The Physics of the Neutron Star Crust-Core Transition: Observable Consequences and Nuclear Symmetry Energy Constraints

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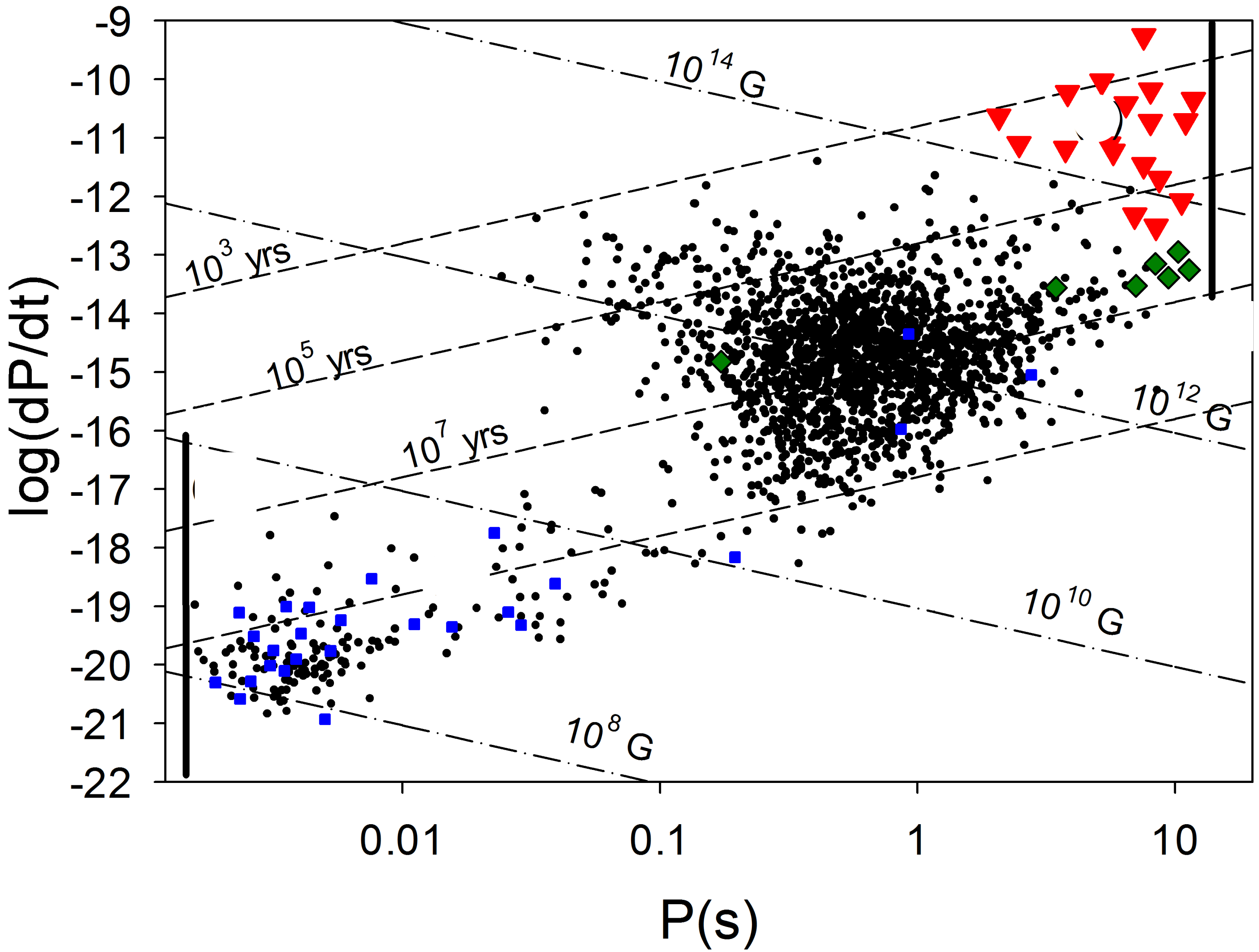
Outline

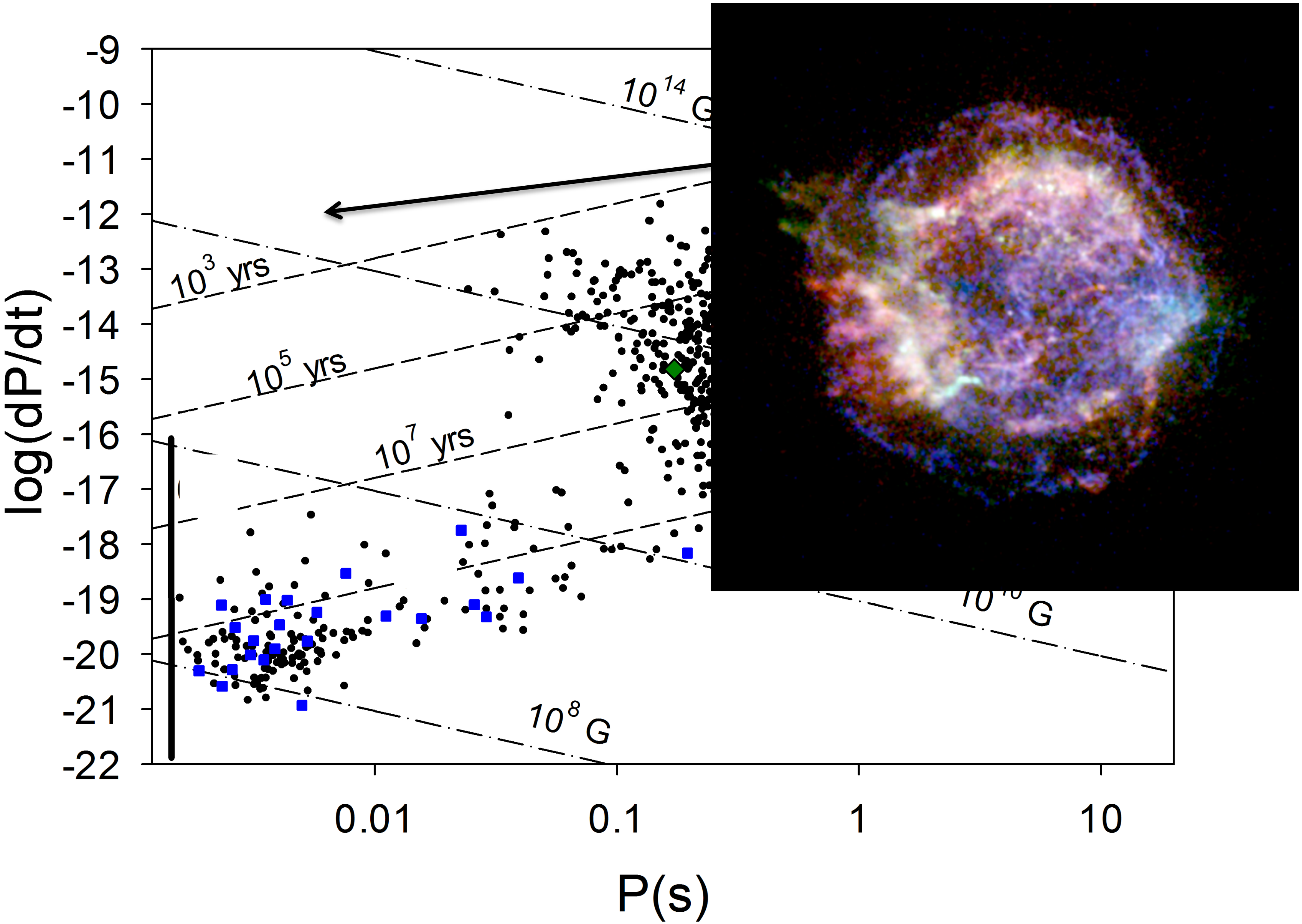
- Introduction
    - Observational motivation
    - Theoretical motivation
    - Neutron star structure
    - EOS and symmetry energy
- Neutron star models
    - Symmetry energy correlations with bulk crust properties
- Observable I: Cooling of the Cas A NS
- Observable II: Glitches in the Vela pulsar
- (Observable III: limiting periods of pulsars)
- (Observable V: Precursor flares to short Gamma-ray bursts)
- Conclusions: overview of observational constraints

Observational motivation



Neutron star zoo – Alice Harding 1302.0869; Vicki Kaspi, Proc. Nat. Ac. Sci. 107, 16, 7147 (2010)

Observational motivation



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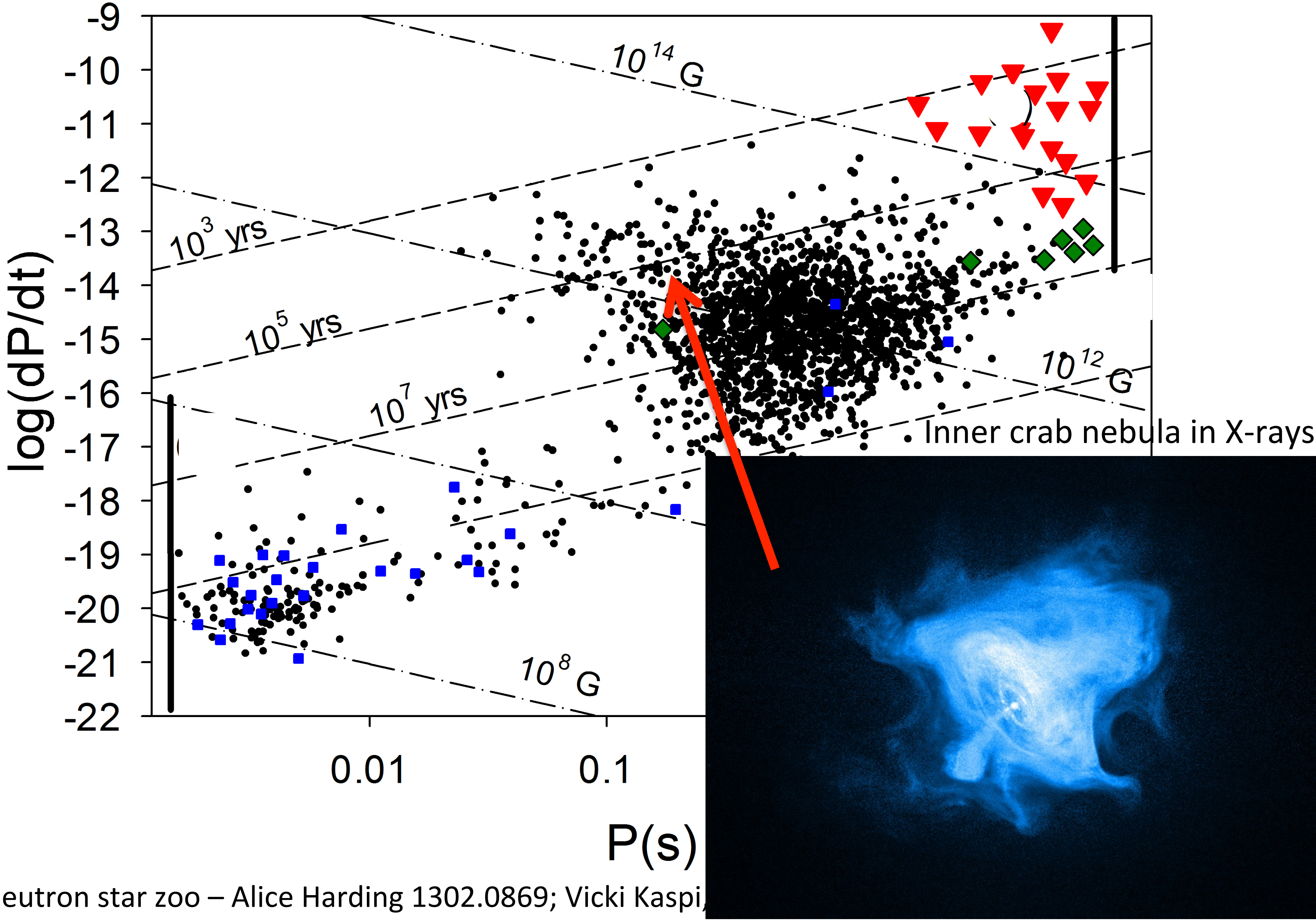
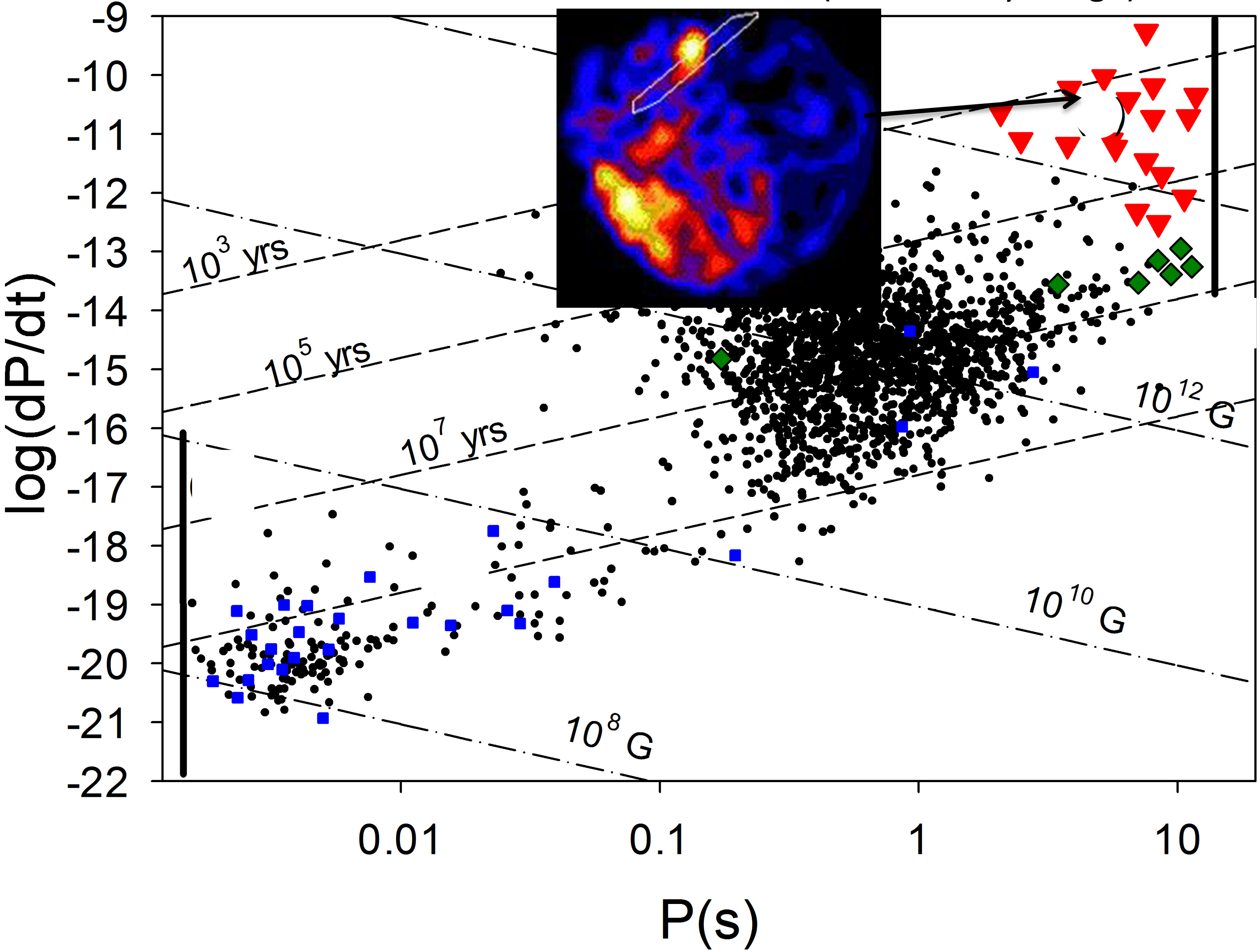


• Inner crab nebula in X-rays

Neutron star zoo – Alice Harding 1302.0869; Vicki Kaspi,

Observational motivation

SGR in SN remnant N49 (Gamma-ray image)



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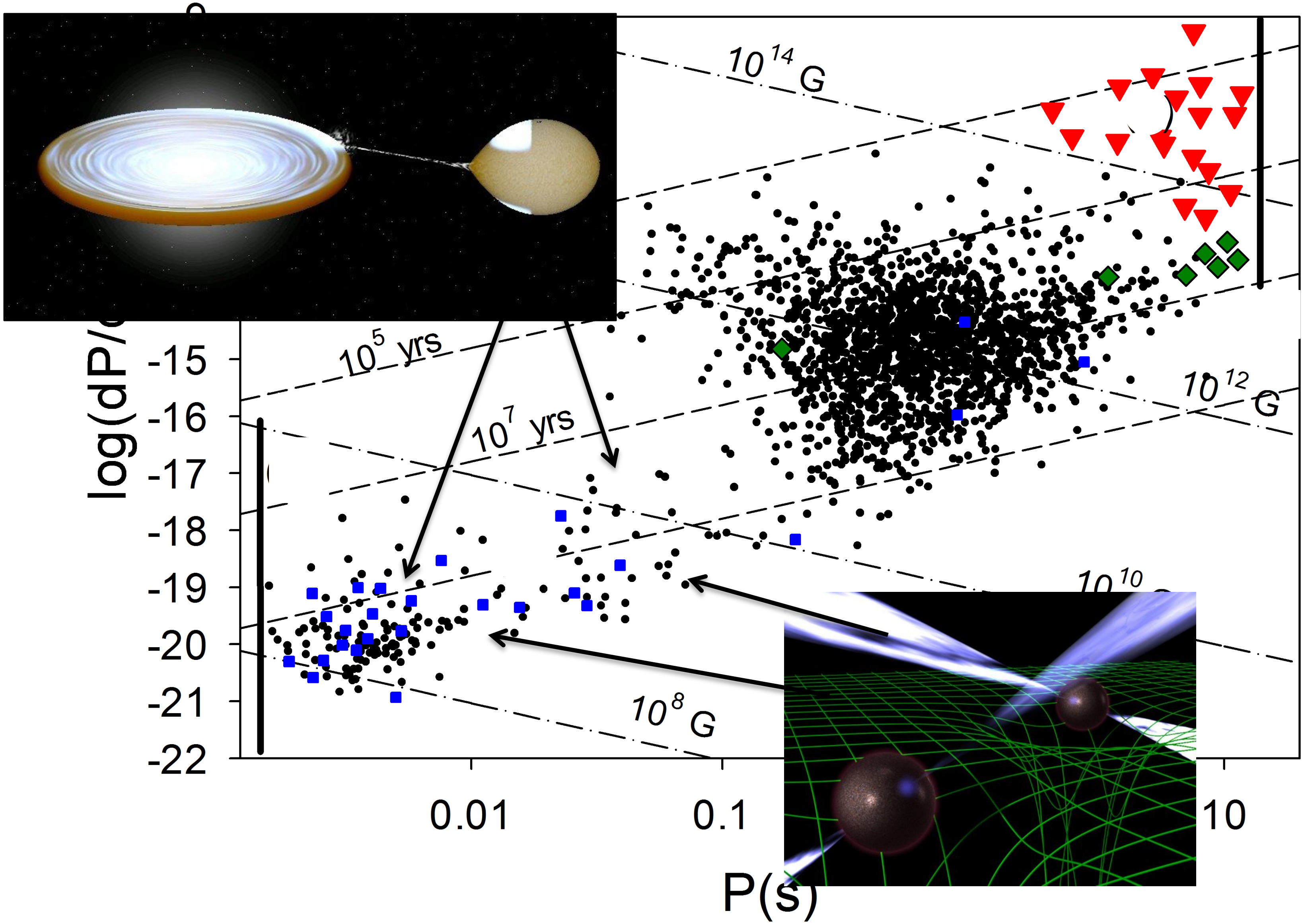

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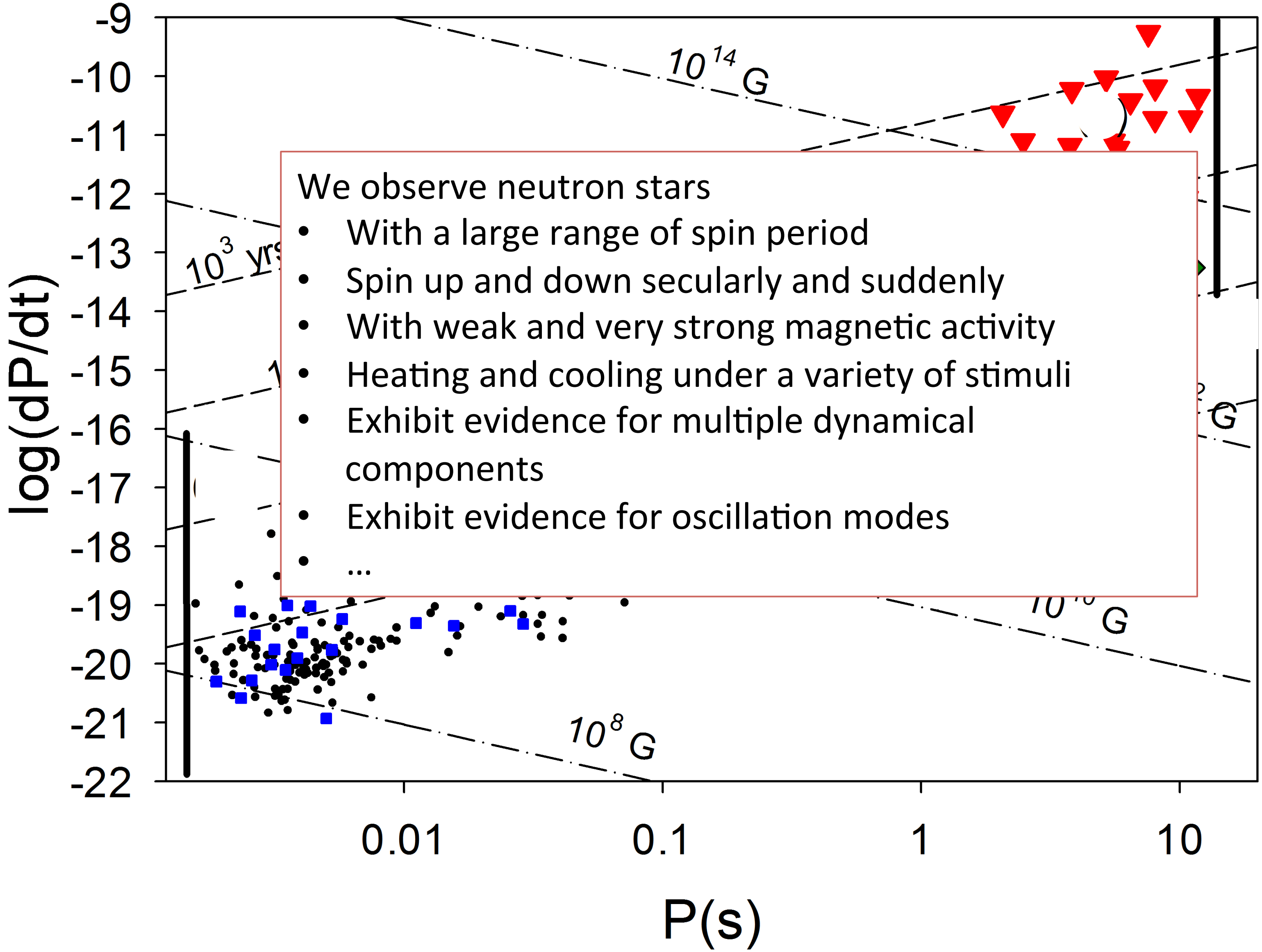

We observe neutron stars

- With a large range of spin period
- Spin up and down secularly and suddenly
- With weak and very strong magnetic activity
- Heating and cooling under a variety of stimuli
- Exhibit evidence for multiple dynamical components
- Exhibit evidence for oscillation modes
- …

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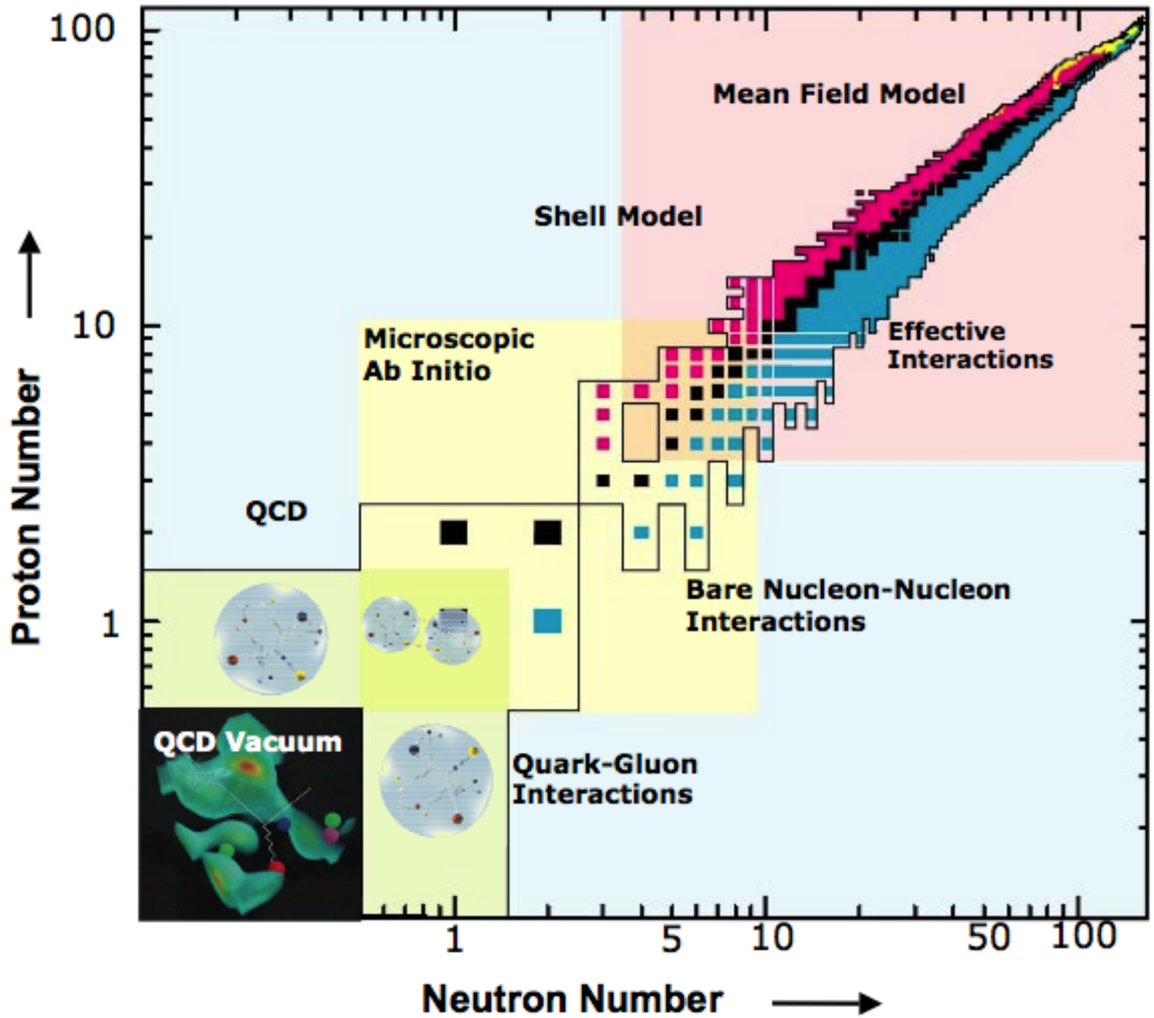


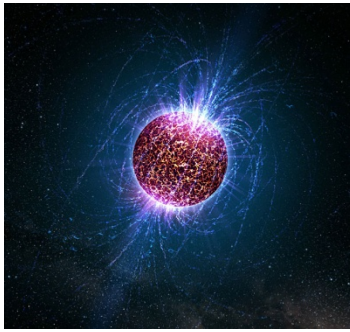
Picture courtesy of Achim Schwenk

Theoretical motivation

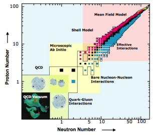
10^{56}

Proton number

NEUTRON STAR;
- Result of stellar core collapse
- $\approx 1.4\ M_{SUN}$, $R \approx 10km$
- Bound by gravitational, not nuclear, Forces
- Nuclear forces determine structure of star



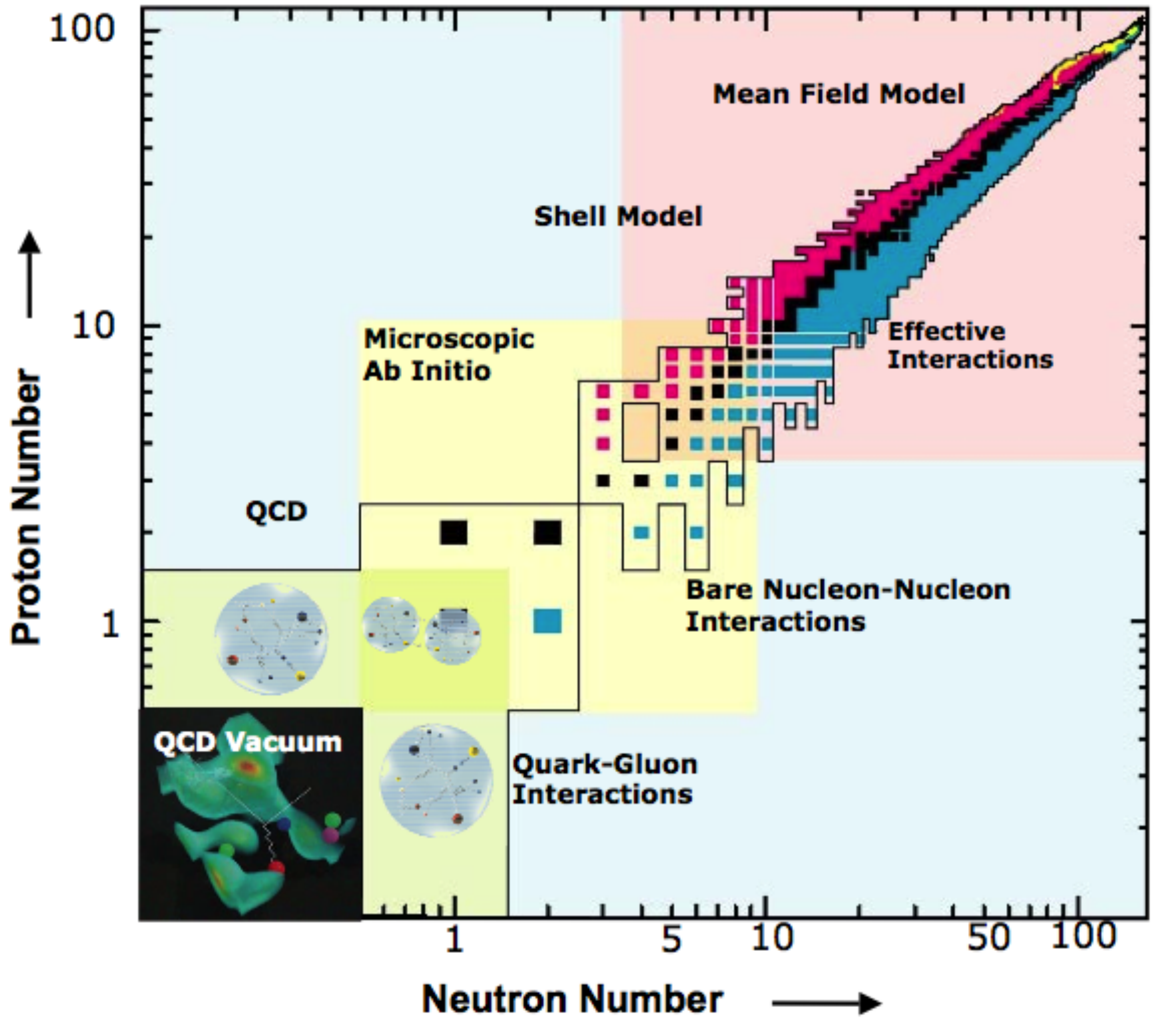
NASA



Neutron number

10^{57}

Theoretical motivation



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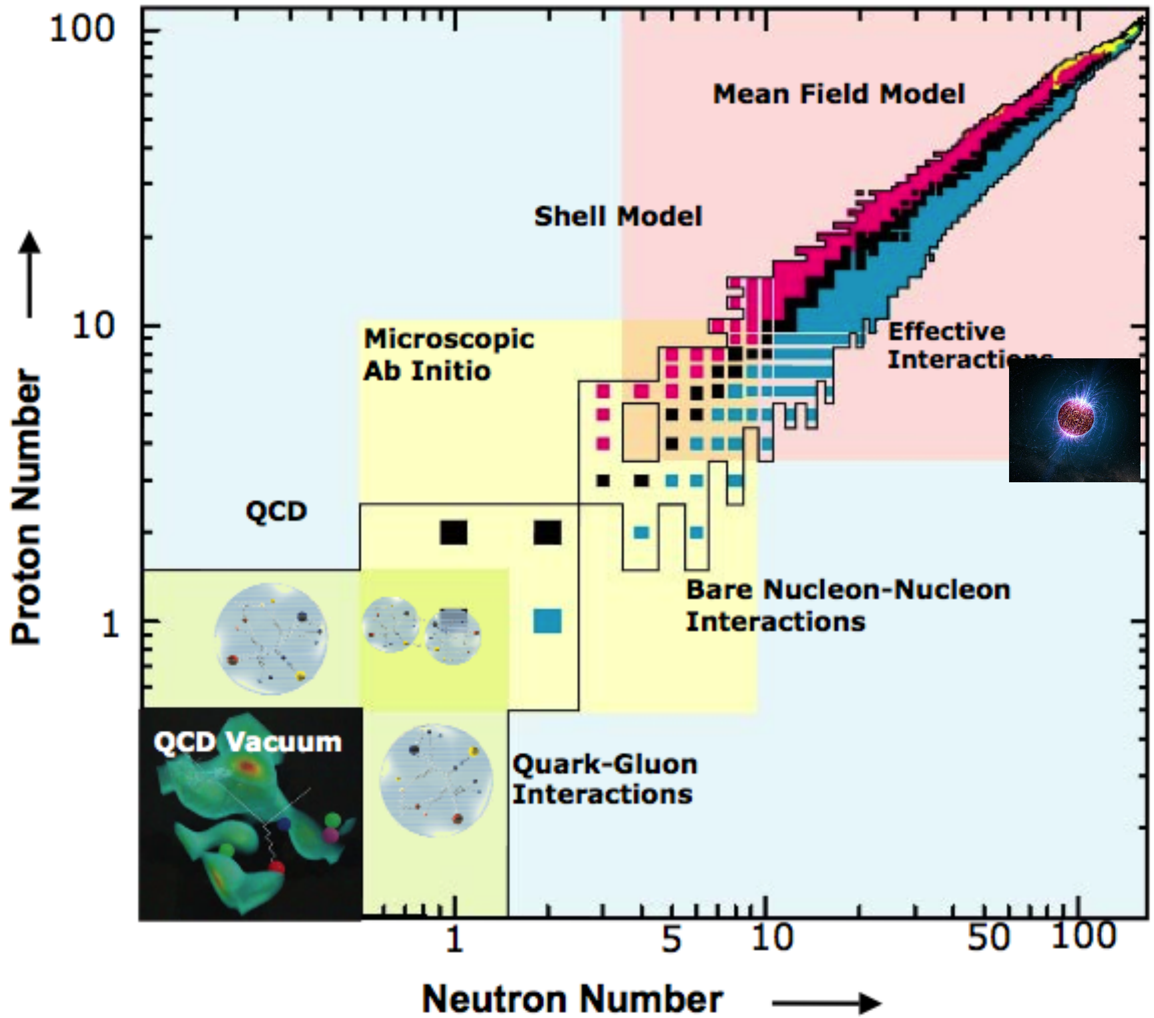
Theoretical motivation



Picture courtesy of Achim Schwenk

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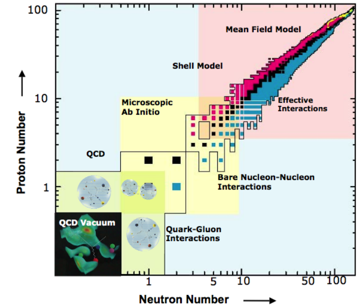
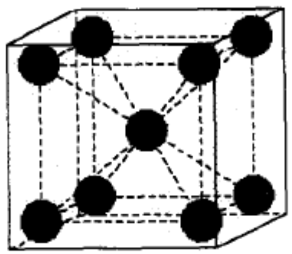


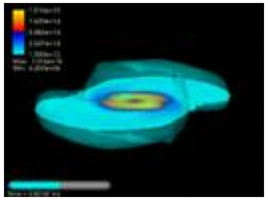
Microphysics of (hot, $>10^{10}$K), dense matter

- Nuclear models/QCD
- Weak interactions



Bulk Properties of neutron star matter (meso/macrophysics):

- Thermal/electrical conductivity
- Elastic properties (Bulk, shear modulus)
- Hydrodynamic properties (superfluid, entrainment)
- Equation of State $P = P(\rho,T)$

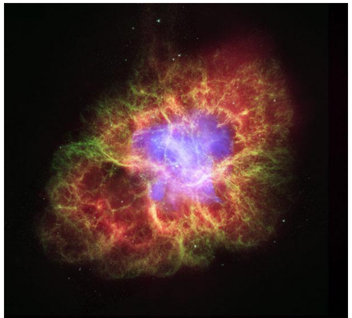


Macrophysical Stellar Models

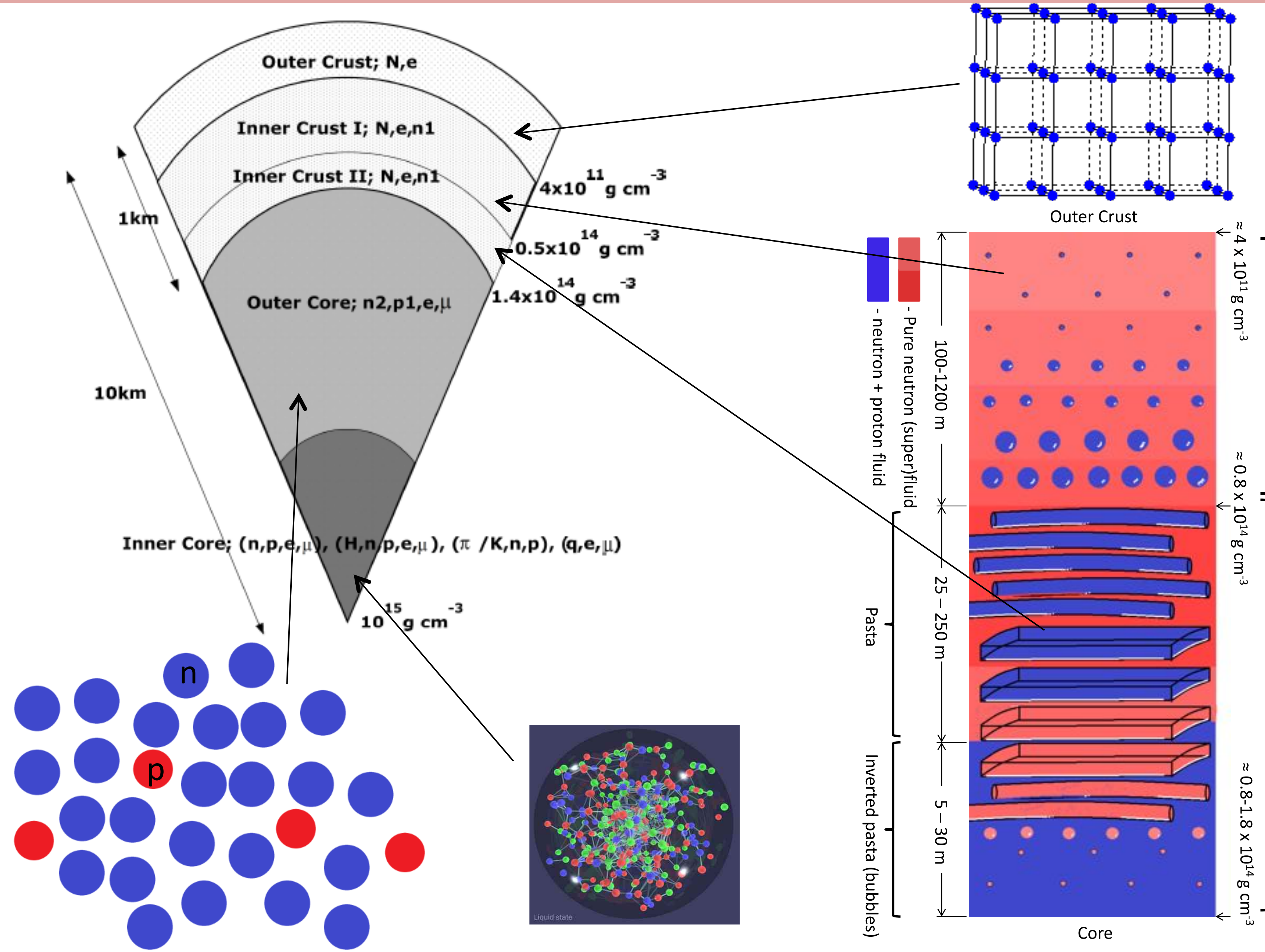
- Inclusion of GR, MHD (with superfluids)

Calculation of observables and confrontation with observation

- Radio/X-ray Pulsars
- Bursts from NSs (XRBs/SGRs)
- NS cooling
- Gravitational waves?

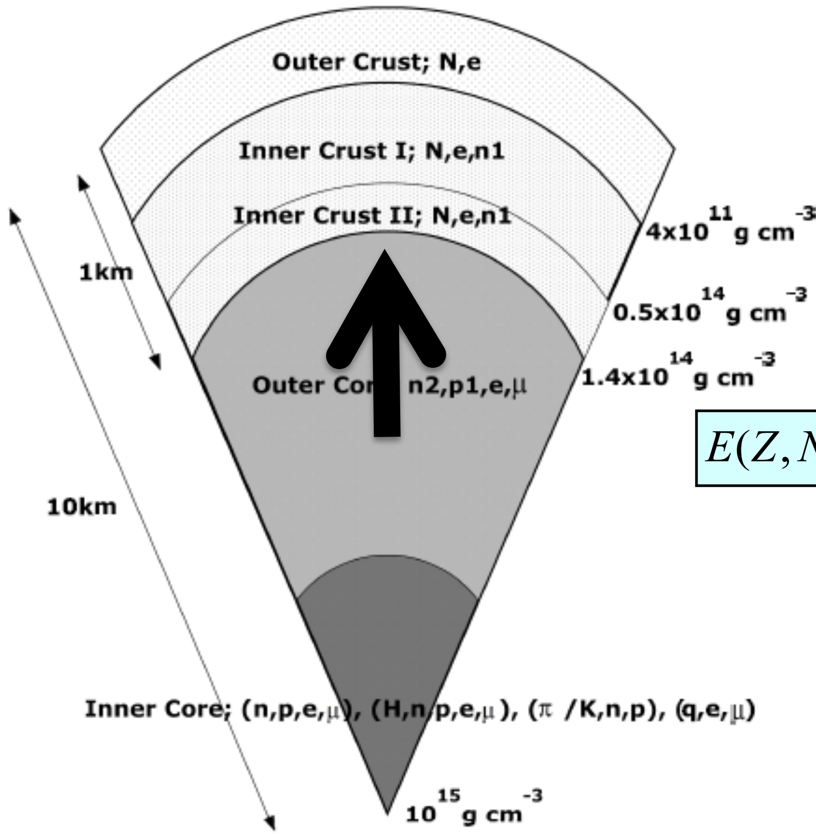


Neutron stars: the theoretical paradigm



Nuclear matter, the symmetry energy and the neutron star EoS

$$\frac{dP}{dr} = -\frac{G}{r^2}\left[M(r)+4\pi r^3\frac{P(r)}{c^2}\right]\left[\rho(r)+\frac{P(r)}{c^2}\right]\left[1-\frac{2GM(r)}{c^2 r}\right]^{-1}$$



Pressure balances gravity; we need EoS

$$P = P(\rho)$$

Obtained from energy density (or energy per Particle) of system:

$$E = E(\rho)$$

We're dealing with a bag of nucleons…

$$E(Z,N) = a_{vol}A + a_{surf}A^{2/3} + a_{Coul}Z^2 / A^{1/3} + a_{symm}(N-Z)^2 / A \; + \ldots$$

…in the thermodynamic limit (N,A,Z to infinity, neglecting Coulomb)

$$E(\rho,\alpha)/A = a_{vol} + a_{symm}\alpha^2 + \ldots$$

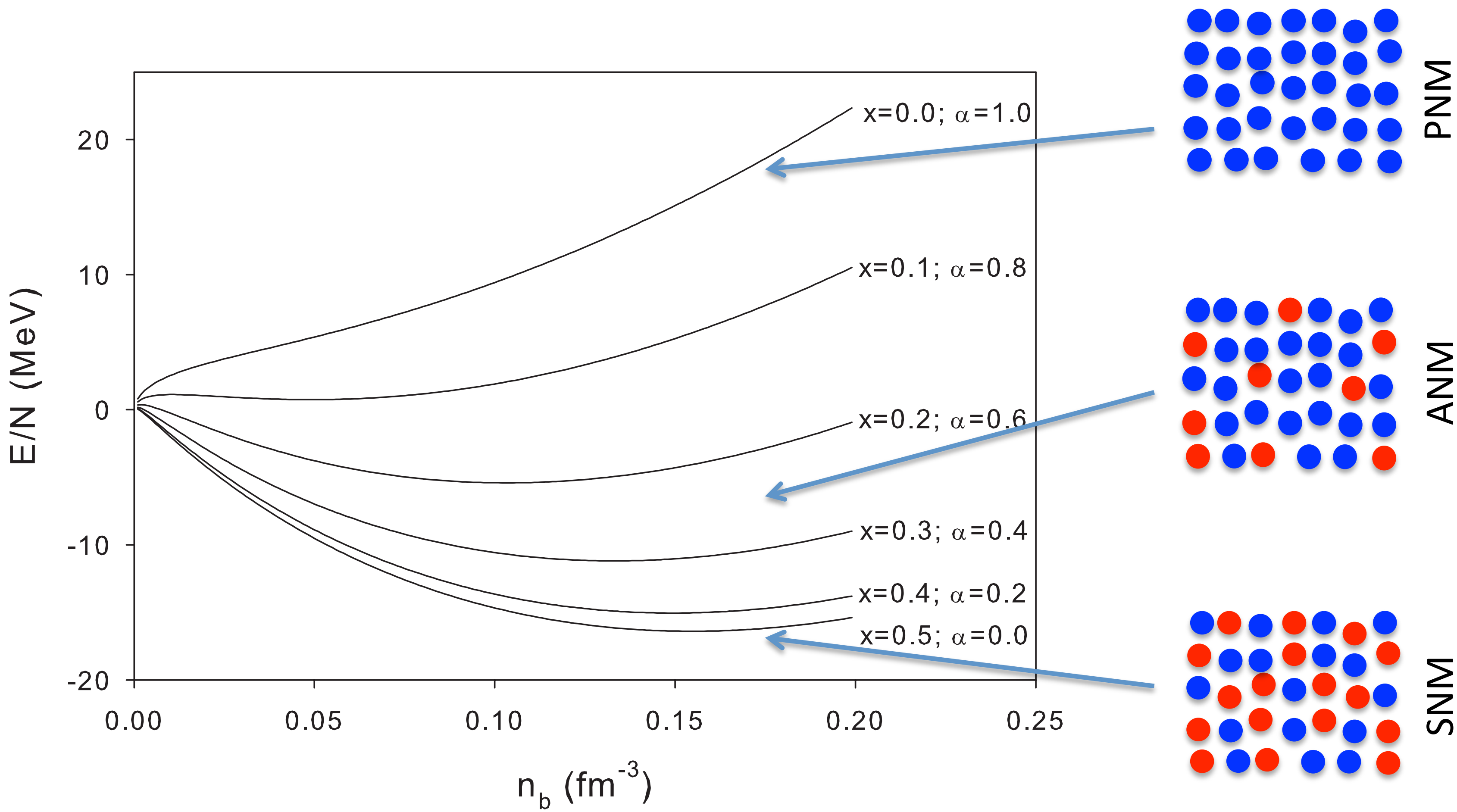
…and giving the coefficients a density dependence

$$E(\rho,\alpha)/A = E(\rho,0)/A + S(\rho)\alpha^2 + \ldots$$

energy/particle of SNM

Symmetry energy – penalty for moving away from N=Z symmetry

Nuclear matter, the symmetry energy and the neutron star EoS



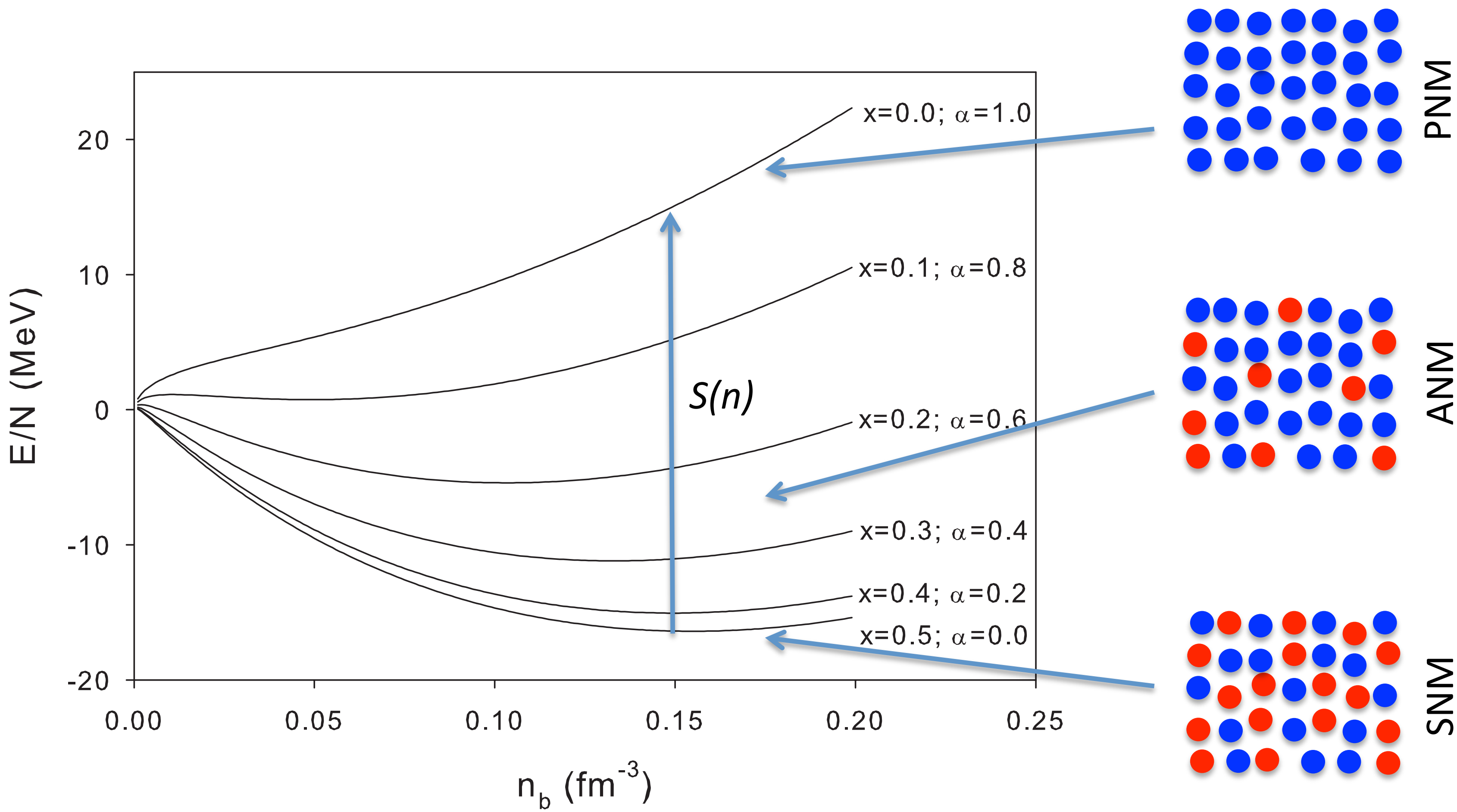
$$E(n,\delta) = E_0(n) + S(n)\delta^2 + \ldots$$

$$\delta = 1 - 2x$$

n – baryon number density

x – proton fraction

Nuclear matter, the symmetry energy and the neutron star EoS



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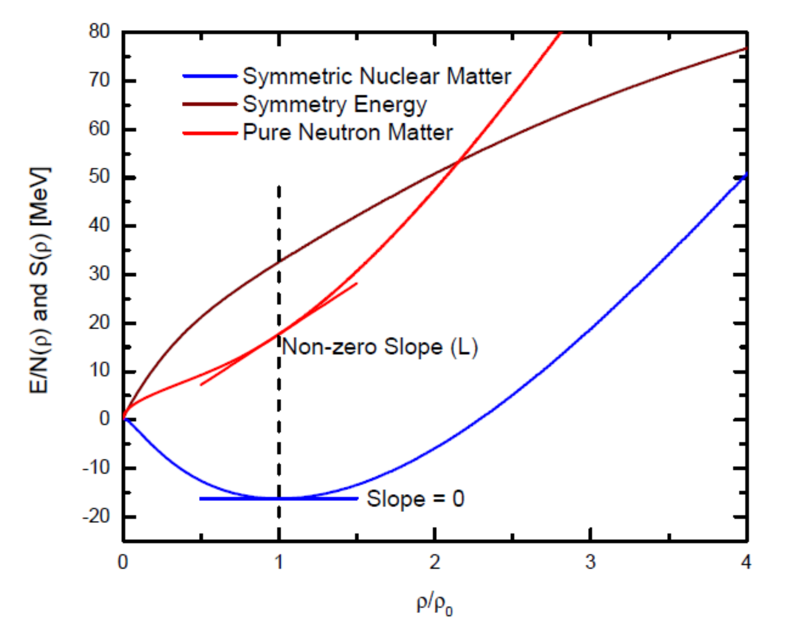
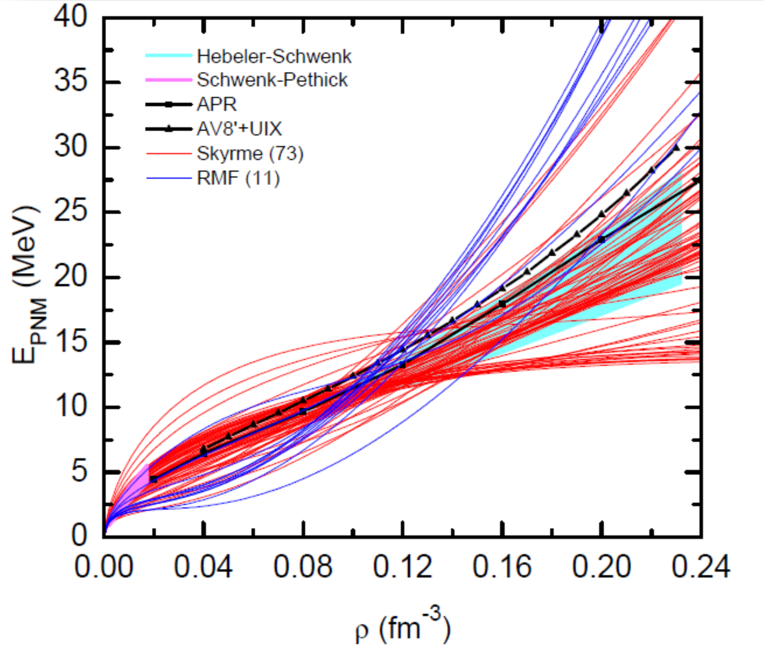
Nuclear matter, the symmetry energy and the neutron star EoS





Farrukh Fattoyev, 2013

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

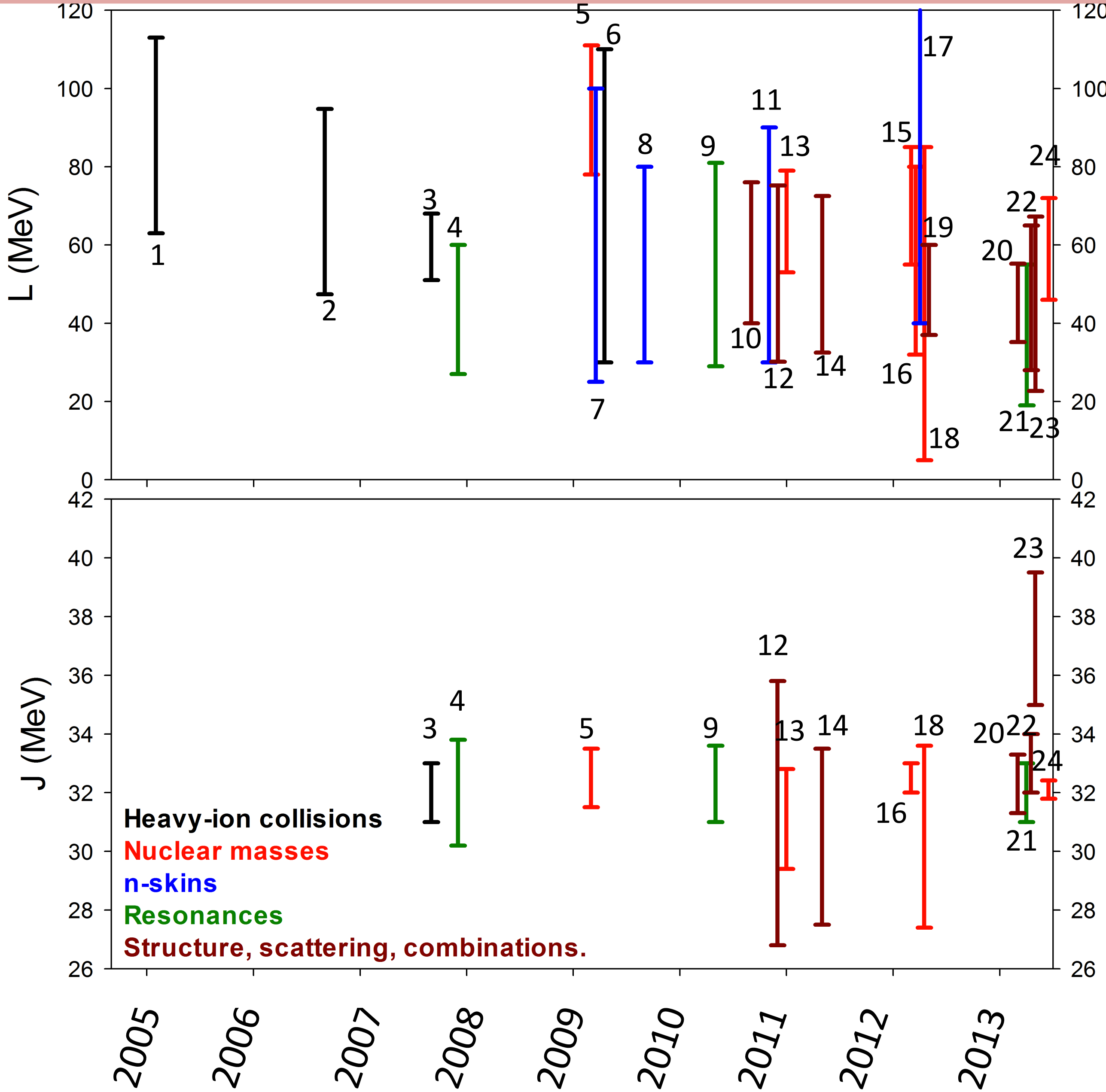
$$S(n) = J + L\chi + \frac{K_{\rm sym}}{2}\chi^2 + \ldots \qquad \chi = \frac{n-n_0}{3n_0}$$

Other notations are available

Combined with Coulomb and beta-equilibrium conditions, obtain NS core EoS.

$$P_{\rm NS}(n_0) \approx \frac{n_0}{3}L + 0.048n_0\left(\frac{J}{30}\right)^3\left(J - \frac{4}{3}L\right)$$

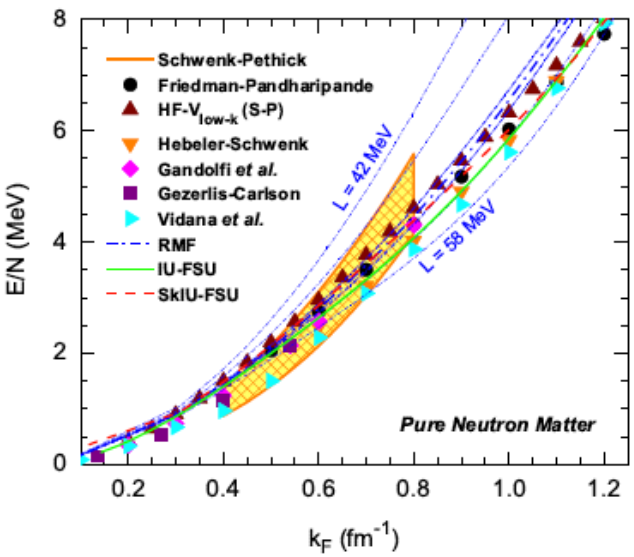
Symmetry energy constraints



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. Abrahamyan et al, PRL108
18. Dong et al; PRC85
19. Piekarewicz et al; PRC85
20. Zhang, Chen; arxiv:1302.5327
21. Roca-Maza et al. PRC87
22. Wang, Ou, Liu, PRC87
23. Li et al. PLB721
24. Agrawal et al, arxiv:1305:5336

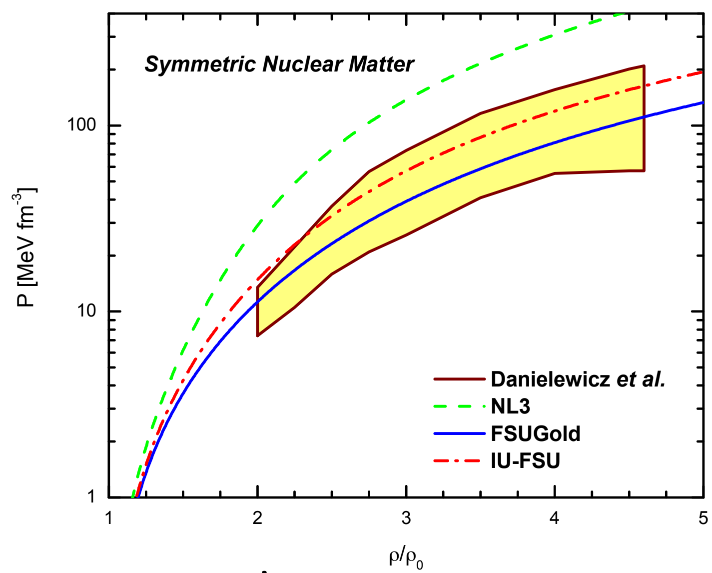
Symmetry energy constraints

Microscopic PNM calculations



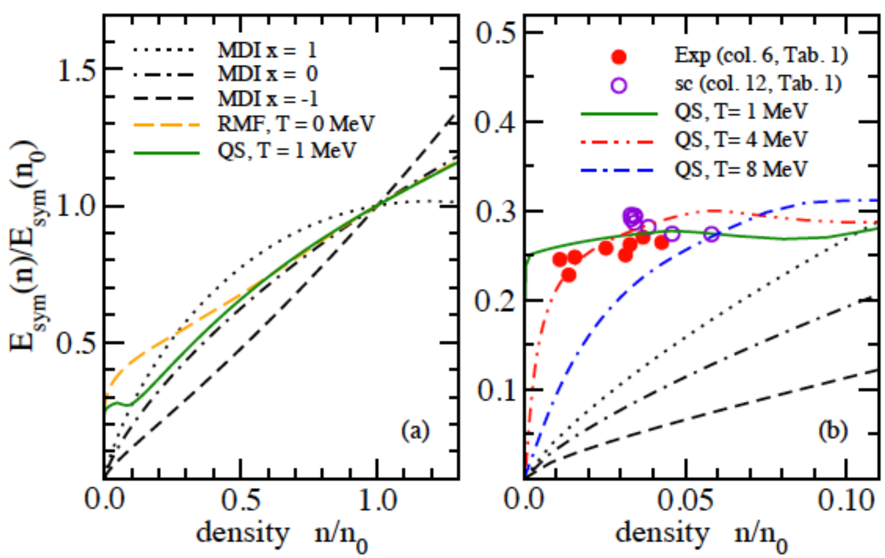
(taken from F. Fattoyev, PhD Thesis)

High density SNM constraints



(taken from F. Fattoyev, PhD Thesis)

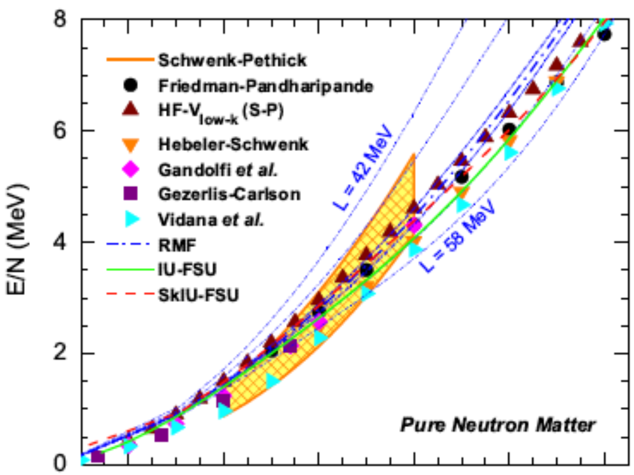
Low density symmetry energy constraints



Natowitz et al, PRL104 (2010)

Symmetry energy constraints

Microscopic PNM calculations



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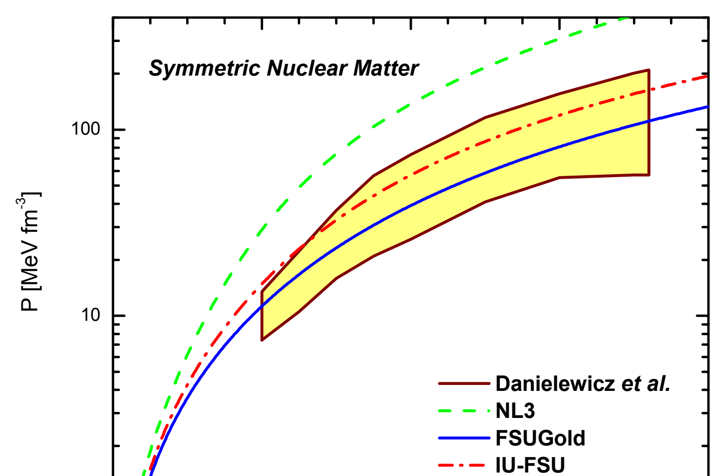
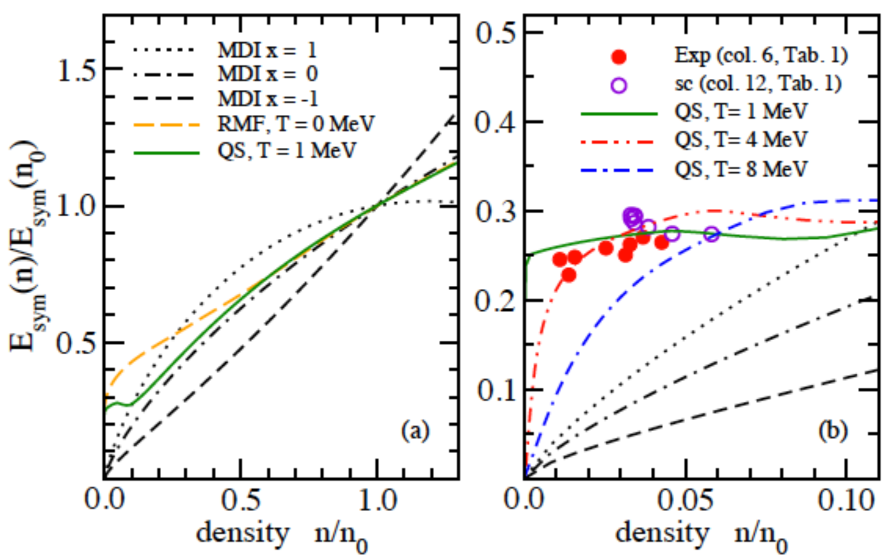
High density SNM constraints



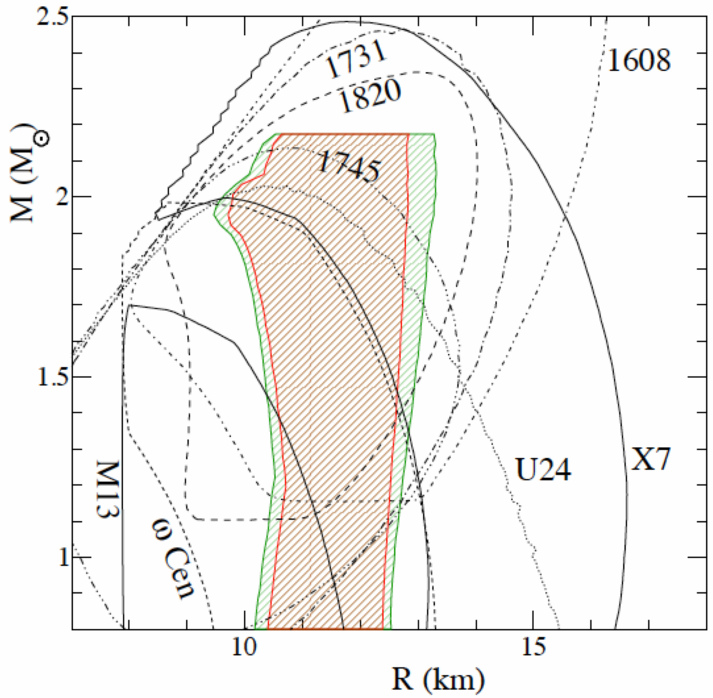
en from F. Fattoyev, PhD Thesis)

- What constraints can we add from astrophysical observation?
- How can experimental/theoretical constraints inform our interpretation of observations?



Natowitz et al, PRL104 (2010)

Symmetry energy constraints: NS radii



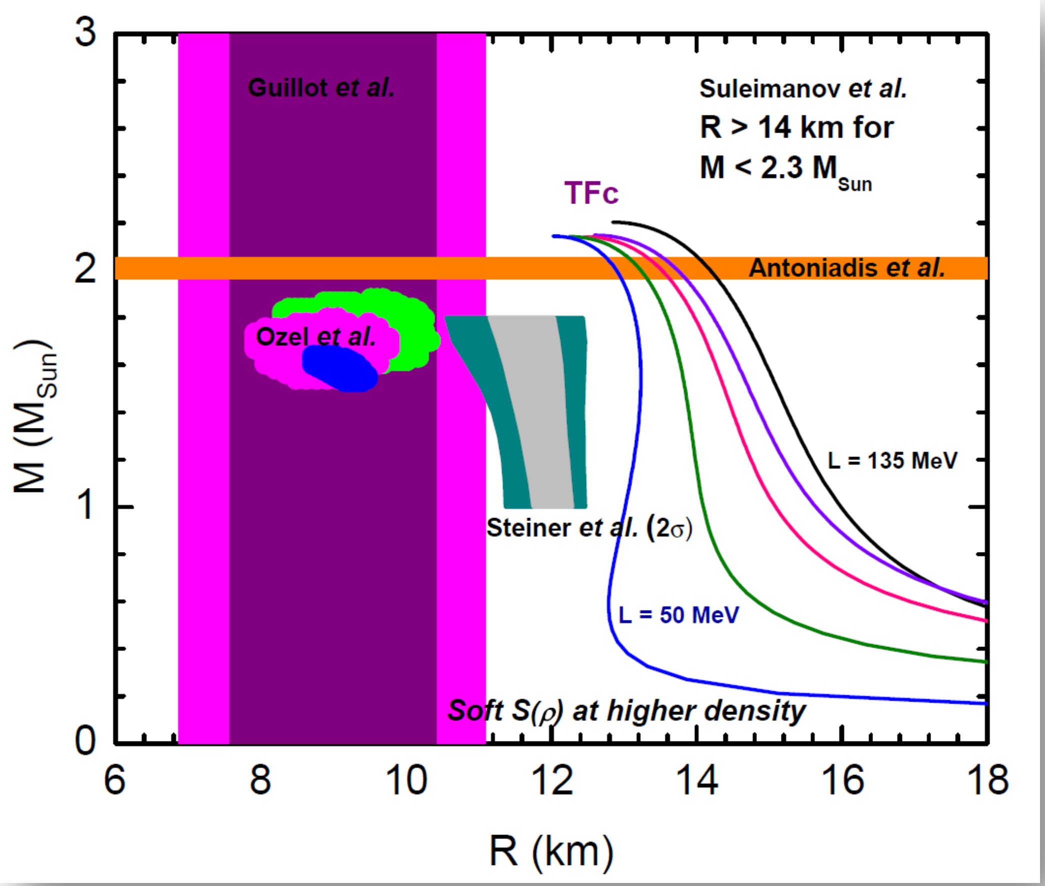
Steiner, Lattimer, Brown ApJ765 (2013)

Lattimer, Steiner arXiv:1305.3242

- Bayesian analysis of inferred M/R ranges from transiently accreting/bursting NS sources
  - (Eddington luminosity, angular diameter and gravitational radius all f(M,R))
- Latest inferred L: 41 – 84 MeV
- Observational uncertainties: Hydrogen column density, X-ray spectral models, data precision
- Theoretical uncertainties: EOS model dependence?

Symmetry energy constraints: NS radii

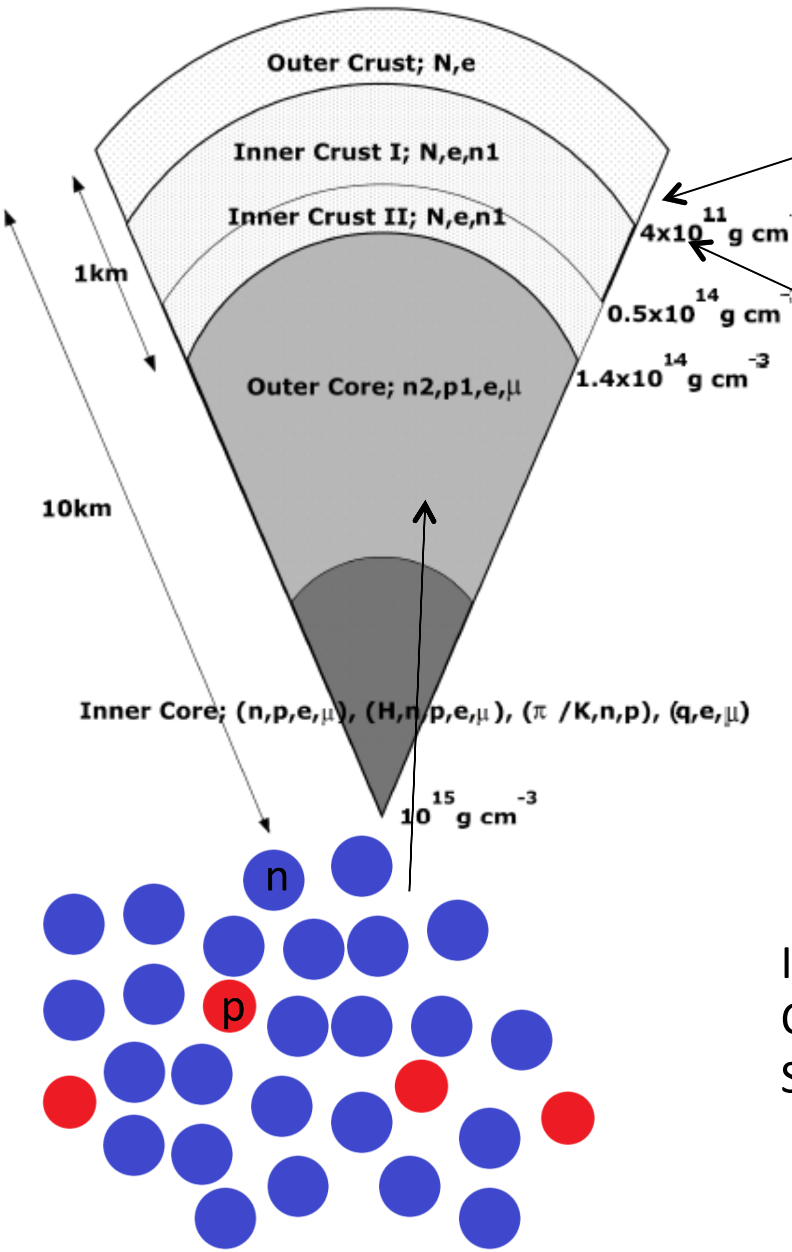
Fattoyev, Piekarewicz PRL 111 (2013)

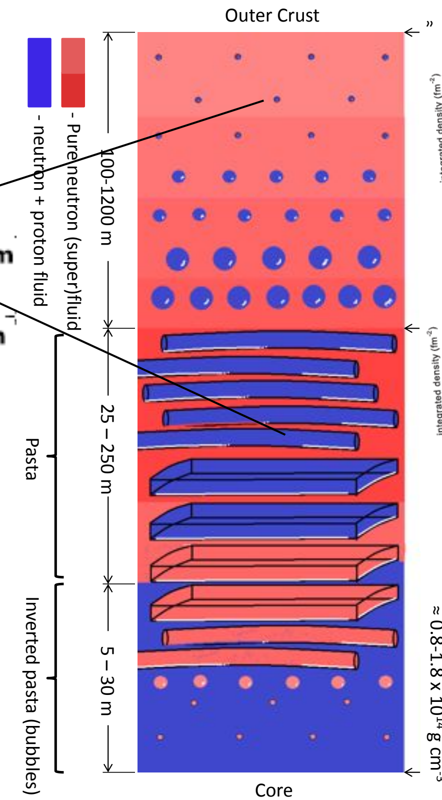


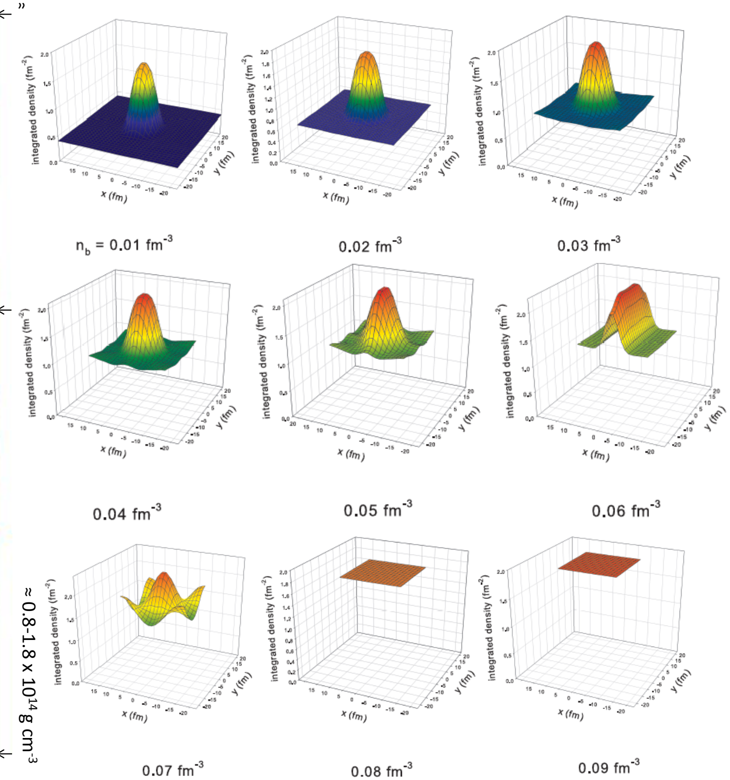
- Observational uncertainties: Hydrogen column density, X-ray spectral models, data precision
- Theoretical uncertainties: EOS model dependence?
- More independent astrophysical symmetry energy measurements needed!

CREATE SETS OF NEUTRON STAR MODELS BY SYSTEMATICALLY VARYING L AND TEST THE SENSITIVITY OF OBSERVABLES

Neutron star modeling: consistent crust-core models







Newton, Stone PRC79 (2009), Stone, Pais PRL109 (2012), Newton, Stone in prep

Inner crust: Compressible liquid drop model/3DHF
Core: neutrons, protons, electrons, muons;
Same underlying nuclear EoS used for both

Neutron star modeling: systematic variation of J,L

- Skyrme-Hartree-Fock (SHF) model of nuclear matter:

$$\begin{aligned}
\mathscr{H} &= \frac{\hbar^2}{2M}\tau + t_0\left[(2+x_0)\rho^2 - (2x_0+1)\left(\rho_{\rm n}^2+\rho_{\rm p}^2\right)\right]/4 \\
&+ t_3\rho^\sigma\left[(2+x_3)\rho^2 - (2x_3+1)\left(\rho_{\rm n}^2+\rho_{\rm p}^2\right)\right]/24 \\
&+ \left[t_2(2x_2+1) - t_1(2x_1+1)\right](\tau_n\rho_n + \tau_p\rho_p)/8 + \left[t_1(2+x_1)+t_2(2+x_2)\right]\tau\rho/8 \\
&+ \left[3t_1(2+x_1) - t_2(2+x_2)\right](\nabla\rho)^2/32 - \left[3t_1(2x_1+1)+t_2(2x_2+1)\right]\left[(\nabla\rho_{\rm n})^2+(\nabla\rho_{\rm p})^2\right]/32 \\
&+ W_0\left[\vec{J}\cdot\nabla\rho + \vec{J}_{\rm n}\cdot\nabla\rho_{\rm n} + \vec{J}_{\rm p}\cdot\nabla\rho_{\rm p}\right]/2 + (t_1-t_2)\left[J_{\rm n}^2+J_{\rm p}^2\right]/16 - (t_1x_1+t_2x_2)J^2/16\,.
\end{aligned}$$

-9 parameters $\{t_0, t_1, t_2, t_3, x_0, x_1, x_2, x_3, \sigma\}$

-2 purely isovector parameters: x_0, x_3

- Relativistic Mean Field (RMF) model of nuclear matter:

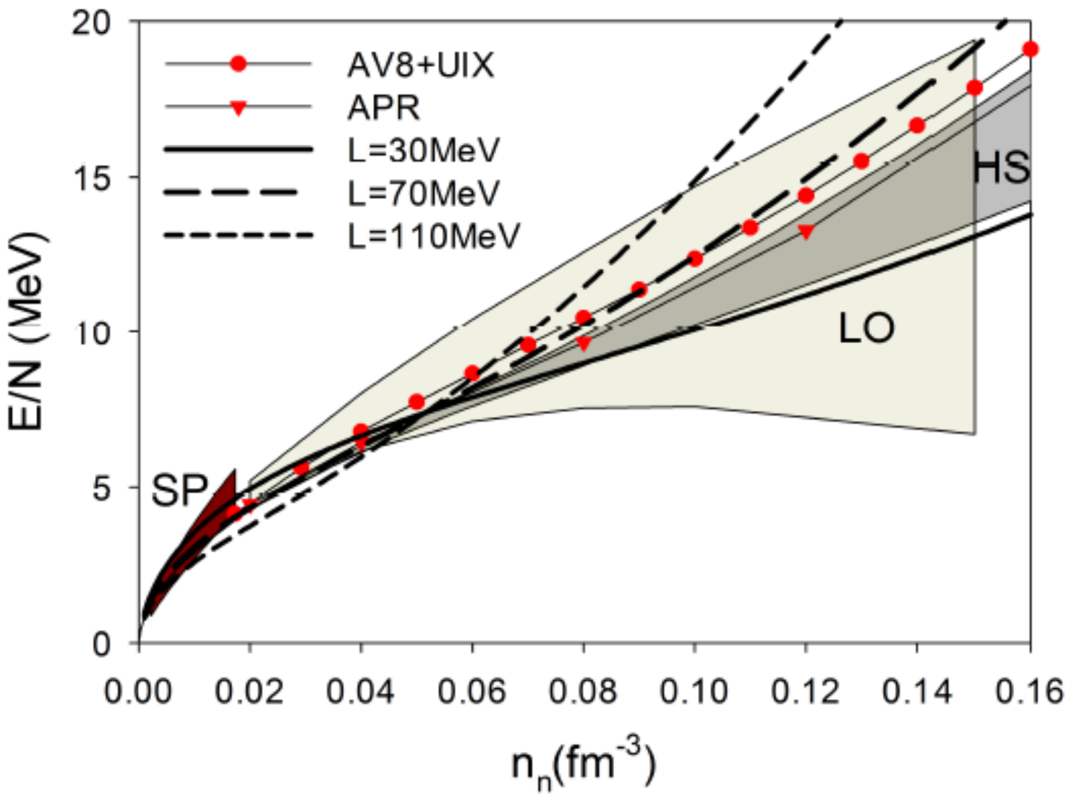
$$\begin{aligned}
\mathscr{L} &= \bar\psi\left[\gamma^\mu\left(i\partial_\mu - g_{\rm v}V_\mu - \frac{g_\rho}{2}\boldsymbol{\tau}\cdot\mathbf{b}_\mu - \frac{e}{2}(1+\tau_3)A_\mu\right) - (M-g_{\rm s}\phi)\right]\psi + \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - \frac{1}{2}m_{\rm s}^2\phi^2 \\
&- \frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}m_{\rm v}^2V^\mu V_\mu - \frac{1}{4}\mathbf{b}^{\mu\nu}\cdot\mathbf{b}_{\mu\nu} + \frac{1}{2}m_\rho^2\,\mathbf{b}^\mu\cdot\mathbf{b}_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - U(\phi, V_\mu, \mathbf{b}_\mu)\,,
\end{aligned}$$

$$U(\phi, V^\mu, \mathbf{b}^\mu) = \frac{\kappa}{3!}(g_{\rm s}\phi)^3 + \frac{\lambda}{4!}(g_{\rm s}\phi)^4 - \frac{\zeta}{4!}g_{\rm v}^4(V_\mu V^\mu)^2 - \Lambda_{\rm v}g_\rho^2\,\mathbf{b}_\mu\cdot\mathbf{b}^\mu g_{\rm v}^2V_\nu V^\nu$$

-7 parameters $\{g_{\rm s}, g_{\rm v}, g_\rho, \kappa, \lambda, \zeta, \Lambda_{\rm v}\}$

-2 purely isovector parameters g_ρ, $\Lambda_{\rm v}$

PNM sequence of EOSs

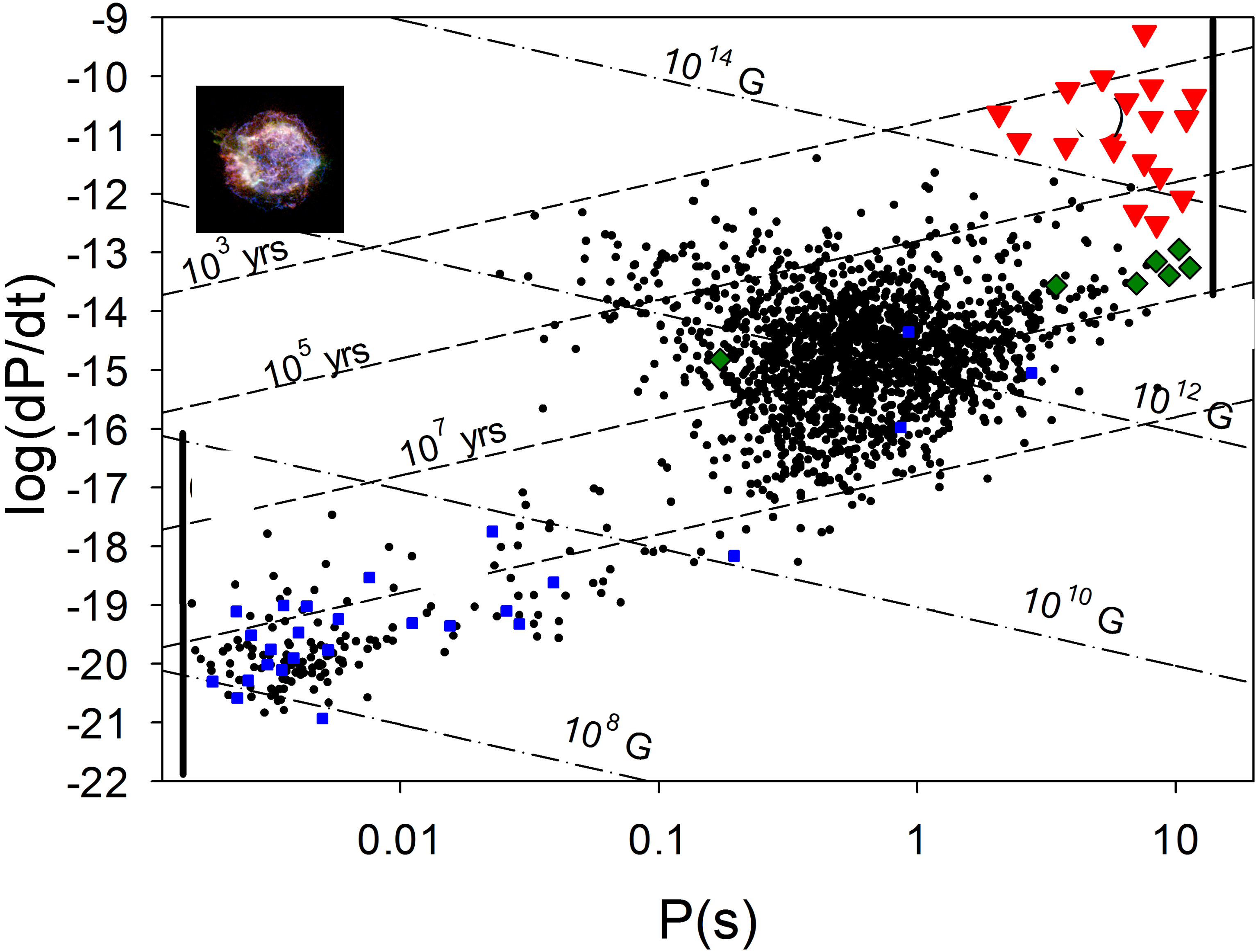


(SP - Schwenk 2005, HS - Hebeler 2010, LO - Gezerlis 2013, AV8+UIX - Gandolfi 2010, APR - Akmal 1998)

Consistently calculate:

- Crust EOS
- Crust composition
- Crust-core transition density/ Pressure
- Extent and sequence of pasta phases
- Core EOS/composition

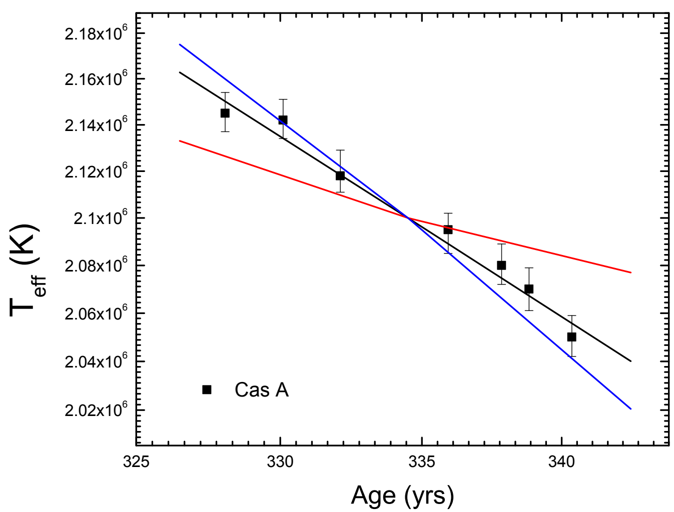
Observable I: Cooling of Cas A NS

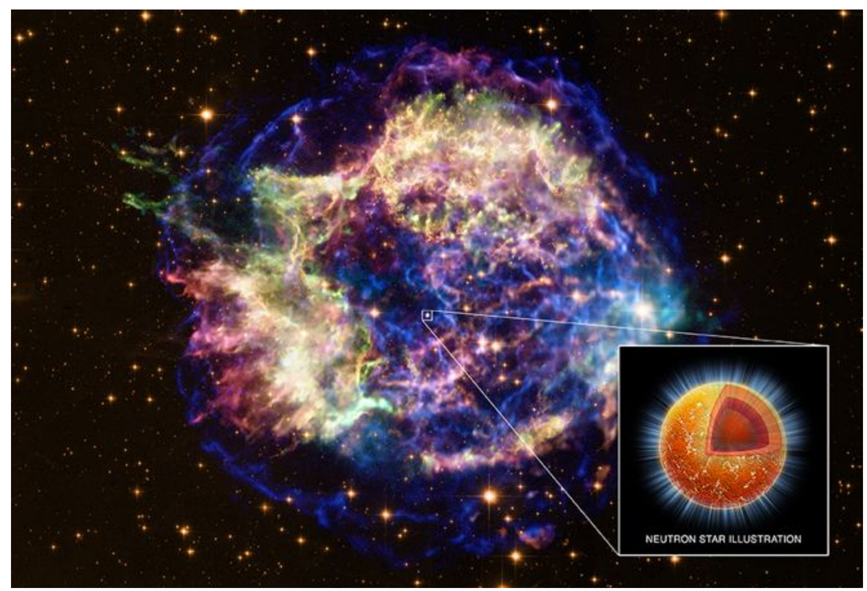


Cooling of Cas A NS

- Cas A NS: birth date 1680 ± 20yr (Fesen et al 2006)
- Thermal emission best fit* using a Carbon atmosphere model (Ho & Heinke 2009)
  ➔ $\langle T_{eff} \rangle \approx 2.1 \times 10^6$ K.
- Subsequent analysis of Chandra data taken over the previous decade ➔ evidence for rapid decrease in surface temperature by ≈ 4% (Heinke & Ho 2010).
- Detailed analysis of Chandra all X-ray detectors and modes ➔ 2-5.5% temperature decline over the same time interval (Elshamouty et al. 2013).
- Definitive measurements difficult (surrounding bright and variable supernova remnant)

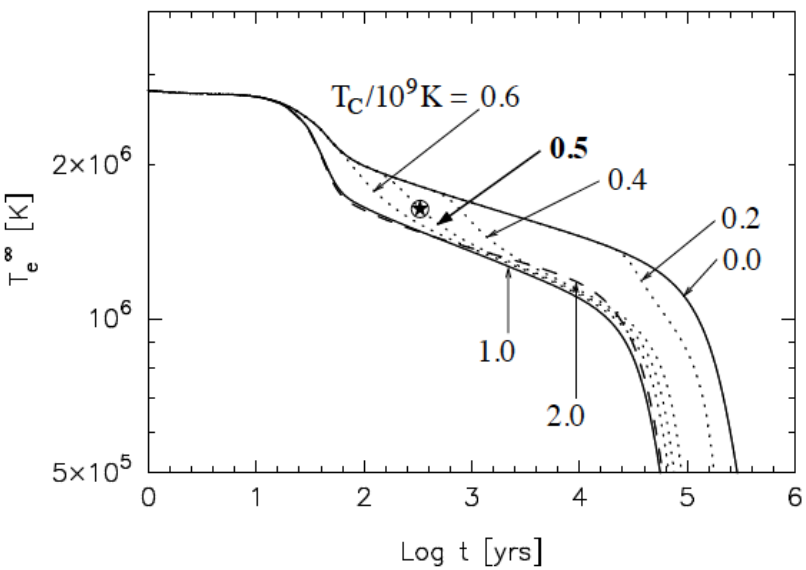
* "best" means most consistent with an emitting area of order the total neutron star surface



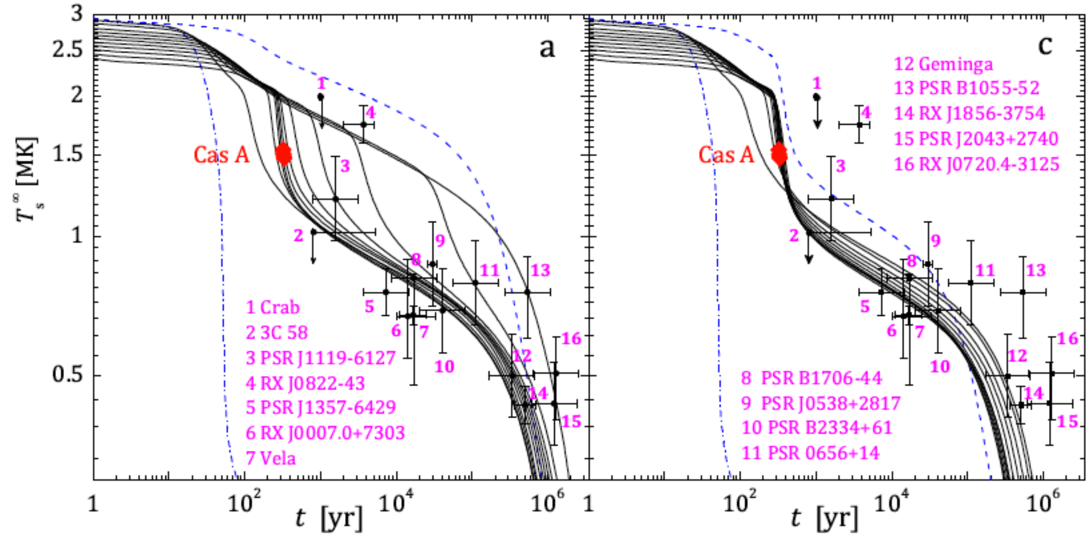


Cooling of Cas A NS: Evidence for an astrophysical superfluid transition?

Page et al 2011

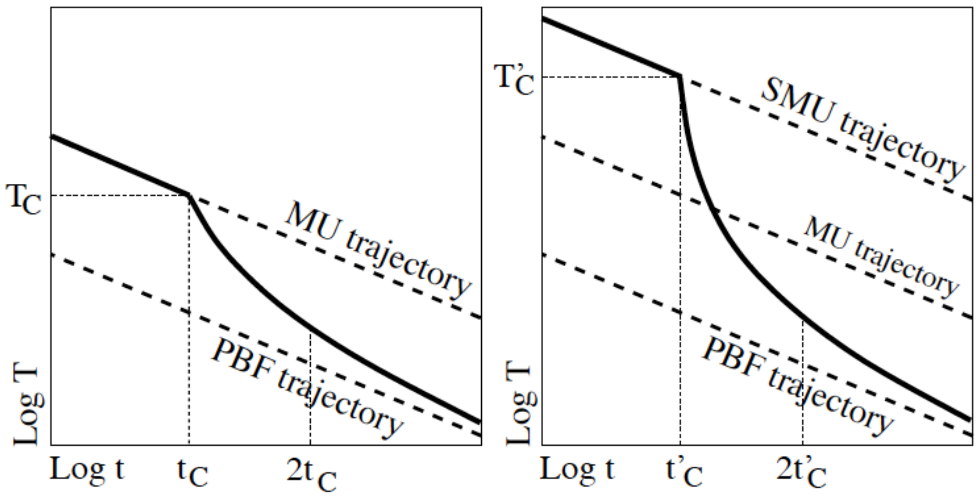


Shternin et a 2011



- Minimal cooling paradigm (MCP) (Page et al 2004) (only nucleonic components; fast ν-emission processes (dUrca) excluded):
- Rapid cooling of the Cas A NS (CANS) from enhanced neutrino emission from neutron $^3P_2$ Cooper pair breaking and formation (PBF) in the core (superfluid phase transition)
- Alternatives: medium modifications to standard ν-emission processes, quark phases… (Blaschke et al. 2012; Sedrakian 2013)

Cooling of Cas A NS: Evidence for an astrophysical superfluid transition?



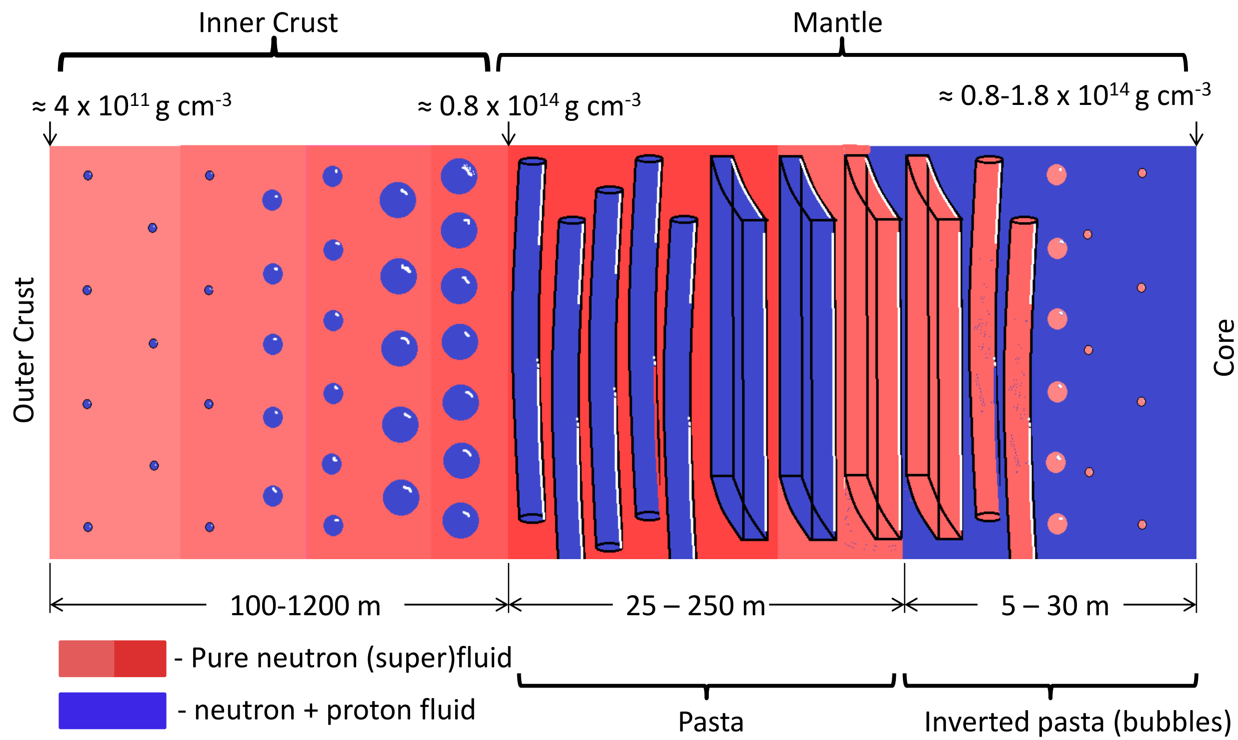
- Max. of critical temperature T_c^{max} controls age at which star enters PBF cooling phase
- Core temperature at onset of PBF cooling phase, T_{PBF}, controls subsequent cooling *rate* > make steeper by suppressing mUrca process with proton superconductivity throughout core.

Cooling of Cas A NS: Parameter Space in Minimal Cooling Scenario

In the Minimal Cooling Paradigm, three additional parameters affect the cooling trajectories of the NSs (Page et al.2004):

- The equation of state (EOS) of nuclear matter (NM).
- The mass of light elements in the atmosphere ΔM_{light} parameterized as $\eta = \log(\Delta M_{light})$ (best fit $-13 < \eta < -8$ (Yakovlev et al. 2011))
  - More light elements means higher thermal conductivity and lower core temperature for a given T_{eff}.
- The mass of Cas A NS ≈ 1.25 – $2M_{SUN}$ with a most likely value of $1.65M_{SUN}$ Yakovlev et al. 2011).

ν-emission in Nuclear pasta: Bubble cooling processes

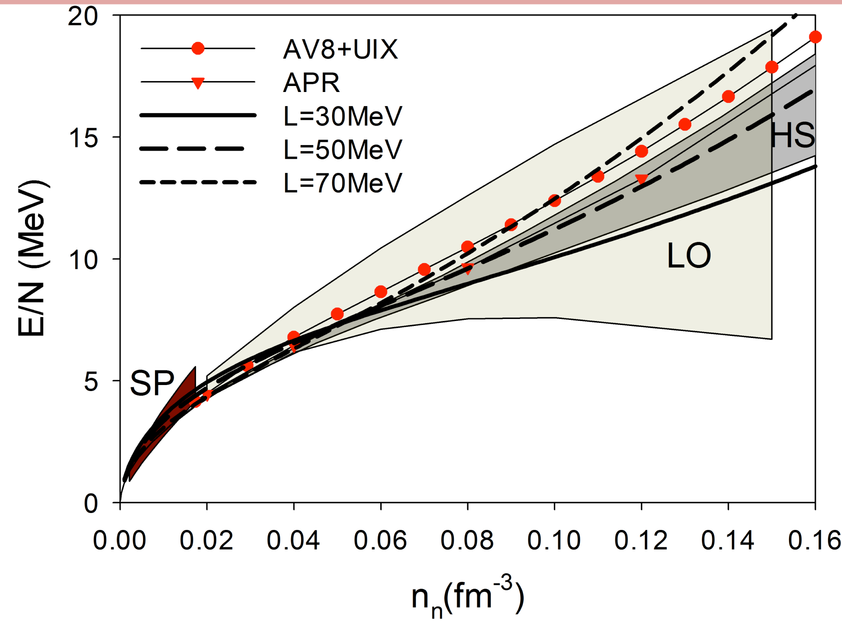


- Neutron scattering off of bubble phases of pasta can lead to:
  dUrca (Gusakov et al. 2004)
  neutrino and anti-neutrino pair emission (Leinson 1993)
- Luminosity comparable with Modified Urca at core temperatures around onset of PBF cooling phase

$$L_\nu^{BCP} \sim 10^{40} T_9^6 \qquad L_\nu^{MU} \sim 10^{40} T_9^8$$

$$T_9 = T_{\rm core}/10^9 {\rm K}$$

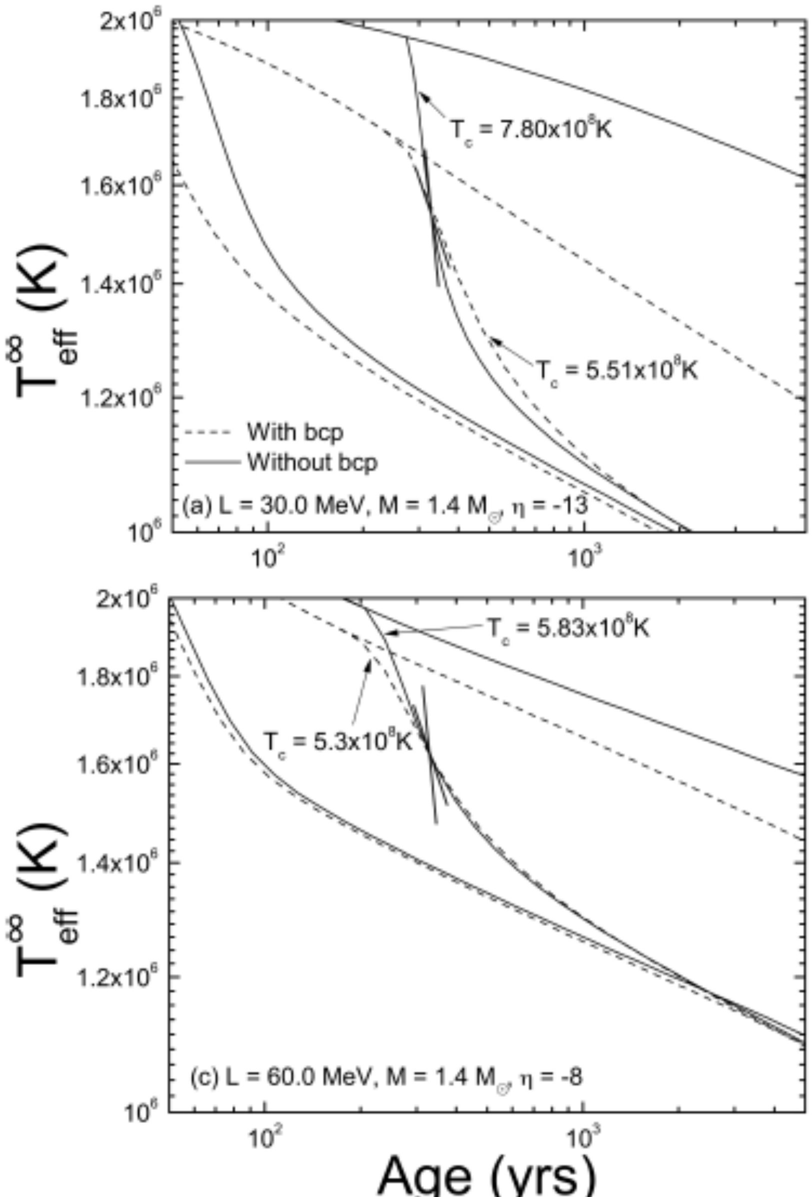
Model



(SP - Schwenk 2005, HS - Hebeler 2010, LO - Gezerlis 2013, AV8+UIX - Gandolfi 2010, APR - Akmal 1998)

- NS Crust and core EOSs and compositions calculated consistently using SkIUFSU Skyrme model (Fattoyev et al. 2012) which is fit to nuclear properties and ab-initio pure neutron matter calculations.
- Two Skyrme parameters are adjusted to vary the symmetry energy J and its density slope L at n_0. EOSs were created with L between 30MeV and 80MeV.
- With a fixed stellar mass, as L increases, the stellar radius and crust thickness increases and the fraction of the crust by mass composed of the bubble phases decreases (Newton et al. 2013).
- Cooling trajectories calculated using Dany Page's public code NSCool

Results



Even the lowest cooling rate (2%) inferred by Elshamouty et al is relatively rapid, favoring a relatively high core temperature and:

- Smaller value of L (smaller radii)
- Smaller stellar masses M
- Smaller η
- Less cooling from BCPs.

Newton, Murphy, Hooker, Li, ApJL 2013

Cas A NS Cooling: Results and Summary

$M(M_\odot)$	η=-8; BCP	η=-13; BCP	η=-8; no BCP	η=-13; no BCP
1.25	$\lesssim 45$	-	$\lesssim 70$	$\lesssim 55$
1.40	-	$\lesssim 35$	$\lesssim 55$	$\lesssim 55$
1.60	-	$\approx$ 35-45	-	$\approx$ 35-55
1.80	-	-	-	-

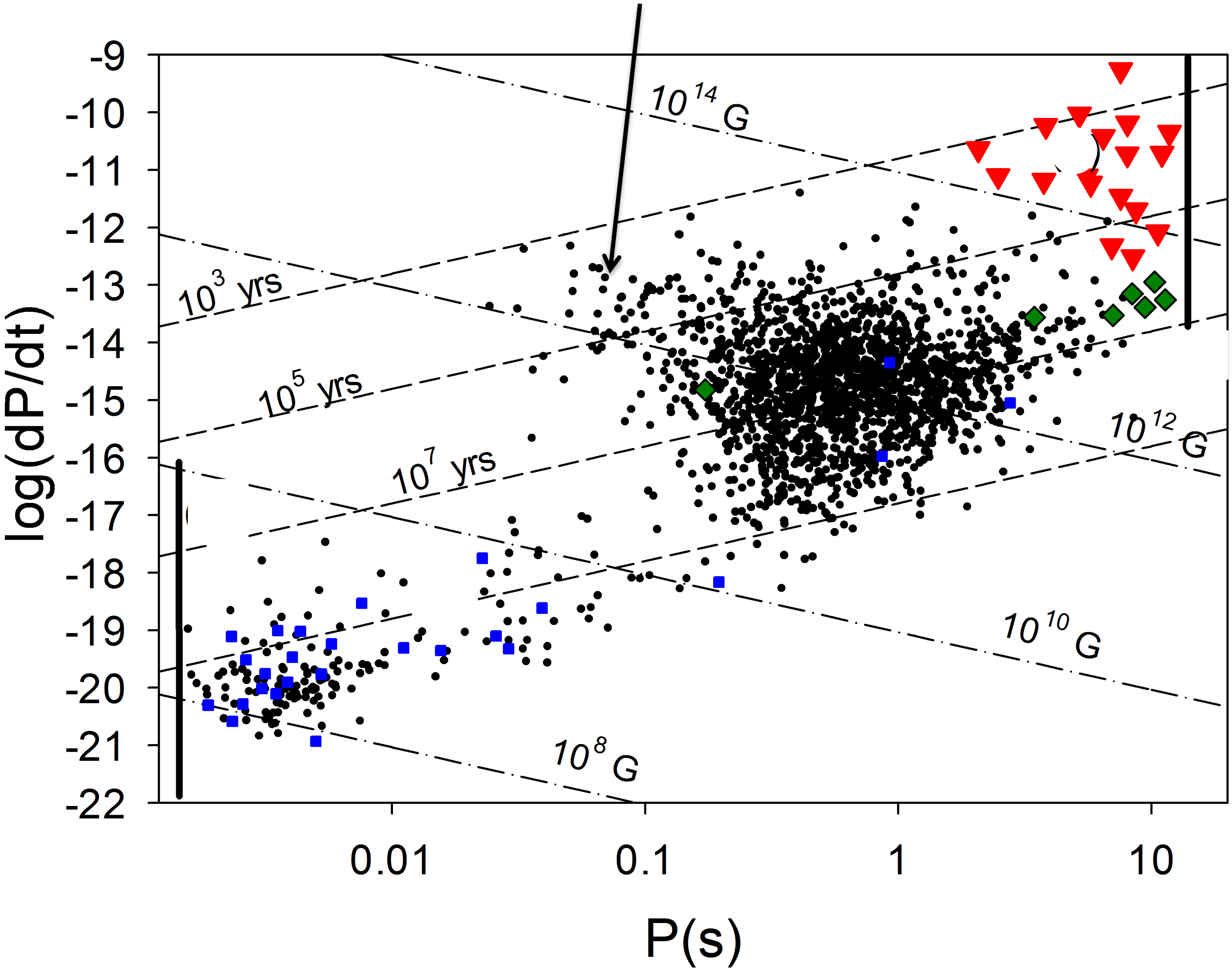
Ranges of L for which model cooling trajectories fall within the inferred rate from Elshamouty et al 2013

- Within minimal cooling paradigm, and using the inferred Cas A NS cooling rate from Elshamouty et al (2013), L < 70 MeV
- *With the addition of enhanced cooling from ν-emission processes in pasta phases* L < 45 MeV – i.e. cooling from the pasta phases can have an observable effect

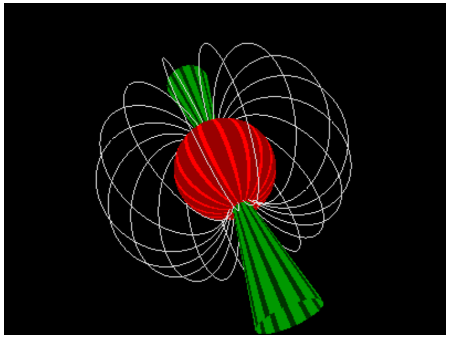
CAVEATS

- Carbon atmosphere model preferred largely because it results in emitting area of order neutron star size.
- Enhanced superfluidity in crust would suppress ν-emission processes in pasta phases (gap parameter space not explored here).
- Posselt et al; arxiv:1311.0888 – Chandra Cas A data consistent with *no cooling* in past decade!

Observable I: Glitches in the Vela pulsar



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

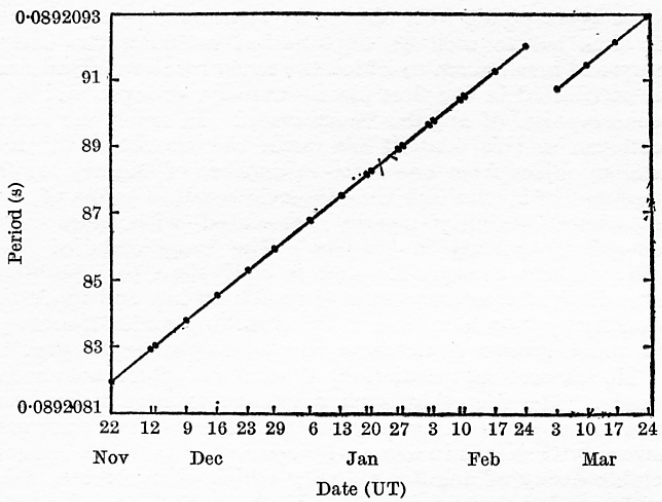


Fig. 1. The barycentric period of *PSR* 0833–45 as observed from November 22, 1968, to March 24, 1969, showing the 134 ns decrease between February 24 and March 3.

Reichley, Downs; Nature 1969

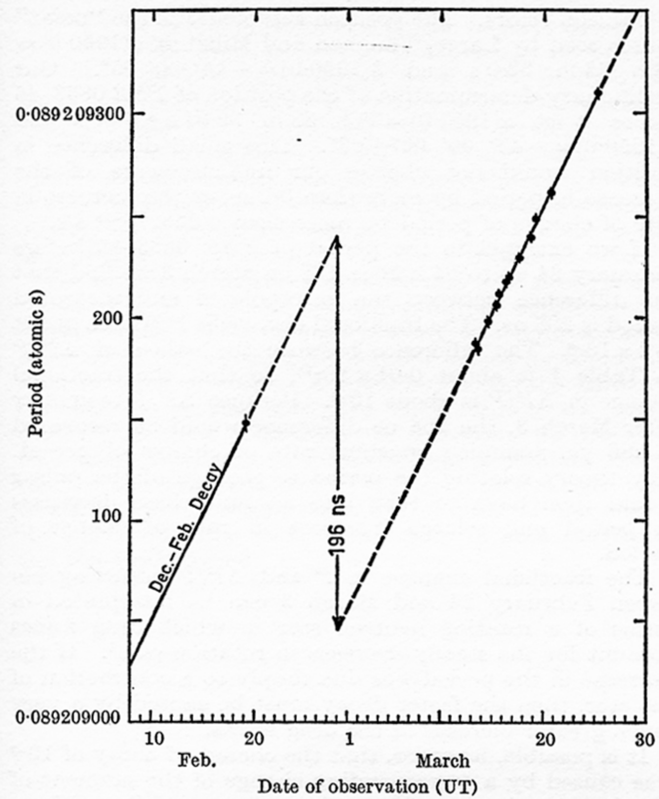
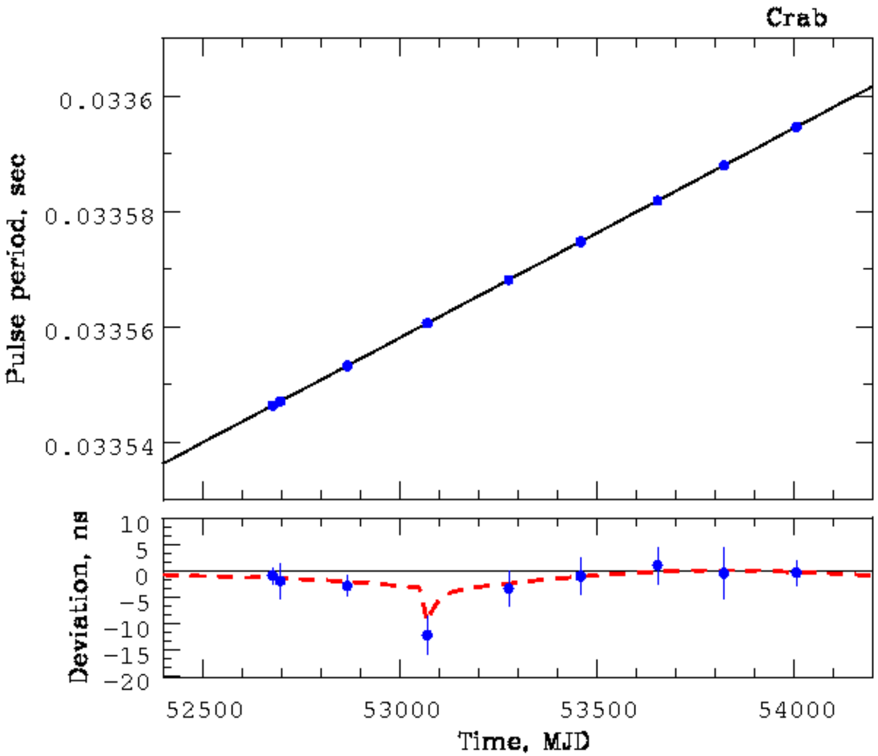


Fig. 1. Heliocentric period of *PSR* 0833–45 observed in February and March 1969, based on position α 08 h 33 m 39·0 s, δ −45° 00′ 05·0″ (epoch 1950·0) (ref. 3). The rate of increase of the period was 10·69±0·20 ns day⁻¹ between December 8, 1968, and February 19, 1969. Since March 13, 1969, the rate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

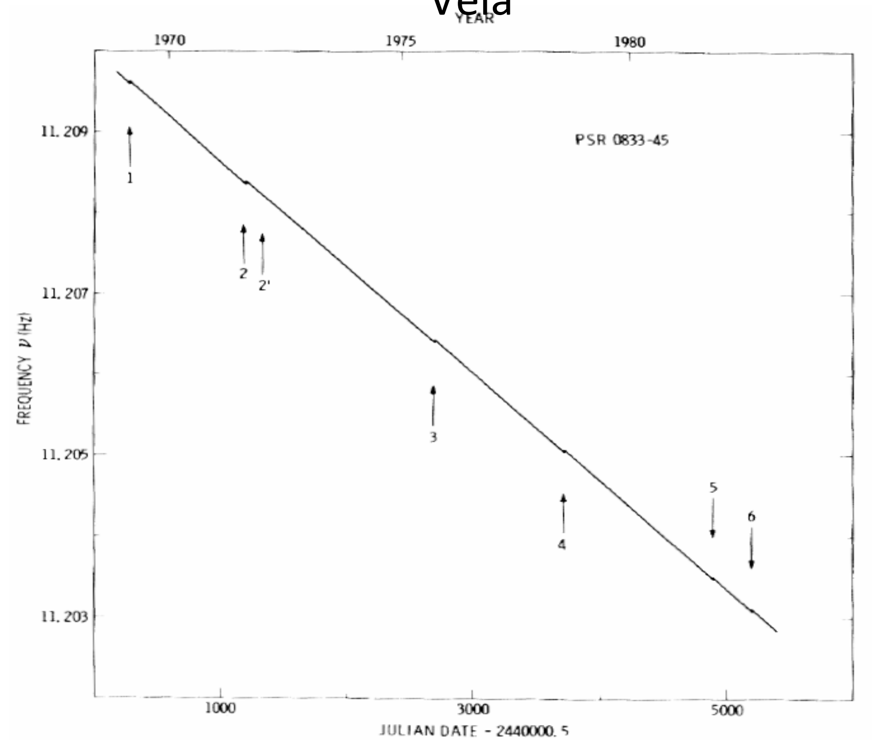
Pulsar glitches: the observations

Crab



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

Vela



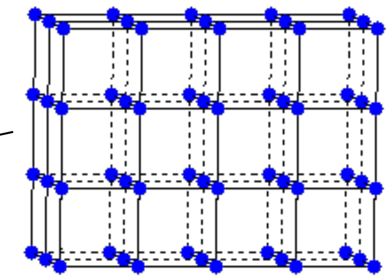
$\Delta\Omega/\Omega \approx 10^{-6}$, $\Delta t_g \sim 1000$ days

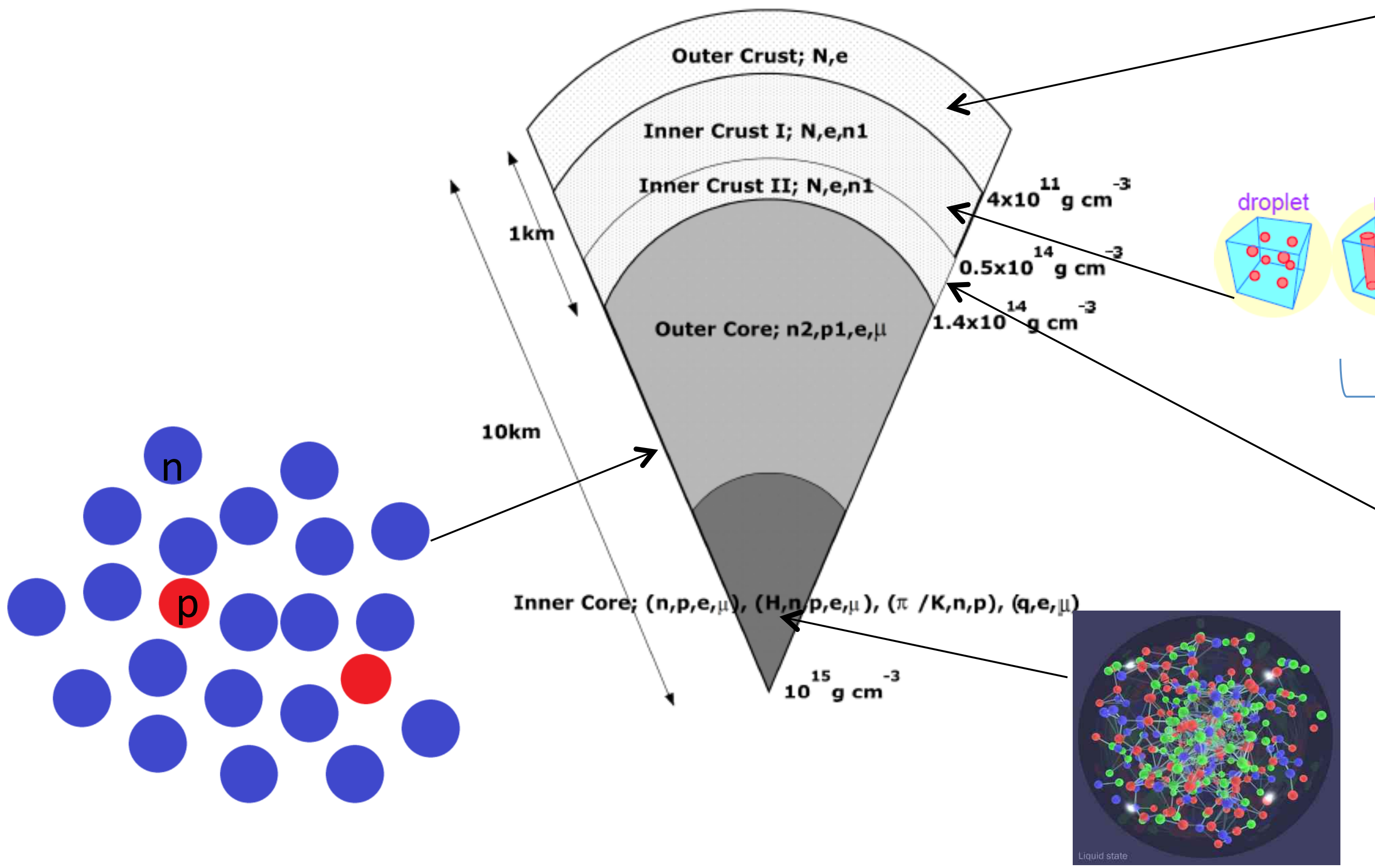
- Activity parameter: $A_g = (1/T_{obs})\,\Sigma\Delta\Omega/\Omega$ = average rate of relative spin-up due to glitches
  - Crab: $A_g \sim 10^{-9}\,yr^{-1}$
  - Vela: $A_g \sim 10^{-7}\,yr^{-1}$

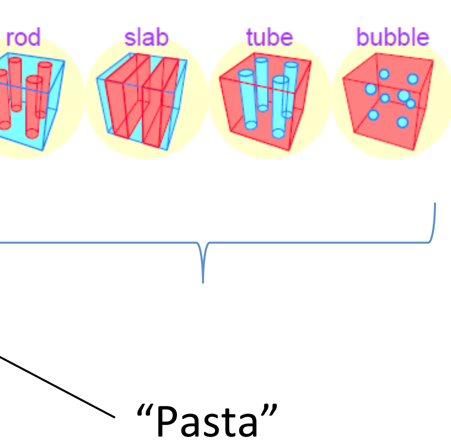
  Espinoza et al 2011

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?

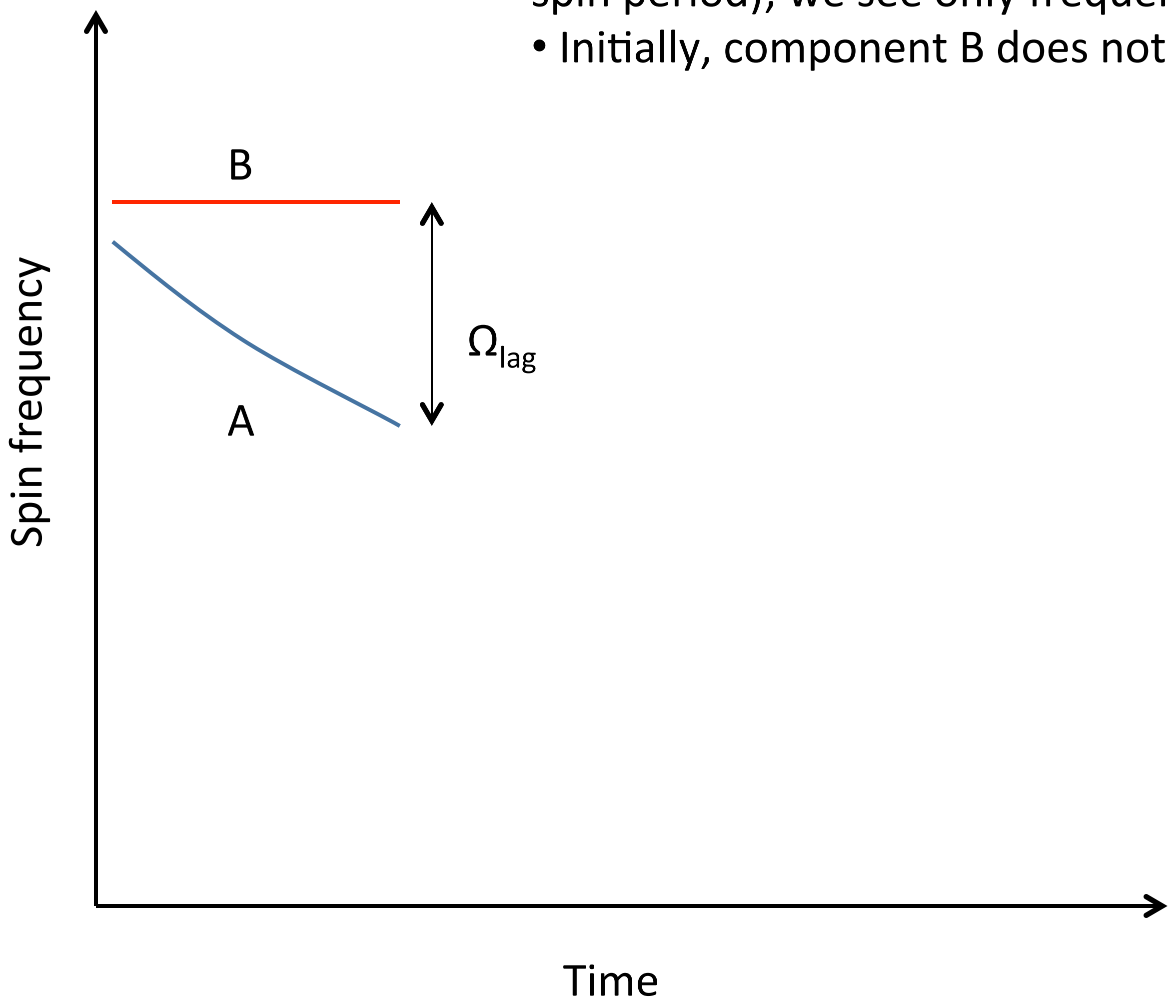




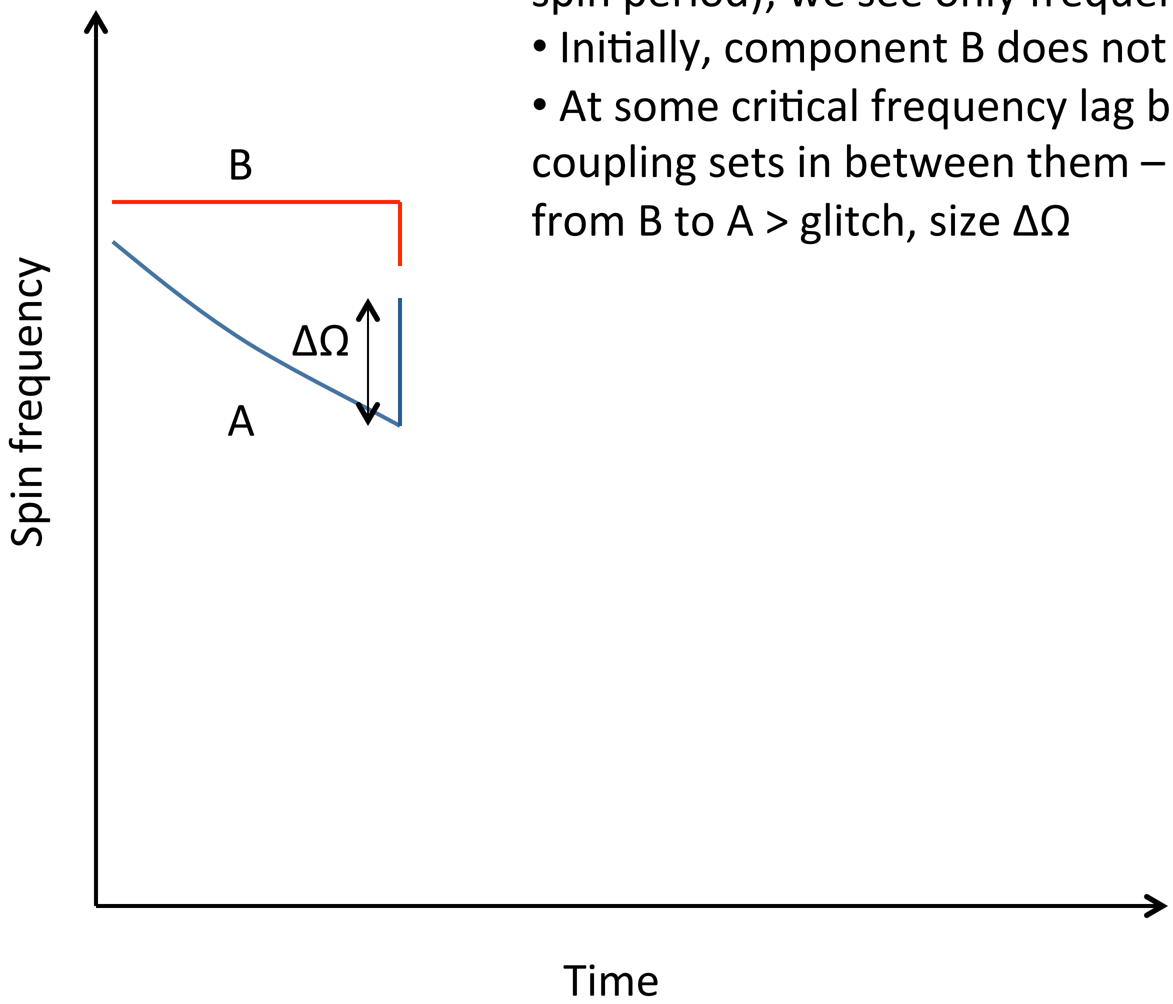


Pulsar glitches: the two component model

- 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



Pulsar glitches: the two component model



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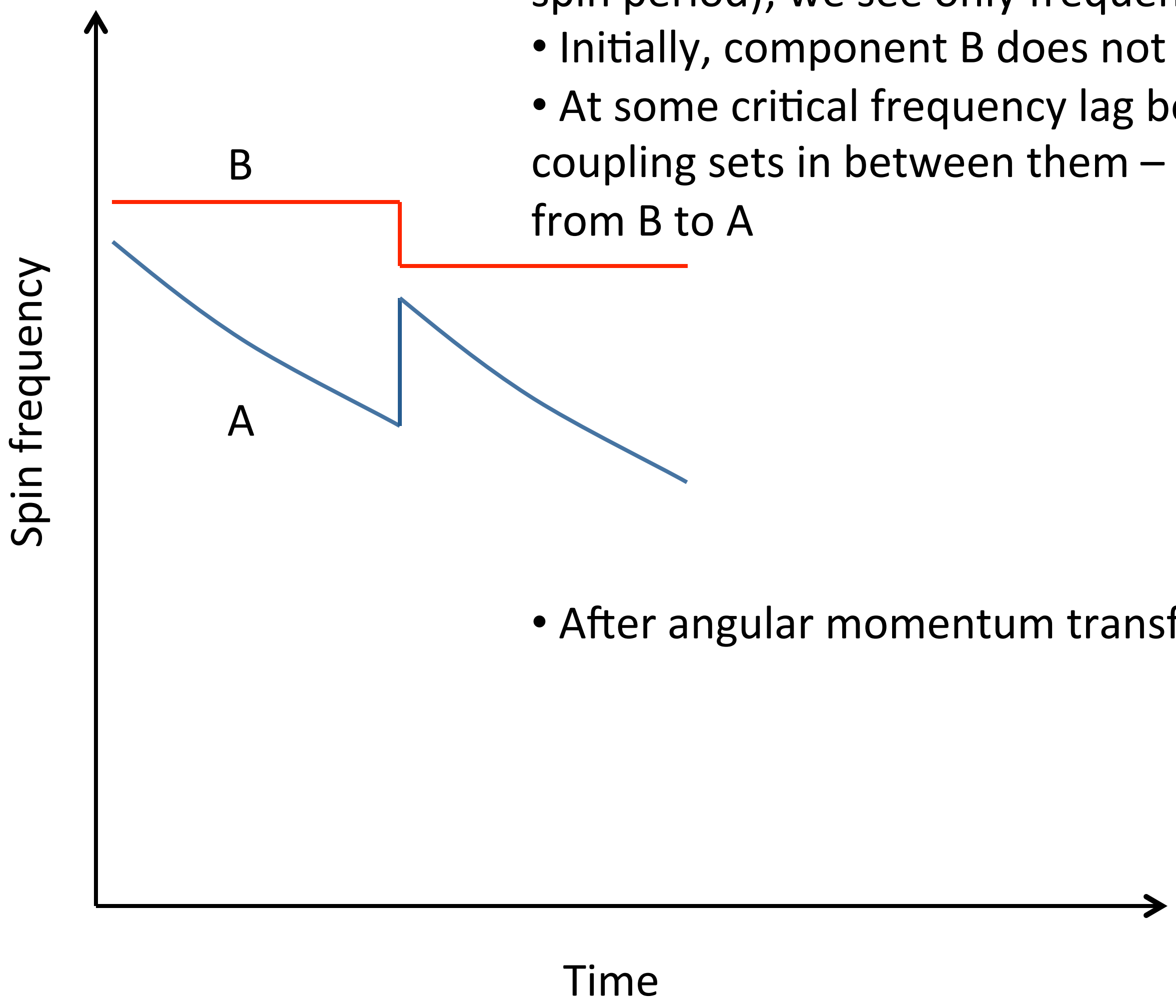
- The B-field is coupled to component A on short timescales (<< spin period); we see only frequency of component A
- Initially, component B does not couple to A
- At some critical frequency lag between A and B, Ω_{lag}, a strong coupling sets in between them – angular momentum transferred from B to A > glitch, size $\Delta\Omega$

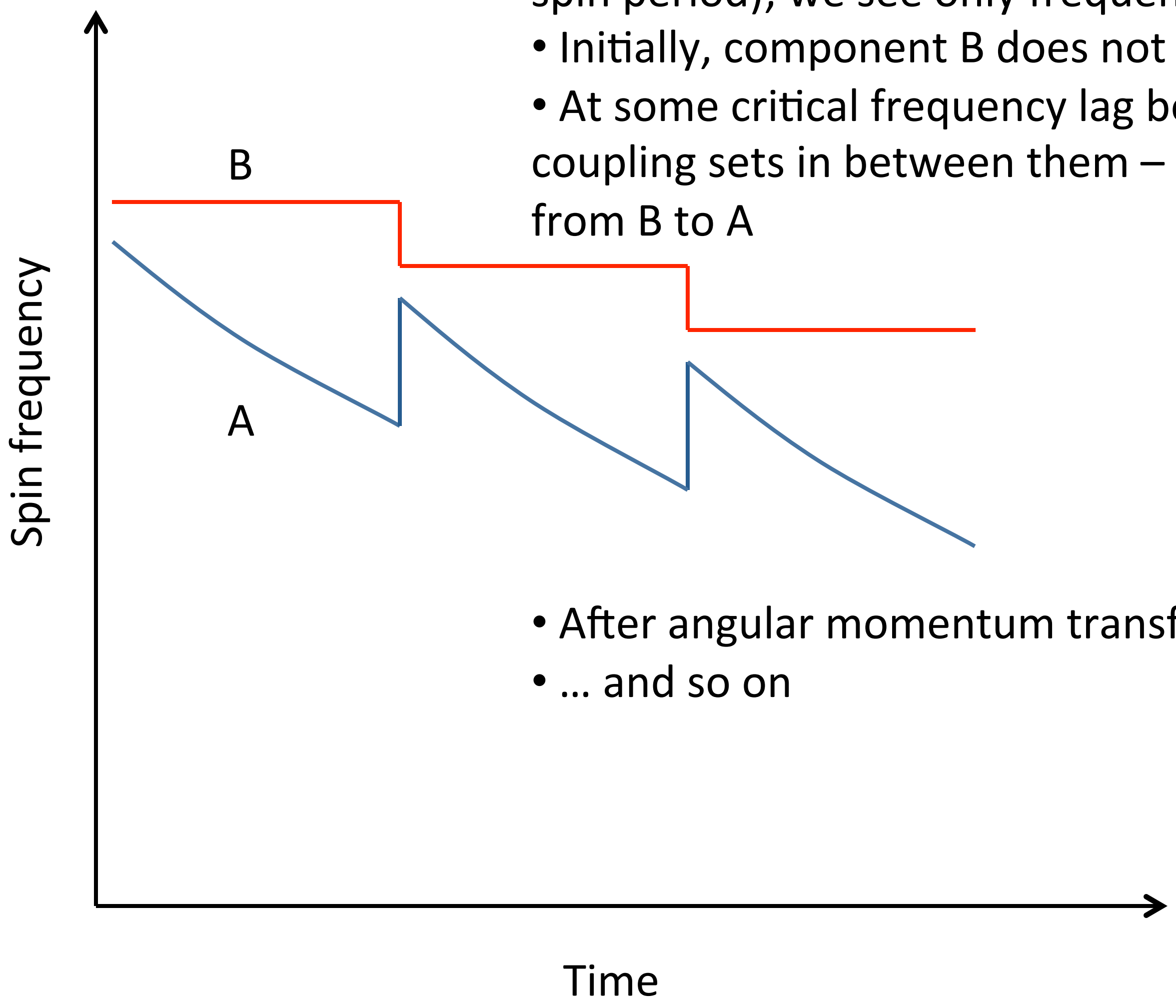
Pulsar glitches: the two component model



- 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
- 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

- After angular momentum transfer, the components decouple

Pulsar glitches: the two component model



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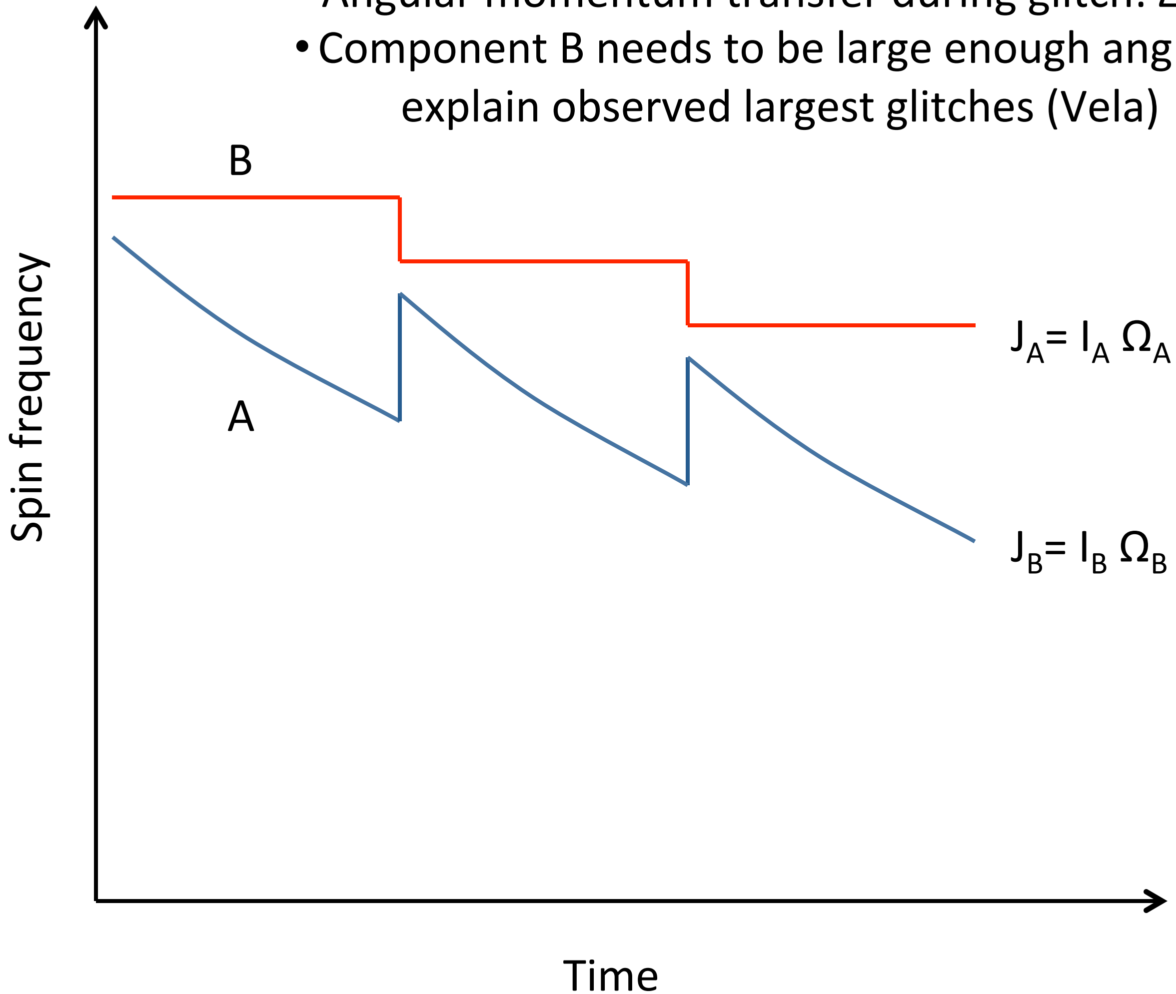
- Initially, component B does not couple to A
- At some critical frequency lag between A and B, Ω_{lag}, a strong coupling sets in between them – angular momentum transferred from B to A

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

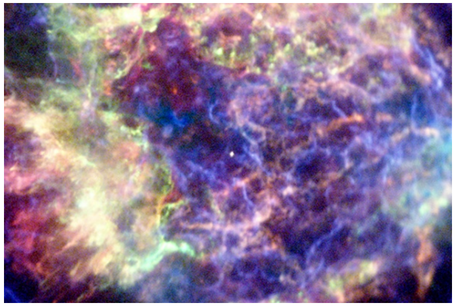
Pulsar glitches: the two component model

- 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)

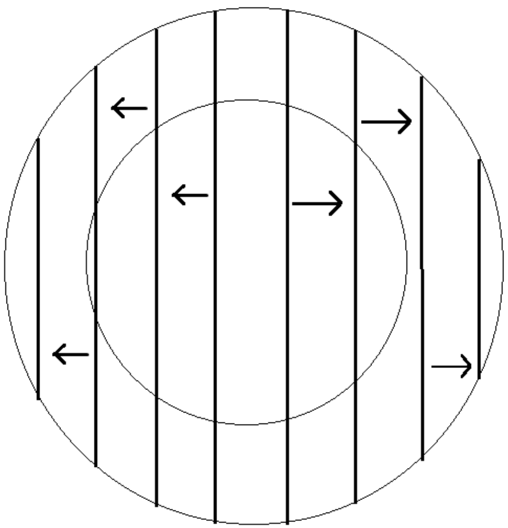


Pulsar glitches: the role of core neutron superfluidity

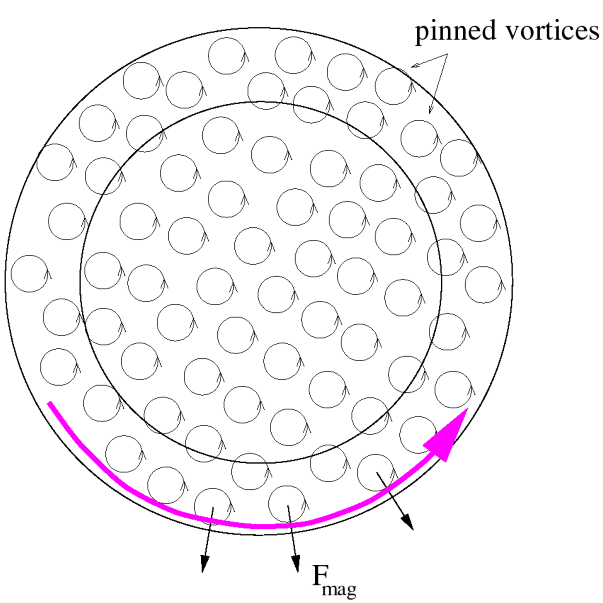
- Neutrons in core and crust expected (from theory) to be superfluid for pulsars older than ≈ 100yr
- Some supporting evidence from rapid Cas A cooling (Shternin et al 2011, Page et al 2011)
- Superfluid component cannot support bulk rotation (gap suppresses interactions which cause, e.g., normal friction)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



Polar cross section

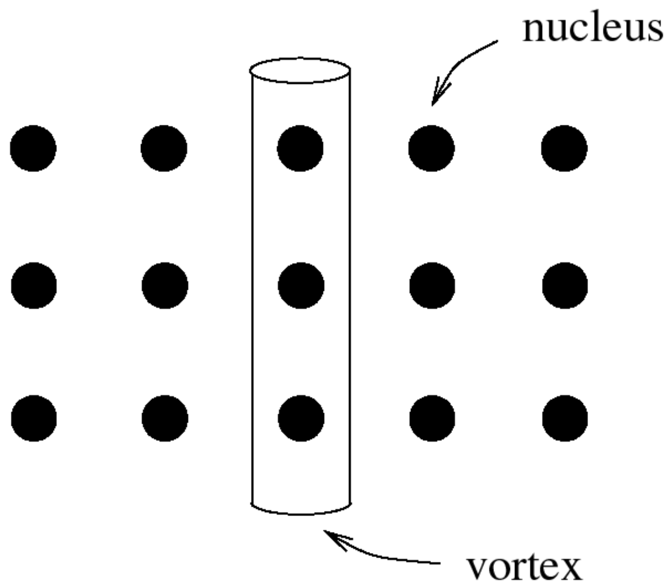


Equatorial cross section



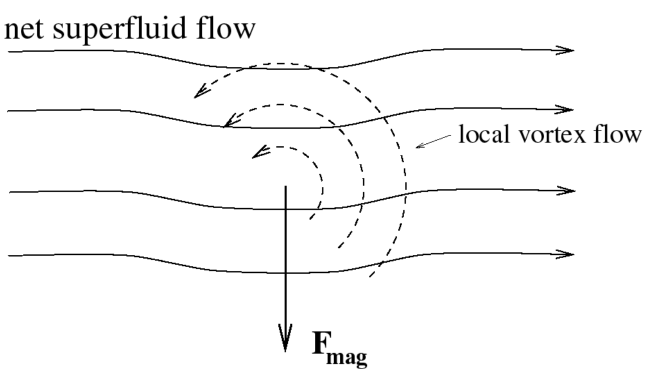
- Spacing of n vortices ~ 10^{-2} cm
- As frequency decreases, vortices move out radially from the spin axis
- Protons entrained by vortices
  - electron scattering couples vortices to crust on timescales $t_{mf} \approx 10\text{-}10{,}000$s
  - Fraction of core neutrons coupled to crust on glitch timescales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

Pulsar glitches: the role of crust neutron superfluidity



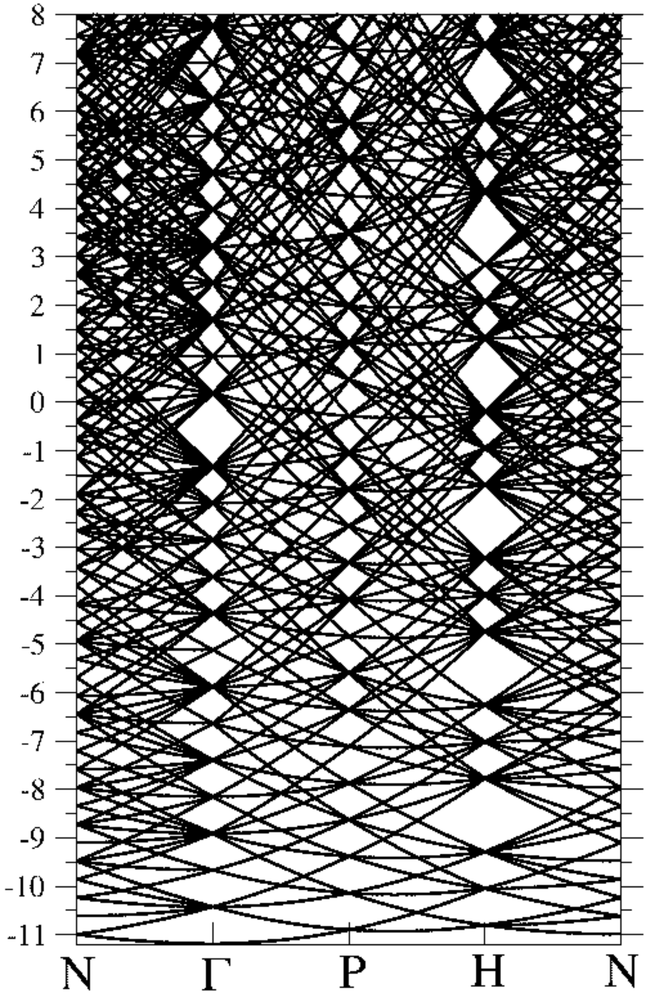
- Energy of nucleus-vortex interaction either favors vortex cores threading nuclei *or* between nuclei in inner crust (~3 MeV/nucleus)
- Either way, work must be done by an external force to move vortices through the lattice
- The vortices are said to be *pinned*

- 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)



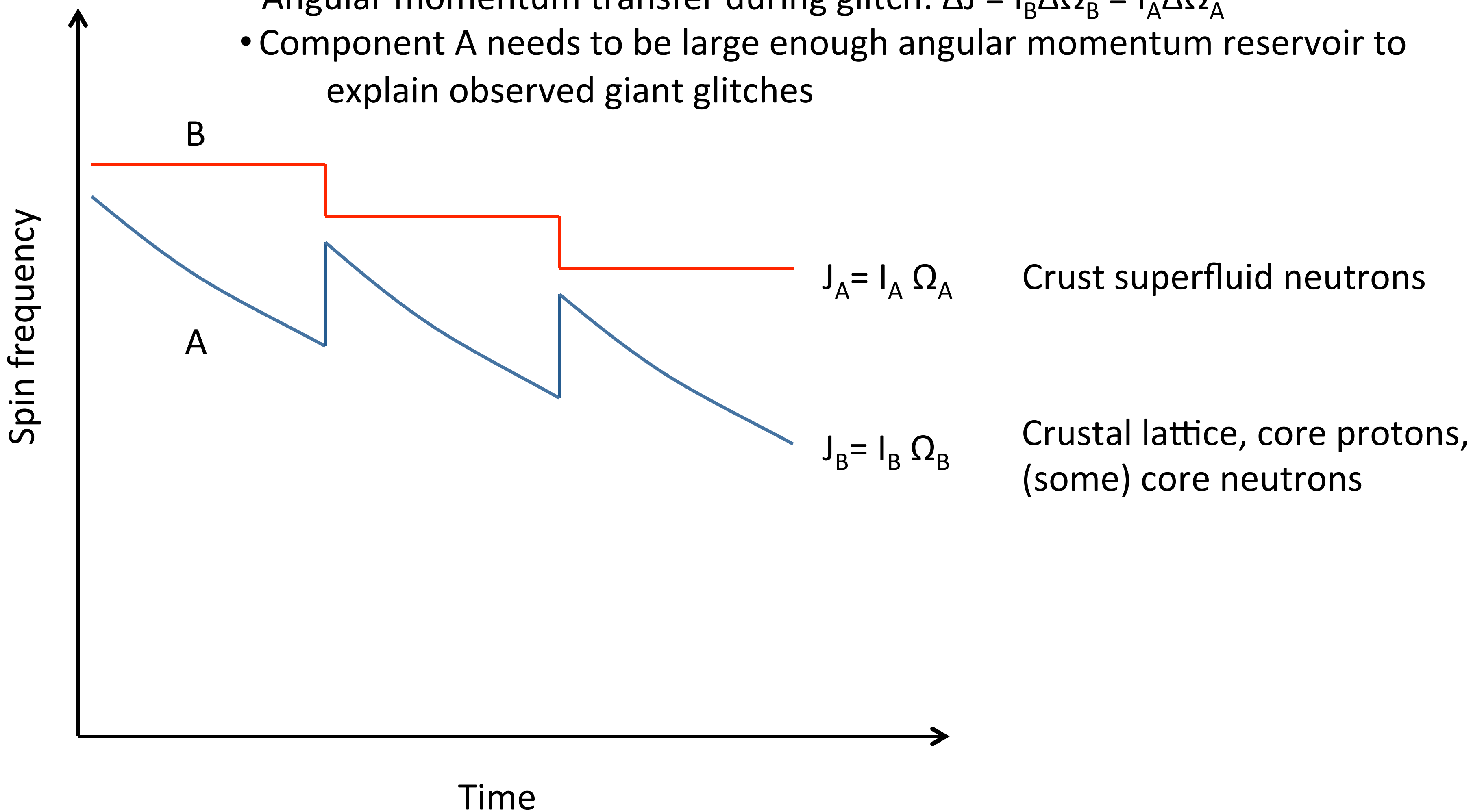
- Bragg scattering of neutrons off nuclei in crust
- Results in neutron band structure analogous to electrons in metals
- Couples 80% free neutrons to lattice

$$m_n^\star = m_n \frac{n_n^{\rm f}}{n_n^{\rm c}}.$$

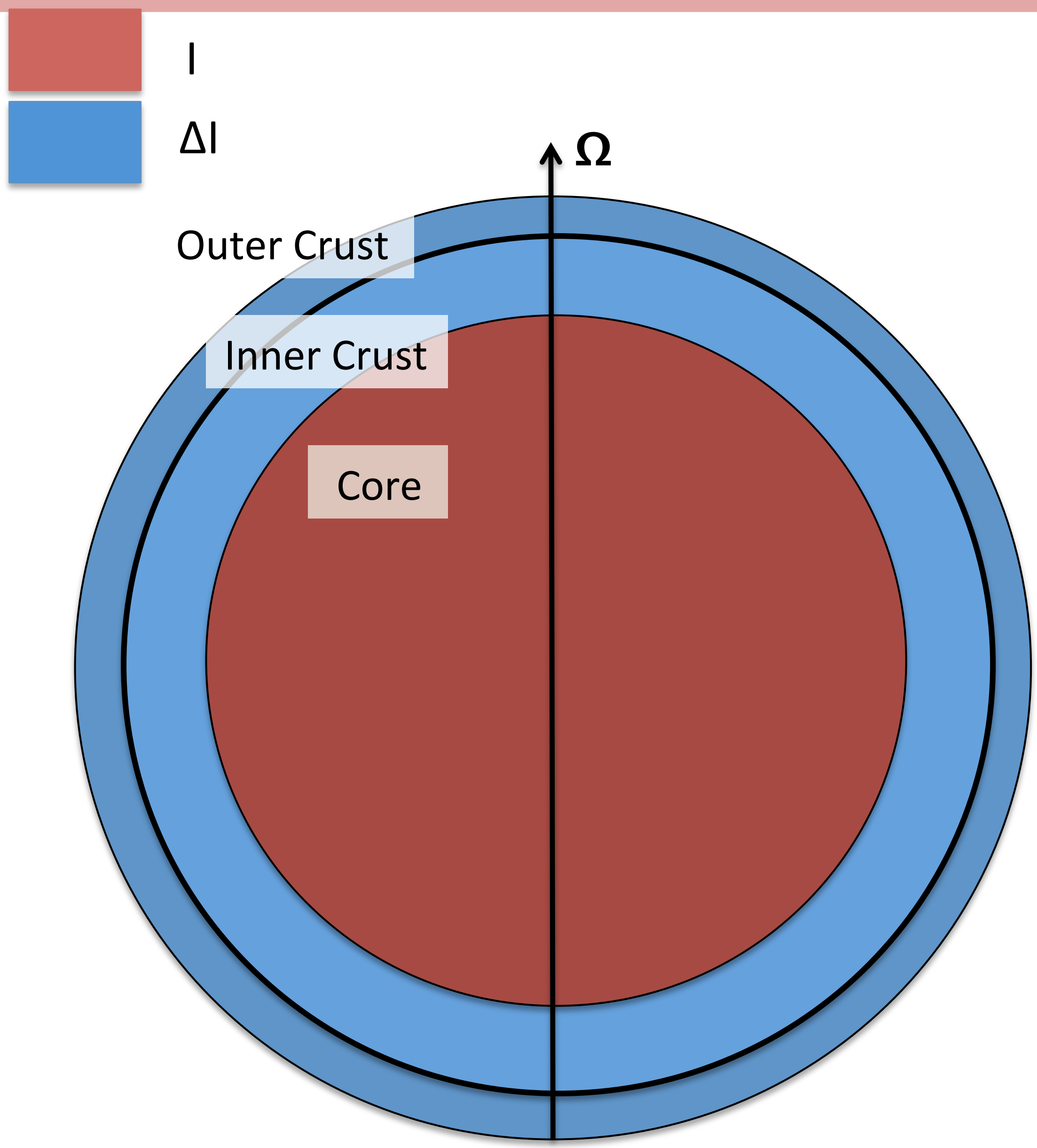
$\bar{n}$ (fm^{-3})	Z	A	$n_n^{\rm f}/n_n$ (%)	$n_n^{\rm c}/n_n^{\rm f}$ (%)	$m_n^\star/m_n$
0.0003	50	200	20.0	82.6	1.21
0.001	50	460	68.6	27.3	3.66
0.005	50	1140	86.4	17.5	5.71
0.01	40	1215	88.9	15.5	6.45
0.02	40	1485	90.3	7.37	13.6
0.03	40	1590	91.4	7.33	13.6
0.04	40	1610	88.8	10.6	9.43
0.05	20	800	91.4	30.0	3.33
0.06	20	780	91.5	45.9	2.18
0.07	20	714	92.0	64.6	1.55
0.08	20	665	104	64.8	1.54

Pulsar glitches: the two component model

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



Confronting model with observation

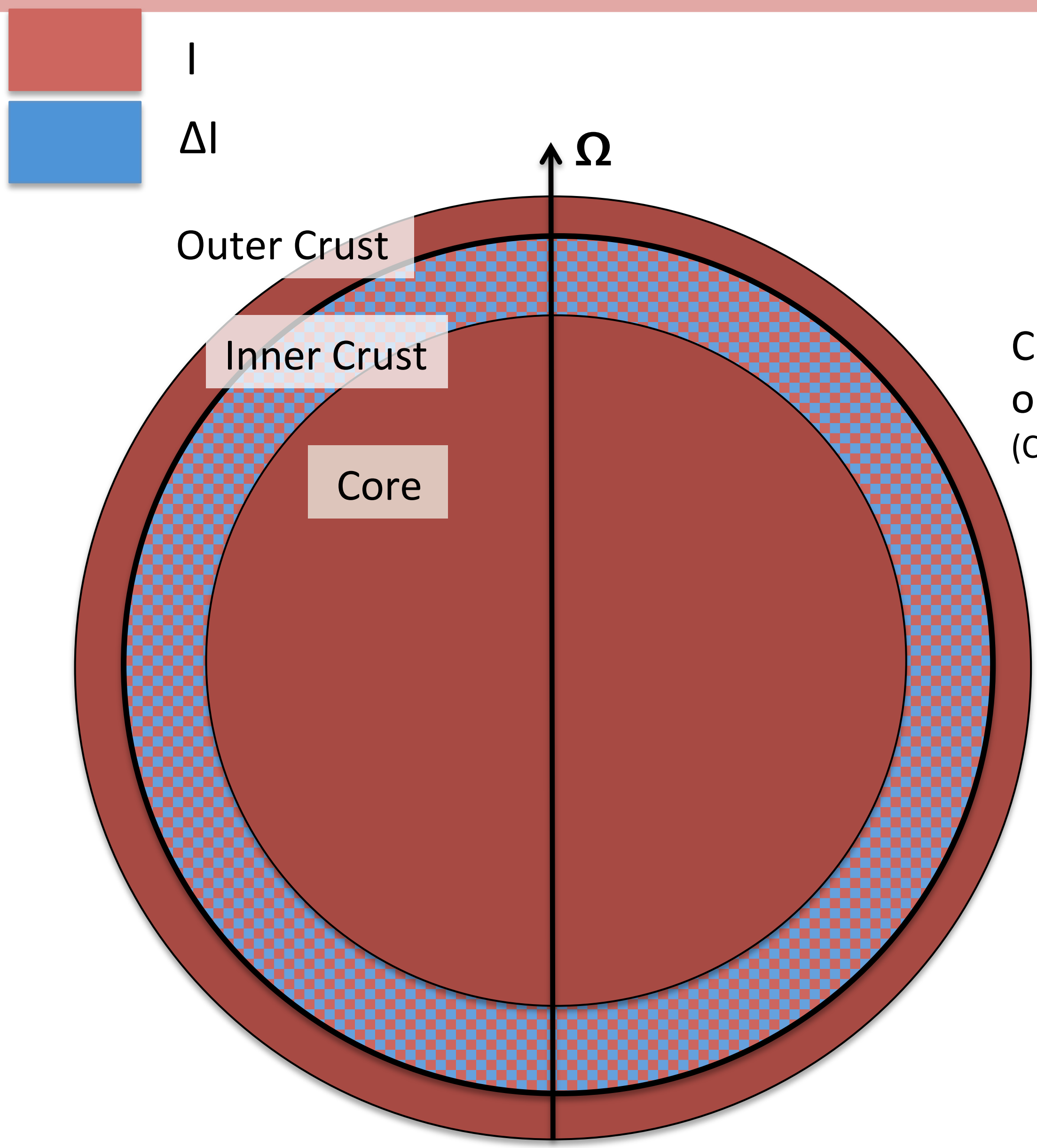


$$\Delta I/I \geqslant \frac{\bar{\Omega}}{|\dot{\Omega}|}\mathcal{A} = 0.016$$

(Link, Epstein, Lattimer; PRL83 1999)

OK for many reasonable EOSs

Confronting model with observation



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

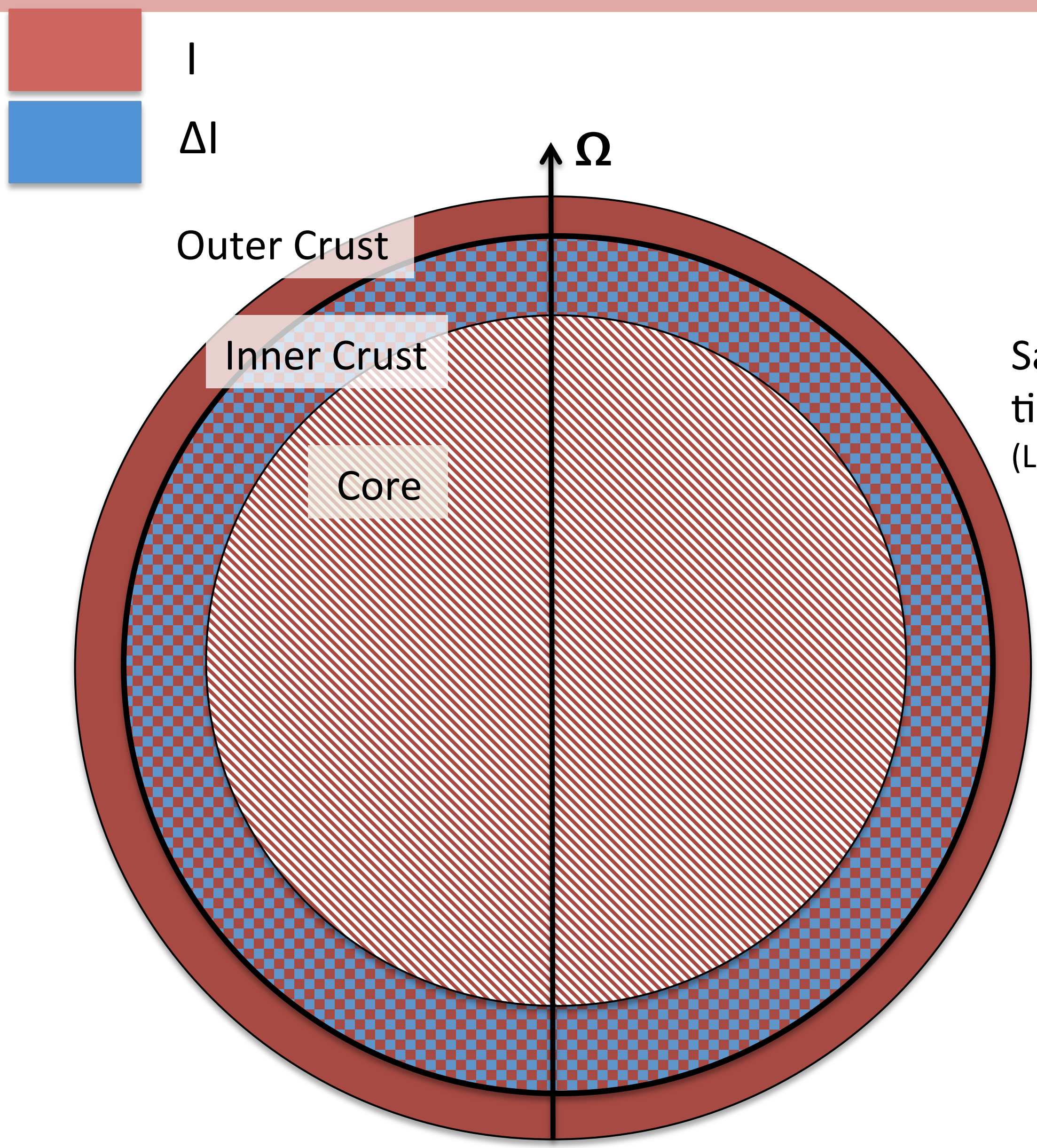
(Link, Epstein, Lattimer; PRL83 1999)

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



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

(Link, Epstein, Lattimer; PRL83 1999)

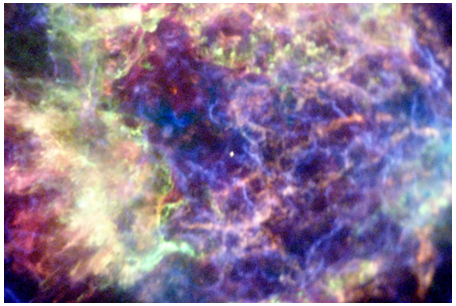
Saved by core superfluid coupling on timescales larger than glitch rise time?
(Link 2012; Haskell et al 2012; Seveso et al 2012)

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

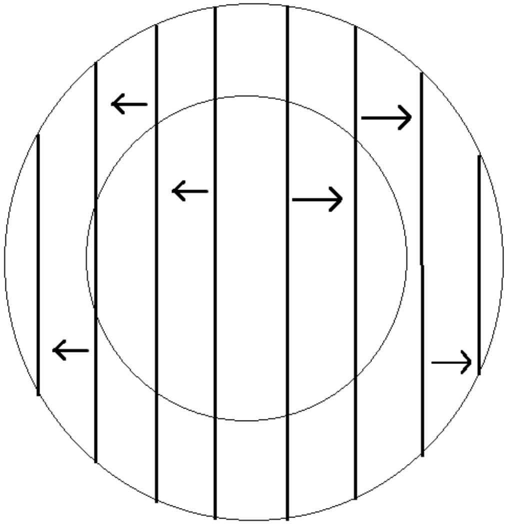
OK for most EOSs

Pulsar glitches: the role of core neutron superfluidity

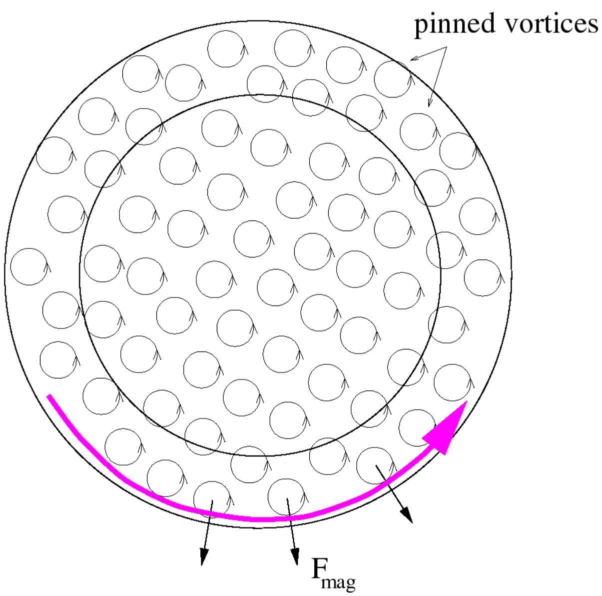
- Neutrons in core and crust expected (from theory) to be superfluid for pulsars older than ≈ 100yr
- Some supporting evidence from rapid Cas A cooling (Shternin et al 2011, Page et al 2011)
- Superfluid component cannot support bulk rotation (gap suppresses interactions which cause, e.g., friction)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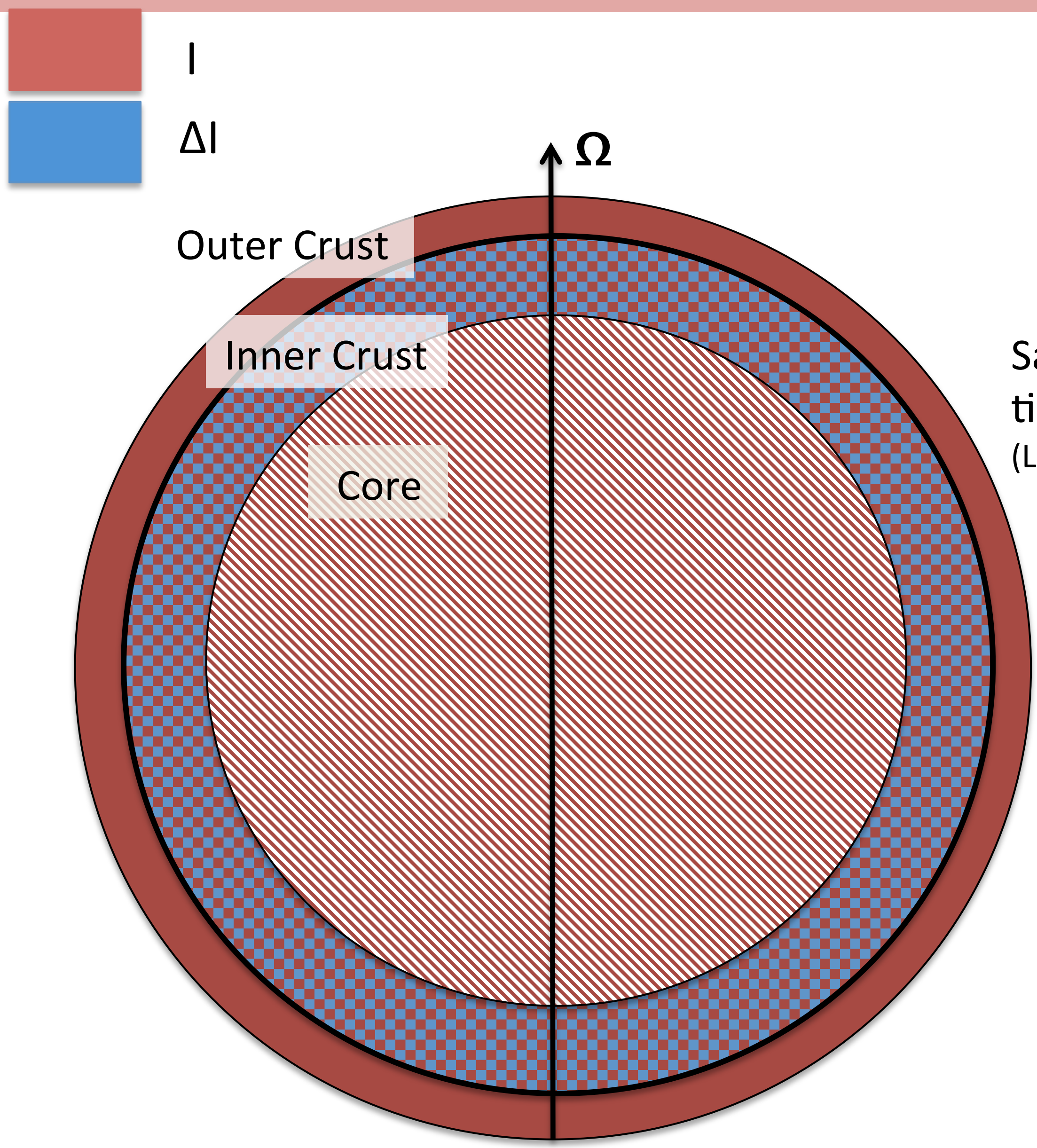
Confronting model with observation



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

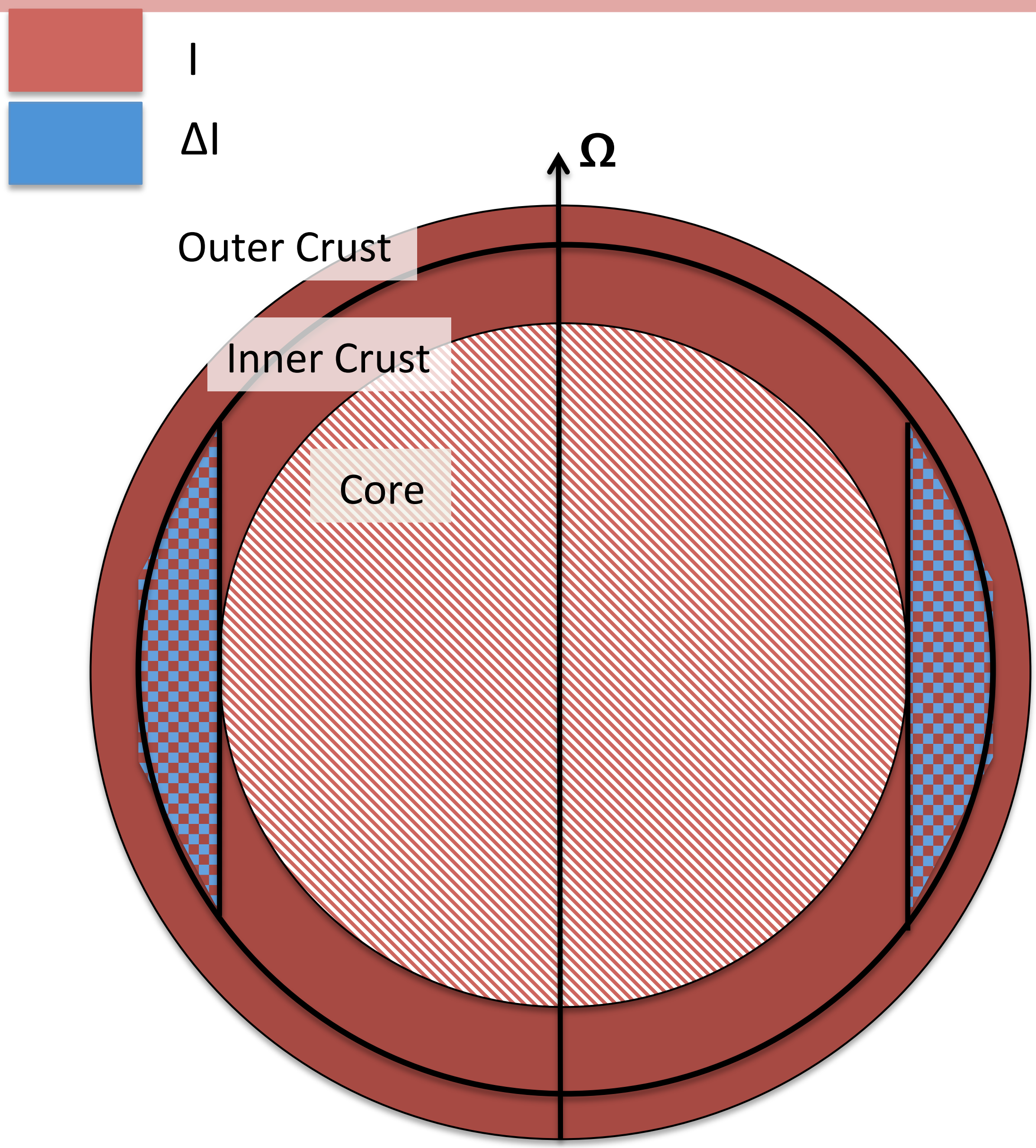
(Link, Epstein, Lattimer; PRL83 1999)

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

Confronting model with observation



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

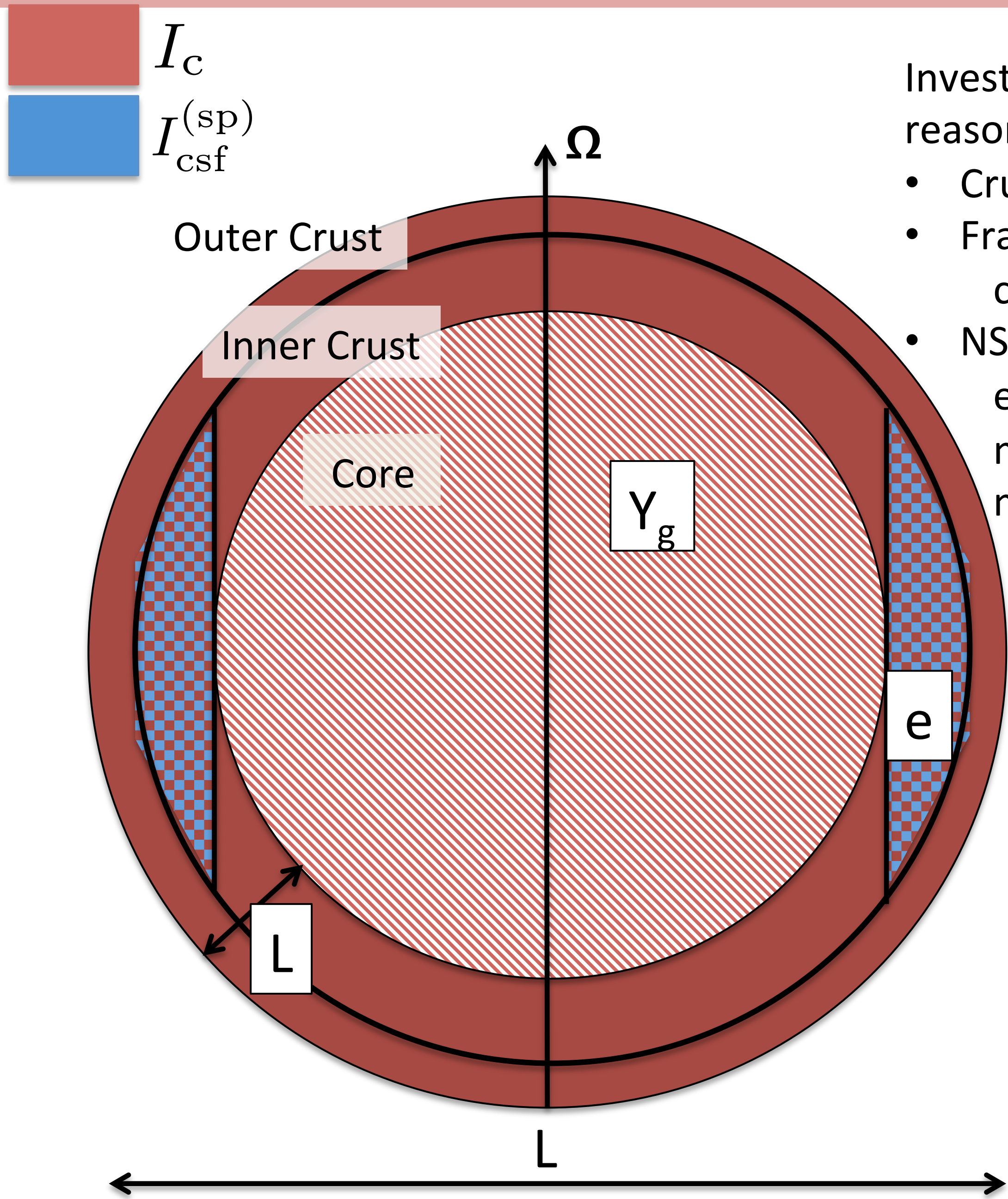
(Link, Epstein, Lattimer; PRL83 1999)

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

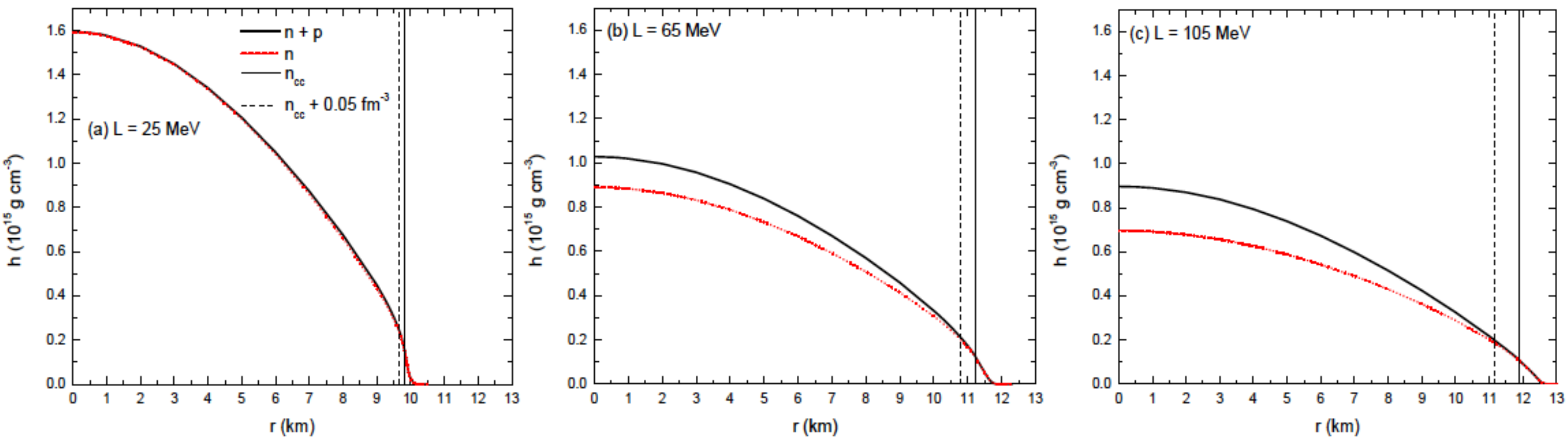


Investigate efficacy of model given reasonable nuclear physics uncertainties

- 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

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

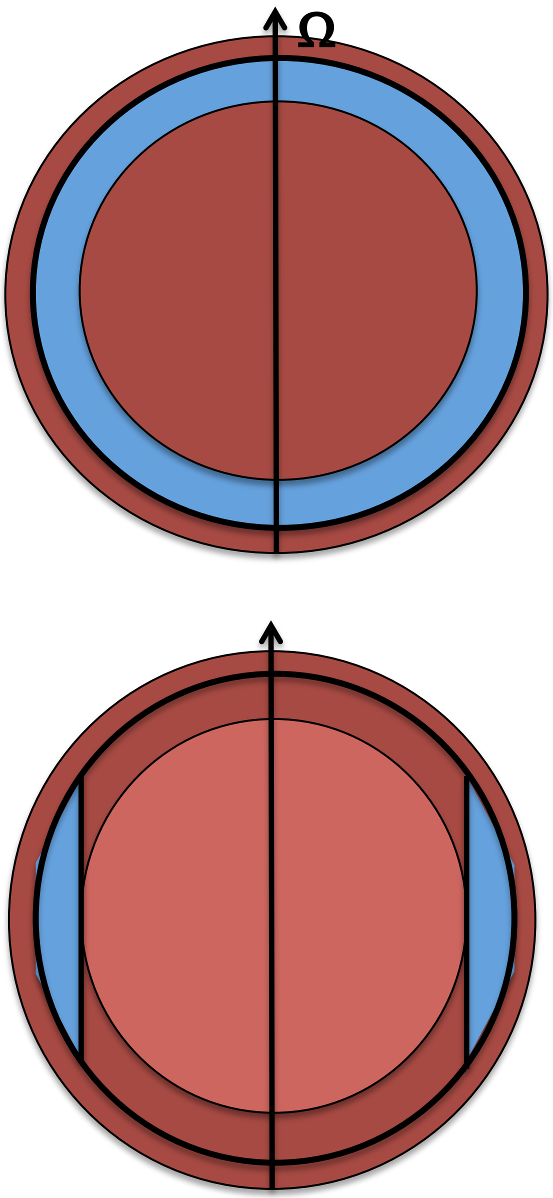
Neutron star structure: 1.4M_{sun}

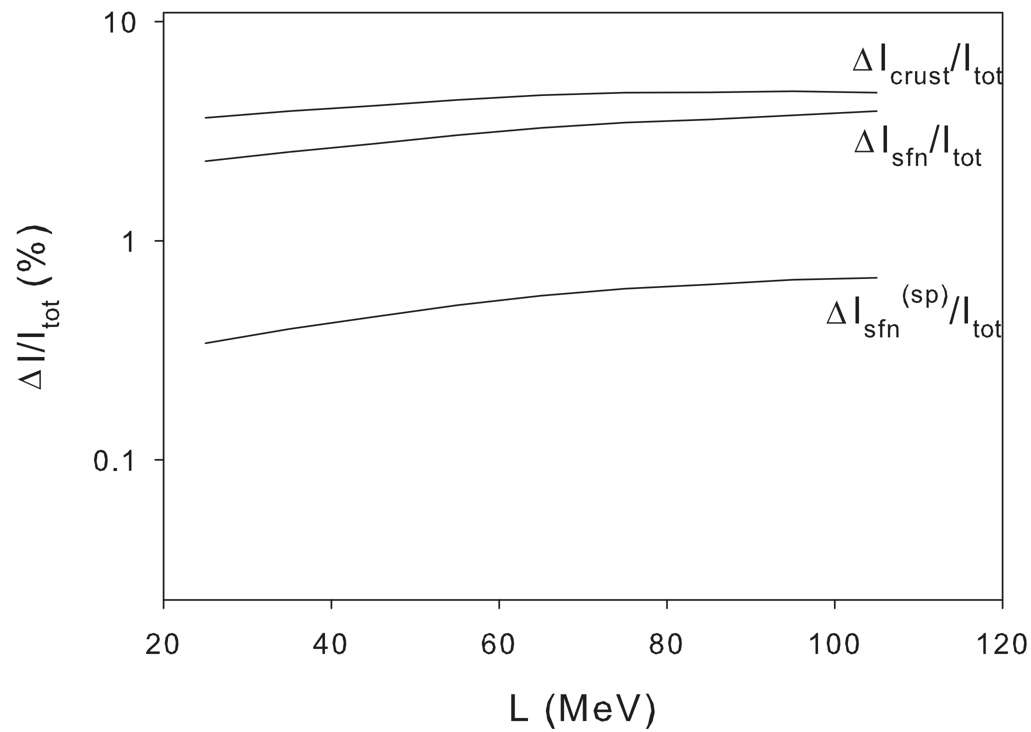


- Effect of L:
  - Stellar radius: L increases, R increases
    - R increases, ΔR increases
  - Crust-core transition pressure: L increases, P_t decreases, ΔR decreases*
  - Core proton fraction: L increases, x_p increases
  - Effect on e, Y_g?

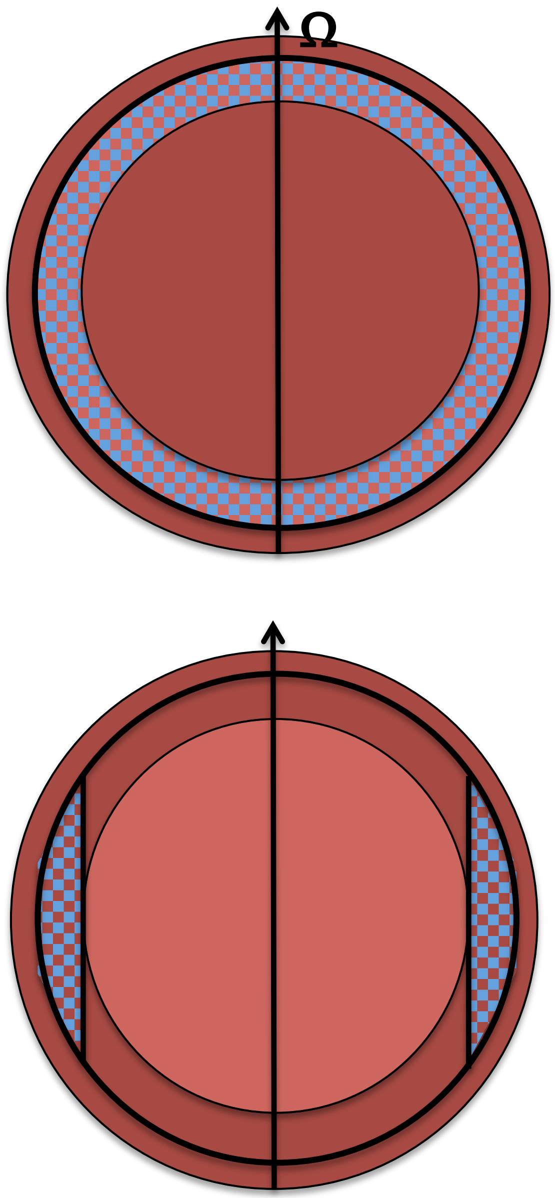
*model dependent

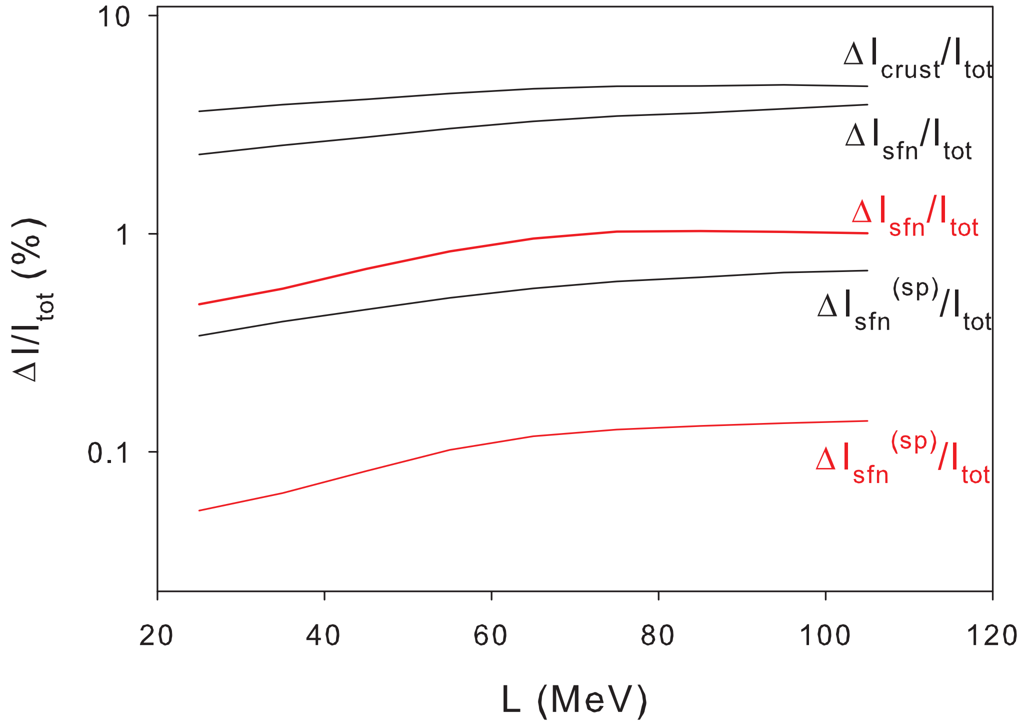
Neutron star structure: $1.4M_{sun}$





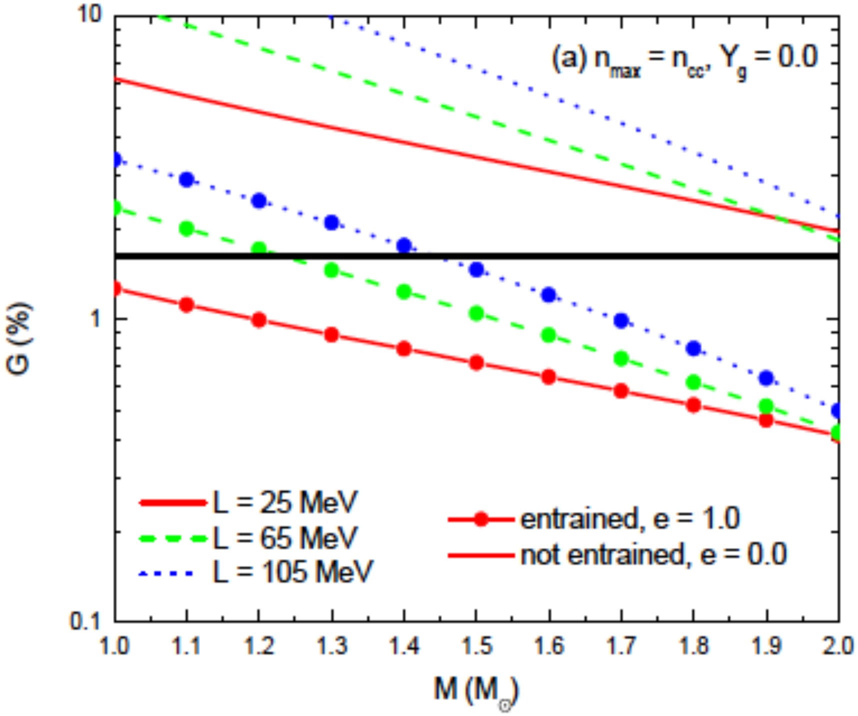
Neutron star structure: $1.4M_{sun}$

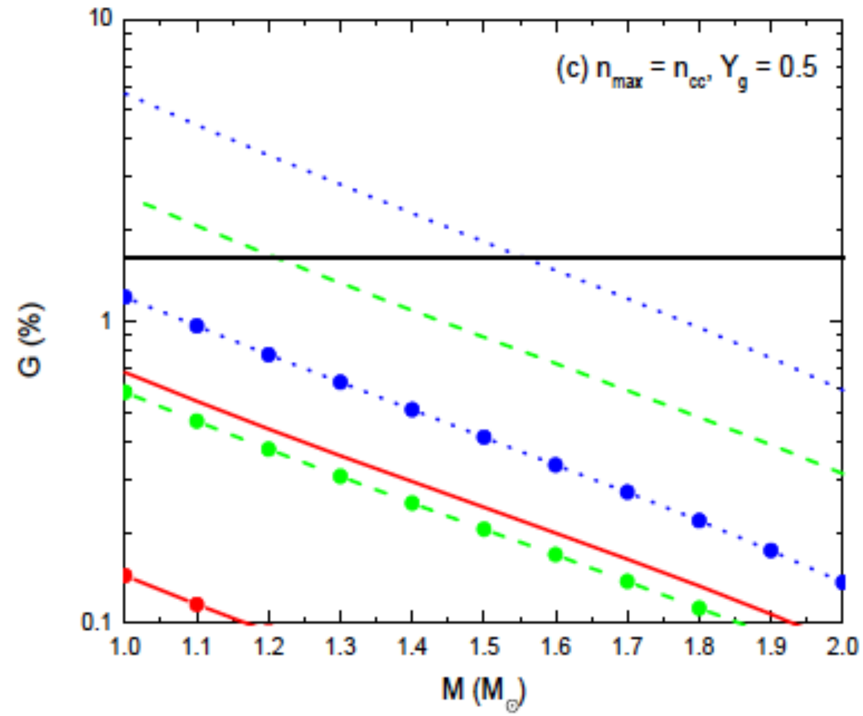




Results

Hooker, Newton, Li; arxiv:1308.0031





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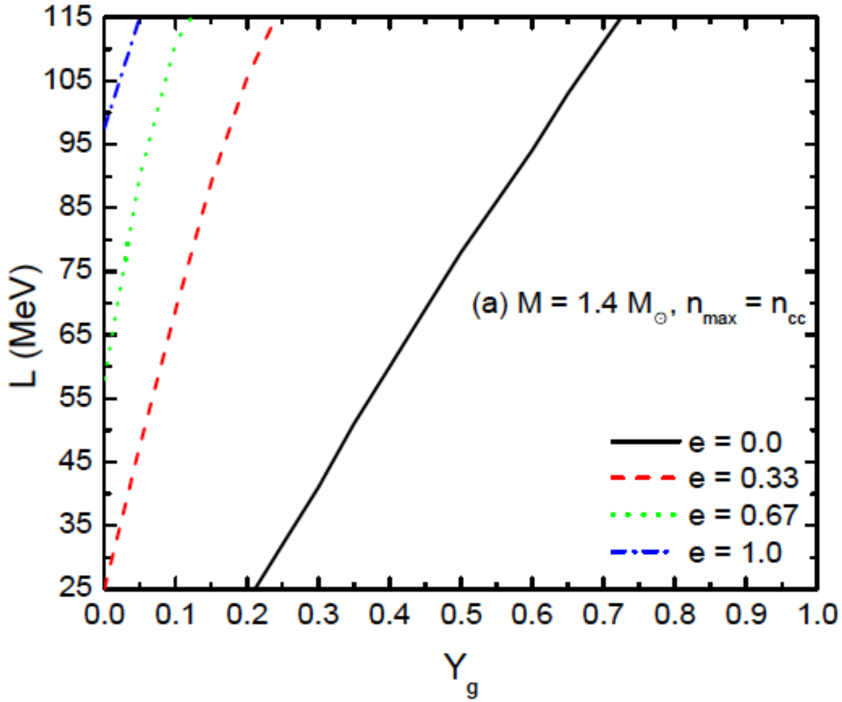
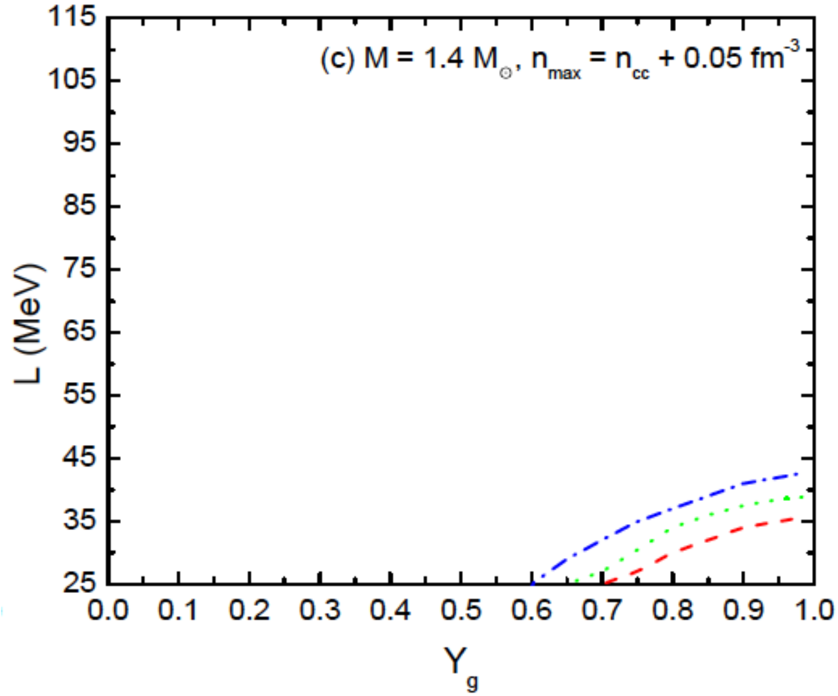




- Constraint on G alone satisfied for very stiff saturation EOSs when e=1
- L>100 MeV
- $Y_g \approx 0$

Solution: extend pinning into the core?

- Type II superconductivity

Pulsar glitches: summary

Crust-driven glitches:

- Full entrainment:
  - G alone: $L > 100$ MeV, $Y_g \approx 0$

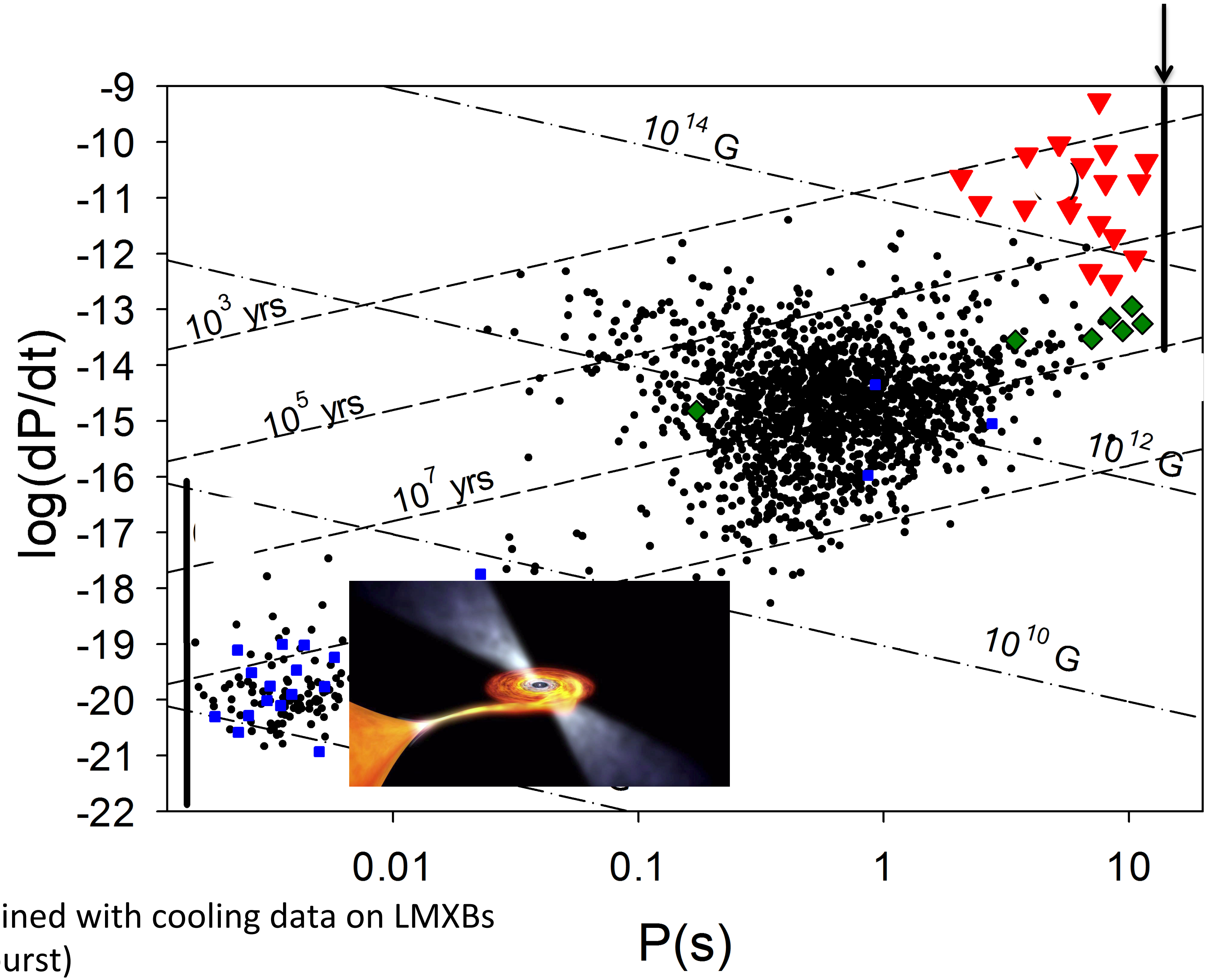
Theoretical uncertainties

- 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?

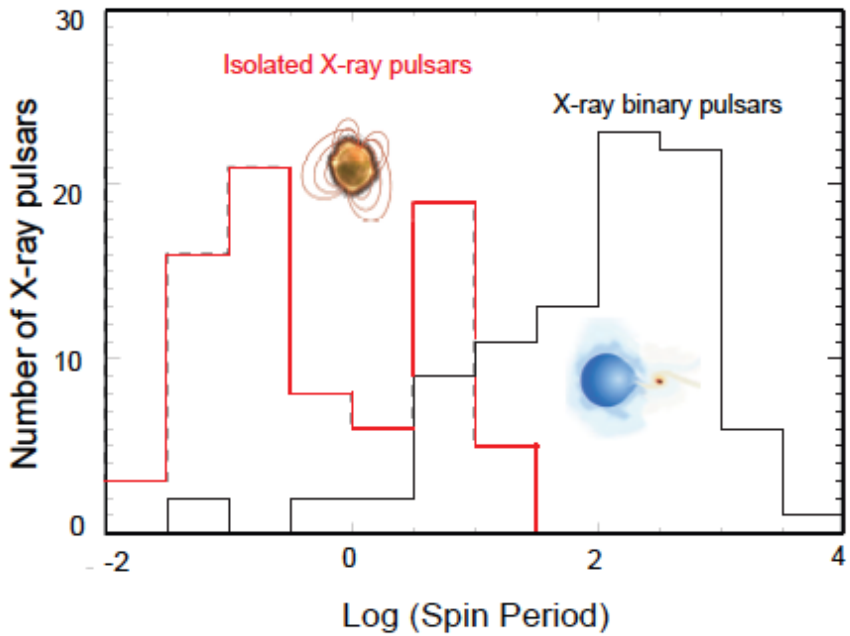
- Pinning penetrates core up to 0.05 fm^{-3} above n_{cc}:
  - G satisfied for any L, Y_g

Observable III: Upper limit on young neutron star periods



(combined with cooling data on LMXBs post-burst)

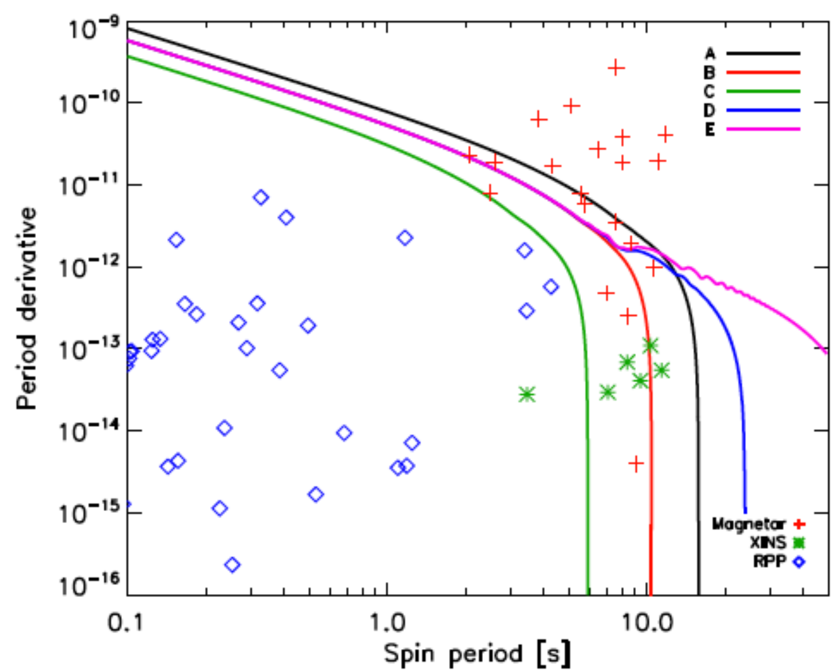
Evidence of Pasta?



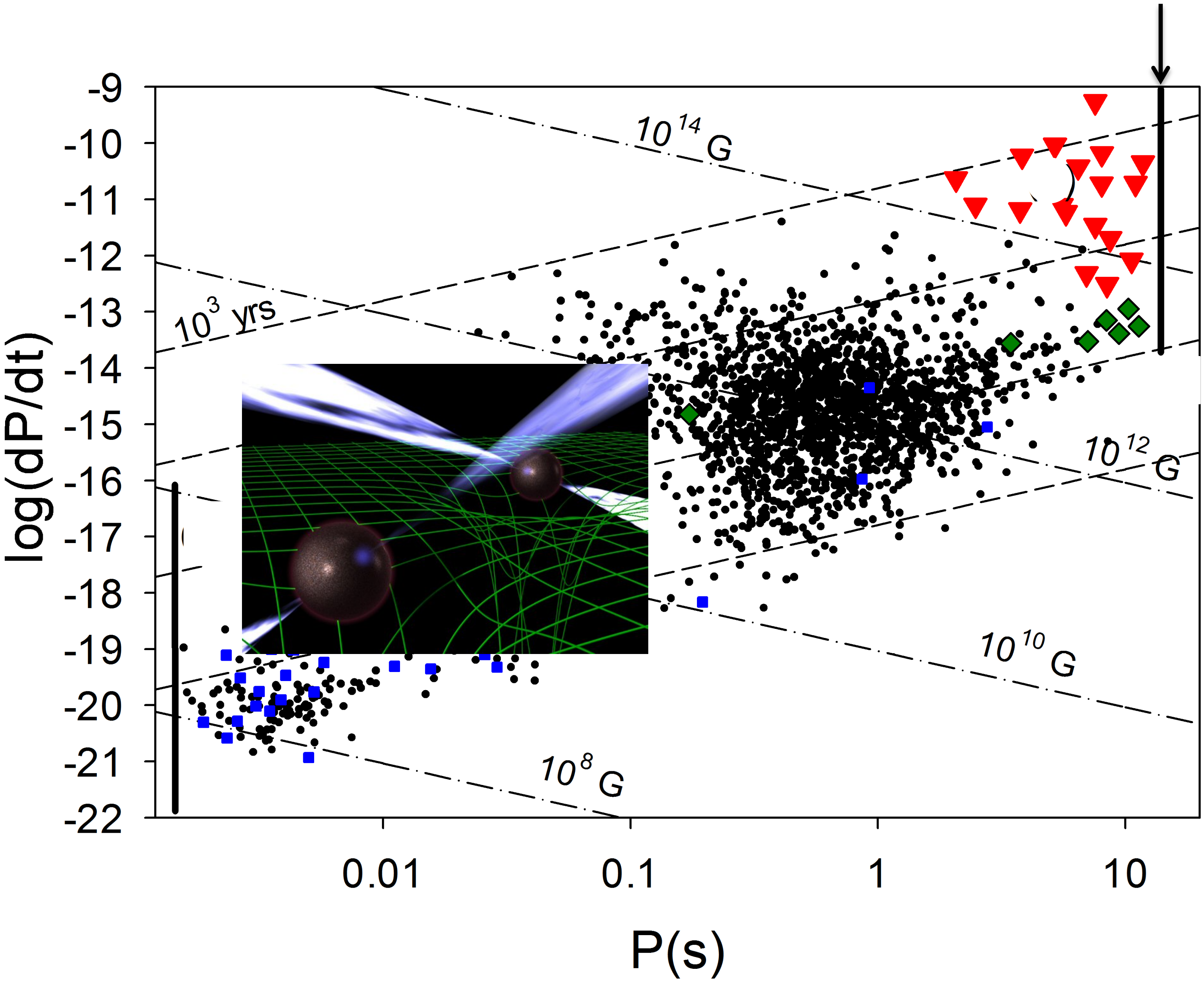
- The population of young X-ray pulsars presents a cutoff in Periods at 10s
- Magnetic field must decay sufficiently fast
- Requires very high electrical resistivity in crust > highly disordered crust
- Simulations/post-thermonuclear burst cooling suggestive of quite pure crust (Hughto et al PRE84 (2011), Shternin et al MNRAS382 (2007, Brown and Cumming, ApJ698, (2009))
- Suggestive of very disordered layer at base of crust
- A lot of pasta favors soft symmetry energy

Model	$M[M_\odot]$	I_{45}	ΔR_{crust} [km]	ΔR_{pasta} [km]	Q_{imp}
A	1.10	0.962	0.94	0.14	100
B	1.40	1.327	0.70	0.10	100
C	1.76	1.755	0.43	0.07	100
D	1.40	1.327	0.70	0.10	10
E	1.40	1.327	0.70	0.10	0.1

Pons, Vigano and Rea, Nature, 2013

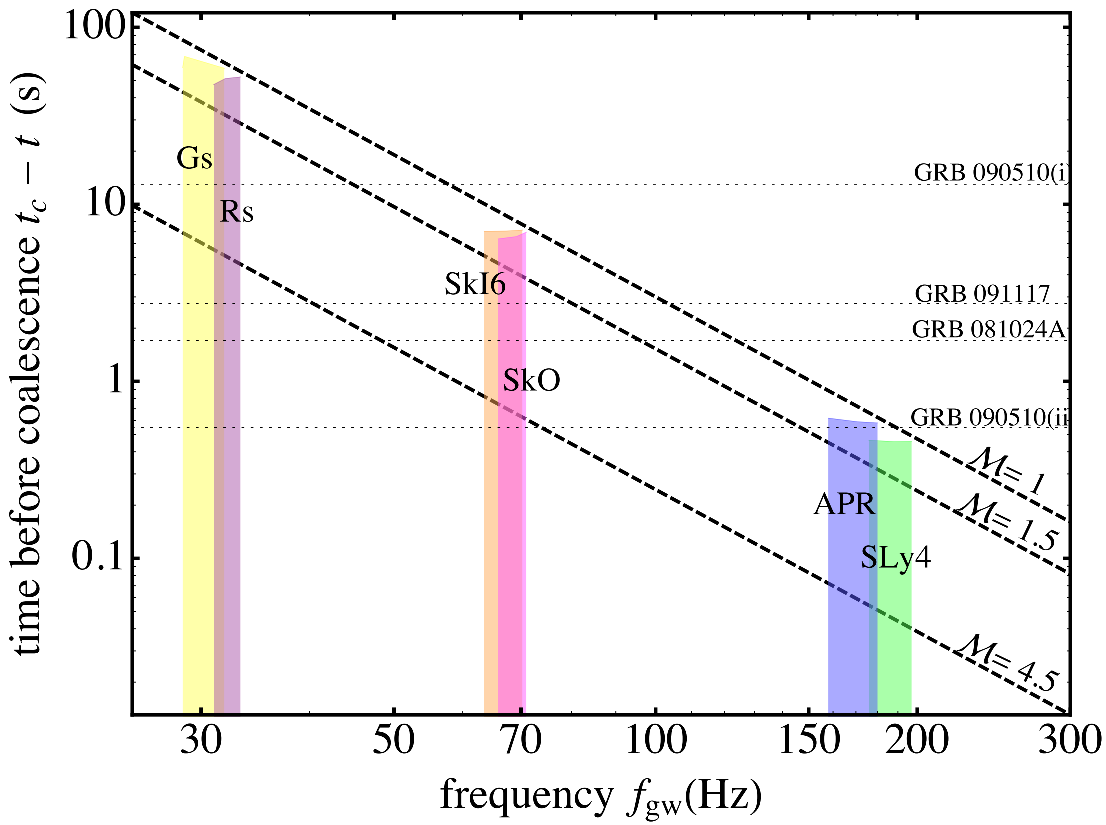


Observable IV: precursor sGRB flares



Observable: sGRB precursor flares

- NS-NS mergers strong candidates for sGRBs
- Precursor flares observed 1-10s before 4 GRBs
- Possible interpretation: crust shattering by tidal excitation of crustal oscillation mode resonance (Tsang et al PRL108, 2012)



L=95 MeV

L = 45 MeV

Overall Conclusions

Observable	L (MeV)	Specific (general) conditions/caveats
Cooling rate of Cas A neutron star	$\lesssim 70$	No pasta cooling processes
	$\lesssim 45$	Pasta cooling processes active and unsuppressed by crust superfluity
		(Minimal cooling paradigm; range of L contingent on atmosphere model)
Limiting spin period of high magnetic field X-ray pulsars	$\lesssim 80$	Magnetic field decay from highly resistive pasta layer, not high resistivity of an amorphous/heterogeneous inner crust
Vela pulsar glitches	$\gtrsim 100$	Full crustal entrainment, very weak crust-core coupling. Glitch mechanism might involve angular momentum transfer from core components.
QPOs in X-ray tails of giant flares from SGRs	$\lesssim 60$	Calculated frequencies fall in range of potential observed fundamental frequencies; consistent crust-core EOS; limiting superfluid, pasta effects included
	$\gtrsim 50$	Exact matching of fundamental mode with lowest observed frequency QPO; inconsistent crust, core models; no superfluid effects;
	$100 \lesssim L \lesssim 130$	Exact matching of all observed frequency with crust modes; inconsistent crust, core models; superfluid effects included
	$58 \lesssim L \lesssim 85$	As above, but with the 2nd lowest observed frequency from SGR1806-20 omitted in mode indentification
		(Alfven wave coupling to crust modes ignored. Low frequency modes could be explained by pure Alfven modes.)
Limiting spin-up frequency of millisecond pulsars	$\lesssim 65$	Consistent crust-core EOS; viscous dissipation at crust-core boundary
	$\gtrsim 50$	Inconsistent crust-core model; viscous dissipation throughout entire core
		(Crust not perfectly rigid. r-mode saturation might allow stars to spin -up into instability window. Superfluid, exotic shear viscosity sources ignored. Alternative physical mechanisms that limit spin-up are possible.)
Observed occurrence times of precursor γ-ray flares before sGRBs	$60 \lesssim L \lesssim 80$	Inconsistent crust-core EOS. Observational interpretation of pre-cursor gamma ray signals tentative.

Newton et al, EPJA 2014

Overall Conclusions

Consistently calculate:

- Crust EOS
- Crust composition
- Crust-core transition density/pressure
- Extent and sequence of pasta phases
- Core EOS/composition

Need to add…

- Superfluid properties, entrainment, mutual friction
- Conductivities (esp. pasta)
- Mechanical properties (shear modulus…)
- …

Observable: sGRB precursor flares

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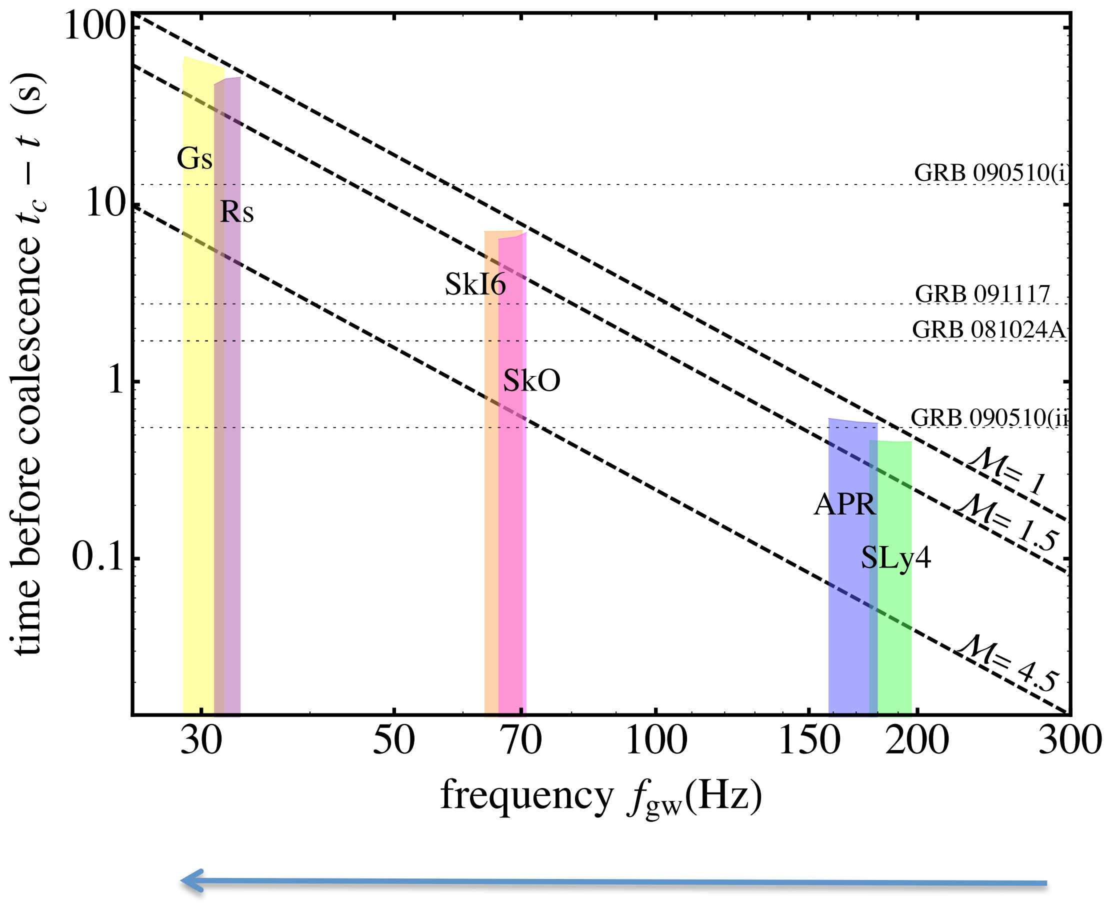
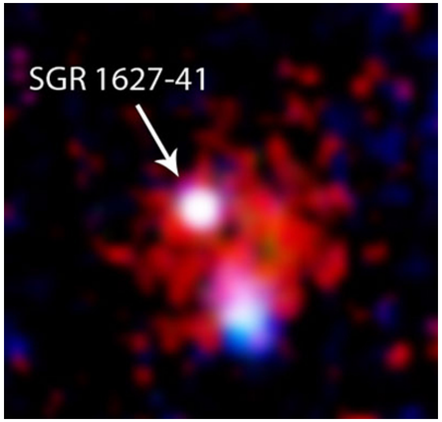


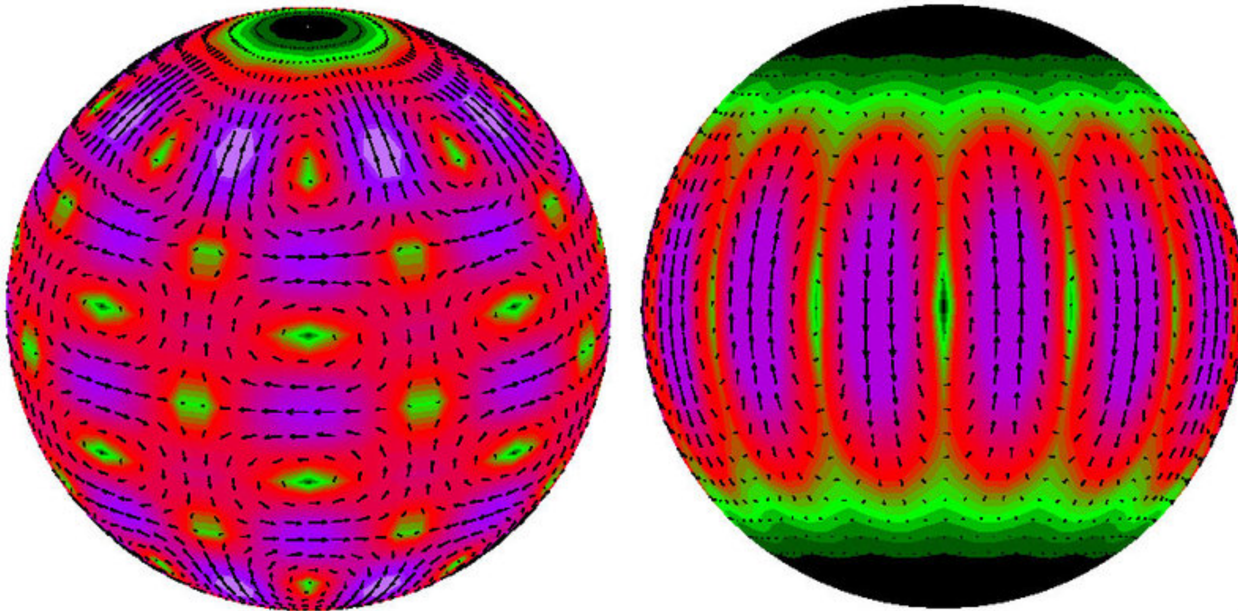
L=95 MeV L = 45 MeV

Observable: QPOs from X-ray tail of SGR flares



- Soft Gamma-ray Repeaters (SGRs)
  - Neutron stars which emit occasional bursts of radiation in hard X-ray and soft gamma-ray
  - Energy from B-field decay; based on energetics of bursts and changes in NS rotation period, $B \approx 10^{15}$G (magnetars)
  - Quasi periodic oscillations in the intensity of the X-ray tail of the lightcurve detected from 3 SGRs

Symmetry energy sensitive observables: QPOs from X-ray tail of SGR flares



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Shear speed at base of crust

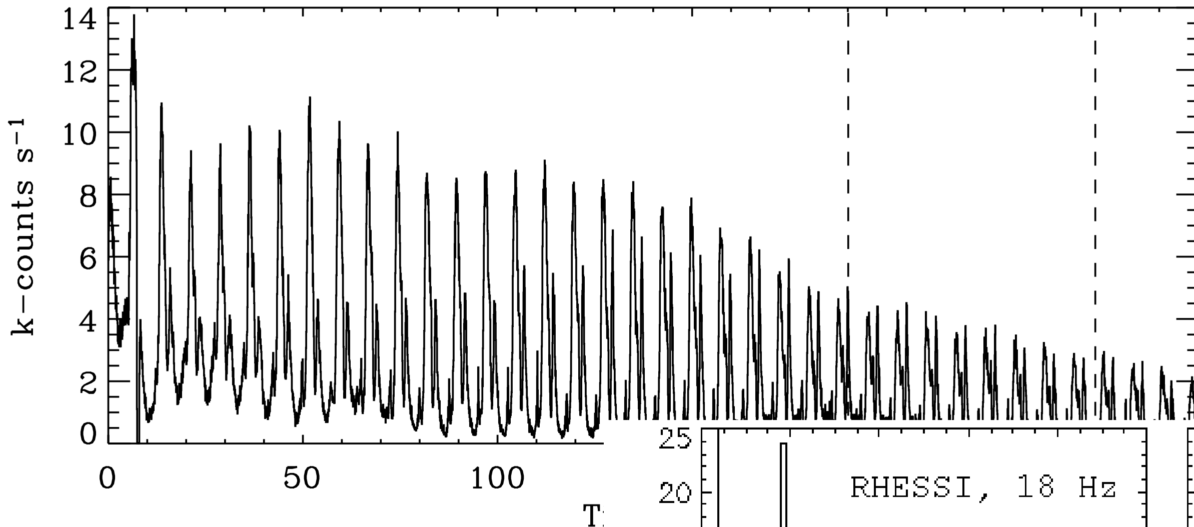
Crust thickness

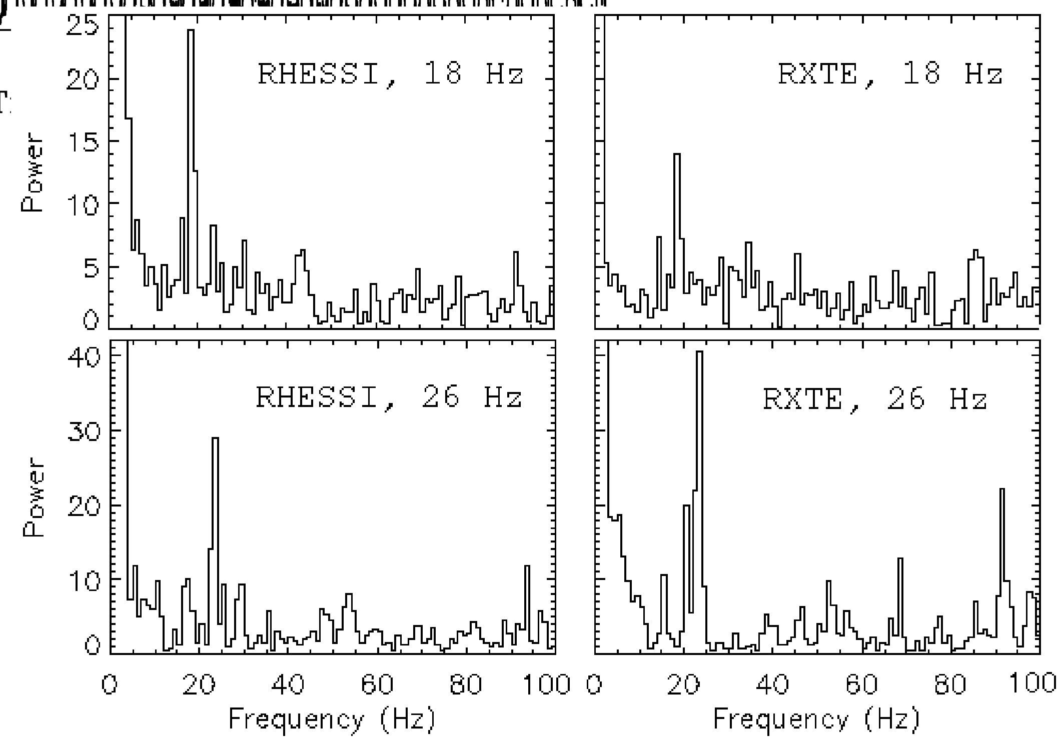
$$\omega_0^2 \approx \frac{e^{2\nu} v_s^2 (l-1)(l+2)}{2RR_c},$$

$$\omega_n^2 \approx e^{\nu-\lambda} \frac{n\pi v_s}{\Delta} \left[1 + e^{2\lambda} \frac{(l-1)(l+2)}{2\pi^2} \frac{\Delta^2}{RR_c} \frac{1}{n^2}\right]$$

Radius, base-of-crust radius

Symmetry energy sensitive observables: QPOs from X-ray tail of SGR flares

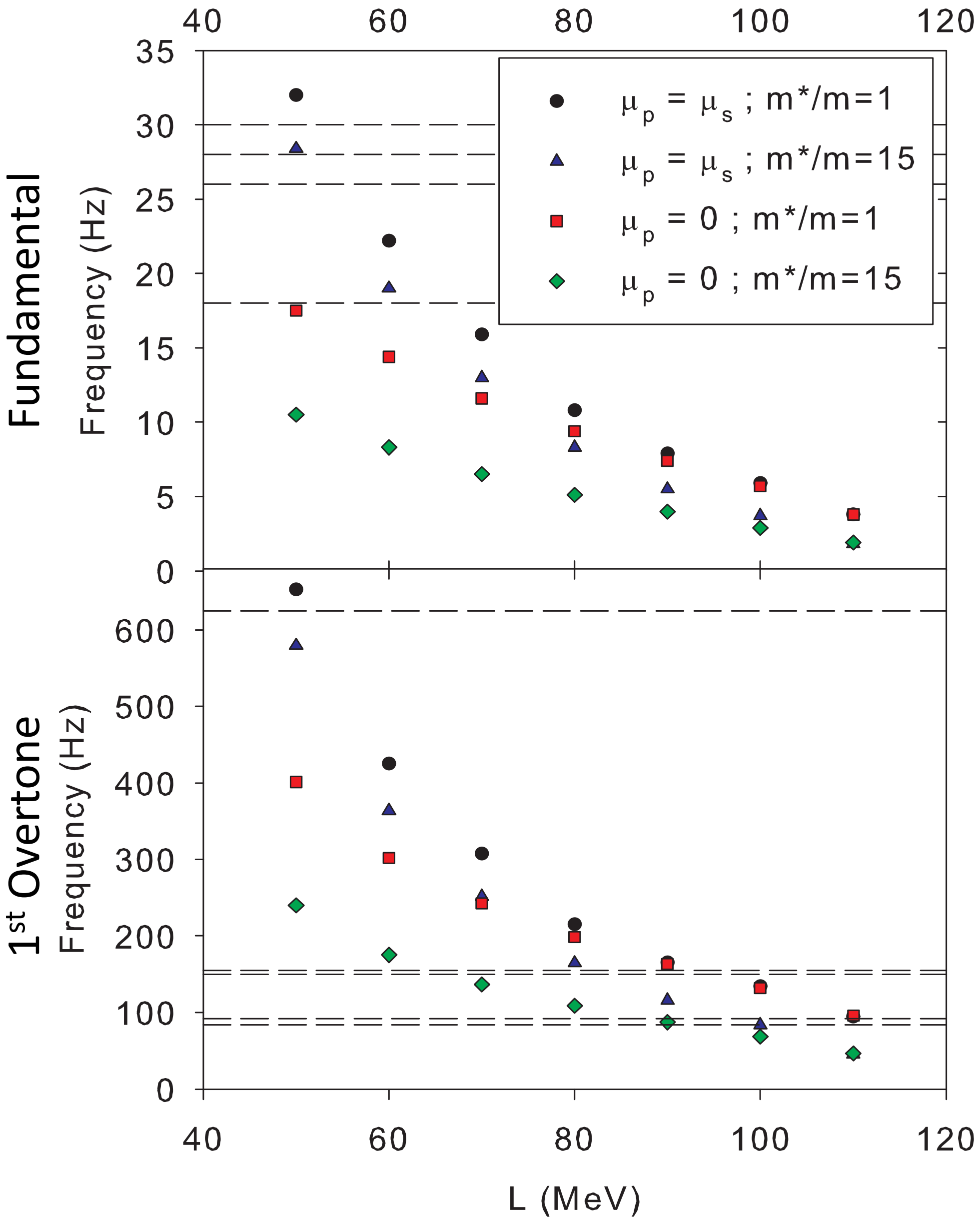




Interpretation:
vibrations of the NS crust
> NS seismology

T. E. Strohmayer, A. L. Watts, APJ **653**, (2006)

Symmetry energy sensitive observables: QPOs from X-ray tail of SGR flares



Gearheart, Newton, Li; MNRAS 418 (2011)

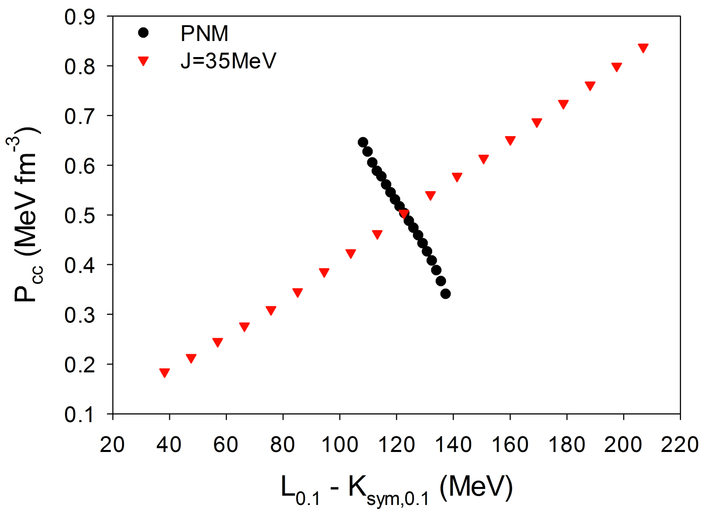
- If one of the low frequency QPOs is the fundamental frequency, L < 70MeV and pasta is solid-like
- compare

- Sotani et al PRL108 (2012):
  L > 50 MeV
- Sotani et al MNRAS428 (2013)
  100 < L < 130 MeV

- Modeling ignores coupling to core modes

Crust-core transition pressure

- Transition pressure most important quantity for determining crust mass, thickness
- Requires knowledge of L, K_{sym} at sub-saturation densities (or L, K_{sym} +… at saturation density)



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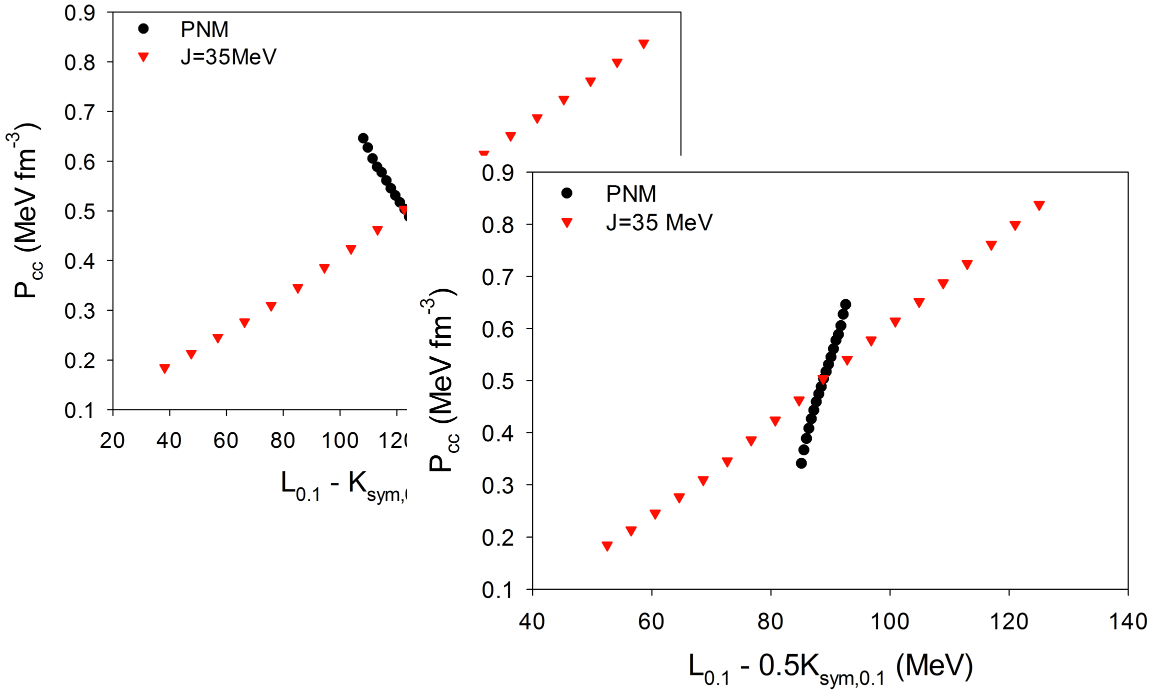

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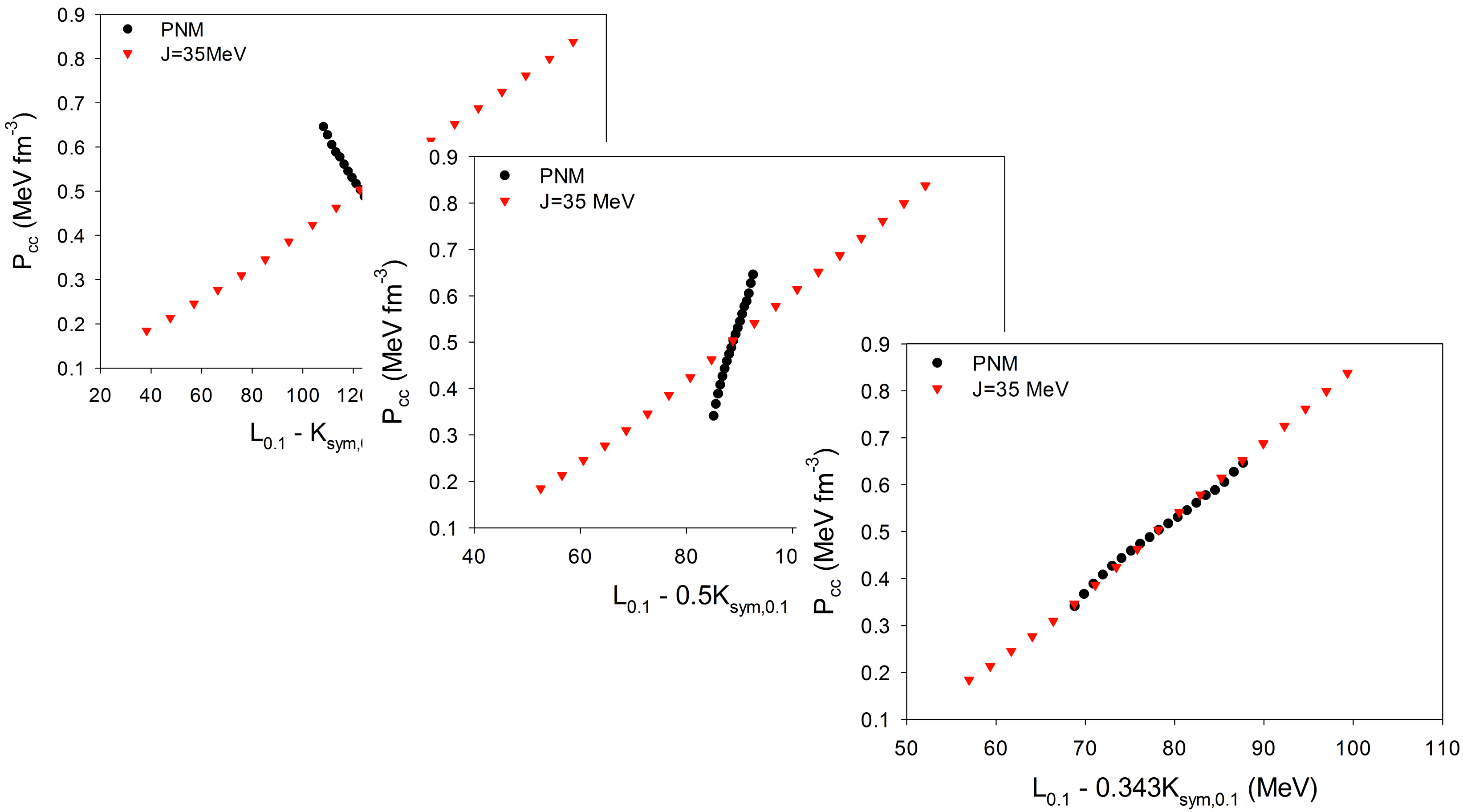

(See Ducoin et al PRC83 (2011))