Beating the Crab pulsar spin-down and other upper limits: new results from the LIGO S5 known pulsar search

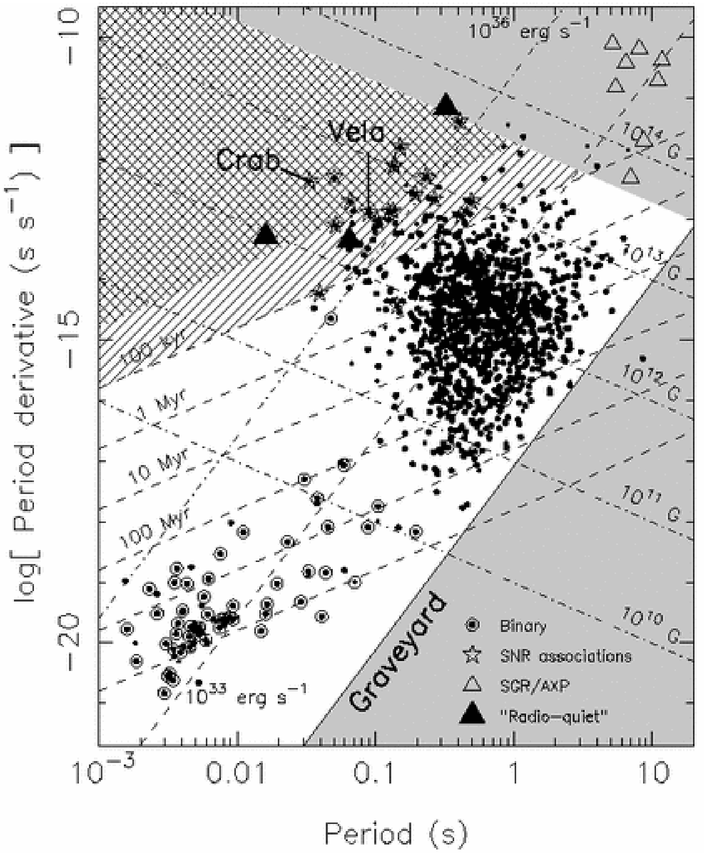
Matthew Pitkin for the LIGO Scientific Collaboration

matthew@astro.gla.ac.uk

LIGO-G070230-00-Z

Targeted pulsar search - Why?

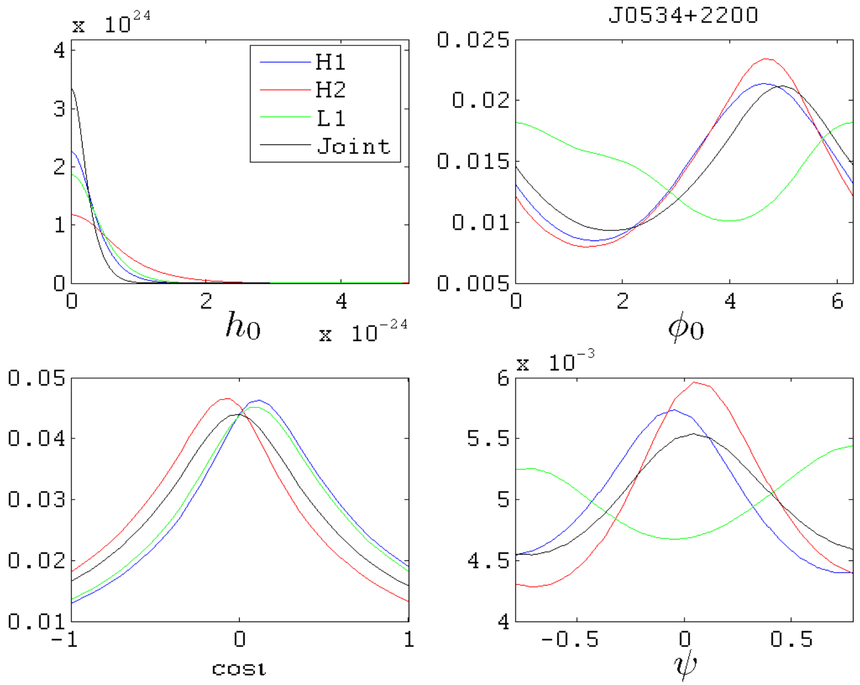
- Rapidly spinning neutron stars provide a potential source of continuous gravitational waves
- To emit gravitational waves they must have some degree of non-axisymmetry e.g. triaxial deformation due to elastic stresses or magnetic fields
- Size of distortions can reveal information about the neutron star equation of state
- Many millisecond and fast young pulsars have very well determined parameters and are generally very stable - good candidates for a targeted search using gravitational detectors!
- The greatly reduced unknown parameter space allows deep, relatively computational inexpensive searches using long time spans of data



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Targeted search - method

- Pulsar signal parameterised by: h_0 - gravitational wave amplitude, ι - pulsar orientation, ϕ - gravitational wave phase, and ψ - polarisation angle
- Signal is Doppler modulated by detector and source motion
- Assume that the gravitational wave emission from triaxial neutron star that is tightly coupled and phase locked with the EM emission
  - Heterodyne time domain data using the known phase evolution of the pulsar
  - Bayesian parameter estimation of unknown pulsar parameters using data from all interferometers
- Within the LIGO sensitive band (ν_{gw} > 50 Hz) there are currently 163 known pulsars
- We have rotational and positional parameter information for 97 of these



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

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

Preliminary results

Joint 95% upper limits from first ~13 months of S5 using H1, H2 and L1 (97 pulsars)

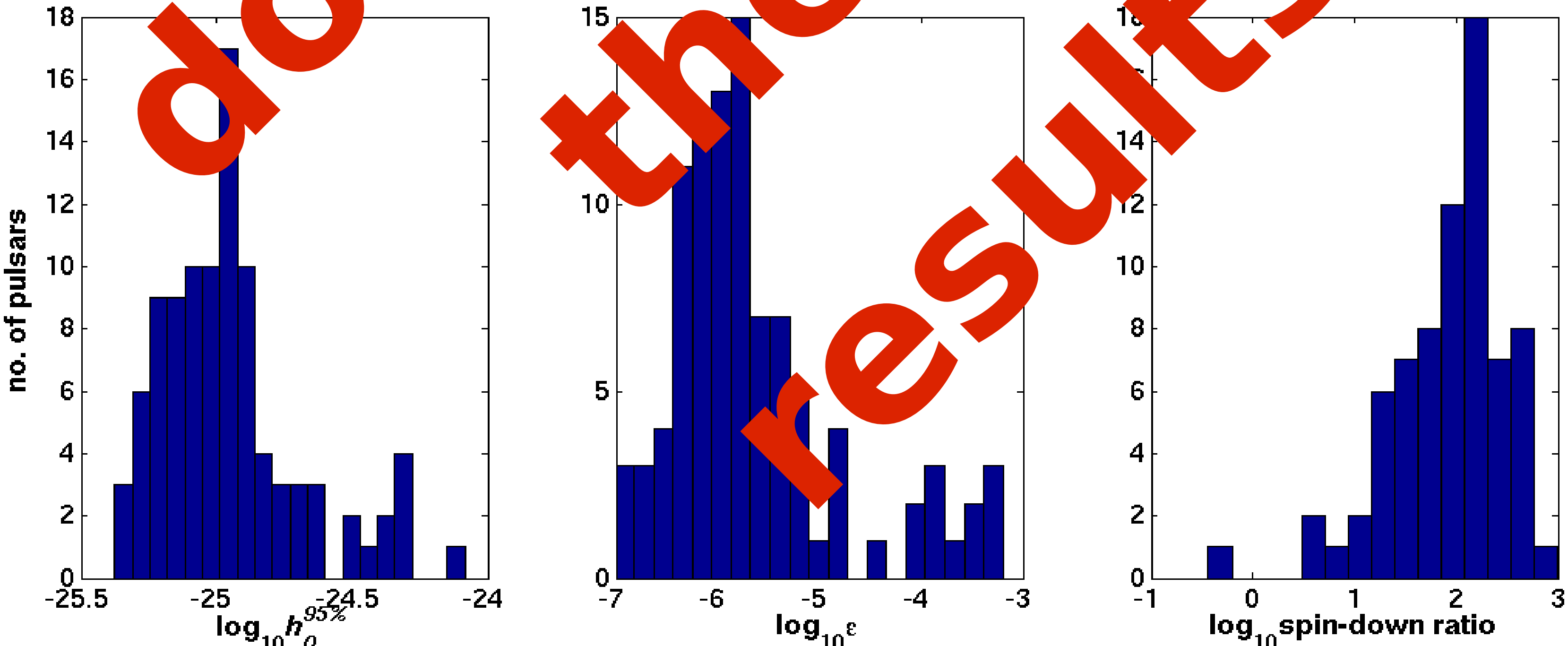
Lowest h_0 upper limit:

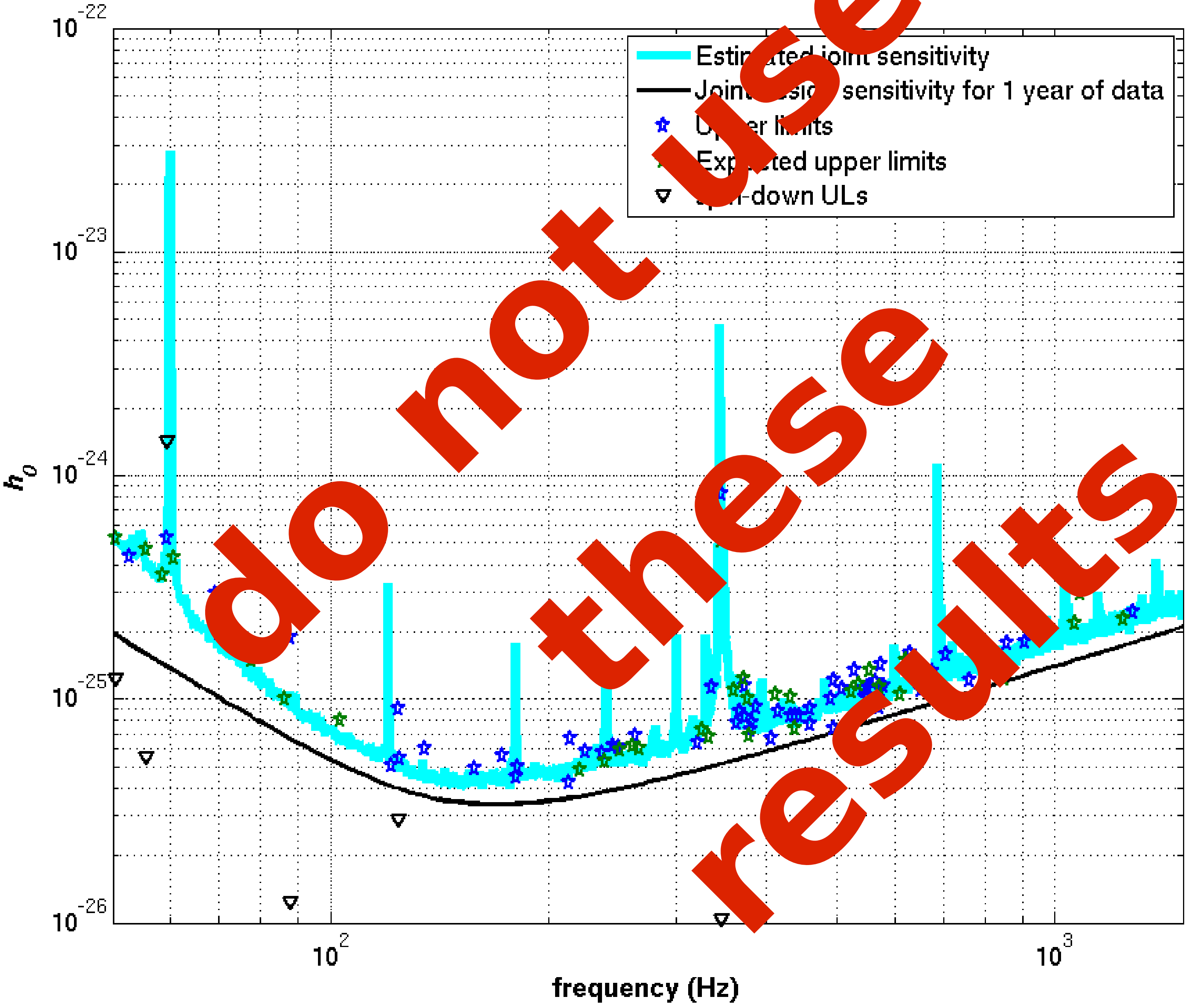
PSR J1435-6100 (ν_{gw} = 214.0 Hz, r = 3.3 kpc) h_{0_min} = 4.2×10^{-26}

Lowest ellipticity upper limit:

PSR J2124-3358 (ν_{gw} = 405.6Hz, r = 0.25 kpc) $\varepsilon = 9.6\times10^{-8}$

Due to pulsar glitches the Crab pulsar result uses data up to the glitch on 23 Aug 2006, and the PSRJ0537-6910 result uses only three months of data between two glitches on 5th May and 4th Aug 2006





- **Black** curve represents one full year of data for all three interferometers running at design sensitivity
- **Blue** stars represent pulsars for which we are reasonably confident of having phase coherence with the signal model
- **Green** stars represent pulsars for which there is uncertainty about phase coherence

Preliminary results

Joint 95% upper limits from first ~13 months of S5 using H1, H2 and L1 (97 pulsars)

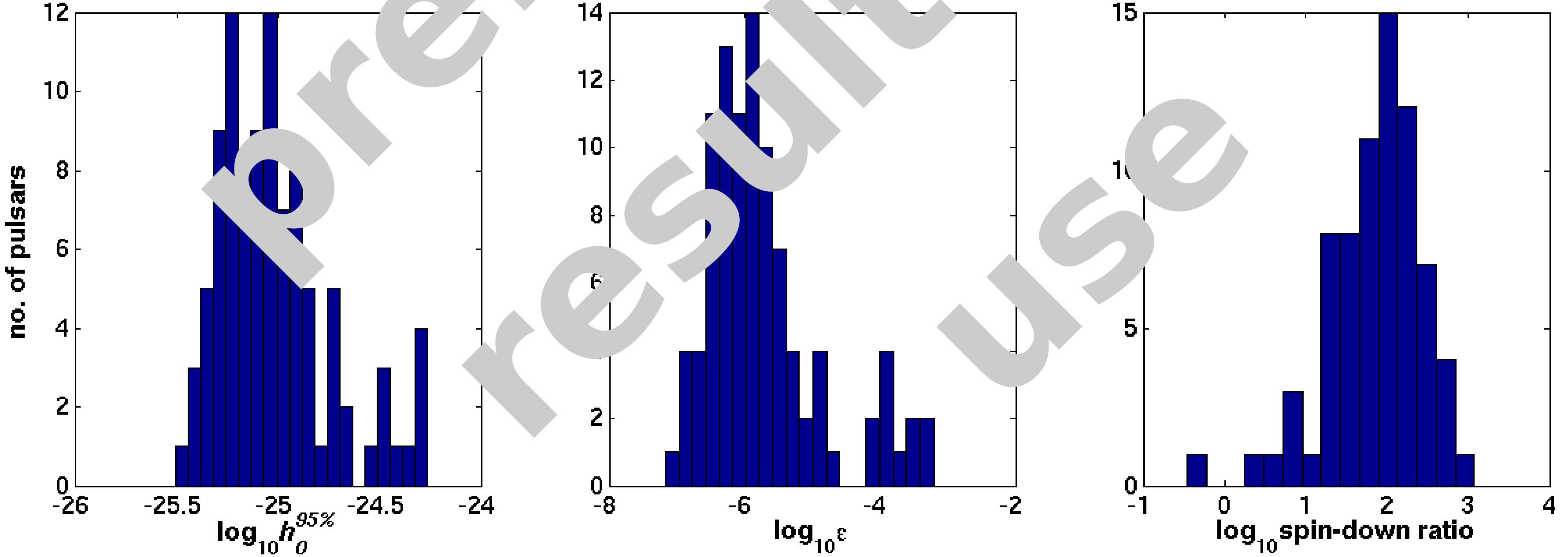
Lowest h_0 upper limit:

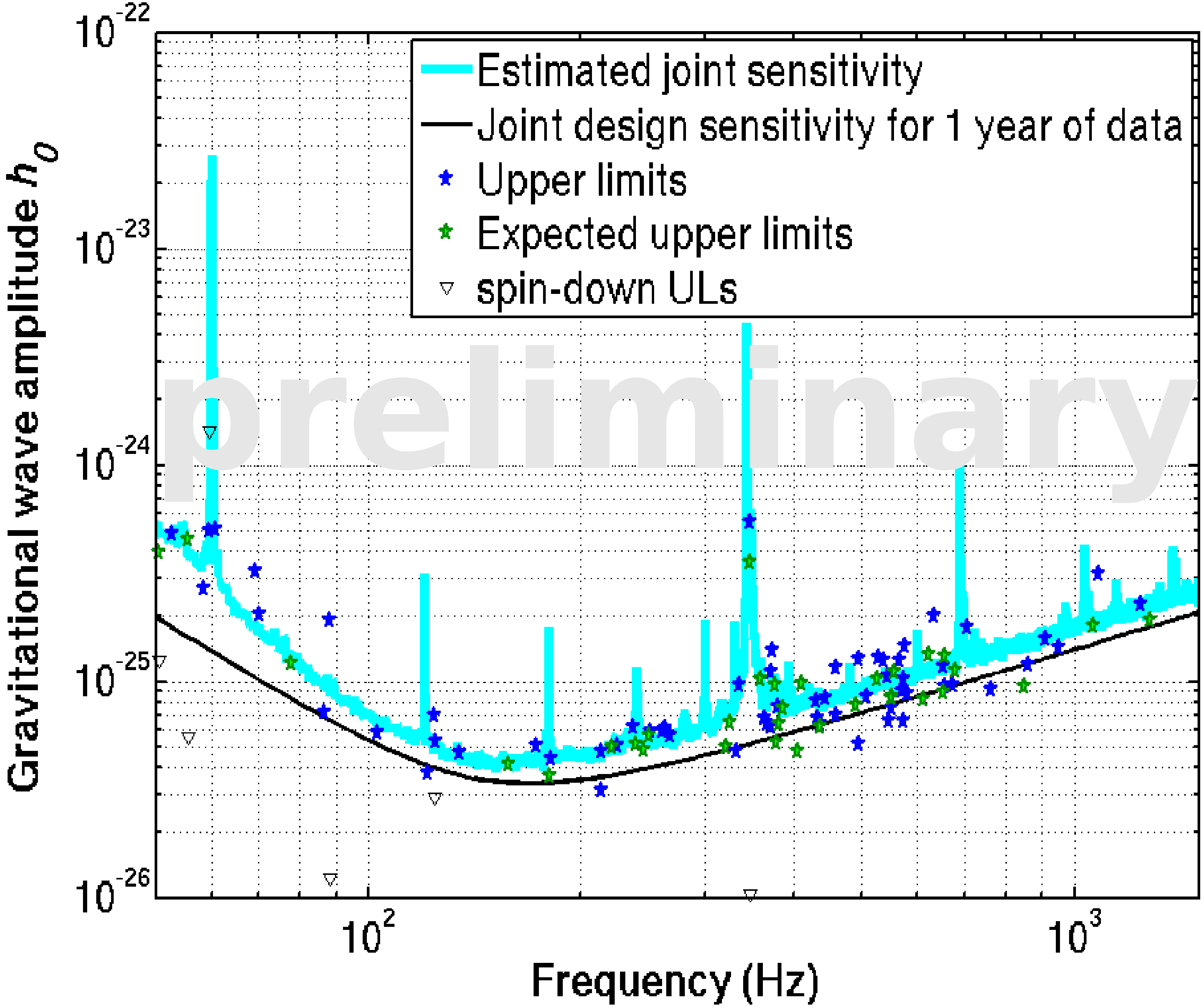
PSR J1623-2631 (ν_{gw} = 180.6 Hz, r = 2.2 kpc) $h_{0\_min} = 3.4\times10^{-26}$

Lowest ellipticity upper limit:

PSR J2124-3358 (ν_{gw} = 405.6Hz, r = 0.25 kpc) $\varepsilon = 7.3\times10^{-8}$

Due to pulsar glitches the Crab pulsar result uses data up to the glitch on 23 Aug 2006, and the PSRJ0537-6910 result uses only three months of data between two glitches on 5th May and 4th Aug 2006





- **Black** curve represents one full year of data for all three interferometers running at design sensitivity
- **Blue** stars represent pulsars for which we are reasonably confident of having phase coherence with the signal model
- **Green** stars represent pulsars for which there is uncertainty about phase coherence

Crab pulsar – spin-down limit

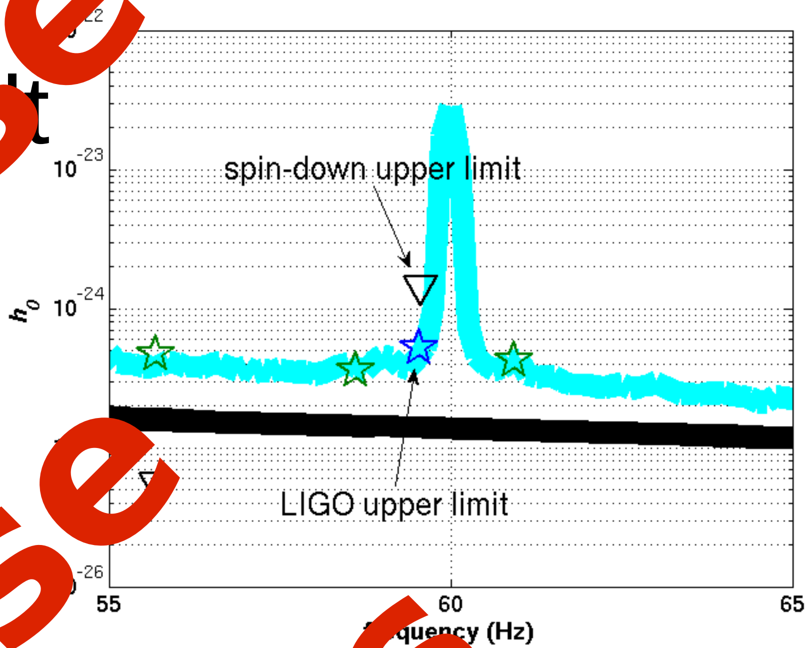
- Spin-down limit assumes all the pulsars rotational energy loss is radiated by gravitational wave
- We know some goes is emitted electromagnetically and is powering the expansion of the Crab nebula
- This is poorly constrained and allows room for gravitational wave emission
- Braking index $\dot{\Omega} = -k\,\Omega^n , n = \frac{\nu \ddot{\nu}}{\dot{\nu}^2}$
  - The braking index of the Crab is n=2.5, not n=3 for purely magnetic dipole radiation, and not n=5 for purely gravitational radiation emission
  - Palomba (2000) allows for a combination of mechanisms to account for this braking index and ends up with a GW spin-down limit which is 2.5 times below the n=5 standard limit.

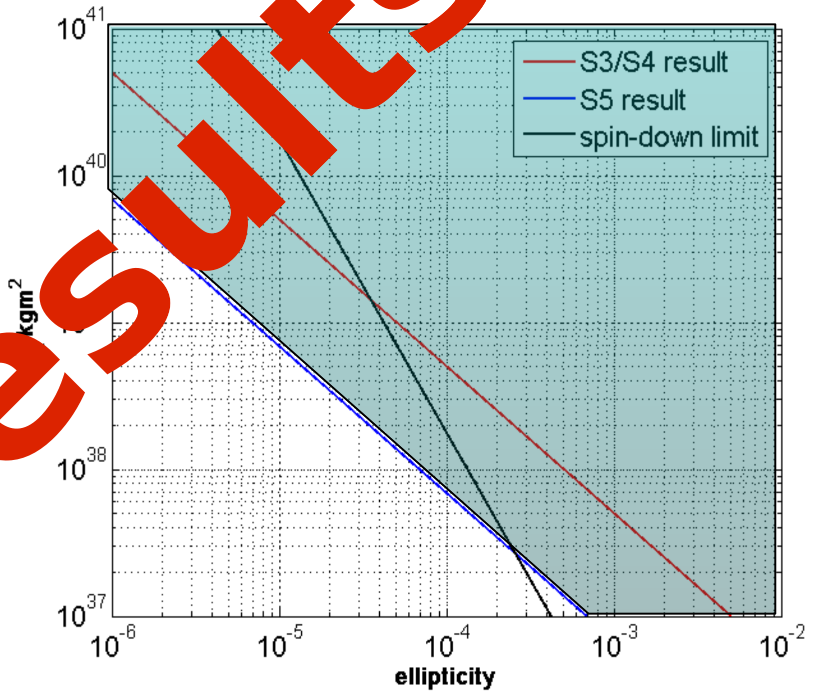
Standard spin-down limit:

$$h_0^{\text{spin-down}} = \left(\frac{5}{2} \frac{G I_{zz} \dot{\nu}}{c^3 r^2 \nu} \right)^{1/2}$$

Crab pulsar - result

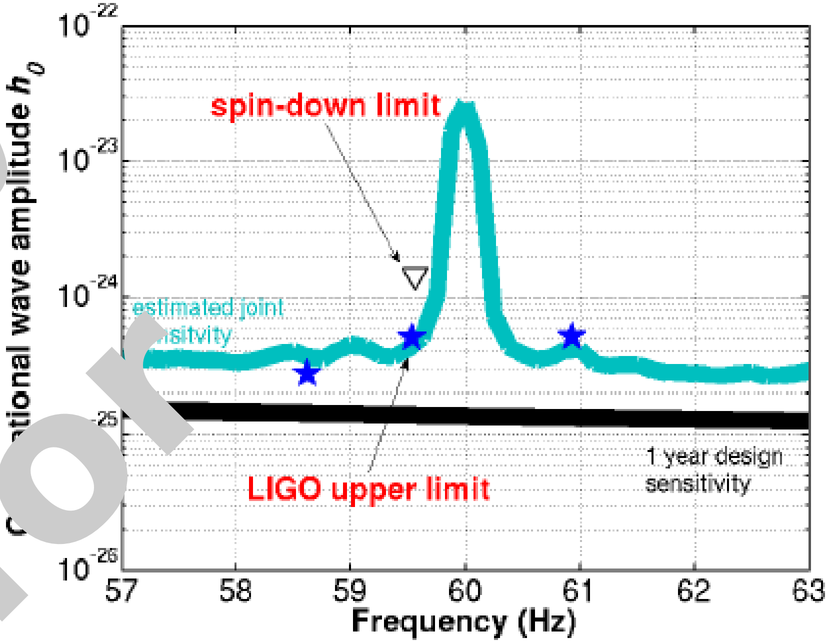
- These results give upper limits for the Crab pulsar of $\varepsilon < 2.8\times10^{-4}$, $h_0 < 5.2\times10^{-25}$
  - » this value of the ellipticity is now in the range of some of the more speculative equations of state (Owen 2005)
- These beat the spin-down limit of $h_0 <$ 1.4×10^{-24} by a factor of 2.7 – for canonical moment of inertia $I = 10^{38}$ kgm^2 - we even beat Palomba's limit
- Start to constrain the amount of spin-down energy in GWs to less than 10% of overall emitted and known spin-down (Palomba 2000, Santostasi)
  - » This is significant: the ***uncertainties*** on all non-GW contributions add up to 80% of the total!
- Moment of inertia is uncertain by about a factor of three, but we can plot the result on the moment of inertia – ellipticity plane to give exclusion regions (Pitkin for the LSC, 2005)

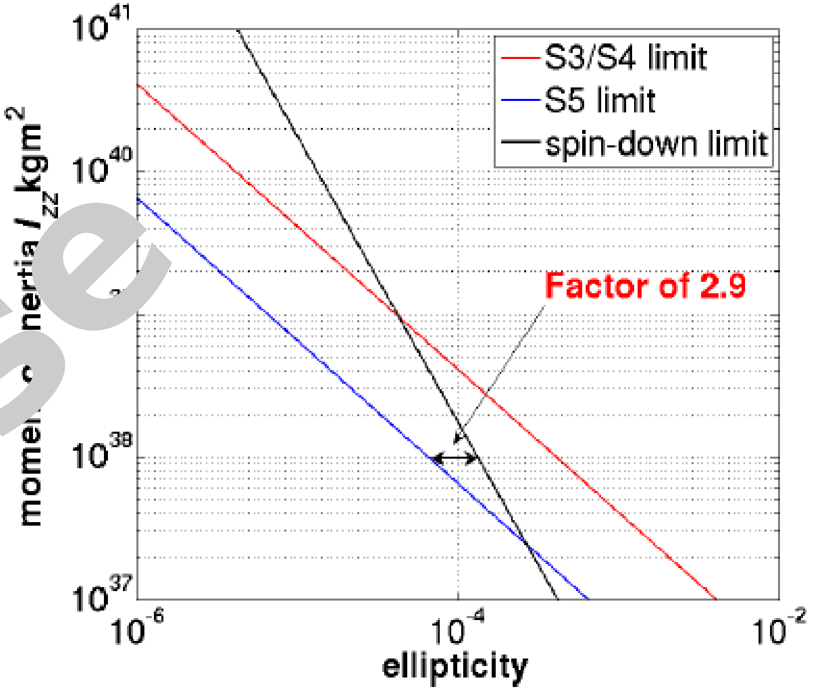




Crab pulsar - result

- These results give upper limits for the Crab pulsar of ε < 2.6x10^{-4}, h_0 < 5.0x10^{-25}
  - this value of the ellipticity is now in the range of some of the more speculative equations of state (Owen, 2005)
- These beat the spin-down limit of h_0 < 1.4x10^{-24} by a factor of 2.9 – for canonical moment of inertia I = 10^{38} kgm^2 - we even beat Palomba's limit
- Start to constrain the amount of spin-down energy in GWs to less than 10% of overall emitted and known spin-down (Palomba, 2000, Santostasi).
  - This is significant: the ***uncertainties*** on all non-GW contributions add up to 80% of the total!
- Moment of inertia is uncertain by about a factor of three, but we can plot the result on the moment of inertia – ellipticity plane to give exclusion regions (Pitkin for the LSC, 2005)





Multi-template search

- The time domain search only operates on a very narrow band – if the gravitational radiation time evolution is different from that of the electromagnetic radiation its possible it may be missing the gravitational waves
- Consider mechanisms by which any emitted gravitational waves will differ from the electromagnetic
- In general, we might assume the following relationship between the GWs and EWs: $f_{gw} = 2\mathrm{f}_{ew}(1+\delta)$ where $\delta \ll 1$
- In the case of free precession, where the spin axis is not aligned with the inertial axis: $\delta \sim \alpha \epsilon$ where $\alpha \sim 1$ and depends on the geometry and ϵ is the ellipticity
- Similarly, if we consider a two-component model, where the GW source spins down separately from the EW, but are connected by some torque acting over a coupling timescale:

$$\delta \sim \frac{\tau_{coupling}}{\tau_{spin-down}}$$

Search parameters continued

- In either of these cases, ϵ is approximately 10^{-4}. In one case roughly the largest imaginable ellipticity, and the other, $\tau_{coupling} \sim 10^{-4} \tau_{spindown} \sim 0.1 \mathrm{years}$ is roughly the longest timescale seen in glitch recovery
- Thus we are naturally led to a frequency band of $\Delta f_{gw} \sim 2 \mathrm{f}_{ew} \delta \sim 6 \times 10^{-3} Hz$
- We also can work out $\Delta \dot{f}_{gw} \sim 3 \dot{f}_{ew} \delta \sim 1.2 \times 10^{-13}$ and $\Delta \ddot{f}_{gw} \sim 8 \dot{f}_{ew} \delta \sim 1 \times 10^{-23}$

Conclusions

- Preliminary and expected upper limits for a large number of pulsars
- Have new timing for some pulsars – need more though over more of S5
  - still need final timings and checks on parameter uncertainties
  - produce final results after the end of S5
- Very interesting result for the Crab pulsar
  - produce results of small parameter search
  - Signal could be incoherent over glitch, so future analysis will use current result as prior on rest of S5 data
- Obtain more pulsar timing e.g. Terzan 5 pulsars and X-ray pulsar (PSRJ0537-6910)
- Carry on analysis…