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The targeted search for GWs from known pulsars

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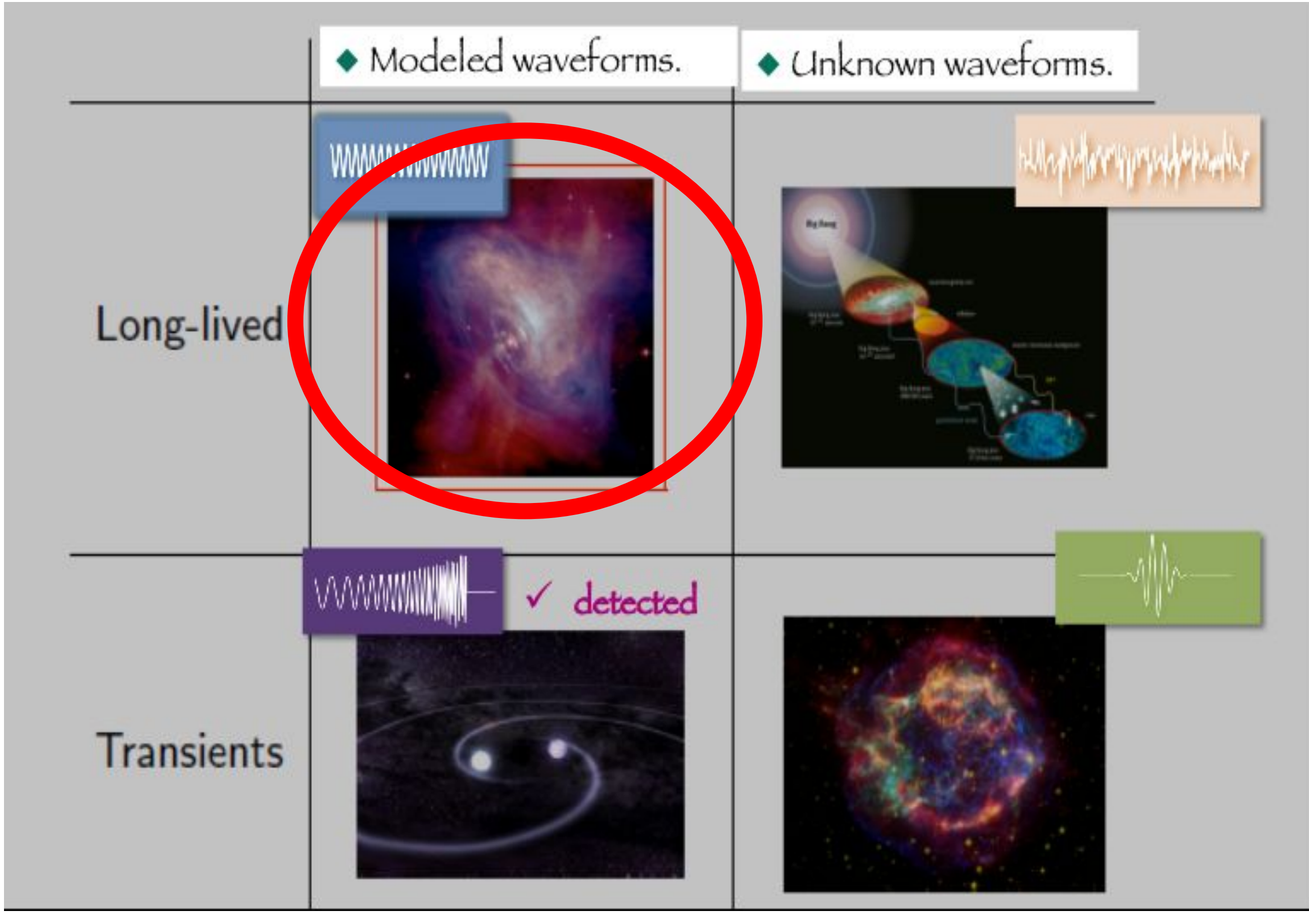
On behalf of LVK Collaboration

LVK+, ApJ 935 1 (2022)

GW sources for ground-based detectors

- ➔ relativistic
- ➔ compact
- ➔ with internal quadrupole motions (e.g. non-spherical collapses and non-axisymmetric rotations)



Continuous gravitational waves (CWs)

<u>SOURCES</u> : Isolated spinning neutron stars with non-axisymmetric mass distribution

- CWs are “long-lived” signals.
- CW frequency is linked to the source rotation frequency
- CW amplitude is expected much weaker than that generated by binary BH/NS coalescences

8 parameters for CW signal :

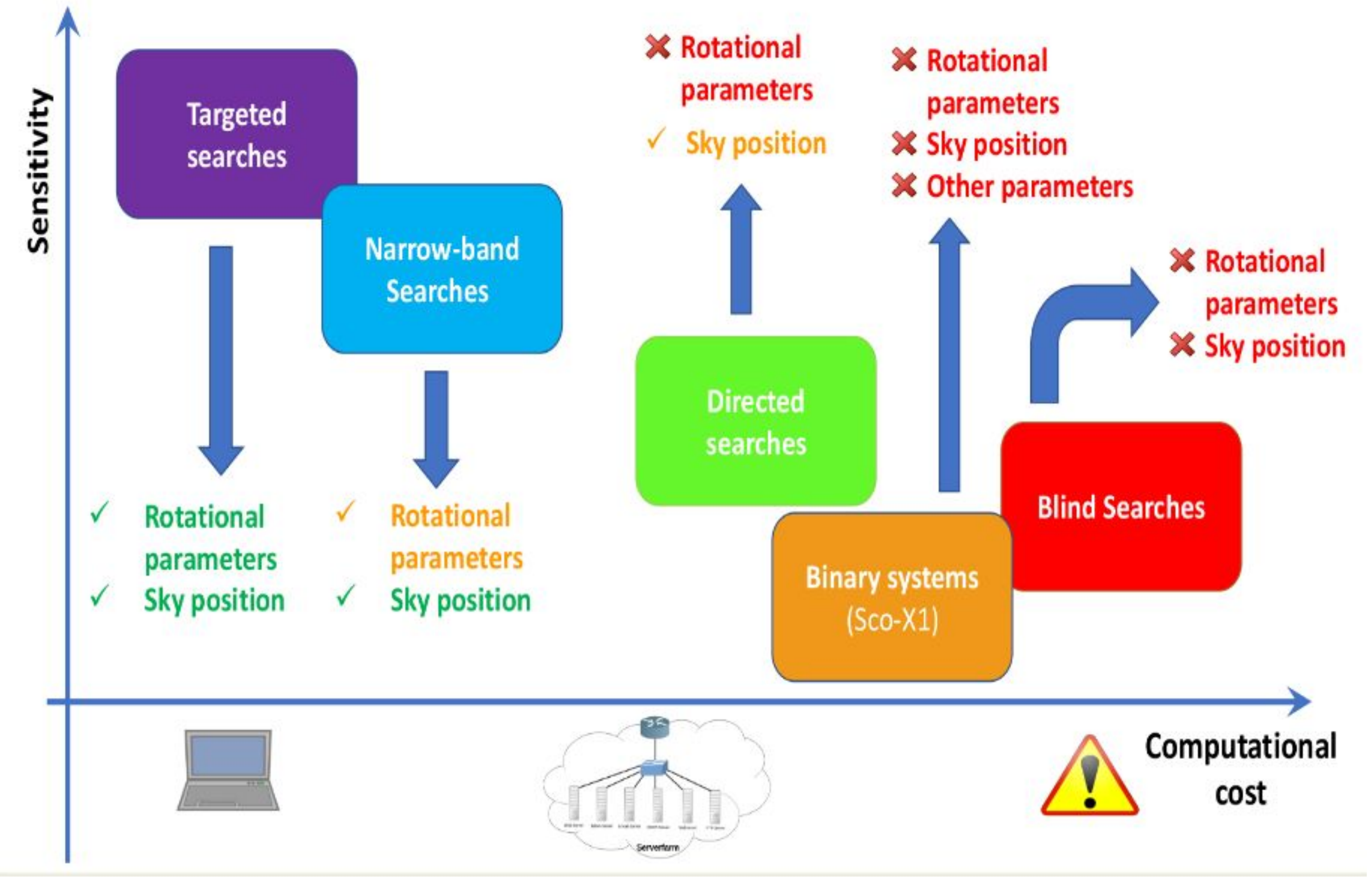
f_{rot} $\dot{f}_{rot}$ α δ → **EXTRINSIC**

h_0 ϕ η ψ → **INTRINSIC**

Different strategies considering source assumptions:

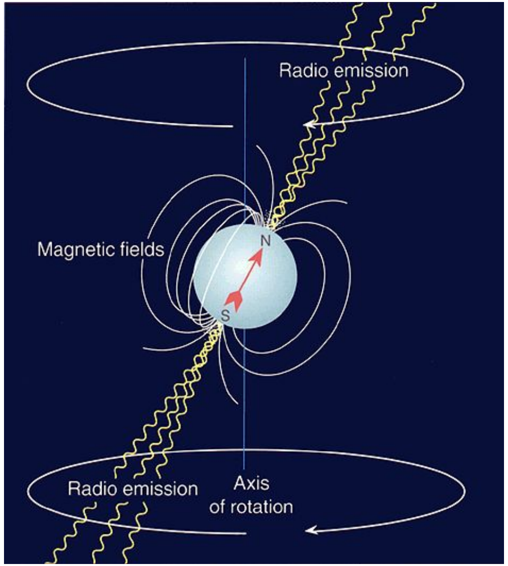
- **<u>Targeted search</u>**;
- Narrow-band search;
- Directed search;
- All-sky search;

CW searches



Credit to:
C. Palomba

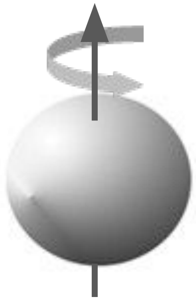
Targeted search
Multi-messenger approach



- CW searches have a strong multi-messenger approach
- EM information constraints extrinsic parameters
- Pulsar observed in radio, X-ray, Gamma-ray band
  - ~ 3000 known pulsars [1] ($10^{8\div9}$ expected NSs)
  - sky position, rotation parameters
- Targeted search for known pulsars:
  - full coherent analysis
- CW detection can return information about the physics of neutron stars (EOS, superfluidity, superconductivity, solid core..) depending on the emission scenarios

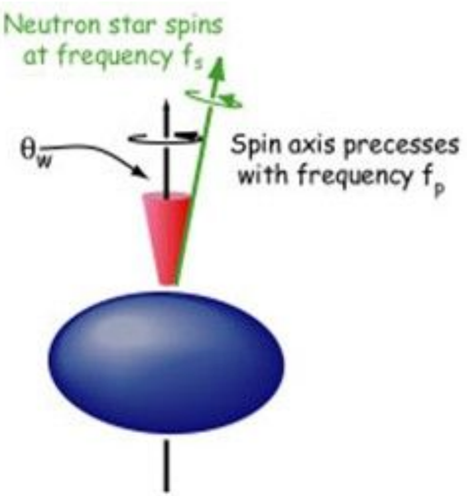
[1] http://www.atnf.csiro.au/research/pulsar/psrcat/

CWs emission



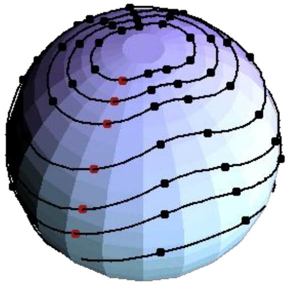
- "bumpy" neutron star [1]

$$f_{gw} = 2f_{rot}$$



- "wobble" radiation [1]
- superfluid component [2]

$$f_{gw} = f_{rot} \text{ and } 2f_{rot}$$



- R-modes [3]

$$f_{gw} \approx \frac{3}{4} f_{rot}$$

[1] Jones, arXiv:2111.08561 (2021)
[2] Jones, Monthly Notices of the Royal Astronomical Society, 402 4 (2010)
[3] Idrisy et al, Phys. Rev. D 91, 024001 (2015)

CW Signal

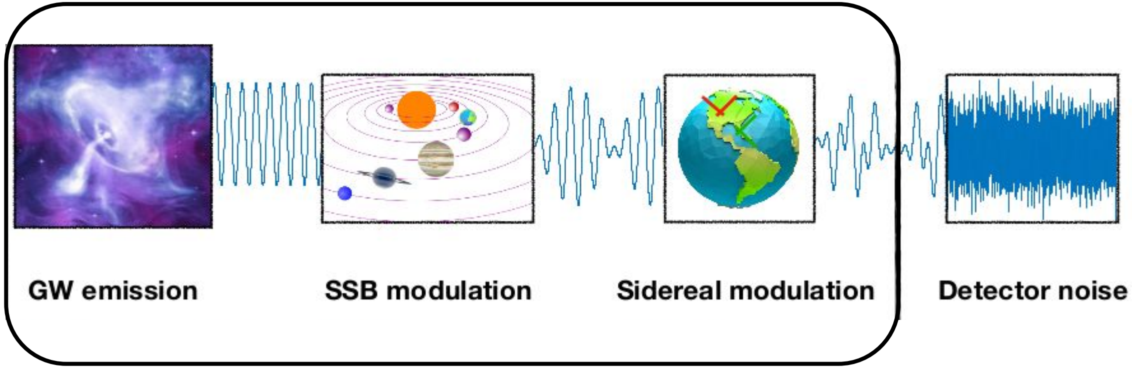
Source as triaxial “bumpy” neutron star rotating around a principal axis of inertia : $f_{gw} = 2 f_{rot}$

$$h_0 \simeq 10^{-27} \left[\frac{f_{gw}}{100\,\mathrm{Hz}}\right]^2 \left[\frac{10\,\mathrm{kpc}}{d}\right] \left[\frac{I}{10^{38}\,\mathrm{kg \cdot m^2}}\right] \left[\frac{\epsilon}{10^{-6}}\right]$$

with $\epsilon = \frac{|I_x - I_y|}{I_z} \approx \frac{\Delta R}{R}$

$$h_0^{SD} = \frac{1}{d}\left(\frac{5}{2}\frac{G I_z}{c^3}\frac{\dot{f}_{rot}}{f_{rot}}\right)^{1/2}$$

→ **Spin-down limit**: theoretical upper limit



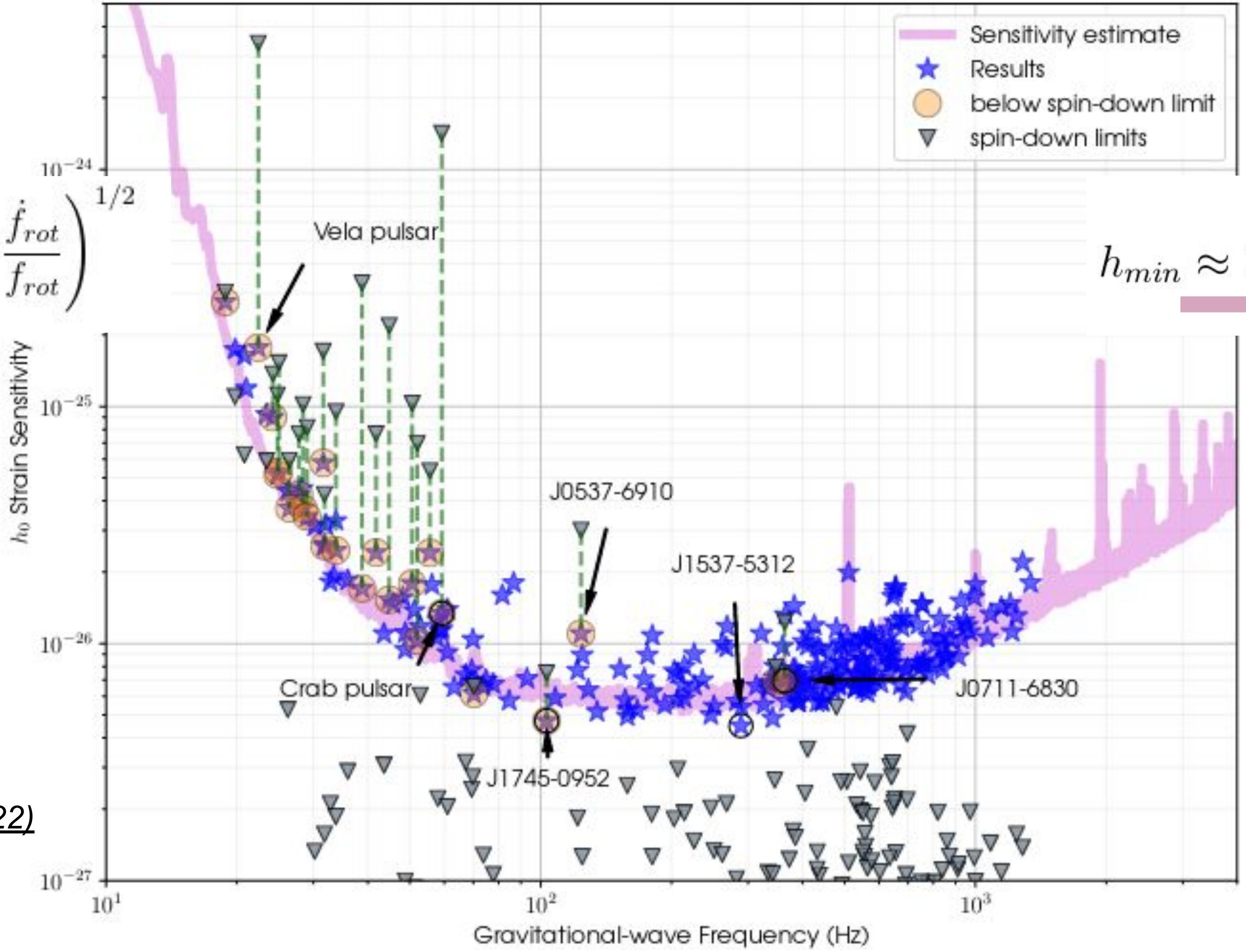
- Doppler correction
- Spin-down correction
- Glitches (Ask me!)

Targeted Search : O3 results

- 236 known pulsars
  - 74 not in previous searches
  - 161 millisecond pulsars
- Three detectors (LIGO and Virgo) : O3 data combined with O2 and O1 data
- Single-harmonic search $f_{gw} = 2f_{rot}$ and Dual-harmonic search $f_{gw} = f_{rot}$ and $2f_{rot}$
- Bayesian analysis
  - F-statistic and 5-vector analysis on high value pulsars
- NO CW detection →upper limits [1]
  - on the amplitude
  - on the ellipticity

[1] *LVK+, ApJ 935 1 (2022)*

O3 results : amplitude



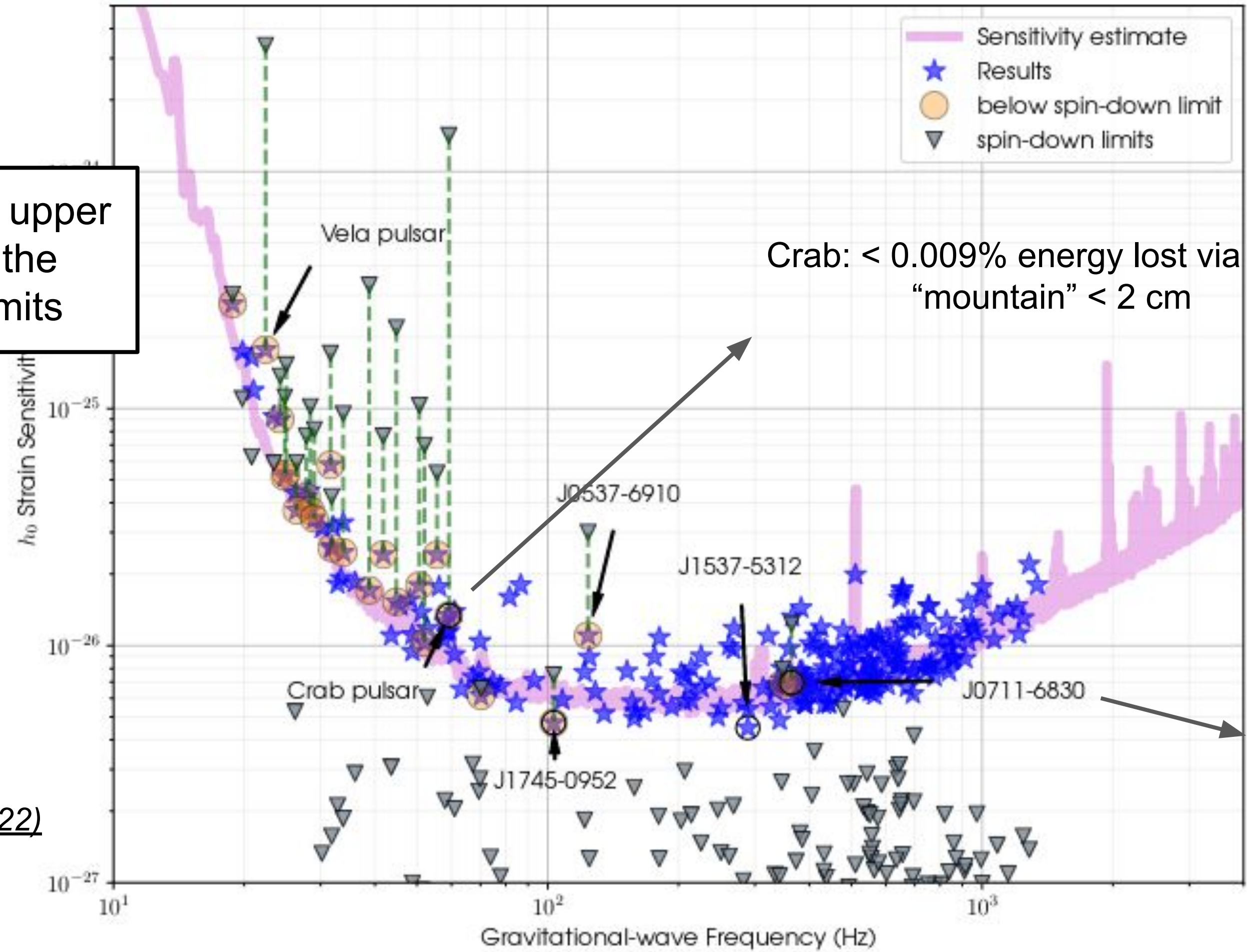
$$h_0^{SD} = \frac{1}{d}\left(\frac{5}{2}\frac{GI_z}{c^3}\frac{\dot{f}_{rot}}{f_{rot}}\right)^{1/2}$$

$$h_{min} \approx 11\sqrt{\frac{S_h(f)}{T_{obs}}}$$ [1]

Credit to:
LVK+, ApJ 935 1 (2022)

[1] Abbott *et al.* Phys. Rev. D 69, 082004 (2004)

O3 results : amplitude



23 pulsars with upper limits below the spin-down limits

Crab: < 0.009% energy lost via GWs, "mountain" < 2 cm

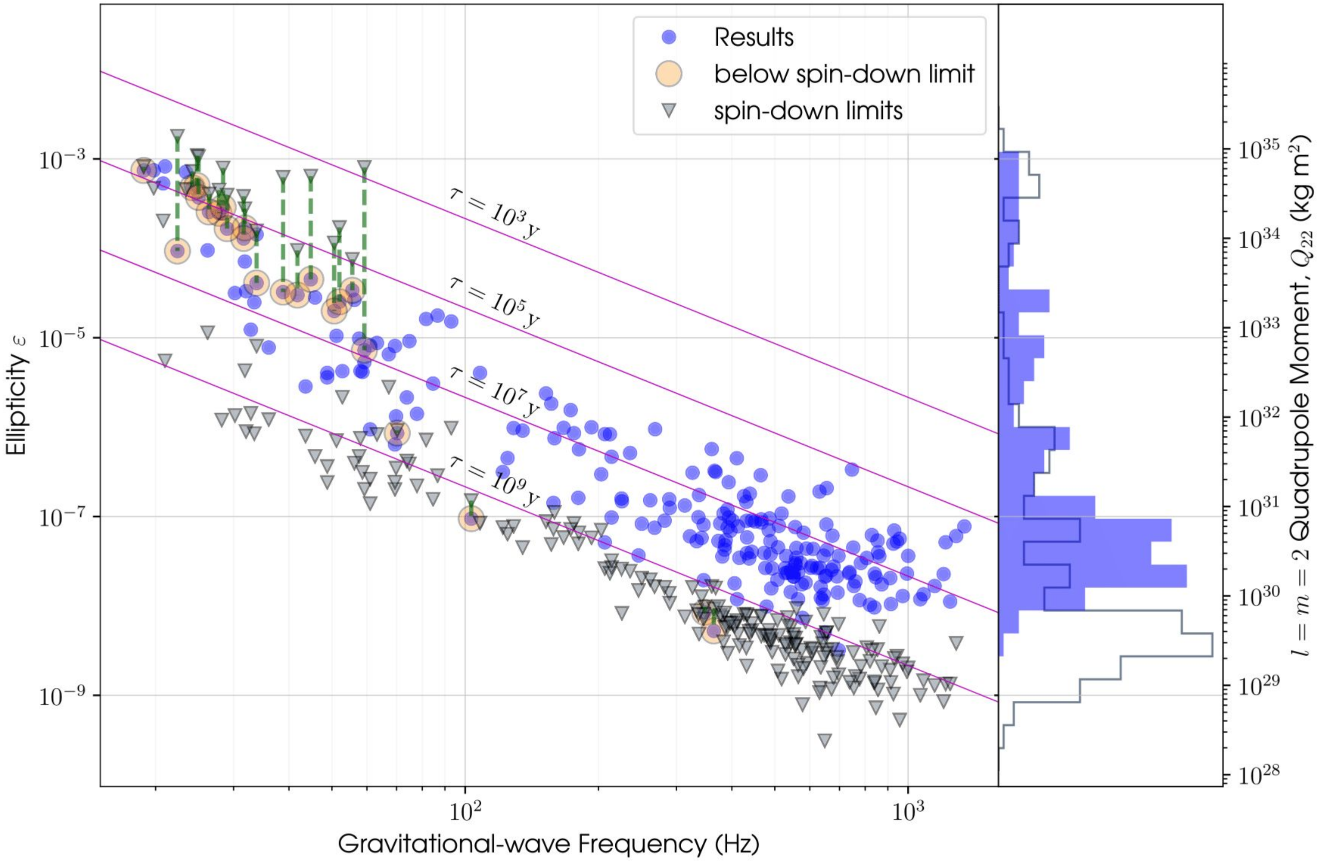
"mountain" < 30 μm

Credit to:
LVK+, ApJ 935 1 (2022)

O3 results : ellipticity

- Best limit on ellipticity was J0711−6830 with 5.26×10^{-9} (at a distance of 0.1 kpc)
- Best overall ellipticity was J0636+5129 with 3.2×10^{-9}

Credit to:
LVK+, ApJ 935 1 (2022)



Conclusion

- Known pulsars are promising sources of CW radiation
- Electromagnetic observations reduce parameter space to explore
  - multi-messenger approach !
- Targeted search is the most sensitive search
- Latest results using O3 LIGO-Virgo detectors' data
  - NO detection
  - 23 out of 236 pulsars with upper limit below the spin-down limit
- Next observing runs will improve sensitivity and bring us closer to detect CWs from pulsars for the first time.

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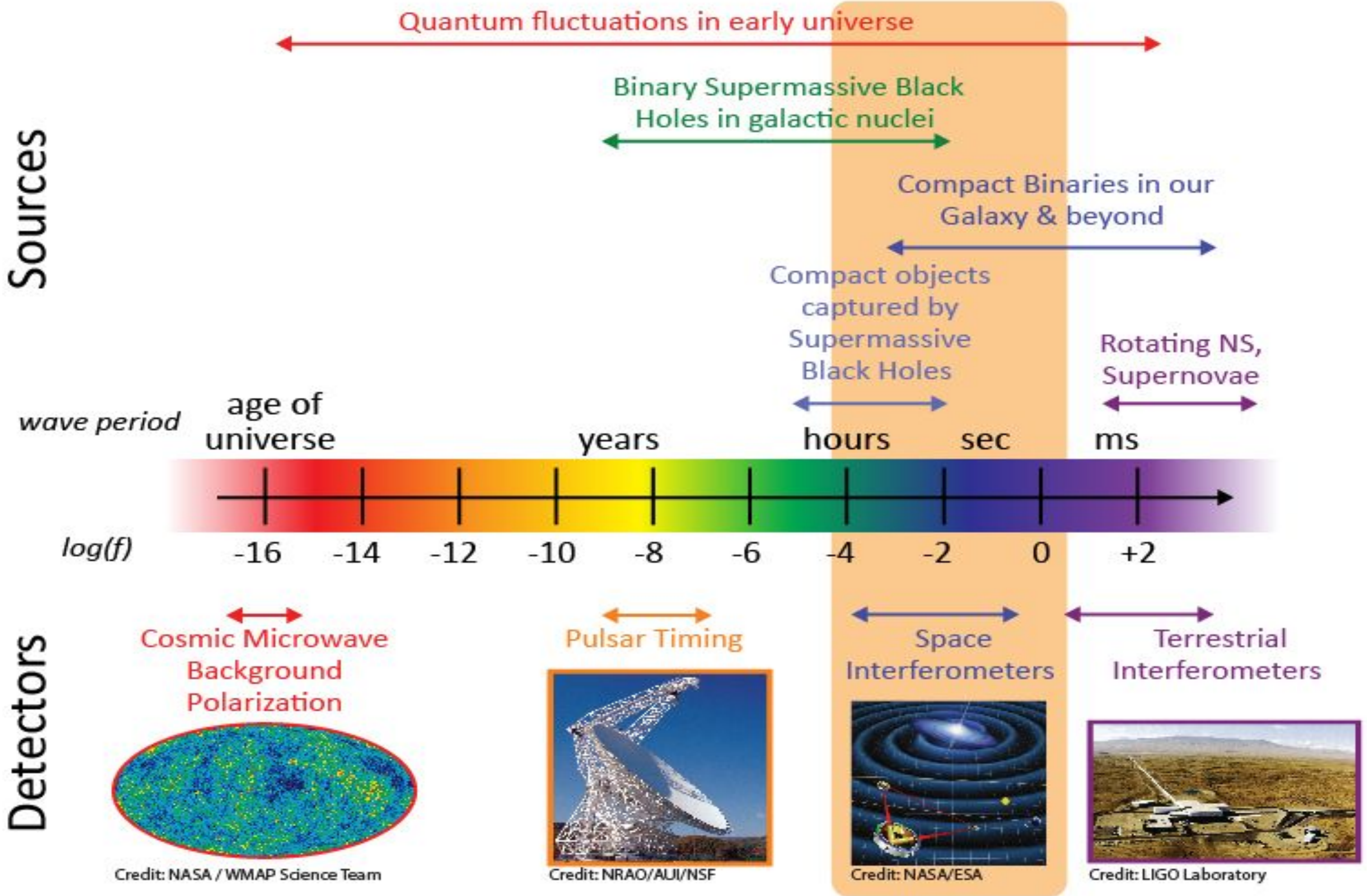
Thank you!

The Gravitational Wave Spectrum



Tools

- **5-vector method**, matched filter in frequency domain

$$x(t) = h(t) + n(t)$$

$$h(t) = H_0(H_+A^+ + H_\times A^\times)e^{\jmath\omega_0 t+\gamma_0}$$

$$H_+ = \frac{\cos 2\psi - \jmath\eta \sin 2\psi}{\sqrt{1+\eta^2}} \qquad H_\times = \frac{\sin 2\psi + \jmath\eta \cos 2\psi}{\sqrt{1+\eta^2}}$$

$$A_+ = a_0 + a_{1c}\cos\Omega t + a_{1s}\sin\Omega t + a_{2c}\cos 2\Omega t + a_{2s}\sin 2\Omega t$$

$$A_\times = b_{1c}\cos\Omega t + b_{1s}\sin\Omega t + b_{2c}\cos 2\Omega t + b_{2s}\sin 2\Omega t$$

It can be rewritten in terms of Signal 5-VECs $\mathbf{A}^+$ $\mathbf{A}^\times$

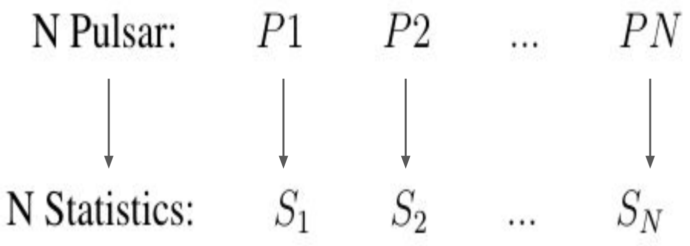
$$\hat{H}_{+/x} = \frac{\mathbf{X}\cdot\mathbf{A}^{+/x}}{|\mathbf{A}^{+/x}|^2} \longrightarrow H_0 e^{i\gamma} H_{+/x}$$

- **5n-vector method,** extension to a network of n detectors

$$\mathbf{X} = [\mathbf{X}_L, \mathbf{X}_H] \qquad \mathbf{A}^+ = [\mathbf{A}_L^+, \mathbf{A}_H^+] \qquad \mathbf{A}^\times = [\mathbf{A}_L^\times, \mathbf{A}_H^\times]$$

$$S = |\mathbf{A}^+|^4|\hat{H}_+|^2 + |\mathbf{A}^\times|^4|\hat{H}_\times|^2$$ → 5n-vec definition

CWs targeted search



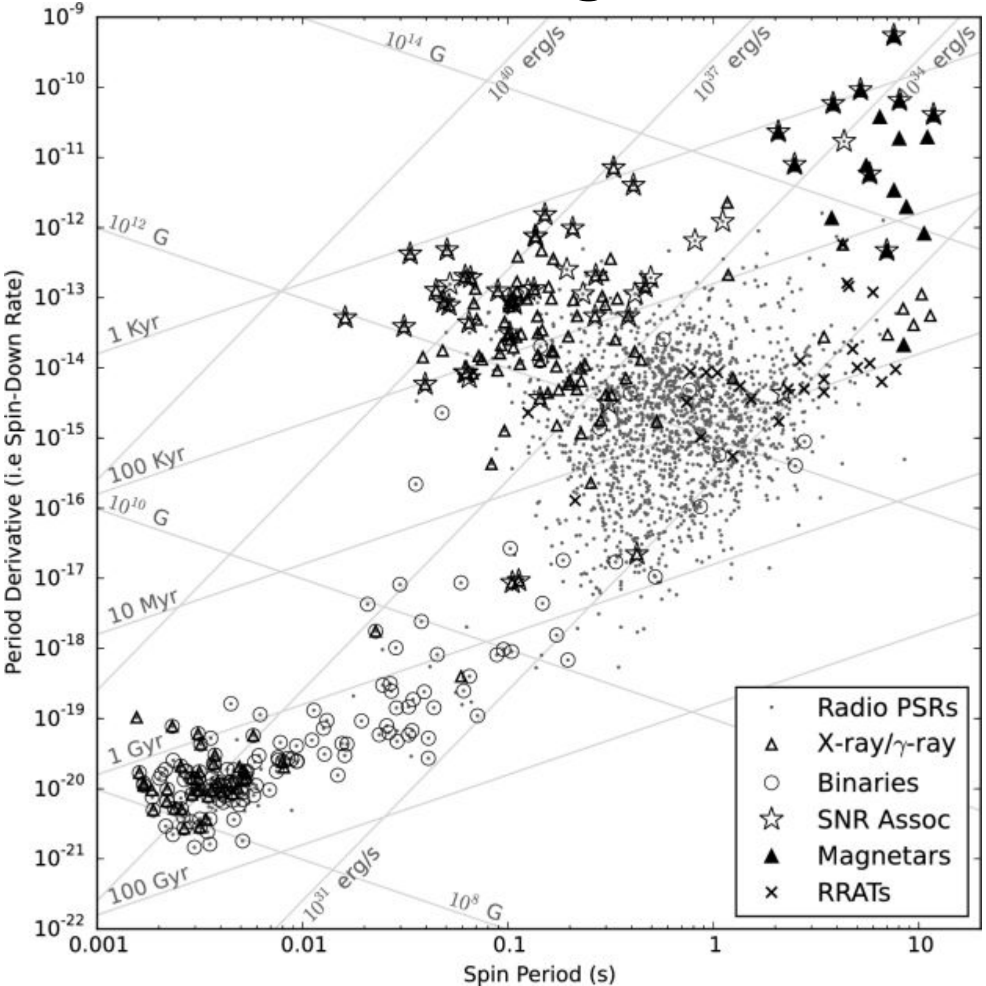
<u>NO evidence of CWs signal in the LIGO/Virgo data</u>

- O3a data : Astrophys.J.Lett. 902 L21

<u>How to improve the detection probability?</u>

- Considering an ensemble of pulsars Giazotto et al. 1997 *Phys.Rev.D* 55
- F-stat Chen et al 2016 Phys.Rev.D 94,
- Bayesian method Pitkin et al 2018 Phys.Rev.D 98
- 5-vector method D'Onofrio et al 2021 Class. Quantum Grav.38 13502
- New paper (submitted to PRD) :
  "The 5n-vector ensemble method for detecting GWs from known pulsars"

P-Pdot diagram



Credit to:
Condon and Ransom, "Essential Radio Astronomy" (2016)

“High accuracy”

Sky position

$$\Delta\theta < 0.1\,\text{arcsec}\left(\frac{10^7\,\text{s}}{T}\right)^2\left(\frac{1\,\text{kHz}}{f_0}\right)$$

Spin-down frequency

$$\frac{1}{1\,\text{yr}} \approx 10^{-7}\,\text{Hz}$$

$$\dot{f}\cdot 1\,\text{yr} < \frac{1}{1\,\text{yr}} \quad \text{or } \dot{f} < 10^{-15}\,\text{Hz/s}$$

See *Maggiore, “Gravitational waves : part I”* for more details