Constraining neutron star properties with current and future gravitational wave observations of glitching pulsars

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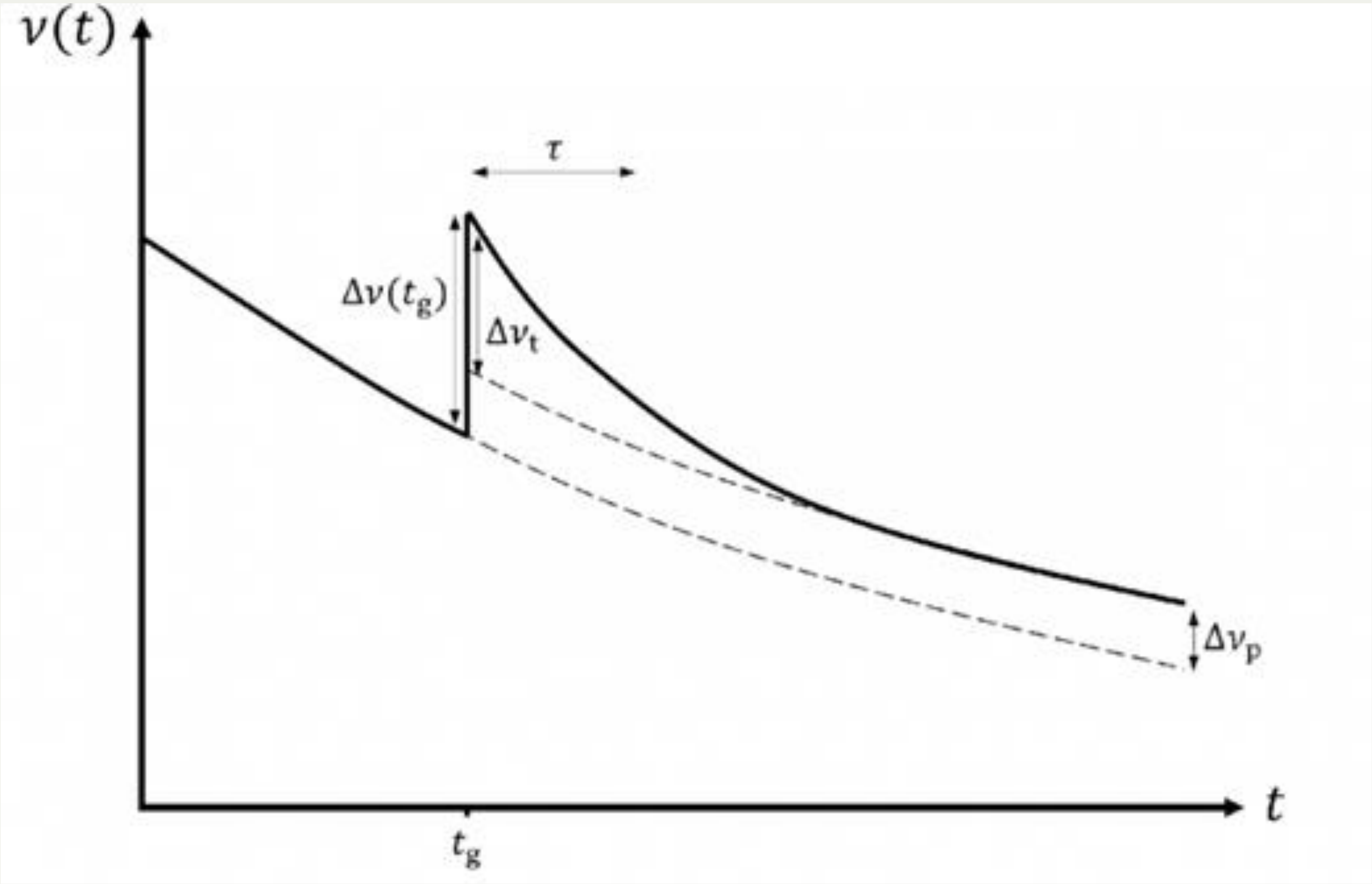
Talk overview

- Search for Gravitational Waves from the 2024 Vela Glitch
  - Details of the search target
  - Results from the search for continuous gravitational waves
  - Results from the search for gravitational wave bursts
  - Astrophysical implications
- Future projections
  - Population-based estimates of future detectability
  - What if the 2024 Vela glitch occurred with different next-generation GW detectors online

Pulsar glitches

- Sudden increases in rotation speed followed by faster decay (Antonopoulou et al. 2022)
- Believed to be due to exchange of momentum between the crust and a superfluid in the interior (e.g. Haskell & Melatos 2015; Zhou et al. 2022)



Exaggerated diagram of a glitch. Image credit: Yim & Jones 2020

Gravitational wave signals from a glitch

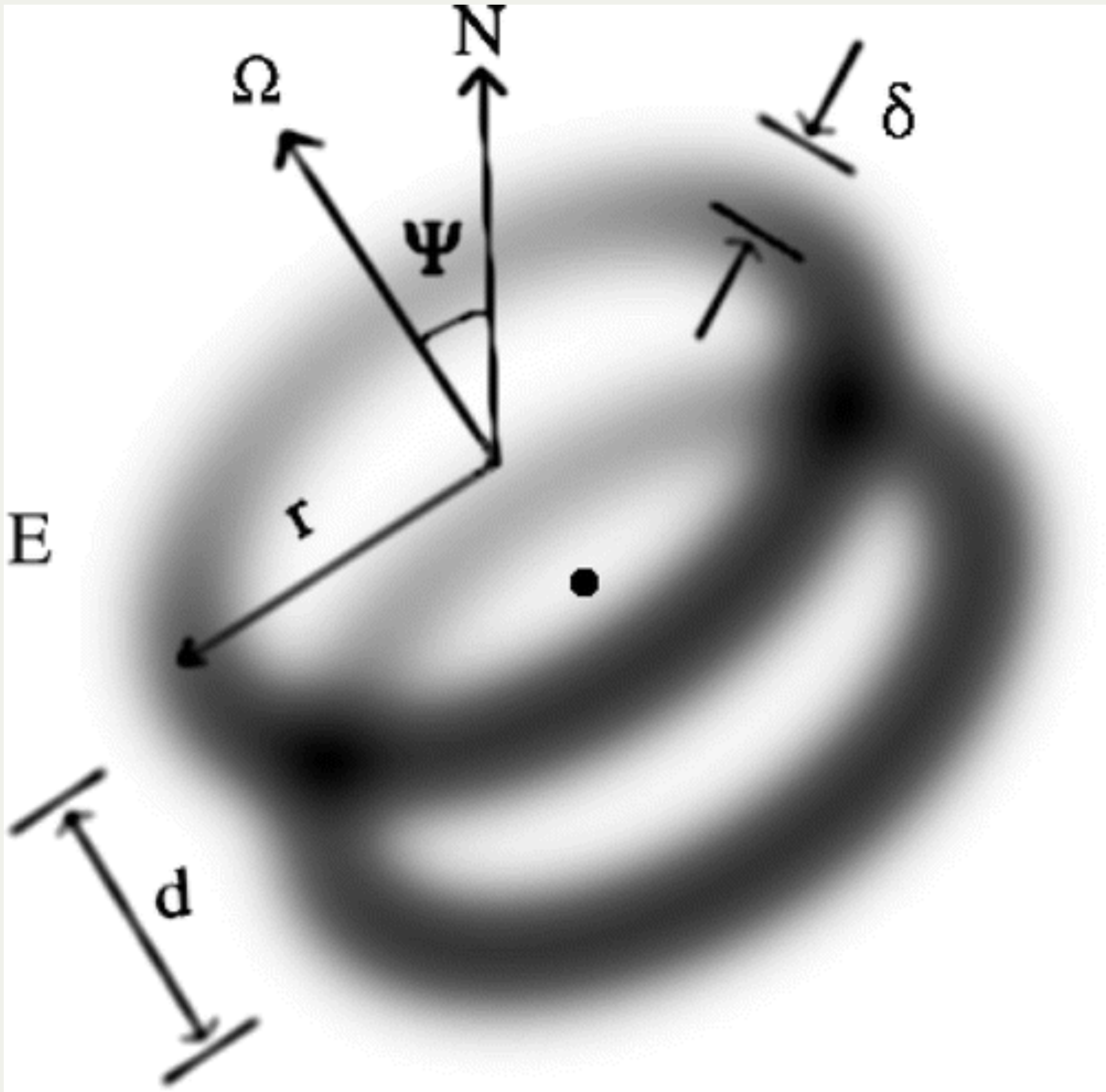
- Small change in moment of inertia may lead to (transient) continuous GW (tCW) emission at 1× or 2× the rotation frequency
  - Deformation of the crust (mountains) due to internal mechanisms (such as elastic fracture, superfluid unpinning)
    - Relaxation of this deformation is attributed to the recovery time
- Induced short-duration oscillations during the initial spin-up possibly due to unpinning of superfluid vortices (e.g. Andersson & Kokkotas 1998)
  - Up to a few seconds in duration
  - Hundreds to a few thousand Hz in frequency

Constraints on gravitational waves from the 2024 Vela pulsar glitch

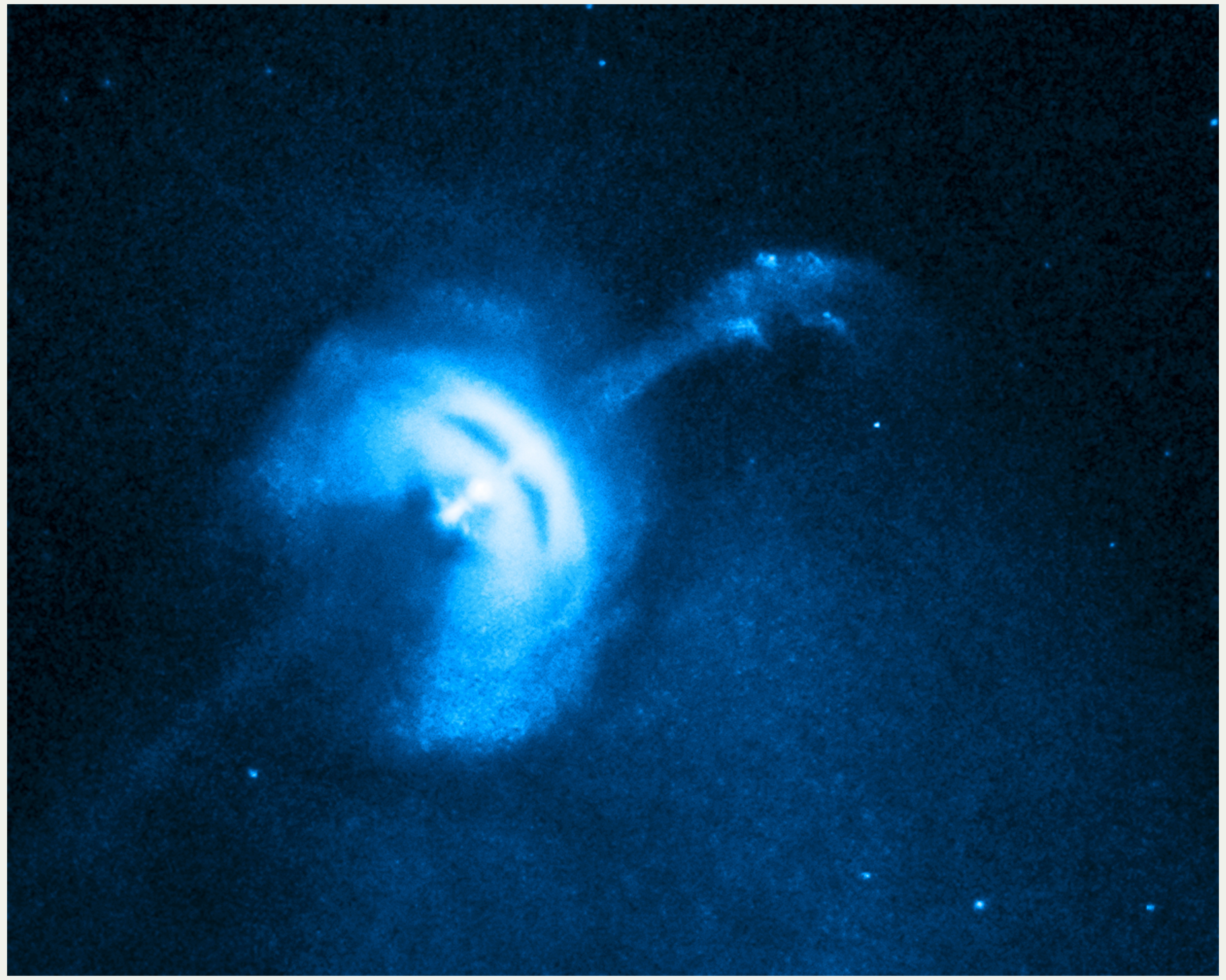
Based on A. G. Abac et al 2026 ApJ 1005 12 (arXiv:2512.17990)

The Vela pulsar

- Rotation rate [Hz]: (11.182888898688 ± 0.000000000002) (IAR; MPRO)
- Distance [pc]: 287^{+19}_{-17} (Dodson et al. 2003)
- Orientation from wind nebula (Ng & Romani 2008)



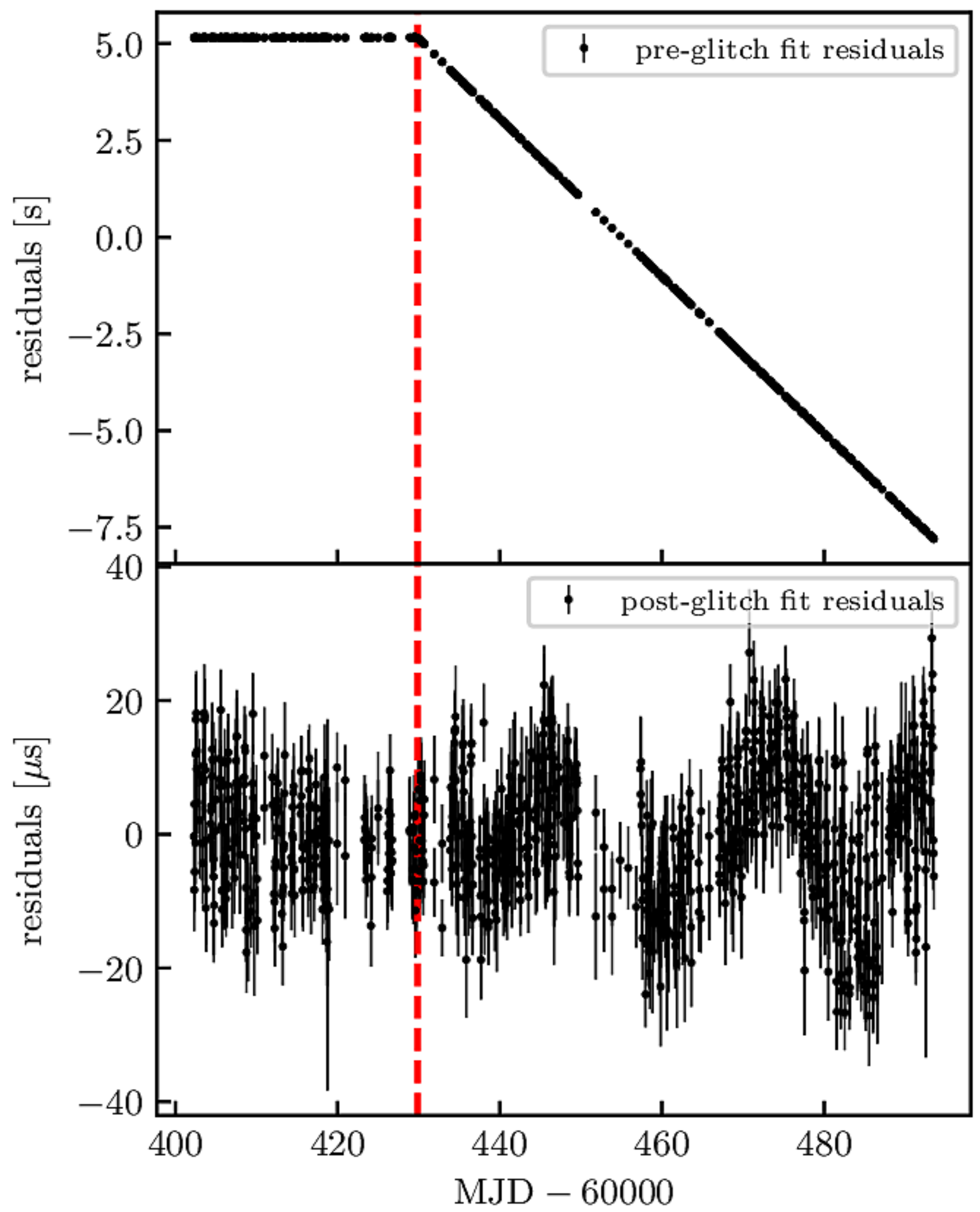
Schematic diagram of wind nebula used to compute Vela orientation. Image credit: Ng & Romani 2008



Vela pulsar jet in x-rays. Image credit: NASA/CXC/Univ. of Toronto/M. Durant, et al.

Properties of the glitch (IAR; MPRO)

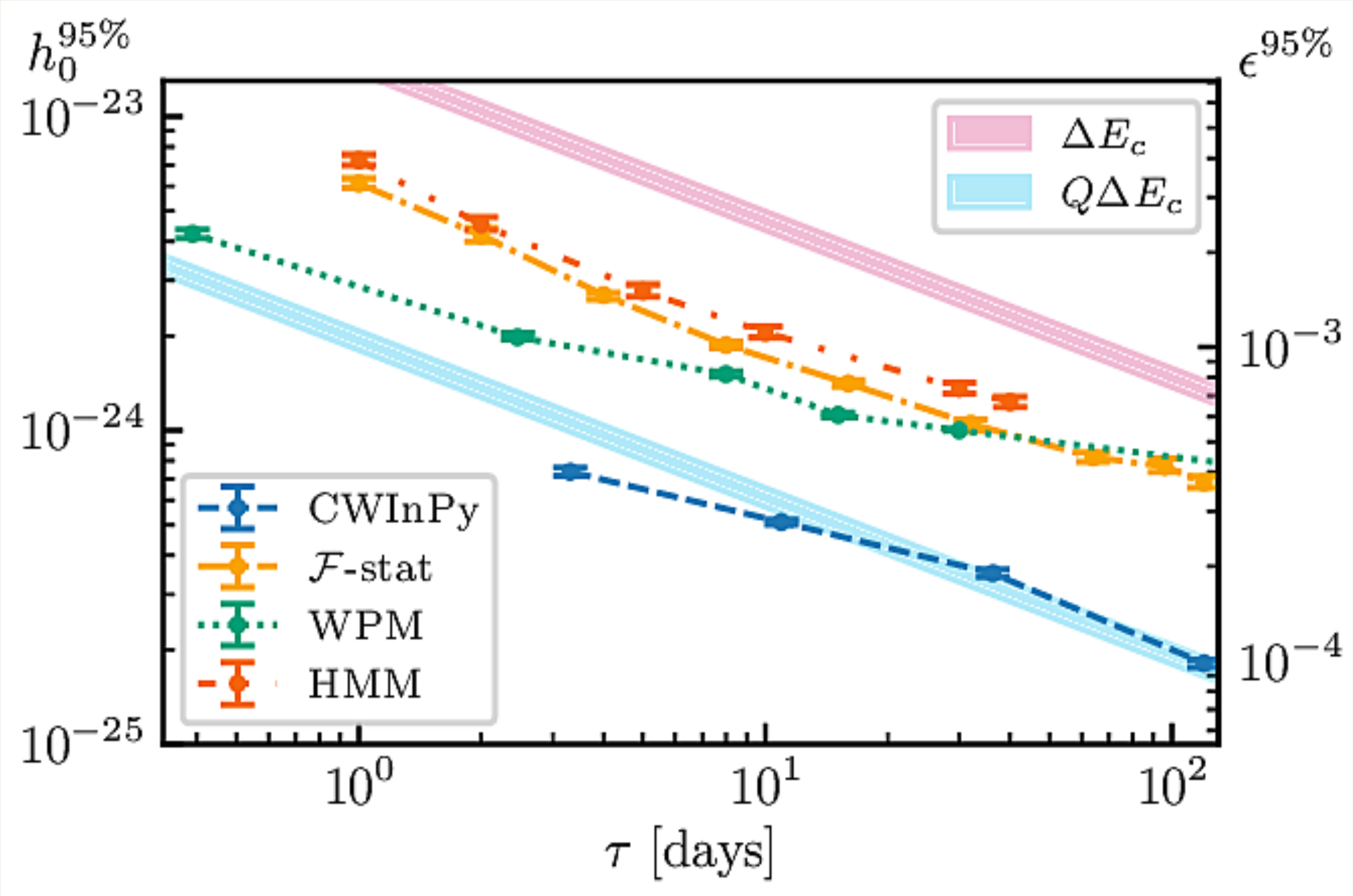
Parameter	**Value**
T_{gl} [d] (MJD)	60429.86975 ± 0.00139
T_{gl} [s] (GPS)	$1398459095.216 \pm 120.096$
Δf_{rot} [Hz]	$(2.65854 \pm 0.00005) \times 10^{-5}$
$\Delta \dot{f}_{rot}$ [Hz,s^{-1}]	$(-1.0298 \pm 0.0009) \times 10^{-13}$
τ_d^1 [d]	15.1 ± 0.1
$\Delta f_{rot}^{d,1}$ [Hz]	$(1.501 \pm 0.004) \times 10^{-7}$
τ_d^2 [d]	2.45 ± 0.06
$\Delta f_{rot}^{d,2}$ [Hz]	$(1.24 \pm 0.03) \times 10^{-7}$
τ_d^3 [d]	0.39 ± 0.03
$\Delta f_{rot}^{d,3}$ [Hz]	$(1.8 \pm 0.1) \times 10^{-7}$



Glitch fitting residuals (Abac et al. 2026)

Continuous Wave search results

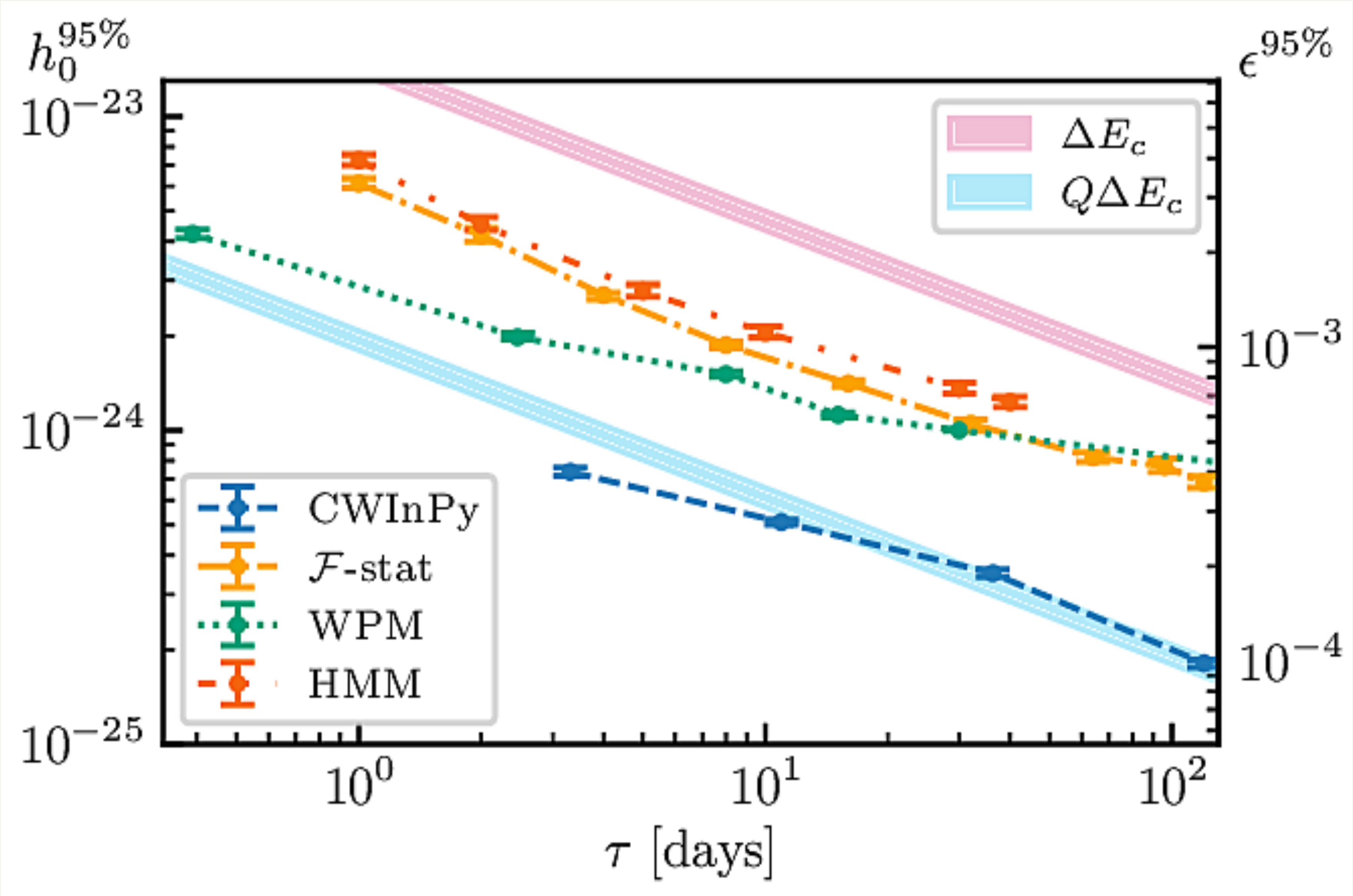
- Searches performed with multiple pipelines:
  - CWInPy (Pitkin 2022)
  - Transient $\mathcal{F}$-statistic search (Prix et al. 2011)
  - Weighted peakmap search (WPM) (Astone et al. 2005; Astone et al. 2014; Piccinni et al. 2019)
  - Hidden Markov model (HMM) (Jaranowski et al. 1998; Suvorova et al. 2016; Sun et al. 2018)
- No candidates found



(Abac et al. 2026)

Continuous wave search implications

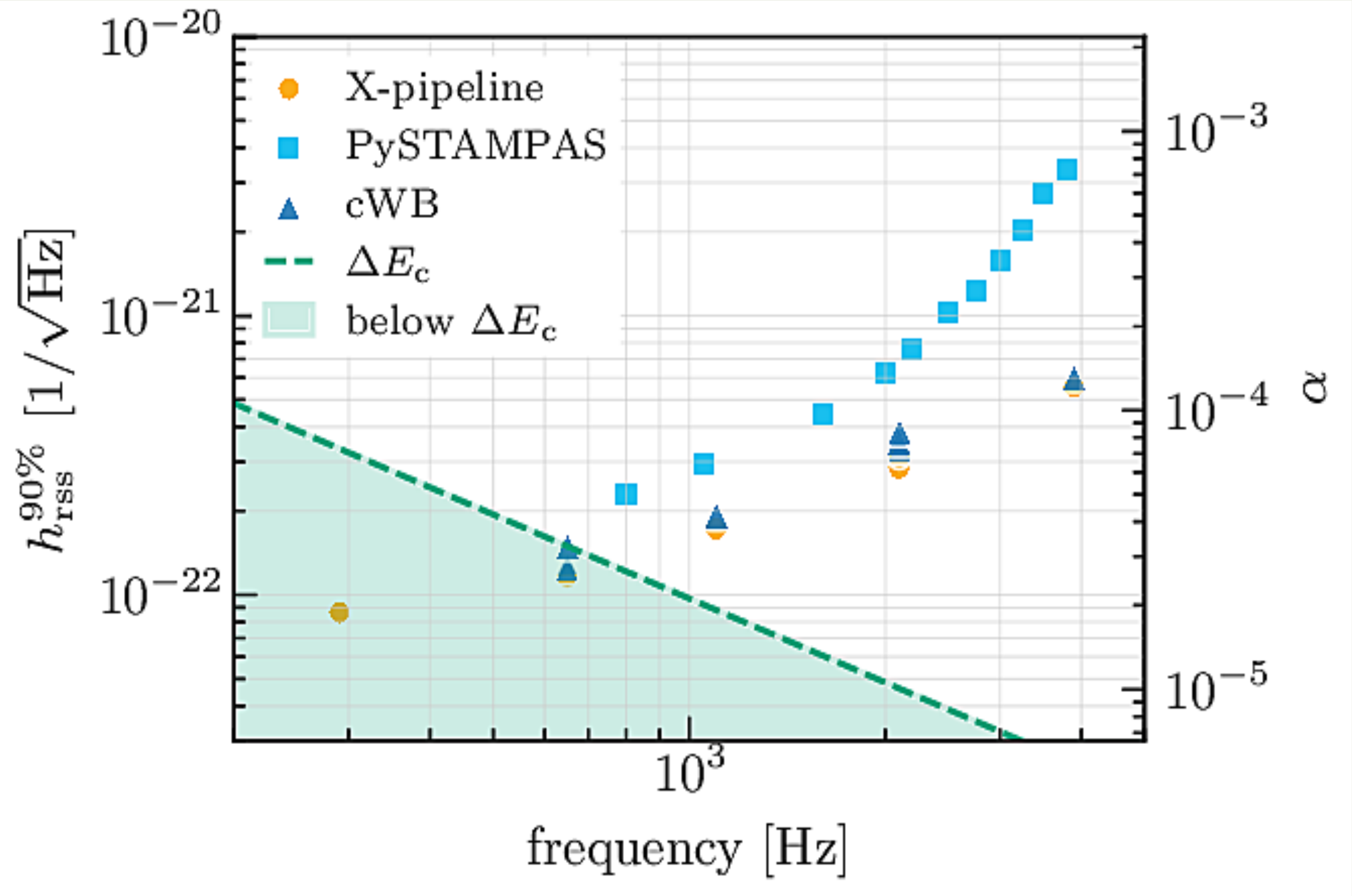
- Transient mountain model still below upper limits by most searches when including healing parameter Q (Yim & Jones 2020)
  - Barely probed by most restrictive CWInPy analysis
  - All analyses probe below characteristic energy ΔE_c



(Abac et al. 2026)

GW burst search results

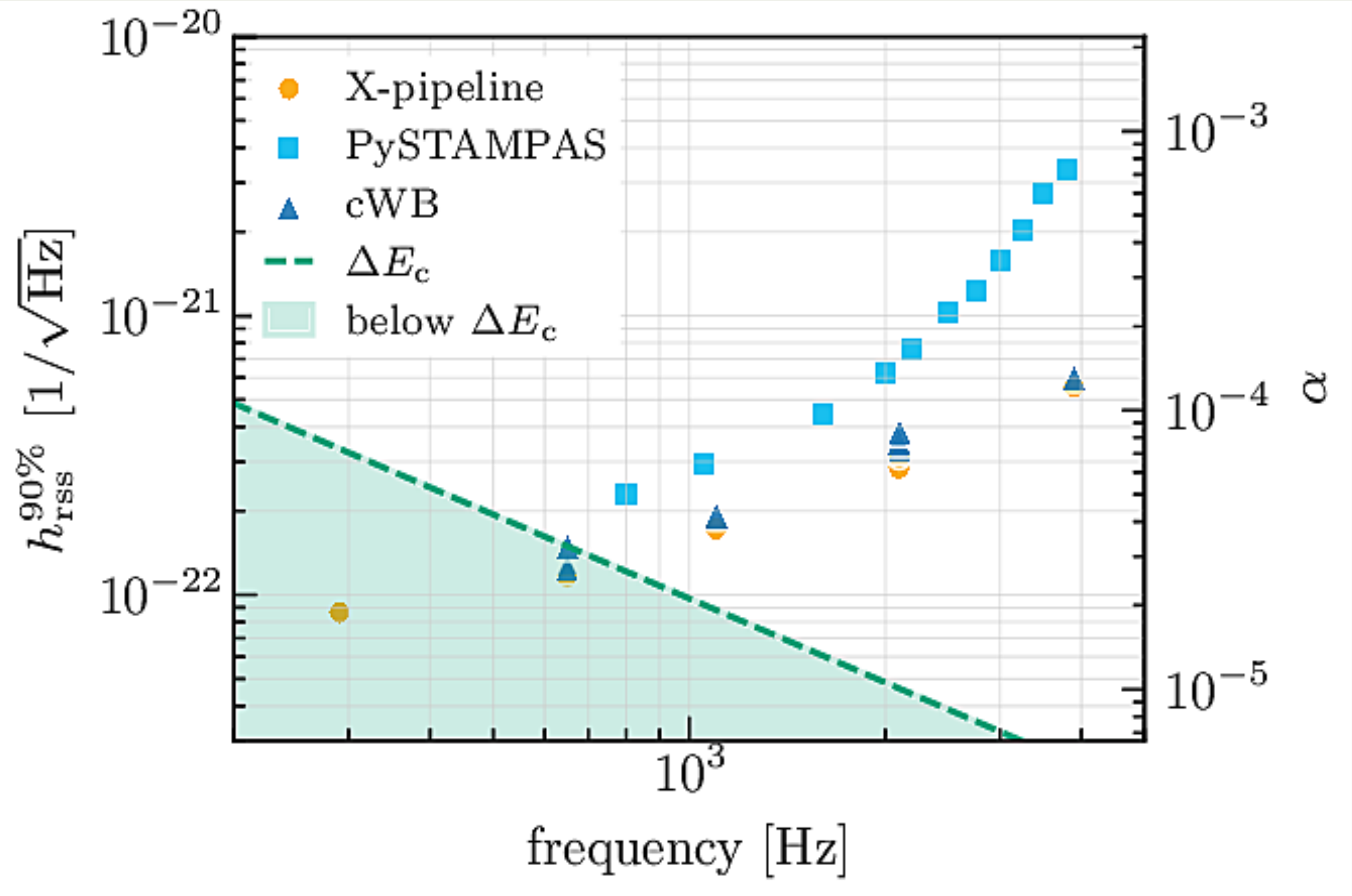
- Searches performed with multiple pipelines:
  - Coherent Wave Burst (cWB) (Klimenko et al. 2016; Drago et al. 2021; Martini et al. 2025)
  - pySTAMPAS (Macquet et al. 2021)
  - X-Pipeline (Sutton et al. 2010; Was et al. 2012)
- No candidates found



(Abac et al. 2026)

GW burst search implications

- Searches probe below characteristic strain below about 800 Hz
- f-mode emission very unlikely at these low frequencies (Wilson & Ho, 2024)
- Upper limits can be converted into a limit on the physical deformation of the surface of the NS (Yim & Jones 2023)
  - For $M = 1.4M_\odot$ and $R = 10^6$ cm, the surface deformation is constrained to $\lesssim 70\,\mathrm{cm}$

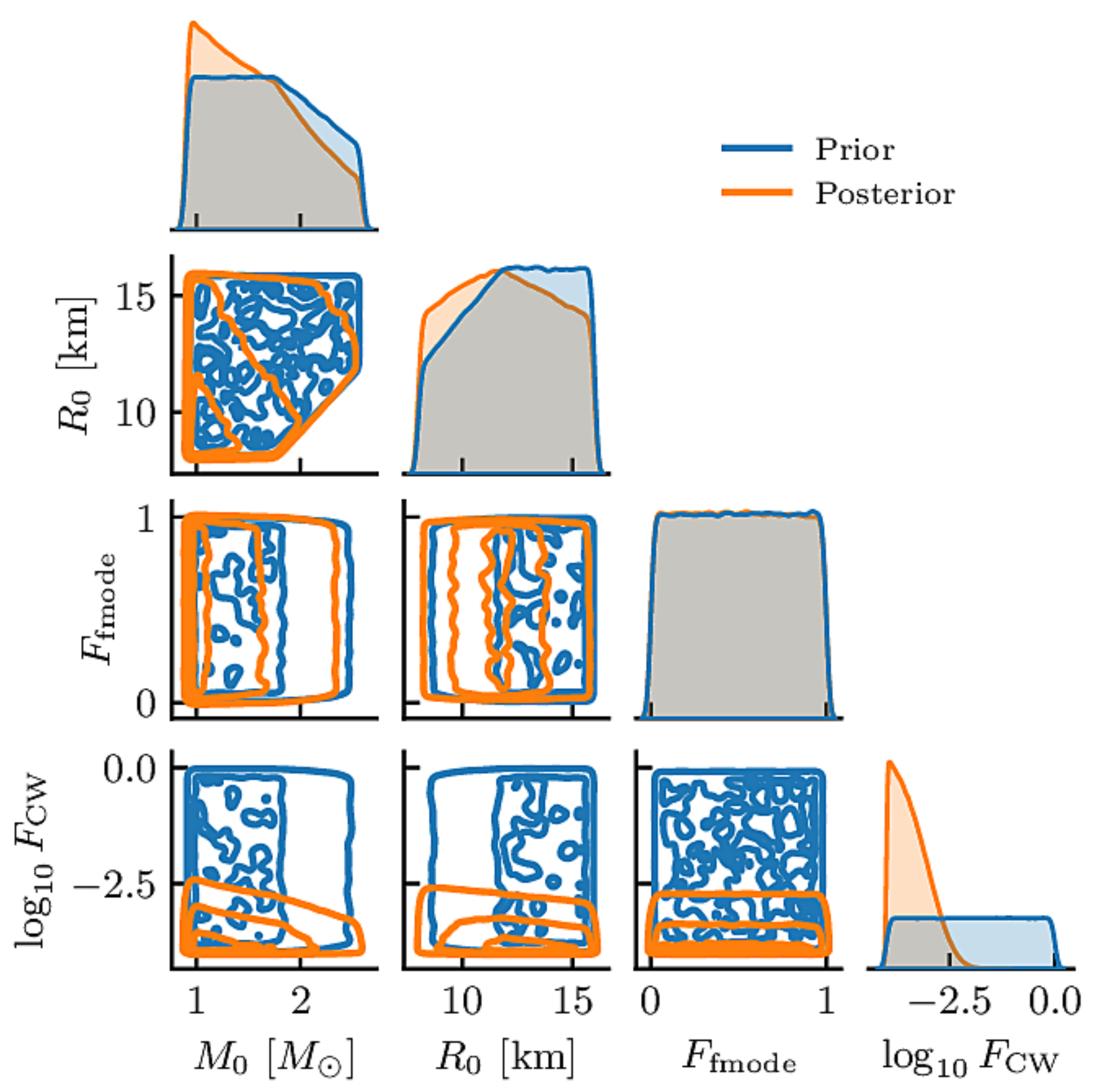


(Abac et al. 2026)

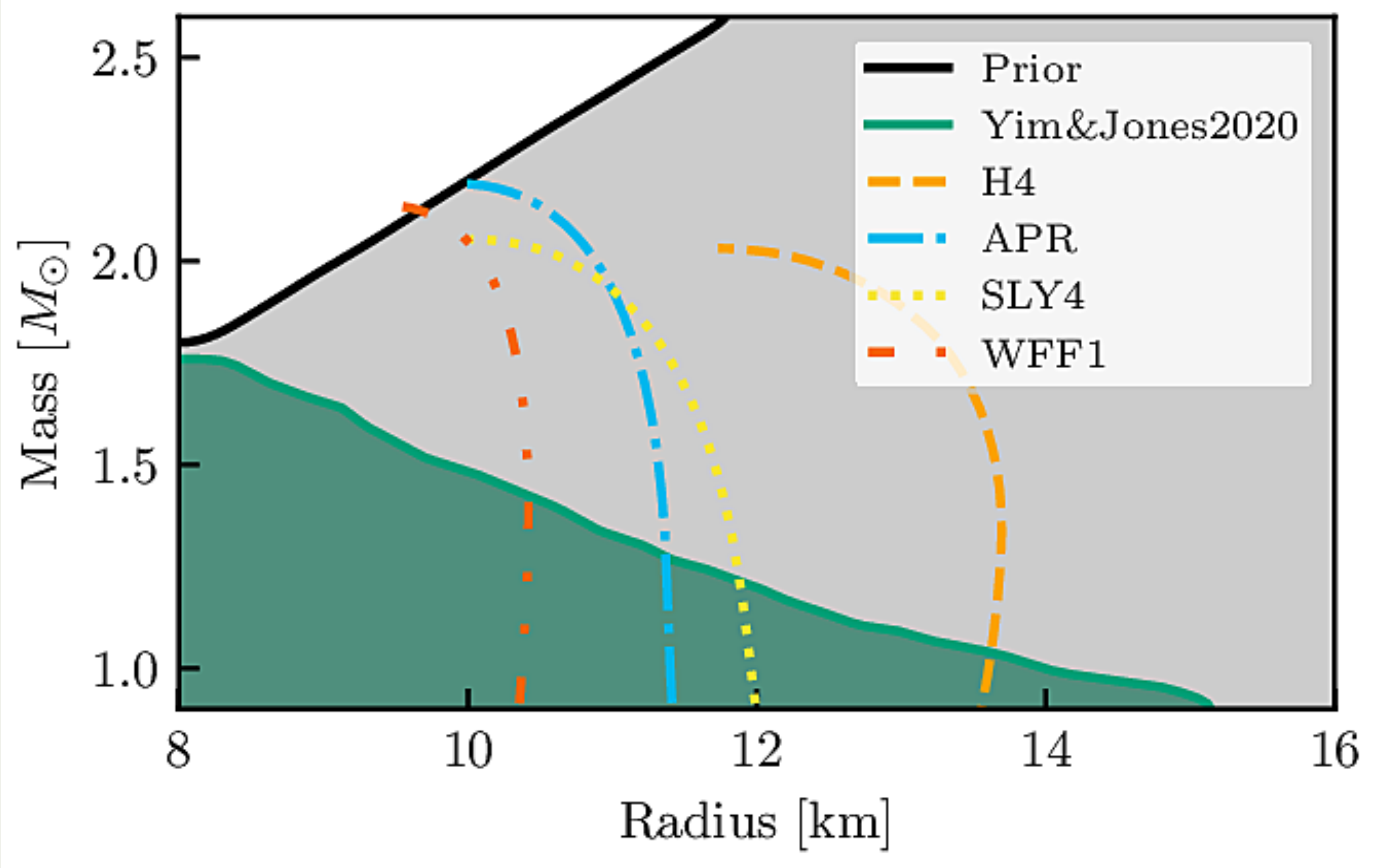
Joint implications from non-detection

- Assume both a tCW and short GW burst were emitted but not detected
- Assume more parameterized model:
  - Transient mountain model for tCW
  - f-mode for burst
  - Energy in each channel given by fractions F_{fmode} and F_{CW} relative to characteristic energy $\Delta E_c = 4\pi^2 \mathcal{I}_{zz} \nu_s \Delta \nu_s$
- Use results from most sensitive (optimistic) pipeline from each search
  - CWInPy for tCW
  - X-Pipeline for burst
- Use equation-of-state independent universal relations to connect mass and radius to the moment of inertia (Yagi & Yunes, 2017) and f-mode frequency & damping time (Pradhan et al. 2022)

Joint implications from non-detection



Allowing $F_{\rm fmode}$ and $F_{\rm CW}$ to freely vary (Abac et al. 2026)



Constraining $F_{\rm fmode} = 0.8$ and $F_{\rm CW} = Q$ (Abac et al. 2026)

Prospects for Simultaneously Detecting Long and Short Duration Gravitational Waves from Pulsar Glitches with Current and Future Detectors

Work in progress

Future detector networks

- Expect both Cosmic Explorer (Evans et al. 2021; Srivastava et al. 2022) and the Einstein Telescope (Branchesi et al. 2023) in the next few decades
- Anticipate an order of magnitude increase in sensitivity over current generation

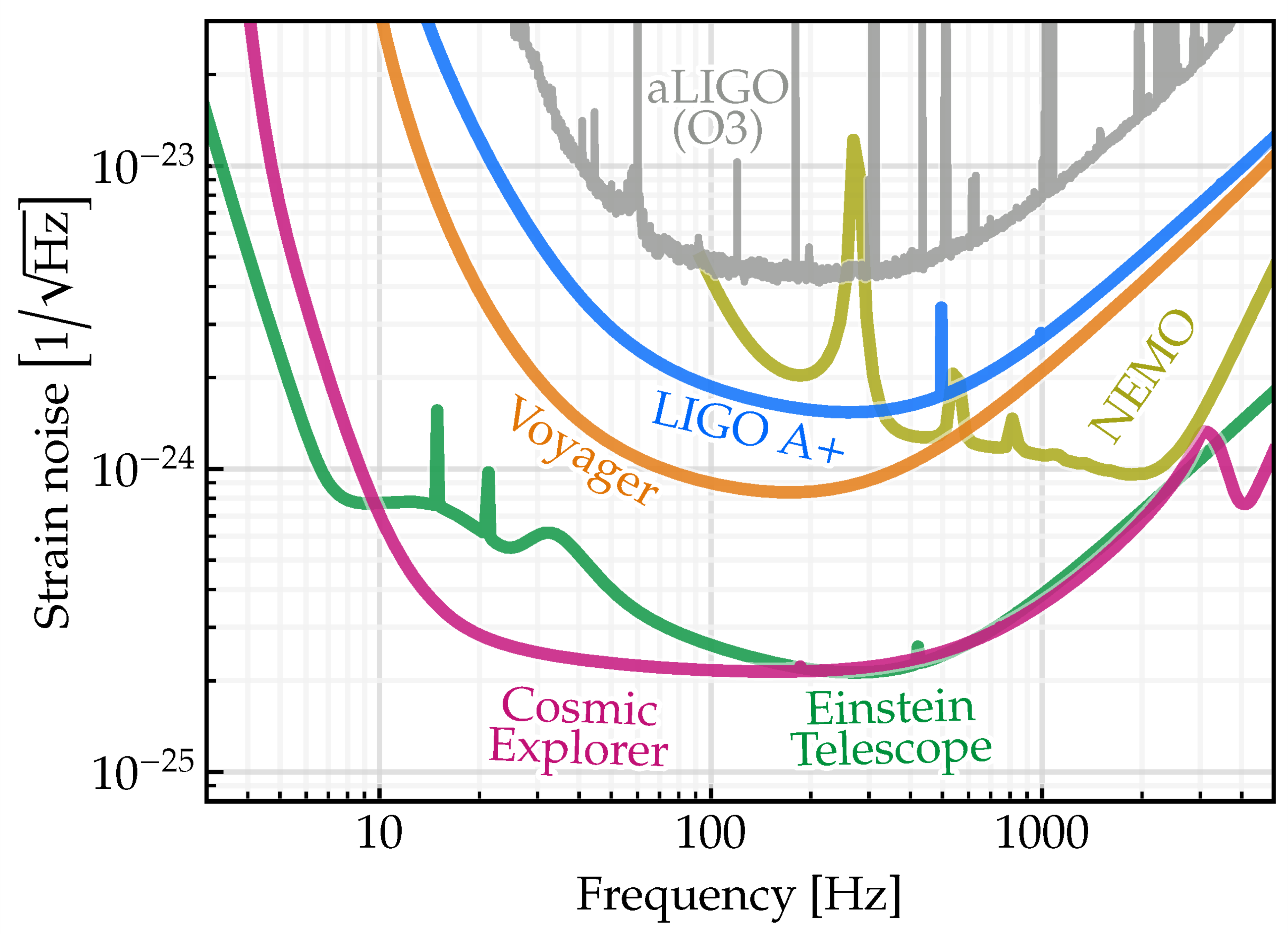


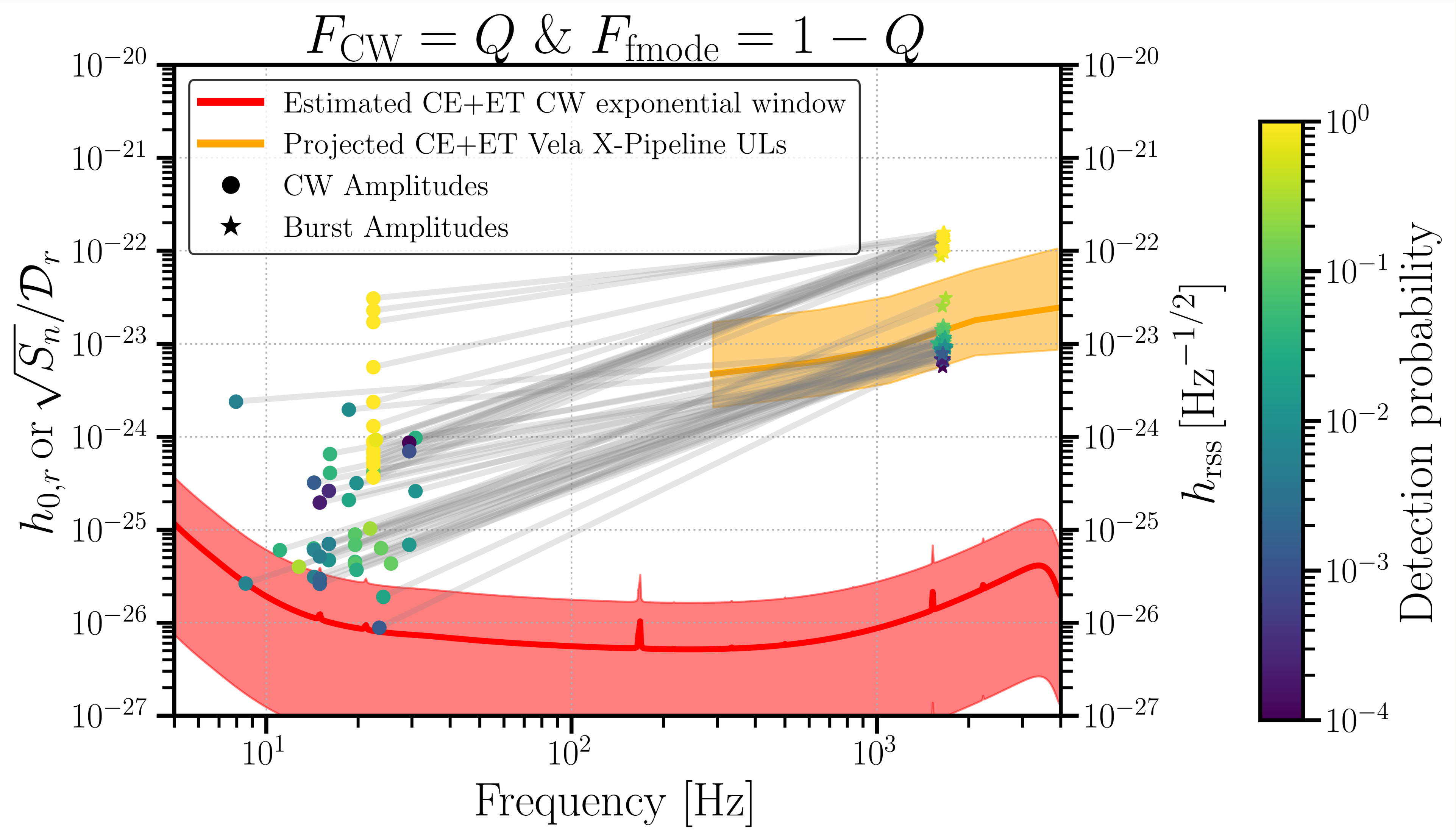
Figure credit: Evan Hall, 2022

Projecting results to future detectors

- Estimating CW limits for future observing runs & detectors via sensitivity depth
  - Sensitivity depth defined as $\mathcal{D} = \sqrt{S_n}/h_0$
  - Sensitivity depth of O5, CE, ET from Moragues et al. (2023)
  - Repeat their method for CE+ET network with cows3 infrastructure (Mirasola & Tenorio 2024)
- Projecting Burst h_{rss} limits to future observing runs & detector networks
  - Assume that detectors have similar degrees of non-gaussianity
  - Assume that pipelines place limits at the same network SNR values
  - Geometric factor of sky location/source orientation/antenna pattern and detector ASD (Sutton 2013)

Prospects of detection in future detectors

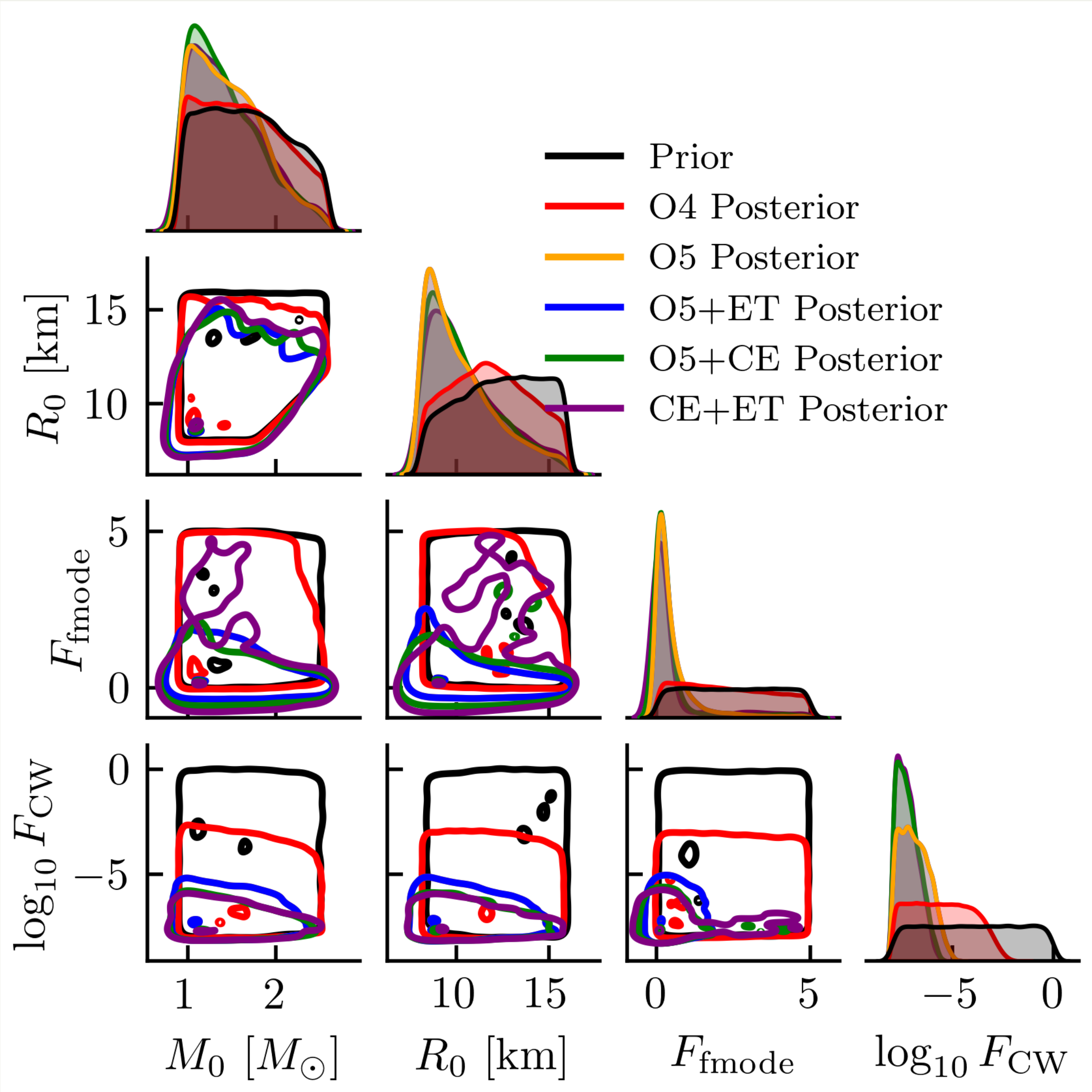
- Catalog of past ATNF pulsar glitches with measured healing parameters (Manchester et al. 2005; ATNF 2026)
- Monte Carlo samples of astrophysical parameters for each glitch & compute fraction of samples that give characteristic amplitude above projected O4 search limits
  - Require both tCW and f-mode GW amplitude to exceed respective search limits
  - Fraction of samples reported as a probability of double-detection
- Fix energy fractions in different scenarios:
  - Equal energy: $F_{\mathrm{CW}} = Q$ and $F_{\mathrm{fmode}} = Q$
  - Both channels add up to characteristic energy: $F_{\mathrm{CW}} = Q$ and $F_{\mathrm{fmode}} = 1 - Q$



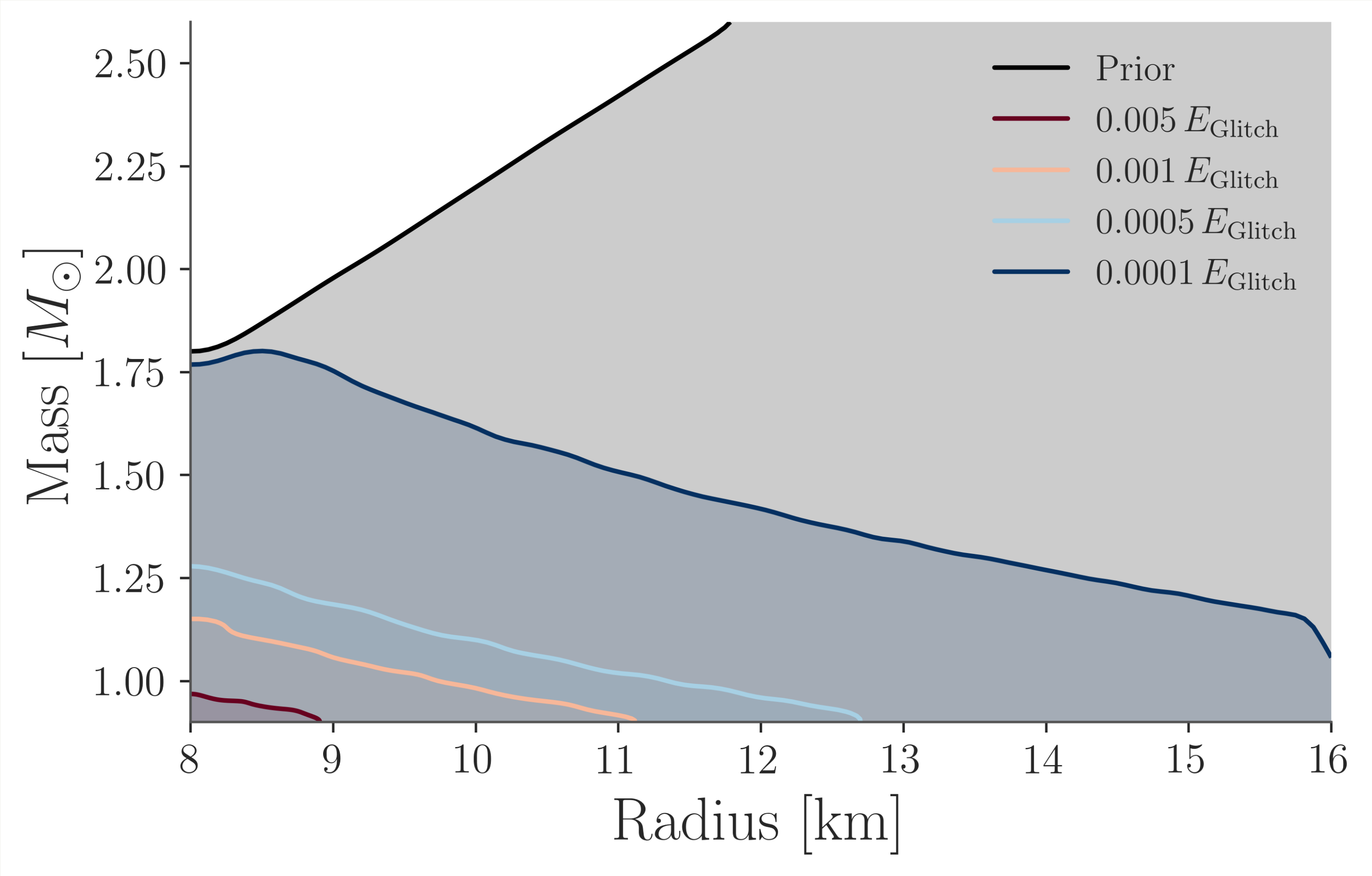
ET & CE network

Implications of non-detection in future detectors

- Uninformed prior on the energy fractions
- Little to learn without limits on energy fractions



- Fixed energy fractions but with a global factor $F_{\rm tot}$ limiting the total GW energy such that $F_{\rm CW} + F_{\rm fmode} = F_{\rm tot}$. Thus, we have $F_{\rm CW}/F_{\rm tot} = Q = 0.017$ and $F_{\rm fmode}/F_{\rm tot} = 1 - Q$



An ET + CE network would match the O4 constraints if the available GW energy was a factor of 10^4 lower than the characteristic glitch energy

Including constraints on the EoS from NICER

- Work with Melissa Mendes (Technische Universität Darmstadt)
- Construct mass/radius prior from NICER posterior (Lucien Mauviard et al 2025)
- Two different priors use different high-density parameterizations to minimize prior dependence
- Re-analyze 2024 Vela glitch under joint analysis framework
  - Greatly restricts allowed mass/radius parameter space
  - Under (many) assumptions, upper limit on the mass could be placed

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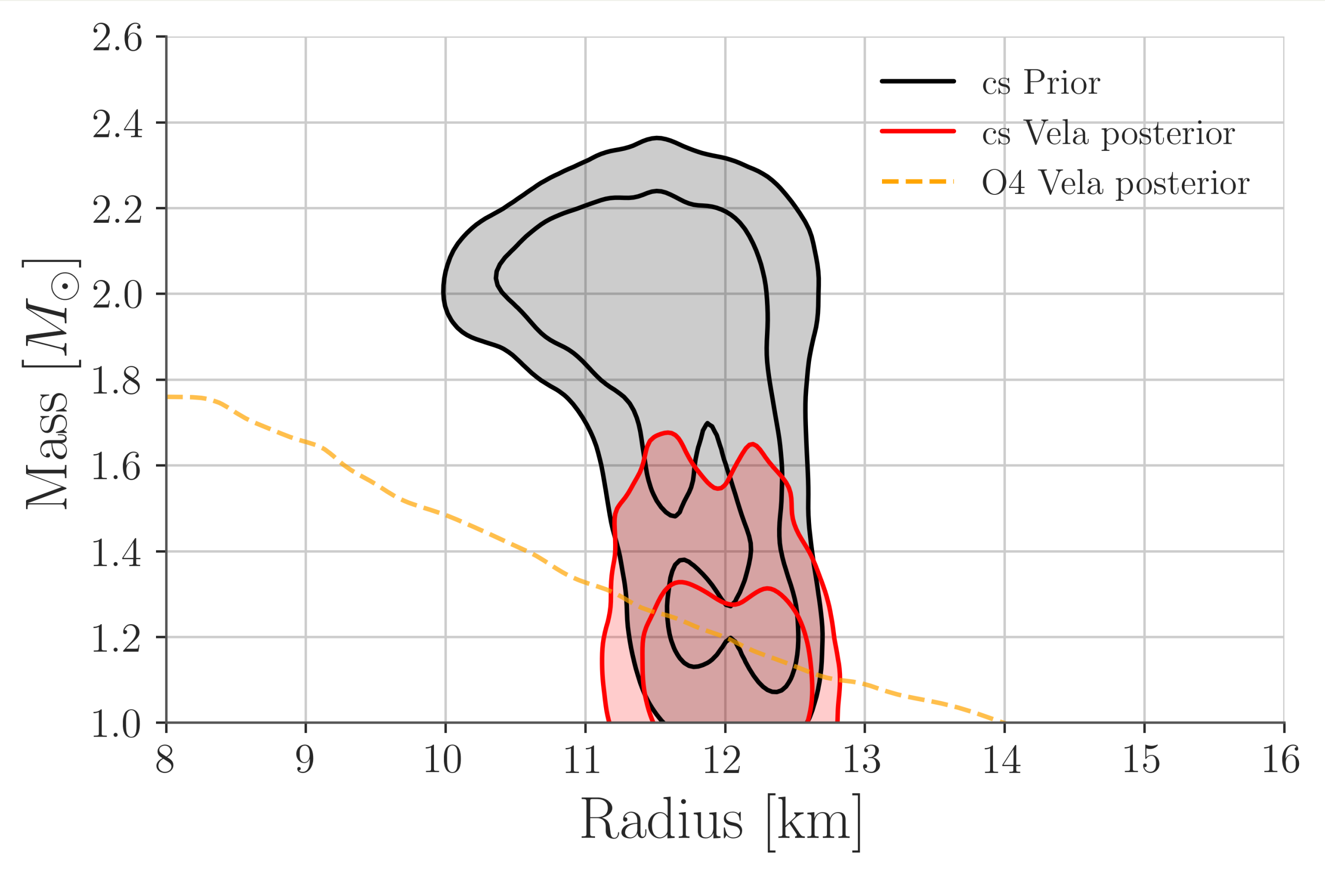
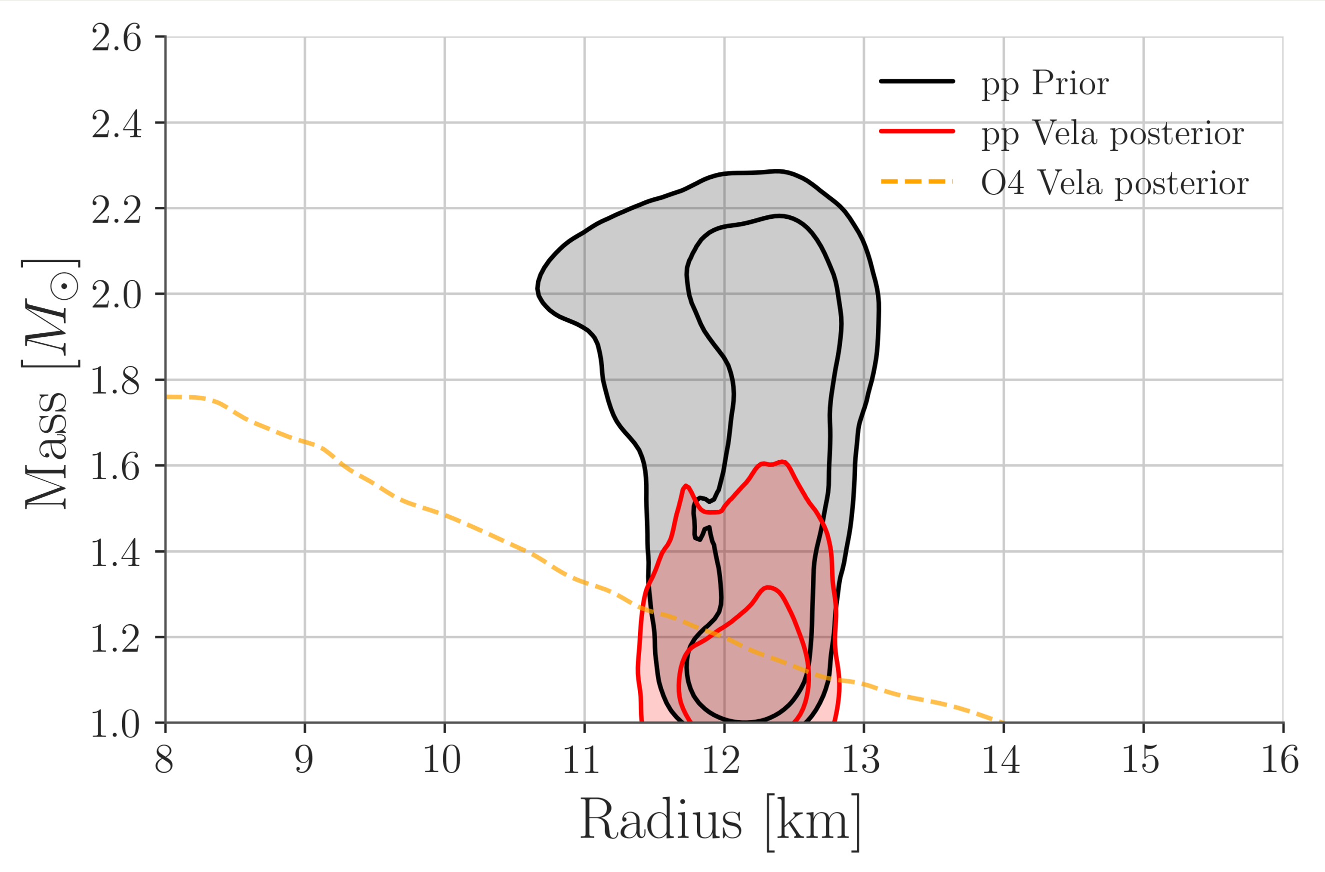


NS speed of sound model



Piecewise-polytropic model

Conclusions/Summary

- O4 search on Vela probes close to model limits for CW emission
  - burst still a ways off
- 3rd generation detectors massively improve detection probability for several pulsars
  - Still will not observe all pulsar glitches
  - Vela still a priority target
- Future searches will either detect something, likely with both CW and burst (assuming targeted searches on every glitch), or start disproving models
- Need more parameterized models to better inform future upper limits

Acknowledgements

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Extra slides

Details on estimating CW sensitivity for future detectors

- Follow methodology detailed in Moragues et al. (2023)
- Use COWS3 python package (Mirasola & Tenorio, 2024)
- Select Crab & Vela pulsars as representative targets
- Network sensitivity is the harmonic mean of the detectors in network
- Generate a distribution of SNR values for a unit sensitivity depth signal for 120 days of observation with 1800s segments for each detector in the network
- Generate a distribution of the χ^2 random variable $2\mathcal{F}$ outliers based on the number of templates used in the original analysis (3.9×10^6 for the Crab pulsar and 3.6×10^5 for the Vela pulsar)
- Fit to a Gumbel distribution, and we take the 99th percentile for this outlier distribution
- Compute the false-dismissal probability for different sensitivity depths using our $2\mathcal{F}$ threshold and unit-depth SNR distribution
- Take the sensitivity depth that gives a false-dismissal probability of 0.05
- This process gives $\mathcal{D} = 30.4/\sqrt{\text{Hz}}$ (Crab) and $\mathcal{D} = 36.7/\sqrt{\text{Hz}}$ (Vela) for CE+ET
- Take the average of $\mathcal{D} = 33.6/\sqrt{\text{Hz}}$ as sky-averaged sensitivity depth

Details on projecting burst results to future detectors

- Sutton, 2013 showed that the relation between the signal-to-noise ratio ρ and $h_{\rm rss}$ for a short-duration, monochromatic signal is

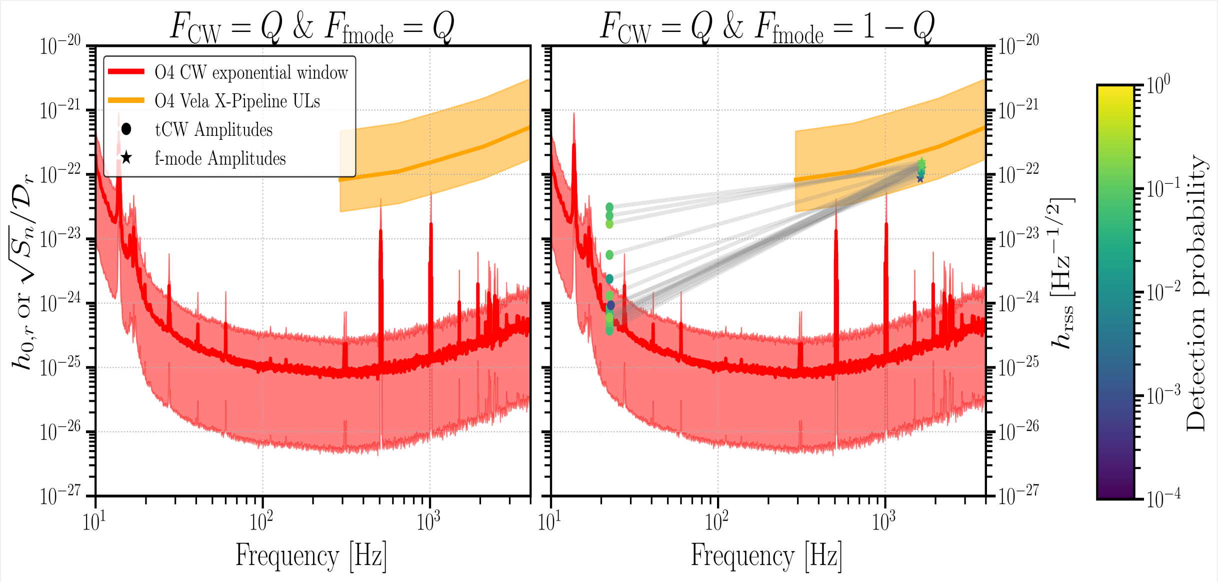
$$\rho^2 = \Theta^2 \frac{h_{\rm rss}^2}{S_n(f_0)}$$

where Θ is a geometric term defined in terms of the detector antenna pattern and source inclination angle for different polarization cases:

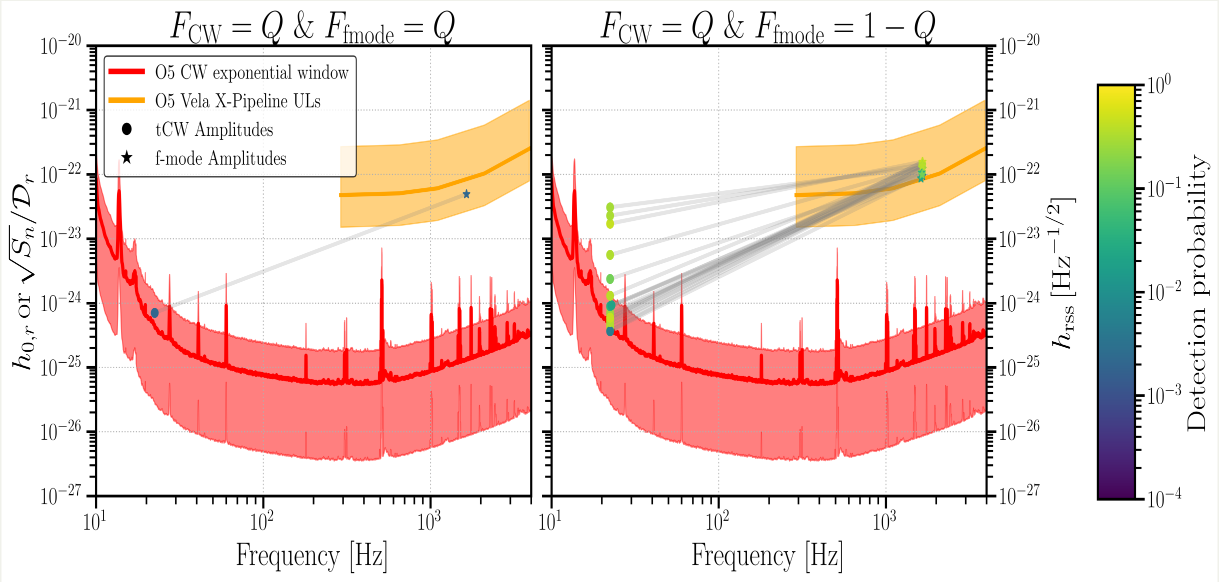
$$\Theta^2 \equiv \begin{cases} F_+^2(\theta,\phi,\psi) + F_\times^2(\theta,\phi,\psi) & \text{Unpolarized} \\ F_+^2(\theta,\phi,\psi)\left(\frac{1+\cos^2(\iota)}{2}\right)^2 + F_\times^2(\theta,\phi,\psi)\cos^2(\iota) & \text{Ellipitical} \\ F_+^2(\theta,\phi,\psi)\, 2\sin^4(\iota) & \text{Linear} \end{cases}$$

- Assuming that a pipeline reaches ``detectability'' at similar ρ for different noise realizations, we equate ρ for different detectors and solve for $h_{\rm rss}$, using the respective detector details for the geometric term Θ.

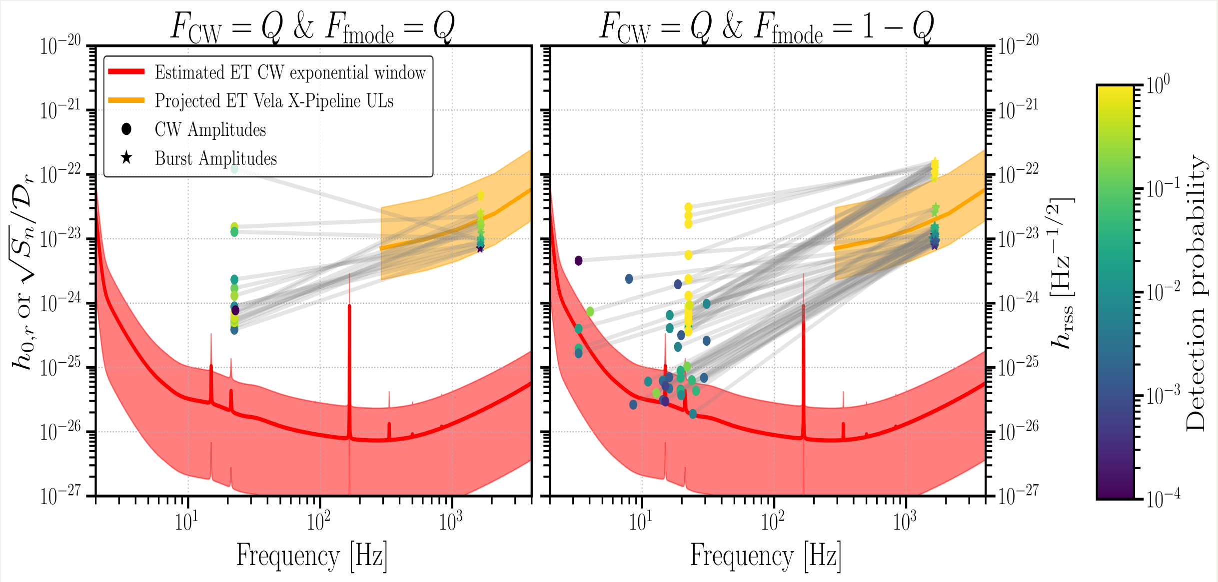
Pulsar glitch dual-detection plots for other detector networks



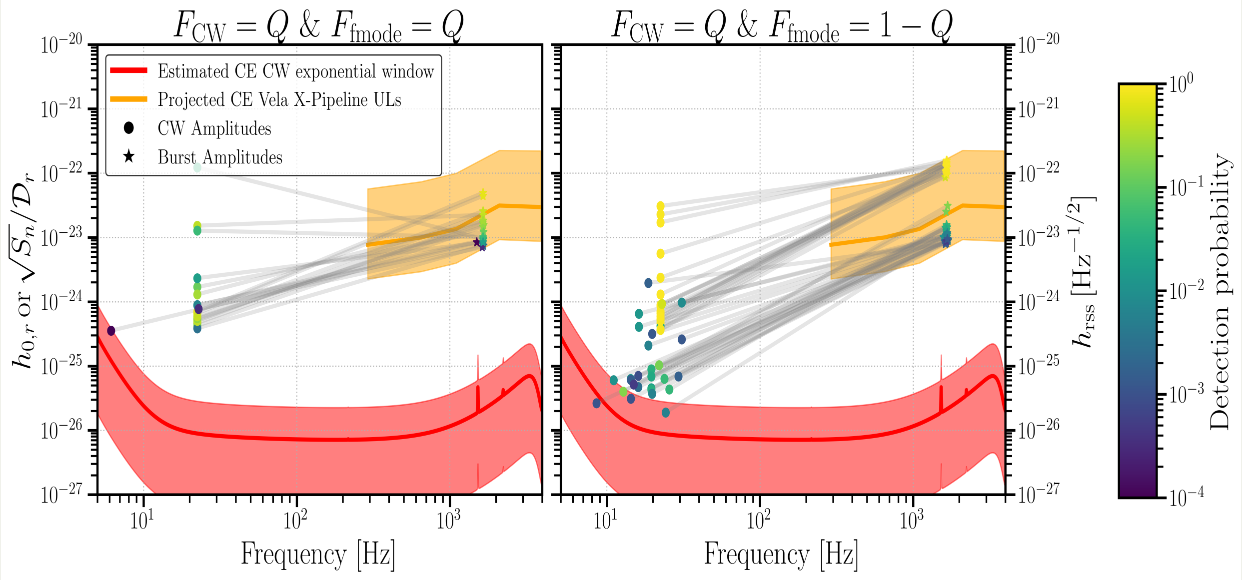
O4 network



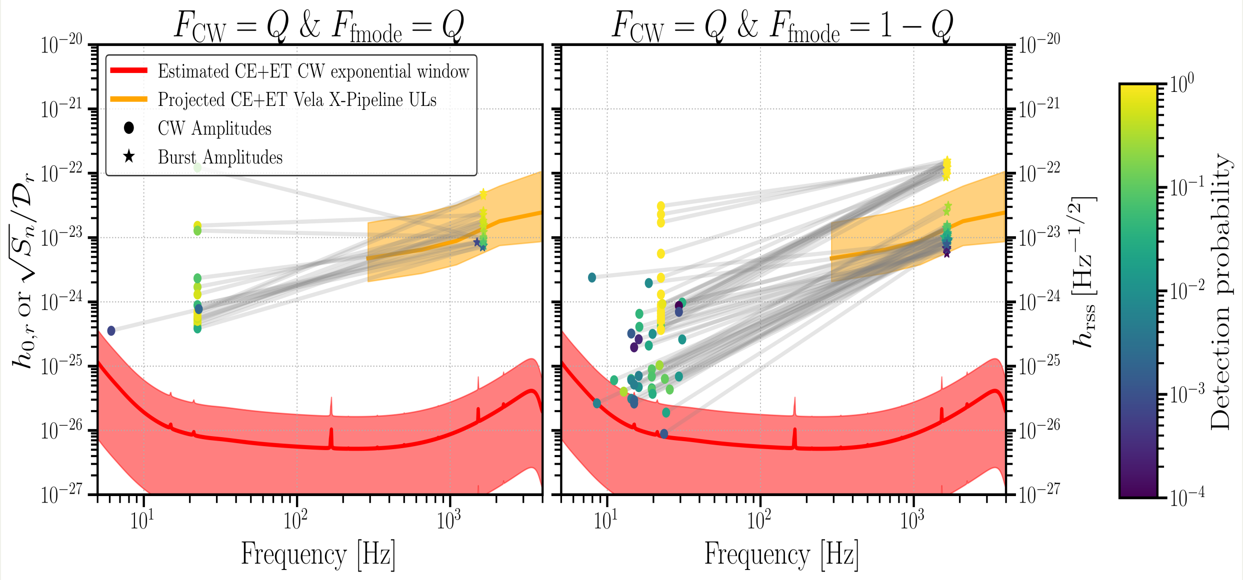
O5 network



ET & O5 network



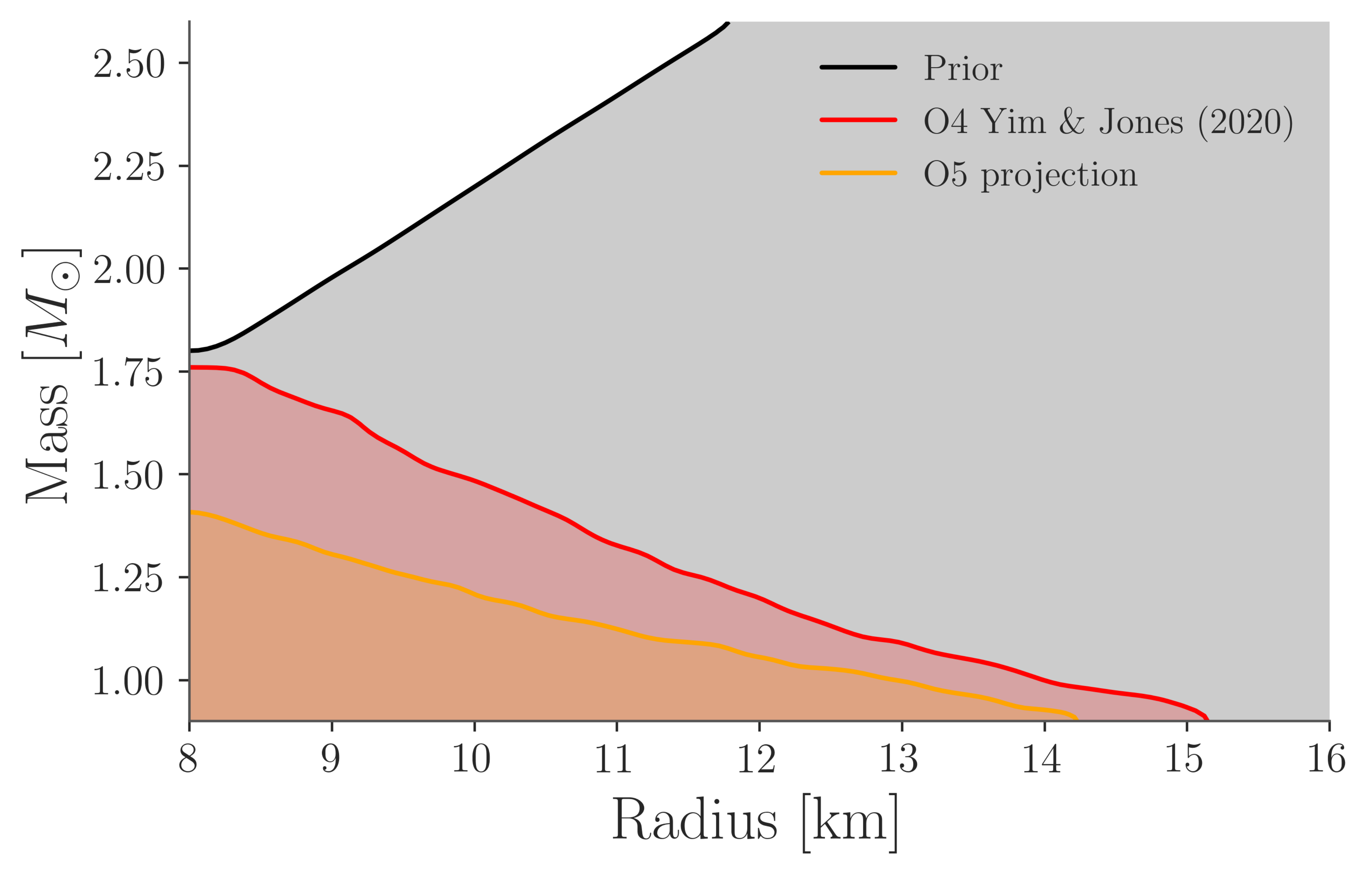
CE & O5 network



ET & CE network

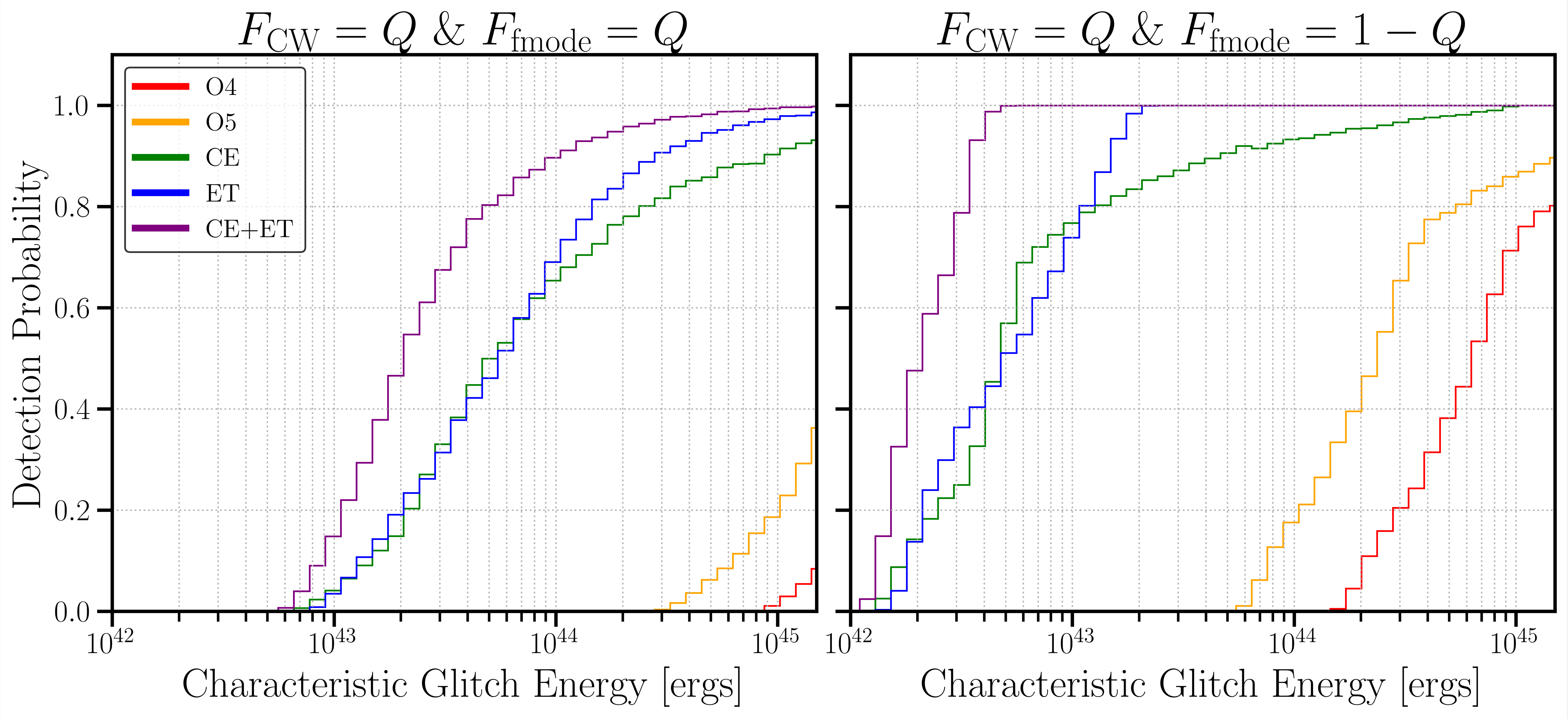
O4 & O5 projected Vela non-detection fixed energy plots

- Repeating the non-detection CW+Burst analysis performed in Abac et. al. (2026) with the projected sensitivity of future detectors
- Using $F_{\mathrm{CW}} = Q = 0.017$ and $F_{\mathrm{fmode}} = 0.8$
- 3rd generation detector sensitivities not compatible with a non-detection under the Yim &Jones (2020) model



Vela detectable energy

- Mass and radius are fixed to 2 $M_\odot$ and 15 km (frequency of peak f-mode detectability)
- Q constrained to below 0.2



Universal relations

- Moment of inertia relation (Yagi & Yunes, 2017)

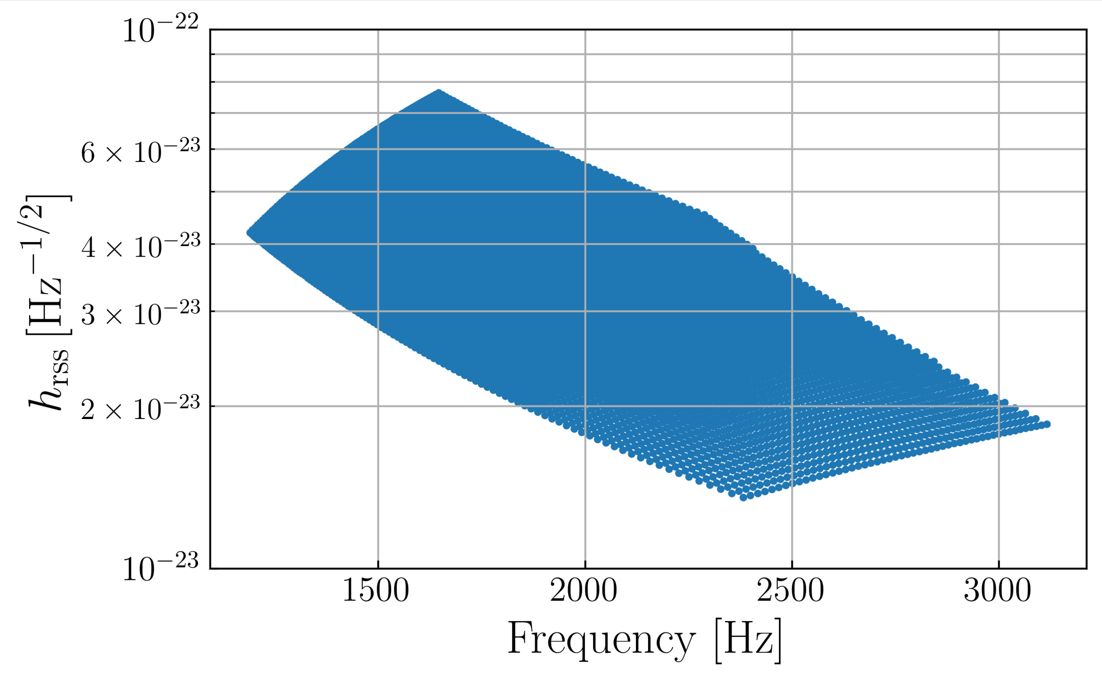
$$\log\left(\frac{I_{zz}}{M^3}\right) = -1.261\log\left(\frac{M}{R}\right) + 0.277$$

- f-mode frequency and damping time relations (Pradhan et al. 2022)

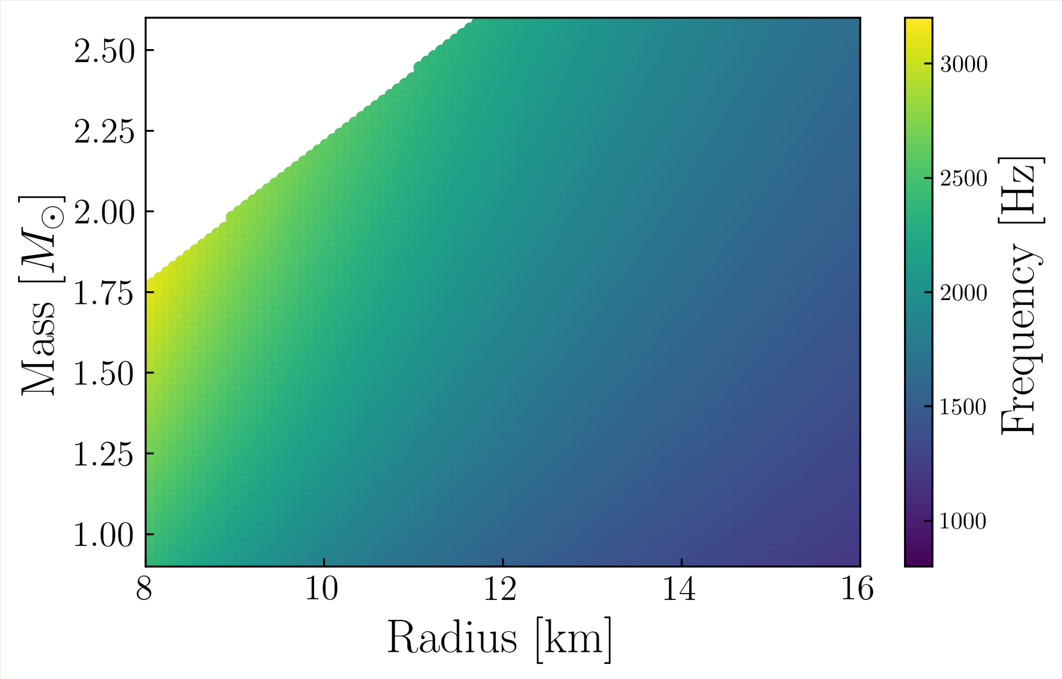
$$\nu_{f,0}(\mathrm{kHz}) \approx 0.535 + 1.646\left(\frac{\overline{M}}{\overline{R}^3}\right)^{1/2}$$

$$\frac{1}{\tau_f(s)} \approx \frac{\overline{M}^3}{\overline{R}^4}\left[21.19 - 13.41\left(\frac{\overline{M}}{\overline{R}}\right)\right]$$

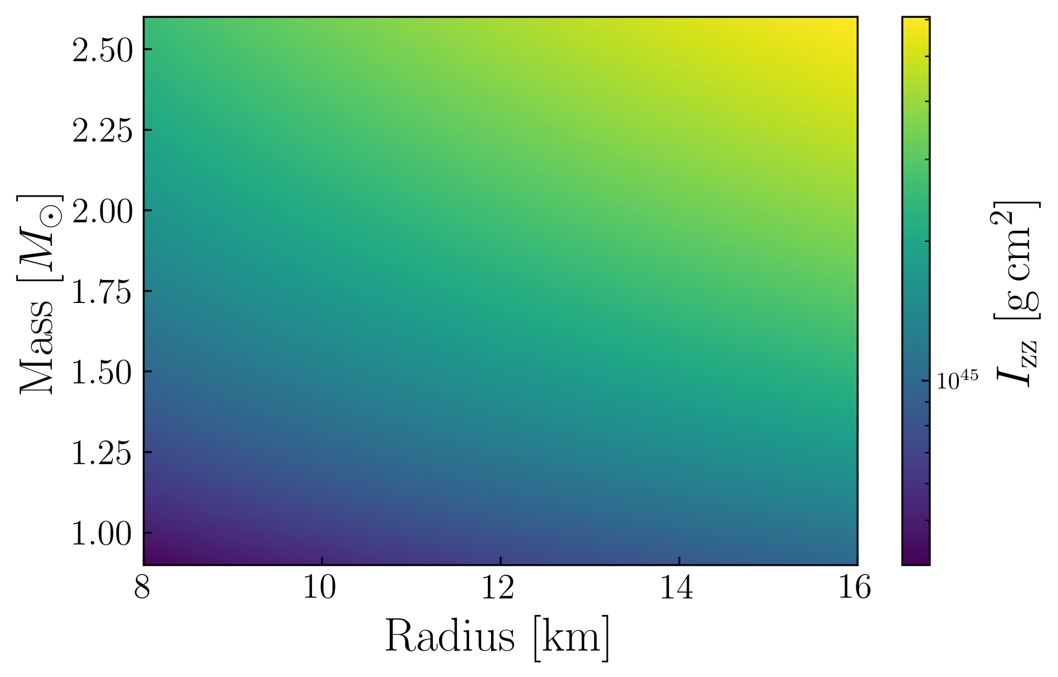
Some limits of the universal relations



f-mode frequency compared to $h_{\rm rss}$



f-mode frequency as function of mass and radius



Moment of inertia