New gravitational wave upper limits for selected millisecond pulsars using LIGO S5 data

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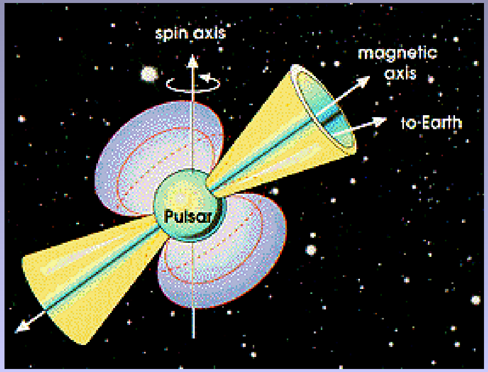
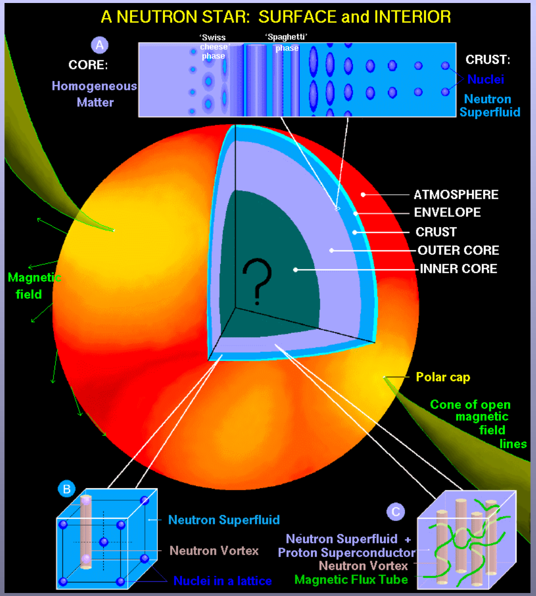
Why search for known pulsars?

- 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 163 known pulsars (from the ATNF pulsar catalogue) - with 98 in binary systems and 91 within globular clusters



Imagine.gsfc.nasa.gov



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

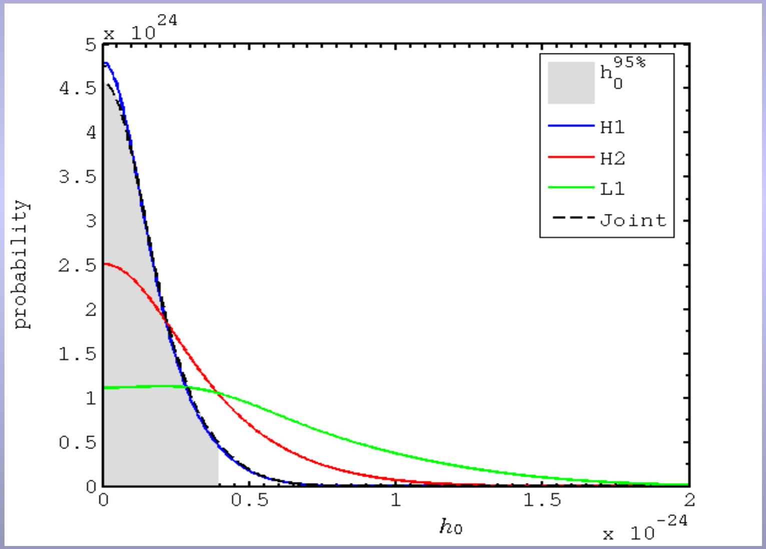
Analysis method

- 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

$$0.95=\int_{h_0=0}^{h_0^{95}} dh_0 \iiint p(a|\,\text{all data})\, d\varphi_0\, d\psi\, d\cos\iota$$

- 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

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

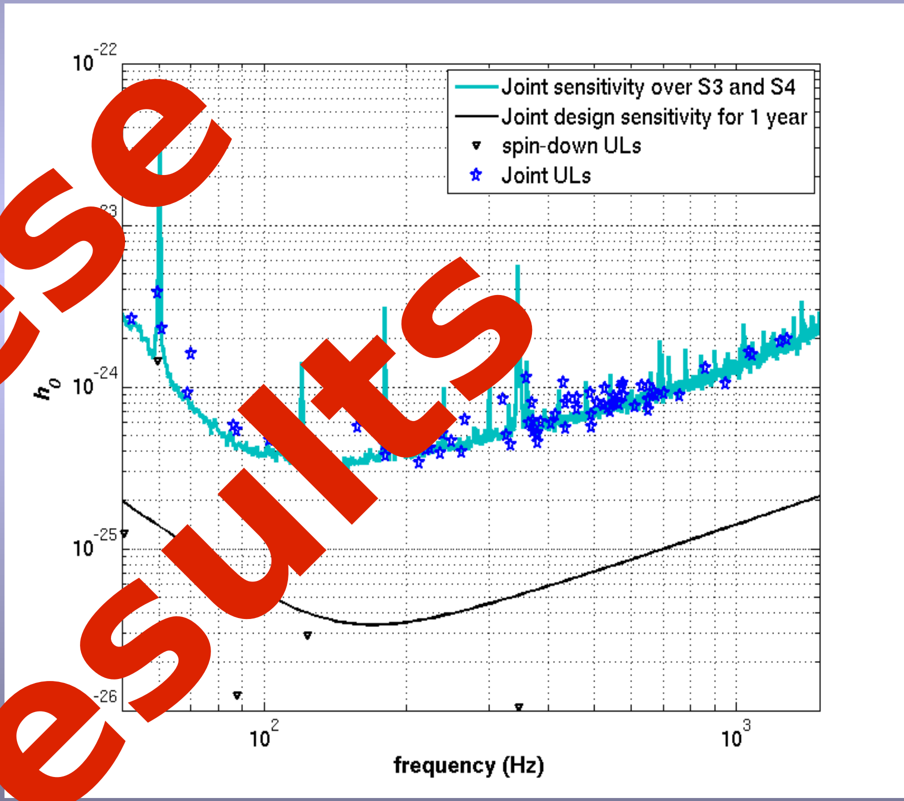


Probability distribution functions for the 3 LIGO interferometers for h0 for PSR J0024-7204C over

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

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**, **94**, 181103, 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 (B. Abbott *et al* to be submitted LIGO-P060011-01-Z)



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do not use these results

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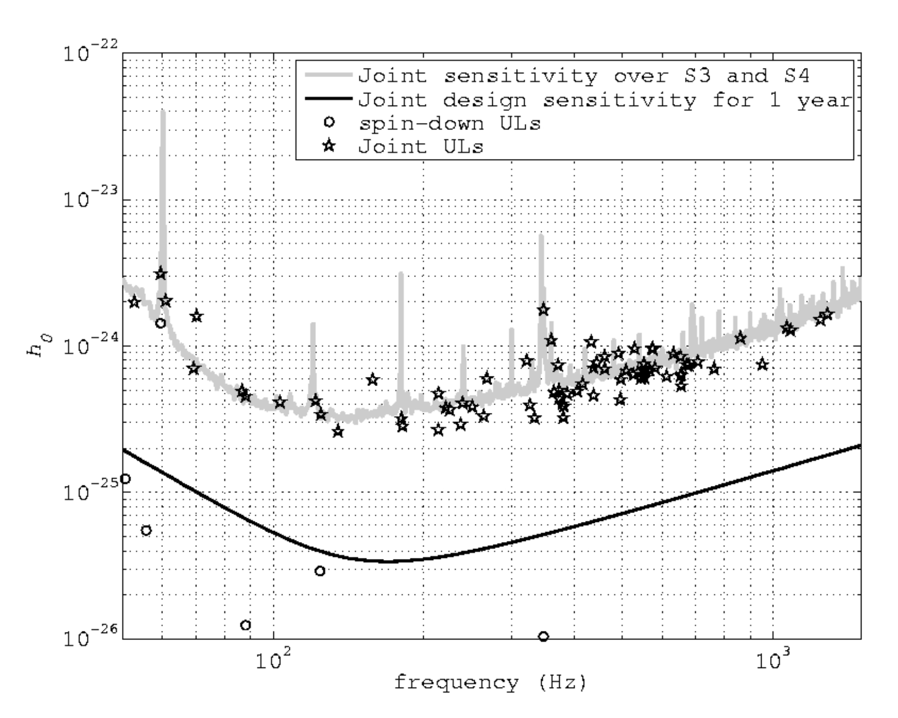

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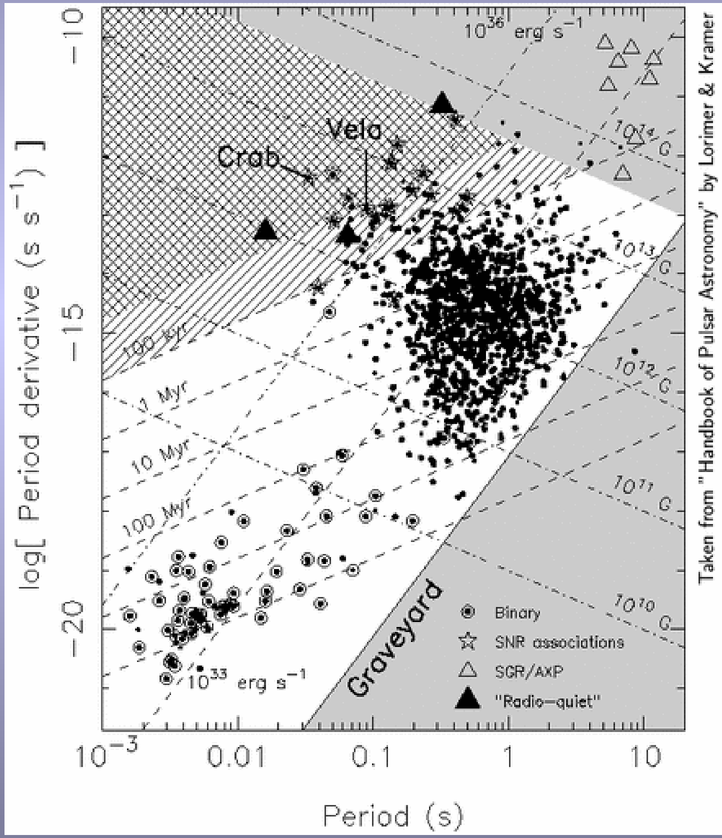
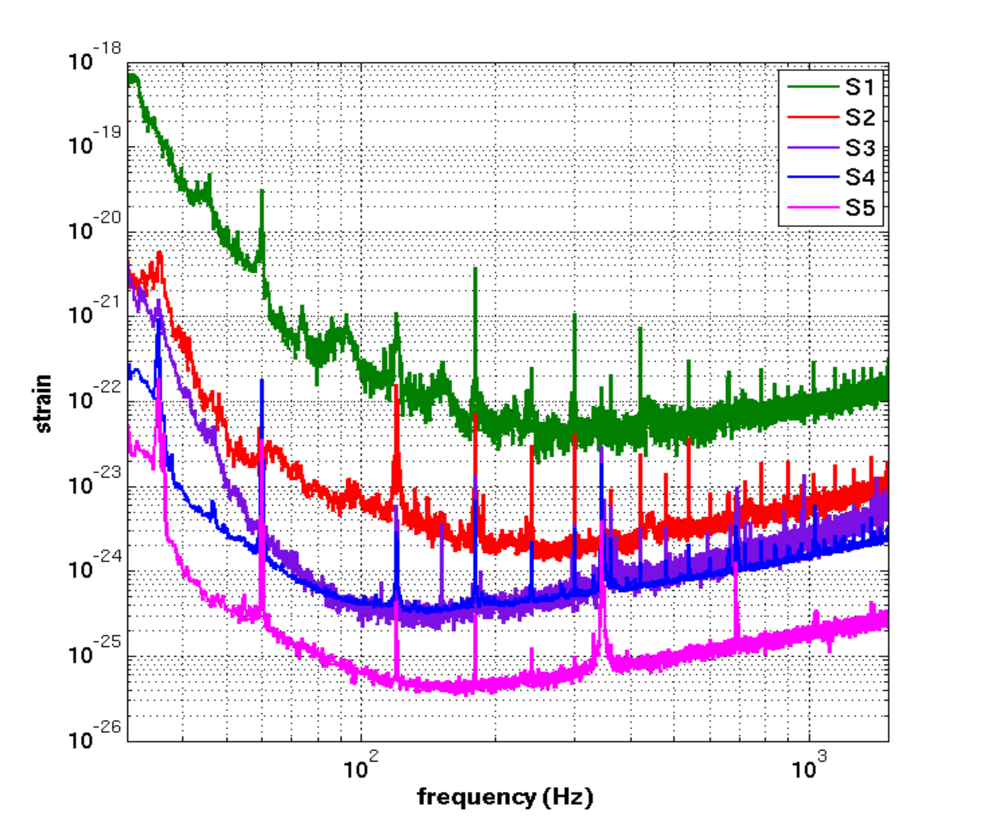
Status of S5 search

- The heterodyning using new code has been performed on first ~10 months of S5 data – from the start of the run to 17th Sept 2006
  - For many pulsars we have used the same timing solutions as used for the S3/S4 analyses
  - New timing data over a few months of S5 has been use to provide new pulsar parameter estimations for **32** pulsar produced by Michael Kramer
  - Have *preliminary* results using these and older timings for 97 pulsars using H1, H2 and L1 data
    - many will require to timing over the period of the run to be sure of phase coherence



Integration times

- **S1 -** L1 5.7 days, H1 8.7 days, H2 8.9 days
- **S2 -** L1 14.3 days, H1 37.9 days, H2 28.8 days
- **S3 -** L1 13.4 days, H1 45.5 days, H2 42.1 days
- **S4 -** L1 17.1 days, H1 19.4 days, H2 22.5 days
- **S5** (4st Nov 2005 - 17th Sep 2006) - L1 180.6 days, H1 223.5 days, H2 255.8 days



Sensitivity curves taken from
http://www.ligo.caltech.edu/~jzweizig/distribution/LSC_Data/

DO NOT USE THE RESULTS IN THIS PRESENTATION – MORE RECENT AND CORRECTED RESULTS CAN BE FOUND IN THE APRIL 07 APS MEETING RESULTS DCC NUMBER LIGO-G070230

Results

Joint 95% upper limits from first ~10 months (4 Nov 2005 – 17 Sep 2006) of S5 using H1, H2 and L1 (97 pulsars)

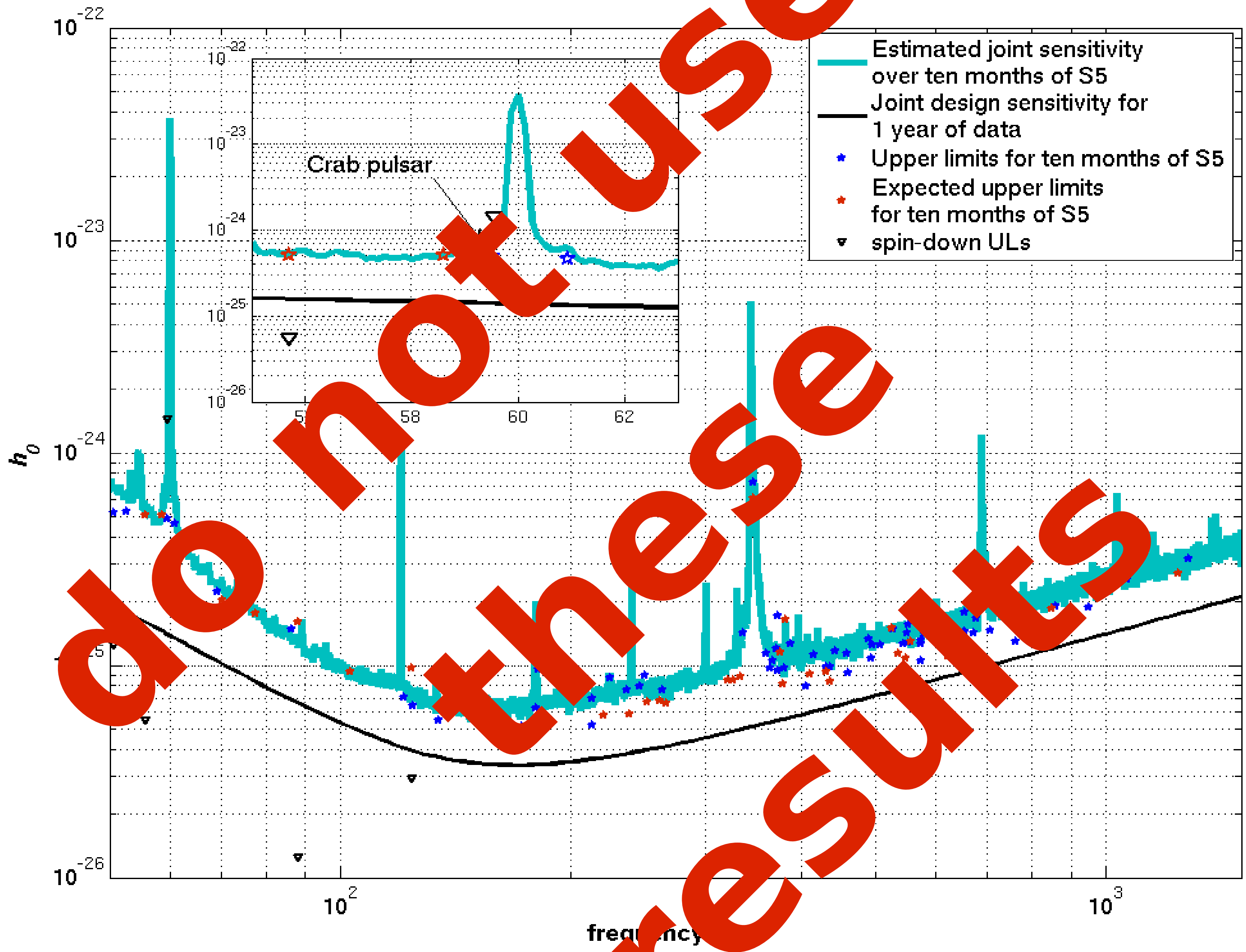
Due to pulsar glitches the Crab pulsar result uses data up to the glitch on 23 Aug 2006, and the PSR J0537-6910 result uses only three months of data between two glitches on 5th May and 4th Aug 2006

Lowest h_0 upper limit:
PSR J1802-2124 (f_{gw} = 158.1 Hz, r = 3.3 kpc) $h_{0\,min} = 4.9\times10^{-26}$

Lowest ellipticity upper limit:
PSR J2124-3358 (f_{gw} = 405.6Hz, r = 0.25 kpc) $\varepsilon = 1.1\times10^{-7}$

h_0	Pulsars
$h_0 < 10^{-25}$	35
$10^{-25} \le h_0 < 5\times10^{-25}$	56
$h_0 \ge 5\times10^{-25}$	6

Ellipticity	Pulsars
$10^{-7} \le \varepsilon < 5\times10^{-7}$	14
$5\times10^{-7} \le \varepsilon < 10^{-6}$	20
$10^{-6} \le \varepsilon < 5\times10^{-6}$	38
$\varepsilon \ge 5\times10^{-6}$	25



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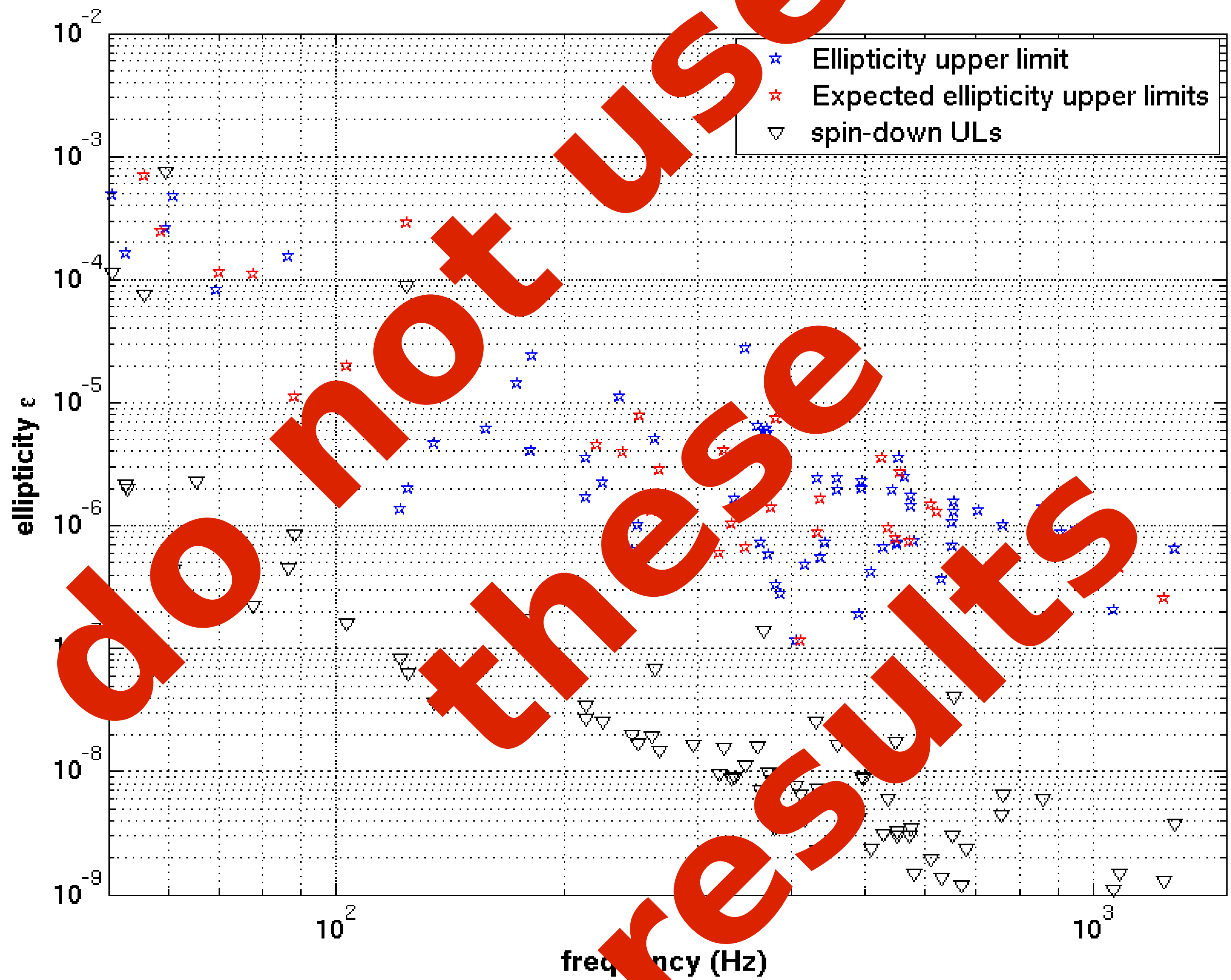
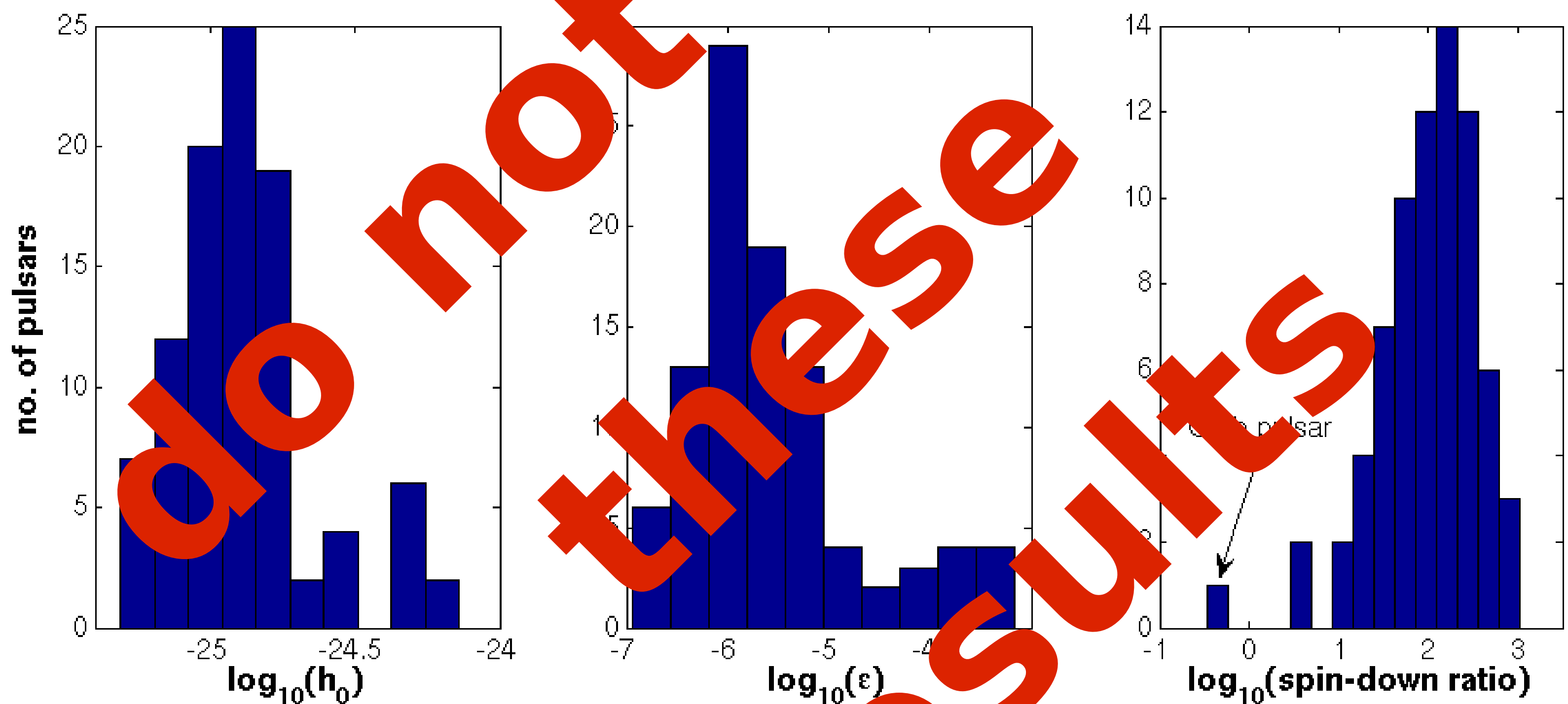
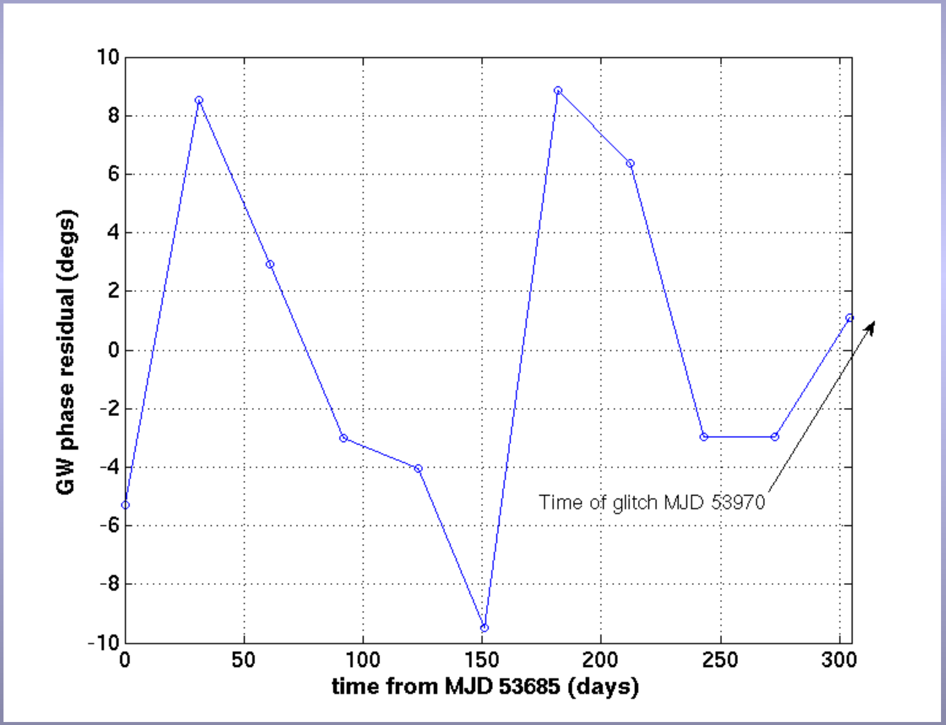


Ellipticity upper limit
Expected ellipticity upper limits
spin-down ULs
ellipticity ε
10^-2
10^-3
10^-4
10^-5
10^-6
10^-8
10^-9
10^2
10^3
do not use these results


no. of pulsars
25
20
15
10
5
0
-25
-24.5
-24
$\log_{10}(h_0)$
20
15
0
-7
-6
-5
$\log_{10}(\varepsilon)$
14
12
10
8
0
-1
0
1
2
3
$\log_{10}$(spin-down ratio)

Crab pulsar – timing noise/glitches

- **A *significant* glitch occurred in the Crab pulsar on 23rd Aug – use this as the natural point to pause this analysis**
  - will continue analysis post-glitch taking into account possible phase change
- Normally perform an extra heterodyne for the Crab pulsar to remove effects of timing noise – use Jodrell Bank monthly Crab pulsar ephemeris to update our phase model
- There has been no large variation in the timing noise – one global model over the whole of the run with only maximum of 10 degree deviations in phase



Timing noise seen in the phase residuals of the Crab pulsar as calculated using data from the Jodrell Bank Crab pulsar ephemeris

Crab pulsar

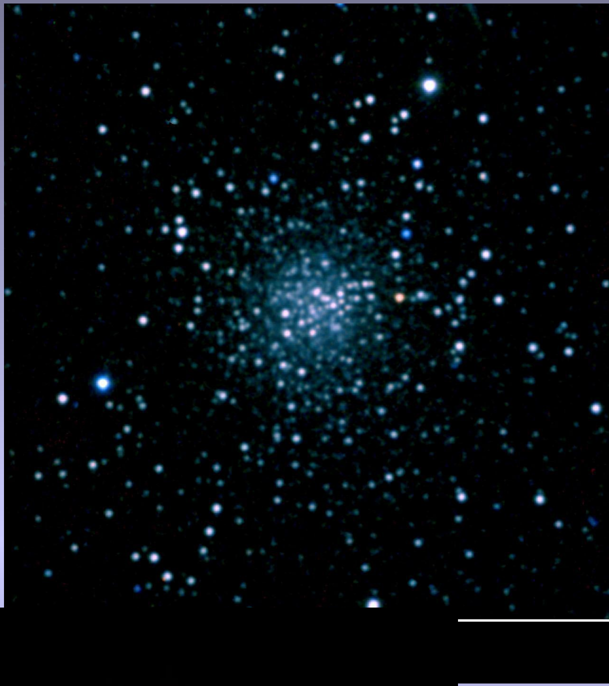
- We have beaten the spin-down limit for the Crab pulsar, but what does this mean?
- We can start to constrain the rather uncertain energy budget of the pulsar
  - large uncertainties on the nebula mass give rather poor constraints onto the amount of energy from the pulsar required to power its expansion
  - we can give limits on energy emitted though gravitational radiation as opposed to other mechanisms
  - a more realistic estimate of the moment of inertia can improve the ellipticity upper limit by up to a factor of 3

Photo credit:NASA/HST/CXC/SAO

Conclusions

- Preliminary upper limits for a large number of pulsars
  - many with $h_0 < 1\times10^{-25}$ and ellipticities approaching 1×10^{-7}
- Have new timing for some pulsars – need more timings over the whole of S5
- We have beaten the spin-down limit for the Crab pulsar
  - current search uses one template – propose doing a small range astrophysically motivated frequency search around this
- S5 still ongoing so more data is there to improve current results
  - expect factor of $\sim2^{1/2}$ improvement for entire run
- Many newly discovered pulsars, or X-ray pulsars to hopefully add to the search
  - consider searches at spin frequency and 4/3 spin frequency

http://www.ioa.s.u-tokyo.ac.jp/~nmatsuna/study/SiOGC.html



http://www.physics.mcgill.ca/~roberts/g11.html