Searching for gravitational waves from known pulsars

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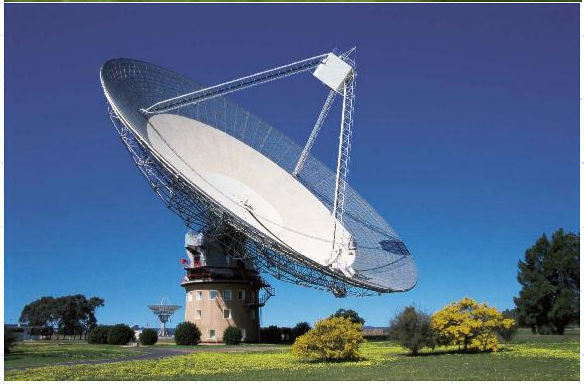
Summary of work to date

- There have been three science runs of the LIGO detectors and two with GEO 600 (S1 and S3) with which **known** pulsar searches have been or are being performed:
  - S1 (23 August – 9 September 2002) – a targeted search for gravitational waves from J1939+2134 using time domain and frequency domain techniques (B. Abbott *et al*, **PRD**, **69**, 2004, `gr-qc/0308050`)
  - S2 (14 February – 14 April 2003) – a targeted search for 28 known **isolated** pulsars with frequencies > 25 Hz using the time domain technique (B. Abbott *et al*, submitted to **PRL**, `gr-qc/0410007`)
  - S3 (31 October 2003 – 9 January 2004) – a targeted search is *underway* for **all** (~110) pulsars with frequencies > 25 Hz including those in binary systems
- These runs are providing the best **direct** upper limits on gravitational wave amplitude and neutron star ellipticity.

S2 summary - analysis

- We had timing information for 28 isolated pulsars with frequencies > 25 Hz from the ATNF catalogue.
- 18 of these were re-timed over the S2 run period, by Michael Kramer (Jodrell Bank). The other 10 are sufficiently stable that older timing data was accurate.
- The chosen pulsars included **14 in globular clusters**, the **Crab pulsar** and the fastest millisecond pulsar **J1939+2134**.
- We performed a time domain heterodyne of the interferometer data with the **known** phase evolution of the pulsar signal.
- The pdfs of the unknown signal parameters (gravitational wave amplitude h_0, orientation angle ι, polarisation angle ψ, and initial phase ϕ_0) were then determined using Bayesian inference.



S2 summary – the injections

- We injected two artificial pulsar signals into the 3 LIGO interferometers for 12 hours.
- This provides end-to-end validation of the search pipeline.
- The injections confirm the phase calibration of the detectors, and verify that a joint coherent analysis can be used.

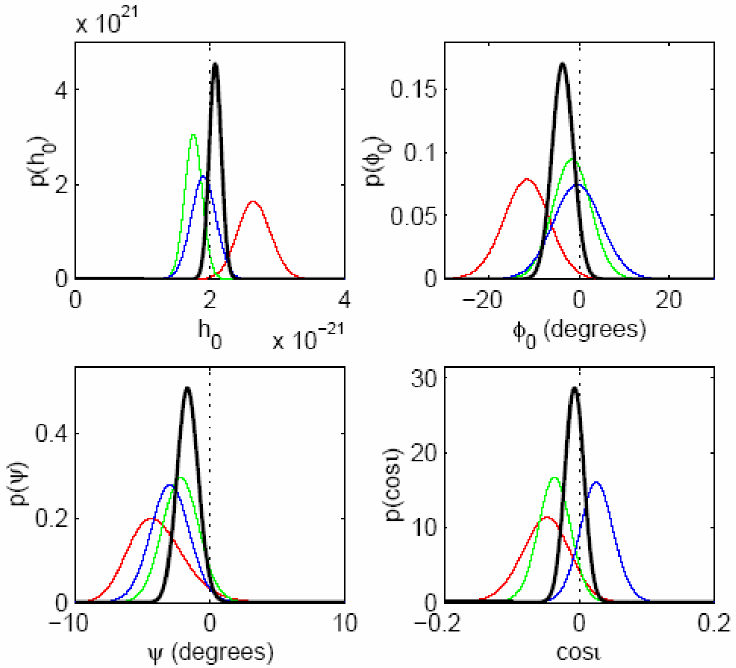


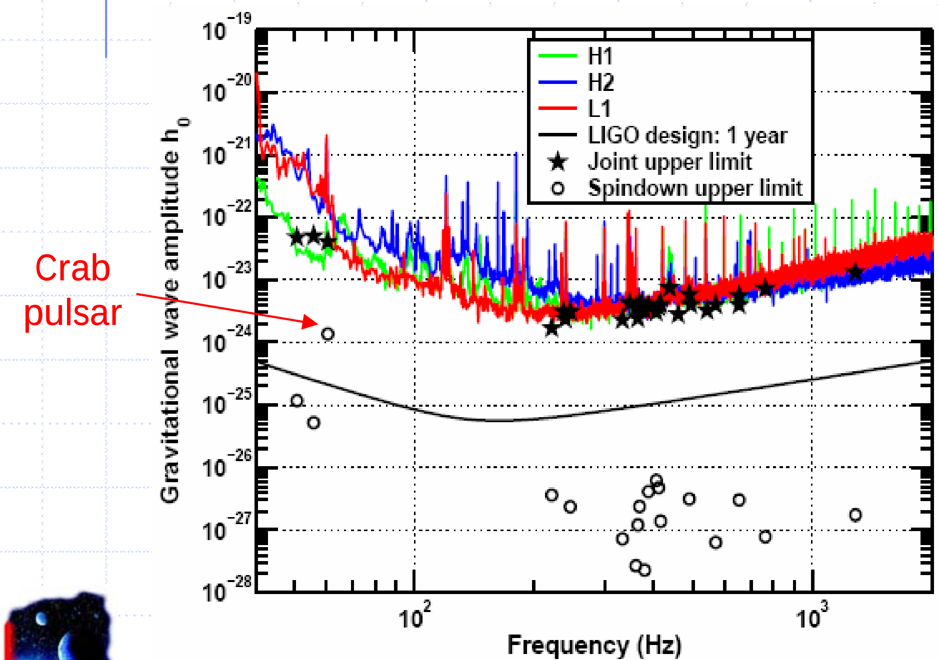
FIG. 2: Parameters of the artificial pulsar P1, recovered from 12 h of strain data from the Hanford and Livingston interferometers. The results are displayed as marginal pdfs for each of the four signal parameters. The vertical dotted lines show the values used to generate the signal, the colored lines show the results from the individual detectors (H1 green, H2 blue, L1 red), and the black lines show the joint result from combining coherently data from the three.

(from B. Abbott *et al*, gr-qc/0410007)

S2 summary - results

h_0 95% UL	Pulsars
1e-24 < h_0 < 5e-24	20
5e-24 < h_0 < 1e-23	4
h_0 > 1e-23	4

ellipticity ε	Pulsars
1e-6 < ε < 1e-5	4
1e-5 < ε< 1e-4	16
ε > 1e-4	8



- Lowest 95% UL on h_0 = 1.7e-24 (J1910-5959D)
- Lowest bound on ε = 4.5e-6 (J2124-3358)
- Crab pulsar:
  - h_0 = 4.1e-23
  - ε = 2.1e-2 (~30 times spin-down upper limit)

S2 results – astrophysics

- Whilst our upper limits for these pulsars are generally well above those permitted by spin-down constraints and neutron star equations-of-state they have *some* astrophysical interest.
- We provide the first *direct* upper limits on gravitational wave emission for 26 of the 28 pulsars.
- For the 14 globular cluster pulsars we provide the first limits independent of the cluster dynamics.
- Our most stringent ellipticities (4.5e-6) are starting to reach into the range permitted by at least one exotic theory of neutron star structure (B. Owen, submitted to **PRL**).

S3 analysis

- Our S3 analysis includes all (110) pulsars with rotational frequencies > 25 Hz
- Includes binary systems (70) in analysis adding extra complexity to the signal
- Both LIGO and GEO 600 data are available

☐ (shaded) Analysis underway (78)
☐ Awaiting timing data (32)

J0024-7204C	J0218+4232	J1537+1155	J1745-0952	J1918-0642
J0024-7204D	J0437-4715	J1603-7202	J1748-2446A	J1939+2134
J0024-7204E	J0514-4002A	J1618-39	J1748-2446C	J1952+3252
J0024-7204F	J0534+2200	J1623-2631	J1757-5322	J1955+2908
J0024-7204G	J0537-6910	J1629-6902	J1804-0735	J1959+2048
J0024-7204H	J0613-0200	J1640+2224	J1804-2717	J2019+2425
J0024-7204I	J0621+1002	J1641+3627A	J1807-2459	J2033+17
J0024-7204J	J0635+0533	J1641+3627B	J1810-2005	J2051-0827
J0024-7204L	J0711-6830	J1643-1224	J1823-3021A	J2124-3358
J0024-7204M	J0737-3039A	J1701-3006A	J1824-2452	J2129+1210D
J0024-7204N	J0751+1807	J1701-3006B	J1843-1113	J2129+1210E
J0024-7204O	J1012+5307	J1701-3006C	J1857+0943	J2129+1210F
J0024-7204P	J1022+1001	J1701-3006D	J1905+0400	J2129+1210G
J0024-7204Q	J1024-0719	J1701-3006E	J1909-3744	J2129+1210H
J0024-7204R	J1045-4509	J1701-3006F	J1910+0004	J2129-5721
J0024-7204S	J1300+1240	J1709+2313	J1910-5959A	J2130+1210C
J0024-7204T	J1312+1810	J1713+0747	J1910-5959B	J2140-2310A
J0024-7204U	J1420-5625	J1721-2457	J1910-5959C	J2140-23B
J0024-7204V	J1435-6100	J1730-2304	J1910-5959D	J2145-0750
J0024-7204W	J1455-3330	J1732-5049	J1910-5959E	J2229+2643
J0030+0451	J1518+0205A	J1740-5340	J1911-1114	J2317+1439
J0034-0534	J1518+0204B	J1744-1134	J1913+1011	J2322+2057

Binary pulsar signal

- For an isolated pulsar the signal received at the detector needs to be corrected to the solar system barycentre (SSB) by calculating Doppler delays and relativistic effects.
- For a pulsar in a binary system we also need to take account of the pulsar motion within that system.
- This adds time delays equivalent to those for the solar system

$$\Delta T_{\text{bin}} = \Delta_{\text{R}_{\text{bin}}} + \Delta_{\text{E}_{\text{bin}}} + \Delta_{\text{S}_{\text{bin}}} + \Delta_{\text{A}}$$

Roemer delay (light travel time)

Einstein delay

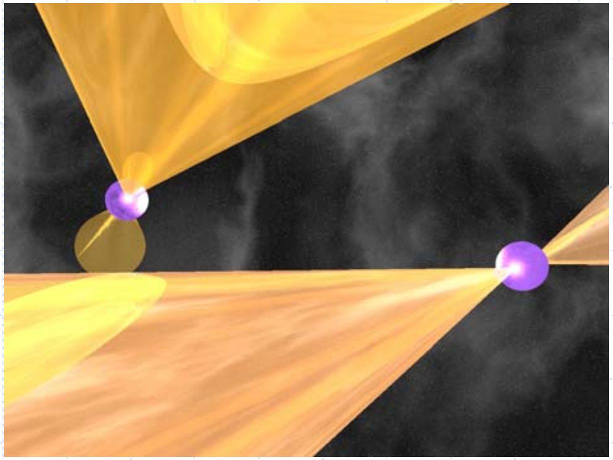
Shapiro delay

Aberration delay (caused by pulsar rotation)

- These time delays are parameterised by various measurable properties of the binary system (period P, eccentricity e, angular velocity ω, time of periastron T, projected semi-major axis $a\sin(\iota)$, and relativistic parameters).

Binary pulsar signal

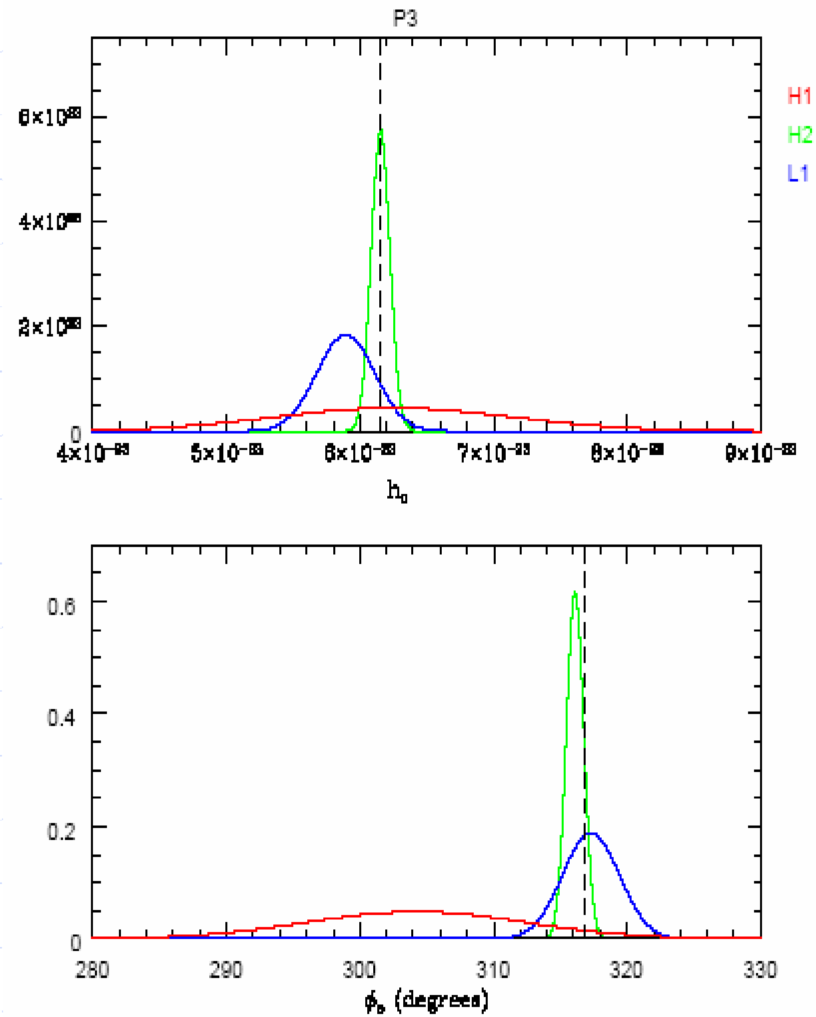
- These parameters are found by fitting radio observations (using the standard TEMPO data reduction package) to various binary models (see Taylor and Weisberg, ApJ, **345**, pp. 434-450, 1989).
- The model used will depend on how relativistic the system is or which parameters you wish to fit (e.g. for low eccentricity orbits use ELL1, to get binary mass information use DDGR).
- 70 binary pulsars fall mainly into two model catagories:
  - **32 ELL1** (low eccentricity)
  - **33 BT** (Blandford-Teukolsky)
  - 1 BT2P (two orbiting planets)
  - 4 DD (Damour-Deruelle) including double pulsar binary J0737-3039A



Artist's impression of double pulsar system. Credit: Michael Kramer

S3 injections

- In S3 we injected 10 artificial pulsar signals with a wide range of signal parameters.
- Signal strengths ranged from the marginally detectable to very strong.
- Very strong signals could have parameters extracted to such accuracy that the systematic errors in the instrument calibration become visible.

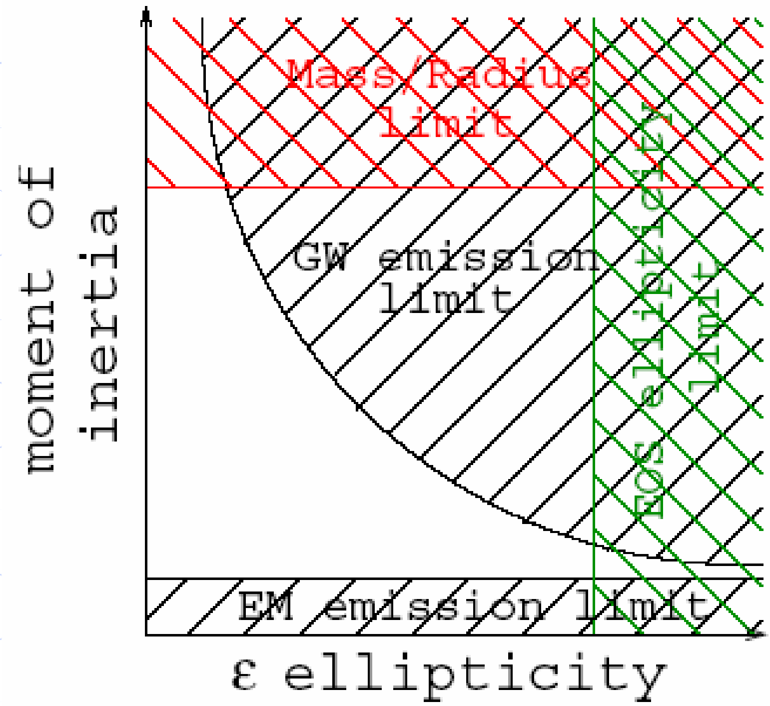


Extracted values of h_0 and ϕ for one of the injected pulsar signals (R. Dupuis, PhD thesis)

Interpreting results on the I-ε plane

- We do not really know neutron stars' moment of inertia – so far we've been using the canonical value.
- Rather than use the upper limit on h_0 to set a limit on ε we can instead use it as an upper limit on the quadrupole moment ,Iε.
- This can then be plotted on a I-ε plane providing exclusion regions on both the moment of inertia and ellipticity.

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



S3 – further work

- Analysis is currently underway for all pulsars with up-to-date timing from Michael Kramer (78 pulsars).
- We will complete evaluation of systematic uncertainties from calibration errors, pulsar distance errors, etc.
- We expect ~ order of magnitude improvements over S2 on some upper limits i.e. getting the Crab pulsar UL to a factor of a few above the spin-down limit.
- MCMC methods for searching for possible known sources with uncertain parameters will be applied (see poster by J. Veitch).