Searching for gravitational-wave emission due to r-modes from the pulsar PSR J0537–6910 in LIGO O3 data

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What is pulsar J0537–6910?

- A young (~ 5 kyr) pulsar Located in the supernova remnant N157B in the Large Magellanic Cloud at a distance of 49.6 kpc.
- Spin frequency $\nu \approx 62$ Hz (spin period $P \approx 16$ ms).
- Highest spin-down energy loss rate $\dot{E} = 4.9 \times 10^{38}$ $[\mathrm{erg/s}]$ among more than 3300 known pulsars[†].
- Exhibits large glitches ($\Delta\nu/\nu \approx 10^{-7}$ every 100 days).
- Shows a strong positive correlation between the size of each glitch and the waiting time until the following one[‡].

[†] https://www.atnf.csiro.au/people/pulsar/psrcat/

[‡] J. R. Fuentes, C. M. Espinoza and A. Reisenegger *Astron. Astrophys.* **630** (2019) A115.

Behavior of J0537

- Breaking index
$$n = \frac{\nu\ddot{\nu}}{\dot{\nu}^2}$$
where ν is the spin frequency.

- Average value per 13 years of observation $n \approx -1.2^{\dagger}$.

- But between glitches $n \approx 7\ ^{\ddagger}$.
  - A large value would suggest not only electromagnetic emission.
  - A value $n \approx 7$ can be caused by r-mode scenario of emission.

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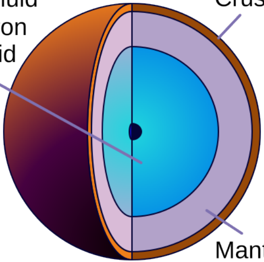
†D. Antonopoulou et al. *Mon. Not. Roy. Astron. Soc.* **473** (2018) 2, 1644-1655.

‡N. Andersson et al. *Astrophys. J.* **510** (1999) 846, R. D. Ferdman et al. *Astrophys. J.* **852** (2018) 123, R. Abbott et al. *Astrophys. J. Lett.* **913** (2021) L27, W. C. G. Ho et al. *Mon. Not. Roy. Astron. Soc.* **498** (2020) 4, 4605–4614.

R-modes



- R-modes are non-radial oscillations.
- Amplitude of the GW[‡]

$$h_0 = \sqrt{\frac{8\pi}{5}}\,\frac{8\pi^3 f^3 \alpha M R^3 \tilde{J}}{r}$$

where α is r-mode amplitude, M and R are star's mass and radius, $\tilde{J}$ is normalized angular momentum, f is GW frequency, r is distance to the star.

- The r-modes correspond to oscillating flows of material (currents) in the star that arise due to the Coriolis effect. The r-mode frequency is proportional to the angular velocity.

[‡]Benjamin J. Owen *Phys. Rev. D* **82** *(2010) 104002.*

R-mode GW frequency

- The GW frequency f depends on the equation of state (EoS).
- We use the following fit of f to star's spin frequency ν [†]:

$$f = A\nu - B\left(\frac{\nu^2}{\nu_K^2}\right)\nu$$

where ν_K — the Keplerian frequency, with range of values of A, B and ν_K[‡]:

$$1.39 < A < 1.57; \quad 0 < B < 0.195; \quad \nu_K \simeq 506\ \mathrm{Hz}.$$

This gives GW frequency range for J0537 from $\sim$ 86 to $\sim$ 97 Hz.

[†] S. Caride, R. Inta, B. J. Owen, and B. Rajbhandari *Phys. Rev. D* **100** (2019) 064013.

[‡] Conservative assumption 716 $\mathrm{Hz}/\sqrt{2}$.

Previous study of J0537-6910[‡]

- First search for gravitational waves from r-modes.
- Used the publicly available data from O1 and O2 observation runs.
- Search input consisted of short time baseline Fourier transforms.
- Performed a fully coherent multi-detector search using the matched filtering ($\mathcal{F}$-statistic).
- No signal found.
- Upper limits obtained: six values of h_0 from 1.05×10^{-25} to 1.35×10^{-25}.

[‡] L. Fesik and M. A. Papa. "First Search for r-mode Gravitational Waves from PSR J0537–6910." *The Astrophysical Journal* **895** (2020) 11.

New study of J0537-6910 presented in this talk[†]

Search of LIGO O3 data

- Glitches during the O3 scientific run

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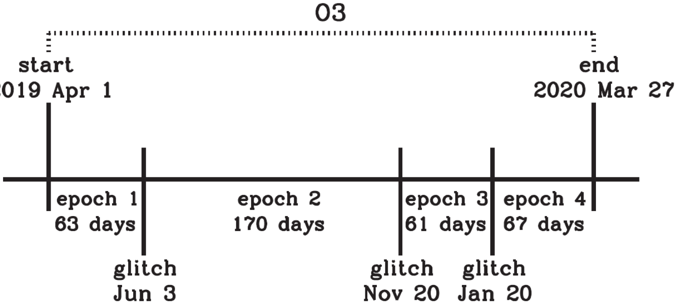

Figure 1. Timeline of O3 observing run, glitches, and epochs between glitches.

The glitch times are from the NICER mission observations.

[†]Abbott et el. *Astrophys. J.* **922** (2021) 71

Search pipelines

- Two pipelines:
  - $\mathcal{F}/\mathcal{G}$-statistic*.
    $\mathcal{G}$ - statistic† can be applied as orientation of the spin axis of J0537 can be assumed from the observations of pulsar's wind nebula‡ ($\Psi = 131.001^\circ,\ \iota = 87.20^\circ$).
  - 5-vector§.

- Coherent search within each intra-glitch period.
  - 5-vector performs also an incoherent combination of the analysis in each segment.

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*P. Jaranowski, A. Królak, B. F. Schutz *Phys. Rew. D* **58** (1998) 063001.

†P. Jaranowski and A. Królak. *Class. Quantum Gravity* **27** (2010) 19, 194015.

‡C.-Y. Ng and R. W. Romani. *Astrophys. J.* **673** (2008) 411–417.

§P. Astone, A. Colla, S. D'Antonio, S. Frasca, C. Palomba, R. Serafinelli *Phys. Rev. D* **89** (2014) 062008.

$\mathcal{F}/\mathcal{G}$-statistic search pipeline description

- Parameter space:

$$
\begin{aligned}
\nu\left(A_{\min} - B_{\max}\frac{\nu^2}{\nu_K^2}\right) \leqslant & \quad f & \leqslant \nu A_{\max} \\
-\dot{\nu}\left(\frac{f}{\nu} - 2B_{\max}\frac{\nu^2}{\nu_K^2}\right) \leqslant & \quad -\dot{f} & \leqslant -\dot{\nu}\frac{f}{\nu} \\
0 \leqslant & \quad \ddot{f} & \leqslant \ddot{\nu}\frac{f}{\nu}
\end{aligned}
$$

- The search band of 86–97 Hz.
- The band is divided into 2 Hz overlapping intervals.
- Known interferences in the data are vetoed.

5-vector search pipeline description

- The range in f and $\dot{f}$ is defined by:

$$
\begin{aligned}
A &= \frac{1}{2}\left(3\frac{f}{\nu} - \frac{\dot{f}}{\dot{\nu}}\right), \\
B &= \frac{\nu_K^2}{2\nu^2}\left(\frac{f}{\nu} - \frac{\dot{f}}{\dot{\nu}}\right).
\end{aligned}
$$

$$1.39 \leqslant A \leqslant 1.57; \qquad 0 \leqslant B \leqslant 0.195.$$

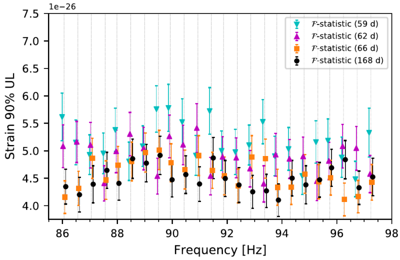
- The band of 86–97 Hz is divided into 1 Hz intervals.

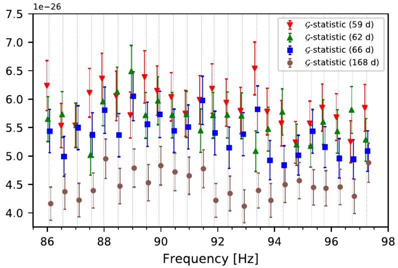
- Known interferences in the data are vetoed.

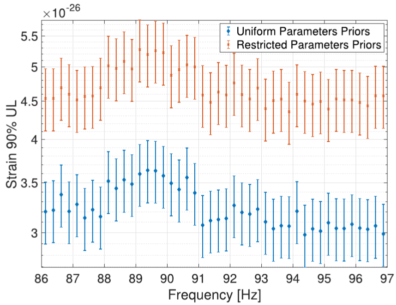
Results of the search

- $\mathcal{F}/\mathcal{G}$-statistic:
  - None of the candidates crossed the threshold of 0.1% false alarm probability (FAP).
  - There were several crossings of the 1% threshold for the longest 168 day interglitch segment but no coincident candidates in the remaining 3 segments were found.
  - We conclude that no valid GW signal candidate was found.
- 5-vector:
  - None of the candidates crossed the 1% p-value threshold.

Upper limits







- Upper limits at 90% confidence level.
- For $\mathcal{F}/\mathcal{G}$ — 0.5 Hz bands.
- For 5-vector — 0.25 Hz bands.

Astrophysical constraints

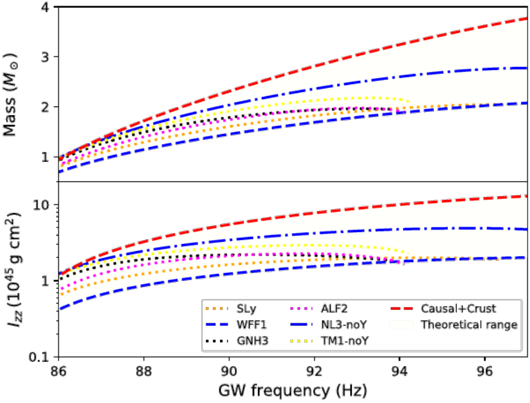


Figure 16. Ranges of theoretically possible mass M and moment of inertia I_{zz} consistent with r-mode emission at the GW frequencies explored in our searches. These ranges reflect our uncertainty in the true equation of state of dense matter, and make no assumption as to whether the observed spindown is driven by r-modes. The upper limit is set by the stiffest possible equation of state (EoS) from Haskell et al. (2018), which is causally limited in the core and attached to a realistic crustal model, and the lower limit is set by the softest EoS we consider, WFF1, that is still compatible with the observations of a $\approx 2\,M_\odot$ neutron star, as described in Idrisy et al. (2015).

- Neglecting second order in rotation terms, we can extract the compactness from the frequency[b].
- Only 1 free parameter is left (mass or moment of inertia).

[b] A. Idrisy, B. J. Owen, and D. I. Jones *Phys. Rev. D* **91** (2015) 024001

Comparing upper limits with spin-down limit

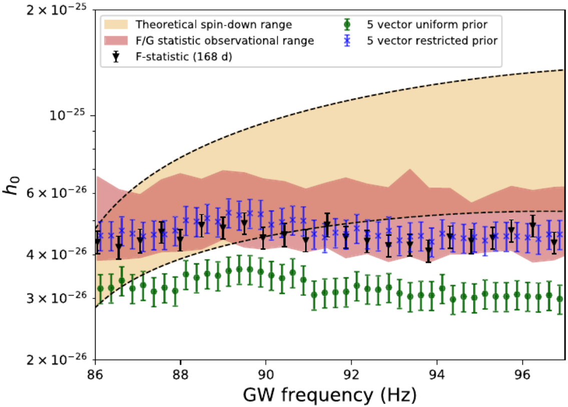


Figure 17. Upper limits on gravitational-wave amplitude $h_0(f)$ obtained from searches using the $\mathcal{F}/\mathcal{G}$-statistic and 5-vector methods. For ease of understanding we plot the results of the $\mathcal{F}$-statistic pipeline only for the longest stretch of data, and indicate the full range of results of the $\mathcal{F}/\mathcal{G}$-statistic pipeline as a shaded band. The dashed lines are set by the stiffest and softest EoSs considered here and enclose a range of theoretical h_0 (see the text for details).

$$h_{sd} = \frac{1}{r}\sqrt{\frac{10G}{c^3} I_{zz} \frac{\nu|\dot{\nu}|}{f^2}}$$

The searches are digging well into the theoretical parameter space for the model, and below the spin-down limit!

Upper limits on the r-mode amplitude α

THE ASTROPHYSICAL JOURNAL, 922:71 (22pp), 2021 November 20 Abbott et al.

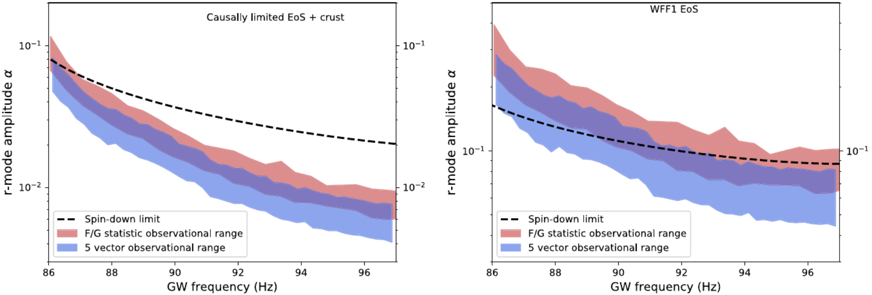


Figure 18. Upper limits on the r-mode amplitude α calculated for two different EoSs. Results for the stiffest EoS we consider, the causally limited EoS with crust, are plotted in the left panel and results for the softest case in our analysis, the WFF1 EoS, are plotted in the right panel. The dotted lines show the amplitude α that would correspond to the spin-down limit.

$$\alpha = \sqrt{\frac{5}{8\pi}}\,\frac{h_0}{8\pi^3 f^3}\,\frac{r}{MR^3\tilde{J}}$$

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Final summary

- No signal detected.
- Upper limits set on GW amplitude:
  - Upper limits improved by a factor of up to 3 over the previous analysis.
- Constraints set on astrophysical parameters of the pulsar.

Thank you for your attention!