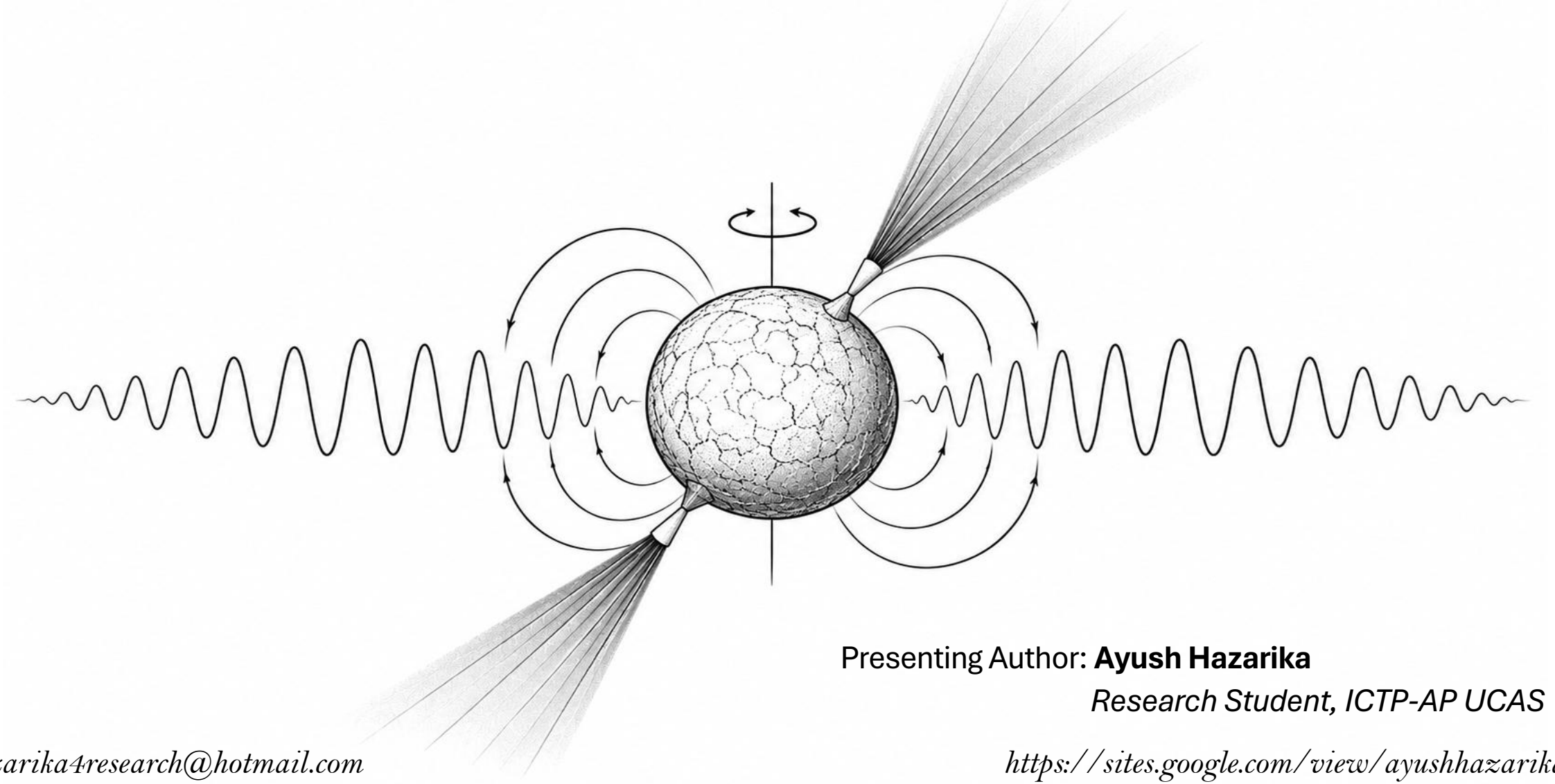
BRICS-AGAC Symposium 2026
November 6-10, 2026

A continuous wave window into neutron star structure

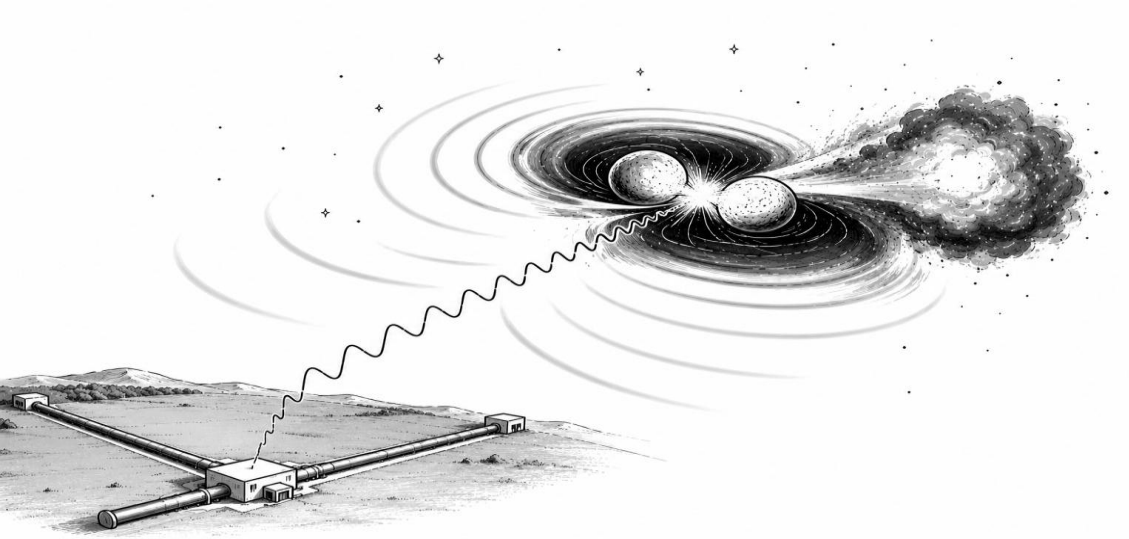


Presenting Author: **Ayush Hazarika**
Research Student, ICTP-AP UCAS

hazarika4research@hotmail.com
https://sites.google.com/view/ayushhazarika

GW170817

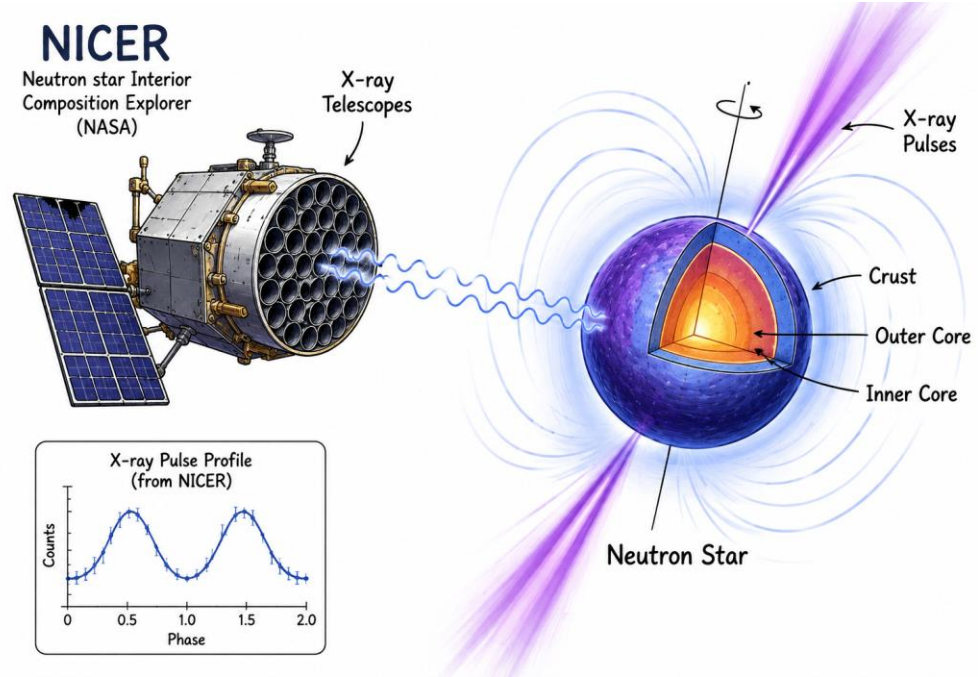
Measured - the tidal deformability during the late inspiral

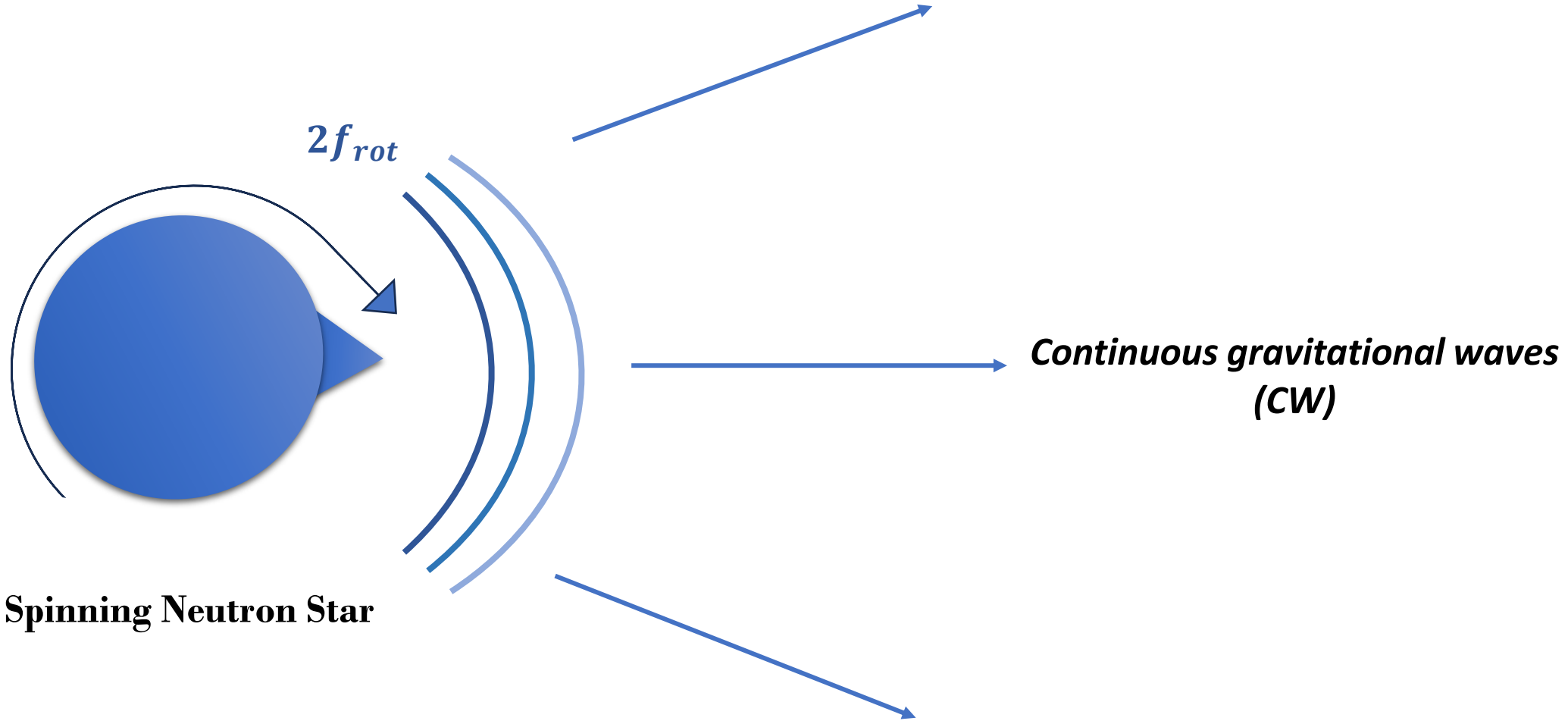


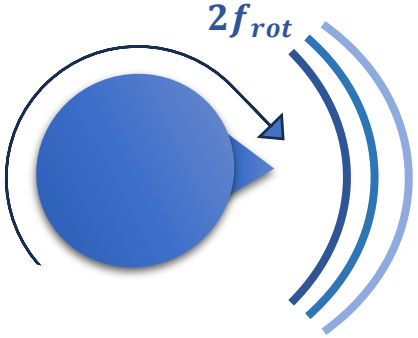
Neutron star Interior Composition Explorer (NICER)

Relativistically distorted X-ray pulses from surface hot spots

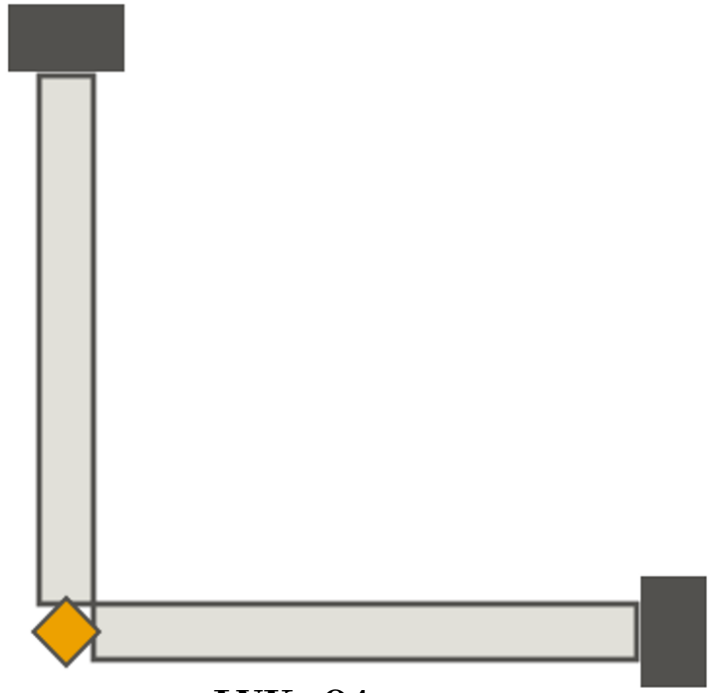
X-ray timing instrument on the ISS




$2f_{rot}$
Continuous gravitational waves (CW)
Spinning Neutron Star







LVK- O4a run

No detection → 95% UL on h_0

The Astrophysical Journal, 983:99 (34pp), 2025 April 20 https://doi.org/10.3847/1538-4357/adb3a0
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OPEN ACCESS

Search for Continuous Gravitational Waves from Known Pulsars in the First Part of the Fourth LIGO-Virgo-KAGRA Observing Run

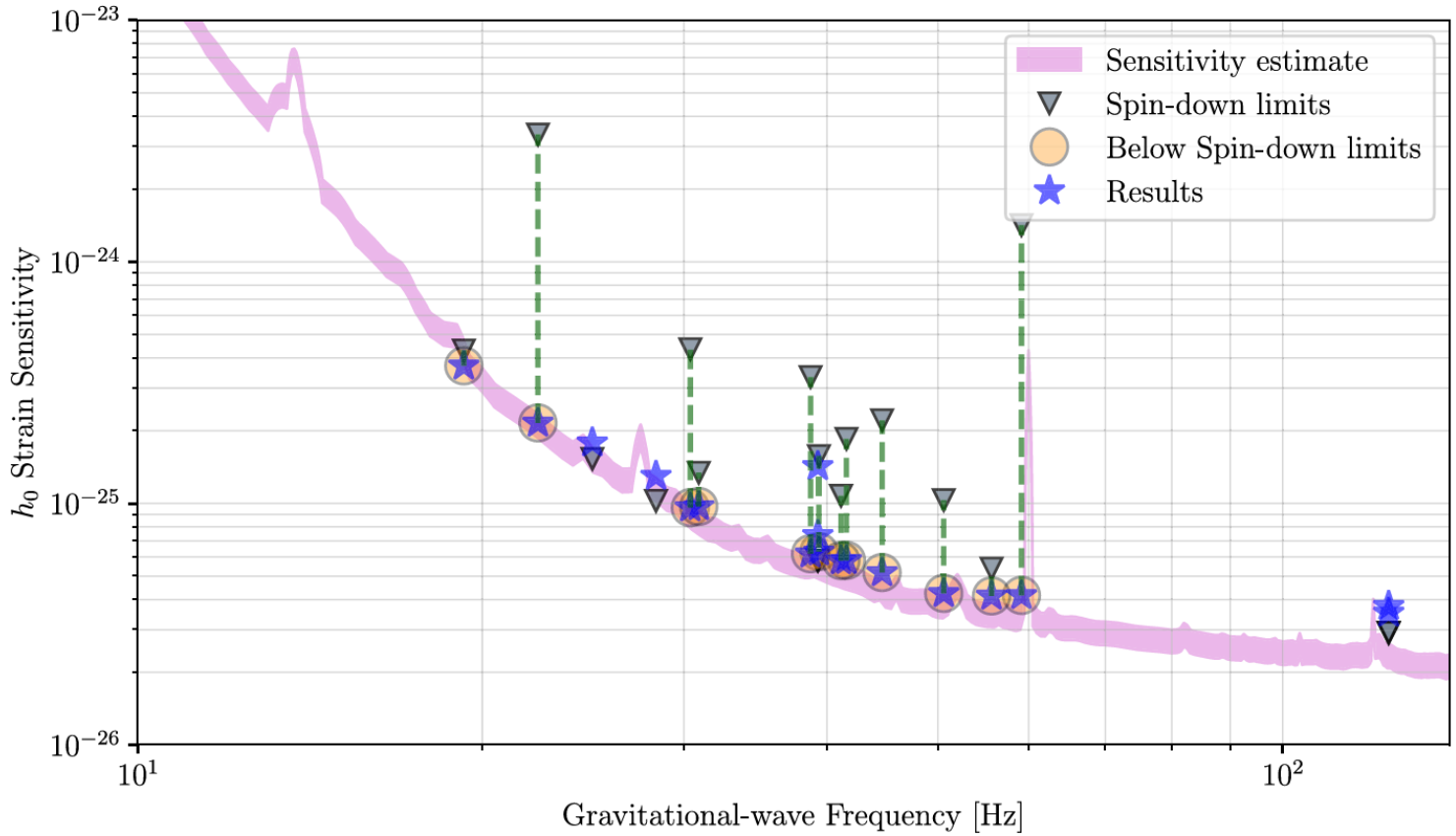
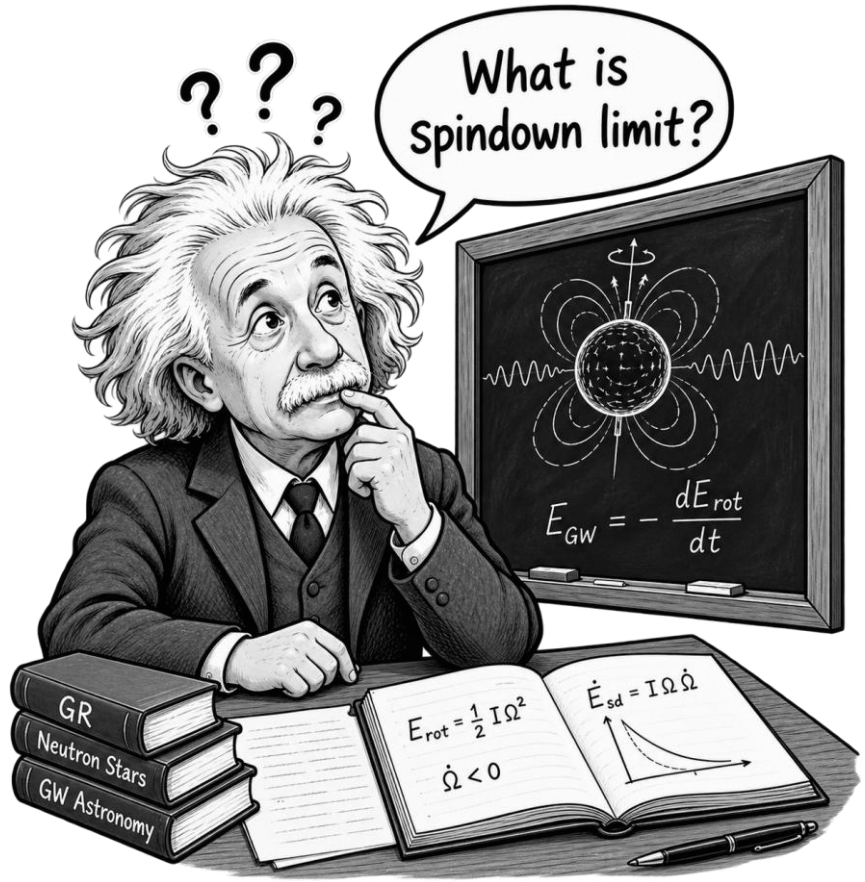
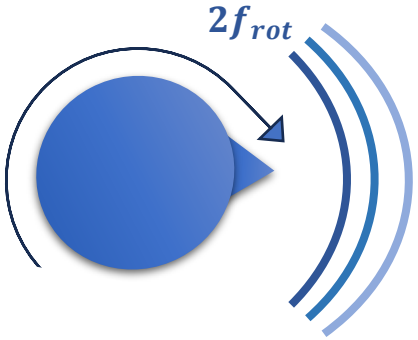


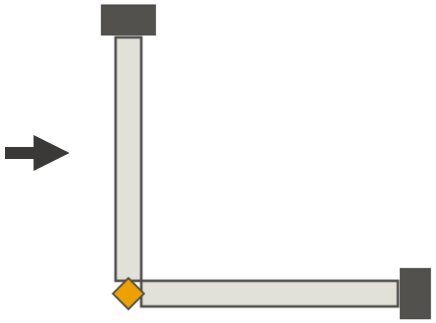
Figure 5. Expected sensitivity of the narrowband search using the O4a (shaded pink region) data set from the two LIGO detectors considering the single-harmonic emission model. The curve is compared with the spin-down limits (triangles) and the upper limits (stars) averaged over all the 10^{-4} Hz bands for each source. Upper limits below the spin-down limit are highlighted with orange circles.



Maximum physically allowed ellipticity under the assumption that GWs account for 100% of the observed spin-down



Spinning Neutron Star

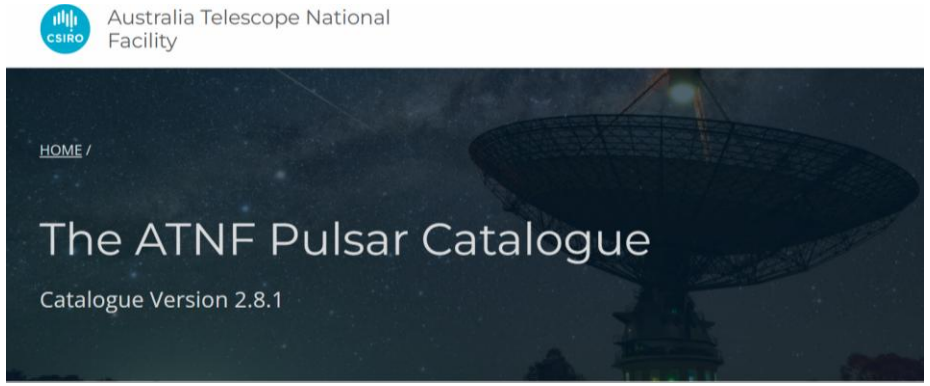


LVK- O4a run

No detection → 95% UL on h_0

Amplitude physics

$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\,\varepsilon\,f_{\rm rot}^2}{d} \equiv A_j\,I_{zz}\,\varepsilon$$

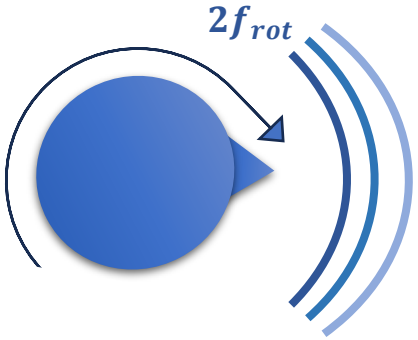


f_{rot} - spin frequency

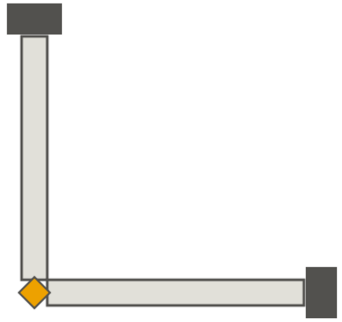
d - distance of the source

The equatorial ellipticity:

$$\varepsilon \equiv \frac{|I_{xx} - I_{yy}|}{I_{zz}}$$



Spinning Neutron Star



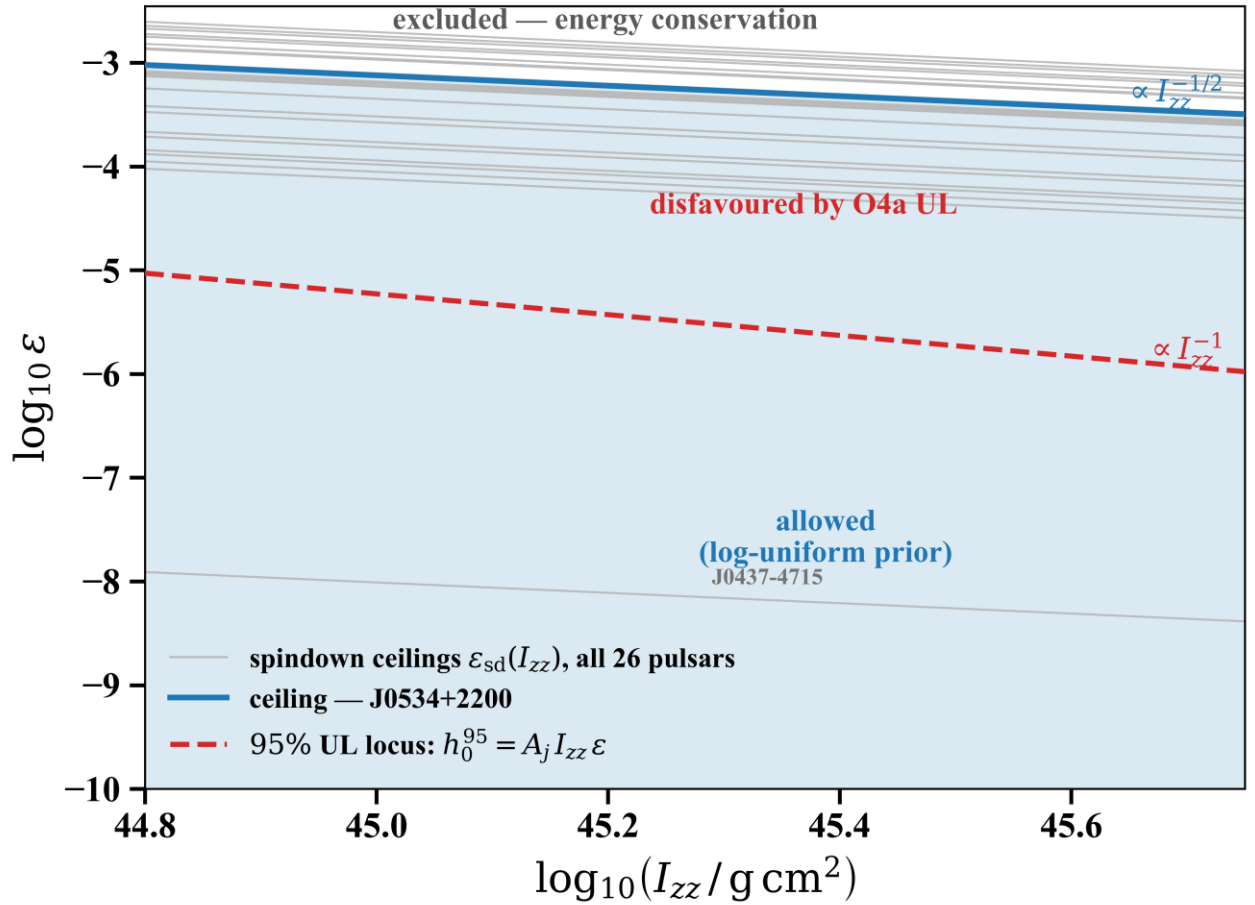
LVK- O4a run

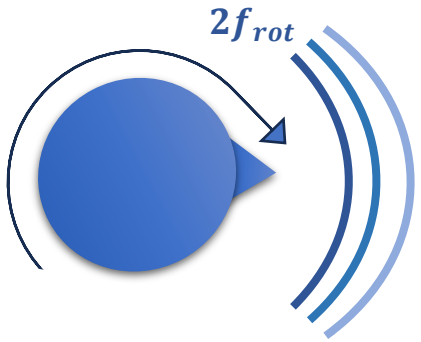
Amplitude physics

$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\,\varepsilon\,f_{\rm rot}^2}{d} \equiv A_j\,I_{zz}\,\varepsilon$$

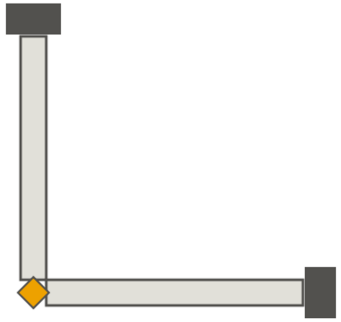
Spindown Wedge

No detection → 95% UL on h_0





Spinning Neutron Star



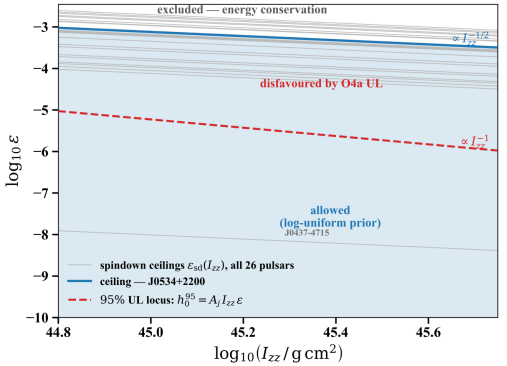
LVK- O4a run

No detection → 95% UL on h_0

Amplitude physics

$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\,\varepsilon\,f_{\rm rot}^2}{d} \equiv A_j\,I_{zz}\,\varepsilon$$

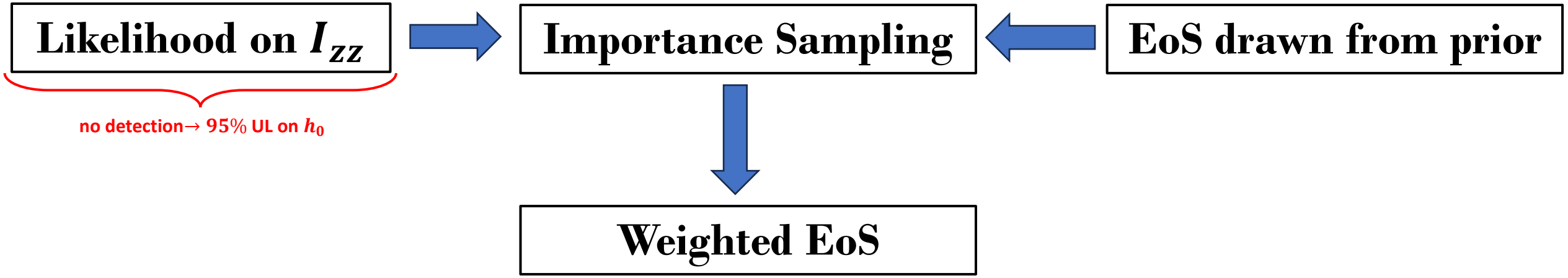
Spindown Wedge



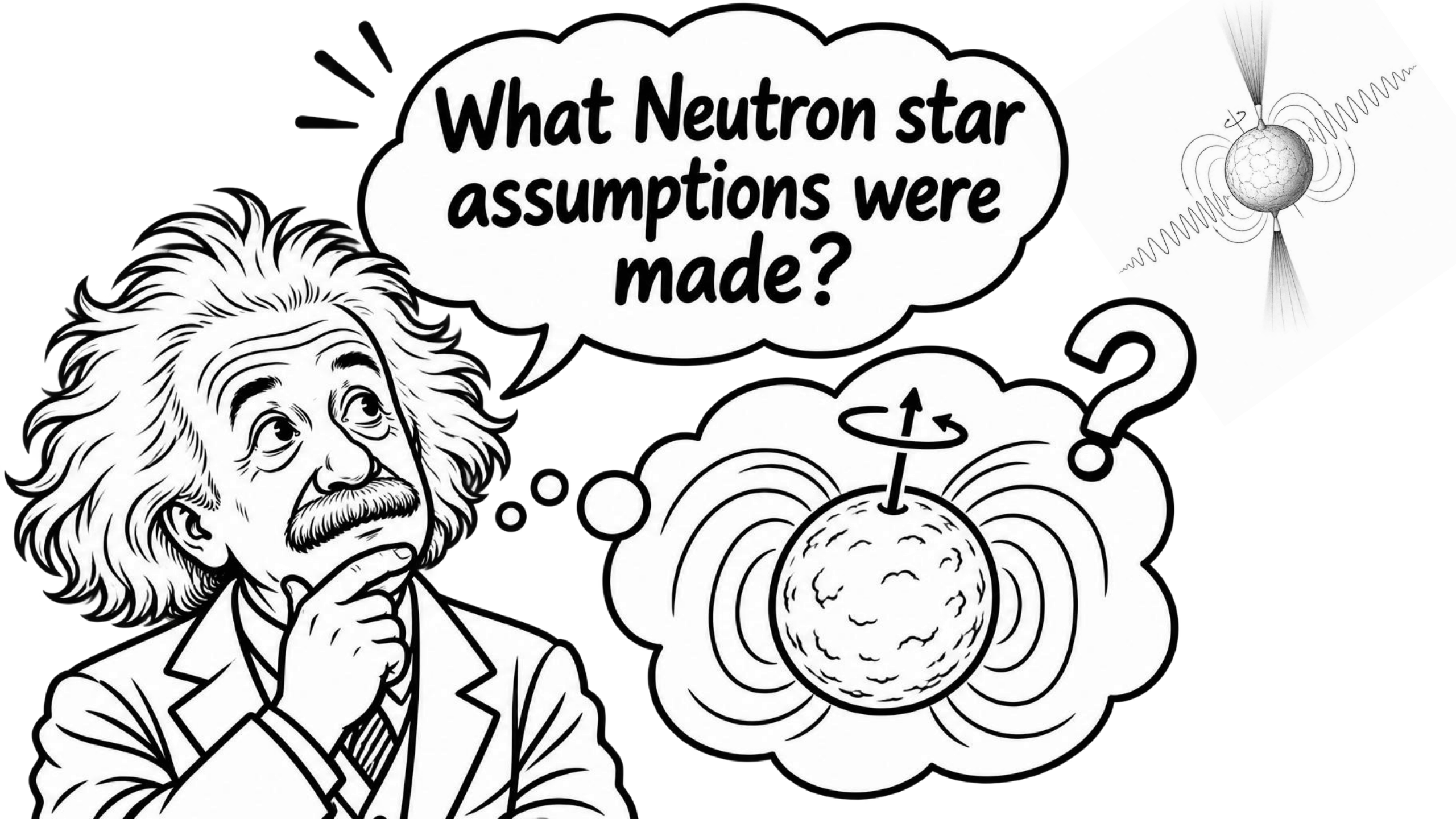
Hierarchical Bayesian Inference

Assumptions

- TOV + Hartle rotation
- EoS Bank - 100000
- SLy crust + piecewise polytropes
- Prior range



EoS	Character	$R_{1.4}$ [km]	Prior w_i	ℓ_{i1}	ℓ_{i2}	ℓ_{i3}	$L_i = \prod_j \ell_{ij}$	Posterior w_i
A	very soft	9.5	0.200	1.00	1.00	1.00	**1.00**	**0.333**
B	soft	11.0	0.200	1.00	1.00	0.90	**0.90**	**0.300**
C	medium	12.5	0.200	1.00	0.80	0.75	**0.60**	0.200
D	stiff	14.0	0.200	0.80	0.75	0.50	**0.30**	0.100
E	very stiff	15.5	0.200	0.80	0.50	0.50	**0.20**	0.067
			$\Sigma = 1.000$				$\Sigma L = 3.00$	$\Sigma = 1.000$


What Neutron star assumptions were made?

The Stellar Structure Engine

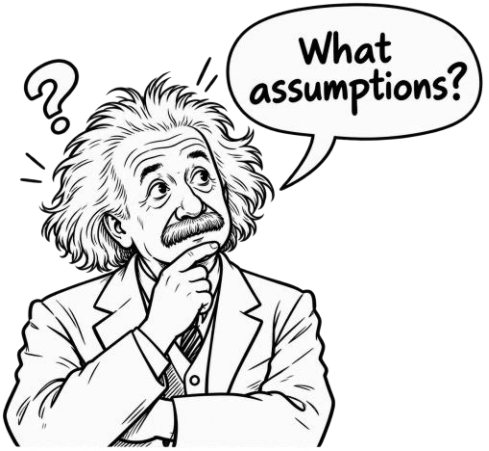
Tolman–Oppenheimer–Volkoff equations

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon(r), \qquad \frac{dp}{dr} = -\frac{\left[\varepsilon(r)+p(r)\right]\left[m(r)+4\pi r^3 p(r)\right]}{r\left[r-2m(r)\right]}, \qquad \frac{d\nu}{dr} = \frac{2\left[m(r)+4\pi r^3 p(r)\right]}{r\left[r-2m(r)\right]}$$

Hartle slow rotation

$$\frac{1}{r^4}\frac{d}{dr}\left[r^4 j(r)\frac{d\bar{\omega}}{dr}\right] + \frac{4}{r}\frac{dj}{dr}\bar{\omega}(r) = 0, \qquad j(r) \equiv e^{-\nu(r)/2}\sqrt{1-\frac{2m(r)}{r}}$$

$$J = \frac{R^4}{6}\left.\frac{d\bar{\omega}}{dr}\right|_{r=R}, \qquad \Omega = \bar{\omega}(R) + \frac{2J}{R^3}, \qquad I_{zz} = \frac{J}{\Omega}$$



The stellar spin: Ω

The star's angular momentum: J

The frame-dragging frequency: $\omega(r)$

Angular velocity of the fluid relative to the local inertial frame: $\bar{\omega}(r) = \Omega - \omega(r)$

The Equation-of-State Ensemble

SLy crust + piecewise polytrope

$$p(\rho) = K_i \, \rho^{\Gamma_i}, \qquad \rho_{i-1} \leq \rho < \rho_i$$

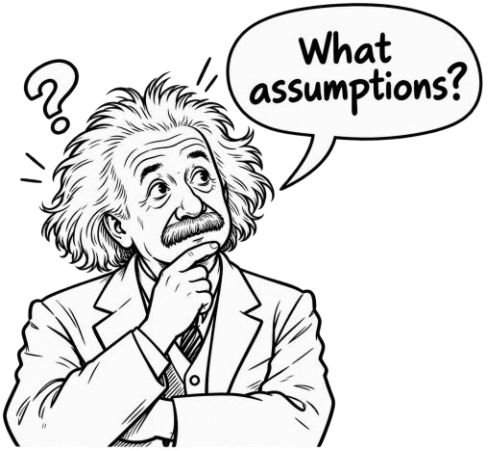
The polytropic constant: K_i

The adiabatic index of segment i: Γ_i

The energy density is obtained from the first law of thermodynamics for cold matter:

$$\varepsilon(\rho) = (1 + a_i)\, \rho + \frac{K_i}{\Gamma_i - 1} \, \rho^{\Gamma_i}$$

Integration constant: a_i

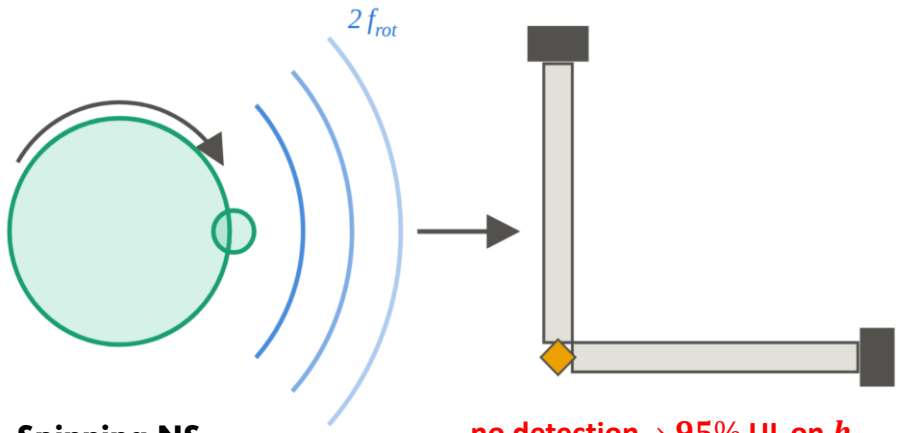


The causality condition: $c_s^2 = \dfrac{dp}{d\varepsilon} \leq c^2$

The Mighty Prior

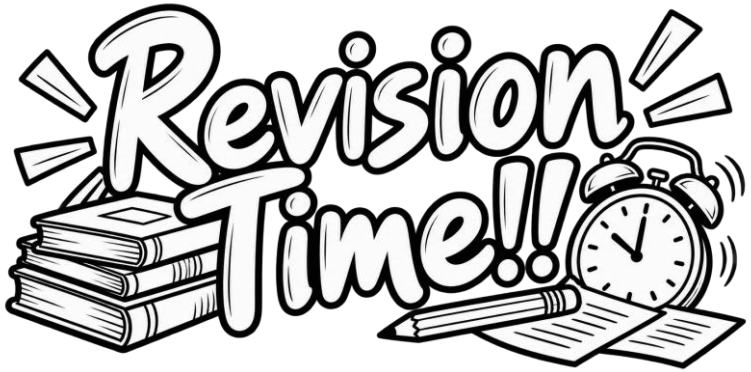
Parameter	Description	Prior
$\log_{10}(p_1/\mathrm{dyn\,cm^{-2}})$	pressure at $\rho_1 = 10^{14.7}\,\mathrm{g\,cm^{-3}}$	$\mathcal{U}(33.70, 34.90)$
Γ_1	core index, $\rho \leq \rho_1$	$\mathcal{U}(1.90, 4.50)$
Γ_2	core index, $\rho_1 < \rho \leq \rho_2$	$\mathcal{U}(1.20, 4.20)$
Γ_3	core index, $\rho > \rho_2$	$\mathcal{U}(1.20, 4.20)$
M_j	mass of pulsar j	$\mathcal{U}(1.0, \min[3.0, M_{\max}(\boldsymbol{\theta})])\,M_\odot$
ε_j	ellipticity of pulsar j	log-uniform on $\left[10^{-10}, \varepsilon_{\mathrm{sd}}(I_j)\right]$





Spinning NS

no detection→ 95% UL on h_0

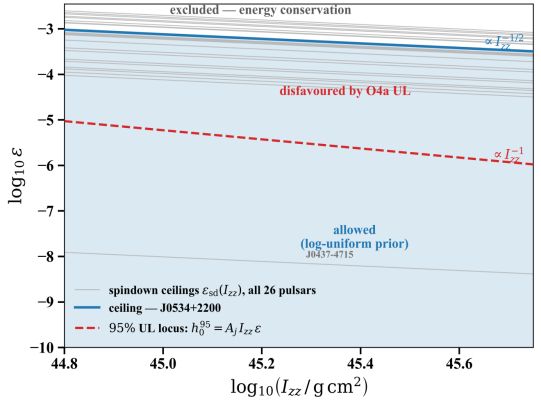


AMPLITUDE PHYSICS

$$h_0 = A \cdot I_{zz} \cdot \varepsilon$$

$A = 16\pi^2 G f^2 / (c^4 d)$

I_{zz} — the EoS-sensitive lever



Spindown wedge

Hierarchical Bayesian inference

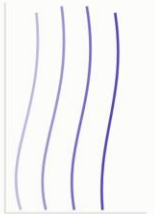
shared EoS $\theta = (p_1, \Gamma_1, \Gamma_2, \Gamma_3)$

per-pulsar (M_j, ε_j) marginalized

exact E_1 ε-marginal, 26 pulsars

importance sampling + diagnostics

EoS bank — 100,000 candidates



piecewise polytropes,

SLy crust + 3 core Γs

TOV + Hartle rotation

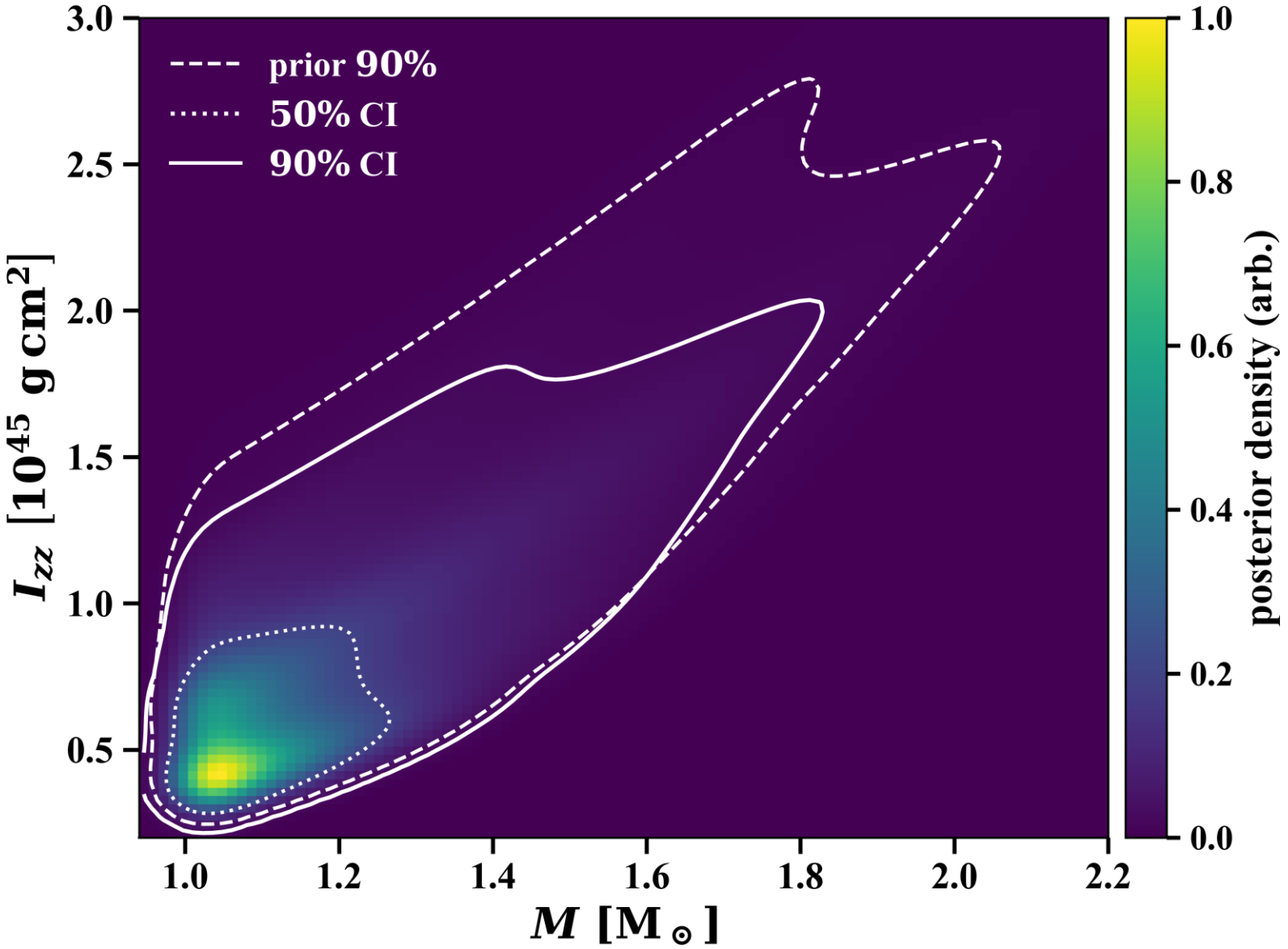
→ $M(R)$, $I_{zz}(M)$, M_{max}

First contact with the interior

The strain knows exactly one number about the star: I_{zz}

This is what 26 silences say about it

An upper limit can only disfavor large I_{zz}

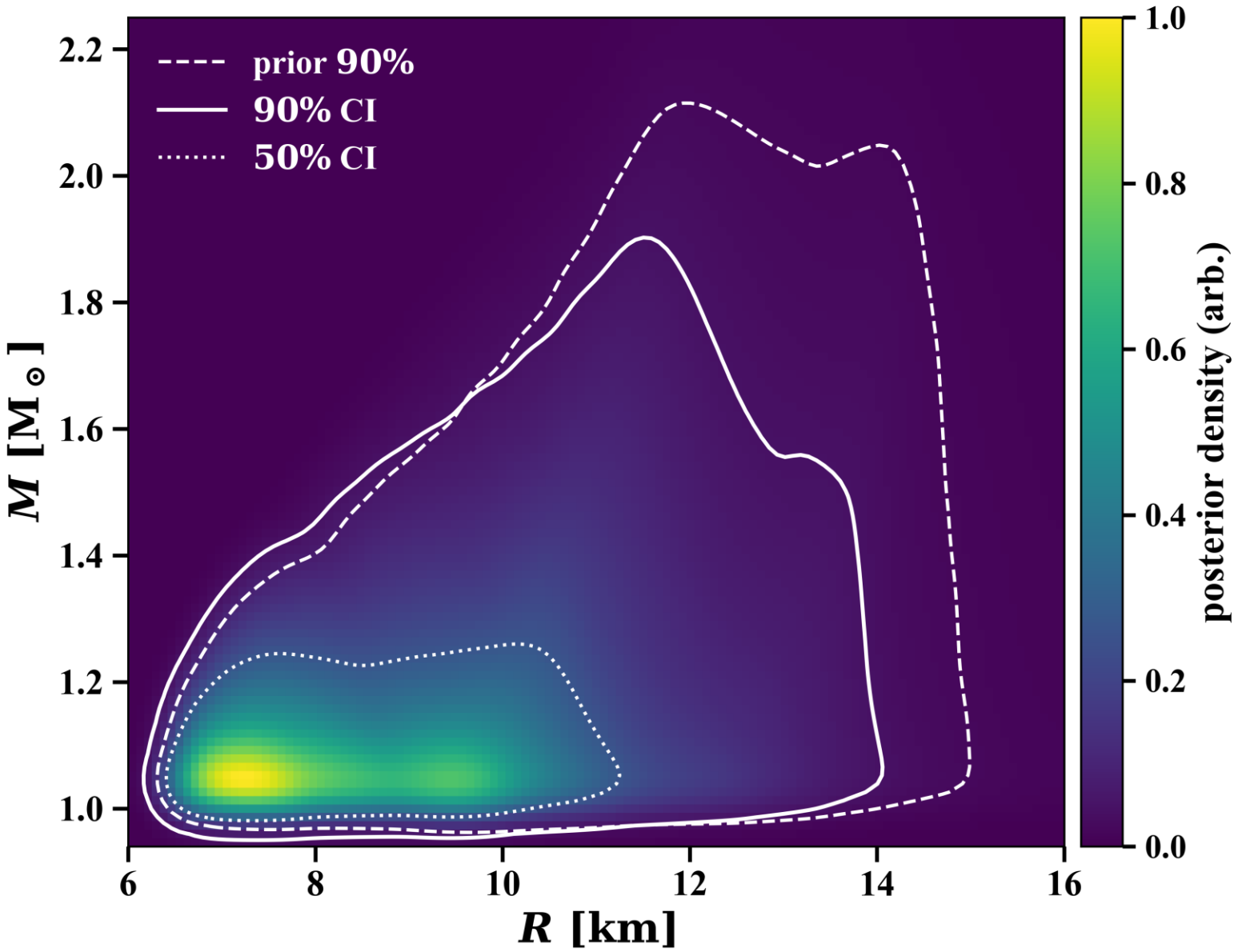


Silence prefers softer stars

Smaller I_{zz} at fixed mass means a smaller star

Non-detection favors softer EoS

The high-mass tail thins because a stiff EoS lets every pulsar be heavy, and heavy means large I_{zz}

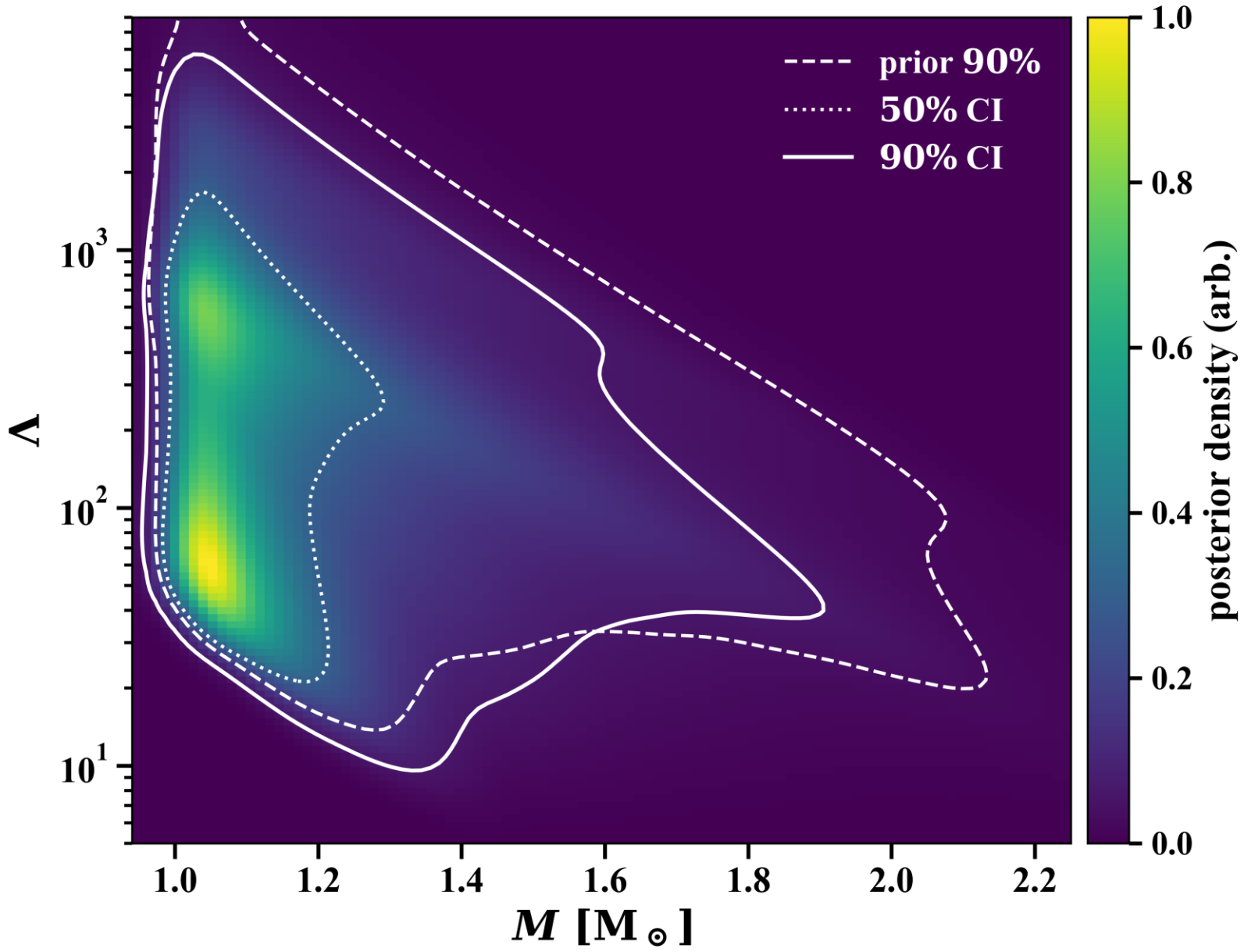


Tidal deformation without a merger

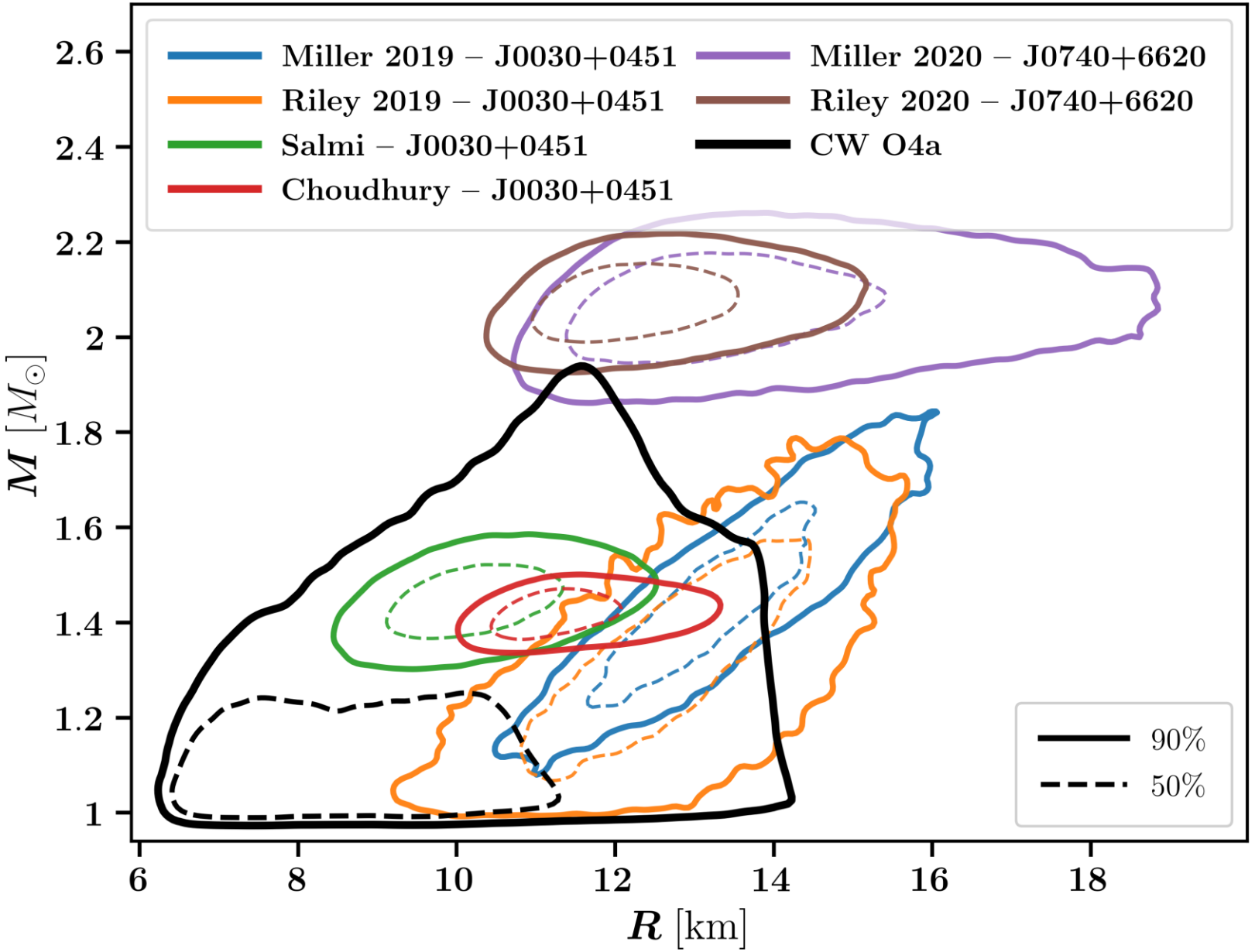
Λ is never observed here.

Λ inferred, not measured: the equation of state carries it

The CW limits weigh the EoS; every surviving EoS brings its own $\Lambda_\theta(M)$.



The third witness takes the stand



GW170817 + nuclear data + low-mass X-ray binaries

$$I_{1.4} = 1.43^{+0.30}_{-0.13} \times 10^{38}\,\mathrm{kg\,m^2},\ \Lambda_{1.4} = 390^{+280}_{-210}$$

$$R_{1.4} = 11.8^{+1.2}_{-0.7}\,\mathrm{km}$$

The Astrophysical Journal, 885:39 (10pp), 2019 November 1 https://doi.org/10.3847/1538-4357/ab44b2
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The Equation of State and Some Key Parameters of Neutron Stars: Constraints from GW170817, the Nuclear Data, and the Low-mass X-Ray Binary Data

Jin-Liang Jiang[1,2], Shao-Peng Tang[1,2], Dong-Sheng Shao[1,2], Ming-Zhe Han[1,2], Yin-Jie Li[1,2], Yuan-Zhu Wang[1], Zhi-Ping Jin[1,2], Yi-Zhong Fan[1,2], and Da-Ming Wei[1,2]
[1] Key Laboratory of dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing, 210033, People's Republic of China
tangsp@pmo.ac.cn, yzfan@pmo.ac.cn
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Received 2019 August 3; revised 2019 September 12; accepted 2019 September 13; published 2019 October 29

NICER PSR J0437–4715

$$R = 11.36^{+0.95}_{-0.63}\,\mathrm{km}$$

A NICER View of the Nearest and Brightest Millisecond Pulsar: PSR J0437–4715

Devarshi Choudhury, Tuomo Salmi, Serena Vinciguerra, Thomas E. Riley, Yves Kini, Anna L. Watts, Bas Dorsman, Slavko Bogdanov, Sebastien Guillot, Paul S. Ray Show full author list

Published 2024 August 8 • © 2024. The Author(s). Published by the American Astronomical Society.
The Astrophysical Journal Letters, Volume 971, Number 1
Citation Devarshi Choudhury *et al* 2024 *ApJL* **971** L20
DOI 10.3847/2041-8213/ad5a6f

CW O4a Run (*no detection*)

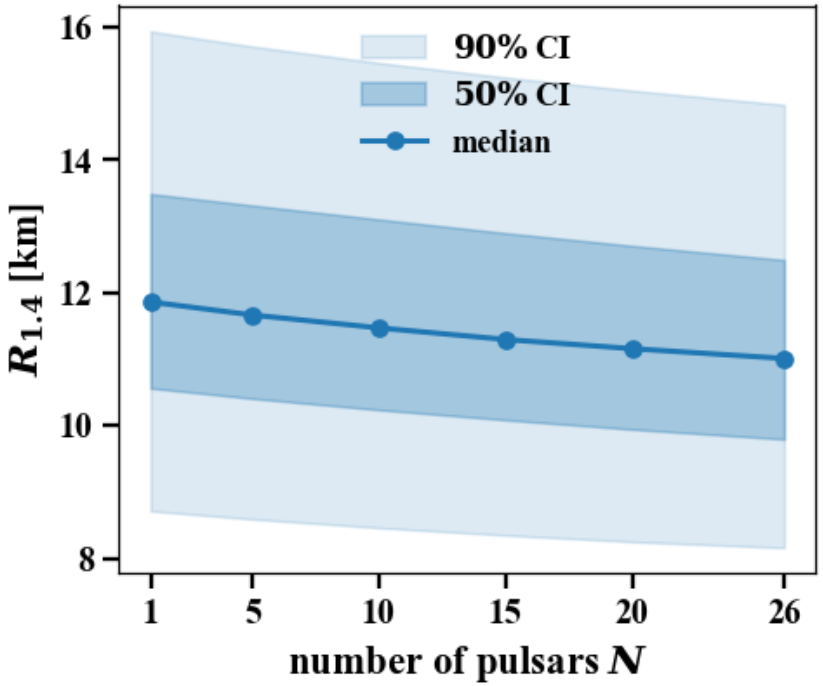
$$I_{1.4} = 1.24^{+0.73}_{-0.49} \times 10^{45}\,\mathrm{g\,cm^2}$$

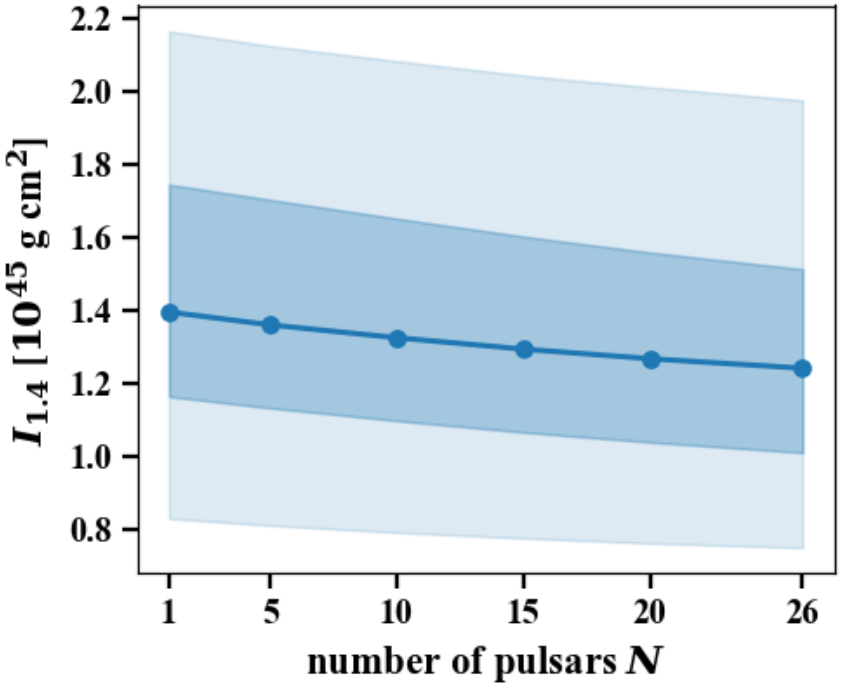
$$R_{1.4} = 11.01^{+3.82}_{-2.85}\,\mathrm{km}$$

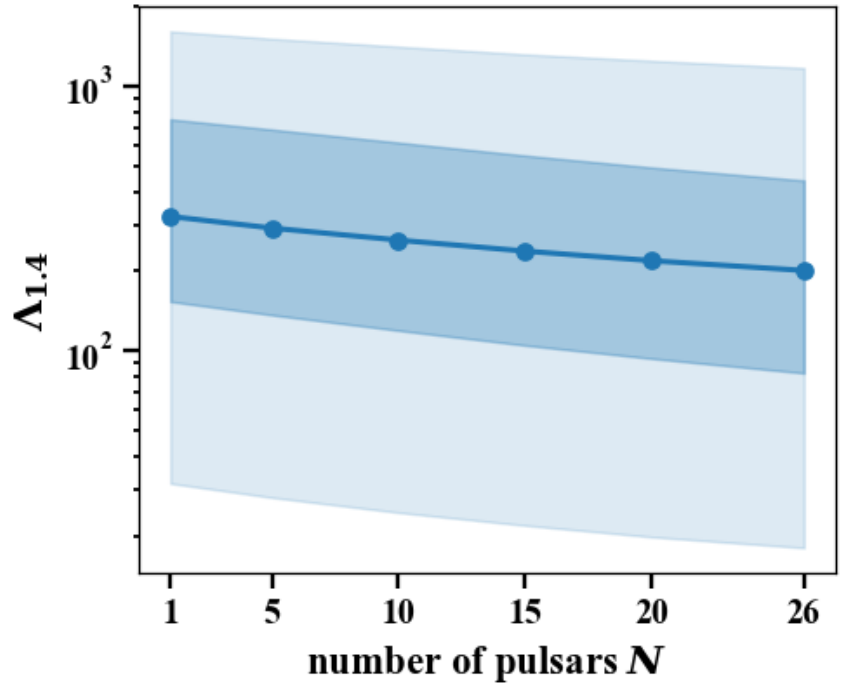
$$\Lambda_{1.4} = 201.4^{+969.3}_{-183.3}$$

Paper loading……

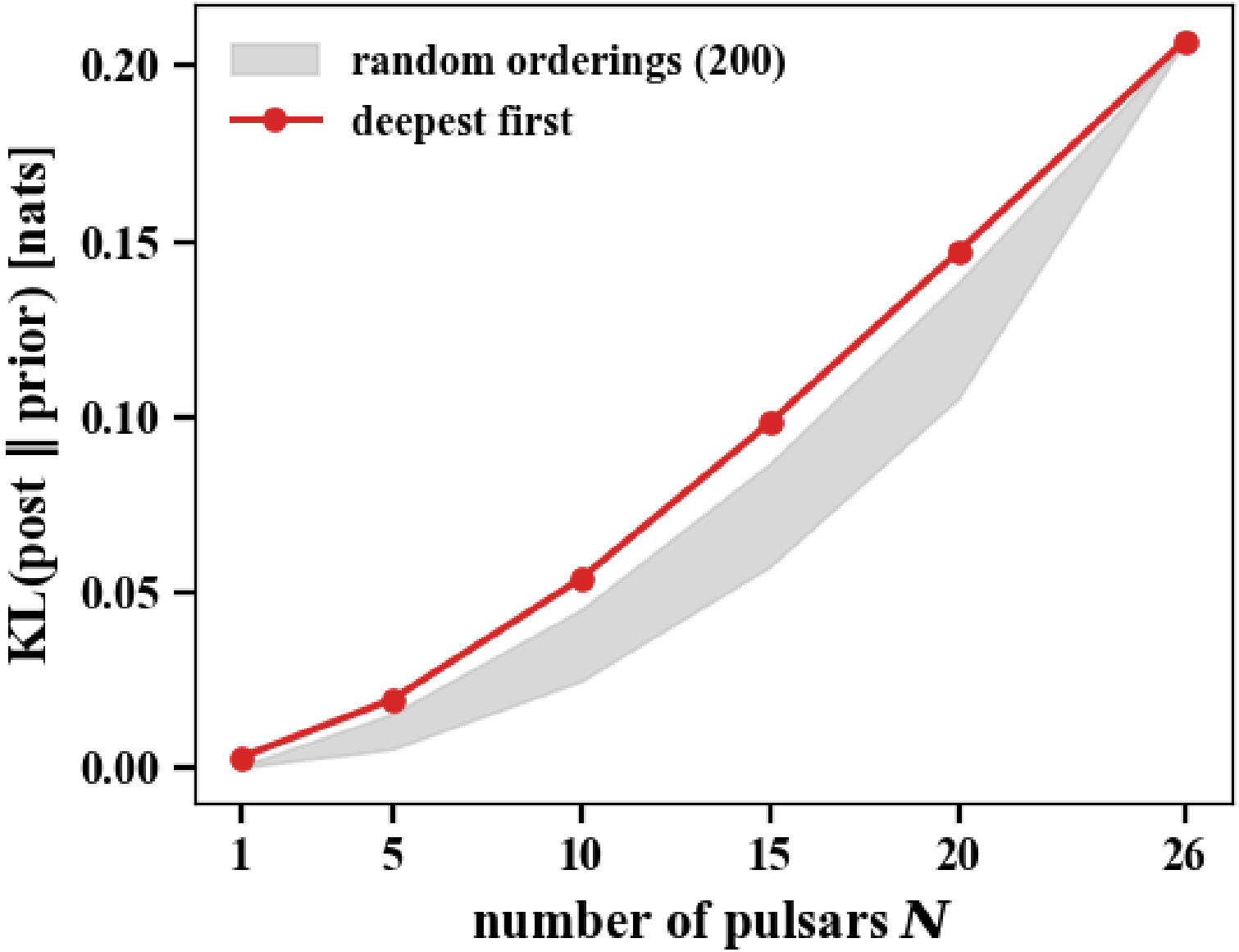
The Power of More Pulsars







Quantifying the Posterior Shift



Current focus

To do a simulated detection

To reduce assumptions

To do an example study with CW constraint

To perform population inference

To increase machine accuracy

Acknowledgement



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University of Auckland



Our group @ ICTP-AP



Andrew L. Miller

Group Leader

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Students

Charchit Kumar Sethi



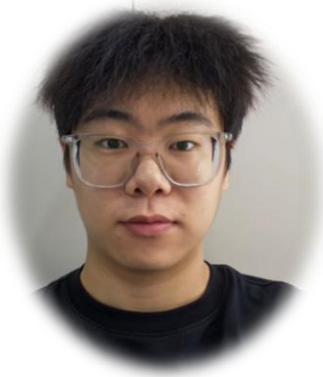
GW probes of BBHs with DM spikes

Ayush Hazarika



CWs to constrain NS

Hang Yang 杨航



GW from mass transfer of boson clouds in BBHs

Verónica Vázquez-Aceves



Visiting Scientist

EMRIs, intermediate mass BH, GW physics

Jiahang Wang 王佳杭



Intern (*UG student*)

Generalized Frequency Hough Transform algorithm

Postdocs (*Joining in ~Oct.*)

An Kiet Pham



Direct searches for DM with LIGO; SGWB searches

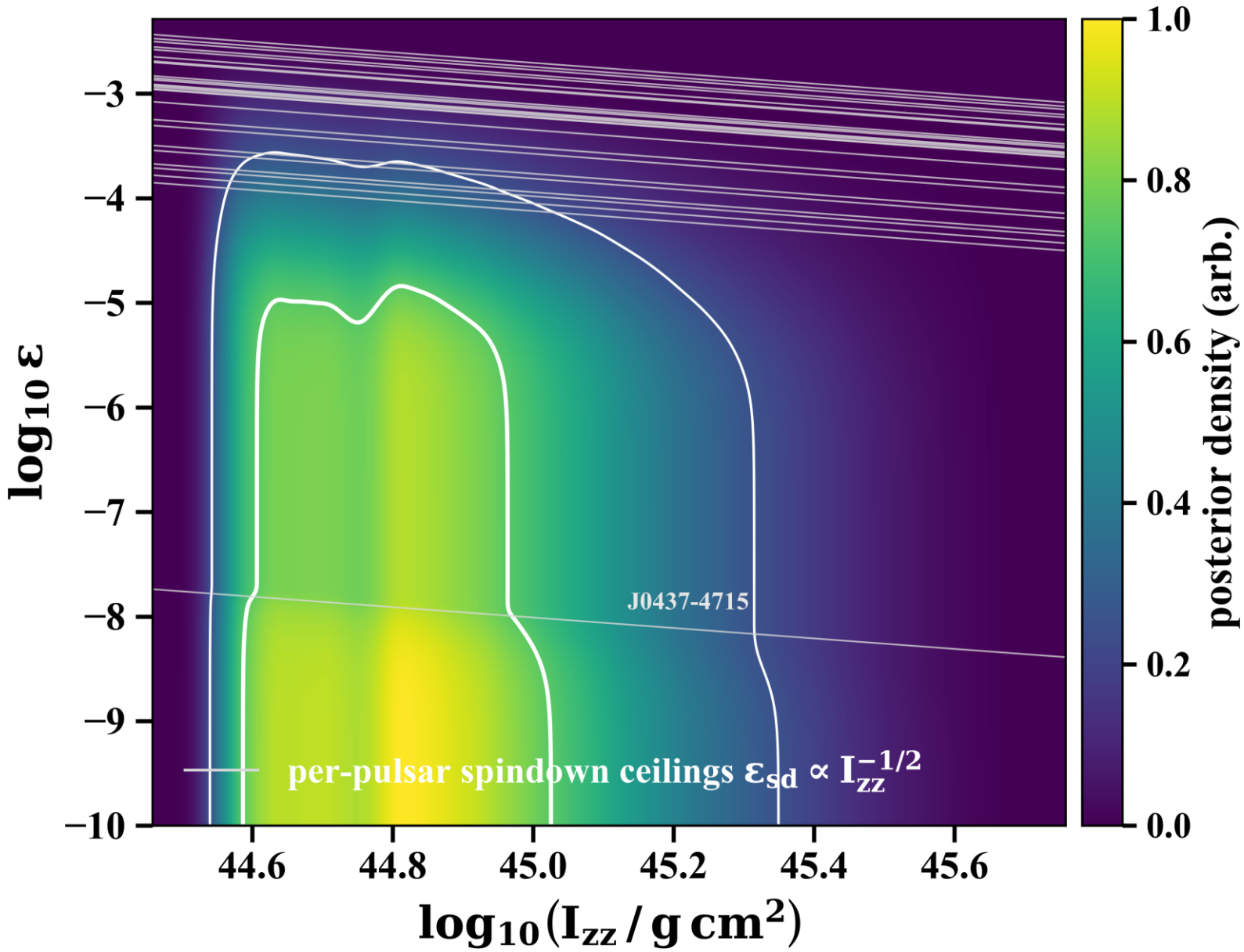
Debtroy Das

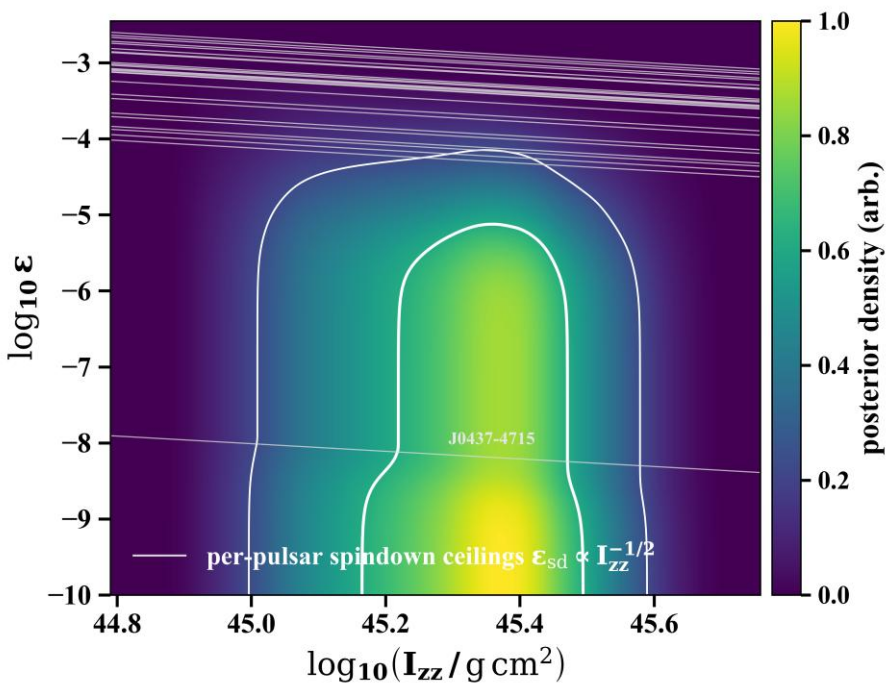


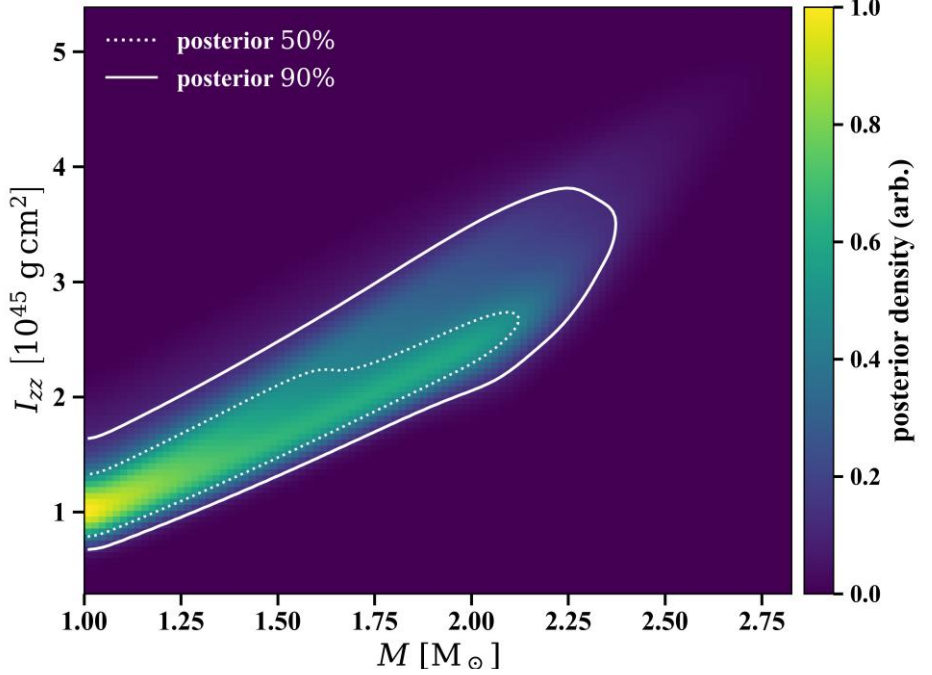
Search for EMRIs in future detectors; testing GR

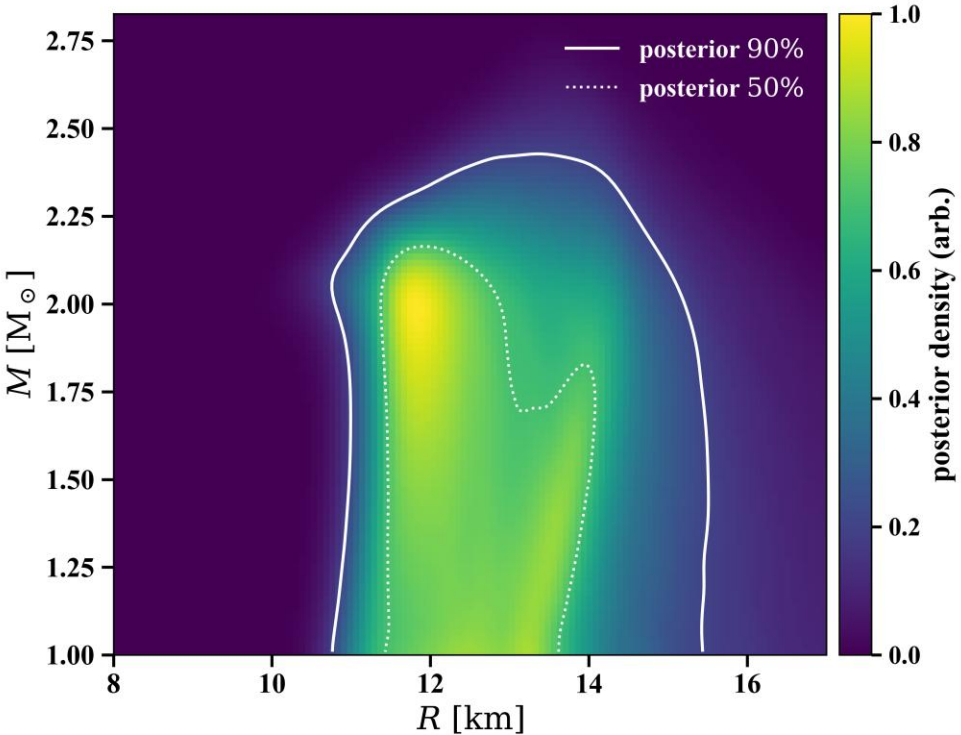

THANK YOU

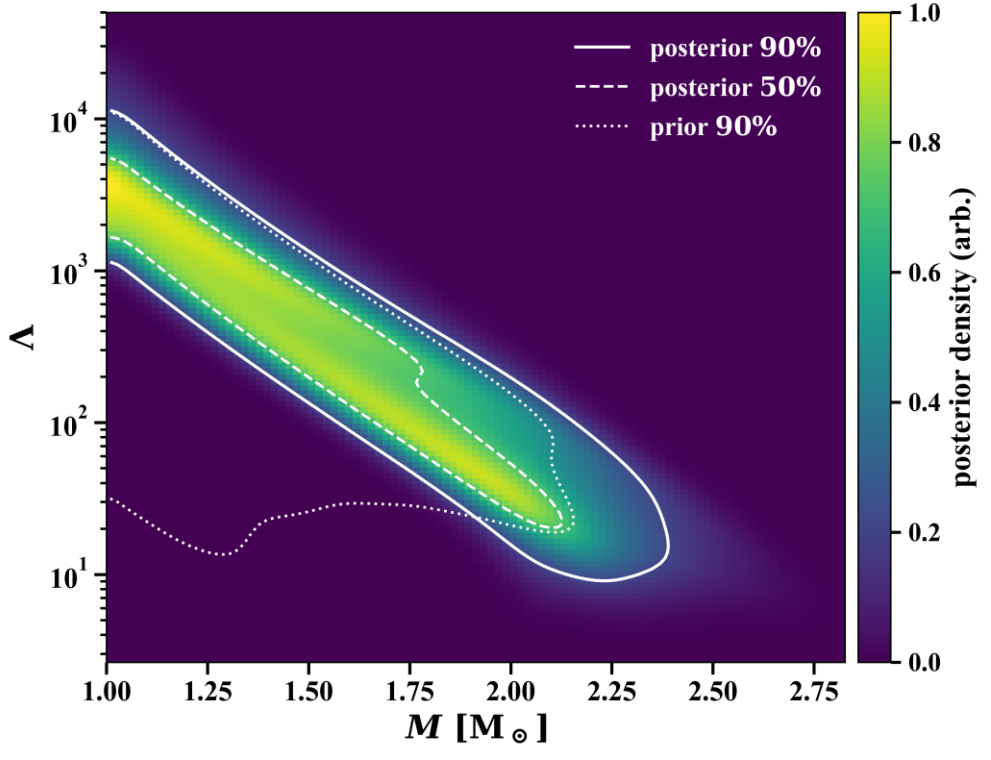
What the silence says by itself

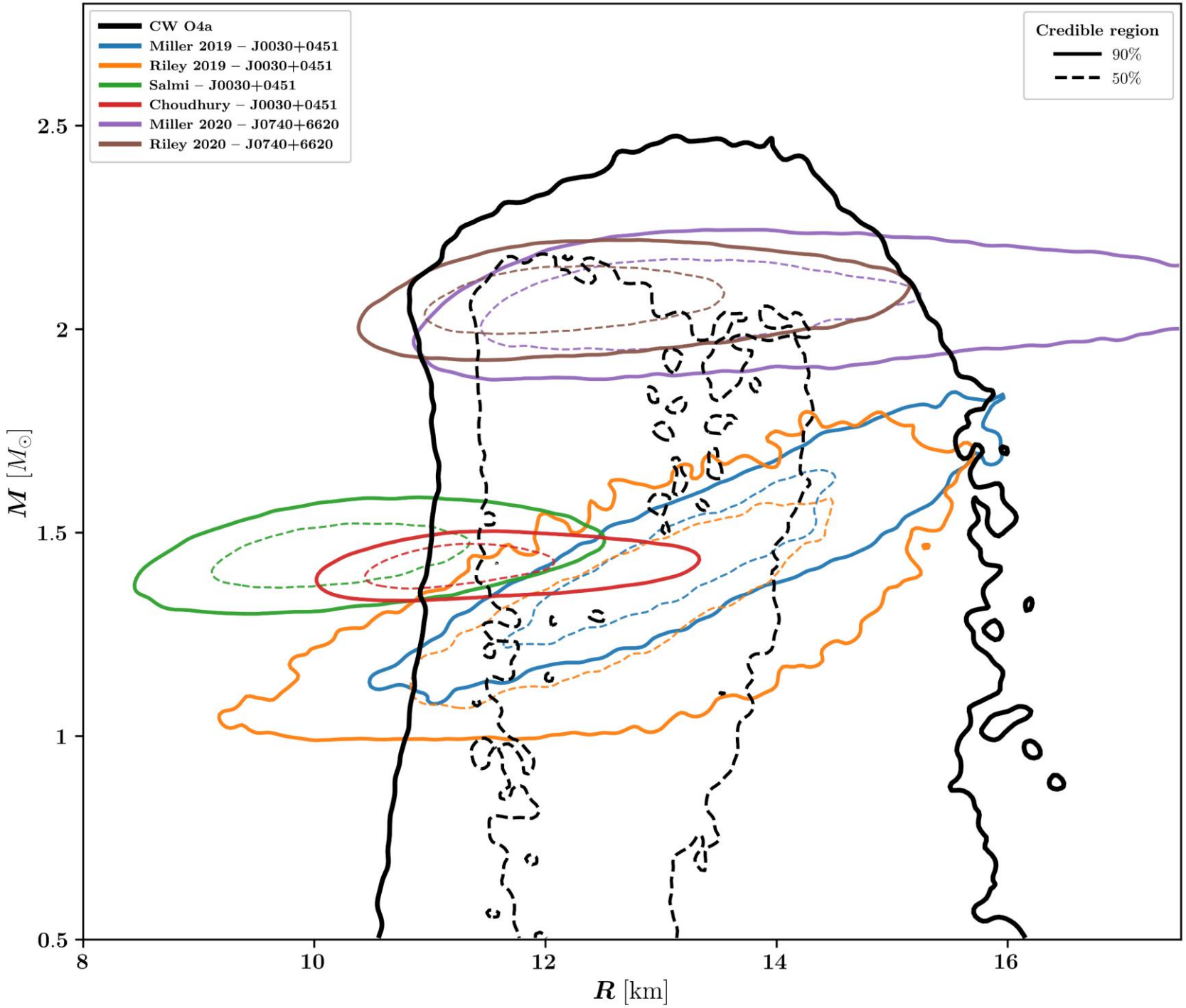



J0437-4715
per-pulsar spindown ceilings $\varepsilon_{sd} \propto I_{zz}^{-1/2}$
$\log_{10}\varepsilon$
$\log_{10}(I_{zz}/\mathrm{g\,cm^2})$
posterior density (arb.)


posterior 50%
posterior 90%
I_{zz} [10^{45} g cm^2]
M [M$_\odot$]
posterior density (arb.)


posterior 90%
posterior 50%
M [M$_\odot$]
R [km]
posterior density (arb.)


posterior 90%
posterior 50%
prior 90%
Λ
M [M$_\odot$]
posterior density (arb.)


CW O4a
Miller 2019 – J0030+0451
Riley 2019 – J0030+0451
Salmi – J0030+0451
Choudhury – J0030+0451
Miller 2020 – J0740+6620
Riley 2020 – J0740+6620
Credible region
90%
50%
2.5
2
1.5
1
0.5
M [$M_\odot$]
8
10
12
14
16
R [km]

$$p(\boldsymbol{\theta}, \{M_j, \varepsilon_j\} \mid \{\mathcal{D}_j\}, \{m_k\}) \;=\; \frac{1}{\mathcal{Z}} \;\underbrace{\pi(\boldsymbol{\theta})}_{\text{EoS prior}} \;\underbrace{\Lambda_{\text{heavy}}(\boldsymbol{\theta})}_{\text{heavy pulsars}} \prod_{j \in \mathcal{S}} \underbrace{p(M_j \mid \boldsymbol{\theta})}_{\text{mass prior}} \underbrace{p(\varepsilon_j \mid I_j)}_{\text{wedge prior}} \underbrace{\mathcal{L}_j(\mathcal{D}_j \mid h_{0,j})}_{\text{CW UL likelihood}}$$

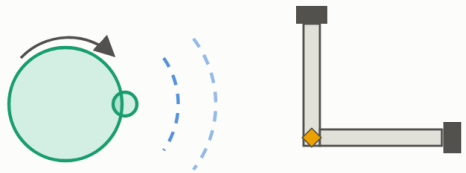
$$h_{0,j} \;=\; \frac{16\pi^2 G}{c^4} \frac{I_{zz}\, \varepsilon\, f_{\text{rot},j}^2}{d_j} \;\equiv\; A_j\, I_j\, \varepsilon_j, \qquad I_j \equiv I_{zz}(M_j; \boldsymbol{\theta}), \qquad A_j = \frac{16\pi^2 G f_{\text{rot},j}^2}{c^4 d_j}$$

$$p(\boldsymbol{\theta}, \{M_j, \varepsilon_j\} \mid \mathcal{D}) \;\propto\; \frac{\mathbb{1}[\boldsymbol{\theta} \in \text{prior box}]}{V_{\text{box}}} \;\times\; \prod_{k=1}^{2} \Phi\!\left(\frac{M_{\max}(\boldsymbol{\theta}) - m_k}{\sigma_{m_k}}\right)$$

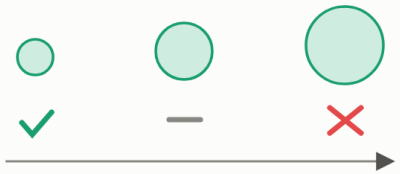
$$\times \prod_{j \in \mathcal{S}} \left[\frac{\mathbb{1}[M_{\text{lo}} \le M_j \le m_{\text{hi}}(\boldsymbol{\theta})]}{m_{\text{hi}}(\boldsymbol{\theta}) - M_{\text{lo}}} \;\times\; \frac{\mathbb{1}[\varepsilon_{\min} \le \varepsilon_j \le \varepsilon_{\text{sd}}(I_j)]}{\varepsilon_j\, W_j(I_j)} \;\times\; \exp\!\left(-\frac{A_j^2 I_j^2 \varepsilon_j^2}{2\sigma_j^2}\right) \right]$$

$$\ln p(\boldsymbol{\theta}_i \mid \mathcal{D}) = \text{const} + \underbrace{\sum_{j \in \mathcal{S}} \mathcal{L}_{ji}}_{\ln w_i^{\text{cw}}} + \underbrace{\textstyle\sum_k \ln \Phi\big[(M_{\max,i} - m_k)/\sigma_{m_k}\big]}_{s_i \;(\texttt{lnsoft})}$$

LIKELIHOOD ON Izz



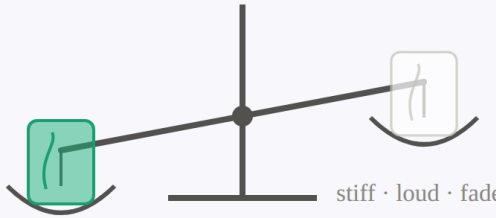
no detection → 95% UL



larger I_{zz} → louder → penalized

26 silent pulsars → one exact likelihood over the moment of inertia

IMPORTANCE SAMPLING



stiff · loud · fades

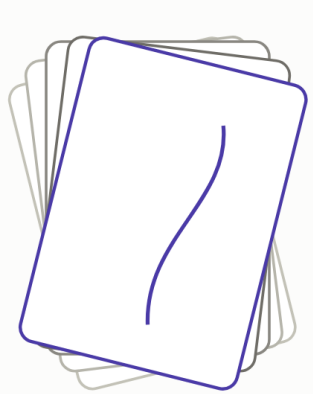
soft · quiet · kept

every EoS is weighed by all 26 silences at once

$$w_i \propto \exp \Sigma_j \ln\langle L_j \rangle(\theta_i)$$

no re-runs — the bank is reweighted, not rebuilt

EoS DRAWN FROM PRIOR



random draws

100,000 candidate EoS

every one solved: TOV + Hartle

→ M, R, I_{zz}, Λ — all equal weight

WEIGHTED EoS = POSTERIOR



same 100,000 EoS — now carrying the data: credible bands for M–R, I_{zz}(M), Λ(M)