Timing noise as a probe of neutron star interiors

Crust-superfluid coupling timescales for 105 UTMOST pulsars

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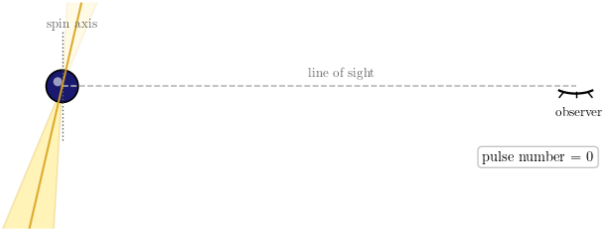
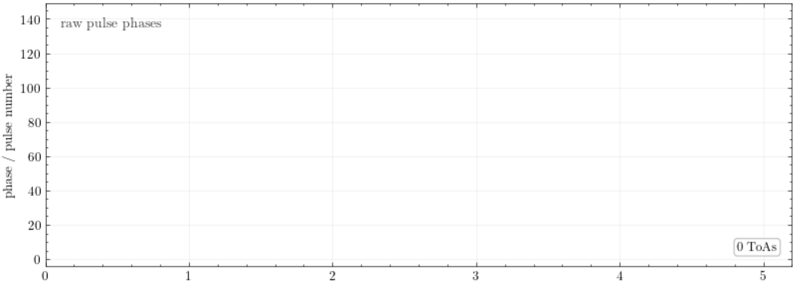
SCALES 1st General Meeting

Dong+ (2026)

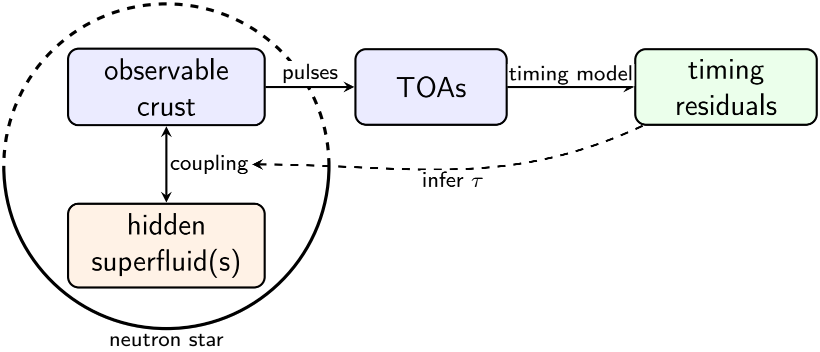
The quiet channel: what happens between glitches?





Skematic illustration for pedagogy.

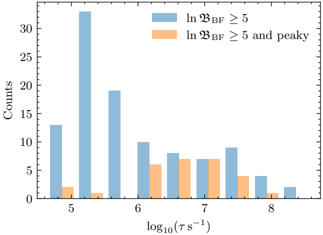
Observable crust, hidden superfluid



We only observe the crust directly (through pulses); timing noise can still constrain how it relaxes against a hidden angular-momentum reservoir.

Results flash

- 105 pulsars show strong evidence for two-component model over one-component WTN model
- 28/105 have resolved coupling timescales τ
  - ranging from days to years



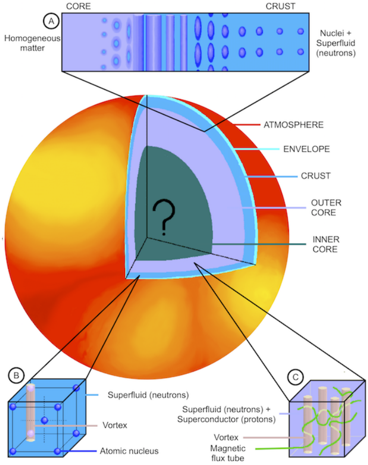
Population-level scaling, e.g. $\tau(\Omega_{\rm c}, \dot{\Omega}_{\rm c})$.

Three big unsolved questions

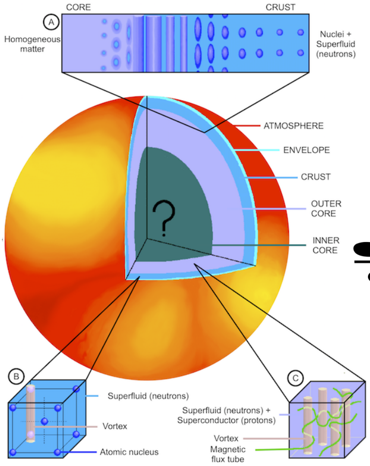
1. Can we distinguish between one- and two-component stars from timing noise?
2. Is the star's internal friction the same between glitches and during glitches?
3. Is the crust-superfluid coupling time-scale consistent with superfluid mutual friction across the pulsar population?

What strategy could the community adopt in addressing these questions?

From many internal degrees of freedom to an effective reservoir



From many internal degrees of freedom to an effective reservoir



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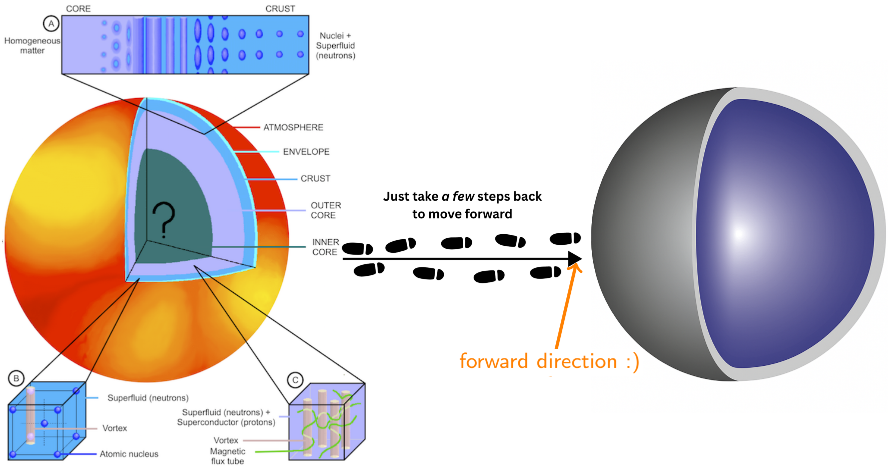
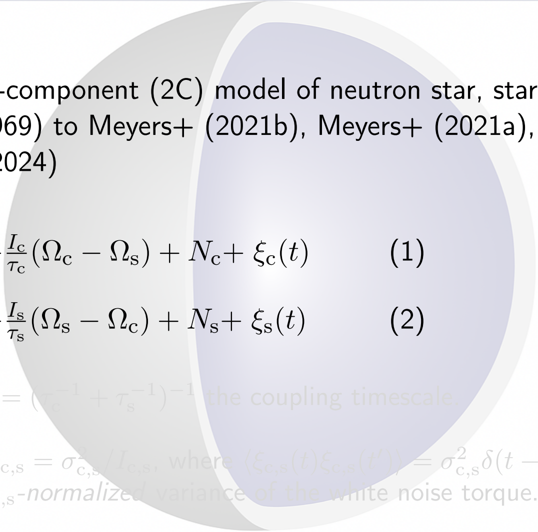


Just take *a few* steps back to move forward

forward direction :)

The two-component model



Classic two-component (2C) model of neutron star, starting from Baym+ (1969) to Meyers+ (2021b), Meyers+ (2021a), and O'Neill+ (2024)

$$I_\mathrm{c}\frac{\mathrm{d}\Omega_\mathrm{c}}{\mathrm{d}t} = -\frac{I_\mathrm{c}}{\tau_\mathrm{c}}(\Omega_\mathrm{c}-\Omega_\mathrm{s}) + N_\mathrm{c} + \xi_\mathrm{c}(t) \qquad (1)$$

$$I_\mathrm{s}\frac{\mathrm{d}\Omega_\mathrm{s}}{\mathrm{d}t} = -\frac{I_\mathrm{s}}{\tau_\mathrm{s}}(\Omega_\mathrm{s}-\Omega_\mathrm{c}) + N_\mathrm{s} + \xi_\mathrm{s}(t) \qquad (2)$$

-
    - $\tau = (\tau_\mathrm{c}^{-1} + \tau_\mathrm{s}^{-1})^{-1}$ the coupling timescale.
    - $Q_\mathrm{c,s} = \sigma^2_\mathrm{c,s}/I_\mathrm{c,s}$, where $\langle \xi_\mathrm{c,s}(t)\xi_\mathrm{c,s}(t')\rangle = \sigma^2_\mathrm{c,s}\delta(t-t')$. I.e. $I_\mathrm{c,s}$-*normalized* variance of the white noise torque.

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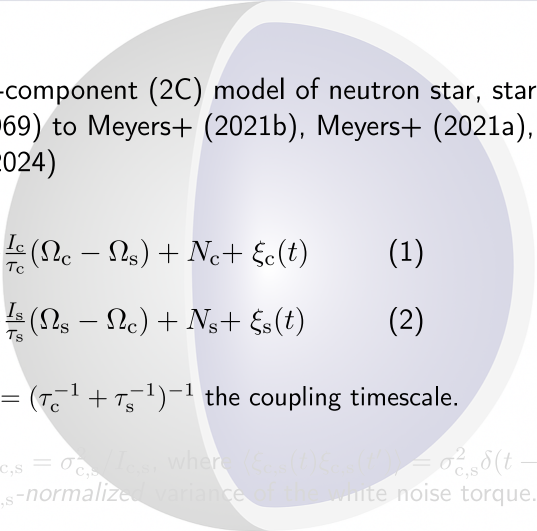

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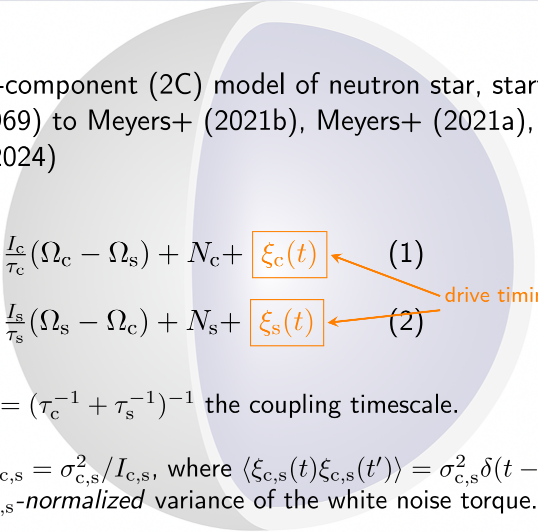

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drive timing noise.

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Model comparison

We run two models using TOAs returned by `tempo2`:

2C timing-noise model

- hidden superfluid reservoir
- lag relaxation timescale τ
- stochastic torques $Q_{\rm c}$ and $Q_{\rm s}$
- white measurement noise

vs.

1C WTN model

- no hidden reservoir
- deterministic quadratic spin-down
- no stochastic torques
- white measurement noise

Bayes theorem, Bayes factor, and all that

Bayes theorem

$$\overset{\text{posterior}}{p(\boldsymbol{\theta}|\boldsymbol{Y},\mathcal{M})} = \frac{\overset{\text{likelihood}}{\mathcal{L}(\boldsymbol{Y}|\boldsymbol{\theta},\mathcal{M})}\,\overset{\text{prior}}{\pi(\boldsymbol{\theta}|\mathcal{M})}}{\underset{\text{evidence}}{\mathcal{Z}_{\mathcal{M}}}} \tag{1}$$

- $\mathcal{Z}_{\mathcal{M}}$: evidence $=$ likelihood averaged over prior volume

Bayes factor

$$\mathfrak{B}_{\rm BF} = \frac{\mathcal{Z}_{\rm 2C}}{\mathcal{Z}_{\rm WTN}} \tag{2}$$

- $\ln \mathfrak{B}_{\rm BF} \geq 5 \equiv$ strong evidence for 2C over WTN

`dynesty` nested sampler: posterior samples $+$ evidence.

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`dynesty` nested sampler: posterior samples + evidence.

Likelihood evaluation: Why a Kalman filter?

- System is Markovian.
- Joint likelihood $\mathcal{L}_{\text{joint}}$ decomposes into

$$\prod_{n=1}^{N_{\text{TOA}}} \mathcal{L}(\boldsymbol{Y}_n | \boldsymbol{Y}_{n-1}, \boldsymbol{\theta})$$

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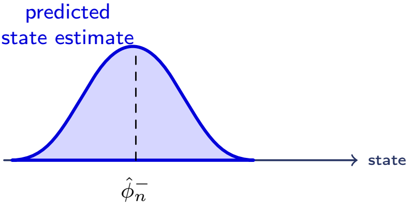

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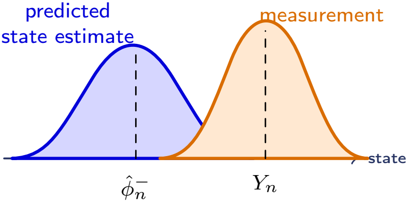

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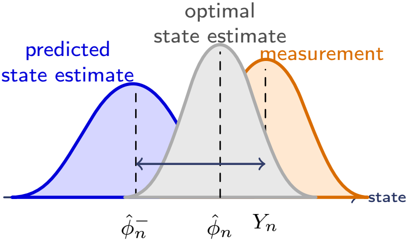

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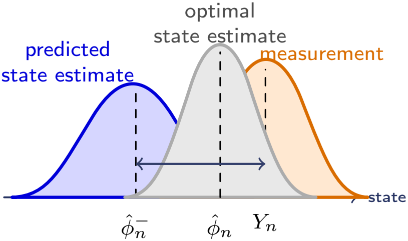
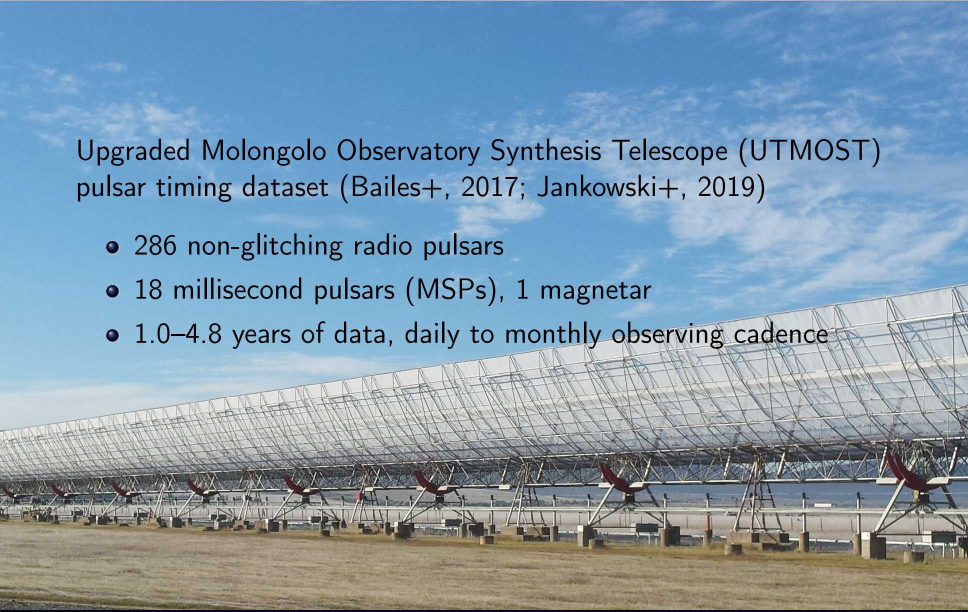
- The likelihood is evaluated sequentially from one TOA to the next.



- linear complexity $\mathcal{O}(N_{\text{TOA}})$

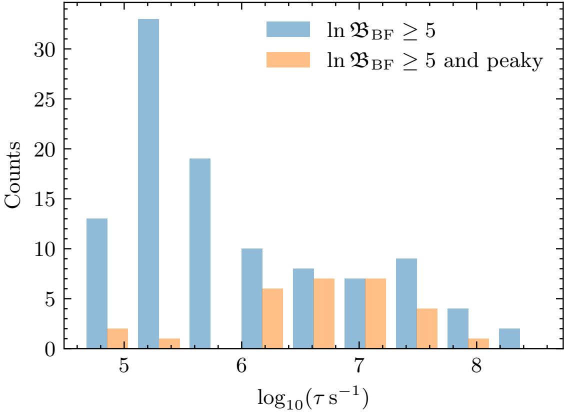
UTMOST dataset



Upgraded Molongolo Observatory Synthesis Telescope (UTMOST) pulsar timing dataset (Bailes+, 2017; Jankowski+, 2019)

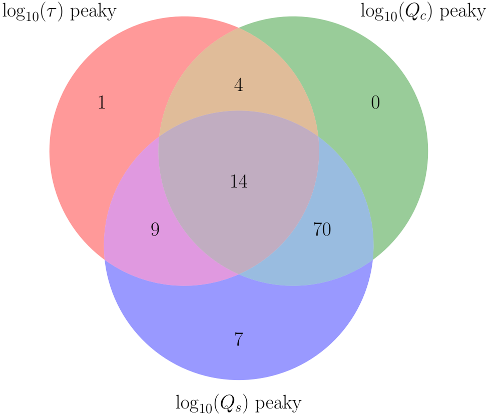
- 286 non-glitching radio pulsars
- 18 millisecond pulsars (MSPs), 1 magnetar
- 1.0–4.8 years of data, daily to monthly observing cadence

Result reiterate: τ is resolved in 28 objects



- 105/286 with $\ln \mathfrak{B}_{\mathrm{BF}} \geq 5$
- 28/105 have resolved (peaky) τ

Result reiterate: τ is resolved in 28 objects

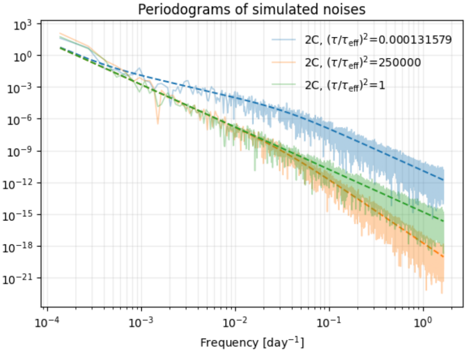


Why can't we resolve more τ?

$$P_{\delta\phi_{\rm c}}(f) \propto f^{-4}\,\frac{(2\pi f)^2 + \tau_{\rm eff}^{-2}}{(2\pi f)^2 + \tau^{-2}}, \qquad \tau_{\rm eff}^{-2} = \tau_{\rm c}^{-2}\left(\frac{\tau_{\rm c}^2}{\tau_{\rm s}^2} + \frac{Q_{\rm s}}{Q_{\rm c}}\right)$$

- Different f regimes behave as different power laws (Meyers+, 2021a; Antonelli+, 2023)

2C PSD can resemble generic red noise



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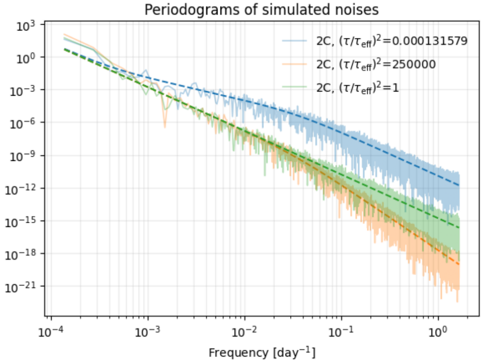

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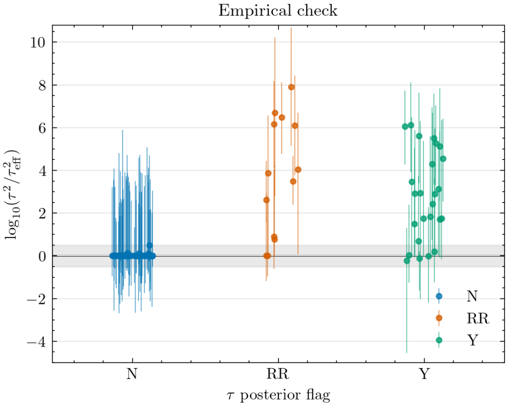

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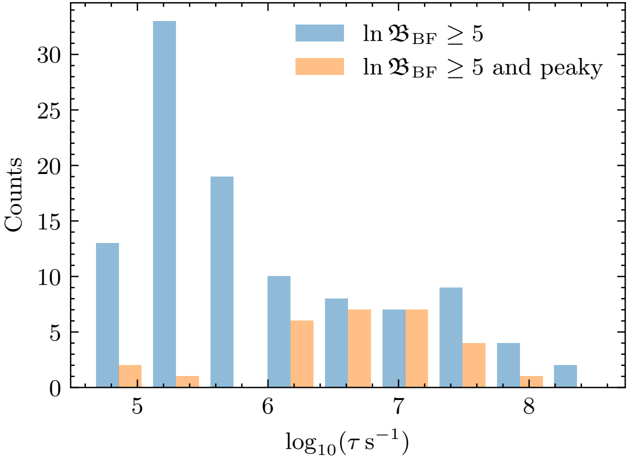
The three obscure clouds

1. Can we distinguish between one- and two-component stars from timing noise?

Partial answer: 2C vs. 1C + white: ✓;
2C vs. 1C + red: unclear.

2. Is the star's internal friction the same between glitches and during glitches?
3. Is the crust-superfluid coupling timescale consistent with superfluid mutual friction across the pulsar population?

From individual pulsars to population constraints



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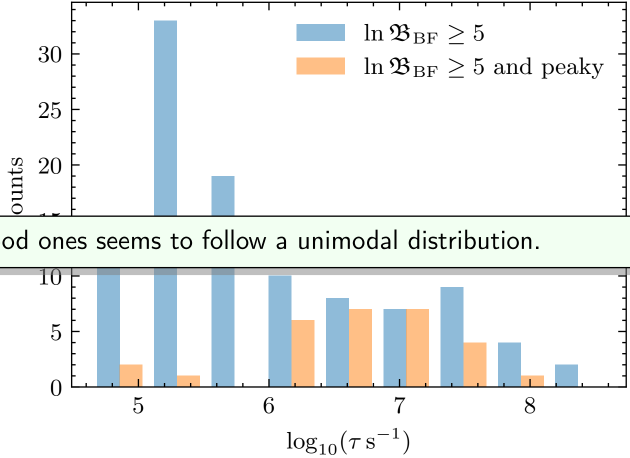
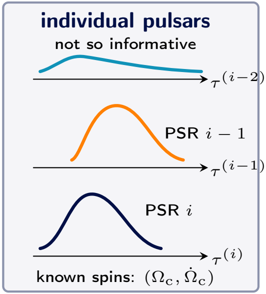


The good ones seems to follow a unimodal distribution.

Hierarchical model: population-level coupling law



- use each pulsar's posterior for $\tau^{(i)}$, not a point estimate

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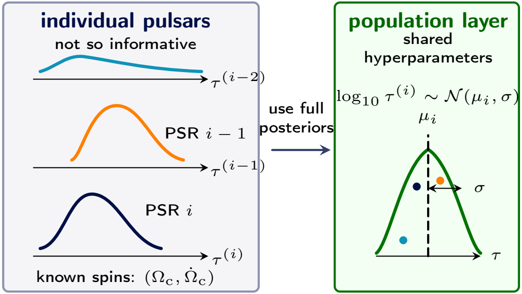

individual pulsars

not so informative

known spins: $(\Omega_{\rm c}, \dot{\Omega}_{\rm c})$

use full posteriors

population layer

shared hyperparameters

$\log_{10} \tau^{(i)} \sim \mathcal{N}(\mu_i, \sigma)$

- use each pulsar's posterior for $\tau^{(i)}$, not a point estimate
- assume $\log_{10} \tau^{(i)}$ are drawn from a Gaussian population with mean μ_i and object-to-object scatter σ

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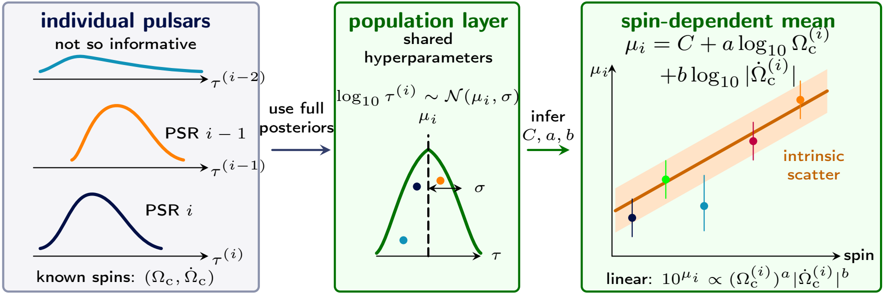

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$\log_{10}\tau^{(i)} \sim \mathcal{N}(\mu_i, \sigma)$

spin-dependent mean

$$\mu_i = C + a\log_{10}\Omega_c^{(i)} + b\log_{10}|\dot{\Omega}_c^{(i)}|$$

use full posteriors

infer C, a, b

known spins: $(\Omega_c, \dot{\Omega}_c)$

linear: $10^{\mu_i} \propto (\Omega_c^{(i)})^a |\dot{\Omega}_c^{(i)}|^b$

- use each pulsar's posterior for $\tau^{(i)}$, not a point estimate
- assume $\log_{10}\tau^{(i)}$ are drawn from a Gaussian population with mean μ_i and object-to-object scatter σ
- put spin scaling in μ_i

MATH: foundation of hierarchy (for secret Bayesian enthusiasts)

$$p[\{\boldsymbol{\theta}^{(i)}\},\boldsymbol{\Lambda}\mid\{\boldsymbol{d}^{(i)}\}] \propto \mathcal{L}[\{\boldsymbol{d}^{(i)}\}\mid\{\boldsymbol{\theta}^{(i)}\},\boldsymbol{\Lambda}]p[\{\boldsymbol{\theta}^{(i)}\},\boldsymbol{\Lambda}] \tag{10}$$

$$= \pi(\boldsymbol{\Lambda})\prod_{i=1}^{N_{\rm psr}}\mathcal{L}[\boldsymbol{d}^{(i)}\mid\boldsymbol{\theta}^{(i)}]p[\boldsymbol{\theta}^{(i)}\mid\boldsymbol{\Lambda}] \tag{11}$$

$$\mathcal{L}[\{\boldsymbol{d}^{(i)}\}\mid\{\boldsymbol{\theta}^{(i)}\},\boldsymbol{\Lambda}] = \mathcal{L}[\{\boldsymbol{d}^{(i)}\}\mid\{\boldsymbol{\theta}^{(i)}\}] \tag{12}$$

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$$p[\boldsymbol{\Lambda}\mid\{\boldsymbol{d}^{(i)}\}] = \int \mathrm{d}\{\boldsymbol{\theta}^{(i)}\}\, p[\{\boldsymbol{\theta}^{(i)}\},\boldsymbol{\Lambda}\mid\{\boldsymbol{d}^{(i)}\}] \tag{15}$$

$$p[\boldsymbol{\theta}^{(i)}\mid\{\boldsymbol{d}^{(i)}\}] = \int \mathrm{d}\boldsymbol{\Lambda}\int \mathrm{d}\{\boldsymbol{\theta}^{(j)}\}_{j\neq i}\, p[\{\boldsymbol{\theta}^{(j)}\},\boldsymbol{\Lambda}\mid\{\boldsymbol{d}^{(i)}\}] \tag{16}$$

$\boldsymbol{\theta}^{(i)} = [\tau^{(i)}, Q_{\rm c}^{(i)}, Q_{\rm s}^{(i)}]$; $\boldsymbol{\Lambda}$: population hyperparameters. Assumptions: exchangeability across pulsars. Practical reweighting implementation: see our paper, Sec. 3.2.

Population result: τ is weakly dependent on spin variables

Applying for 101 canonical pulsars,

$\mu \propto \Omega_\mathrm{c}^a \lvert\dot{\Omega}_\mathrm{c}\rvert^b$	τ	Q_c	Q_s
a	$0.19^{+0.50}_{-0.52}$	$1.23^{+0.80}_{-0.75}$	$0.71^{+0.76}_{-0.78}$
b	$0.18^{+0.18}_{-0.19}$	$0.49^{+0.27}_{-0.32}$	$1.27^{+0.30}_{-0.28}$
σ	$0.35^{+0.15}_{-0.13}$	$0.86^{+0.14}_{-0.13}$	$0.62^{+0.16}_{-0.12}$

- The population mean of τ is consistent with
  - little or no dependence on Ω_c.
  - weak evidence that τ depends weakly on $\lvert\dot{\Omega}_\mathrm{c}\rvert$.

$$\tau \propto \Omega_\mathrm{c}^{0.19^{+0.50}_{-0.52}} \lvert\dot{\Omega}_\mathrm{c}\rvert^{0.18^{+0.18}_{-0.19}}$$

- The stochastic torques $Q_\mathrm{c,s}$ carry spin-variable dependence.

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- The stochastic torques $Q_{\mathrm{c,s}}$ carry spin-variable dependence.
- Mapping $\Omega_{\mathrm{c}}^{a} \lvert \dot{\Omega}_{\mathrm{c}} \rvert^{b} \mapsto T_{\mathrm{age}}^{a'} B_{\mathrm{surf}}^{b'}$
  - $a' = -(a + 3b)/2 < 0$
  - $b' = -(a + b) < 0$

The three obscure clouds

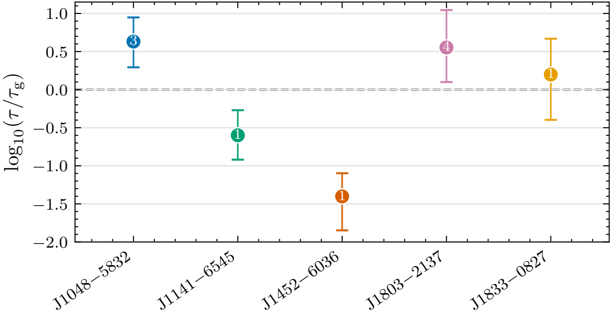
1. Can we distinguish between one- and two-component stars from timing noise?

Partial answer: 2C vs. 1C + WTN: ✓;
2C vs. 1C + stochastic torque: unclear.

2. Is the star's internal friction the same between glitches and during glitches?
3. Is the crust-superfluid coupling timescale consistent with superfluid mutual friction across the pulsar population?

Are timing-noise τ and glitch-recovery τ_g the same?

- Use population-informed τ posteriors.
- Five objects in the selected sample have measured glitch-recovery timescales τ_g.



- Only one object has τ consistent with τ_g, taking into account uncertainties and glitch-to-glitch variability.

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Attempt: Too early to say. More work needed.

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τ and mutual friction?

- 2004 Vela glitch: $B_{\rm mf} = \mathcal{R}/(1+\mathcal{R}^2) \sim 4 \times 10^{-5}$ at face value

$$\tau_{\rm mf} \sim 10^3 \left(\Omega_{\rm c}/10\,{\rm rad\,s^{-1}}\right)^{-1} \left(B_{\rm mf}/4 \times 10^{-5}\right)^{-1}\ {\rm s}. \qquad (3)$$

- $\implies$ effective $B_{\rm mf} \sim 10^{-9}$? strong vortex pinning?
- different form? nonlinear mutual friction?
  - vortex-flux-tube tangles (Drummond+, 2018; Thong+, 2023)
  - polarized turbulence? (Peralta+, 2006; Andersson+, 2007)

τ and mutual friction?

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$$\tau_{\rm mf} \sim 10^3 \left(\Omega_{\rm c}/10\,{\rm rad\,s^{-1}}\right)^{-1} \left(B_{\rm mf}/4 \times 10^{-5}\right)^{-1} \,{\rm s}. \qquad (3)$$

timescale too short!

- $\Longrightarrow$ effective $B_{\rm mf} \sim 10^{-9}$? strong vortex pinning?
- different form? nonlinear mutual friction?
  - vortex-flux-tube tangles (Drummond+, 2018; Thong+, 2023)
  - polarized turbulence? (Peralta+, 2006; Andersson+, 2007)

τ and mutual friction?

drag-to-lift ratio

- 2004 Vela glitch: $B_{\rm mf} = \mathcal{R}/(1+\mathcal{R}^2) \sim 4 \times 10^{-5}$ at face value

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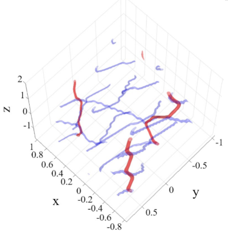
timescale too short!
Scaling not matching!



Thong+ (2023), Fig. 2

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The three obscure clouds

1. Can we distinguish between one- and two-component stars from timing noise?

Partial answer: 2C vs. 1C + WTN: ✓;
2C vs. 1C + stochastic torque: unclear.

2. Is the star's internal friction the same between glitches and during glitches?

Attempt: Too early to say. More work needed.

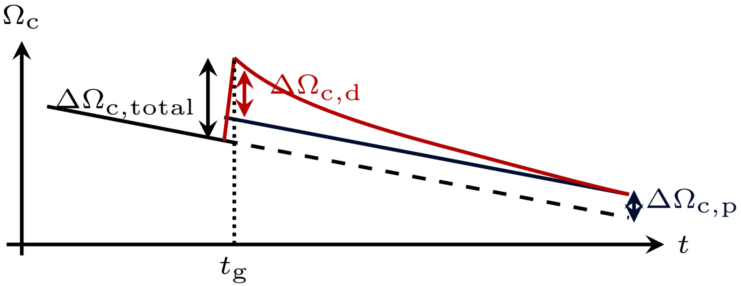
3. Is the crust-superfluid coupling timescale consistent with superfluid mutual friction across the pulsar population?

Attempt: Seems not, but maybe vortices are tangled or pinned magnetically?

Healing parameter in glitch recovery

Healing parameter:

$$q_{\rm heal} = \frac{\Delta\Omega_{\rm c,d}}{\Delta\Omega_{\rm c,total}}$$



Are two components enough?

How many effective components in a neutron star?

Healing parameter:

$$q_{\rm heal} = \frac{\Delta\Omega_{\rm c,d}}{\Delta\Omega_{\rm c,total}}$$

- during glitch and glitch recovery:
  - $q_{\rm heal} \lesssim 1$ for most glitches, but 2C model predicts $q_{\rm heal} = 1$
  - more components needed? e.g., three-component (crust + two superfluid reservoirs) (Montoli+, 2020)
- inter-glitch timing noise:
  - two components seem to be sufficient
  - but not necessarily the same components as during glitch recovery? glitch-based $x_{\rm s} = I_{\rm s}/(I_{\rm c} + I_{\rm s}) \ll$ timing-based $x_{\rm s} \lessapprox 1$

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Takeaways

- Timing noise can be used as a continuous probe of crust-superfluid coupling.
- First population-scale timing-noise estimates of τ.
- Hierarchical Bayesian framework is used to infer population-level scaling of τ with spin variables.
- The magnitude of the inferred τ is not trivially explained by naive mutual friction, nor does it follow the expected scaling.

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Thanks for listening and having me!

Happy to collaborate and discuss any of the points in more detail.

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