Pulsar glitches

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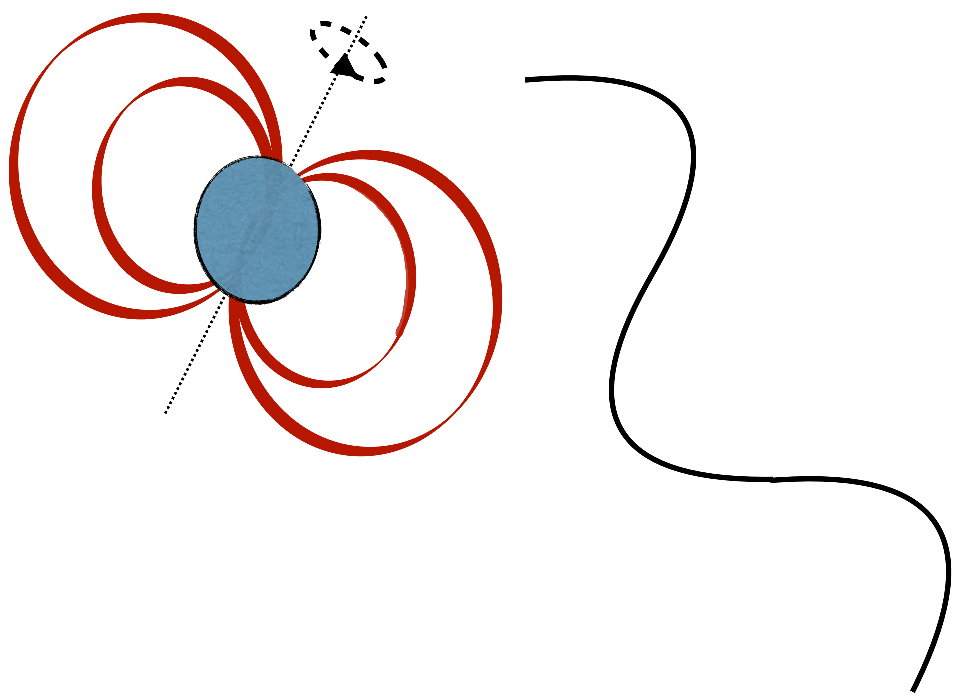
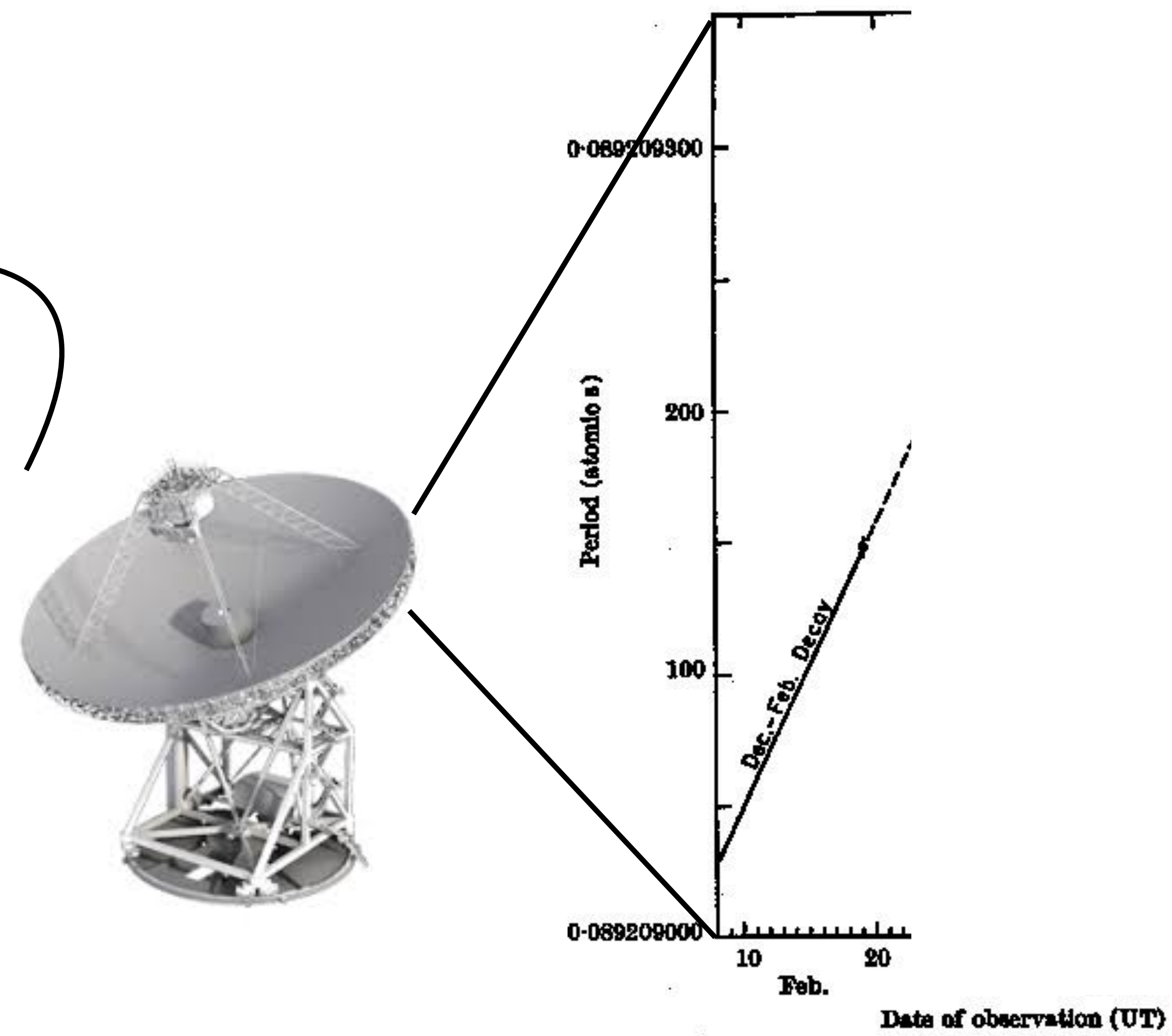
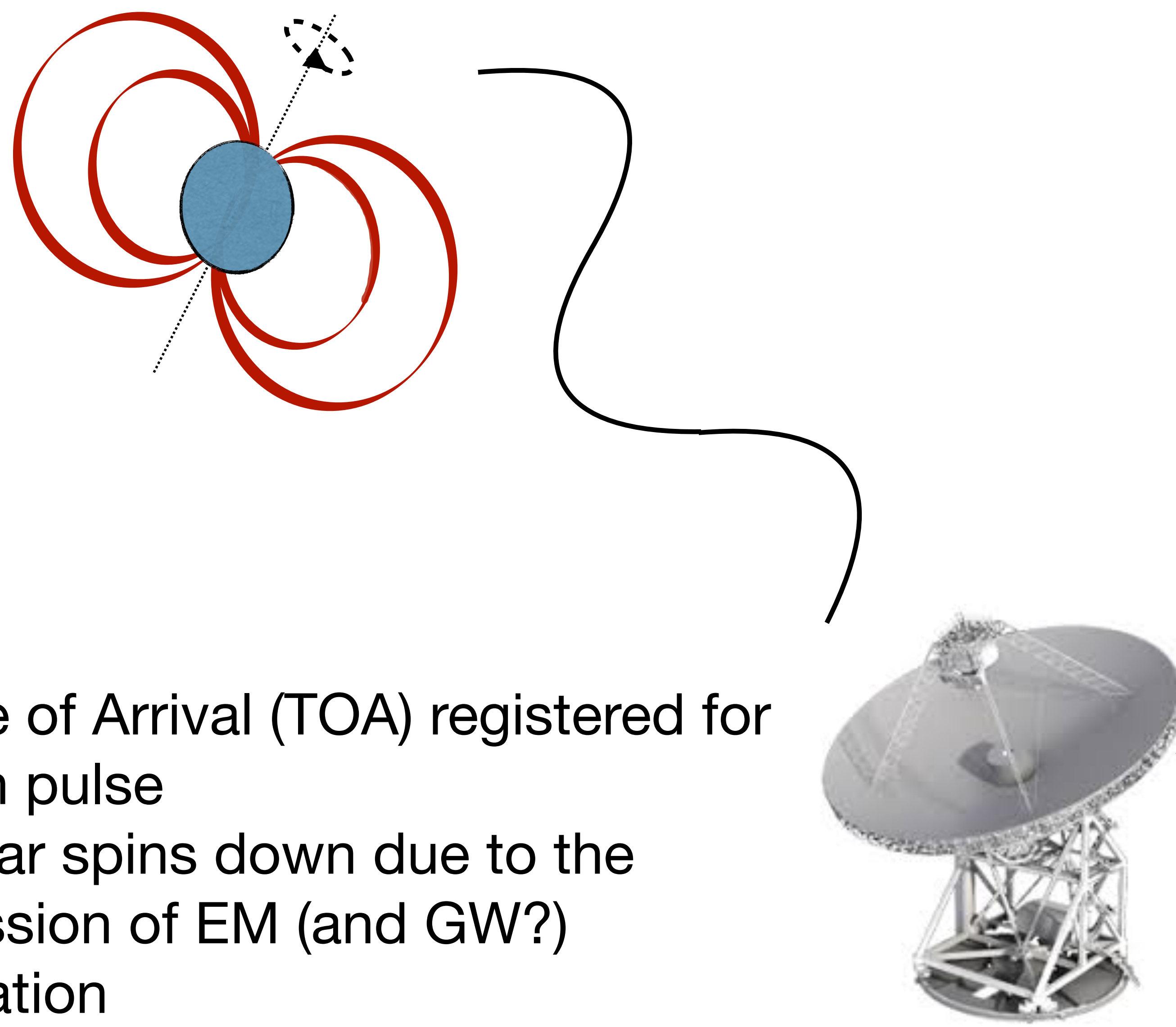
Pulsar Timing

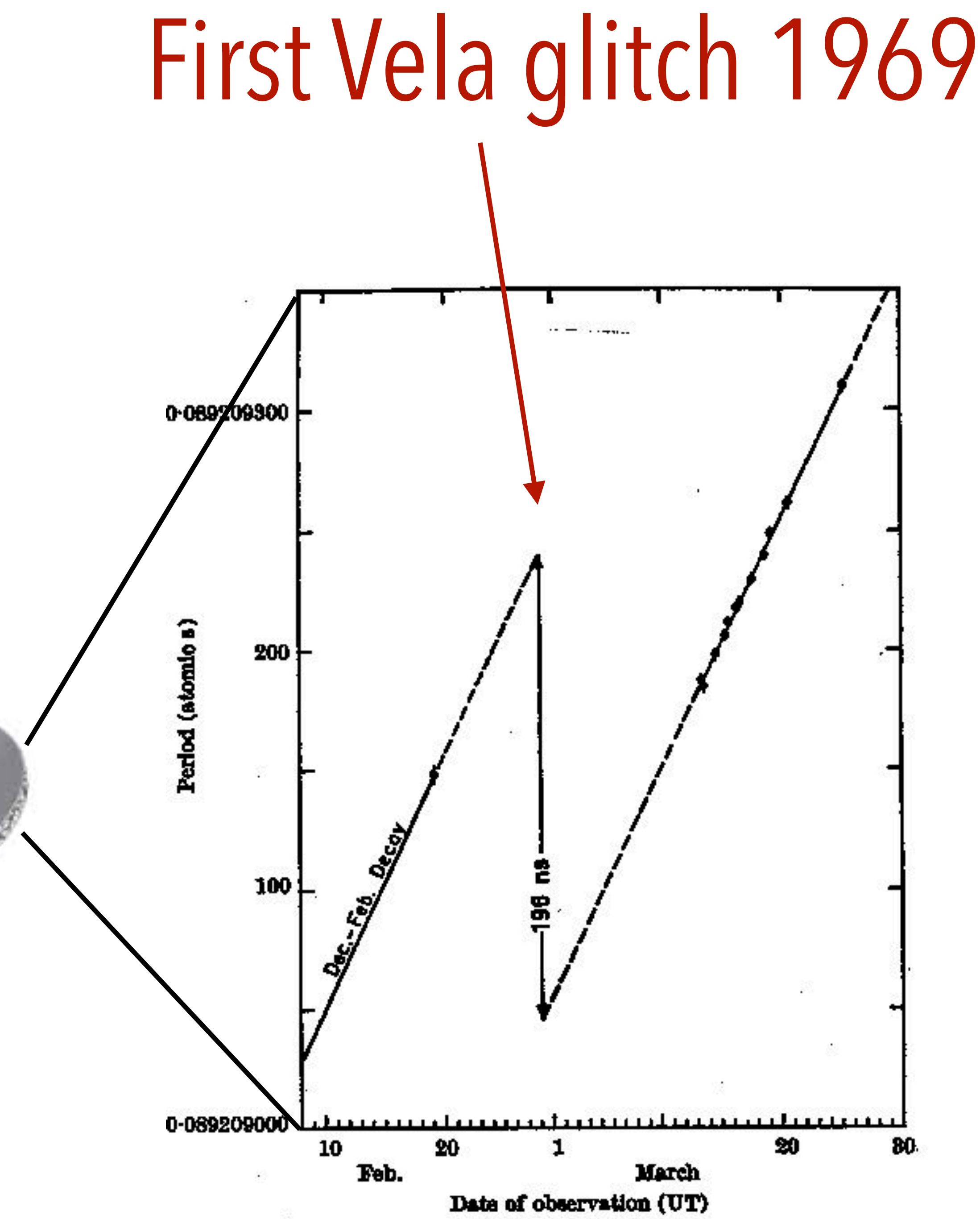




- Time of Arrival (TOA) registered for each pulse
- Pulsar spins down due to the emission of EM (and GW?) radiation

Pulsar Timing





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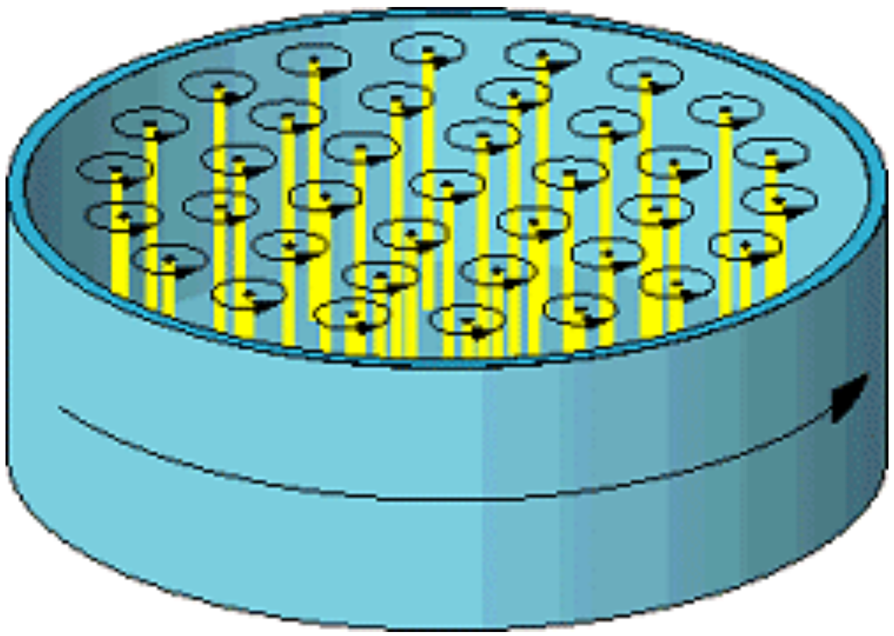
What is happening?



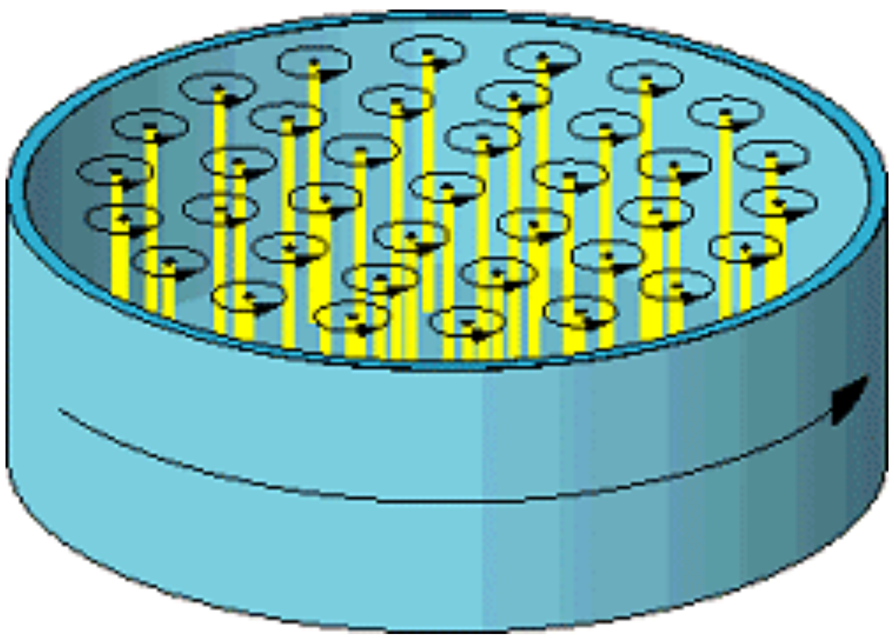
- Superfluids rotate by forming quantised vortices
- Vortex density determines spin : vortices must move out to spin down the fluid!

Magnus Force

$$\text{FREE}: \quad \boxed{\epsilon^{ijk}\hat{k}_j(v_k^{\mathrm{v}} - v_k^{\mathrm{n}})} + \mathcal{R}(v_{\mathrm{c}}^i - v_{\mathrm{v}}^i) = 0$$

$$\text{PINNED}: \quad \epsilon^{ijk}\hat{k}_j(v_k^{\mathrm{v}} - v_k^{\mathrm{n}}) + F_{\mathrm{p}}^i = 0$$

What is happening?



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MoI of superfluid reservoir

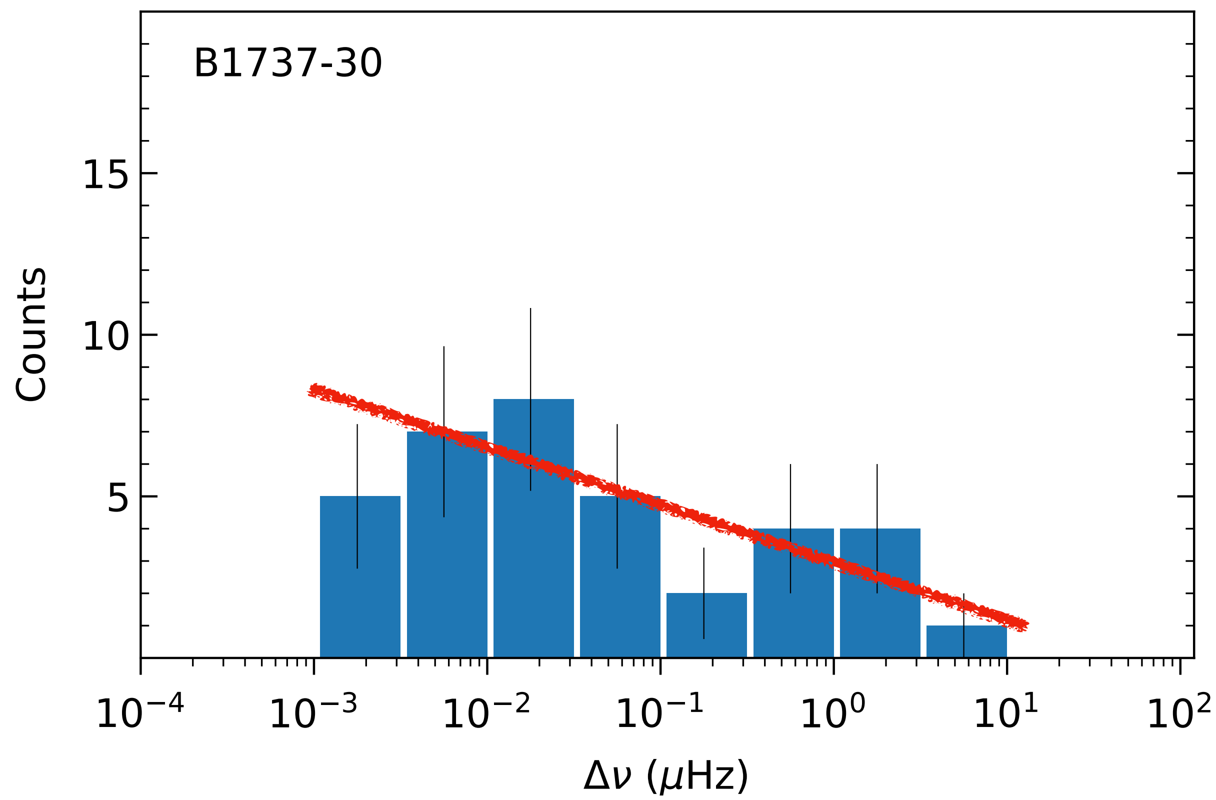
Observed

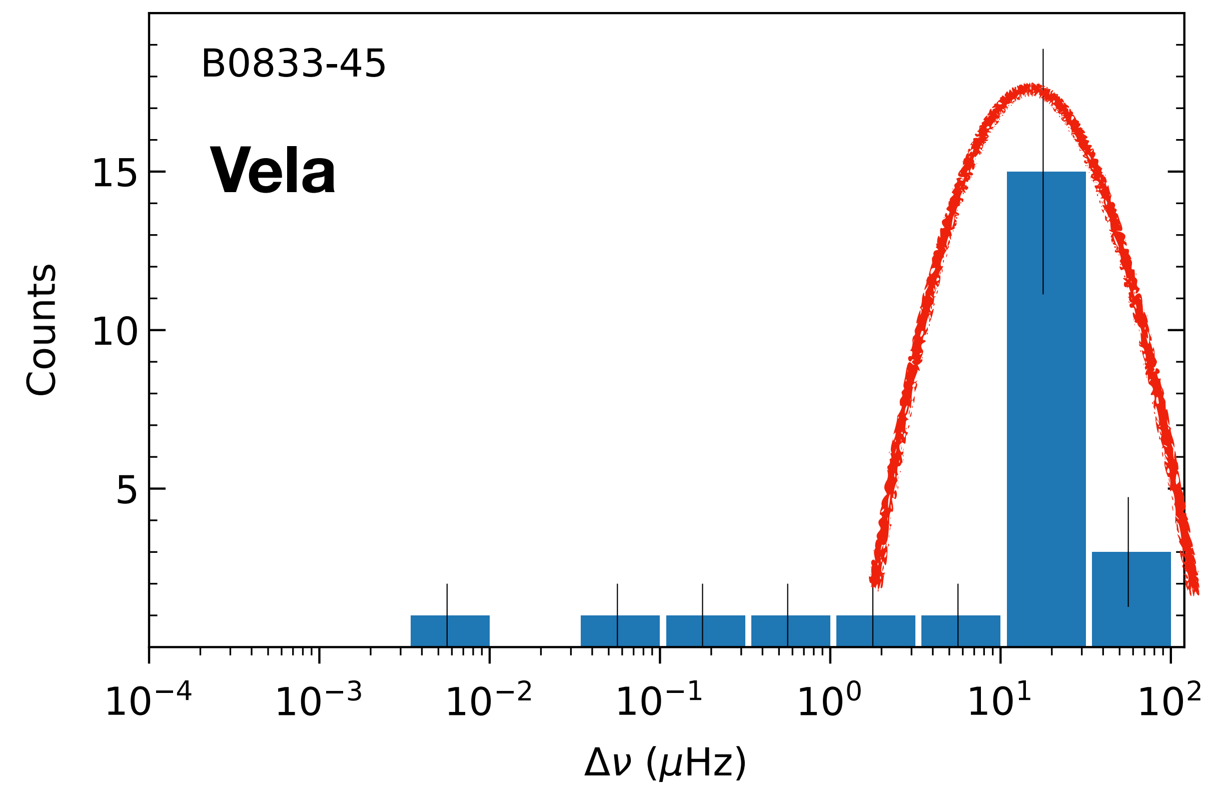
$$\Delta\Omega = \frac{I_n}{I_T}(\Omega_{\mathrm{n}} - \Omega_{\mathrm{c}})$$

Internal lag before the glitch

Depends on pinning force

Sizes - what can we learn





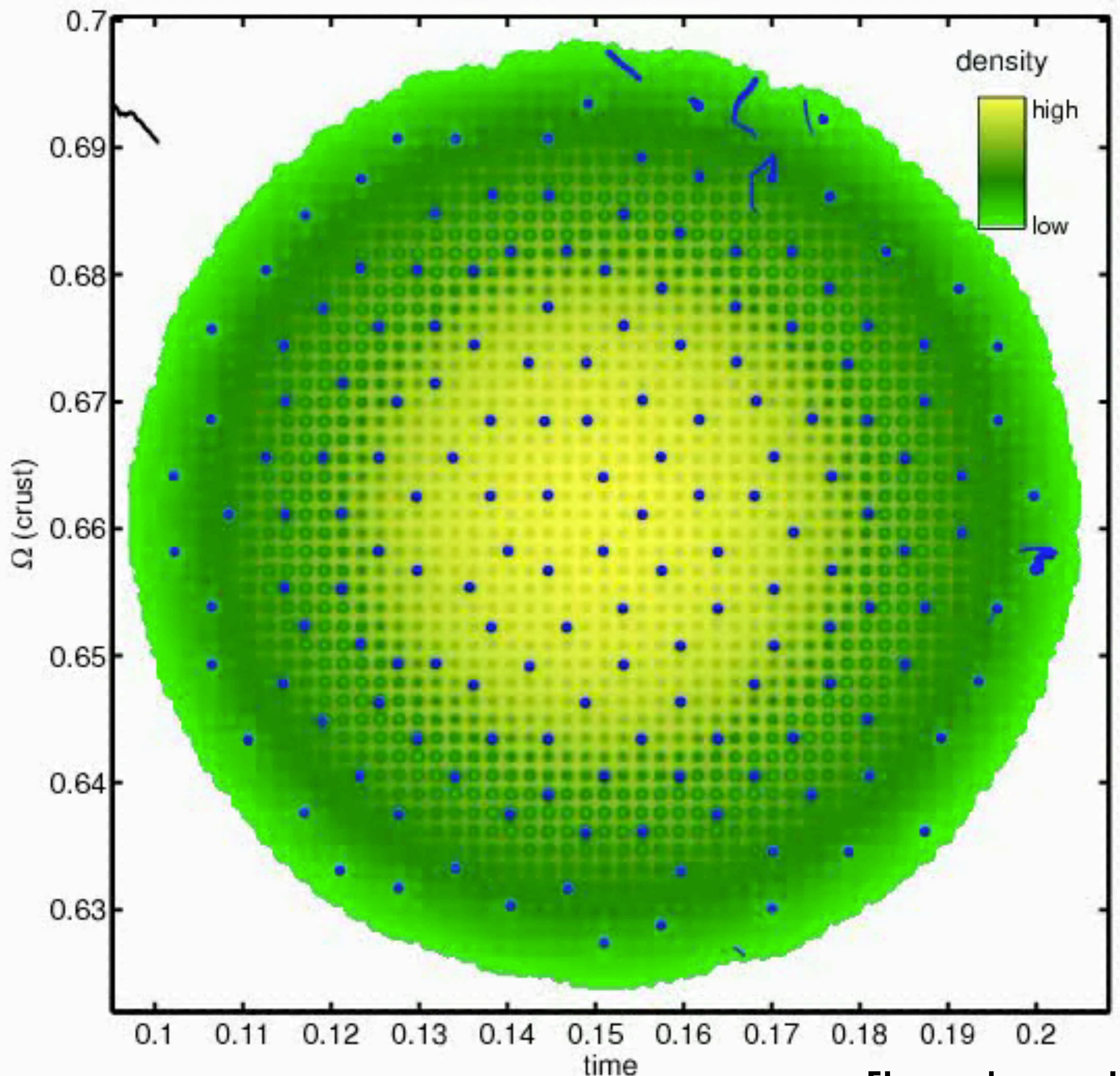
- Glitch sizes in most pulsars span several orders of magnitude - distribution consistent with a power law (waiting times exponential)
- In a handful of systems there appears to be a characteristic size, and a regular process (e.g. Vela)

[Fuentes et al. 2017]

[Howitt et al. 2018]

[Antonopoulou et al. 2022- submitted]

Triggers

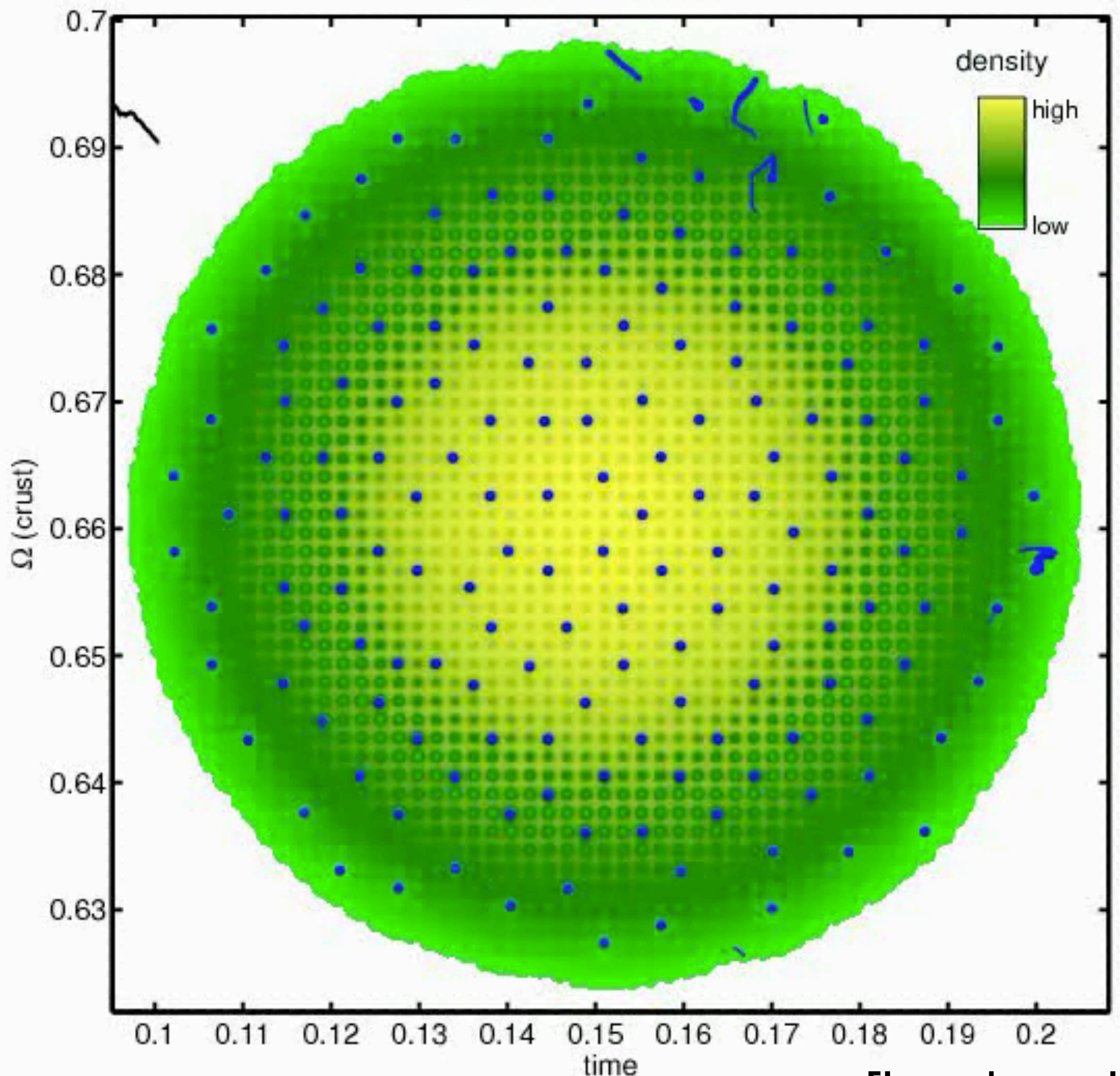


[Lonnborn, Haskell and Melatos 2019]

- Vortex avalanches can lead to scale independent behaviour [Melatos et al. 2008, Warszawski & Melatos 2011, 2013]

- Rapidly driven systems only glitch once they reach the maximum of the pinning force? (snowplow) [Pizzochero 2011] …or instabilities [Glampedakis et al. 2009]

Triggers



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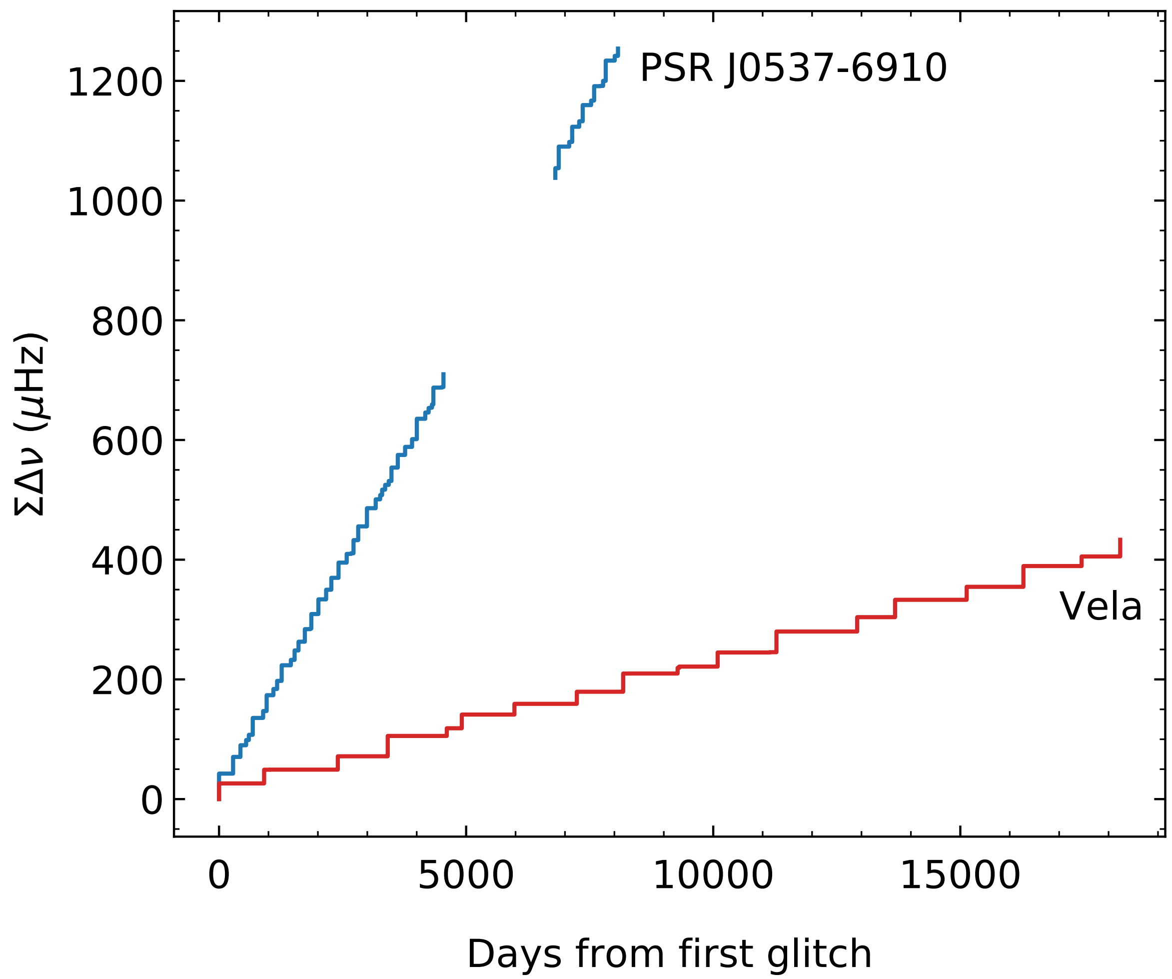
Activity



[Antonopoulou et al. 2022- submitted]

$$\mathcal{A} = \frac{1}{T_{\rm obs}} \sum_i \frac{\Delta\Omega_i}{2\pi}$$

$$\frac{I_n}{I_T} \gtrsim \frac{\mathcal{A}}{|\dot{\nu}|}(1 - \varepsilon_n)$$

Entrainment:
large=few conduction neutrons

- If we include strong entrainment, the crust is not enough to explain the activity of the Vela pulsar - are quasi-periodic glitches triggered in the crust? [Andersson et al. 2012, Chamel 2013]

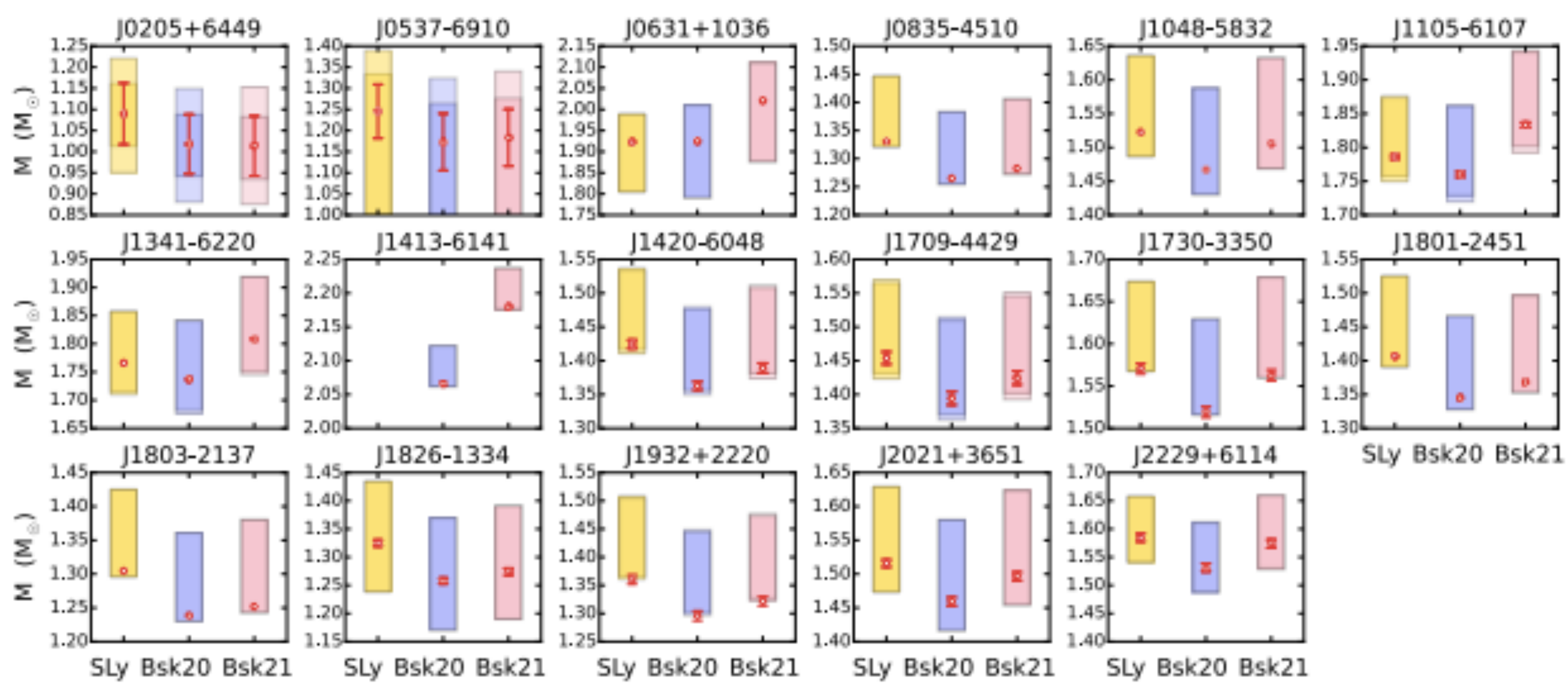
Measuring masses

Table 2. Mass, radius, and total moment of inertia of glitching pulsars for three nuclear equation of state models

PSR	M ($M_{\rm Sun}$)	R (km)	I ($M_{\rm Sun}$ km^2)
	BSk20 EOS		
J0537−6910	$1.83^{+0.04}_{-0.04}$	$11.5^{+0.05}_{-0.05}$	$81.4^{+1.5}_{-1.6}$
B0833−45	$1.51^{+0.04}_{-0.04}$	$11.7^{+0.02}_{-0.02}$	$66.7^{+2.0}_{-2.0}$
B1046−58	$1.53^{+0.36}_{-0.08}$	$11.7^{+0.03}_{-0.3}$	$67.7^{+16.0}_{-4.0}$
B1338−62	$1.52^{+0.11}_{-0.10}$	$11.7^{+0.03}_{-0.06}$	$67.2^{+5.4}_{-5.1}$
B1706−44	$1.69^{+0.19}_{-0.17}$	$11.6^{+0.1}_{-0.2}$	$75.4^{+7.9}_{-8.2}$
B1757−24	$1.46^{+0.43}_{-0.12}$	$11.7^{+0.03}_{-0.3}$	$64.1^{+19.5}_{-6.2}$
B1800−21	$1.30^{+0.37}_{-0.35}$	$11.8^{+0.01}_{-0.1}$	$55.8^{+18.7}_{-18.3}$
B1823−13	$1.53^{+0.58}_{-0.10}$	$11.7^{+0.03}_{-0.9}$	$67.7^{+19.8}_{-5.1}$
1E 1841−045	$1.61^{+0.16}_{-0.14}$	$11.7^{+0.06}_{-0.1}$	$71.6^{+7.3}_{-7.0}$
	BSk21 EOS		
J0537−6910	$2.11^{+0.04}_{-0.05}$	$12.1^{+0.1}_{-0.1}$	$106.8^{+0.7}_{-1.3}$
B0833−45	$1.82^{+0.04}_{-0.04}$	$12.5^{+0.03}_{-0.03}$	$94.9^{+2.1}_{-2.1}$
B1046−58	$1.85^{+0.35}_{-0.09}$	$12.5^{+0.06}_{-0.7}$	$96.5^{+11.0}_{-4.8}$
B1338−62	$1.82^{+0.12}_{-0.11}$	$12.5^{+0.06}_{-0.1}$	$94.9^{+5.9}_{-6.1}$
B1706−44	$2.01^{+0.16}_{-0.16}$	$12.3^{+0.2}_{-0.4}$	$103.8^{+3.9}_{-7.3}$
B1757−24	$1.77^{+0.43}_{-0.13}$	$12.5^{+0.05}_{-0.7}$	$92.2^{+15.2}_{-7.4}$
B1800−21	$1.56^{+0.44}_{-0.42}$	$12.6^{+0.01}_{-0.3}$	$80.0^{+23.3}_{-27.5}$
B1823−13	≥ 1.71	≤ 12.6	≥ 88.9
1E 1841−045	$1.90^{+0.16}_{-0.15}$	$12.4^{+0.1}_{-0.2}$	$99.0^{+6.5}_{-7.8}$
	APR EOS		
J0537−6910	$2.05^{+0.04}_{-0.03}$	$10.9^{+0.07}_{-0.1}$	$86.4^{+0.7}_{-0.7}$
B0833−45	$1.80^{+0.03}_{-0.03}$	$11.3^{+0.03}_{-0.03}$	$77.6^{+1.3}_{-1.3}$
B1046−58	$1.82^{+0.29}_{-0.07}$	$11.3^{+0.07}_{-0.5}$	$78.4^{+8.9}_{-3.1}$
B1338−62	$1.81^{+0.09}_{-0.09}$	$11.3^{+0.09}_{-0.1}$	$78.0^{+3.7}_{-4.0}$
B1706−44	$1.96^{+0.14}_{-0.14}$	$11.1^{+0.2}_{-0.3}$	$83.8^{+3.4}_{-5.4}$
B1757−24	$1.76^{+0.35}_{-0.11}$	$11.4^{+0.09}_{-0.6}$	$75.8^{+11.5}_{-5.1}$
B1800−21	$1.60^{+0.33}_{-0.33}$	$11.5^{+0.2}_{-0.3}$	$68.4^{+14.4}_{-15.9}$
B1823−13	$1.82^{+0.36}_{-0.09}$	$11.3^{+0.09}_{-0.9}$	$78.4^{+7.8}_{-4.0}$
1E 1841−045	$1.89^{+0.12}_{-0.13}$	$11.2^{+0.1}_{-0.2}$	$81.3^{+4.1}_{-5.5}$

[Ho et al. 2015]

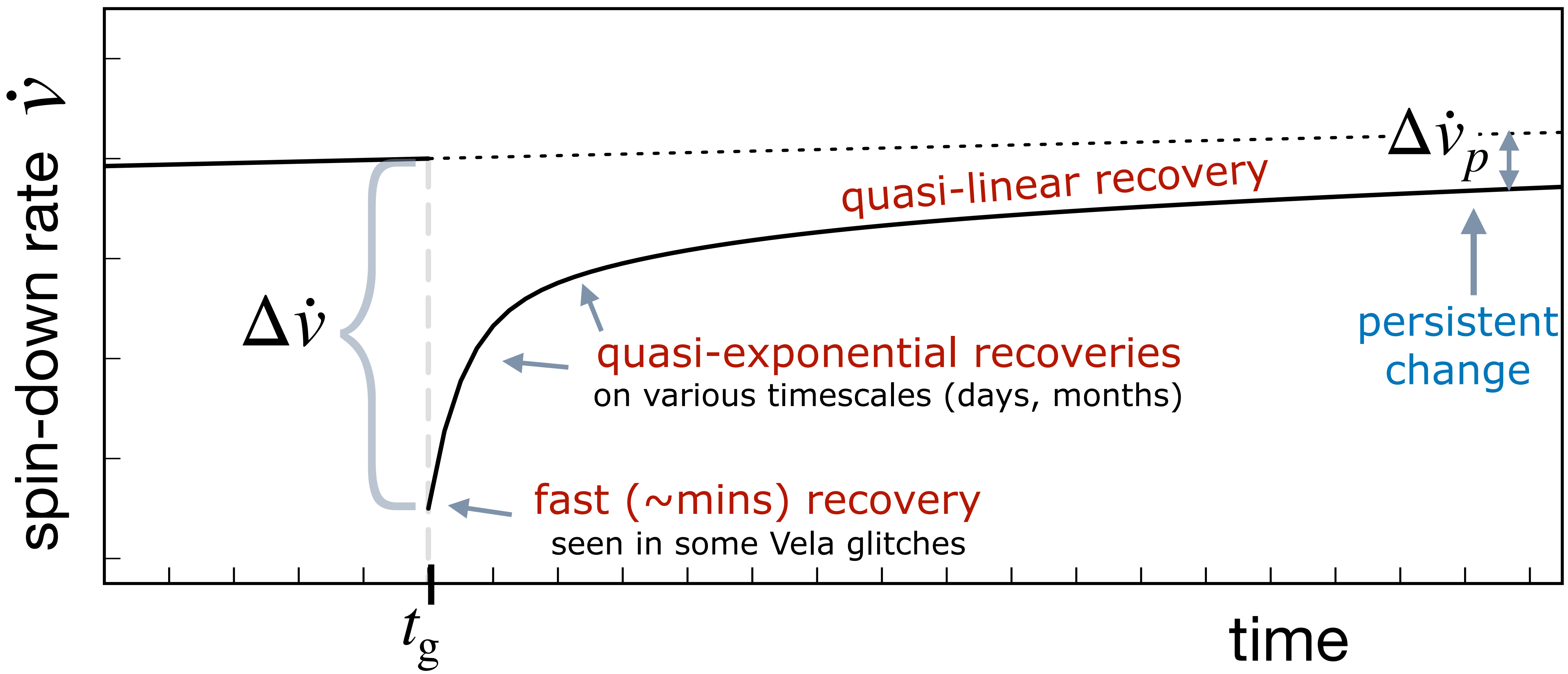
- From the angular momentum reservoir we can estimate NS masses



[Pizzochero, Antonelli, BH & Seveso 2016]

Recoveries

[Antonopoulou et al. 2022- submitted]



- Long timescales first suggested superfluid coupling
- Creep theory by Alpar and collaborators [*Alpar et al. 1984*] successful in describing relaxations. Vortices ‘creep’ out, coupling can be linear or non-linear

Equations of motion

$$\dot{\Omega}_{\rm n}(\tilde{r}) \quad = \quad \kappa n_v \frac{\mathcal{B}(\Omega_{\rm p}-\Omega_{\rm n})}{(1-\varepsilon_{\rm n}-\varepsilon_{\rm p})} - f(\varepsilon_{\rm p})\mathcal{A}\Omega_{\rm p}^3$$

$$\dot{\Omega}_{\rm p}(\tilde{r}) \quad = \quad -\kappa n_v \frac{\rho_{\rm n}}{\rho_{\rm p}} \frac{\mathcal{B}(\Omega_{\rm p}-\Omega_{\rm n})}{(1-\varepsilon_{\rm n}-\varepsilon_{\rm p})} - \frac{\mathcal{A}}{I_{\rm p}}\Omega_{\rm p}^3$$

$$\kappa n_v = 2\left[\Omega_{\rm n} + \varepsilon_{\rm n}(\Omega_{\rm p}-\Omega_{\rm n})\right] + \tilde{r}\boxed{\frac{\partial}{\partial \tilde{r}}\left[\Omega_{\rm n} + \varepsilon_{\rm n}(\Omega_{\rm p}-\Omega_{\rm n})\right]}$$

Important in the crust!

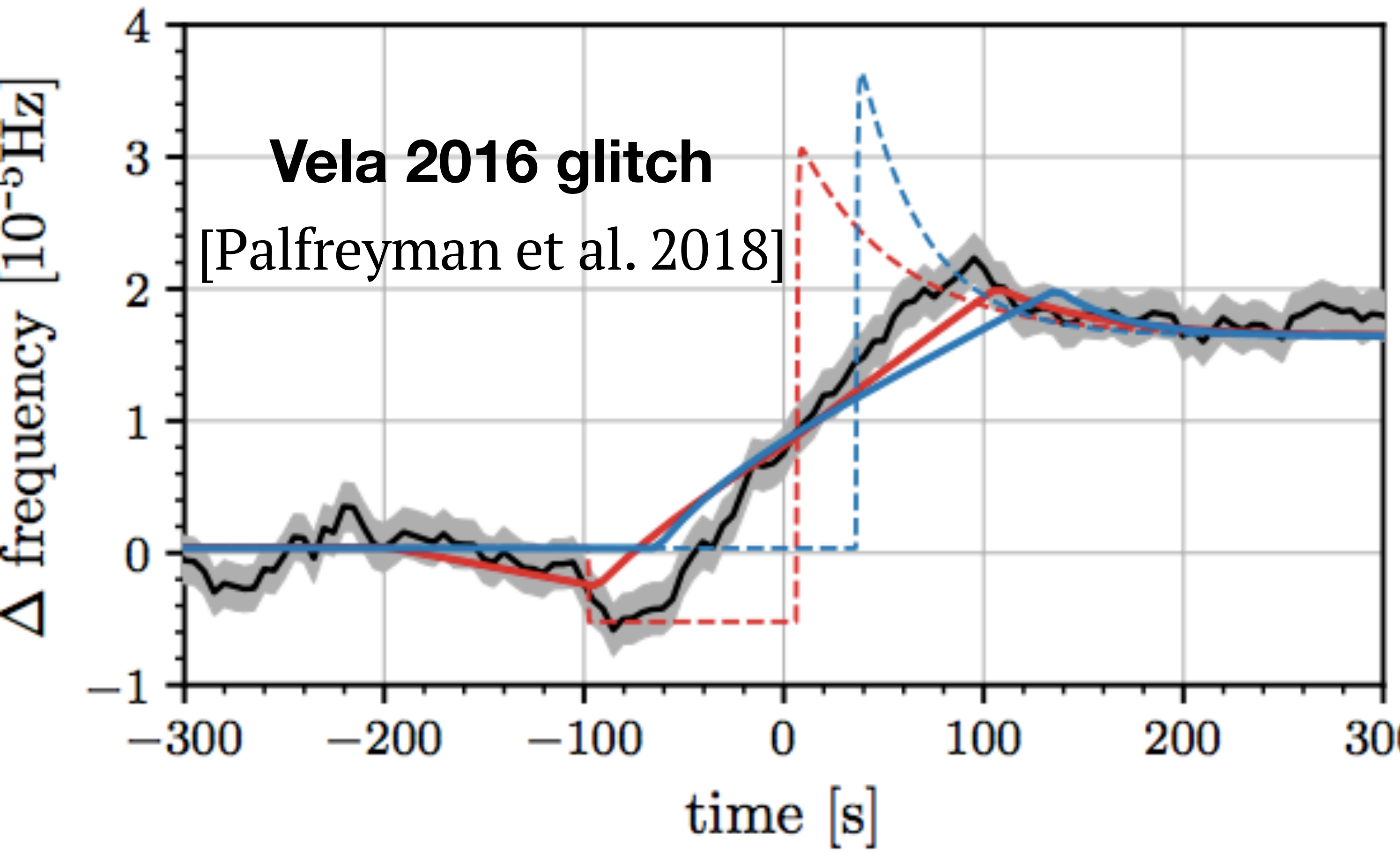
[Chamel 2012]

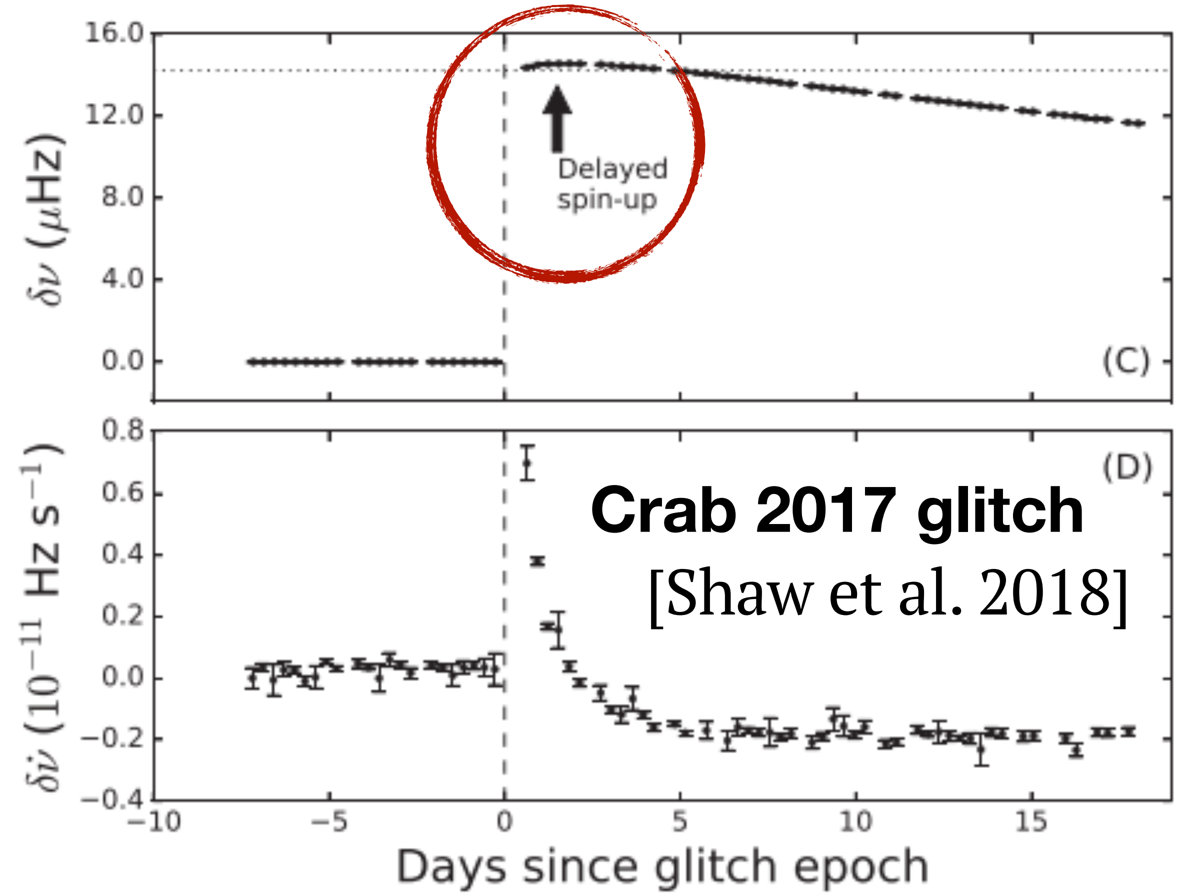
Vortex accumulation:

Burgers like term, gives propagation of vortex fronts

[Khomenko & BH, 2018]

Short timescale behaviour





- Rise constrained to less than 12 s
- Recovery suggests a decoupled component
- Possible core origin?
- Possible precursor

[Ashton et al. 2019, Montoli et al. 2020]

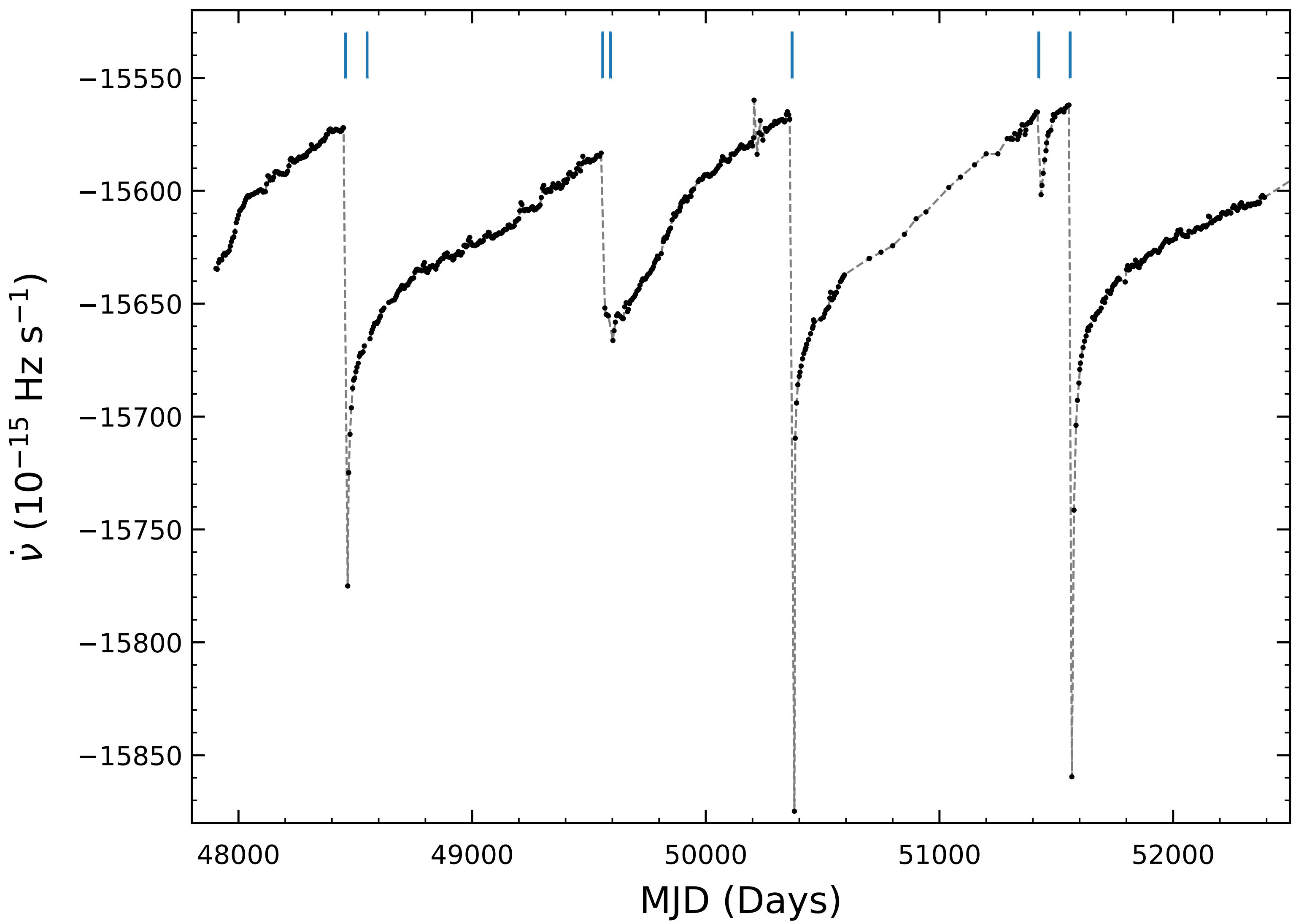
- Slow rise
- Suggests crustal origin

[BH et al. 2018]

- Do crust-quakes play a role?

[Akbal and Alpar, 2018]

Long timescale behaviour



Vela Pulsar

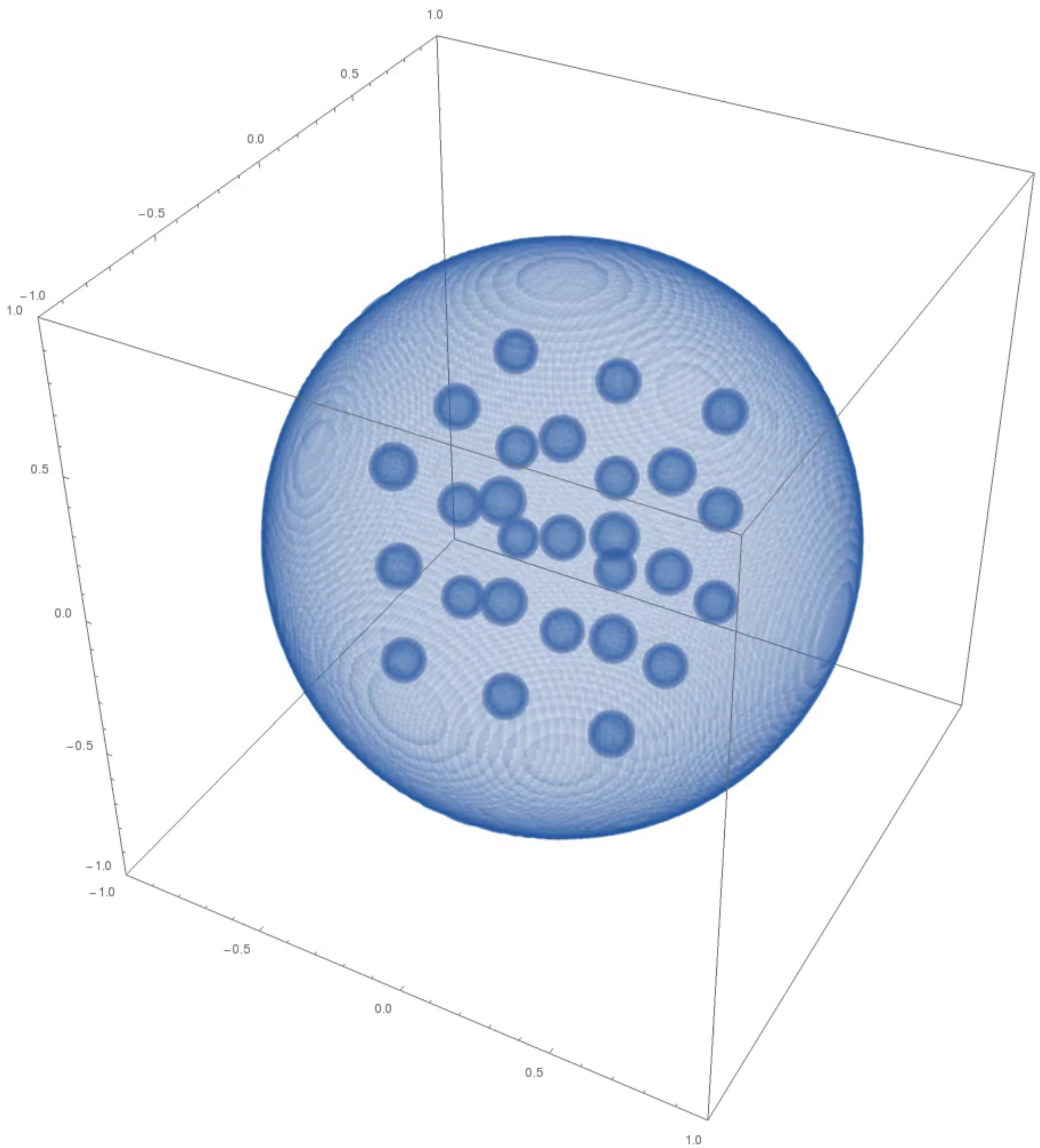
[Antonopoulou et al. 2022- submitted]

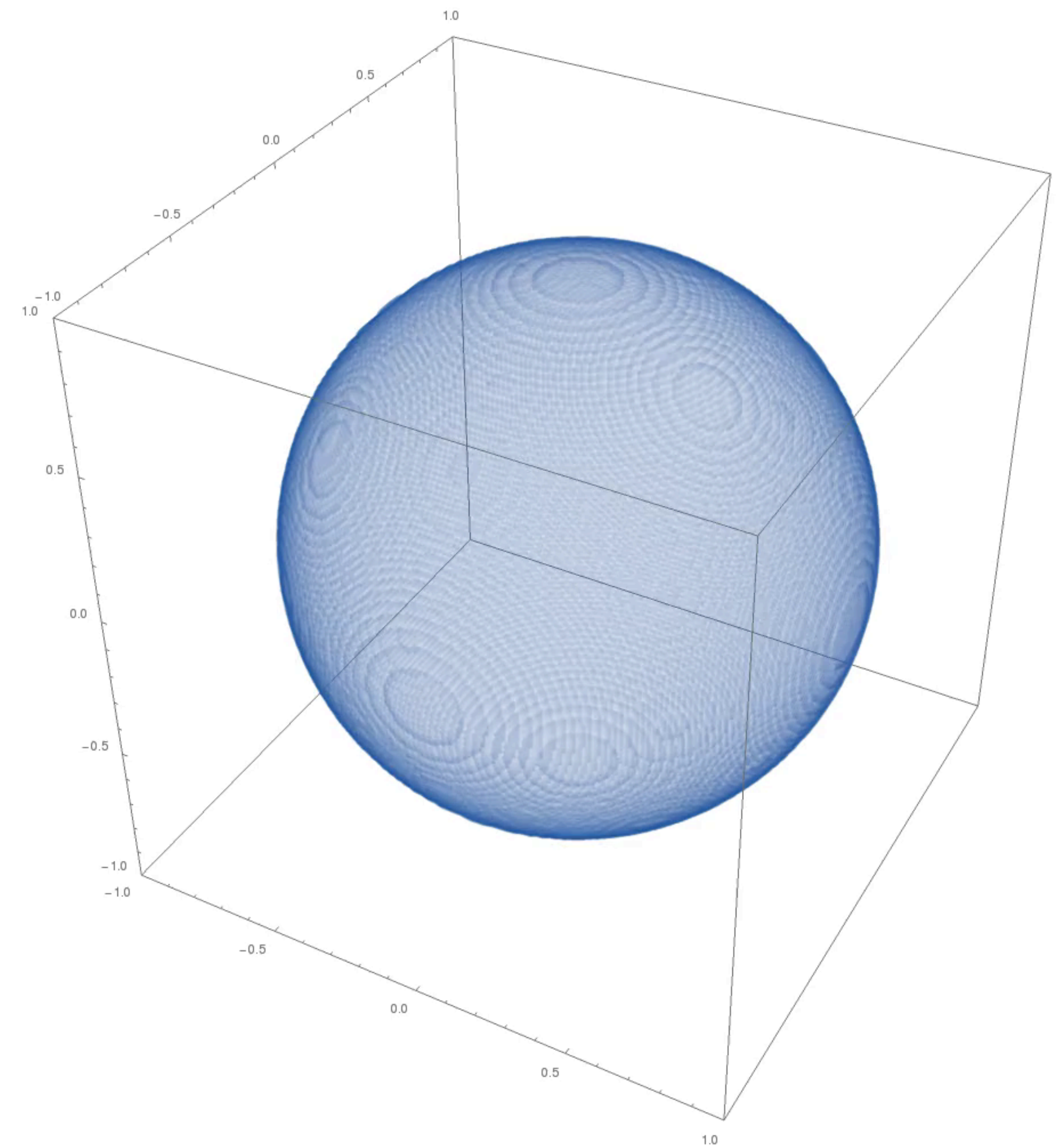
- Evolution with constant $\ddot{\nu}$ Effect of non-linear creep? [Akbal et al. 2017]
- Using the creep model one can also predict the time of the next glitch
- Sign of a threshold process? Correlation between size and waiting time in J0537-6910

[Antonopulou et al. 2017]

Turbulence

Work by Vadym Khomenko, Warsaw





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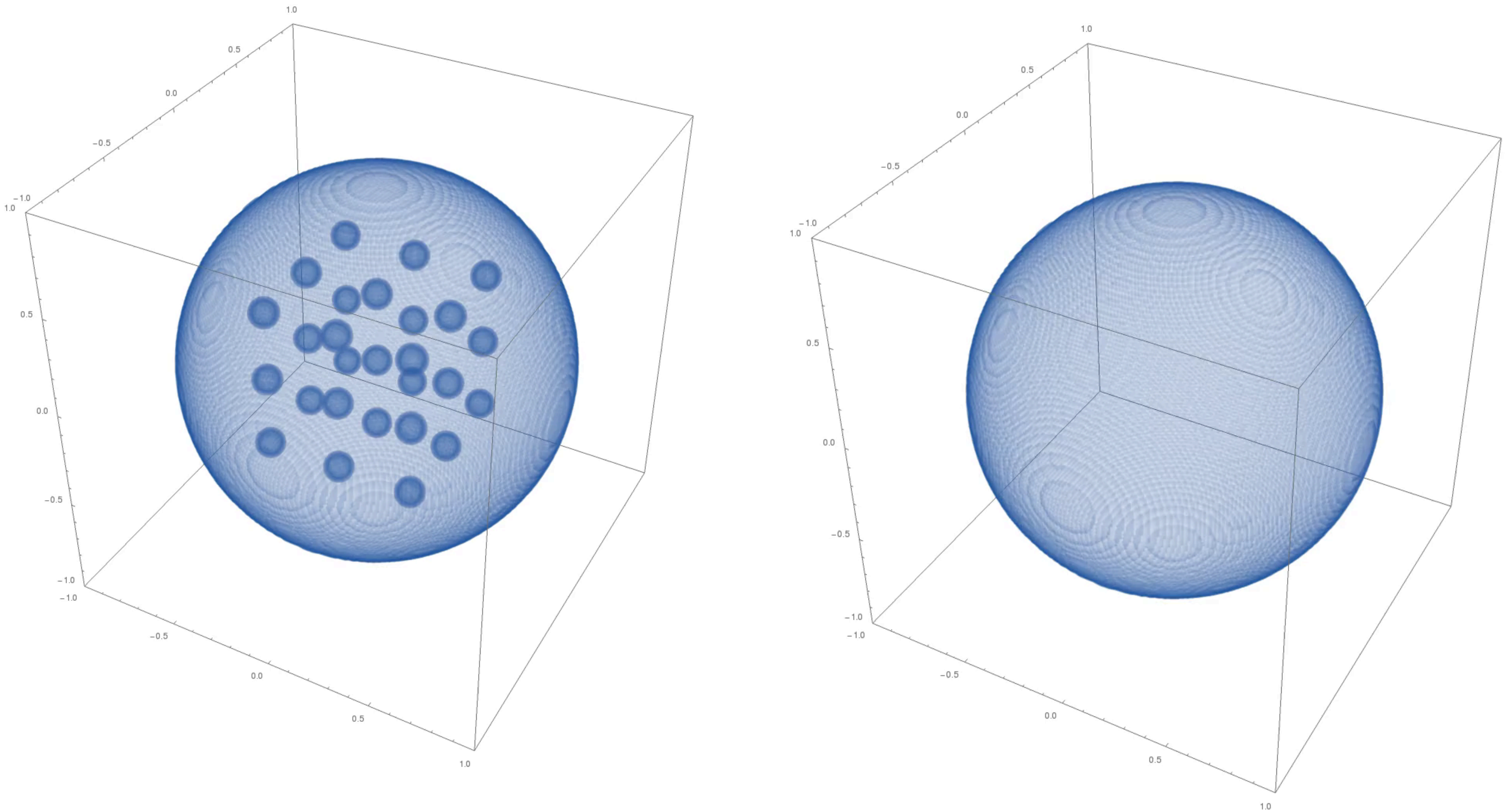


Turbulence

- The form of the Mutual Friction force changes with turbulence

$$F_i = L_s \langle f_i \rangle^{\mathrm{S}} + L_r \langle f_i \rangle^{\mathrm{R}}$$

[BH, Antonopoulou & Barenghi, 2021]

Fraction of unpinned vortices

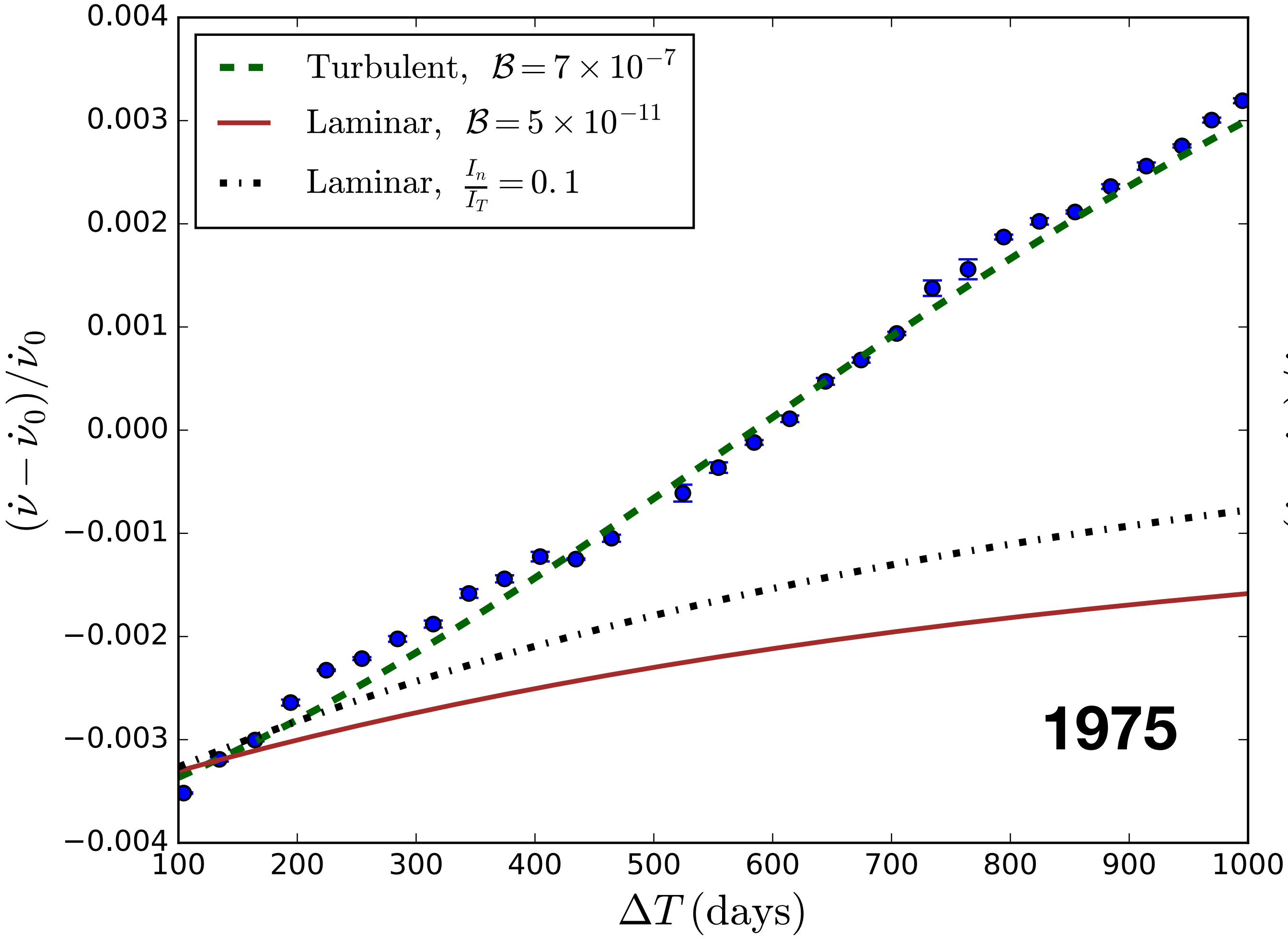
External spin down

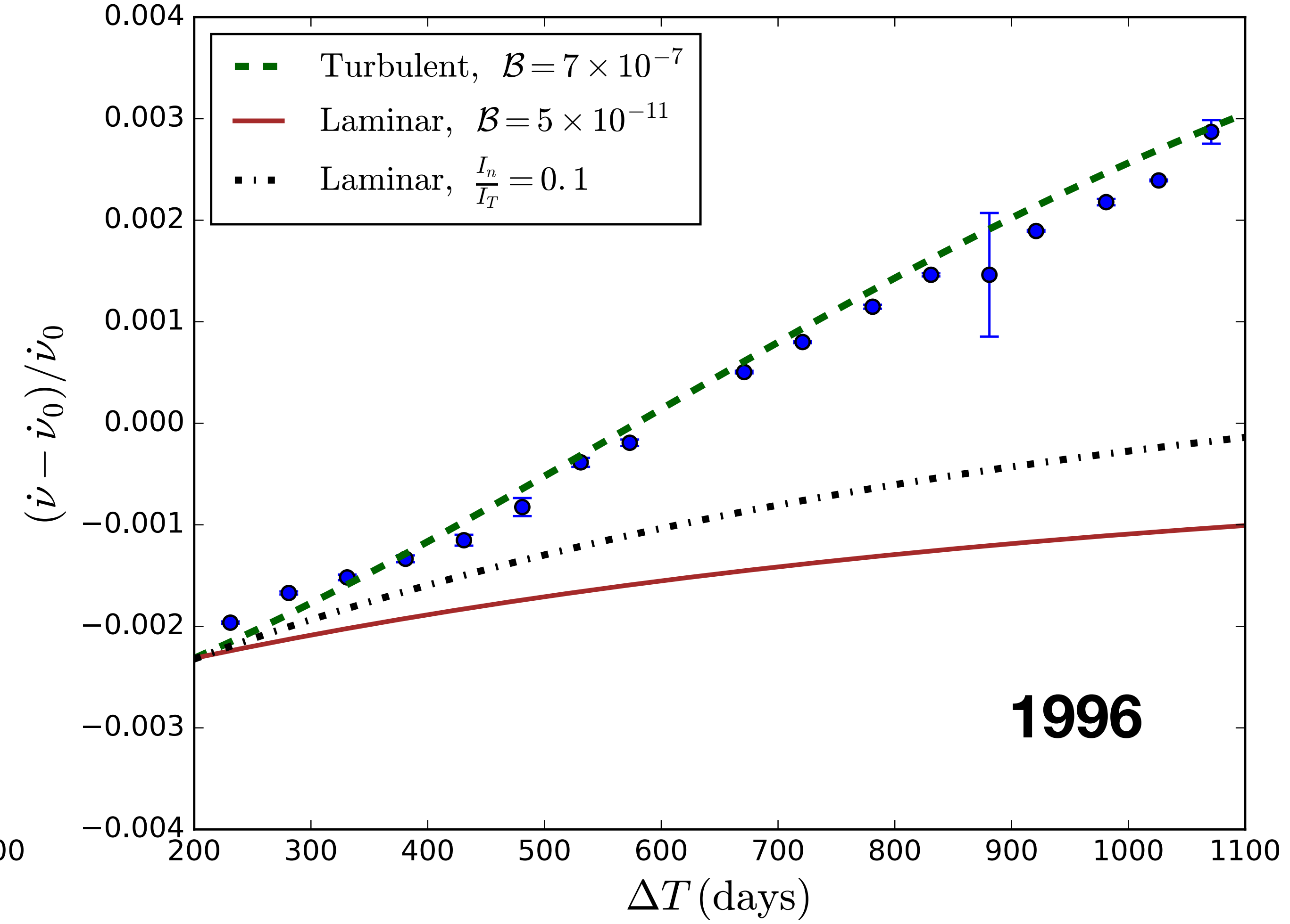
$$\dot{\Omega}_{\mathrm{c}} = 2\Omega_{\mathrm{n}} \gamma \mathcal{B} \Delta\Omega \frac{I_{\mathrm{n}}}{I_{\mathrm{c}}} + \alpha \frac{R^2}{\kappa} \mathcal{B}^3 \Delta\Omega^3 \frac{I_{\mathrm{n}}}{I_{\mathrm{c}}} - \tilde{T}$$

$$\dot{\Omega}_{\mathrm{n}} = -2\Omega_{\mathrm{n}} \gamma \mathcal{B} \Delta\Omega - \alpha \frac{R^2}{\kappa} \mathcal{B}^3 \Delta\Omega^3 + \frac{\varepsilon_{\mathrm{n}}}{(1-\varepsilon_{\mathrm{n}})} \tilde{T}$$

Turbulent term

Entrainment





- Non linear simulations confirm that the turbulent model is a better fit to relaxations
- Correlation predicted between $\ddot{\nu}$ and waiting time since previous glitch

[BH, Antonopoulou & Barenghi, 2021]

- Comparison needed to more pulsars [Lower et al. 2021]

Conclusions

- Sizes and statistics can help probe the trigger mechanism
  - only one or more? (vortex avalanches, instabilities etc..)
  - crust or core?
  - model independent tests? Meta-models developed in Melbourne [Melatos et al. 2018, Carlin and Melatos 2019, 2020]
- Relaxations probe superfluid coupling
  - How 'fast' is the mutual friction? do regions of the star decouple? [Celora et al. 2020]
  - What happens at late times? Non linear creep may play a role. Does turbulence play a role?
- Quantitative statements require models in GR [Sourie et al. 2017, Gavassino et al. 2020]