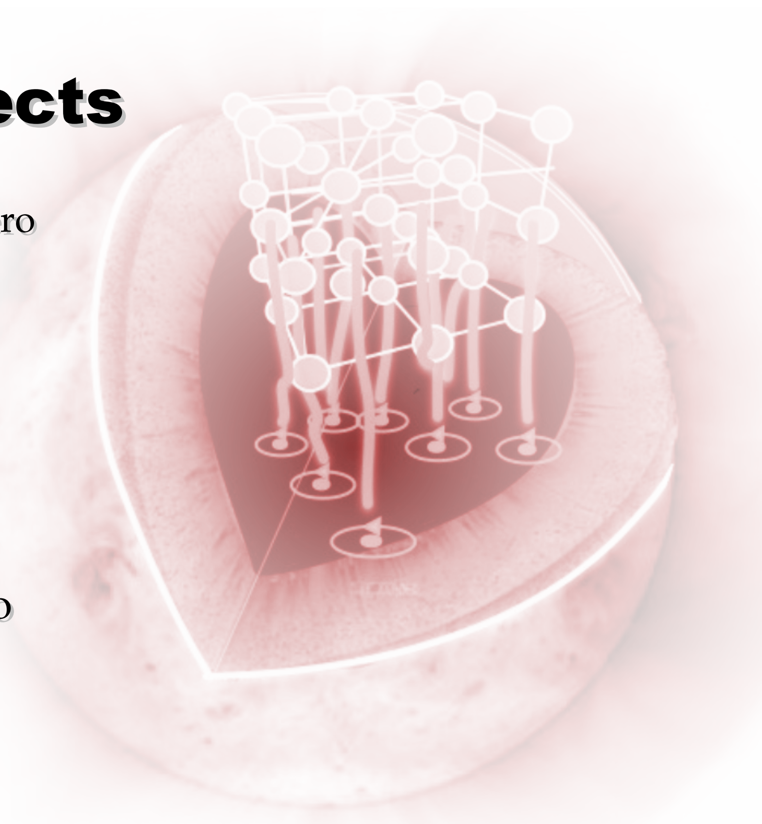
NUMAT / NUclear MATter and compact stellar objects

Responsabile locale: Prof. P. Pizzochero



Marco Antonelli

Università degli Studi di Milano

Consiglio di Sezione - INFN

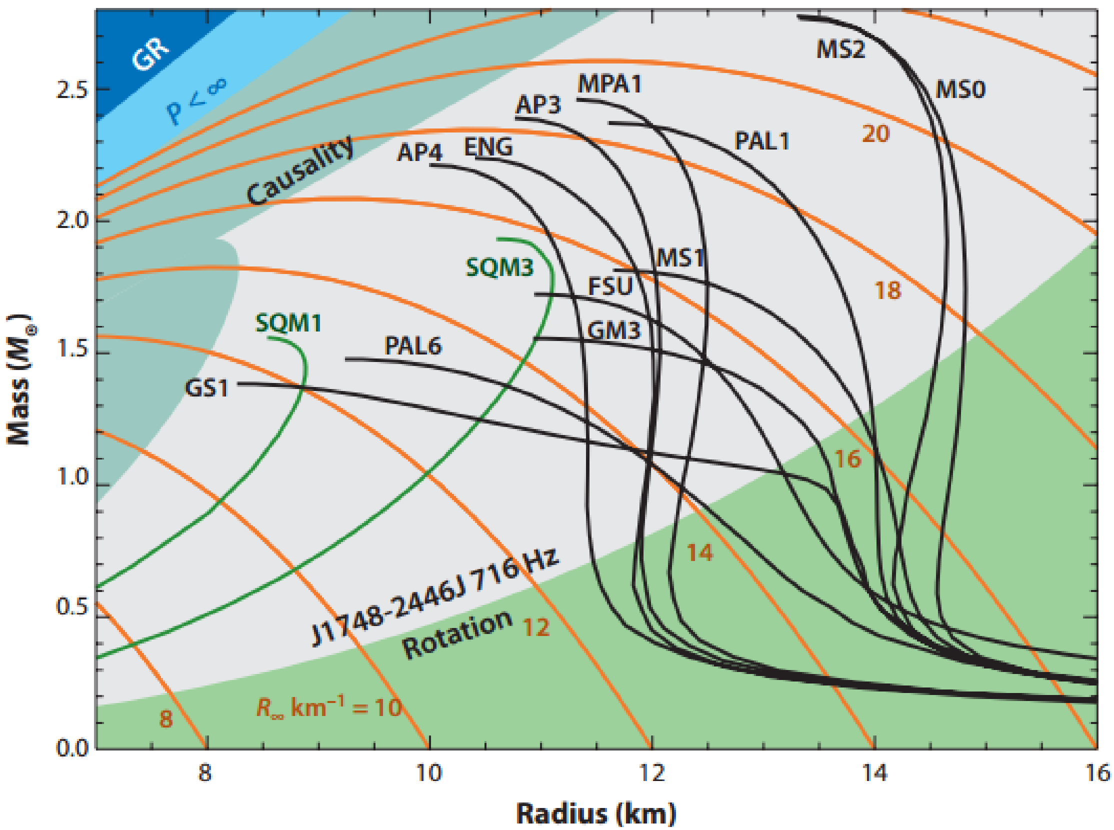
Milano - 11 Luglio 2016

Istituto Nazionale di Fisica Nucleare

compstar

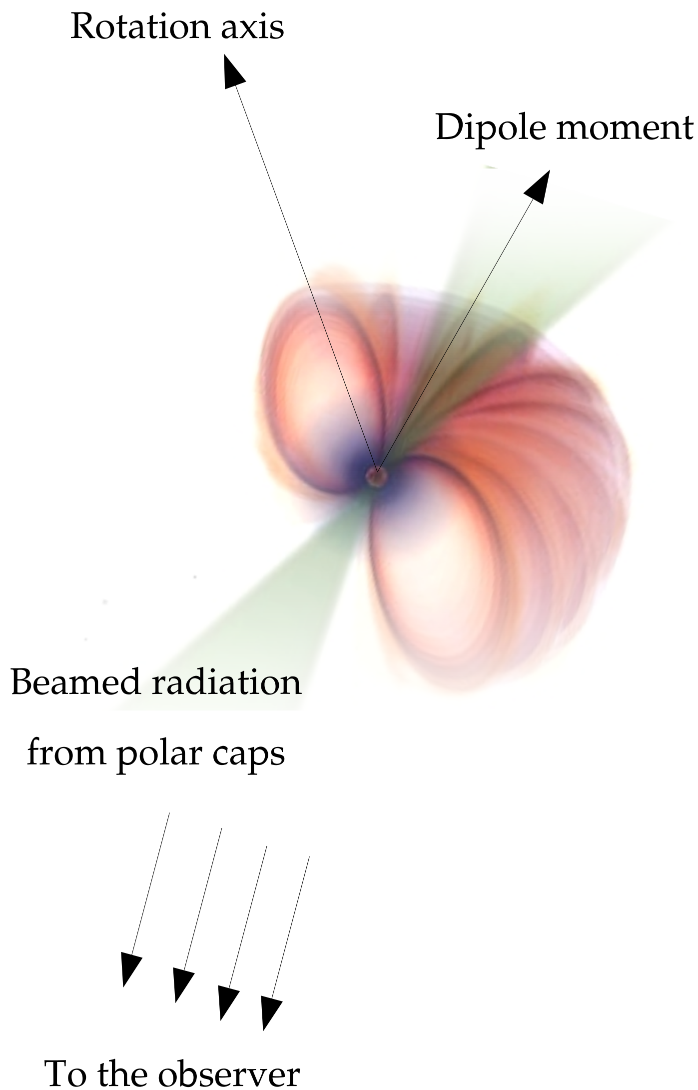
Neutron stars: “astro lab” for nuclear physics

Mass – Radius relation: EOS → Integrate TOV EQs

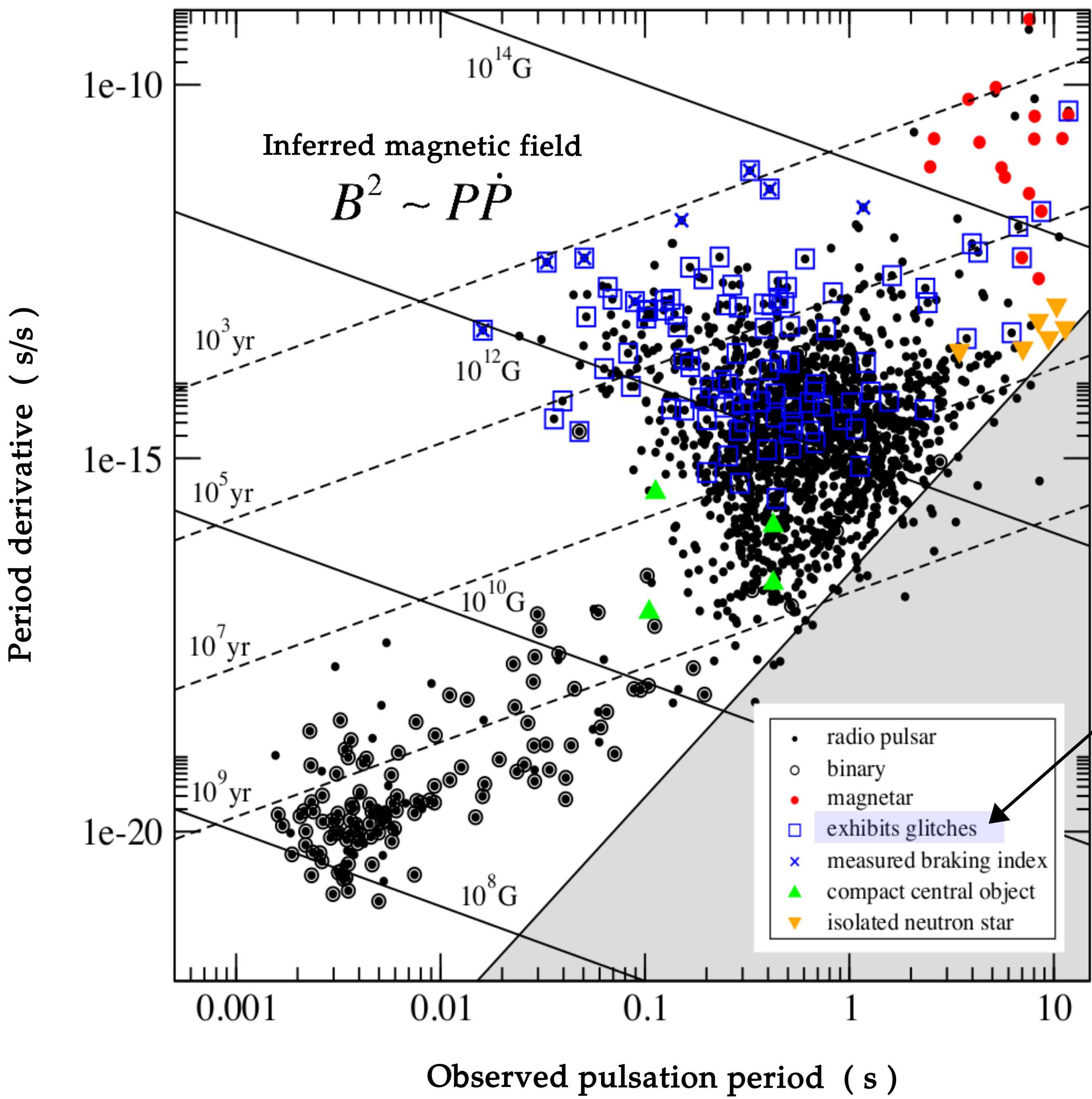


→ matter at very high densities

→ observed as PULSARS



Pulsar timing



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

- Different classes populate different regions (inferred age and magnetic field).

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

→ it's interesting to study the rotational dynamics:

- evidence of superfluidity

- alternative to cooling

PULSAR GLITCHES (basic facts)

- Lack of radiative/pulse profile changes

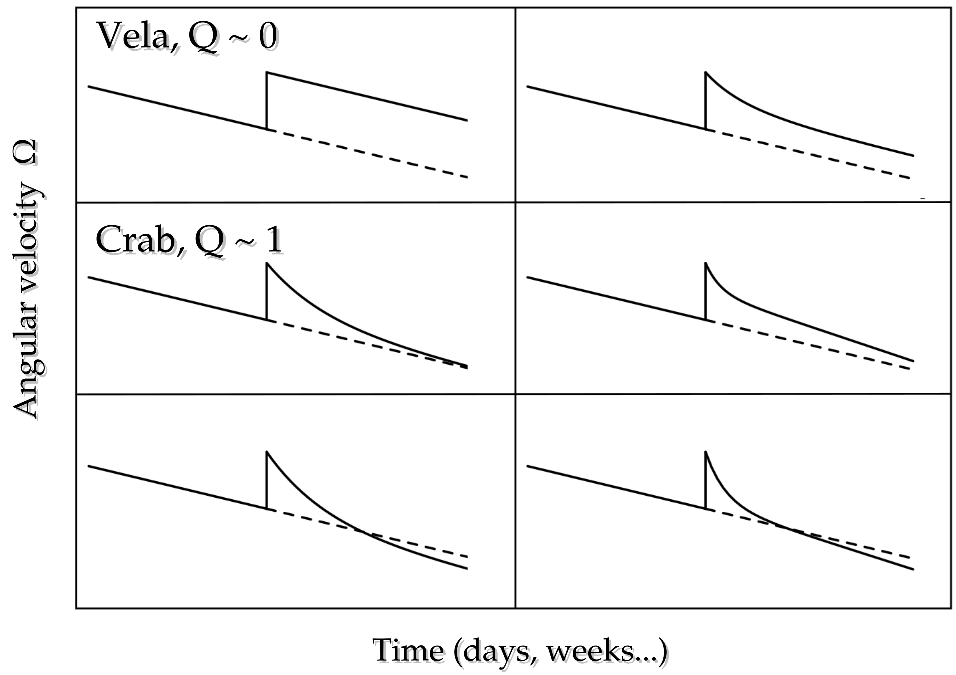
→ Evidence for internal origin

- Long recoveries

→ Thought to be due to superfluid component in the star

- Diverse phenomenology

→ different ages/mass/rotational parameters...

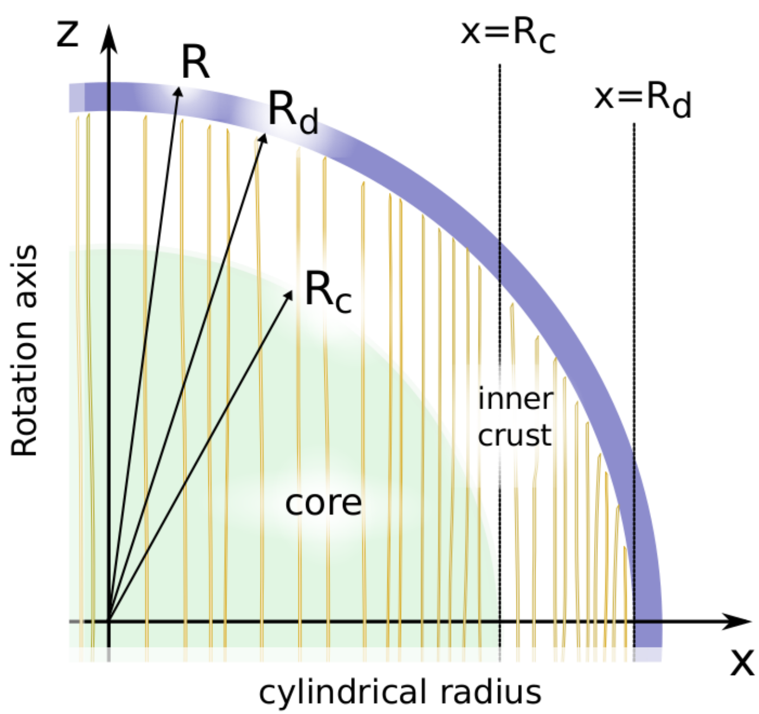


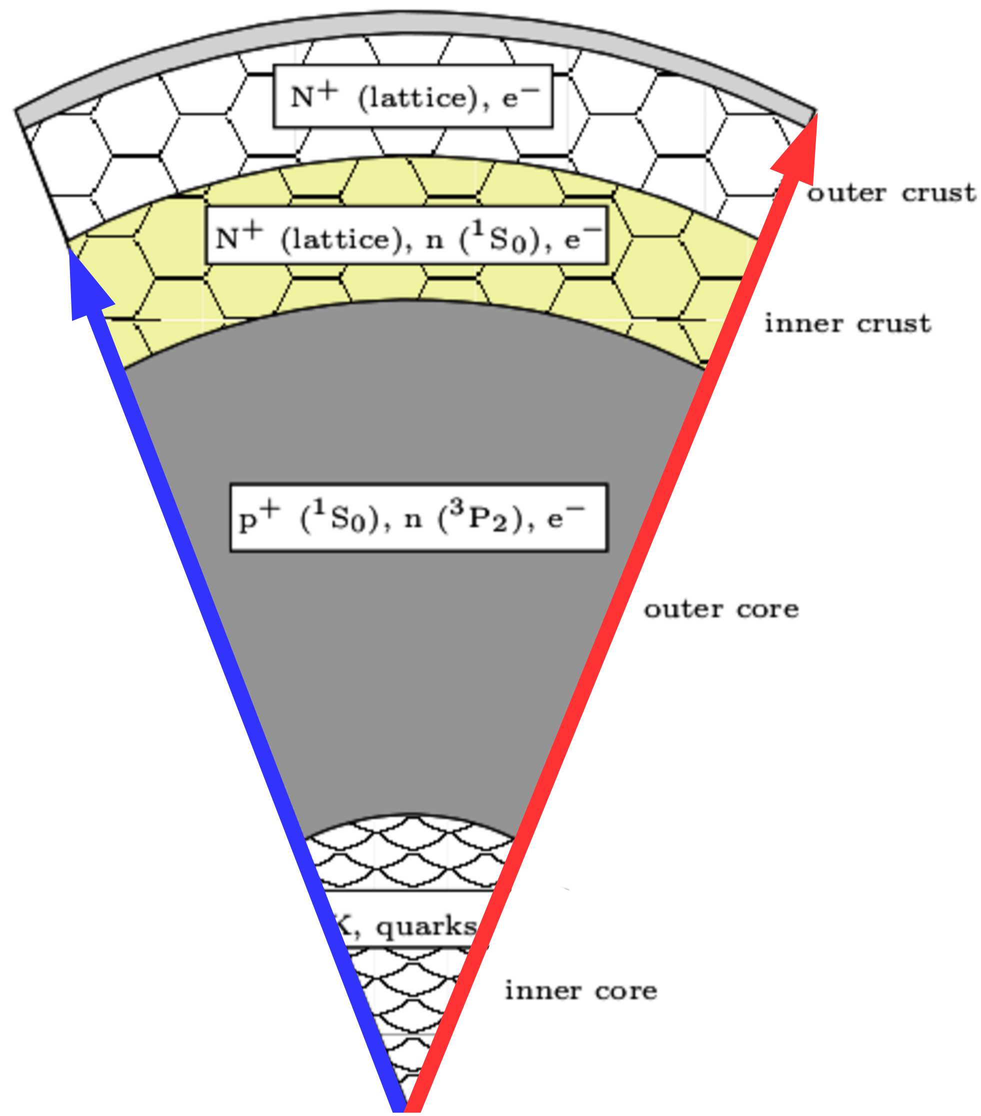
Key point: to describe glitches we need that a NS is comprised of (at least) **two components** that exchange angular momentum.

Which part of the NS provides the angular momentum to **spin-up** the "observable component" ?

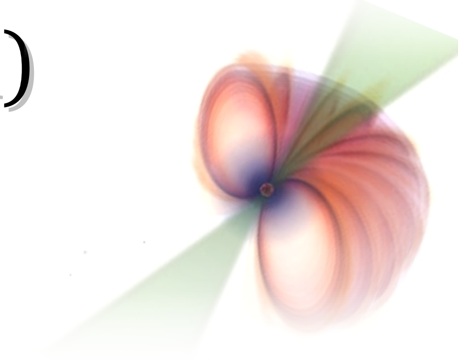
A “minimal model” for pulsar rotational dynamics

The inner crust & core contain 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).





Glitch mechanism (vortex-mediated)



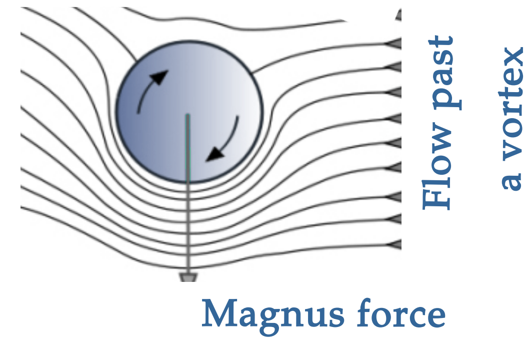
- "p" follows the observed spin down of the pulsar

- Pinning → "n" cannot follow "p"

  A velocity lag builds up between "n" and "p"

  Motion of a neutron vortex is affected by fluid flow past it

  → Magnus force

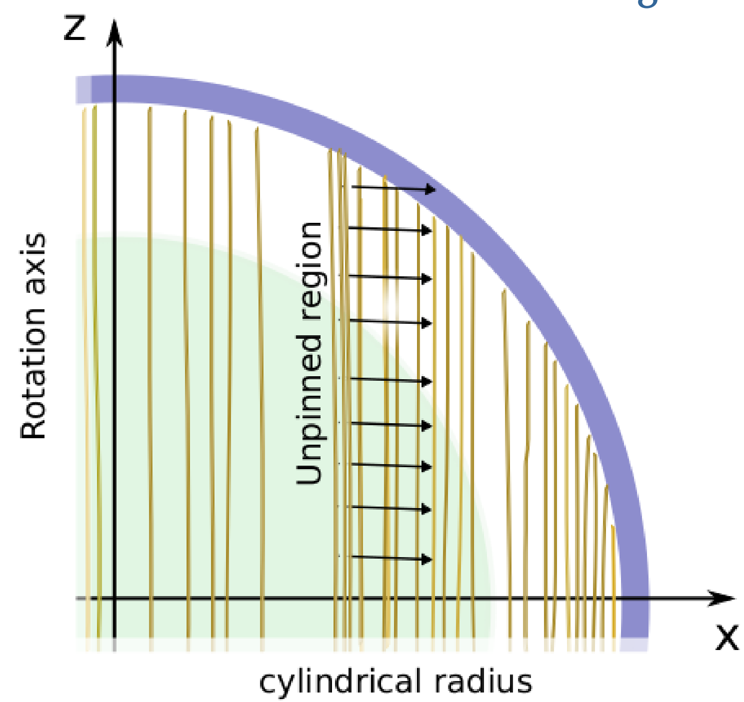


- Magnus force ≃ pinning force

  The vortex line unpins and is expelled

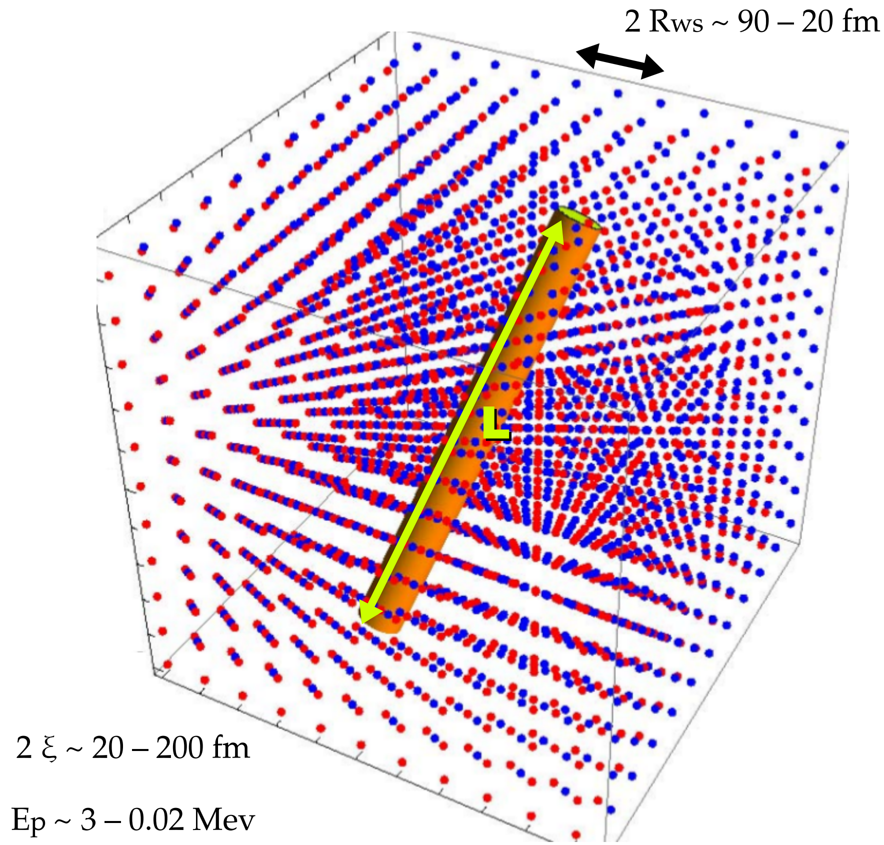
  → "n" looses angular momentum

  → "p" gains angular momentum



Mesoscopic pinning forces

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



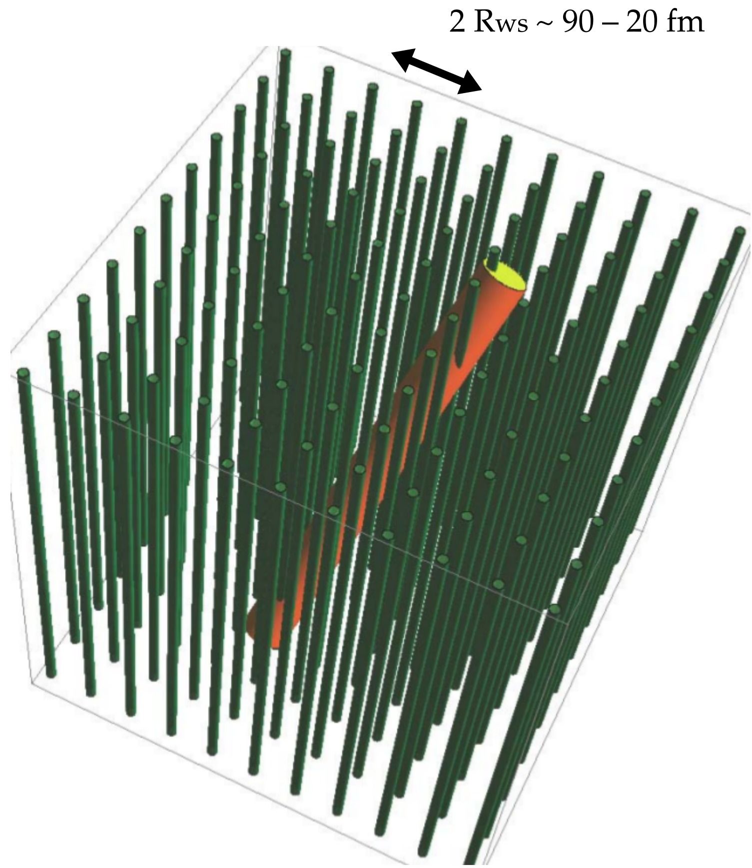
Inner crust:

Vortex-nucleus interaction → Vortex-lattice interaction per unit length of vortex line

Consider a segment of vortex line

(the length L is given by the tension)

Average over traslations and rotations of the total pinning force divided by L



Core:

Vortex-flux tube interaction → Vortex-array interaction

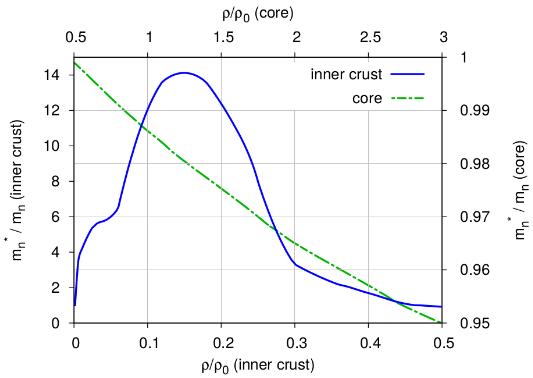
Pinning to flux-tubes negligible for normal pulsars

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

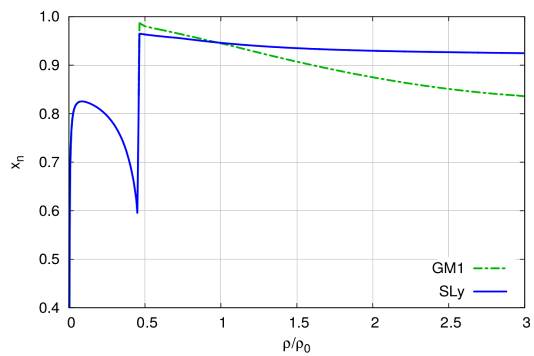
$$\xi_n \approx 16\, x_n^{1/3} \rho_{14}^{1/3} \Delta_n (\mathrm{MeV})^{-1} \mathrm{fm}$$

Macroscopic quantities:

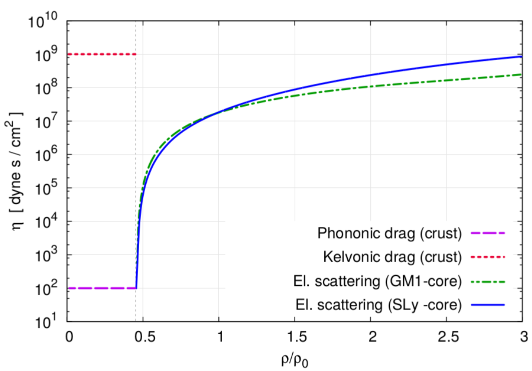
Entrainment parameters



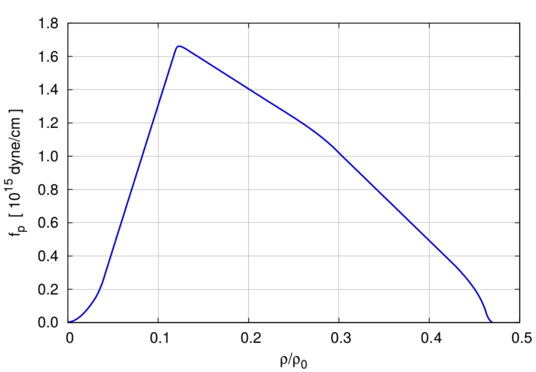
Superfluid fraction



Drag parameters



Mesoscopic pinning forces



+ EOS

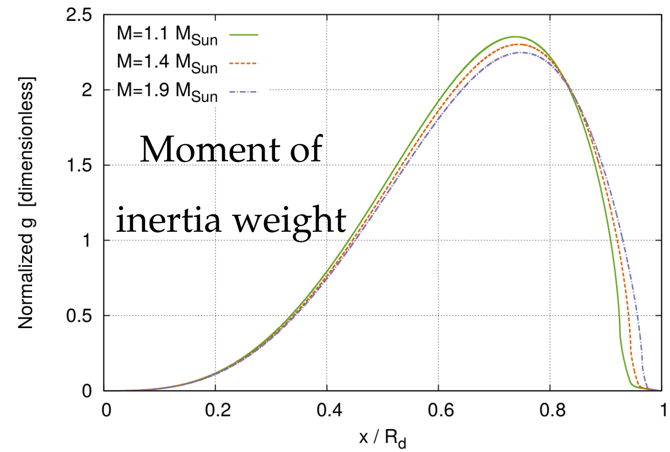
↓

Solve TOV and obtain the spherical profiles

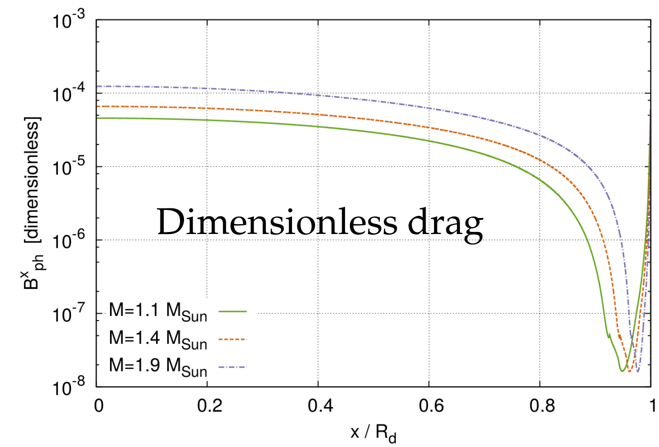
↓

Use the "1D" prescriptions to project to a cylindrical model

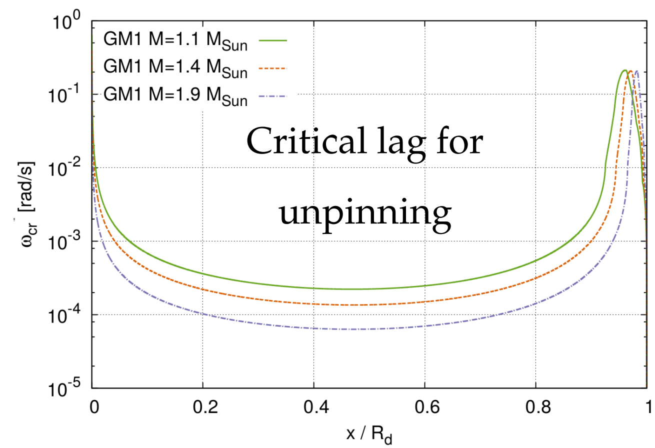
$g(x)$



$\mathcal{B}^x(x)$



$\omega_{cr}(x)$



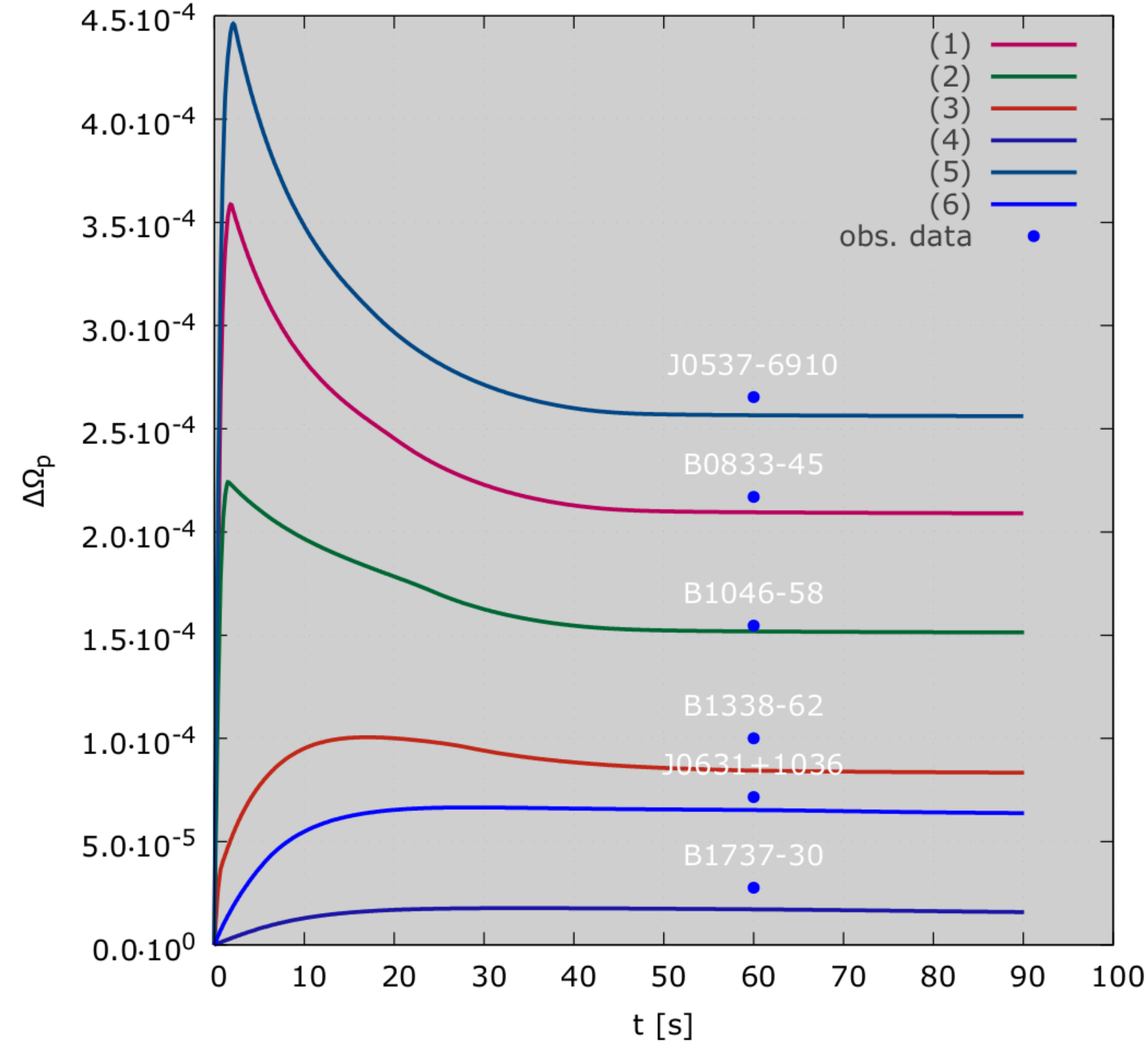
$q = I_v / I_p$ "super/normal" ratio

Dynamical simulations of pulsar glitches

→ **Study how different EOSs and parameters can influence the glitch activity**

Dynamical simulations with:

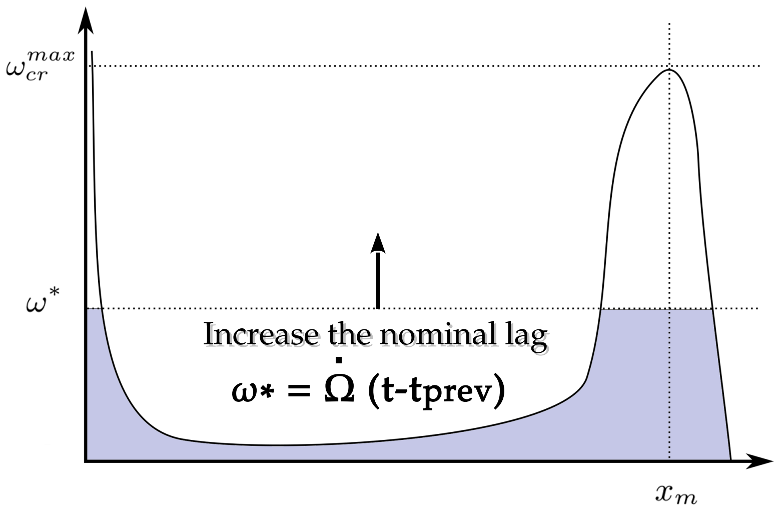
- GM1 EOS
- EOS consistent proton fractions
- Entrainment in the core & crust (Chamel)
- Consistent drag in the core (el. scattering, Alpar, Andersson…)
- Drag in the crust (phonons, Jones 1991)
- New MESOSCOPIC pinning forces (Seveso, Haskell, Pzzochero 2016)



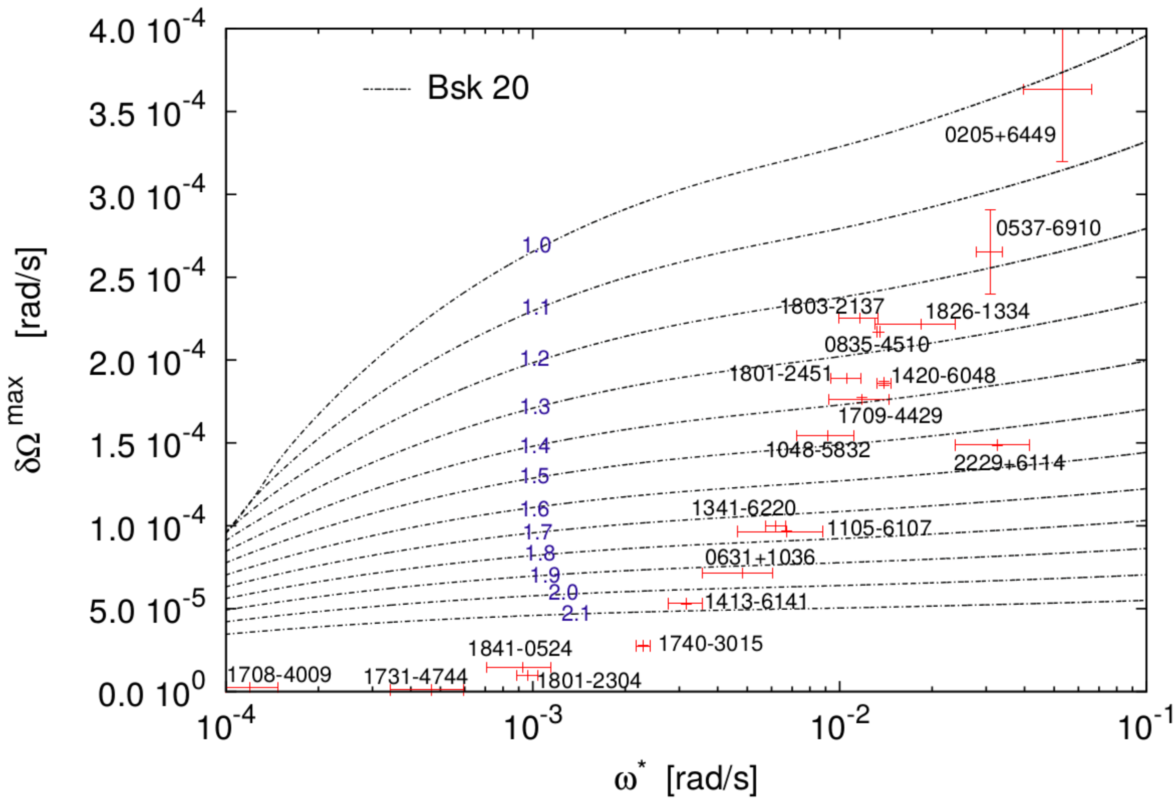
Large glitch → low mass
(true for all the EOSs that we used)

Dynamical simulation: S. Seveso

Mass upper bounds...



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



For every pulsar, consider:

- The glitch amplitude of its maximal glitch **δΩmax**
- The waiting time mutiplied by the observed spin down rate → "nominal lag" **$\omega* = \dot{\Omega}$ (t-tprev)**

In the plane **δΩmax** – **ω∗** we also plot the curves obtained by filling the critical lag as **ω∗** increases For different masses. We must have that:

δΩmax (ω∗) > δΩmax "observed"

This constrains the mass of the glitching pulsar!

NOTE: it is possible to do the same job by using thedirectly the dynamical equations instead of using this simple prescription

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MNRAS (2016):

S. Seveso, P. Pizzochero, F. Grill, B. Haskell

"Mesoscopic pinning forces in neutron star crusts"

ArXiv / Submitted to MNRAS:

M. Antonelli, P. Pizzochero

"Axially symmetric equations for differential pulsar rotation with superfluid entrainment"

In preparation:

M. Antonelli, B. Haskell,
P. Pizzochero, S. Seveso

"Measuring NS masses with pulsar glitches"

Ultime tesi specialistiche:

"Modeling Pulsar Glitches with different Equations of State" - A.A. 2014-2015

"Strains and maximum stresses in the crust of spinning-down pulsars" - A.A. 2015-2016

"Constraining the EOS of neutron stars with dynamical simulatons of pulsar glitches" - Work in progress

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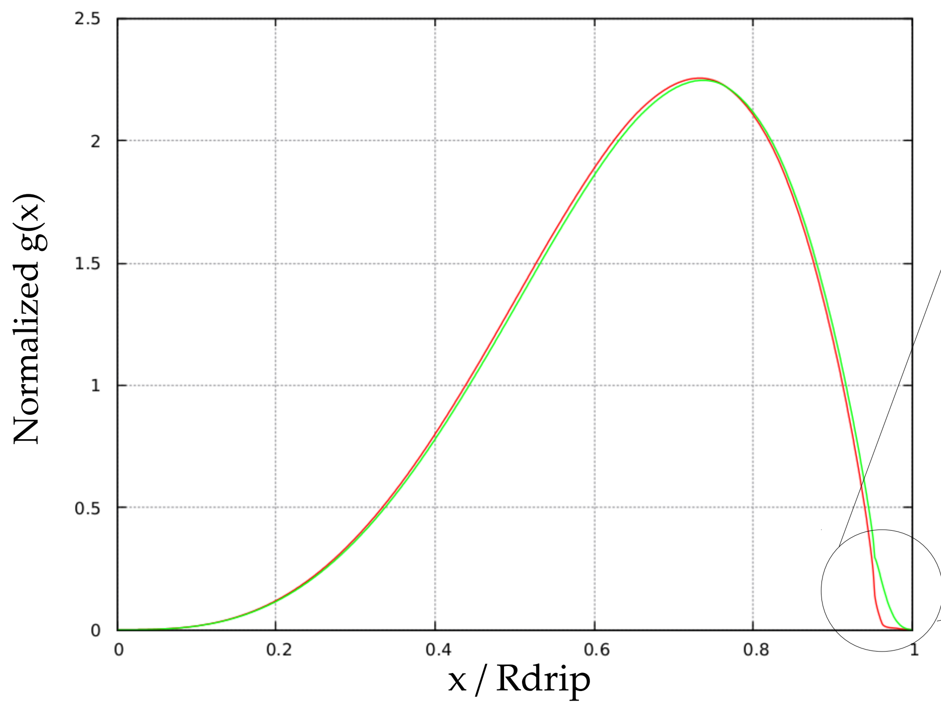
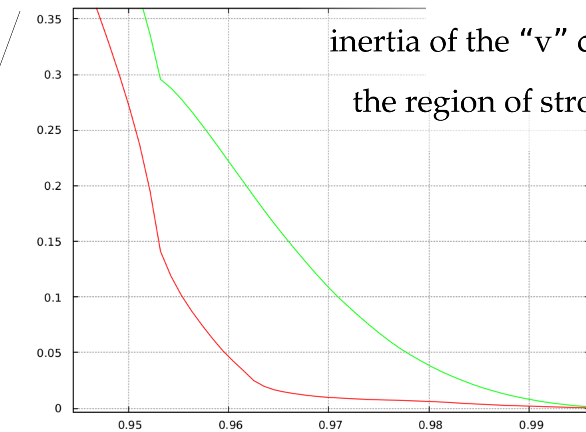
comp star

Example of entrainment corrections



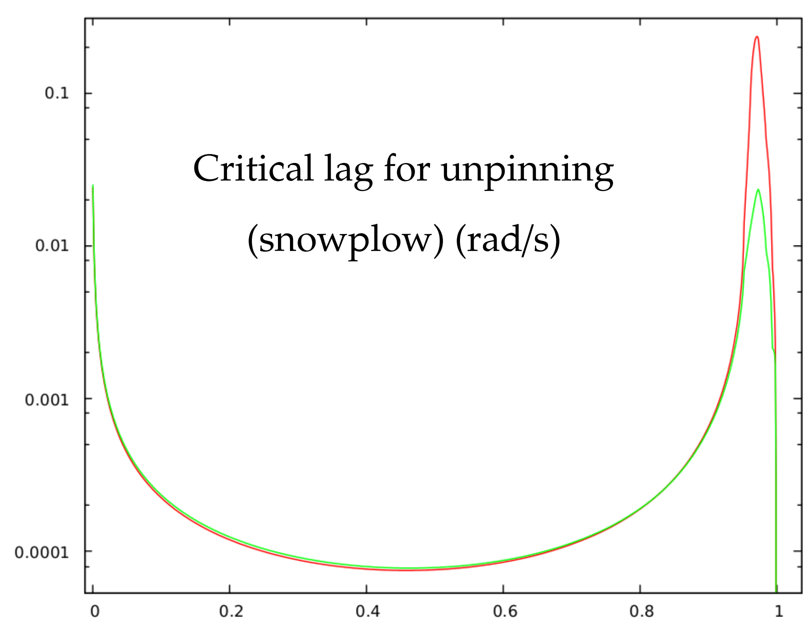


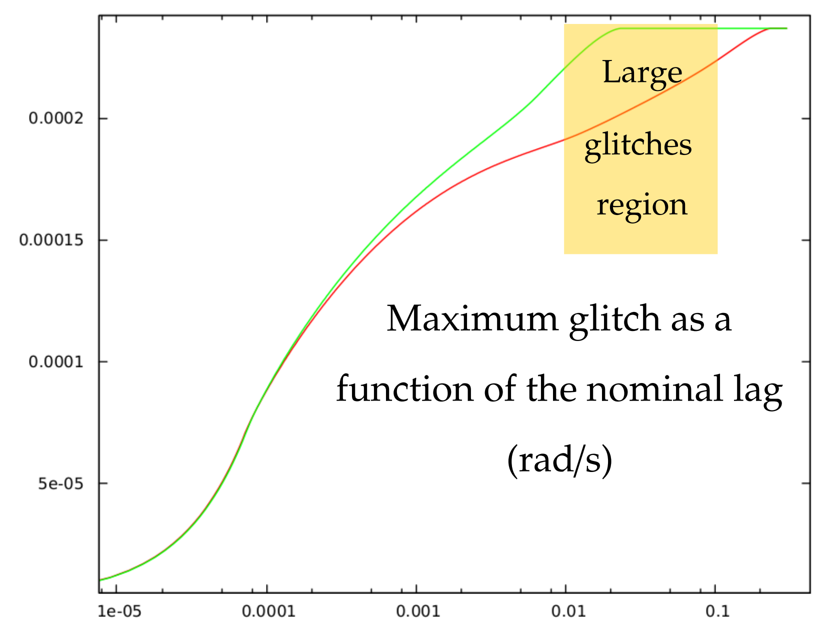
Entrainment: less moment of inertia of the “v” component in the region of strong pinning

Eos: Sly, M = 1.4 Msun

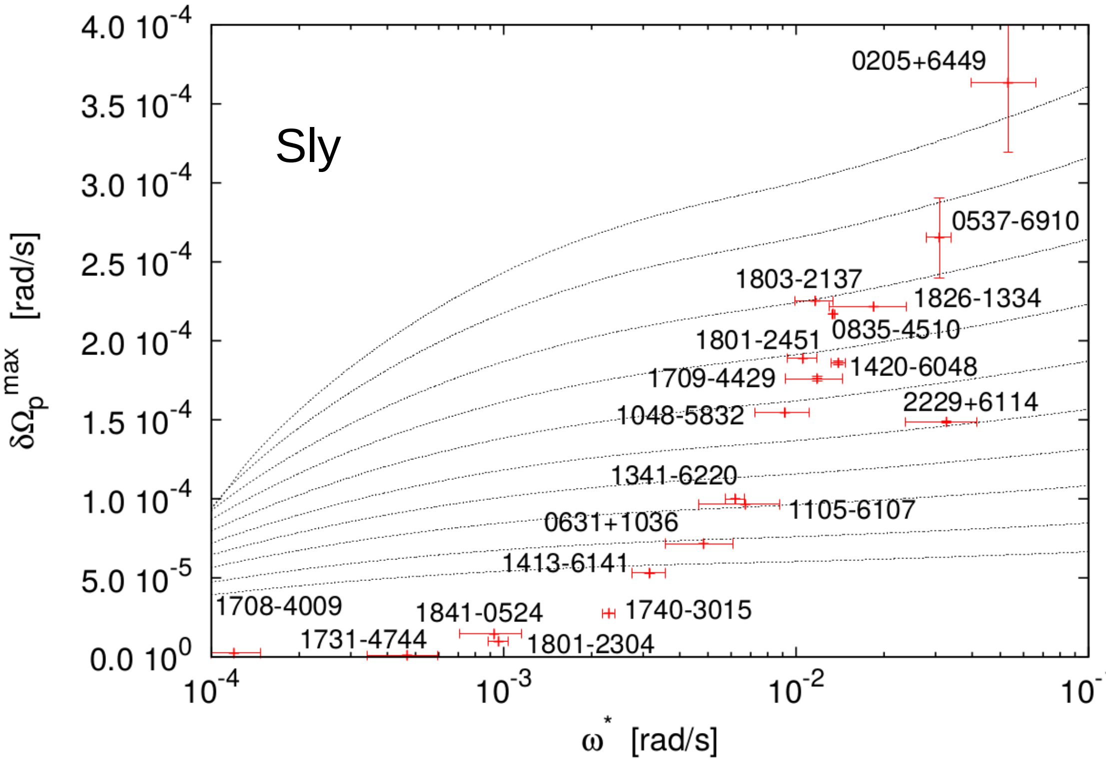
Red → with entrainment (Chamel)

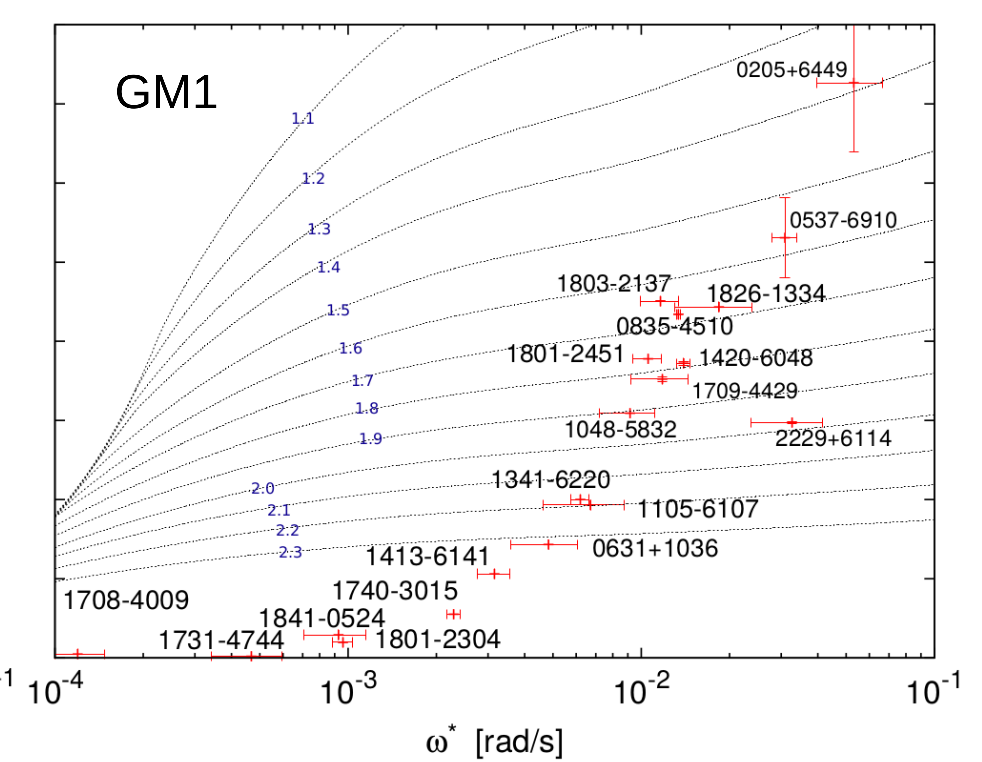
Green → no entrainment

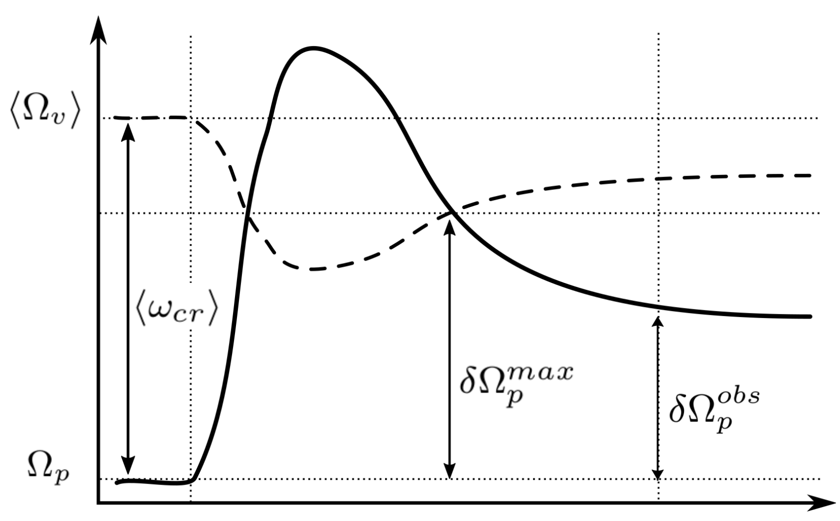




Maximal glitch amplitude





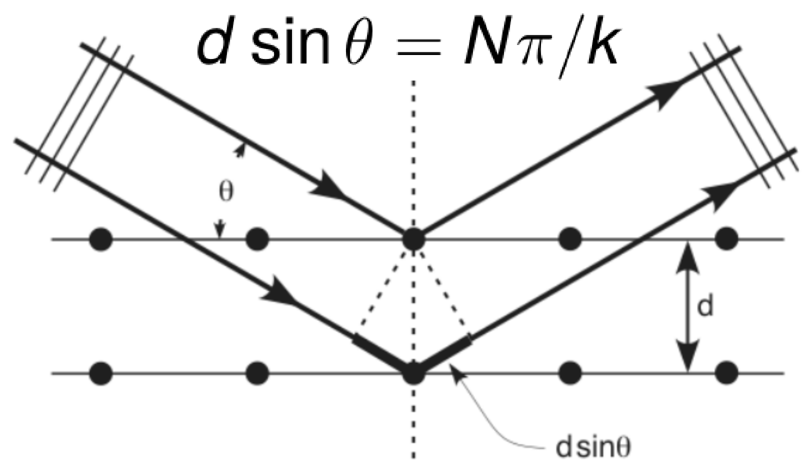


Entrainment effects in neutron stars

- **In the crust:**

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

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



- **In the core:**

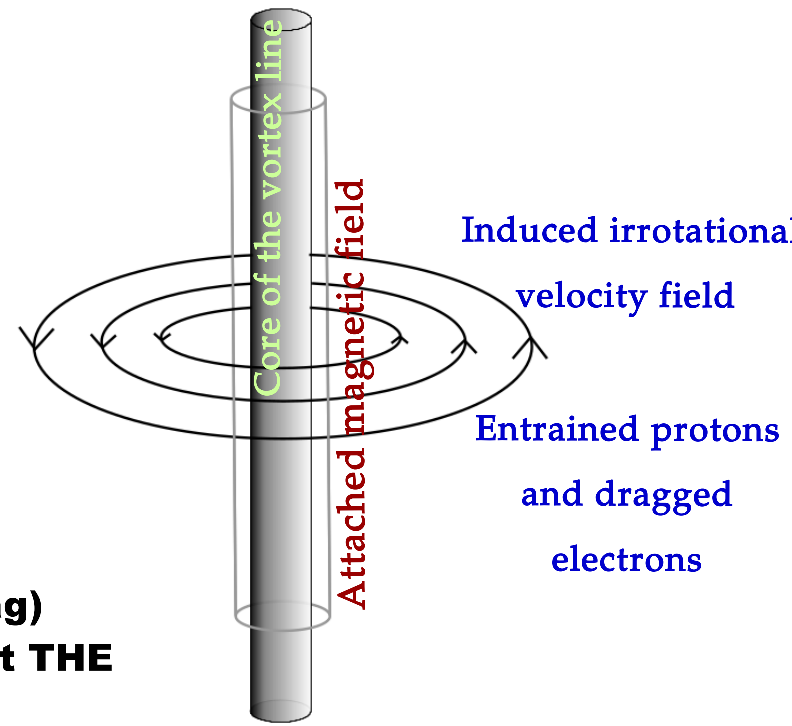
  Entrainment is due to:

  - Interaction between protons and neutrons

  Effects: vortex lines are magnetized!

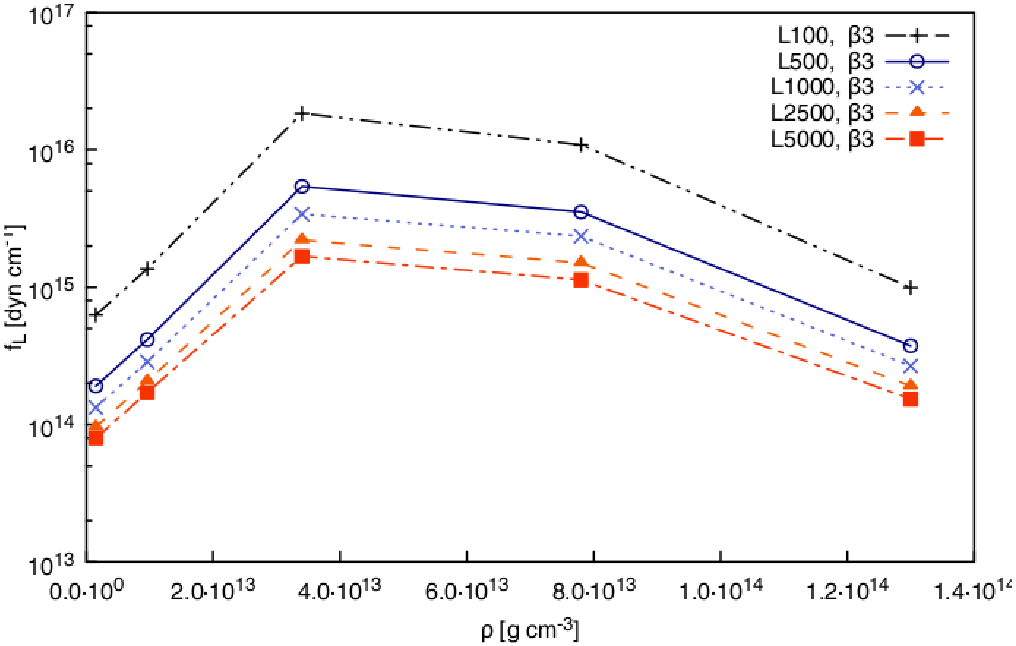
  Scattering of electrons → vortex is dragged

  Dipole-Dipole interaction with fluxtubes (core pinning?)



→ the conclusion is that the core should be coupled to the crust on the timescale of a second (el. scattering drag)
→ glitches originate in the crust... but thanks to entrainment THE CRUST IS NOT ENOUGH!

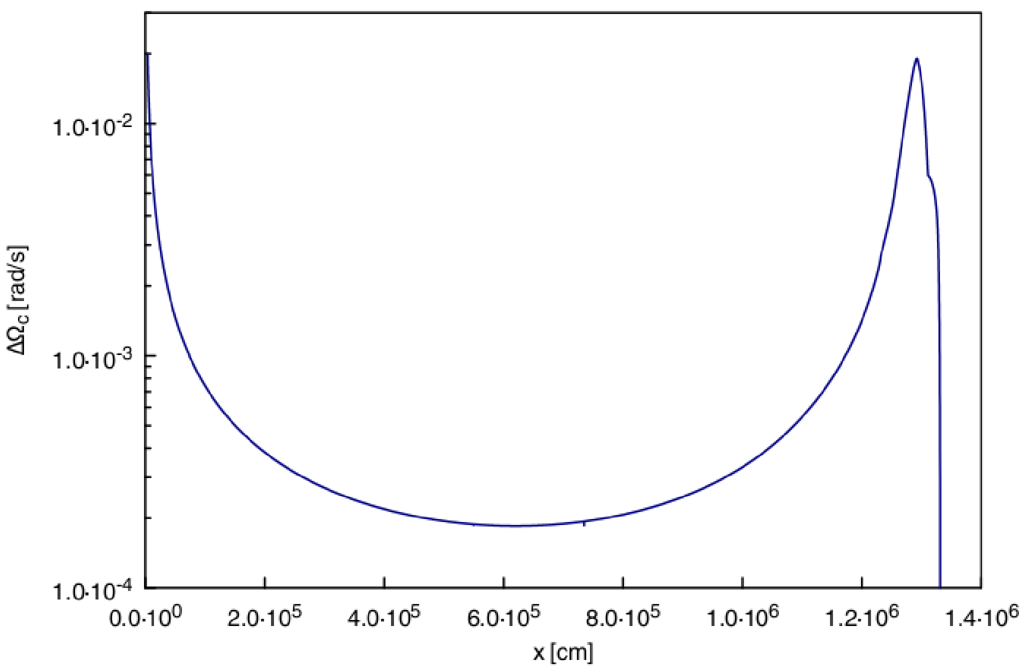
Mesoscopic pinning forces



Mesoscopic pinning forces

(vortex-lattice interaction per unit length of vortex line)

S. Seveso, F. Grill,
P. Pizzochero, B. Haskell

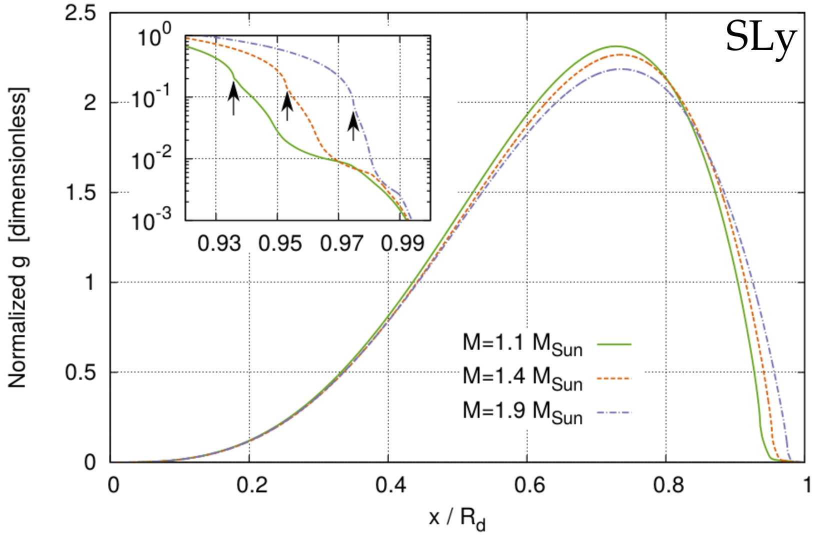


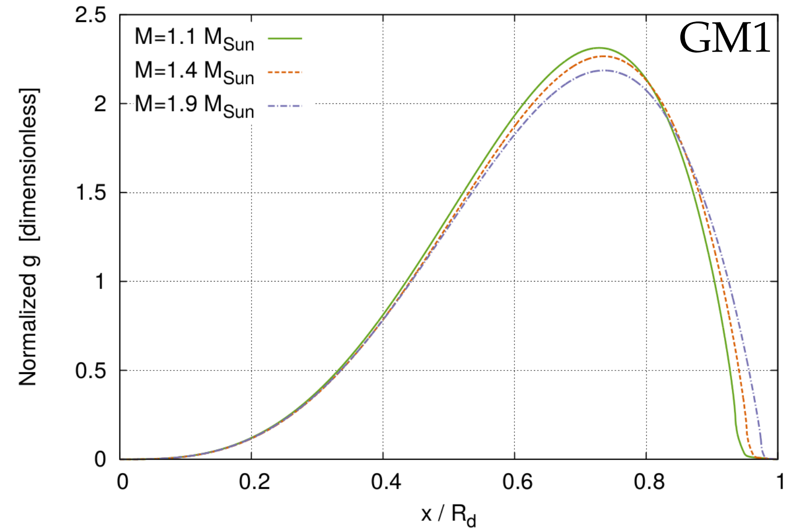
Resulting critical lag for unpinning (without entrainment)

$$Y[\omega, x] = \theta(|\omega(x)| - \omega_{cr}(x))$$

Some results for Sly & GM1 equations of state

Moments of inertia weights look the same (also because of normalization on the unit interval)





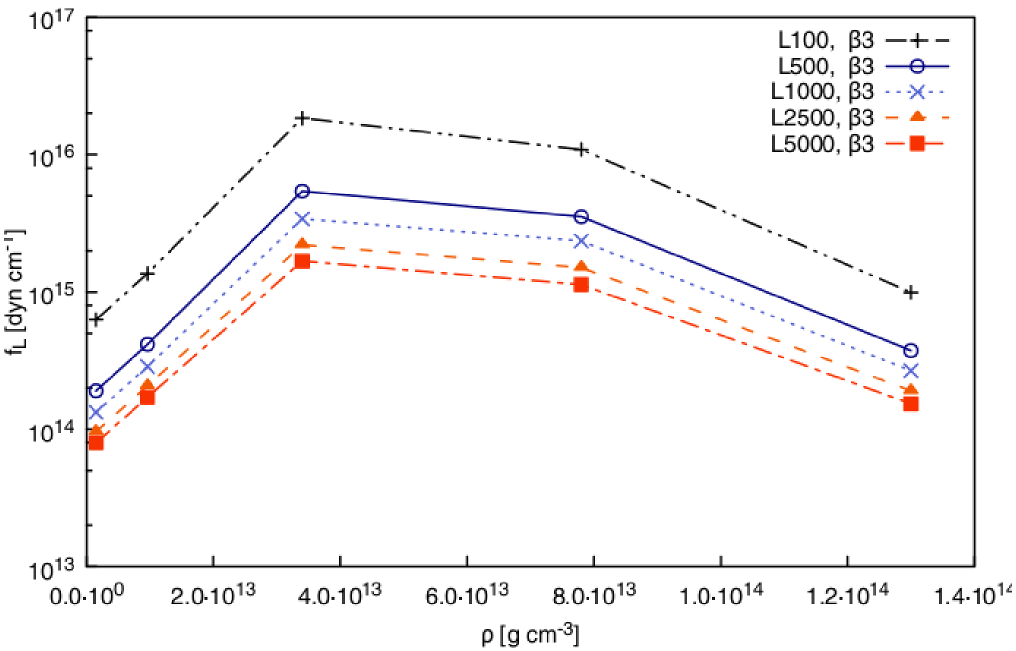
$$\tau^{-1} = 2(1+q)\langle \mathcal{B}^x_{\text{eff}} \rangle \Omega_p$$

	M ($M_\odot$)	R_d (km)	R_c (R_d)	$I/10^{45}$ (g cm^2)	I_v (I)	q	τ_{ph} (P)	τ_{kv} (P)	$\langle \omega_{cr} \rangle$ (10^{-4}rad/s)	$\delta\Omega_p^{max}$ (10^{-4}rad/s)
SLy	1.1	11.41	0.936	0.86	0.928	12.9	62.1	13.2	4.17	3.87
	1.4	11.43	0.953	1.09	0.941	16.1	29.2	12.1	2.51	2.37
	1.9	10.92	0.974	1.35	0.958	22.9	9.0	7.2	0.92	0.89
GM1	1.1	13.08	0.926	1.14	0.901	9.2	445	13.9	6.99	6.30
	1.4	13.28	0.945	1.51	0.913	10.5	261	17.1	4.37	3.92
	1.9	13.24	0.966	2.04	0.916	10.9	136	26.3	2.04	1.87

Estimates of the rise time

(all vortices unpinned)

Mesoscopic pinning forces



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(vortex-lattice interaction per unit length of vortex line)

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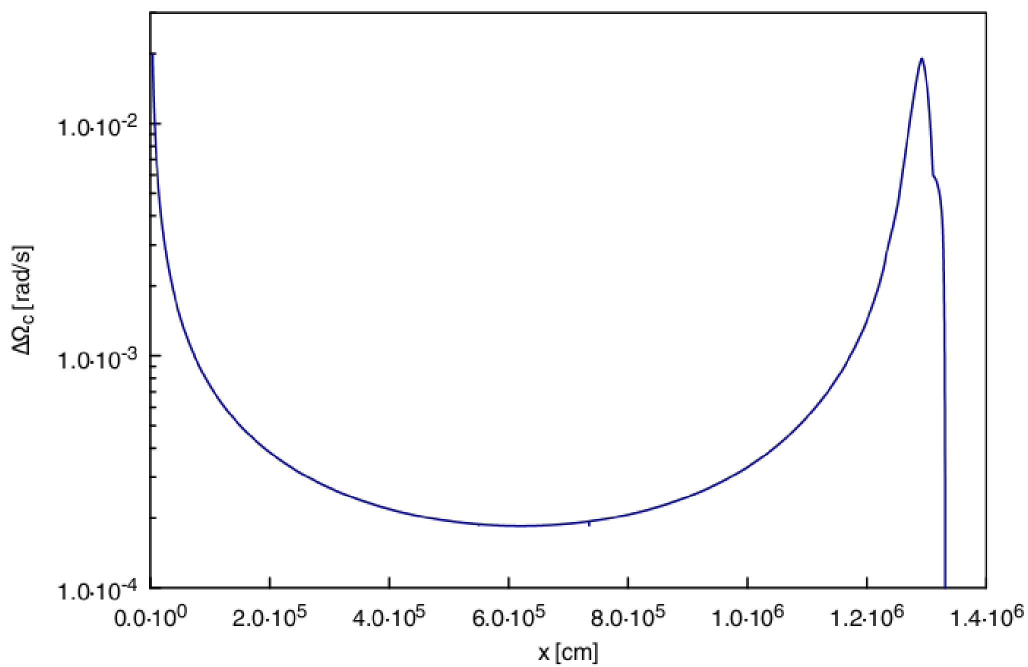

Resulting critical lag for unpinning (without entrainment)

$$Y[\omega, x] = \theta(|\omega(x)| - \omega_{cr}(x))$$