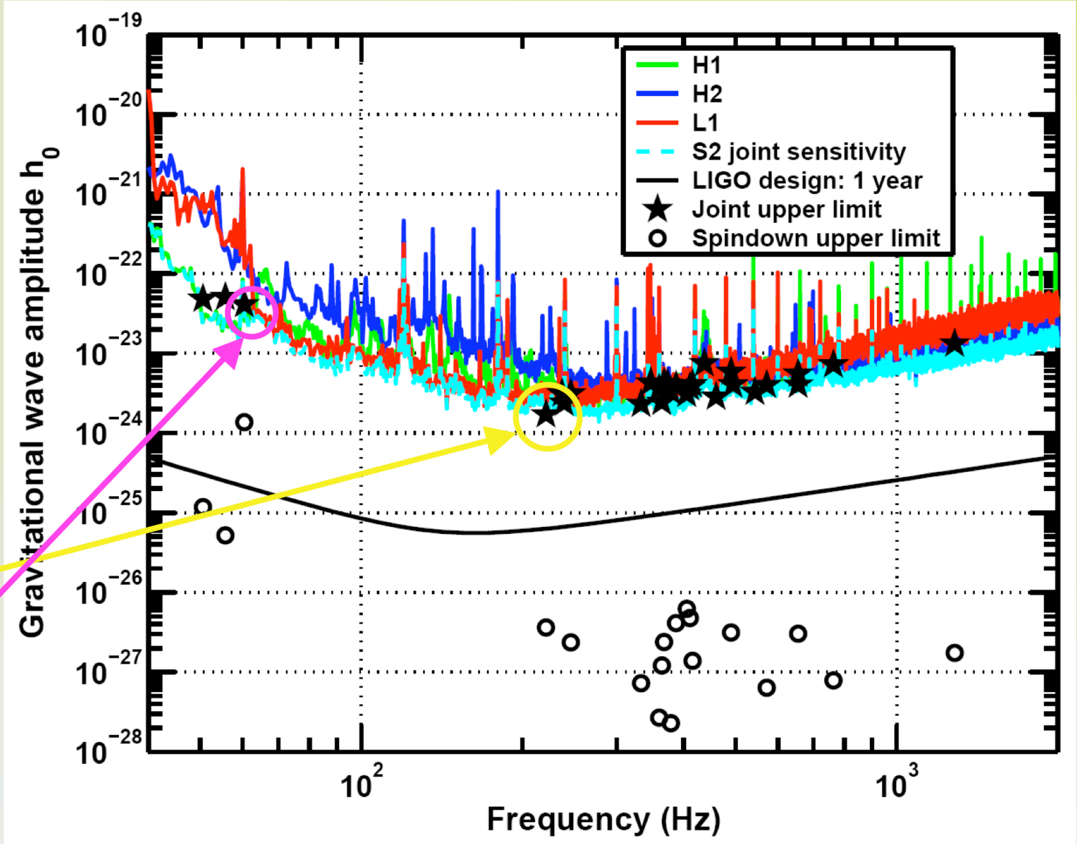
- Validates the analysis pipeline.

- Verifies that the relative phase of the detectors is known (from calibration), so a joint coherent analysis can be performed.



S2 Analysis

- No GW signal.
- First direct upper limit for 26 of 28 sources studied.
- Best UL is for J1910-5959D where 95% CL that $\mathbf{h_0<1.7x10^{-24}}$
- Crab $\mathbf{h_0<4.1x10^{-23}}$



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.

S3 Analysis

- There are 82 more pulsars with $f_{rot} > 25$ Hz, most of them in binary systems.
- Need extra terms in the timing to account for motion in the binary.
- Already have analyzed 80 pulsars, awaiting timing data for the remaining 30.
- Expect some ellipticity upper limits at the level of 10^{-6}
- Significant improvements in limits for 28 pulsars analyzed during S2.

Summary

- Upper Limits for 28 isolated pulsars, including 26 new direct upper limit measurements.
- Best upper limits are a few times 10^{-24}.
- Best constraints on ellipticity < 10^{-5}.
- Time domain analysis complements frequency domain analysis.
- S3 & S4 analyses already in progress, including binary pulsars.