Symmetry energy constraints from the neutron star crust

Nuclear experiment confronting astrophysical models

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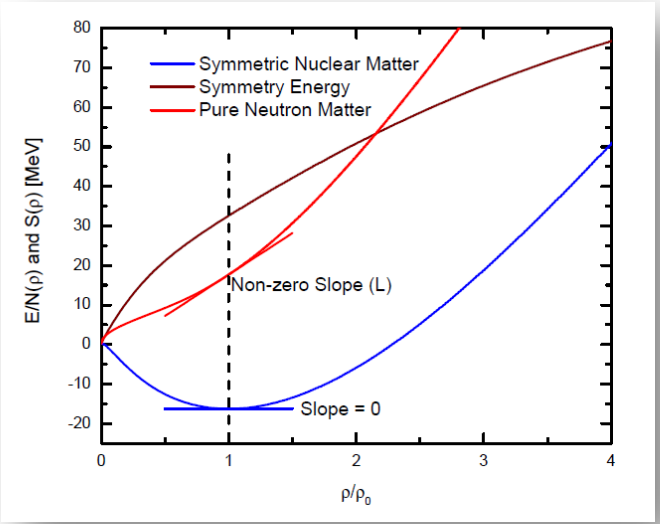
Outline

- What nuclear physics has to say about glitch models
- What nuclear physics has to say about stellar evolution
- A quick review of some other symmetry energy constraints from astrophysical observables

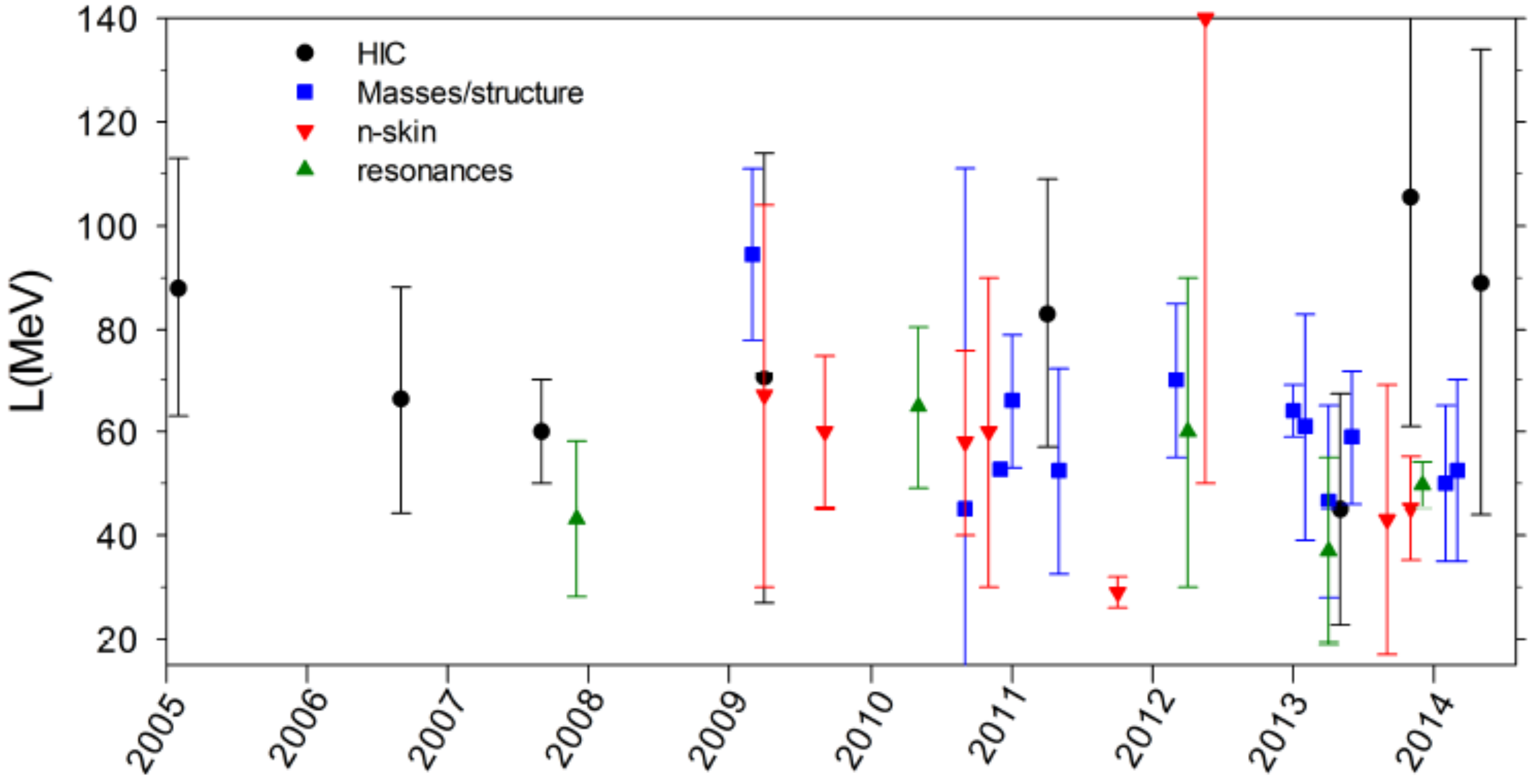


$$E(n,\delta) = E_0(n) + S(n)\delta^2 + \ldots$$

$$S(n) = J + L\chi + \frac{K_{\mathrm{sym}}}{2}\chi^2$$

Other notations are available

Nuclear experimental constraints on L



<u>Masses/structure</u>
Kortelainen et al, PRC82 (2010)
Danielewicz, Lee NphysA818 (2009)
Xu et al, PRC82 (2010)
Liu et al PRC82 (2010)
Chen, PRC82 (2011)
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Fan et al PRC89 (2014)
Danielewicz,Lee NPhysA922 (2014)

<u>HIC</u>
Chen, Ko, Li PRL94(2005)
Famiano et al PRL97(2006)
Shetty et al PRC76(2007)
Tsang et al PRL102 (2009)
Russotto et al PLB697 (2011)
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<u>n-skins</u>
Centelles et al PRL102 (2009)
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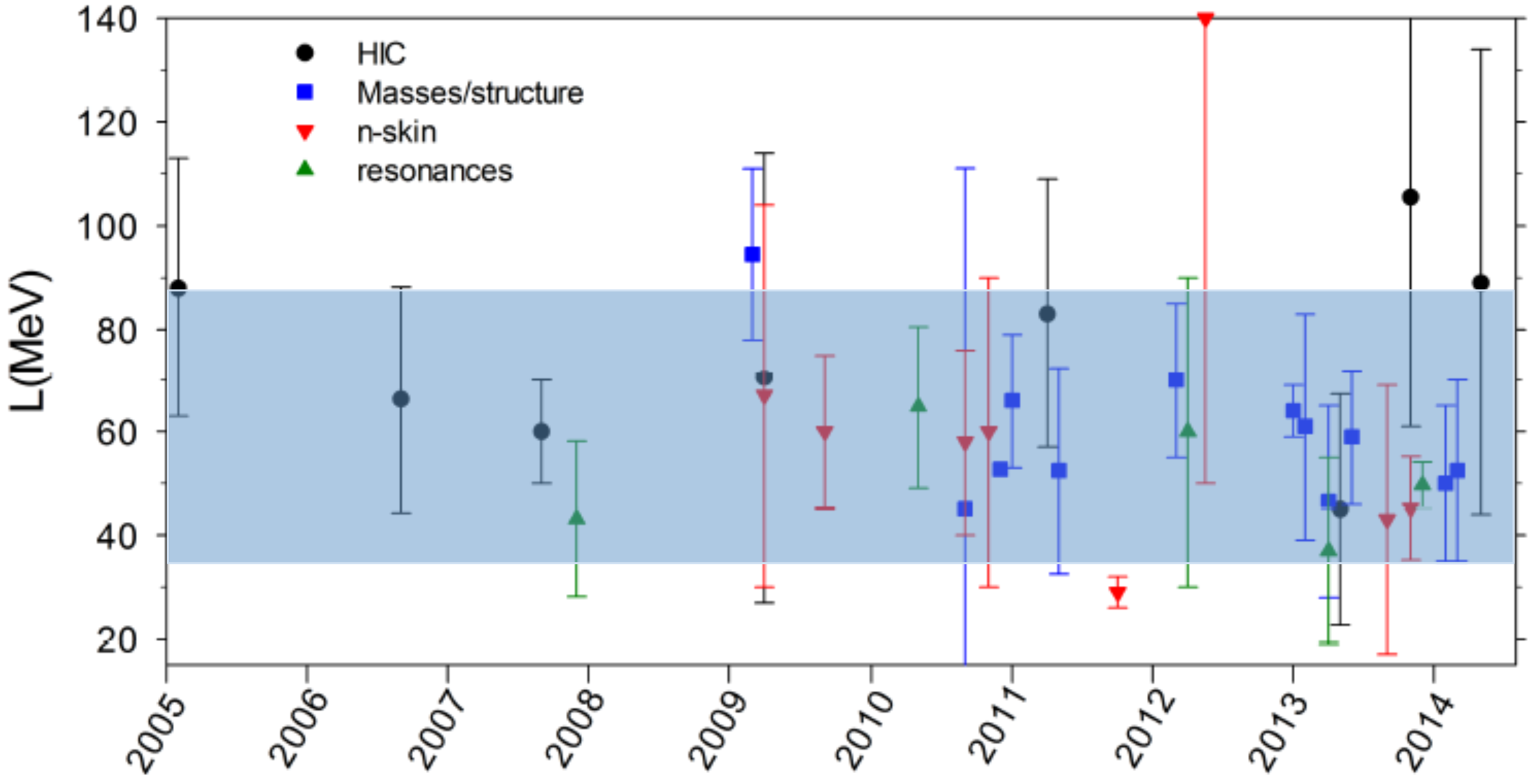
Zhang and Chen, PLB726 (2013)
Abrahamyan et al

<u>resonances</u>
Klimkiewicz et al, PRC76(2007)
Carbone et al PRC81, (2010)
Chen, Gu JPhG39 (2012)
Roca-Maza et al PRC87, (2013)
Krashnahorkay et al, arxiv:1311.1456

Nuclear experiment: naïve community constraint L=35-86 MeV



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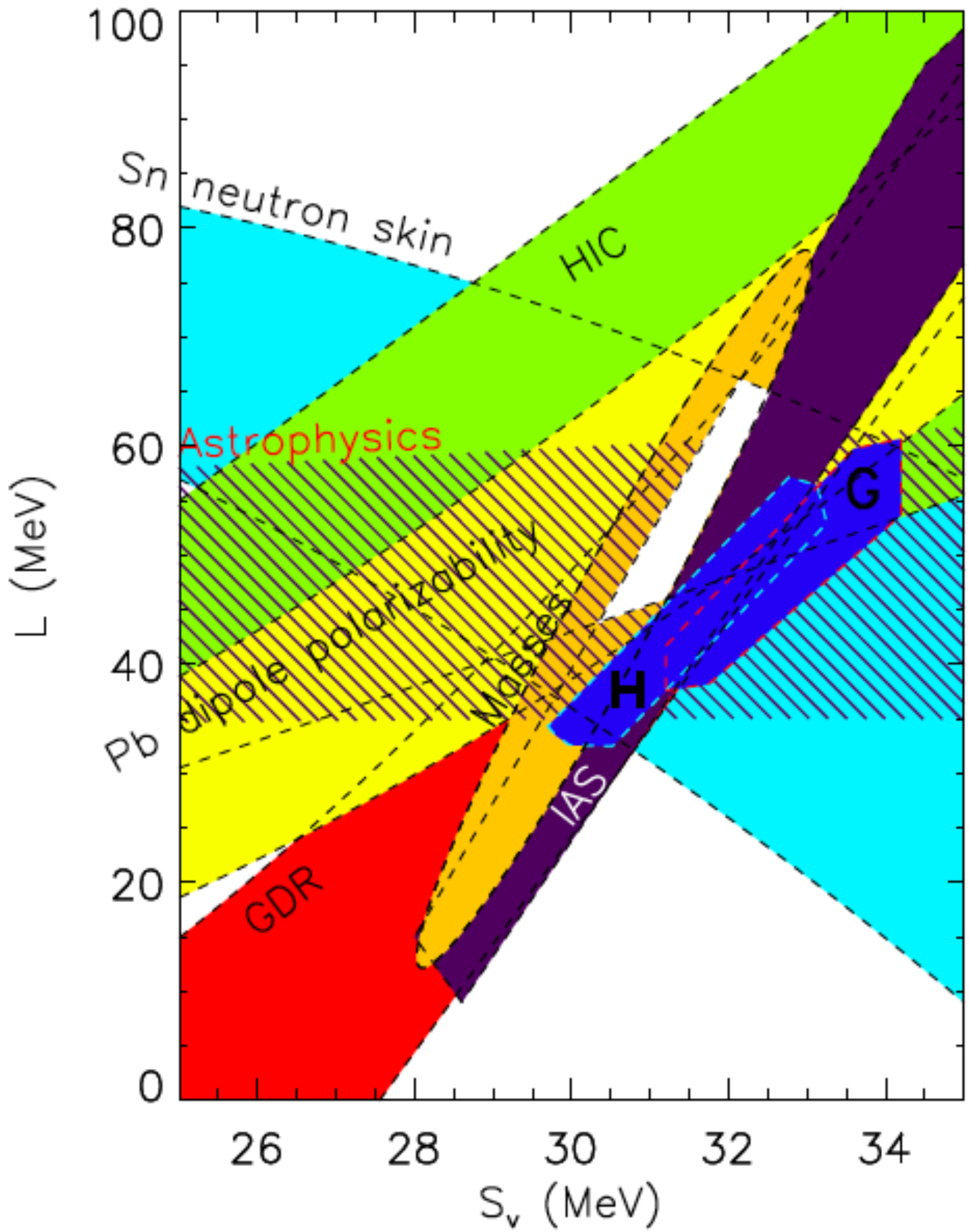
Nuclear Experimental Constraints



L=44-66MeV

Lattimer, Lim ApJ771 (2013)
Lattimer, Steiner EPJA50 (2013)

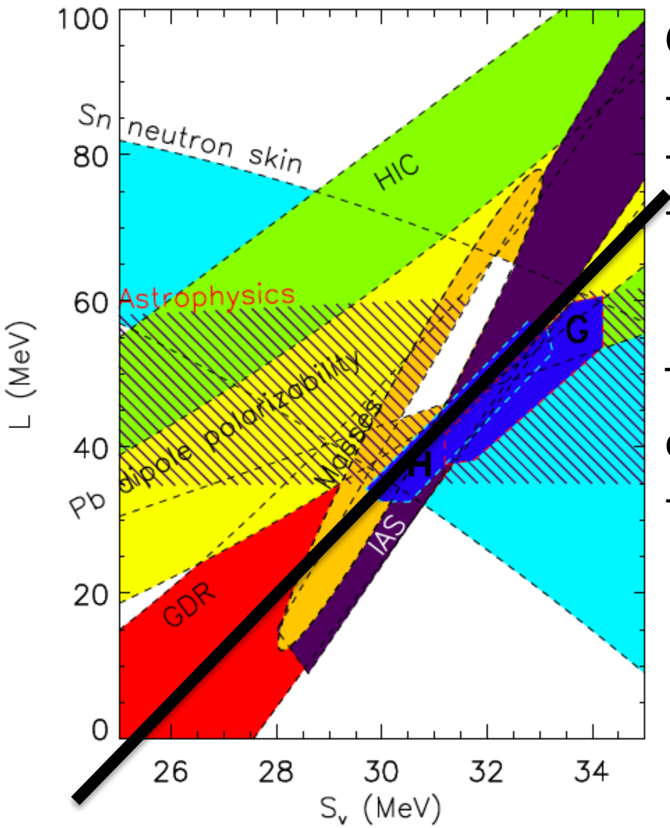
Δr_{np}= 0.09-0.19 fm

(pion photoproduction
Tarbert et al PRL112, 2014)

Δr_{np}= 0.33 +16/-18 fm

(PREX, Abrahamyan et al PRL108, 201)

Connecting nuclear experiment to neutron stars

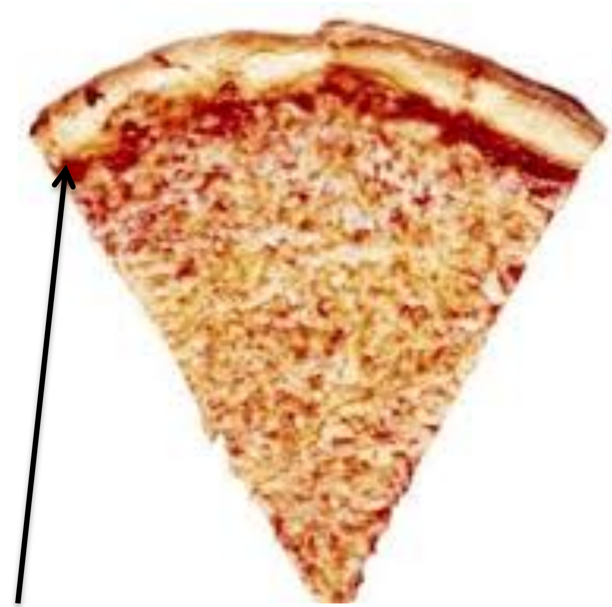


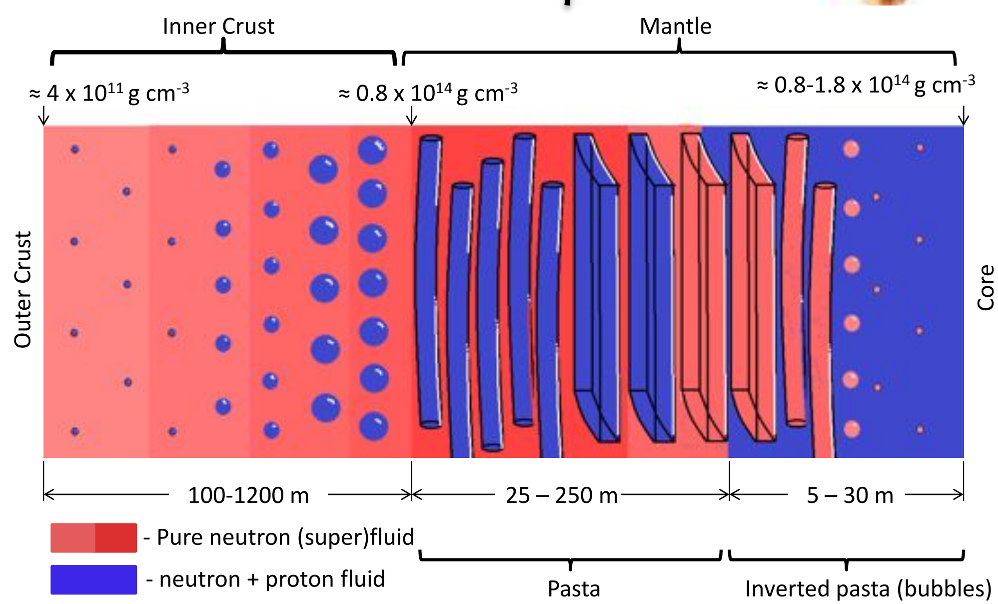
Consistent crust-core models:

- Skyrme or RMF
- Crust: CLDM/3DHF
- Vary L; J follows PNM correlation to ensure sensible crustal neutrons

To compare to some recent experimental results:

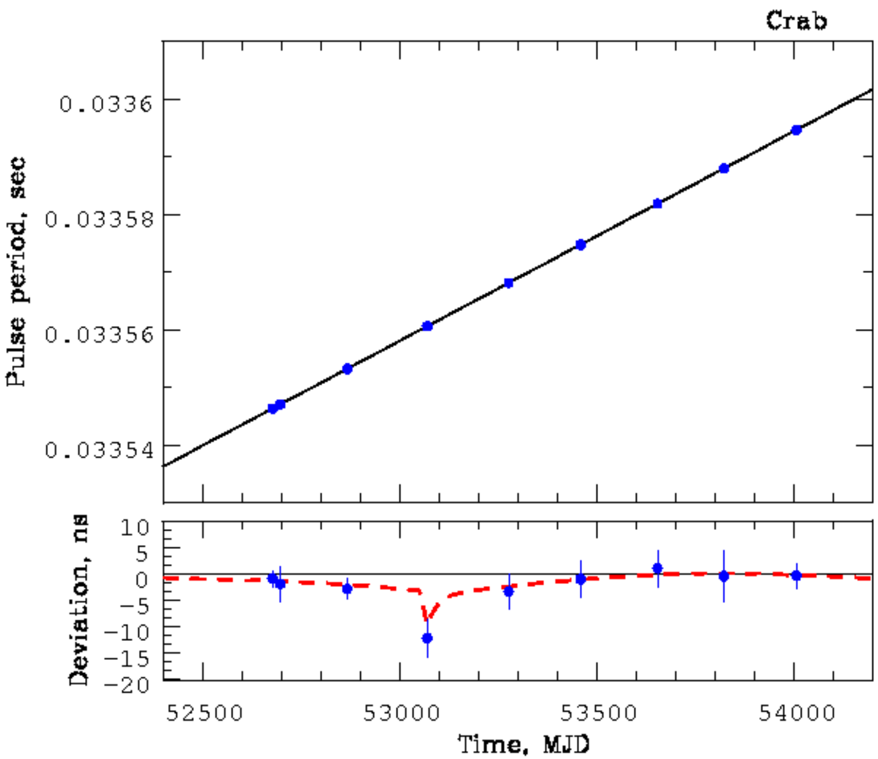
- 3DHF calculations the neutron skin of Pb208



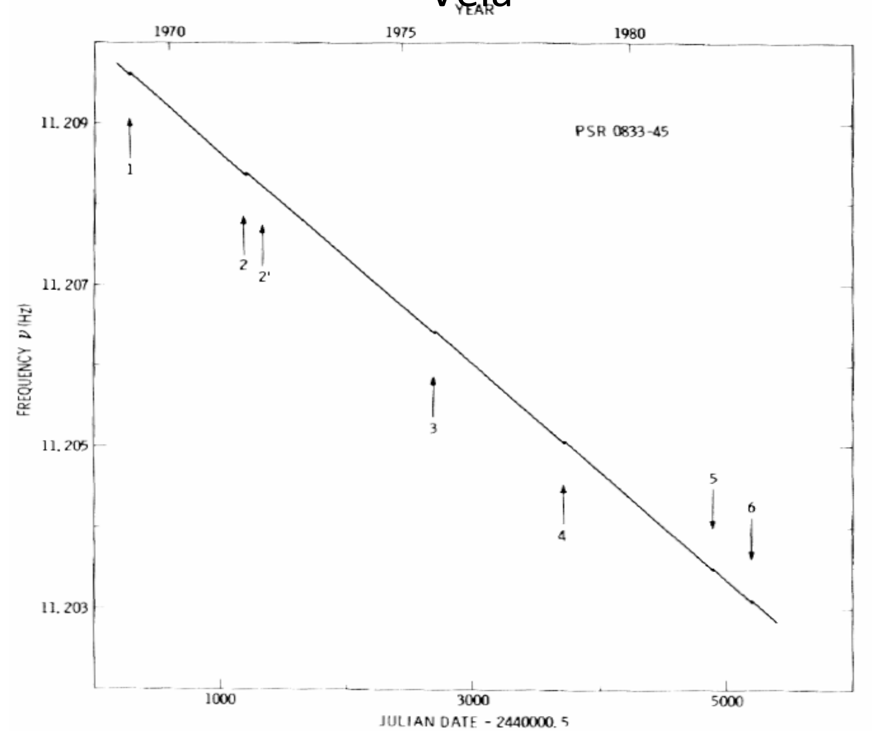


Pulsar glitches: the observations

Crab



Vela



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

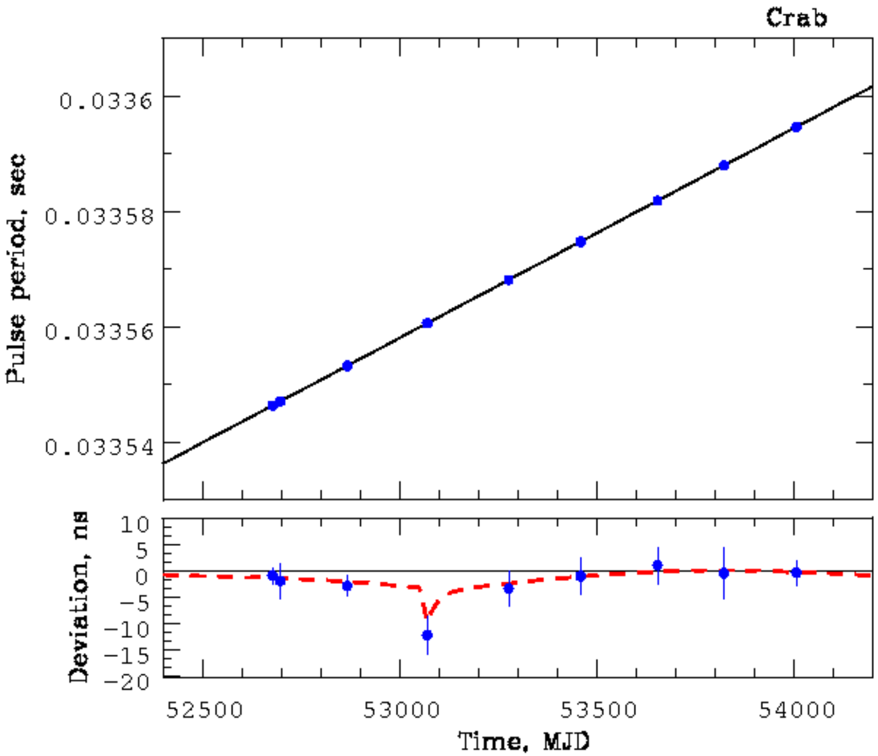
$\Delta\Omega/\Omega \approx 10^{-6}$, $\Delta t_g \sim 1000$ days

- 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: $A_g \sim 10^{-7}\,\mathrm{yr}^{-1}$

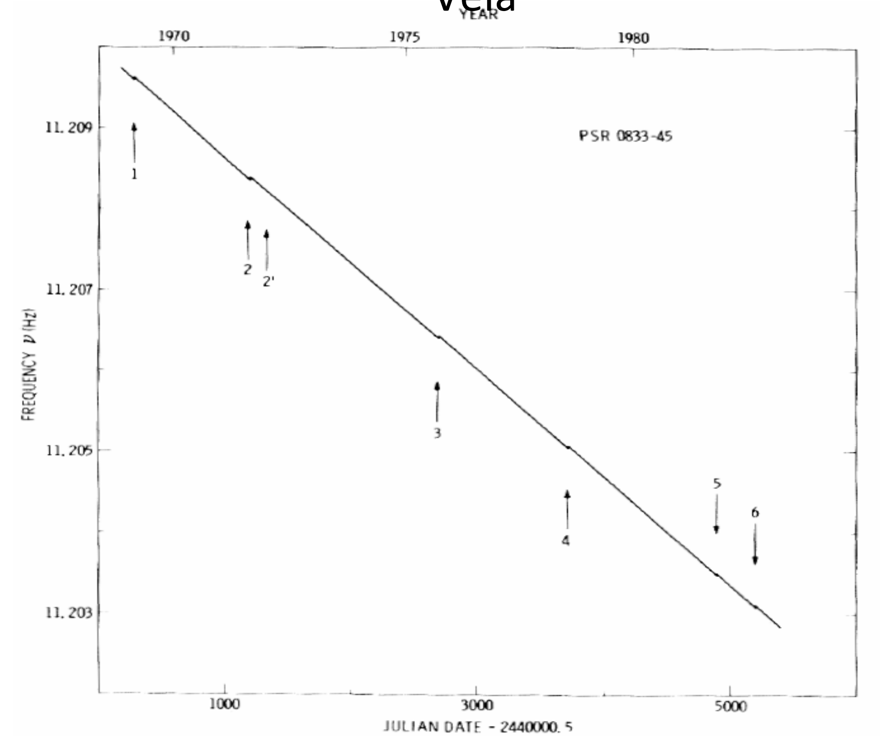
  Espinoza et al 2011

Testing glitch models with nuclear experiment

Crab



Vela



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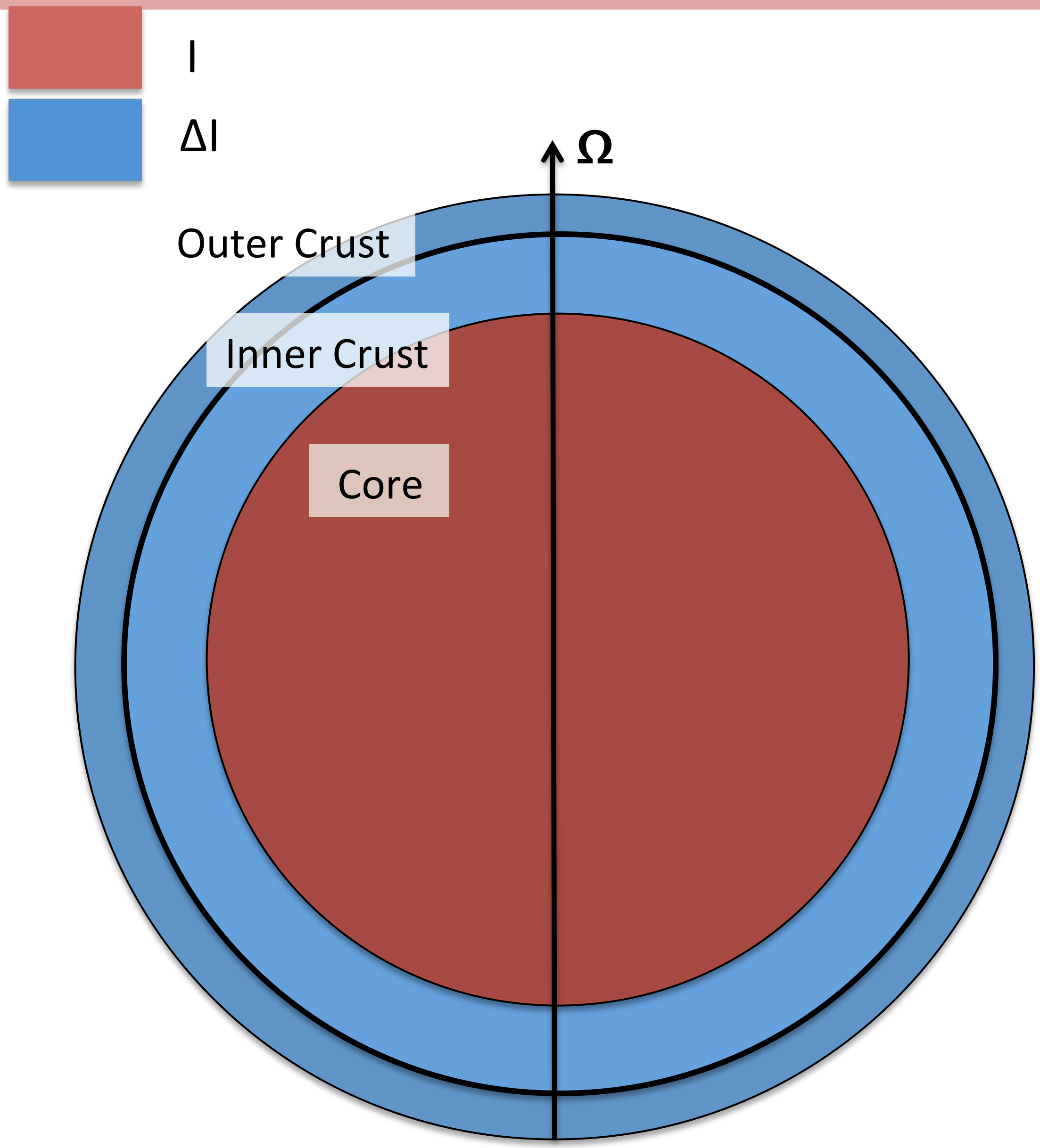
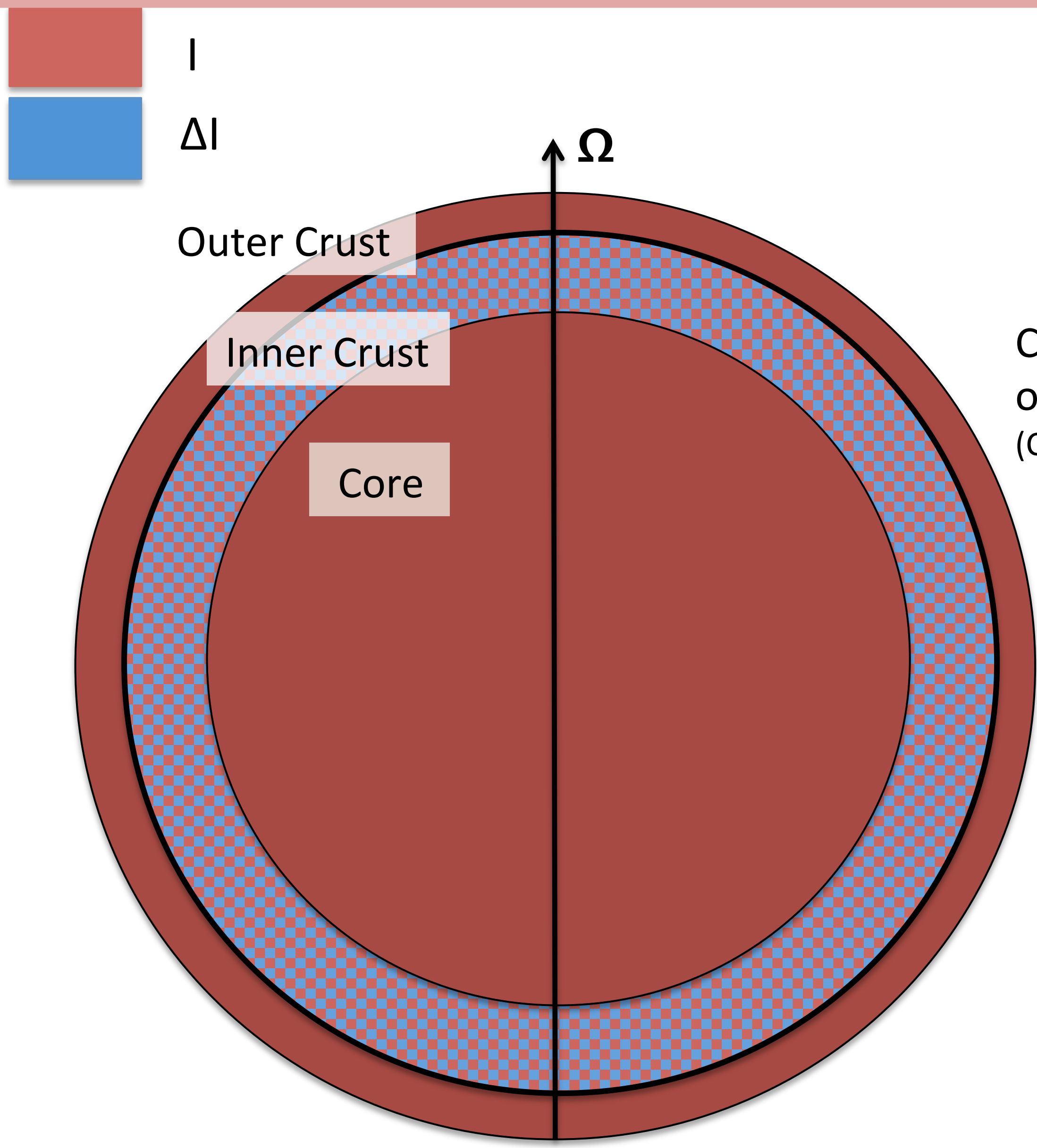


$$\Delta I/I \geqslant \frac{\bar{\Omega}}{|\dot{\Omega}|}\mathcal{A} = 0.016$$

(Link, Epstein, Lattimer; PRL83 1999)

OK for many reasonable EOSs

Testing glitch models with nuclear experiment



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

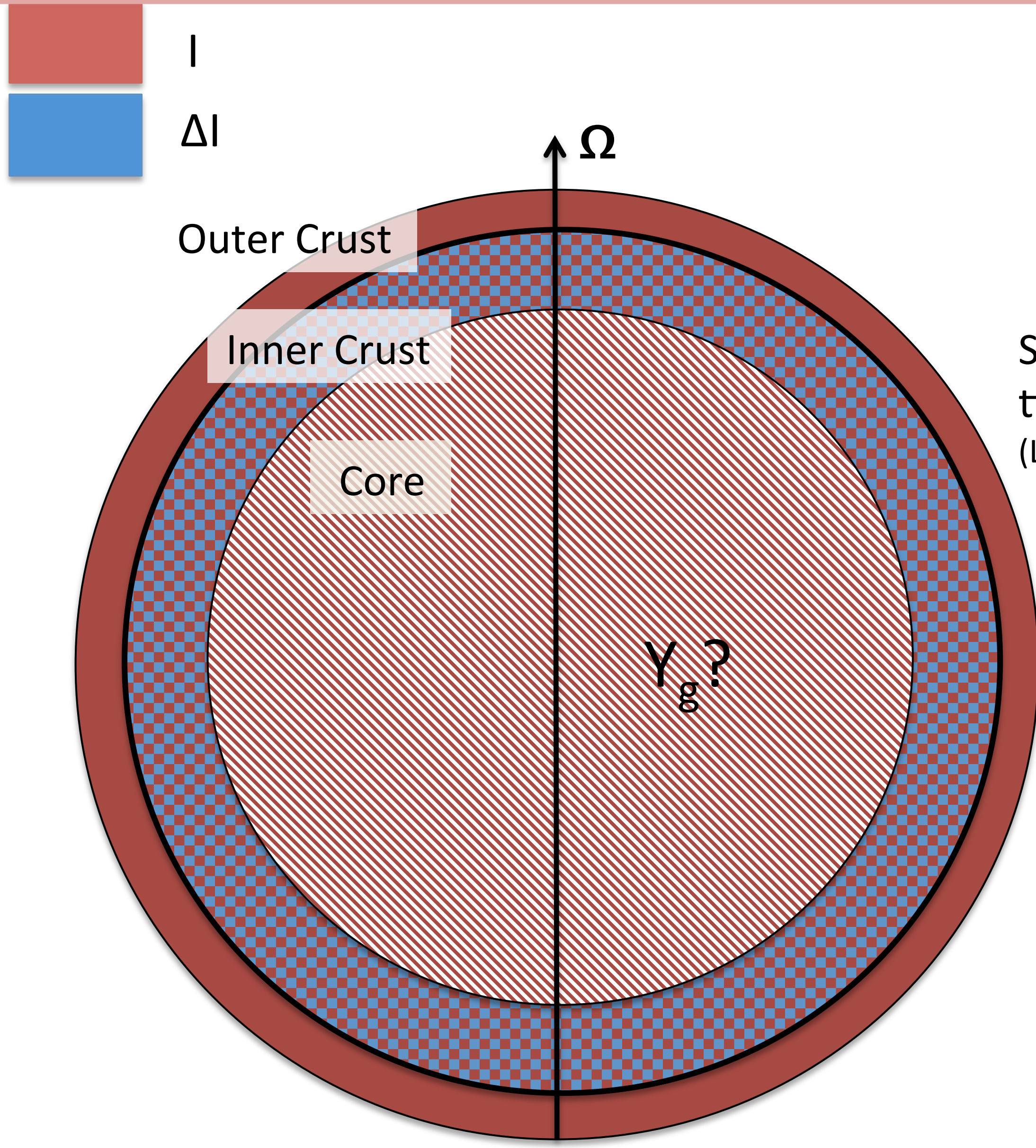
(Link, Epstein, Lattimer; PRL83 1999)

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

ΔI reduced by factor of 5

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

Testing glitch models with nuclear experiment



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

(Link, Epstein, Lattimer; PRL83 1999)

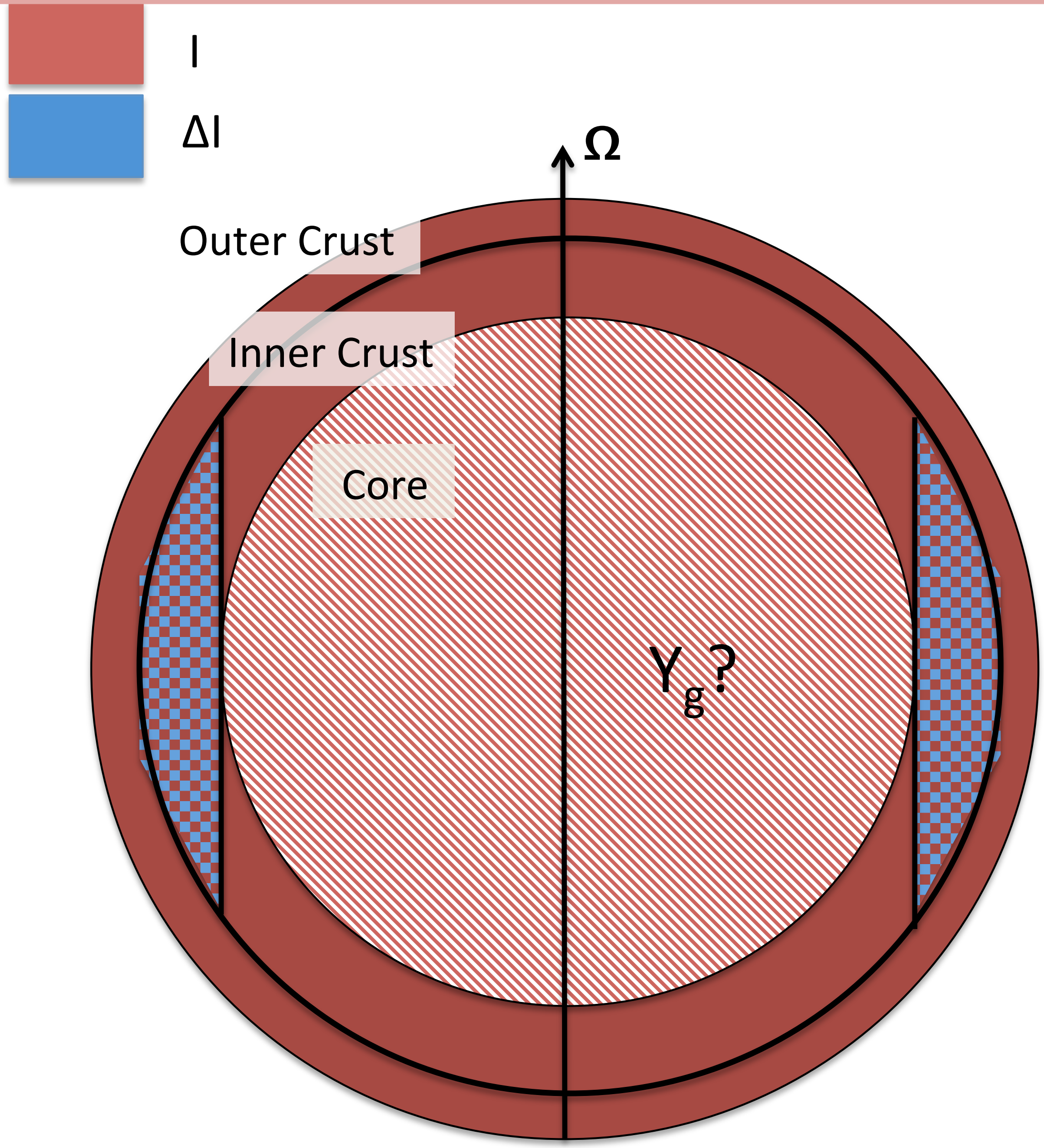
Saved by core superfluid coupling on timescales larger than glitch rise time?
(Link 2012; Haskell et al 2012; Seveso et al 2012)

- Mutual friction couples core neutrons to core protons; strength quite uncertain
- Fraction of core neutrons coupled to crust on glitch timescales $Y_g \approx t_{glitch}/t_{mf} = 1 - 10^{-3}$

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

OK for most EOSs

Testing glitch models with nuclear experiment



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

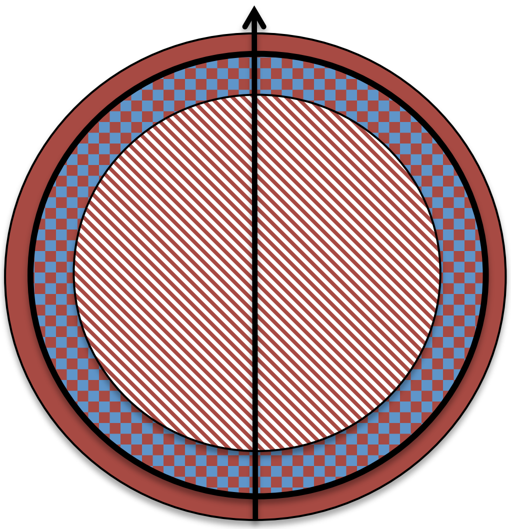
(Link, Epstein, Lattimer; PRL83 1999)

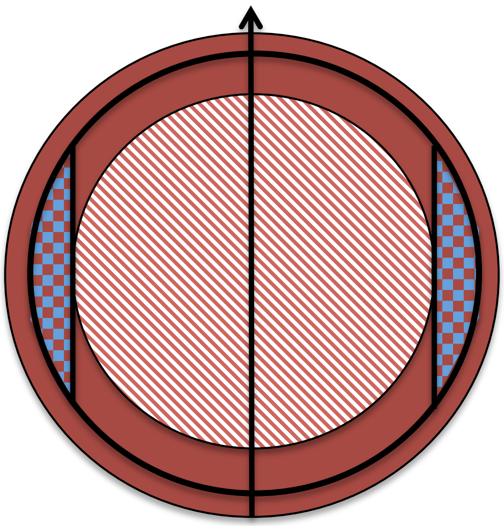
Pinning only happens when vortices completely immersed in crust (the strong pinning region)
(Haskell et al 2012; Seveso et al 2012)

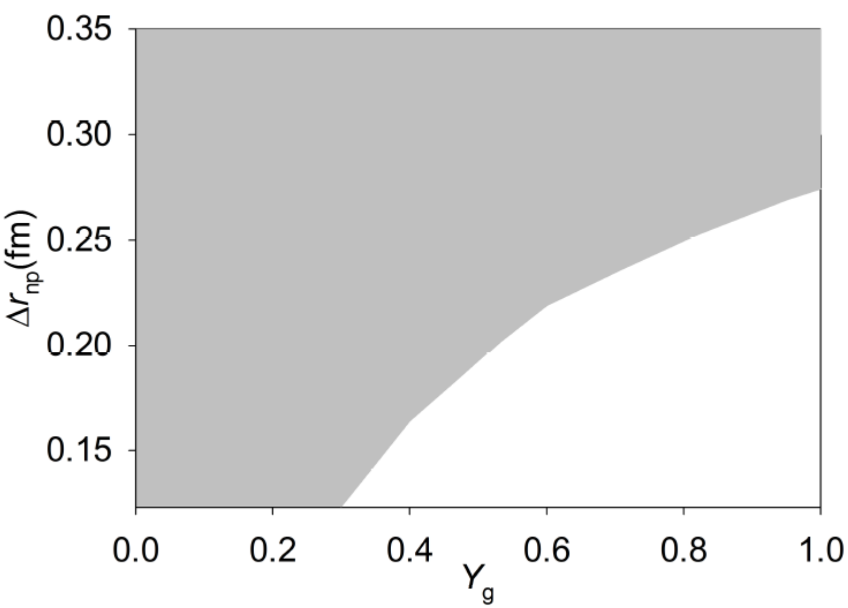
ΔI reduced by factor of 5
I reduced by factor of 2-100
ΔI reduced by factor of approx. 10

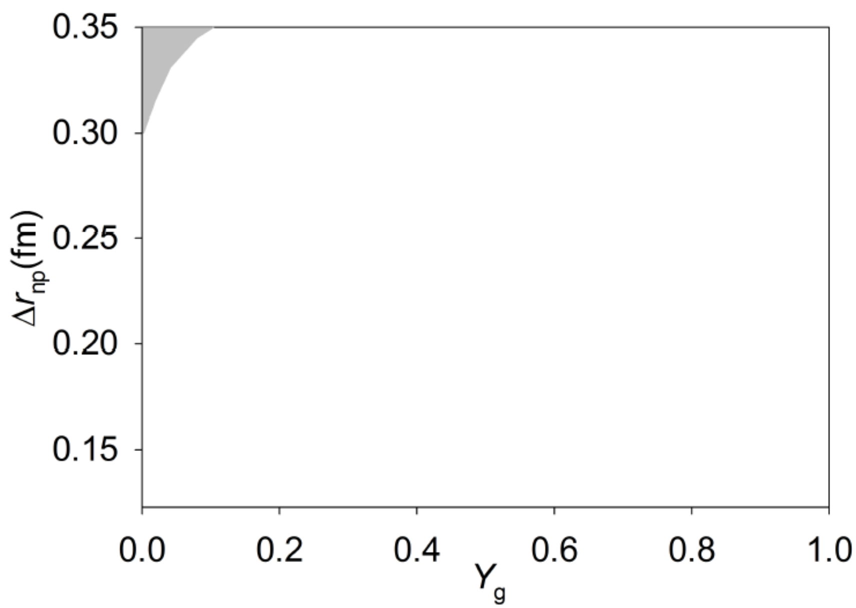
Satisfied by “reasonable” EOSs?

Testing glitch models with nuclear experiment

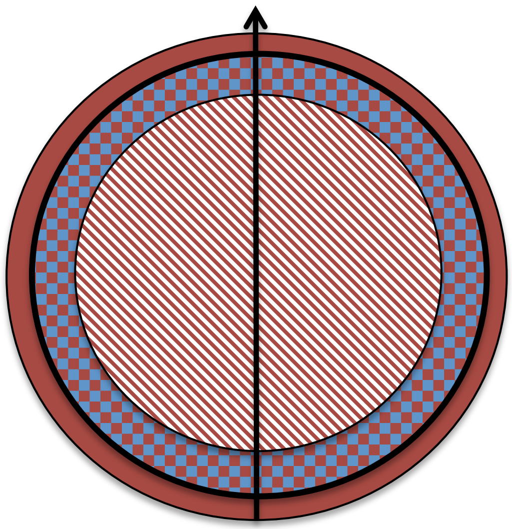


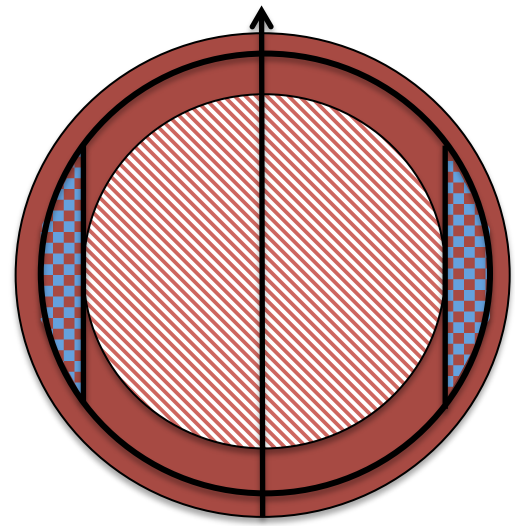


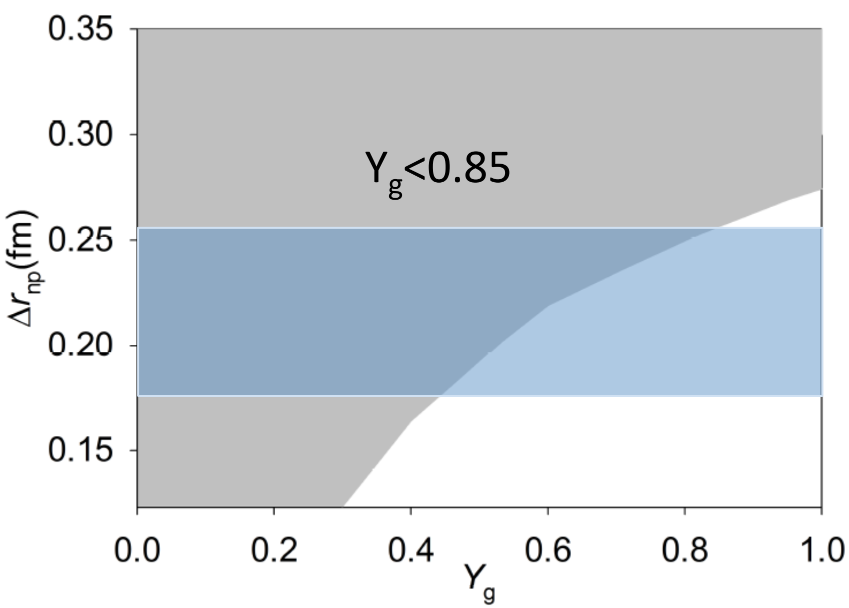


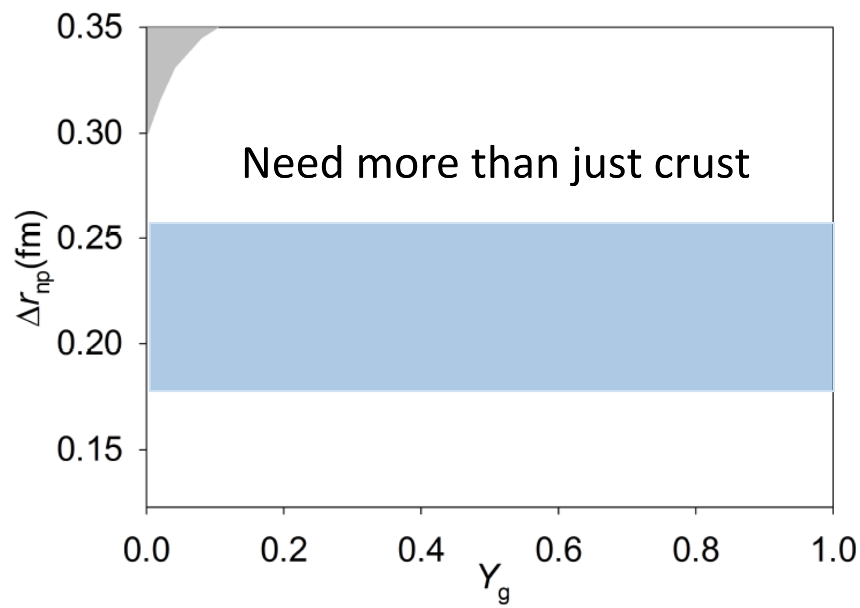


Testing glitch models: naïve community constraint L=35-86MeV

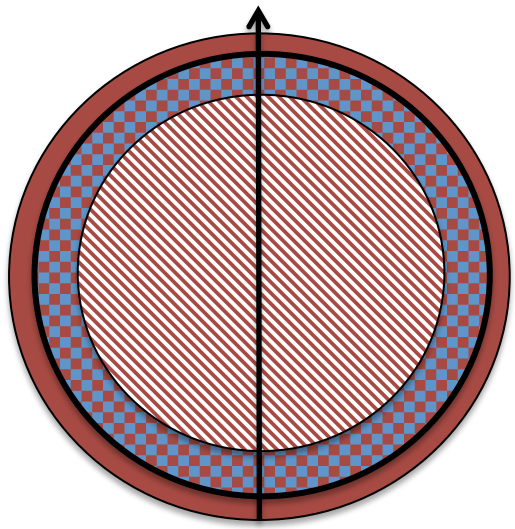


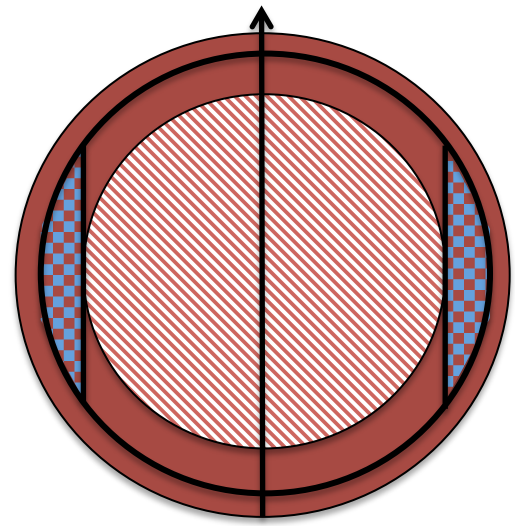


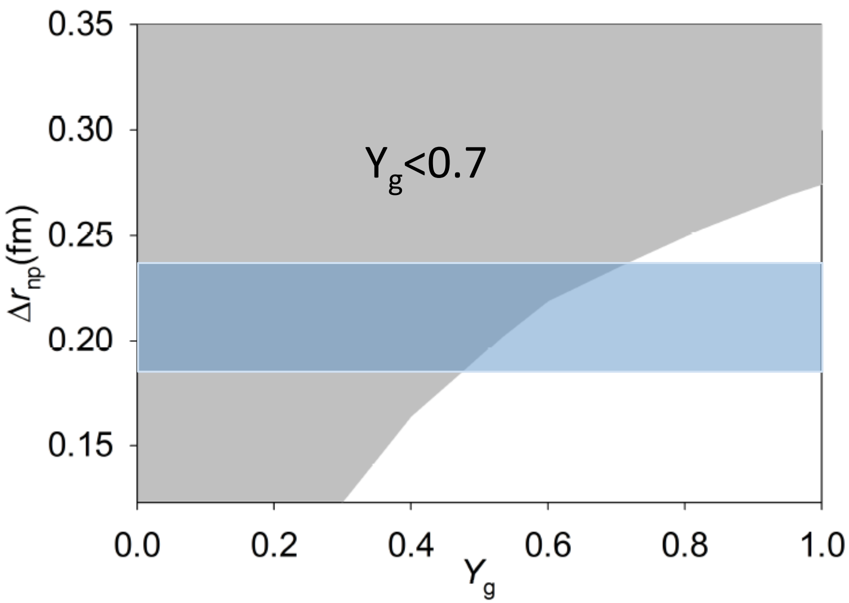


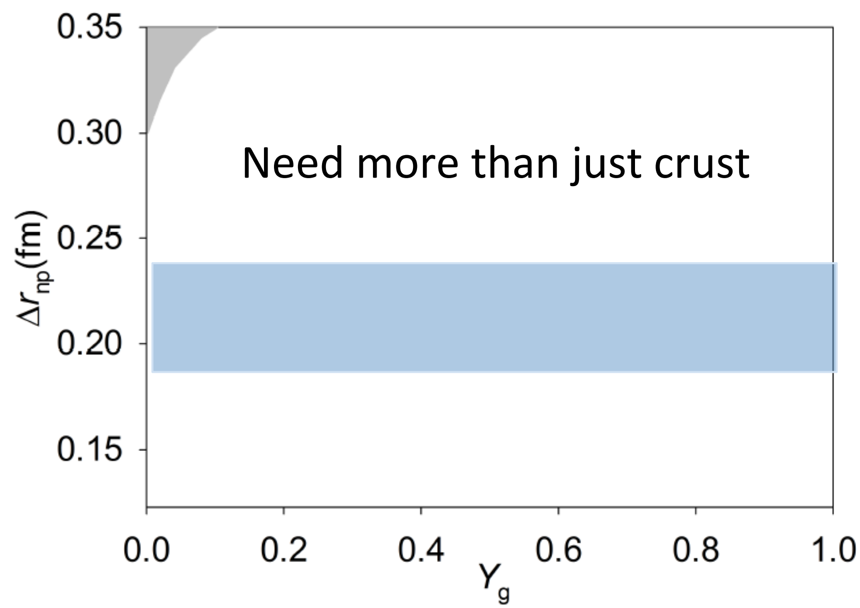


Testing glitch models: overlap of experimental J-L correlations L=44-66MeV

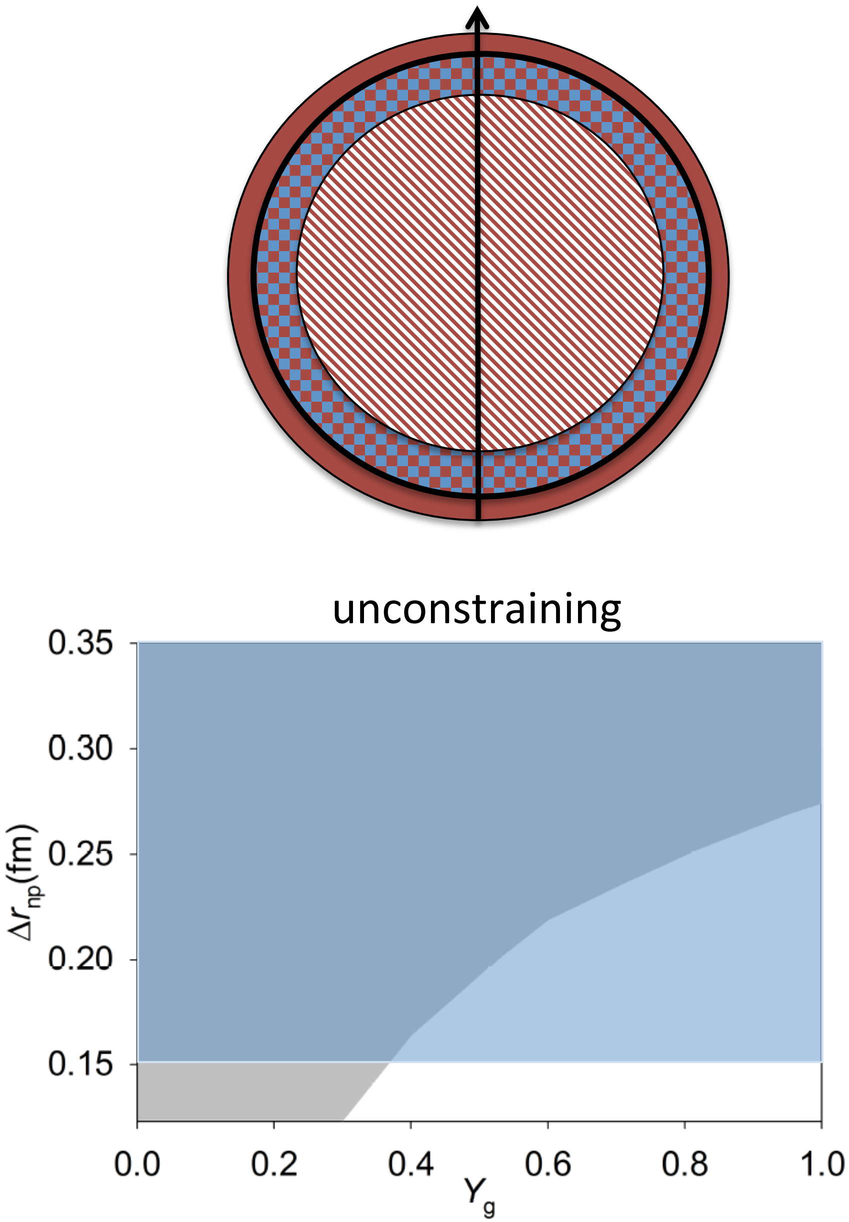


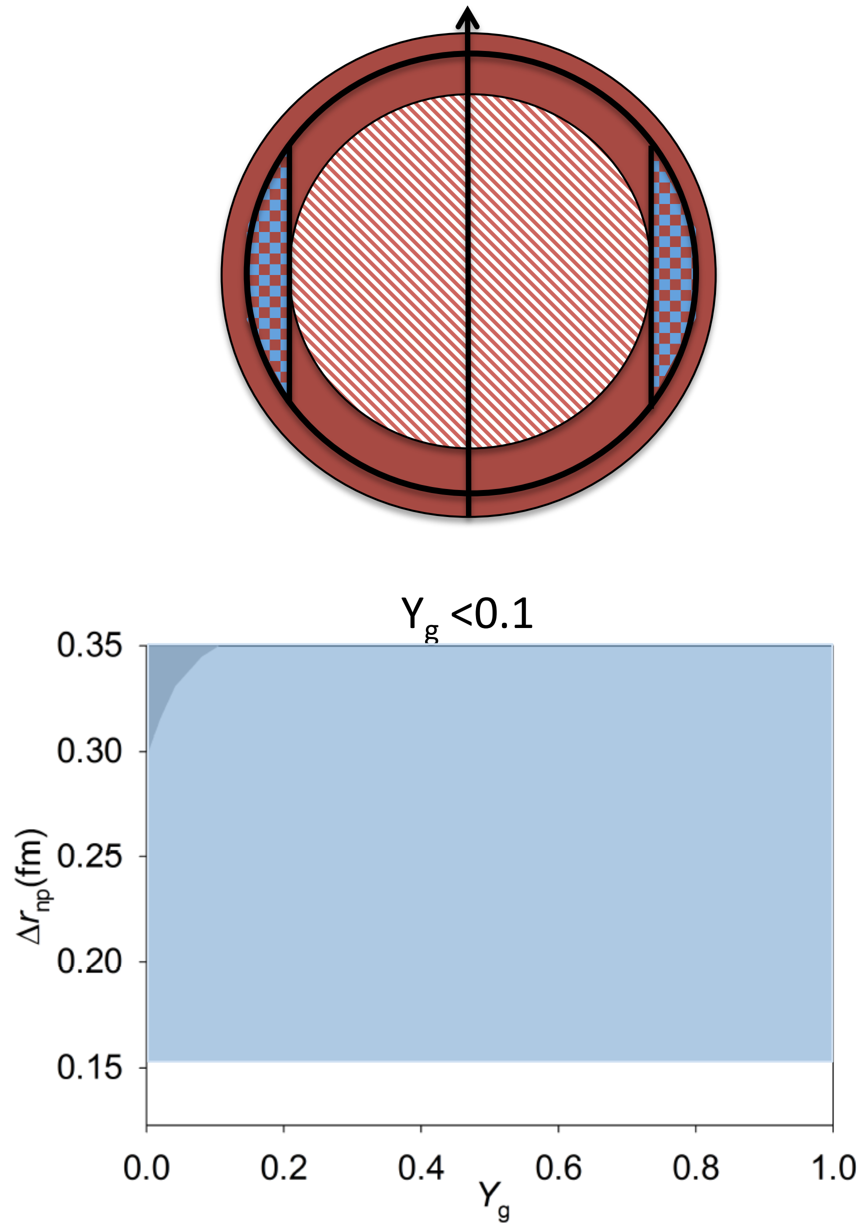




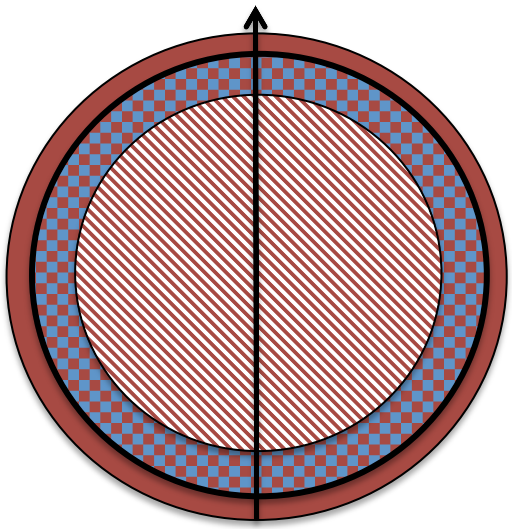


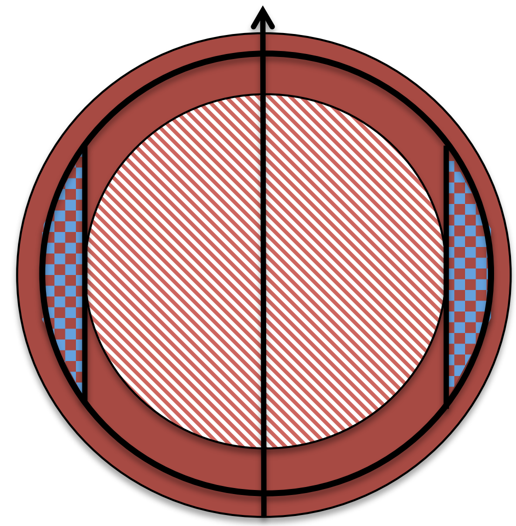
Testing glitch models: electroweak measurement of Pb208 neutron skin (PREX: Abrahamyan et al PRL108 2012)

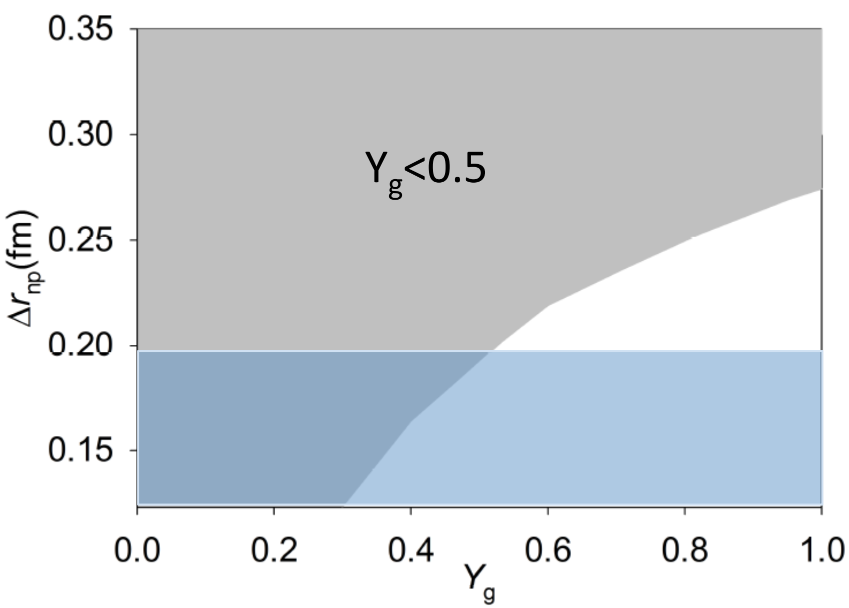


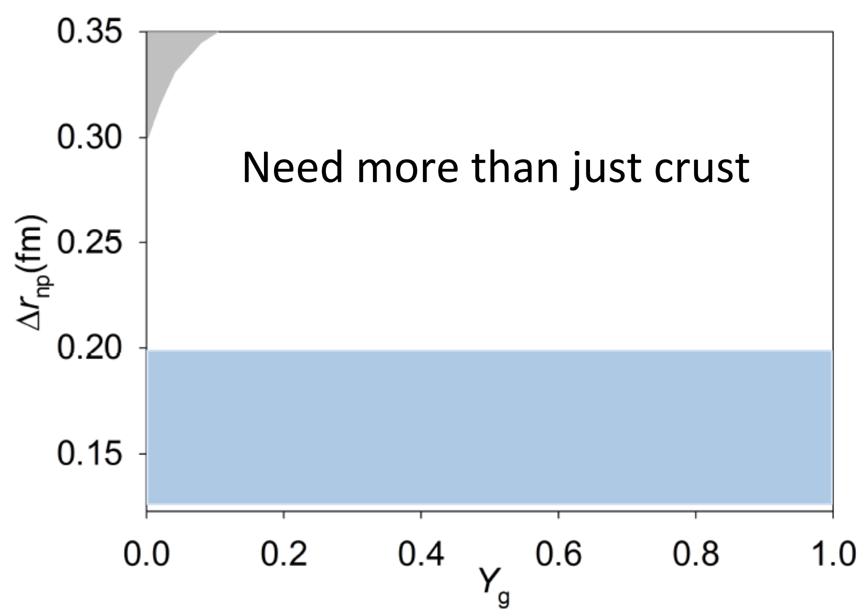


Testing glitch models: coherent pion photoproduction measurement of Pb208 neutron skin (Tarbert et al PRL112 2014)

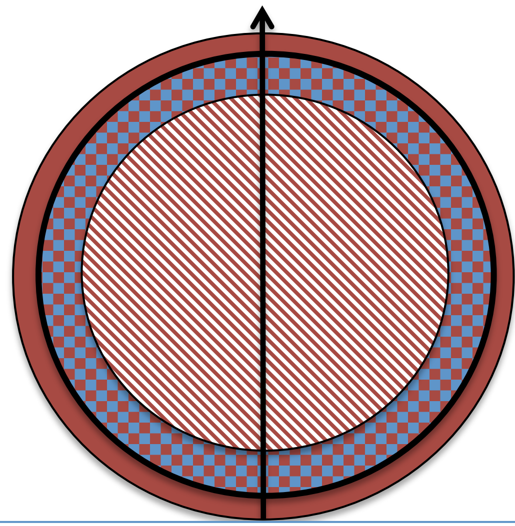




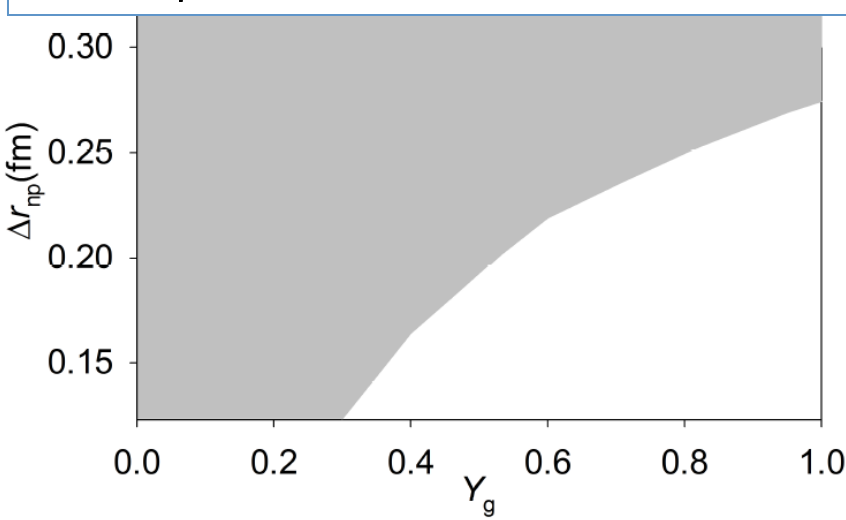


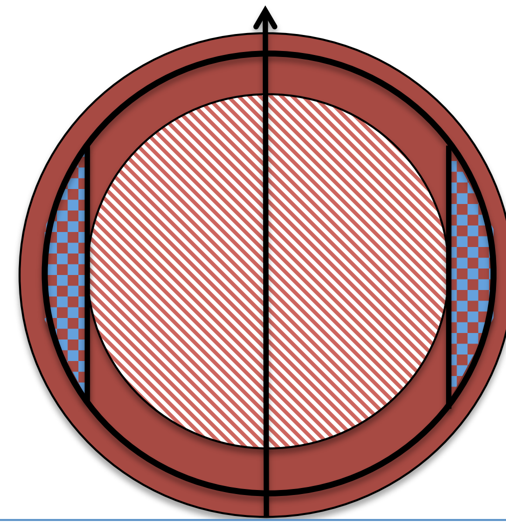


Testing glitch models with nuclear experiment

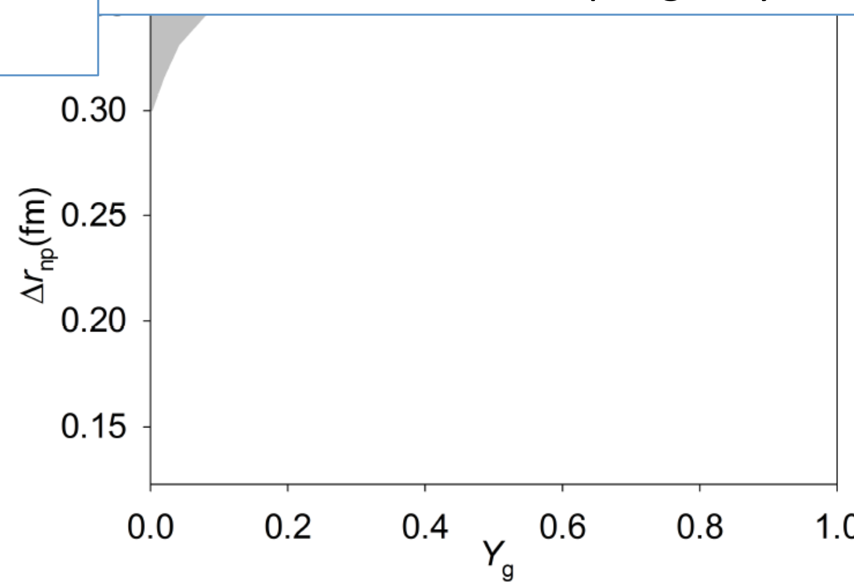


Consistent with nuclear experiment,
As long as significant fraction of core neutrons not coupled on timescales of order min

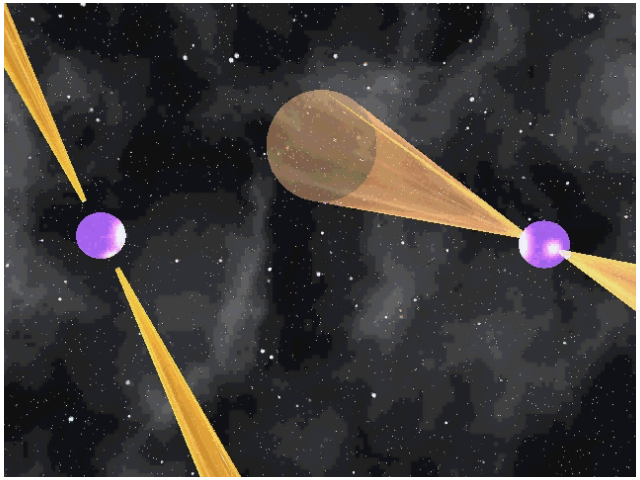




At odds with nuclear experiment
unless core neutron coupling very weak



The Formation of J0737-3039b



Pulsar A: Discovered April 2003
$P = 22.7$ ms
$M = 1.3381 \pm 0.0007\ M_{SUN}$

Pulsar B: Discovered Dec 2003
$P = 2.77$ s
$M = 1.2489 \pm 0.0007\ M_{SUN}$

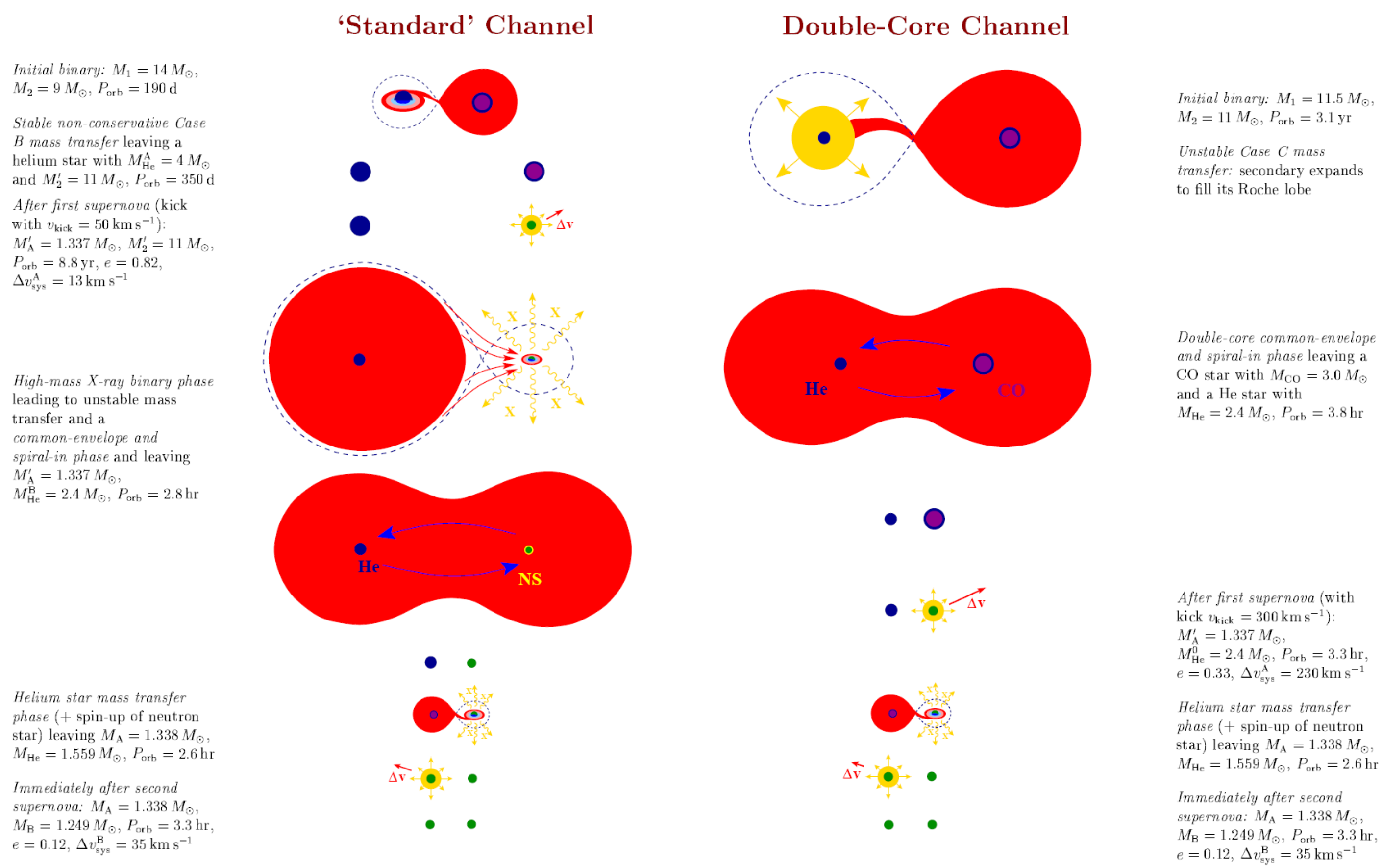
- low orbital eccentricity $e = 0.088$ (rather circular for a system that's undergone 2 SNe)
- Low mass of pulsar B: $\approx 1.25\ M_{SUN}$
- Low transverse velocity of J0737-3039 ($v_t \approx 10$km/s) – statistically unlikely that SNB provided a large kick
- Small angle between pulsar A's spin and orbital angular momentum
- Stability of pulsar A's pulse profile

Suggests an *electron-capture supernova*

The Formation of J0737-3039b

e-capture SN: important features

- thought to be responsible for (at least some of)Type Ib/c Sne
- how the lowest mass stars that undergo supernovae, do so
- timescale for explosion much shorter than timescale for large instabilities to develop
  – symmetric SN > low kick
- ONeMg Core collapses at a a well defined mass of ≈ 1.37 M_{SUN}
- Simulations indicate very little core mass ejected during supernova (< 10^{-3} M_{SUN})



Ph. Podsiadlowaki et al MNRAS 361, 1243 (2005)

The Formation of 1756-2251b

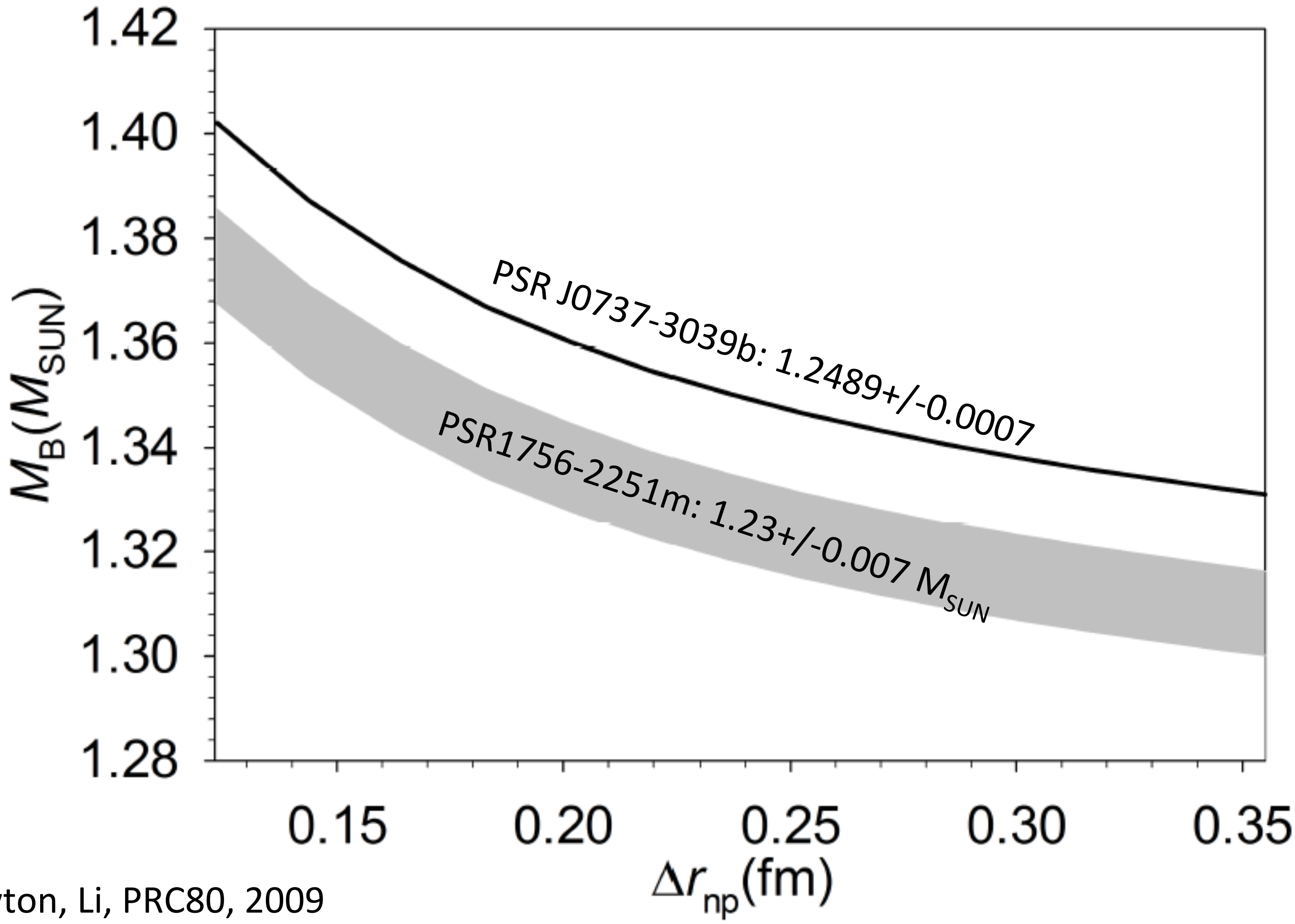
PSR J1756−2251: a pulsar with a low-mass neutron star companion

R. D. Ferdman,[1⋆] I. H. Stairs,[2] M. Kramer,[3,4] G. H. Janssen,[5,4] C. G. Bassa,[5,4] B. W. Stappers,[4] P. B. Demorest,[6] I. Cognard,[7,8] G. Desvignes,[3] G. Theureau,[7,8,9] M. Burgay,[10] A. G. Lyne,[4] R. N. Manchester,[11] and A. Possenti[10]

ABSTRACT

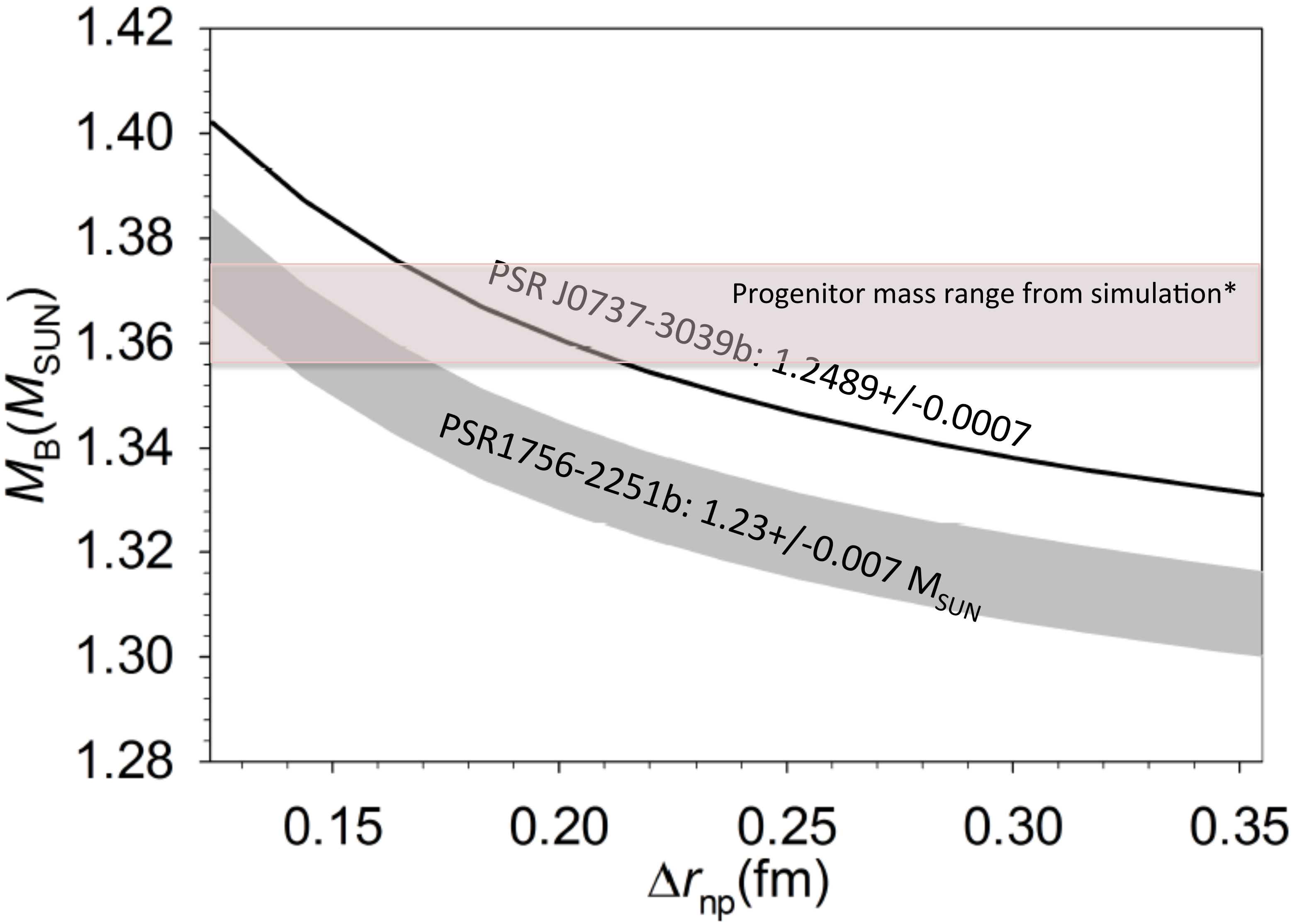
The pulsar PSR J1756−2251 resides in a relativistic double neutron star (DNS) binary system with a 7.67-hr orbit. We have conducted long-term precision timing on more than 9 years of data acquired from five telescopes, measuring five post-Keplerian parameters. This has led to several independent tests of general relativity (GR), the most constraining of which shows agreement with the prediction of GR at the 4% level. Our measurement of the orbital decay rate disagrees with that predicted by GR, likely due to systematic observational biases. We have derived the pulsar distance from parallax and orbital decay measurements to be $0.73^{+0.60}_{-0.24}$ kpc (68%) and < 1.2 kpc (95% upper limit), respectively; these are significantly discrepant from the distance estimated using Galactic electron density models. We have found the pulsar mass to be $1.341 \pm 0.007\,M_\odot$, and a low neutron star (NS) companion mass of $1.230 \pm 0.007\,M_\odot$. We also determined an upper limit to the spin-orbit misalignment angle of 34° (95%) based on a system geometry fit to long-term profile width measurements. These and other observed properties have led us to hypothesize an evolution involving a low mass loss, symmetric supernova progenitor to the second-formed NS companion, as is thought to be the case for the double pulsar system PSR J0737−3039A/B. This would make PSR J1756−2251 the second compact binary system providing concrete evidence for this type of NS formation channel.

Testing stellar evolution: Observed gravitational mass + gravitational binding energy (EOS dependent) = estimate of progenitor baryon mass



Newton, Li, PRC80, 2009

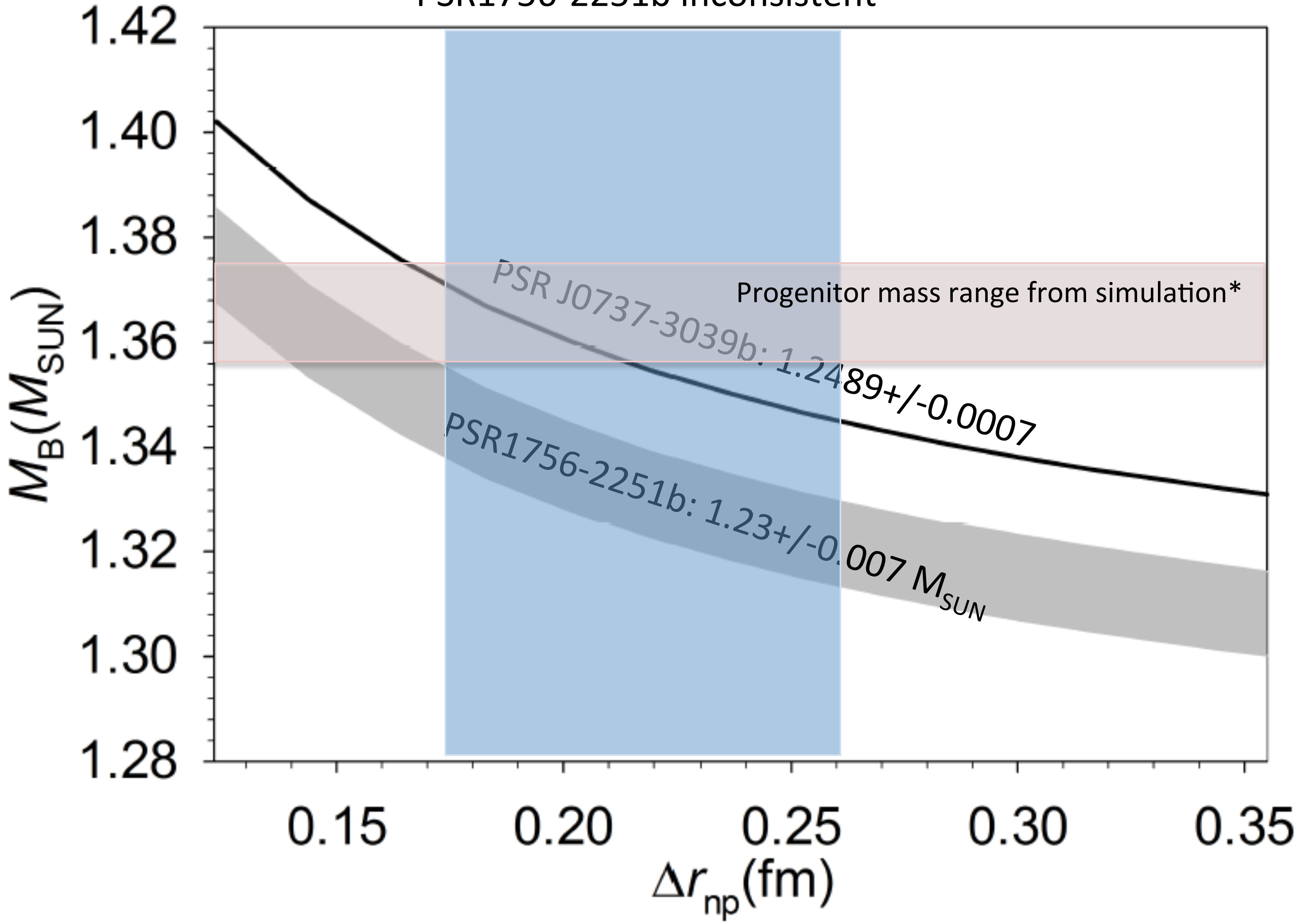
Testing stellar evolution



*Podsiadlowski et al, MNRAS361, 2005; Kitaura et al A&A450, 2006; Wanajo et al ApJL15, 2011

Testing stellar evolution: naïve community constraint L=35-86MeV

PSR1756-2251b inconsistent



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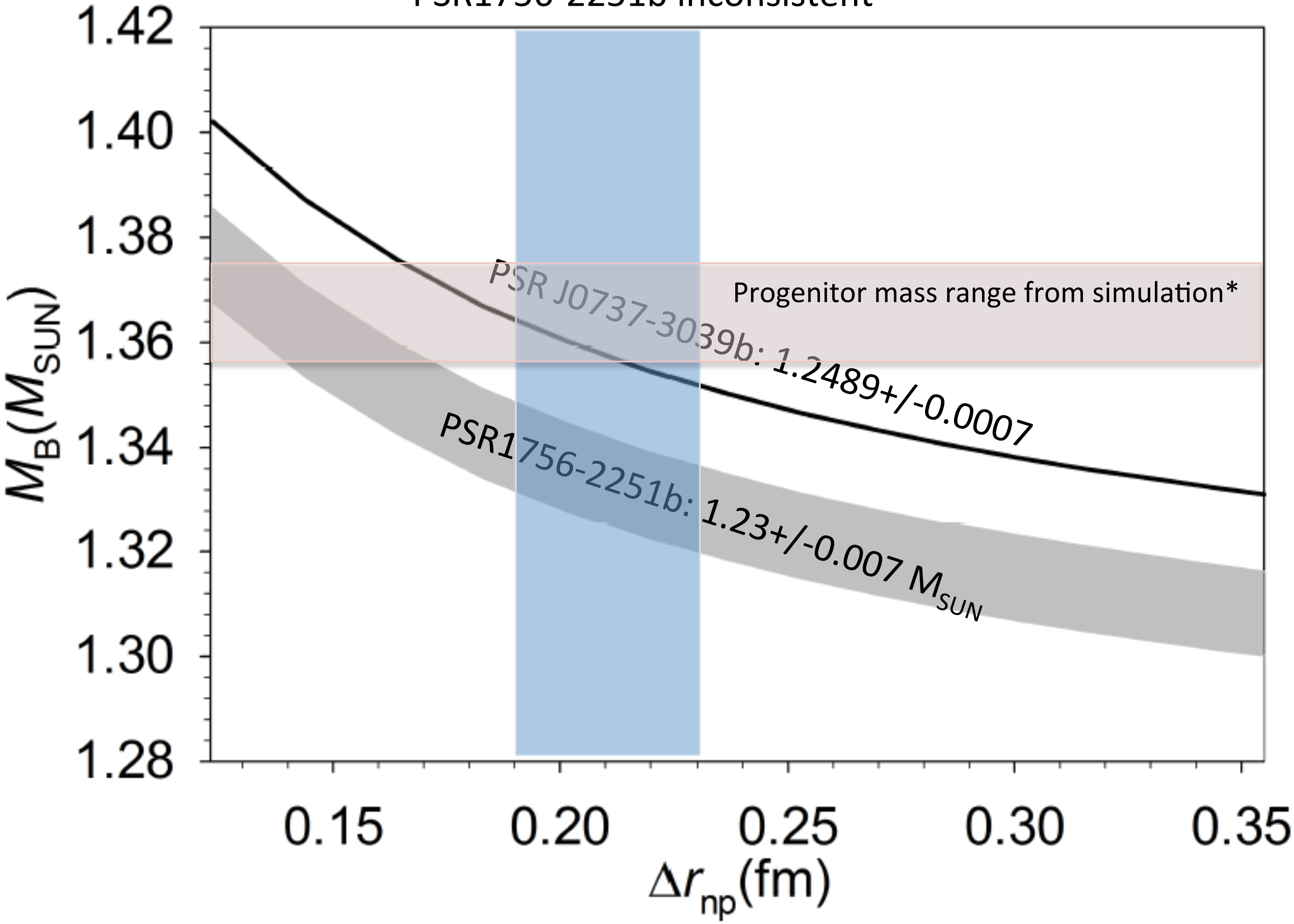

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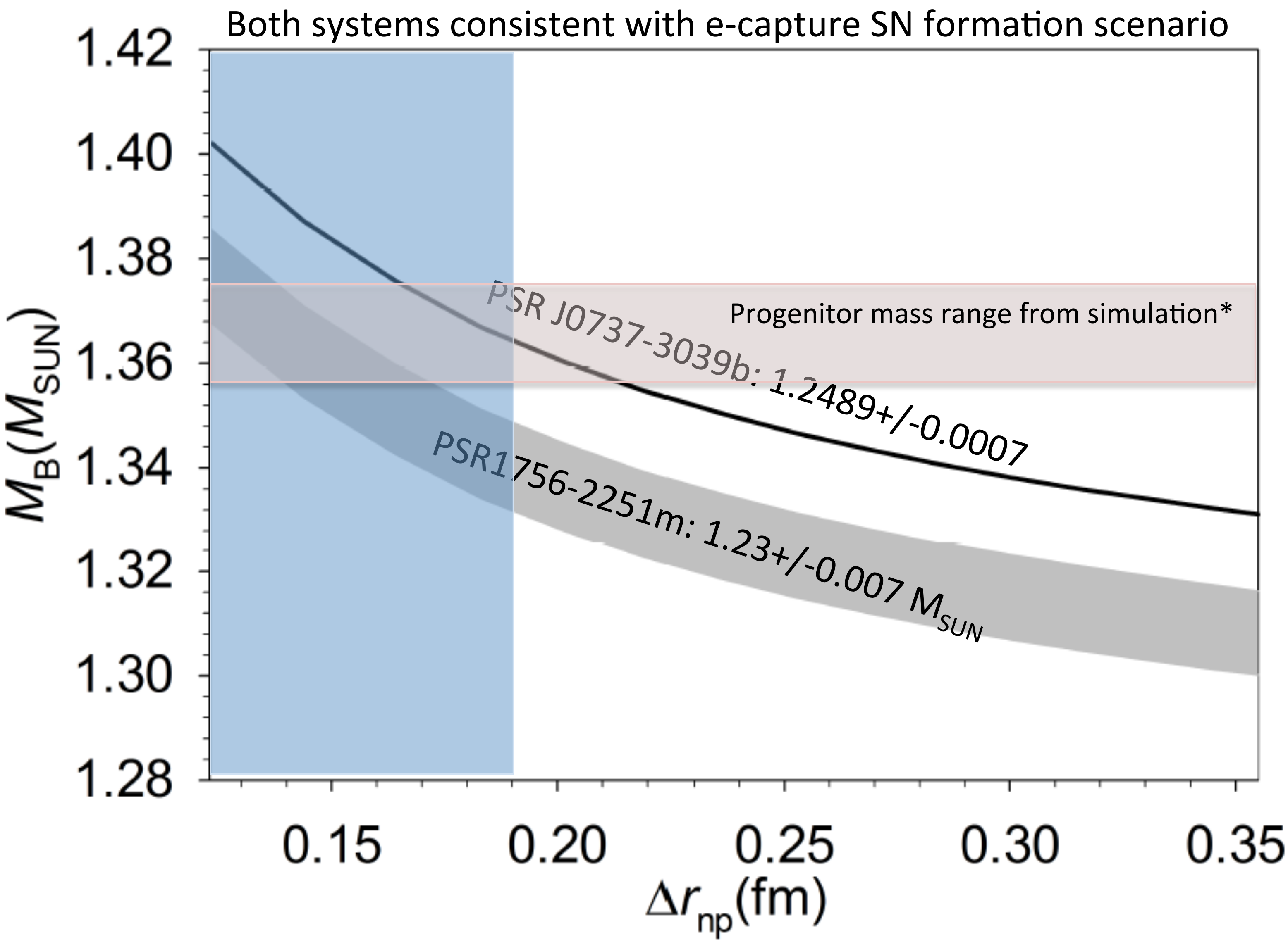
Testing stellar evolution: coherent pion photoproduction measurement of Pb208 neutron skin (Tarbert et al PRL112 2014)



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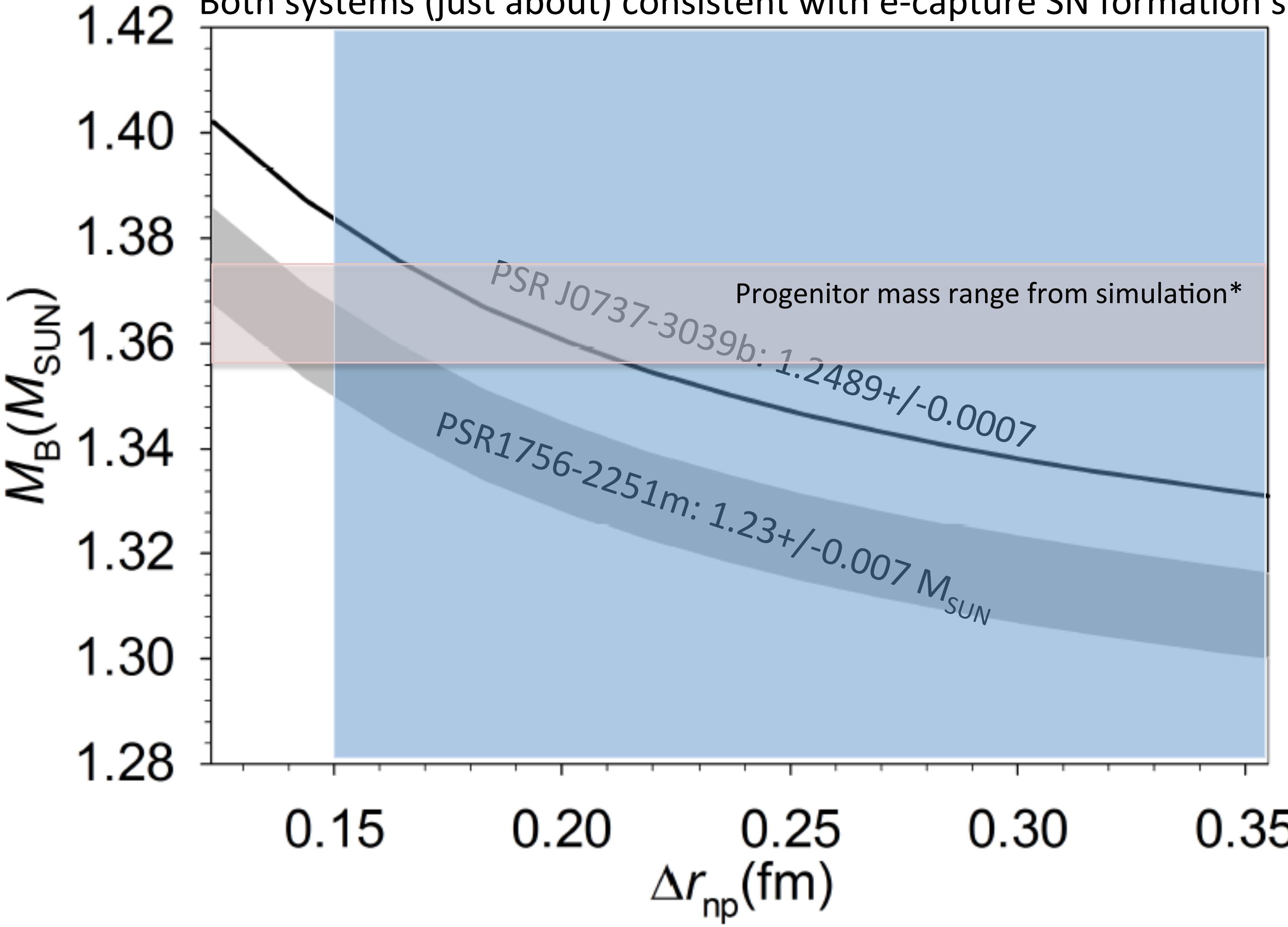
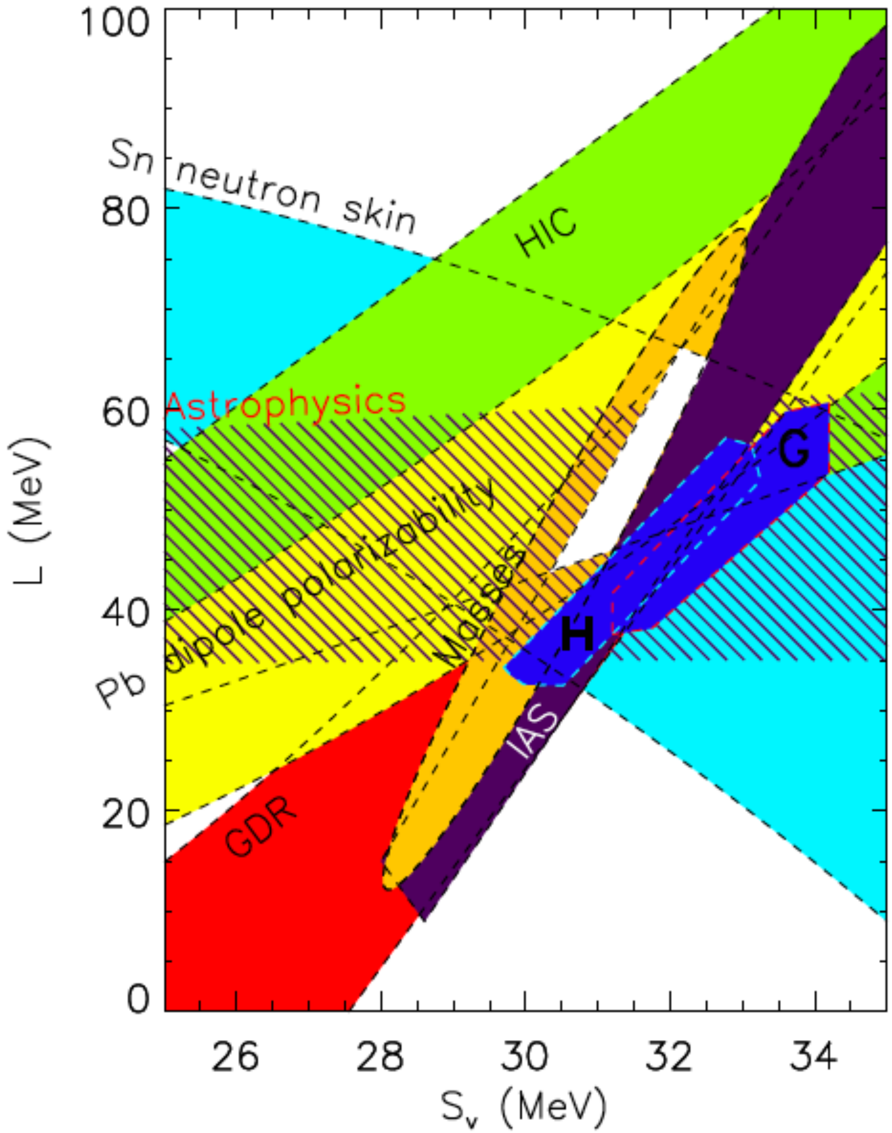
Testing stellar evolution: electroweak measurement of Pb208 neutron skin (PREX: Abrahamyan et al PRL108 2012)

Both systems (just about) consistent with e-capture SN formation scenario



*Podsiadlowski et al, MNRAS361, 2005; Kitaura et al A&A450, 2006; Wanajo et al ApJL15, 2011

Can we add to the wealth of experimental constraints on L from *multiple independent* astrophysical observables?



Combined mass/radius constraints

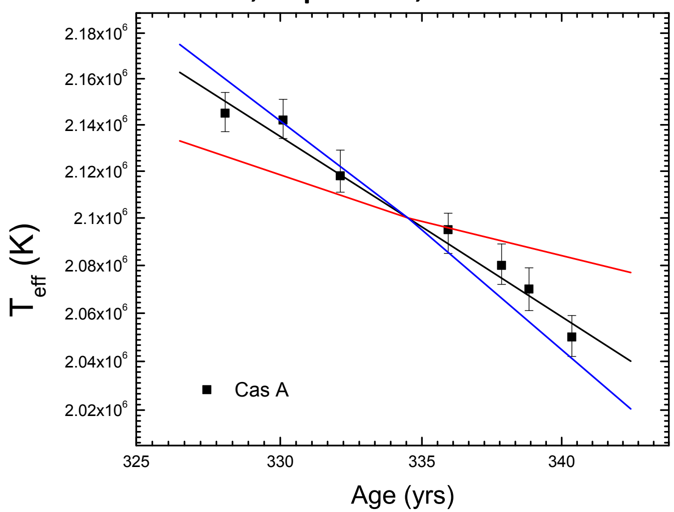
Lattimer,Steiner EPJA50, 40 (2014)

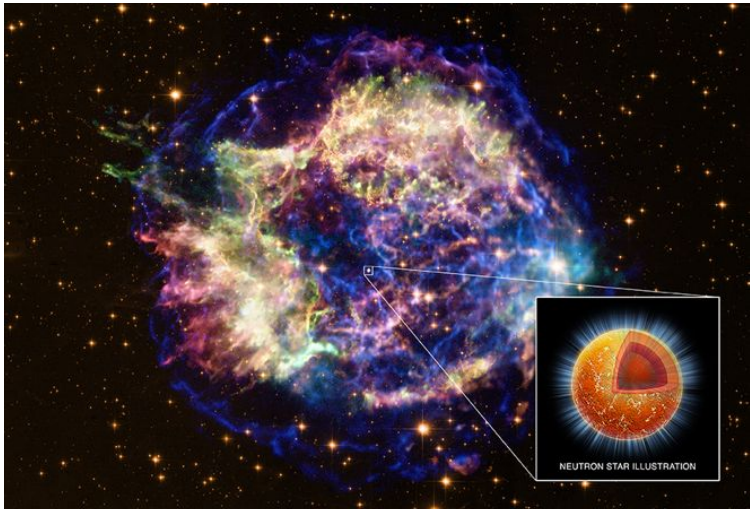
Quick review of symmetry energy constraints from astrophysical observables: Cooling rate of Cas A

L (MeV)	Specific (general) conditions/caveats
$\lesssim 70$	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)

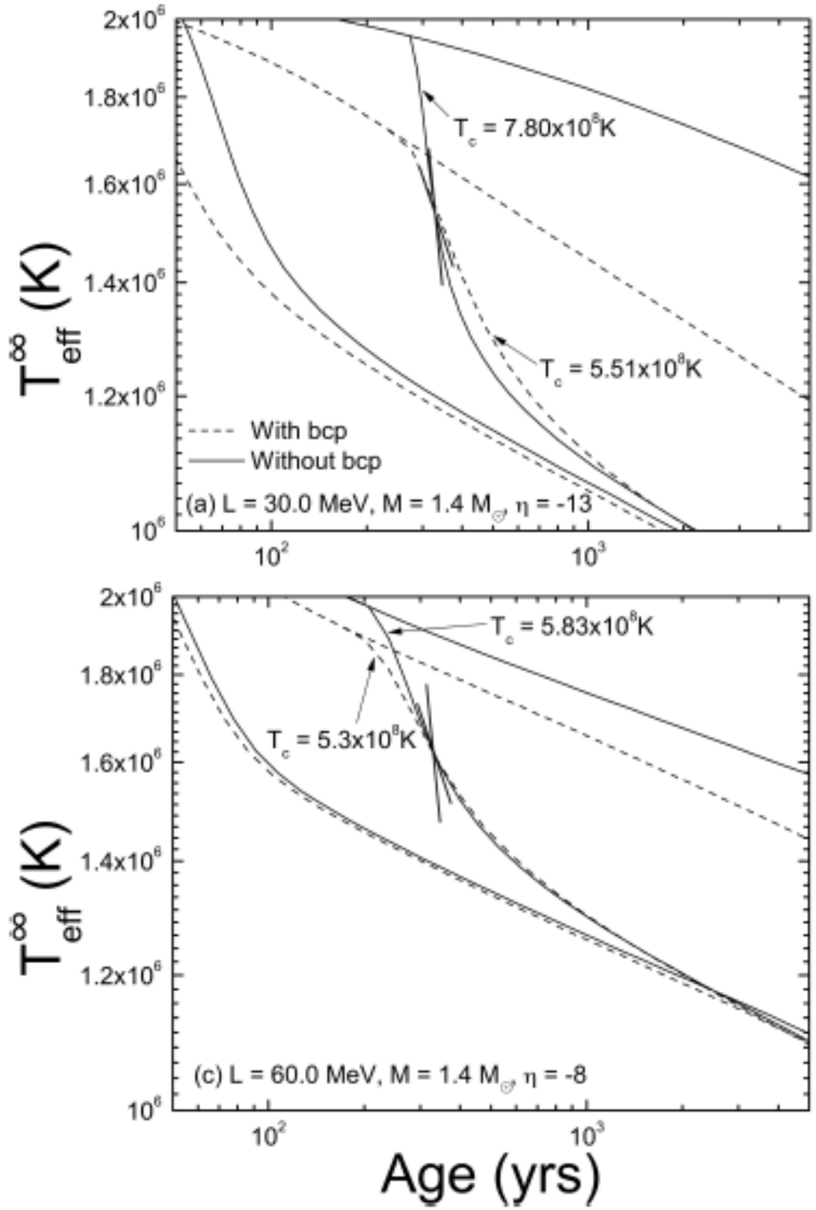
Newton et al ApJL779, 2013

- Rapid cooling evidence of superfluid phase transition
  (Page et al PRL106, 2011; Shternin et al MNRAS L108, 2011)
- Subsequent analysis of Chandra data taken over the previous decade ➔ evidence for rapid decrease in surface temperature by ≈ 4%/decade (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).
- Posselt et al; ApJ779, 186 – Chandra Cas A data consistent with *no cooling* in past decade





Quick review of symmetry energy constraints from astrophysical observables: Cooling rate of Cas A



Newton, Murphy, Hooker, Li, ApJL 2013

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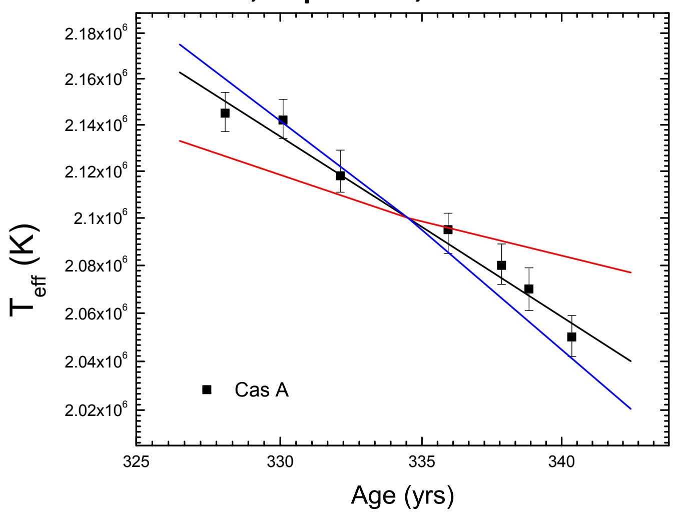
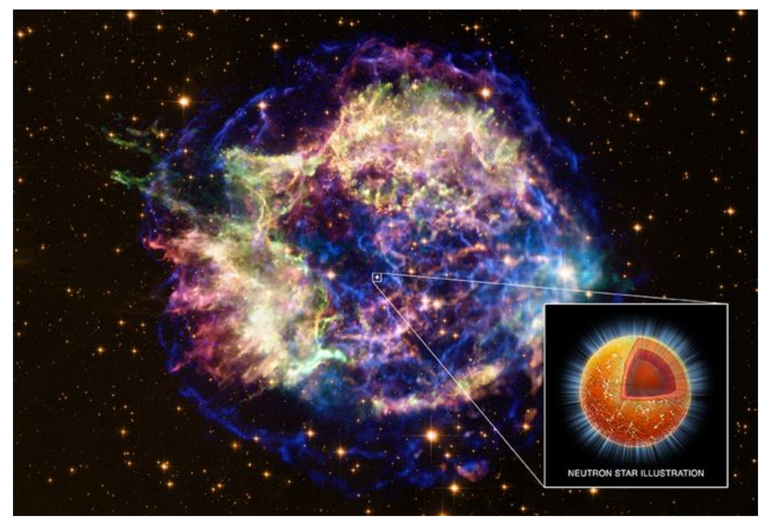
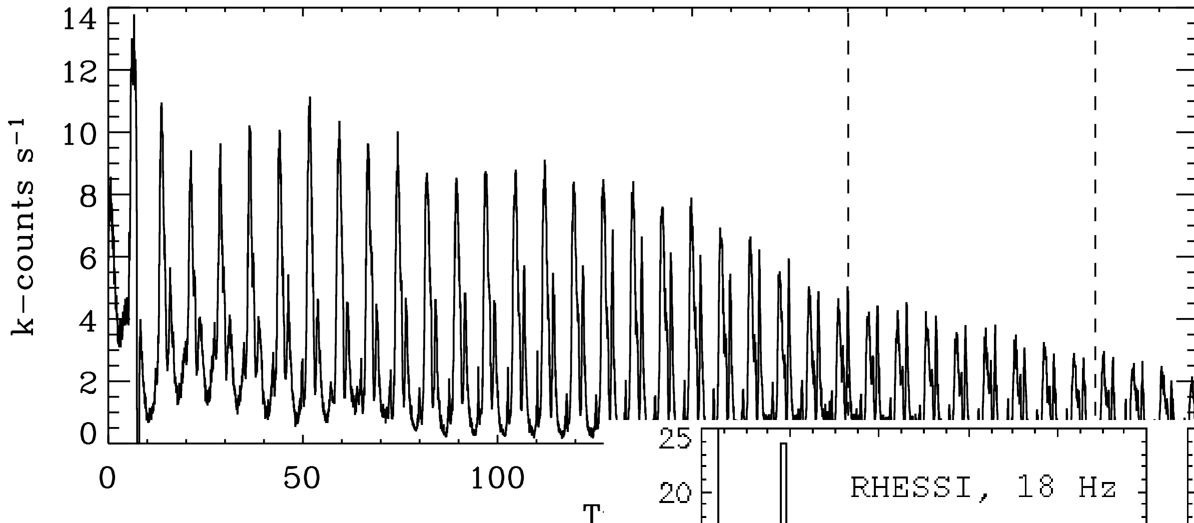
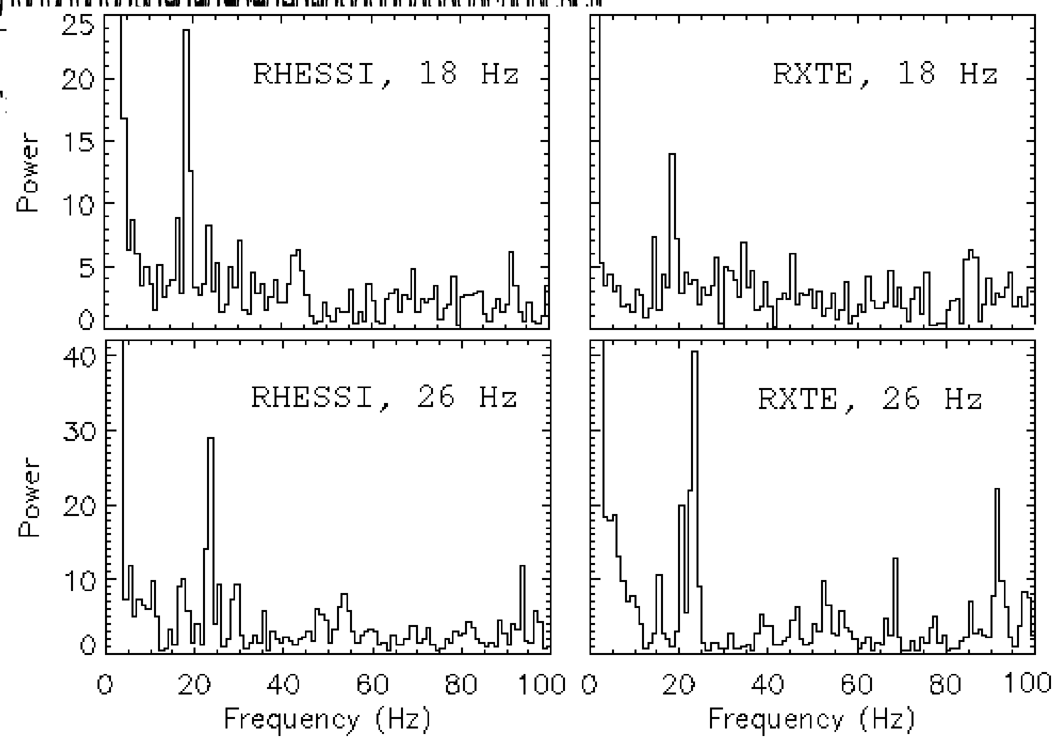




Modeling QPOs from X-ray tail of SGR flares as signatures of crust oscillations

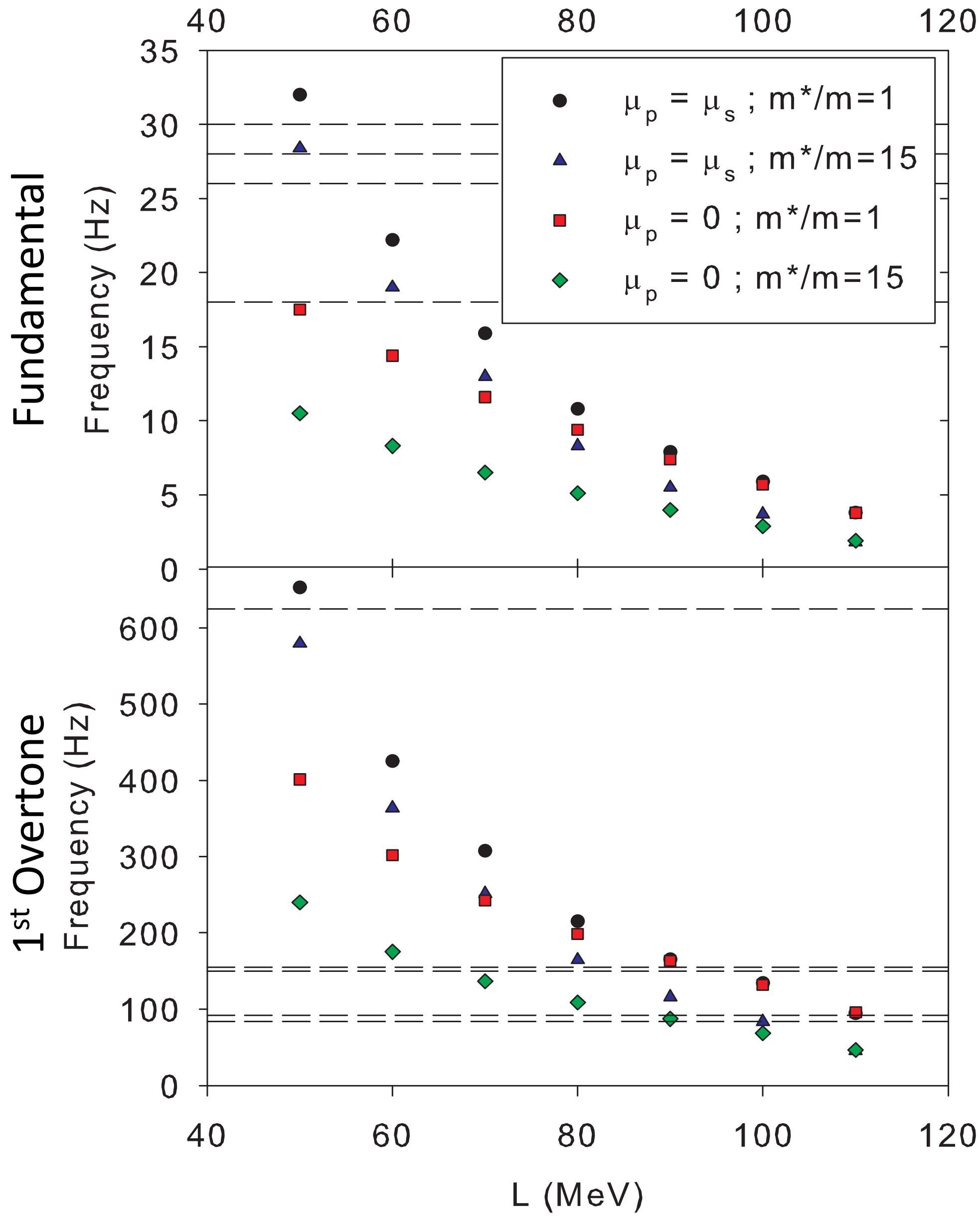




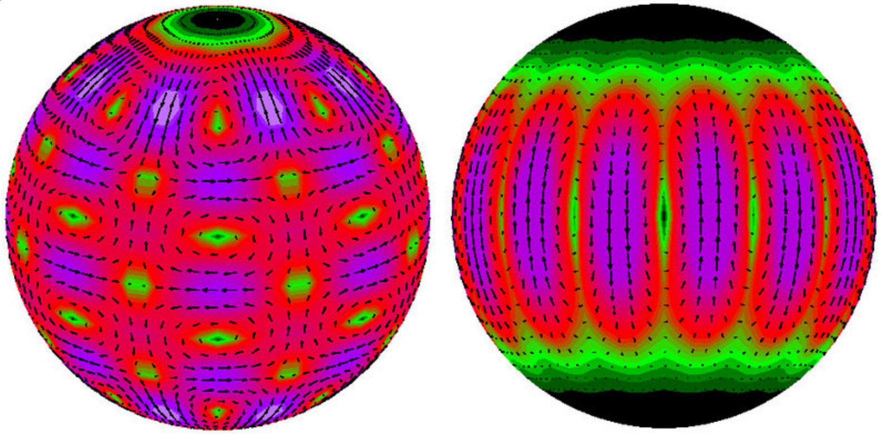
Interpretation:
vibrations of the NS crust
> NS seismology

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

Modeling QPOs from X-ray tail of SGR flares as signatures of crust oscillations



Gearheart, Newton, Li; MNRAS 418 (2011)



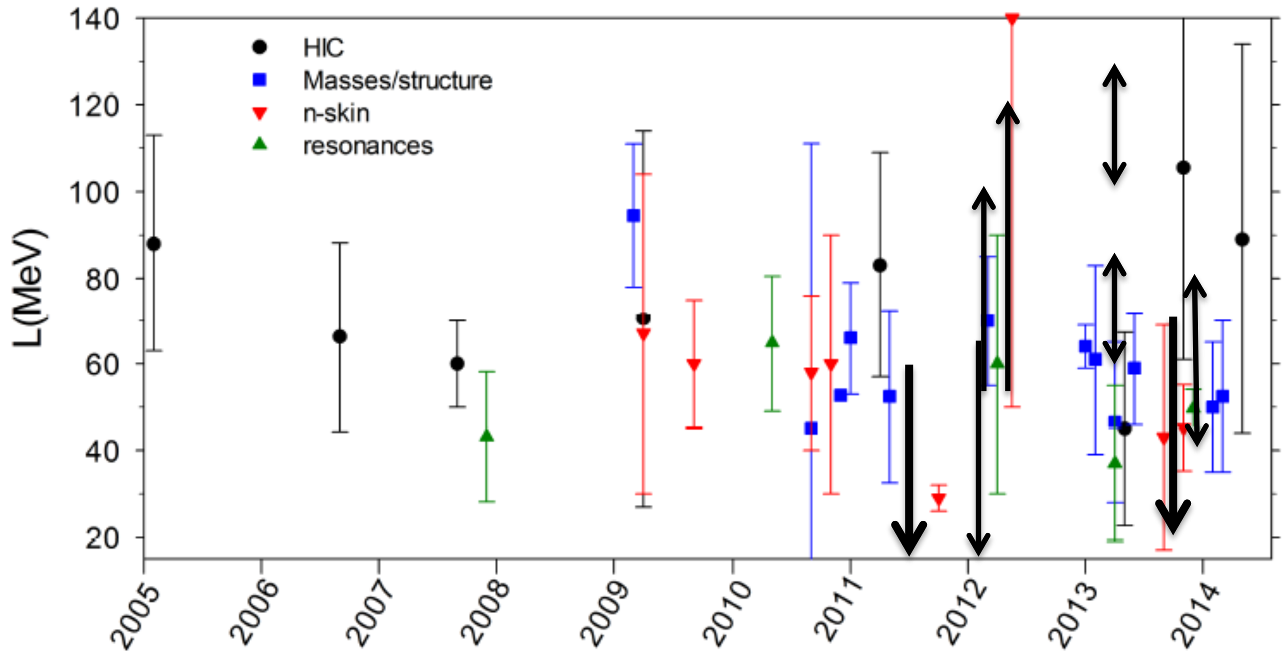
- If one of the low frequency QPOs is the fundamental frequency, L < 60MeV and pasta has shear modulus close to that of crustal lattice

Quick review of symmetry energy constraints from astrophysical observables: QPOs in X-ray tails of SGR giant flares

$\lesssim 60$	Calculated frequencies fall in range of potential observed fundamental frequencies; consistent crust-core EOS; limiting superfluid, pasta effects included	(1)
$\gtrsim 50$	Exact matching of fundamental mode with lowest observed frequency QPO; inconsistent crust, core models; no superfluid effects;	(2)
$100 \lesssim L \lesssim 130$	Exact matching of all observed frequency with crust modes; inconsistent crust, core models; superfluid effects included	(3)
$58 \lesssim L \lesssim 85$	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.)	(4)

(1) Gearheart, Newton, Li MNRAS (2011)
(2) Sotani et al PRL108 (2012)
(3) Sotani et al MNRAS 428 (2013)
(4) Sotani et al MNRAS 434 (2013)

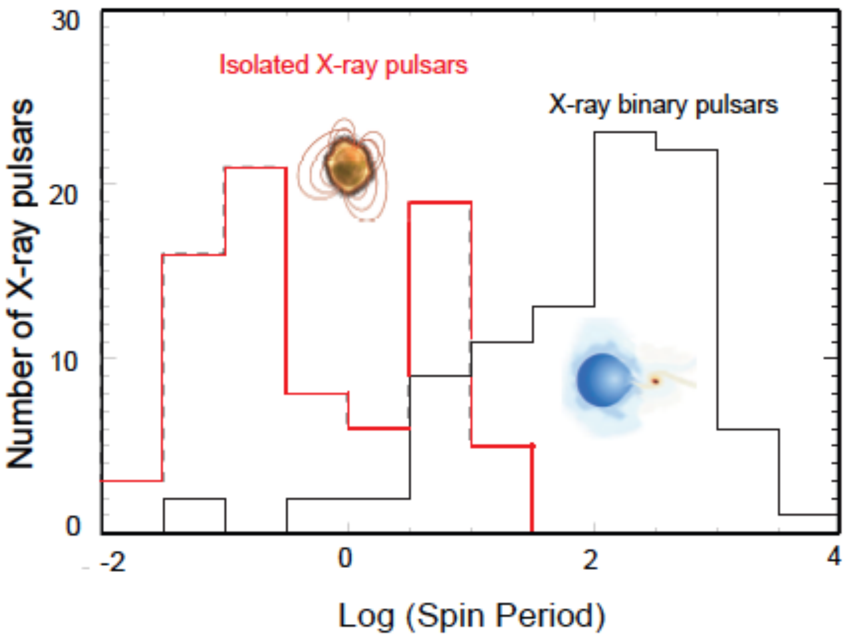
Conclusions



- We have entered an era where a significant number of independent astrophysical observables are placing quantitative constraints on symmetry energy parameters
- Many still depend critically on the details of the astrophysical model
- With consistent nuclear physics modeling, details of astrophysical models can now be tested using nuclear experimental data; more speculative mechanisms assessed in the light of independent nuclear and astrophysical data

Review of symmetry energy constraints: Newton et al, EPJA 50,41 (2014)

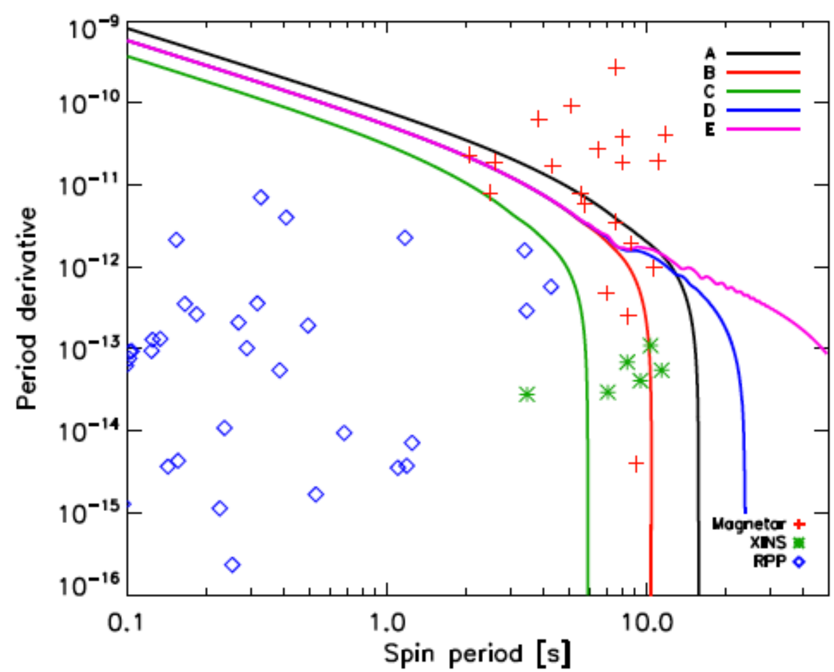
Evidence of Pasta?



- 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

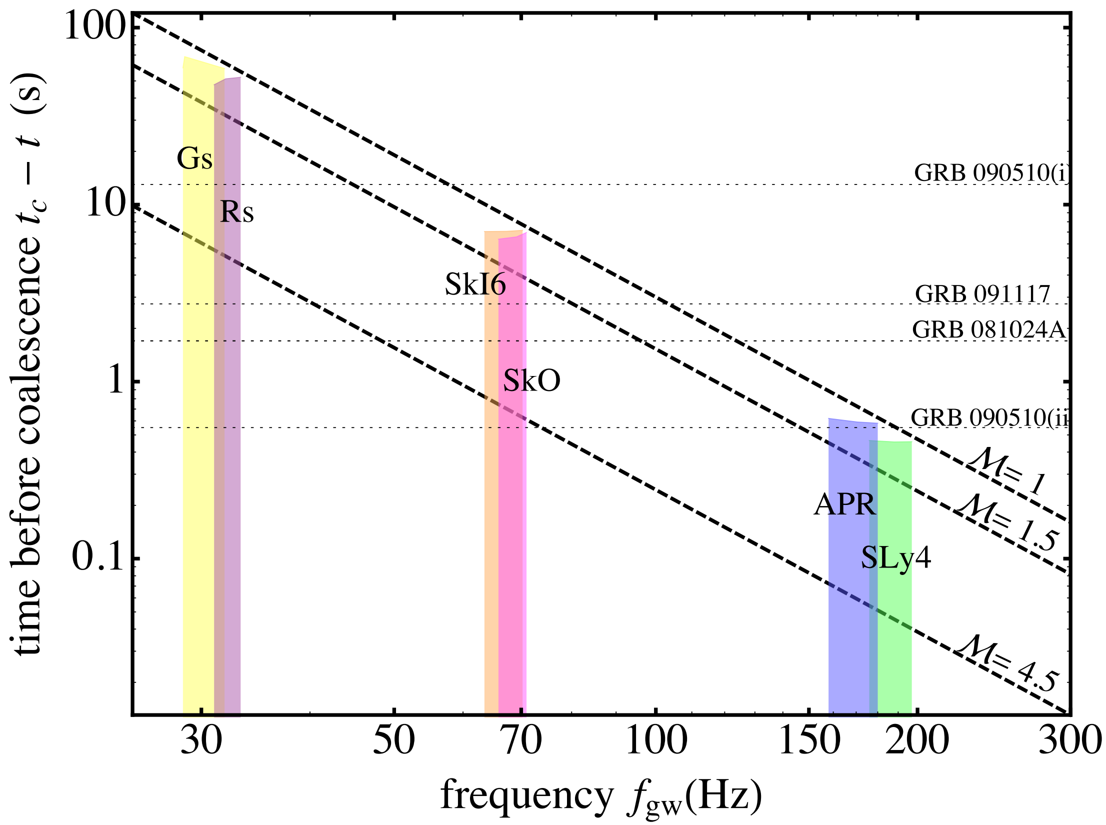
Model	$M[M_\odot]$	I_{45}	ΔR_{crust} [km]	ΔR_{pasta} [km]	Q_{imp}
A	1.10	0.962	0.94	0.14	100
B	1.40	1.327	0.70	0.10	100
C	1.76	1.755	0.43	0.07	100
D	1.40	1.327	0.70	0.10	10
E	1.40	1.327	0.70	0.10	0.1

Pons, Vigano and Rea, Nature, 2013



Observable: 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