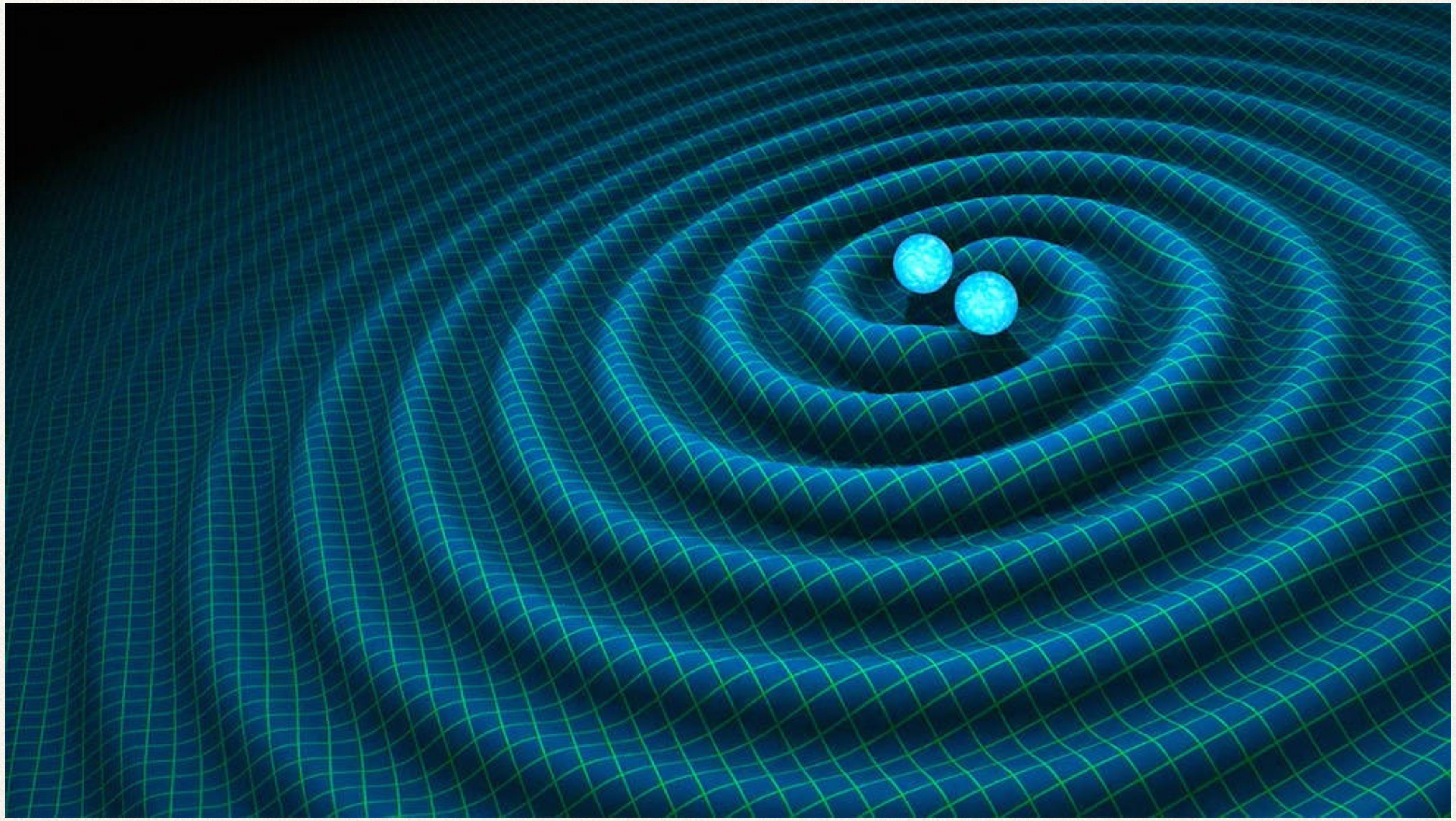
Gravitational waves from neutron stars

Sebastien Guillot (IRAP)



(Continuous) gravitational waves from isolated neutron stars

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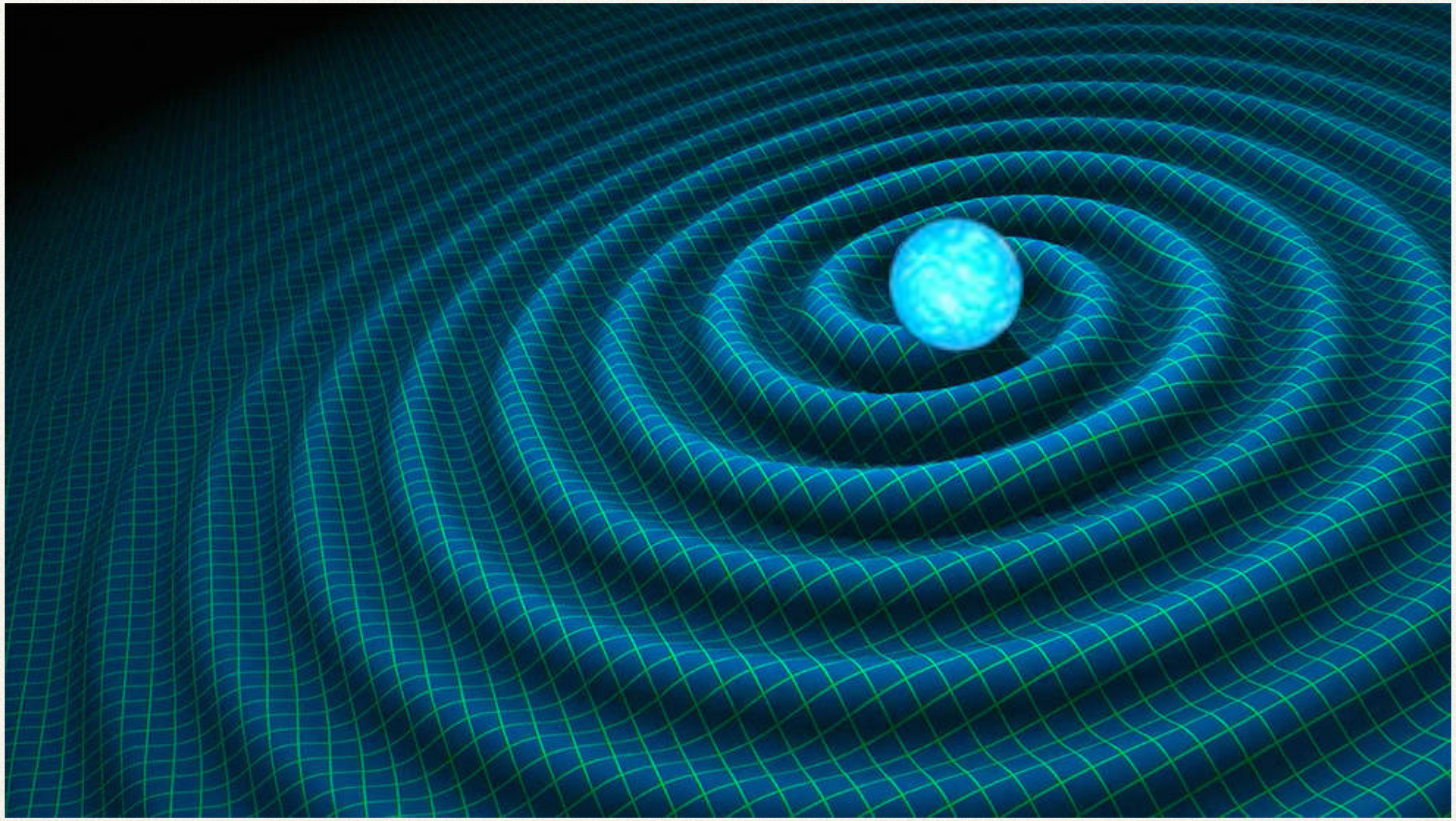
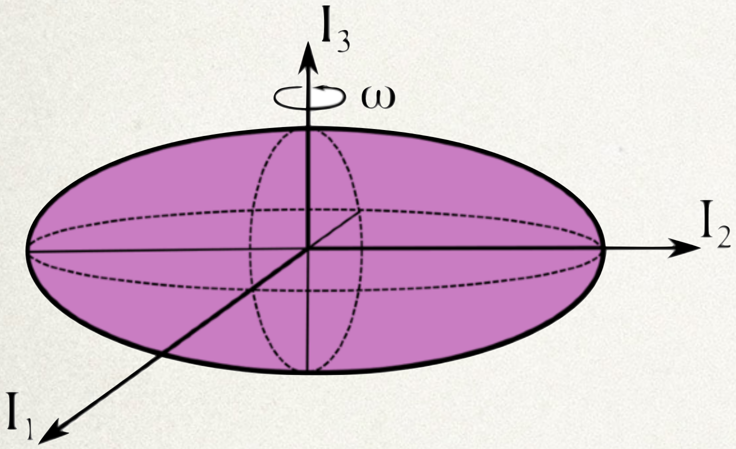


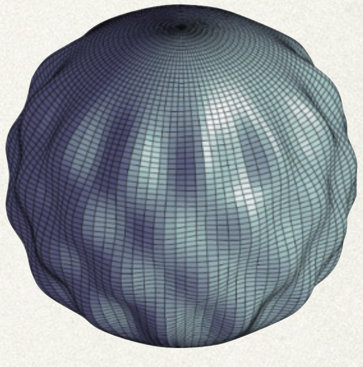
How does an isolated neutron star emit continuous gravitational waves (cGW) ?

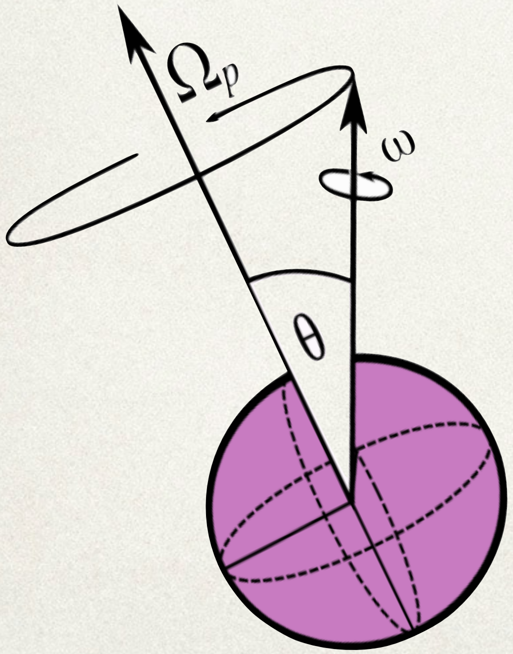
Any non-axisymmetric mass quadrupole distribution:



- Deformation / mountains due to cooling or magnetic fields

- Interior fluid oscillations





- Wobble / Precession

Figures from Sieniawska and Bejger 2019

cGW signal amplitude and frequencies will depend on many factors

- For deformed NSs: $f_{\text{cGW}} = 2f_{\text{spin}}$ and/or $f_{\text{cGW}} = f_{\text{spin}}$

Simple case of a tri-axial start

Moment of inertia

Neutron star ellipticity

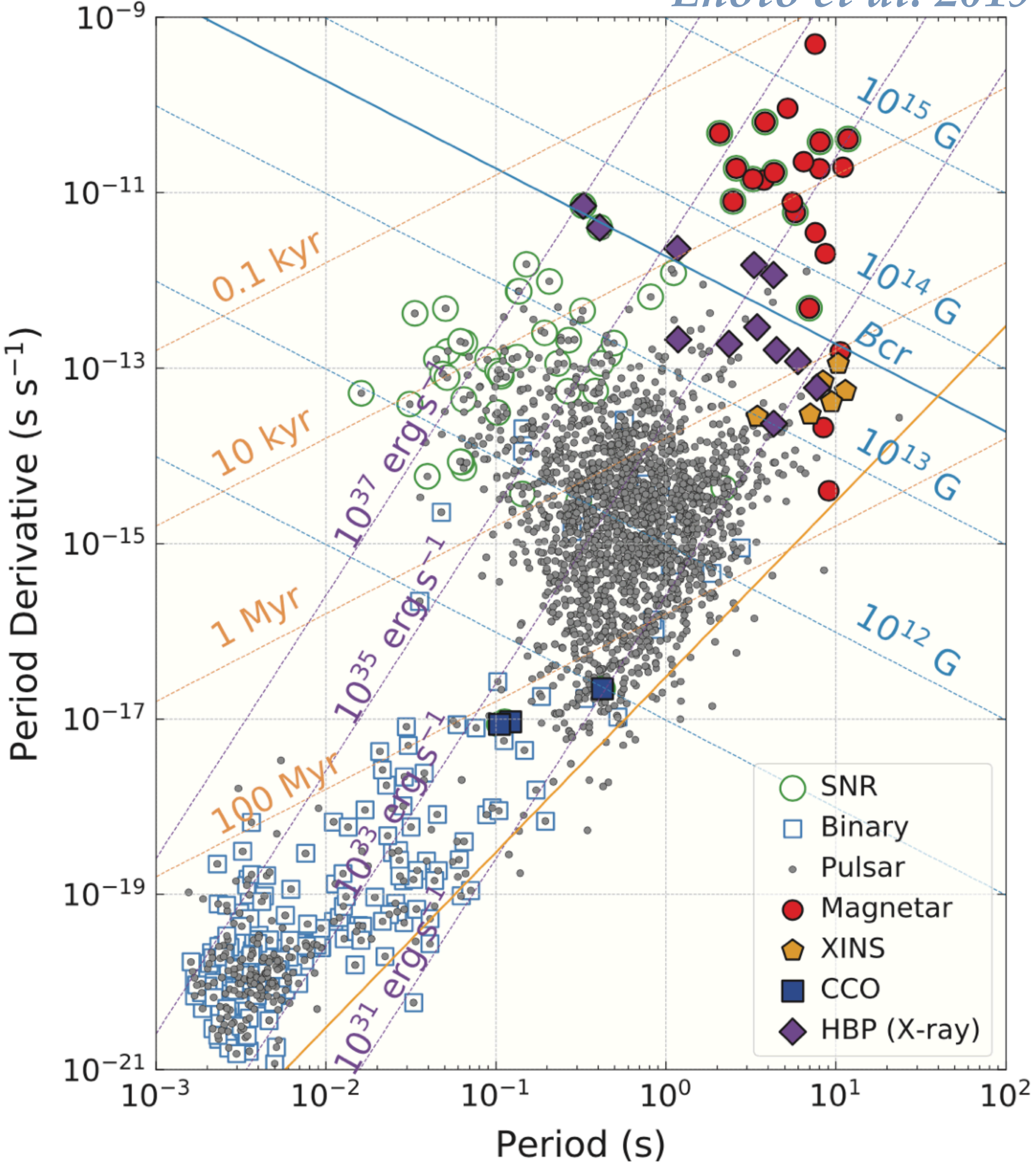
$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz} f_{\text{spin}}^2}{d} \varepsilon$$

Distance

- For fluid oscillations: $f_{\text{cGW}} \sim 4f_{\text{spin}}/3$
- For free precession: $f_{\text{cGW}} = 2f_{\text{spin}}$ and $f_{\text{cGW}} = f_{\text{spin}} + f_{prec}$

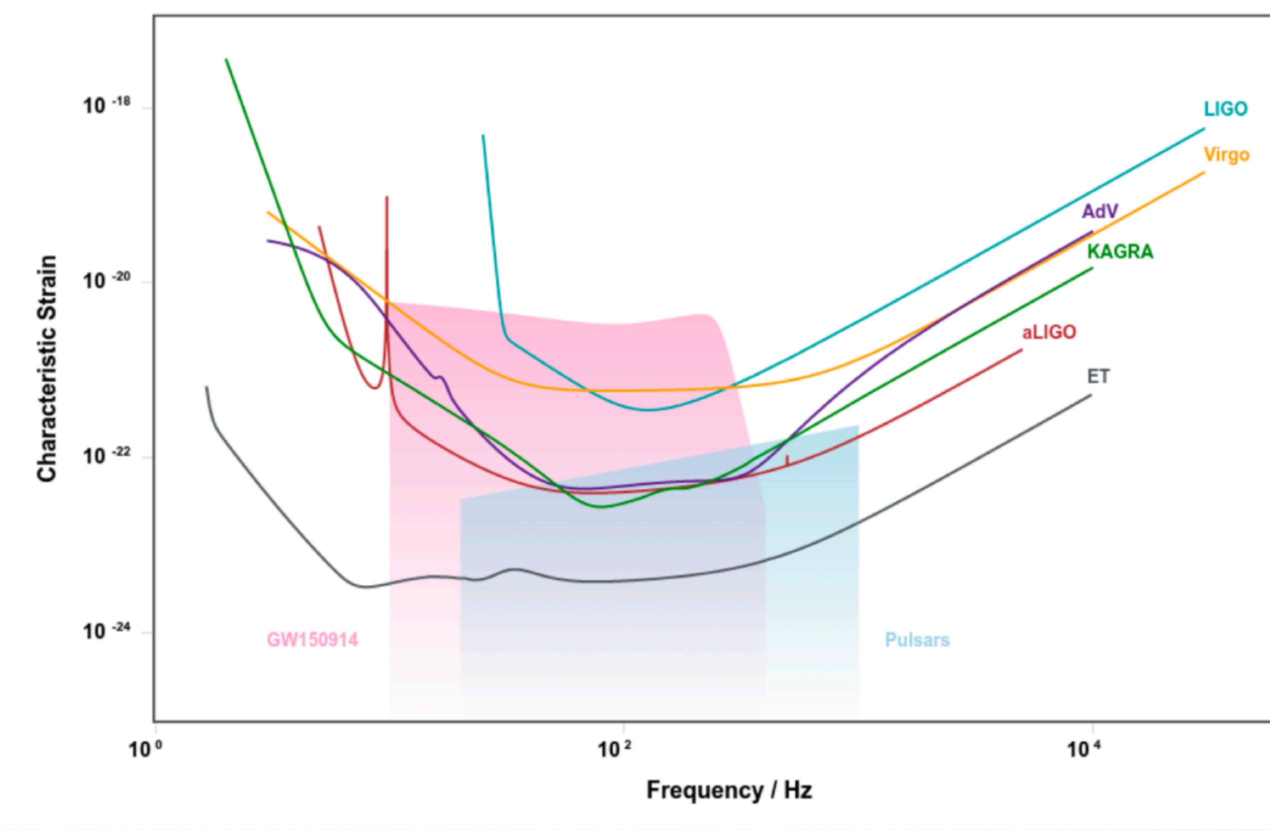
There are numerous potential sources of cGW from inside our Galaxy.

- **Demography**: 10^8 NSs in the Galaxy, and ~200 000 pulsars (*Lorimer, 2008*)
- **Catalogued**: 3000+ NSs known as pulsars (*Manchester et al. 2005*) and X-ray sources
- **Relevant**: About 300 NSs with measured f_{spin} and $\dot{f}_{\text{spin}}$ are in the frequency range of LVK



Enoto et al. 2019

How to search for cGW from isolated NSs ?



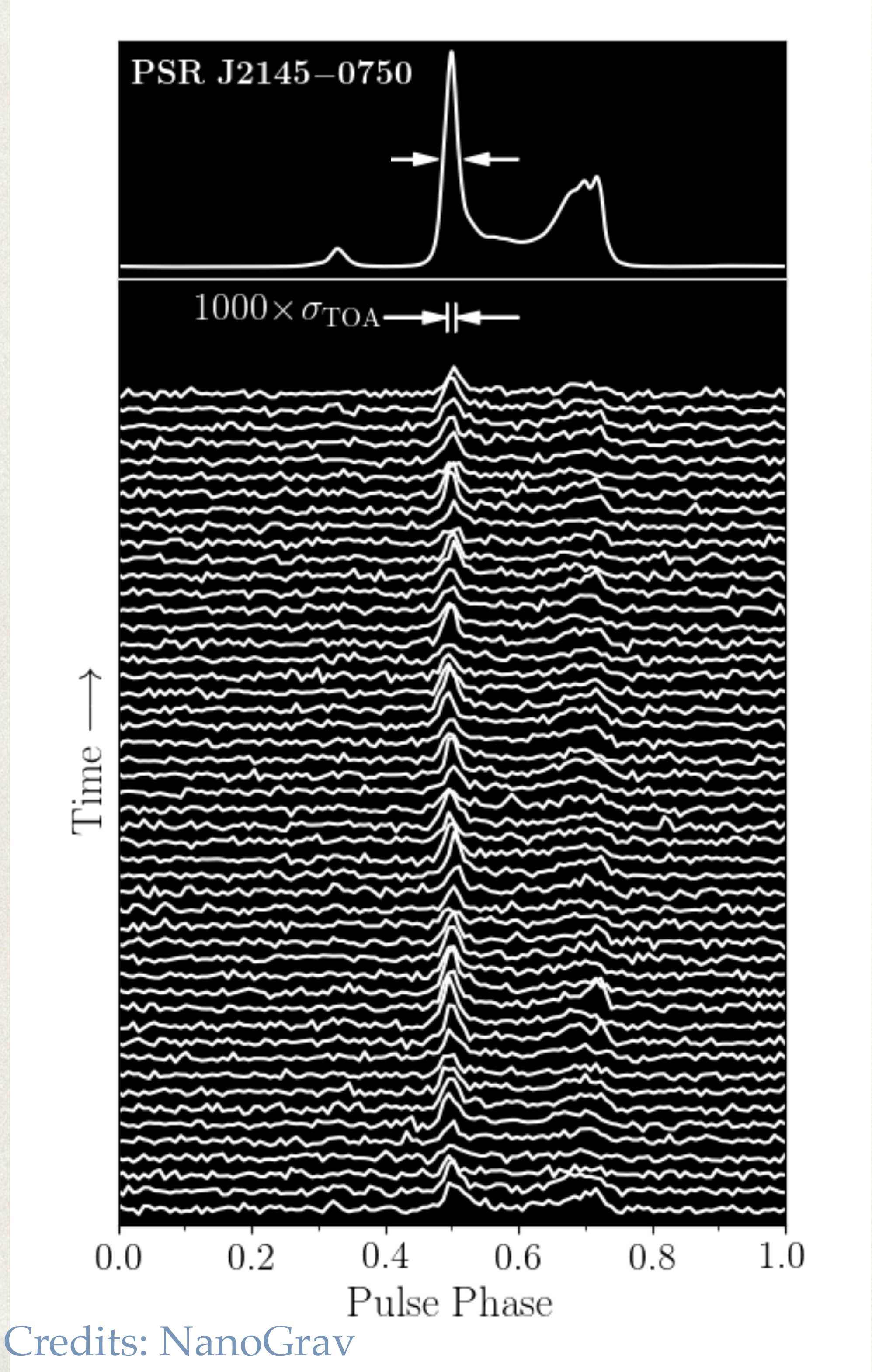
Sieniawska & Bejger, 2019

The targets for searches are selected with the following criteria:

- Within the LVK frequency range
- Youngest NSs
  - higher B-field
  - High spin-down power
  - with potential fluid oscillations
- Precisely timed NSs (spin, location, proper motion - *see side note*)
- Nearby NSs if possible, since $h_0 \propto d$
- Glitching NSs (*see aside note*)

Pulsars timing: Accounting for every single rotation.

Side Note



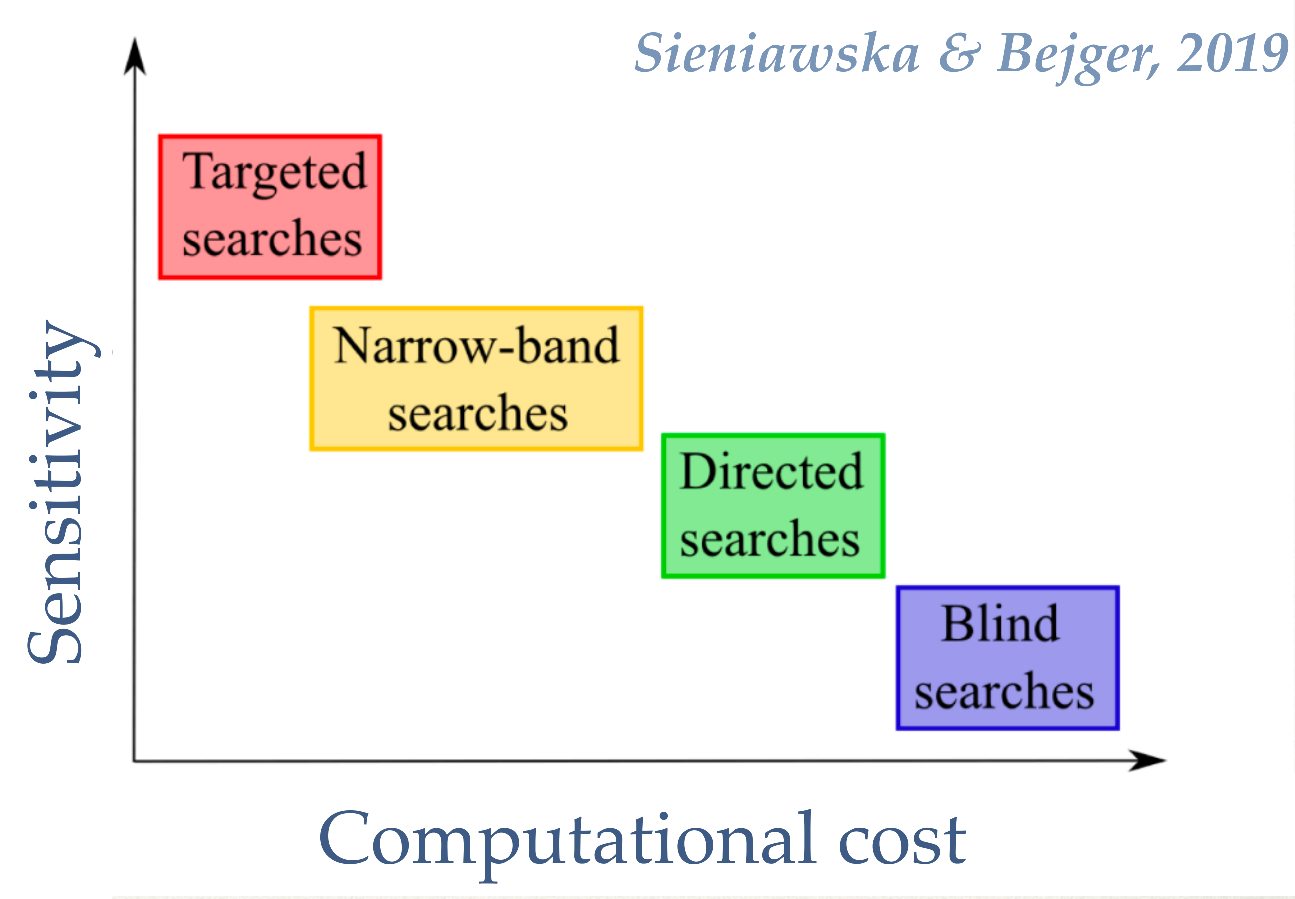
Credits: NanoGrav

This allows extremely precise measurements of :

- the rotation frequency
- the frequency derivative (spin down, or up)
- the location and proper motion via parallax

NOTE: The spin-down power $\dot{E} \propto f_{\mathrm{spin}}\, \dot{f}_{\mathrm{spin}}$ tells us the loss rate of rotational energy

Several methods exist to search for cGW in the LVK data



- **Targeted searches** with exact values of $f_{\rm spin}$, $\dot{f}_{\rm spin}$, etc…
- **Narrow band searches** allow for small mismatch between $f_{\rm spin}$ and $f_{\rm cGW}$
    - Possible if differential rotation (core/crust)…
- **Directed searches** (i.e., fixed location) for NS with unknown $f_{\rm spin}$.
- **Blind search**, for people with big computers

Results 1: Targeted searches on O2+O3 data sets

236 pulsars with $f_{\text{spin}} > 10\,\text{Hz}$ having timing information from radio and X-ray

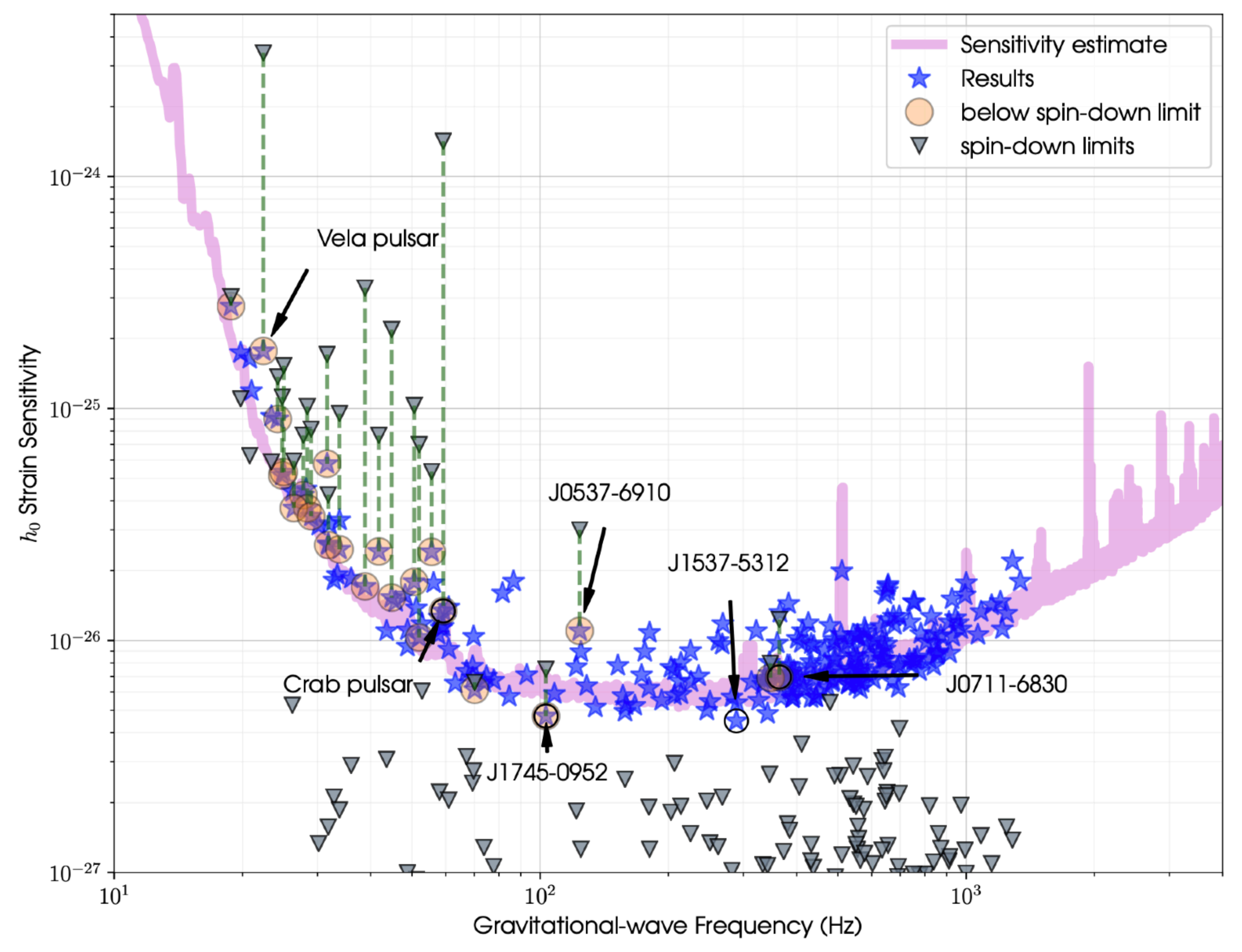
Includes 168 pulsars in binary systems

Best h_0 limit

4.72×10^{-27}

Spin-down limit h_0^{SD}

Strain limit assuming all the pulsar spin-down energy is due to the emission of gravitational waves and none to the EM radiation



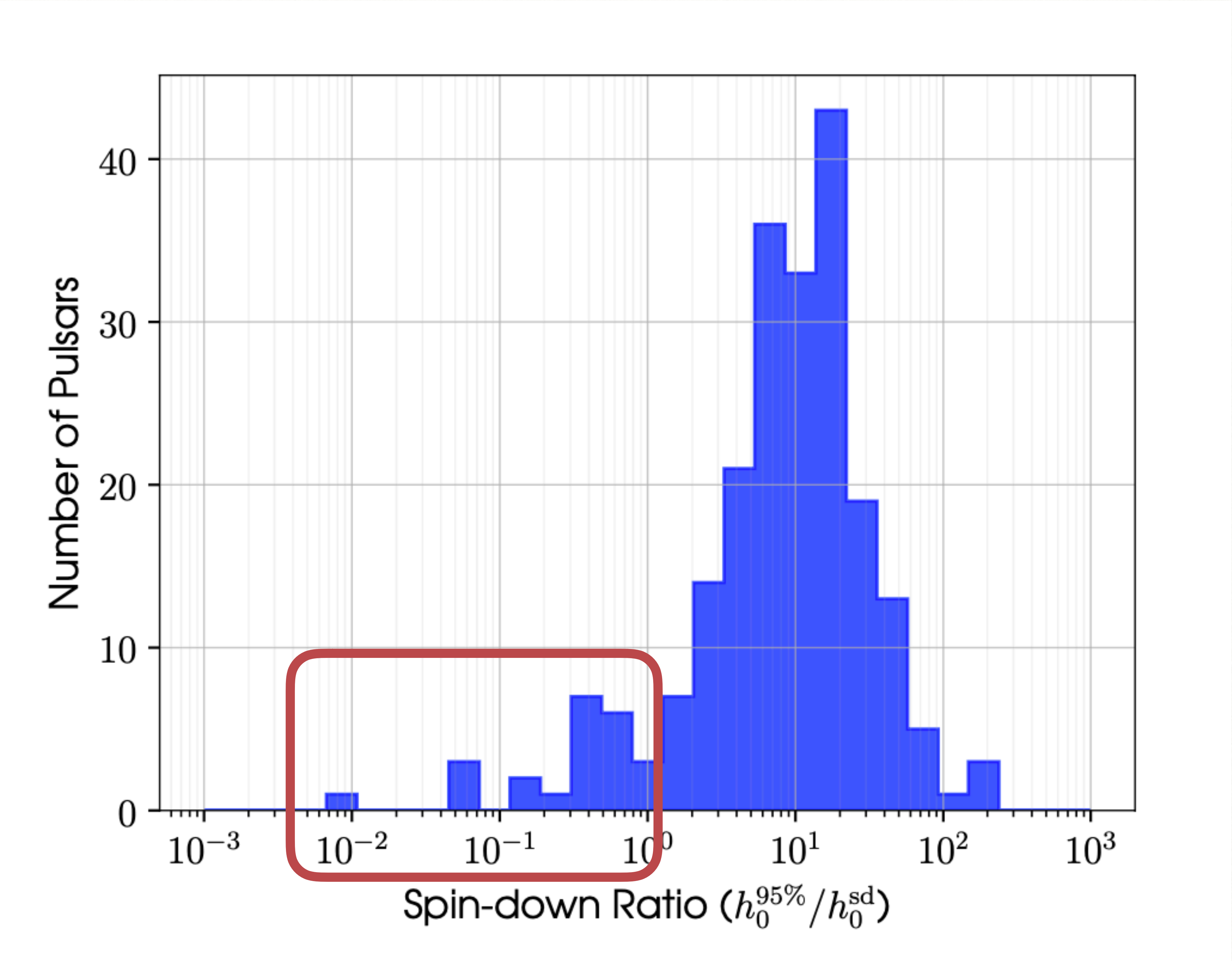
LVK Collab. et al. 2021a, submitted (ArXiv:2111.13106)

Results 1: Targeted searches on O2/O3 data sets

23 pulsars have upper limit on h_0 lower that their spin down limits, i.e., $h_0 / h_0^{SD} < 1$

Best constraint for the Crab Pulsar

$$h_0 / h_0^{SD} = 0.009$$



LVK Collab. et al. 2021a, submitted (ArXiv:2111.13106)

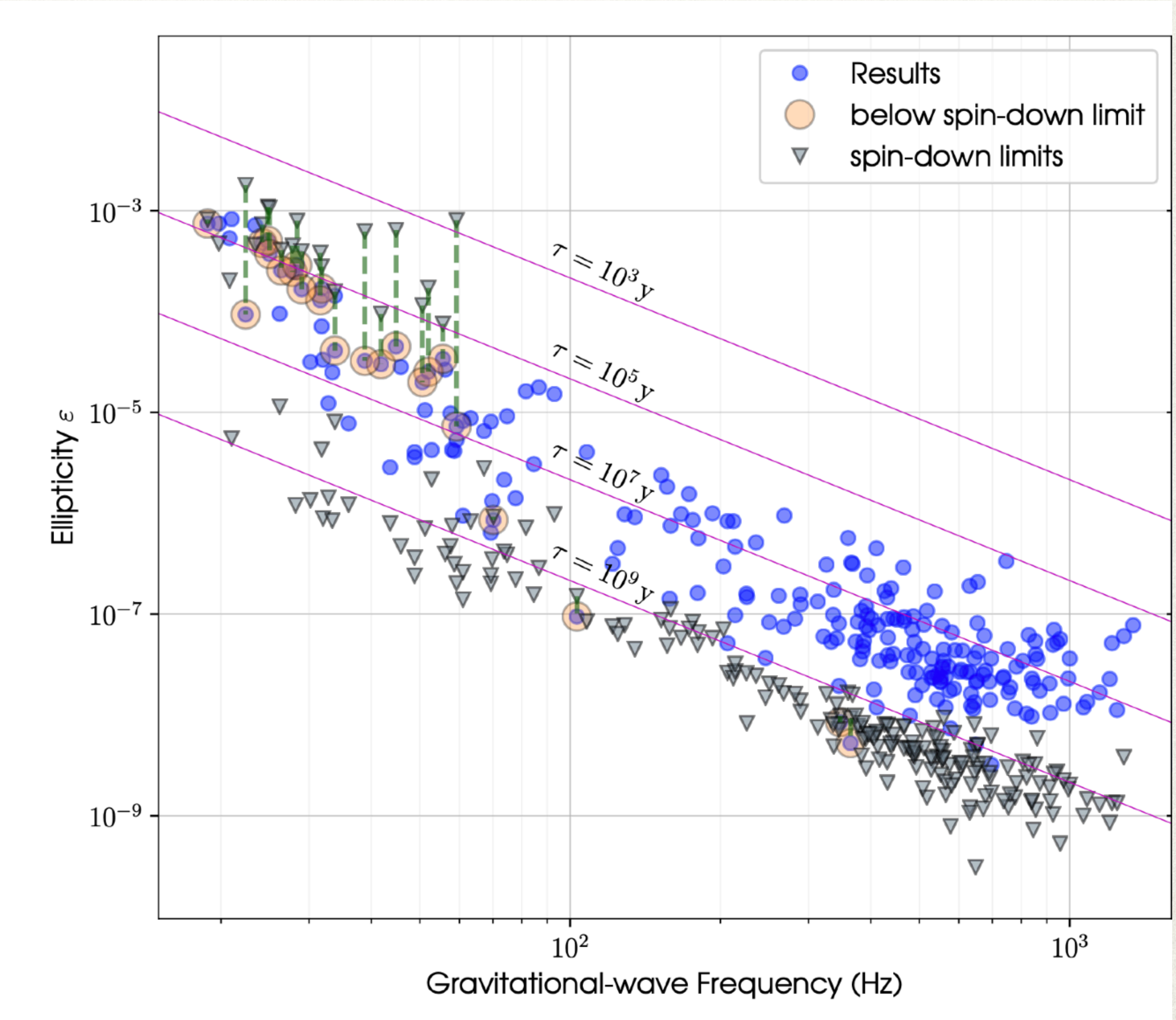
Results 1: Targeted searches on O2/O3 data sets

For these 23 pulsars, we constrain their ellipticity.

Best ellipticity constraint

$\varepsilon < 5.26 \times 10^{-9}$

Deformation with respect to perfect sphere of < 0.1 mm



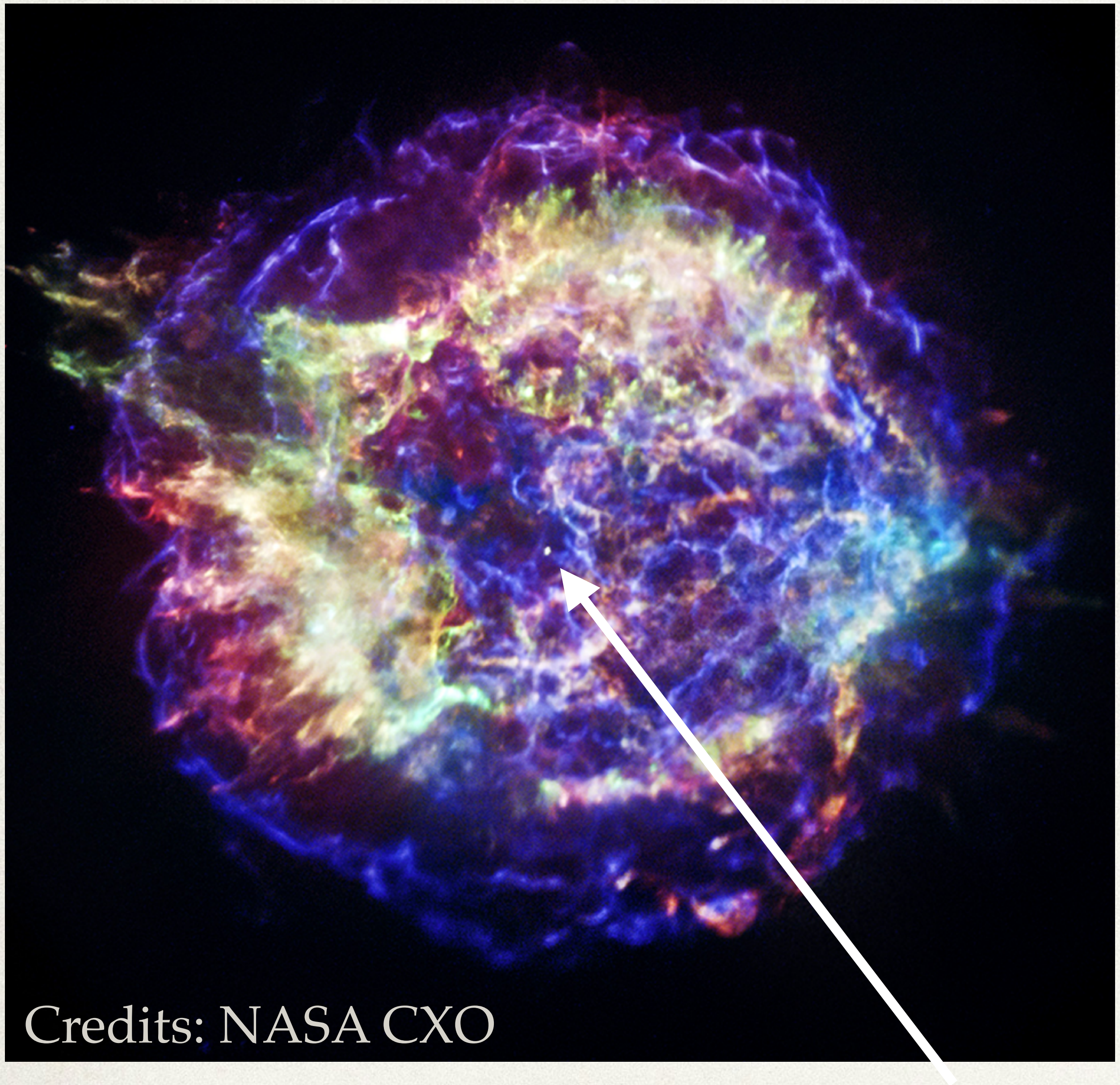
LVK Collab. et al. 2021a, submitted (ArXiv:2111.13106)

Results 2: Narrow-band searches from O3

- 18 key pulsars with timing information from radio or X-ray
    - Selection: expected spin-down limit within 3 times the expected sensitivity of the O3 run
- The nature of the search is somewhat less sensitive than the targeted search

LVK Collab. et al. 2021, not submitted yet…

Recent Directed Searches: The case of Cassiopeia A



Credits: NASA CXO

Neutron star: X-ray point source, no pulsations, so no spin information

- If $f_{\text{spin}} << f_{\text{spin},0}$ and spin-down due to cGW emission:

$$h_{\text{age}} = (2.3 \times 10^{-24}) \left(\frac{1\,\text{kpc}}{r}\right) \sqrt{\left(\frac{1000\,\text{yr}}{\tau}\right)\left(\frac{I_{zz}}{I_0}\right)}$$

- For Cas A, $h_{\text{age}} \sim 1.2 \times 10^{-24}$
- Search in $f_{\text{spin}} = [20{,}956]$ Hz
- For assumed ages > 300 years
- $h_{\text{age}} < 6.3 \times 10^{-26}$
- $\varepsilon < 3 \times 10^{-6}$ for $f_{\text{spin}} = 300$ Hz

LVK Collab. et al. 2021b, (ArXiv:2111.15116)

Why keep searching ?

Finding cGW would help:

- Constrain the equation of state of dense matter
- Determine the phase of cGW vs EM (lock, drift ?)
- Testing GR and theories of gravity

What about Fast Radio Bursts?


Credits: Danielle Futselaar / ASTRON

- Millisecond duration, bright, and Mpc-distant bursts of radio
  - Repeating vs non-repeating
  - Non-destructive vs cataclysmic events

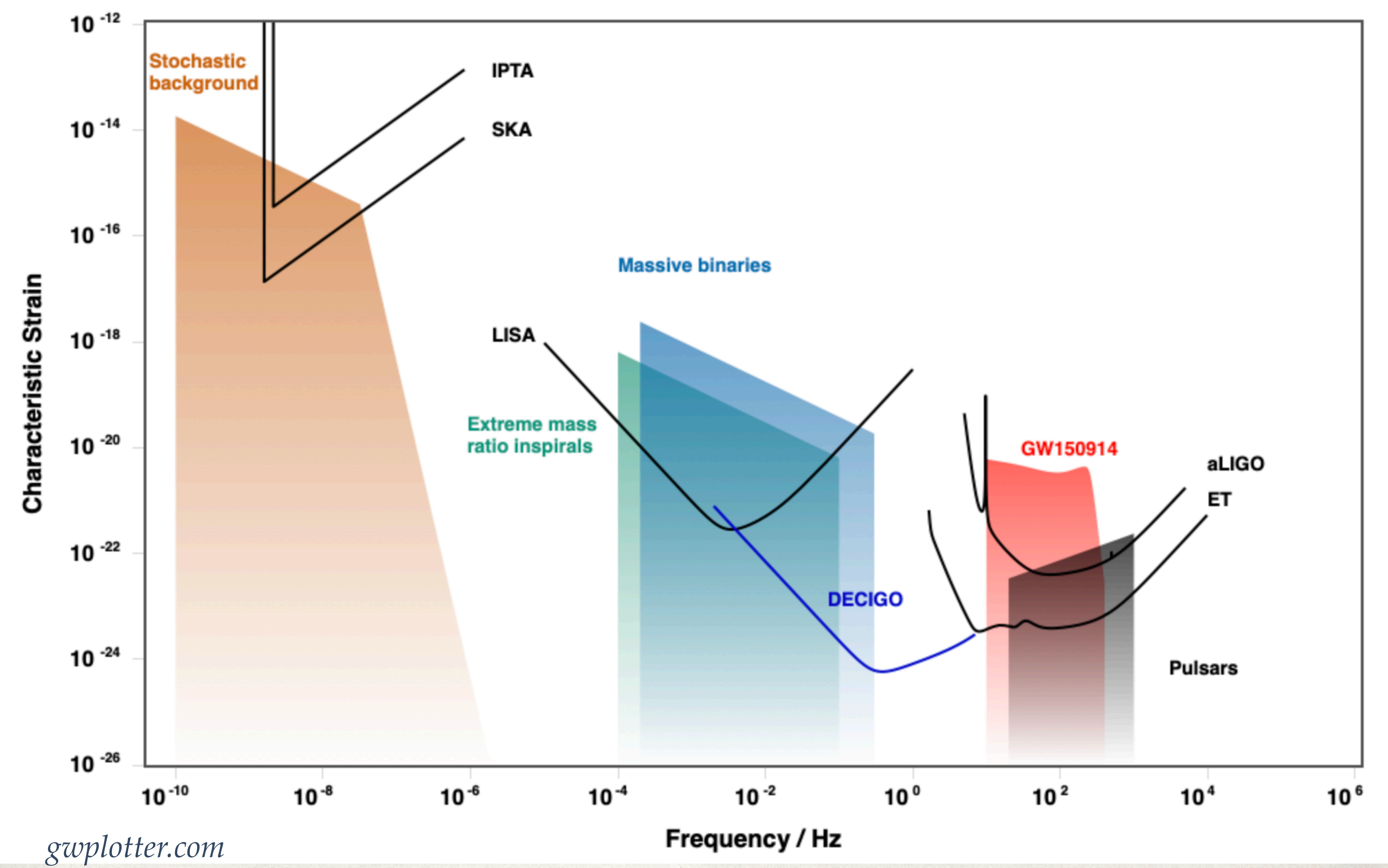
- Recent discoveries:
  - FRB ⇔ Galactic magnetar (high B-field neutron star)
  - FRB ⇔ extragalactic globular cluster (unlikely to host magnetars)

What about
Fast Radio Bursts?


Credits: Danielle Futselaar / ASTRON

- FRB ⇔ GW association ?
    - Nothing found in 2007-2013 for 14 FRBs (Abbott et al. 2016)
    - No publication since then with runs O1, O2 and O3
- Possible sources of FRB ⇔ GW associations:
    - Magnetar bursts?
    - Compact object mergers?
- What would be the frequency of GW signals associated with FRBs ?

And afterwards? ET, LISA, …



gwplotter.com

Conclusion

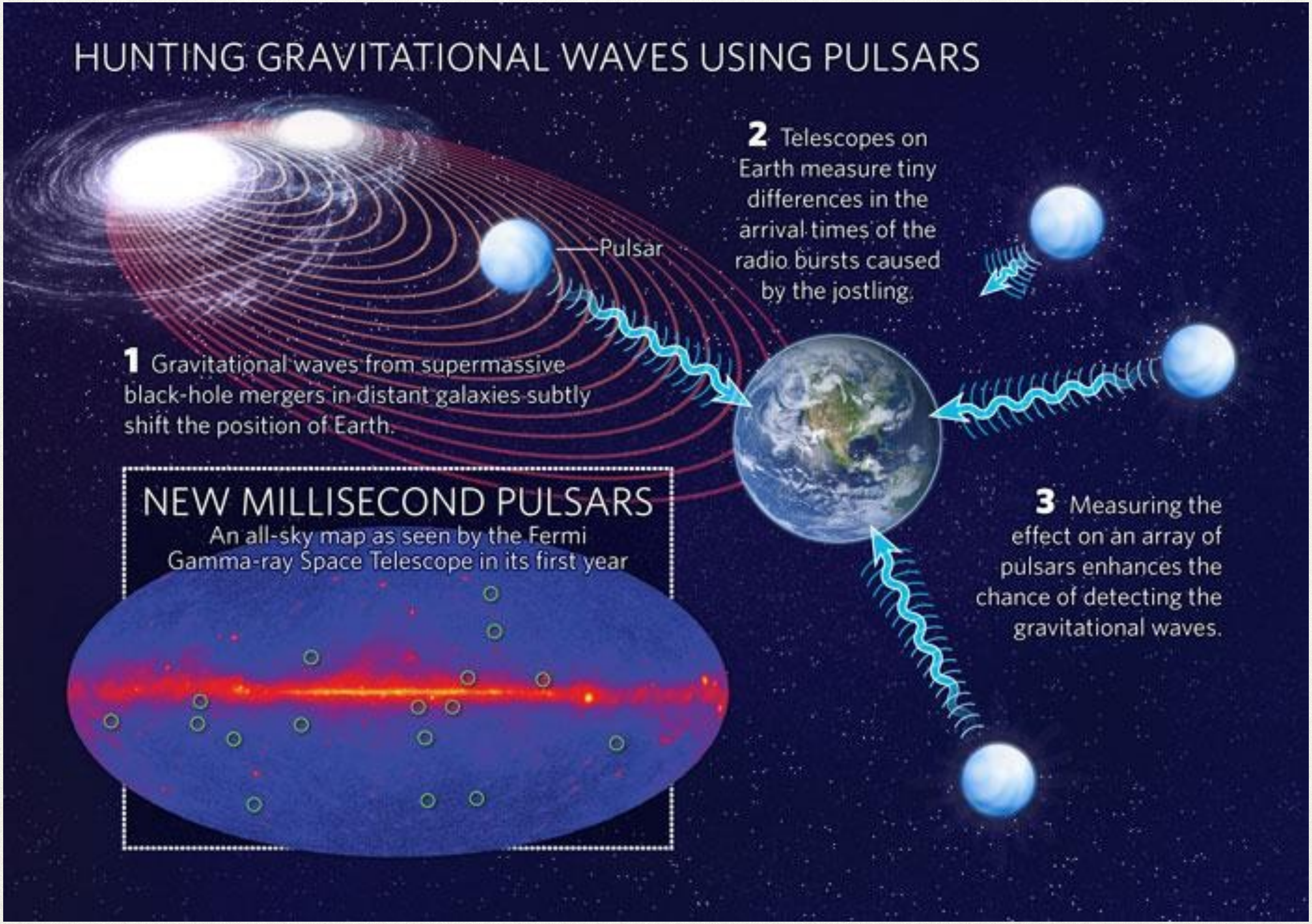
- Still no detection, but the search must go on
  - With different methods
  - For the association with FRBs

- Slower neutron stars still remain out of range…until LISA (maybe) or DECIGO.

For more info, see two recent reviews:

  - Sieniawska & Bejger, *Universe*, 2019
  - Haskell & Schwenzer, 2021 (ArXiv: 2104.03137)

Pulsar Timing Arrays



HUNTING GRAVITATIONAL WAVES USING PULSARS

1 Gravitational waves from supermassive black-hole mergers in distant galaxies subtly shift the position of Earth.

2 Telescopes on Earth measure tiny differences in the arrival times of the radio bursts caused by the jostling.

3 Measuring the effect on an array of pulsars enhances the chance of detecting the gravitational waves.

NEW MILLISECOND PULSARS

An all-sky map as seen by the Fermi Gamma-ray Space Telescope in its first year

(Credit: NASA/DOE/Fermi LAT Collaboration via Nature)

Extra: Signal-to-Noise Ratio

$$S/N \propto h_0\sqrt{T}$$

NS-NS Mergers

T~0.2 sec

$h_0 \sim 10^{-21}$

S/N ~ 24

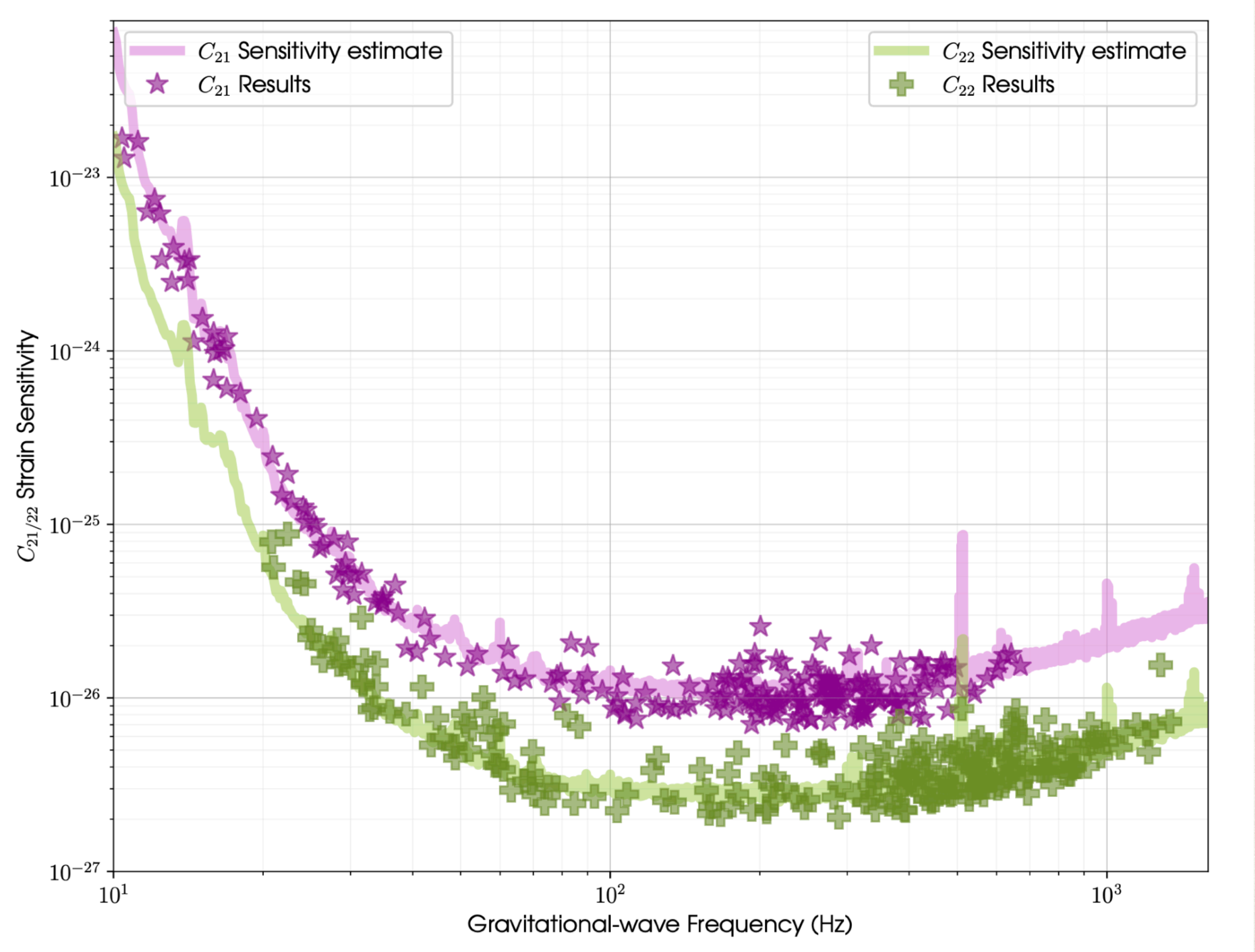
cGW

T~10^7 sec

$h_0 \sim 10^{-26}$

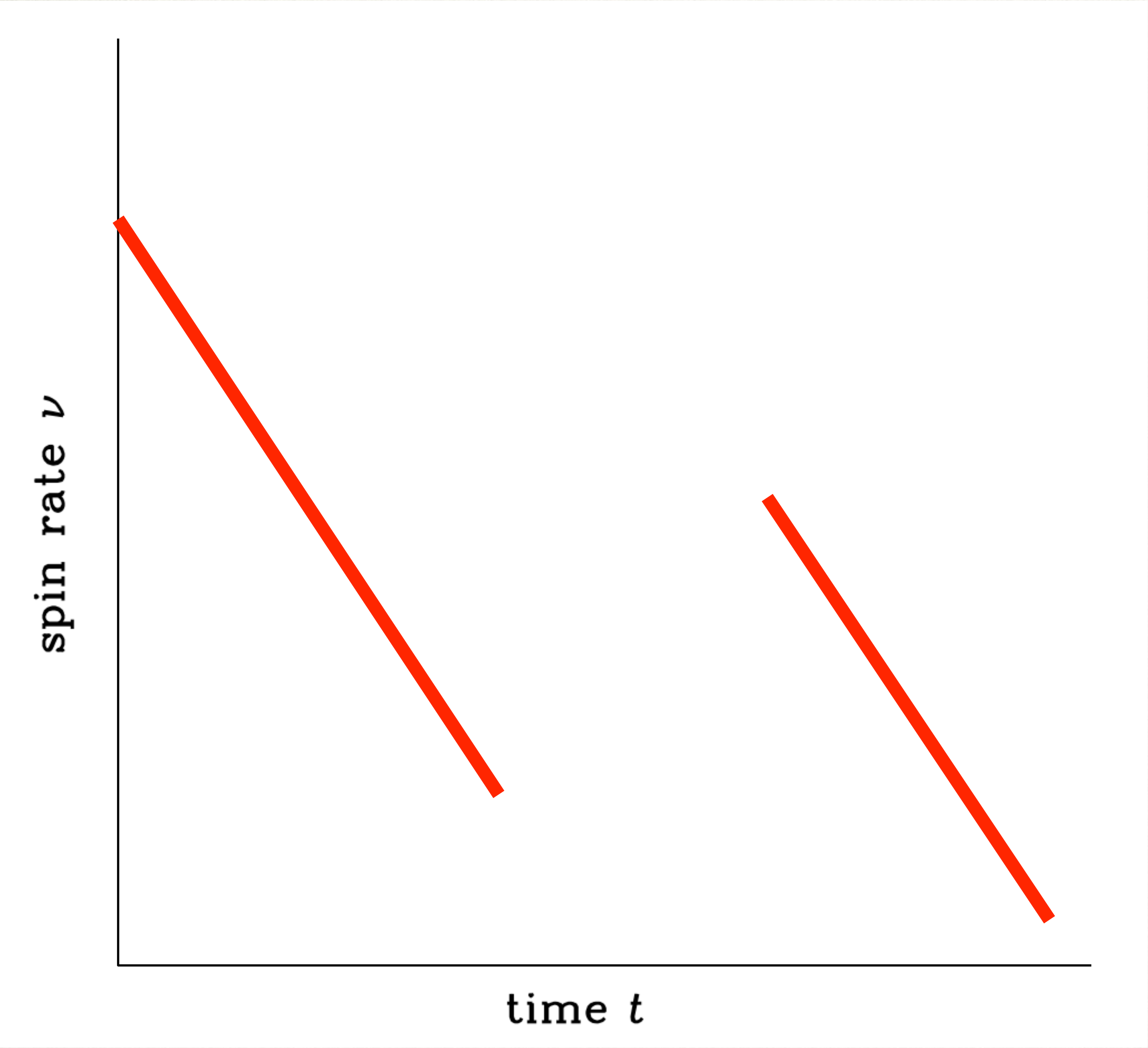
S/N ~ 5

Extra: Targeted searches (dual harmonics)



Glitches of pulsars: Unexpected jumps in the spin evolution

Side Note

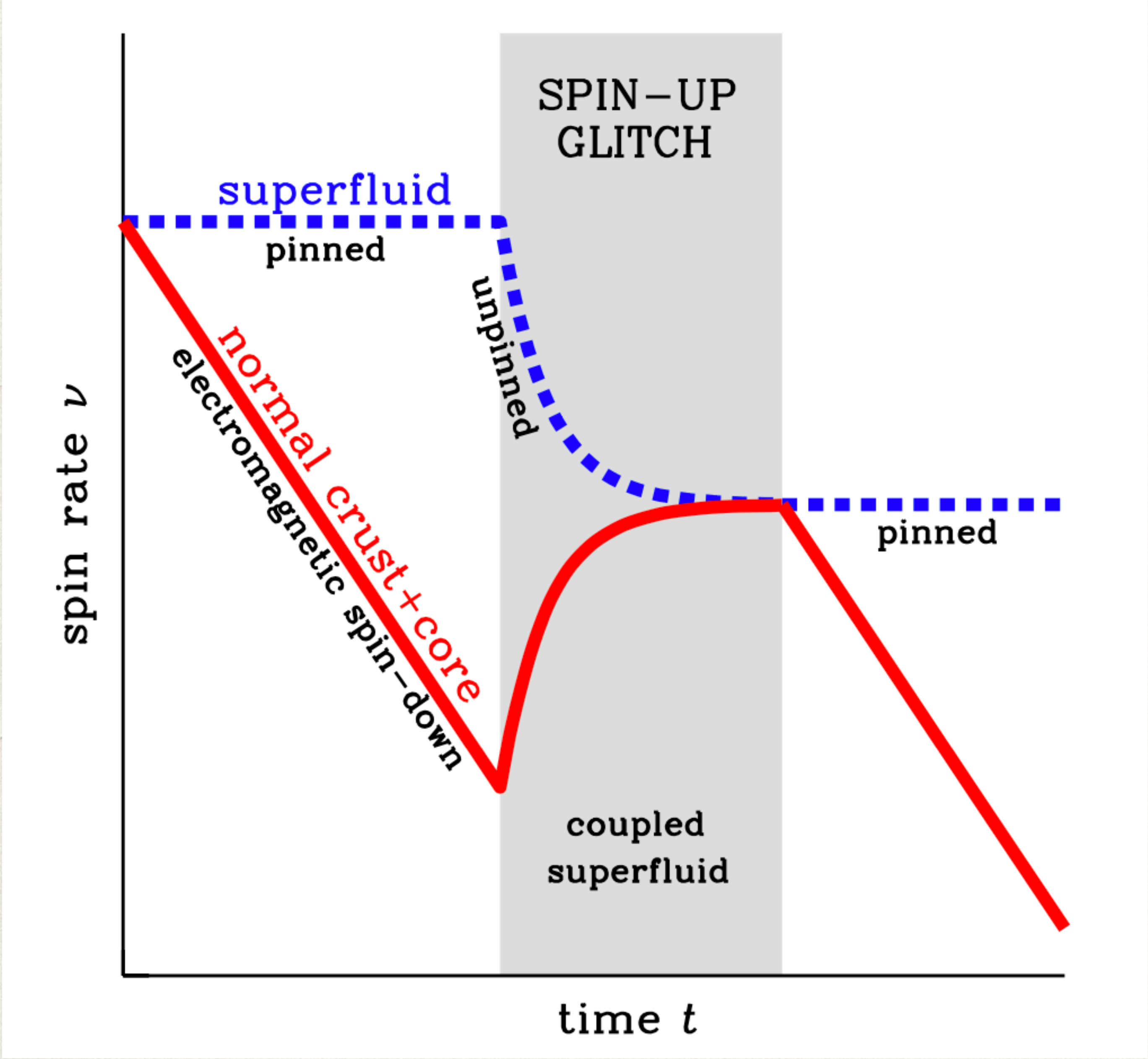


▬ EM measured spin rate of the neutron star, i.e., what we see

Glitches of pulsars: Unexpected jumps in the spin evolution

Side Note

Ray, Guillot et al. 2019



━━ EM measured spin rate of the neutron star, i.e., what we see

▪▪▪▪ Superfluid spin rate inside the neutron star, i.e., what we don't see

Glitches of pulsars: Unexpected jumps in the spin evolution

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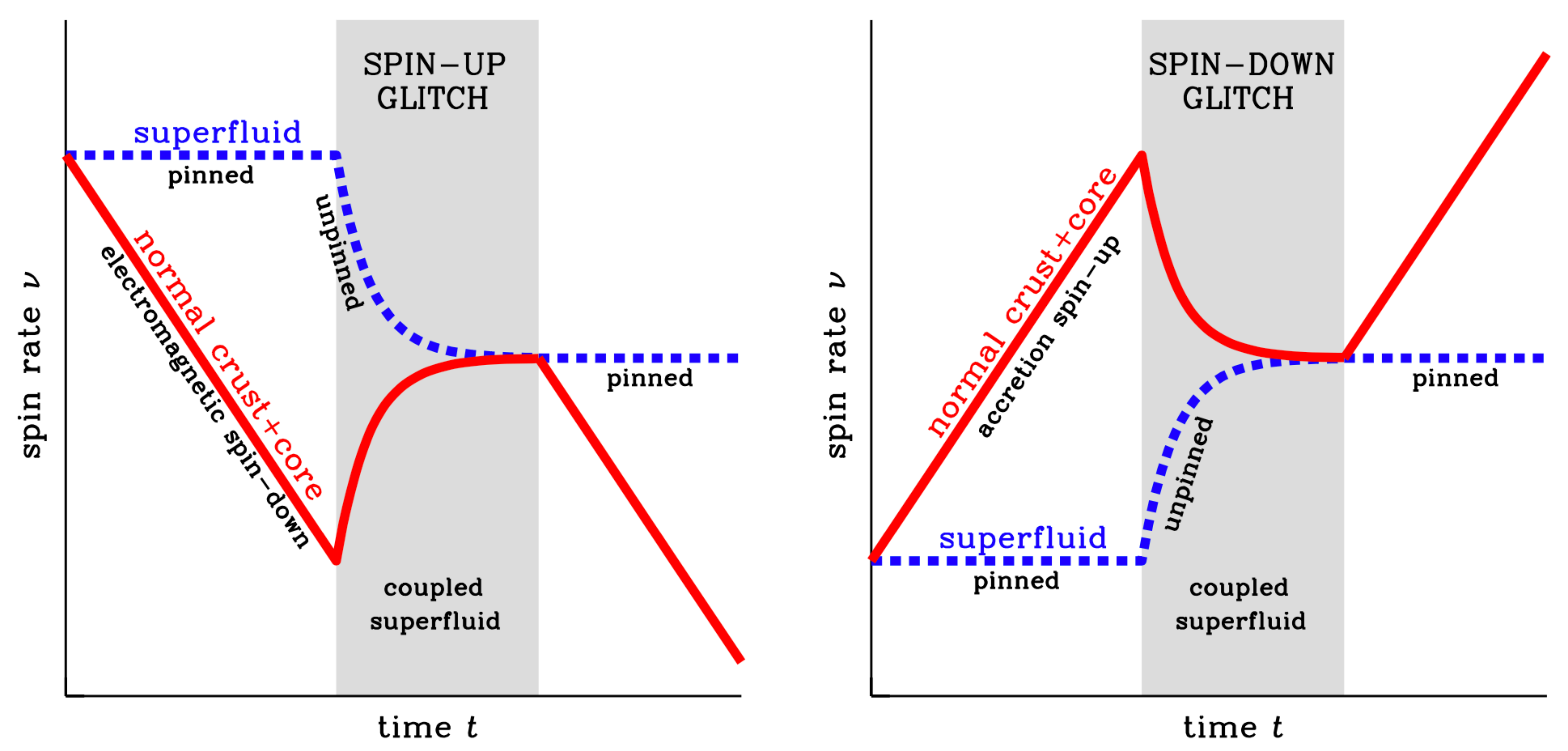
Ray, Guillot et al. 2019



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