A science goal for deci-Hertz gravitational wave detectors:

Relevance and detectability of low frequency Continuous Gravitational Waves

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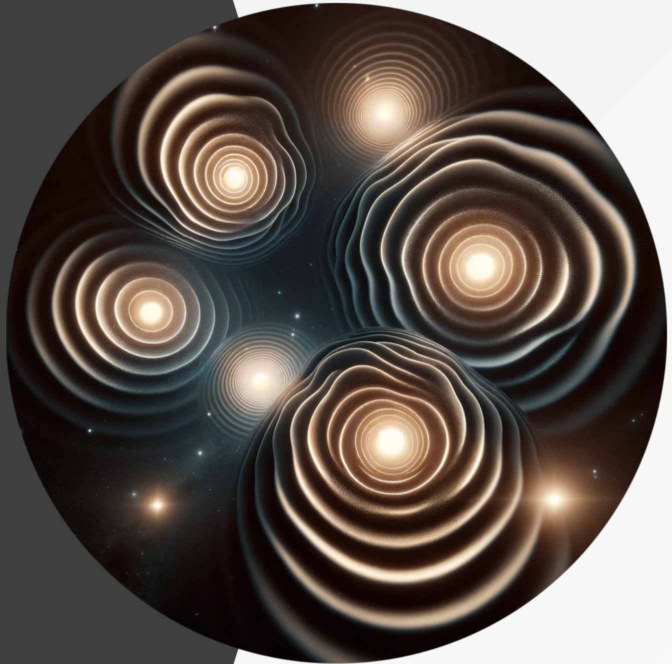
Max Planck Institute for Gravitational Physics, AEI Hannover

2nd Continuous Gravitational Waves and Neutron Stars workshop, Hannover.



Credits: DALL-E

Continuous Waves and their sources

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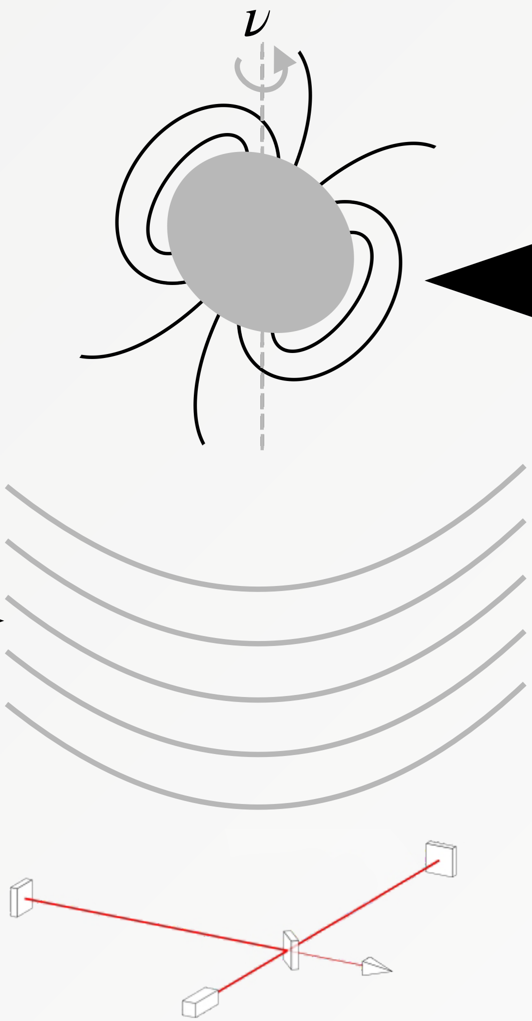

Non-axisymmetrically deformed Neutron Star

POSSIBLE CAUSES:

- strong internal magnetic field [1][2][3]
- crustal temperature anisotropy [4][5]
- accretion driven deformation [4][6][7]
- starquakes [8]

Quasi-monochromatic wave

$f_{GW} = 2 \cdot \nu$ and/or $f_{GW} = \nu$

[1] Chandrasekhar & Fermi, 1953, ApJ 118
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[3] Katz, 1989, MNRAS 239
[4] Bildstein, 1998, ApJL 501
[5] Ushomirsky et al., 2000, MNRAS 319
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[7] Melatos & Payne, 2005, ApJ 623
[8] Giliberti & Cambiotti, 2022, MNRAS 511

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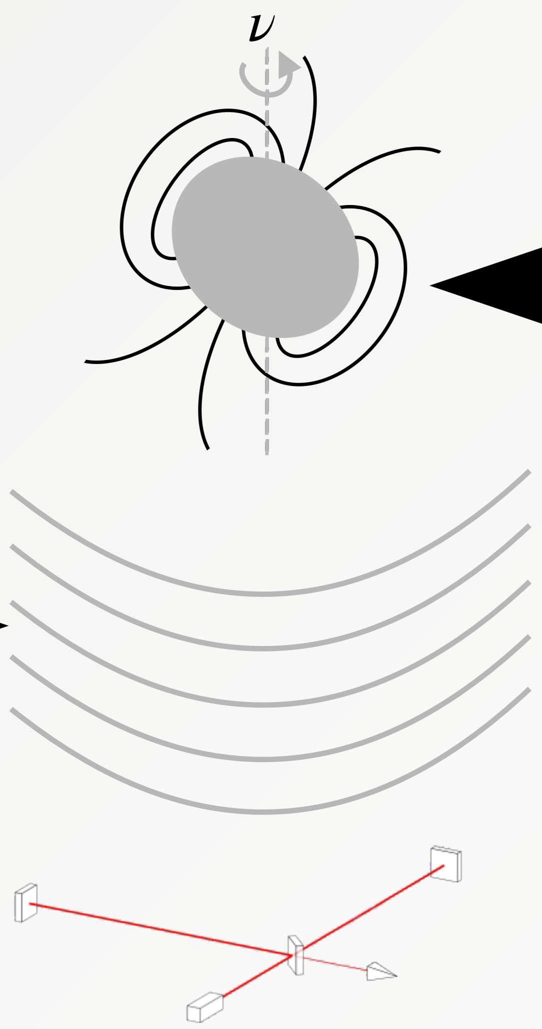

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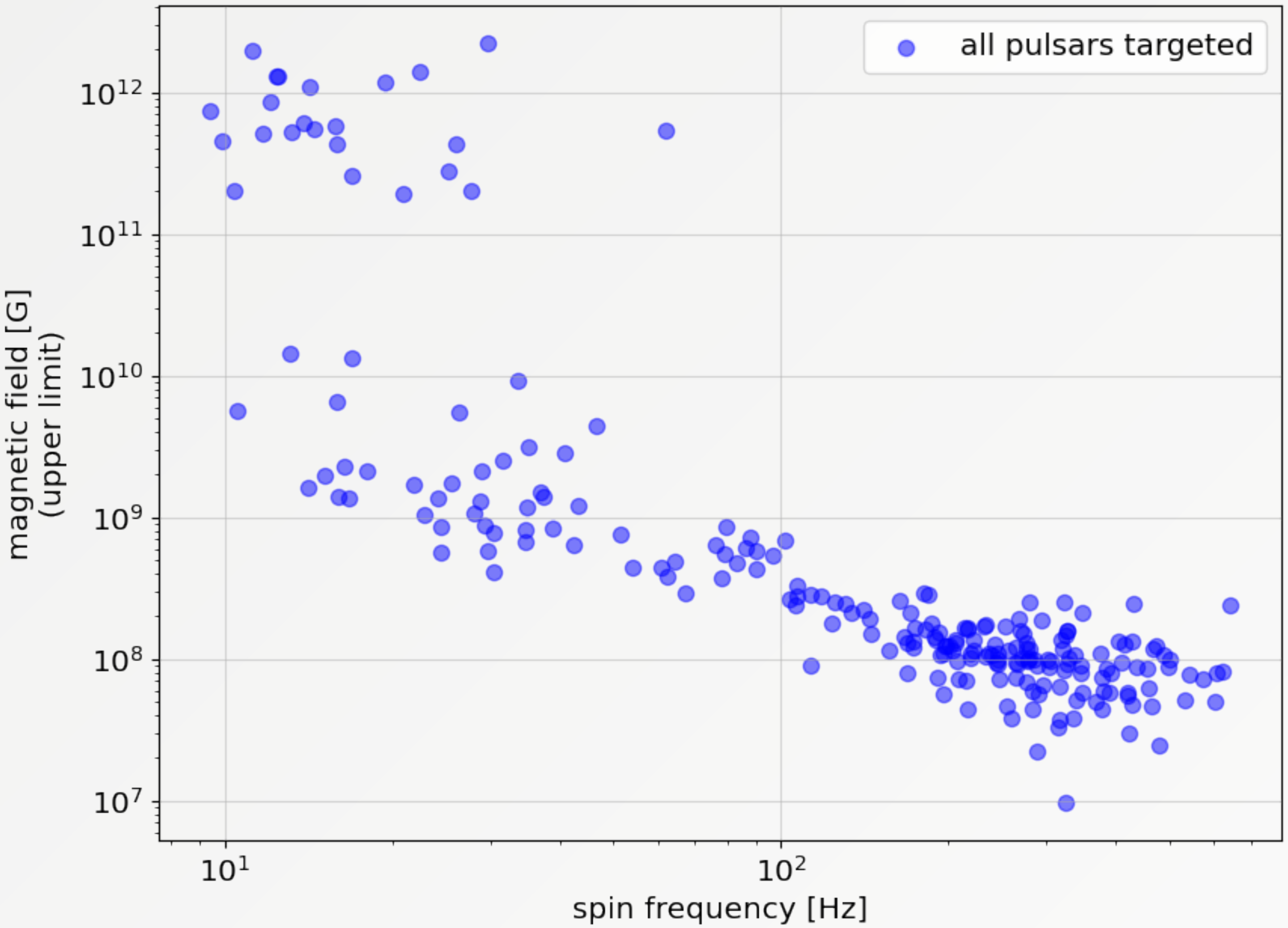
The simplest searches: emission from known pulsars

Pulsars in LIGO band



- NOT HIGHLY MAGNETISED SOURCES:
  - Magnetically induced deformations are too small to be detectable
  - Must hope for some other deformation mechanism

Searches routinely done

SEARCH FOR CWs

DETECTION

NO DETECTION

Estimate the weakest signal we can confidently rule out "Setting upper limits"

GW AMPLITUDE UPPER LIMIT: $h_0^{upper-limit} \longleftrightarrow$ deformation

Latest results

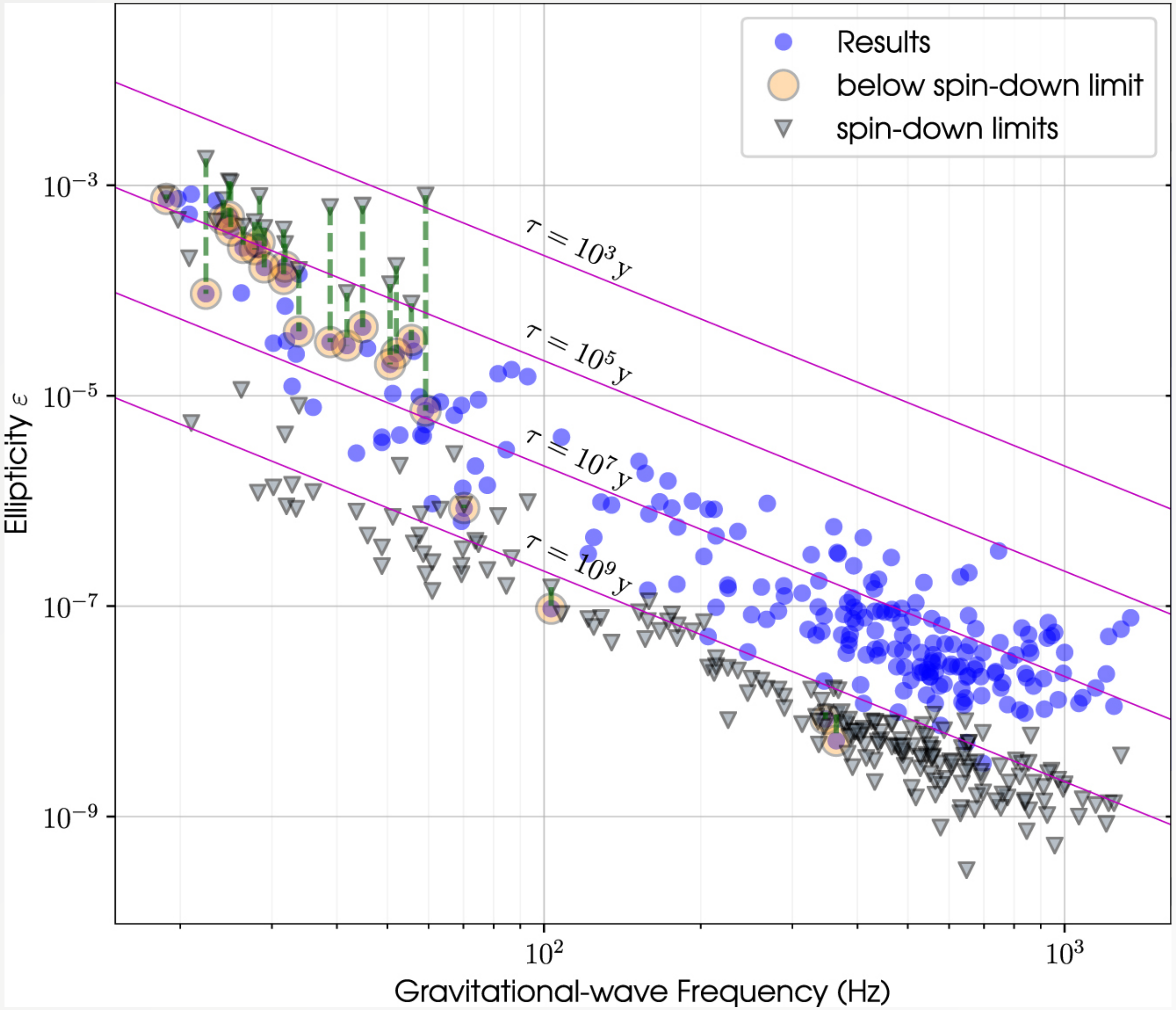
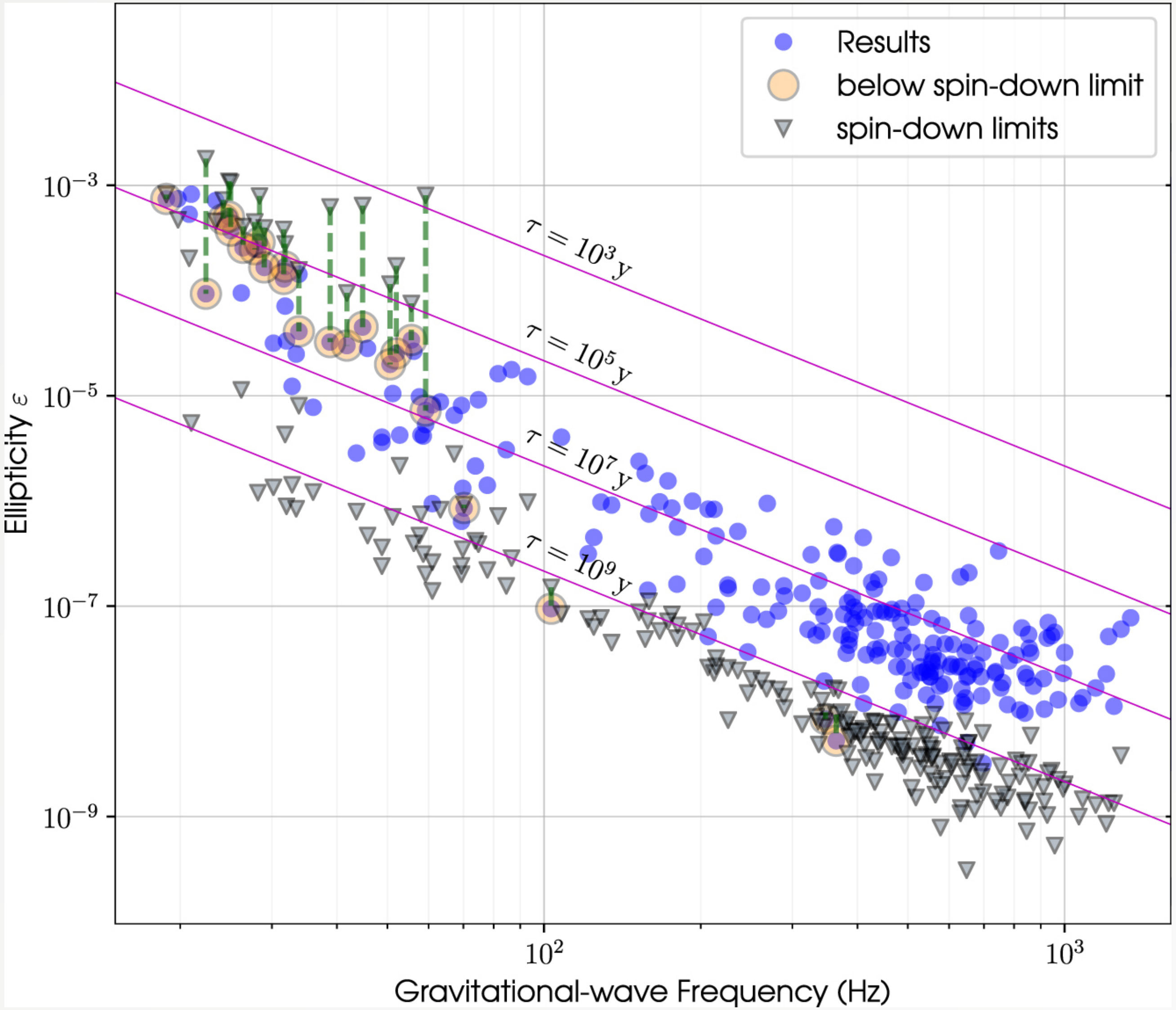


FIGURE 1: Targeted searches ellipticity results from Abbott R. et al. 2022 [9]

[9] Abbott R. et al., 2022, ApJ 935

L a t e s t r e s u l t s



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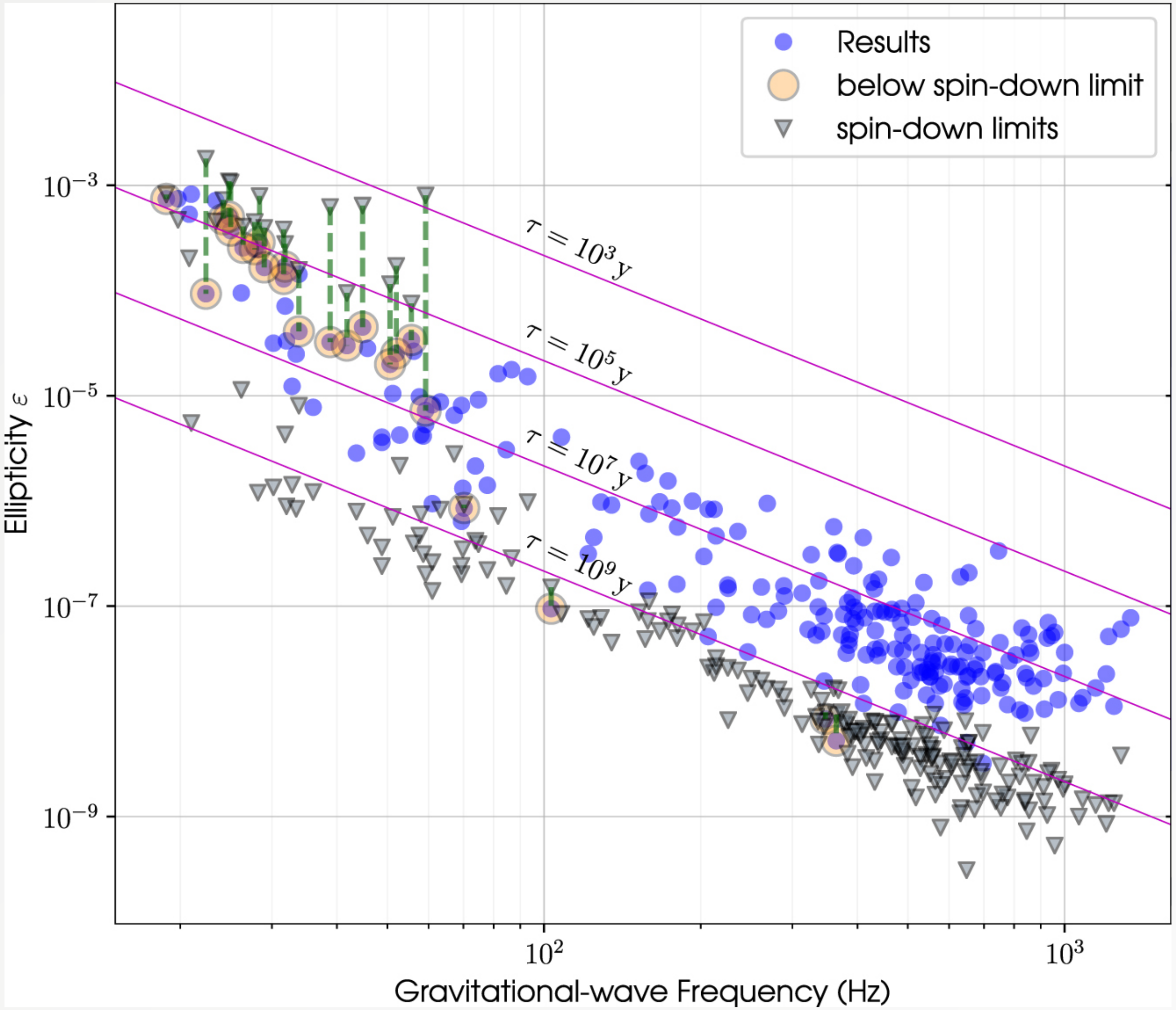

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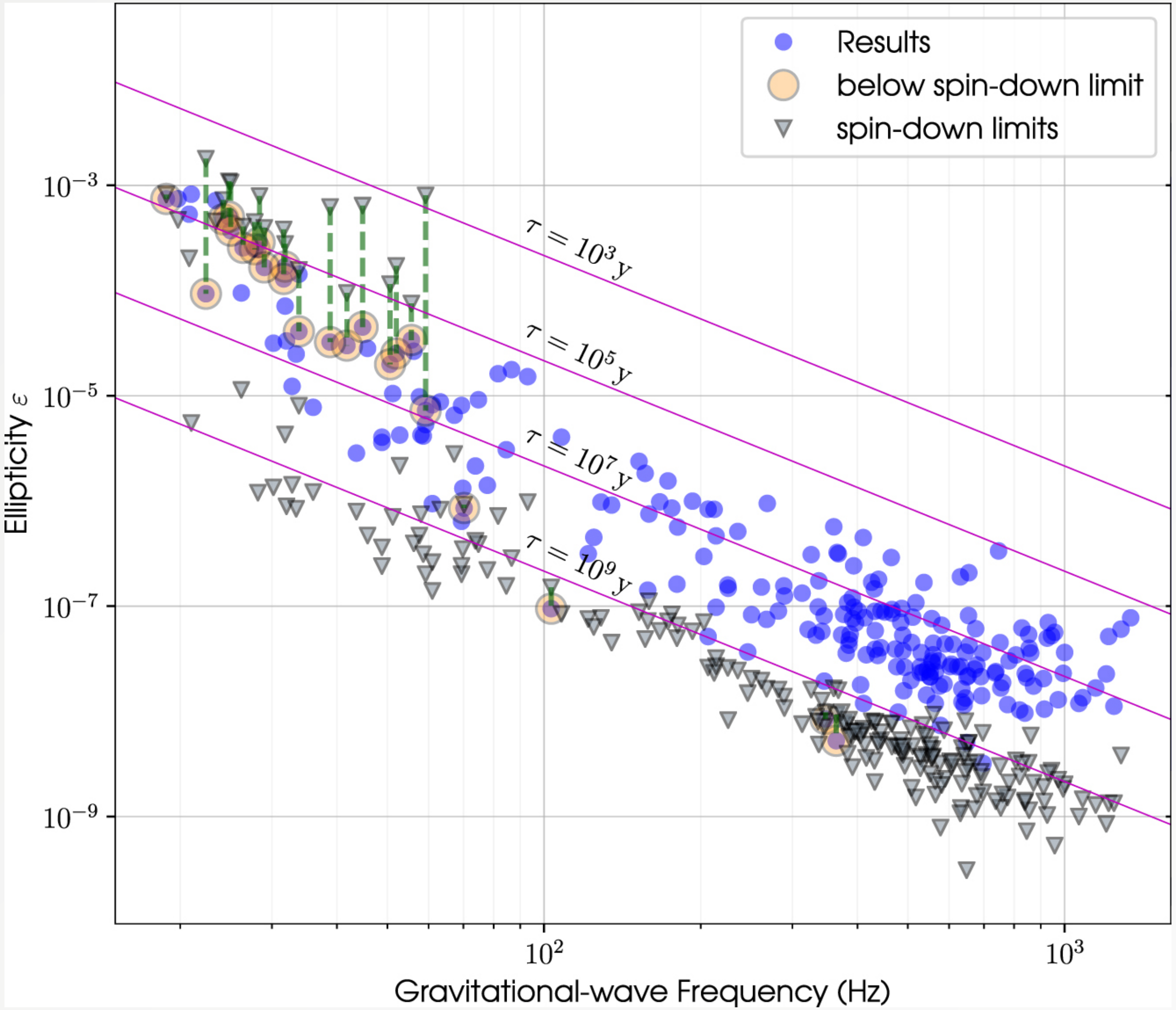

FIGURE 1: Targeted searches ellipticity results from Abbott R. et al. 2022 [9]

At first, deformation constraints look impressive.

However:

- For most pulsars the sensitivity is still not high enough (GW upper limit above spin-down upper limit)
- For most pulsars where GW upper limit is below the spin-down upper limit, ellipticity is very large and the relatively small magnetic field of these unlikely causes such deformations.

[9] Abbott R. et al., 2022, ApJ 935


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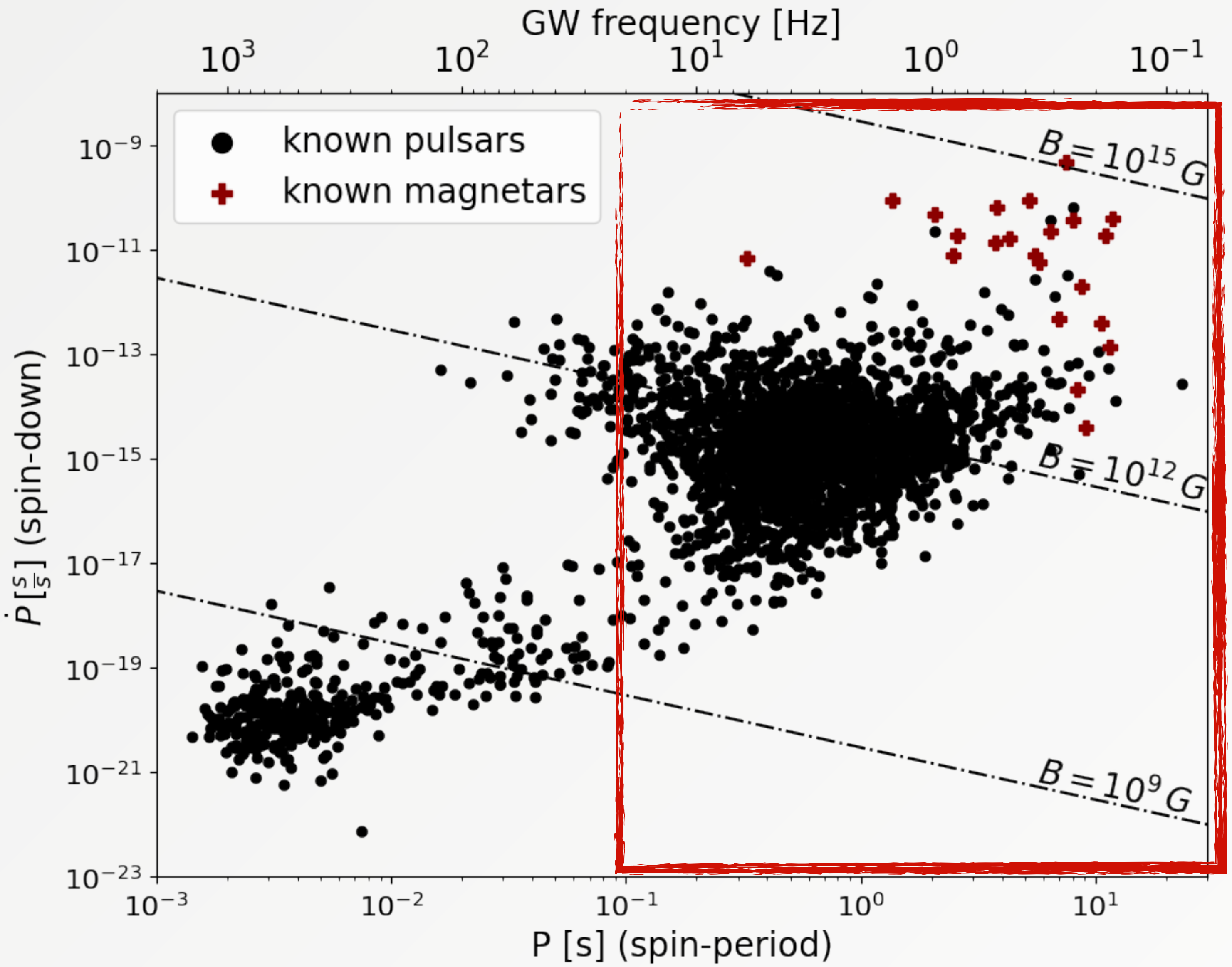
What if we could access the deci-Hz range?

The deci-Hz band



Two types of neutron stars:

- Evolved "LIGO-pulsars", $B \lesssim 10^{12} G$
- Highly magnetised sources, including magnetars

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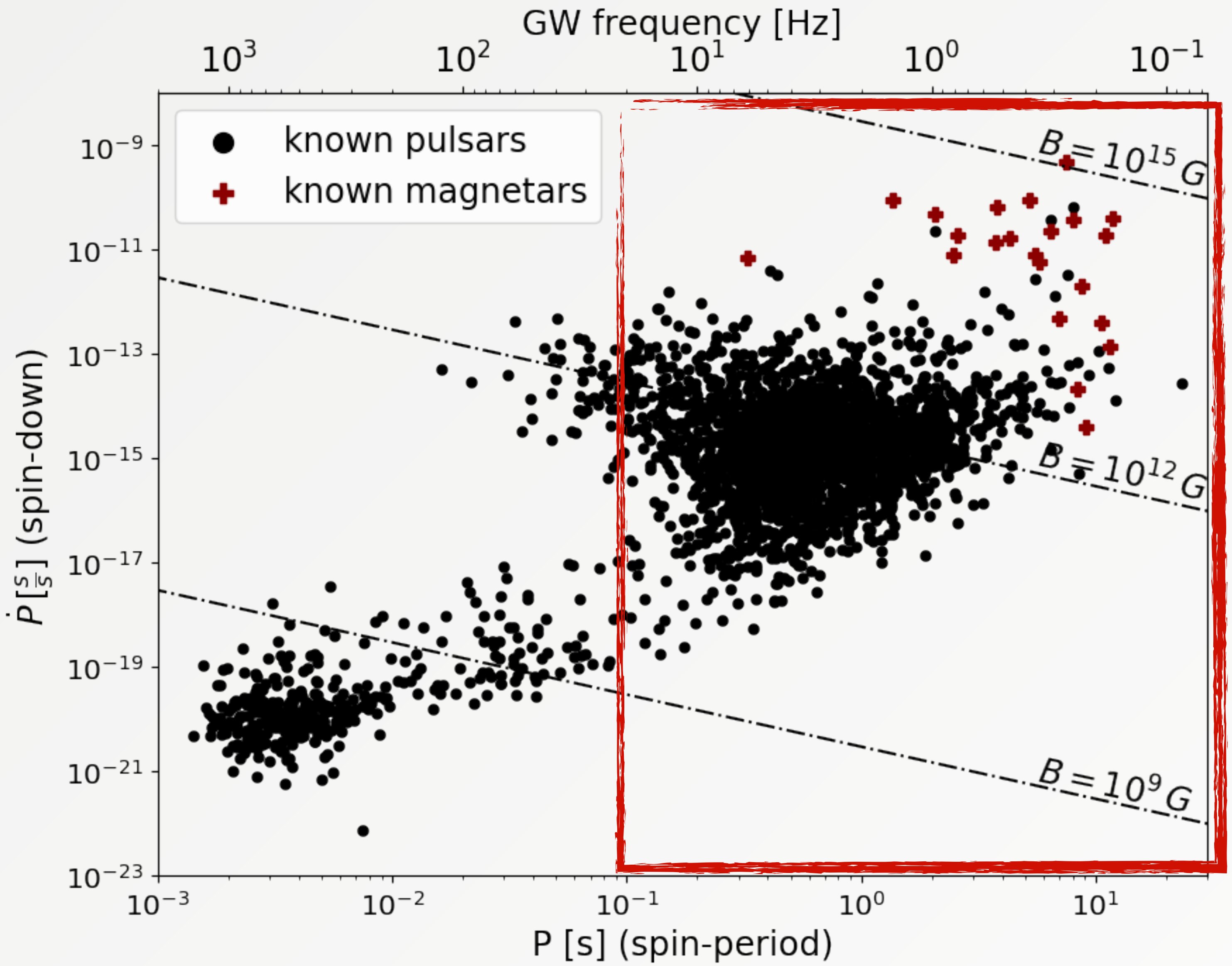

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✓ Observational evidence of highly deformed magnetars (4U 0142+61 [10], SGR 1806-20 [11], XTE 1810-197 [12], $\varepsilon \approx 10^{-4}$)

[10] Makishima et al., 2014, ApJL 112
[11] Makishima, Uchida, Enoto, 2024, arXiv:2404.13799
[12] Desvignes et al., 2024, Nature Astronomy

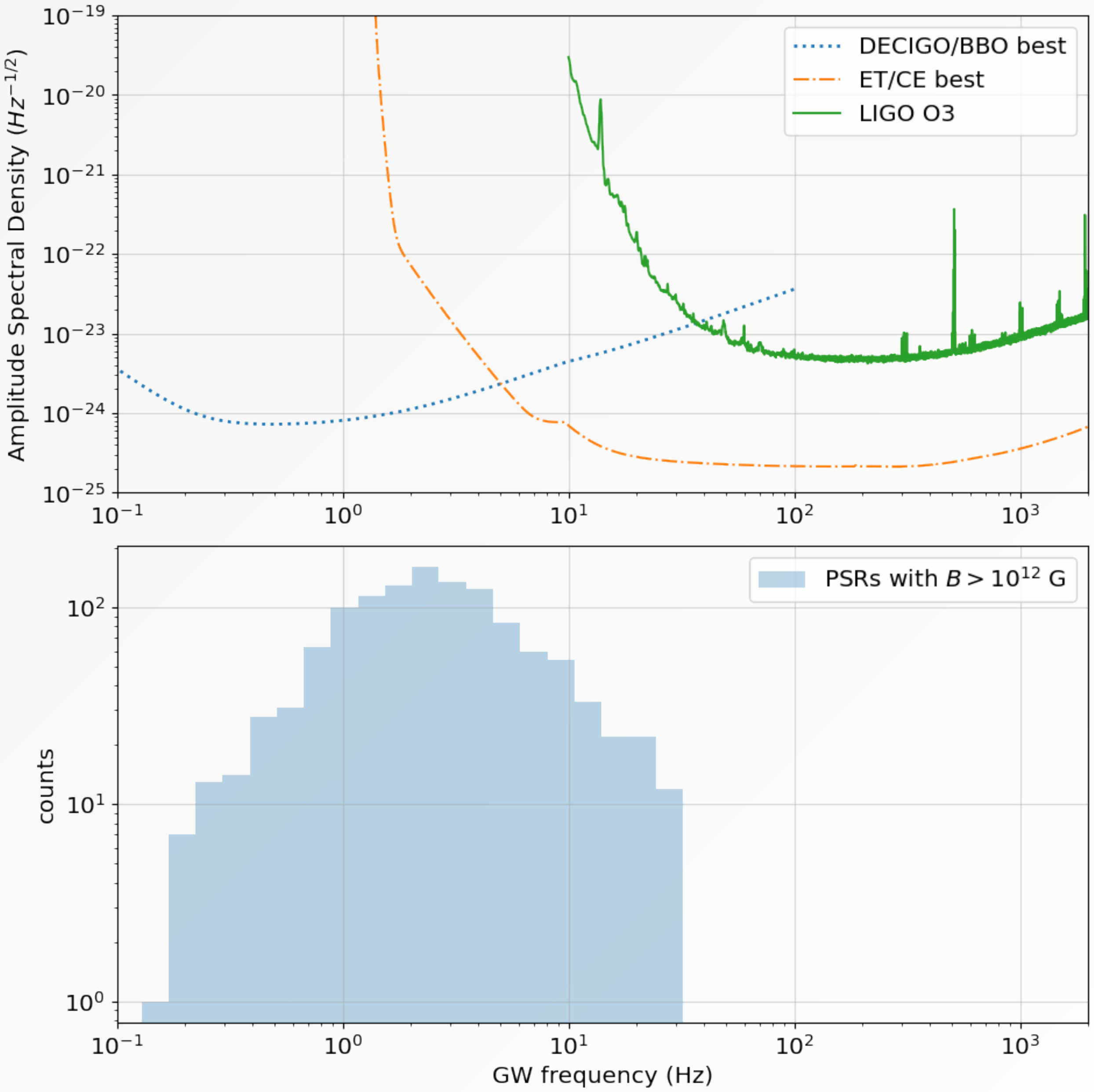
I n s t r u m e n t s

Ground Based Facilities:

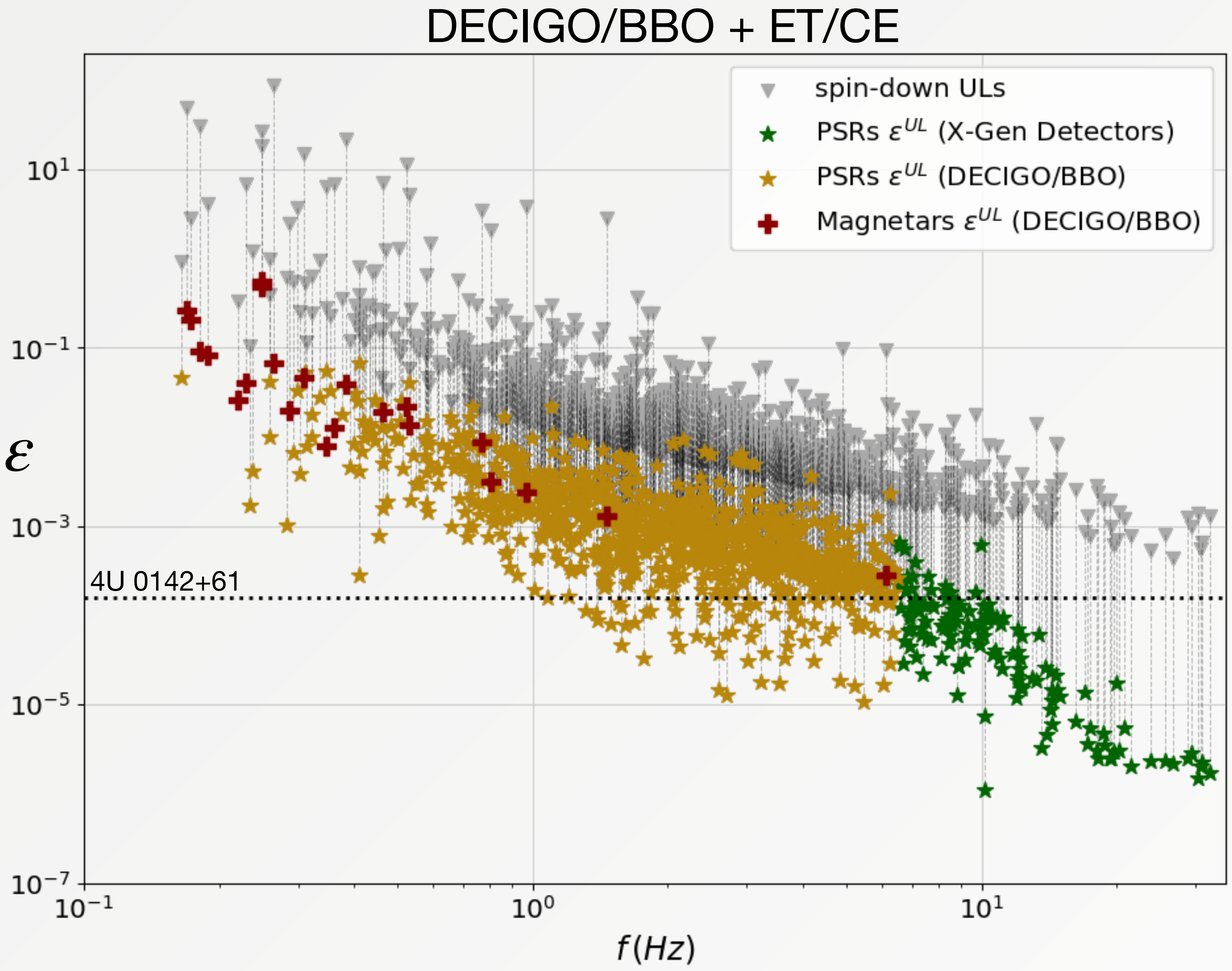
- **EINSTEIN TELESCOPE**:
  equilateral triangle configuration
- **COSMIC EXPLORER**:
  40km single detector configuration

Space Based Facilities:

- **DECIGO/BIG BANG OBSERVER**:
  4 spacecrafts configuration



Surveying the deci-hertz band



- For ~ 90 % of pulsars with $B > 10^{12}$G $\varepsilon^{ul} < \varepsilon^{sd}$ (currently true for only 24 pulsars)
- ~ 800 pulsars would have their power emitted in CWs constrained to $\lesssim 1\,\%$ (currently true for only 2 pulsars)
- Access to the magnetar population:
  - J1846-0258 (Kes 75 magnetar) detectable if $\varepsilon \approx 3 \cdot 10^{-4}$ consistent with 4U 0142+61 measurement.

Data used:
[13] ATNF Catalogue: Manchester et al., 2005, Astron. J. 129
[14] McGill Magnetar Catalogue: Olausen & Kaspi, 2014, ApJS 212
[15] Jodrell Bank Glitch Catalogue: Espinoza et al. 2011, MNRAS 414

Probing internal magnetic fields

From [16]:

$$\varepsilon(B,\Lambda) \approx 1.3 \times 10^{-5} \left(\frac{B}{5 \cdot 10^{14} G}\right)^2 \left(1 - \frac{0.4}{\Lambda}\right)$$

Where

$$\Lambda = \frac{\text{energy stored in poloidal component}}{\text{total magnetic energy}}$$

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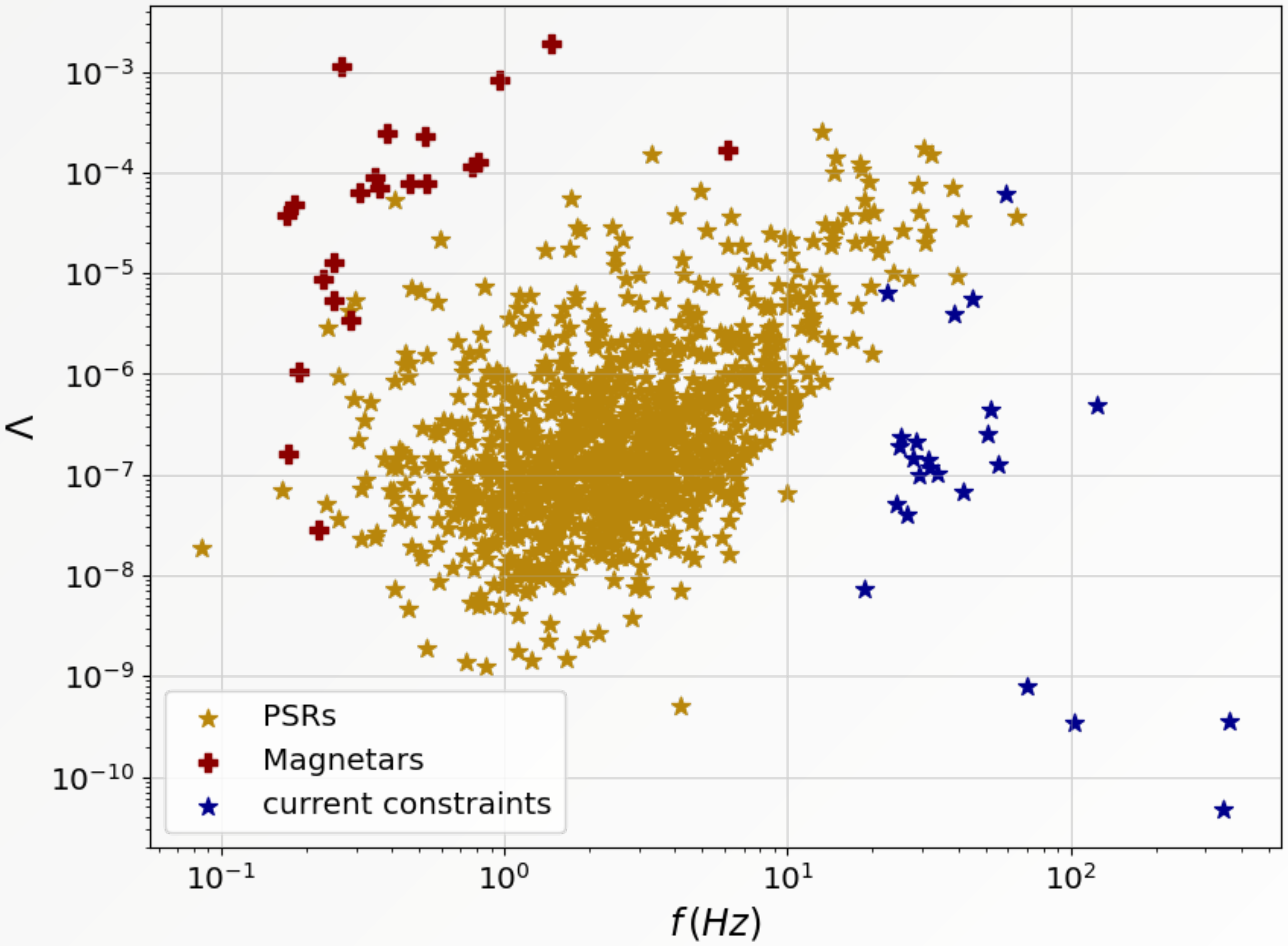

[16] Mastrano et al., 2011, MNRAS 417


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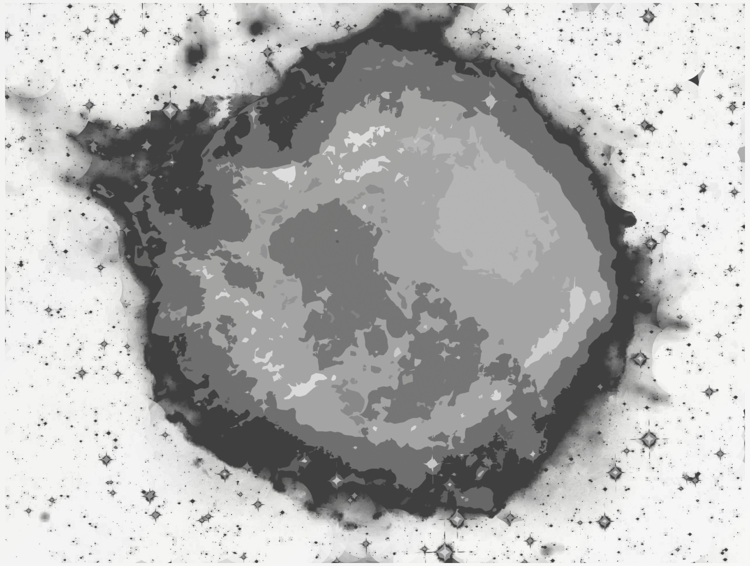
What else at low frequencies?

Central Compact Objects in SNRs



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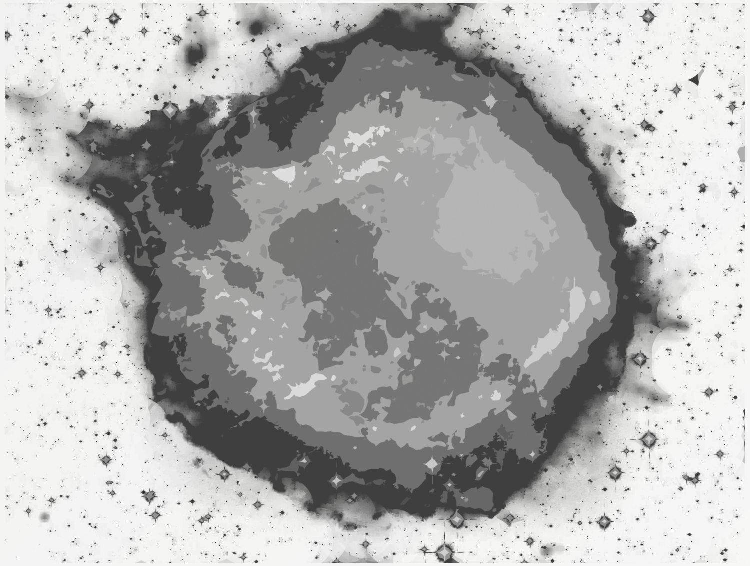

- 10 known CCOs in SNRs [17]
  - 3 of which show pulsations
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[17] De Luca, A., https://www.iasf-milano.inaf.it/~deluca/cco/main.htm

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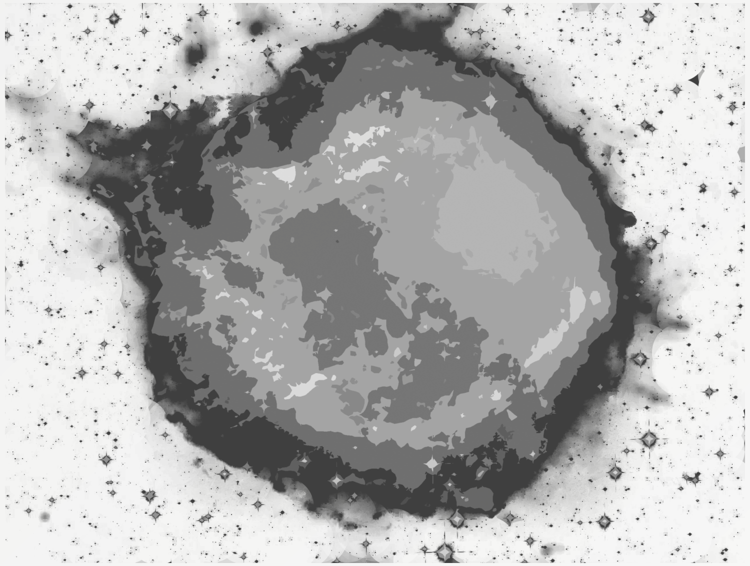

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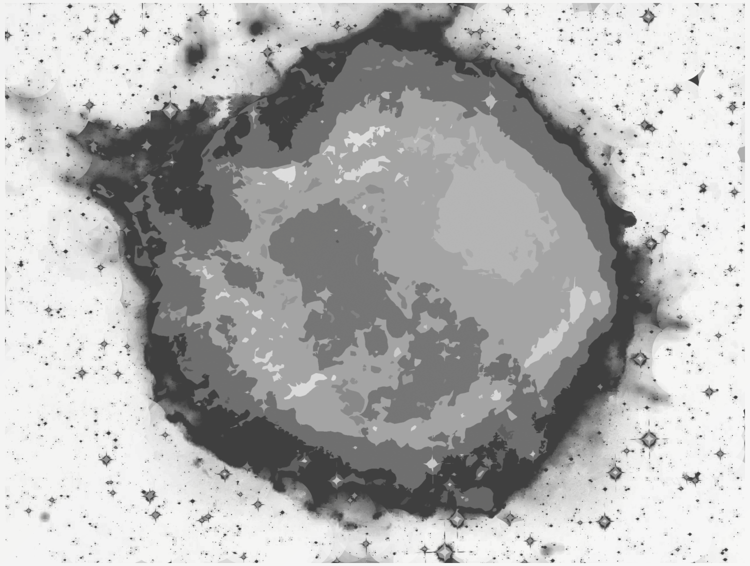

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  - Satisfactory explanation for temperature anisotropies
  - Reasonable amount of accreted mass can account for burial of 10^{14} G field in $\approx 10^5$ yr.

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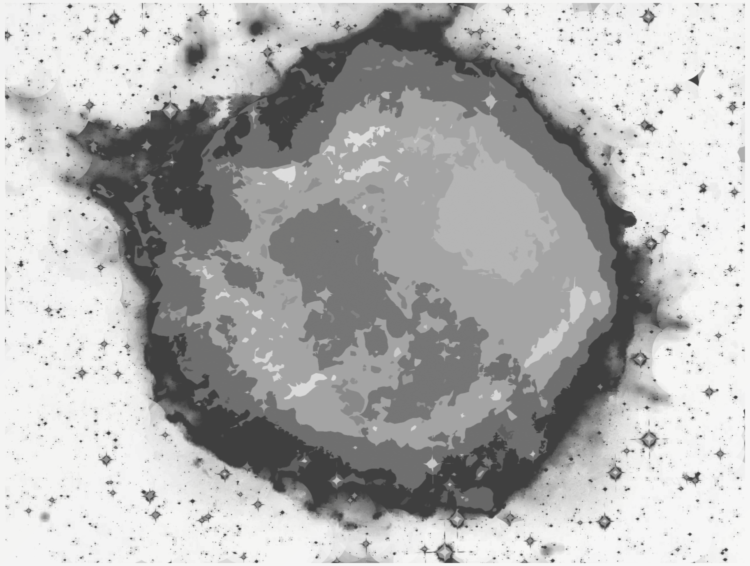

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- "Hidden magnetars"[19]?

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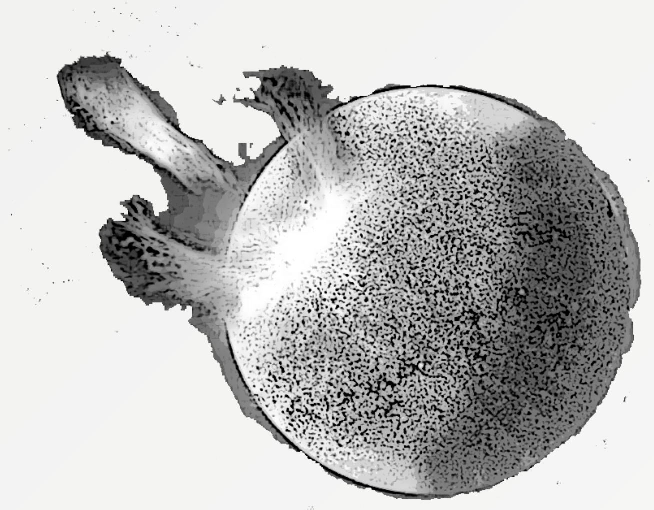
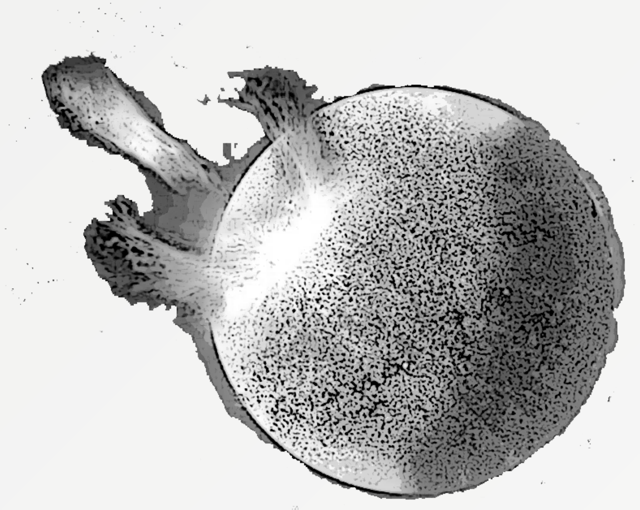
[18] De Luca, 2017 A., J. Phys. Conf. Ser. 932
[19] Geppert et Al., 1999, A&A, 345

Glitching pulsars





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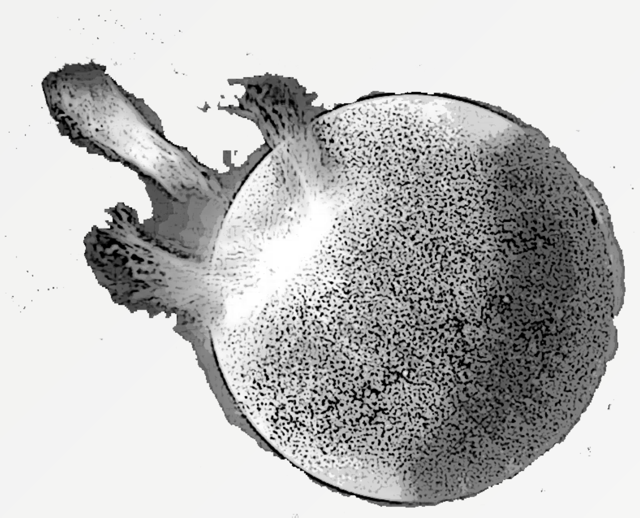

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[21] Prix, R. et Al., 2011, PhRvD, 84

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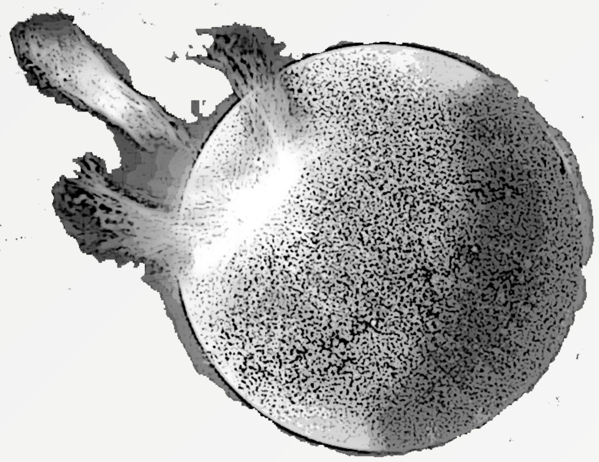

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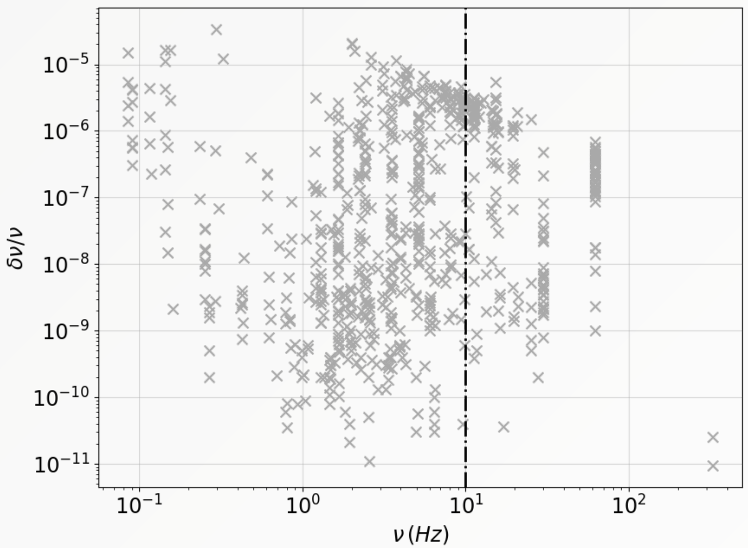
- ~ 250 pulsars (or magnetars) have been glitched at least once
  - ~ 75% of currently recorded glitches fall outside current band



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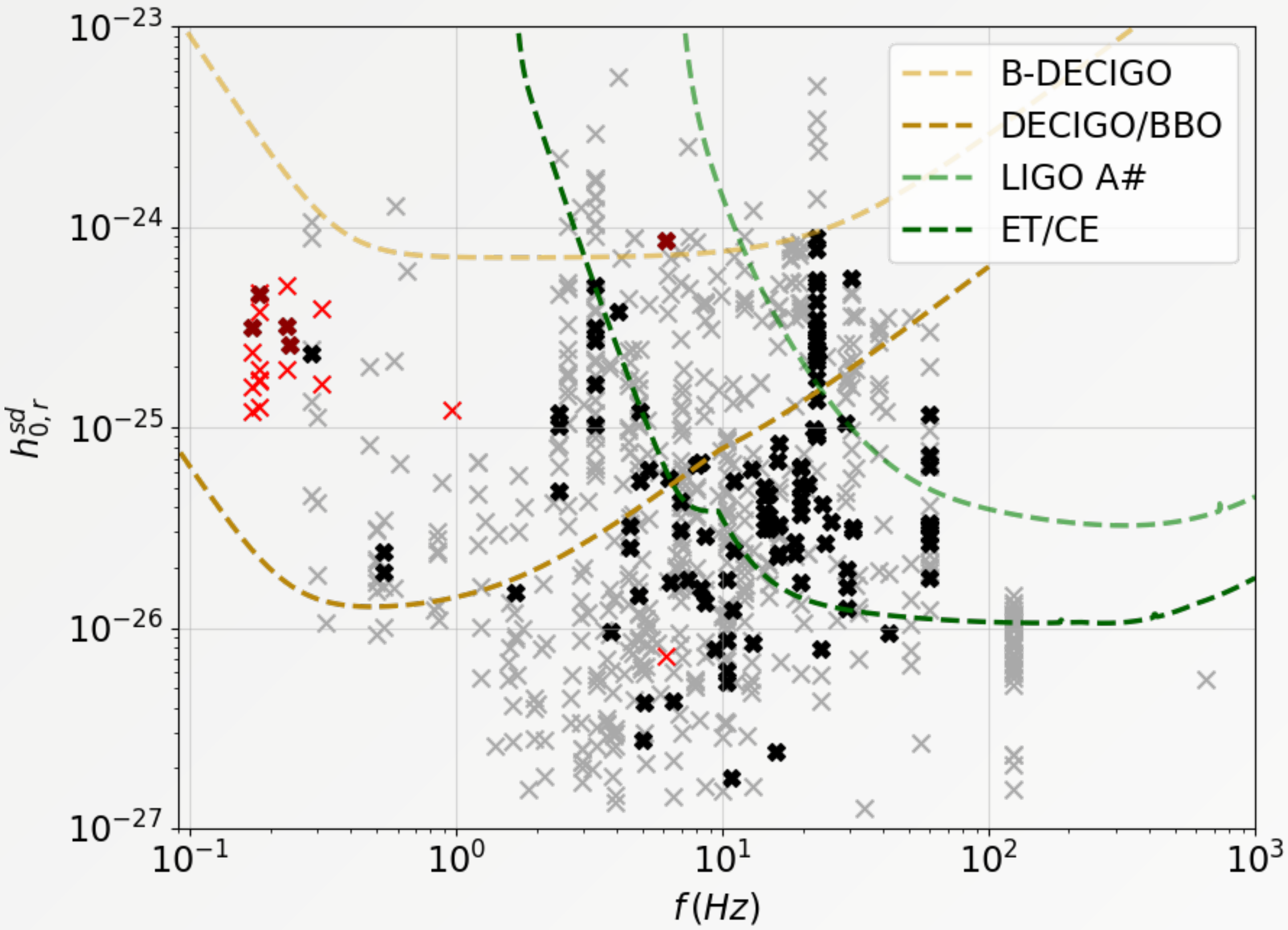


We adapt sensitivity depths as calculated by Moragues et Al. [22]

B-DECIGO	LIGO A#	DECIGO/BBO	ET/CE
3.9%	12%	39.6%	41.4%

TABLE: Fraction of glitches in principle detectable based on superfluid amplitude upper limit calculations.

[22] Moragues J., et Al., 2023, MNRAS, 519

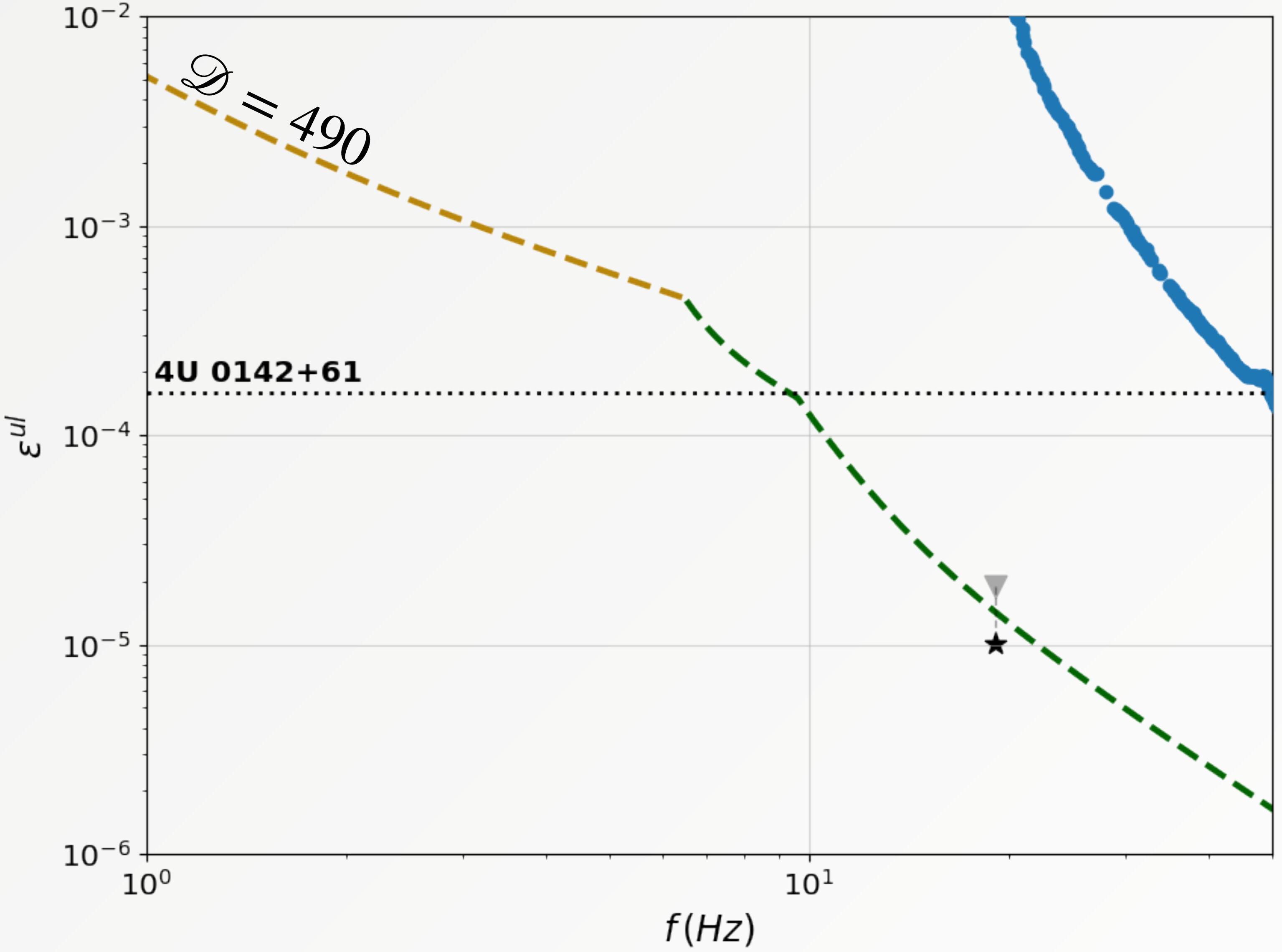
SUMMARY

- Survey the low frequency band is necessary to open-up to highly magnetised sources
- Deformations for such sources need minimal and plausible assumptions
- Highly magnetised sources show observational evidence of deformations
- Low frequency CWs may help understand puzzling phenomenology (CCOs, Glitches)
- Continuous Waves constitute a valid science goal for DECIGO/BBO

THANKS.

EXTRAS

Extra slides



In [17], Mastrano, Suvorov and Melatos consider higher order multipoles.

They apply their model to magnetar SGR 0418+5729.

This magnetar has inferred upper value dipolar field [18]

$B_{dip} \lesssim 7.6 \times 10^{12}$ G.

Using results from [19] who find evidence of higher order multipoles, they obtain:

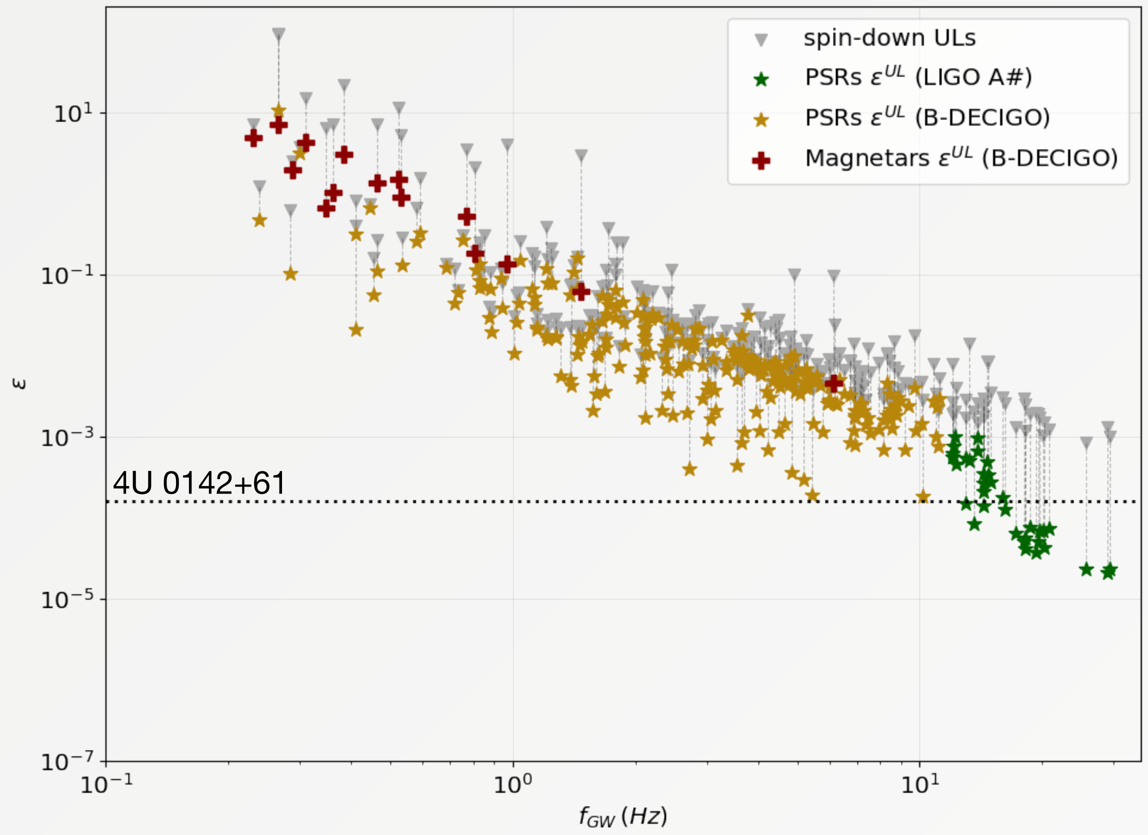
$$\varepsilon(B, \Lambda) \approx 1.7 \times 10^{-1} \left(\frac{B}{5 \cdot 10^{14} G} \right)^2 \left(\frac{\Lambda - 1 + 7 \cdot 10^{-4}}{\Lambda} \right)$$

For $\Lambda \approx 0.4 \ \rightarrow \ \varepsilon \approx 10^{-4}$

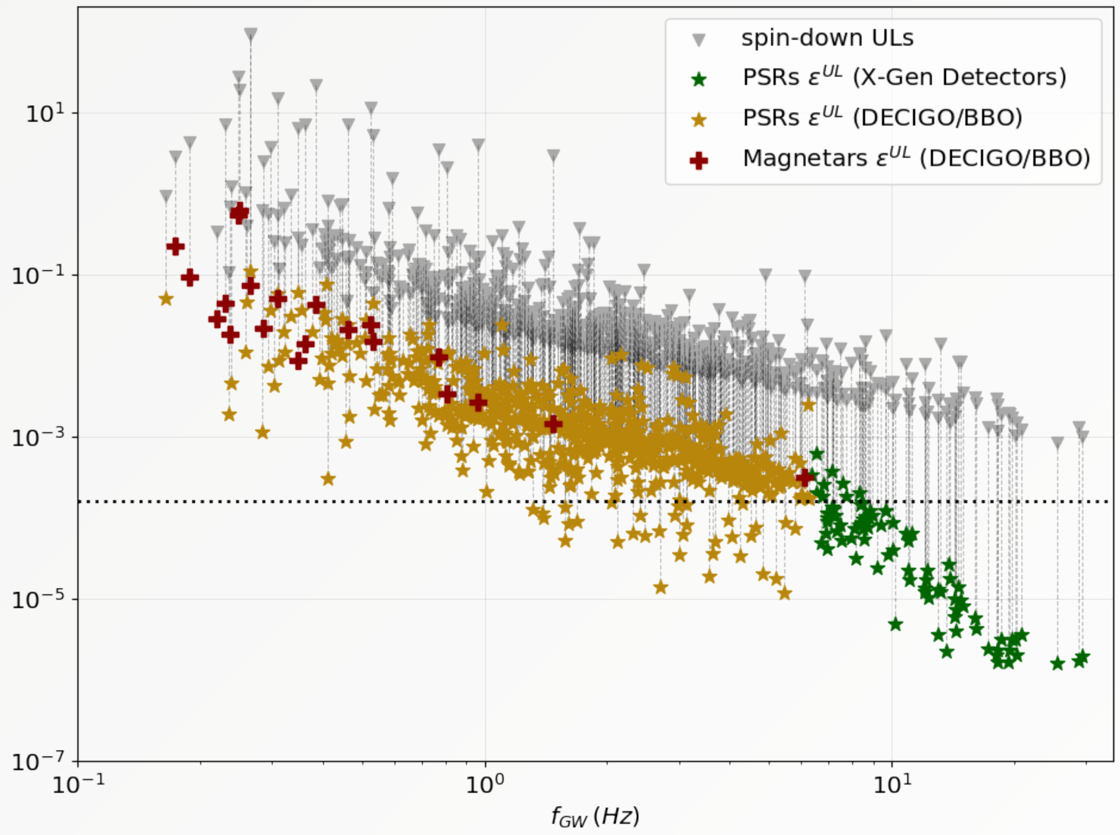
[17] Mastrano, Suvorov, Melatos, 2015, MNRAS 447
[18] Rea et al., 2010, Science 330
[19] Güver, Göğüş, Özel, 2011, MNRAS 418

E x t r a s l i d e s

CLOSE FUTURE PROSPECTS
(B-DECIGO + LIGO A#)



FAR FUTURE PROSPECTS
(DECIGO/BBO + ET/CE)



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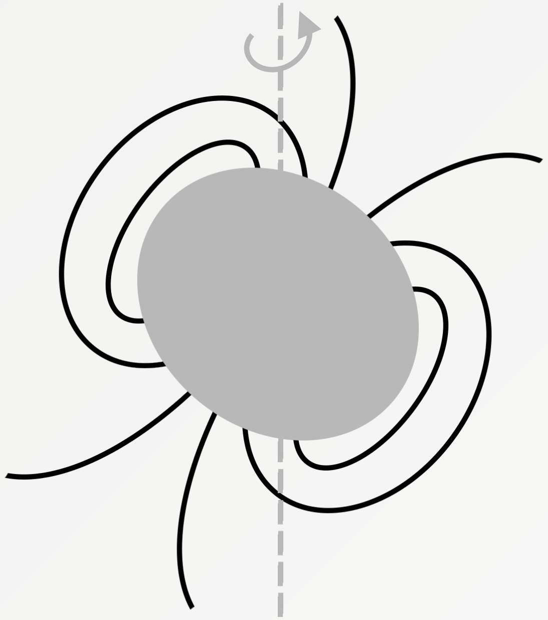
$$\dot{E}_{rot-kin} = 4\pi^2 I \nu \dot{\nu}$$



IF ALL ROTATIONAL KINETIC ENERGY GOES INTO CWs

$$\varepsilon^{sd} \propto \sqrt{\frac{|\dot{\nu}|}{\nu^5}}$$

Extra slides