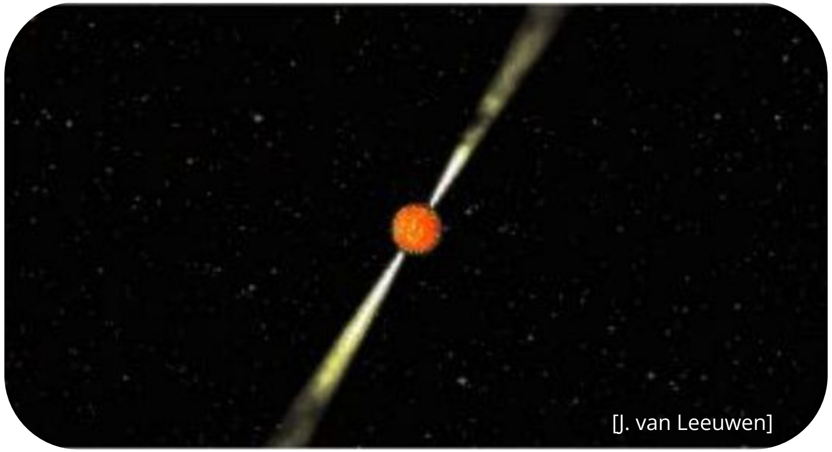
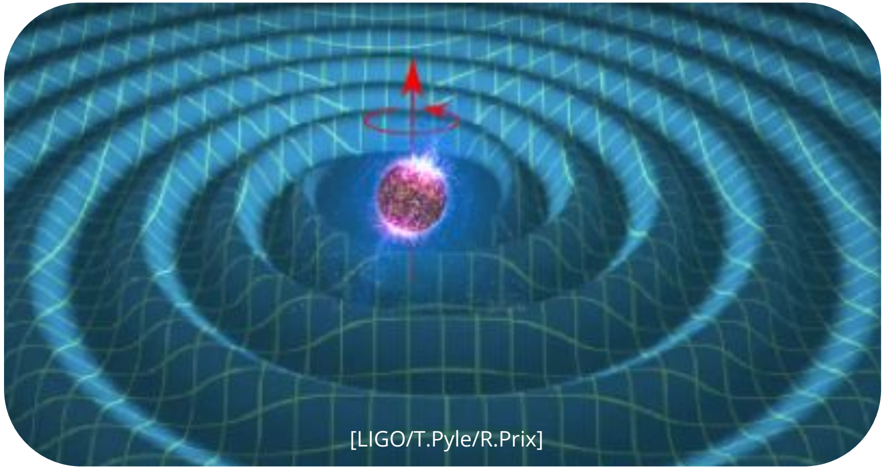




LIGO–Virgo–KAGRA searches for continuous gravitational waves

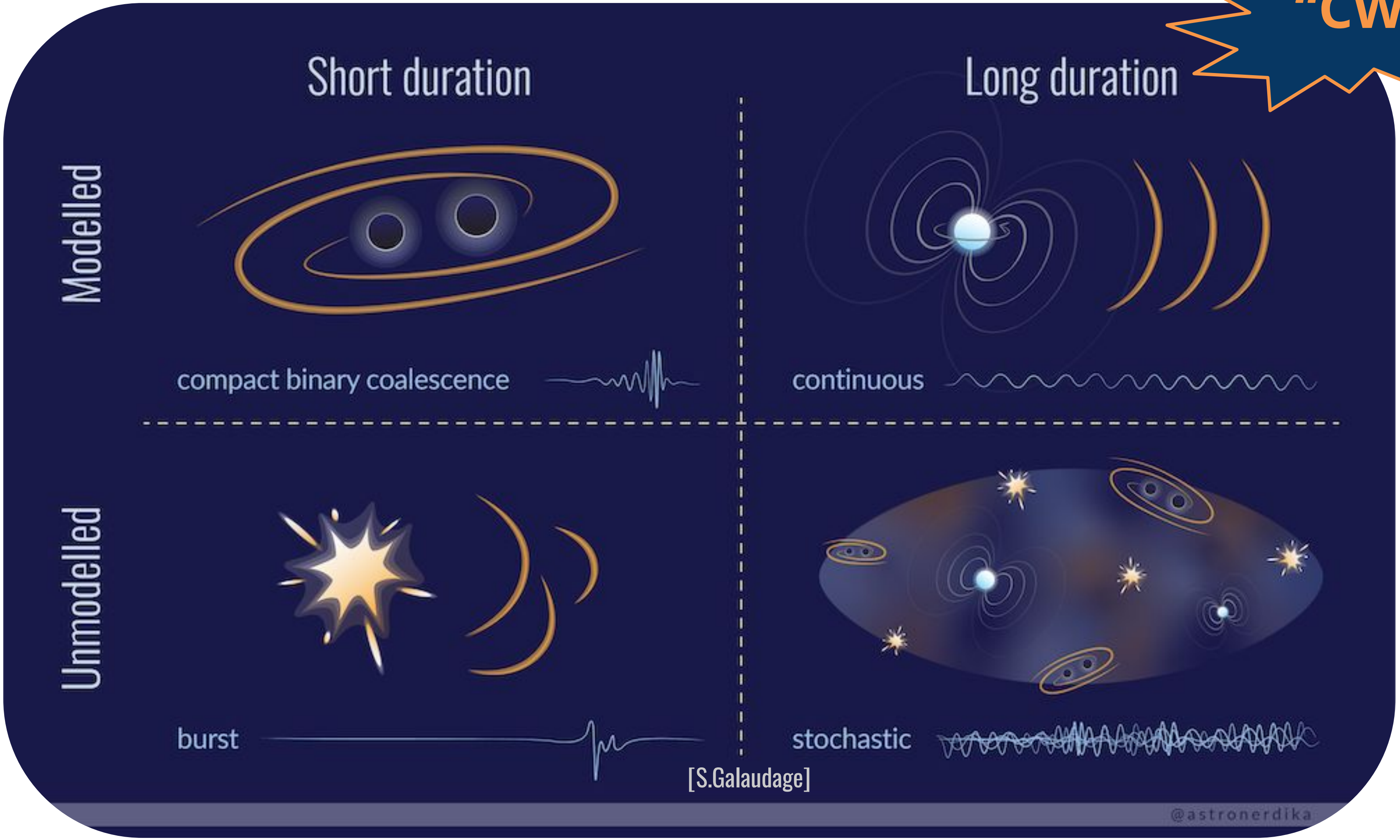
Universitat de les Illes Balears

IAC3 Institut d'Aplicacions Computacionals de Codi Comunitari

David Keitel
(IAC3 / Universitat de les Illes Balears)
for the LIGO–Virgo–KAGRA collaboration

14th Iberian GWs meeting, CIEMAT Madrid, 2025-06-25 DCC: G2501089-v2

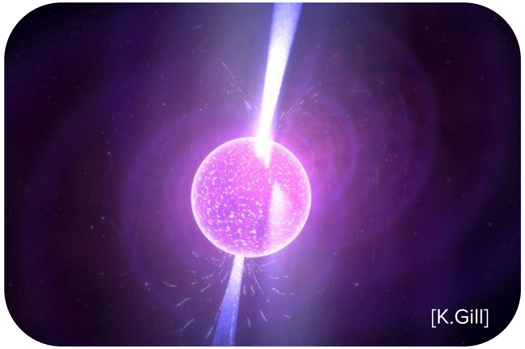
LVK search types



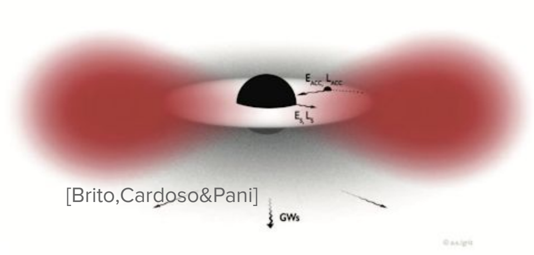
“CWs”

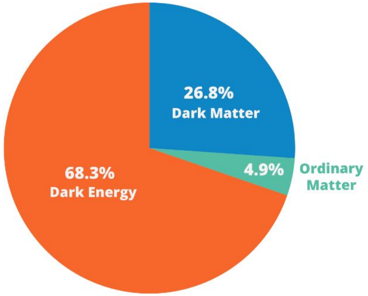
Continuous Waves: persistent, quasi-monochromatic GWs

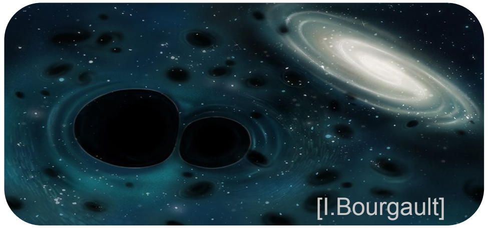
- A completely new GW signal type: first detection will be another revolution.
- No "blink and it's gone" – once we've detected a CW, we can keep observing it, learning more and more about the source.
- **Neutron star** science: probing dense, "cold" nuclear matter, studying the "dark" majority of the galactic population (only ~3000 known out of >10^8).



- Exotic sources: constraints on **dark matter** under various models; of high interest to wider physics community.

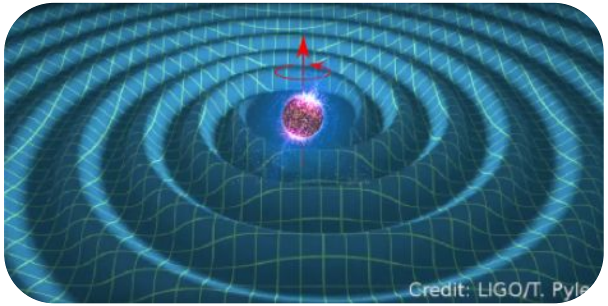




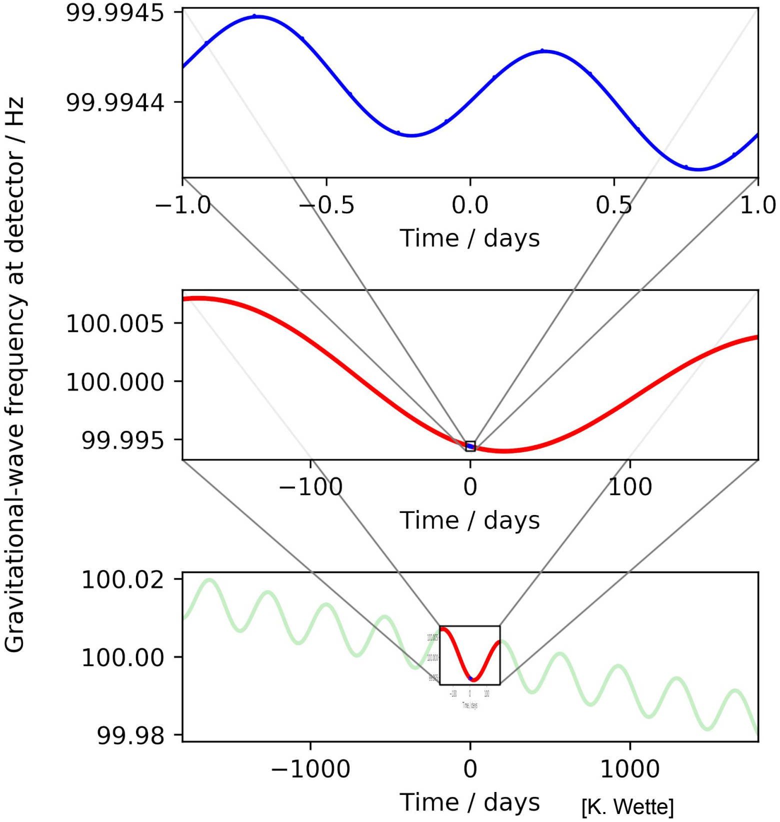


- No guarantee of detection in any given run, but we've started pushing deep into physically allowed parameter ranges: → a first detection could be around the corner!

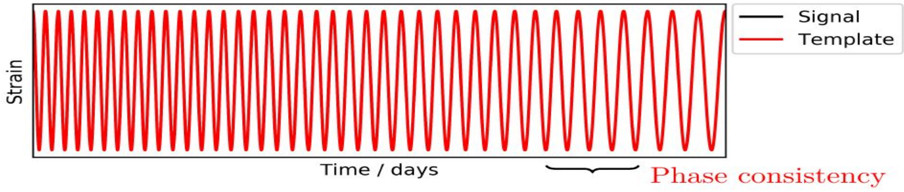
Continuous Waves:
persistent, quasi-monochromatic GWs



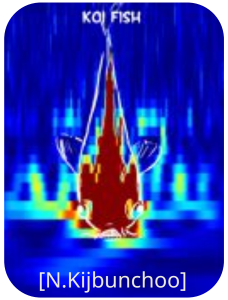
- extremely weak (strain: GW150914 ~10^{-21}, CW $\lesssim 10^{-25}$)
- signal duration > observing time
- quasi-monochromatic signals:
  very slow evolution of frequency and amplitude
- measured strain $h(t)$ depends on intrinsic spin-down, Doppler effect between source and Earth, antenna response ⇒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



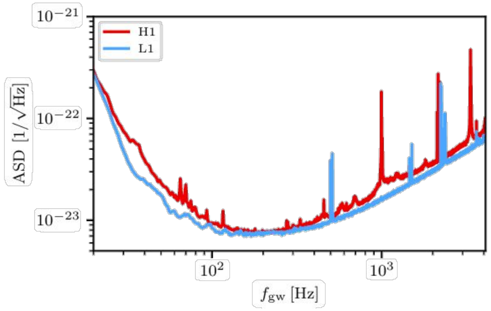
CW data analysis



- simple, deterministic templates → matched filter
- precise frequency resolution from long-term phase coherence
- precise sky localisation, *even with a single detector* (the Earth moves)
- real data challenges:

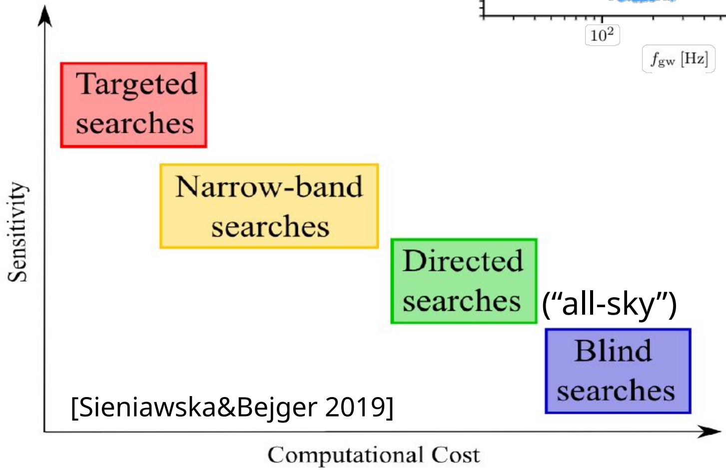


- ○ loud but short glitches
→ require time-domain cleaning/gating



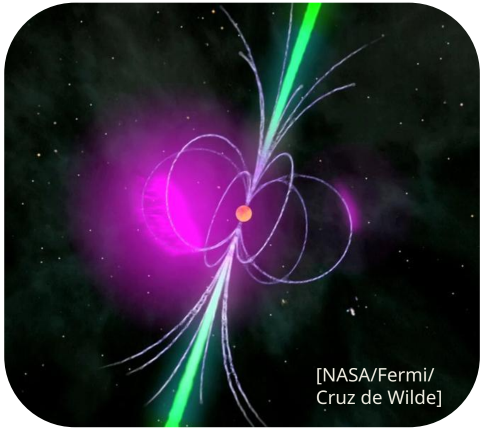
- ○ narrow spectral lines
→ require identification and mitigation

searches classified by amount of prior information:



for an overview:
Riles2023 [LRR26:3]

known pulsar searches



[NASA/Fermi/ Cruz de Wilde]

- detailed pulsar ephemerides from radio, X-, ɣ-rays:
  → ***fully-coherent*** matched filter across full GW observing runs
- indirect ***spin-down upper limit*** assumes all energy loss into GWs: $h_0 \leq \frac{1}{d}\sqrt{\frac{5GI_{zz}}{2c^3}\frac{|\dot{f}_{\mathrm{rot}}|}{f_{\mathrm{rot}}}}$
- 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 $\epsilon = 0.237 h_{-24} r_{\mathrm{kpc}} \nu^{-2} I_{38}$ (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

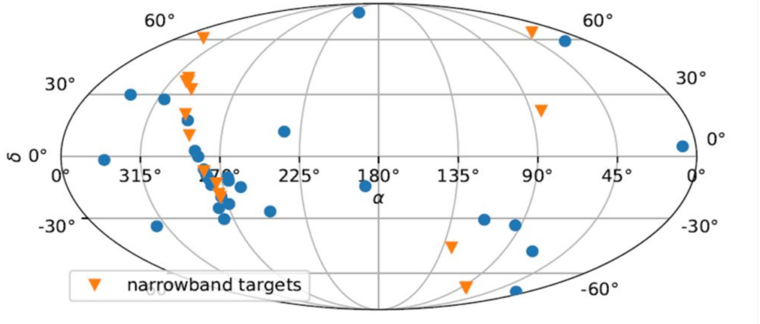
THE ASTROPHYSICAL JOURNAL, 737:93 (16pp), 2011 August 20 doi:10.1088/0004-637X/737/2/93

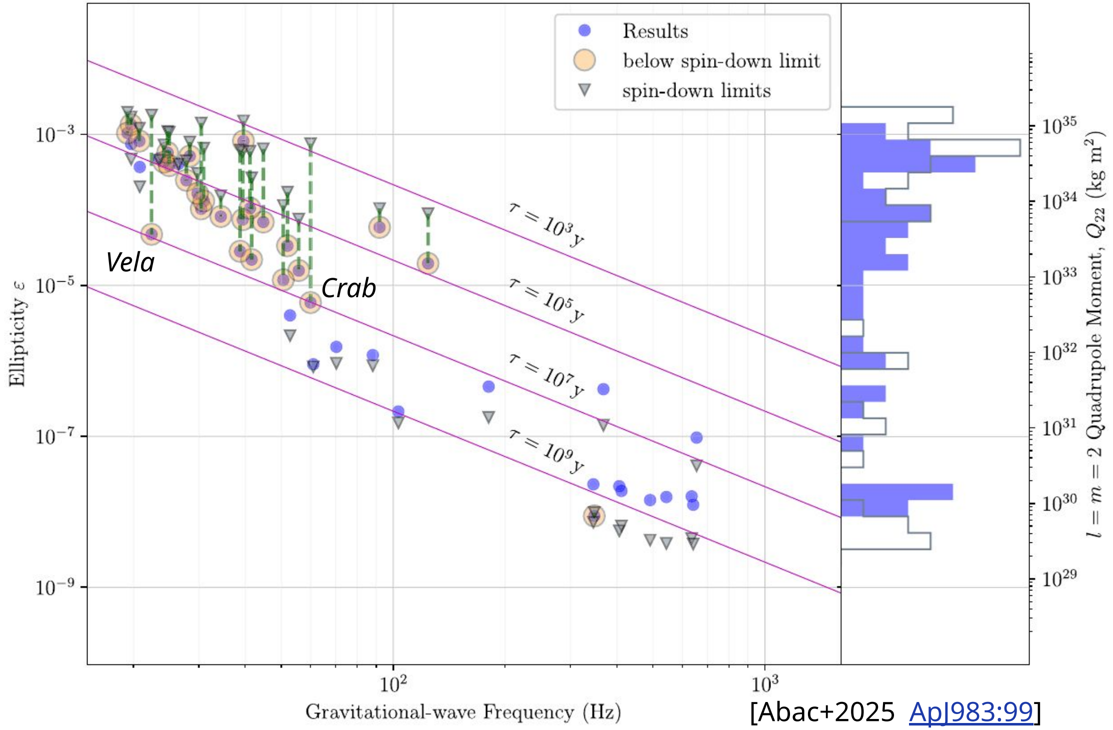
BEATING THE SPIN-DOWN LIMIT ON GRAVITATIONAL WAVE EMISSION FROM THE VELA PULSAR

known pulsars: first O4 results [Abac+ ApJ983:99]

"Fully targeted" searches:

- 45 targets, 29 below spin-down limit
- searched at both $f_{\rm gw} = 2f_{\rm spin}$, $f_{\rm gw} = f_{\rm spin}$





[Abac+2025 ApJ983:99]

"Narrowband" searches:

- relax EM–GW frequency lock
  → small template banks ~<O(10^6)
- 16 targets, 12 below spin-down limit

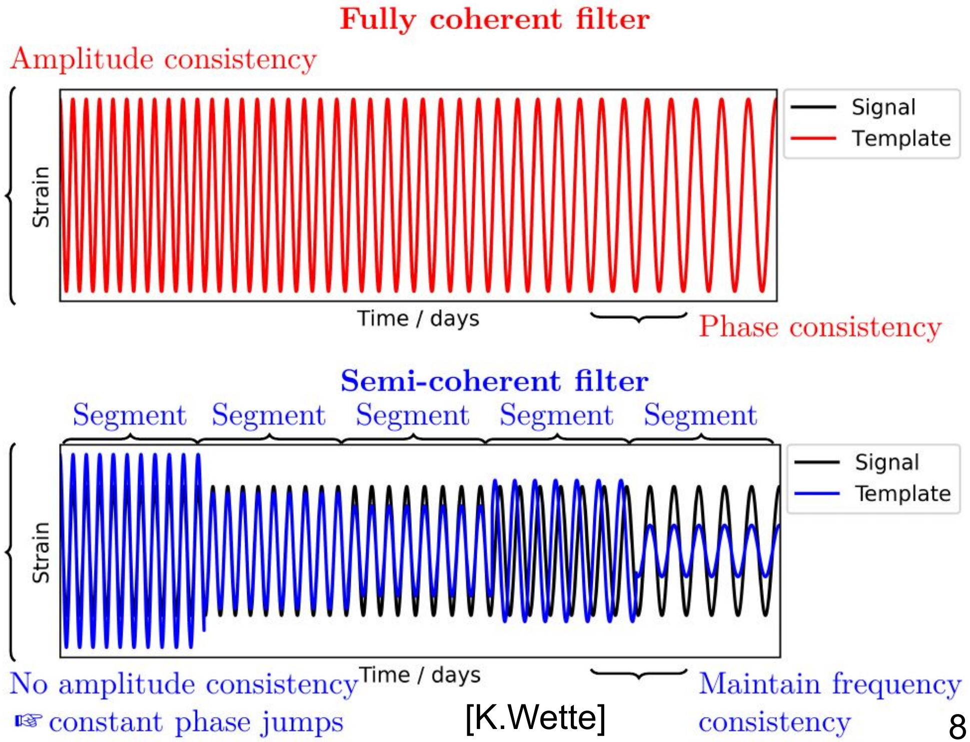
EINSTEIN TELESCOPE

Bright 3G outlook: SNRs up to 10^5 possible with ET! [Pitkin2023 MNRAS415,1849]

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 parameter estimation,
  a curse for searches (dense banks)
- need to break steep computational cost scaling

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

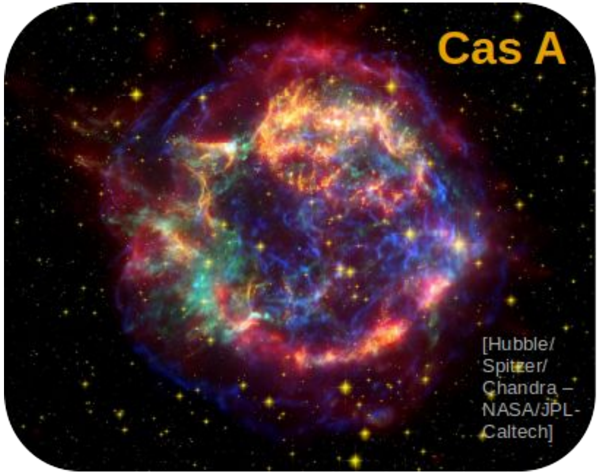


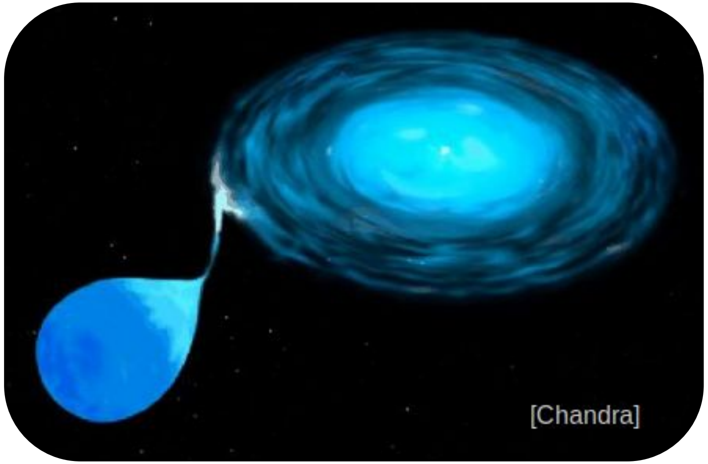
[K.Wette]

O3 directed searches – stay tuned for O4!

Huge diversity of interesting galactic targets:

- Abbott+2022 PRD105,022002: searches for 20 **AMXPs**
- Abbott+2021 ApJ921:80: 15 young **supernova remnants**
- Abbott+2022 PRD105,082005: CasA and Vela Jr. remnants (deeper searches)
- Abbott+2022 PRD106,042003: **galactic centre**
- Abbott+2022 PRD106,062002 and ApJL941:L30: **Scorpius X-1 binary**
  (with updated ephemeris [Killestein+2023 MNRAS527,5317]: Whelan+2023 ApJ949:117, Vargas+2023 PRD111,084040)





O3 all-sky searches – stay tuned for O4!

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

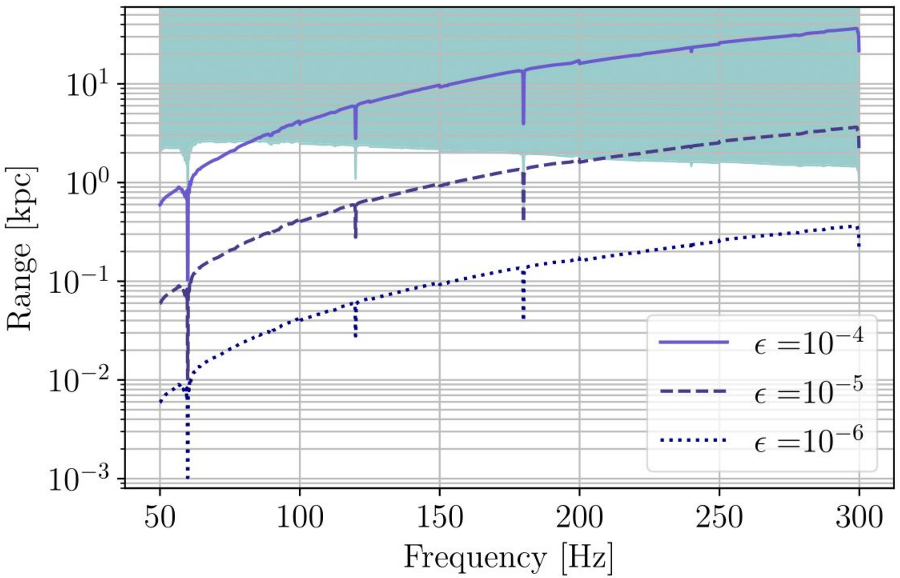
R. Abbott *et al.**
(The LIGO Scientific Collaboration and the Virgo Collaboration)

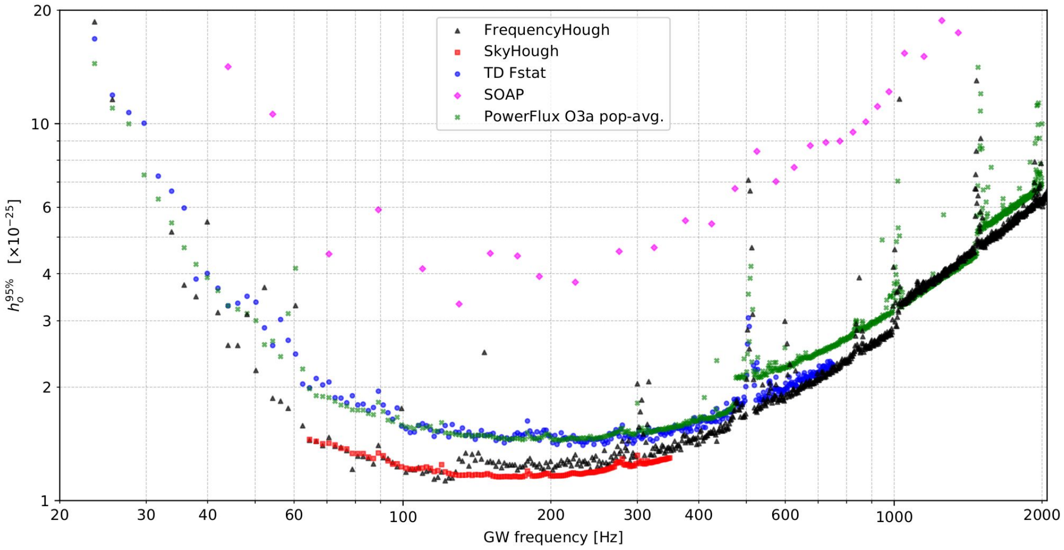
PHYSICAL REVIEW D **106,** 102008 (2022)

[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)



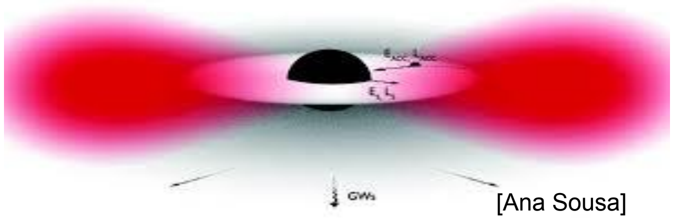


"BinarySkyHough" with GPU optimisations @

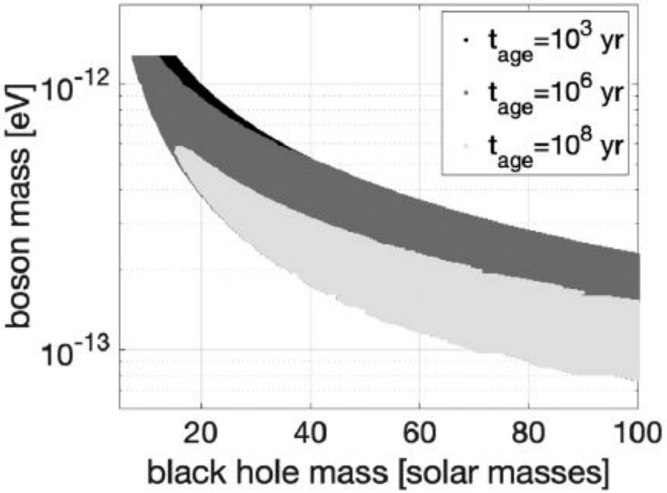
4 pipelines, incl. "SkyHough" @

CWs beyond neutron stars: new physics

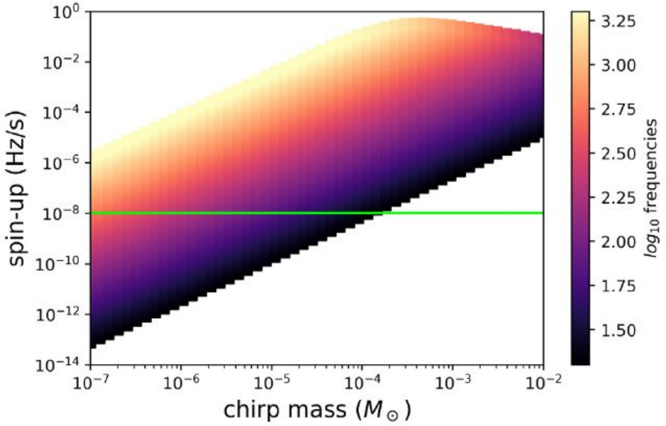
- **Boson clouds** around spinning black holes: superradiant energy extraction and CW-like emission, frequency related to particle mass
  → O3 search: Abbott+2022 PRD105,102001

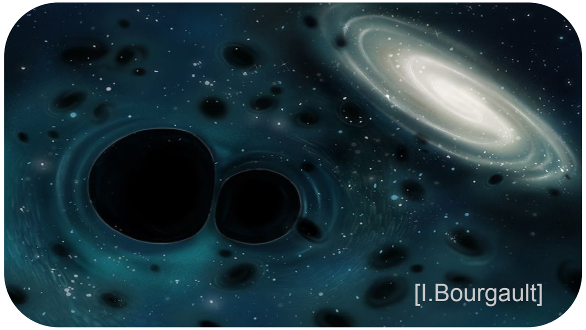


[Ana Sousa]



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

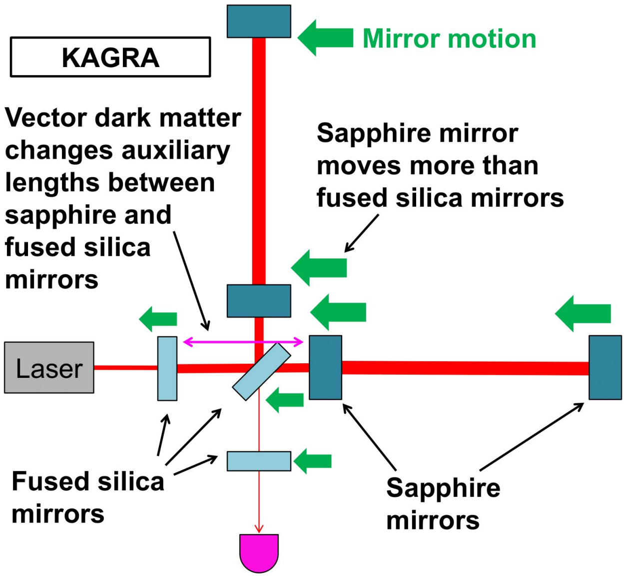


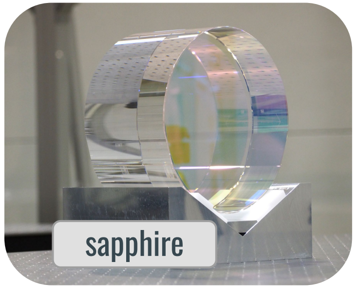


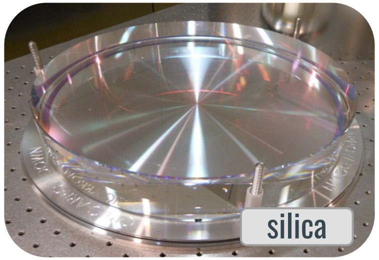
[I.Bourgault]

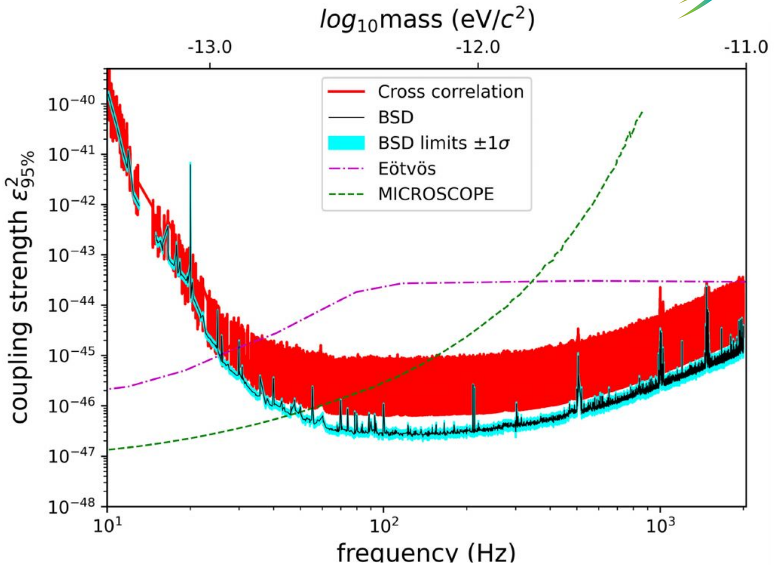
CWs beyond neutron stars: new physics

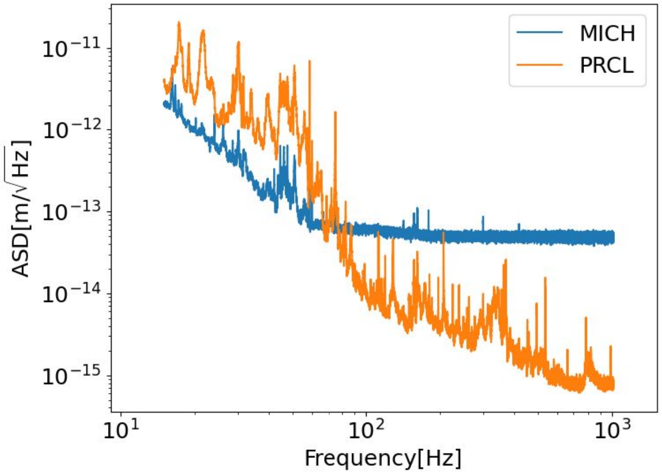
- direct **dark matter** interaction with GW detectors
- no actual GWs involved
- "dark photon" search in O3 LIGO data:
  Abbott+2022 [PRD105,063030]
- "B-L" coupling vector DM search in O3 KAGRA data:
  Abac+2024 [PRD110,042001]



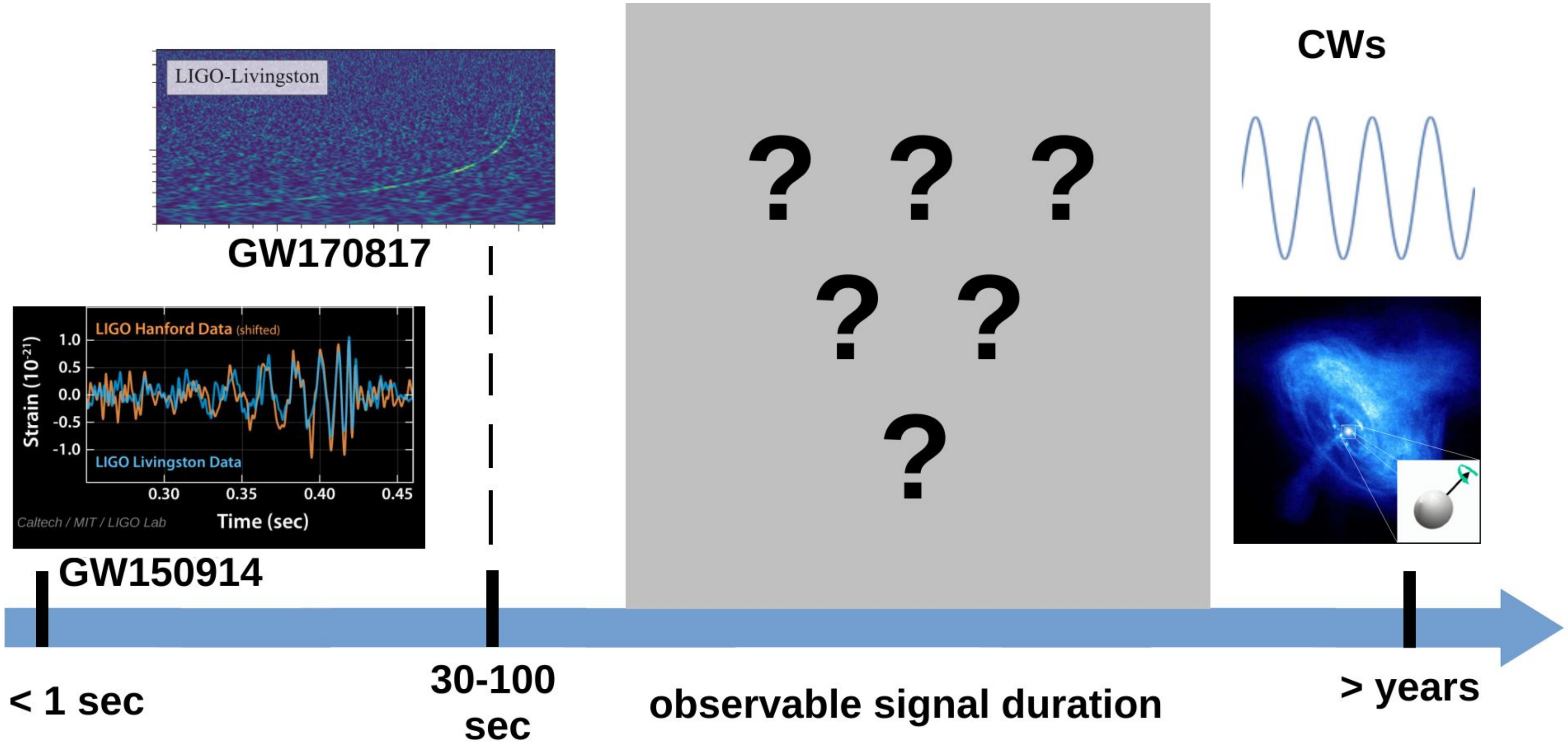








long-duration CW-like transients

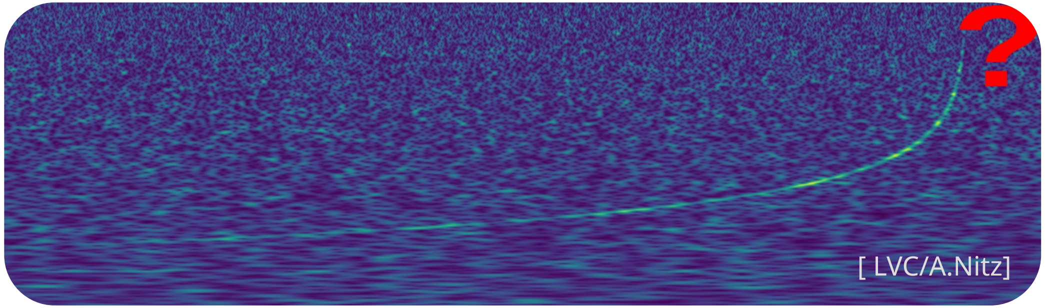


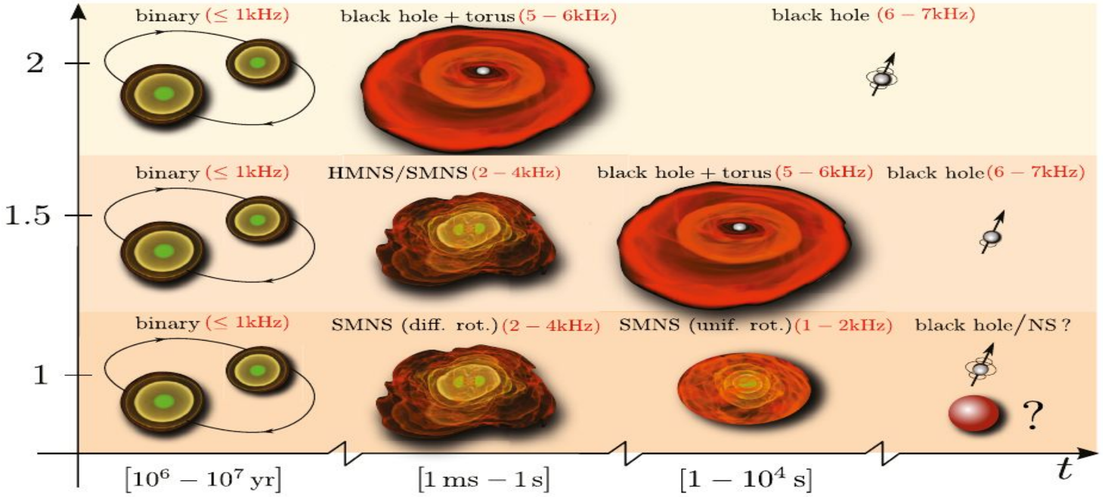
- binary neutron star merger remnants
- pulsar glitches

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

long transients: BNS remnants

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





[Baiotti&Rezzolla2017]

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

long transients: glitching pulsars

THE ASTROPHYSICAL JOURNAL, 932:133 (27pp), 2022 June 20
https://doi.org/10.3847/1538-4357/ac6ad0

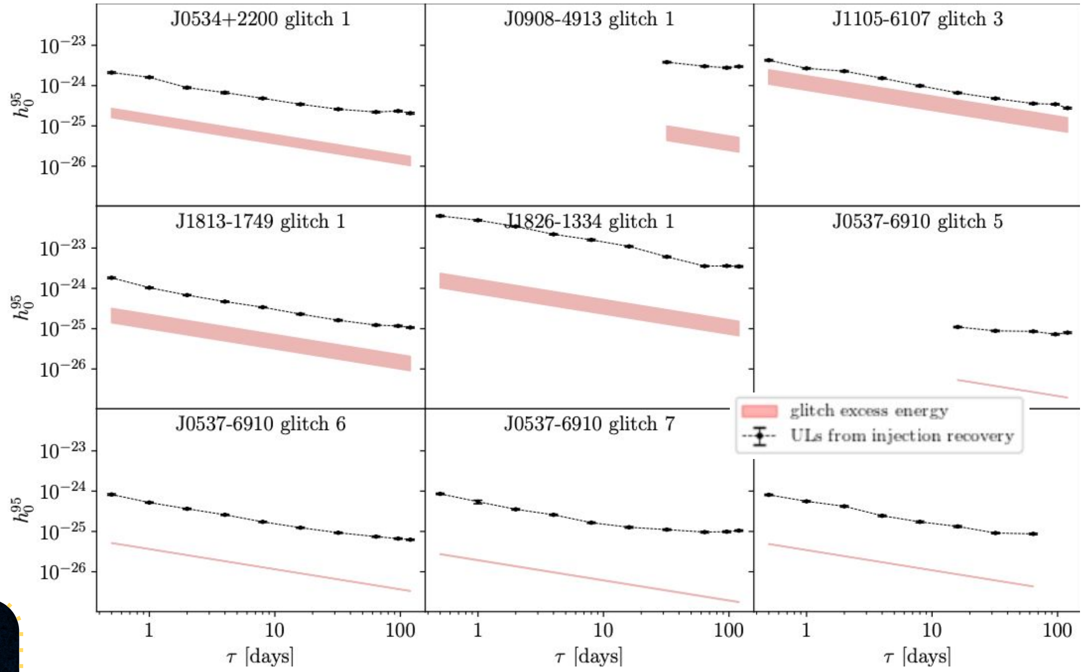
[2112.10990]

CrossMark

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

with contributions from UIB

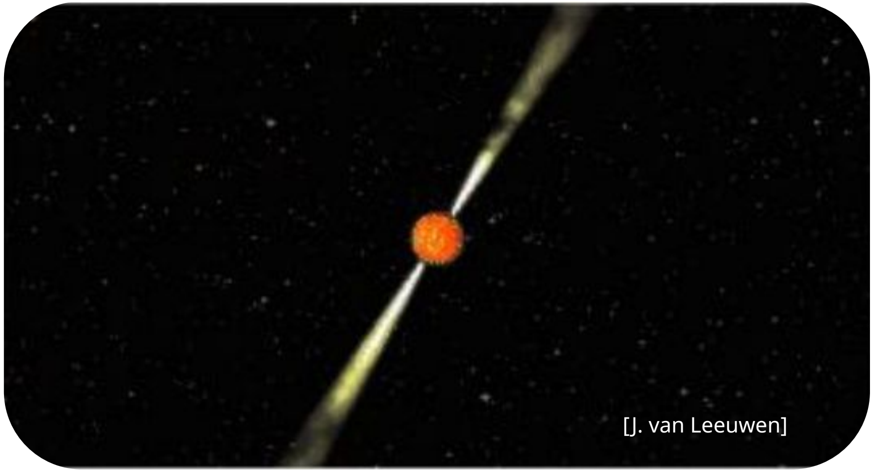
J0534+2200 f_{GW} ~ 60 Hz glitched on 2019/07/23	**J0537-6910** f_{GW} ~ 123 Hz 3 glitches in 2019, 1 glitch in 2020	**J0908-4913** f_{GW} ~ 19 Hz glitched ~ 2019/10/09
J1105-6107 f_{GW} ~ 31 Hz glitched ~ 2019/04/09	**J1813-1749** f_{GW} ~ 45 Hz glitched ~ 2019/08/03	**J1826-1334** f_{GW} ~ 20 Hz glitched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



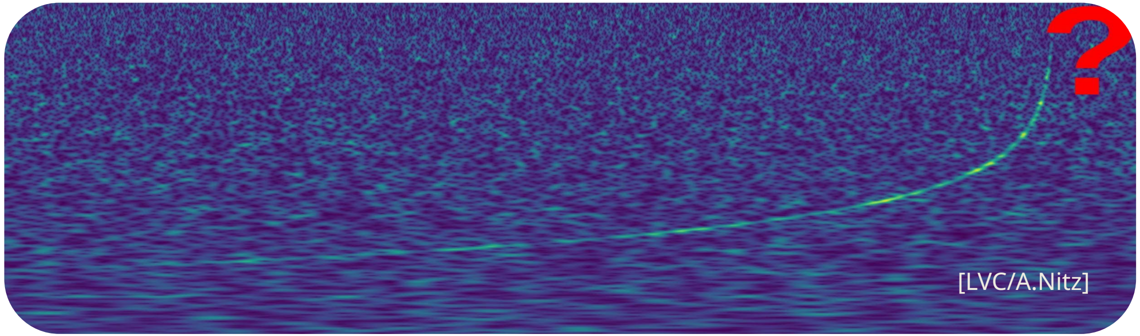
Exciting prospects for O4:
Vela glitch on 2024-04-29
[www.astronomerstelegram.org/?read=16608]

Conclusions: CWs = the next first detection?

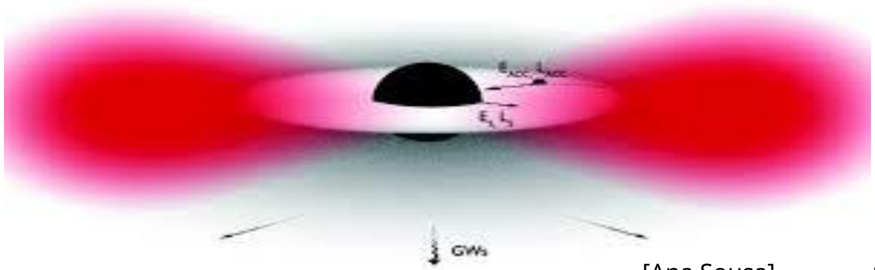
- CWs from known pulsars?
- CWs from unknown neutron stars in our galaxy?
- CWs from exotic objects (PBHs, boson clouds)?
- CW-style dark matter direct detection?
- long transients from...
  - glitching pulsars?
  - newborn neutron stars (supernovae / BNS remnants)?


[J. van Leeuwen]

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



[LVC/A.Nitz]



[Ana Sousa]

Acknowledgments

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