A search for gravitational wave signals from known pulsars using early data from the LIGO S5 run

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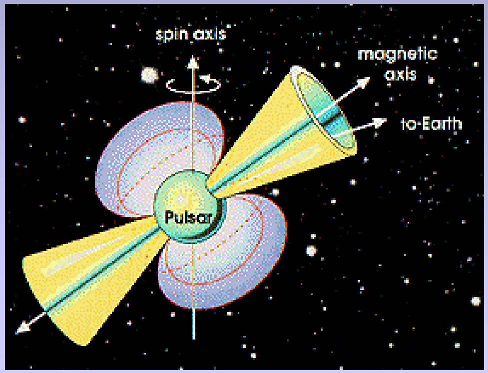
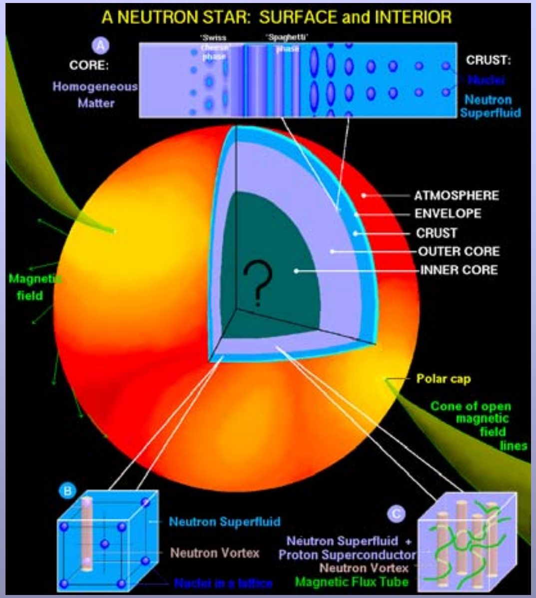
Why search for known pulsars?

- Many millisecond and fast young pulsars have very well determined parameters and are generally very stable - excellent candidates for a targeted search using gravitational detectors!
- Assuming a neutron star is a rigid, asymmetric triaxial body then it will emit very well modelled gravitational waves at twice the rotation frequency
- Measurements of gravitational waves emitted via this mechanism would enable us to constrain pulsar ellipticities and possible neutron star equations-of-state

- Within the LIGO sensitive band (f_{gw} > 50 Hz) there are currently 154 known pulsars (from the ATNF pulsar catalogue) - with 91 in binary systems and 90 within globular clusters



Imagine.gsfc.nasa.gov



www.astroscu.unam.mx/neutrones/NS-Picture/NStar/NStar_lS.gif

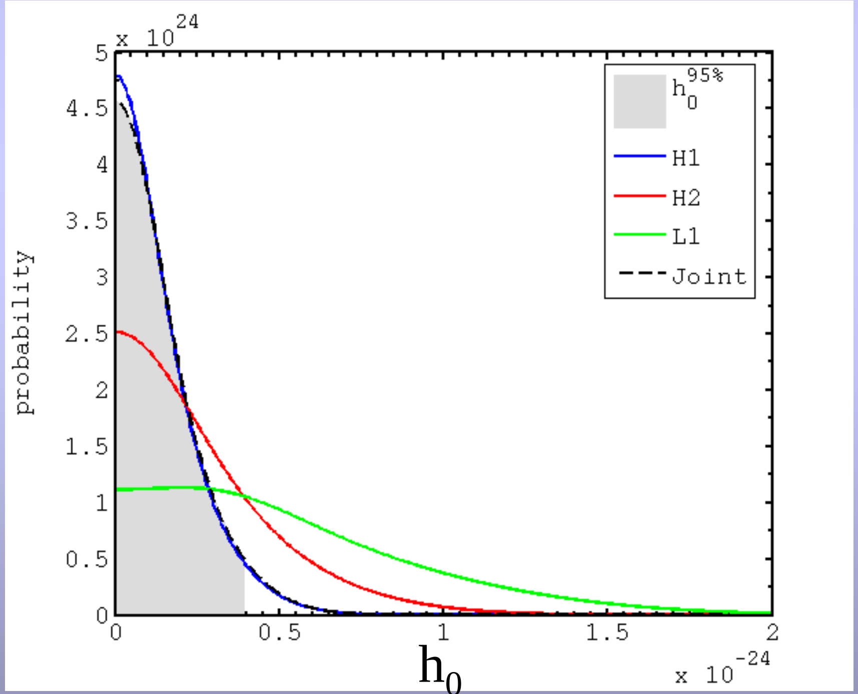
Analysis method

- Heterodyne time domain data using the known phase evolution of the pulsar
  - Bayesian parameter estimation of unknown pulsar parameters: the gravitational wave amplitude h_0, initial phase ϕ_0, polarisation angle ψ and inclination angle ι, using data from all interferometers
  - produce probability distribution functions for unknown parameters and marginalise over angles to set 95% upper limit on h_0

$$0.95 = \int_{h_0=0}^{h_0^{95\%}} \mathrm{d}h_0 \iiint \mathrm{p}\left(\mathrm{a} \mid \text{all data}\right) \mathrm{d}\phi_0 \mathrm{d}\psi \mathrm{d}\cos\iota$$

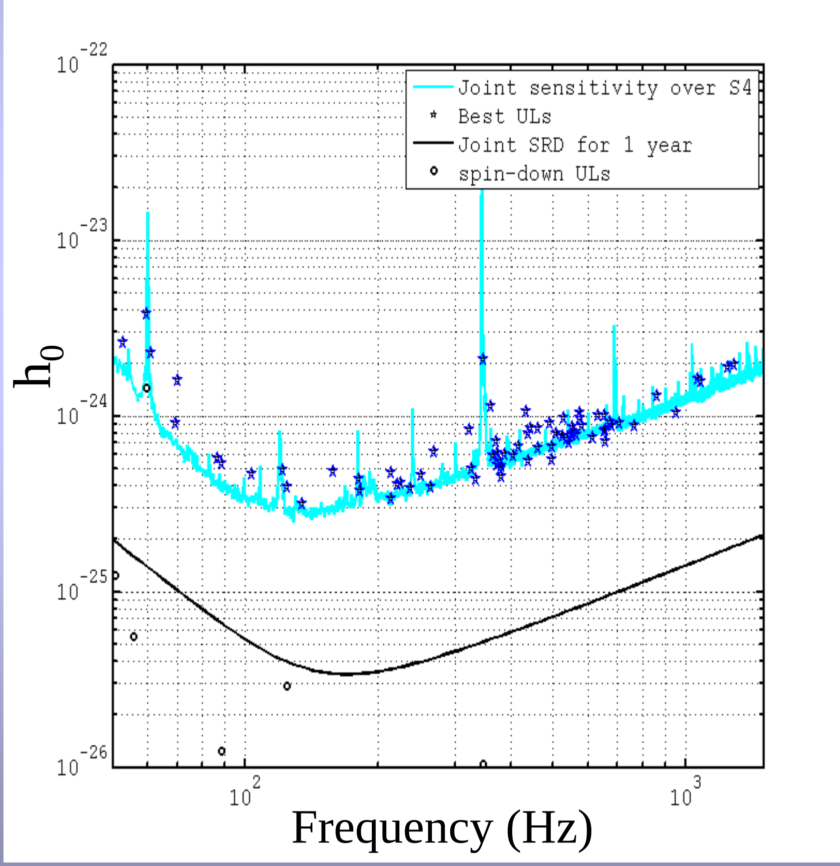
- Set limits on the pulsar ellipticity and compare with limits from spin-down arguments i.e. assuming all energy lost as the pulsar spins-down is dissipated via gravitational waves

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



The searches so far...

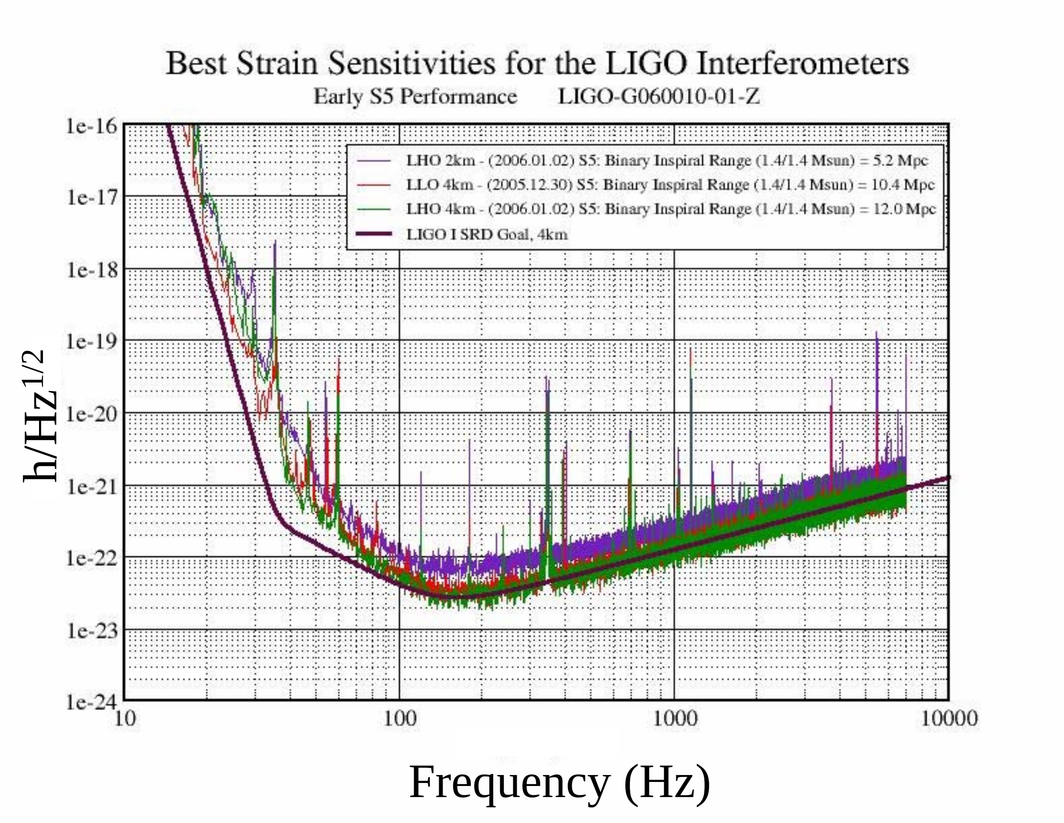
- **S1** (23 Aug – 9 Sep 2002) – a targeted search for gravitational waves from J1939+2134 using time domain and frequency domain techniques (B. Abbott *et al*, **PRD**, **69**, 2004)
- **S2** (14 Feb – 14 Apr 2003) – a targeted search for 28 known **isolated** pulsars with f_{gw} > 50 Hz using the time domain technique (B. Abbott *et al*, **PRL**, 2005)
- **S3** (31 Oct 2003 – 9 Jan 2004)/**S4** (22 Feb – 23 Mar 2005) upper limits for 76 known radio pulsars – 32 isolated + 44 in binary systems; 30 in globular clusters
  - timing data provided by Pulsar group, Jodrell Bank Observatory and the ATNF, to coherently follow their phases over the run
  - upper limits on h_0 of a few x 10^{-25}, an ellipticity of < 10^{-6} for one pulsar, and a result for the Crab pulsar of only a factor 3 above the spin-down upper limit – S3/S4 **Paper in preparation**



Early S5 run

- Search for 73 pulsars
  - 32 isolated + 41 in binary systems; and 29 in globular clusters
  - Used parameters provided by Pulsar Group, Jodrell Bank Observatory for S3 – checked for validity over the period of S5 i.e., whether the intrinsic parameter errors or timing noise were enough to possibly decohere our phase model from the true value

- Analysed from 4 Nov - 31 Dec 2005 using data from the three LIGO observatories - Hanford 4k and 2k (H1, H2) and Livingston 4k (L1)



http://www.ligo.caltech.edu/~lazz/distribution/LSC_Data

S5 Results, 95% upper limits

h_0	Pulsars
$1\times10^{-25} < h_0 < 5\times10^{-25}$	44
$5\times10^{-25} < h_0 < 1\times10^{-24}$	24
$h_0 > 1\times10^{-24}$	5

Lowest h_0 upper limit:
PSR J1603-7202 (f_{gw} = 134.8 Hz, r = 1.6kpc) $h_0 = 1.6\times10^{-25}$
Lowest ellipticity upper limit:
PSR J2124-3358 (f_{gw} = 405.6Hz, r = 0.25kpc) $\varepsilon = 4.0\times10^{-7}$

Preliminary

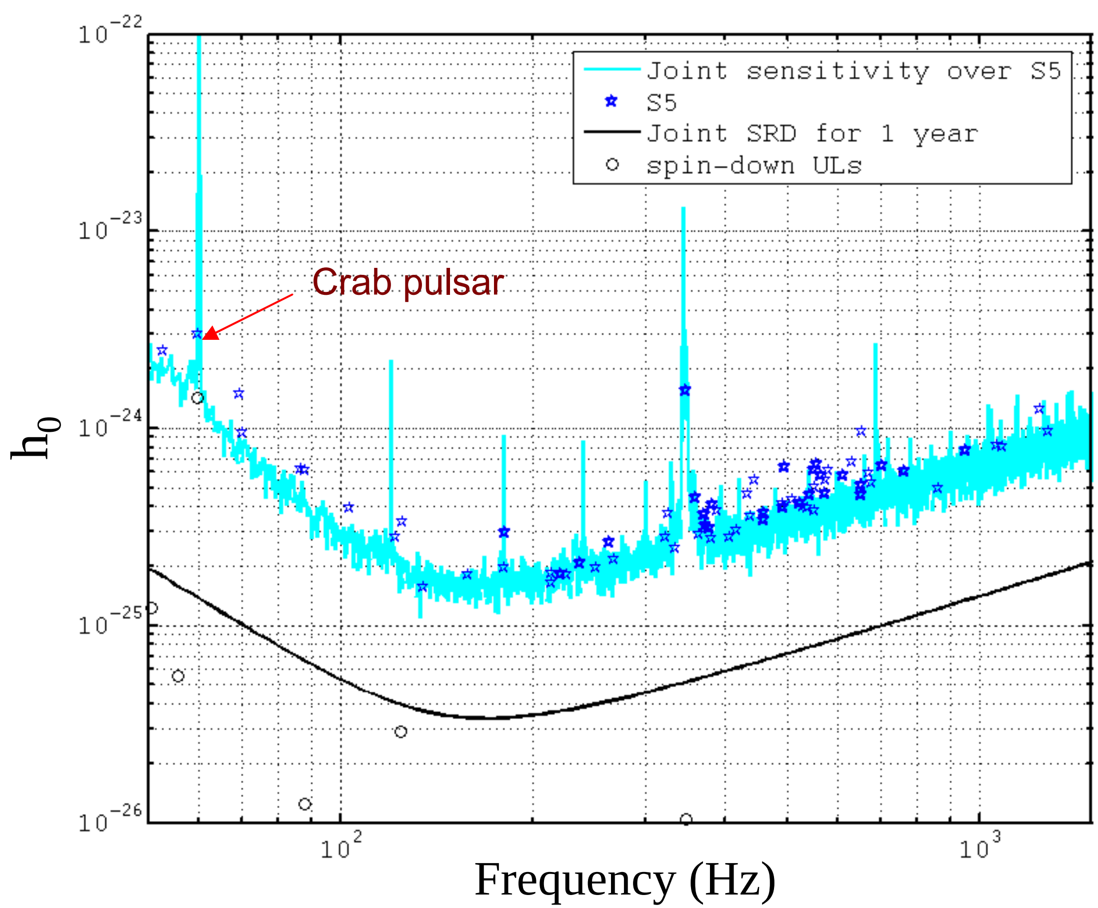
Ellipticity	Pulsars
$\varepsilon < 1\times10^{-6}$	6
$1\times10^{-6} < \varepsilon < 5\times10^{-6}$	28
$5\times10^{-6} < \varepsilon < 1\times10^{-5}$	13
$\varepsilon > 1\times10^{-5}$	26

All values assume $I = 10^{38}$ kgm^2 and no error on distance

$$\varepsilon = 0.237 \frac{h_0}{10^{-24}} \frac{r}{1\text{kpc}} \frac{1\text{Hz}^2}{\nu^2} \frac{10^{38}\,\text{kgm}^2}{I_{zz}}$$

h_0 Results

- Spin-down upper limit calculated with intrinsic spin-down value if available i.e. corrected for Shklovskii transverse velocity effect
- Closest to spin-down upper limit
  - Crab pulsar ~ **2.1** times greater than spin-down (f_{gw} = 59.6 Hz, dist = 2.0 kpc)
  - $h_0 = 3.0 \times 10^{-24}$, $\varepsilon = 1.6 \times 10^{-3}$
  - Assumes $I = 10^{38}$ kgm^2



- Sensitivity curves use:

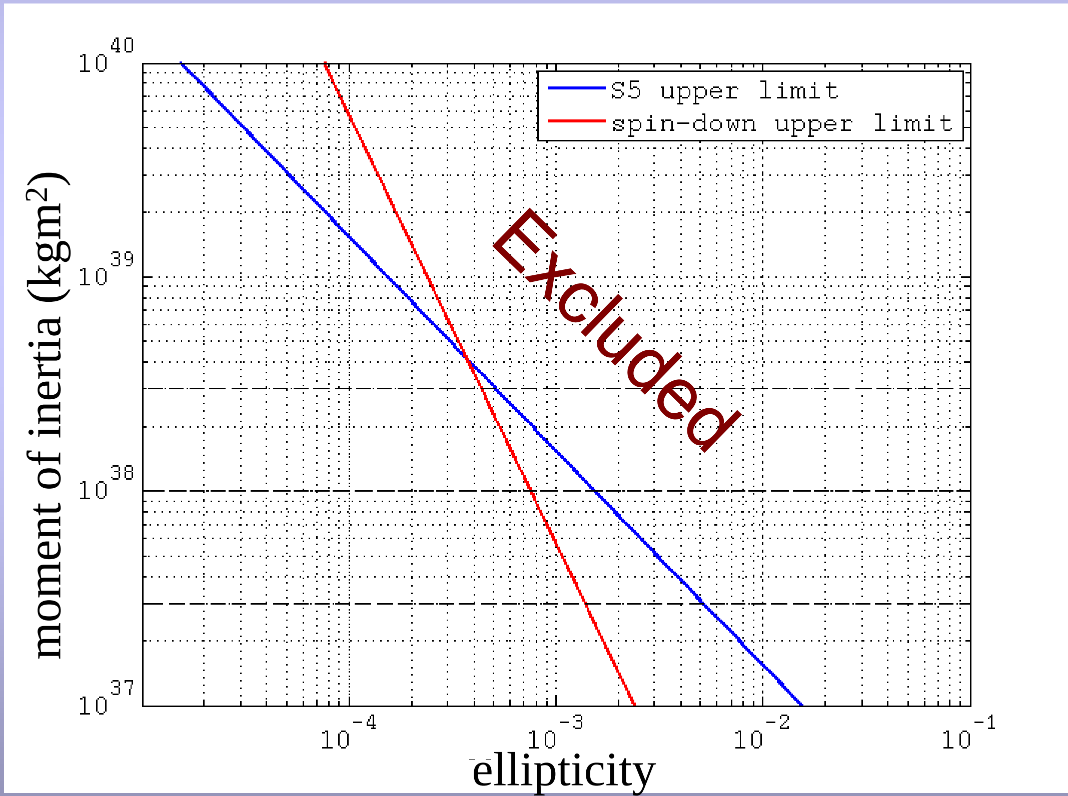
$$S(f) = \left(\frac{T_{\rm obs\ H1}}{S_h(f)_{\rm H1}} + \frac{T_{\rm obs\ H2}}{S_h(f)_{\rm H2}} + \frac{T_{\rm obs\ L1}}{S_h(f)_{\rm L1}} \right)^{-1}$$

$$h_0^{95\%} = 10.8\sqrt{S(f)}.$$

Crab UL in I-ε plane

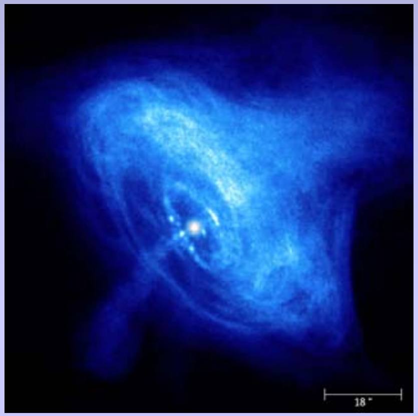
- We can use h_0 as an upper limit on the quadrupole moment Iε – can then be plotted on a I-ε plane providing exclusion regions
- Using the range of moments of inertia 3×10^{37} – 3×10^{38} kgm^2 (Thorne, 300 Years of Gravitation, CUP) we have 1.2 – 4 times the spin-down limit for the Crab pulsar
- Higher moments of inertia possible for high mass neutron stars – seen with ~ 1.7 M_{sun} (Ransom *et al*, 2005, **Science** and Nice *et al*, 2005, astro-ph/0508050)

Crab pulsar – 2.0 kpc



Results - astrophysics

- Our upper limits are generally well above those permitted by spin-down constraints and neutron star equations-of-state they have some astrophysical interest
- For 29 globular cluster pulsars we provide the limits independent of the cluster dynamics (apparent spin-ups seen due to accelerations within the cluster – cannot set spin-down limits)
- Our most stringent ellipticities (4.0×10^{-7}) are starting to reach into the range of neutron star structures for some neutron-proton-electron models (B. Owen, **PRL**, 2005).
- Crab pulsar is nearing the spin-down upper limit

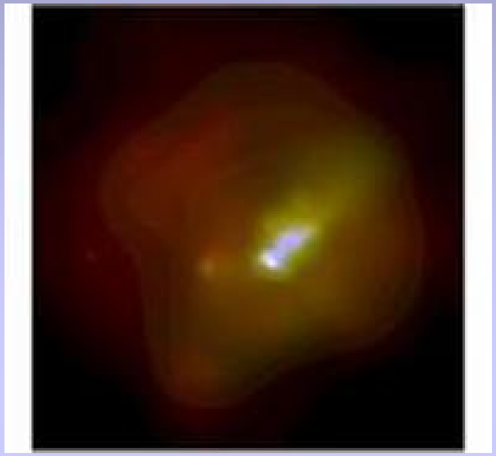


Chandra image: Harvard CfA

2MASS mage: IPAC/Caltech

Future work

- These results show the first two months of S5 only, but give an idea of how the rest of the run will progress
- Goal for the next six months
  - should have more up-to-date pulsar timings for current pulsars and possibly more objects (e.g. large number of pulsars in GC Terzan 5)
  - should have amplitudes of $< 10^{-25}$ and ellipticities $<10^{-6}$ for many objects
  - should be able to reach the spin-down limit for the Crab pulsar – assuming no glitches
- Possibility of some more exciting potential targets, e.g. young X-ray pulsars



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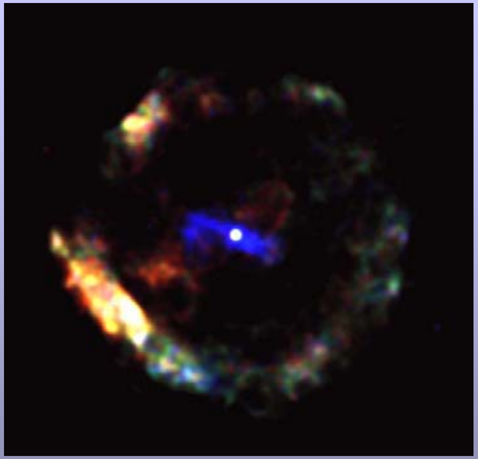

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