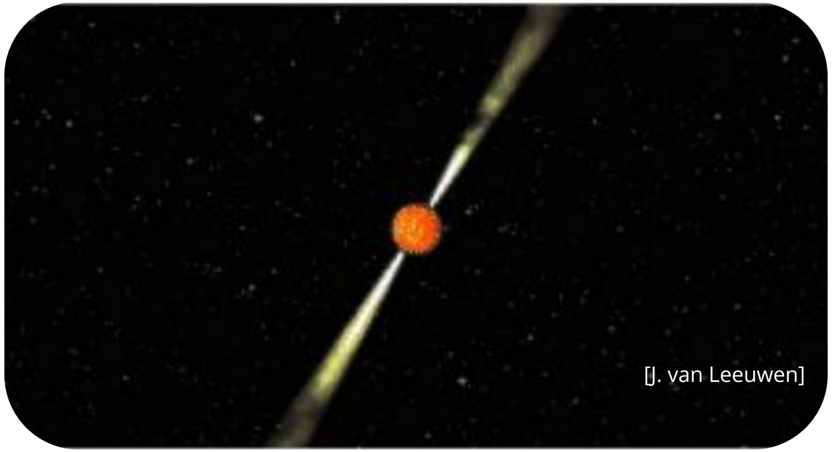
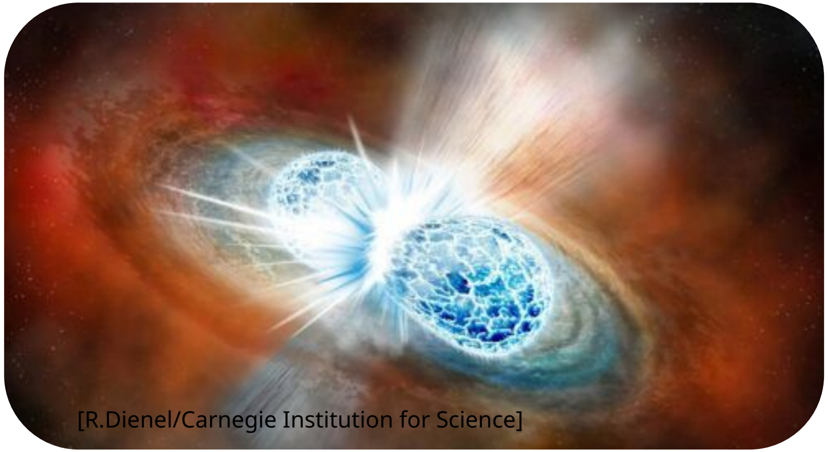

[J. van Leeuwen]


[R.Dienel/Carnegie Institution for Science]

# Long gravitational-wave transients and their detectability

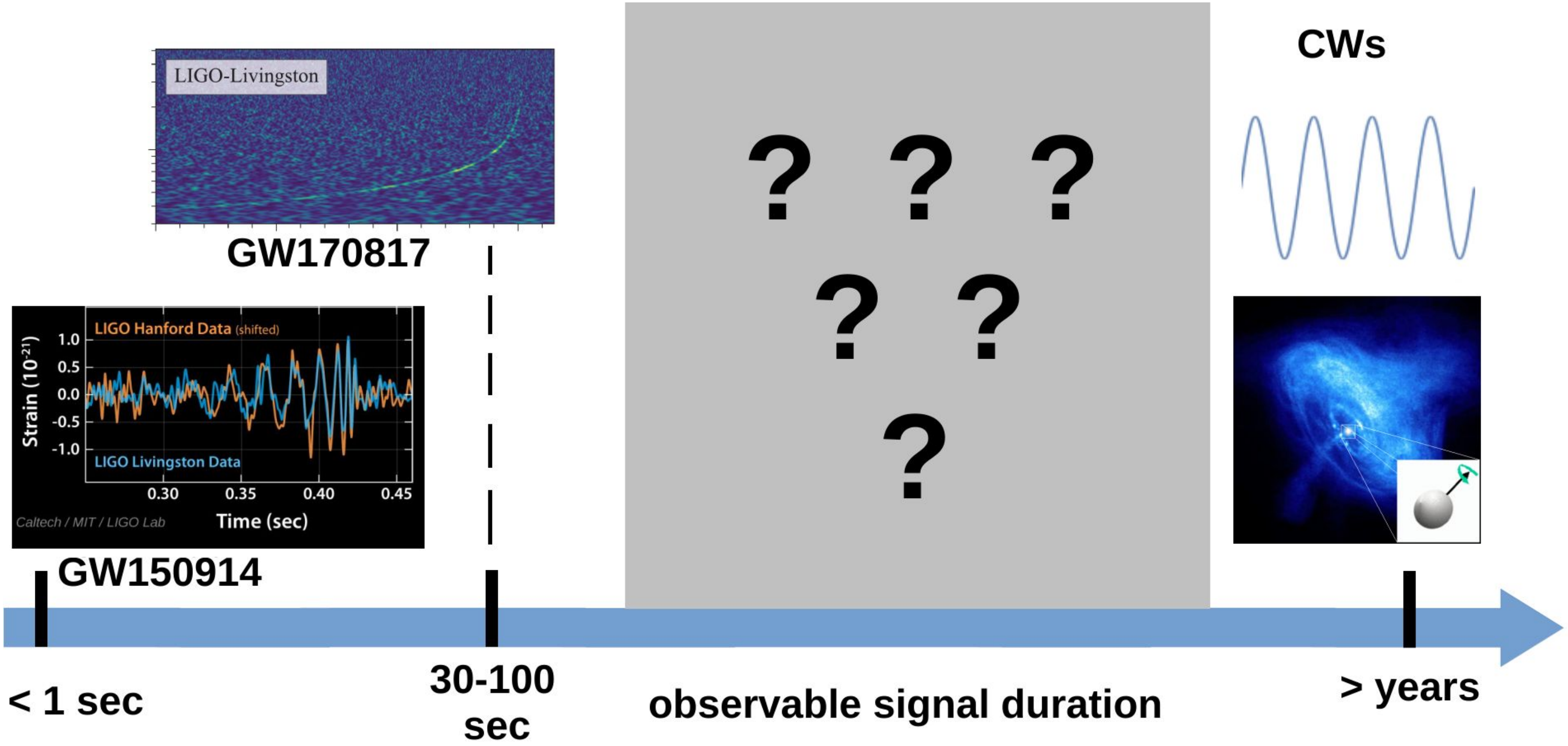
David Keitel
(IAC3 / Universitat de les Illes Balears)

2024/11/22

INT workshop “Discovering Continuous GW with Nuclear, Astro and Particle Physics“, Seattle

DCC: G2402331-v2

# long-duration CW-like transients

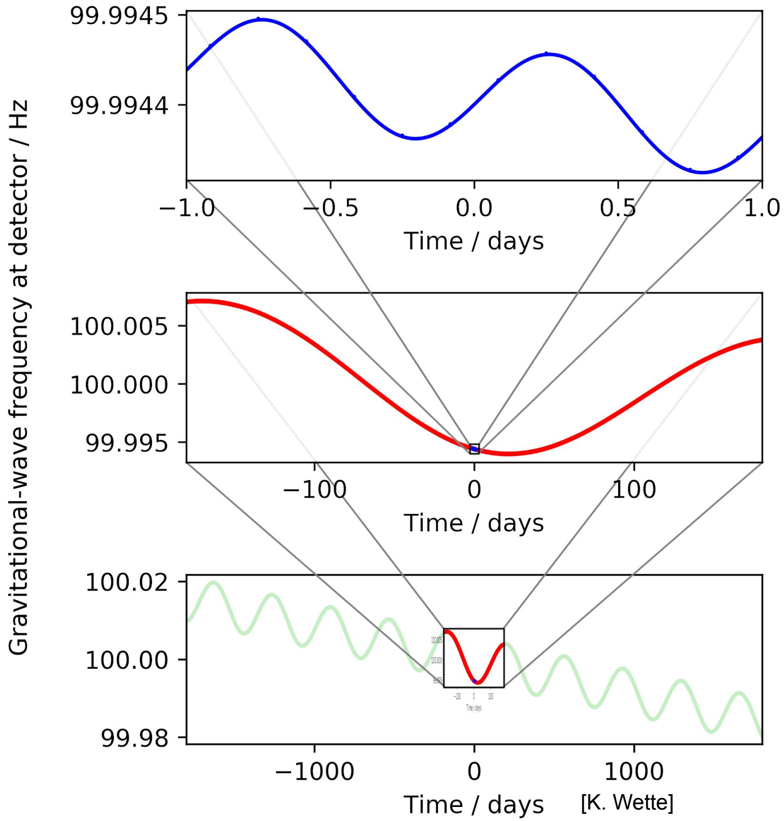


- newborn neutron stars
  (BNS merger remnants / supernovae)
- pulsar glitches

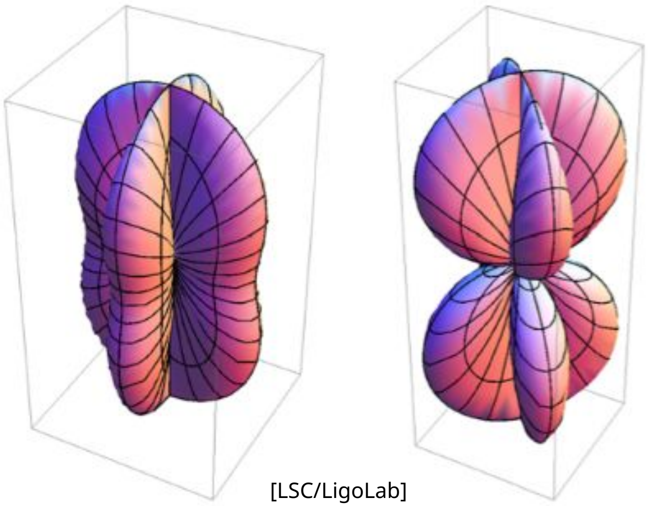
- magnetar and X-ray pulsar bursts
- vector boson clouds
- low-mass PBH binaries

# “CW-like” transients?

- quasi-monochromatic signals:
  very slow evolution of frequency and amplitude
- signal duration < observing time
- but often long enough for time-varying
  - antenna response
  - Doppler effect between source and Earth



[K. Wette]



[LSC/LigoLab]

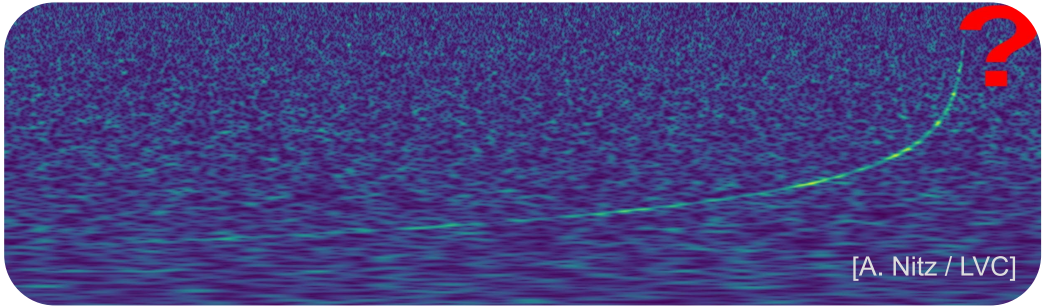
$$h(t;\mathcal{A},\boldsymbol{\lambda}) = F_+(t;\boldsymbol{n},\psi)\,A_+\cos\left[\phi_0+\phi(t;\boldsymbol{\lambda})\right] + F_\times(t;\boldsymbol{n},\psi)\,A_\times\sin\left[\phi_0+\phi(t;\boldsymbol{\lambda})\right]$$

# 1. BNS remnants


[A.Simonnet/LVC]

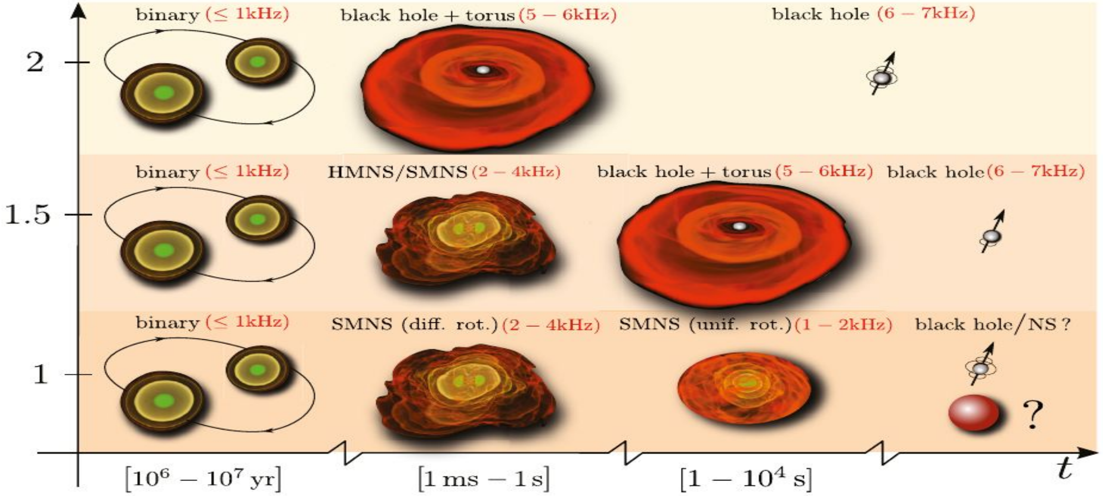
- GW170817:
  - BNS merger
  - $M_{\text{tot}} \approx 2.74\, M_{\text{sun}}$
  - $d \approx 40$ Mpc

[Abbott+ PRL119,161101 (2017)]



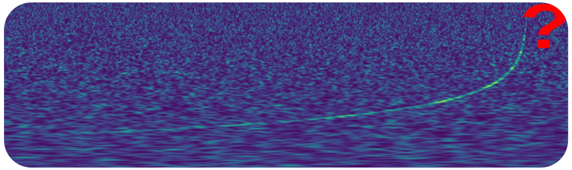
[A. Nitz / LVC]

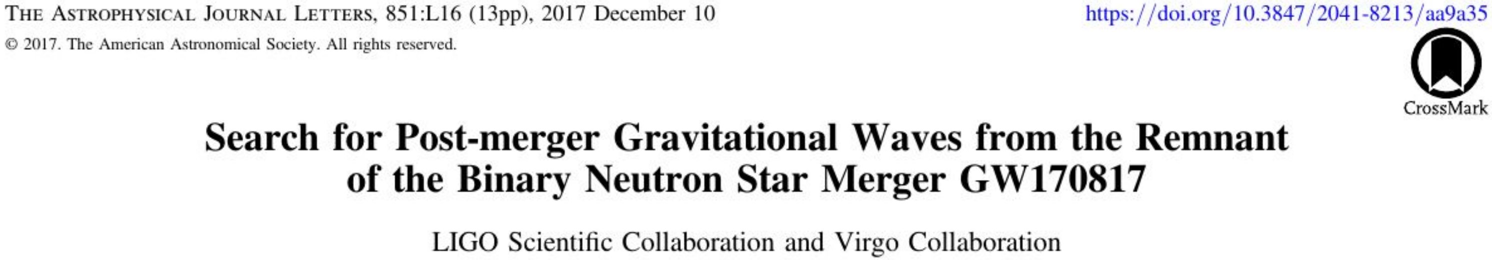
- What was the remnant?
  - direct collapse to BH?
  - [H/S]MNS → BH?
  - stable NS?
- answer would tighten EoS constraints
- indirect EM evidence for 2) [e.g. Gill+ ApJJ876:139 (2019)], but no direct measurement



[Baiotti&Rezzolla2017]

# BNS remnants





THE ASTROPHYSICAL JOURNAL LETTERS, 851:L16 (13pp), 2017 December 10 https://doi.org/10.3847/2041-8213/aa9a35

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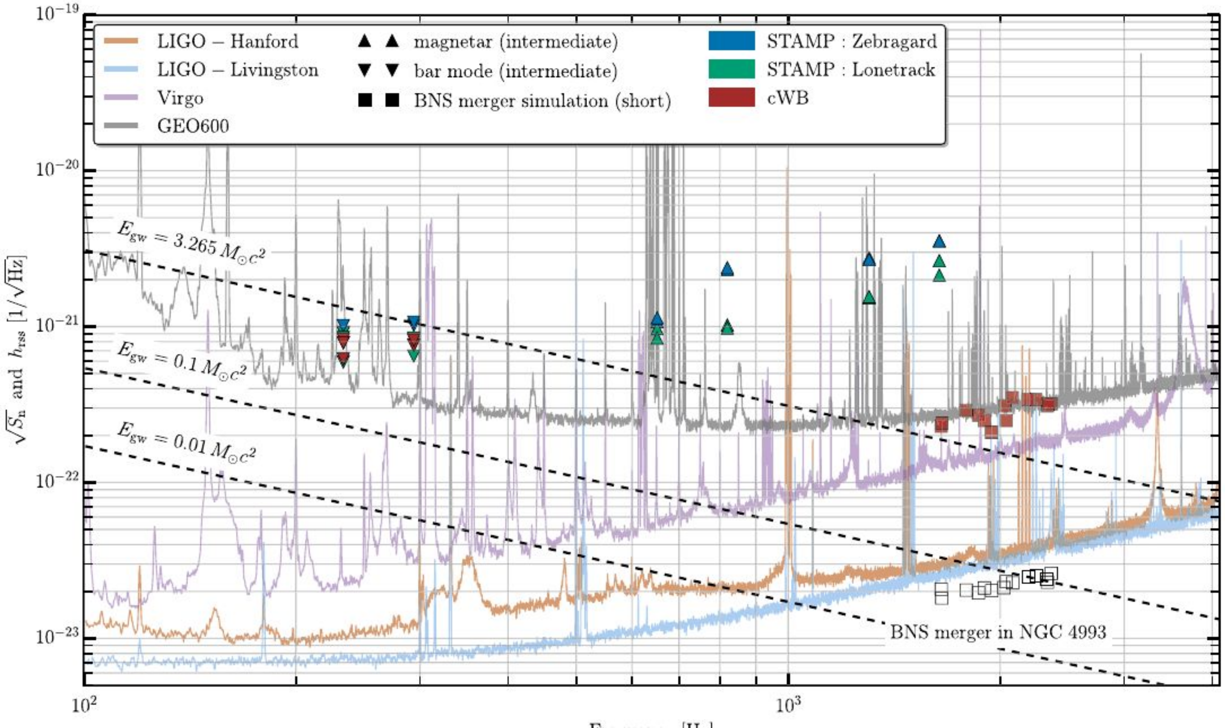
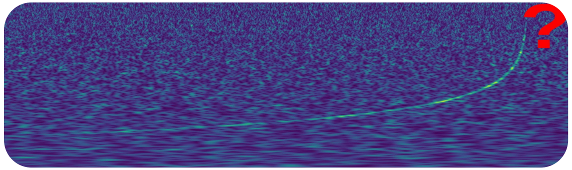
**Search for Post-merger Gravitational Waves from the Remnant of the Binary Neutron Star Merger GW170817**

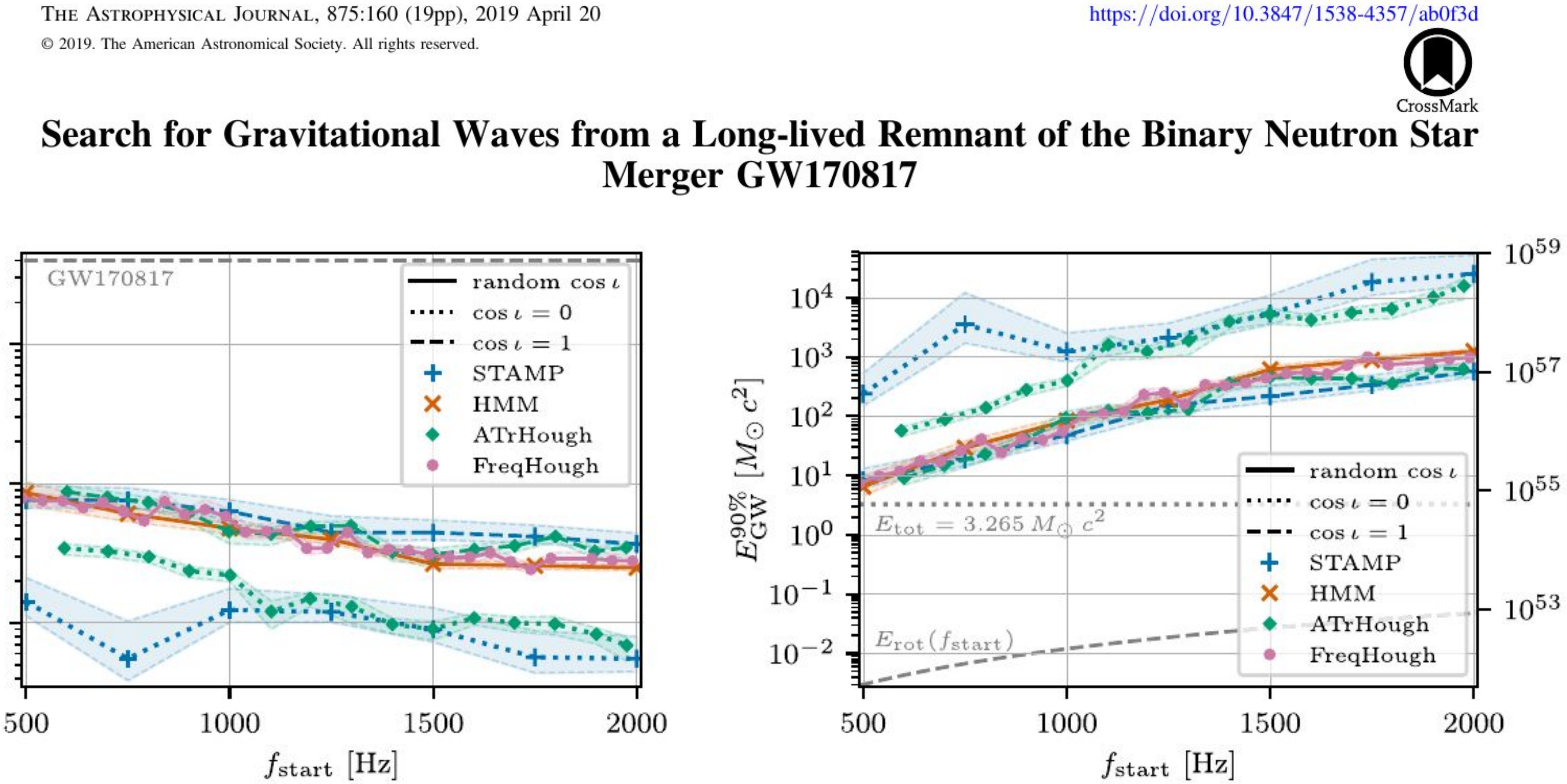
LIGO Scientific Collaboration and Virgo Collaboration



- short (<1s) and intermediate-duration (<500s) searches
- GW burst methods
- model-dependent sensitivity estimates:
    - NR postmerger (<1s)
    - bar modes
    - NS (“magnetar”) spin-down

# BNS remnants




THE ASTROPHYSICAL JOURNAL, 875:160 (19pp), 2019 April 20

https://doi.org/10.3847/1538-4357/ab0f3d

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**Search for Gravitational Waves from a Long-lived Remnant of the Binary Neutron Star Merger GW170817**

- CW methods
- NS (“magnetar”) spin-down
- up to 8.5 days

# BNS remnants

Evolution and GW emission depend on remnant mass and nuclear EoS.

[Sarin&Lasky GRG53:59 (2021)]

**Fig. 2** A post-merger remnant of mass $M \gtrsim 1.5\,M_{\mathrm{TOV}}$ will immediately collapse to form a black hole with an accretion torus and jet

**Fig. 3** A post-merger remnant of mass $1.2\,M_{\mathrm{TOV}} \gtrsim M \gtrsim 1.5\,M_{\mathrm{TOV}}$ will form a hypermassive neutron star which will collapse to a black hole on a timescale $\mathcal{O}(1\ \mathrm{s})$

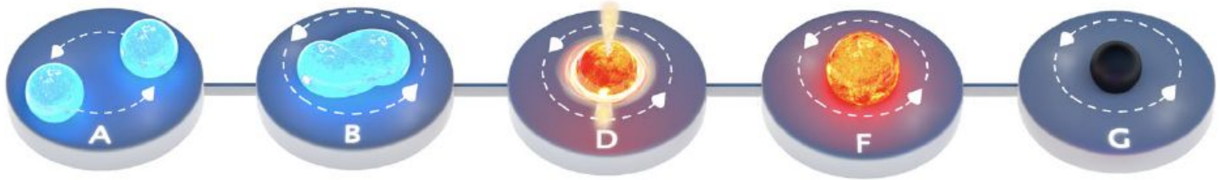


**Fig. 6** A post-merger remnant of mass $1.0\,M_{\mathrm{TOV}} \leq M \gtrsim 1.2\,M_{\mathrm{TOV}}$ will form a supramassive neutron star, which will collapse to a black hole on a timescale $\lesssim 10^5$ s

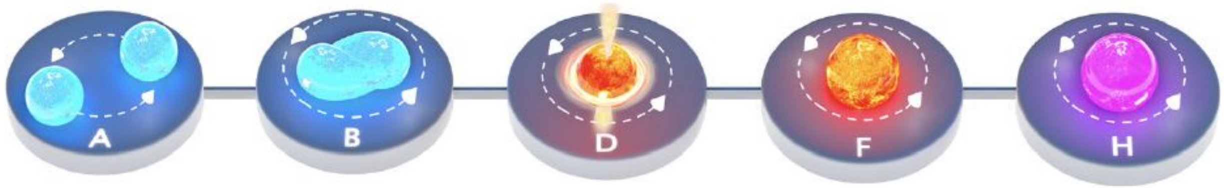
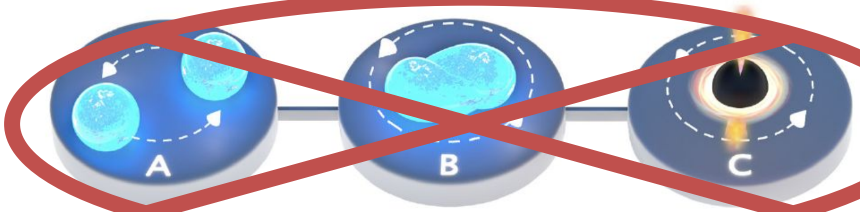


**Fig. 7** A post-merger remnant of mass $M \leq 1\,M_{\mathrm{TOV}}$ will form an infinitely-stable neutron star

# BNS remnants



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[Sarin&Lasky GRG53:59 (2021)]

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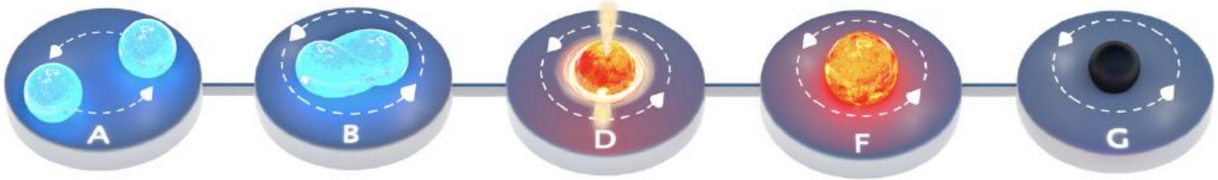
If we had detected ***short*** GW transients…

+ probe rich science of complicated immediate post-merger phase



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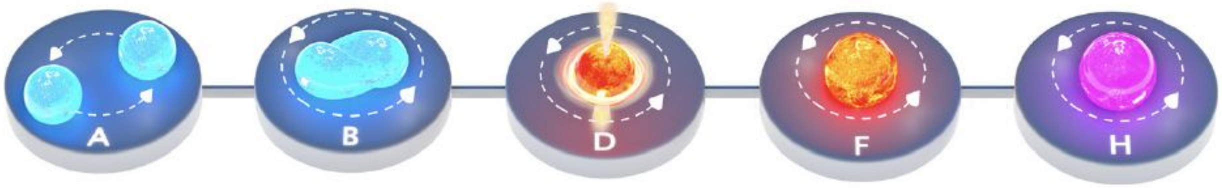


**Fig. 7** A post-merger remnant of mass $M \leq 1\,M_{\mathrm{TOV}}$ will form an infinitely-stable neutron star

# BNS remnants

[Sarin&Lasky GRG53:59 (2021)]

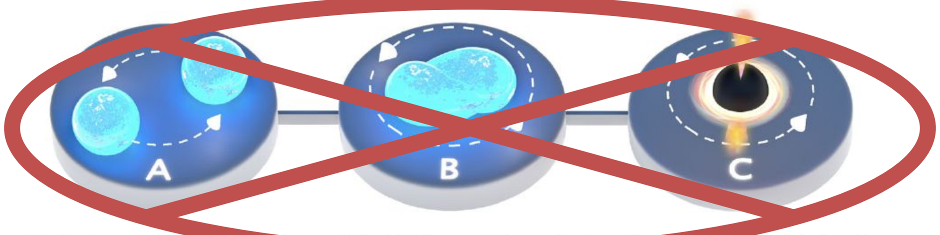


**Fig. 2** A post-merger remnant [illegible] 1.5 [illegible] will immediately [illegible] to form a black hole with an accretion torus and jet

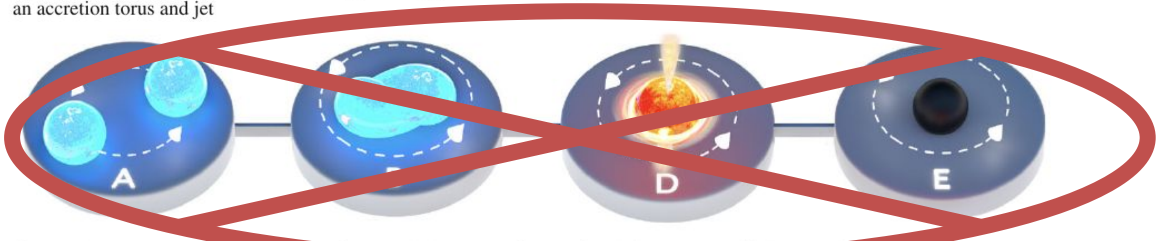


**Fig. 3** A post-merger remnant [illegible] hypermassive neutron star which will collapse to a black hole on a timescale $\mathcal{O}(1\text{ s})$

If we had detected *long* GW transients…

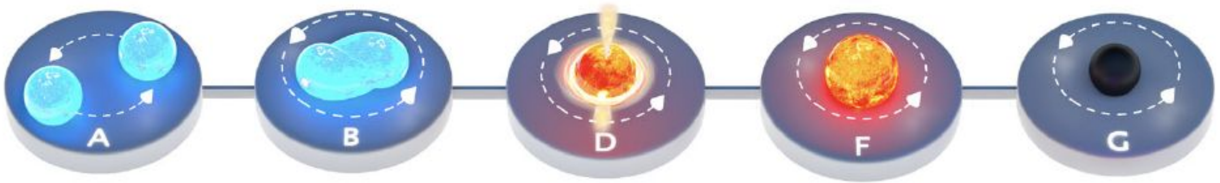


**Fig. 6** A post-merger remnant of mass $1.0\,M_{\rm TOV} \leq M \gtrsim 1.2\,M_{\rm TOV}$ will form a supramassive neutron star, which will collapse to a black hole on a timescale $\lesssim 10^5$ s

- + probe baby NS dynamical evolution (supported ellipticity, braking index)

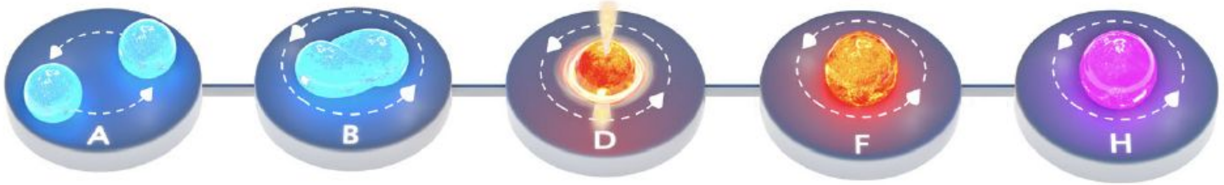


**Fig. 7** A post-merger remnant of mass $M \leq 1\,M_{\rm TOV}$ will form an infinitely-stable neutron star

# BNS and supernovae remnants

- BNS remnants: heavy and might have higher ellipticities, but rare at low distances (local merger rate: 10–1700 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ from GWTC-3 [LVK PRX13,011048 (2023)])

- regular newborn NSs from core-collapse supernovae: R=1.63±0.46 $(100\ \mathrm{yr})^{-1}$ *per MW*
  [Rozwadowska+ New Astro. 83,101498 (2021)]

- shared signal model:
  rapid "power-law" spindown

$$\dot{\Omega} = -k\Omega^{n} \longrightarrow h_0(t) = \frac{4\pi^2 G}{c^4}\,\frac{I_{zz}\epsilon f_{\mathrm{gw},0}^2}{d}\left(1+\frac{t}{\tau}\right)^{\frac{2}{1-n}}$$

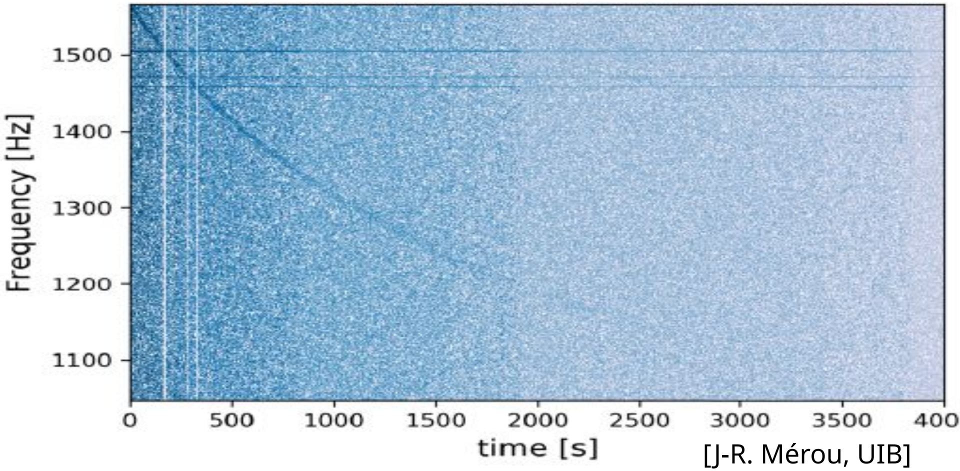
- often called "ms magnetar" model
  [Lasky+ https://dcc.ligo.org/T1700408/public]

n=3 magnetic dipole, n=5 mass quadrupole GWs, n=7 r-mode GWs

- still monochromatic

$$f_{\mathrm{gw}}(t) = f_{\mathrm{gw},0}\left(1+\frac{t}{\tau}\right)^{\frac{1}{1-n}}$$

- with LVK, limited to ~few Mpc,
  3G detectors: ~dozens Mpc



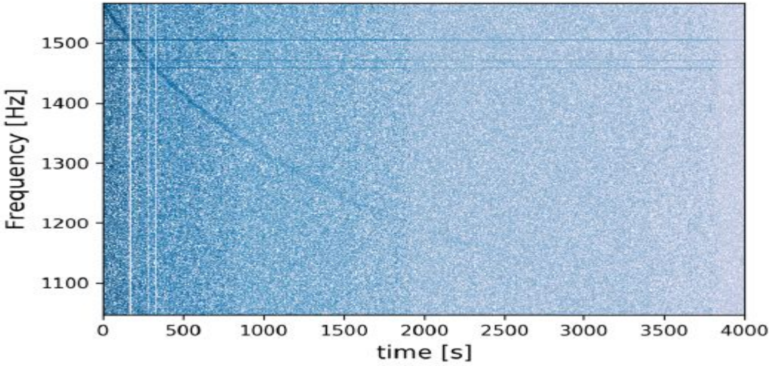
[J-R. Mérou, UIB]

# BNS and supernovae remnants

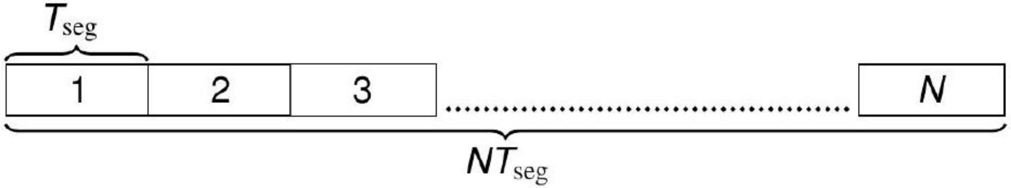
- Search challenges: rapid spindown,
  will cross many instrumental artifacts

- various semi-coherent CW search methods have been adapted and used for GW170817

[Abbott+ ApJ875:160 (2019)]



[J-R. Mérou, UIB]



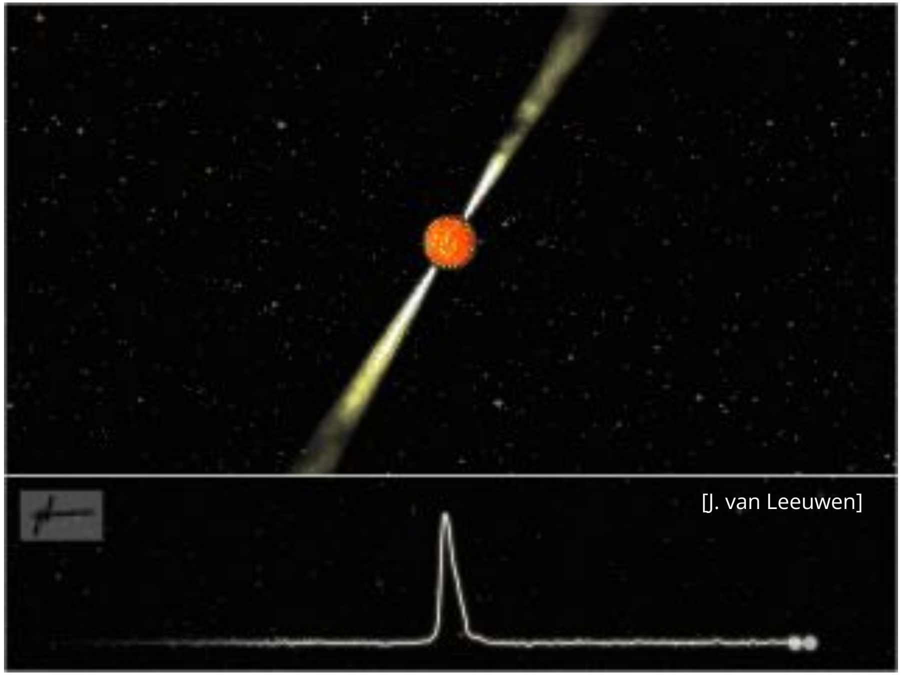
  - AdaptiveTransientHough [Oliver, Keitel & Sintes PRD99,104067 (2019)]
  - Generalized FrequencyHough [Miller+ PRD98,102004 (2018)]
  - HMM-Viterbi [Sun&Melatos PRD99,123003 (2019)]

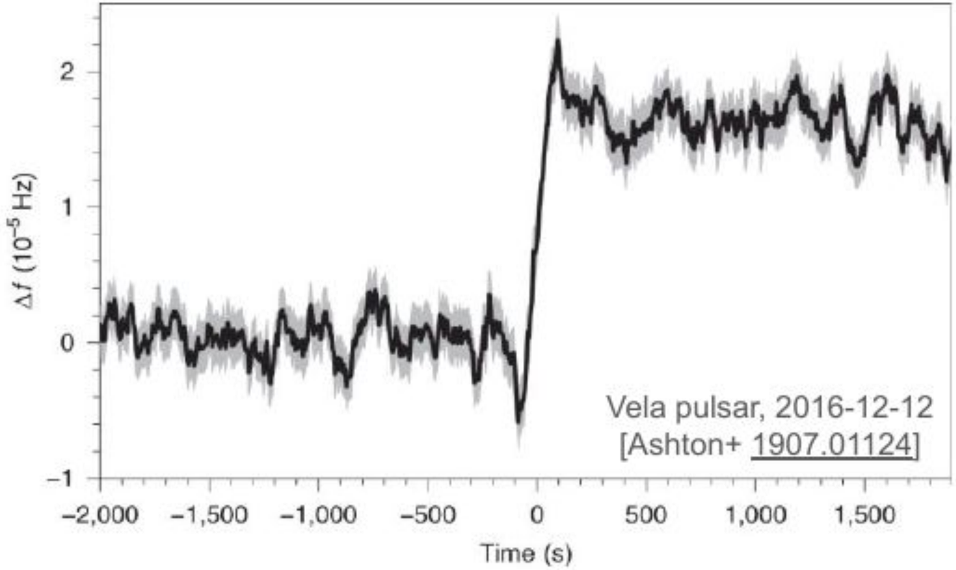
- alternative neural network ideas [Miller+ PRD100,062005 (2019), Attadio+ arXiv:2407.02391]

# BNS and supernovae remnants

- Future outlook:
  - Likely need to get at least one order of magnitude better to see anything.
  - Especially high frequencies (~kHz) relevant, so besides ET/CE, also dedicated detectors, like NEMO discussed in Australia, or some concepts in China.
- **Open questions:**
  - Is $\dot{\Omega} = -k\Omega^n$ general enough? What about evolving *n*(*t*)? [Grace+ PRD108,123045 (2022)]
  - What maximum ellipticity can newborn NSs sustain, more than mature ones?
  - Is phase coherence realistic?
- **(mildly) crazy ideas:**
  - blind all-sky searches?
  - precovery of EM transients?
  - Bayesian combination of GW searches and EM constraints, e.g. long-duration X-rays [Sarin+ PRD98,043011 (2018)]

# 2. pulsar glitches


[J. van Leeuwen]

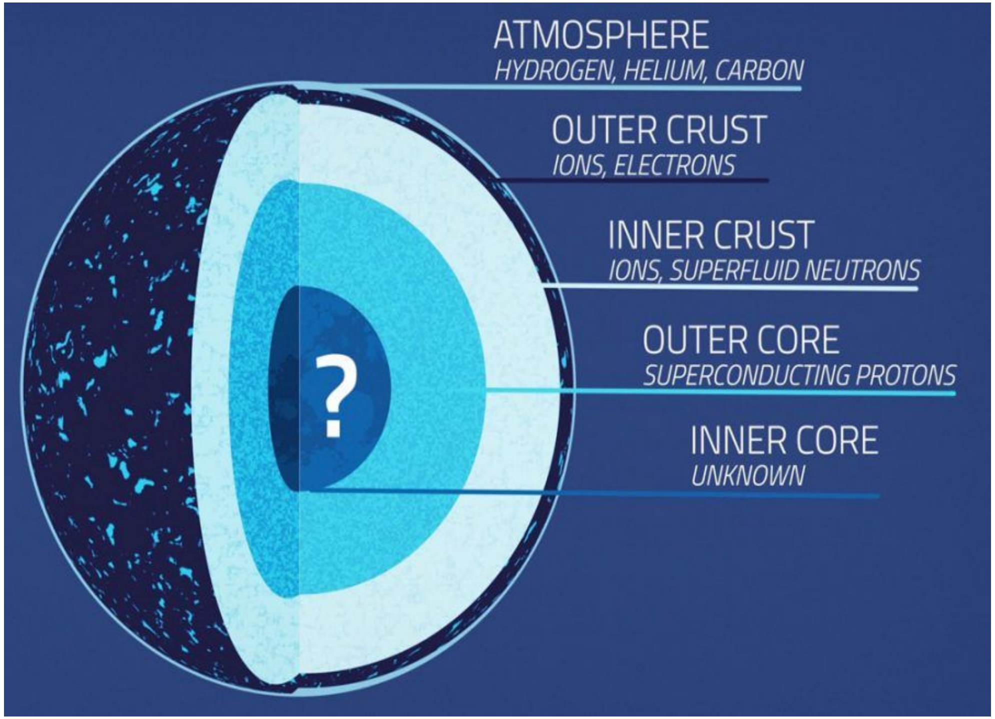


Vela pulsar, 2016-12-12
[Ashton+ 1907.01124]

$$f_{\mathrm{glitch}}(t) = \Theta(t - T_{\mathrm{gl}}) \left[ \sum_{k=0}^{M} \frac{\Delta f_{\mathrm{gl}}^{(k)} (t - T_{\mathrm{gl}})^k}{k!} + \delta f_{\mathrm{R}} e^{-(t - T_{\mathrm{gl}})/\tau_{\mathrm{R}}} \right]$$

- > 3000 known pulsars [ATNF]
- > 740 known glitches
  (as of 2022)

# glitches as probes of NS physics

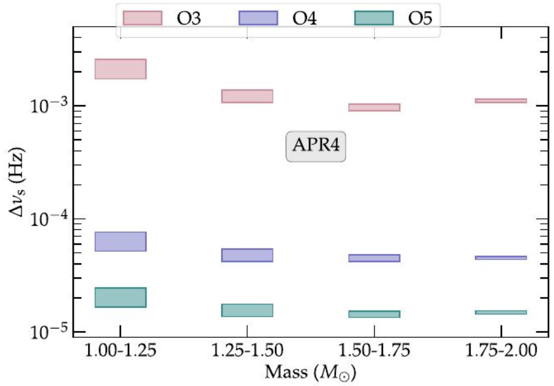


[NASA/Goddard/Conceptual Image Lab]

- pulsars lose energy by EM and GW emission → slow spin-down
- glitches: sudden **spin-up,** followed by relaxation phase with timescale (hours – months)
- energy transfer from internal superfluid
- and/or crustal “starquakes”
- accompanying change in quadrupole moment (e.g. Yim & Jones MNRAS498,3138 (2020)) → GW emission

→ How can we search for such GWs from glitching pulsars?

# GWs from pulsar glitches



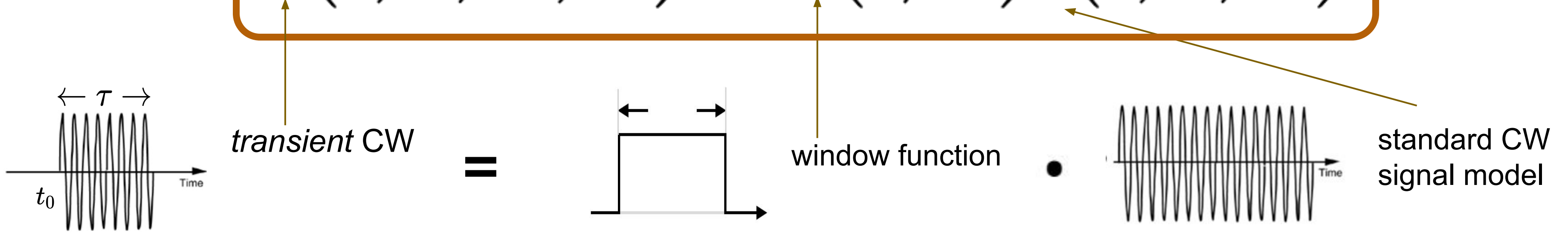
1) short-duration bursts from f-modes excited at the glitch:
   Lopez+ PRD106.103037 (2022) → search with e.g. cWB

2) long-duration transient GWs: “**tCWs**” [Prix+ PRD84,023007 (2011)]

   standard CW model, but in addition to **phase** and **amplitude parameters**, also consider **transient parameters** defining a **window** in time:

$$\lambda = \{\alpha, \delta, f, \dot{f}, \ddot{f} \ldots\} \quad \mathcal{A} = \{h_0, \cos\iota, \psi, \phi_o\} \quad \mathcal{T} = \{t_0, \tau\}$$

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



*transient* CW

=

window function

●

standard CW signal model

# glitch energy budget [Prix+ PRD84,023007 (2011)]

- **indirect upper limit** on emitted GW energy and amplitude: total energy released in glitch
- angular momentum conservation between superfluid and normal component:

$$I_c \delta\Omega + I_s \delta\Omega_s = 0$$

- **superfluid excess energy**:

$$E_s = \frac{1}{2} I_s (\Omega_s^2 - \Omega^2) \approx 4\pi^2 I_s \nu \Delta\nu$$

- **equate with total energy carried by CW-like GWs** with amplitude

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

$$\rightarrow \quad E_{\mathrm{GW}} = \frac{2\pi^2 c^3}{5G} f^2 d^2 \int^T h_0^2(t) dt,$$

glitch excess energy upper limit

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

- fixed energy regardless of transient duration $\tau$
- SNR increases with same sqrt($\tau$) as $h_0$ upper limit
  → **same detectability for short or long transients**

compare with spindown UL for CWs:

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

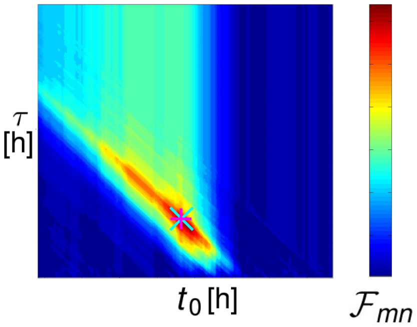
# tCW searches [Prix+ PRD84,023007 (2011)]

Test 2 hypotheses on data $\mathbf{x}$:

$$\begin{cases} \mathcal{H}_{\mathrm{G}} : \mathbf{x}(t) = \mathbf{n}(t) \\ \mathcal{H}_{\mathrm{tS}} : \mathbf{x}(t) = \mathbf{n}(t) + \mathbf{h}(t; \lambda, \mathcal{A}, \mathcal{T}) \end{cases}$$

likelihood ratio:

$$\frac{P(\mathbf{x}|\mathcal{H}_{\mathrm{tS}}; \lambda, \mathcal{A}, \mathcal{T})}{P(\mathbf{x}|\mathcal{H}_{\mathrm{G}})}$$



***maximize*** over $\mathcal{A}$ :

$$\mathcal{F}_{mn} = \mathcal{F}(\lambda, t_{0m}, \tau_n)$$

**"transient $\mathcal{F}$-stat map"**

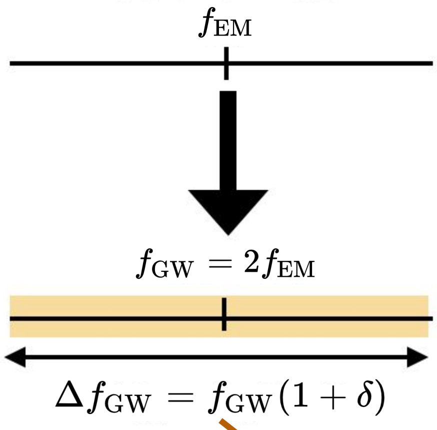
either
***maximize*** over $\mathcal{T}$

$$\max_{\mathcal{T}} \mathcal{F}(\mathbf{x}; \lambda, \mathcal{T})$$

...or
***marginalize*** over $\mathcal{T}$

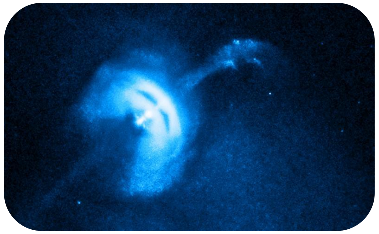
$$\log_{10} B_{\mathrm{tS/G}}(\mathbf{x}; \lambda)$$

"narrowband" searches:

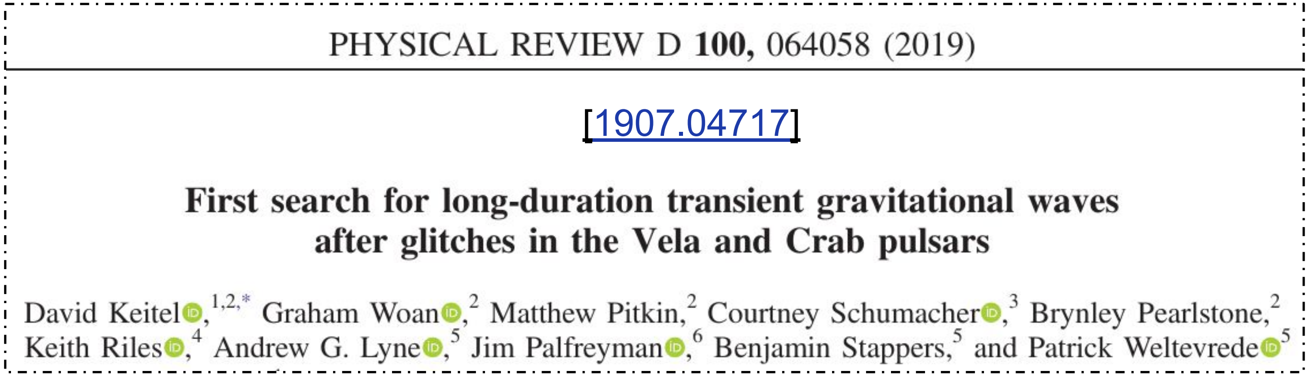


evaluate over a bank of phase-evolution templates $\boldsymbol{\lambda}$

# tCW searches so far – O2 open data



[Chandra/NASA]



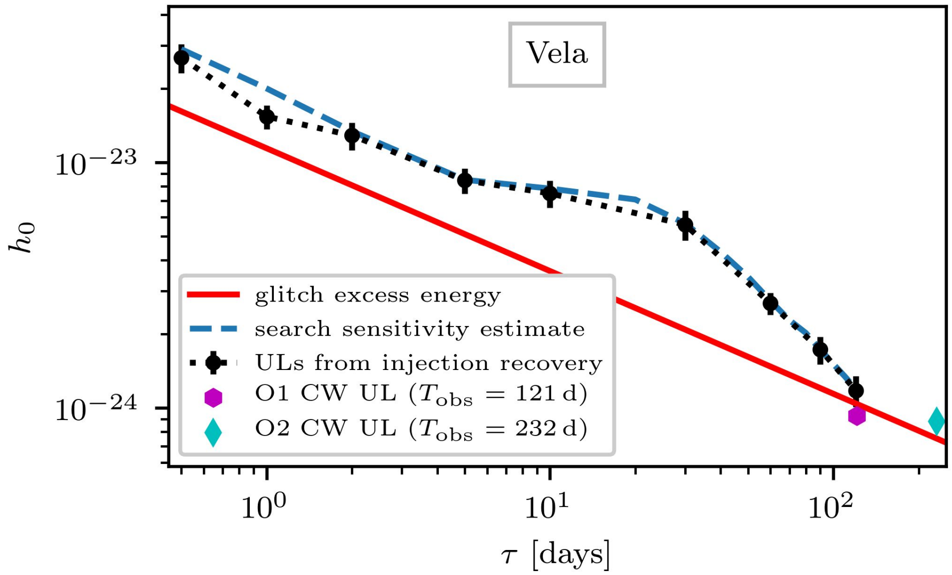
PHYSICAL REVIEW D **100,** 064058 (2019)

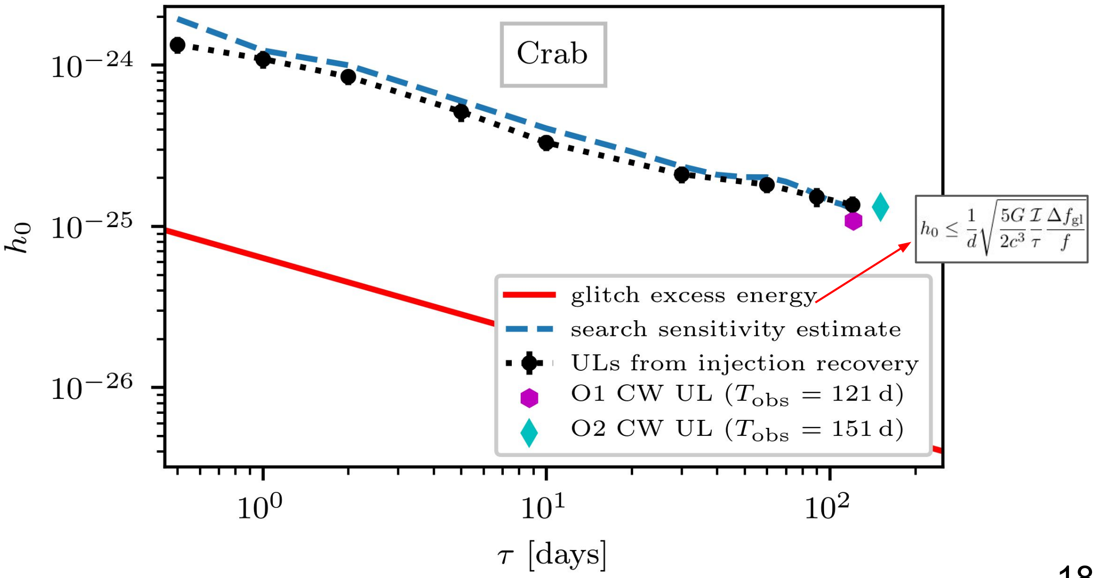
[1907.04717]

**First search for long-duration transient gravitational waves after glitches in the Vela and Crab pulsars**

David Keitel,[1,2,*] Graham Woan,[2] Matthew Pitkin,[2] Courtney Schumacher,[3] Brynley Pearlstone,[2] Keith Riles,[4] Andrew G. Lyne,[5] Jim Palfreyman,[6] Benjamin Stappers,[5] and Patrick Weltevrede[5]

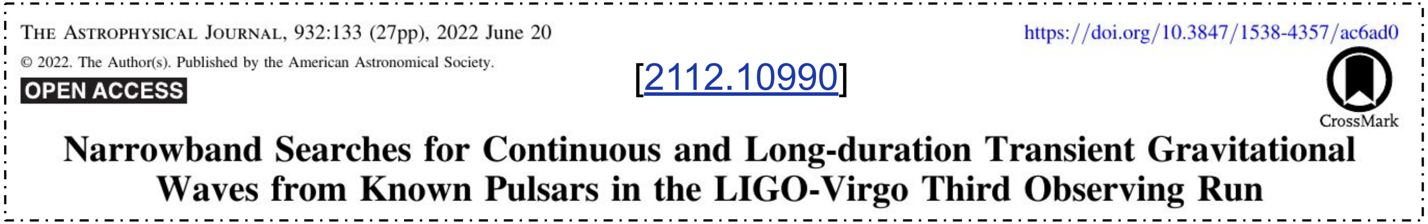
[Chandra/NASA]





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

# tCW searches so far – O3 LVK search



The Astrophysical Journal, 932:133 (27pp), 2022 June 20 https://doi.org/10.3847/1538-4357/ac6ad0

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[2112.10990]

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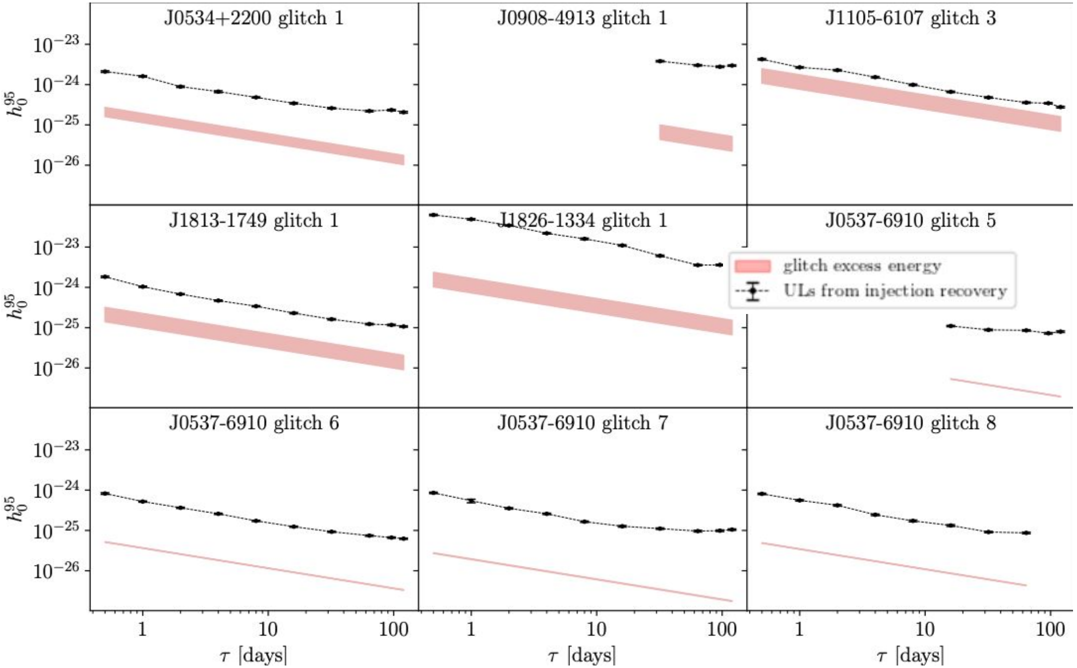
**Narrowband Searches for Continuous and Long-duration Transient Gravitational Waves from Known Pulsars in the LIGO-Virgo Third Observing Run**

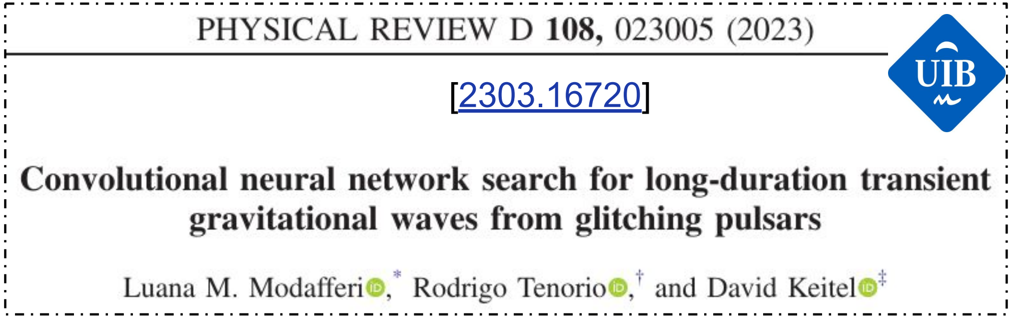
- improved version of O2 search: better setup [*] of template banks, BtS/G statistic [**], “distromax” method [***] for setting thresholds

| | | |
|---|---|---|
| **J0534+2200**<br>$f_{GW}$ ~ 60 Hz<br>glitched on 2019/07/23 | **J0537-6910**<br>$f_{GW}$ ~ 123 Hz<br>3 glitches in 2019, 1 glitch in 2020 | **J0908-4913**<br>$f_{GW}$ ~ 19 Hz<br>glitched ~ 2019/10/09 |
| **J1105-6107**<br>$f_{GW}$ ~ 31 Hz<br>glitched ~ 2019/04/09 | **J1813-1749**<br>$f_{GW}$ ~ 45 Hz<br>glitched ~ 2019/08/03 | **J1826-1334**<br>$f_{GW}$ ~ 20 Hz<br>glitched on 2020/01/31 |



[*] 2201.08785; [**] 1104.1704; [***] 2111.12032

# tCWs with CNNs



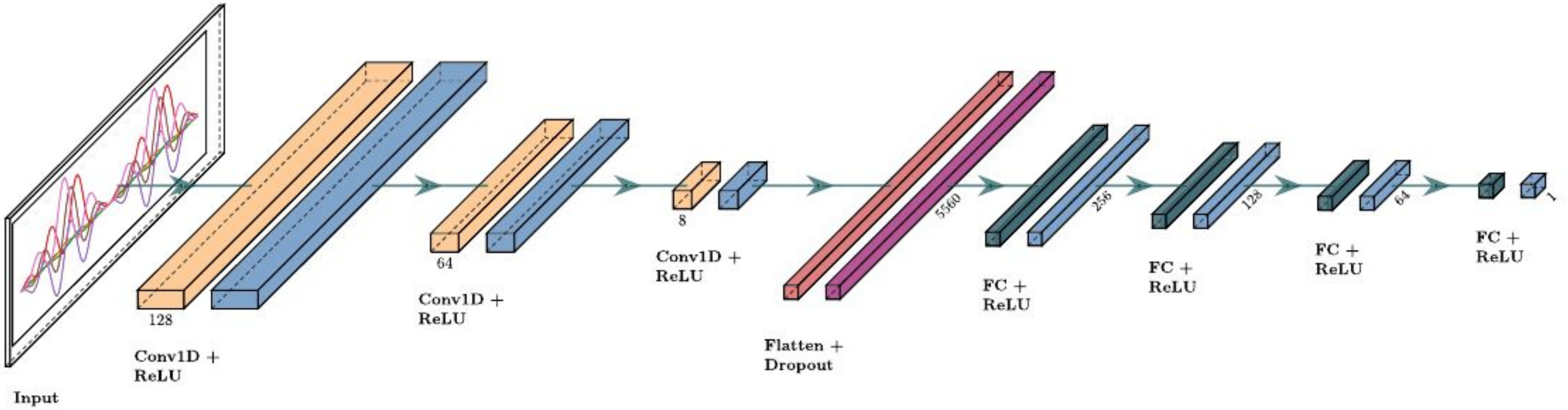
PHYSICAL REVIEW D **108,** 023005 (2023)

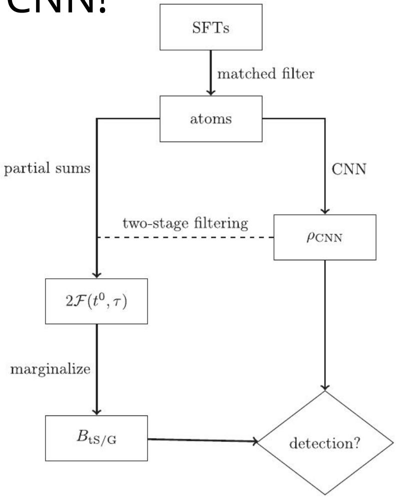
[2303.16720]

**Convolutional neural network search for long-duration transient gravitational waves from glitching pulsars**

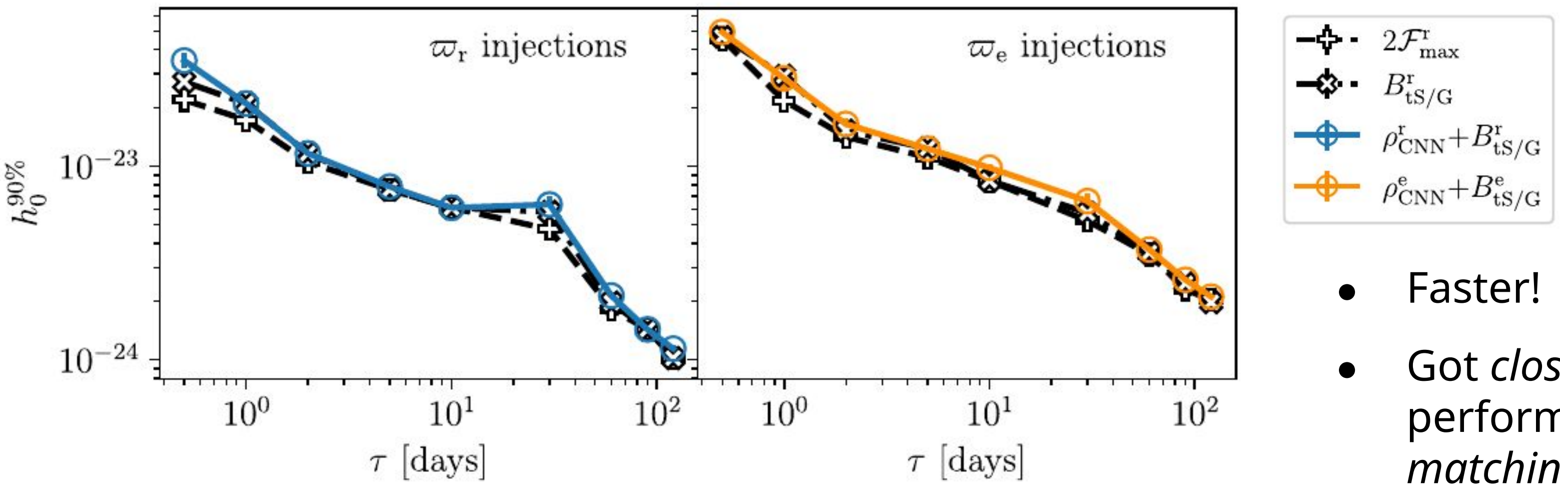
Luana M. Modafferi,[*] Rodrigo Tenorio,[†] and David Keitel[‡]

- transient $\mathcal{F}$-stat searches are computationally limited, mainly from trying many ($t_0$,$\tau$) combinations
- finding a (t)CW in time-frequency data is basically *pattern recognition*
- Convolutional Neural Networks (CNNs) are great at doing that fast. (At least for cats and dogs.)
- But actually limited in finding the very weak, narrow, long tracks. (see Joshi&Prix 2305.01057)
  → our hybrid approach: feed matched-filter intermediate data products to the CNN!





# CNN upper limits on O2 Vela glitch



- Faster!
- Got *close* to pure *F*-stat performance, but *not quite matching* it.

Limitations:

- Allowing for flexible amplitude evolution, but fixed to tCW frequency evolution model.
- Faster than pure transient *F*-stat,  
  but still far too slow for going beyond known pulsars.

→ new approach needed for

“All-Sky All-Frequency All-Time”

searches for unknown glitchers!

# tCWs: prospects

ATNF + Jodrell glitch catalogues
→ 740 known glitches (2022/10/11)
→ extrapolate future prospects

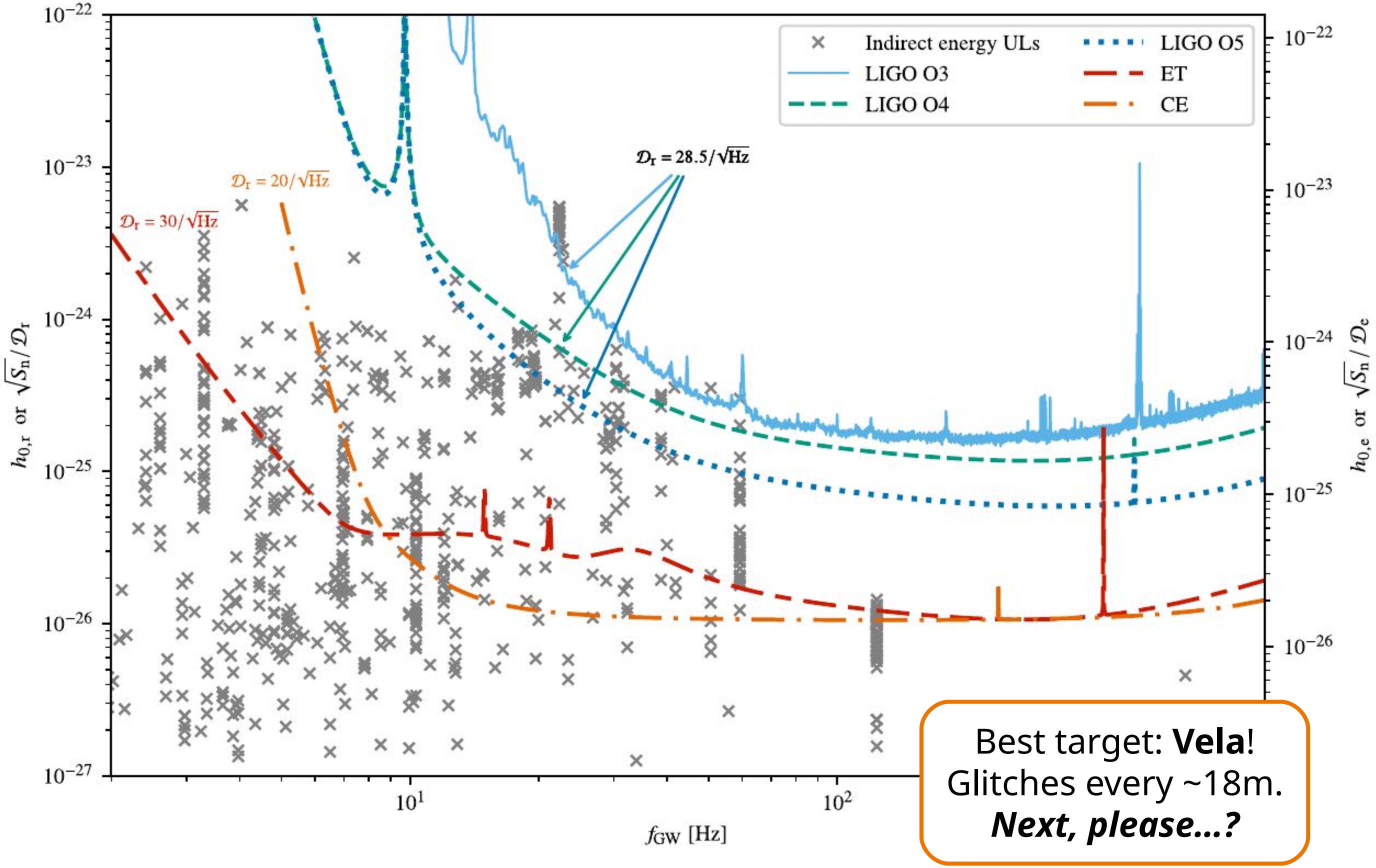
MNRAS **519**, 5161–5176 (2023) https://doi.org/10.1093/mnras/stac3665
Advance Access publication 2022 December 15

[2210.09907]

**Prospects for detecting transient quasi-monochromatic gravitational waves from glitching pulsars with current and future detectors**

Joan Moragues ,★ Luana M. Modafferi , Rodrigo Tenorio and David Keitel ★

*Departament de Física, Universitat de les Illes Balears, IAC3–IEEC, Crta. Valldemossa km 7.5, E-07122 Palma, Spain*



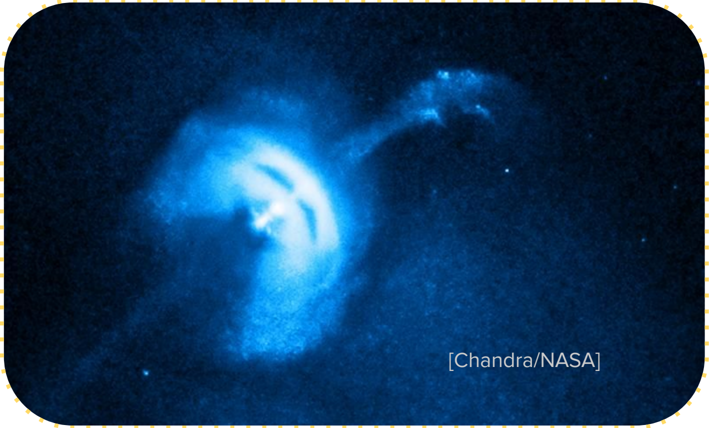
Best target: **Vela**!
Glitches every ~18m.
***Next, please…?***

- Sensitivity depth $\mathcal{D} \equiv \sqrt{S_{\rm n}}/h_0$
  [Behnke+2014,Dreissigacker+2018]
  estimated for *realistic* searches
- compare indirect energy UL:

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

- plot for duration $\tau$ = 10 d
- longer/shorter $\tau$:
  push *both* markers *and* curves down/up by sqrt($\tau$)
  → same detectability

# …2024: Vela glitched again!



[Chandra/NASA]

- Vela pulsar: nearby (287pc), $f_{rot}$ ~ 11 Hz → $f_{gw}$ ~ 22 Hz
- strong glitches ($\Delta f / f$ ~ $10^{-6}$) every 1.5 years or so.
- first LSC search for short bursts from 2006 glitch [Abadie+2011b].
- first tCW search on O2 open data for 2016 glitch [Keitel+2019].
- no glitch during O3, last in 2021, then got lucky in O4!

E. Zubieta+,
Argentine Institute of Radio astronomy
[www.astronomerstelegram.org/?read=16608]

*We observed a glitch occurring* ***between MJD 60428.96 (2024-04-28 23h UTC) and MJD 60431.84 (2024-05-01 20h UTC)****. […] change in the pulsar rotation period of* ***dF0/F0 = 2.3E-6*** *[…]*

(also confirmed by other radio telescopes and FERMI)

J. Palfreyman,
Mt. Pleasant Telescope,
Tasmania
[www.astronomerstelegram.org/?read=16615]

*glitch* ***epoch of MJD 60429.869615 +/- 3.84691e-05 dF0/F0 of 2.40976e-06 +/- 4.88083e-10***

# tCWs from pulsar glitches

- **Open questions:**
  - How to build a “transient mountain”? Does this actually happen?
  - How much of the liberated energy would really be available for this?
  - How much in other channels (e.g. “kicked r-modes”)?
  - How deep into the NS could we look?
  - Which glitchers are the best targets?
  - How flexible do we need to be with the $f(t)$ and $A(t)$ model?

- **(mildly) crazy ideas:**
  - Can we already constrain physics with non-detections below the optimistic UL?
  - blind all-sky, all-frequency, all-time searches for “dark glitches”

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LIGO
VIRGO
KAGRA

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