Searching for periodic gravitational waves from neutron stars

Badri Krishnan
(for the LIGO Scientific Collaboration)

Max Planck Institut für Gravitationsphysik
Albert Einstein Institut
Golm, Germany

ECT, Trento
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Outline

Periodic gravitational waves from neutron stars

Possible emission mechanisms:

- Non-axisymmetric crust (mountains)
- Unstable oscillation modes in interior
- Free precession
- ...

Good reason why some neutron stars are emitting GWs:

- Accreting neutron stars seem to spin much slower than expected theoretically (current record is 716 Hz for a MSP) – theoretically they could exceed a kHz
- Accretion might be balanced by emission of GWs

See talk by B.Owen for further discussion on emission mechanisms

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The waveform

In the rest frame of the star, the signal is a slowly varying sinusoid with a quadrupole pattern:

$$
\begin{aligned}
h_+(\tau) &= A_+ \cos\Phi(\tau) \qquad h_\times(\tau) = A_\times \sin\Phi(\tau) \\
A_+ &= h_0 \frac{1+\cos^2\iota}{2} \qquad A_\times = h_0 \cos\iota \\
h_0 &= \frac{16\pi^2 G}{c^4}\frac{I_{zz}\epsilon f_r^2}{d} \rightarrow \text{Model Dependent}
\end{aligned}
$$

- ι: pulsar orientation w.r.t line of sight
- $\epsilon = (I_{xx} - I_{yy})/I_{zz}$: equatorial ellipticity
- f_r: rotation frequency
- d: distance to star

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The waveform phase

The phase is very simple:

$$\Phi(\tau) = \Phi_0 + 2\pi \left[f(\tau - \tau_0) + \frac{1}{2}\dot{f}(\tau - \tau_0)^2 + \ldots \right]$$

Need to correct for the arrival times

- For an isolated pulsar:

$$\tau = t + \frac{\mathbf{r}_D \cdot \mathbf{n}}{c} + \text{relativistic corrections}$$

- For a pulsar in a binary system:

$$\tau = t + \frac{\mathbf{r}_D \cdot \mathbf{n}}{c} + \frac{\mathbf{r}_P \cdot \mathbf{n}}{c} + \text{relativistic corrections}$$

- **n**: sky-position, $\mathbf{r}_D$: Detector in SSB frame, $\mathbf{r}_P$: Pulsar in binary frame

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The waveform parameters

Three types of parameters:

- The amplitude parameters: $(\cos\iota, \Phi_0, \psi, h_0)$
- The Doppler parameters: $(\{f, \dot{f}, \ldots\}, \mathbf{n})$
- The orbital parameters: $(P, T_{asc}, a\sin i)$
  (Two more orbital parameters for eccentric orbits)
- Total number of parameters is then $4 + 3 + s + 3 = 10 + s$
  (+2 more if including eccentricity)
- s is number of spindowns
- Amplitude parameters are maximized over/marginalized
- Doppler and orbital parameters are the search parameters
  $\Longrightarrow 6 + s$ parameters

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The waveform modulation

- The received signal is amplitude modulated due to the detector antenna pattern

$$h(t) = F_{+}(t)h_{+}(t) + F_{\times}(t)h_{\times}(t)$$

- ...and the frequency is Doppler modulated

$$f(t) - \hat{f}(t) = \hat{f}(t)\frac{\mathbf{v}(t) \cdot \mathbf{n}}{c}.$$

- The Doppler modulation allows us to locate the pulsar in the sky but it is also responsible for the computational cost – each sky location has to be demodulated separately.

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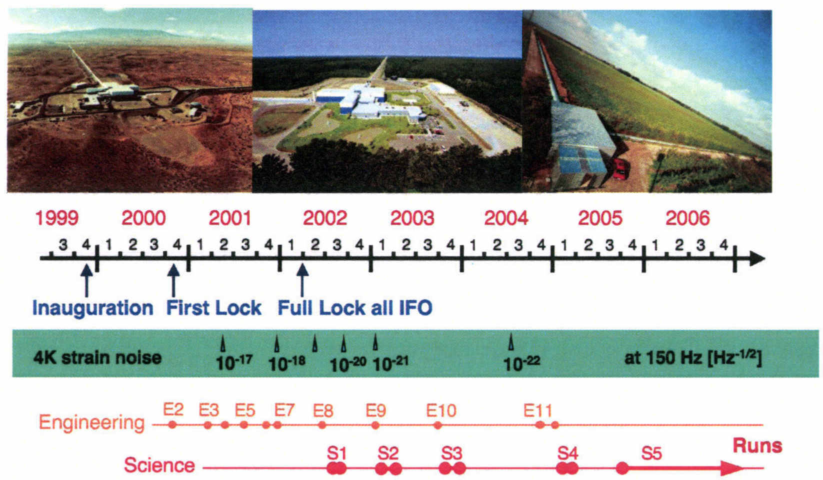
The LSC Detectors



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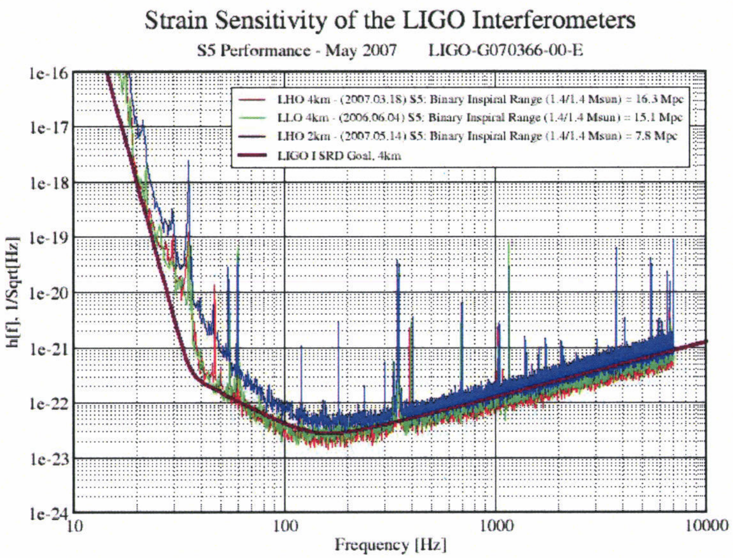
The LSC Detectors



Observational papers for CW searches

- *Upper limits on the strength of periodic gravitational waves from PSR J1939+2134 using S1 data*, PRD (2004)
- *First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the Hough transform*, PRD (2005)
- *Limits on gravitational wave emission from selected pulsars using LIGO data*, PRL (2005)
- *Upper Limits on Gravitational Wave Emission from 78 Radio Pulsars*, PRD (2007)
- *Upper limit map of a background of gravitational waves*, astro-ph/0703234
- *Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run*, To be published in PRD
- *All-sky search for periodic gravitational waves in LIGO S4 data*, arXiv:0708.3818

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Data analysis methods

- Detector output is noise + possible signal
- Hypothesis H_0: no signal present

$$x(t) = n(t)$$

- Hypothesis H: signal is present

$$x(t) = n(t) + h(t)$$

- Optimal statistic for deciding whether signal is present is the likelihood ratio

$$\Lambda = \frac{p(x|H)}{p(x|H_0)}$$

- Need to find maximum of Λ in the parameter space
- Markov chain methods not effective because of large data volume/weak signal $\Longrightarrow$ template based searches required

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Data analysis methods

Since the waveform is known, matched filtering is an effective technique

- Our implementation of the matched filtering is based on the $\mathcal{F}$-statistic
- $\mathcal{F}$ is the maximum of $\ln \Lambda$ over the amplitude parameters $(\cos \iota, \Phi_0, \psi, h_0) \longrightarrow$ This maximization can be done analytically
- Search parameters are then only the Doppler and possibly orbital parameters in the case of binary systems

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Known radio pulsars

- Pulsar parameters known from radio timing observations – Kramer and Lyne at Jodrell bank
- Search for gravitational waves at $f_{GW} = 2 \times f_{rot}$ at single parameter space point corresponding to known sky-position, frequency and spindown
- Details in `gr-qc/0702039`

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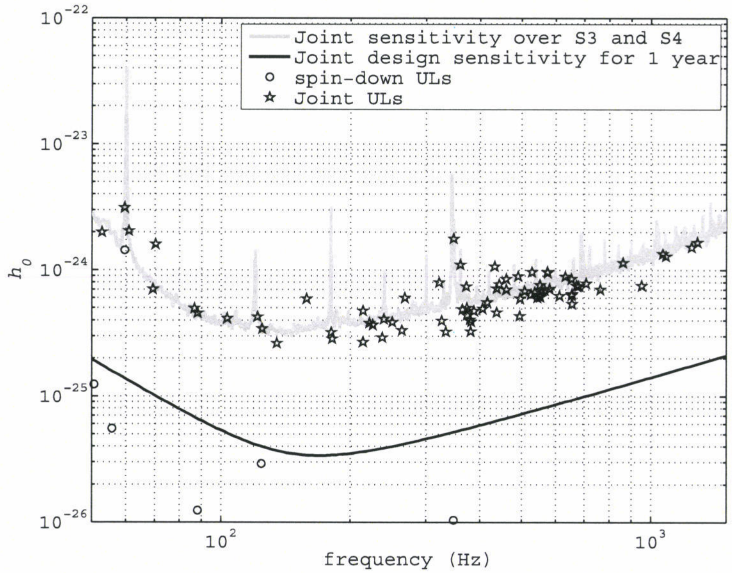
S3-S4 results for known pulsars



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Preliminary S5 results for known pulsars

- Spindown limit for Crab is beaten by factor of ~ 3
- Best limit of h_0 is $\mathcal{O}(10^{-26})$
- Get limit on ellipticity using known h_0 and d, and $I = 10^{38}$ kg-m^2;

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I\epsilon f_r^2}{d}$$

- Best limit on ϵ is $\mathcal{O}(10^{-8})$
- This is already astrophysically interesting – Talk by Owen

Blind searches for isolated pulsars

- Expect to have nearby neutron stars not visible as pulsars
- Some of these might be visible in gravitational waves
- This implies a blind search in $(f, \dot{f}, \mathbf{n})$
- S2 data analyzed this way using $\mathcal{F}$-statistic (gr-qc/0605028)
- Sensitivity goes as $\sqrt{T_{obs}}$

$$h_0 \propto \sqrt{\frac{S_n(f)}{T_{obs}}}$$

- Looked at ~ 10 hours of coincident data in L1 and H1
- All sky search, 160-728.8 Hz, $|\dot{f}| < 4 \times 10^{-10}$ Hz/s
- No detection made
- Best 95% upper limit on h_0 was 6.6×10^{-23}

Blind searches for isolated pulsars

But we have a problem:

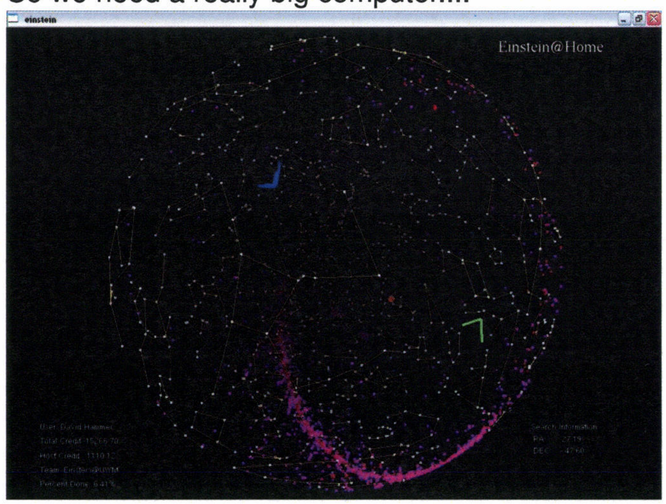
- Number of templates increases rapidly with T_{obs}
- For short T_{obs} ($\ll$ 1 year) we have approximately:

$$N_{templates} \propto T_{obs}^5$$

- This is why the S2 search used only 10 hours of data
- And of course we need a large T_{obs} to get decent SNR

Blind searches for isolated pulsars

So we need a really big computer....



Blind searches for isolated pulsars

- `Einstein@Home` provides $\sim$ 80 TFlops round the clock
- Performed wide area $\mathcal{F}$-statistic search on S3 and S4 data – similar to S2 search
- No detections made
- S3 results available at `http://einstein.phys.uwm.edu/FinalS3Results/`
- But even with `E@H` we can't do more than a few days of coherent integration

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Semi-coherent searches

- Basic idea is to perform a semi-coherent power folding search
- Break up observation time into short segments (30 mins)
- Take the Fourier transform of each segment to create SFTs
- Sum excess power from each segment taking into account Doppler shift and spindown

$$f(t) - \hat{f}(t) = \hat{f}(t)\frac{\mathbf{v}(t)\cdot\mathbf{n}}{c}$$

$$\hat{f}(t) = f_0 + \dot{f}(t - t_{ref})$$

- Details in `http://arxiv.org/abs/0708.3818`

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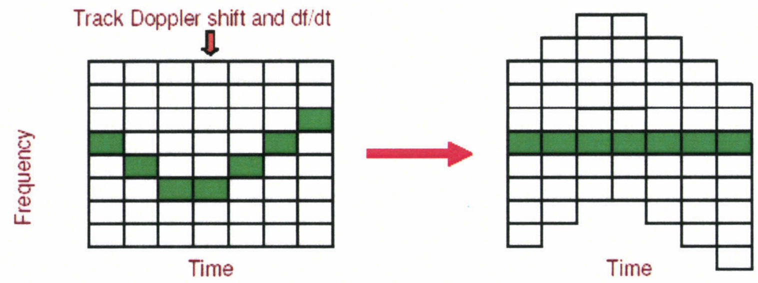
Semi-coherent searches



- Sensitivity is degraded by a factor of $N^{1/4}$ relative to a coherent search

$$h_0 \propto \frac{1}{N^{1/4}} \sqrt{\frac{S_h(f)}{T_{coh}}}$$

- Compensate for theoretical sensitivity by analyzing more data than a coherent search

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Semi-coherent searches

Three different methods used which differ in what is summed:

- Stack-slide sums normalized power

$$\rho = \sum_{i=1}^{N} \left| \tilde{x}_k^{(i)} \right|^2$$

- Hough method sums weighted binary counts

$$\rho = \sum_{i=1}^{N} w_i n_i \quad \text{where} \quad n_i = \begin{cases} 1 & \text{if} \quad \left| \tilde{x}_k^{(i)} \right|^2 \geq \rho_{th} \\ 0 & \text{if} \quad \left| \tilde{x}_k^{(i)} \right|^2 < \rho_{th} \end{cases} .$$

- Power-flux sums weighted normalized power

$$\rho = \sum_{i=1}^{N} w_i \left| \tilde{x}_k^{(i)} \right|^2$$

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Semi-coherent searches

The three methods are complementary

- Powerflux is the most sensitive
- Hough is robust and computationally efficient
- Stackslide is the simplest and does fairly well on sensitivity and cost

A technical detail:

- Hough and Stackslide: frequentist population based upper limits using the loudest candidate event
- Powerflux: strict frequentist upper limits for best and worst case polarizations

Semi-coherent searches

Parameter space searched over

- Frequency range 50-1000 Hz
- All sky
- For Hough: $-2.2 \times 10^{-8}\mathrm{Hz/s} < \dot{f} < 0$
  For Stackslide and Powerflux: $-1.0 \times 10^{-8}\mathrm{Hz/s} < \dot{f} < 0$
- No detections made
- Set upper limits at 95% confidence level

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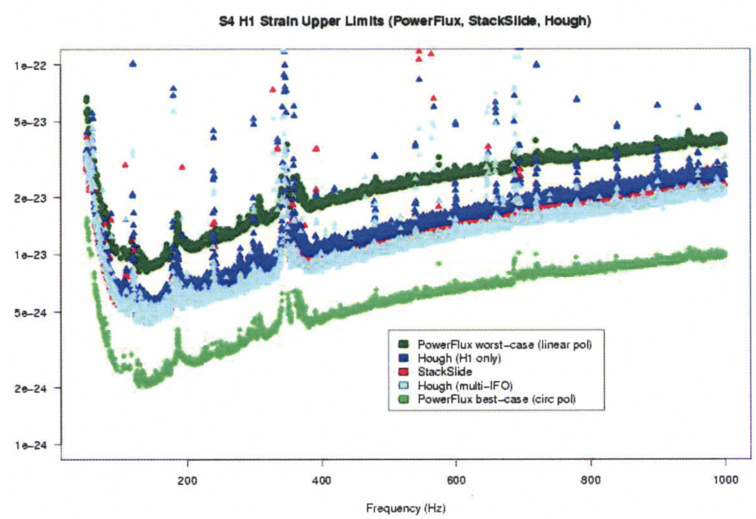
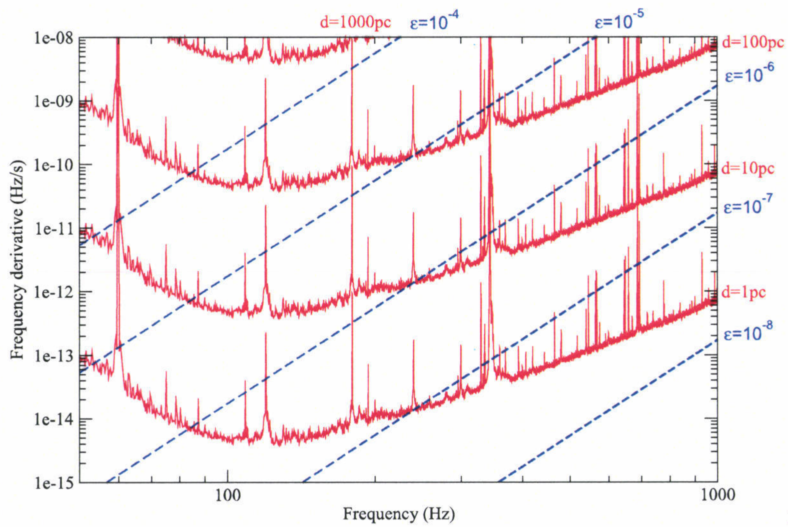
Semi-coherent searches - S4 results



Semi-coherent searches - astrophysical reach



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Gravitational waves from Sco X-1

- Sco X-1 is the brightest LMXB and a promising candidate for detection with Advanced detectors
- Two searches have been carried out for Sco X-1 using completely different methods
- Search parameters are $(f, T_{asc}, P_{orb}, a \sin i)$
- Sky position known, eccentricity and spindown neglected
- Method 1: A coherent $\mathcal{F}$-statistic search using S2 data
- Method 2: Using aperture synthesis of multiple detectors (L1 and H1) using S4 data

The Sco X-1 $\mathcal{F}$-statistic search

- The computational cost problem is even worse for pulsars in binary systems
- For Sco X-1 it turns out that (when $T_{obs} \ll P_{orb}$)

$$N_{templates} \propto T_{obs}^6$$

- We should actually search the full LIGO frequency band
- But this is computationally very hard
- Search used QPO frequency separation to restrict frequency range
- Two 20Hz wide bands considered: 464-484 Hz and 604-624 Hz corresponding to assuming $f_{GW} = 2 \times f_{rot}$
- Computational constraints led to $T_{obs} = 6$ hr
- Best 95% upper limit on h_0 was 1.7×10^{-22}
- Details in `gr-qc/0605028`

The Radiometer search

- L1 and H1 detectors see the same GW signal
- Introduce time delays in the two data streams
- Cross-correlate the data streams to extract the signal – aperture synthesis
- Details in `astro-ph/0703234`
- Basic statistic is the cross-correlation

$$Y_t = \int_{-\infty}^{\infty} \tilde{x}_1^{\star}(f) Q_t(f) \tilde{x}_2(f)$$

- Choice of optimal filter can be used to "point" the radiometer
- Upper limits are in 0.25 Hz bands

$$h^{rms} = 3.4 \times 10^{-24} \left(\frac{f}{200\text{Hz}} \right) \quad \text{for} \quad f > 200\,\text{Hz}$$

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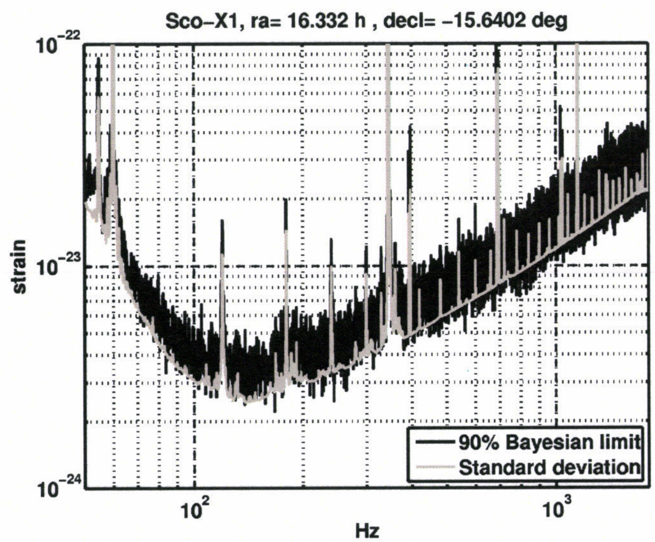
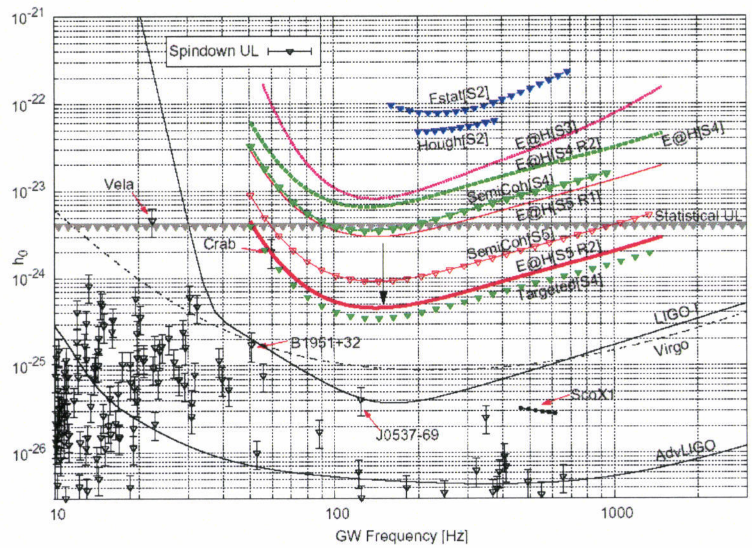
The Radiometer search



Summary of observational results



(R.Prix, Heraeus 2006)

Outlook

- Periodic wave searches by the LSC making significant progress
- No detection yet but limits are becoming astrophysically interesting
- Detectors and data analysis techniques are becoming more sensitive
- Data from long S5 run is being analysed
- Enhanced LIGO is only a couple of years away
- Opportunity for fruitful interaction between GW searches and astrophysics