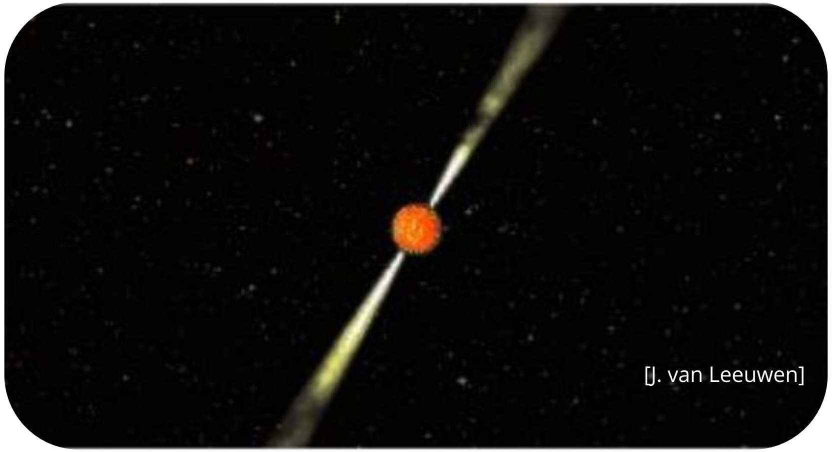
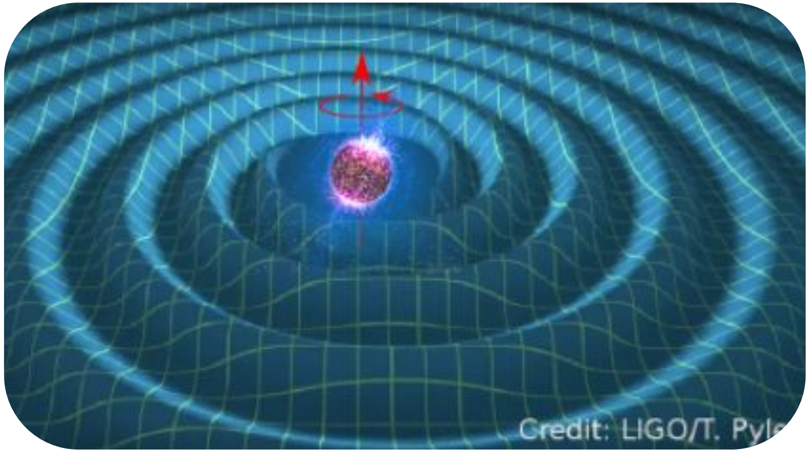




Individual neutron stars as GW sources: continuous and long-transient signals

Universitat de les Illes Balears

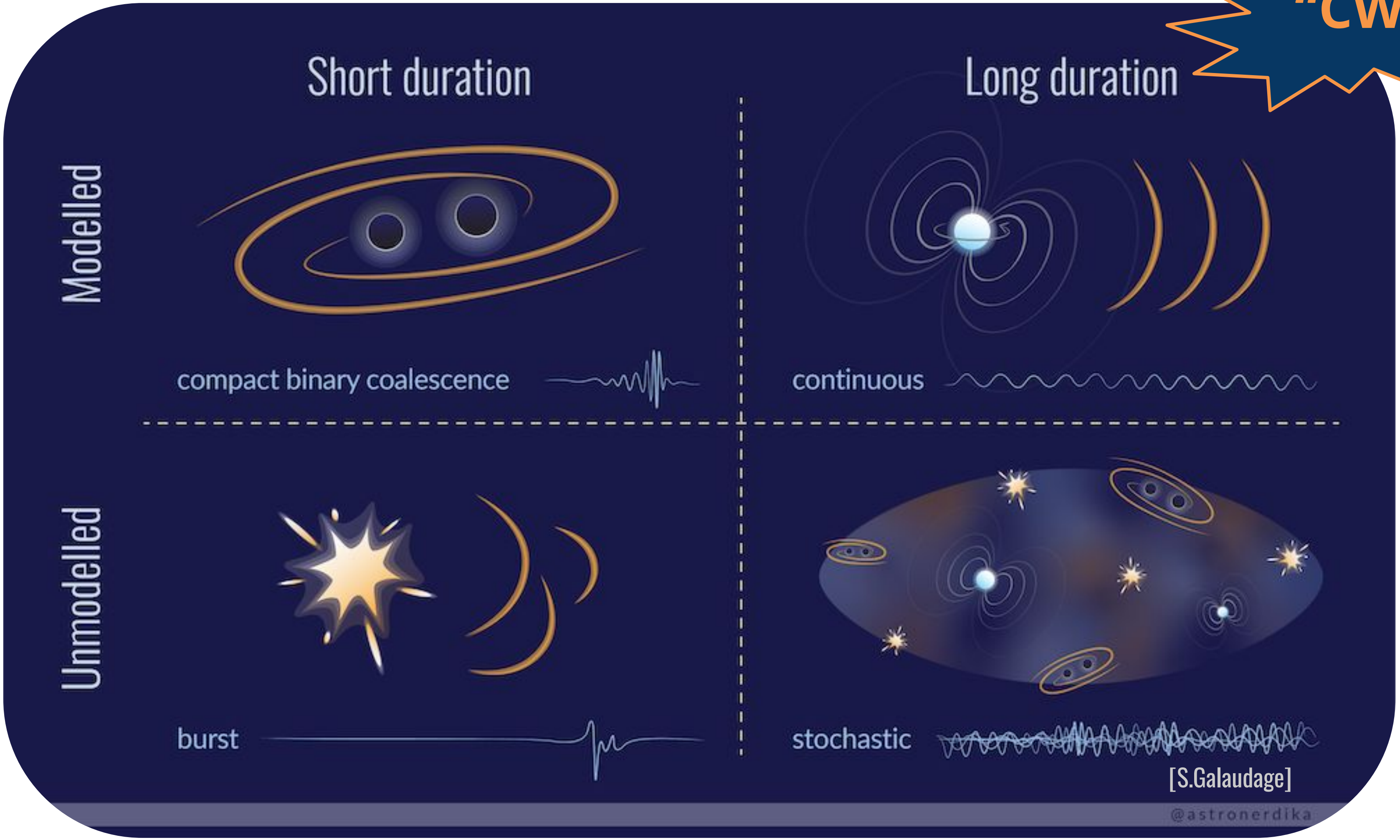
IAC3 Institute of Applied Computing & Community Code.

David Keitel
(IAC3 / Universitat de les Illes Balears)

GraSP24, Pisa, 2024/10/25

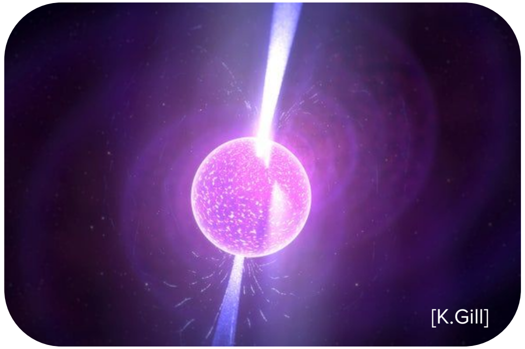
DCC: G2401742-v2

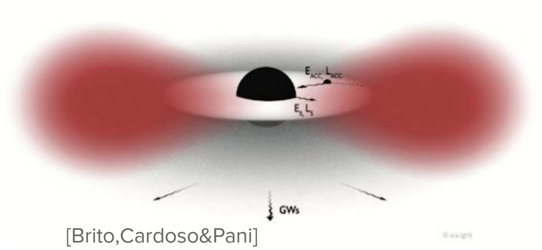
LVK search types

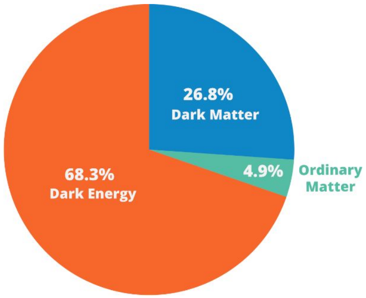


Continuous Waves: persistent, quasi-monochromatic GWs

- A completely new GW signal type: first detection will be another revolution.
- No “blink and it’s gone” – once we’ve detected a CW, we can keep observing it, learning more and more about the source.
- **Neutron star** science: probing dense, “cold” nuclear matter, studying the “dark” majority of the galactic population.
- Exotic sources: constraints on **dark matter** under various models; of high interest to wider physics community.



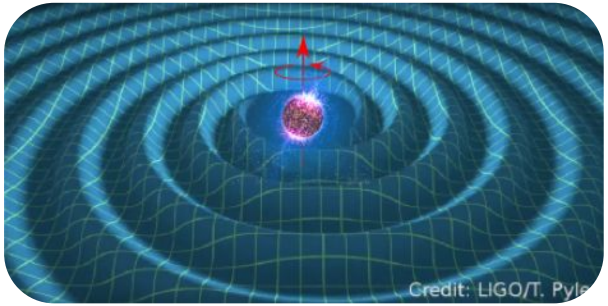


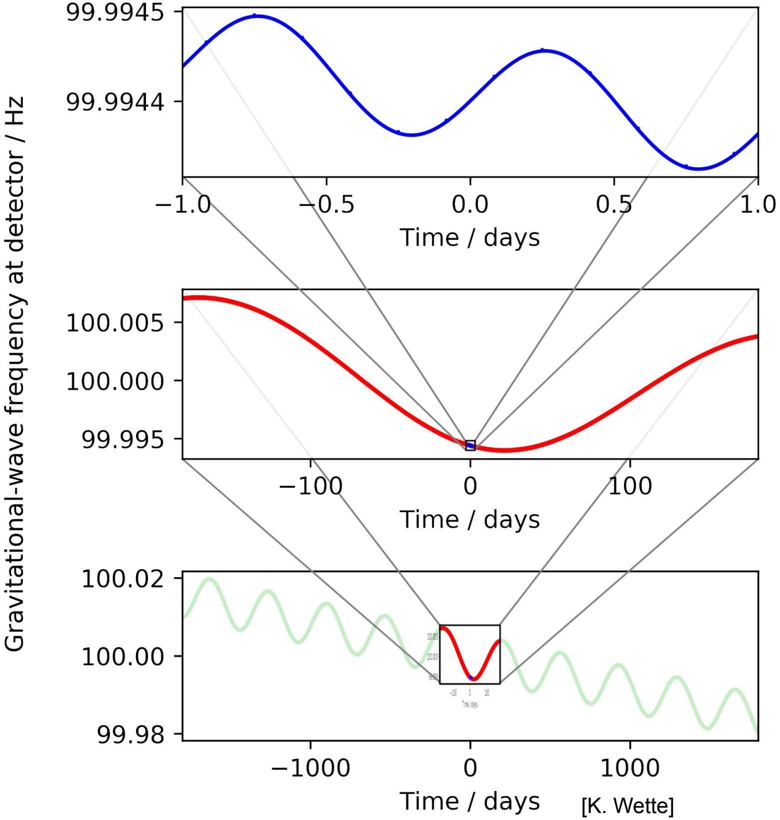


- No guarantee of detection in any given run, but we’ve started pushing deep into physically allowed parameter ranges: → a first detection could be around the corner!

Continuous Waves

- extremely weak (strain: GW150914 ~10^{-21}, CW $\lesssim 10^{-25}$)
- signal duration > observing time
- quasi-monochromatic signals:
  very slow evolution of frequency and amplitude
- measured strain $h(t)$ depends on intrinsic spin-down, Doppler effect between source and Earth, antenna response ⇒ $h(t, h_0, f, df/dt, \ldots, \alpha, \delta)$
  (+extra parameters for sources in binaries)
- Matched-filter searches are effective, but need to sample the parameter space very finely.
- Signal-to-noise increases with $\sqrt{T_{obs}}$,
  but computing cost grows much faster.



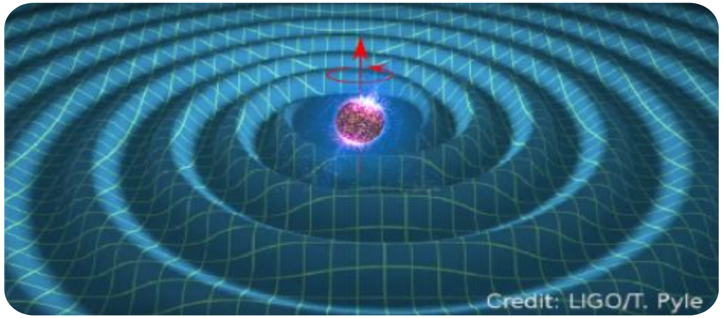


[K. Wette]

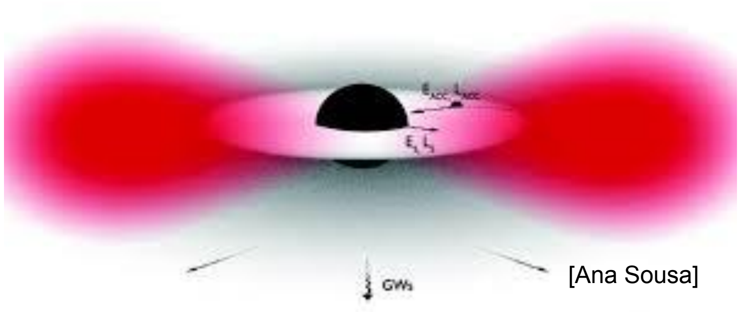
CWs – what are they good for?

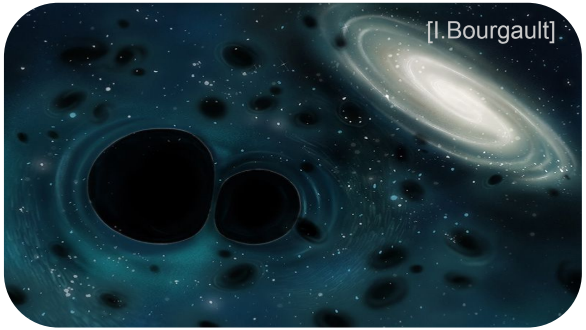
- first detection can be one of the next breakthroughs of GW astronomy
- prime targets: spinning deformed neutron stars
  - cold nuclear matter at extreme densities: "celestial laboratories"
  - once detected, we can keep observing and do long-term astrophysics studies
  - >10^8 neutron stars in our galaxy, only ~3000 known

    → can we find the "dark" ones?

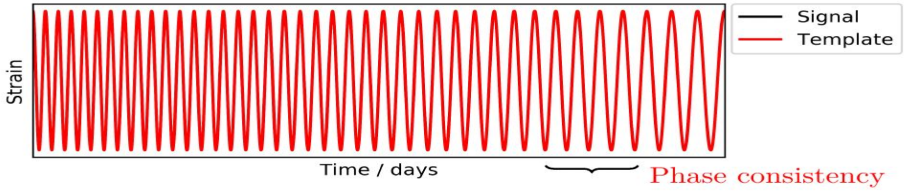


- new physics searches:
  - modified gravity
  - dark matter: indirect & direct detection
  - primordial black holes

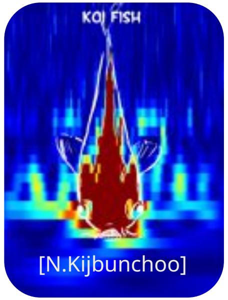


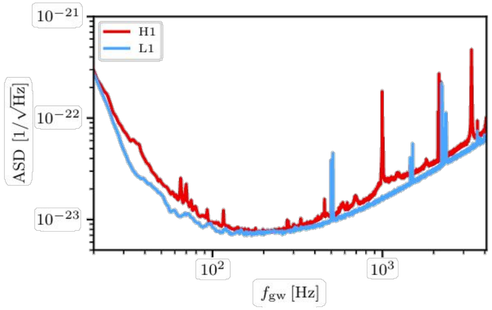


CW data analysis



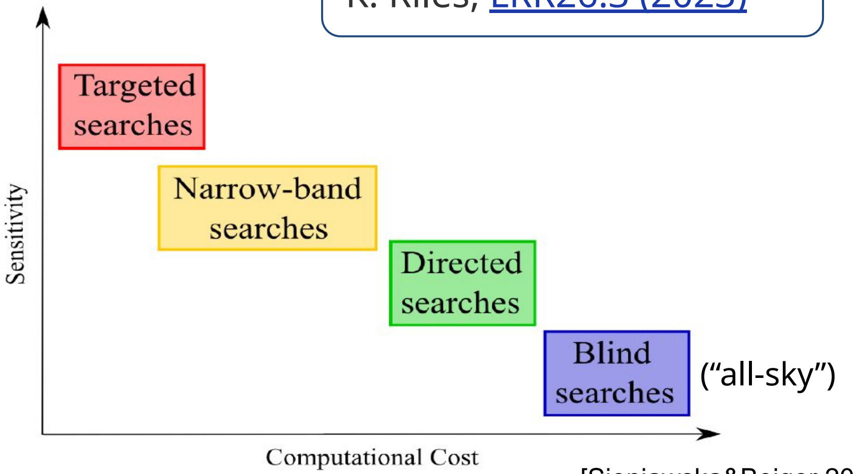
- simple, deterministic templates → matched filter
- precise frequency resolution from long-term phase coherence
- precise sky localisation, *even with a single detector* (the Earth moves – "*E pur si muove*")
- real data challenges:
  - loud but short glitches → require time-domain cleaning/gating
  - narrow spectral lines → require identification and mitigation





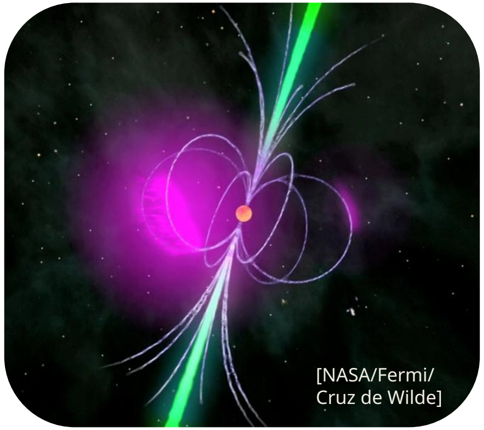
for an overview:
K. Riles, LRR26:3 (2023)

searches classified by amount of prior information:



[Sieniawska&Bejger 2019]

known pulsar searches



- detailed EM pulsar ephemerides
  → ***fully-coherent*** matched filter across full GW observing runs
- indirect ***spin-down upper limit***
  assumes all energy loss into GWs: $h_0 \leq \frac{1}{d}\sqrt{\frac{5GI_{zz}}{2c^3}\frac{|\dot{f}_{\rm rot}|}{f_{\rm rot}}}$
- for **Crab** and **Vela** (nearby energetic young pulsars with great timing cadence):
  already "beaten" this limit with initial LIGO/Virgo in the 2000s.

THE ASTROPHYSICAL JOURNAL, 683: L45–L49, 2008 August 10

BEATING THE SPIN-DOWN LIMIT ON GRAVITATIONAL WAVE EMISSION FROM THE CRAB PULSAR

In the single-template search the joint (i.e., multidetector) posterior probability distribution for the gravitational wave amplitude peaks at zero, indicating that no signal is visible at our current sensitivity. The joint 95% upper limit on the gravitational wave amplitude, using uniform priors on all the parameters, is $h_0^{95\%} = 3.4 \times 10^{-25}$. In terms of the pulsar's ellipticity, given by $\epsilon = 0.237 h_{-24} r_{\rm kpc} \nu^{-2} I_{38}$ (Abbott et al. 2007c), where h_{-24} is h_0 in units of 1×10^{-24}, this gives $\epsilon = 1.8 \times 10^{-4}$ using the canonical moment of inertia and $r = 2$ kpc. This is 4.1 times lower than the spin-down upper limit and also 1.6

THE ASTROPHYSICAL JOURNAL, 737:93 (16pp), 2011 August 20 doi:10.1088/0004-637X/737/2/93

BEATING THE SPIN-DOWN LIMIT ON GRAVITATIONAL WAVE EMISSION FROM THE VELA PULSAR

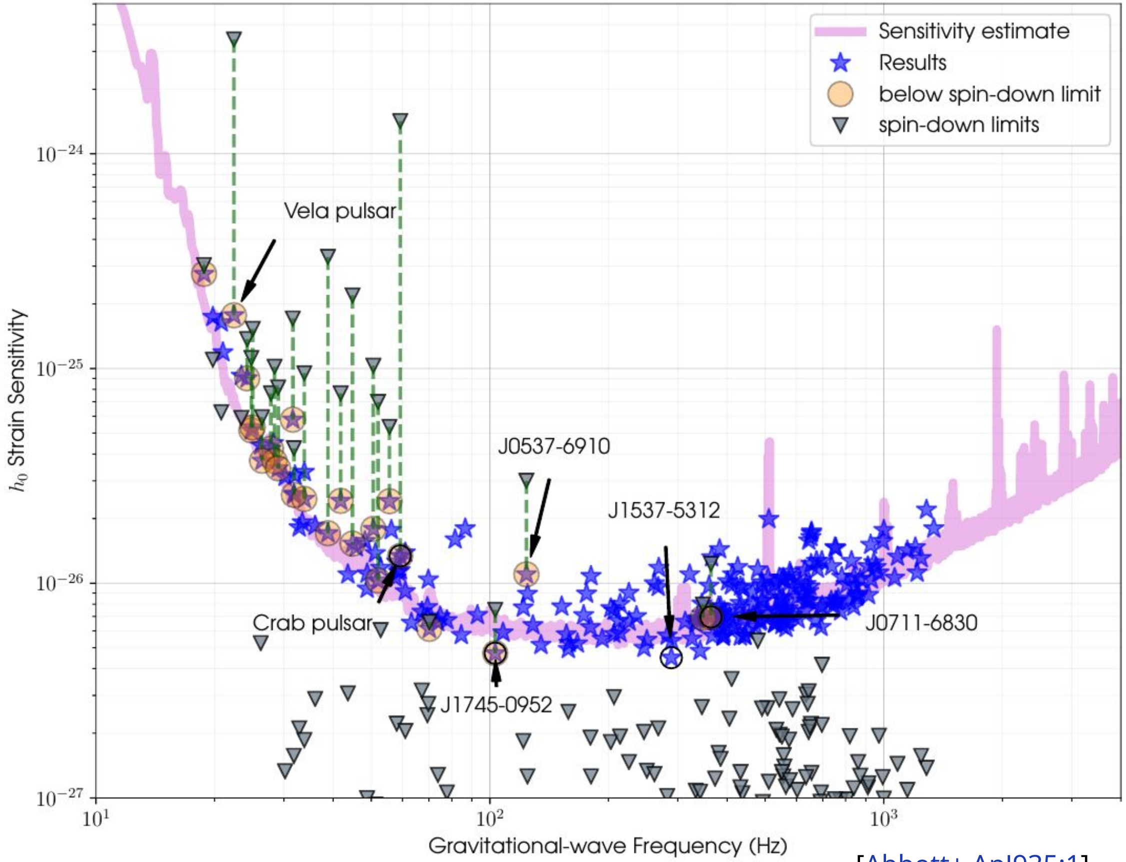
known pulsars: selected O3 results

“Fully targeted” searches:

- [Abbott+ ApJ935:1 (2021)]
- 236 targets, 23 below spin-down limit
- searched at both $f_{\rm gw} = 2f_{\rm spin},\ f_{\rm gw} = f_{\rm spin}$

“Narrowband” searches:

- relax EM–GW frequency lock
  → small template banks ~<O(10^6)
- [Abbott+ ApJ932:133 (2022)]
- 18 targets, 7 below spin-down limit



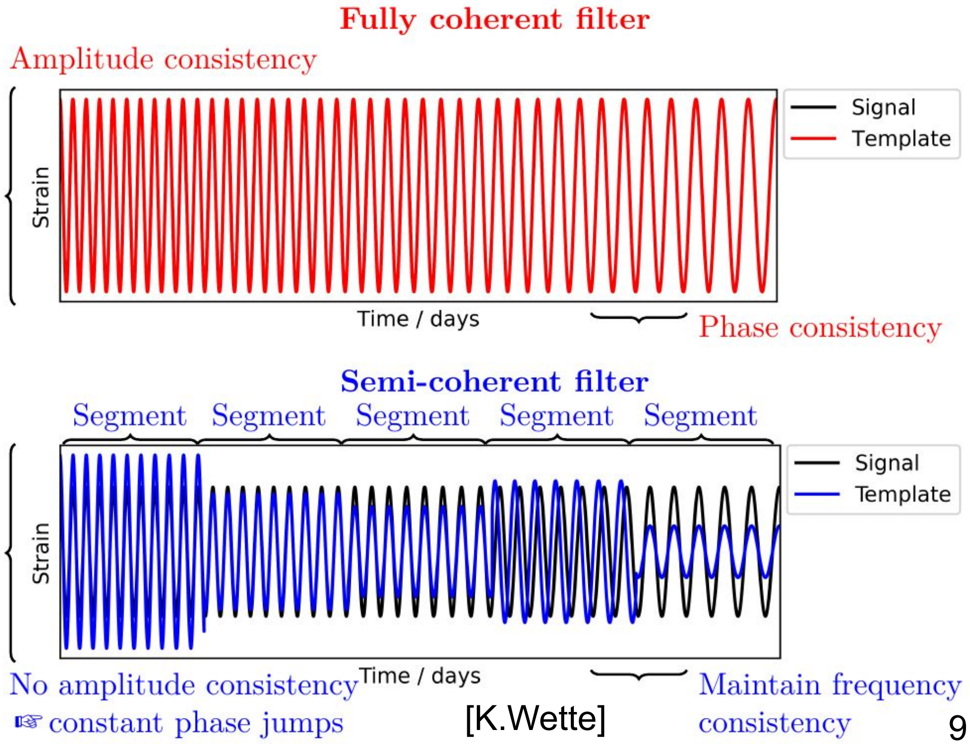
[Abbott+ ApJ935:1]

Bright 3G outlook: SNRs up to 10^5 possible with ET! [Pitkin MNRAS415,1849 (2011)]

directed & all-sky searches

- cover a large parameter space at affordable computational cost
- simple signal model, per-template evaluation ~O(ms)
- broad ranges in frequency, spin-downs, sky location; curved and highly structured space
- long observing times → high resolution:
  a blessing for PE,
  a curse for searches (dense banks)
- need to break steep computational cost scaling

  (at least $\propto T_{\rm obs}^6\, f^2$ for blind all-sky searches)
- semi-coherent methods:
  statistically “suboptimal”,
  but best sensitivity at fixed cost



[K.Wette]

O3 all-sky searches

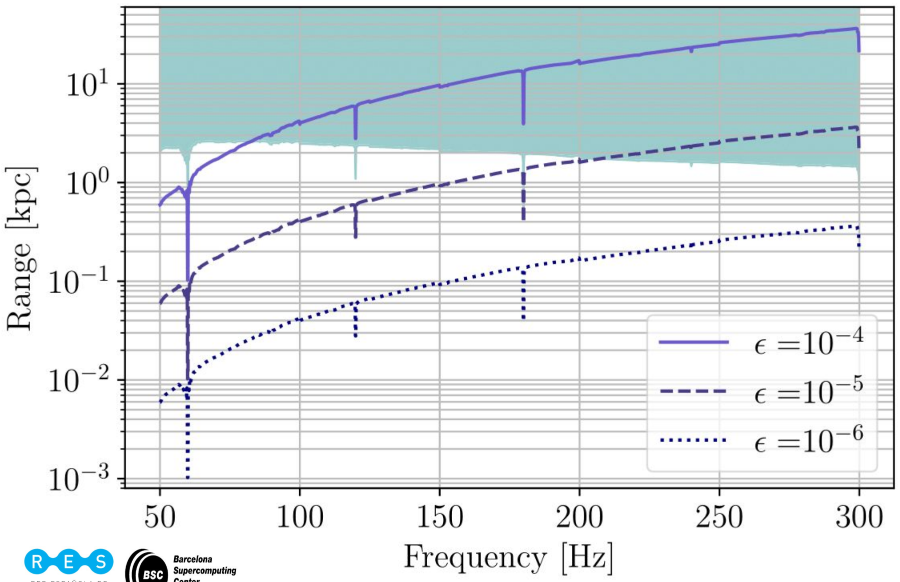
PHYSICAL REVIEW D **103,** 064017 (2021)

[2012.12128]

All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems

R. Abbott *et al.**
(The LIGO Scientific Collaboration and the Virgo Collaboration)

"BinarySkyHough" with GPU optimisations @ UIB



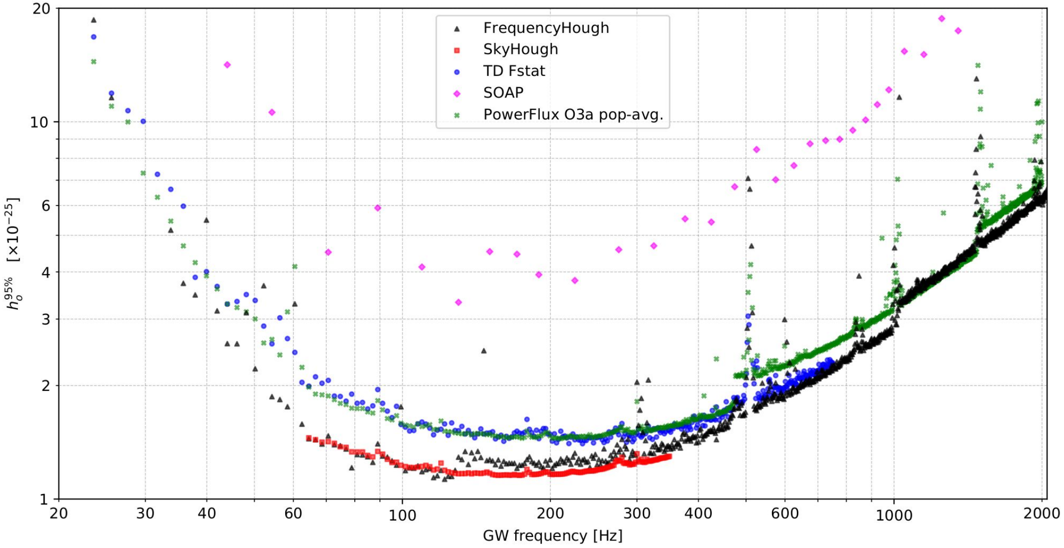
PHYSICAL REVIEW D **106,** 102008 (2022)

[2201.00697]

All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO and Advanced Virgo O3 data

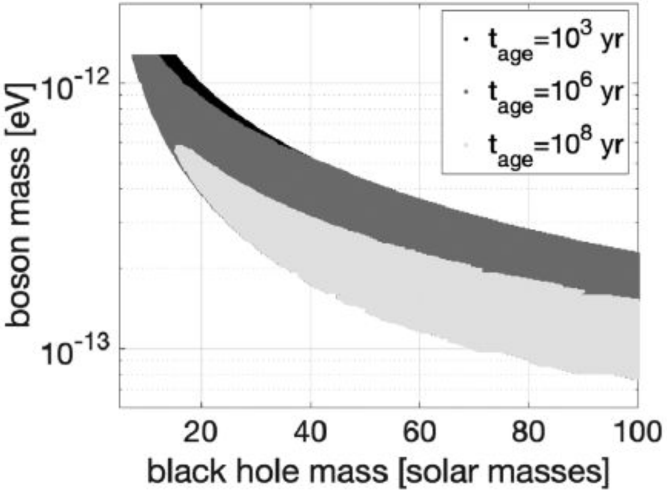
R. Abbott *et al.**
(LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)

4 pipelines, incl. "SkyHough" @ UIB

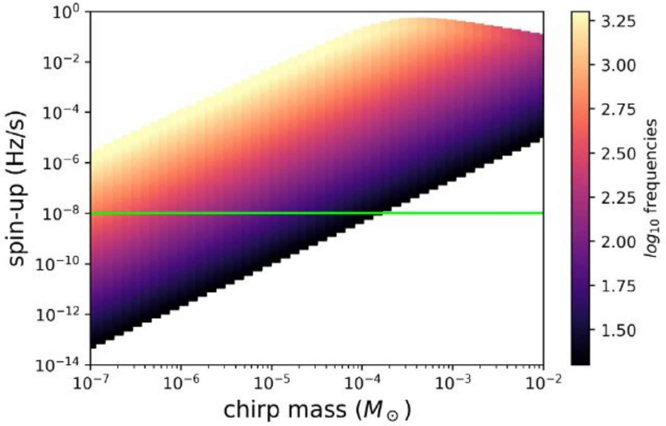


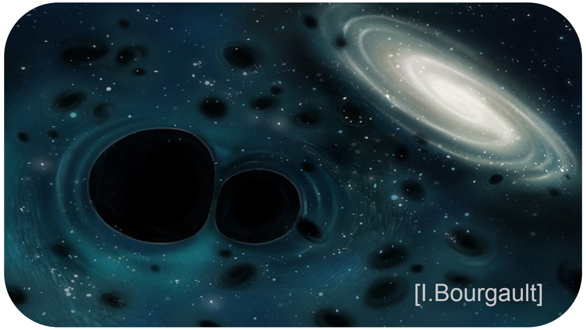
CWs beyond neutron stars: new physics

- **Boson clouds** around spinning black holes: superradiant energy extraction and CW-like emission, frequency related to particle mass
  → O3 search: Abbott+ PRD105,102001 (2022)



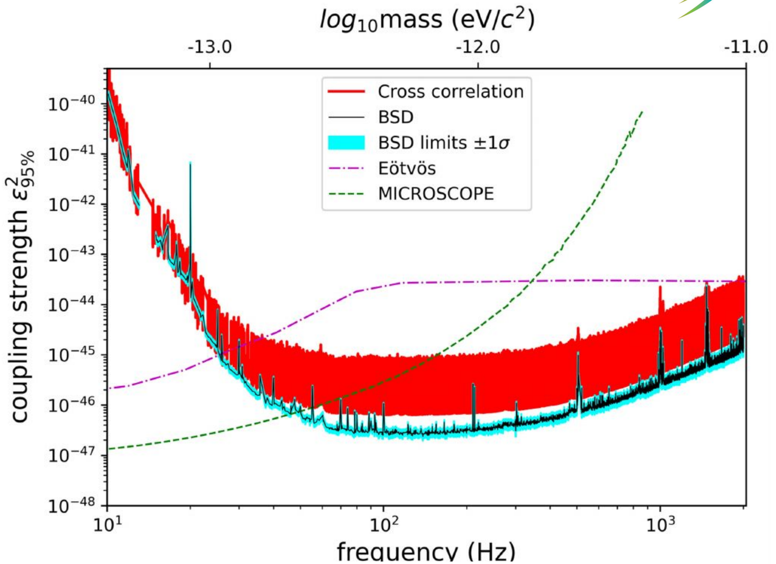
- low-mass compact binaries: CW-like early inspiral, e.g. **primordial black holes** [Miller+ PhDU32,100836 (2021)].

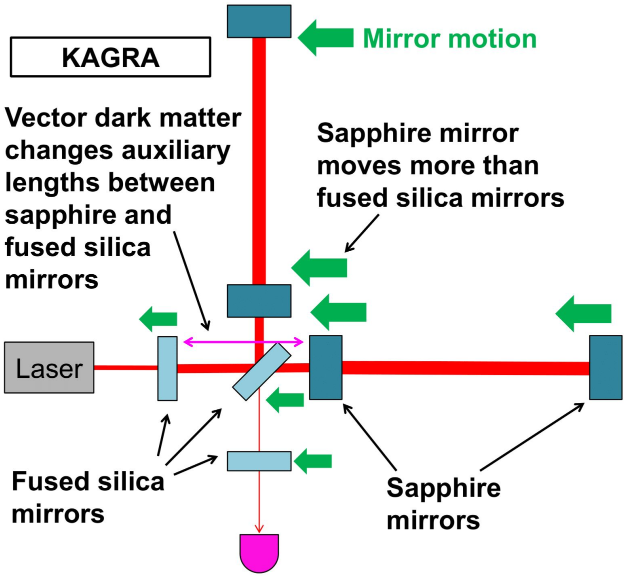


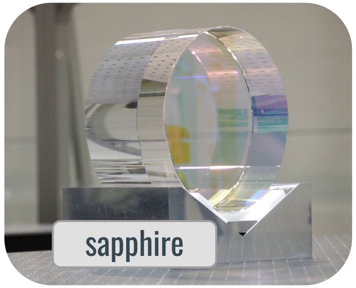


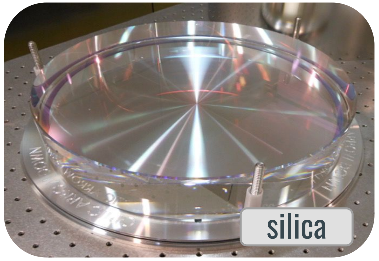
CWs beyond neutron stars: new physics

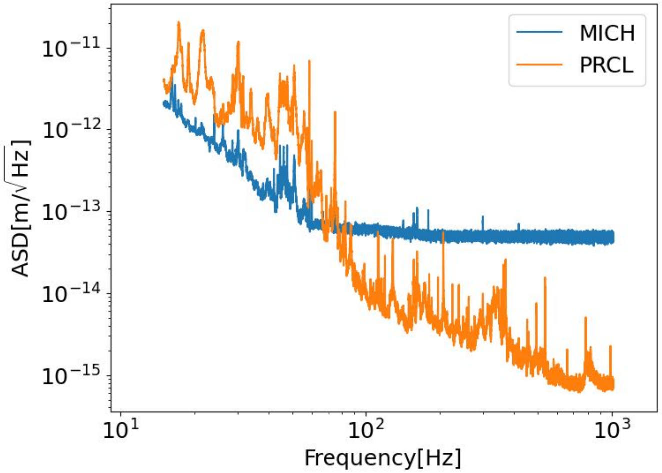
- direct **dark matter** interaction with GW detectors
- no actual GWs involved
- "dark photon" search in O3 LIGO data: [Abbott+ PRD105,063030 (2022)]
- "B-L" coupling vector DM search in O3 KAGRA data: [Abac+ PRD110,042001 (2024)]



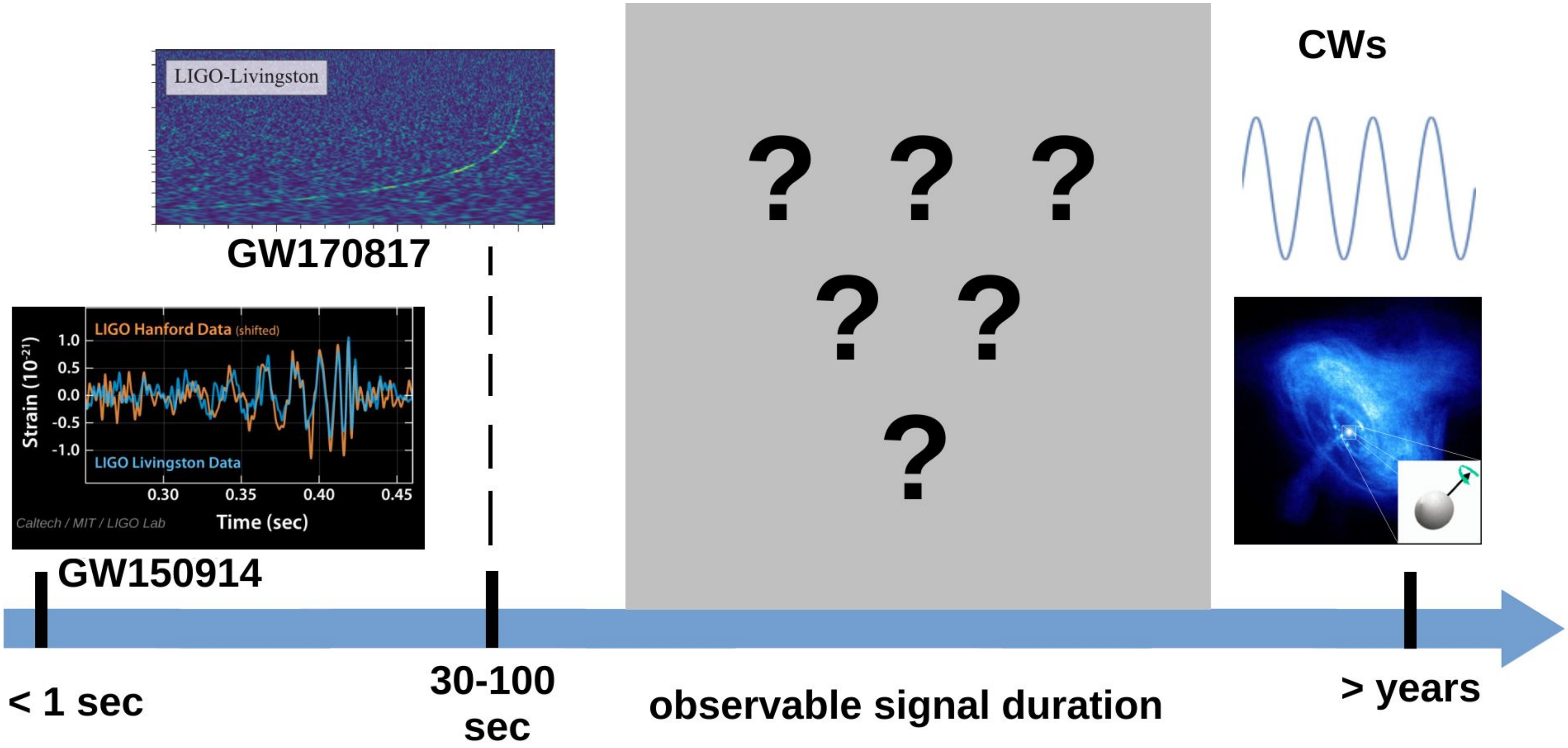








long-duration CW-like transients



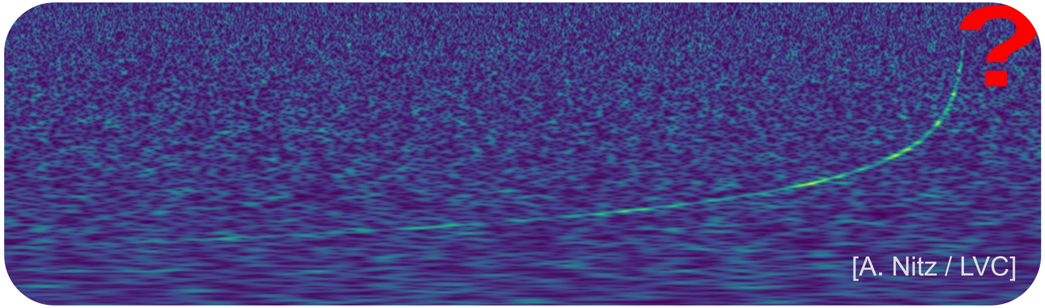
- binary neutron star merger remnants
- pulsar glitches

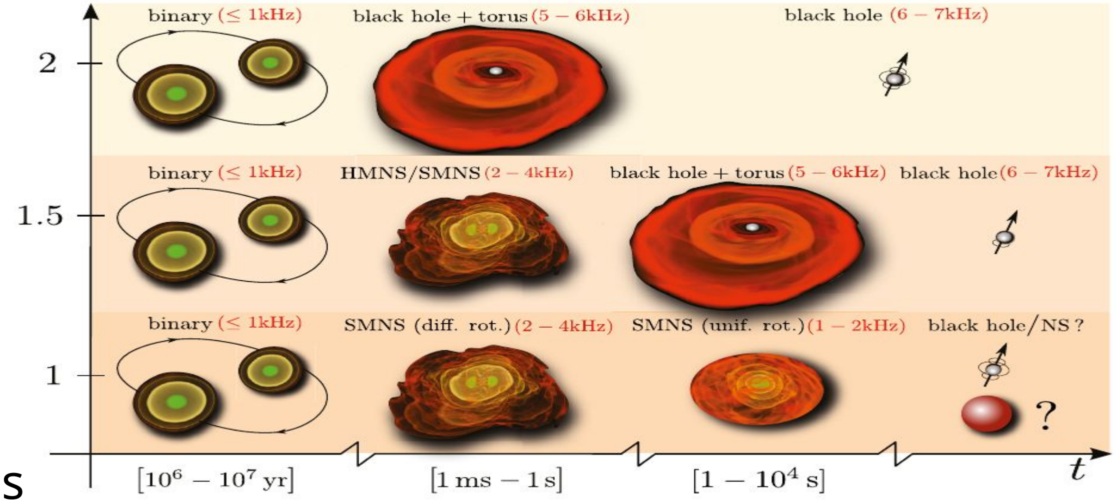
- magnetar and X-ray pulsar bursts
- vector boson clouds around spinning black holes

long transients: BNS remnants

- GW170817: BNS merger at ≈ 40 Mpc [Abbott+ PRL119,161101 (2017)]
- What was the remnant?
  - direct collapse to BH?
  - [H/S]MNS → BH?
  - stable NS?
- answer would tighten EoS constraints
- indirect EM evidence for 2), but no direct measurement

- LVC searches for short [ApJL851:L16 (2017)] and long-duration [ApJ875:160 (2019)] signals
- long-duration CW-like signals from HM / stable NS remnant → only sensitive to < 1Mpc in O2

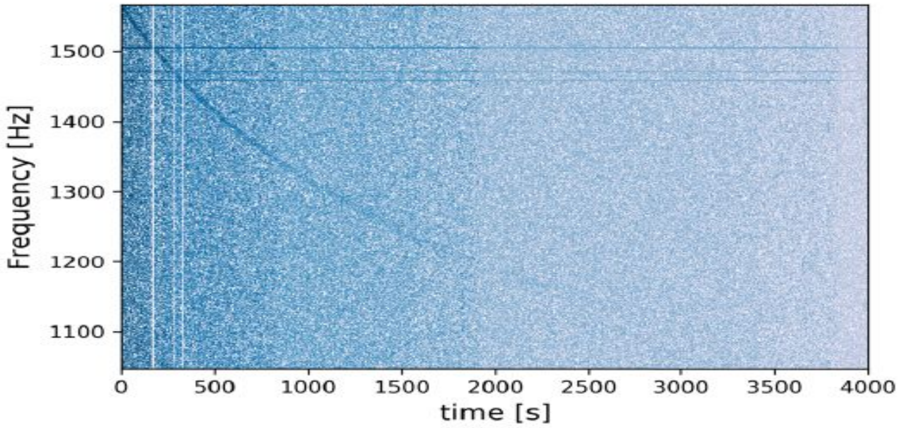




[Baiotti&Rezzolla2017]

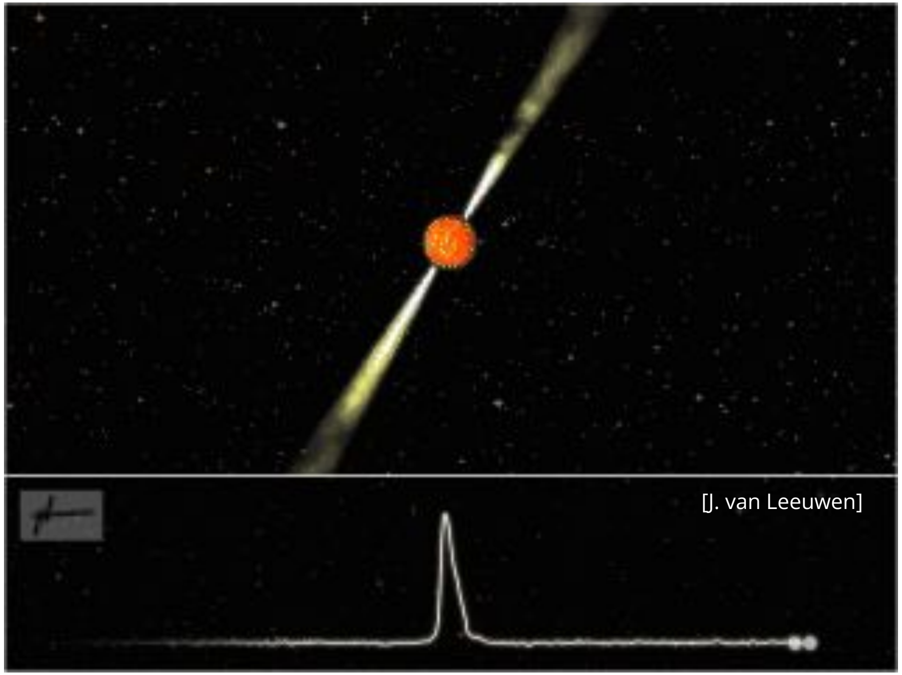
long transients: BNS and supernovae remnants

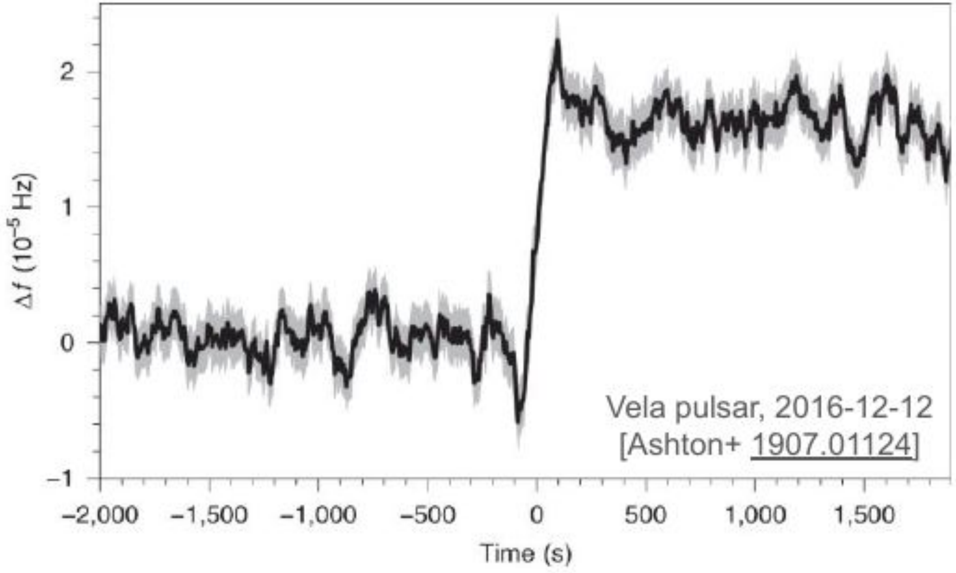
- BNS remnants: heavy and might have higher ellipticities, but rare at low distances
- regular newborn NSs from core-collapse supernovae: a bit more common
- shared signal model: rapid “power-law” spindown, but still monochromatic
- with LVK, limited to ~few Mpc,
  3G detectors: ~dozens Mpc



- various semi-coherent CW search methods have been adapted, including @UIB “AdaptiveTransientHough” pipeline: Oliver, Keitel & Sintes PRD99,104067 (2019)
- used in GW170817 remnant search [Abbott+ ApJ875:160 (2019)]

long transients: pulsar glitches

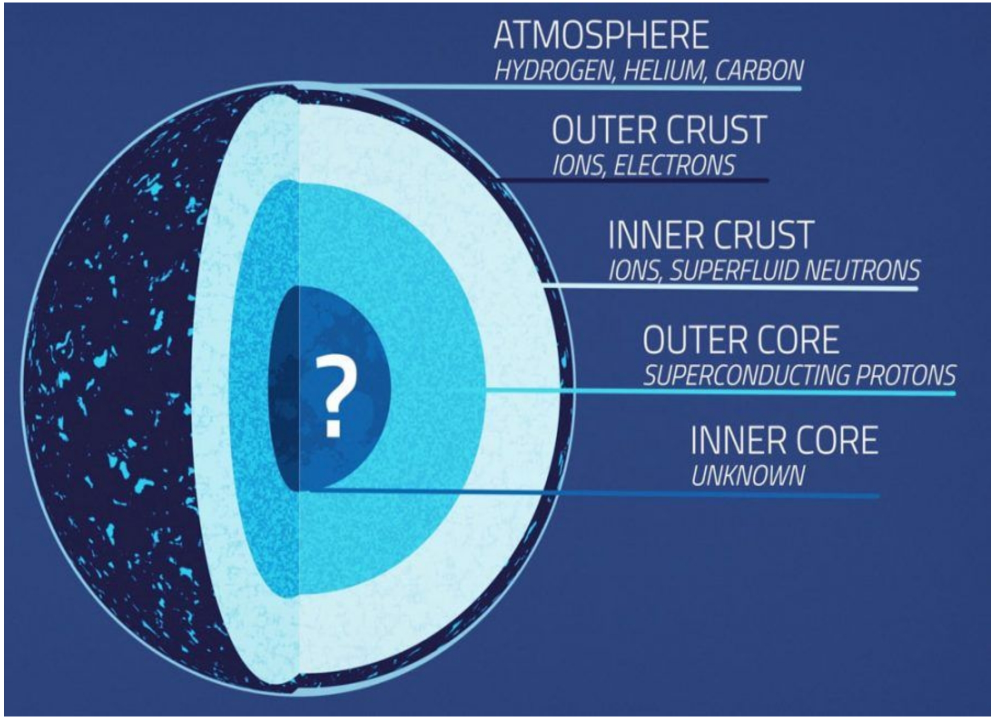




- > 3000 known pulsars [ATNF]
- > 740 known glitches
  (as of 2022)

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

long transients: pulsar glitches

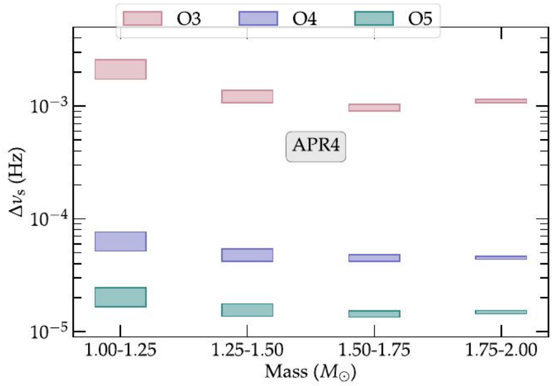


[NASA/Goddard/Conceptual Image Lab]

- 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?

long transients: pulsar glitches



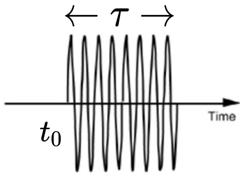
1) short-duration bursts from f-modes excited at the glitch: Lopez+ PRD106.103037 (2022) → search with e.g. cWB

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:

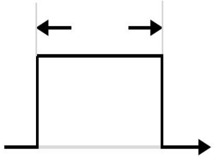
$$\lambda = \{\alpha, \delta, f, \dot{f}, \ddot{f} \dots\} \quad \mathcal{A} = \{h_0, \cos\iota, \psi, \phi_o\} \quad \mathcal{T} = \{t_0, \tau\}$$

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



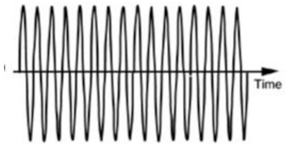
transient CW

=



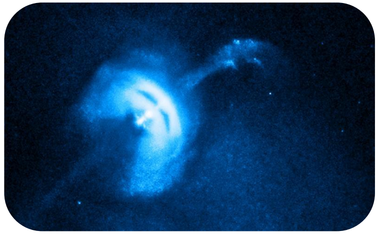
window function

•



standard CW signal model

tCW searches so far – O2 open data



[Chandra/NASA]

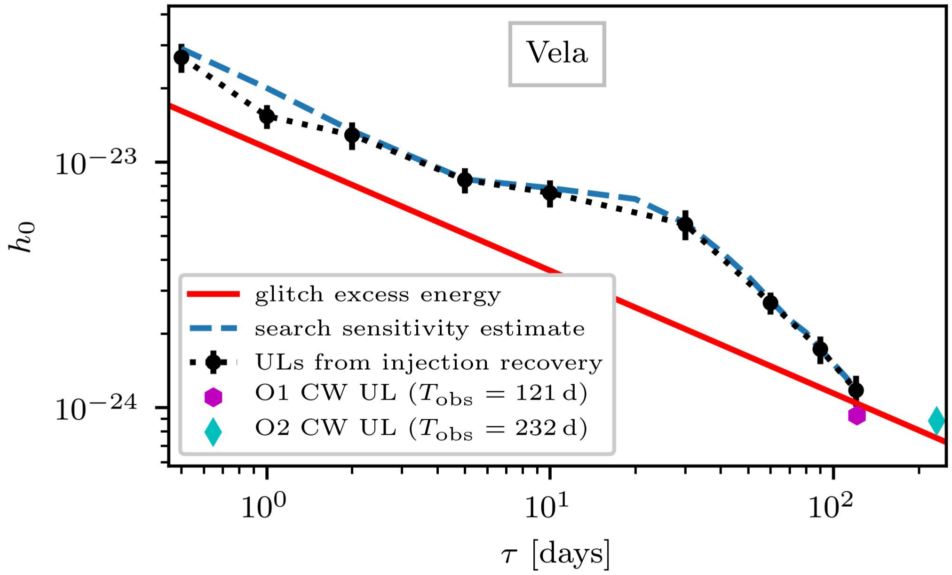
PHYSICAL REVIEW D **100,** 064058 (2019)

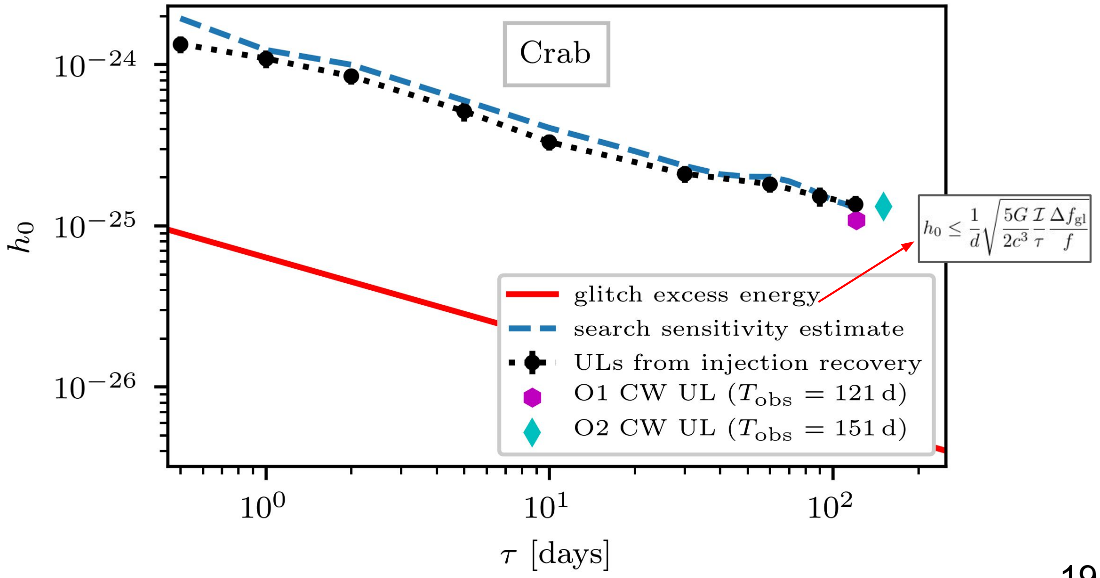
[1907.04717]

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]





tCW searches so far – O3 LVK search

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

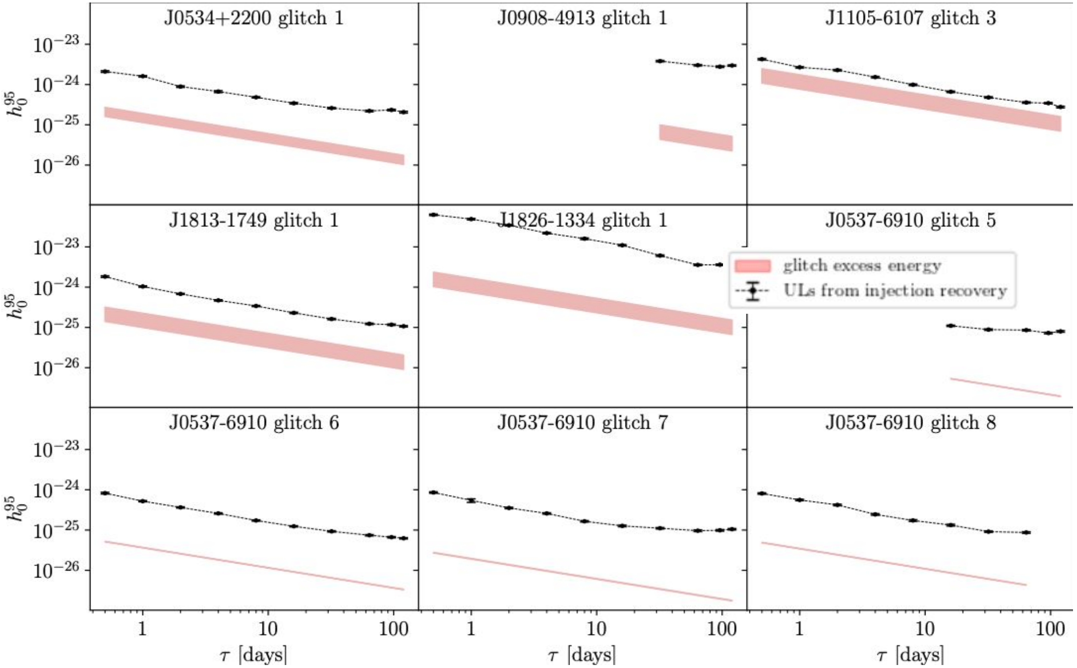
[2112.10990]

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

With contributions from UIB

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

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



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

tCWs with CNNs

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

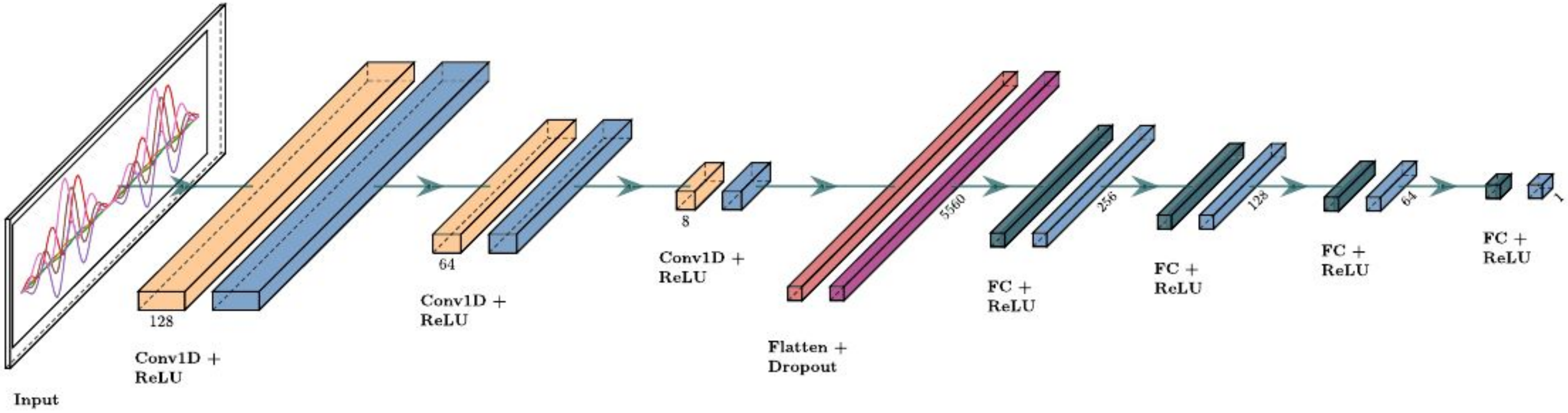
[2303.16720]

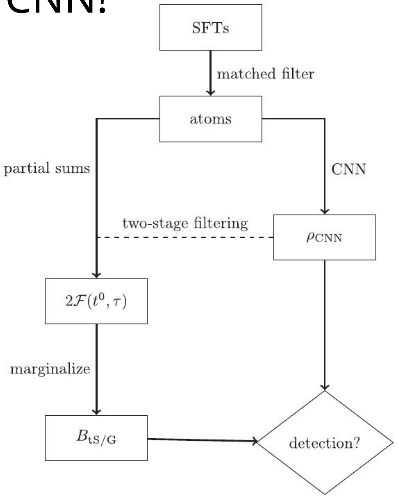
Convolutional neural network search for long-duration transient gravitational waves from glitching pulsars

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

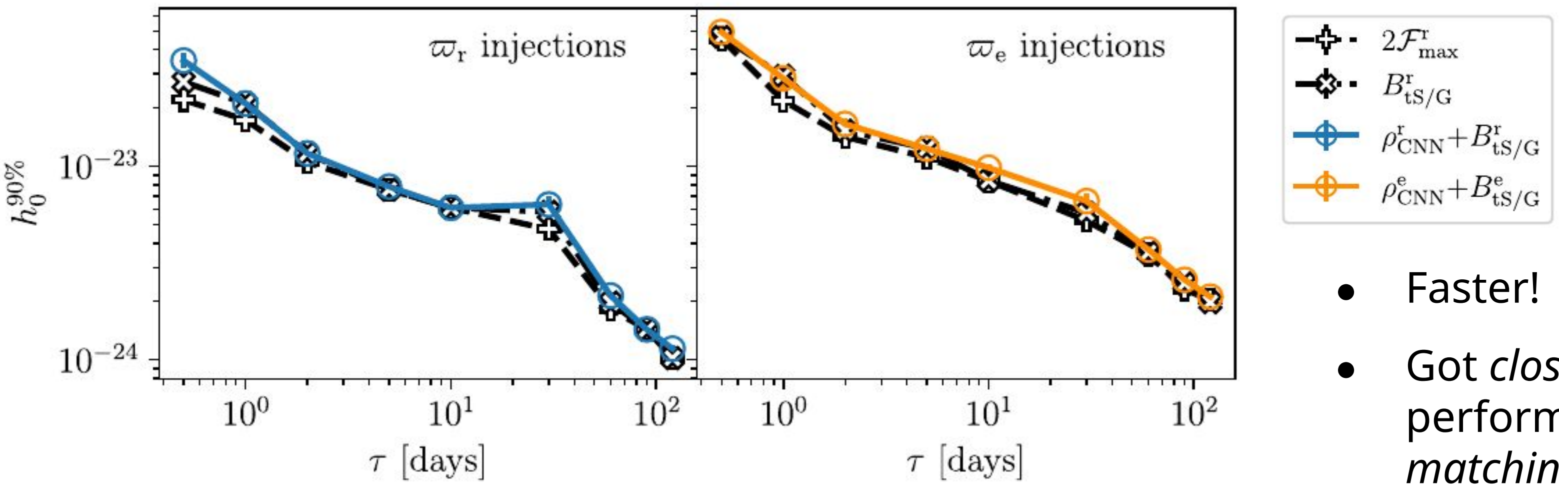
- transient $\mathcal{F}$-stat searches are computationally limited, mainly from trying many (t_0,τ) combinations
- finding a (t)CW in time-frequency data is basically *pattern recognition*
- Convolutional Neural Networks (CNNs) are great at doing that fast. (At least for cats and dogs.)
- But actually 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.

<u>Limitations:</u>

- 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

MNRAS 519, 5161–5176 (2023)
Advance Access publication 2022 December 15
[2210.09907]
https://doi.org/10.1093/mnras/stac3665

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

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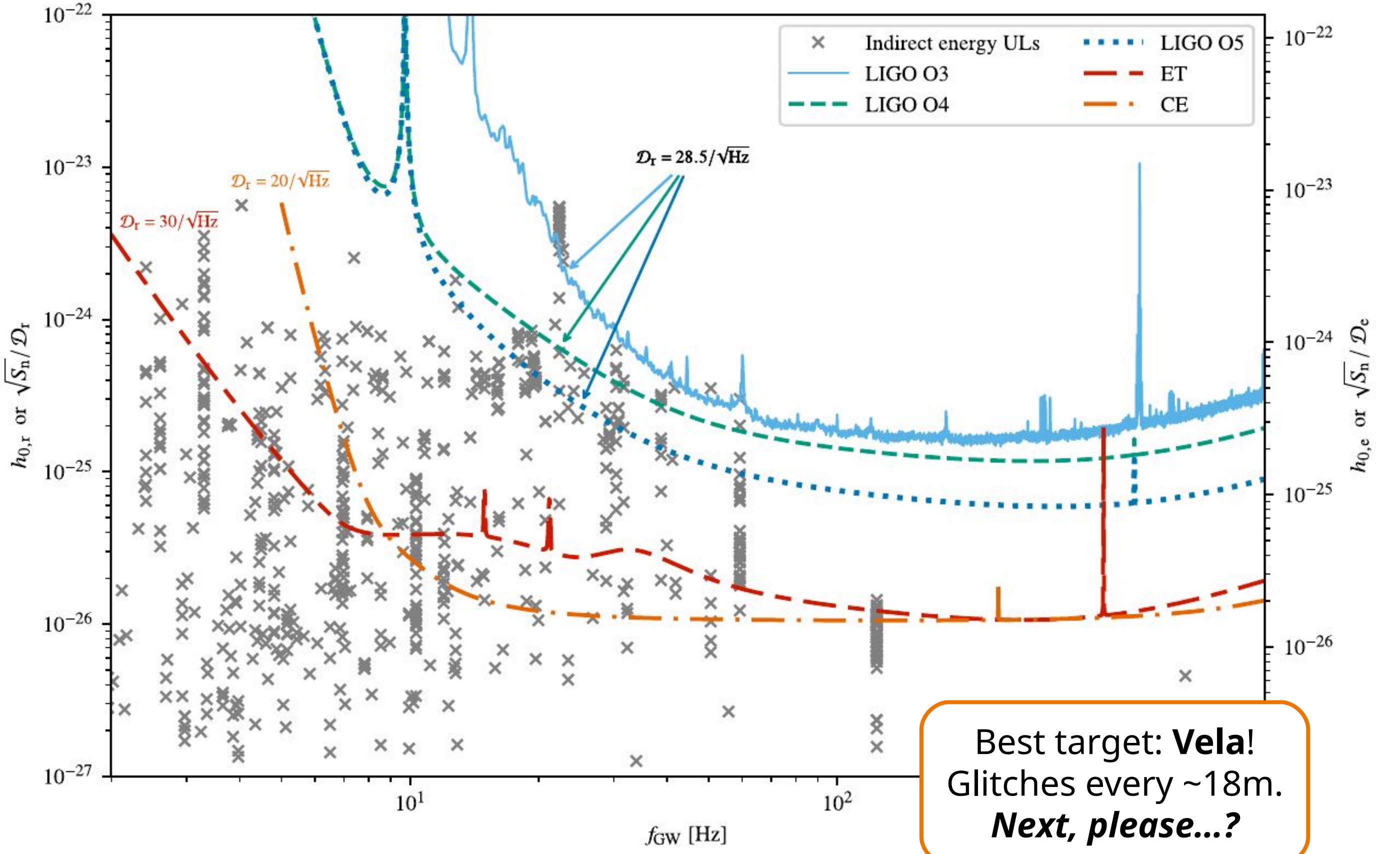
ATNF + Jodrell glitch catalogues
→ 740 known glitches (2022/10/11)
→ extrapolate future prospects



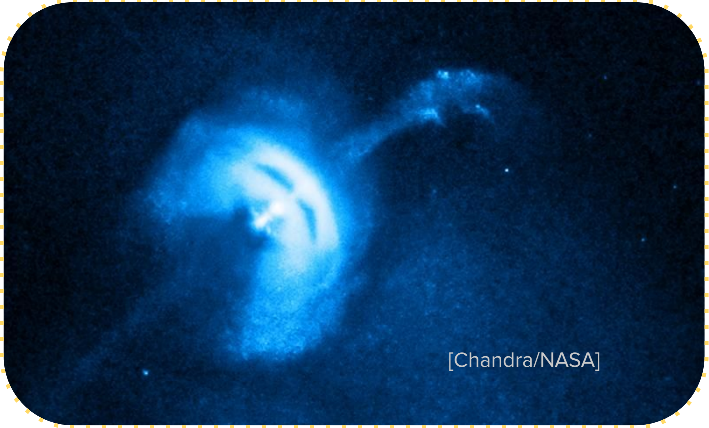
Best target: **Vela**!
Glitches every ~18m.
Next, please…?

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

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

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

...2024: Vela glitched again!



- 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*** *[...]*

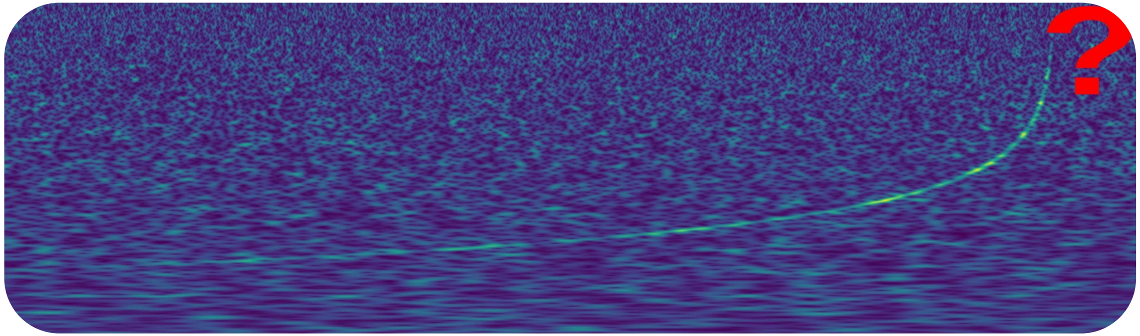
(also confirmed by other radio telescopes and FERMI)

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***

Conclusions: the next first detection?

- continuous waves from known pulsars?
- continuous waves from unknown neutron stars in our galaxy?
- continuous waves from exotic objects (PBHs, boson clouds)?
- CW-style dark matter direct detection?
- long transients from glitching pulsars?
- long transients from newborn neutron stars (supernovae / BNS remnants)?



- Either way: rich potential for astrophysics, nuclear physics, and fundamental physics

[Ana Sousa]

Acknowledgments

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