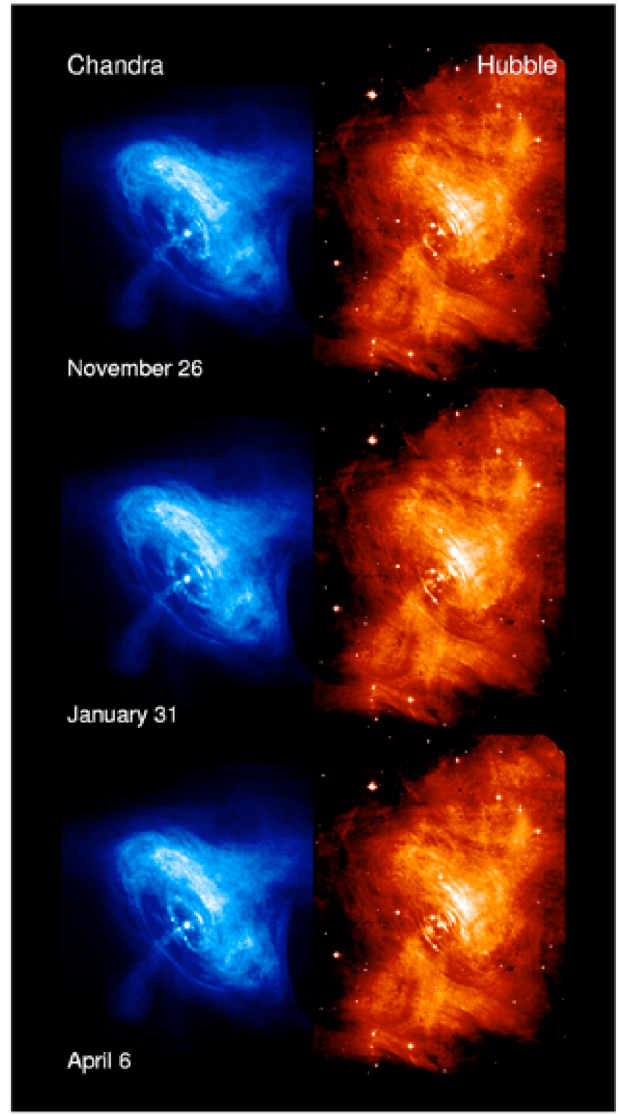
Beating the spin-down limit on gravitational wave emission from the Crab pulsar



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Talk overview

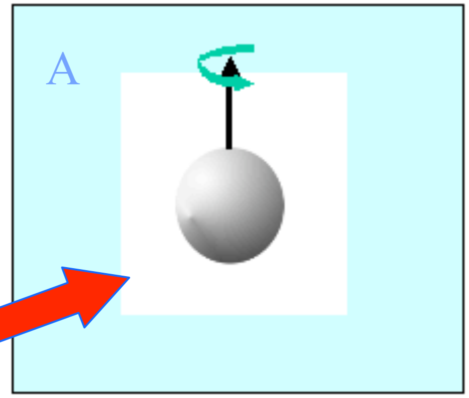
- Spinning compact objects as sources of gravitational waves
- Spindown limit
- Two searches for gravitational waves from the Crab pulsar:
  - Time-domain search with single template
  - Frequency-domain search of f and f-dot parameter space
- No detection: set preliminary upper limits
  - Direct upper limits on Crab better than that inferred from spindown from radio observations

Sources

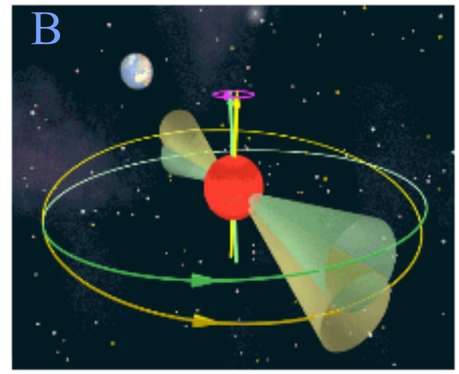
~~Inspirals!~~

In general, LSC all-sky search methods can detect any of these type of periodic sources

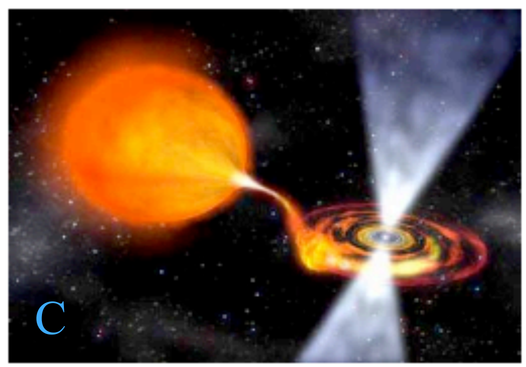
Here however, upper limits are set on gravitational wave amplitude, h_0, of rotating triaxial ellipsoid



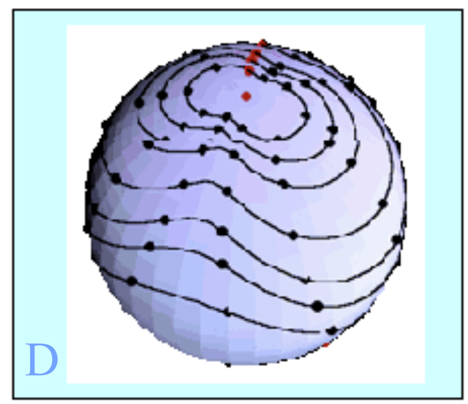
Mountain on neutron star



Precessing neutron star



Accreting neutron star



Oscillating neutron star

Credits:

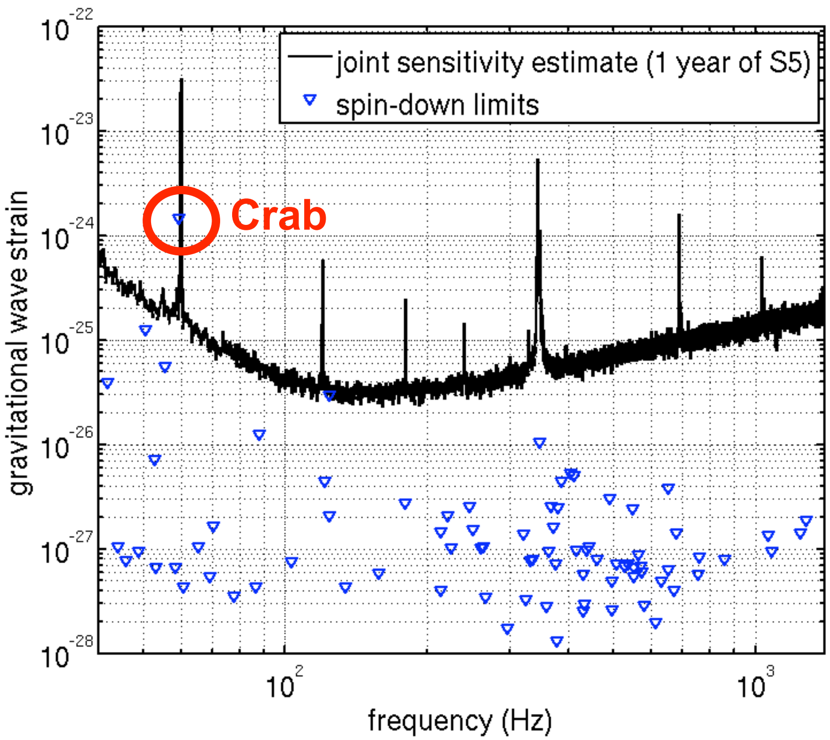
A. image by Jolien Creighton; LIGO Lab Document G030163-03-Z.

B. image by M. Kramer; Press Release PR0003, University of Manchester - Jodrell Bank Observatory, 2 August 2000.

C. image by Dana Berry/NASA; NASA News Release posted July 2, 2003 on Spaceflight Now.

D. image from a simulation by Chad Hanna and Benjamin Owen; B. J. Owen's research page, Penn State University.

Expected sensitivity



Estimated search sensitivity, or one year of S5 data, employing all three LIGO interferometers. Also shown: spindown limits for known pulsars in the LIGO band

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} ($I_{zz}=I_{38}=10^{38}$ 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

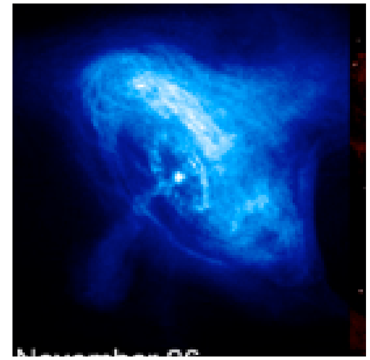
The two searches

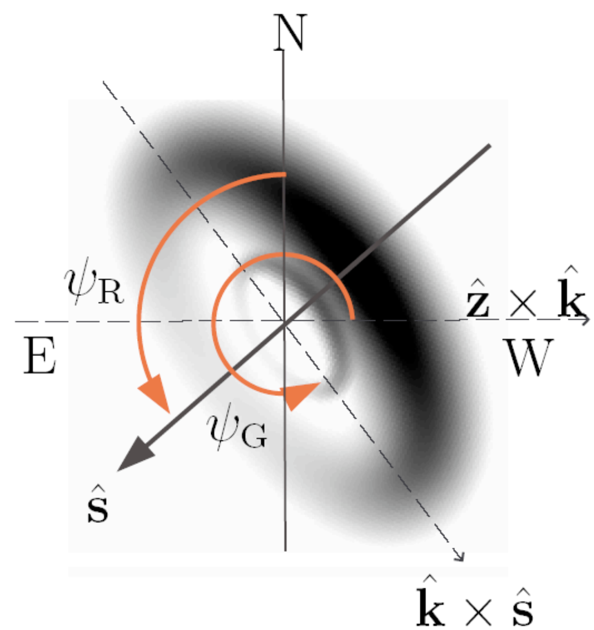
- The two fully coherent searches for continuous gravitational waves from the Crab pulsar use data from the start of the S5 run on 4th Nov 2005 to 23rd Aug 2006; on this second date the pulsar glitched which could cause the EM and GW signals to decohere
- Time-domain search: twice the rotation frequency (= 59.55 Hz)
- Frequency domain search: Δf_{gw}=1.2 x 10^{-2} *Hz*, $\Delta \dot{f}_{gw}$=3x10^{-13} *Hz/s*, $\ddot{f}$ = 1.24 x 10^{-20} *Hz/s²*
- 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 polarization angle ψ

Radio timing provided by Jodrell Bank Pulsar Group

Astrophysical input

- Both searches have been performed using both a uniform pdf on all 4 unknown parameters and an observationally motivated pdf for the inclination and polarization angles
- 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 polarization angle are well constrained by X-ray observations (Ng and Romani, Ap. J., 2004, 2008)
- We choose Gaussian pdfs about these values, relating to the statistical and systematic errors given, of ι = 62.2^o +/- 2.2^o and ψ = 125.2^o +/- 1.4^o





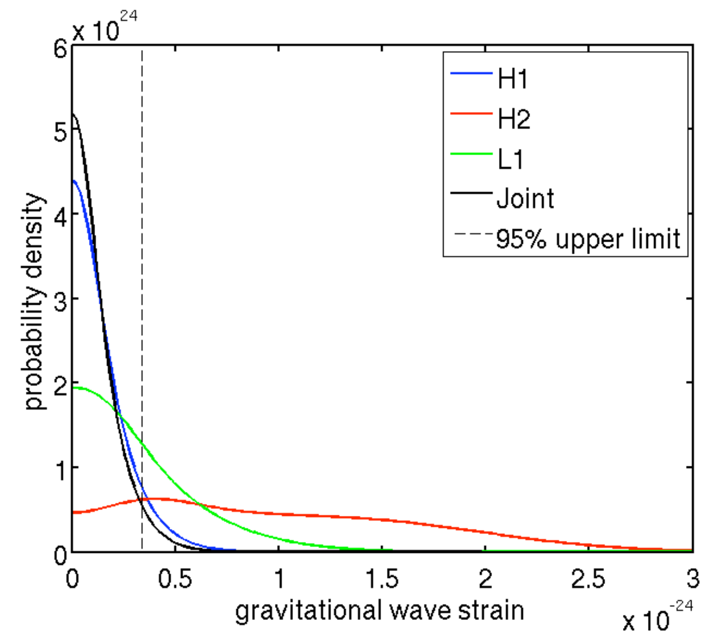
Ng and Romani, ApJ 601 (2004) 479

Time-domain results

(single template search)

PRELIMINARY

- Using uniform pdfs gives an upper limit for the Crab pulsar GW emission of $h_0 = 3.4\times10^{-25}$
- Lower than the classical spin-down limit of $h_0 = 1.4\times10^{-24}$ by a factor of 4.2 (for $I_{zz}=I_{38}$, r=2 kpc)
- With the restricted pdfs we get a joint upper limit of 2.7×10^{-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 $\varepsilon = 1.8\times10^{-4}$

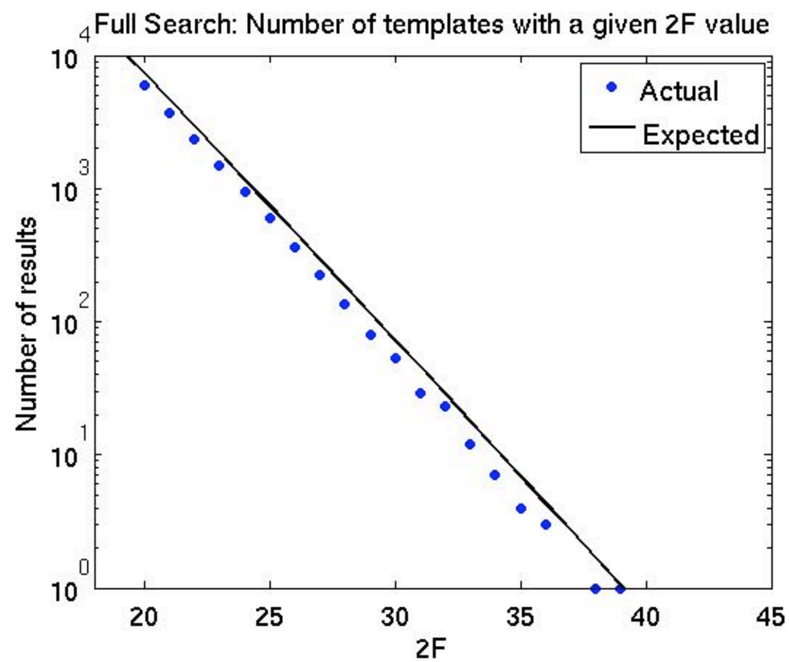


Probability distributions for the gravitational wave amplitude for the three LIGO detectors, plus the combined result (using uniform priors on all four unknown parameters)

Frequency domain results

(multi-template search)

- The result of this search was consistent with Gaussian noise
- The frequentist 95% confidence upper limit found for uniform pdfs 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 observationally motivated pdfs 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



Results of the frequency domain search

Summary

- 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 by a factor of 4.2
- I_{zz} known only to within a factor of ~2
- 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, pushing 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
- The LIGO Scientific Collaboration is interested in working with astronomers to improve knowledge of astrophysical objects, e.g. radio timing of pulsars