Narrowband searches for continuous and long-duration transient gravitational waves from known pulsars in the LIGO-Virgo third observing run

David Keitel
on behalf of the LIGO-Virgo-KAGRA collaborations

UIB Universitat de les Illes Balears

IAC3

LIGO VIRGO KAGRA

based on results from Abbott et al., arXiv:2112.10990 (ApJ accepted)

Iberian GW Meeting, 08 June 2022

david.keitel@ligo.org
DCC: LIGO-G2200833-v2

arXiv.org > gr-qc > arXiv:2112.10990

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General Relativity and Quantum Cosmology

[Submitted on 21 Dec 2021]

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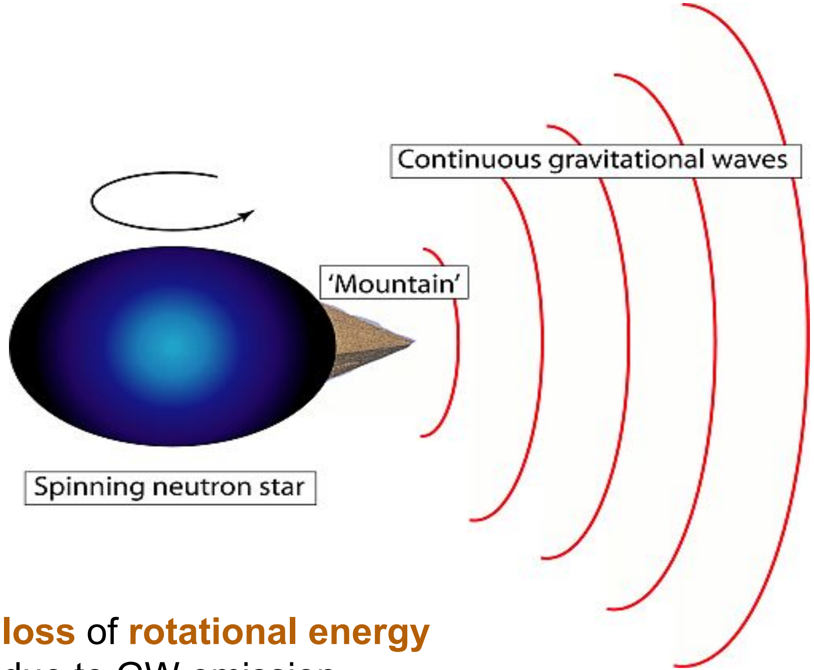
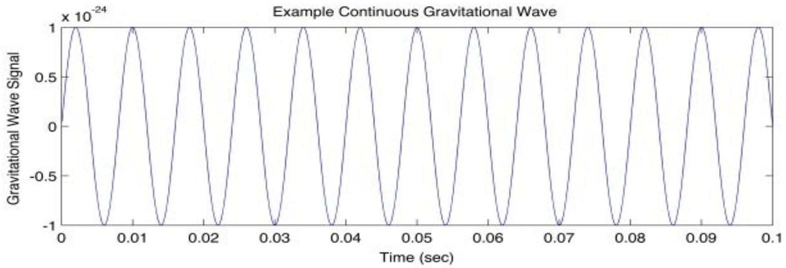
The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration: R. Abbott, T. D. Abbott, F. Acernese, K.

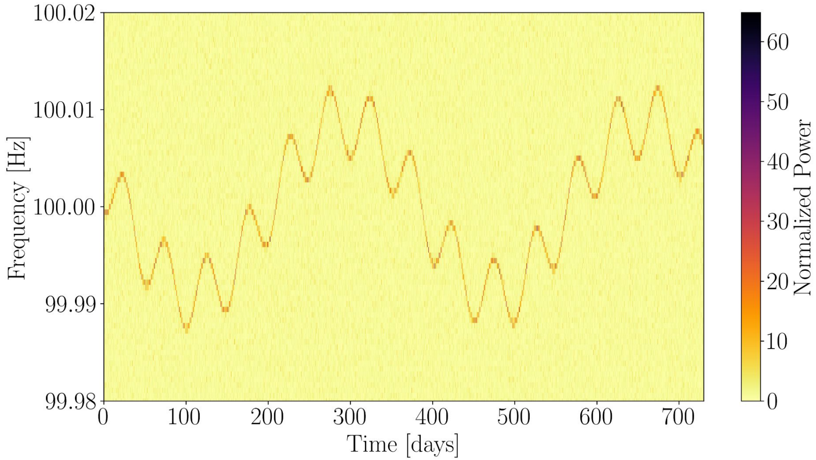
arxiv.org/abs/2112.10990

Gravitational waves from neutron stars





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



loss of **rotational energy** due to GW emission

→ spindown upper limit for known pulsars:

$$h_{\rm sd} = \frac{1}{d}\sqrt{\frac{5G}{2c^3} I \frac{|\dot{\nu}|}{\nu}}$$

Gravitational waves from neutron stars

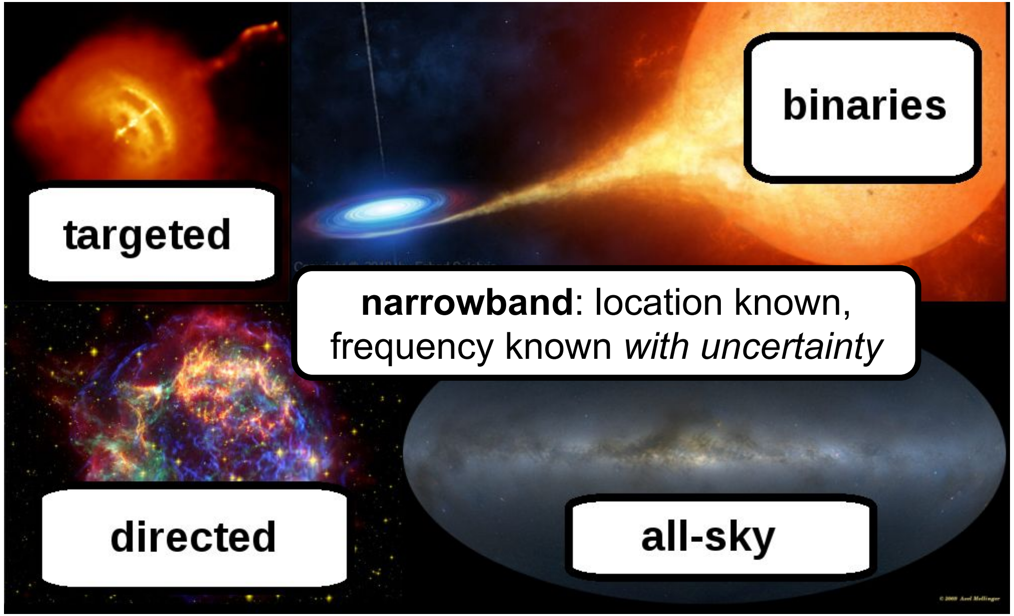
- Measured strain *h(t)* depends on intrinsic spin-down, Doppler effect between source and Earth, antenna response pattern:

$$\Rightarrow h(t, h_0, f, df/dt, \ldots, \alpha, \delta)$$

(+extra parameters for NSs in binaries)

- Matched-filter searches are effective, but need to sample parameter space very finely.
- Signal-to-noise increases with $\sqrt{T_{obs}}$, computing cost much faster.

- Ideal search algorithm and strategy depends on target and computing budget.



- recent review: Tenorio, Keitel & Sintes Universe 2021, 7(12), 474: "Search methods for continuous gravitational-wave signals from unknown sources in the advanced-detector era"

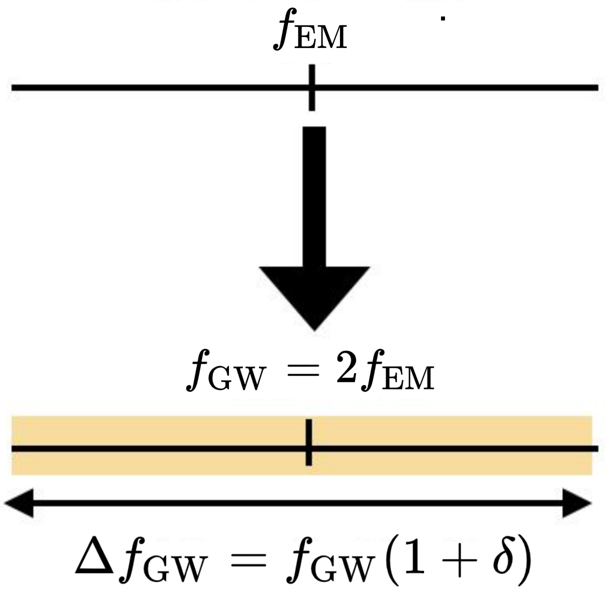
O3 narrowband searches [Abbott+ 2112.10990]

2 fully-coherent matched filter pipelines:

➔ 5n-vector search (Mastrogiovanni+ 1703.03493, already used for O2, Abbott+ PRD99,122002)

➔ search using $\mathcal{F}$ -stat (new for narrowband, code from Wette+ 1804.03392)

Narrow-band searches allow some uncertainty in frequency and spin-downs around the EM value



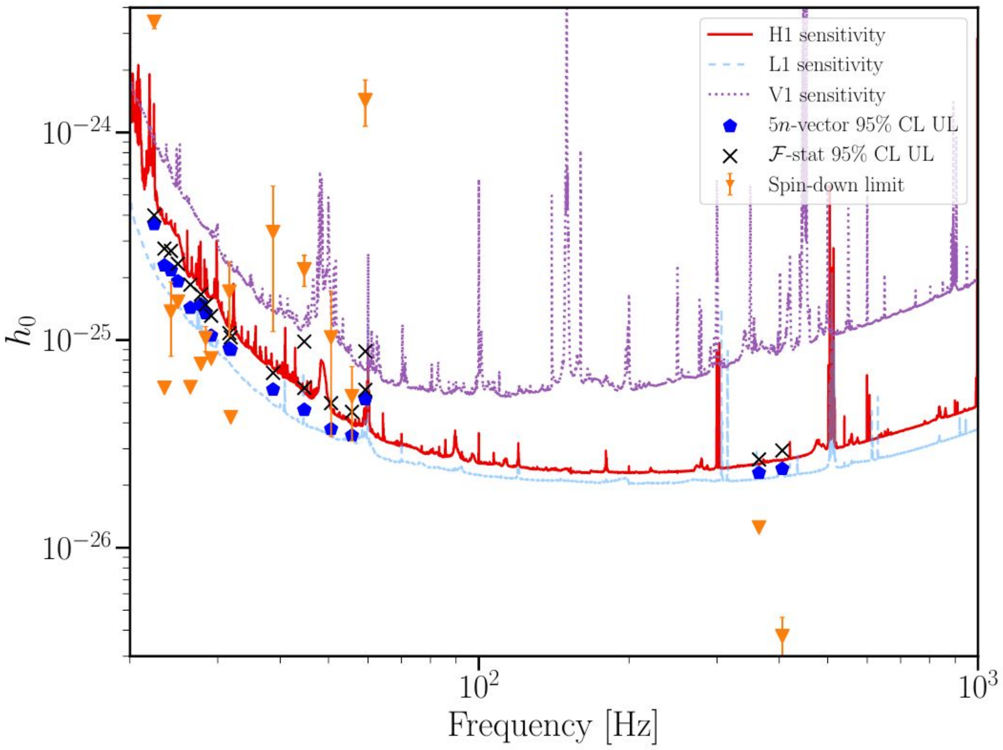
GW data: full **3rd observing run** from 3 detectors (**LIGO** H+L, **Virgo**), April 2019 to March 2020 (break in October 2019)


EM data: ephemerides from Jodrell Bank Observatory, Nançay Radio Telescope, UTMOST, MeerTime, CHIME, NICER, Mt. Pleasant Observatory

selected **18 isolated pulsars**, including Crab and Vela, with GW frequencies between 20 and 700 Hz

CW narrowband results: upper limits

- No remaining outliers
  (after excluding detector artifacts).
- 95% confidence upper limits on strain h_0
- More constraining than spindown limits
  for 7 pulsars,
  J1105-6107 and J1913+1011 for the first time.



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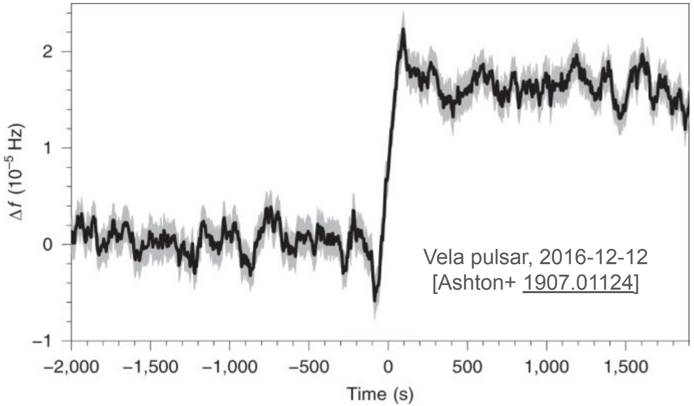
GWs from pulsar glitches [Prix+ 1104.1704]



Pulsar glitch: frequency suddenly increases!

- The glitch could be associated to a change in quadrupole moment of the pulsar, which could also lead to GW emission.
- Assuming all the energy is emitted through GWs, one can compute the indirect upper limit on emitted GW energy and amplitude: total energy released in glitch.

glitch excess energy upper limit

$$h_0 \leq \frac{1}{d}\sqrt{\frac{5G}{2c^3}\frac{\mathcal{I}}{\tau}\frac{\Delta f_{\rm gl}}{f}}$$

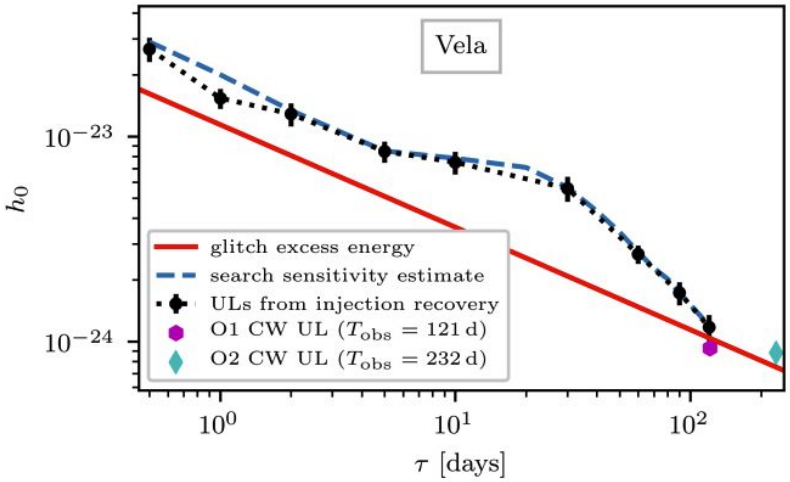
- SNR increases with same sqrt(τ) scaling as h_0 upper limit → same basic *detectability* for short or long transients

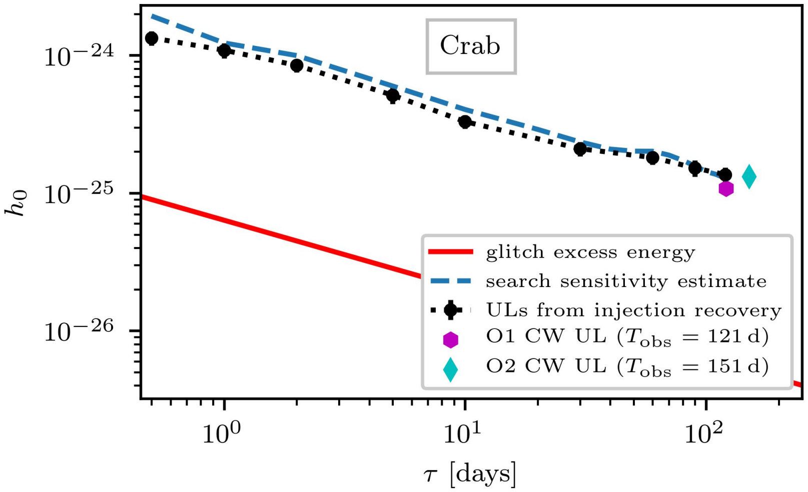
- compare with spindown UL for CWs:

$$h_{\rm sd} = \frac{1}{d}\sqrt{\frac{5G}{2c^3}I\frac{|\dot{\nu}|}{\nu}}$$

Previous GW glitch searches

- search for ***short**-duration transients* (bursts) from Vela glitch in 2006 [Abadie+ 1011.1357], all sky search for short-duration transients [Abbott+ 2107.03701]
- search for ***long**-duration transients* from Vela & Crab glitches during O2 [Keitel+ 1907.04717] (using Prix+ 1104.1704 method)





O3 search based on procedures in Keitel+ 1907.04717.

Detecting "transient continuous waves" [Prix+ 1104.1704]

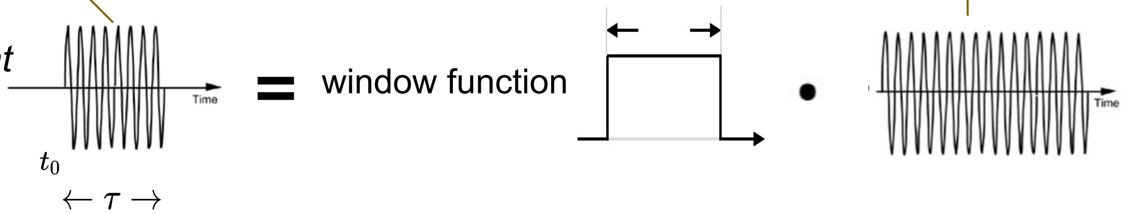
CW signals depend on **phase** (Doppler effect due to Earth's motion, source frequency and spindowns) and **amplitude parameters** (signal amplitude, source orientation):

$$\lambda = \{\alpha, \delta, f, \dot{f}, \ddot{f} \ldots\} \qquad \mathcal{A} = \{h_0, \cos\iota, \psi, \phi_o\}$$

add **transient parameters**: $\mathcal{T} = \{t_0, \tau\}$

$$\mathbf{h}(t;\theta) = h(t, \lambda, \mathcal{A}, \mathcal{T}) = \omega(t;\mathcal{T})h(t, \lambda, \mathcal{A})$$

transient CW = window function • standard CW signal model

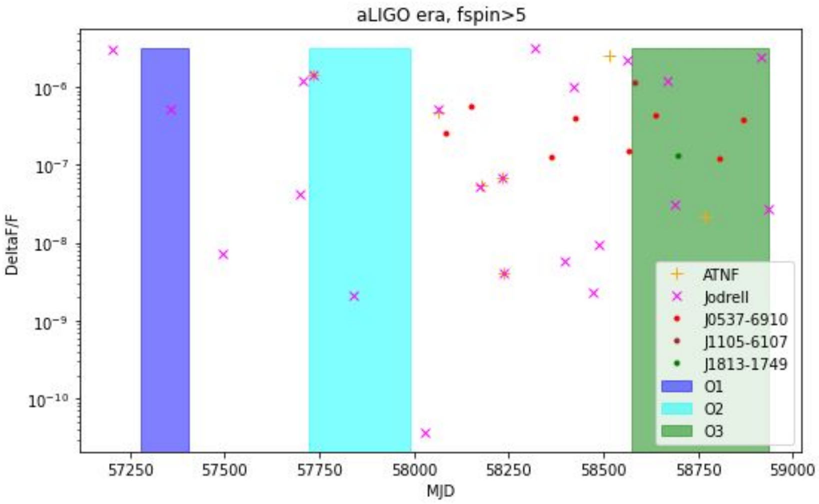


signal-vs-noise likelihood ratio

$$\frac{P(\mathbf{x}|\mathcal{H}_{\mathrm{tS}};\lambda,\mathcal{A},\mathcal{T})}{P(\mathbf{x}|\mathcal{H}_{\mathrm{G}})} \xrightarrow[\text{over } \mathcal{A}]{\textit{maximize}} \mathcal{F}_{mn} = \mathcal{F}(\lambda, t_{0m}, \tau_n) \xrightarrow[\text{over } \mathcal{T}]{\textit{marginalize}} \boxed{B_{\mathrm{tS/G}}(\mathbf{x};\lambda)}$$

detection statistic

O3 Post-glitch target selection



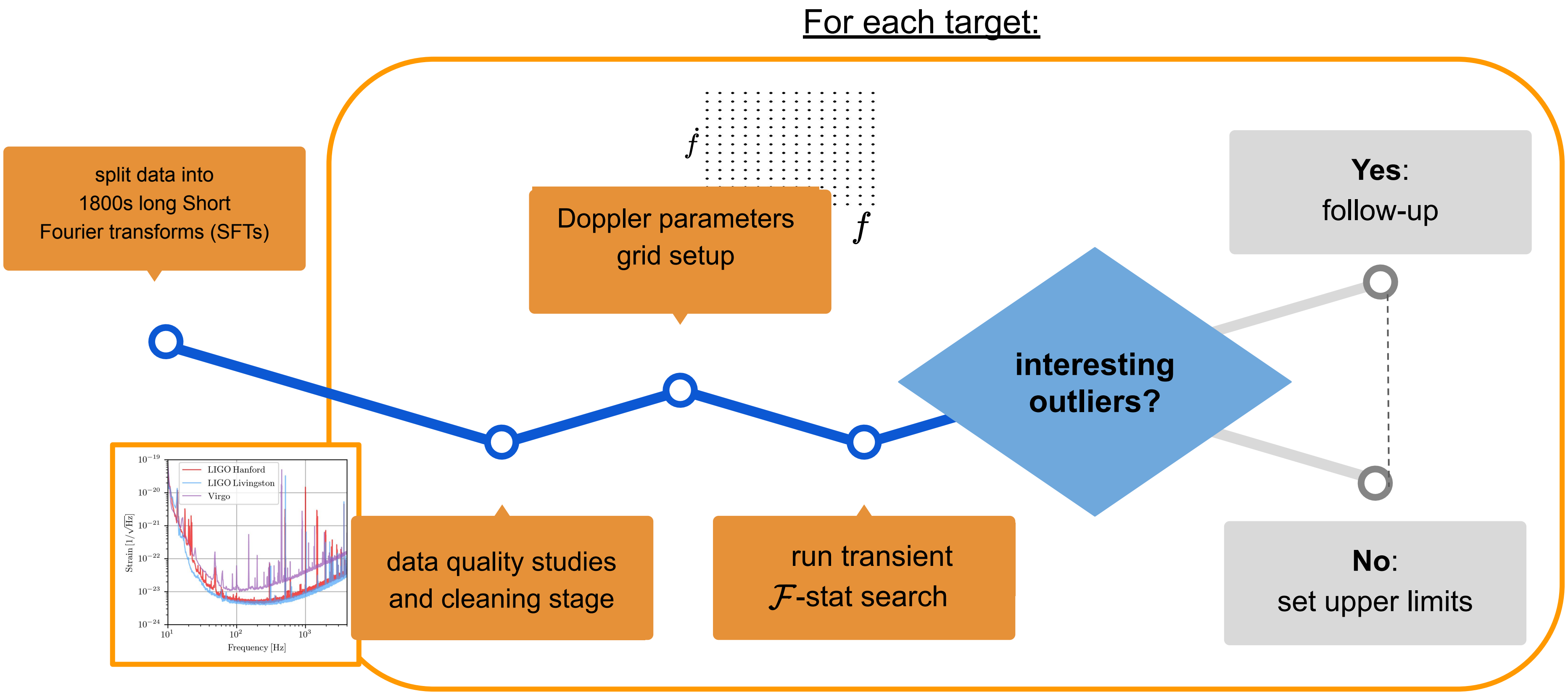
Glitching pulsars are rare, so we target all during O3 with decent f_{GW}, regardless of energy constraint [Prix+ 1104.1704].

Ephemerides provided by radio and X-ray observing partners (Jodrell Bank, UTMOST, NICER).

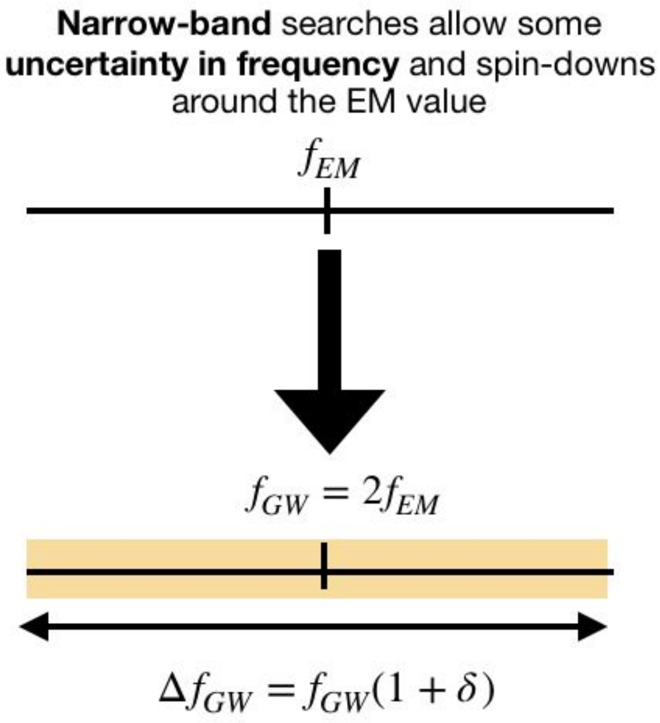
J0534+2200 "the Crab"	J0537-6910 "big glitcher"	J0908-4913	J1105-6107	J1813-1749	J1826-1334
f_{GW} ~ 60 Hz	f_{GW} ~ 123 Hz	f_{GW} ~ 19 Hz	f_{GW} ~ 31 Hz	f_{GW} ~ 45 Hz	f_{GW} ~ 20 Hz
glitched on 2019/07/23	4 glitches for O3, ± (3–8) days	glitched ~ 2019/10/09 ± 4.5 days	glitched ~ 2019/04/09 ± 2 days	glitched ~ 2019/08/03 ± 1 day	glitched ~ 2020/01/31 ± 21 days

extra targets not searched: J2021+3651 (glitch time too uncertain: ±114 days); J1801-2451 (glitched before O3, low freq)

Transient search: general procedure



Transient search: setup [Modafferi+ 2201.08785]



$(f, \dot{f}, \ddot{f} \ldots)$

- **narrow-band approach**: allow mismatch between the true GW frequency and its nominal value
- **template bank**: metric grid in $(f, \dot{f}, \ddot{f} \ldots)$ where the number of spindowns depends on the ephemerides

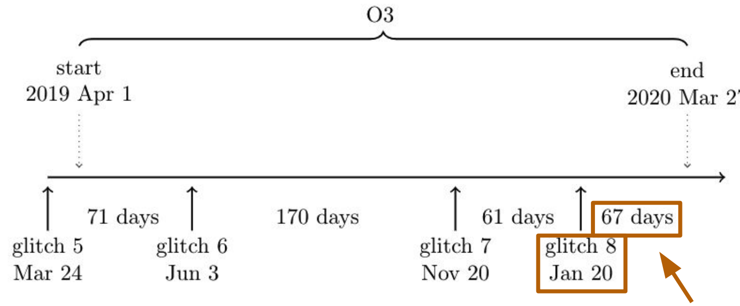
$\mathcal{T} = t_0, \tau$

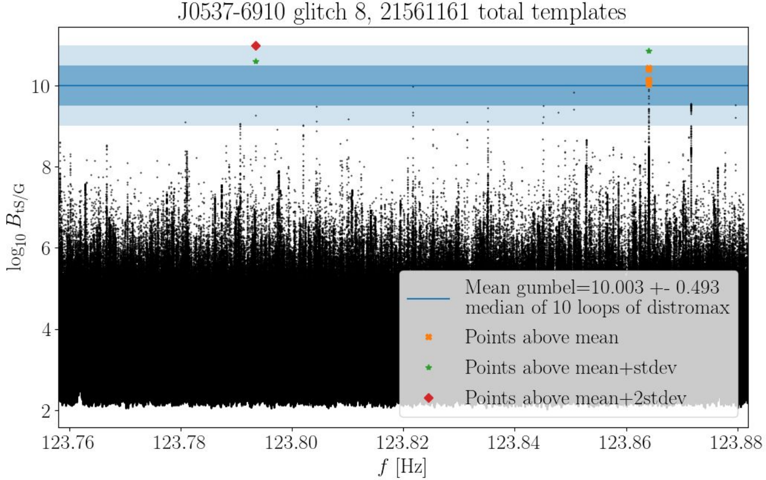
- search for transients **starting** in a range centered at the glitch time with width ΔT_{glitch} (~days)
- transient **durations** τ up to **4 months**
- window function: rectangular (no amplitude evolution)

Transient search: results and outliers

- get **detection threshold** from the expected distribution in the absence of a signal (`distromax` method [Tenorio+ 2111.12032])
- 8 out of 9 searches: **no outliers** above threshold
- **J0537–6910 glitch 8 search**: found 2 marginal outliers
- signal durations of 60 and 45 days, signal-to-noise ratios 6 – 7
- **they pass several vetoes**: no known/unknown lines nearby, time evolution of spectra also clean, H1–L1 consistency…
- multiple follow-ups with independent codes also see these, but at low/negligible significance

→ **cannot be ruled out decisively, but not exciting.**





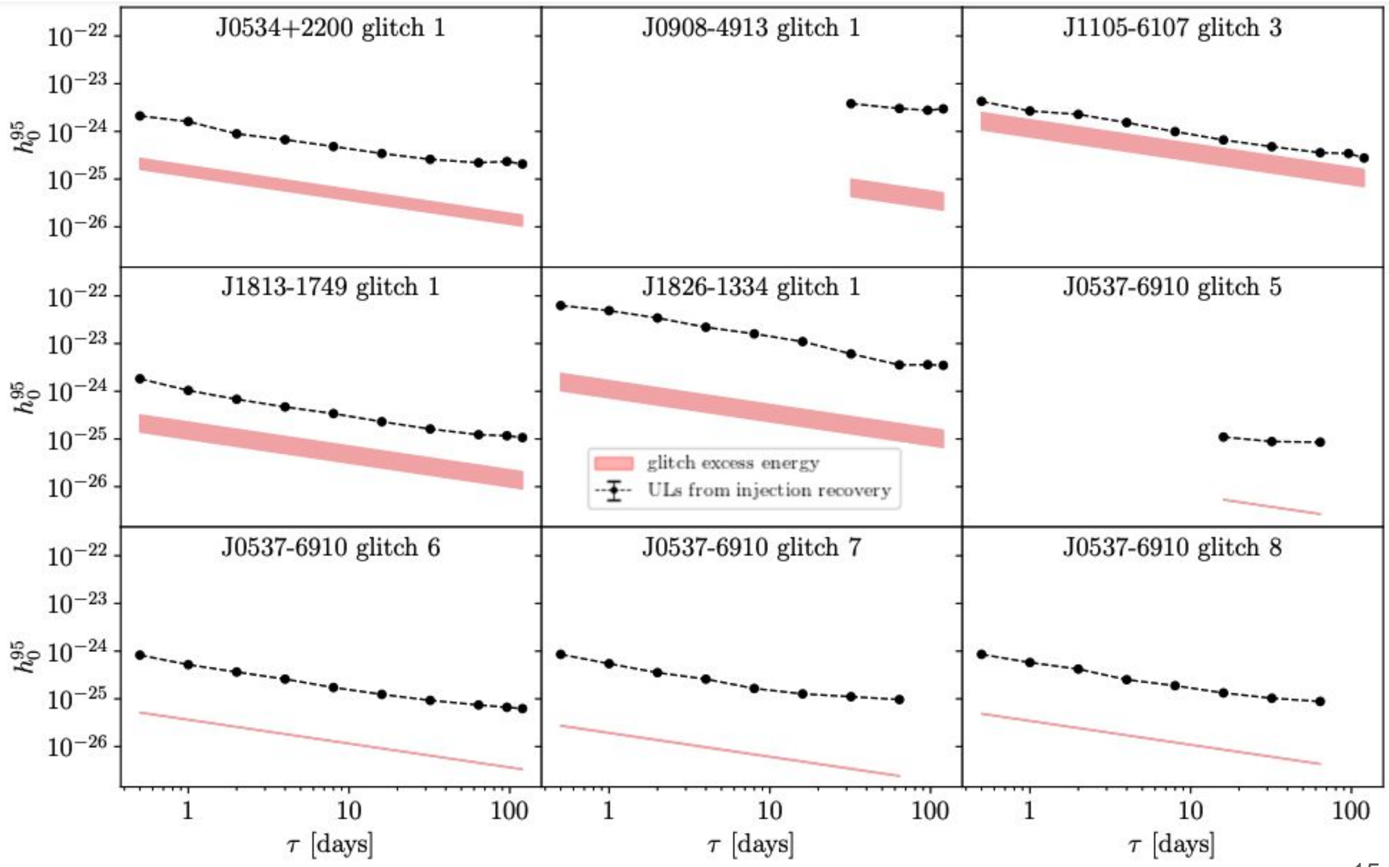
Transient search: upper limits results

- injections of simulated signals at different durations **τ**
- for each **τ** get h_0^{95}

$$h_0 \leq \frac{1}{d}\sqrt{\frac{5G}{2c^3}\frac{\mathcal{I}}{\tau}\frac{\Delta f_{\rm gl}}{f}}$$

glitch excess energy

[Prix+ 1104.1704]



O3 narrowband CW & tCWs conclusions arxiv.org/abs/2112.10990

- Narrow-band searches for **continuous gravitational waves** from 18 pulsars:
  - **No evidence for GWs**, no remaining outliers.
  - Upper limits for 7 target below indirect spin-down limits (including 2 pulsars for the first time).
- Narrow-band searches for **post-glitch transient gravitational waves** from 6 pulsars (9 glitches):
  - Two remaining marginal outliers, **but no clear evidence of GWs**.
  - Upper limits were set, all above indirect energy constraints.

    (closest to beating those: within factor 1.6 for J1105–6107)
- **Future outlook:** O4 run will make all CW searches more sensitive,

  and should also bring first glitches within reach of beating indirect limits.

  (details in slides from Joan Moragues’ talk yesterday)

Acknowledgements

Thank you for listening!

david.keitel@ligo.org

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