Pulsar glitches and neutron star masses

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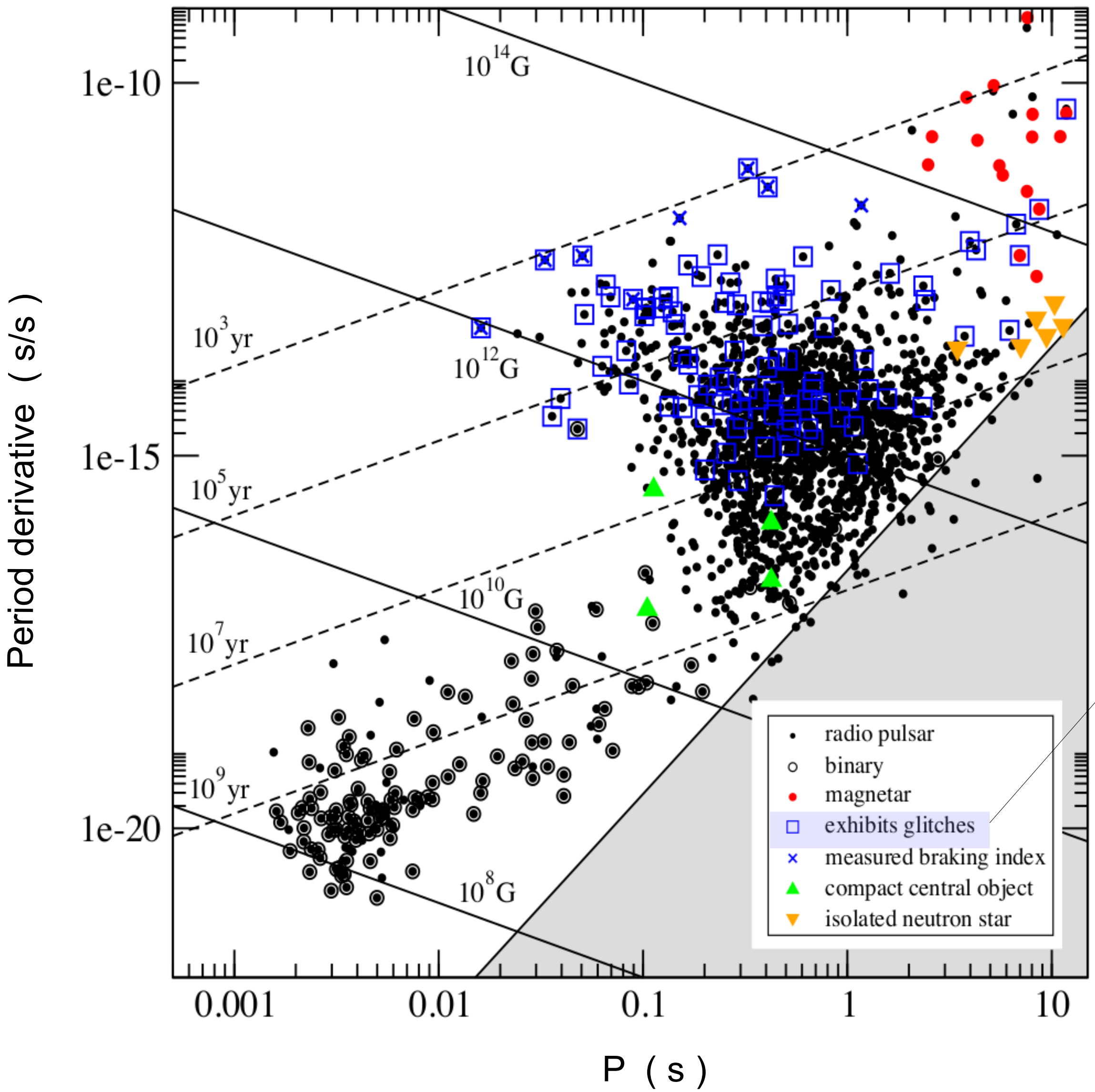
Pulsar timing



- Period P and spin-down rate (period derivative) are precisely determined.

- Different classes populate different regions (inferred age and magnetic field). Sanity check from the braking index, but the second derivative of P is needed.

- Stable clocks with predictable spin-down... except for random timing irregularities

Glitches:

Evidence for nuclear superfluidity in NS interiors, alternative to cooling.

Pulsar glitches

- Lack of radiative/pulse profile changes:

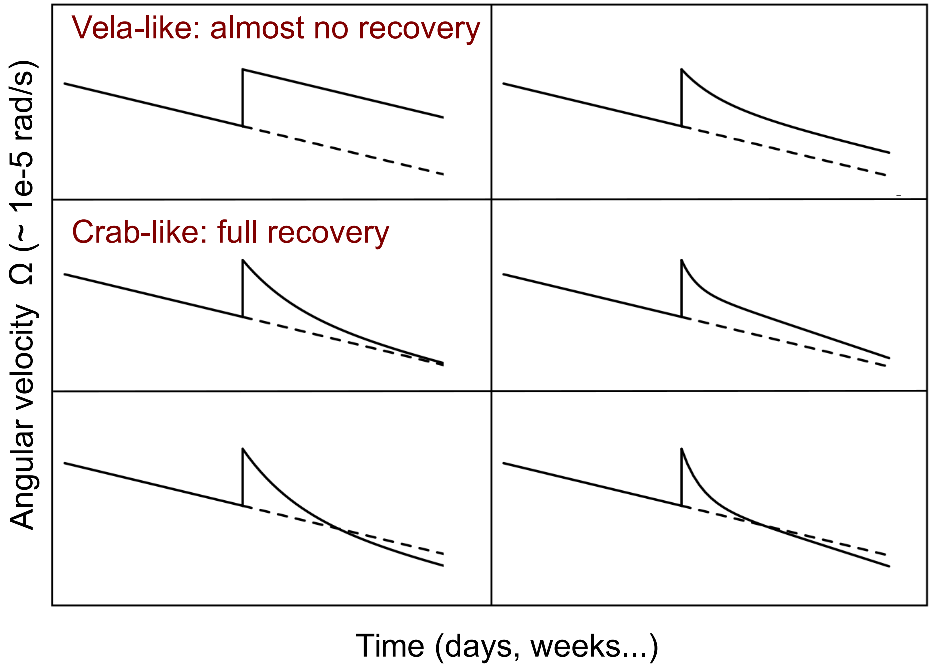
→ Evidence for internal origin

- Long recoveries:

→ Thought to be due to superfluid component in the star

- Diverse phenomenology:

→ probably due to different age, mass, rotational parameters...
we are mainly interested in the absolute amplitude of very large glitches:
$\Delta\Omega > 5 \times 10^{-5}$ rad/s (~ 50 pulsar sample)

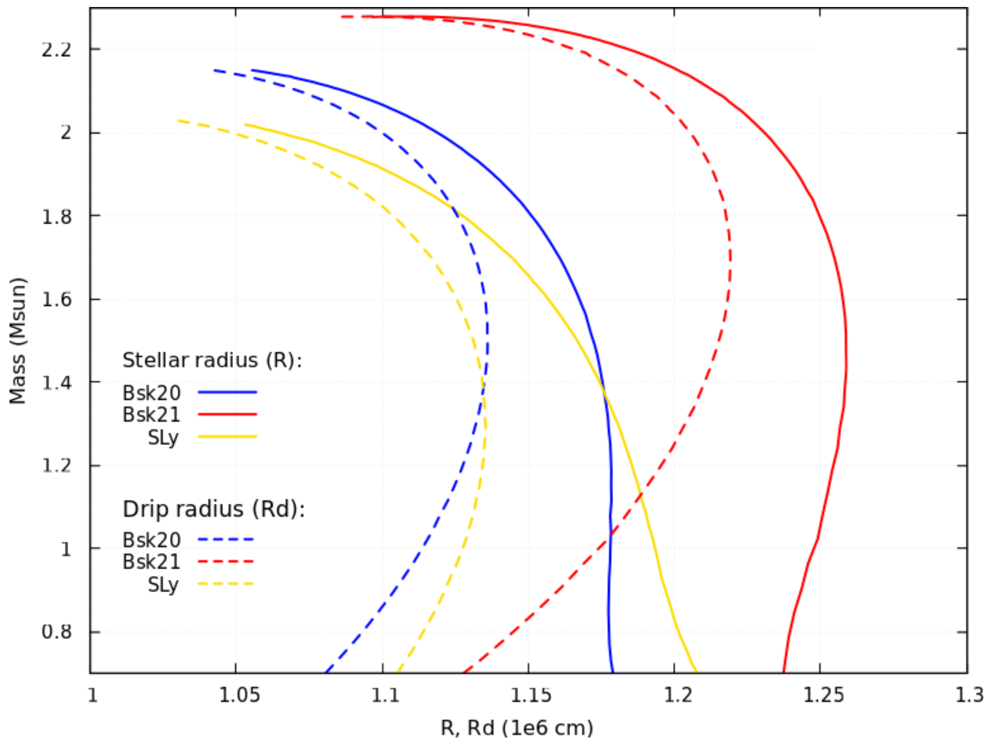


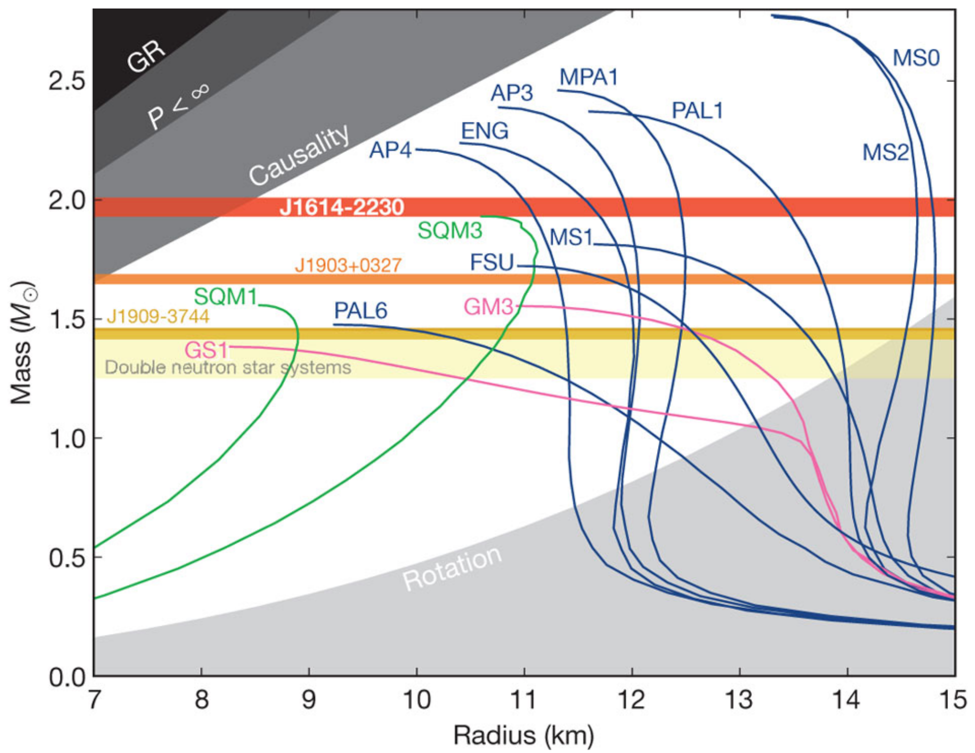
Key point: to describe glitches we need that a NS is comprised of (at least) two components that exchange angular momentum.

Can we identify the (two?) components ?

Which part of the NS provides the angular momentum needed to spin-up the “observable component” ?

Neutron star mass-radius diagram





The three EOSs the we use: BSK21, BSK20, SLY4:
Radius (solid) and “drip-radius” (dotted)

PB Demorest *et al. Nature* **467**, 1081-1083 (2010)

EOS lines not intersecting the J1614-2230 band are ruled out by this measurement. Most EOS curves involving exotic matter (kaon condensates or hyperons) tend to predict maximum masses well below 2 M⊙ and are therefore ruled out.
The effect of neutron star rotation increases the maximum possible mass for each EOS:
≲2% correction for a 3-ms spin period.

Minimal ingredients

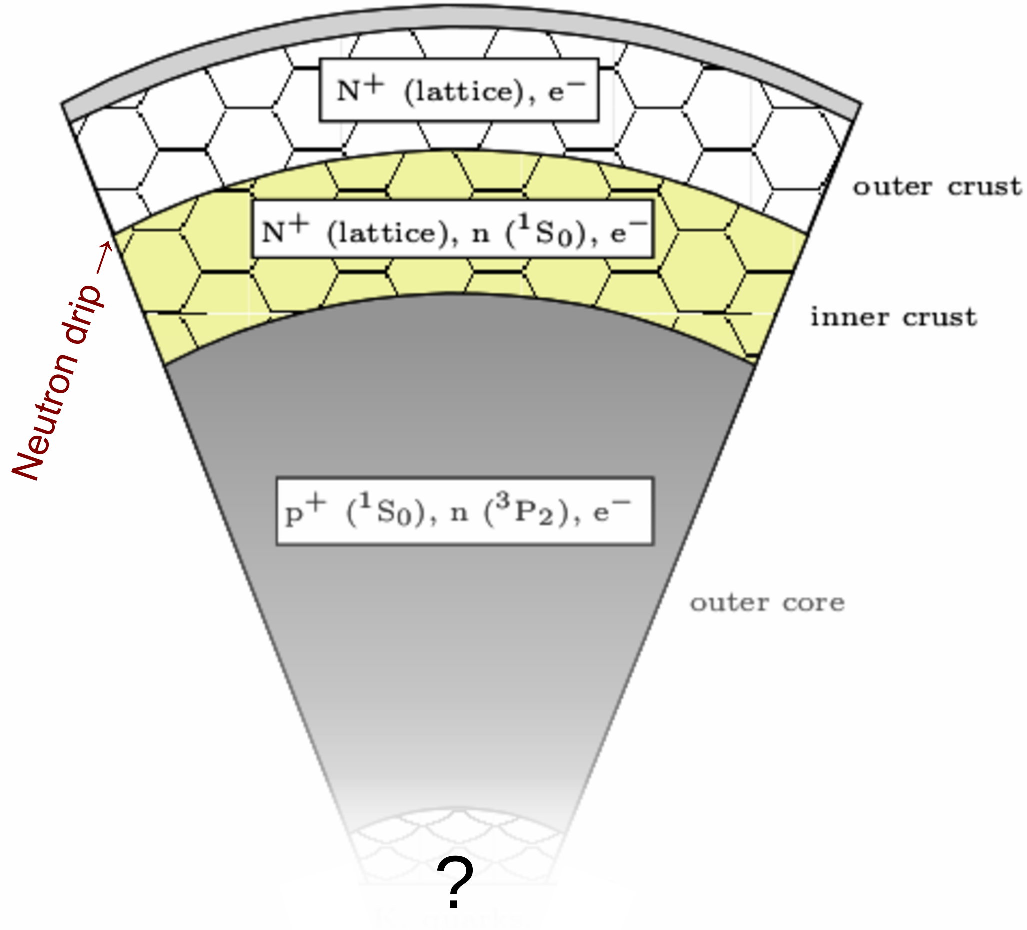
The inner crust (and core) contains a neutron superfluid (superfluid n-component).

Everything else (proton superconductor, electron gas) is locked with the solid crust into the magnetic field (rigid p-component).

braking torque

"crust" $$I_c\dot{\Omega}_c = -\alpha - \underbrace{\frac{I_c}{\tau_c}(\Omega_c - \Omega_n)}_{\text{Mutual friction}}$$

"neutrons" $$I_n\dot{\Omega}_n = \underbrace{\frac{I_c}{\tau_c}(\Omega_c - \Omega_n)}_{\text{Mutual friction}}$$



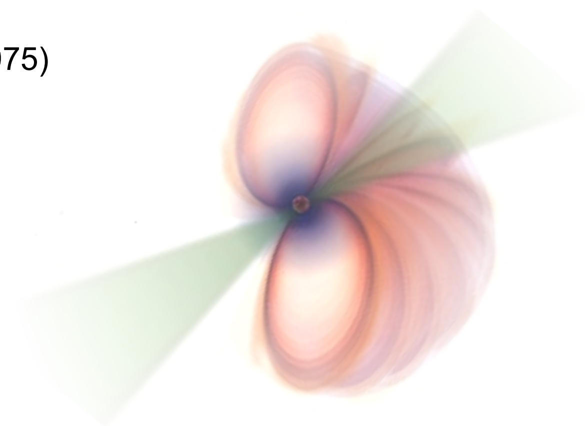
"Starquake model" of Baym, Pethick, Pines, Ruderman (1969)

Spin-up is given by the settling of the crust under gravitational stresses
Phenomenological coupling timescale:
→ fitted from post-glitch relaxation

IMPOSSIBLE TO EXPLAIN LARGE VELA GLITCHES!

Glitch mechanism (vortex mediated)

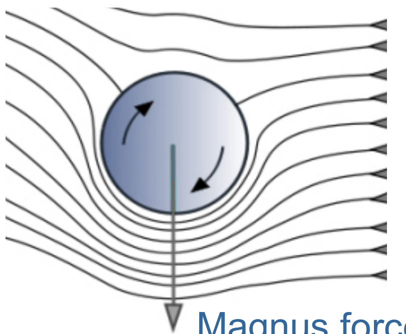
Anderson & Itoh “Pulsar glitches and restlessness as a hard superfluidity phenomenon”, Nature (1975)



- The charged component steadily looses angular momentum

- Vortices are **pinned** (next slide!), the superfluid cannot spin-down

→ vortex line carried by the charged component
→ a velocity lag builds up
→ neutron current in the frame of the normal component



- Magnus force ≃ pinning force: the vortex line unpins

→ analogy between unpinning lag and critical current in superconductors
→ vortices can move: mutual friction between the components

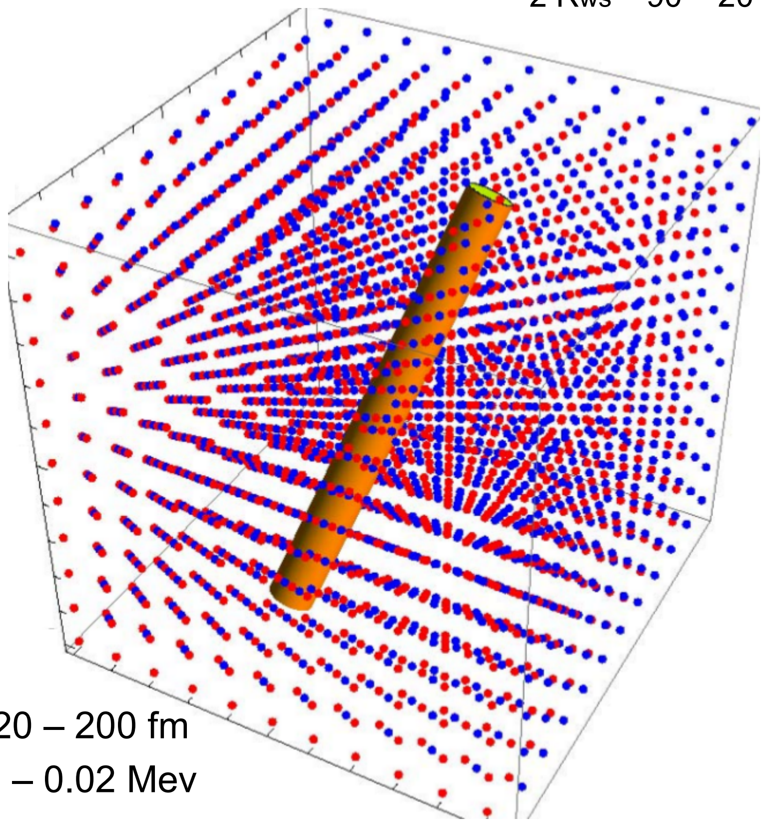
Expulsion of vortex lines from bulk superfluid

Local: vortex creep (thermally activated)	Global: vortex avalanche (trigger?)

Ingredients: pinning forces

(S. Seveso et al., MNRAS, 2016)

2 Rws ~ 90 – 20 fm



2 ξ ~ 20 – 200 fm

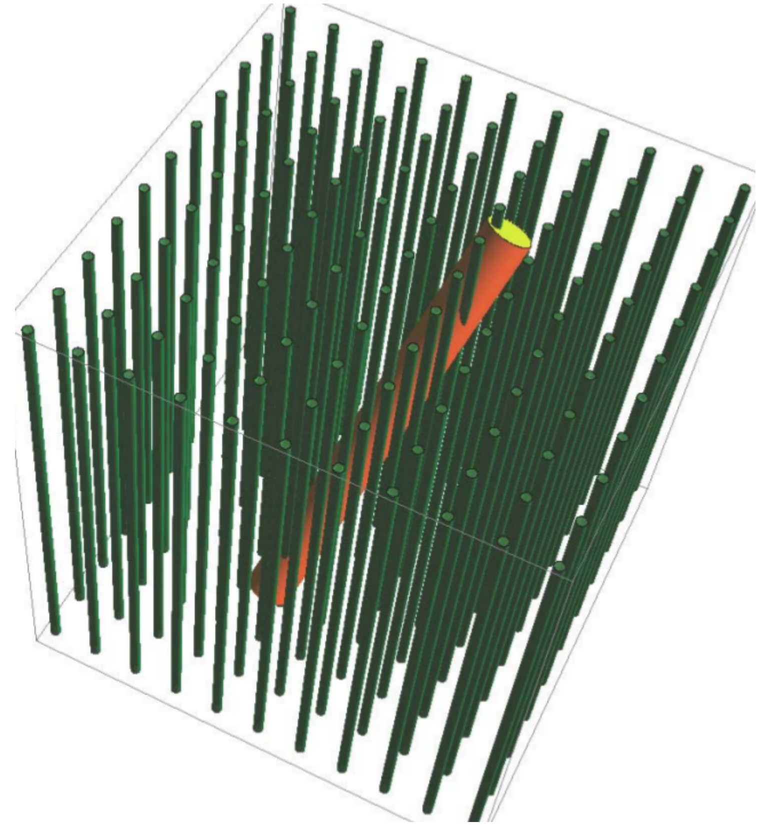
Ep ~ 3 – 0.02 Mev

Inner crust:

Vortex-nucleus interaction → Vortex-lattice interaction
Strong pinning: the coherence length ξ of a vortex is smaller than the lattice spacing.

IDEA: consider a segment of vortex line (the length L is given by the tension) and average over translations and rotations of the total pinning force divided by L

2 Rws ~ 90 – 20 fm



Core:

Vortex-flux tube interaction → Vortex-array interaction
Pinning to flux-tubes negligible for normal pulsars

$$\xi_p \approx 16\, x_p^{1/3} \rho_{14}^{1/3} \Delta_p (\mathrm{MeV})^{-1} \mathrm{fm}$$

$$\xi_n \approx 16\, x_n^{1/3} \rho_{14}^{1/3} \Delta_n (\mathrm{MeV})^{-1} \mathrm{fm}$$

Coherence length estimates: (Mendell, Astrophys. J., 380:515, 1991)

Ingredients: entrainment coupling

- Andreev-Baskin (1975): Three-velocity Hydrodynamics of Superfluid solutions

Normal viscous mixture → different velocity fields cannot coexist inside the same fluid
Superfluid mixture → each superfluid can flow with its own velocity
Interactions between particles → non-dissipative entrainment

Superfluid momenta in the frame of the normal fluid

$$\begin{cases} \mathbf{p}_1 = \rho_{11}^{(s)} (\mathbf{v}_1 - \mathbf{v}_n) + \rho_{12}^{(s)} (\mathbf{v}_2 - \mathbf{v}_n) \\ \mathbf{p}_2 = \rho_{21}^{(s)} (\mathbf{v}_1 - \mathbf{v}_n) + \rho_{22}^{(s)} (\mathbf{v}_2 - \mathbf{v}_n) \end{cases}$$

1: velocity of the superfluid "1"

2: velocity of the superfluid "2"

n: velocity of the normal component

...the momentum of one fluid is a linear combination of the velocities.

- Carter multi-fluid formalism:

Entrainment also arise when a fluid is flowing through a solid...
...like electrons in metals or "free" neutrons in NS crust

→ non dissipative coupling between "n" and "p"

→ NOT to be confused with the (dissipative) mutual friction

$$\begin{aligned} \frac{\bar{p}_i^{\rm n}}{m_{\rm n}} &= v_i^{\rm n} + \varepsilon_{\rm n}(v_i^{\rm p} - v_i^{\rm n}) \\ \frac{\bar{p}_i^{\rm p}}{m_{\rm p}} &= v_i^{\rm p} + \varepsilon_{\rm p}(v_i^{\rm n} - v_i^{\rm p}) \end{aligned}$$

Ingredients: entrainment coupling

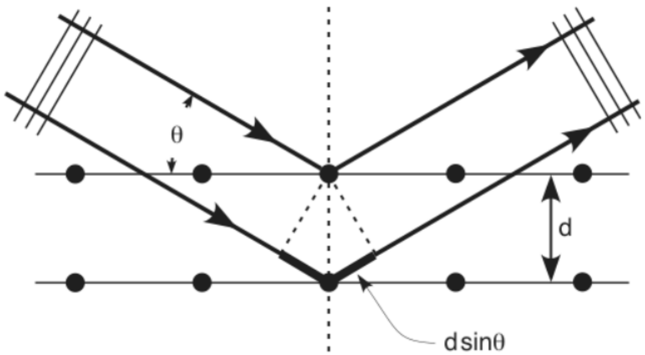
- In the crust:

- The entrainment parameters can be expressed in terms of effective masses of free neutrons:

- Bragg scattering by crustal lattice

- Conduction bands (like electrons in metals)

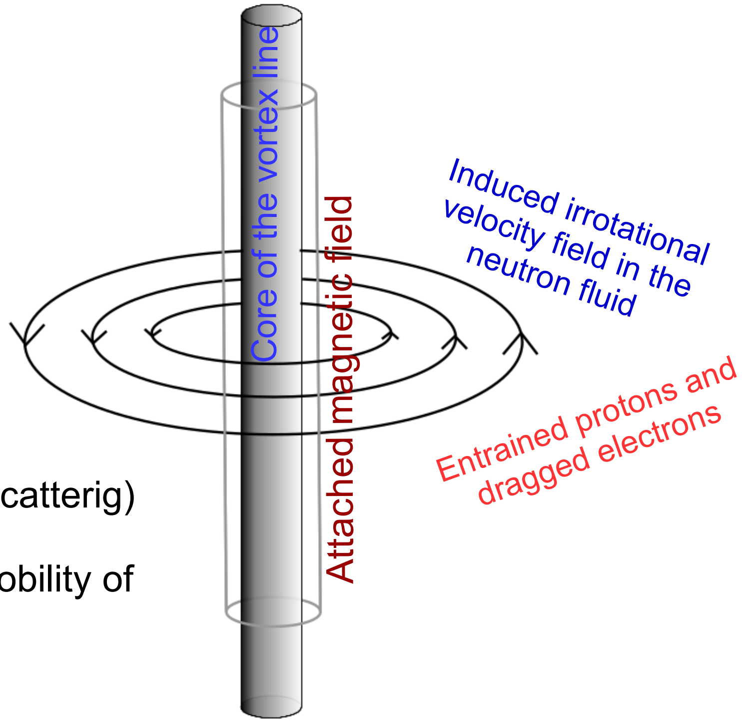
$$d \sin\theta = N\pi/k$$



- In the core:

Entrainment is due to:
- Strong interaction between protons and neutrons

Effects: vortex lines are magnetized (like a little solenoid)
Scattering of electrons → vortex is dragged
Dipole-dipole interaction with flux-tubes (core pinning?)



→ The core is coupled to the crust on the timescale of a second (electron scatterig)

→ The crustal superfluid is entrained by the normal component: reduced mobility of free neutrons is a potential problem for pulsar glitch theory.

Andersson N. et al. “Pulsar Glitches: The Crust is not Enough”. Phys. Rev. Lett. (2012)
Chamel N. “Crustal Entrainment and Pulsar Glitches”, Phys. Rev. Lett. (2013)

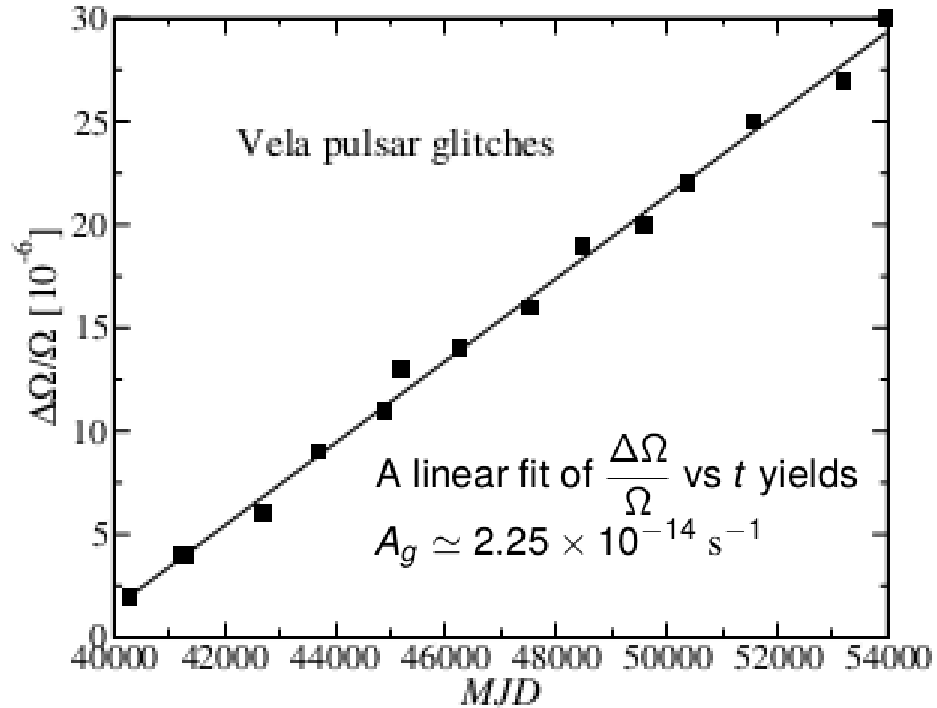
For pulsars that have glitched many times it is possible to estimate the moment of inertia of the superfluid component (at least ~2% of the total).

Moment of inertia of the crustal superfluid would be sufficient to explain the observations, as long as entrainment is ignored.

Entrainment: Bragg scattering in the crust lowers the effective moment of inertia by a factor ~5.

This is problematic.

(Cumulated glitch amplitude)/Ω



Entrainment correction on the moment of inertia of the superfluid

$$J_s = I_{ss}\Omega_s + (I_s - I_{ss})\Omega_c$$

Activity parameter

$$A_g = \frac{1}{t}\sum_i \frac{\Delta\Omega_i}{\Omega}$$

A simple but robust model assures that:

$$\frac{(I_s)^2}{I_{ss} I} \geq A_g \frac{\Omega}{|\dot{\Omega}|}$$

$$\frac{(I_s)^2}{I_{ss} I} \geq 1.6\%$$

By using values for the Vela (this is problematic as implies very low masses or very stiff EOS)

Hydrodynamical model

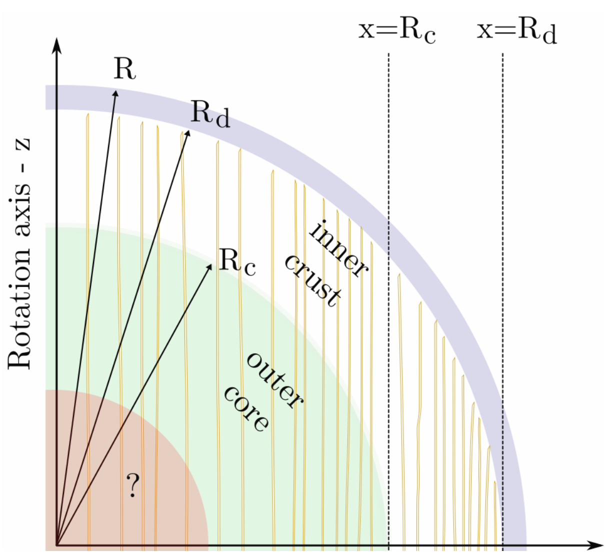
- Exchange of angular momentum → 2 components
- Long timescales → one component is superfluid
- Non relativistic fluids (vel. equator < 20% c)

$$\frac{\bar{p}_i^{\mathrm{n}}}{m_{\mathrm{n}}} = v_i^{\mathrm{n}} + \varepsilon_{\mathrm{n}}(v_i^{\mathrm{p}} - v_i^{\mathrm{n}})$$
$$\frac{\bar{p}_i^{\mathrm{p}}}{m_{\mathrm{p}}} = v_i^{\mathrm{p}} + \varepsilon_{\mathrm{p}}(v_i^{\mathrm{n}} - v_i^{\mathrm{p}})$$

$$\partial_t \rho_{\mathrm{x}} + \nabla_i(\rho_{\mathrm{x}} v_{\mathrm{x}}^i) = 0$$

$$(\partial_t + v_{\mathrm{x}}^j \nabla_j)(v_i^{\mathrm{x}} + \varepsilon_{\mathrm{x}} w_i^{\mathrm{yx}}) + \nabla_i(\tilde{\mu}_{\mathrm{x}} + \Phi) + \varepsilon_{\mathrm{x}} w_{\mathrm{yx}}^j \nabla_i v_j^{\mathrm{x}} = f_i^{\mathrm{x}}/\rho_{\mathrm{x}} + \nabla_j D_i^j$$

$$f_i^{\mathrm{x}} = 2\rho_{\mathrm{n}} \mathcal{B}' \epsilon_{ijk} \Omega^j w_{\mathrm{xy}}^k + 2\rho_{\mathrm{n}} \mathcal{B} \epsilon_{ijk} \hat{\Omega}^j \epsilon^{klm} \Omega_l w_m^{\mathrm{xy}}$$ (Vortex mediated mutual friction)



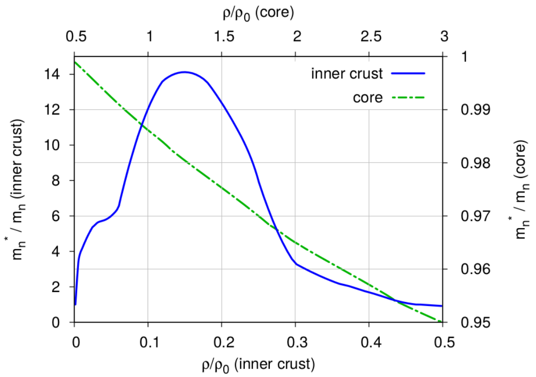
Simplified (consistent) model: Antonelli+ MNRAS 2017

By assuming columnar flow we can project the complicated 3D problem into a simpler one → inside the star the vorticity of the superfluid is assumed to be parallel to the rotation axis of the star

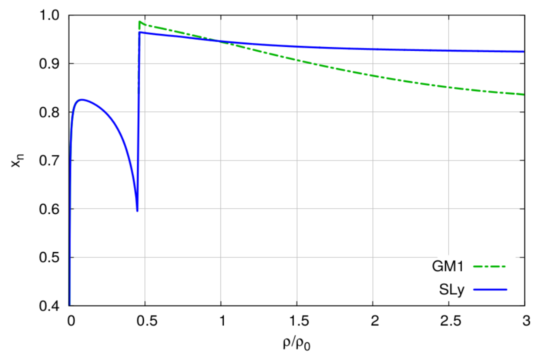
Details: Antonelli & Pizzochero, Axially symmetric equations for differential pulsar rotation, MNRAS (2017) 464 (1)

Microscopic quantities: functions of density

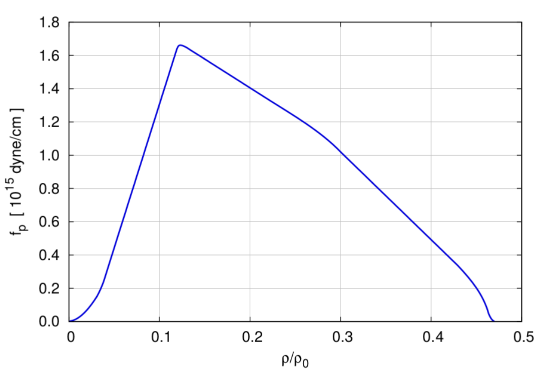
Entrainment parameters



Superfluid fraction



Mesoscopic pinning forces



+ EOS

↓

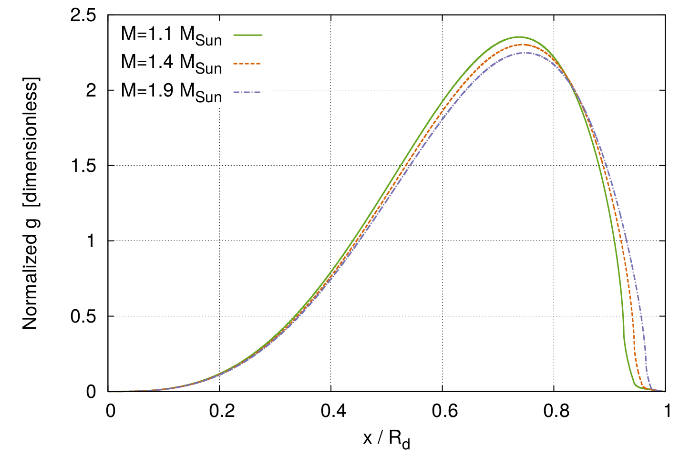
Solve TOV and obtain the spherical profiles

↓

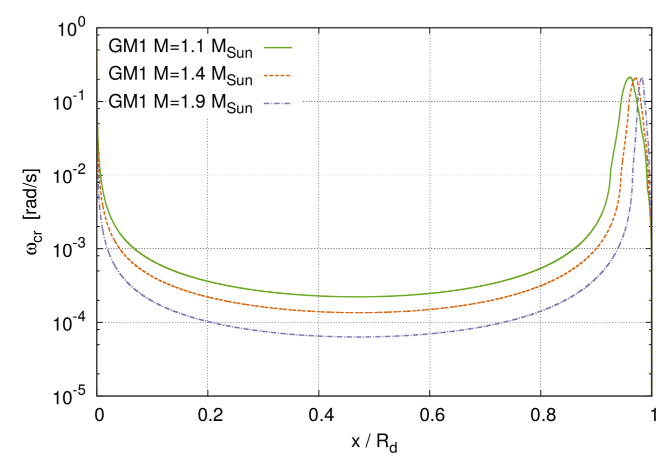
Obtain the cylindrical profiles needed to simulate the dynamical equations

Macroscopic quantities: functions of cylindrical radius

Moment of inertia weight



Critical lag for unpinning



$$q = I_v / I_p$$

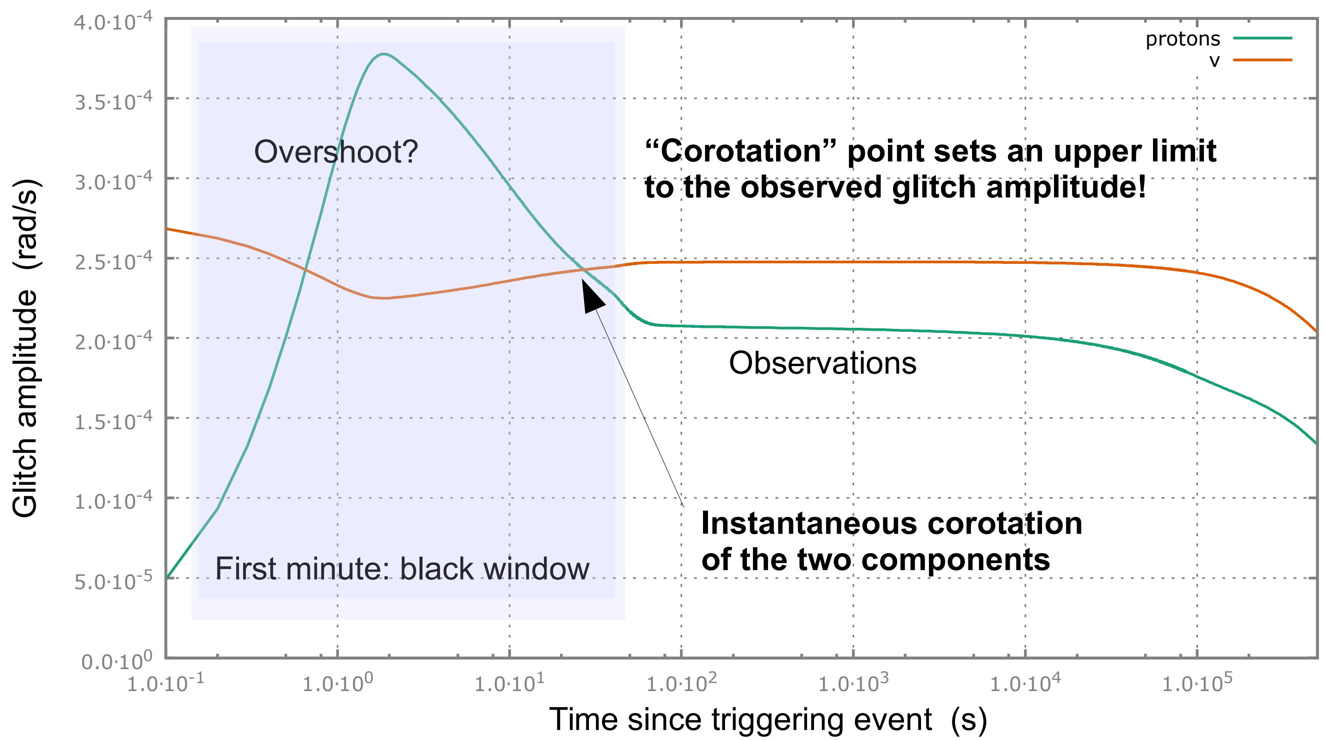
Simulation of a Vela-like glitch

Consistent (stratification, entrainment and pinning) hydrodynamical model of Antonelli & Pizzochero (2017):

$$\partial_t \Omega_v(x,t) = \overbrace{-\mathcal{B}[\Omega_v, \Omega_p, x]\,(2\Omega_v + x\partial_x \Omega_v)(\Omega_v - \Omega_p)}^{\text{Non-linear mutual friction}}$$

$$\partial_t \Omega_p(t) = -(1+q)\dot{\Omega}_\infty - q\langle\, \partial_t \Omega_v(t)\,\rangle$$ ← Pulsar angular momentum decreases due to radiation

Glitch amplitude (Vela-like): $\Delta f / f \sim 10^{-6} \rightarrow \Delta f \sim 10^{-5}$ Hz



Maximum glitch amplitude

- Simulations are interesting for the post glitch relaxation or the spin-up phase…
  …but still a lot of unclear physics (repinning, drag)

- However the amplitude at the "corotation point" can be calculated very simply as

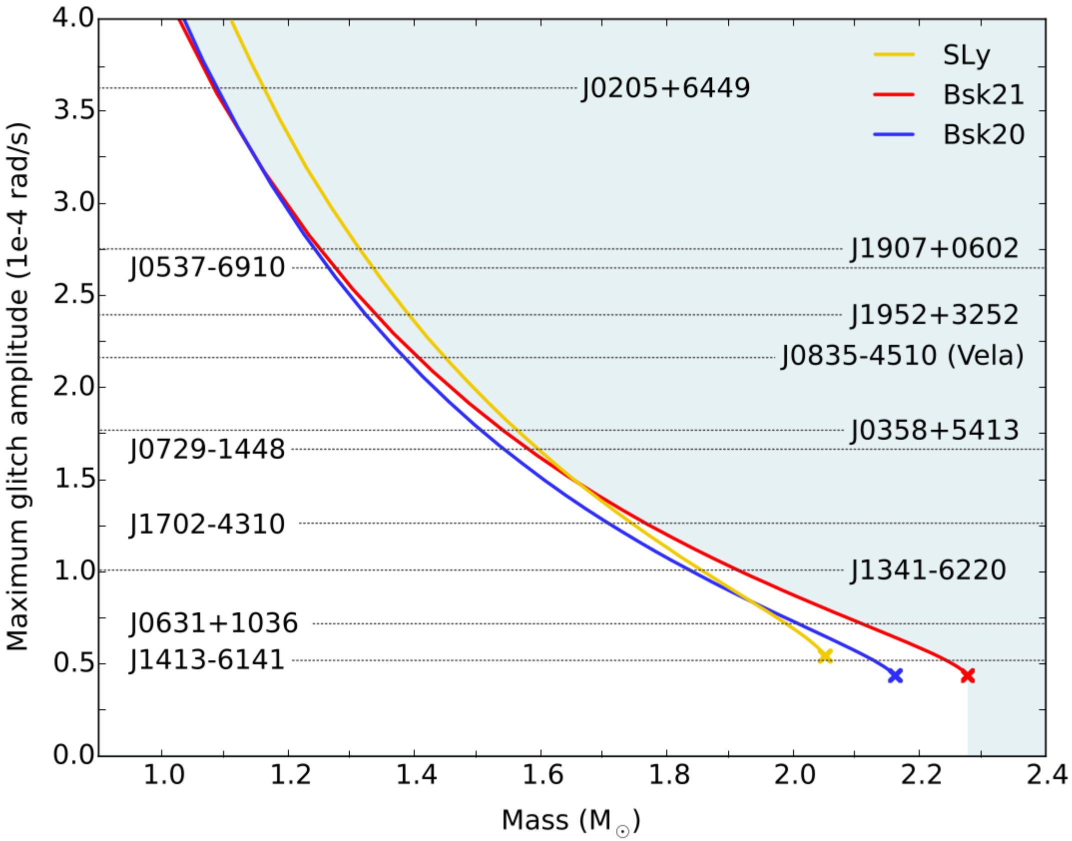
$$\Delta\Omega_{\mathrm{max}} = \frac{1}{I}\int d^3x\, i_v(\mathbf{x})\,\omega_{cr}(\mathbf{x}) = \frac{\pi^2}{I\kappa}\int dr\, r^3\, f_p(r)$$

"Maximum glitch amplitude" at corotation:

→ only dependent on pinning forces and on the mass of the star

→ entrainment independent

→ no need to consider straight vortex lines



Mass constraints

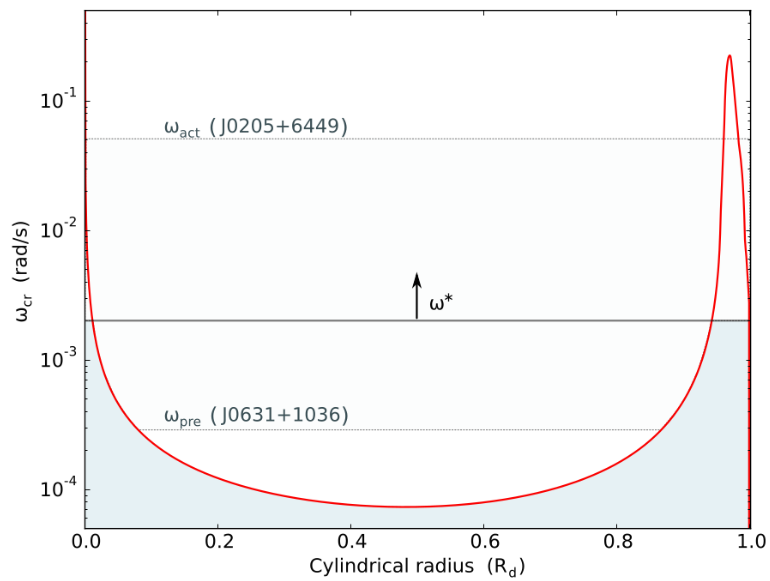
Pizzochero, Antonelli, Haskell, Seveso
"Constraints on pulsar masses from the maximum observed glitch"
Nature Astronomy 1 (2017)

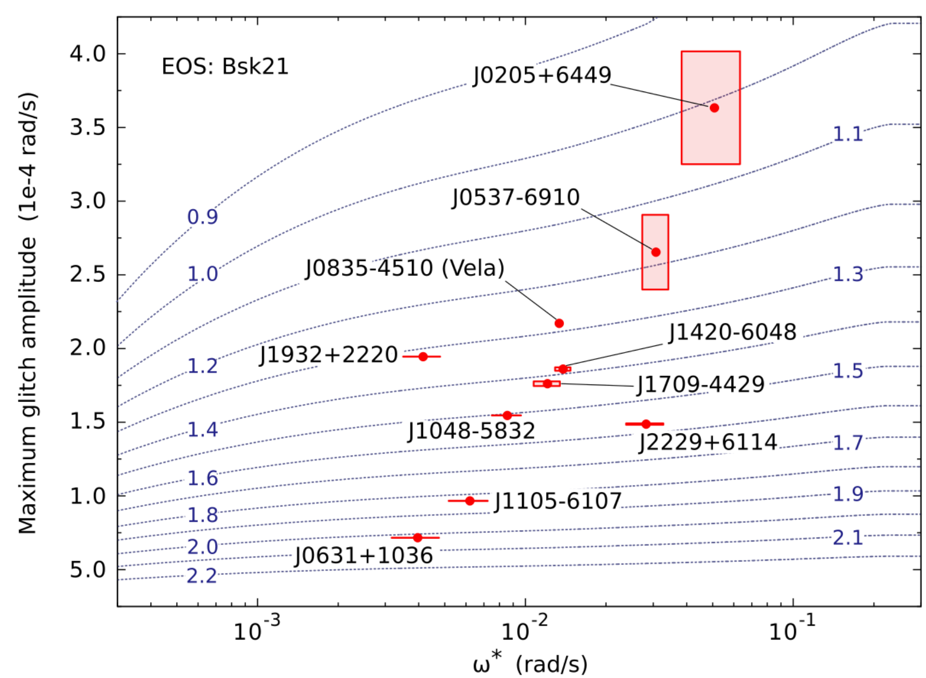
- To improve the upper limit on the mass we need more than the observed largest glitch

→ General idea: if you have a hydrodynamical model for the angular momentum reservoir, follow its evolution starting from corotation

$$\Delta\Omega_{\mathrm{t}} = \frac{I_v}{I} \langle \omega_{\mathrm{t}}(x) \rangle$$

→ We test a "unified" scenario that can treat all pulsar at the same time without the need to solve the hydrodynamical equations with the specific rotational parameters 1of each pulsar





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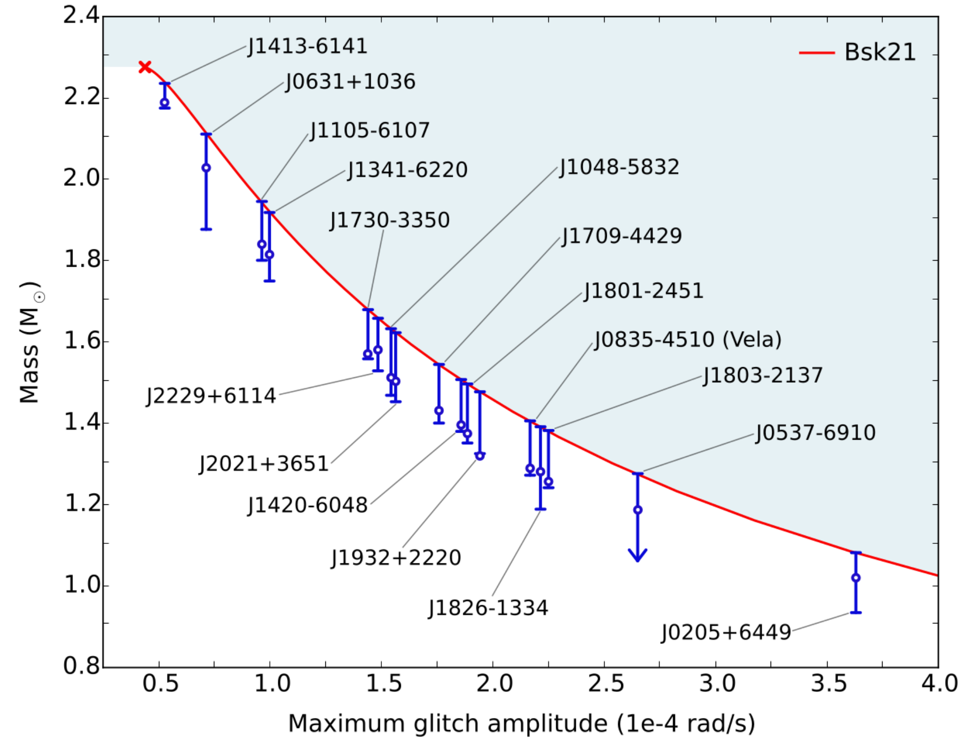


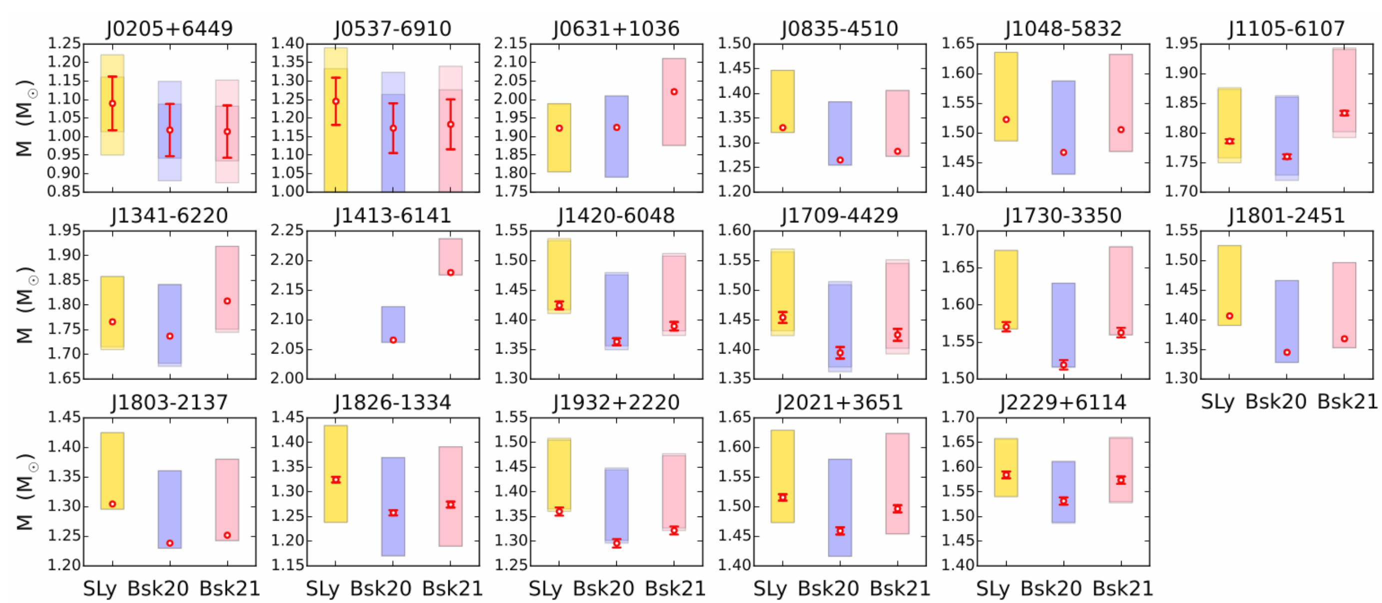
In the "average time" between two large glitches the pulsar must be able to build a reservoir of angular momentum that is enough to produce the observed angular velocity jump.

$$\omega^*_{\rm act} \;=\; t_{\rm act}\,|\dot{\Omega}| \;=\; |\dot{\Omega}|\Delta\Omega/\mathcal{A}_a$$

$$\Delta\Omega_{\rm t}(\omega^*_{\rm act}, M_{\rm act}) \;=\; \Delta\Omega$$

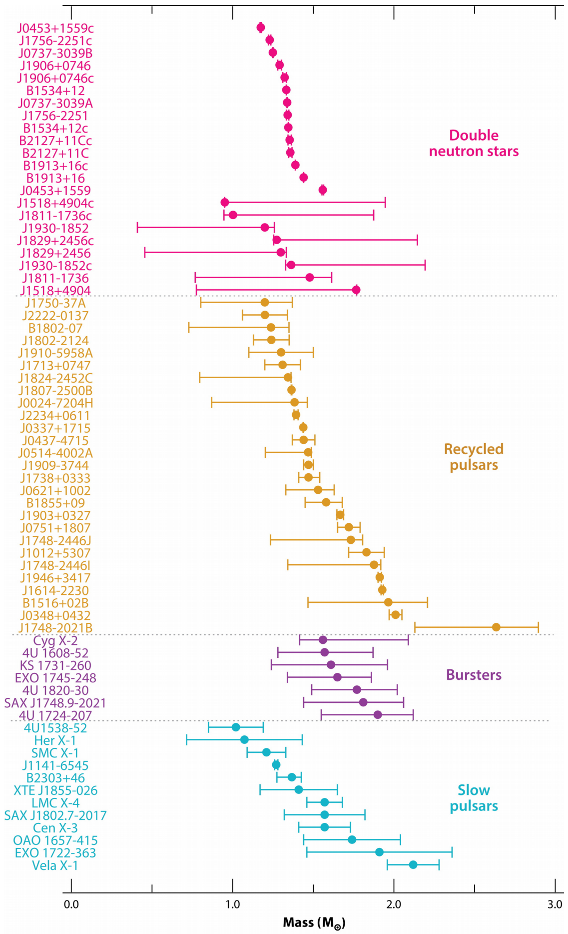
All the three EOS (except very stiff like GM1) give compatible results for the mass estimates.

Vela: 1.25 – 1.45 Msun
J0537: M < 1.4 Msun



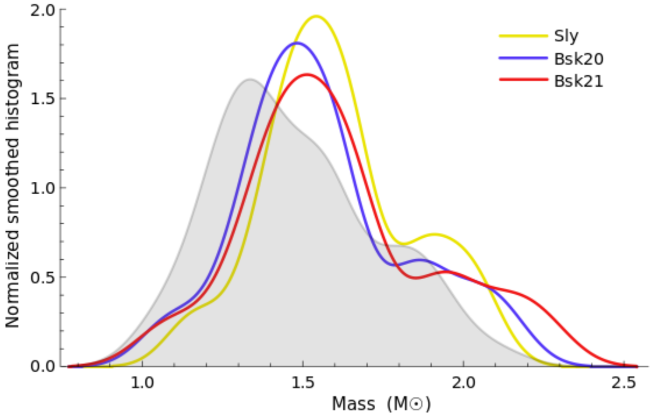
Mass constraints: mass distribution

Measured NS masses
(review: Ozel, Freire, 2016)

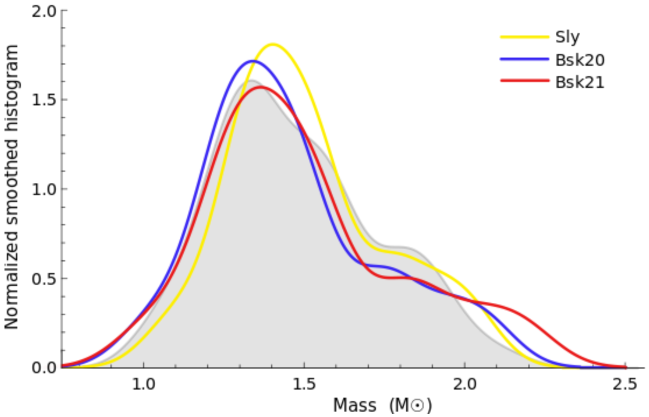


Özel F, Freire P. 2016.
Annu. Rev. Astron. Astrophys. 54:401–40

“Mabs” (51 pulsars)



“Mact” (17 pulsars)



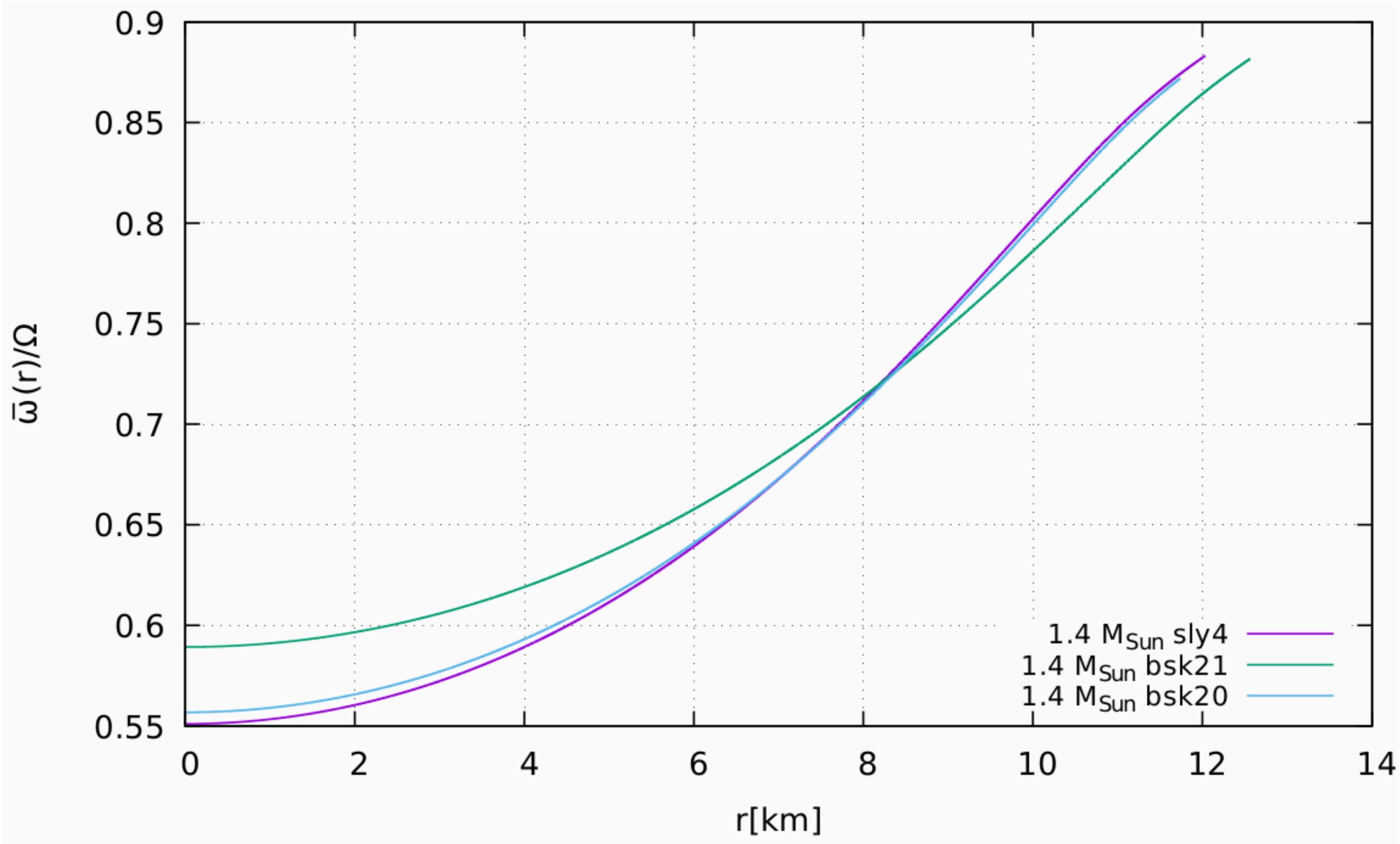
Work in progress:

Grey curve: observed distribution of NS masses. Usually given for different classes, here unified.

Left: distribution obtained by using “Mabs”: upper limit to the pulsar mass.

Right: distribution obtained by using “Mact”, the pulsar mass estimated by using both activity and the largest glitch amplitude.

Relativistic corrections: frame drag



Frame drag in the surrounding of a spinning NS has deep impact on the pulsar rotational dynamics.
Slow rotation approximation (Hartle & Sharp, 1967): equatorial velocity much less than c (non-millisecond).

Total moment of inertia is “reduced”

$$I = \frac{8\pi}{3}\int_0^R \mathrm{d}r\; r^4 e^{-\Phi+\lambda}\left(n_n + n_p\right)\frac{\mu}{c^2}\frac{\overline{\omega}}{\Omega}$$

Moment of inertia of the superfluid
(corrected by entrainment, Antonelli et al. 2017)

$$I_v = \frac{8\pi}{3}\int_0^R \mathrm{d}r\; r^4 e^{-\Phi+\lambda}\left(\rho + \frac{P}{c^2}\right) x_n(r)\cancel{\frac{\overline{\omega}}{\Omega}}\,\frac{m_n}{m_n^*(r)}$$

Conclusions & Outlook

- Message: the largest glitch can be used to constrain the mass of “Vela-like” glitchers or (more conservative) provides a test for newly calculated pinning forces

- Study/propose angular momentum reservoirs that are:

  → consistent with the EOS used
  → possibly encode dynamical behavior of vortex lines
  → consider finite temperature effects (expected to lower the maximum reservoir)

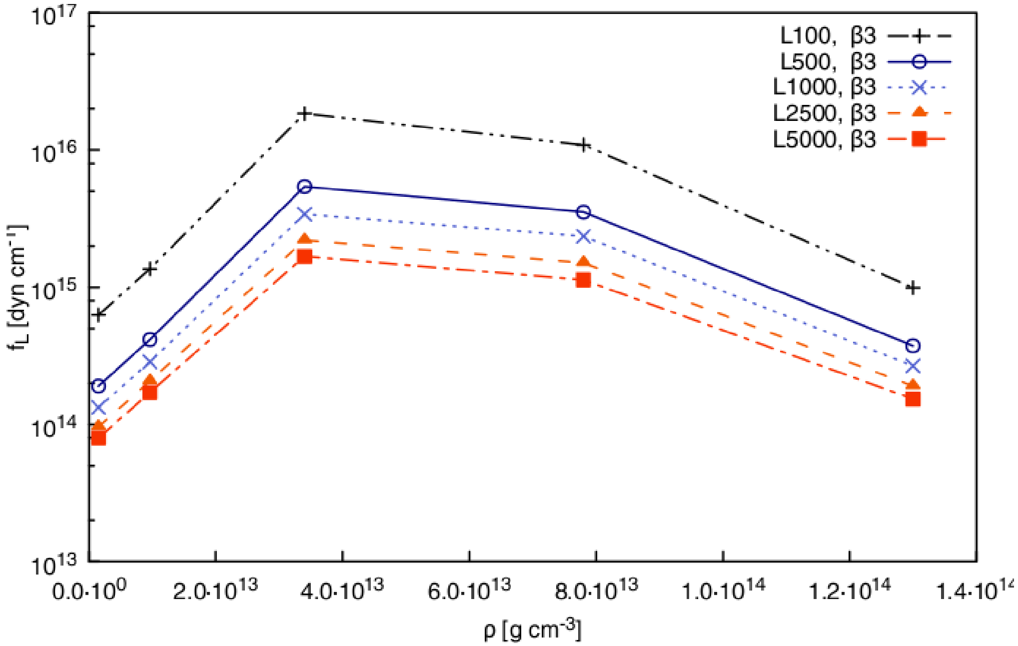
- All EOSs (except very stiff like GM1) give similar results for our “mass estimates”

  → good if you want to test pinning forces or give mass constraints
  → not so good if you want to pin down the EOS of nuclear matter with glitches
  (but can be still useful if used together with combined radius measurement)

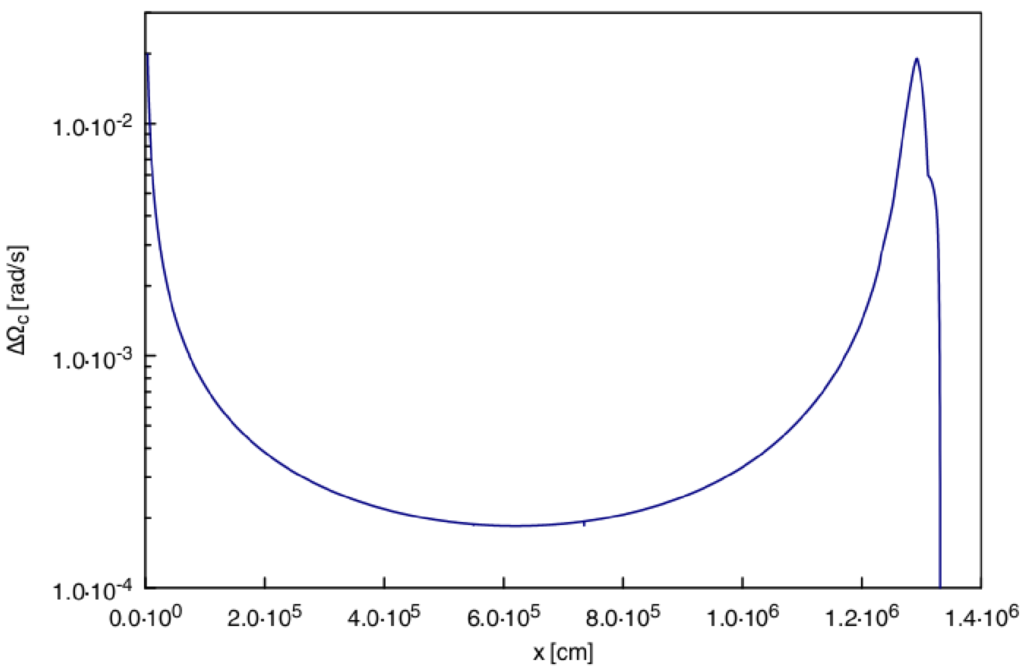
- The mass distribution obtained by using the mass upper limits (as well as the one obtained by using the punctual mass estimates) are similar to the observed one.

Thank you!

Mesoscopic pinning forces



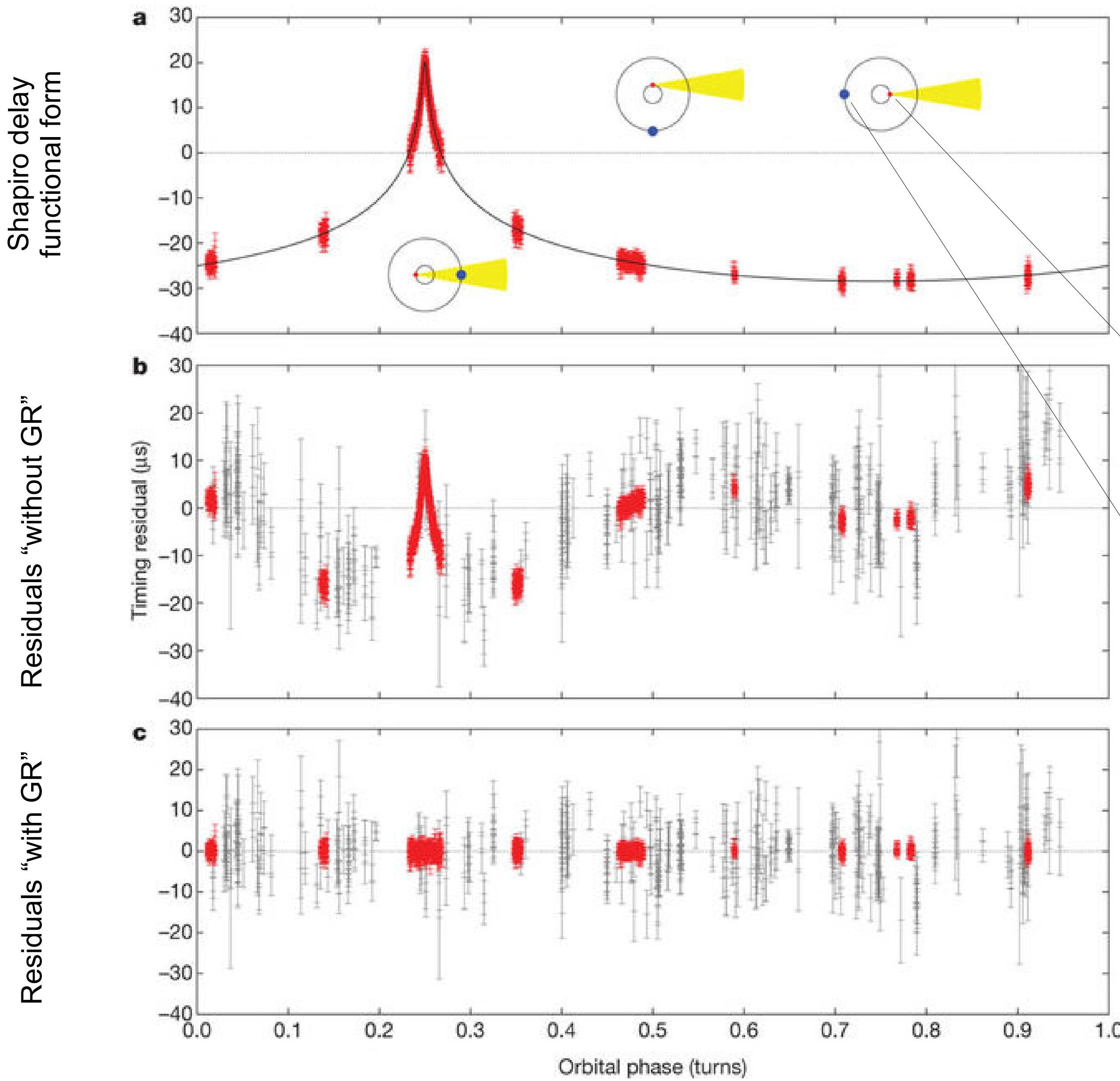
Mesoscopic pinning forces
(vortex-lattice interaction per unit length of vortex line)
S. Seveso, F. Grill, P. Pizzochero, B. Haskell



Critical lag for unpinning (without entrainment)

Shapiro delay for PSR J1614-2230

PB Demorest *et al.* *Nature* **467**, 1081-1083 (2010)



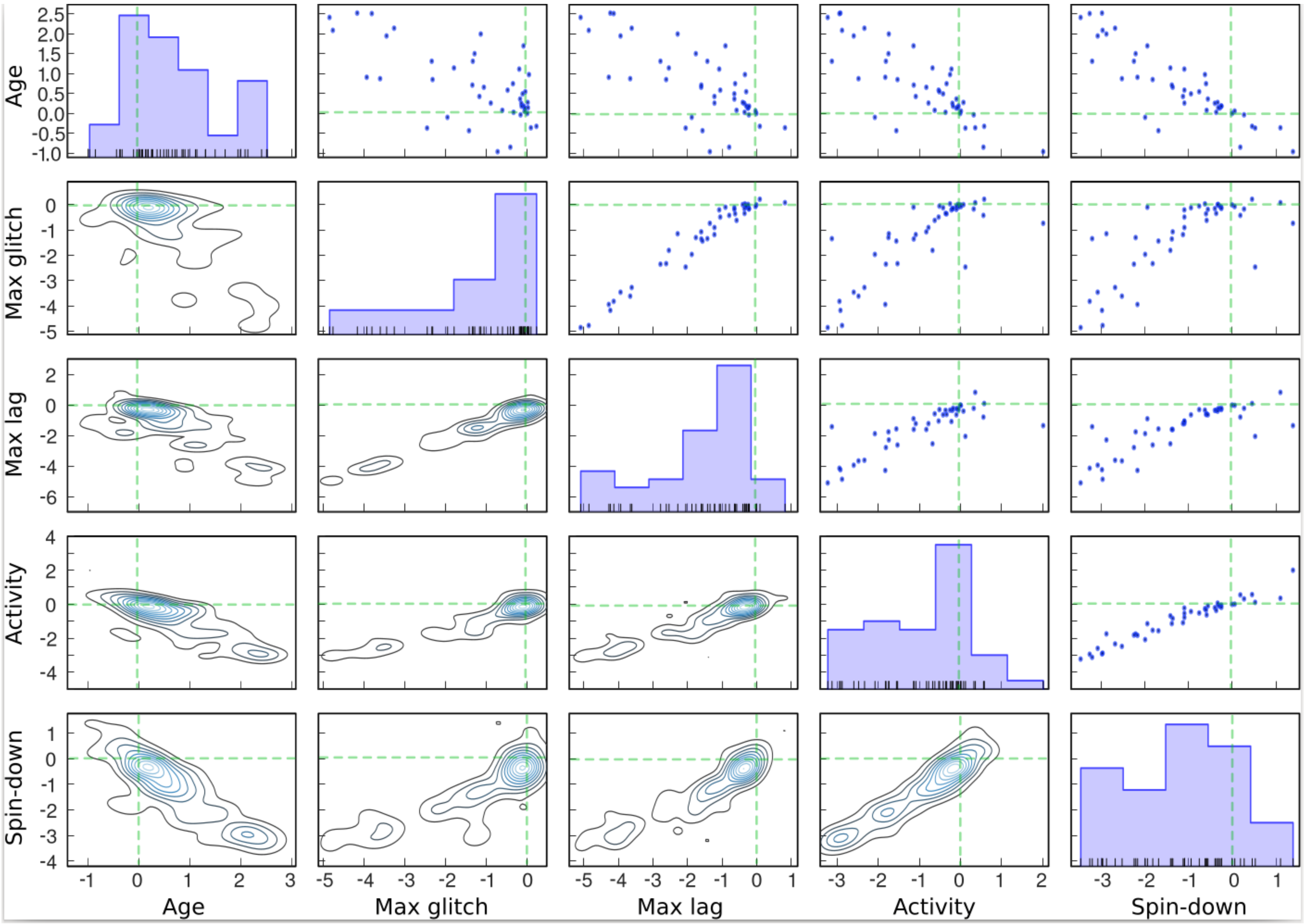
For highly inclined (nearly edge-on) binary millisecond radio pulsar systems, Shapiro delay allows to infer the masses of both the neutron star and its binary companion to high precision.

Millisecond pulsar
(1.97±0.04)M⊙

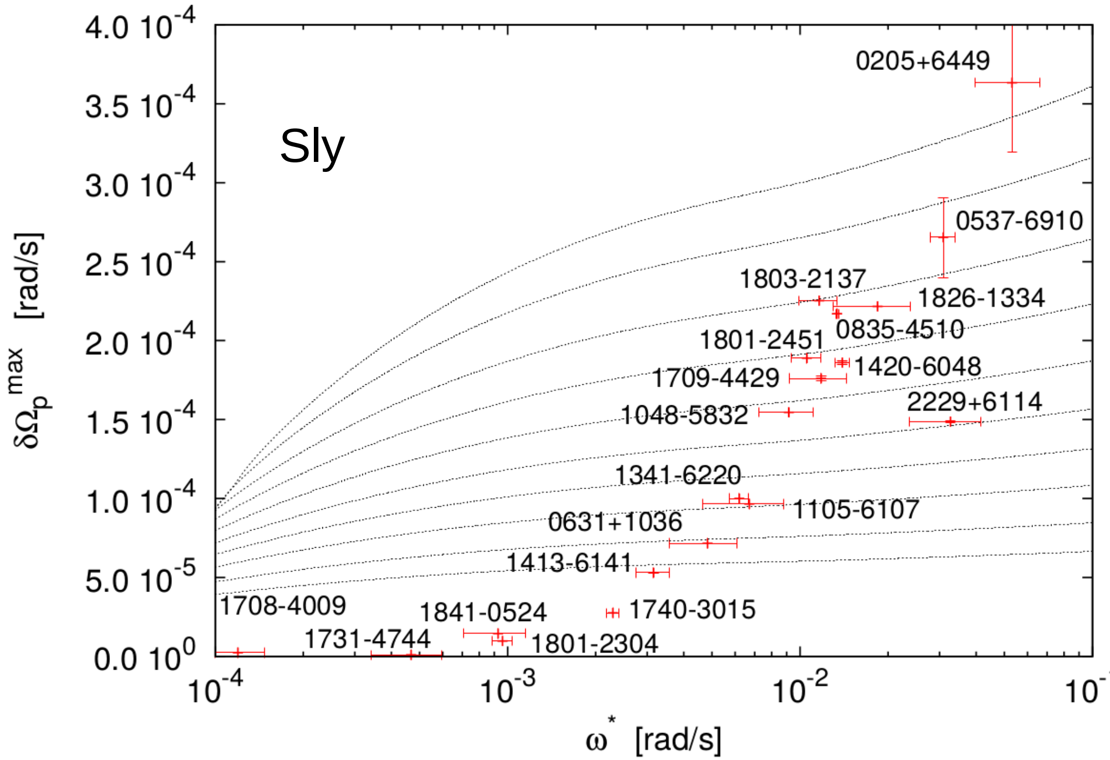
Companion:
helium-carbon-oxygen WD
(0.500±0.006)M⊙

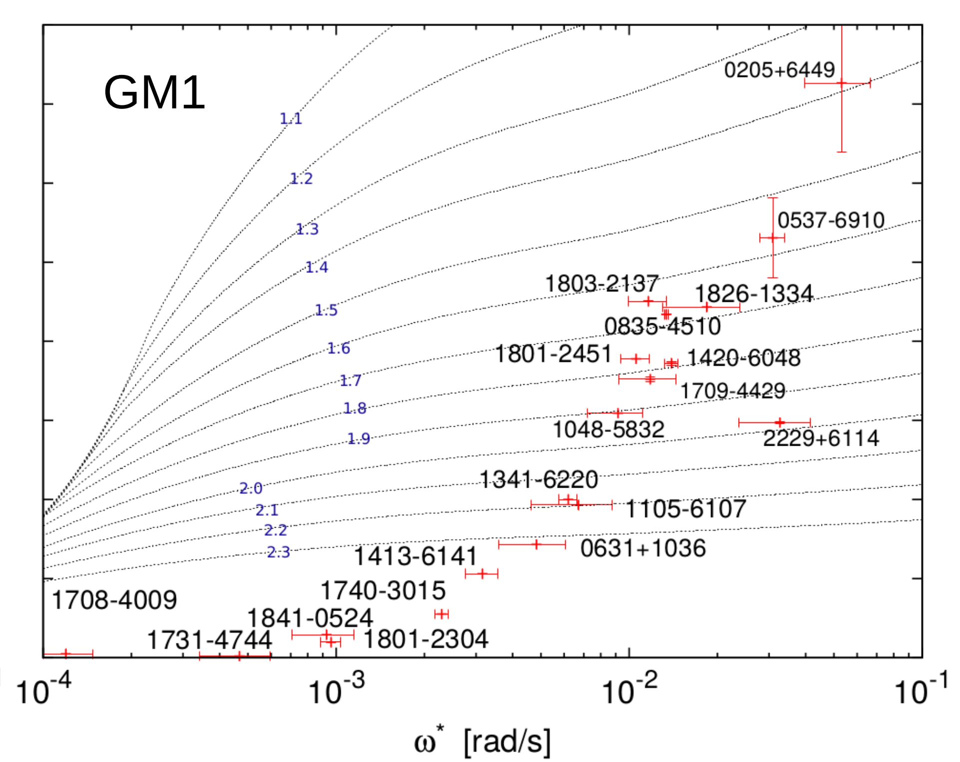
In contrast with X-ray-based mass/radius measurements, Shapiro delay provides no information about the NS radius.

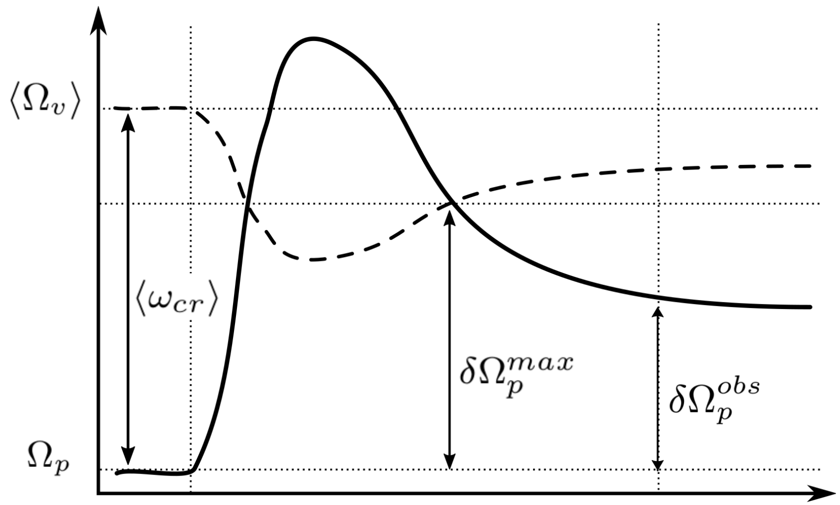
Glitching pulsars: search for correlations



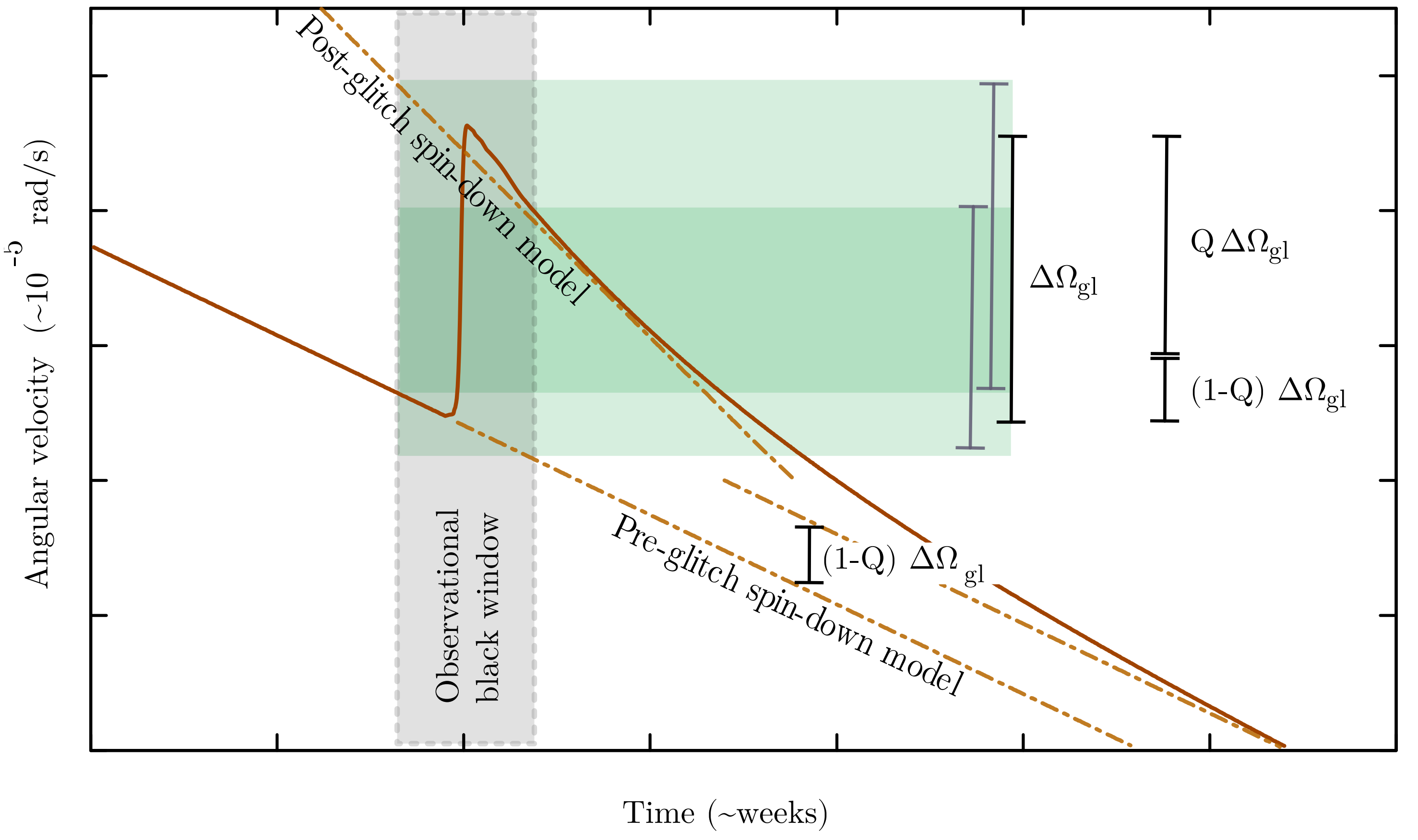
Maximum glitch amplitude







Glitch recovery



Vortex-mediated glitch theory in a nutshell

When $f_M = f_P$ vortices are unbound from the lattice

$\Downarrow$

Outward motion of vortices toward the crust

$\Downarrow$

Angular momentum is quantized in vortices

$\Downarrow$

Vortices give their angular momentum to the crust

$\Downarrow$

Glitch!