Searches for gravitational waves from known pulsars in the LIGO and Virgo data

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arXiv:1309.4027 (J. Aasi et al. 2014 ApJ 785 119)

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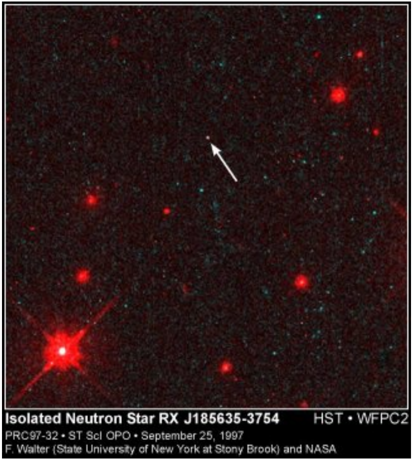
Outline

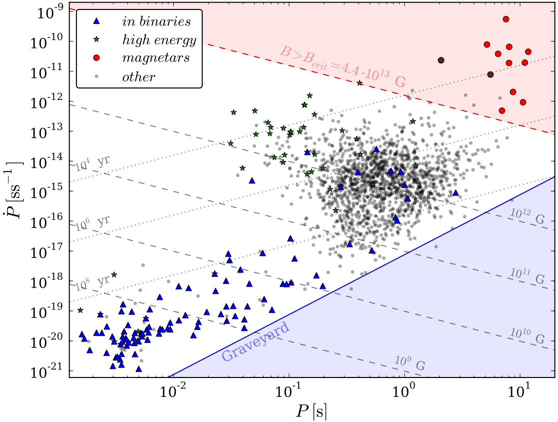
- $\star$ Mechanism of GW emission & spin-down limit,
- $\star$ Description of the VSR2/VSR4/S6 search,
  $\rightarrow$ `arXiv:1309.4027` (J. Aasi et al. 2014 ApJ 785 119),
- $\star$ Results & highlights.



- mass M $1-2M_{\odot}$,
- $N \simeq 10^{57}$ baryons,
- radius $R \simeq 10\ \mathrm{km}$,
- mean density $\rho \sim 10^{14}\ \mathrm{g/cm^3}$,
- magnetic field $10^{8}\ \mathrm{G} < B < 10^{15}\ \mathrm{G}$,
- rotation $f \sim 1000/s$,
- compactness $r_g/R \simeq 0.25$ ($r_g = 2GM/c^2$),
- Pressure by degenerate nucleons (mostly neutrons) + strong forces!

Pulsar = a magnetized, rotating neutron star. First approximation: rotating, radiating EM dipole.

Estimates of the magnetic field B and characteristic age τ from observed spin period P and spin period derivative $\dot{P}$:

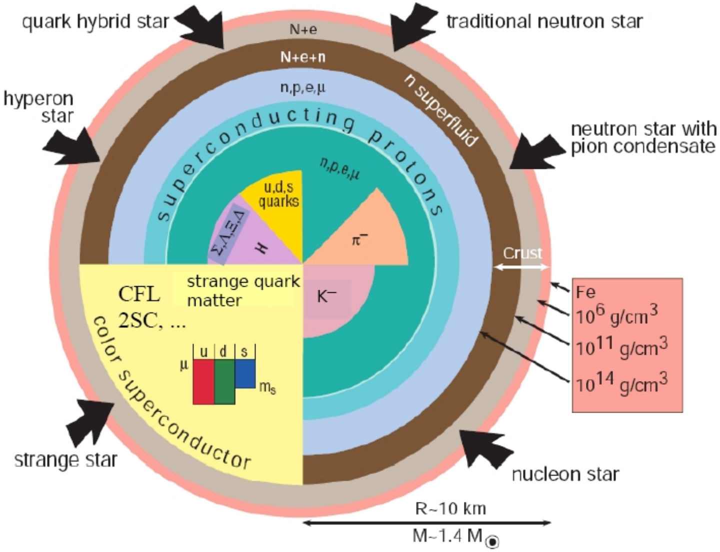


$$B > \left(\frac{3c^3 I}{8\pi^2 R^6}\right)^{1/2} \sqrt{P\dot{P}},$$

$$\tau = P/(2\dot{P})$$

where I is the moment of inertia, and R the radius of the star.

The mystery of neutron stars' interior



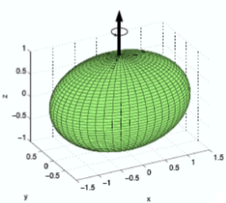
(by F. Weber)

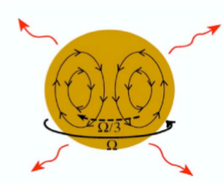
Time-varying quadrupole moment needed:

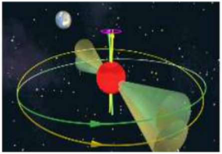
- ⋆ Mountains (supported by elastic and/or magnetic stresses in the NS crust and/or core),
- ⋆ Oscillations (r-modes)
- ⋆ Free precession,
- ⋆ Accretion from the companion (deformations, thermal gradients, magnetic fields).

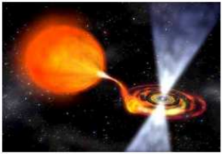
Main characteristics of such GWs:

- ⋆ periodic, $f_{\mathrm{GW}} \propto f_{\mathrm{rot}}$,
- ⋆ long-lived, $T > T_{\mathrm{obs}}$.



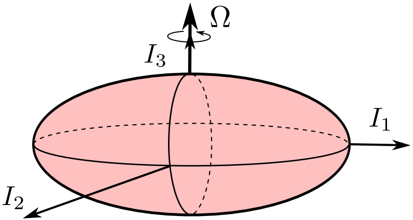






GW emission model

Triaxial rotating star:



GW strain:

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

with

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_3 \varepsilon f_{rot}^2}{d}.$$

- ⋆ GW amplitude h_0,
- ⋆ inclination of the star's rotation axis to the line-of-sight ι,
- ⋆ GW polarization angle ψ related to the antenna patterns $F_+(t,\psi)$ and $F_\times(t,\psi)$,
- ⋆ GW phase $\phi(t)$.

→ 4 model parameters: h_0, ϕ_0, ι and ψ.

$\phi(t)$ is phase-locked to the electromagnetic pulse phase evolution, but with double the value ($f_{GW} = 2f_{rot}$) and with an initial phase offset, ϕ_0.

GW amplitude is estimated using the quadrupole formula:

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

$$= 4 \times 10^{-25} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I}{10^{45}\ \mathrm{g\ cm^2}}\right) \left(\frac{f}{100\ \mathrm{Hz}}\right)^2 \left(\frac{100\ \mathrm{pc}}{d}\right)$$

where $\epsilon = (I_1 - I_2)/I$, $I = I_3$ - moment of inertia along the principal axis of its tensor, d - the distance.

Theoretical predictions for maximal possible deformations:

- "Normal matter", $\epsilon \leq 10^{-5}$,
- Hybrid stars, $\epsilon \leq 10^{-3}$,
- Superconducting quark matter, $\epsilon \leq 10^{-1}$

(Johnson-McDaniel & Owen 2013)

Related quantity, $m = l = 2$ mass quadrupole moment:

- $Q_{22} \propto I\epsilon$

Spin-down limit for known pulsars

Limit on h_0, assuming that all rotational energy is lost in GWs:

- ⋆ Change of rotational energy: $E_{\rm rot} = 2\pi^2 I f^2, \ \dot{E}_{\rm rot} \propto I f \dot{f}$
- ⋆ GW luminosity: $\dot{E}_{\rm GW} \propto \epsilon^2 I^2 f^6$

$$\dot{E}_{\rm GW} = \dot{E}_{\rm rot} \quad \to \quad h_{\rm sd} = \frac{1}{d}\sqrt{\frac{5GI}{2c^3}\frac{|\dot{f}\,|}{f}} =$$

$$= 8 \times 10^{-24}\sqrt{\left(\frac{I}{10^{45}\ {\rm g\ cm^2}}\right)\left(\frac{|\dot{f}\,|}{10^{-10}\ {\rm Hz/s}}\right)\left(\frac{100\ {\rm Hz}}{f}\right)\left(\frac{100\ {\rm pc}}{d}\right)}.$$

$h_0 \leq h_{\rm sd} \to$ **upper limit on the deformation ϵ:**

$$\epsilon_{\rm sd} = 2 \times 10^{-5}\sqrt{\left(\frac{10^{45}\ {\rm g\ cm^2}}{I}\right)\left(\frac{100\ {\rm Hz}}{f}\right)^5\left(\frac{|\dot{f}\,|}{10^{-10}\ {\rm Hz/s}}\right)}.$$

or

$$\epsilon_{\rm sd} = 0.2\left(\frac{h_{\rm sd}}{10^{-24}}\right) f^{-2} I_{45}^{-1} d_{kpc}$$

Data analysis methods

Three semi-independent methods were used to analyze the signal:

One using the frequency-domain data, Short Fourier Transform Database (SFTD):

- $\star$ (Astone et al., 2010), $5n$-vector method: matched filter on the $+$ and $\times$ signal Fourier components at 5 frequencies of the signal and phase modulation $\rightarrow$ detection statistics,

Two using time-domain heterodyned data:

- $\star$ (Dupois & Woan 2005) Bayesian parameter estimation,
  $\rightarrow$ Previous results (S5) used as priors
- $\star$ (Jaranowski & Królak 2010) Matched filter maximum-likelihood F/G-statistic.

In case of no detection, all three methods produce upper limits on the GW amplitude (here, 95% credibility/confidence values)

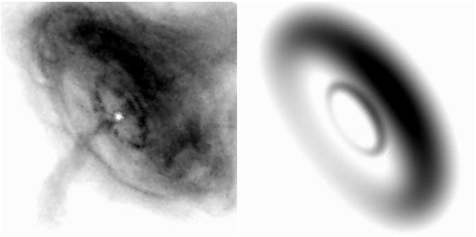
Previous known-pulsar searches

- **S5 Crab pulsar search** (ApJ Lett., 683, L45, 2008)
  8 months of LIGO (H1, H2 and L1) data used to search for the Crab.
  Beat the spin-down limit. Two methods used:
  - Coherent, single phase template Bayesian time domain method,
  - F-statistic based "fuzzy" (or directed) search covering a small f, $\dot{f}$ and $\ddot{f}$ range.
- **S5 multi-source search** (ApJ, 713, 671, 2010)
  All LIGO S5 data used to search for 116 pulsars with the coherent Bayesian time domain method (allowing for small errors in the phase model based on radio fit uncertainties)
- **VSR2 Vela pulsar search** (ApJ, 737, 93, 2011)
  Virgo VSR2 data used to search for Vela pulsar. **Beat the spin-down limit**. Three independent methods used:
  - Glasgow Bayesian time domain method (PRD, 72, 102002, 2005)
  - Polgraw F and G-statistic method (CQG, 27, 194015, 2010)
  - Rome group 5-vector frequency domain method (CQG, 27, 194016, 2010)

Collaboration with the EM pulsar community

Timing input from many EM facilities:

- ⋆ Robert C. Byrd Green Bank Radio Telescope,
- ⋆ Lovell Radio Telescope at Jodrell Bank,
- ⋆ Parkes radio telescope,
- ⋆ 15 m XDM Telescope at Hartebeesthoek,
- ⋆ Nançay Decimetric Radio Telescope,
- ⋆ Giant Metrewave Radio Telescope,
- ⋆ Rossi X-ray Timing Explorer,
- ⋆ Fermi Gamma-ray Space Telescope.



The inclination angle ι and polarisation angle ψ, from the pulsar wind nebula X-ray observation & torus fitting (Ng & Romani, Ap. J., 601, 479, 2004, Ng & Romani, Ap. J., 673, 411, 2008)

IMPLIED ORIENTATIONS OF PULSARS FROM THEIR PULSAR WIND NEBULAE OBSERVATIONS (NG & ROMANI 2004, 2008).

Pulsar	ι	ψ
J0534+2200 (Crab pulsar)	$62^\circ.2 \pm 1^\circ.9$	$35^\circ.2 \pm 1^\circ.5$
J0537−6910	$92^\circ.8 \pm 0^\circ.9$	$41^\circ.0 \pm 2^\circ.2$
J0835-4510 (Vela pulsar)	$63^\circ.6 \pm 0^\circ.6$	$40^\circ.6 \pm 0^\circ.1$
J1833−1034	$85^\circ.4 \pm 0^\circ.3$	$45^\circ \pm 1^\circ$
J1952+3252[†]	...	$-11^\circ.5 \pm 8^\circ.6$

Current search

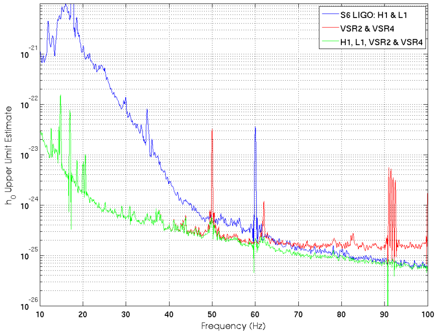
- Search for pulsars with $f_{rot} > 10$ Hz ($f_{gw} > 20$ Hz), currently 368 such pulsars listed in the ATNF pulsar catalogue.
- We report of 195 pulsars, 73 not studied previously.
  - 64 in globular clusters (32 in Ter 5 and 18 in 47 Tuc)
  - 101 in binary systems
  - 5 glitching pulsars (four glitches in J0537-6910, one in Vela, one in J1813-1246, one in J1833-1034 and one in J1952+3252)
- 11 of the S5 targets and another 5 from S3/S4 *not included (no good timing solutions)*.

Science Runs

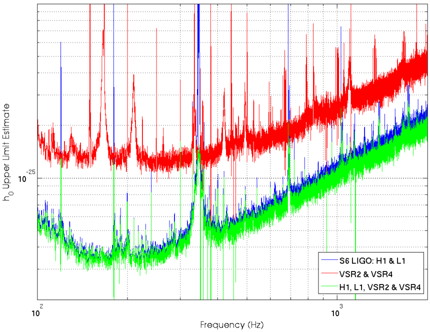
Run	Dates	Duty Factor (%)	Data Length (days)
VSR2	2009 Jul 7 (20:55 UTC) – 2010 Jan 8 (22:00 UTC)	80.4	149
VSR4	2011 Jun 3 (10:27 UTC) – 2011 Sep 5 (13:26 UTC)	81.0	76
S6 Hanford (H1)	2009 Jul 7 (21:00 UTC) – 2010 Oct 21 (00:00 UTC)	50.6	238
S6 Livingston (L1)	2009 Jul 7 (21:00 UTC) – 2010 Oct 21 (00:00 UTC)	47.9	225

Current search: data used

All LIGO S6 (H1 and L1) data and all Virgo VSR2 and VSR4 data was used.



$f < 100$ Hz



$f > 100$ Hz

Estimated sensitivity for a joint VSR2 & VSR4 analysis, a LIGO S6 analysis, and a joint VSR2, VSR4 & S6 analysis.

Results

Upper limits for 7 pulsars lie within the factor of 4 of the canonical spin-down limit:

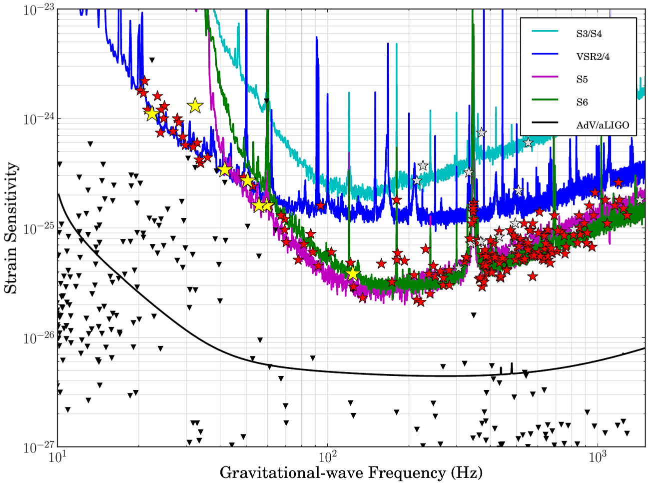
- ⋆ Only Crab and Vela pulsar results beat the spin-down limit, now constrain 1% and 10% of their respective spin-down power being emitted via gravitational waves *(previous studies: 6% and 45%)*,
- ⋆ Another 5 pulsars within a factor of 4 of the spin-down limit, but
  - ⋆ moment of inertia uncertain within the range of $I \simeq 1 - 3 \times 10^{45}\ \mathrm{g\,cm^2}$ (factor $\sqrt{3}$ in h_{sd}),
  - ⋆ distances generally have 20% uncertainty, but can be uncertain by a factor of two.

Results

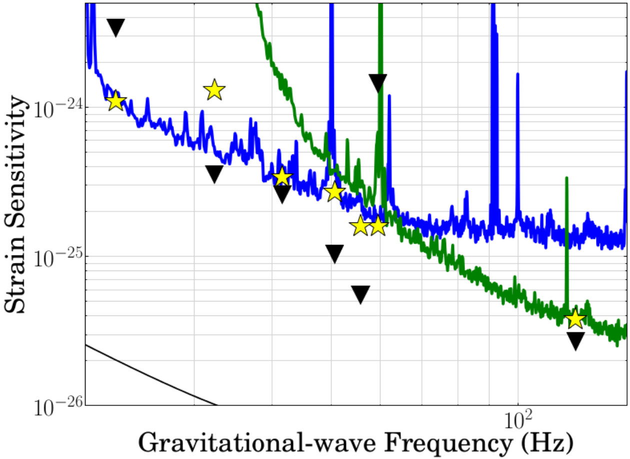
UPPER LIMITS FOR THE HIGH INTEREST PULSARS. LIMITS WITH CONSTRAINED ORIENTATIONS ARE GIVEN IN PARENTHESES.

Analysis	$h_0^{95\%}$	ε	Q_{22} (kg m^2)	$h_0^{95\%}/h_0^{\rm sd}$	$\dot{E}_{\rm gw}/\dot{E}$ %
			J0534+2200 (Crab)		
Bayesian	$1.6\,(1.4)\times10^{-25}$	$8.6\,(7.5)\times10^{-5}$	$6.6\,(5.8)\times10^{33}$	0.11 (0.10)	1.2 (1.0)
$\mathcal{F}/\mathcal{G}$-statistic	$2.3\,(1.8)\times10^{-25}$	$12.3\,(9.6)\times10^{-5}$	$11.6\,(7.4)\times10^{33}$	0.16 (0.13)	2.6 (1.7)
5n-vector	$1.8\,(1.6)\times10^{-25}$	$9.7\,(8.6)\times10^{-5}$	$7.4\,(6.6)\times10^{33}$	0.12 (0.11)	1.4 (1.2)
			J0537−6910		
Bayesian	$3.8\,(4.4)\times10^{-26}$	$1.2\,(1.4)\times10^{-4}$	$0.9\,(1.0)\times10^{34}$	1.4 (1.7)	200 (290)
$\mathcal{F}/\mathcal{G}$-statistic	$1.1\,(1.0)\times10^{-25}$	$3.4\,(3.1)\times10^{-4}$	$2.6\,(2.4)\times10^{34}$	4.1 (3.9)	1700 (1500)
5n-vector	$4.5\,(6.7)\times10^{-26}$	$1.4\,(2.1)\times10^{-4}$	$1.1\,(1.6)\times10^{34}$	1.6 (2.4)	260 (580)
			J0835−4510 (Vela)		
Bayesian	$1.1\,(1.0)\times10^{-24}$	$6.0\,(5.5)\times10^{-4}$	$4.7\,(4.2)\times10^{34}$	0.33 (0.30)	11 (9.0)
$\mathcal{F}/\mathcal{G}$-statistic	$4.2\,(9.0)\times10^{-25}$	$2.3\,(4.9)\times10^{-4}$	$1.8\,(3.8)\times10^{34}$	0.13 (0.27)	1.7 (7.3)
5n-vector	$1.1\,(1.1)\times10^{-24}$	$6.0\,(6.0)\times10^{-4}$	$4.7\,(4.7)\times10^{34}$	0.33 (0.33)	11 (11)
			J1813−1246		
Bayesian	3.4×10^{-25}	3.5×10^{-4}	2.7×10^{34}	1.3	170
$\mathcal{F}/\mathcal{G}$-statistic	7.1×10^{-25}	7.4×10^{-4}	5.7×10^{34}	2.7	730
5n-vector	4.8×10^{-25}	4.9×10^{-4}	3.8×10^{34}	1.8	320
			J1833−1034		
Bayesian	$1.3\,(1.4)\times10^{-24}$	$5.7\,(6.1)\times10^{-3}$	$4.4\,(4.7)\times10^{35}$	4.3 (4.6)	1800 (2100)
$\mathcal{F}/\mathcal{G}$-statistic	$1.2\,(1.2)\times10^{-24}$	$5.2\,(5.2)\times10^{-3}$	$4.0\,(4.0)\times10^{35}$	3.9 (3.9)	1500 (1500)
5n-vector	$1.4\,(2.0)\times10^{-24}$	$6.1\,(8.7)\times10^{-3}$	$4.7\,(6.7)\times10^{35}$	4.6 (6.6)	2100 (4400)

Results



⋆: 95% upper limits on the gravitational wave strain amplitude for 195 pulsars using data from the LIGO S3-S6, and Virgo VSR2 and VSR4 runs (LIGO S3-S5 shown as gray stars). The ▼'s show the spin-down limit estimates from EM observations.



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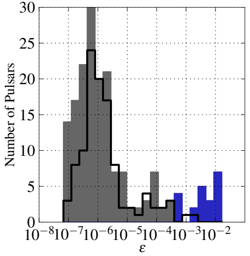
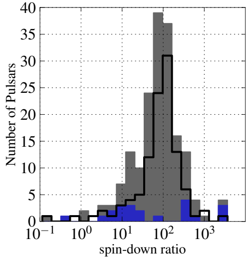
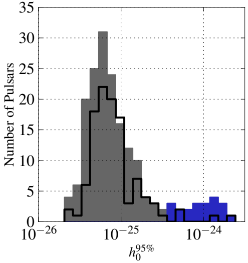
Results



Histograms of the upper limits in terms of stars' ellipticities.



Upper limits in terms the ratio of the observed upper limit to the spin-down limit.



Upper limits in terms the gravitational wave strain h_0.

The filled grey histogram shows the results of S6/VSR2/VSR4 data, the filled blue histogram shows the result for several pulsars that just used Virgo VSR2 and VSR4 data, and the black line shows results using LIGO S5 data.

$\rightarrow$ low-frequency young pulsars (Virgo only data) have the highest amplitude limits, but they have an approximately uniform spread in spin-down limit ratios (due to their high spin-down luminosities)

Summary & outlook

- ⋆ The largest set of pulsars - 195 with the data from the Initial Era,
- → h_0 upper limits for continuous waves in the broad range of frequencies,
- ⋆ 7 pulsars within the factor 4 of the spin-down limit (Crab & Vela below, 1% and 10% of the spin-down energy), several other within the factor of 10,
- → 19 new pulsars studied using the Virgo data alone,
- ⋆ Good collaboration with EM astronomers (ephemerids),
- ⋆ Pipelines with more realistic models (e.g., GWs at $1f/2f$, EM/GW offset) designed and tested for the Advanced Era.