Results from searches for a continuous gravitational wave signal from the Crab pulsar

Matthew Pitkin for the LIGO Scientific Collaboration

http://www.ligo.org

matthew@astro.gla.ac.uk

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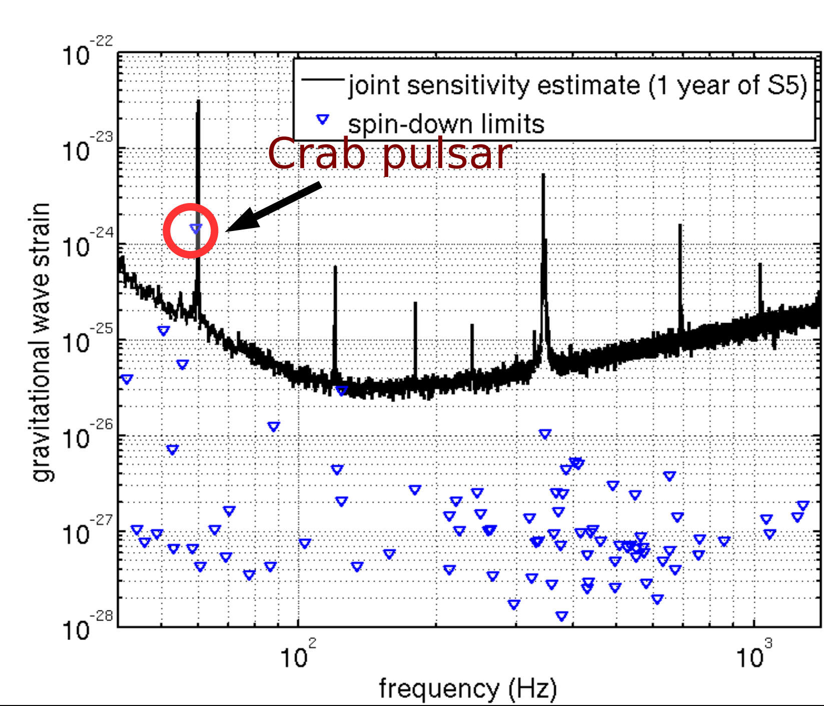
Search motivation

- Known pulsars provide an enticing, well defined, target for gravitational wave (GW) searches
- Crab pulsar has largest spin-down rate of any known radio pulsar at 3.7×10^{-10} Hz/s
- If all energy were dissipated by GW emission, the spin-down upper limit would be 1.4×10^{-24} ($I_{zz}=I_{38}=10^{38}\mathrm{kgm}^2$, r=2 kpc)
  - largest for any pulsar within the LIGO frequency band and beatable with several months of LIGO fifth science run data (S5)
- Nebula emission and acceleration are powered by the spin-down, but uncertainties in the error budget could leave ~80% of the available energy unaccounted for – plenty of room for GW emission

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



An estimate of the joint LIGO sensitivity for known pulsar searches using 1 year S5 data, and spin-down upper limits for known millisecond pulsars

The searches

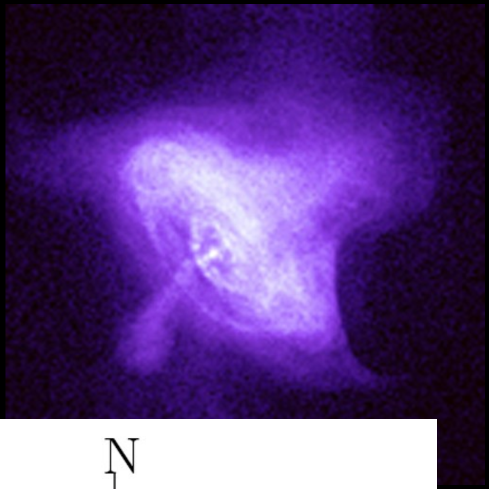
- We present two fully coherent searches for continuous gravitational waves from the Crab pulsar using data from the start of the S5 run on 4th Nov 2005 to 23rd Aug 2006; on this second date the pulsar glitched which could cause the EM and GW signals to decohere
- Both assume a triaxial neutron star emitting gravitational waves at, or near, twice the rotation frequency (59.55 Hz) and combine data from the three LIGO detectors (the 4km H1 and L1 detectors and the 2km H2 detector)
- Use the Jodrell Bank Crab Pulsar monthly ephemeris (http://www.jb.man.ac.uk/~pulsar/crab.html) to track the phase, and search over the four unknown signal parameters of gravitational wave amplitude h_0, pulsar spin-axis inclination angle ι, initial phase ϕ_0, and polarisation angle ψ

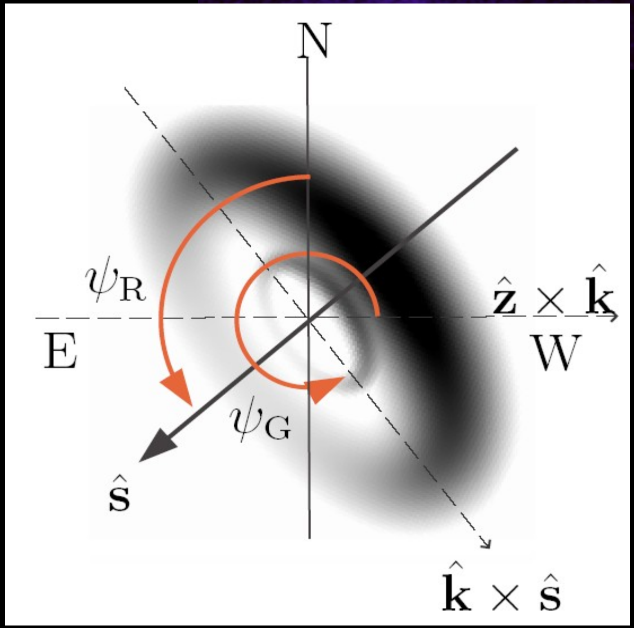
The searches

- ***Time domain search*** - tracks the EM phase evolution precisely and performs a Bayesian parameter estimation over the four unknown parameters (Dupuis and Woan, *Phys. Rev. D*, 2005)
- ***Frequency domain search*** - allows a small physically motivated frequency offset from twice the rotation frequency and uses a frequentist maximum likelihood-based statistic to assess detection (Jaranowski et al, *Phys. Rev. D*, 1998; Cutler and Schutz, *Phys. Rev. D*, 2006)
- In the absence of a signal, 95% confidence upper limits on h_0 are calculated: by marginalising over the other parameters for the time domain method; by performing Monte-Carlo injections for the frequency domain method
- The searches have been performed using both a uniform prior on all 4 unknown parameters and an observationally motivated prior for the inclination and polarisation angles

Prior information on orientation

- There is observational evidence that identifies the orientation of the pulsar from the geometry of the Crab Pulsar Wind Nebula
- The values of the inclination angle and polarisation angle are well constrained by X-ray observations (Ng and Romani, *Ap. J.*, 2004, 2007)
- We choose Gaussian priors about these values, relating to the statistical and systematic errors given, of ι = 62.2 +/- 2.2 and ψ = 125.2 +/- 1.4 degs



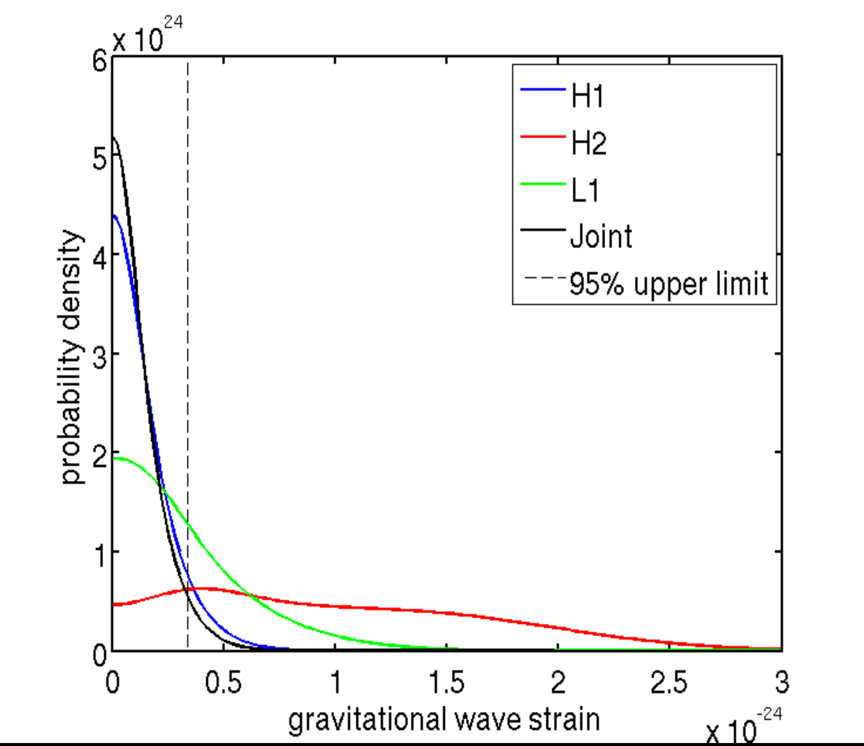


Ng & Romani, *Ap. J.*, 2004

Time domain result - preliminary

- Using uniform priors gives an upper limit for the Crab pulsar GW emission of h_0 **= 3.4x10^{-25}**
- **Lower than the classical spin-down limit of h_0 = 1.4x10^{-24} by a factor of 4.2** (for $I_{zz}=I_{38}$, r=2 kpc)
- With the restricted priors we get a joint upper limit of 2.7x10^{-25}
- Results have a combined systematic and statistical uncertainty from the data calibration of ±20%
- In terms of the pulsar's equatorial ellipticity this gives **ε = 1.8x10^{-4}**

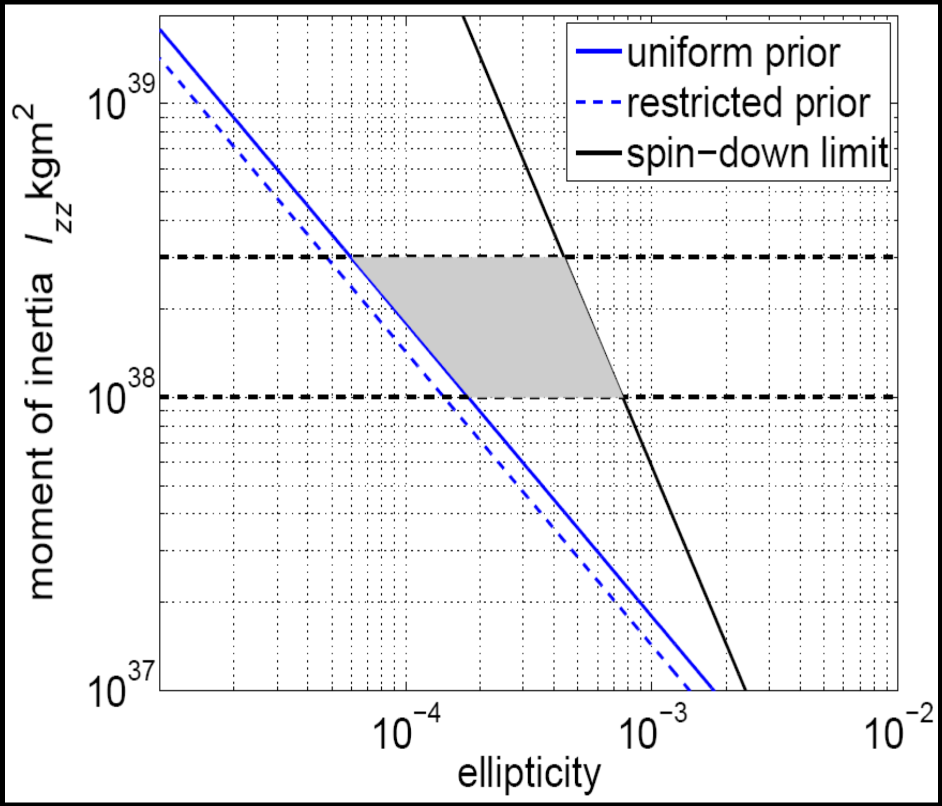
$$\epsilon = 0.237\left(\frac{h_0}{10^{-24}}\right)\left(\frac{r}{1\,kpc}\right)\left(\frac{1\,Hz}{\nu}\right)^2\left(\frac{I_{38}}{I_{zz}}\right)$$



The probability distributions for the gravitational wave amplitude for the three LIGO detectors and the combined result using uniform priors on all four unknown parameters

Uncertain moment of inertia

- We can cast the result in terms of the quadrupole moment $\sim I\varepsilon$ which relaxes the assumption of the canonical moment of inertia
- Assuming maximum and minimum allowable moments of inertia of 1-3x10^{38} kgm^2 we exclude a region of this parameter space



The upper limit results as exclusion regions on the moment of inertia-ellipticity plane

Time domain recap

- We have a preliminary limit on $h_0 = 3.4 \times 10^{-25}$ which is lower than the classical spin-down limit by a factor of 4.2
- Ellipticity of 1.8×10^{-4} is in the range permitted by some exotic quark star equations of state (Owen, *Phys. Rev. Lett*, 2004, Lin, *Phys. Rev. D*, 2007, Haskell et al, *Phys. Rev. Lett*., 2007)
- Constrains the amount of the available spin-down power radiated away via GWs to less than 6%
- Observational constraints of angular parameters can be used and improve our limit to be 5.3 times lower than spin-down
- Pulsar's braking index of n=2.5 shows that pure GW emission is *not* responsible for spin-down (n=5), and from this Palomba (*A&A,* 2000) suggest a spin-down limit 2.5 times lower than the classical one – we beat this limit by 1.7 times

Motivation for a wide parameter search for the Crab pulsar

- We can imagine some simple physical mechanisms by which the GWs and EM pulses would have different frequencies
  - Free precession
  - Two component model
- Considering these models leads to estimates of possible differences in the frequency of the GWs and EM pulses
- These estimates are larger than the resolution of a single template for 9 months of data – roughly 5×10^{-8} Hz
  - Necessary to run a multiple template search on a larger parameter space

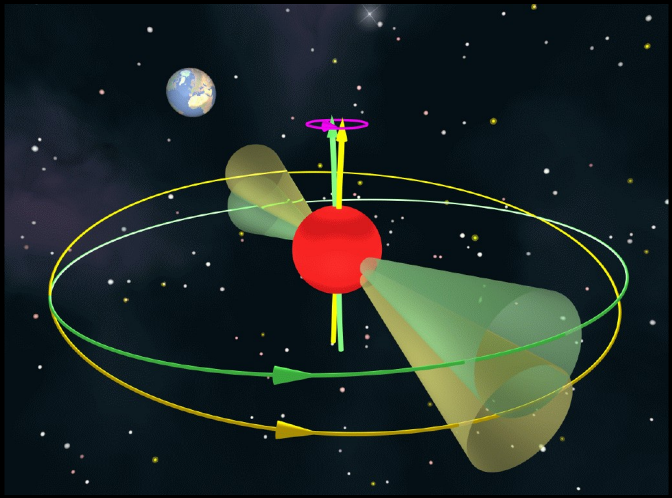
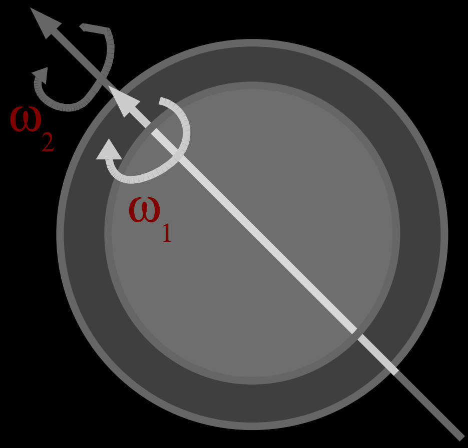


Image credit: M. Kramer



Final Parameter space

- The size of the parameter space searched is:

$$\Delta f_{gw} = 1.2 \times 10^{-2}\, Hz$$

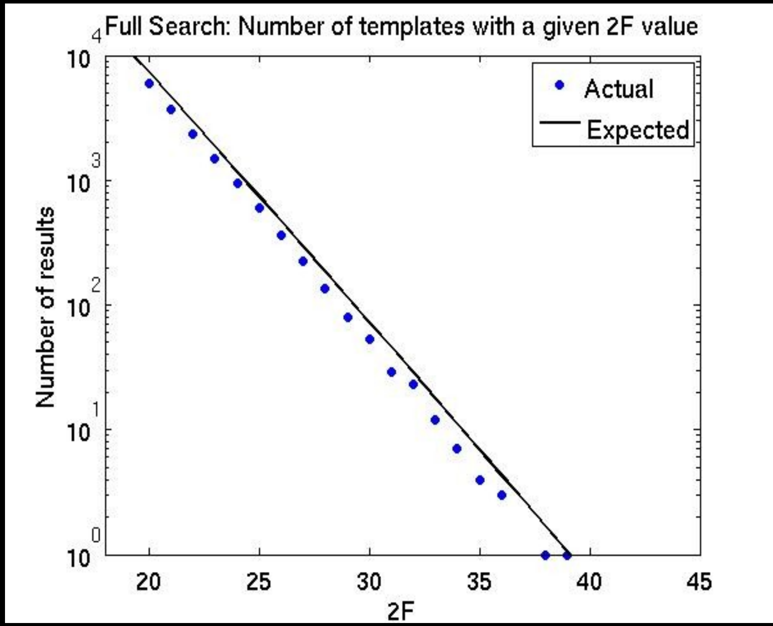
$$\Delta \dot{f}_{gw} = 3 \times 10^{-13}\, Hz/s$$

$$\ddot{f}_{gw} = 1.24 \times 10^{-20}\, Hz/s^2$$

- Parameter space was chosen in part because it is:
  - physically motivated
  - computationally reasonable
- Requires a total of $3\text{x}10^7$ templates each defining the known right ascension and declination, frequency, 1^{st} derivative of frequency + 1 value for the 2^{nd} derivative of frequency

Upper limit - preliminary

- The result of this search was consistent with Gaussian noise
- The frequentist 95% confidence upper limit found for a uniform parameter space over the unknown values was $h_0 = 1.7\times10^{-24}$ (cf. $h_0=3.4\times10^{-25}$ for time domain search)
  - loss in sensitivity when one searches a larger parameter space
- The 95% confidence upper limit found using the Gaussian prior ranges for ι and ψ was $h_0 = 1.3\times10^{-24}$ (cf. $h_0=2.7\times10^{-25}$ for time domain search)
  - **below spin-down limit**



The number of search templates for each value of the maximum likelihood *F*-statistic for the S5 data compared with the expected values

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Conclusions

- No plausible continuous GW signal from the Crab pulsar was found using data from the first ~9 months of LIGOs S5 run
- The classical spin-down limit was beaten
  - likely that less than 4% of the spin-down energy loss is due to GWs (for single template, restricted parameter search)
  - gravitational wave observations are providing *new* information unobtainable by previous EM observations
- The search will continue for the full S5 data set
  - push the Crab pulsar limit further down
  - potentially reach the spin-down limit for 2 more pulsars (beatable with Enhanced LIGO)
  - Advanced LIGO should beat spin-down limits for many pulsars
- Paper in preparation