Pulsar Glitches
is the crust enough?

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Based on arXiv:1207.0633
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Glitch demographics

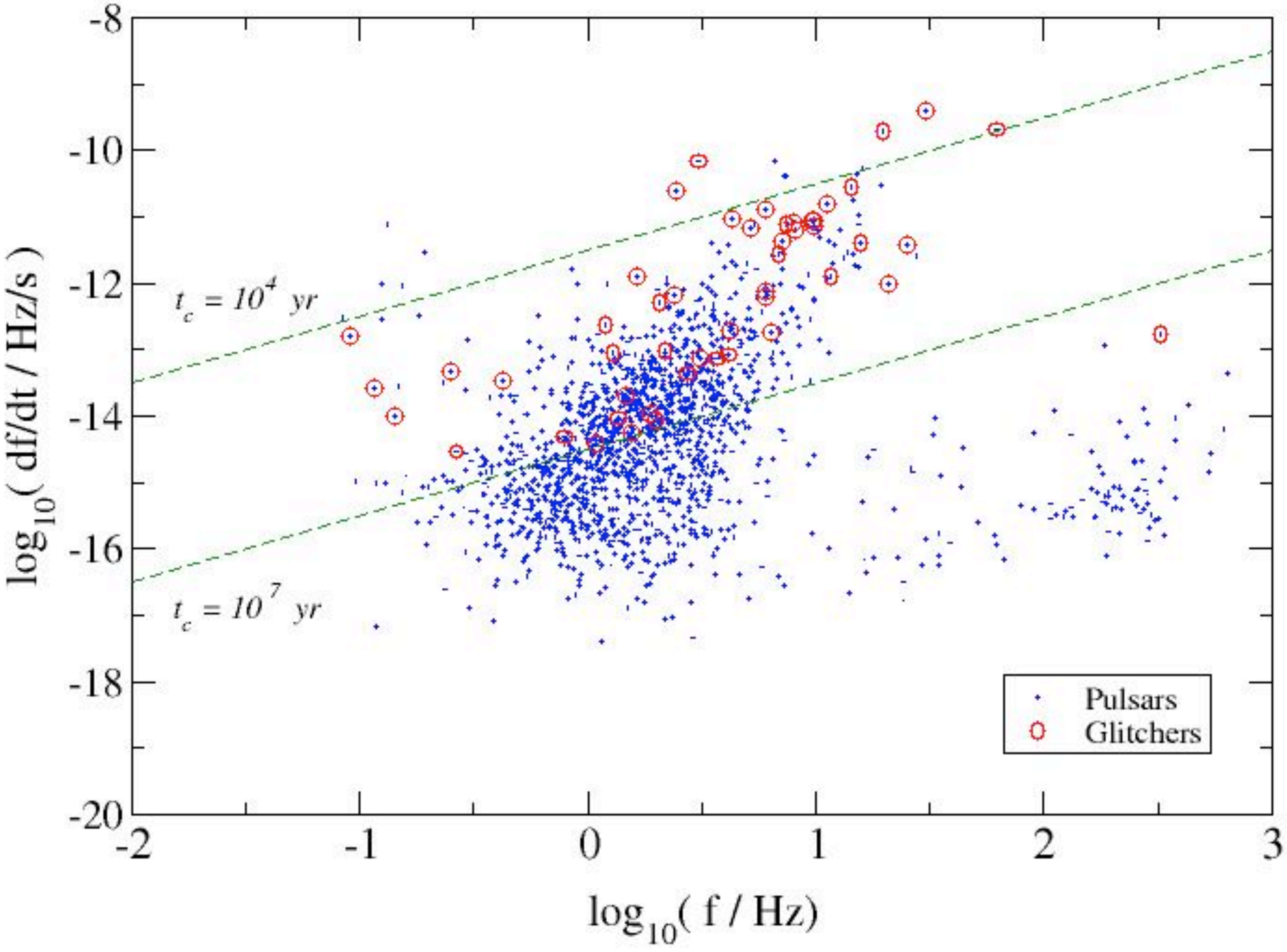
- Several hundreds, observed in > 100 radio pulsars.

- Present in young systems only.

- Range of spin jumps:

$$\frac{\delta\Omega}{\Omega} \sim 10^{-9} - 10^{-5}$$

- Also observed in other neutron star families (e.g. magnetars)



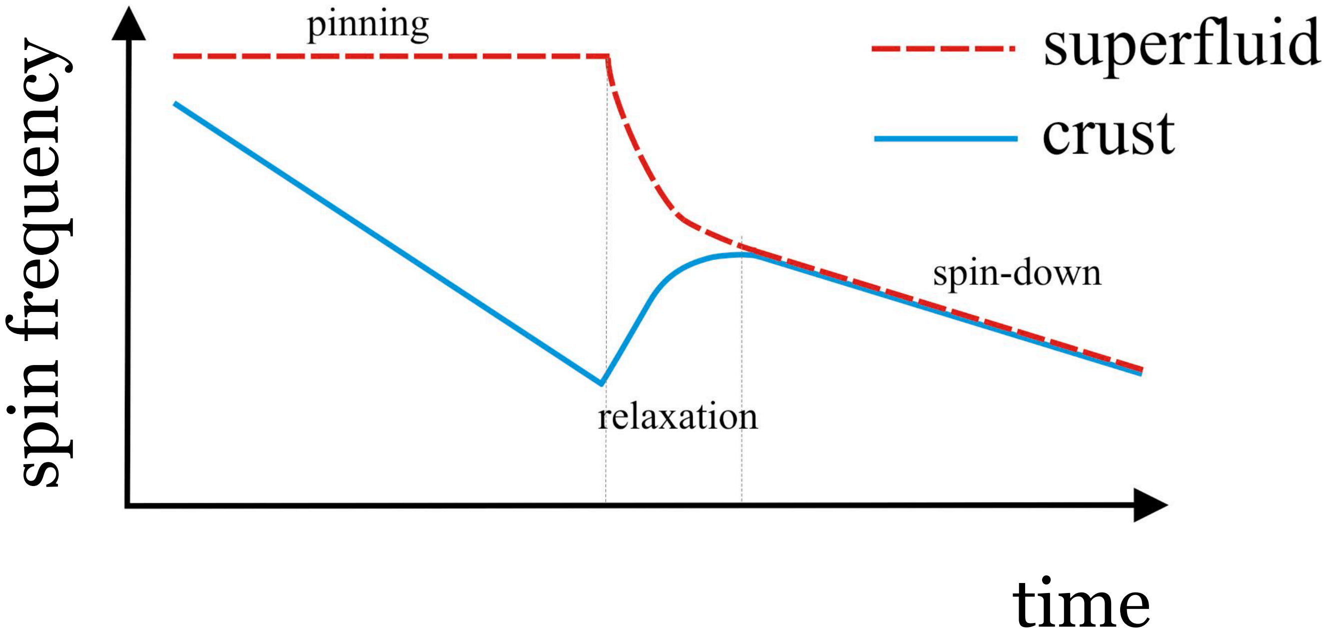
(figure credit: Ian Jones)

Glitches: the standard model

- The star comprises “superfluid” and “normal” fluid components (Anderson & Itoh 1975)

- The normal component is electromagnetically spun down.

- The superfluid’s spin frequency may decrease slower (or at all) if the neutron vortices are efficiently “pinned” onto another stellar component (e.g. the crustal lattice).



- Once a critical spin-lag has been reached, a global vortex unpinning occurs and the superfluid spins down transferring angular momentum to the normal component.

Glitches: long-term dynamics

- The spin-evolution between successive glitches is given by:

$$\dot{\Omega}_{\rm S} = 0 \qquad I_{\rm N}\dot{\Omega}_{\rm N} = N_{\rm EM}$$

S = Superfluid

N = Normal

- During the time interval $t_{\rm glitch}$ between successive events, the accumulated spin lag between the superfluid and the normal fluid is:

$$\Omega_{\rm SN} \equiv \Omega_{\rm S} - \Omega_{\rm N} \approx \Omega \frac{t_{\rm glitch}}{2\tau_c}$$

$$\tau_c = -\Omega/2\dot{\Omega}$$ is the usual spindown timescale

- Theory: still unclear as to what triggers vortex unpinning.

Glitches: short-term dynamics

- The short-term dynamics during a glitch obey total angular momentum conservation (assuming constant moments of inertia):

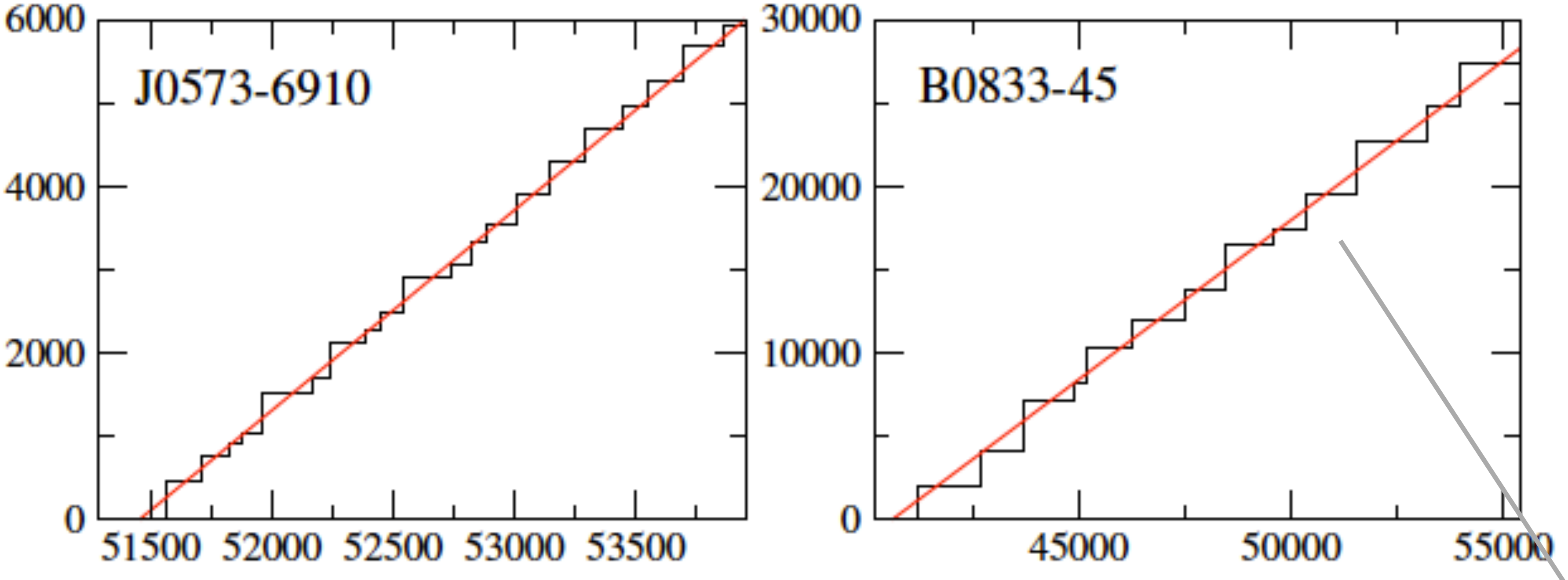
$$\delta J_{\rm tot} = I_{\rm S}\delta\Omega_{\rm S} + I_{\rm N}\delta\Omega_{\rm N} = 0 \qquad \longrightarrow \qquad \delta\Omega = \delta\Omega_{\rm N} = -\frac{I_{\rm S}}{I_{\rm N}}\delta\Omega_{\rm S}$$

- The observed spin-jump is that of the normal component (which includes the crust).
- Then: $\dfrac{I_{\rm S}}{I_{\rm N}} \geq \dfrac{2\tau_c}{t_{\rm glitch}}\left(\dfrac{\delta\Omega}{\Omega}\right)$ $\qquad |\delta\Omega_{\rm S}| \leq \Omega_{\rm SN}$
- For a series of glitches during a total time of observation $t_{\rm obs}$:

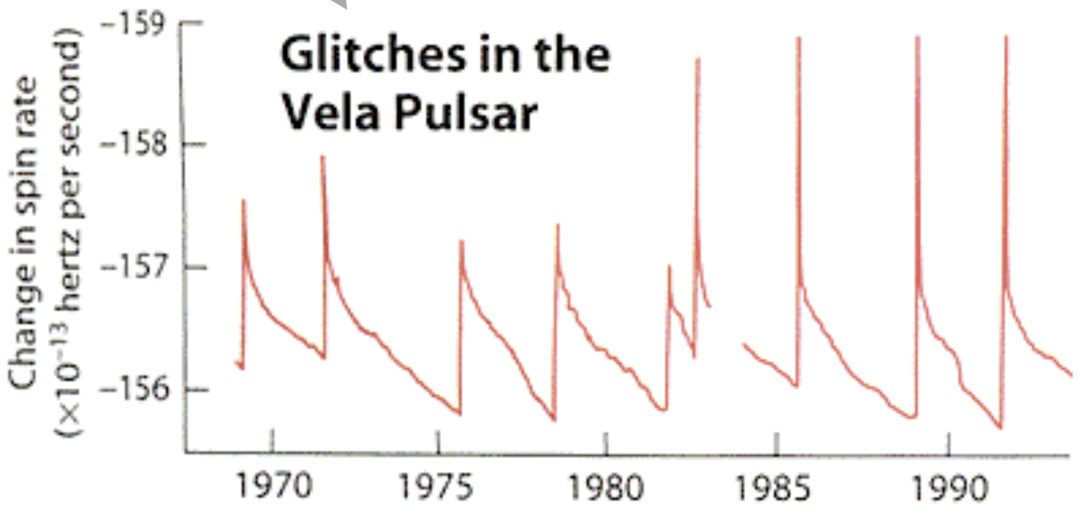
$$\frac{I_{\rm S}}{I_{\rm N}} \geq 2\tau_c\mathcal{A} \quad \text{where} \quad \mathcal{A} = \frac{1}{t_{\rm obs}}\sum_i \left(\frac{\delta\Omega}{\Omega}\right)_i$$

Glitch data: cumulative spin-jump

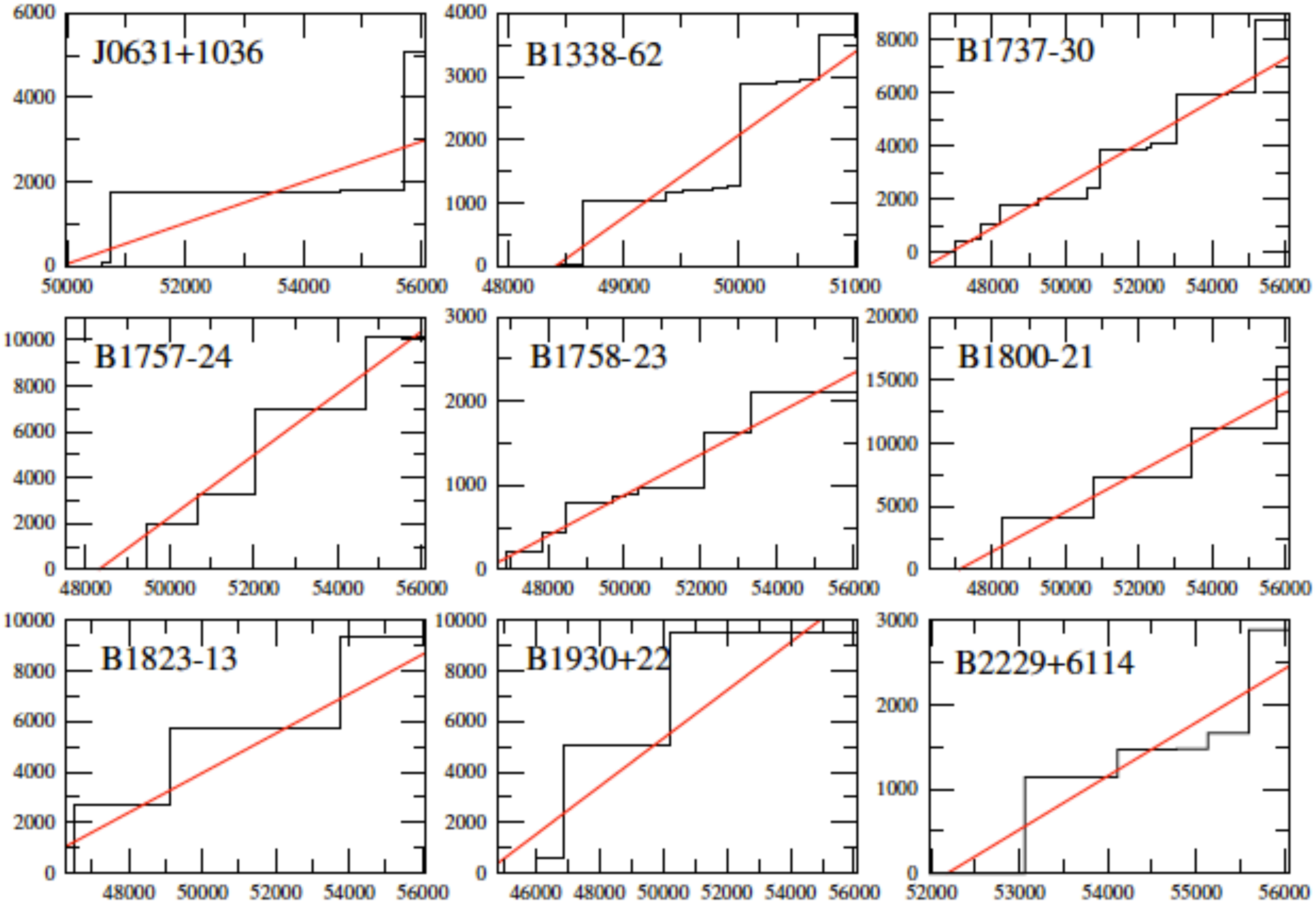
The red line's slope represents the "activity" parameter *A*



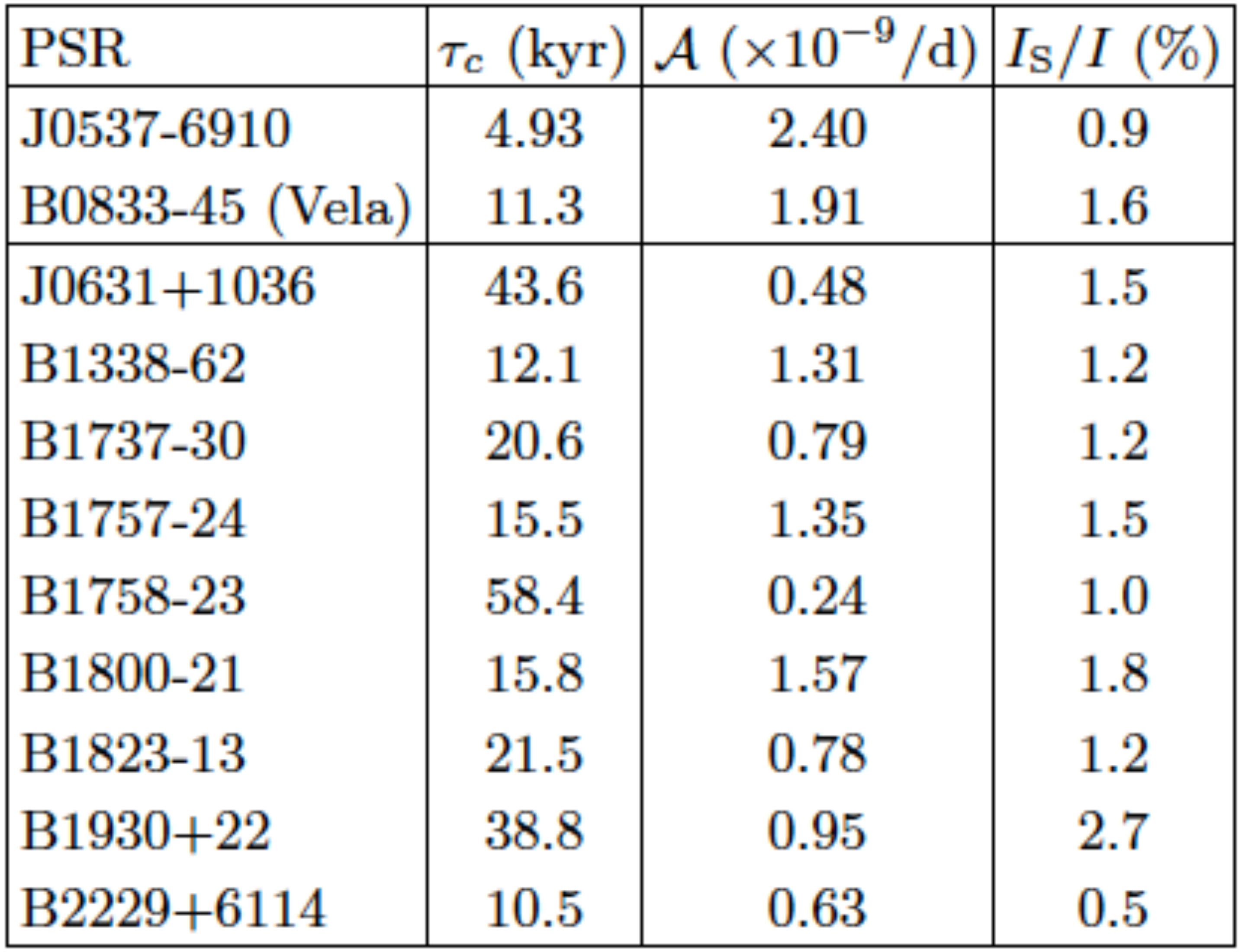
(Data from Espinoza et. al. 2011)



More glitch data



Full table of data



PSR	τ_c (kyr)	$\mathcal{A}$ ($\times 10^{-9}$/d)	I_S/I (%)
J0537-6910	4.93	2.40	0.9
B0833-45 (Vela)	11.3	1.91	1.6
J0631+1036	43.6	0.48	1.5
B1338-62	12.1	1.31	1.2
B1737-30	20.6	0.79	1.2
B1757-24	15.5	1.35	1.5
B1758-23	58.4	0.24	1.0
B1800-21	15.8	1.57	1.8
B1823-13	21.5	0.78	1.2
B1930+22	38.8	0.95	2.7
B2229+6114	10.5	0.63	0.5

Constraint on SF moment of inertia

Some conclusions so far

- The remarkable glitch regularity in systems like Vela is a strong indication of a *SF reservoir that is fully spent and replenished periodically*.

- The moment of inertia fraction *Is/I* ~ 1-2 % involved in glitches is *comparable* to the amount of neutron SF expected in the crust.

- This has been taken as evidence of a *SF reservoir located in the crust* (the crust can also provide the required pinning sites for the vortices). (Link et al. 1999)

- *Is this conclusion robust?*

  As first suggested by Chamel & Carter (2006), the multifluid physics of the crust may cast doubt on the previous "standard glitch model".

Entrainment in neutron star crusts

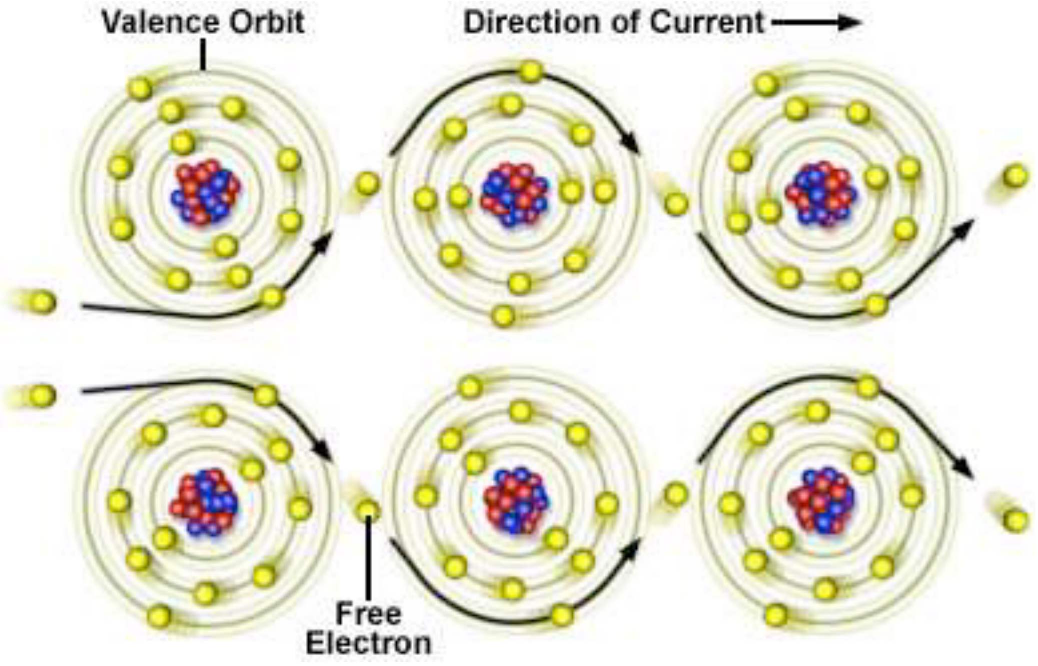
- The “dripped” SF neutrons are not entirely free. They move against the background of nuclei with an effective mass $m_{\mathrm{n}}^{\star} > m_{\mathrm{n}}$.

- This entrainment effect leads to a misalignment between the neutron momentum and velocity:

$$\mathbf{p}_{\mathrm{n}} = m_{\mathrm{n}}[\underbrace{\mathbf{v}_{\mathrm{n}}}_{\text{neutron SF}} - \varepsilon_{\mathrm{n}}(\underbrace{\mathbf{v}_{\mathrm{c}}}_{\text{crust lattice}} - \mathbf{v}_{\mathrm{n}})]$$

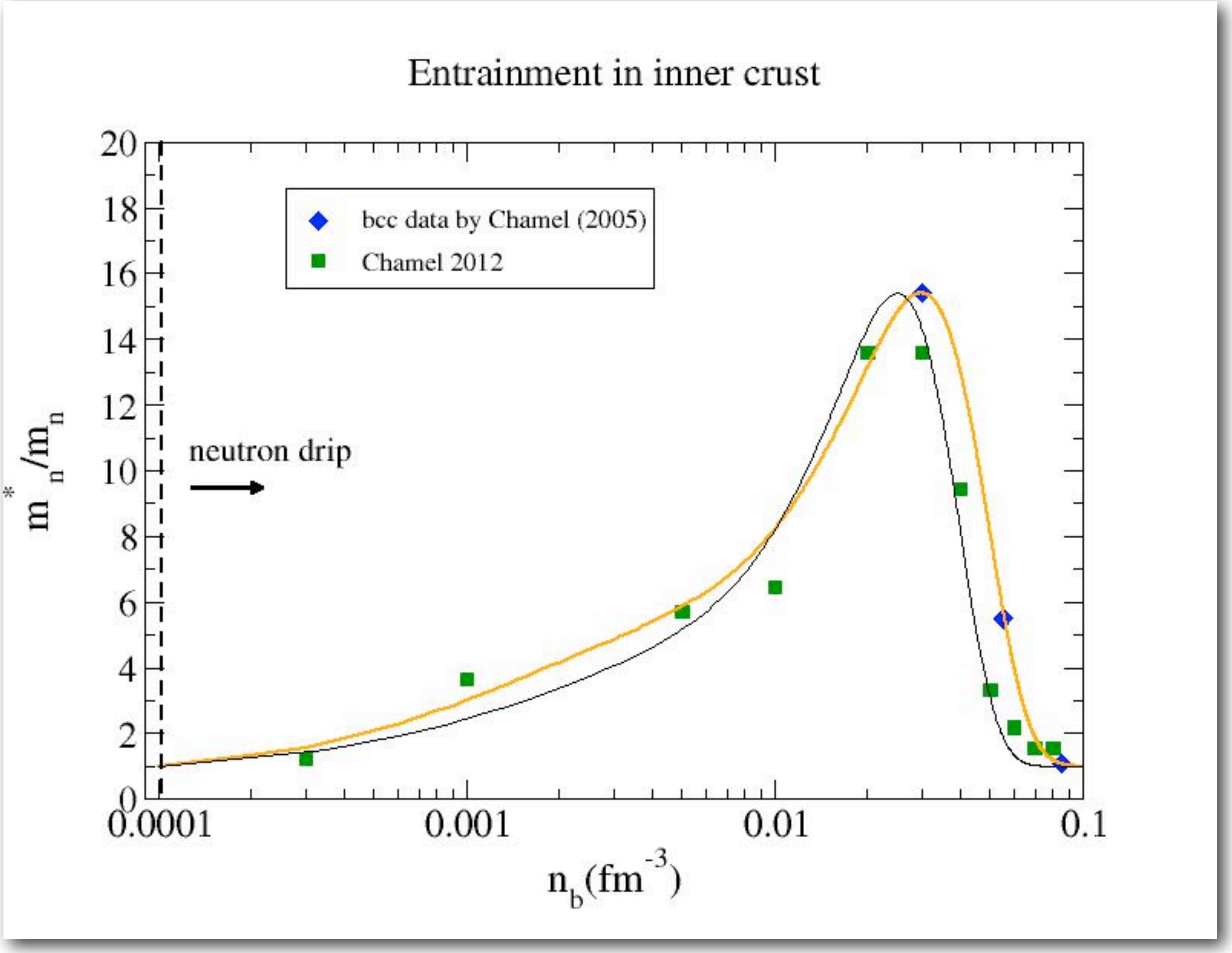
entrainment parameter:

$$\varepsilon_{\mathrm{n}} = 1 - \frac{m_{\mathrm{n}}^{\star}}{m_{\mathrm{n}}}$$



(Figure credit: N. Chamel)

Entrainment in neutron star crusts



Revised glitch model with entrainment

- The angular momenta now contain additional entrainment pieces:

$$J_{\rm S} = I_{\rm S}\left[\,\Omega_{\rm S} - \varepsilon_{\rm n}(\Omega_{\rm S} - \Omega_{\rm N})\,\right] \qquad J_{\rm N} = I_{\rm N}\Omega_{\rm N} + \varepsilon_{\rm n} I_{\rm S}(\Omega_{\rm S} - \Omega_{\rm N})$$

$$\varepsilon_{\rm n} = 1 - \frac{\langle m_{\rm n}^\star\rangle}{m_{\rm n}}$$ body-averaged entrainment

- The spin evolution is given by the body-averaged equations:

$$\dot{J}_{\rm S} = 0, \qquad \dot{J}_{\rm N} = N_{\rm EM}$$

- Combining these: $\tilde{I}\dot{\Omega} = N_{\rm EM}$ where $\tilde{I} = I - \frac{m_{\rm n}}{\langle m_{\rm n}^\star\rangle} I_{\rm S}$

Revised moment of inertia constraint

- Despite pinning, the SF spin decreases as:

$$\dot{\Omega}_{\rm S} = \left(1 - \frac{m_{\rm n}}{\langle m_{\rm n}^{\star} \rangle}\right) \dot{\Omega}$$

- The spin-lag just before a glitch is reduced: $\Omega_{\rm SN} \approx \frac{m_{\rm n}}{\langle m_{\rm n}^{\star} \rangle} \Omega \frac{t_{\rm glitch}}{2\tau_c}$

- As before, we use conservation for the total angular momentum:

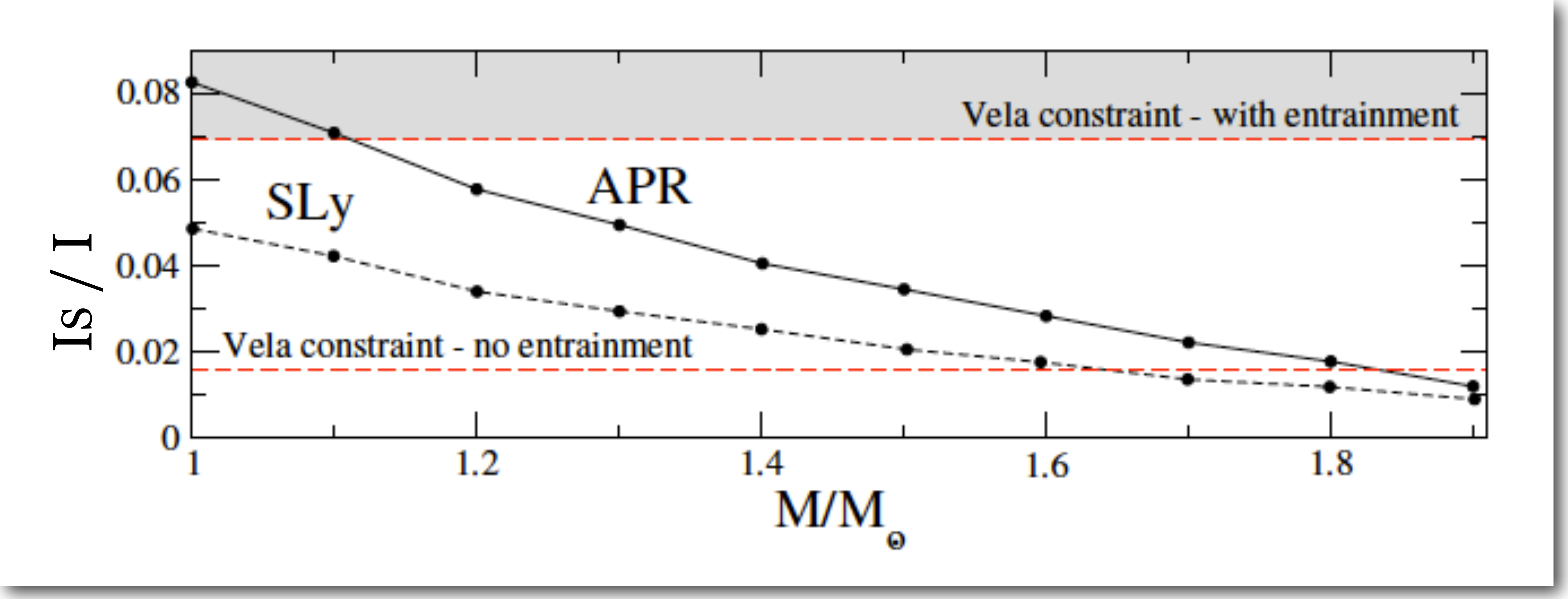
$$\frac{\delta\Omega}{\Omega} \leq \frac{m_{\rm n}}{\langle m_{\rm n}^{\star} \rangle} \left(\frac{I_{\rm S}}{I_{\rm N}}\right) \frac{t_{\rm glitch}}{2\tau_c} \quad \longrightarrow \quad \frac{I_{\rm S}}{I_{\rm N}} \geq 2\tau_c \mathcal{A} \frac{\langle m_{\rm n}^{\star} \rangle}{m_{\rm n}}$$

- *Is this new constraint compatible with the amount of SF in the crust?*

The crust is not enough (most likely)

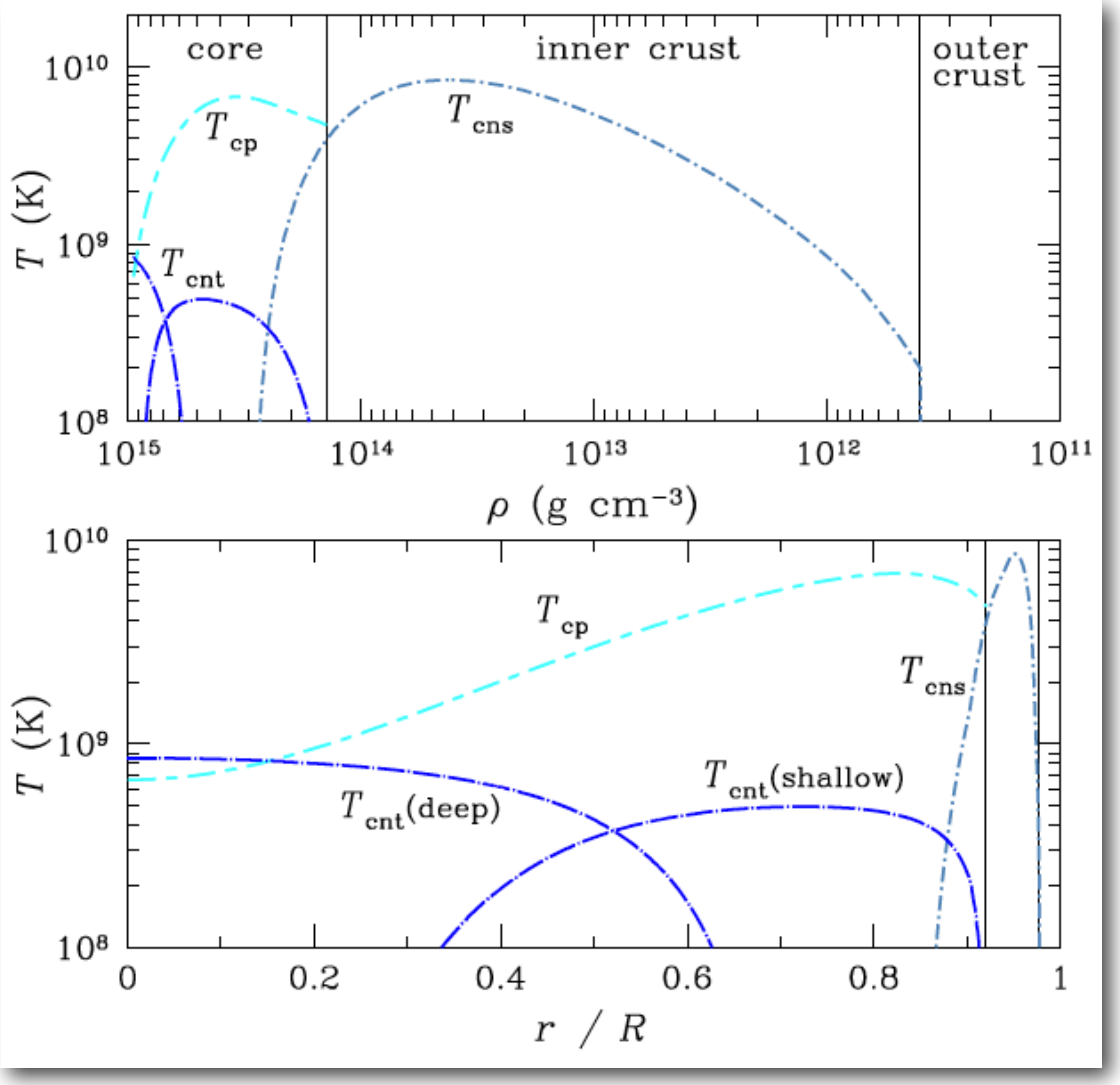
- Fully relativistic TOV stellar models.
  Model I : APR core EoS, NV crust EoS
  Model II: Douchin Haensel Sly EoS.

- Unless the stellar mass is quite low, the crust is unlikely to contain enough SF that could drive large glitches.



Superfluid pairing gaps

- As a reminder, we show ‘typical” neutron and proton pairing gaps.
- This particular example, has been used in modeling the cooling curve of Cassiopeia A.
- Note that neutron singlet pairing extends over the crust and outer core.



(Ho et al. 2012)

Crust SF + ?

- There are (at least) three interpretations of our results (apart from the "low-mass systems" option):

✓ The core SF actually participates in glitches. If true, why don't we see events with much larger SF reservoir I_s/I (~ 1) ?

✓ "Fine-tuning":
the core contains just about the required amount of neutron SF. This is not what gap theorists would be happy with.

✓ "Lack of precision":
the effective neutron mass in the crust may be much smaller than what current work suggests. This is not very likely, but there is a clear need for more detailed work.

Summary

- If the entrainment effect in neutron star crusts is as strong as current theory predicts it would imply a reduced mobility of the neutron SF with respect to the solid crust.

- Effectively, strong entrainment leads to a reduced crust SF reservoir for glitches.

- We have shown that the revised SF capacity of neutron star crusts cannot explain large, Vela-like, glitches thus pointing to a revision of the standard glitch model. Unless the various glitchers are all low-mass systems, our results indicate a partial involvement of the core SF.