Pulsar glitches from a nuclear physics perspective

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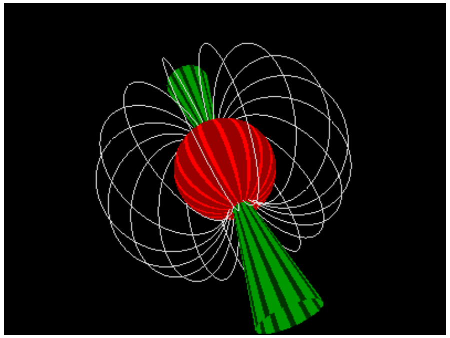
Outline

- Pulsar glitches: observation
- Pulsar glitches: crust superfluid driven glitch models
- Model efficacy considering nuclear physics uncertainties
- Summary and nuclear physics to-do list

Pulsar glitches: the observations



- Sudden spin-up of pulse frequency on timescales of <10s of minutes, against steady spin-down
- First observed in 1969 in Crab, Vela pulsars

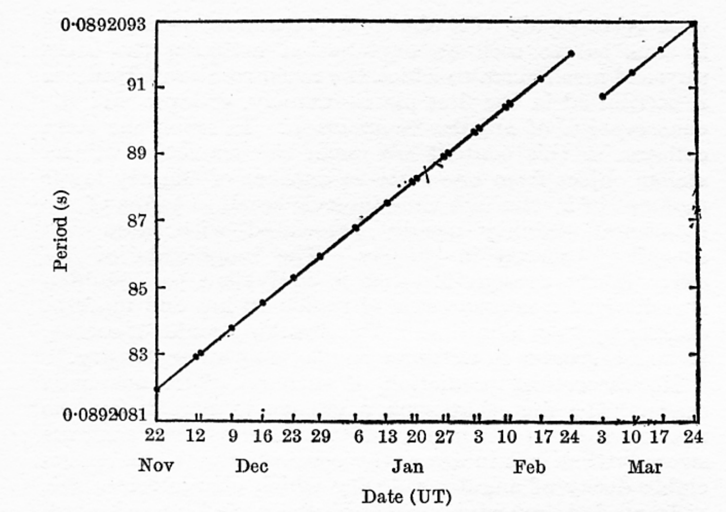


Fig. 1. The barycentric period of *PSR* 0833–45 as observed from November 22, 1968, to March 24, 1969, showing the 134 ns decrease between February 24 and March 3.

Reichley, Downs; Nature 1969

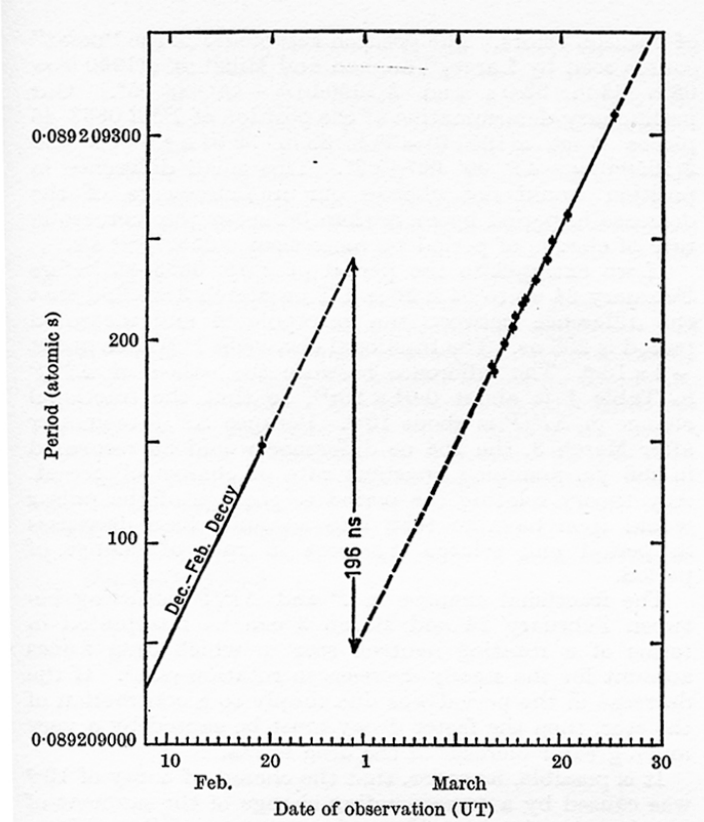
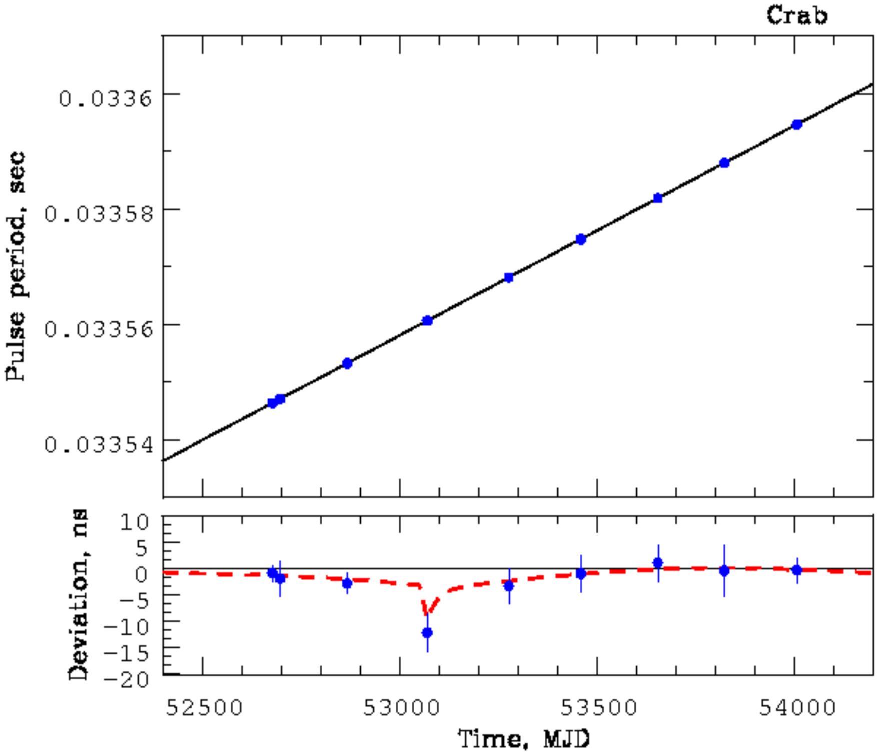


Fig. 1. Heliocentric period of *PSR* 0833–45 observed in February and March 1969, based on position α 08 h 33 m 39·0 s, δ −45° 00′ 05·0″ (epoch 1950·0) (ref. 3). The rate of increase of the period was 10·69 ± 0·20 ns day^{-1} between December 8, 1968, and February 19, 1969. Since March 13, 1969, the rate of decay has been 10·64 ± 0·20 ns day^{-1}. At some time between February 19 and March 13 the period decreased by 196 ns.

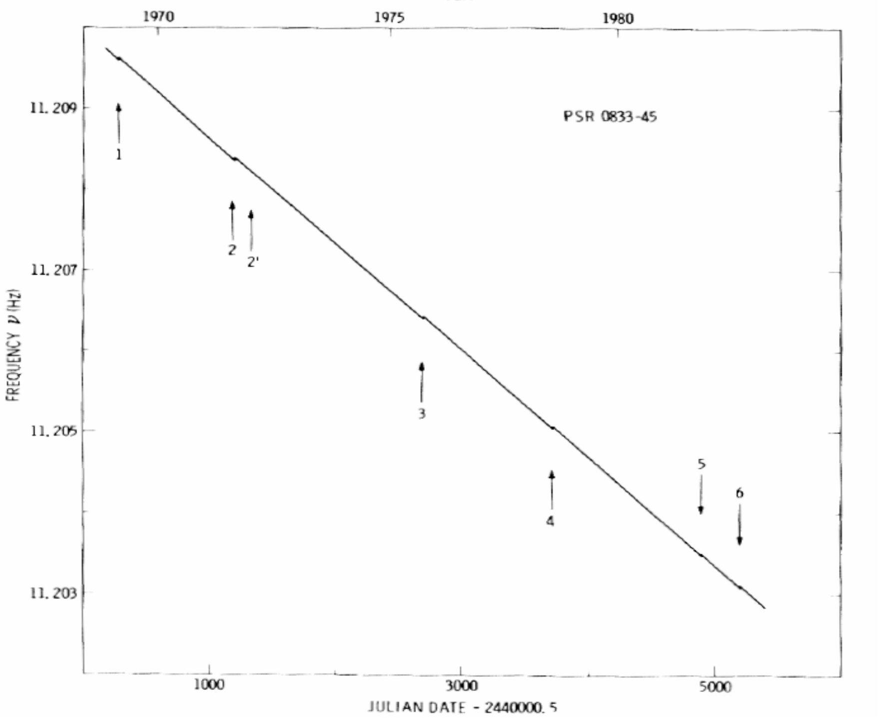
Radhakrishnan, Manchester; Nature 1969

Pulsar glitches: the observations

Crab



Vela



$\Delta\Omega/\Omega \approx 10^{-9}$, $\Delta t_g \sim 200$ days

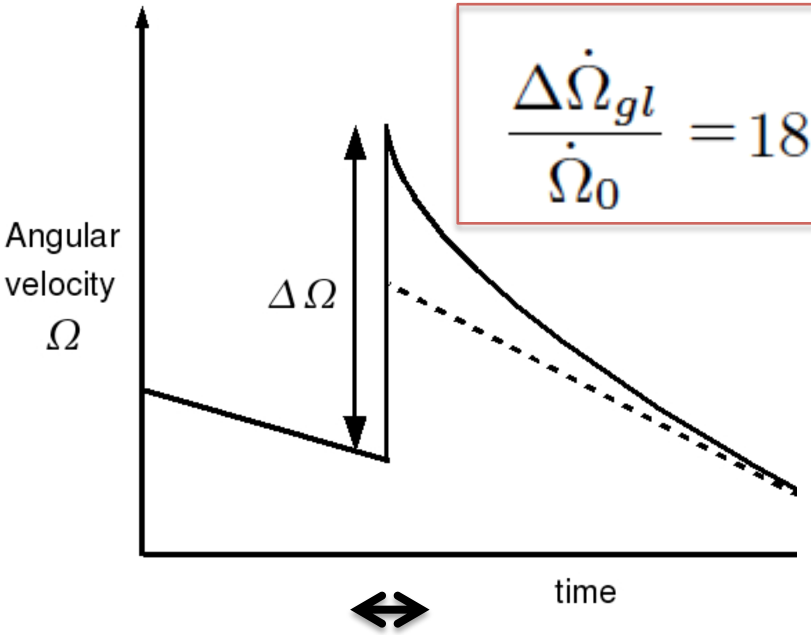
$\Delta\Omega/\Omega \approx 10^{-6}$, $\Delta t_g \sim 1000$ days

- Activity parameter: $A_g = (1/T_{obs})\, \Sigma\Delta\Omega/\Omega$ = average rate of relative spin-up due to glitches
  - Crab: $A_g \sim 10^{-9}\,\mathrm{yr}^{-1}$
  - Vela: $A_g \sim 10^{-7}\,\mathrm{yr}^{-1}$

  Espinoza et al 2011

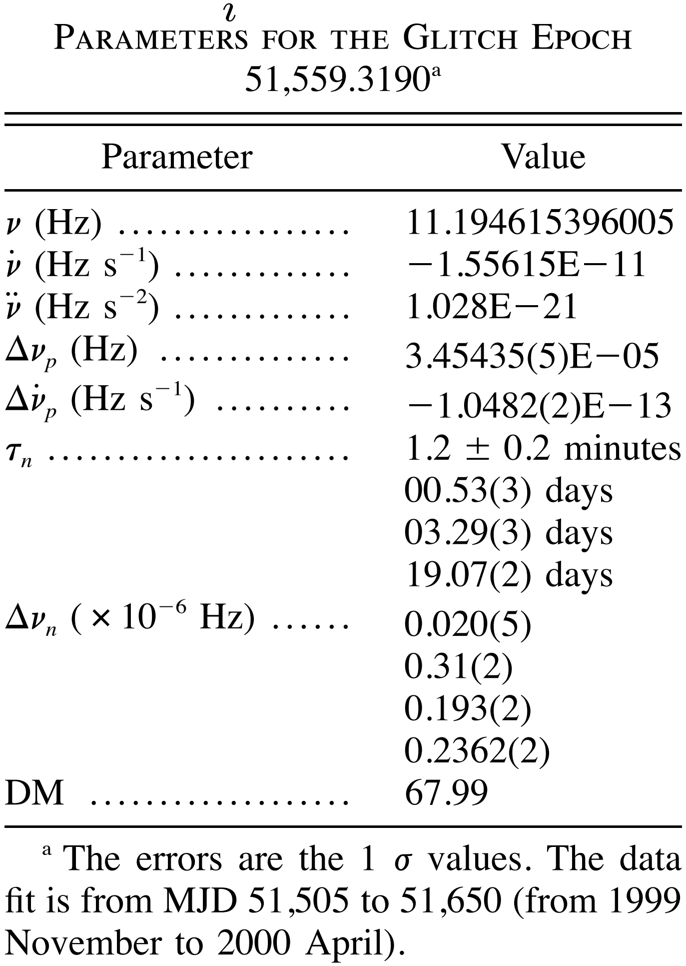
Pulsar glitches: the observations

$$\nu(t) = \nu_0 + \dot{\nu}_0 t + \frac{1}{2}\ddot{\nu}_0 t^2 + \Delta\nu_p + \Delta\dot{\nu}_p t + \sum_i \Delta\nu_i \exp\left(-t/\tau_i\right)$$



$$\frac{\Delta\dot{\Omega}_{gl}}{\dot{\Omega}_0} = 18 \pm 6$$

Glitch rise time $t_{glitch} < 40$s



PARAMETERS FOR THE GLITCH EPOCH 51,559.3190[a]

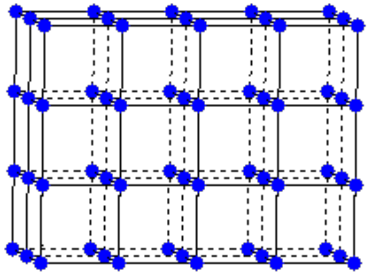
Parameter	Value
ν (Hz)	11.194615396005
$\dot{\nu}$ (Hz s^{-1})	$-$1.55615E$-$11
$\ddot{\nu}$ (Hz s^{-2})	1.028E$-$21
$\Delta\nu_p$ (Hz)	3.45435(5)E$-$05
$\Delta\dot{\nu}_p$ (Hz s^{-1})	$-$1.0482(2)E$-$13
τ_n	1.2 ± 0.2 minutes 00.53(3) days 03.29(3) days 19.07(2) days
$\Delta\nu_n$ (× 10^{-6} Hz)	0.020(5) 0.31(2) 0.193(2) 0.2362(2)
DM	67.99

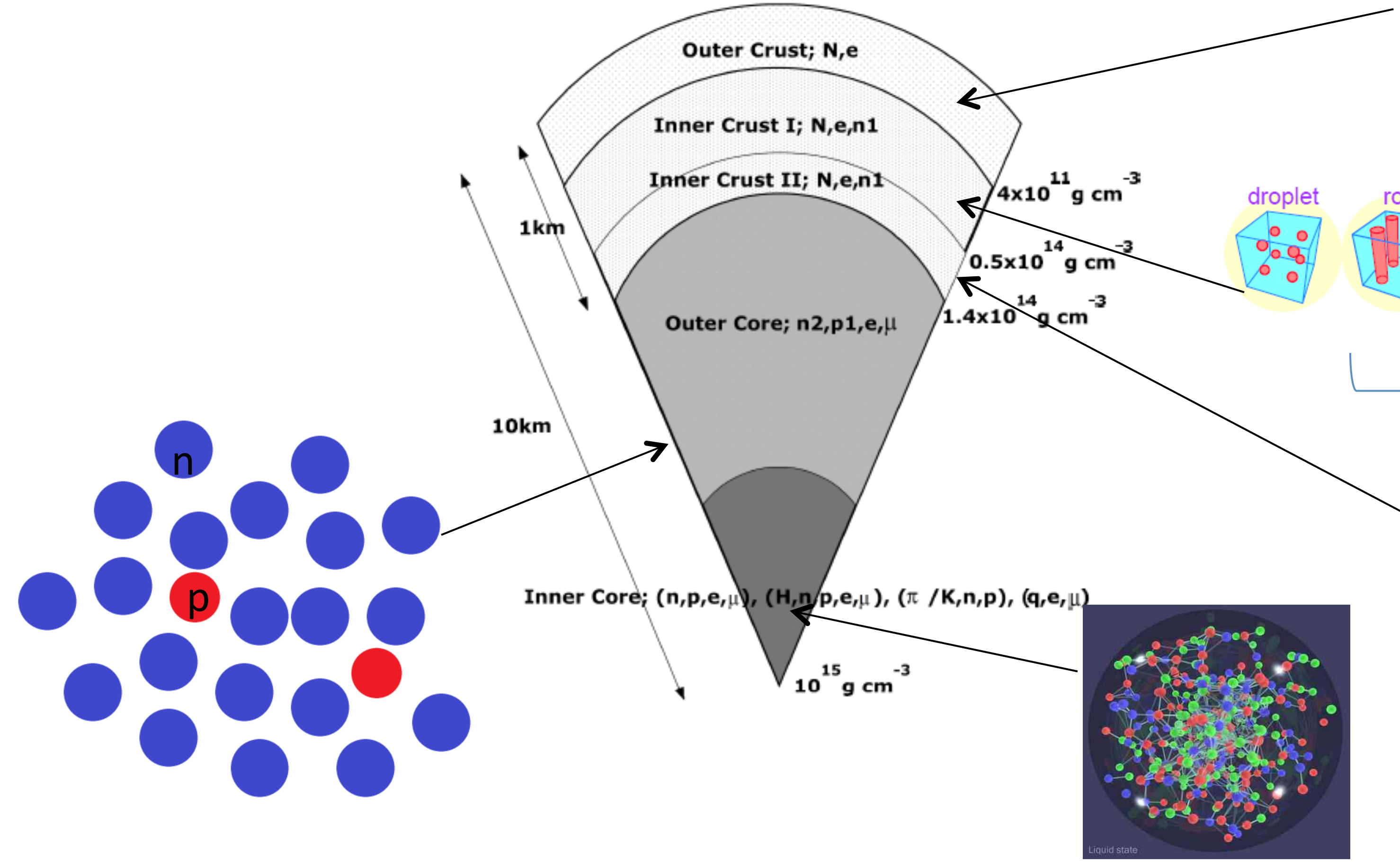
[a] The errors are the 1 σ values. The data fit is from MJD 51,505 to 51,650 (from 1999 November to 2000 April).

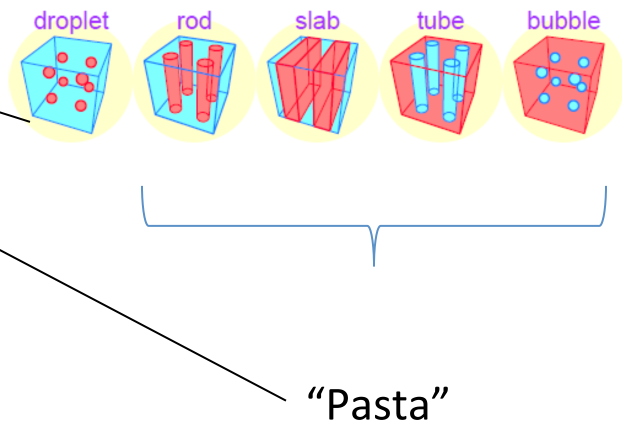
2000 Vela glitch: Dodson, McCulloch, Lewis 2002

Pulsar glitches: the candidate model

- Starquake models: cannot explain glitch activity of even Crab pulsar
- Two component models currently the leading *class* of candidates
  - (A) Visible component (observed rotational frequency): couples to B-field on t<40s
    - *At least* crust lattice and protons in core
    - Usually assumed to be core neutrons too
  - (B) Rotationally decoupled component: crust superfluid neutrons?

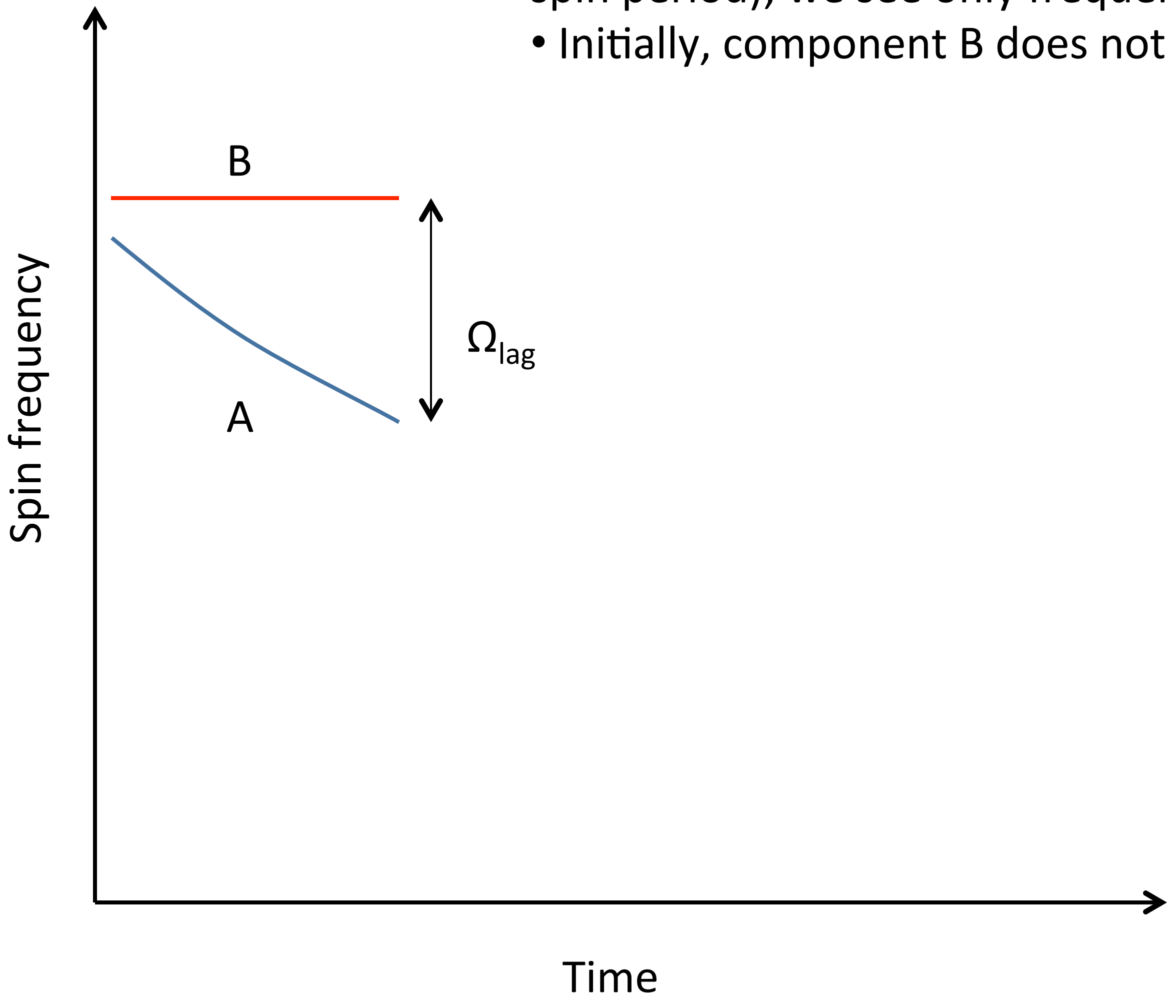






Pulsar glitches: the two component model

- Two dynamically distinct components of the star, A and B
- The B-field is coupled to component A on short timescales (<< spin period); we see only frequency of component A
- Initially, component B does not couple to A



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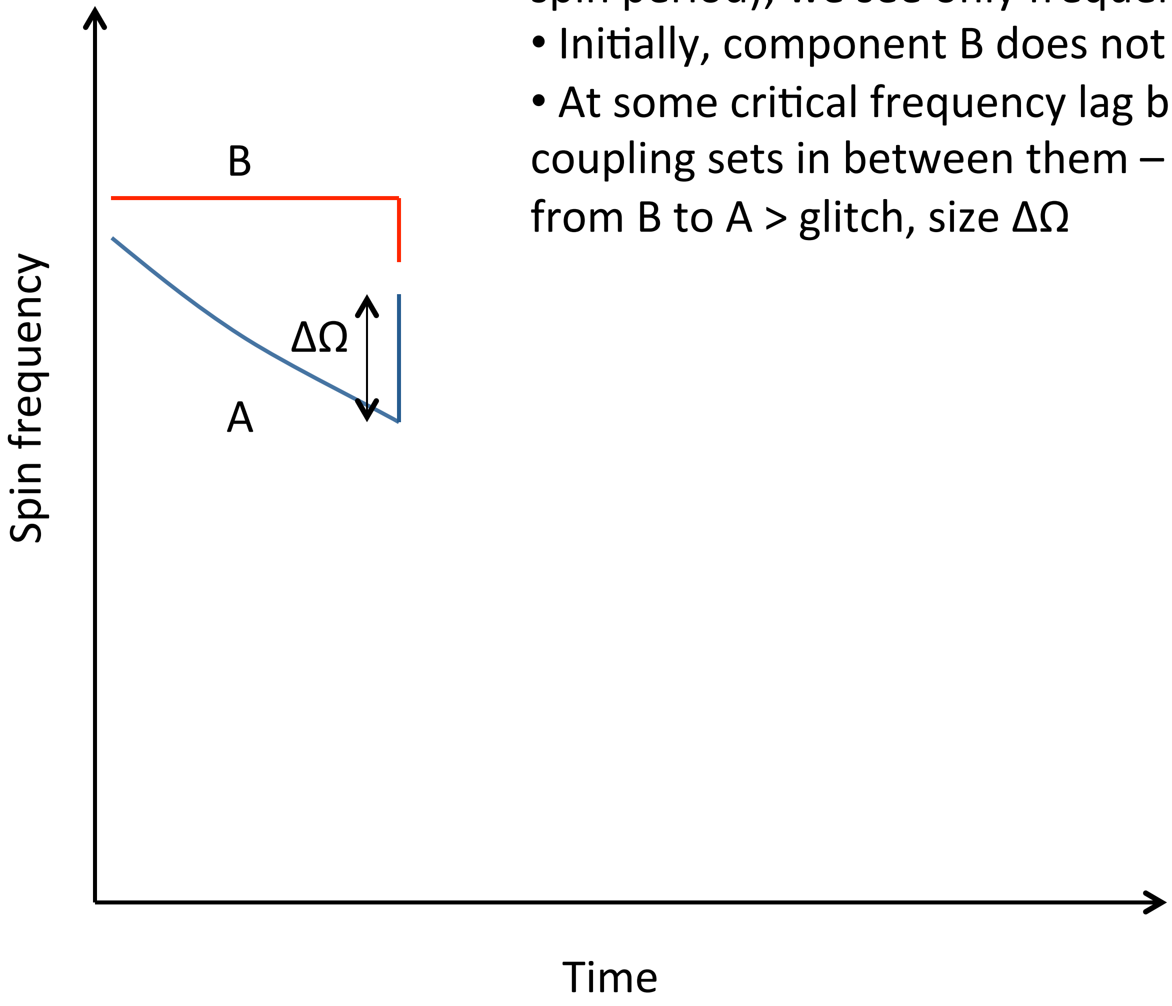

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- At some critical frequency lag between A and B, Ω_{lag}, a strong coupling sets in between them – angular momentum transferred from B to A > glitch, size ΔΩ

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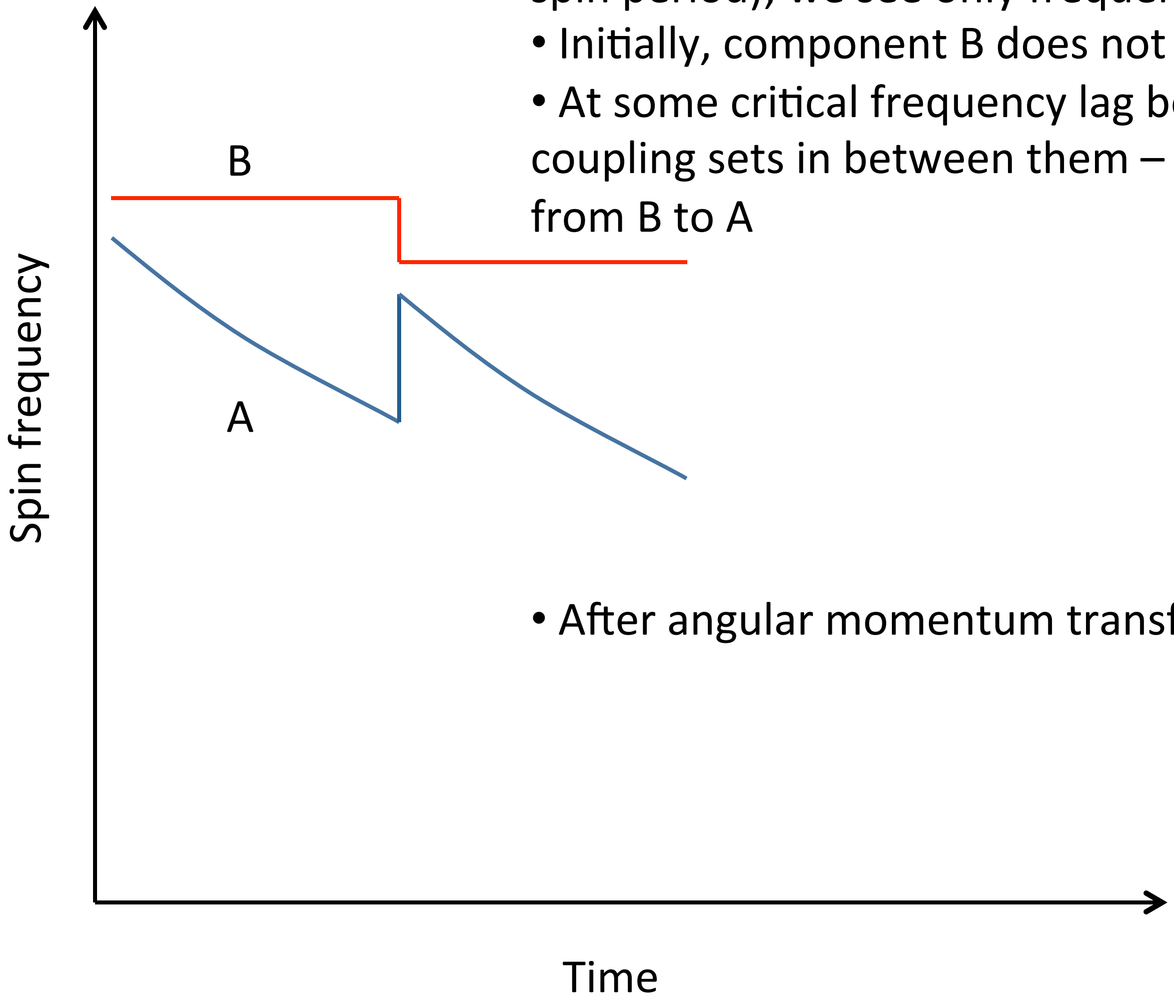

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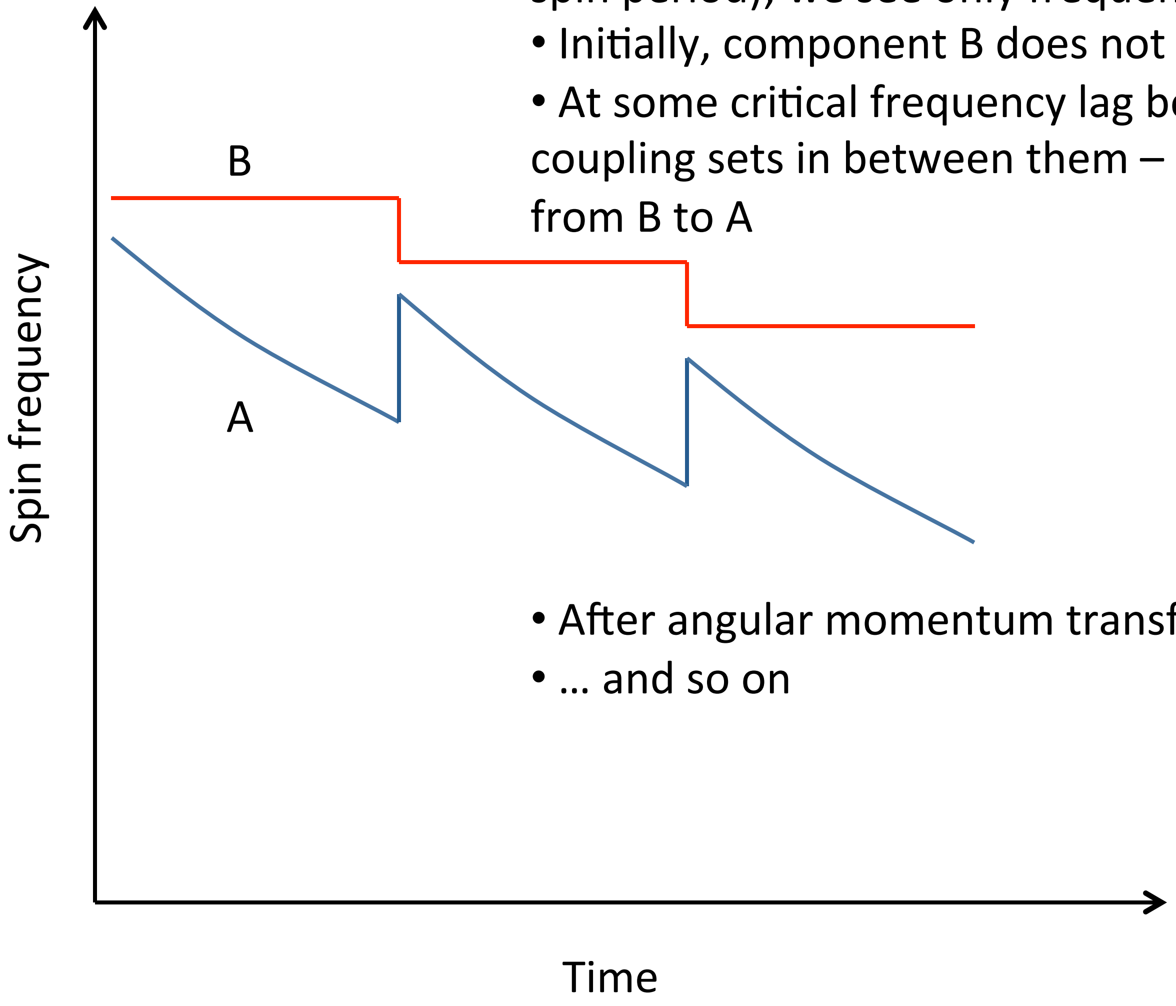
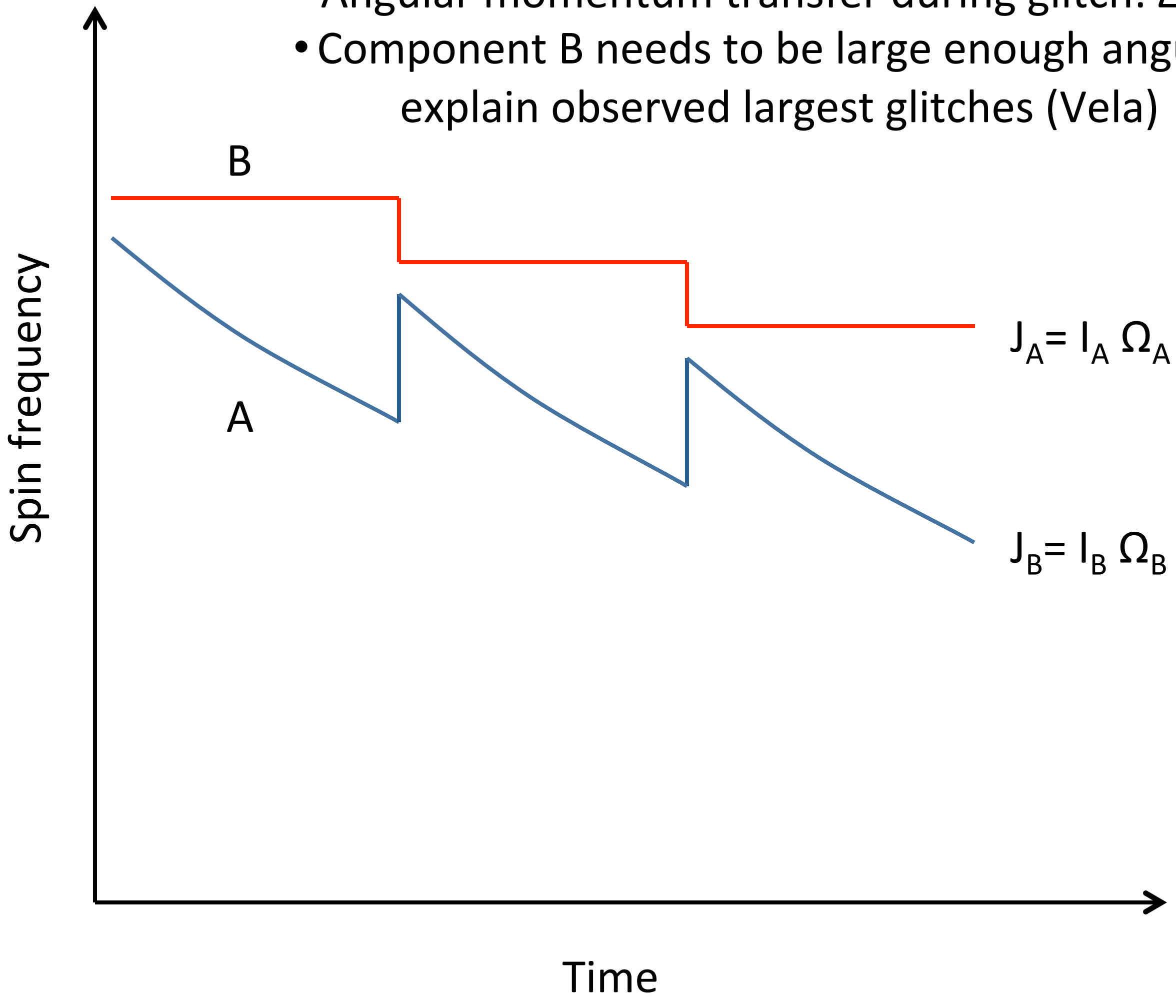


- After angular momentum transfer, the components decouple
- … and so on

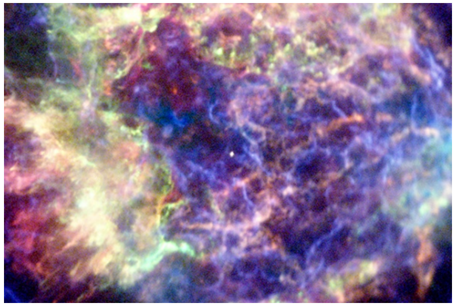
Pulsar glitches: the two component model

- Between glitches, angular momentum accumulates in the reservoir (B); released at time of glitch
- Angular momentum transfer during glitch: $\Delta J = I_B \Delta\Omega_B = I_A \Delta\Omega_A$
- Component B needs to be large enough angular momentum reservoir to explain observed largest glitches (Vela)

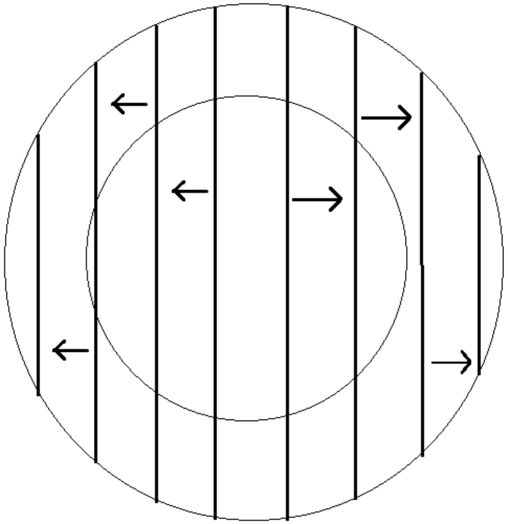


Pulsar glitches: the role of core neutron superfluidity

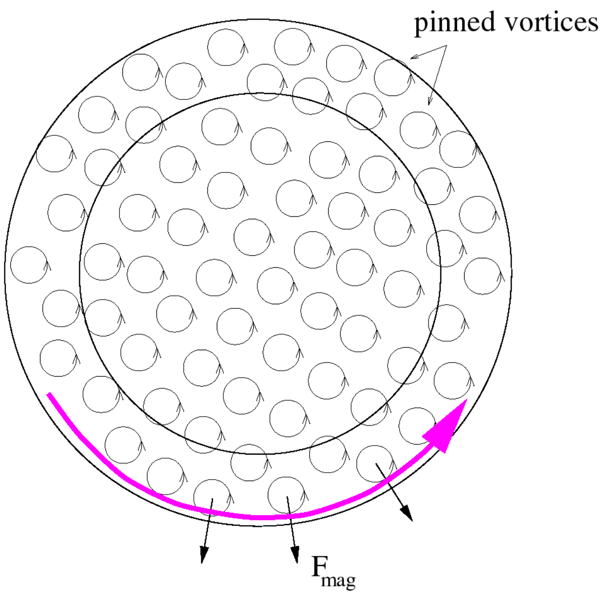
- Neutrons in core and crust expected (from theory) to be superfluid for pulsars older than ≈ 100yr
- Some supporting evidence from rapid Cas A cooling (Shternin et al 2011, Page et al 2011)
- Superfluid component cannot support bulk rotation (gap suppresses interactions which cause, e.g., friction)
- Vorticity quantized



Polar cross section

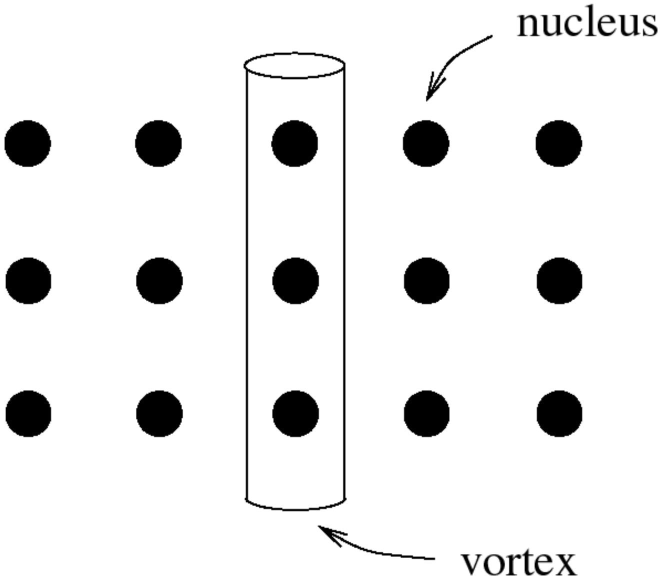


Equatorial cross section



- Spacing of n vortices ~ 10^{-2} cm
- As frequency decreases, vortices move out radially from the spin axis
- Protons entrained by vortices
  - electron scattering couples vortices to crust on timescales $t_{mf} \approx$ 10-10,000s
  - Fraction of core neutrons coupled to crust on glitch timescales $Y_g \approx t_{glitch}/t_{mf} = 1 - 10^{-3}$

Pulsar glitches: the role of crust neutron superfluidity

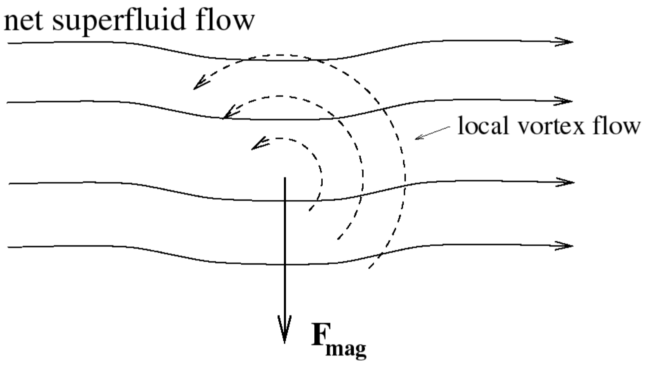


- Energy of nucleus-vortex interaction either favors vortex cores threading nuclei *or* between nuclei in inner crust (~3 MeV/nucleus)
- Either way, work must be done by an external force to move vortices through the lattice
- The vortices are said to be *pinned*

- Pinning can sustain differential velocity up to ~ 10 rad / s

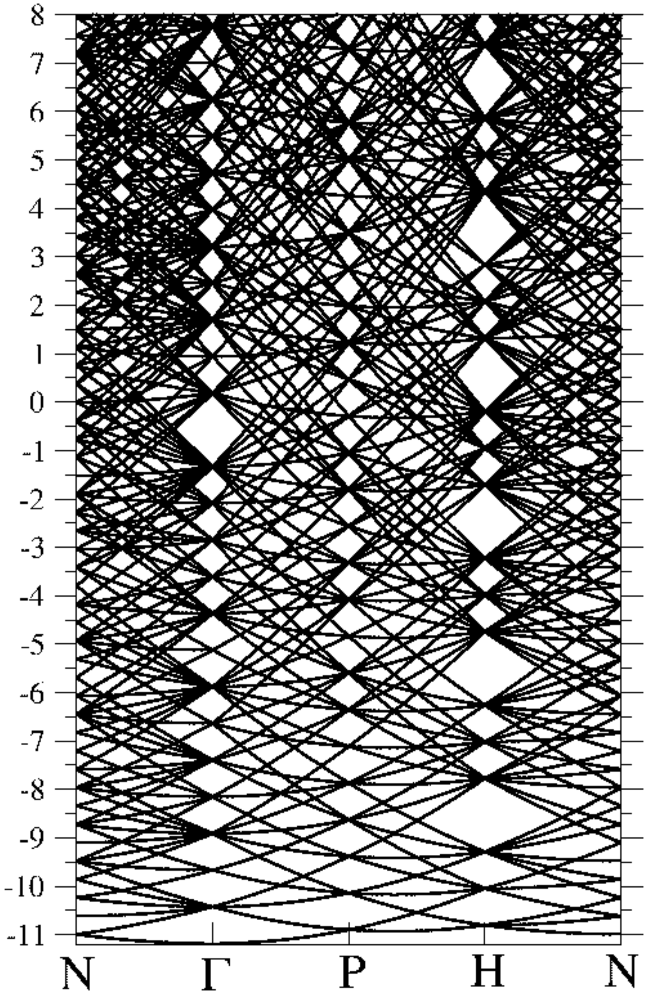
⇒large angular momentum reservoir! (Large enough?)

- When some critical velocity differential is reached, Magnus force unpins vortices > angular momentum transfer to crustal lattice



Pulsar glitches: the role of crust neutron superfluidity

Chamel PRC85, 03992 (2012)



- Bragg scattering of neutrons off nuclei in crust
- Results in neutron band structure analogous to electrons in metals
- Couples 80% free neutrons to lattice

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- Angular momentum transfer during glitch: $\Delta J = I_B \Delta\Omega_B = I_A \Delta\Omega_A$
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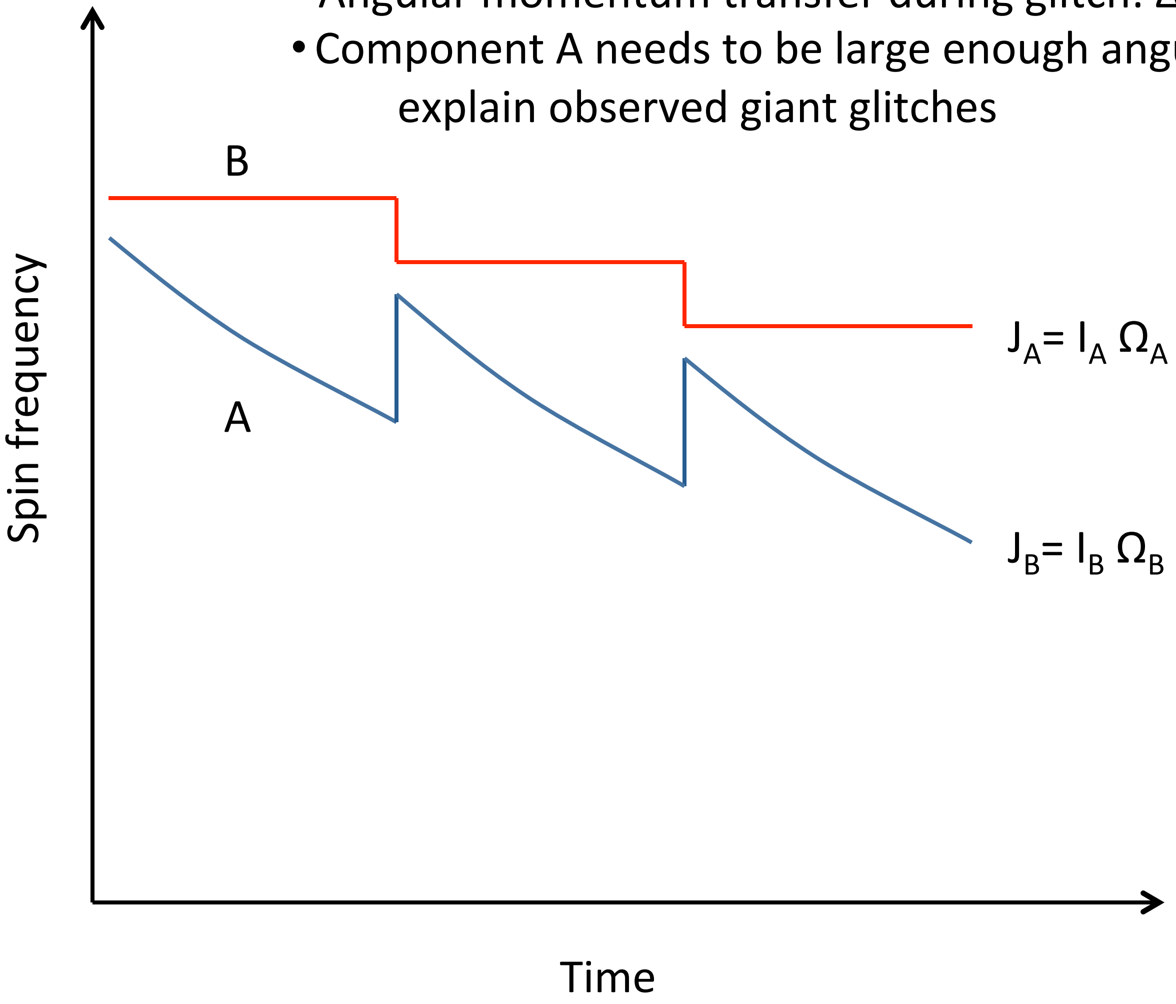


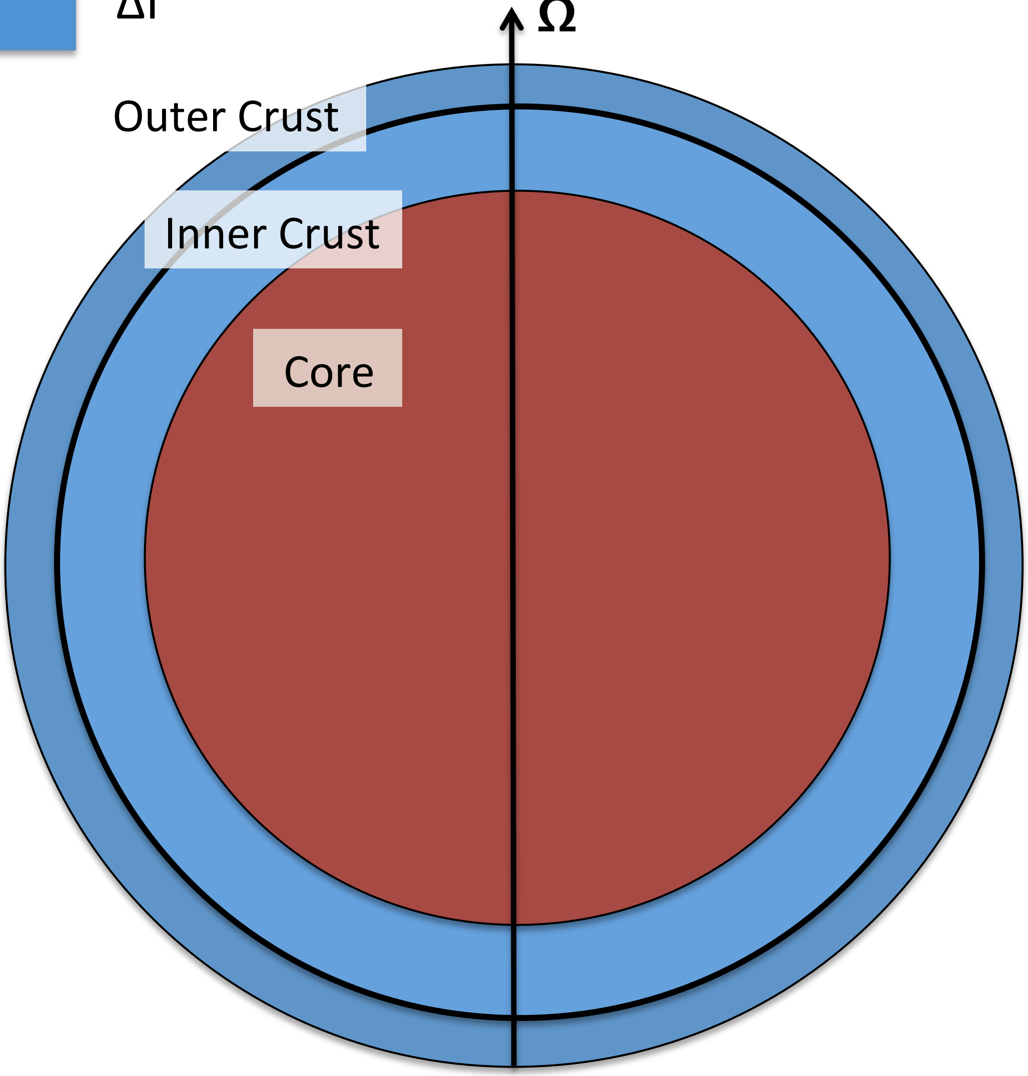
Crust superfluid neutrons

Crustal lattice, core protons, (some) core neutrons

Confronting model with observation

🟥 I

🟦 ΔI

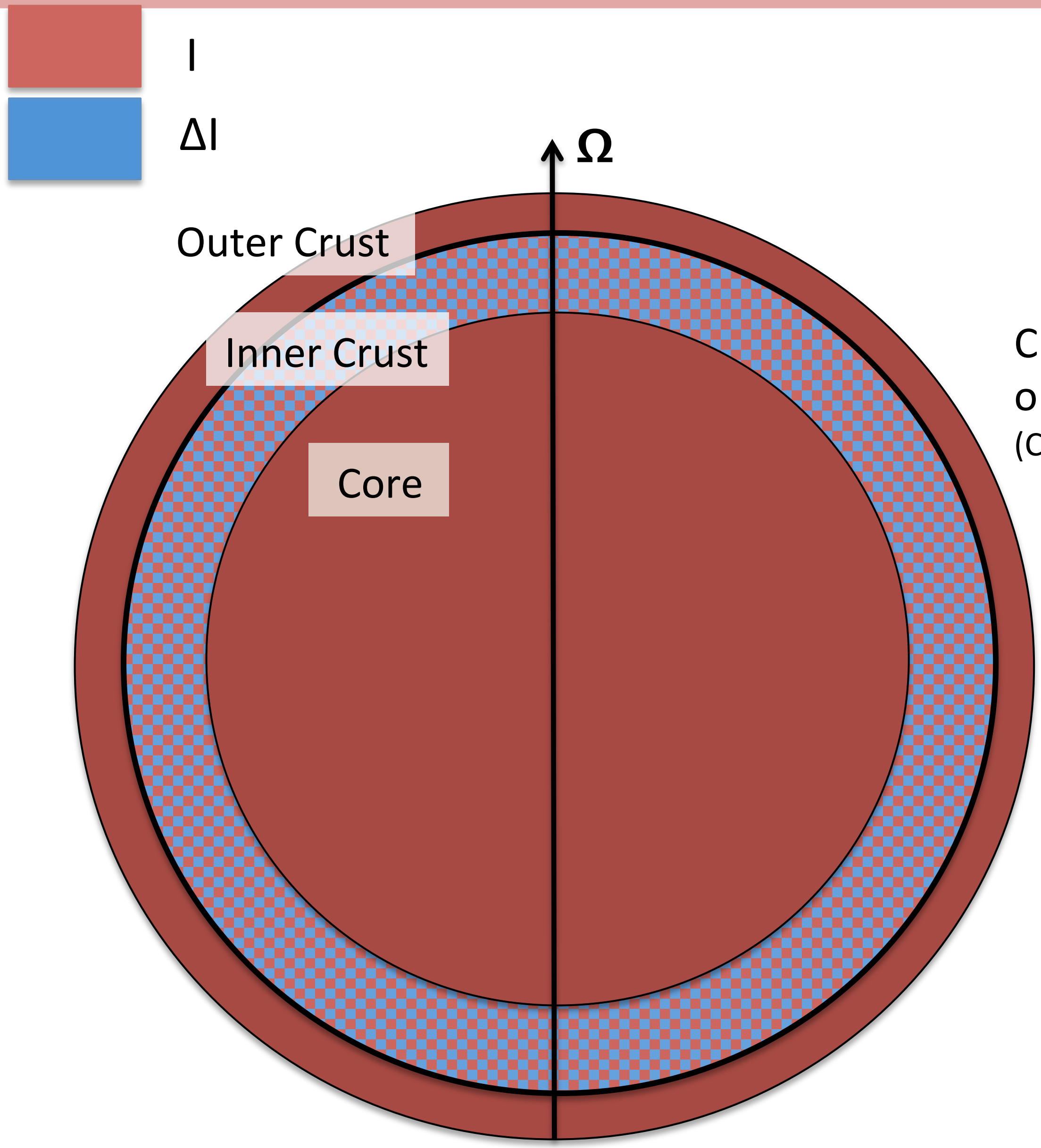


$$\Delta I/I \geqslant \frac{\bar{\Omega}}{|\dot{\Omega}|}\mathcal{A} = 0.016$$

(Link, Epstein, Lattimer; PRL83 1999)

OK for many reasonable EOSs

Confronting model with observation



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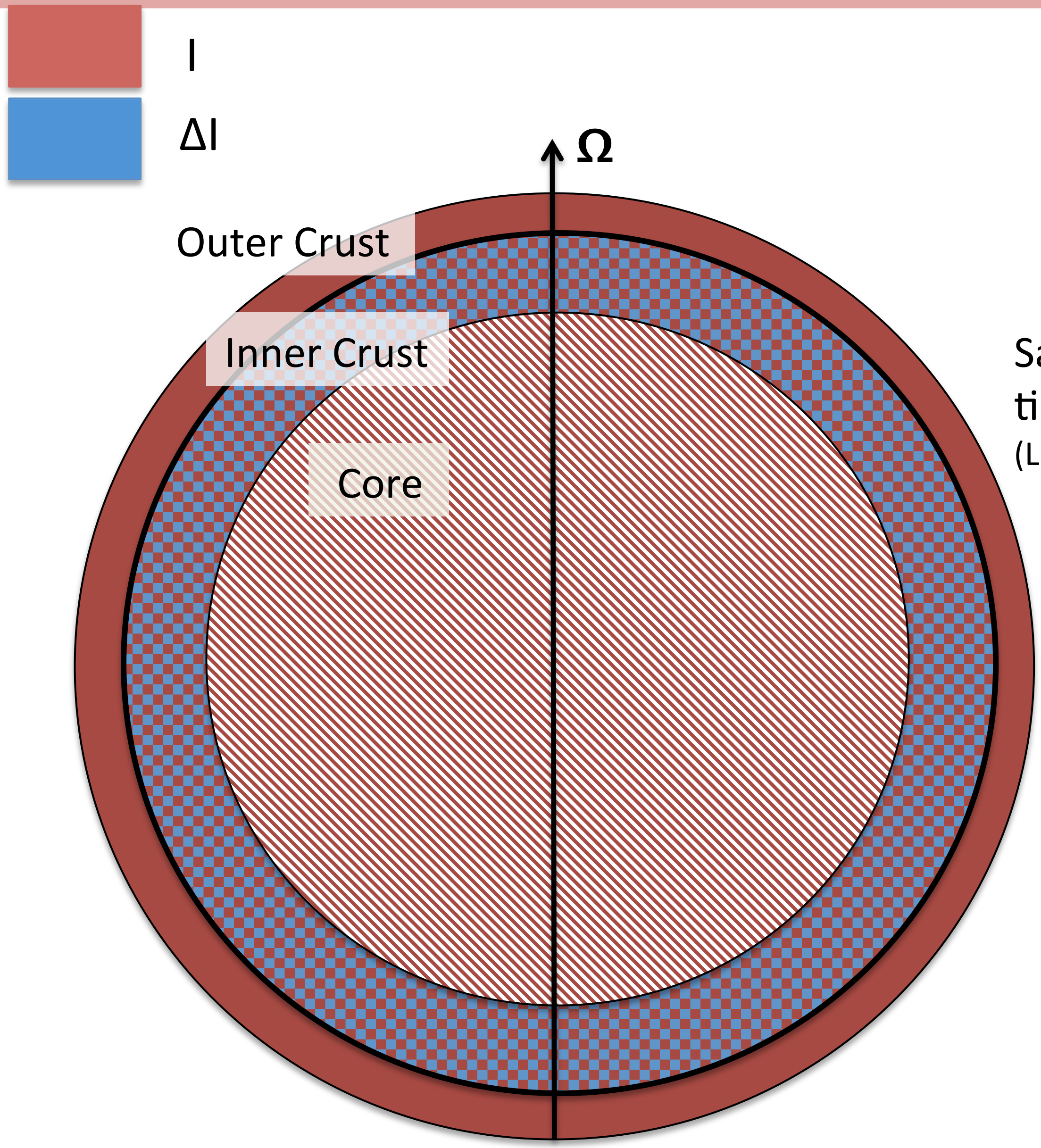
Crust entrainment kills crust superfluid origin for glitches?
(Chamel, 2012; Andersson et al2012)

ΔI reduced by factor of 5

Cannot be satisfied by ``reasonable'' EOSs (requires v. stiff @ saturation L>100 MeV, soft@high densities)

Confronting model with observation



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Saved by core superfluid coupling on timescales larger than glitch rise time?
(Link 2012; Haskell et al 2012; Seveso et al 2012)

ΔI reduced by factor of 5
I reduced by factor of 2-1000

OK for most EOSs

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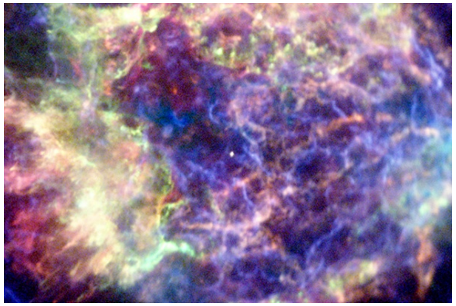

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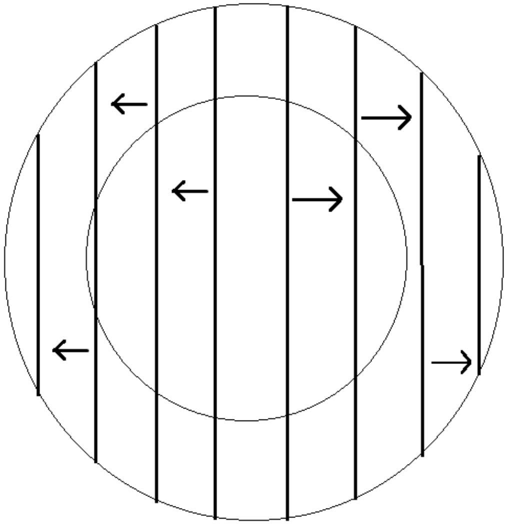

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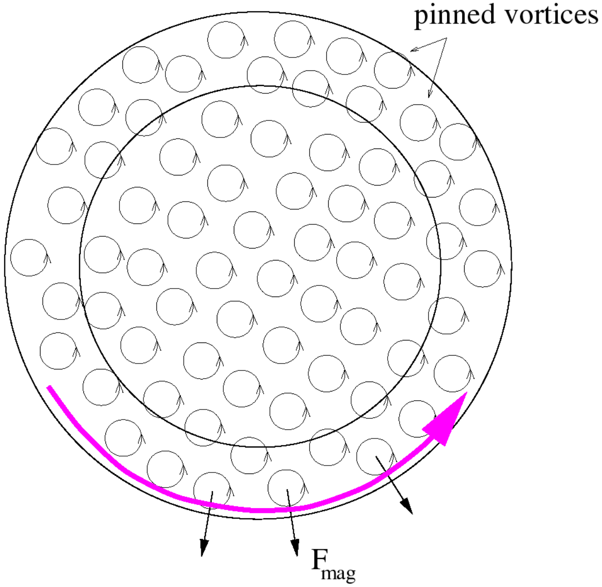

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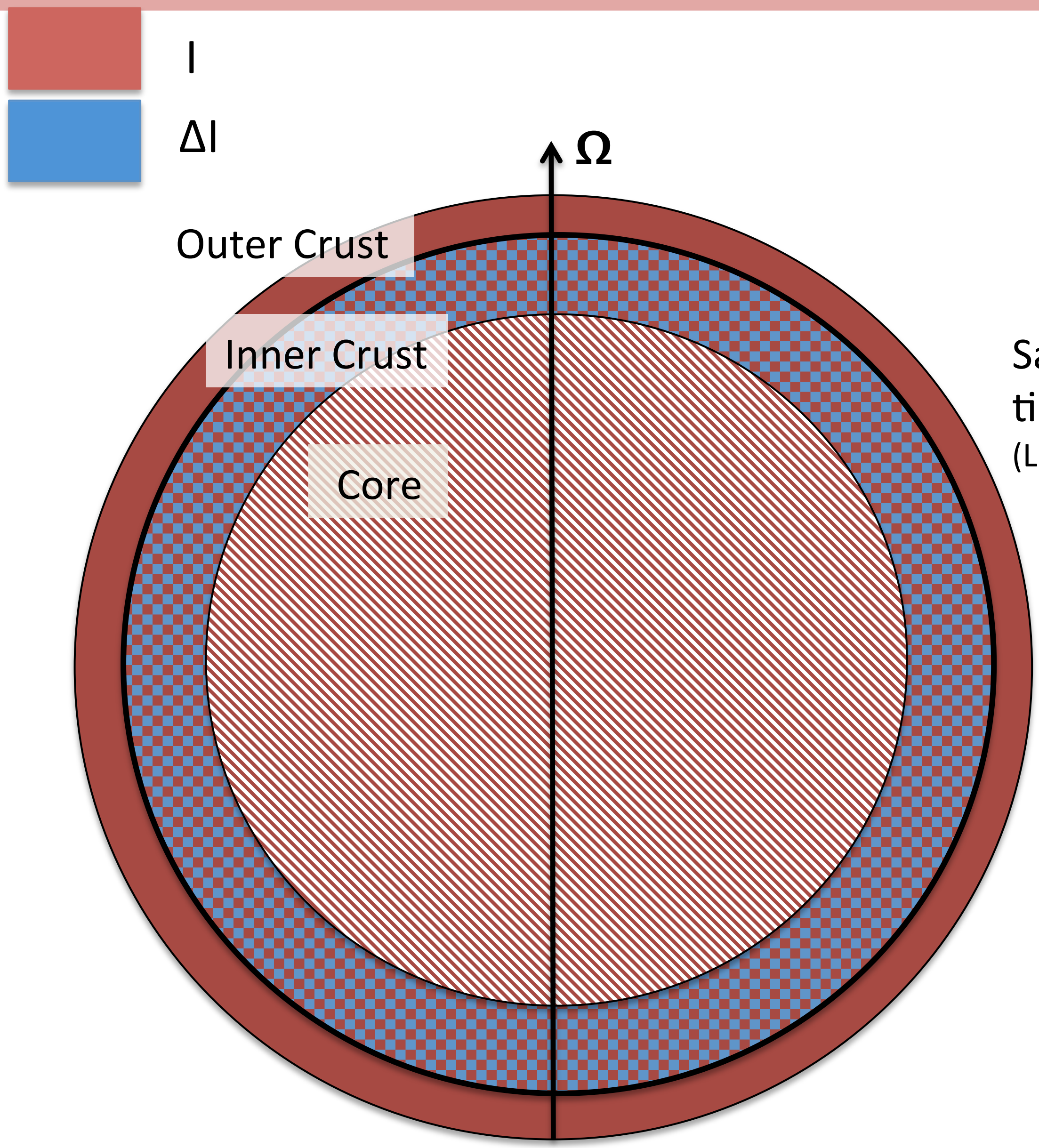

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OK for most EOSs

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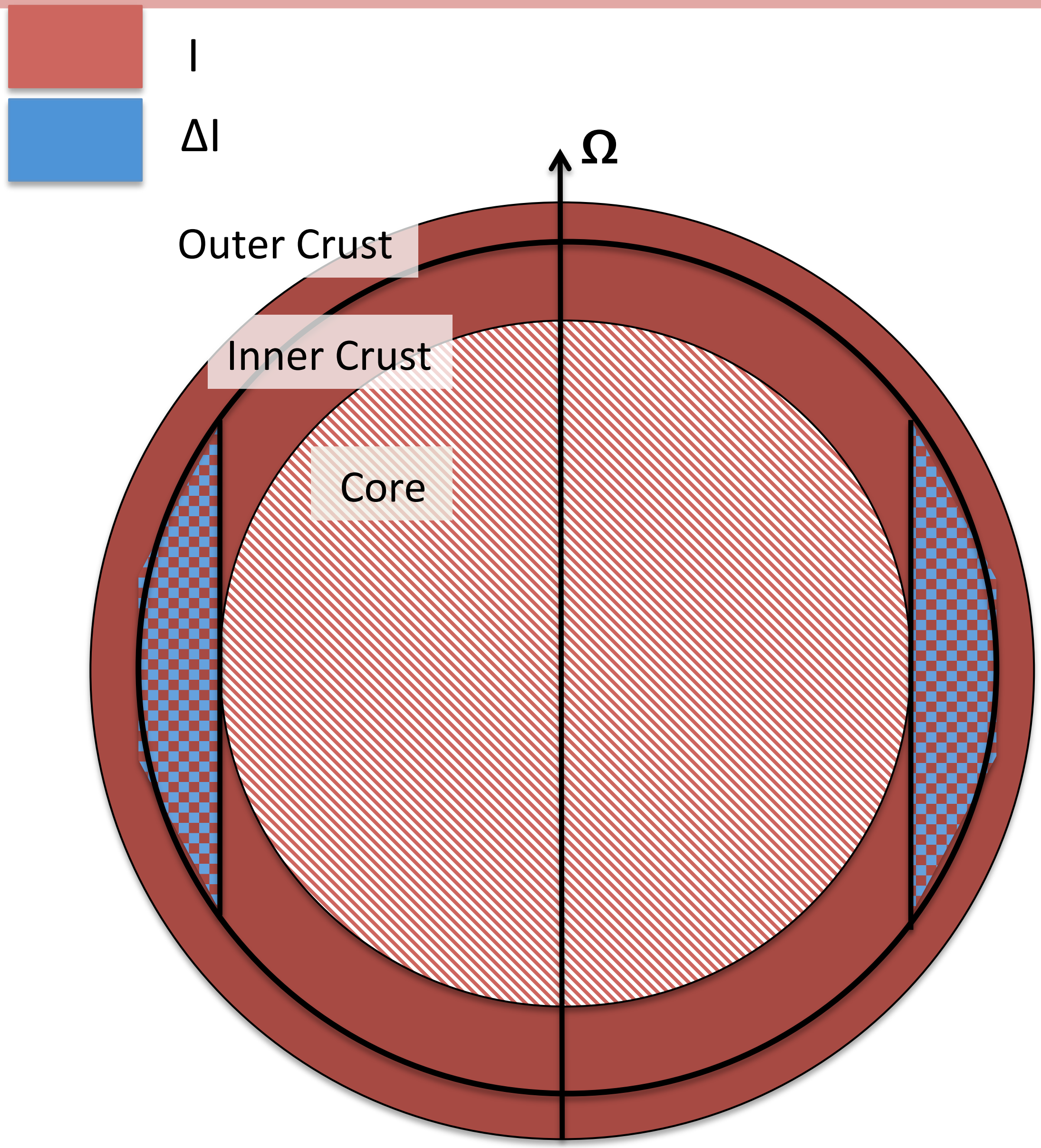

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Pinning only happens when vortices completely immersed in crust (the strong pinning region)

(Haskell et al 2012; Seveso et al 2012)

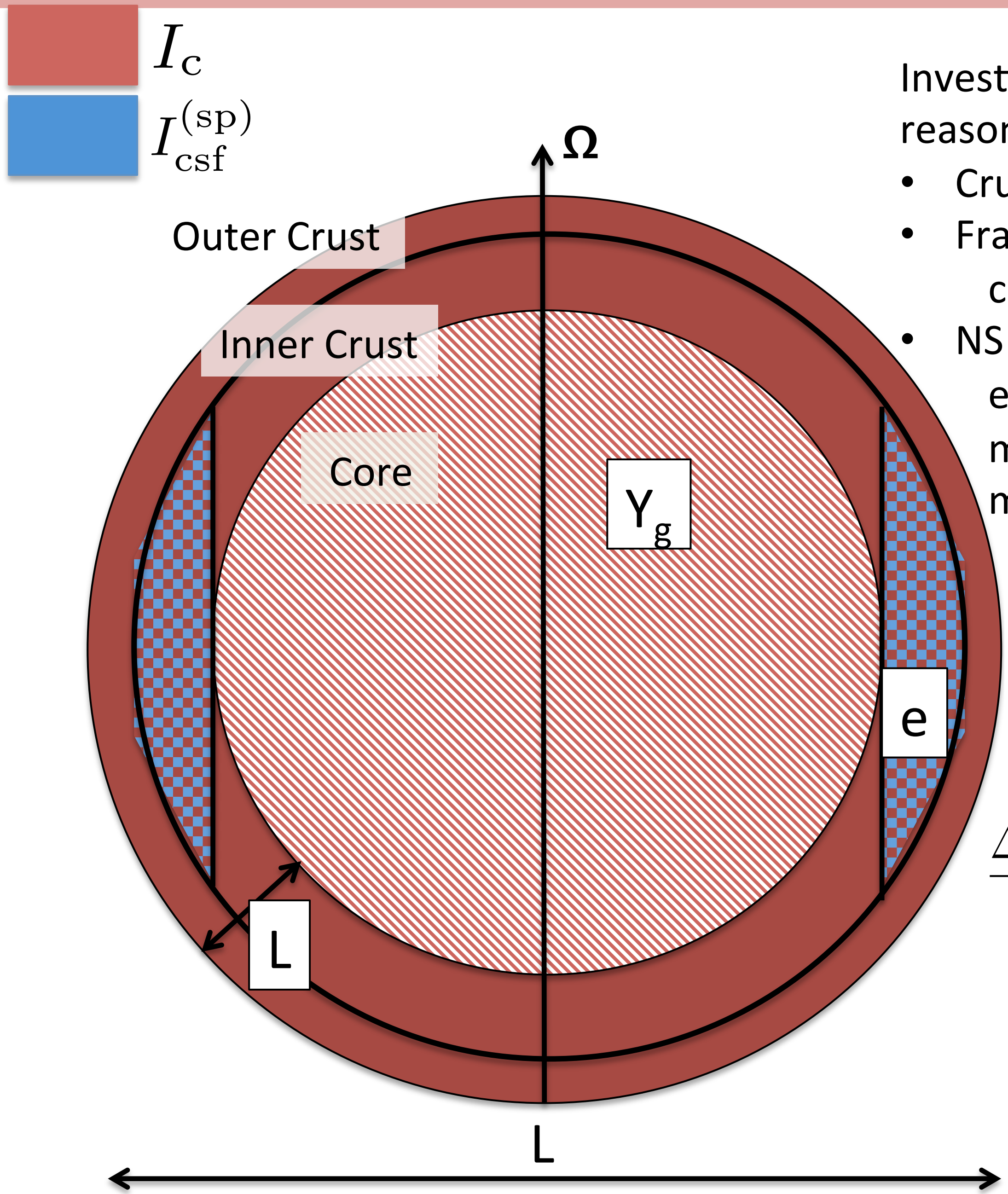
ΔI reduced by factor of 5**?**

I reduced by factor of 2-100

ΔI reduced by factor of approx. 10

Satisfied by “reasonable” EOSs?

Confronting model with observation



Investigate efficacy of model given reasonable nuclear physics uncertainties

- Crustal entrainment strength e: 0-1
- Fraction of core sf neutrons coupled to crust on glitch rise timescale Y_g
- NS EOSs parameterized by symmetry energy slope L=25-115 MeV while maintaining good fit to low-density microscopic PNM calculations

$$G \equiv \frac{I_{\rm csf}^{\rm (sp)}}{I_{\rm c}} \geqslant \frac{\bar{\Omega}}{|\dot{\Omega}|}\mathcal{A} = 0.016$$

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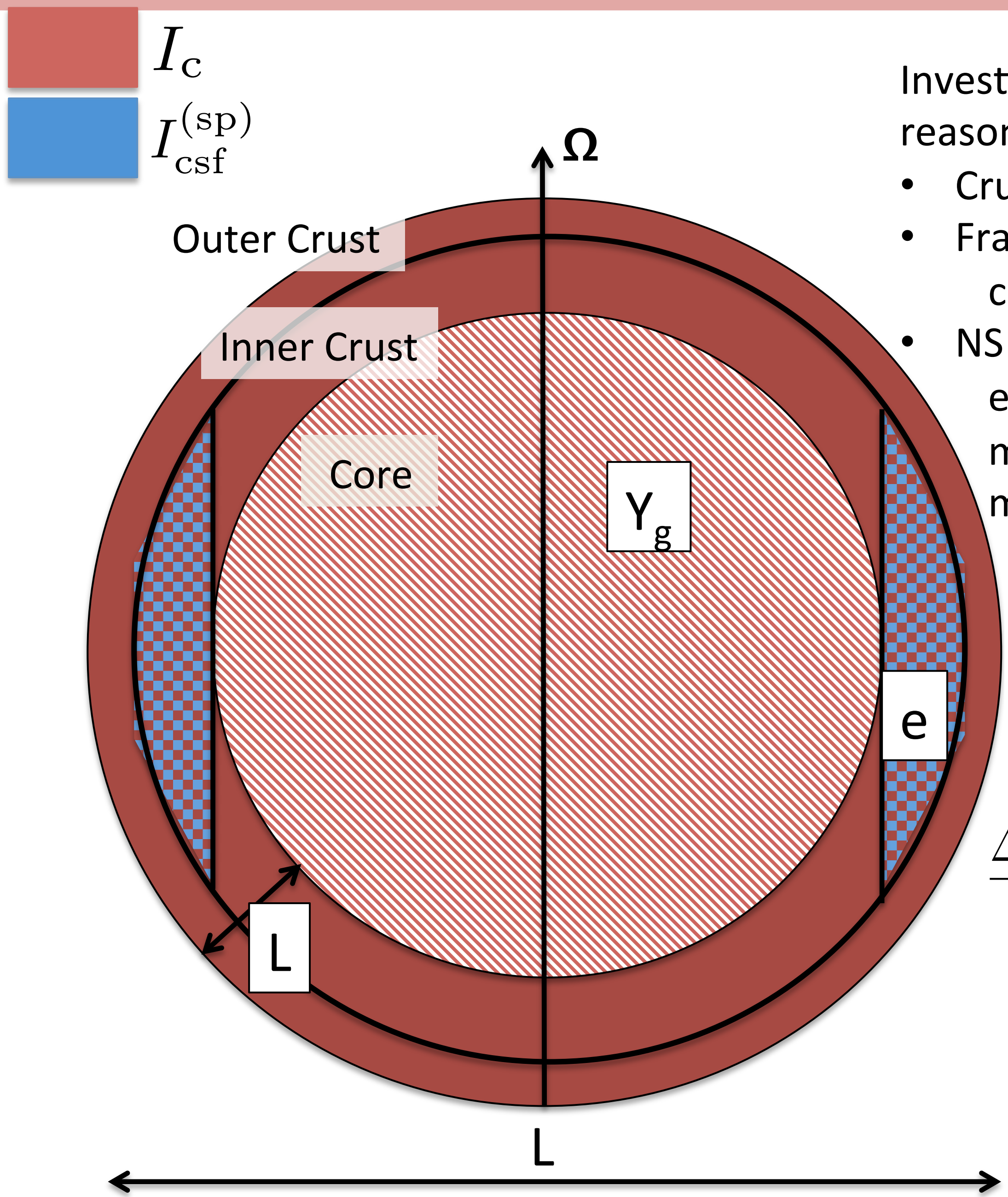

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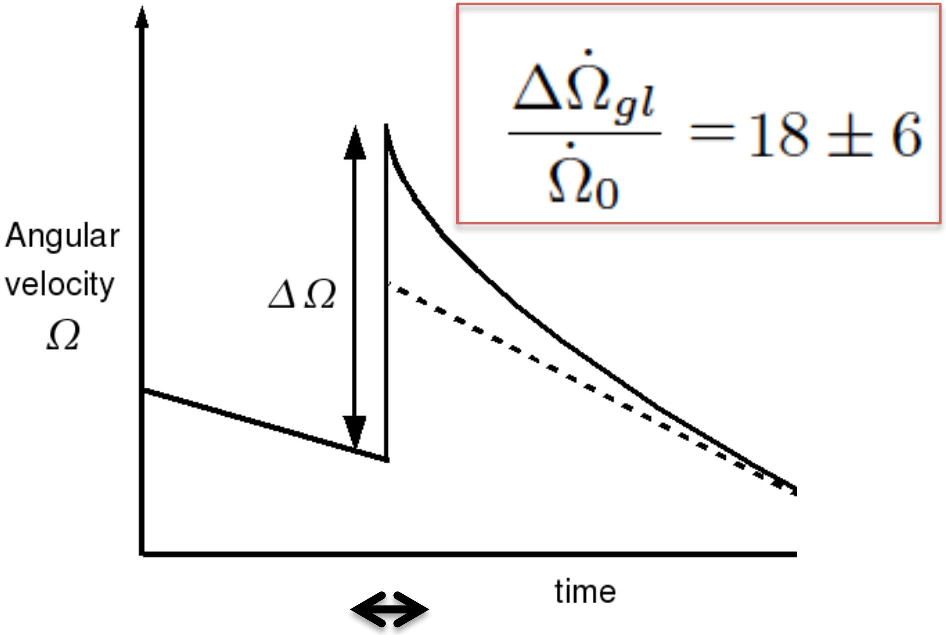

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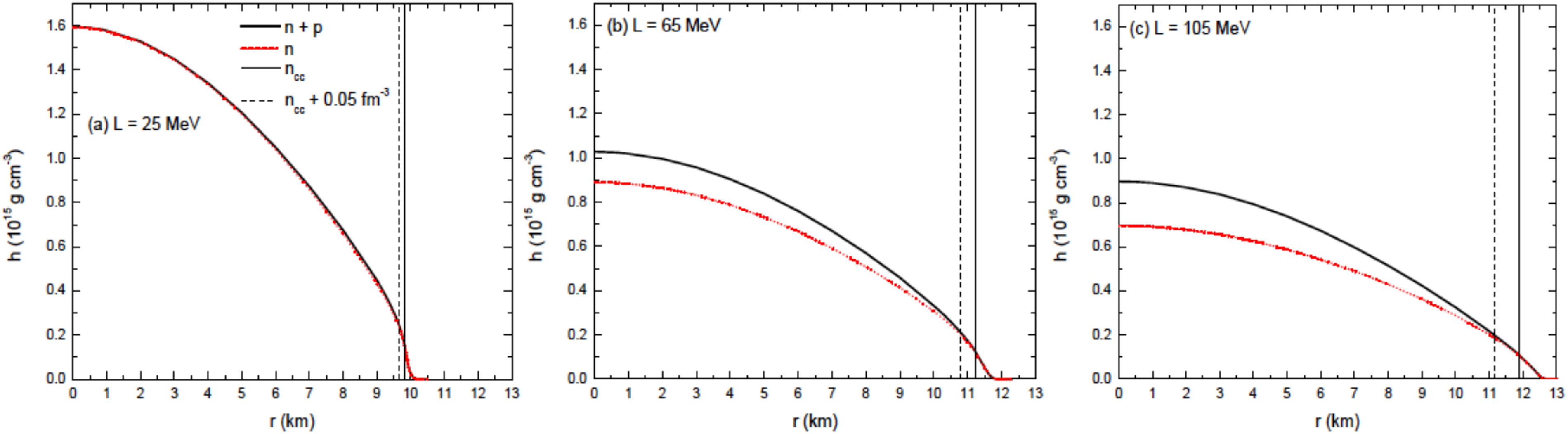
Neutron star structure: $1.4M_{sun}$

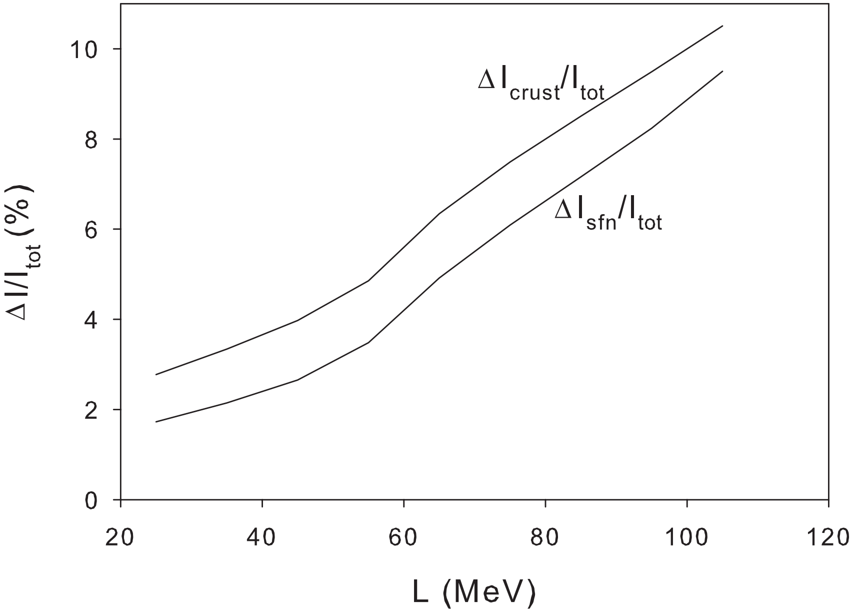


- Effect of L:
  - Stellar radius: L increases, R increases
    - R increases, ΔR increases
  - Crust-core transition pressure: L increases, P_t decreases, ΔR decreases*
  - Core proton fraction: L increases, x_p increases
  - Effect on e, Y_g?

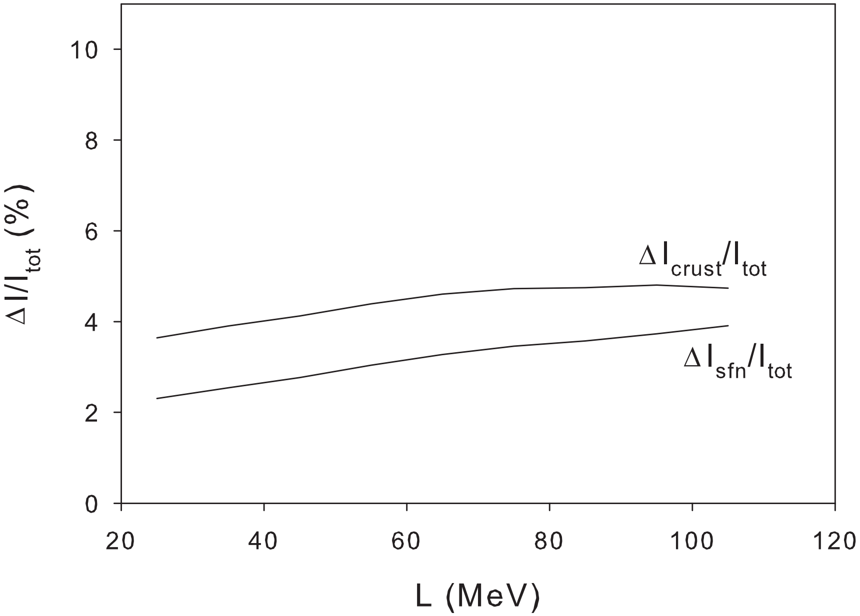
*model dependent

Neutron star structure: $1.4M_{sun}$

Fixed crust-core transition



Consistent crust-core transition



c.f. Fattoyev, Piekarewicz 2010

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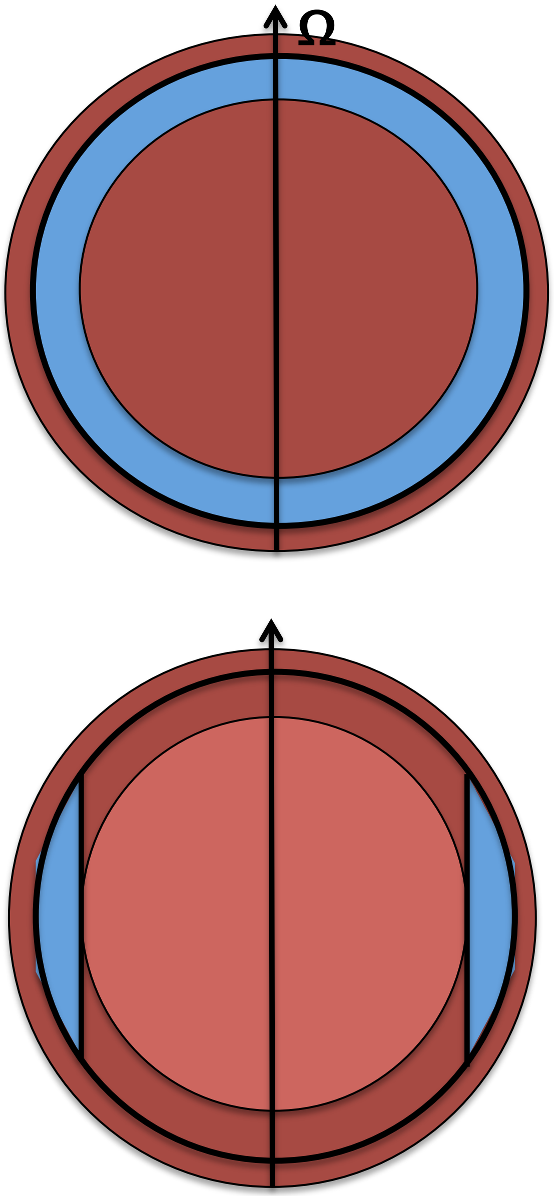

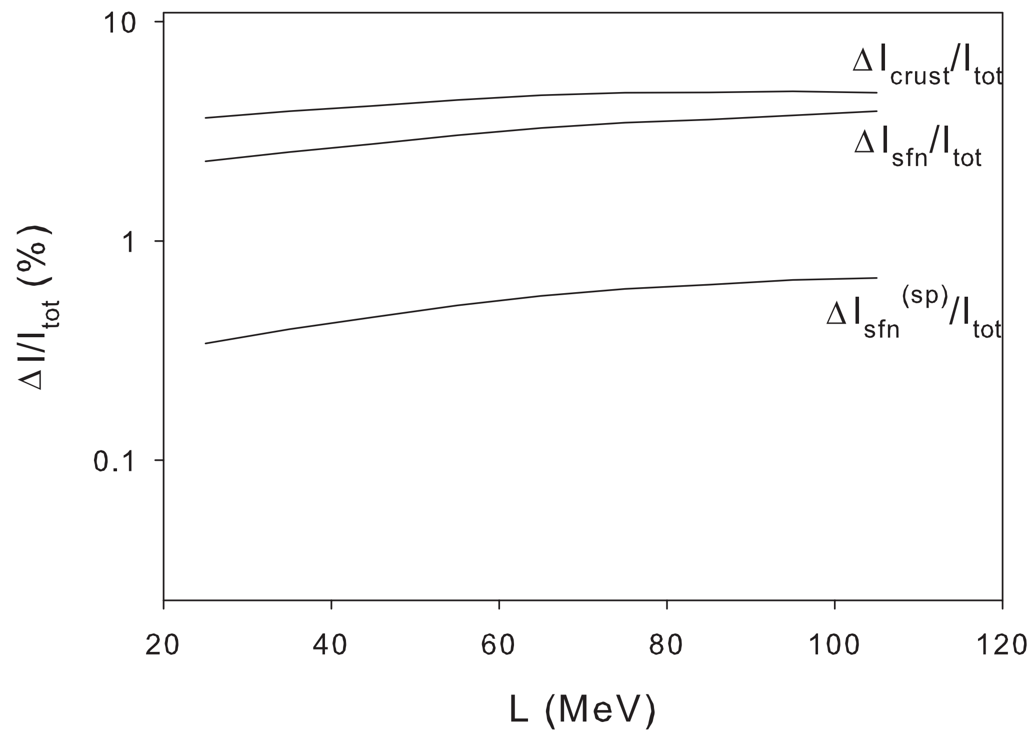

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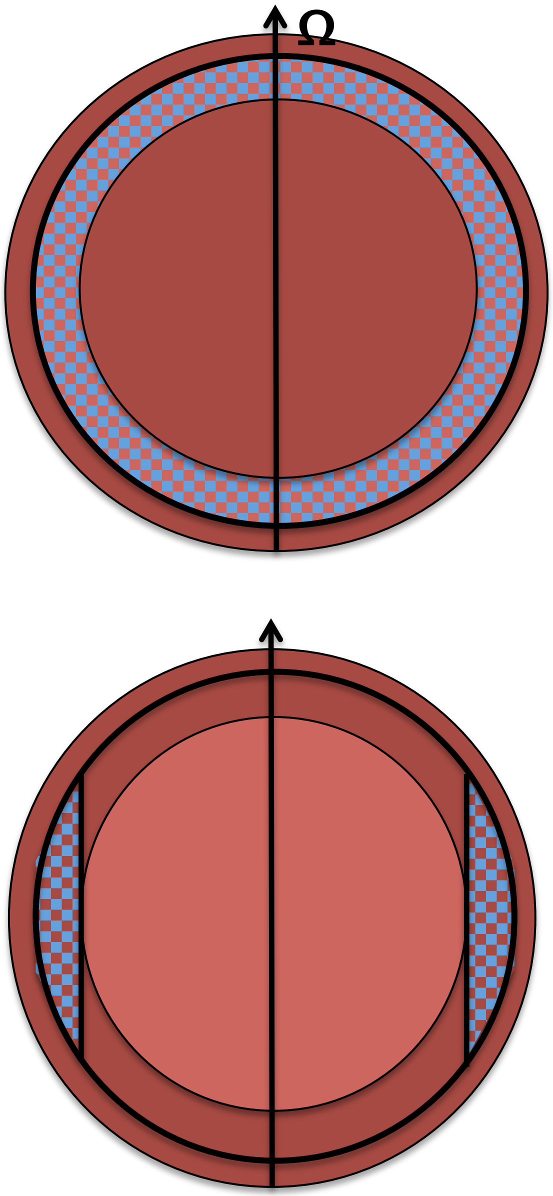
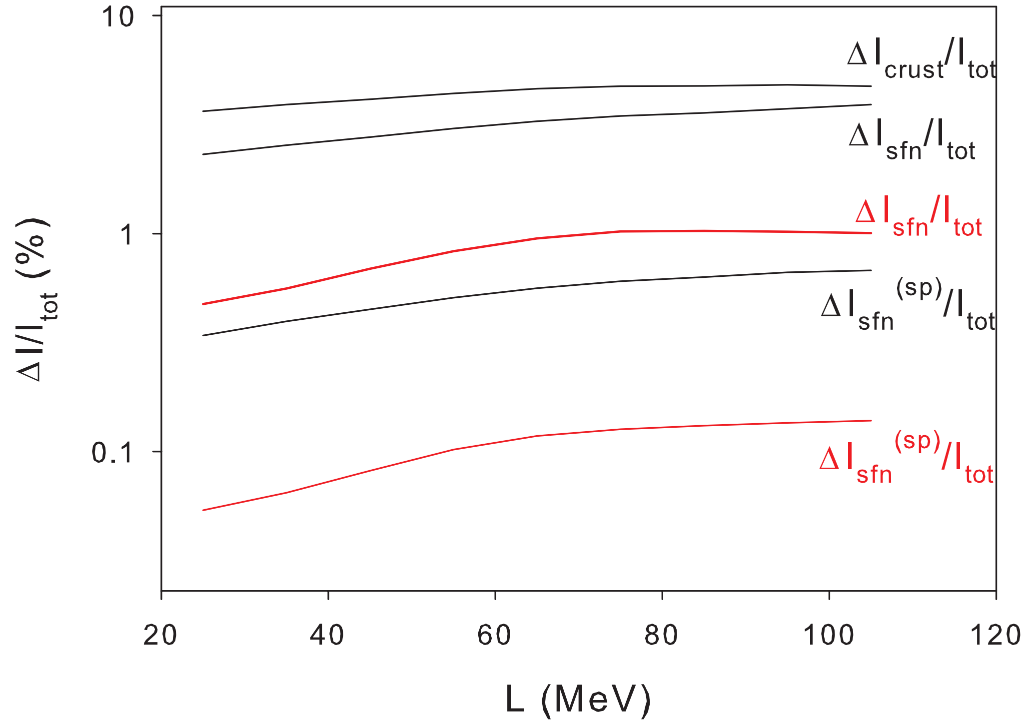
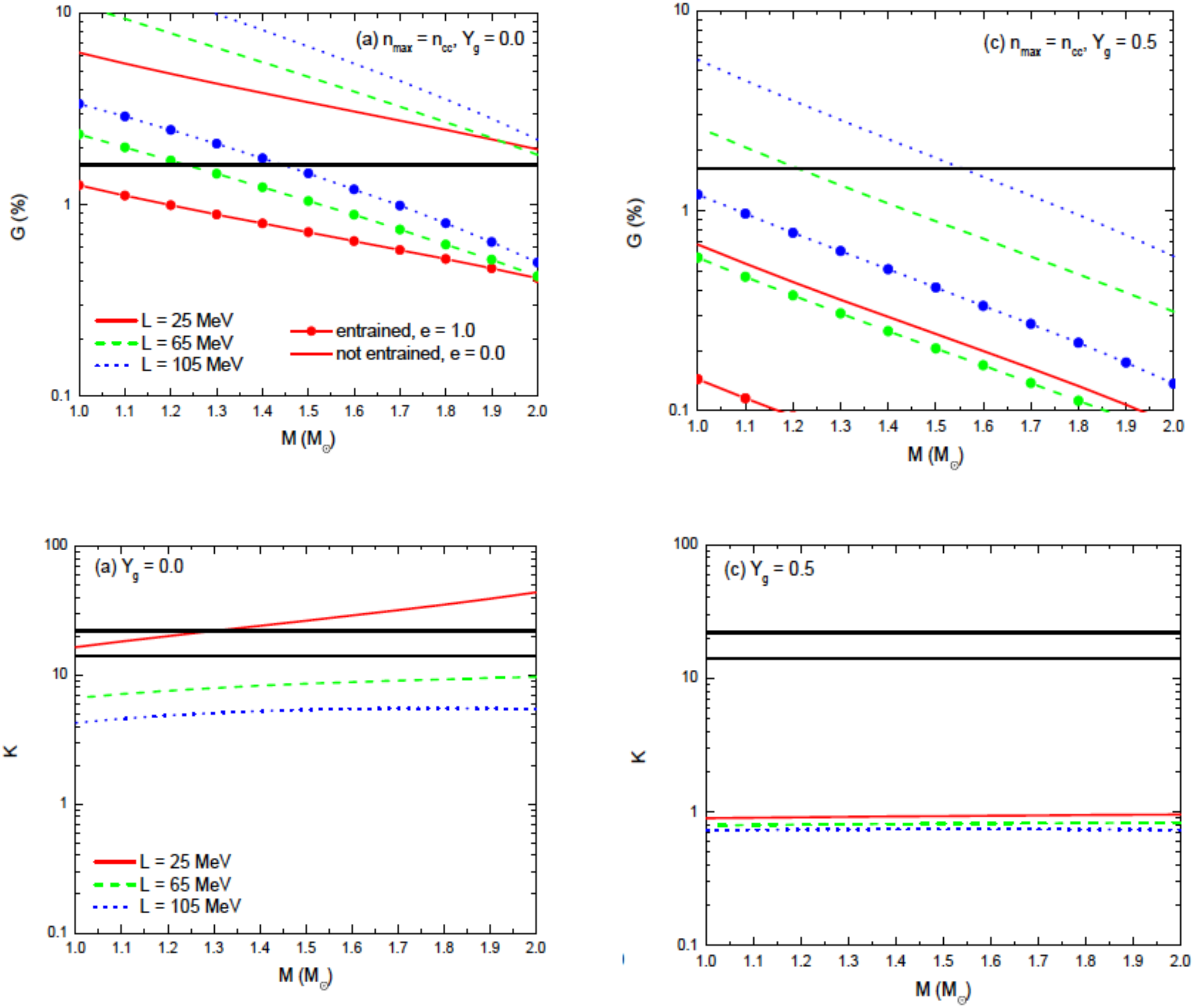


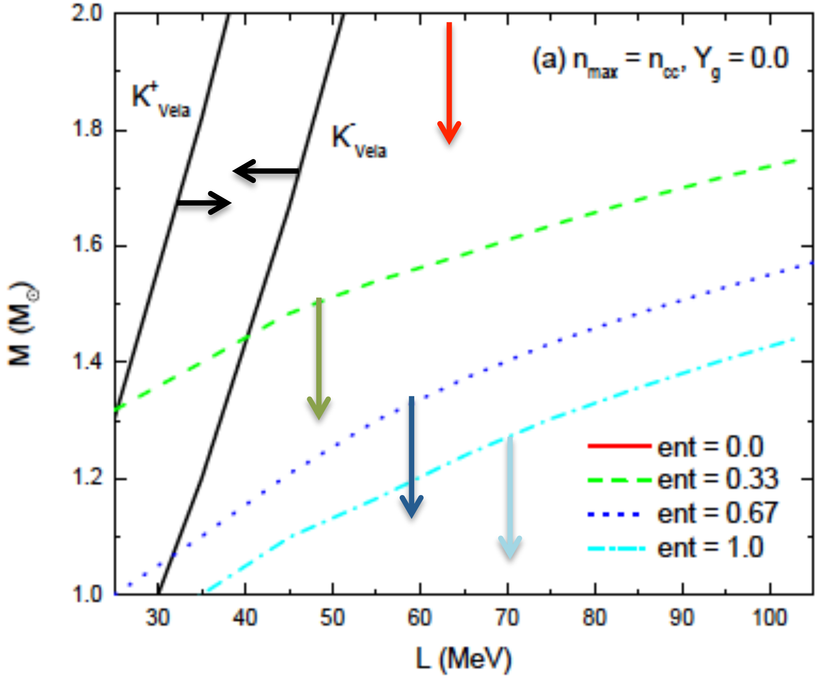


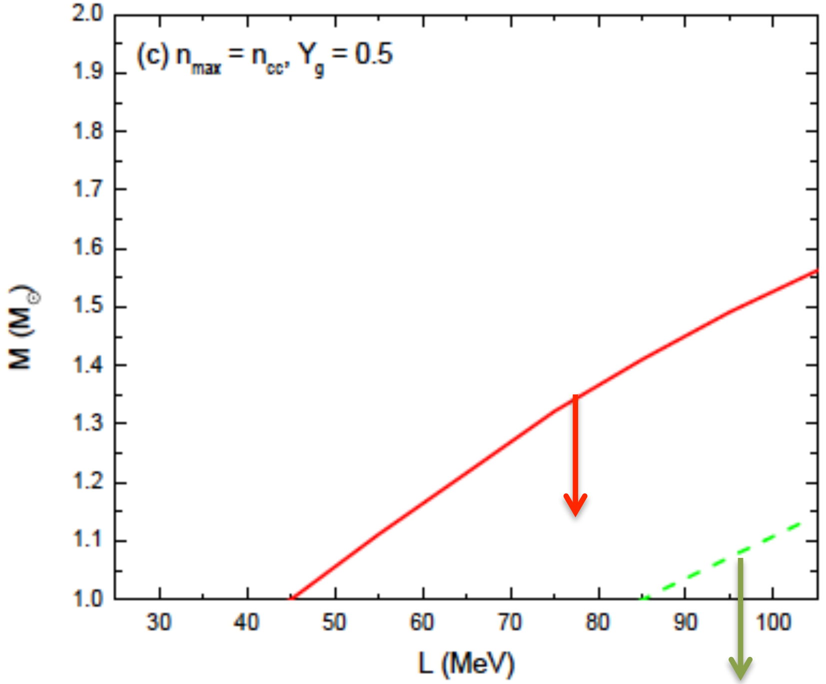
Results

Hooker, Newton, Li; arxiv:1308.0031



Results

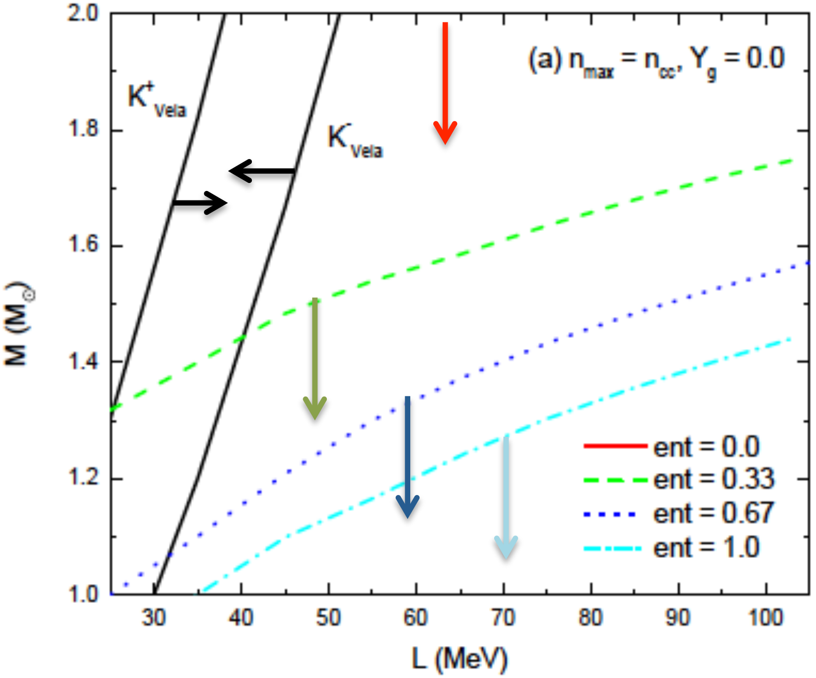


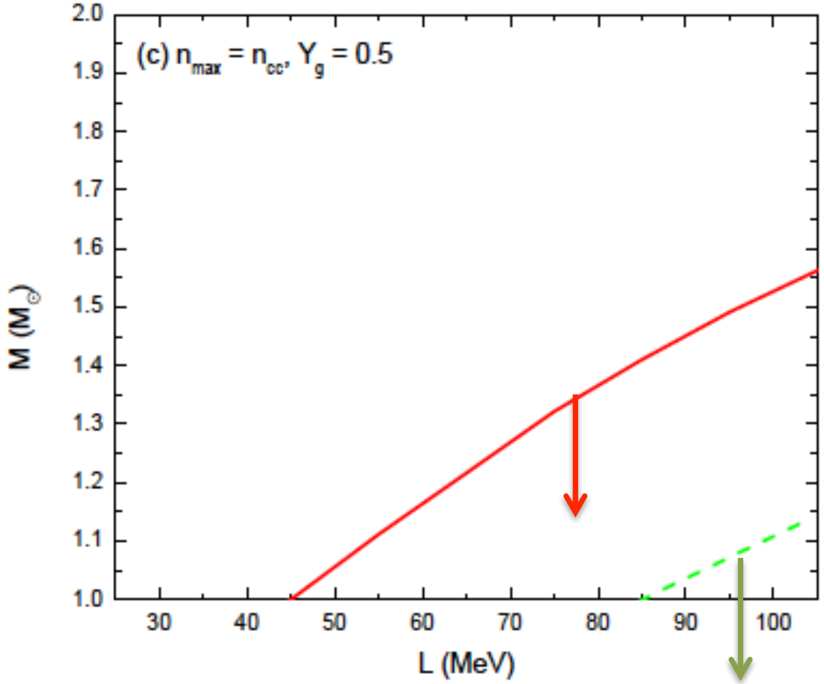


Hooker, Newton, Li; arxiv:1308.0031

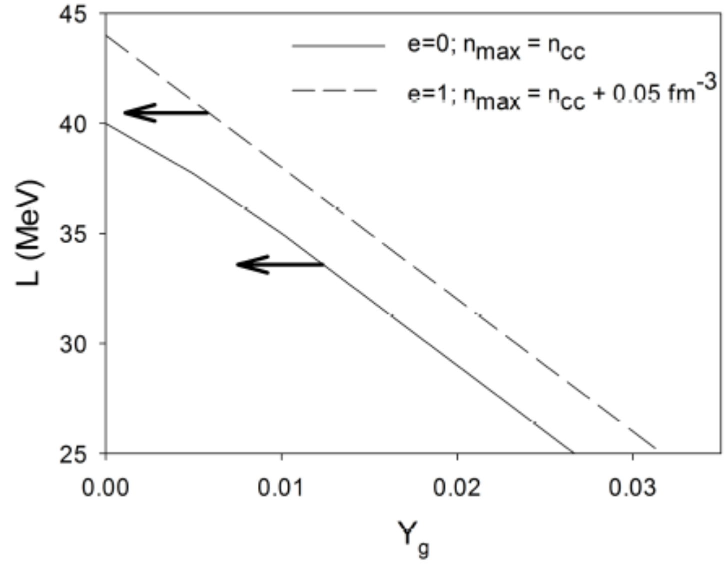
Results

Hooker, Newton, Li; arxiv:1308.0031



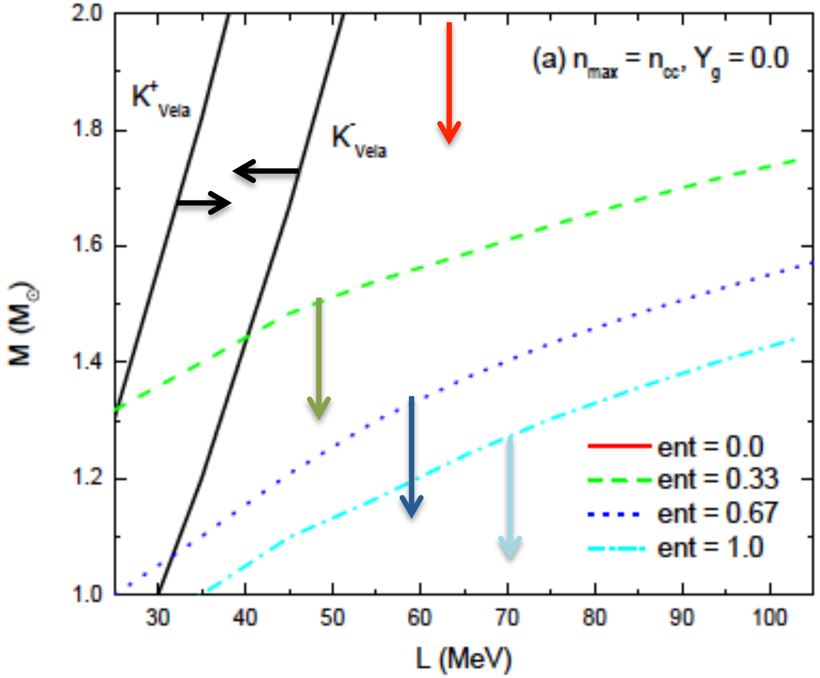


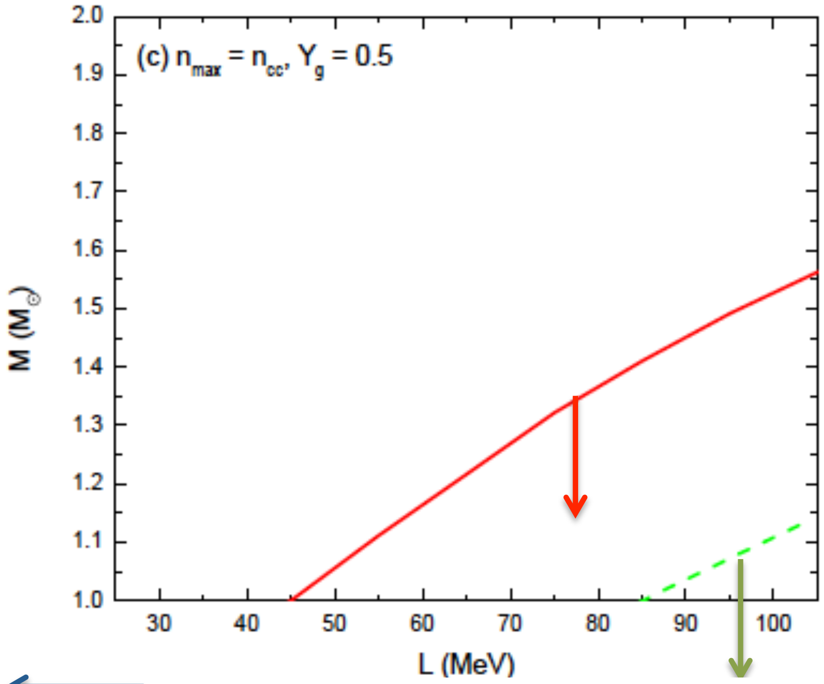
- Simultaneously satisfy G and K constraints only when entrainment is weak: e=0 – 0.33
- L < 40 MeV
- $Y_g < 0.03$

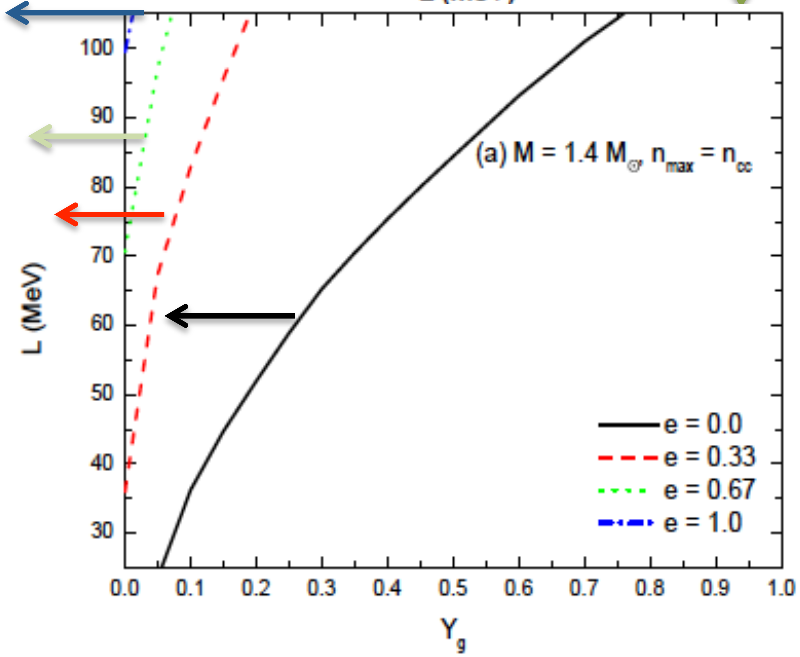


Results

Hooker, Newton, Li; arxiv:1308.0031



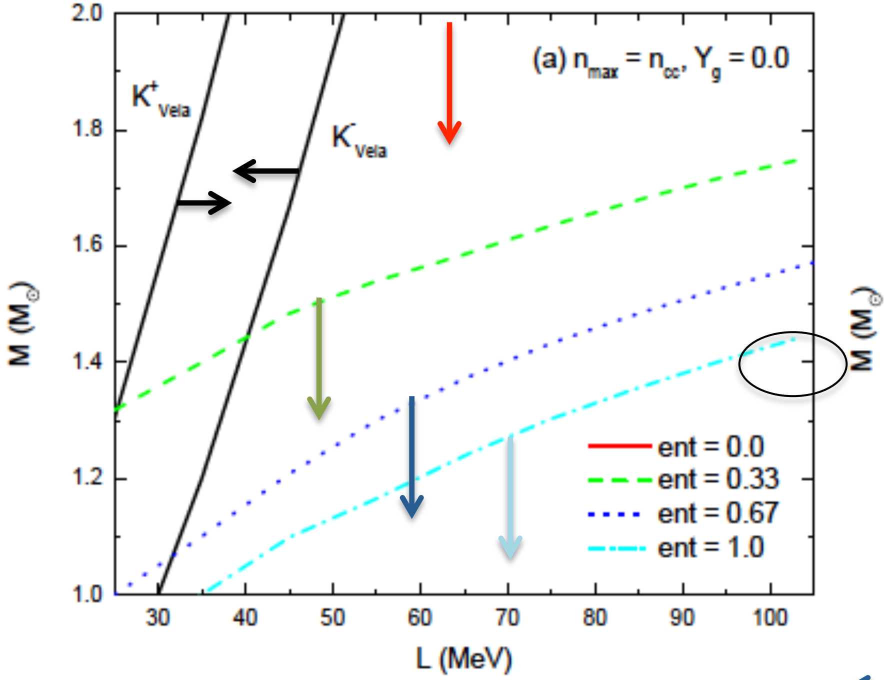


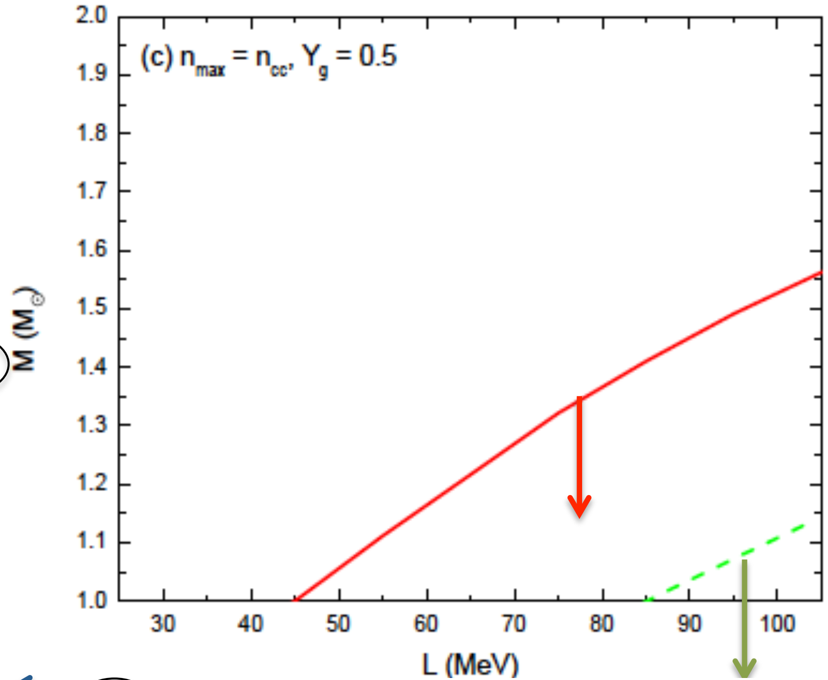


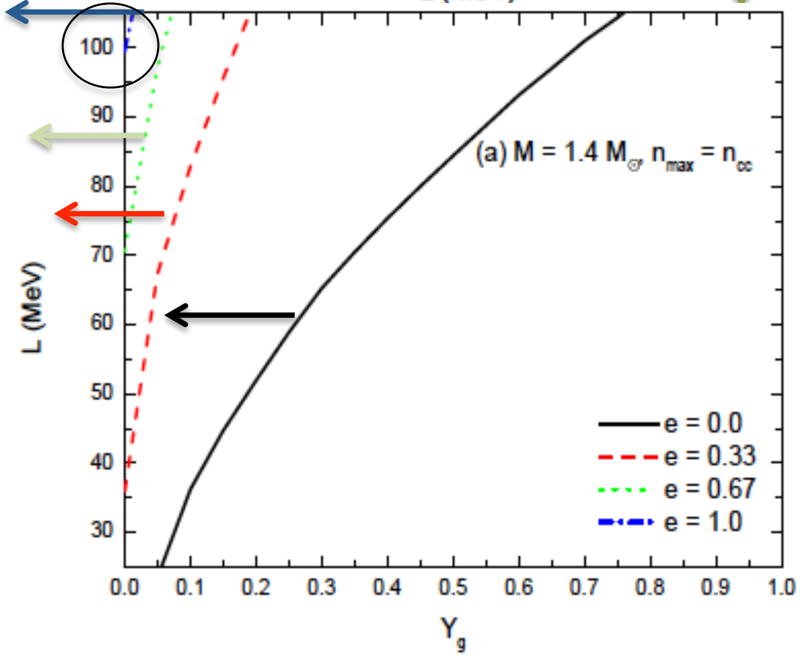
- Constraint on G alone satisfied for very stiff saturation EOSs when e=1
- L>100 MeV
- $Y_g \approx 0$

Results

Hooker, Newton, Li; arxiv:1308.0031







- Constraint on G alone satisfied for very stiff saturation EOSs when e=1
- L>100 MeV
- $Y_g \approx 0$

Summary/Future Work

Crust-driven glitches:

- Weak entrainment:
  - satisfy G, K simultaneously for L<40 MeV, Y < 0.03
- Full entrainment:
  - G, K can't simultaneously be fit
  - G alone: L > 100 MeV, $Y_g \approx 0$

Interpretation of observations: caveats

- Only one observational measurement of K
- Interpretation of shortest timescale rather uncertain (mutual friction driven,….)

Theoretical uncertainties

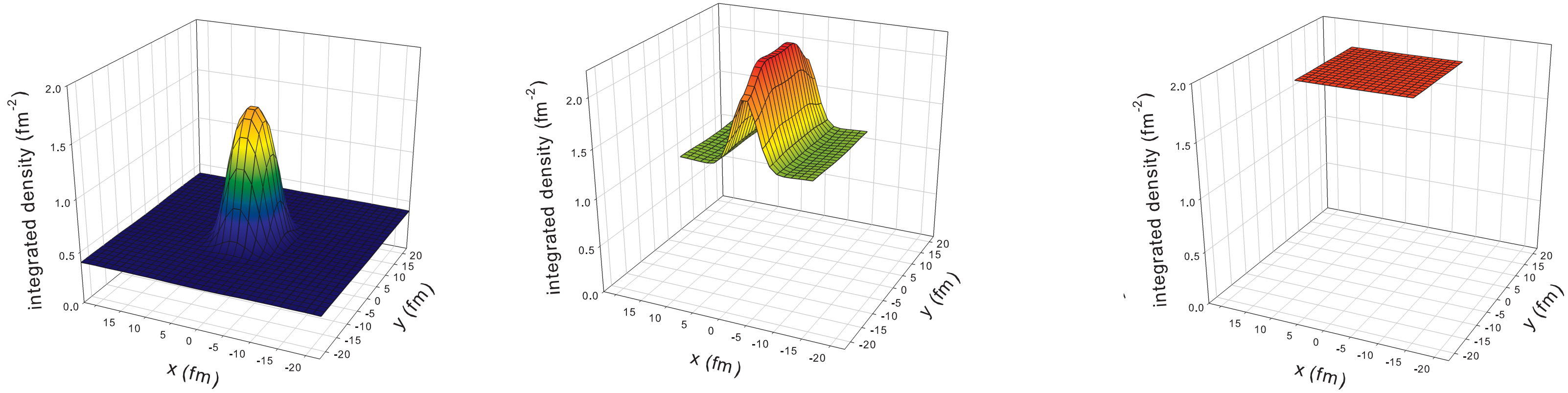
- Superfluid gaps! (density dependence)
- Crust entrainment (e): dependence on (i) nuclear force (ii) presence of pasta
- Core mutual friction (Y_g); off-shell protons?
- Pinning force strength in core?

Pinning in core?

- Pinning penetrates core up to 0.05 fm^{-3} above n_{cc}:
  - G satisfied for any L, Y_g
  - G and K together satisfied for L < 45 MeV, $Y_g < 0.05$

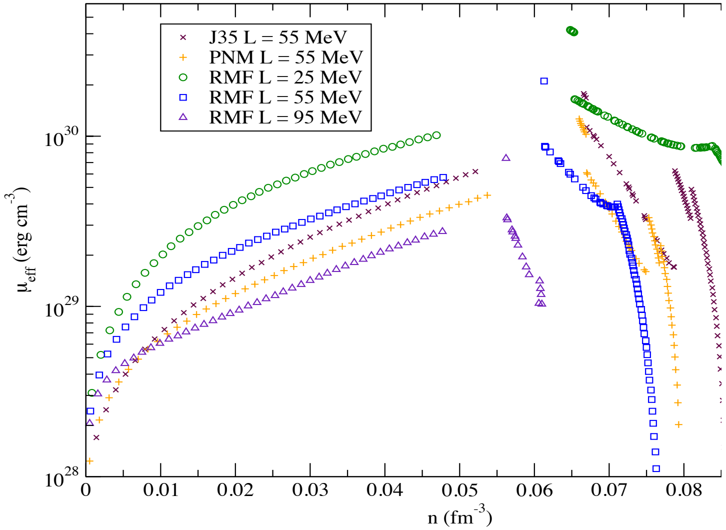
Conclusions/Future Directions

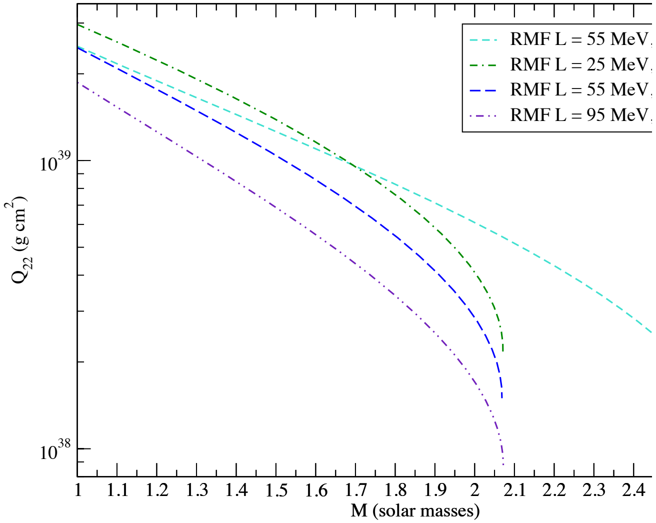
- More accurate treatment of the crust-core transition using 3D Hartree-Fock method



$n_b = 0.01\ \mathrm{fm}^{-3}$ $0.06\ \mathrm{fm}^{-3}$ $0.09\ \mathrm{fm}^{-3}$

- In progress: accurate evaluation of shear modulus of inner crust including pasta layers (plots and calculations by Nathan Johnson-McDaniel)





THE STARQUAKE MODEL... AND WHY IT DOESN'T WORK

- Vela pulsar: $\Delta\Omega/\Omega \approx 10^{-6}$ > ~ 1cm shift in crust surface

BUT: Initial ellipticity < 10^{-6}; a single Vela glitch would relax the crust to a spherical shape!

Starquakes cannot be the cause of Vela glitches

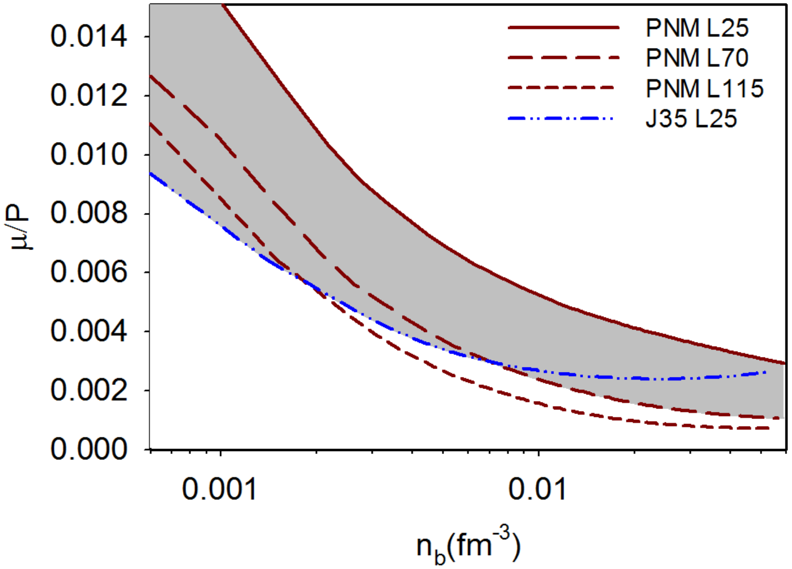
- Crab pulsar: $\Delta\Omega/\Omega \approx 10^{-9}$ > ~ 0.01mm shift in crust surface

Activity parameter?

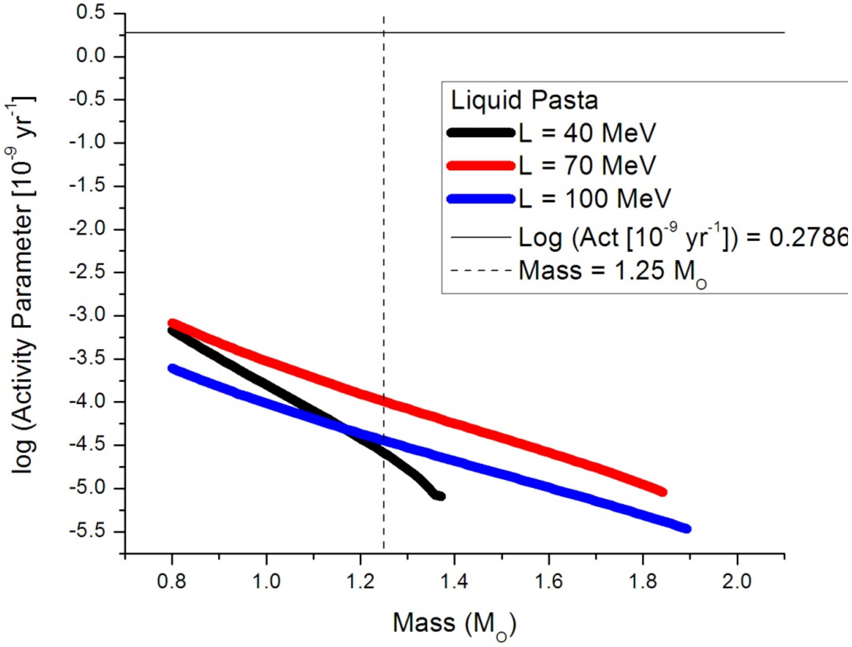
$$\frac{\Delta\Omega}{\Omega}\frac{1}{t_q} = \frac{\Omega^2 B I_0}{2A^2}\frac{\dot{\Omega}}{\Omega}$$

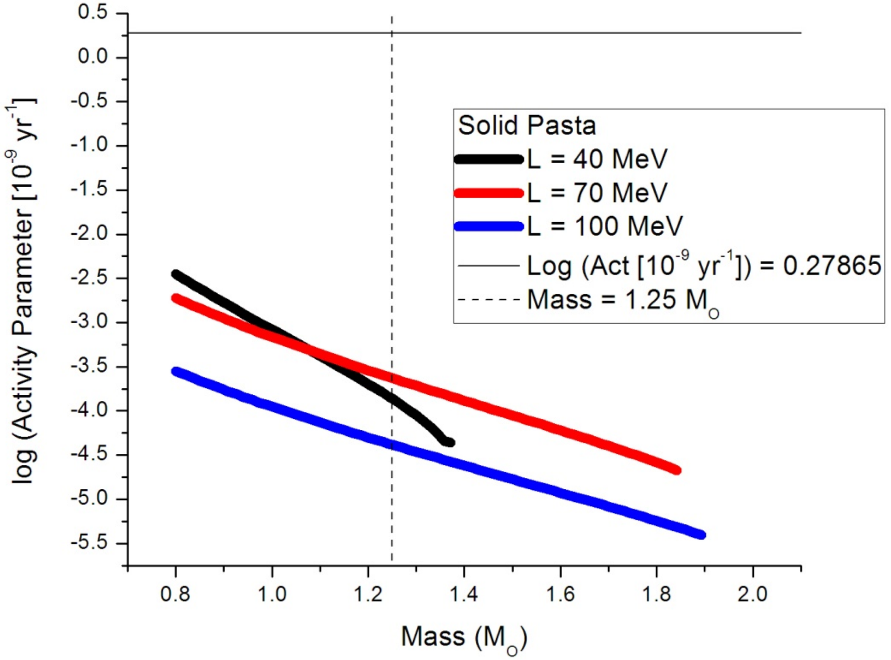
$$B = \frac{V_c \mu}{2}$$

$$A = \frac{-W_0}{5}$$



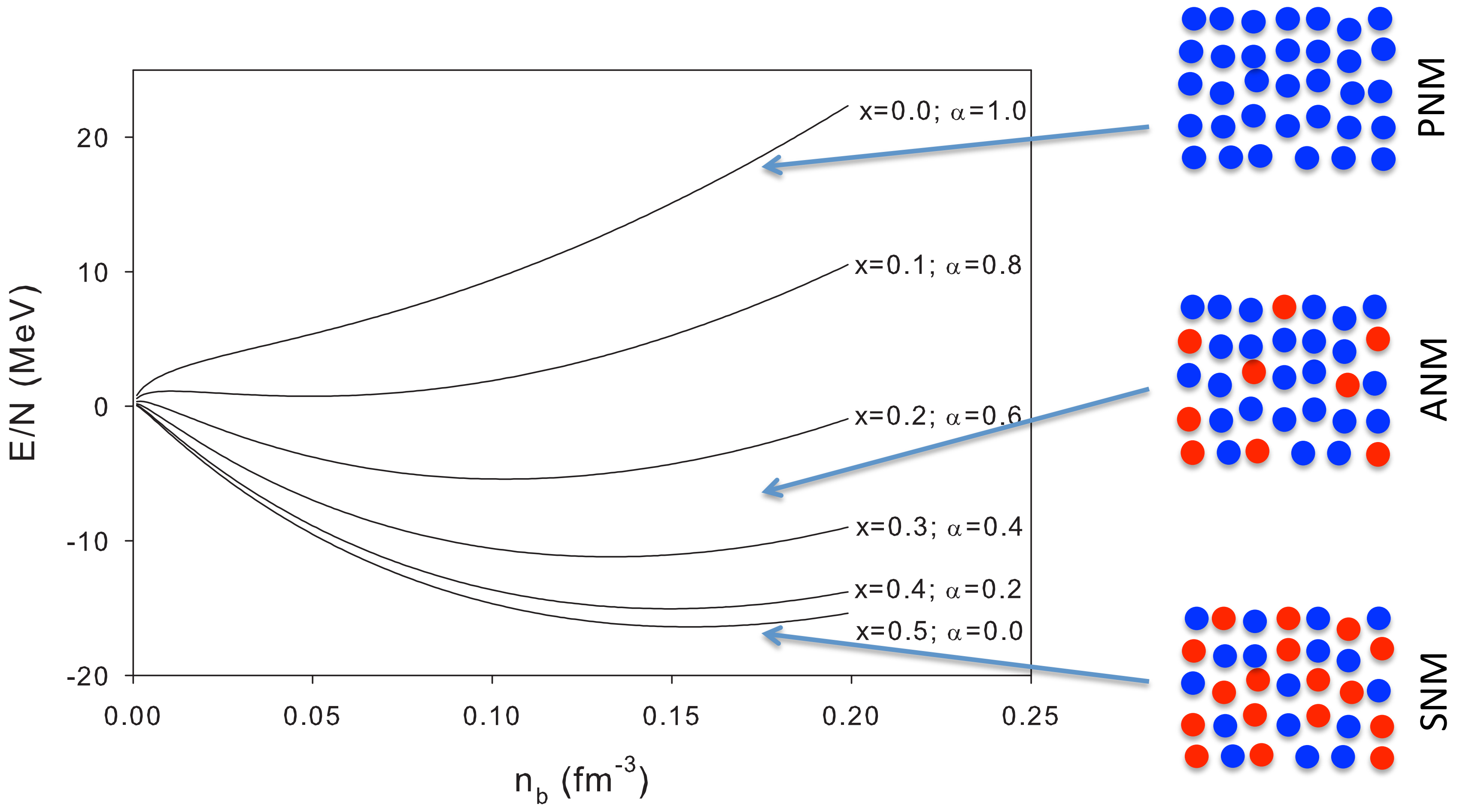
THE STARQUAKE MODEL... AND WHY IT DOESN'T WORK





- Depending on the pressure of neutrons and the mechanical properties of pasta, and mass of star, the starquake activity parameter varies by 3 orders magnitude…
- BUT is always at least three orders of magnitude less than the Crab
    - The crust cannot store enough mechanical energy to power glitches

Nuclear Matter EoS/Symmetry energy

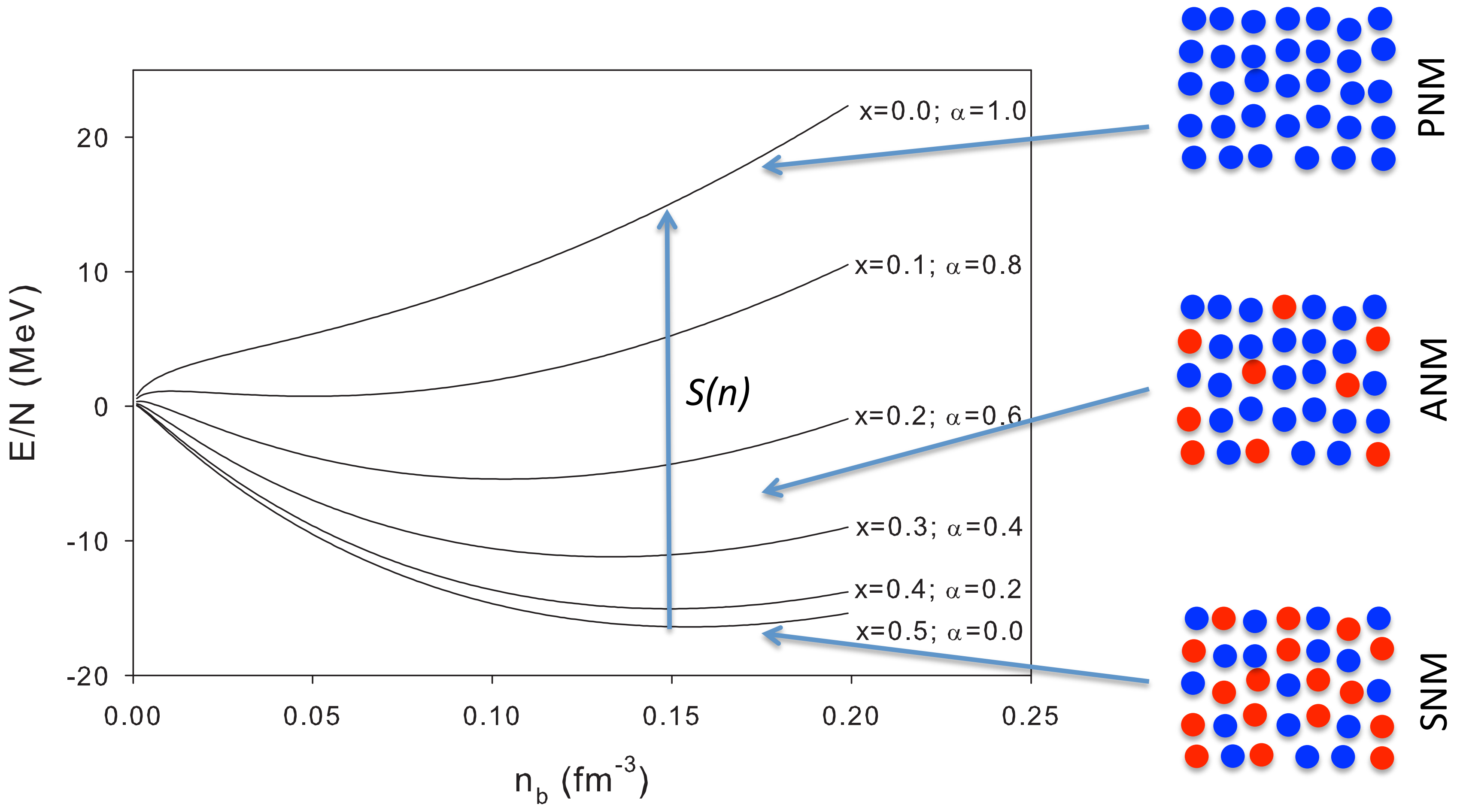


$$E(n,\delta) = E_0(n) + S(n)\delta^2 + \ldots$$

$$\delta = 1 - 2x$$

n – baryon number density
x – proton fraction

Nuclear Matter EoS/Symmetry energy



$$E(n, \delta) = E_0(n) + S(n)\delta^2 + \dots$$

$$\delta = 1 - 2x$$

n – baryon number density
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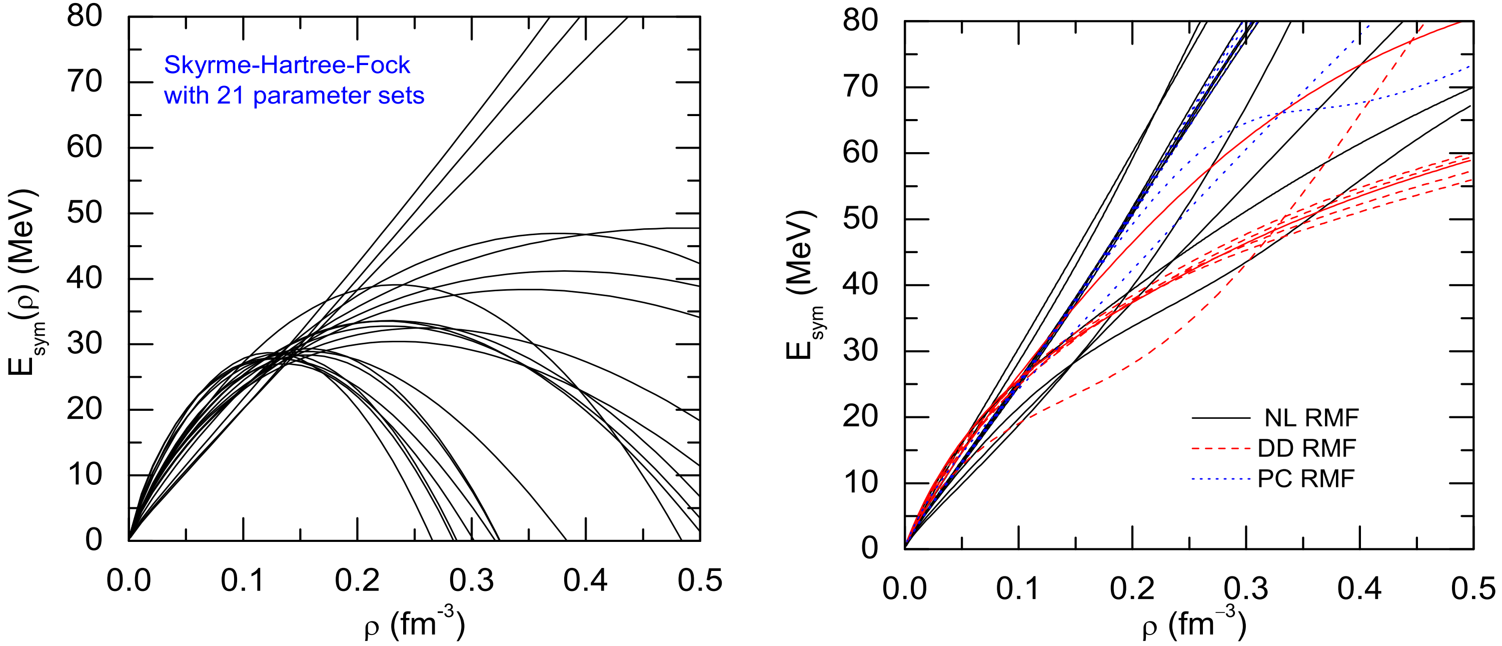
Symmetry energy



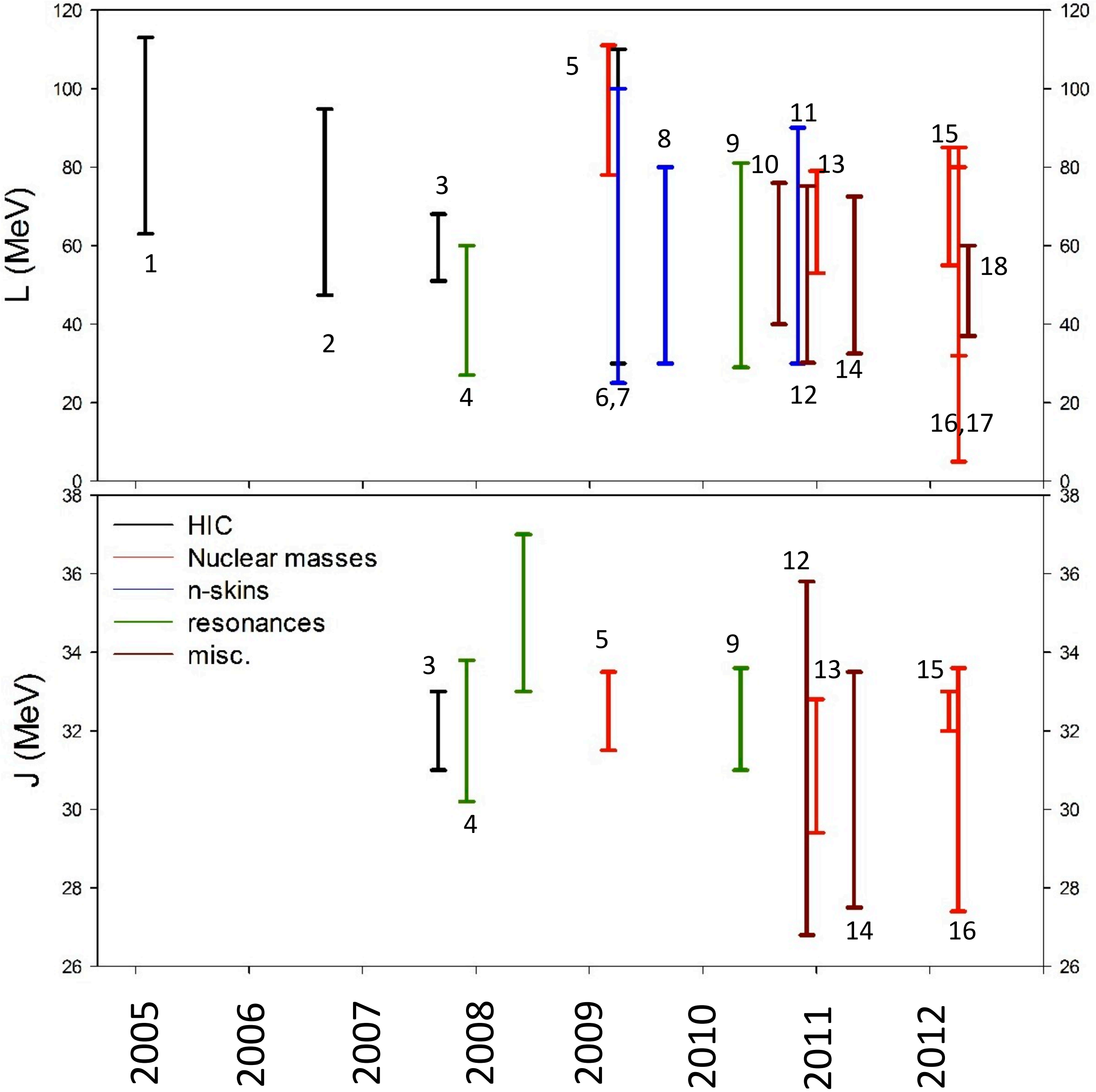
Li, Chen, Ko, Phys. Rep. 464 (2008)

$$E(n,\delta) = E_0(n) + S(n)\delta^2 + \ldots \qquad \delta = 1 - 2x$$

$$S(n) = J + L\chi + \frac{K_{\rm sym}}{2}\chi^2 + \ldots \qquad \chi = \frac{n-n_0}{3n_0}$$

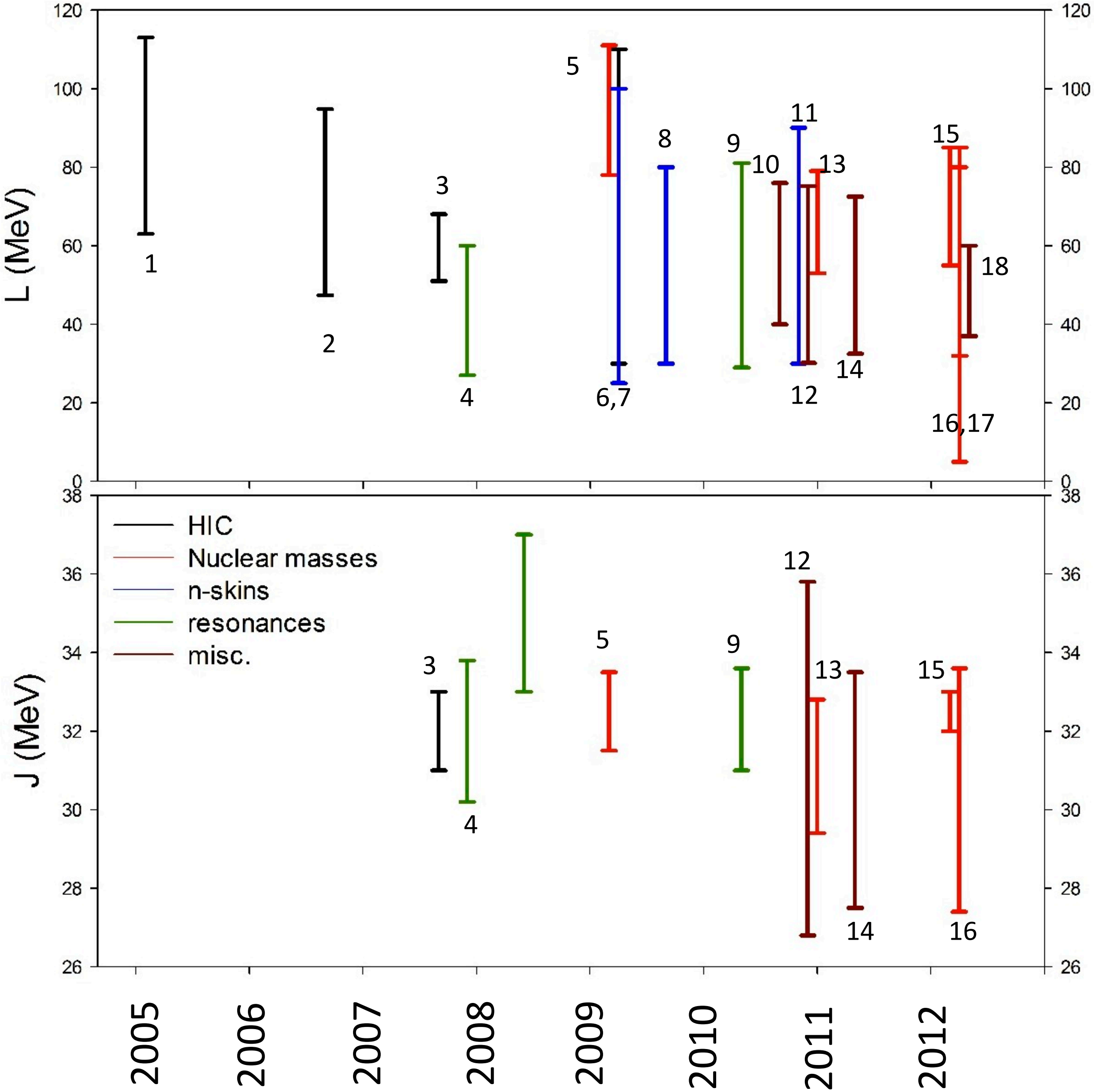
$$P_{\rm NS}(n_0) \approx \frac{n_0}{3}L + 0.048 n_0 \left(\frac{J}{30}\right)^3 \left(J - \frac{4}{3}L\right) \qquad x_{\rm NS}(n_0) \approx \frac{1}{3\pi^2 n_0}\left(\frac{4J}{\hbar c}\right)^3$$

Experimental/Observational Constraints



1. Chen,Ko,Li; PRL94
2. Famiano et al; PRL97
3. Shetty et al; PRC76
4. Klimkiewicz et al; PRC76
5. Danielewicz, Lee; NPhys A818
6. Tsang et al; PRL102
7. Centelles et al; PRL102
8. Warda et al; PRC80
9. Carbone et al; PRC81
10. Chen, Ko, Li, Xu; PRC82
11. Zenihiro et al; PRC82
12. Xu, Li, Chen; PRC82
13. Liu et al; PRC82
14. Chen; PRC83
15. Möller et al; PRL108
16. Lattimer, Lim; arxiv:1203.4286
17. Dong et al; PRC85
18. Piekarewicz et al; PRC85

Experimental/Observational Constraints



What neutron star observables bear the imprint of the symmetry energy?

1. Chen,Ko,Li; PRL94
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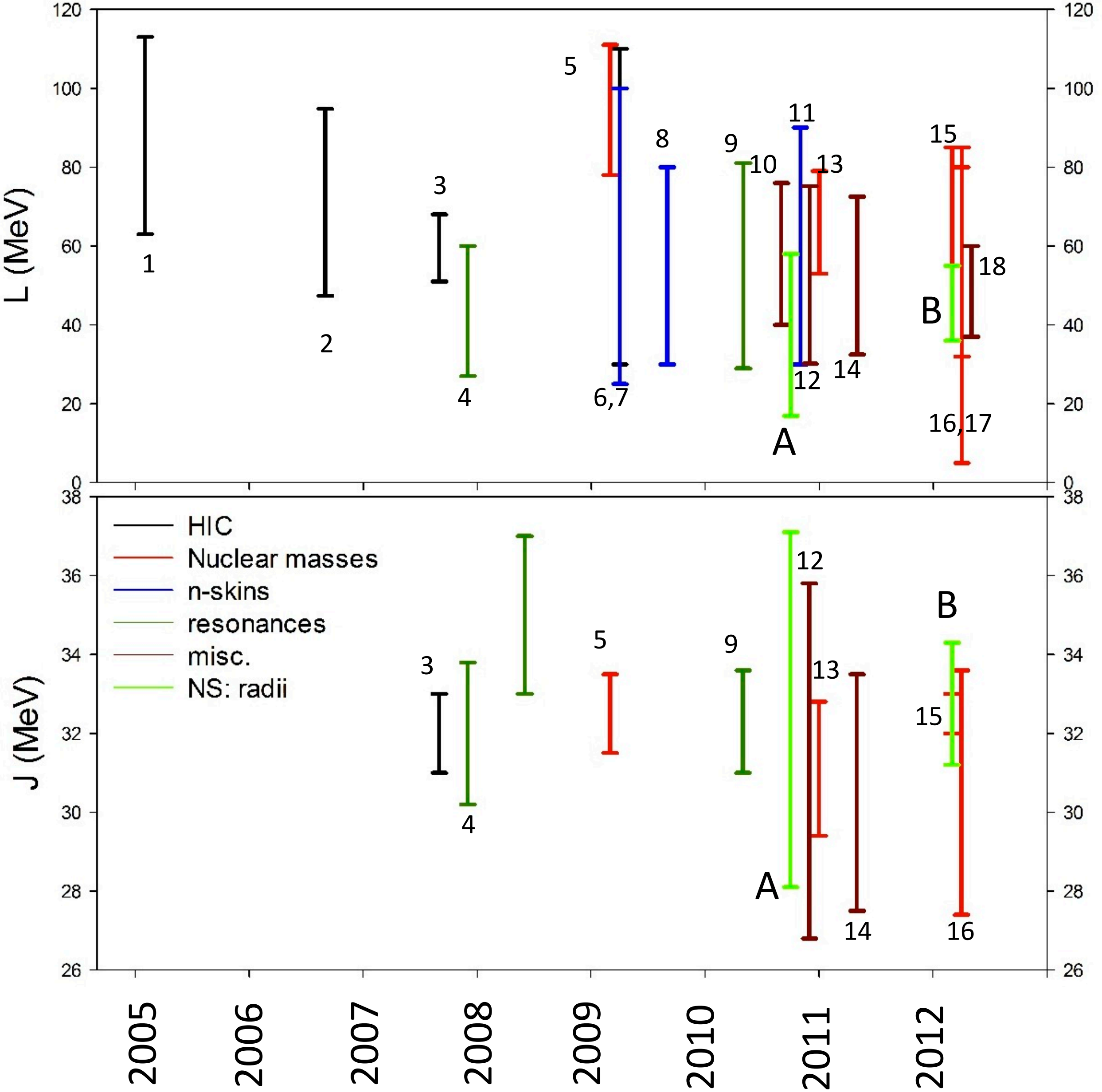

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16. Lattimer, Lim; arxiv
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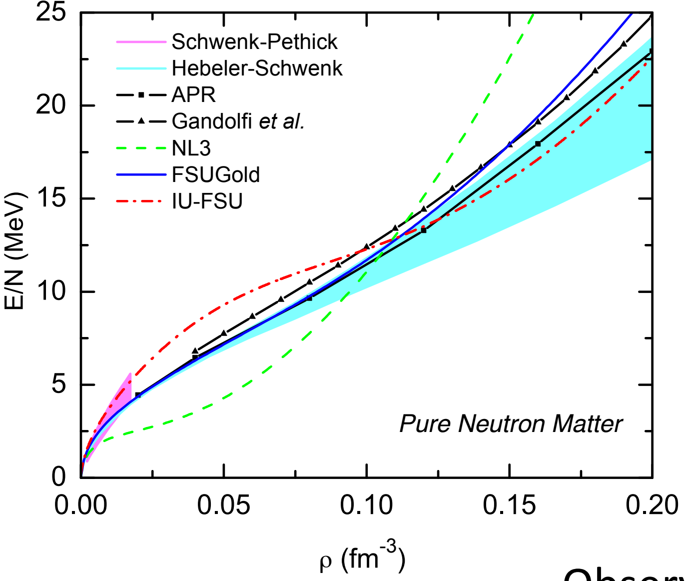
18. Piekarewicz et al; PRC85

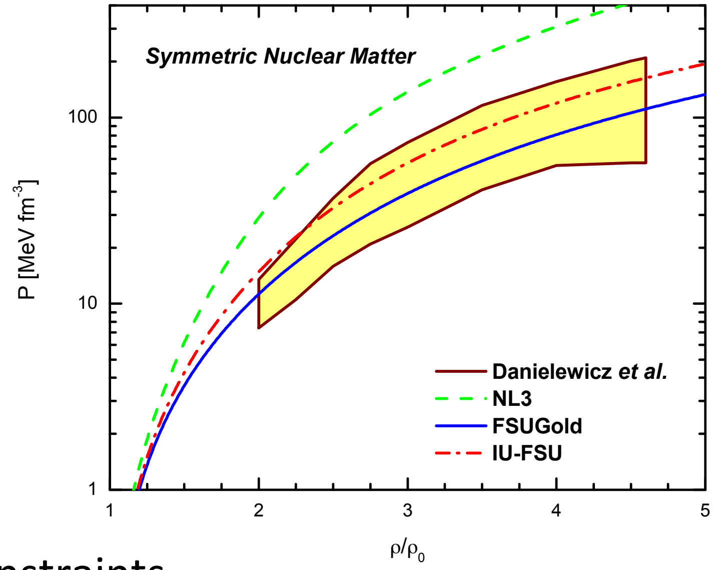
A. Steiner et al; ApJ722 (2010)
B. Steiner,Gandolfi; PRL108 (2012)

Experimental/Observational Constraints

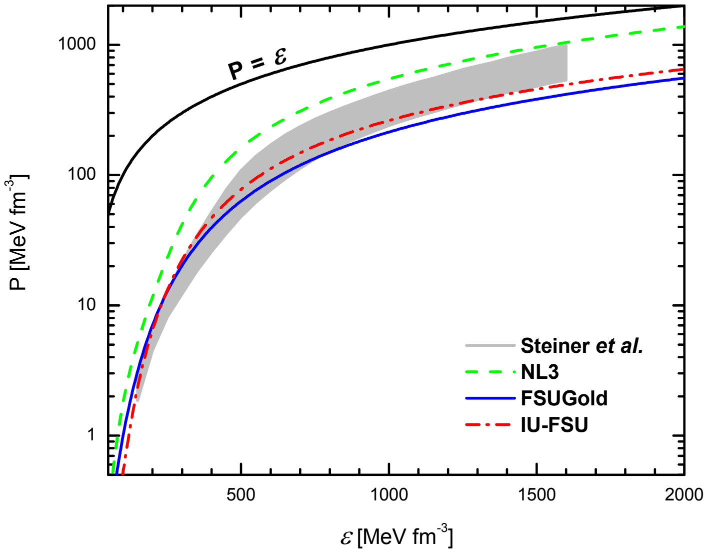
Microscopic calculations



Experimental constraints



Observational constraints

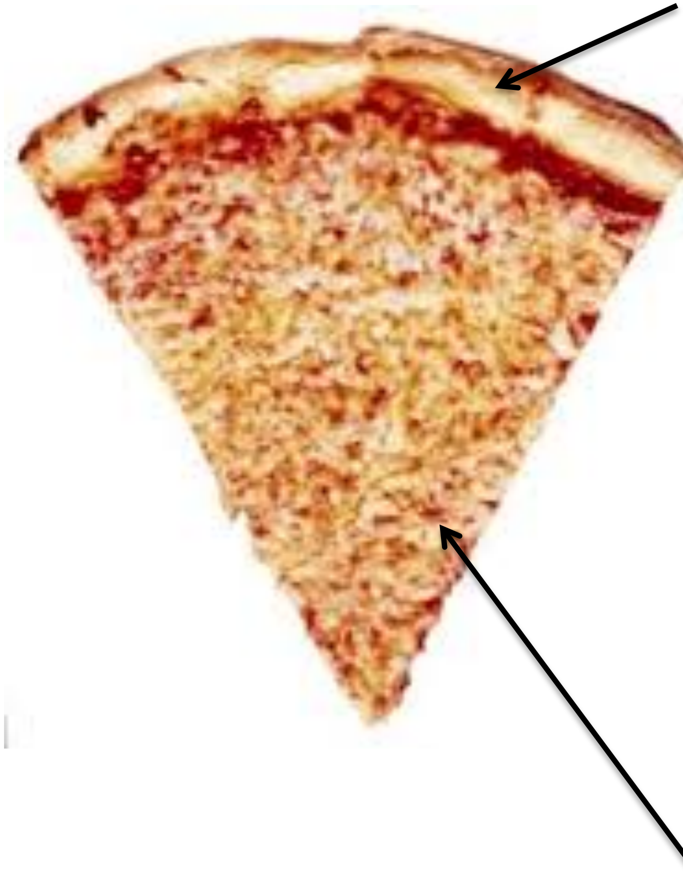


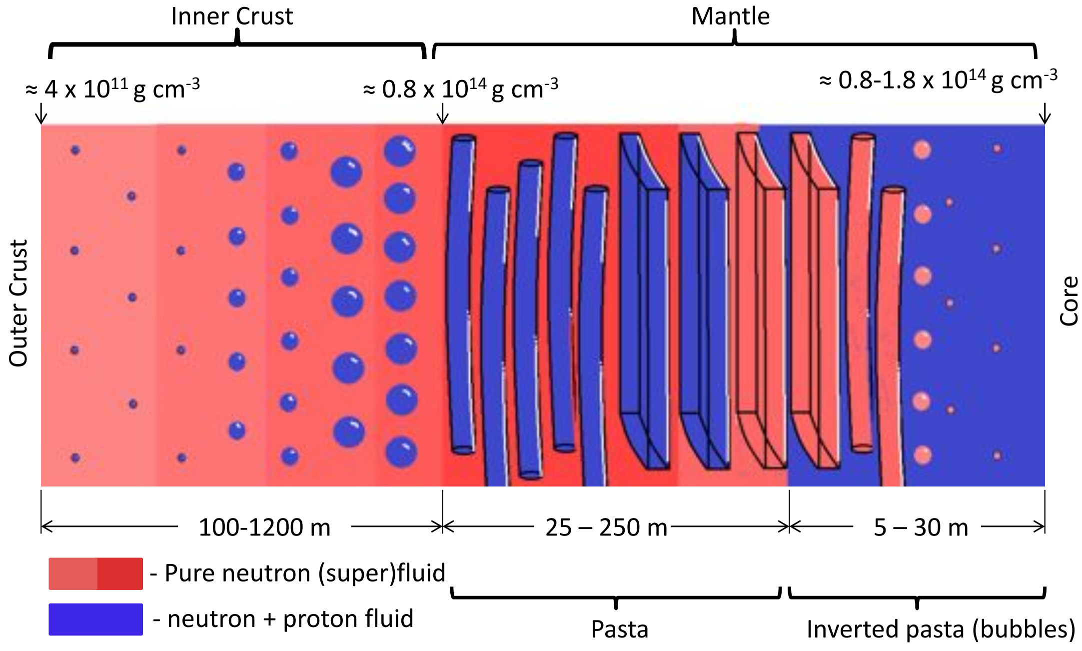
(Pictures from
Farrukh Fattoyev, PhD Thesis)

Micro-physically consistent crust-core models

- Skyrme/RMF models used for nuclear matter in crust and core
    - Each contain two parameters that allow for independent variation of *J* and *L* while leaving Symmetric Nuclear Matter properties unaltered; for given value of L, J adjusted to match PNM constraints

Crust: EoS, composition and crust core transition densities obtained using Compressible Liquid Drop model



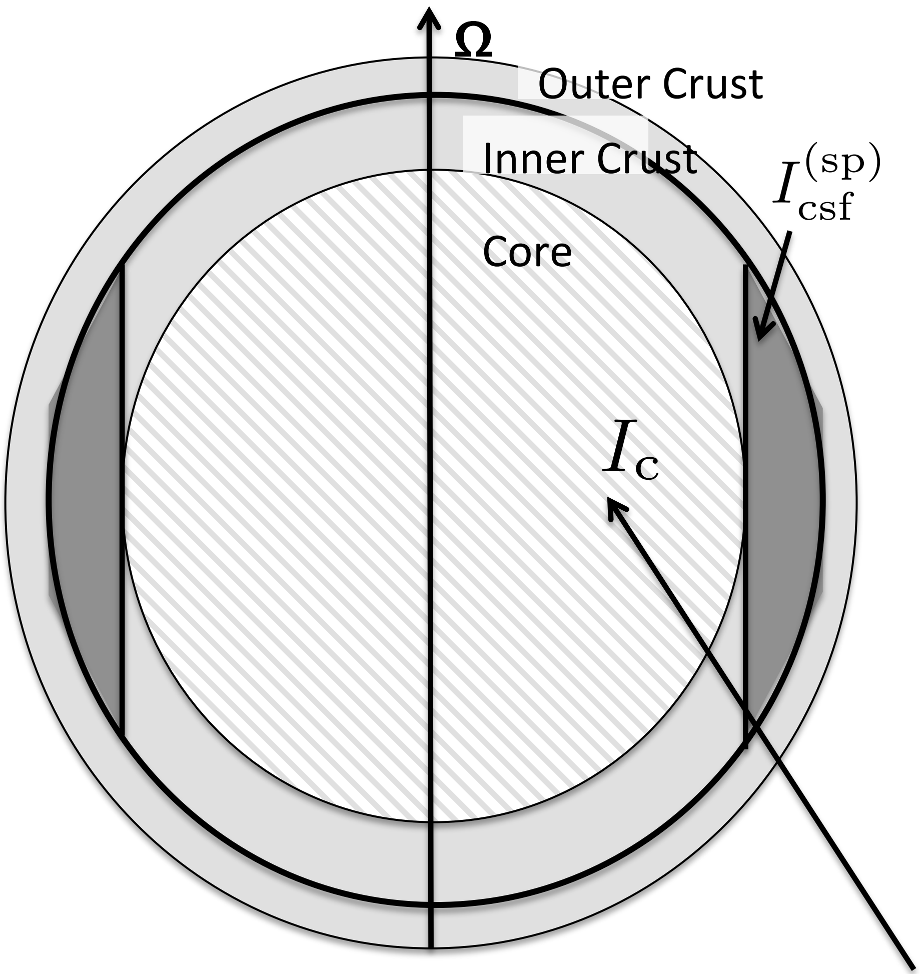


Core: EoS and composition; minimal model (npeμ)

(Gearheart, Newton, Li 2011; De-Hua, Newton, Li 2012; Newton, Gearheart, Li 2013)

Application: Glitches

- Can enough angular momentum be stored by inner crust neutrons to account for Vela glitches? i.e. is $I_{csf}^{(sp)}/I_c$ large enough?



$\Delta I/I$ confronted by Vela glitch activity – constrains EOS

(Link, Epstein, Lattimer; PRL83 1999)

Crust entrainment kills crust superfluid origin for glitches?

(Chamel, 2012; Andersson, Glampedakis, Ho, Espinoza 2012)

Saved by core superfluid coupling on timescales larger than glitch rise time?

(Link 2012; Haskell et al 2012; Seveso et al 2012)

Model parameters:

- Entrainment strength *e* (Chamel PRC 85 (2012))
- Fraction of core neutrons coupled to crust Y_g when glitch happens
- Symmetry energy slope at saturation *L*

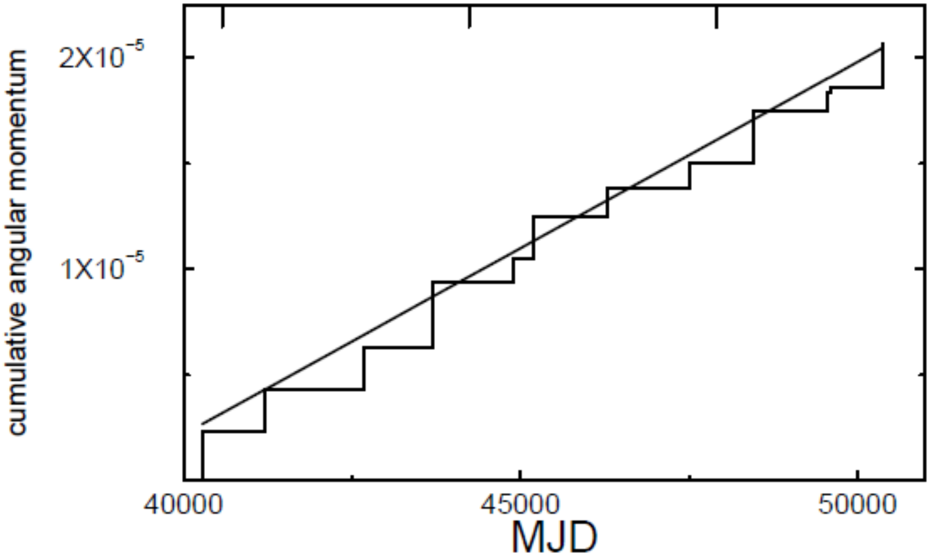
Pulsar Glitches: the Observations

PAR

$$\nu(t) = \nu_0 + \dot{\nu}_0 t + \frac{1}{2}\ddot{\nu}_0 t^2 + \Delta\nu_p + \Delta\dot{\nu}_p t + \sum_i \Delta\nu_i \exp\left(-t/\tau_i\right)$$

P	
ν (Hz)	11.194615396005
$\dot{\nu}$ (Hz s^{-1})	−1.55615E−11
$\ddot{\nu}$ (Hz s^{-2})	1.028E−21
$\Delta\nu_p$ (Hz)	3.45435(5)E−05
$\Delta\dot{\nu}_p$ (Hz s^{-1})	−1.0482(2)E−13
τ_n	1.2 ± 0.2 minutes
	00.53(3) days
	03.29(3) days
	19.07(2) days
$\Delta\nu_n$ (× 10^{-6} Hz)	0.020(5)
	0.31(2)
	0.193(2)
	0.2362(2)
DM	67.99

[a] The errors are the 1 σ values. The data fit is from MJD 51,505 to 51,650 (from 1999 November to 2000 April).



Link, Epstein, Lattimer 1999

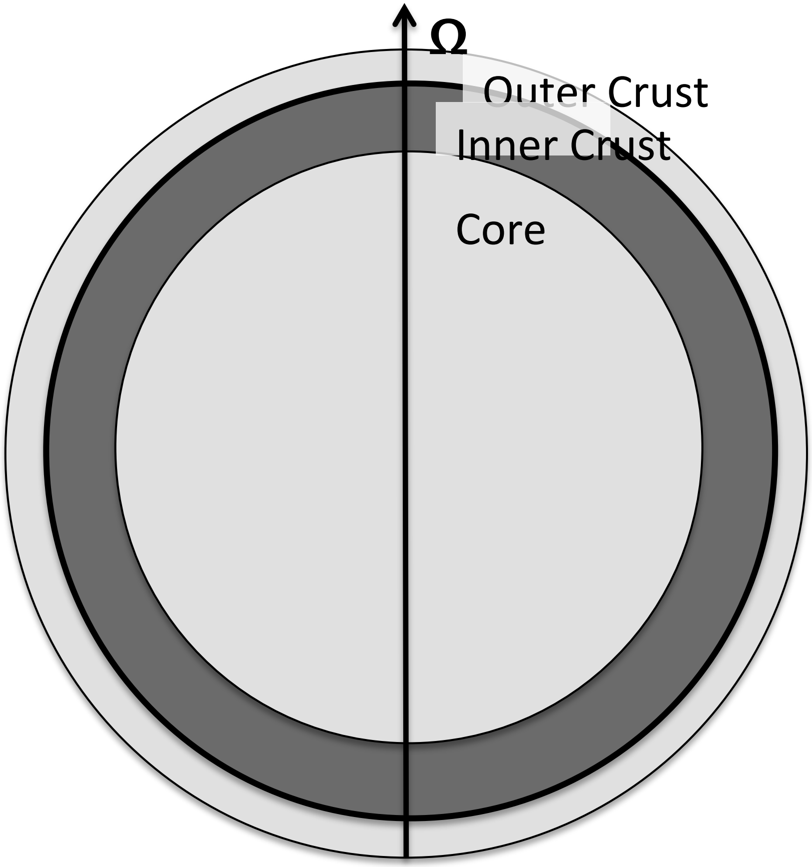
$$\frac{\Delta\dot{\Omega}_{gl}}{\dot{\Omega}_0} = \frac{(I_{\rm tot} - I_{\rm c})}{I_{\rm c}} \equiv K$$

$$K_{\rm Vela} = 18{\pm}6$$

$$\frac{I_{\rm csf}^{\rm (sp)}}{I_{\rm c}} \geqslant \frac{\bar{\Omega}}{|\dot{\Omega}|}\mathcal{A} \equiv G$$

$$G_{\rm Vela} > 1.6\%$$

Application: Glitches



$\Delta I/I$ confronted by glitch activity

(Link, Epstein, Lattimer; PRL83 1999)

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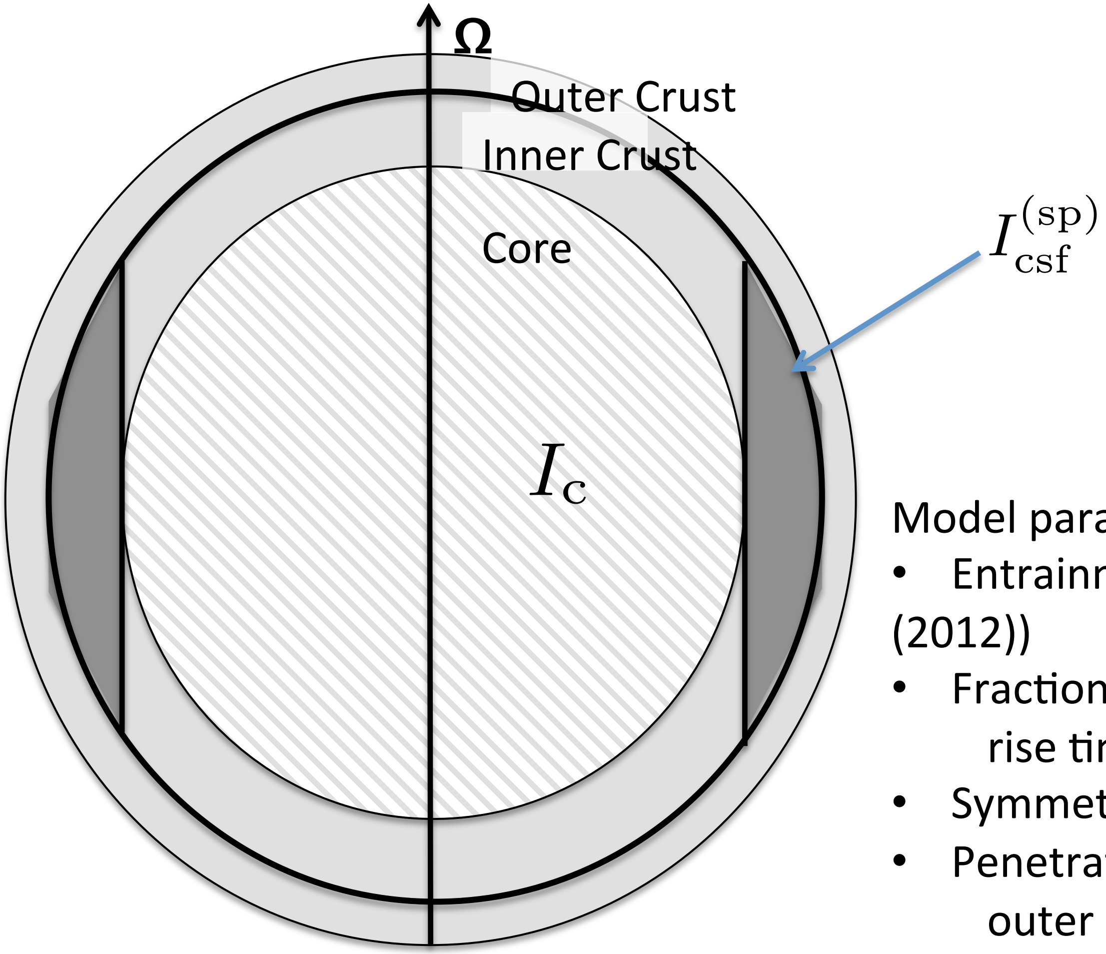

Model parameters:

- Entrainment strength *e* (Chamel PRC 85 (2012))
- Fraction of core neutrons coupled on glitch rise time $Y_{\rm g}$
- Symmetry energy slope at saturation *L*
- Penetration of strong pinning region into outer core $n_{\rm max}$ (e.g. vortex pinning to flux tubes)

Micro-physically consistent crust-core models