What the symmetry energy has to say about neutron star radii and the neutron star crust

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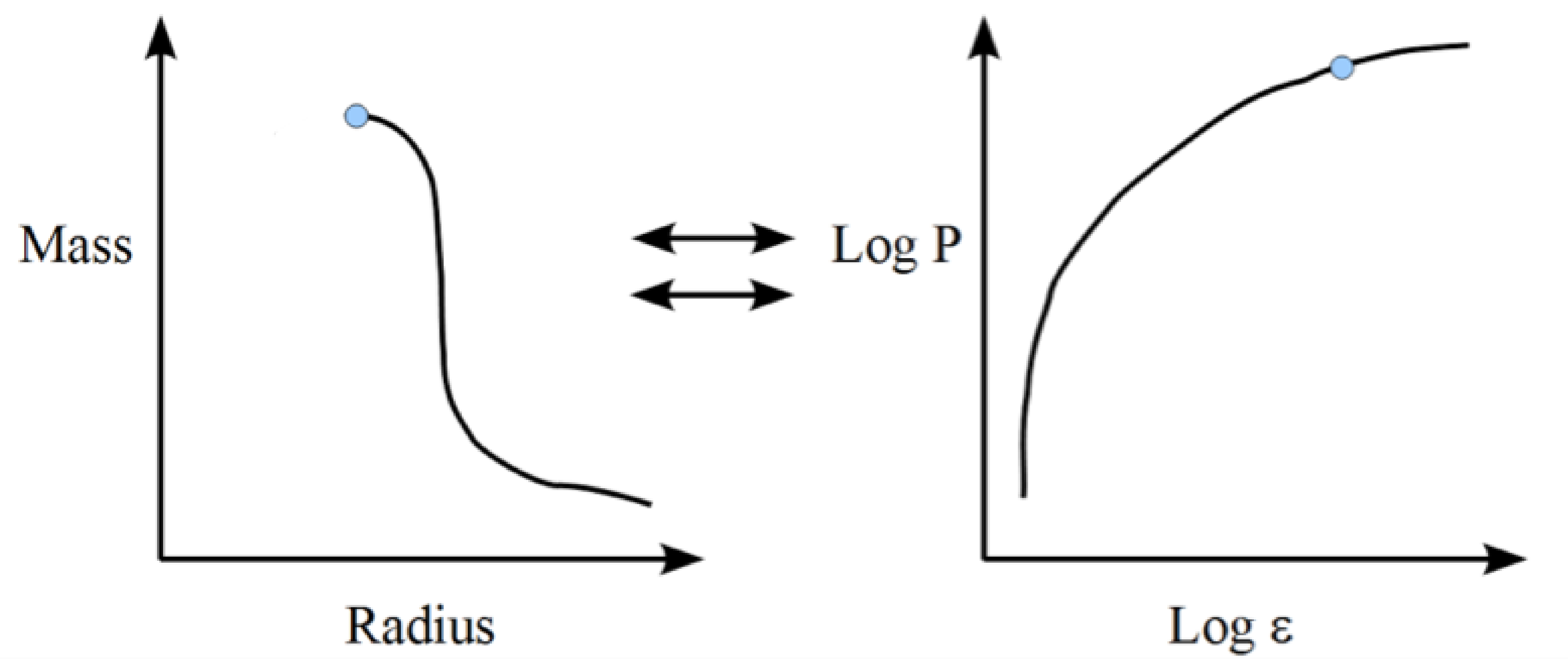
Outline

- Neutron star masses and radii
- Recent observational developments
- Connection to the symmetry energy
- Pulsar glitches and moments of inertia
- Entrainment

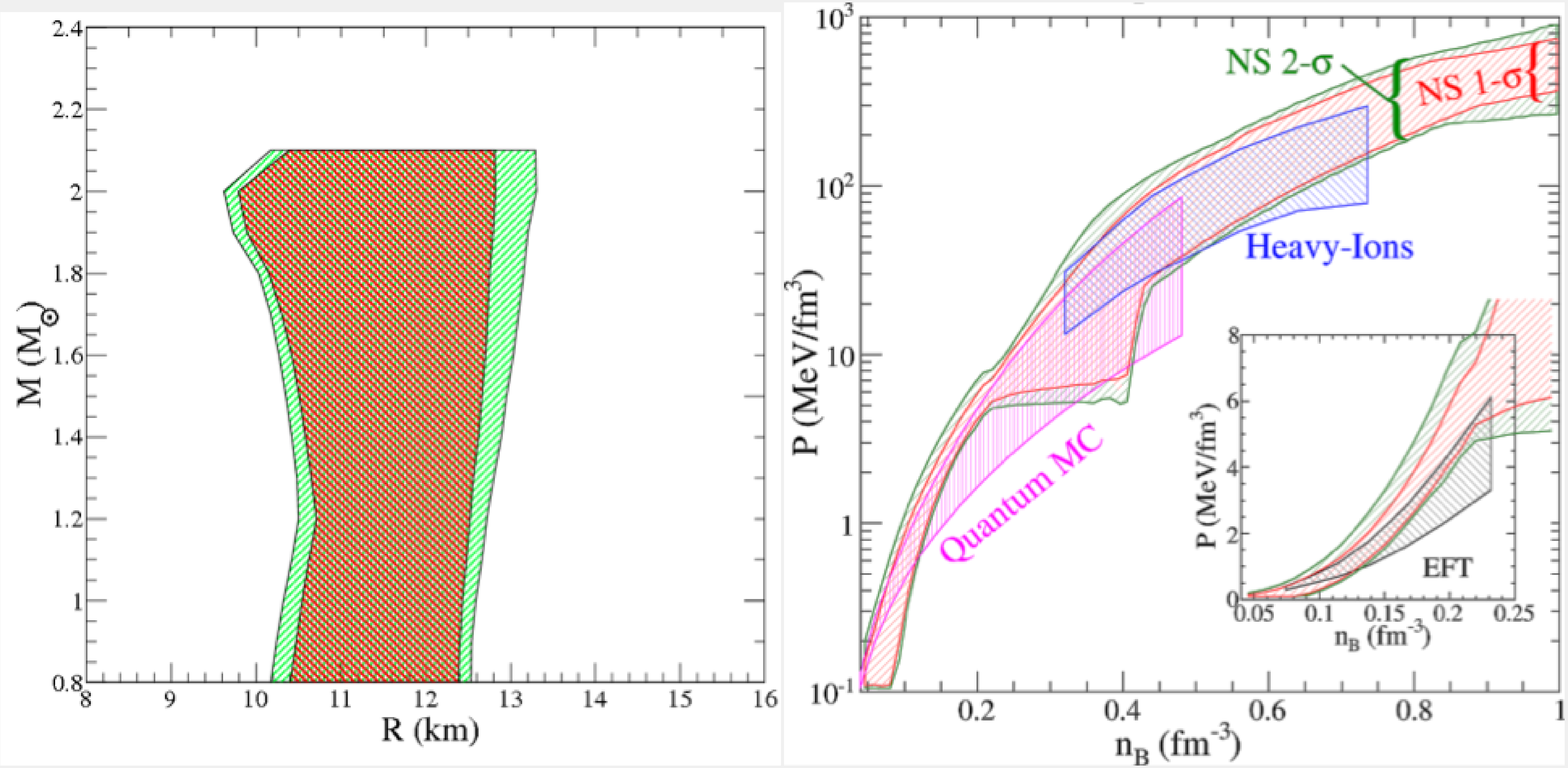
Neutron Star Masses and Radii and the EOS

- Neutron stars (to better than 10%) all lie on one universal mass-radius curve
  (Largest correction is rotation - work in progress)
- Recent measurement of two 2 $M_\odot$ neutron stars
  Demorest et al. (2010), Antoniadis et al. (2013)
- As of 2007 neutron star radii constrained to 8-15 km, now 10-13 km
  Lattimer and Prakash (2007); Steiner, Lattimer and Brown (2013)



- Einstein's field equations provide a 1-1 correspondence
- Formally an underconstrained problem, but effectively over constrained if you have enough precise data (we don't yet)

The M-R curve and the EOS of Dense Matter



Steiner, Lattimer, and Brown (2013); red and green outlines 68% and 95% regions

- Full Bayesian MCMC sampling of the likelihood (times prior)
- Radius of a 1.4 solar mass neutron star is 10.4 - 12.9 km
- Note the uncertainty in the EOS at a few times saturation
- These results are limited by strong systematic uncertainties
- No assumption that pressure is correlated between low and high-densities

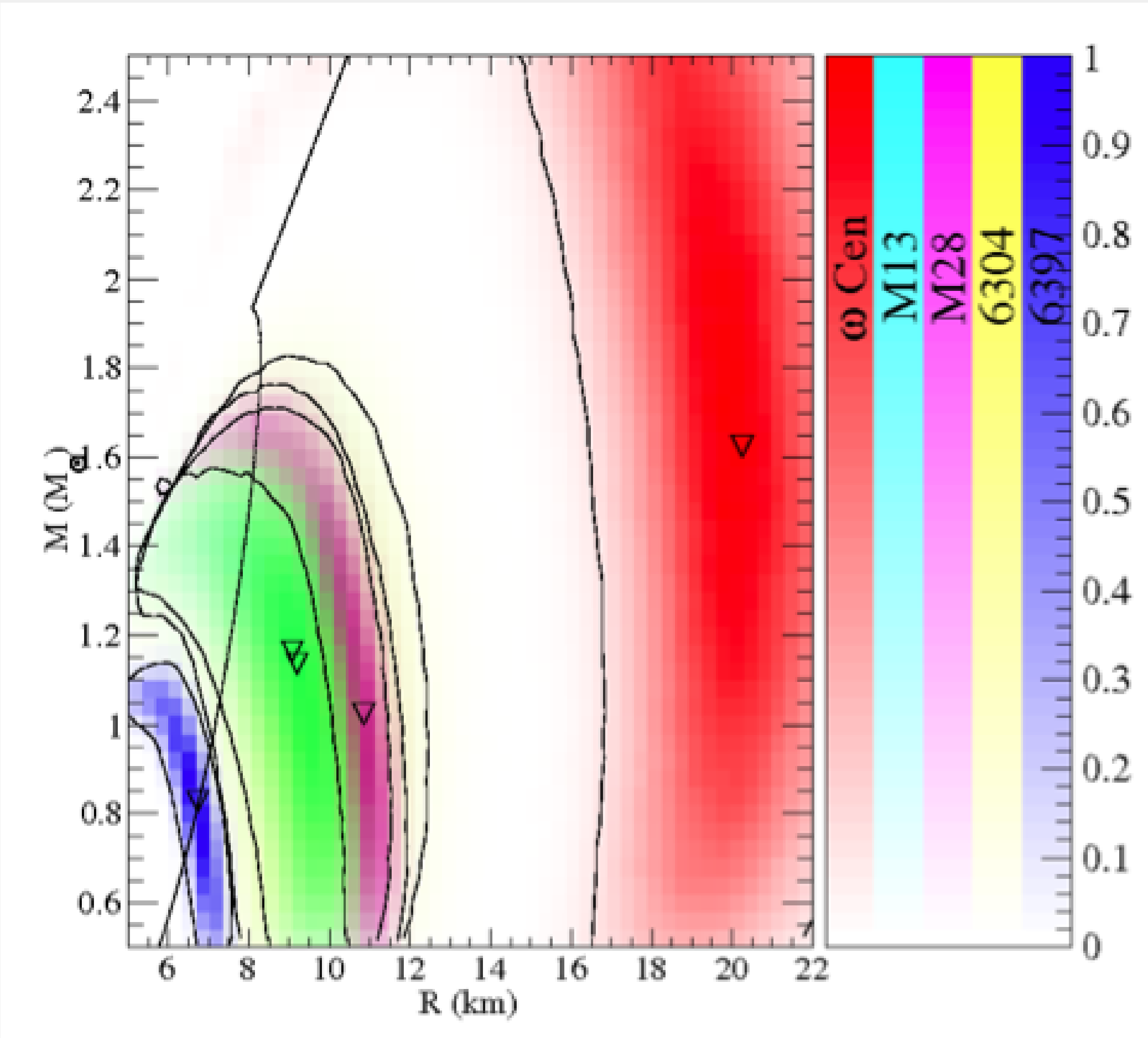
The M-R curve and the EOS of dense matter

EOS Model	Data modifications	$R_{95\%>}$	$R_{68\%>}$ (km)	$R_{68\%<}$	$R_{95\%<}$
Variations in the EOS model					
A	-	11.18	11.49	12.07	12.33
B	-	11.23	11.53	12.17	12.45
C	-	10.63	10.88	11.45	11.83
D	-	11.44	11.69	12.27	12.54
Variations in the data interpretation					
A	I	11.82	12.07	12.62	12.89
A	II	10.42	10.58	11.09	11.61
A	III	10.74	10.93	11.46	11.72
A	IV	10.87	11.19	11.81	12.13
A	V	10.94	11.25	11.88	12.22
A	VI	11.23	11.56	12.23	12.49
Global limits		10.42	10.58	12.62	12.89

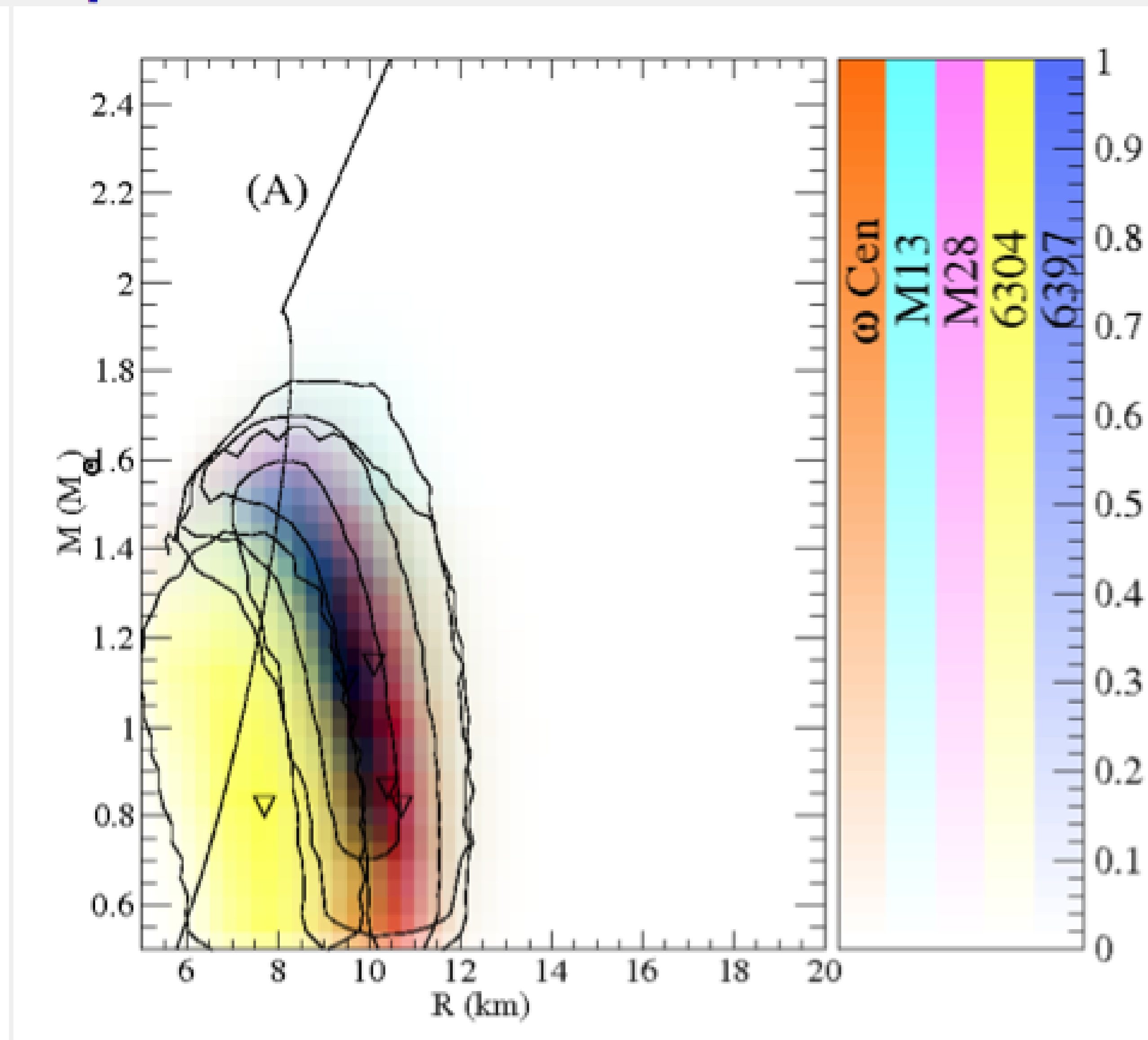
Steiner, Lattimer, and Brown (2013)

- Critical component: trying different EOS parameterizations and different interpretations of the data
- Model C allows for strong phase transitions
- Try several different models to assess systematics

As of last year...



Results from Guillot et al. (2013) slightly adapted for Lattimer and Steiner (2014) before any assumption about the M-R curve

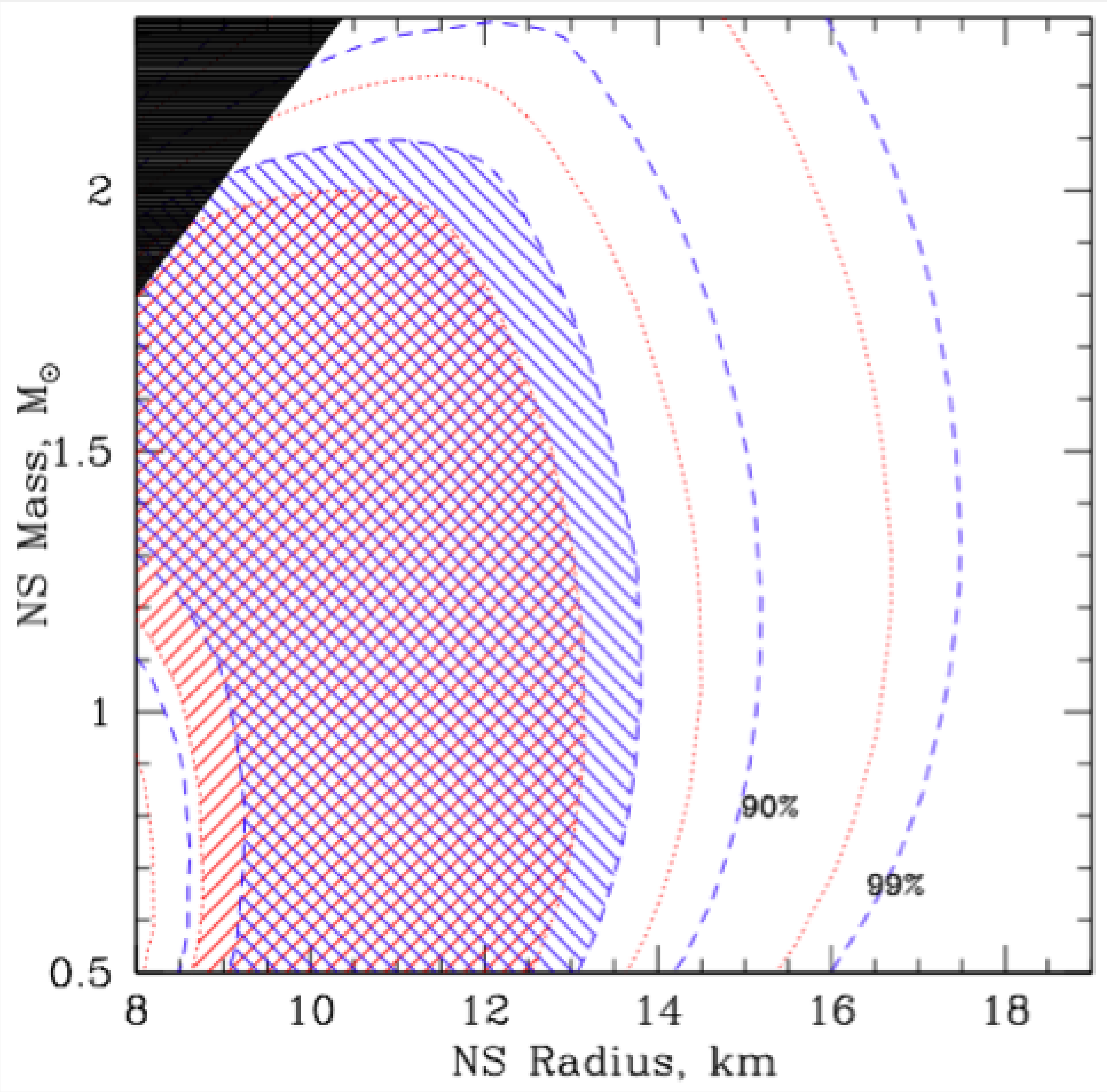


Lattimer and Steiner (2014)

- $R_{\mathrm{NS\ in}\ \omega\ \mathrm{Cen}}$: 11 km or 20 km!
- $R_{\mathrm{NS\ in\ NGC\ 6397}} \sim 7$ km?
- We tried different N_H values, different distances, and Helium atmospheres
- We obtained Bayes factors of ~1200 for alternate models

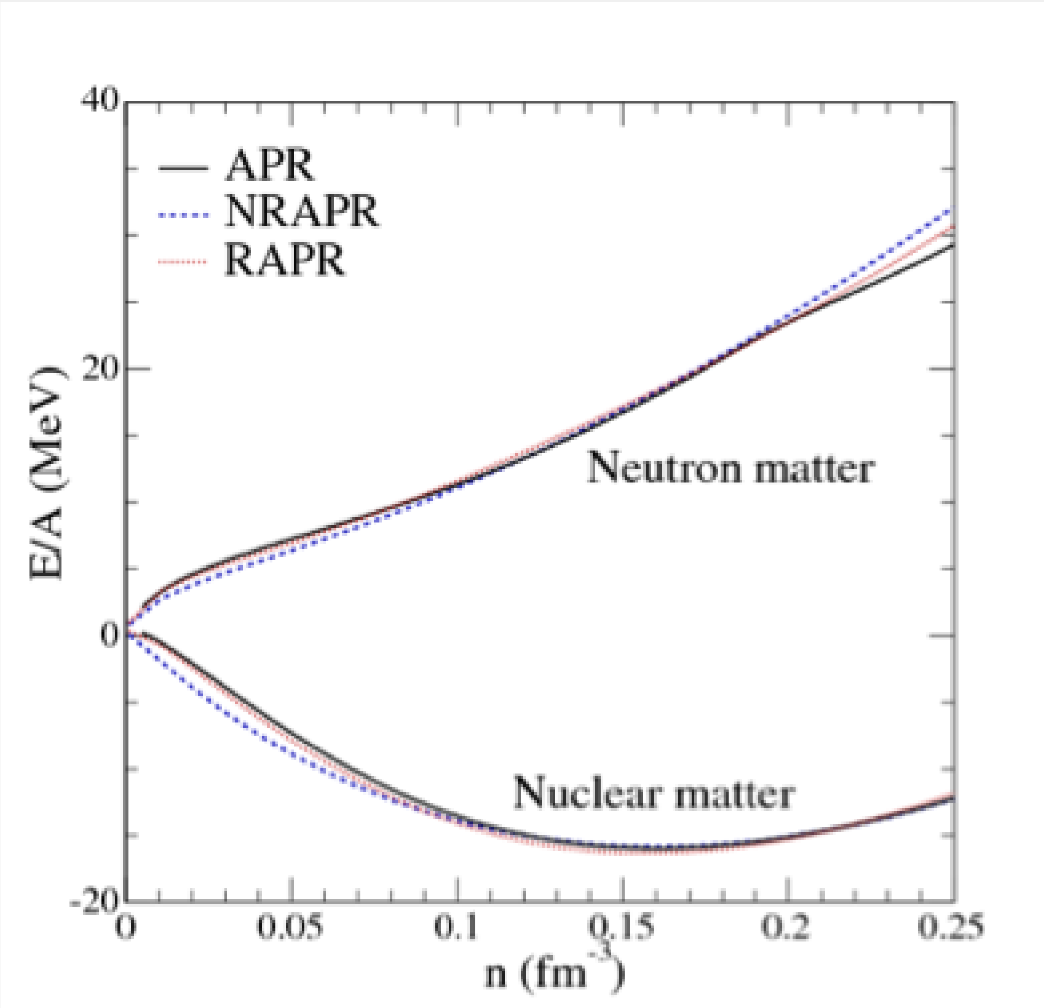
Recent Updates

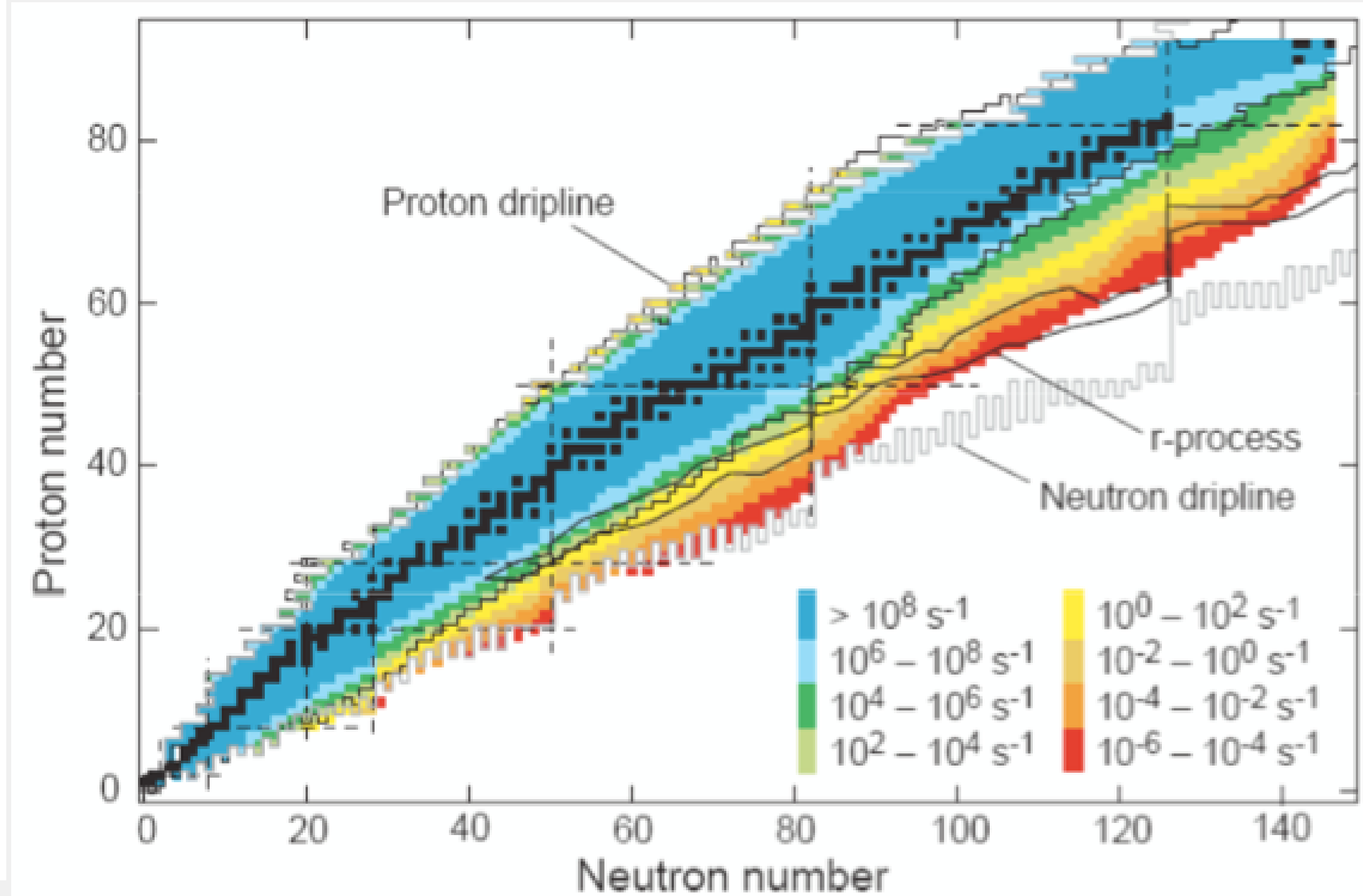
- Heinke et al. (2014) confirms smaller N_H values for ω Cen with different model for the ISM and new data
- Confirmation of expectations from nuclear physics
- Radius ranges don't change that much from Steiner et al. (2013)



Heinke et al. (2014)

The Nuclear Symmetry Energy

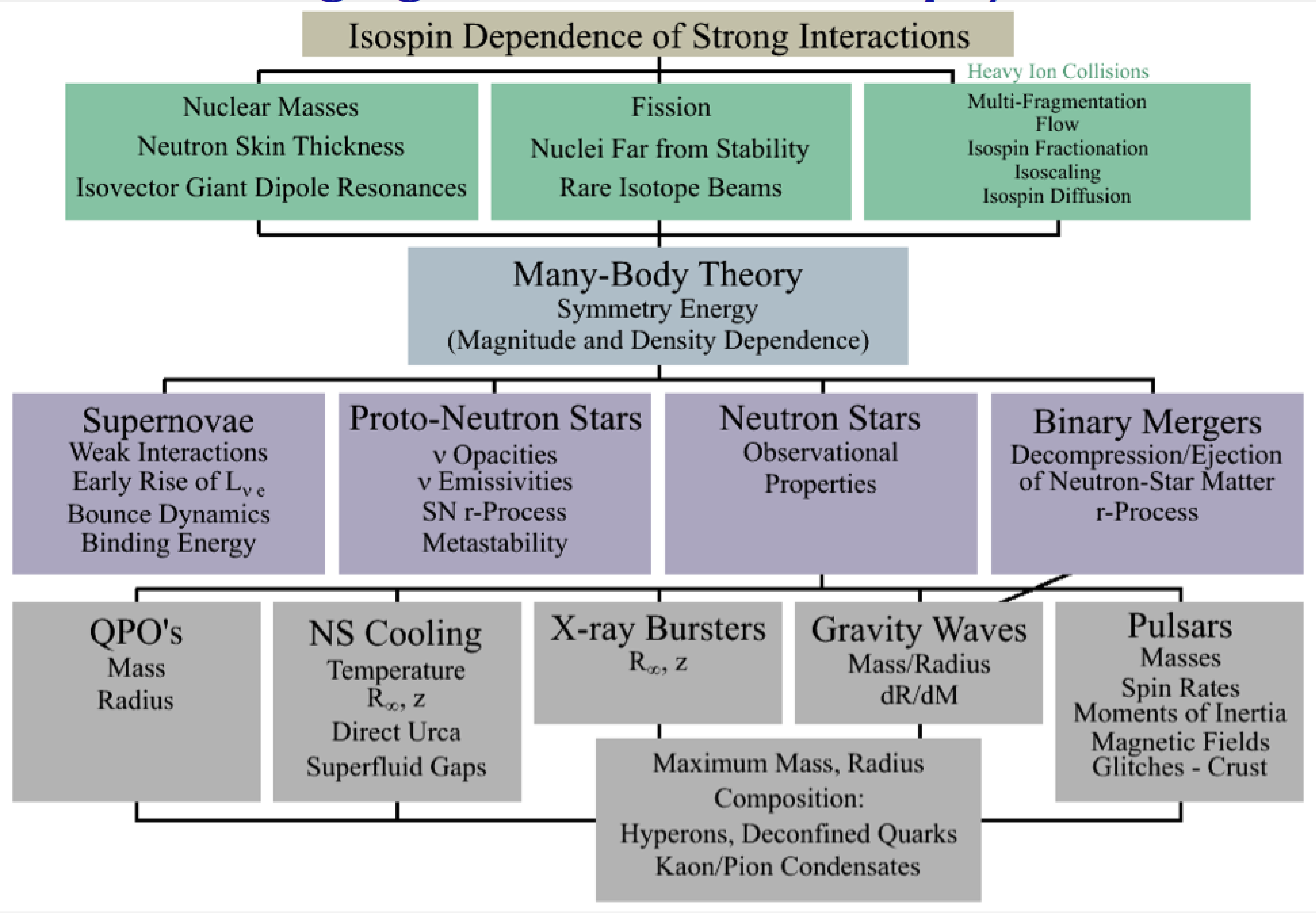




Steiner et al. (2005)

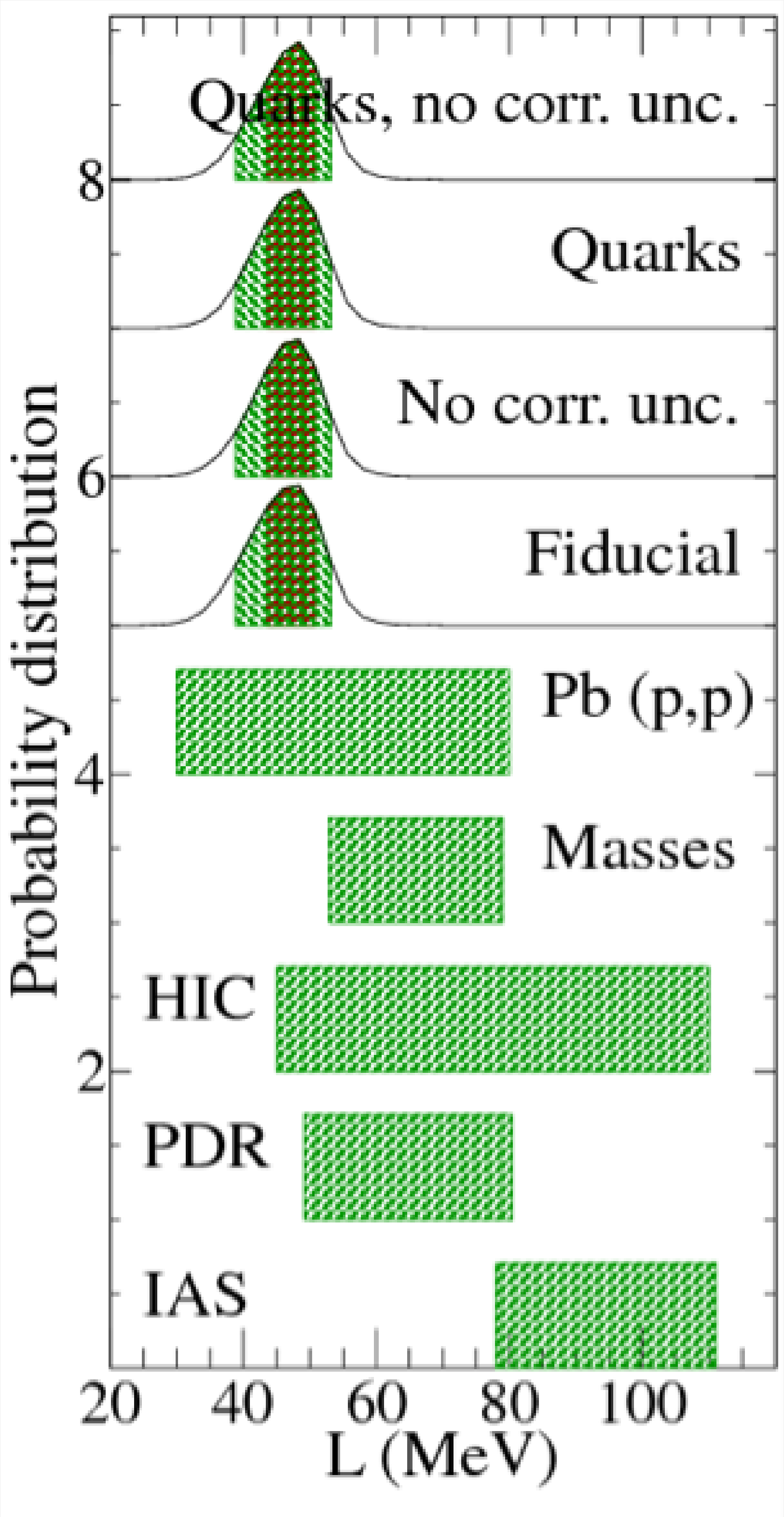
- $S(n_B) \equiv E_{\rm neut}(n_B) - E_{\rm nuc}(n_B)$
- S is the value at the nuclear saturation density $S = S(n_0)$
- L is the derivative, $L = 3 n_0 S'(n_0)$

Bridging Nuclear and Astro-physics

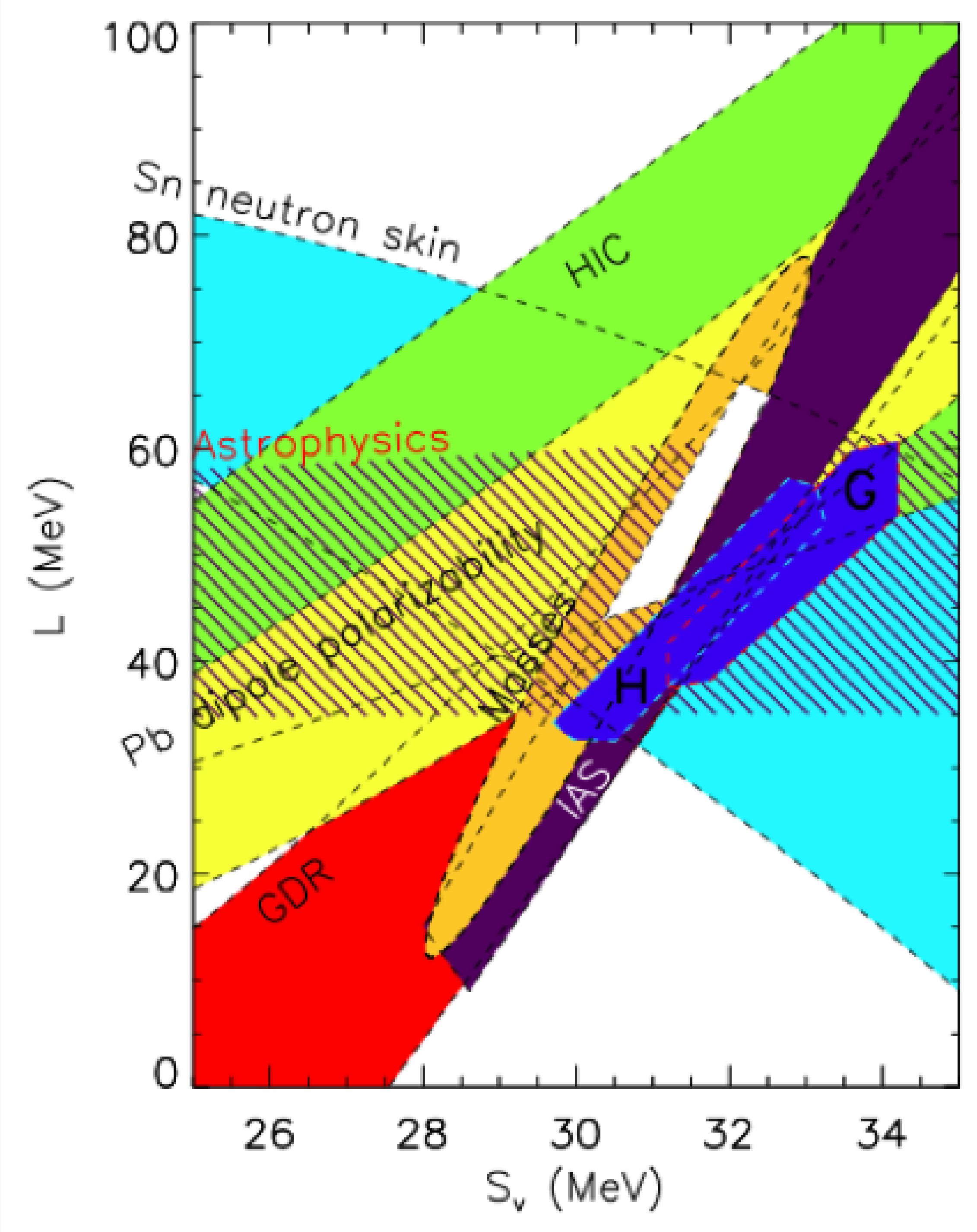


Steiner, Prakash, Lattimer, and Ellis (2005)

Neutron Star Constraints on L



Steiner and Gandolfi (2012)
(IAS results have since come down)

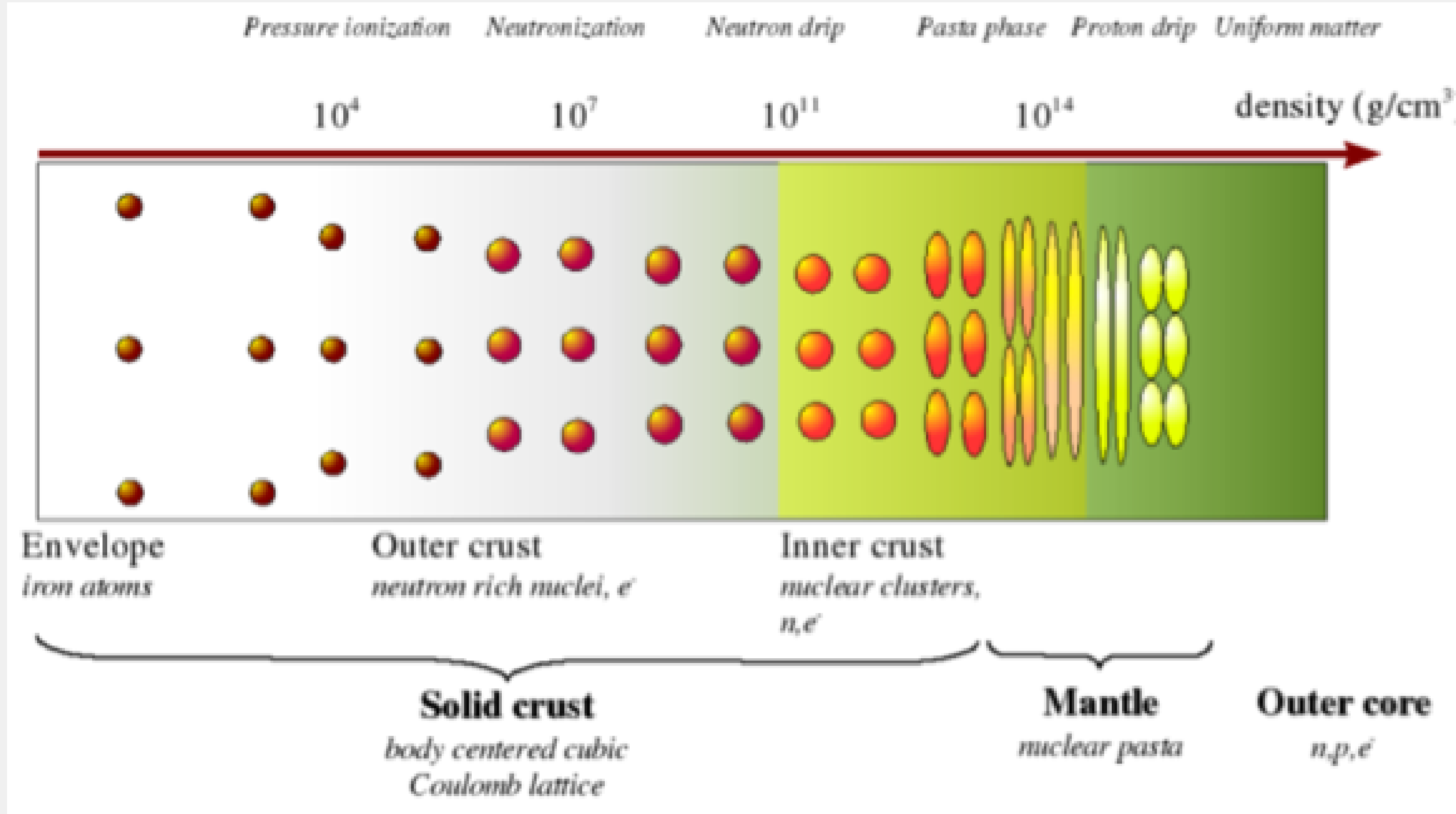


Lattimer and Steiner (2013)

- Neutron stars strongly constrain L
- We also found $R_n - R_p < 0.2$ fm

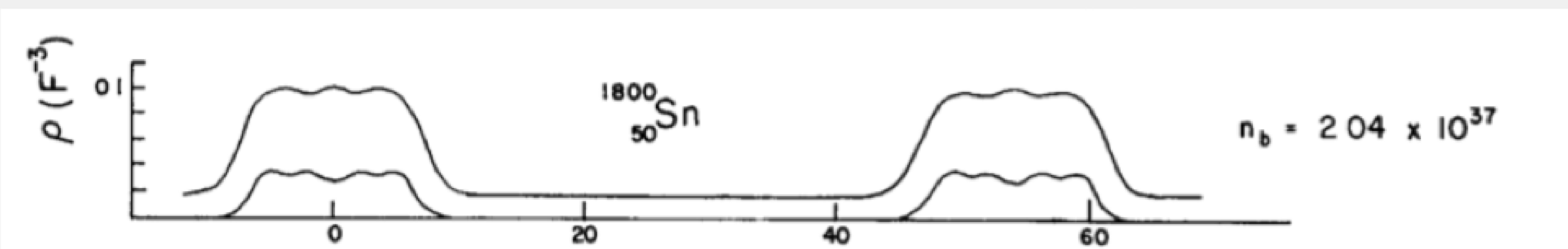
  Confirmed by MAMI data

Structure of Matter in the Neutron Star Crust



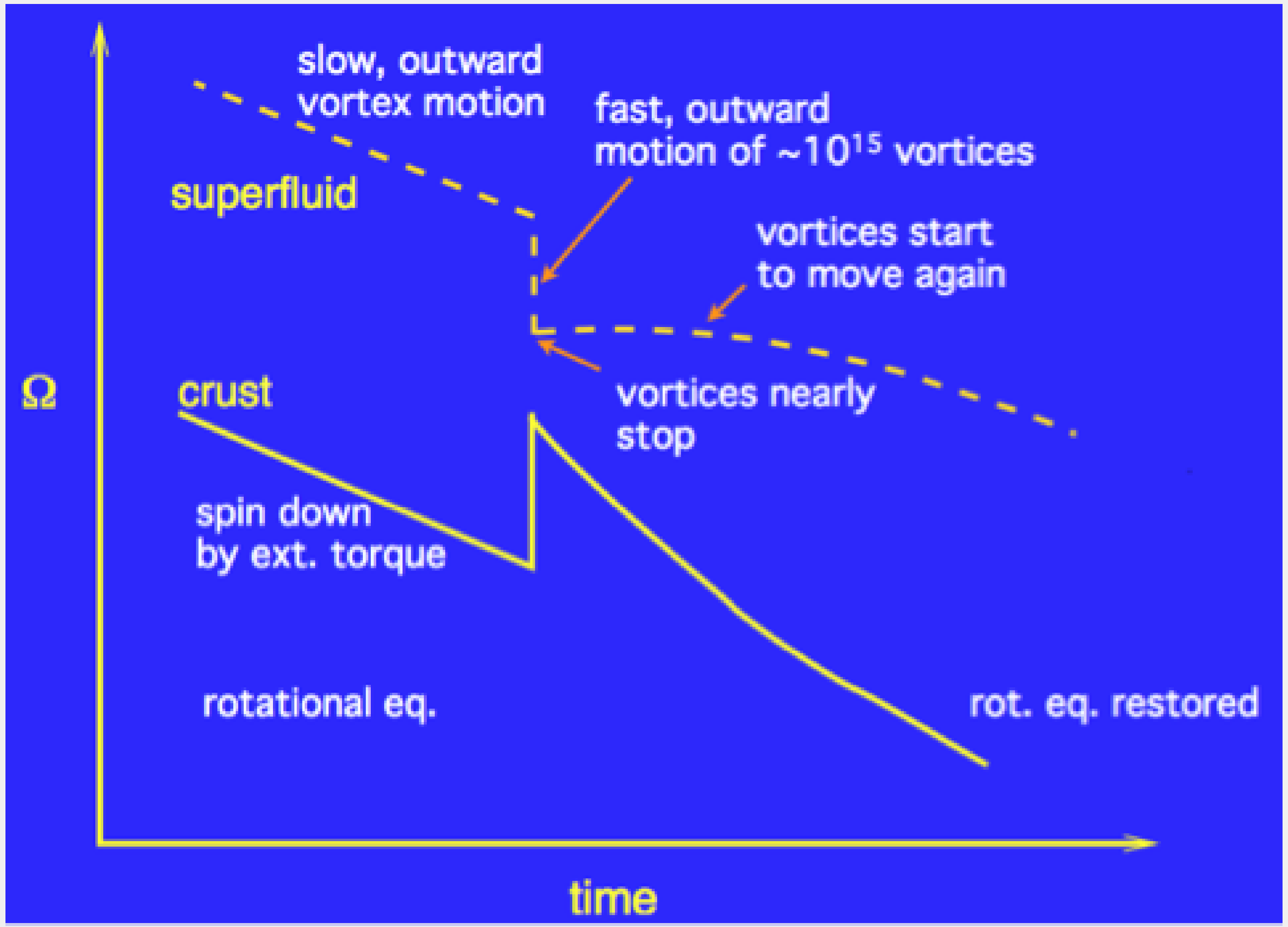
Picture from N. Chamel

- Neutron-rich nuclei
- Sea of superfluid neutrons
- Crust-core transition



Negele and Vautherin (1973!)

Pulsar Glitch Mechanism



Picture from B. Link

- Superfluid component, decoupled from rotation at the surface
- Natural to associate the superfluid component with the superfluid neutrons in the crust
- What is the mechanism for the sudden change?

- Superfluid vortices pinned to the lattice
- Neutron star spins down, vortices bend creating tension, eventually they must shift lattice sites
- Quasi-free neutrons are entrained with the lattice
  Chamel 2012, Chamel et al. 2013

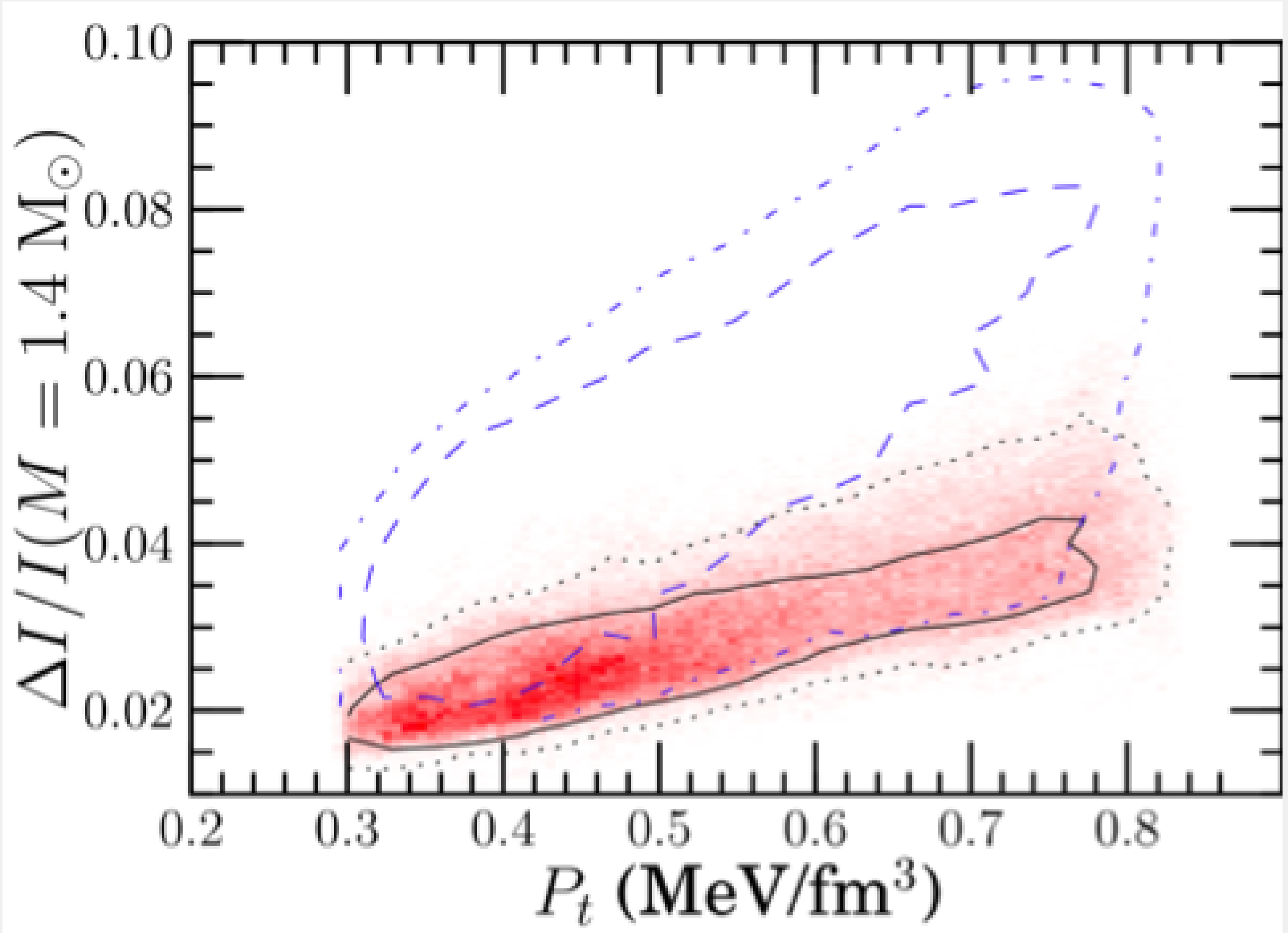
Is There Enough Superfluid in the Crust?

- We require 1.6% of I to explain glitches in Vela
  Link, Epstein, and Lattimer (1999)

- Entrainment: 75-85% of otherwise superfluid neutrons 'connected' to the lattice
  N. Chamel (2012)

- Current M and R observations suggest there is not enough I in the crust
  See Andersson et al. (2012)

- Unless the systematics force much larger neutron star radii and P_t is large



Steiner et al. (2014); black and red are with M & R observations, blue contours are with $I = 70\ \mathrm{M}_\odot\ \mathrm{km}^2$

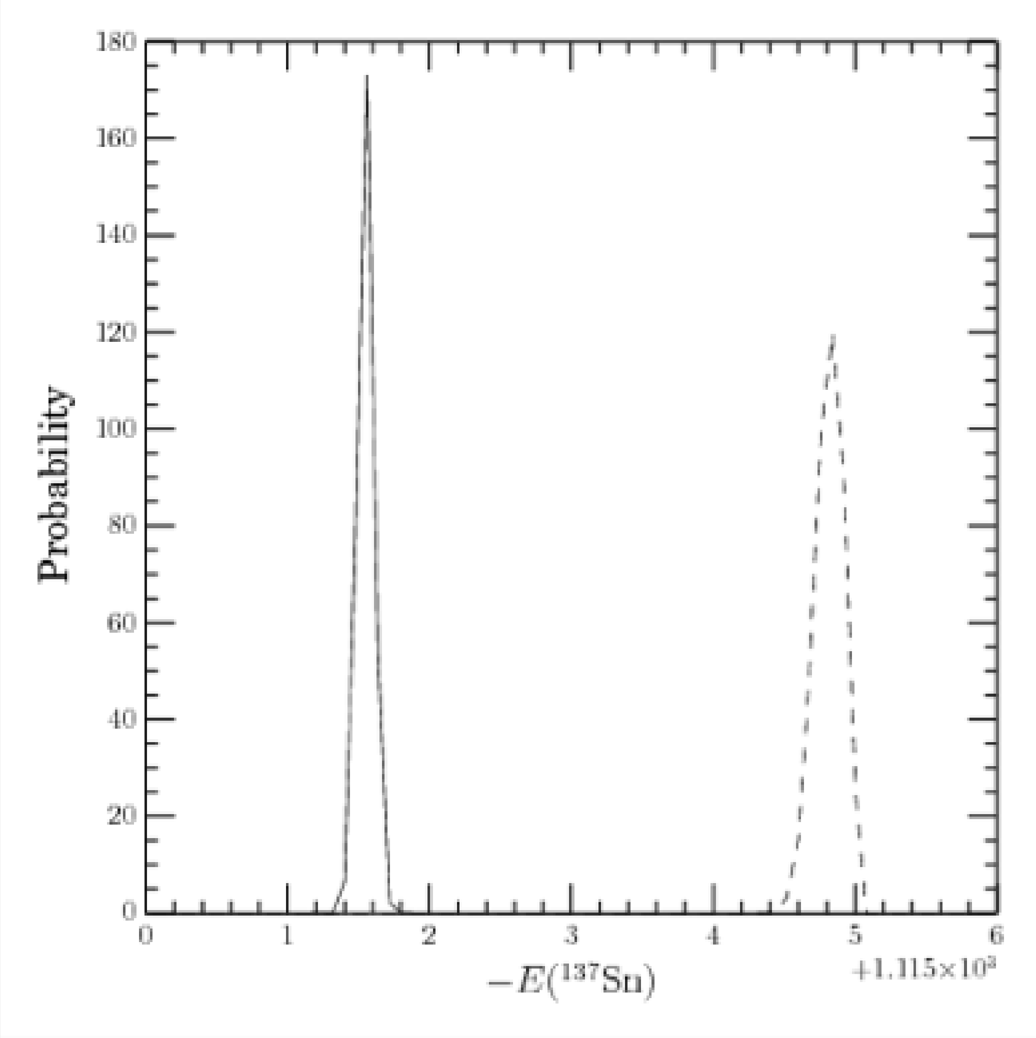
How to determine the symmetry energy (at the saturation density)

- Neutron star radii are great at determining L, but experimental information is probably better and/or faster
- Theory methods work great for neutron matter, but nuclear matter seems difficult
- A lot of work is focused on finding the 'best' energy density functional: this doesn't necessarily help

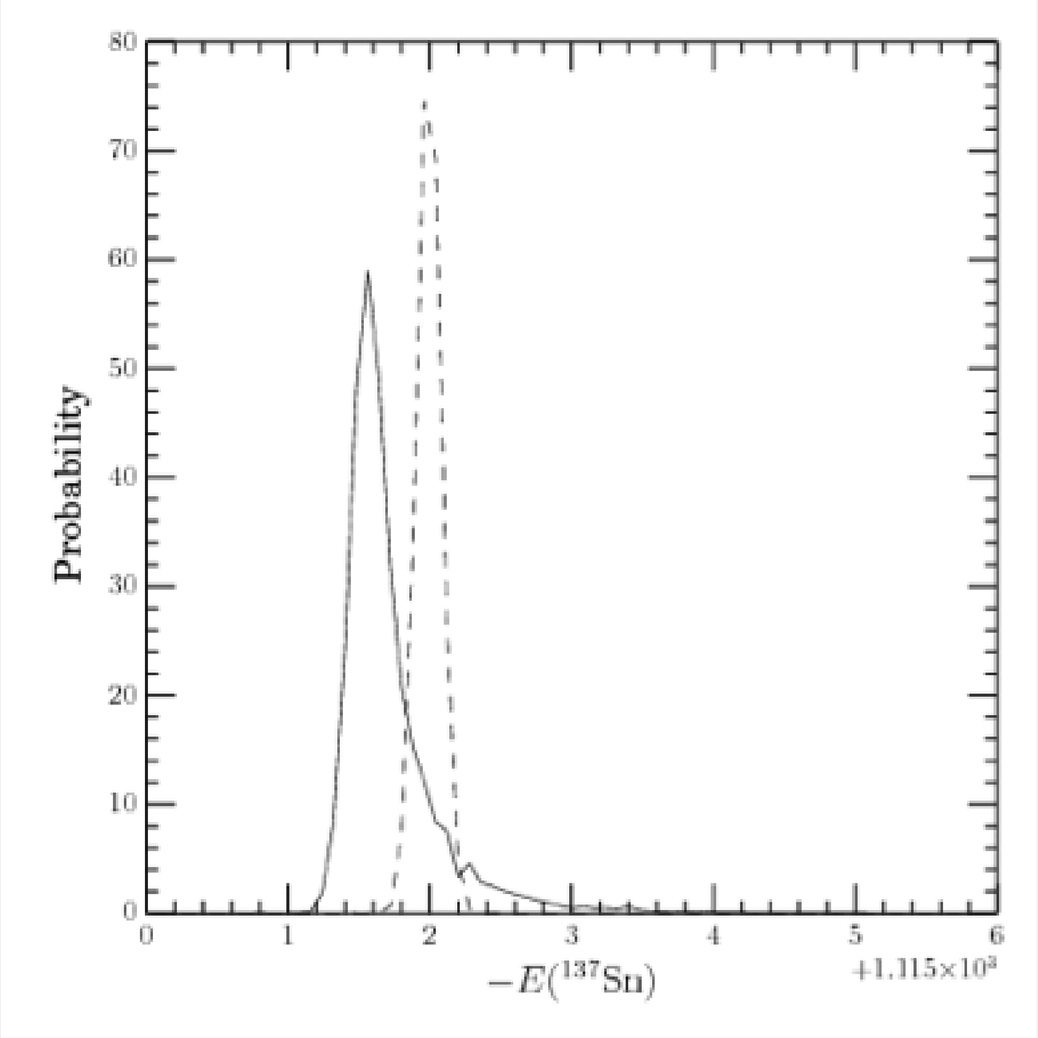
We need:

- Several models, of comparable accuracy, all fit to the same data set which is optimized to ensure that
  1. systematics from model-dependence
  2. and uncertainties within each model

  are both small.
- Plus a bit of care with our fitting,
- and probably some information from giant resonances



Steiner (2014); Fit to all measured masses



Steiner (2014); Fit to a small range of masses

Status

- Currently available neutron star mass and radius observations constrain the universal neutron star $M - R$ curve
  - Neutron star radii are likely between 10.4 and 12.9 km
  - We now have constraints on the EOS
  - $60 < I < 75\ M_{\odot}\ \mathrm{km}^2$
  - $1 < \lambda < 3 \times 10^{36} g\ \mathrm{cm}^2\ \mathrm{s}^2$
- Constrain the nucleon-nucleon interaction and QCD.
  - (41) 43 MeV $< L <$ 67 (83) MeV
- Current observations imply there is not enough I to explain glitches
- But we need to know more about entrainment
- We can make real progress in determining S and L at the saturation density