Dense Matter and Neutrinos

J. Carlson - LANL

- Neutron Stars and QCD phase diagram
- Nuclear Interactions
- Quantum Monte Carlo
- Low-Density Equation of State
- High-Density Equation of State
- Neutron Star Matter
  (protons, hyperons, etc.)
- Mass/Radius relations and observations
- Neutrinos - neutron star cooling
- Future

Collaborators:
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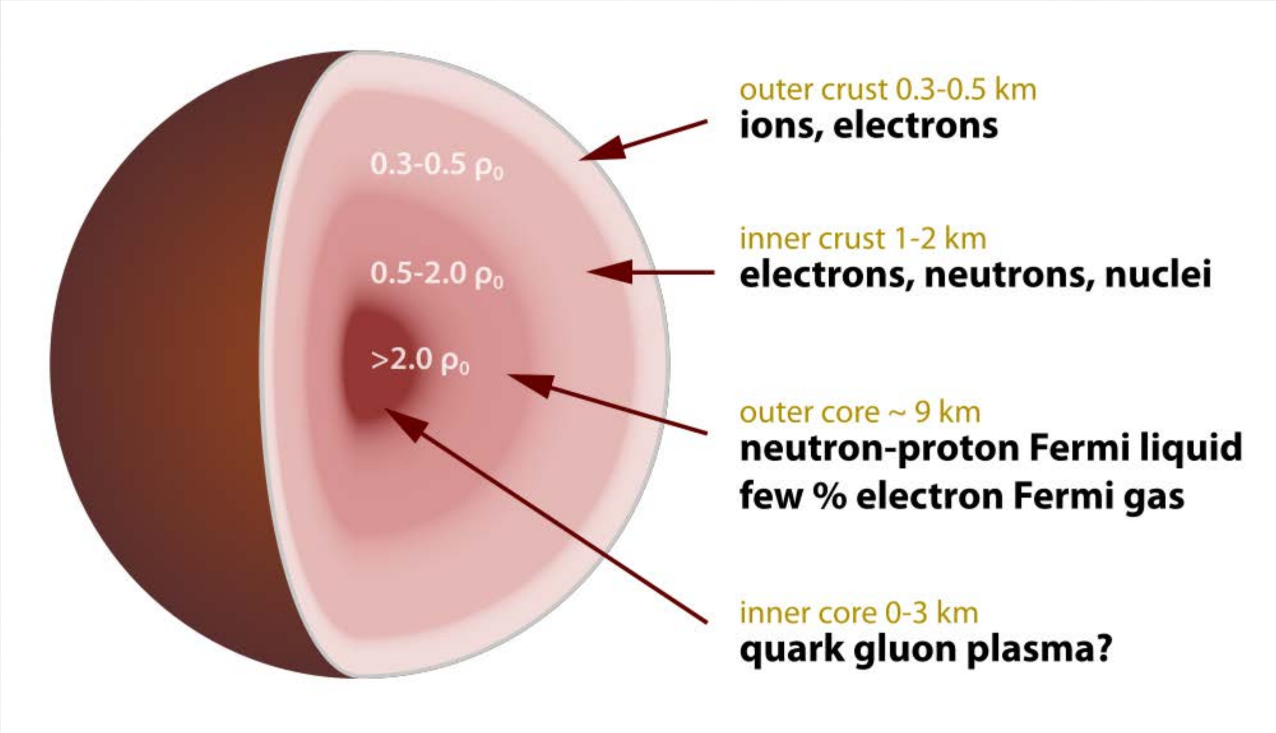
A. Lovato (ANL)
S. Reddy (UW/INT)

Neutron Stars

1-2 Solar Masses
~12 km radius

Predicted by Baade and Zwicky 1 year after discovery of the neutron



Outer Crust
nuclei + electrons

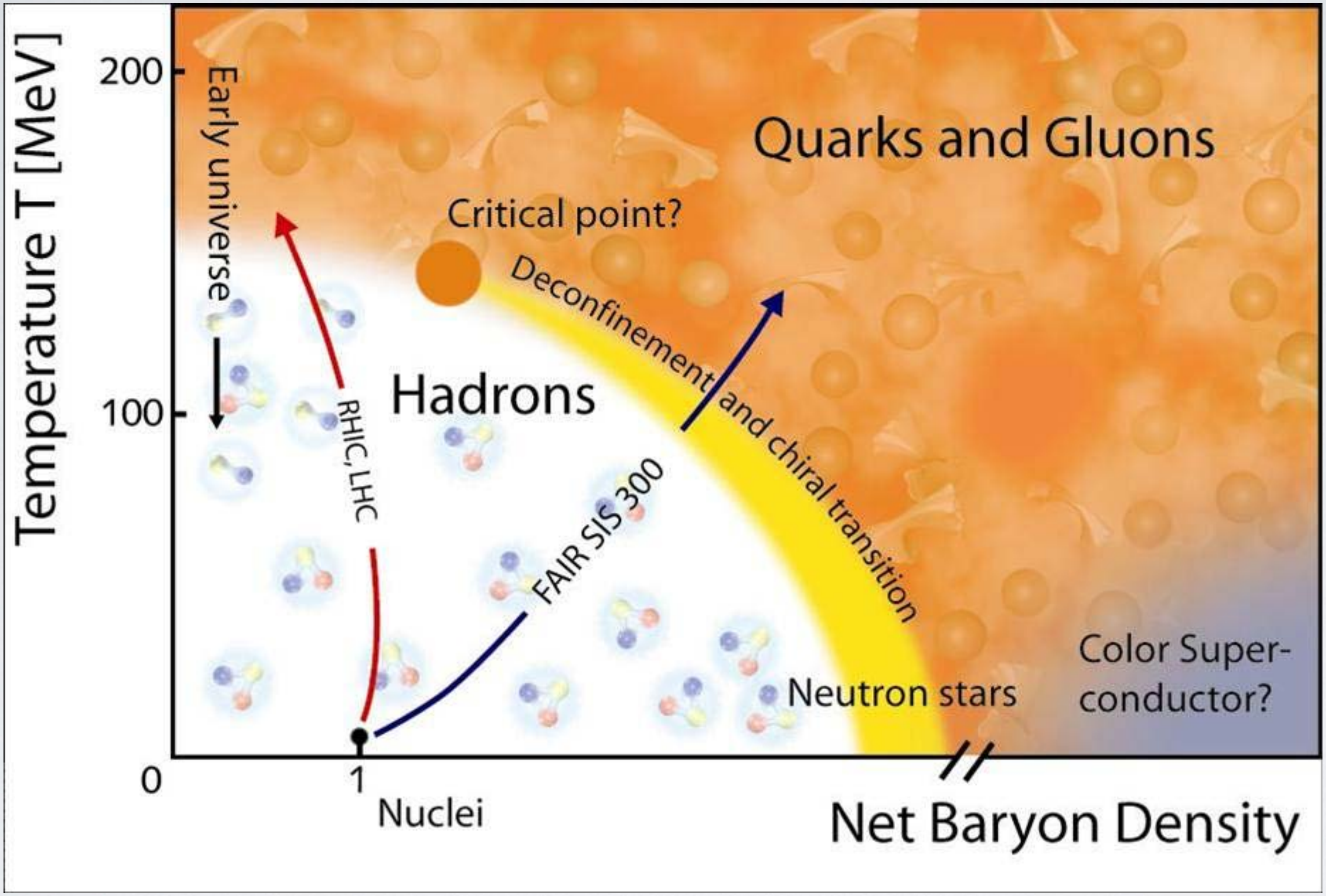
Inner Crust
nuclei + neutrons + electrons

Core
neutrons+protons+electrons+…

We will concentrate on the core: bulk of the star
dominates the M/R curve
important for neutrino cooling

charge neutrality + small electron mass → ~10% electrons, protons

QCD phase diagram (minimal)



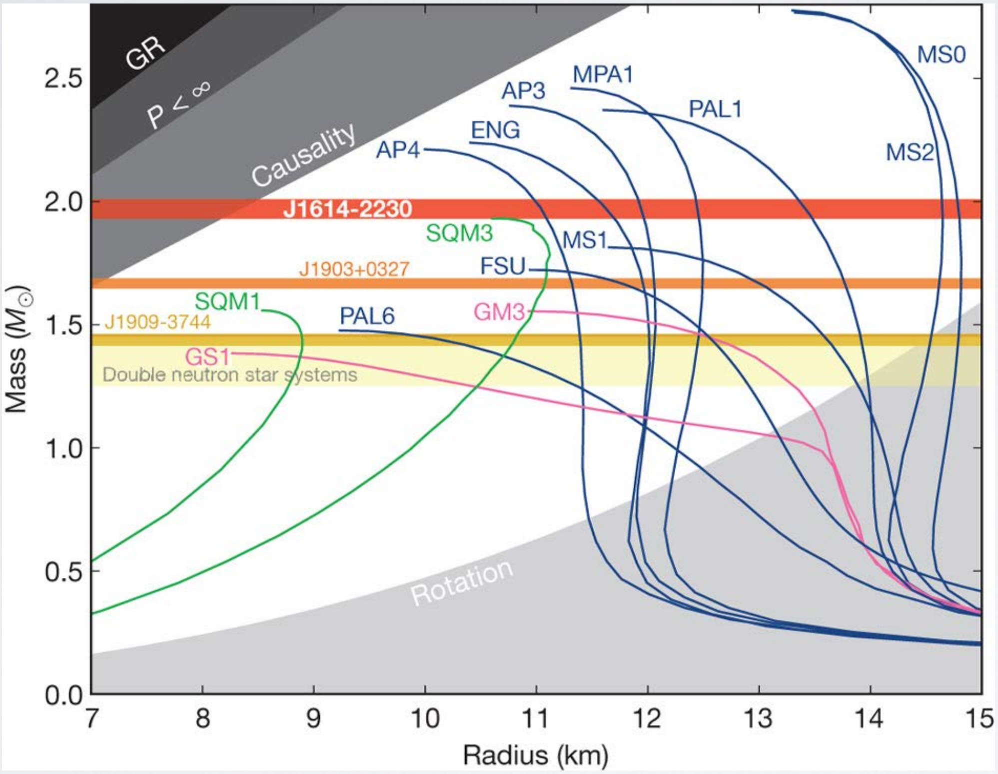
from FAIR, new facility in Darmstadt

high density and cold very difficult to reach in experiments

Color superconductor at very high density; important for neutron stars?

Neutron Star Mass/Radius Relations

For many years only ~1.4-1.5 solar mass neutron stars observed
Recently several observed with ~ 2 solar masses!



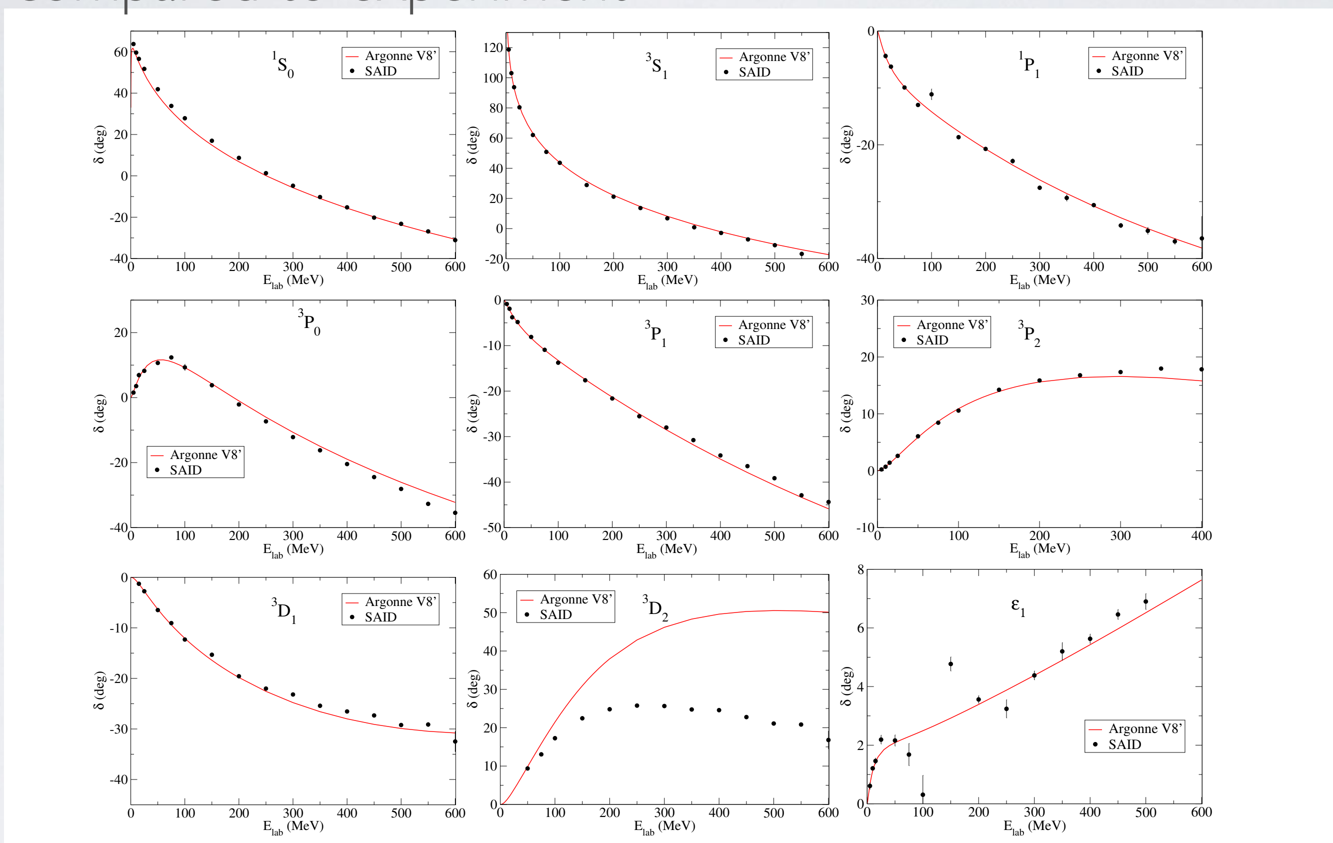
see Demorest, et al
Nature 467: 2081 (2010)

Transitions to superconducting quark matter
Wide range of predictions for mass/radius relationship

Nuclear Interactions

Up to ~2-3 x nuclear densities, matter can be described as a system of interacting nucleons

phase shifts for NN scattering - simple model (AV8') compared to experiment

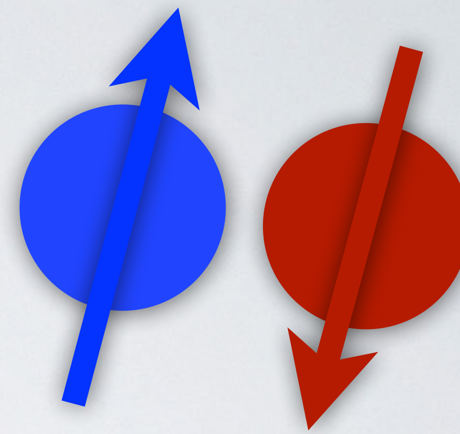


At r=2 ρ_0 : $k_F \sim 2$ fm^{-1}

implies 2 nucleons at Fermi surface have E_{CM} = 160 MeV; $E_{lab} \sim 320$ MeV

Nuclear Interactions

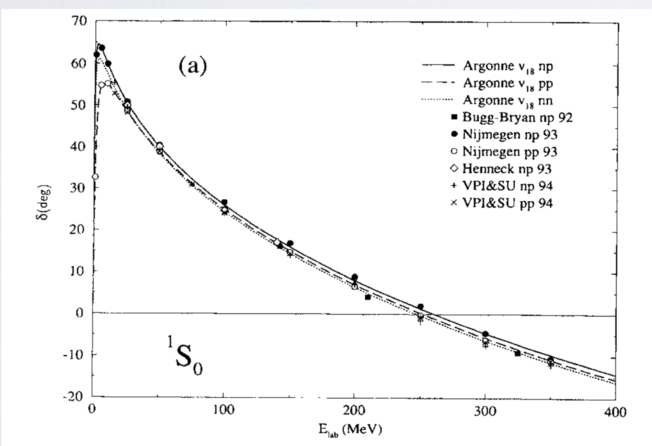
Very low densities dominated by $^1S_0$ interaction

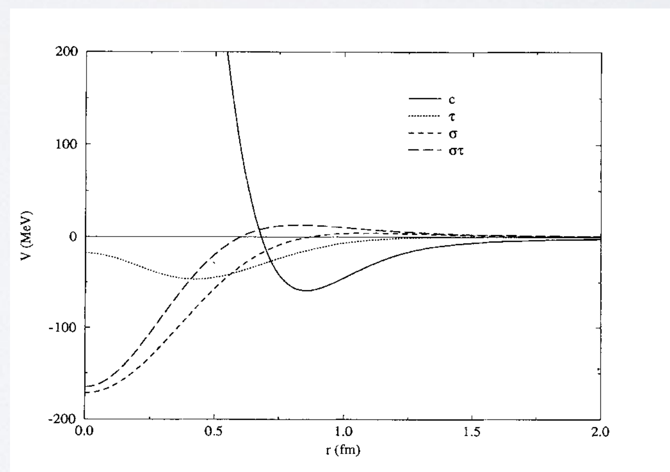


Very similar to cold atomic Fermi Gases

$$H = \sum_i \frac{p_i^2}{2m} + \sum_{i<j} V_0 \; \delta(\mathbf{r_{ij}})$$

Neutron-Neutron Scattering length ~ -18 fm





pion + 2-pion + short-range repulsion

Quantum Monte Carlo Methods

$$H = \sum_i \frac{p_i^2}{2m} + \sum_{i<j} V_{ij} + \ldots$$

$$\begin{aligned} V_{ij} &= \sum_k V_{ij}^k(r_{ij})\ O_{ij}^k \\ O_{ij}^k &= \left[1, \sigma_i \cdot \sigma_j, \sigma_i \cdot r_{ij} \sigma_j \cdot r_{ij}, L \cdot S_{ij}\right] \times [1, \tau_i \cdot \tau_j] \end{aligned}$$

$$H\ \Psi = E\ \Psi$$

$$\Psi = \sum_{i=1}^{2^A \binom{A}{Z}} \psi(i)(\mathbf{R})$$

$2^A = 7 \times 10^{19}$ amplitudes
for 66 neutrons
in 3A=198 dimensions

Quantum Monte Carlo (Auxiliary Field Diffusion Monte Carlo)

$$\Psi_0 = \exp\left[-H\tau\right] \Psi_T$$

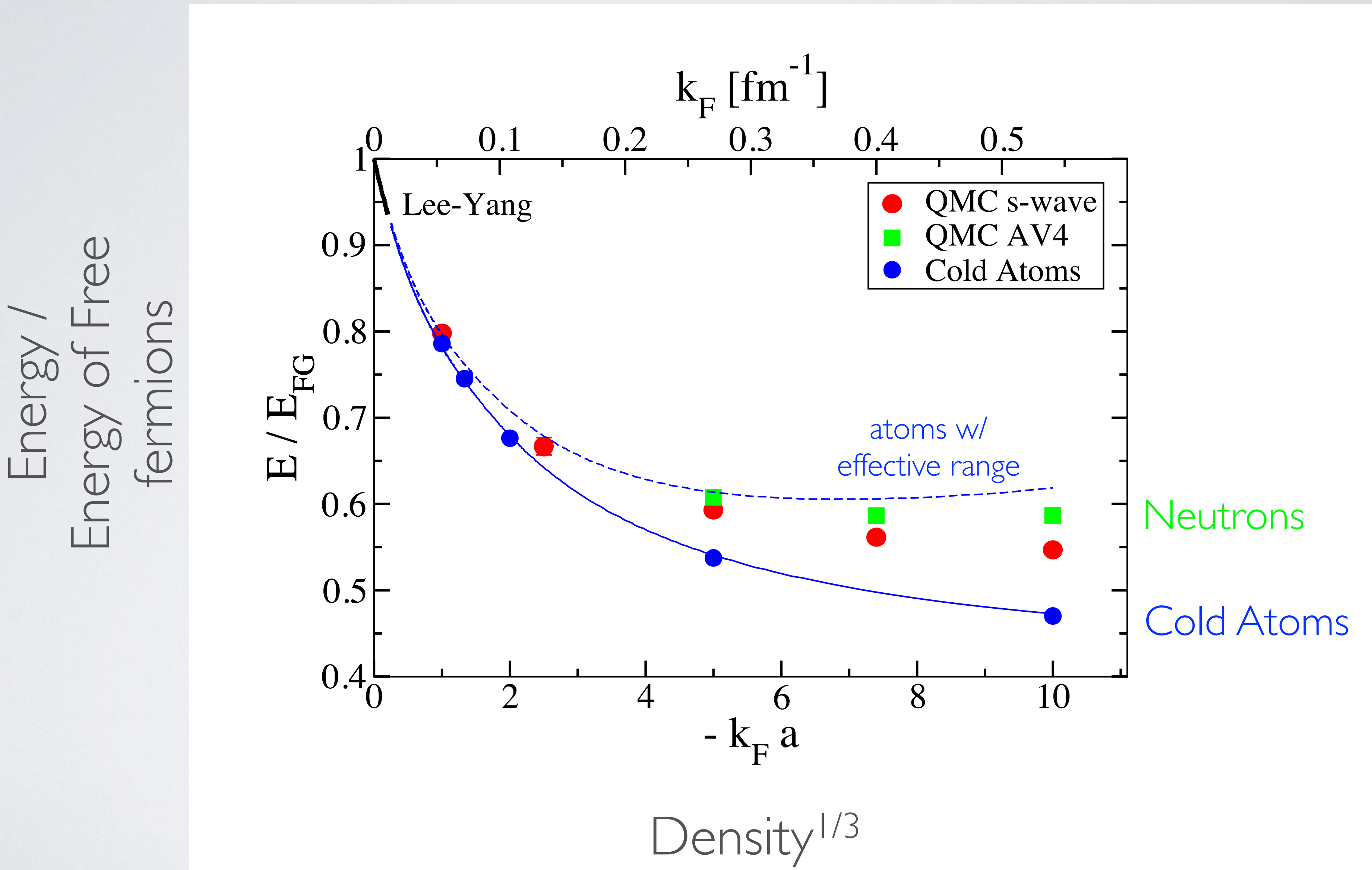
$$\exp[-H\tau] \approx \exp[-V\tau/2]\exp[-T\tau]\exp[-V\tau/2]$$

Kinetic Term is a diffusion process in 3A coordinates
Spin-dependent potential terms rewritten as coupled
to an auxiliary field which is sampled by Monte Carlo,
giving rotations of spins (and isospins)

$$\exp[-V\sigma_i \cdot \sigma_j \tau] = \sum_{x=\pm 1} \exp[-V^{1/2}\tau^{1/2}\sigma_i \cdot x]\ \exp[-V^{1/2}\tau^{1/2}\sigma_j \cdot x]$$

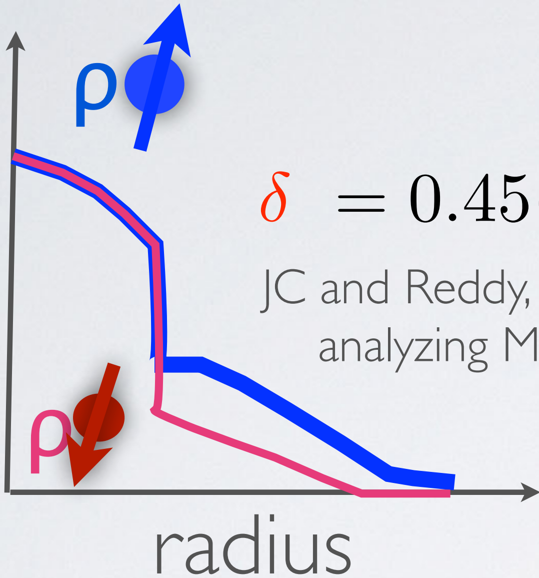
The simulation is a branching random walk in 3A coordinates and A spins and isospins.

Equation of State (E/A) for neutrons and cold Fermi atoms



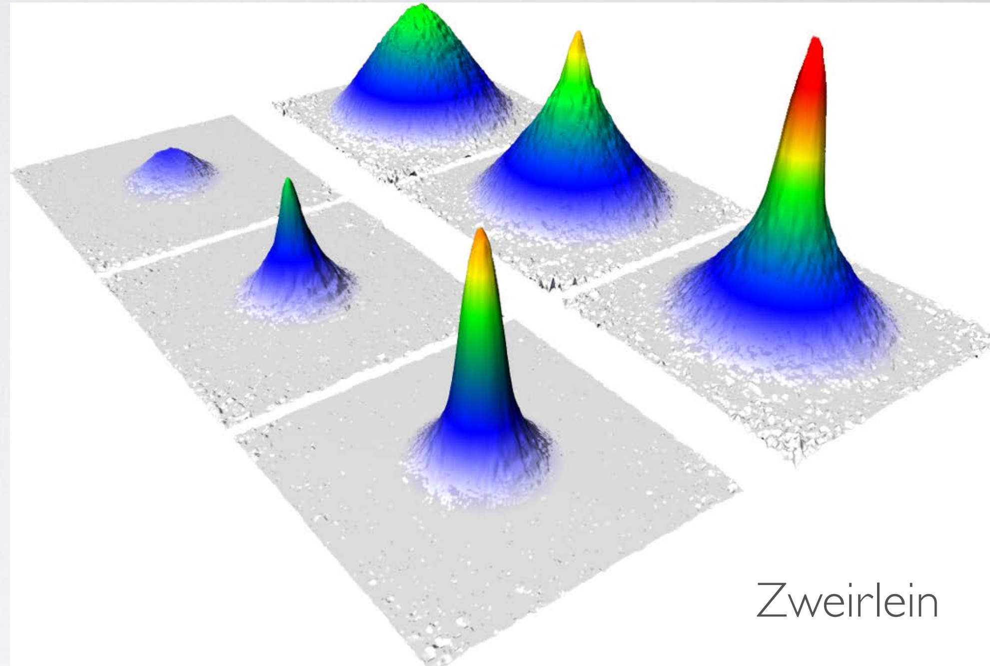
Superfluidity (s-wave)

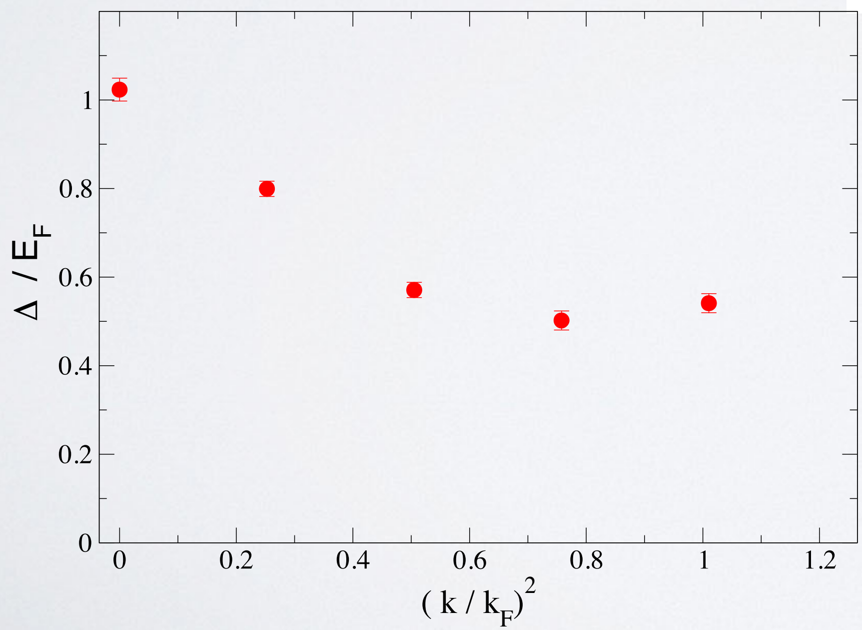
Spin up, down densities in a trap



$$\delta = 0.45(05)$$

JC and Reddy, PRL 2007
analyzing MIT data





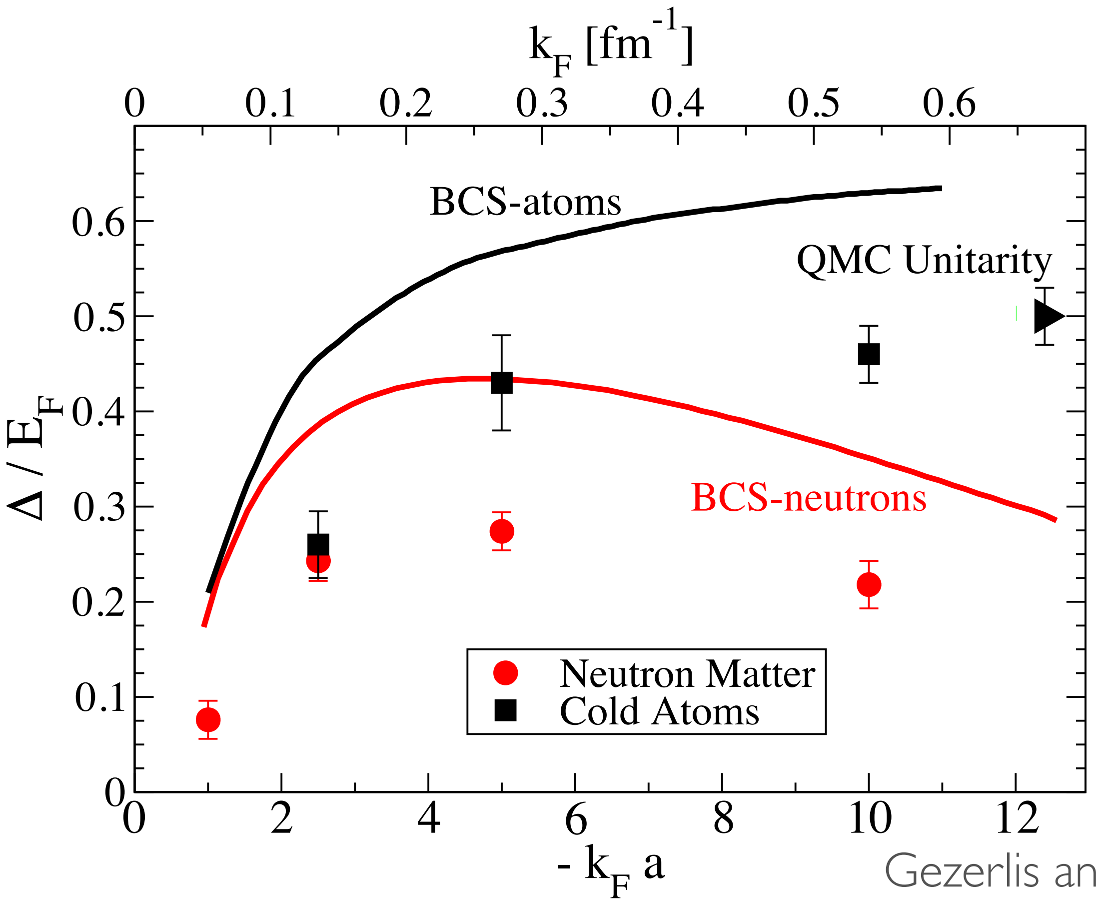
$$\Delta = \delta \frac{\hbar^2 k_F^2}{2m}$$

$$\delta = 0.50\ (03)$$

$$(k_{min}/k_f)^2 = 0.80(10)$$

JC and Reddy, PRL 2005

Superfluid Pairing Gap

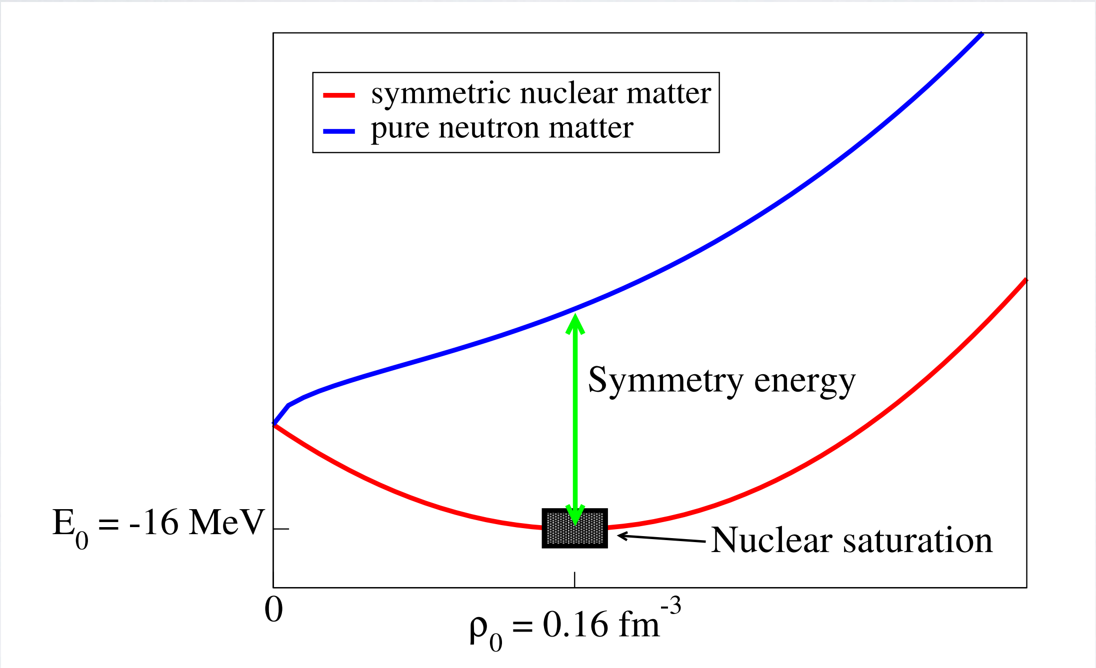


Solid lines:
BCS mean-field theory
Points w/ error bars:
QMC

Gezerlis and Carlson, PRC 2010, 2012

Cold Atoms have highest superfluid gap / E_F of any system;
Neutrons have highest pairing gap / E_F in nature.

Equation of State at Higher Densities: near nuclear saturation

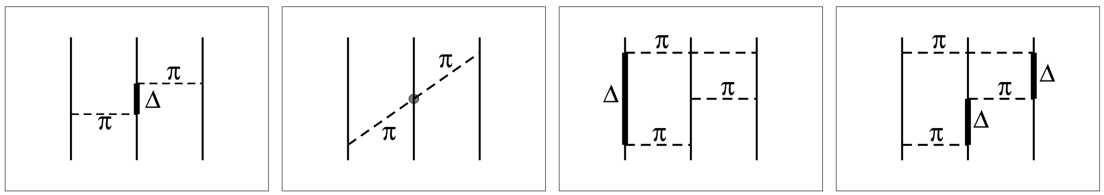


From experiments:

$$E_{SNM}(\rho_0) = -16 MeV\,, \quad \rho_0 = 0.16 fm^{-3}\,, \quad E_{sym} = E_{PNM}(\rho_0) + 16$$

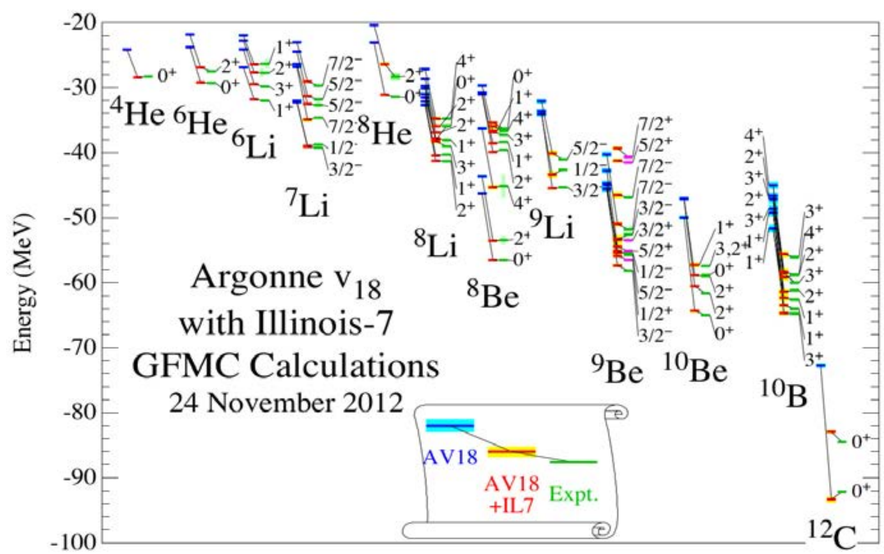
The symmetry energy is accesible (indirectly) by experiment

At higher densities three-nucleon interactions start to become important



+ short-range correlations (spin/isospin independent).

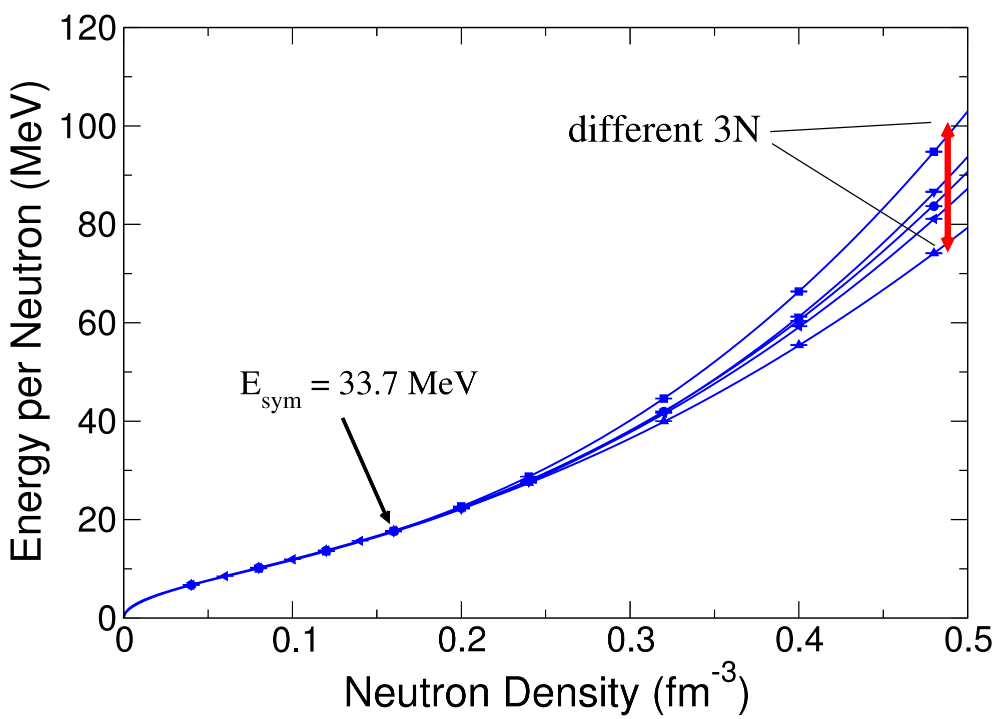
Calibrated to light nuclei



Carlson, Pieper, Wiringa, many papers

Consider a wide range of three-nucleon forces that give the same symmetry energy and then see how they extrapolate to high density

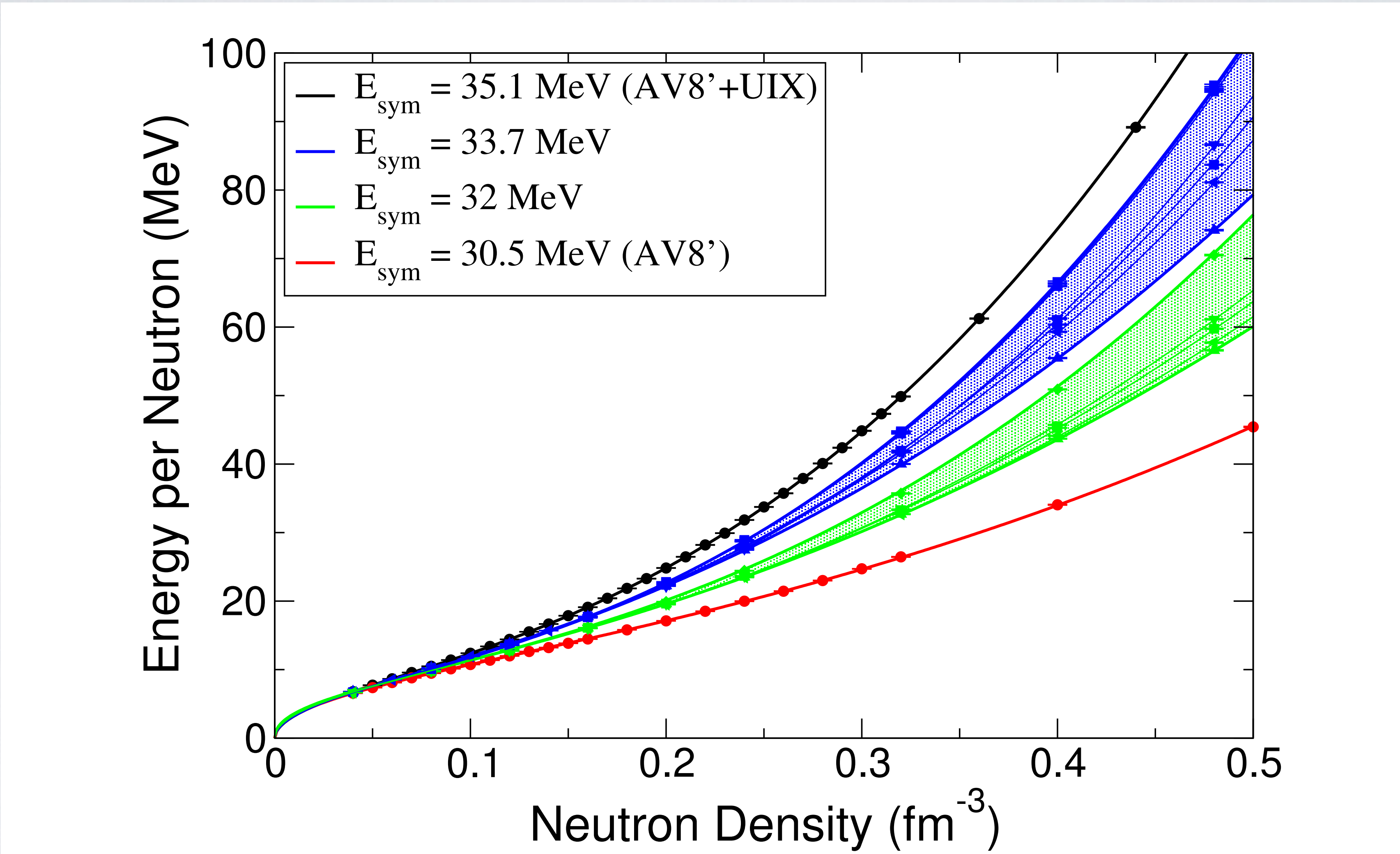
We consider different forms of three-neutron interaction by only requiring a particular value of E_{sym} at saturation.



different 3N:

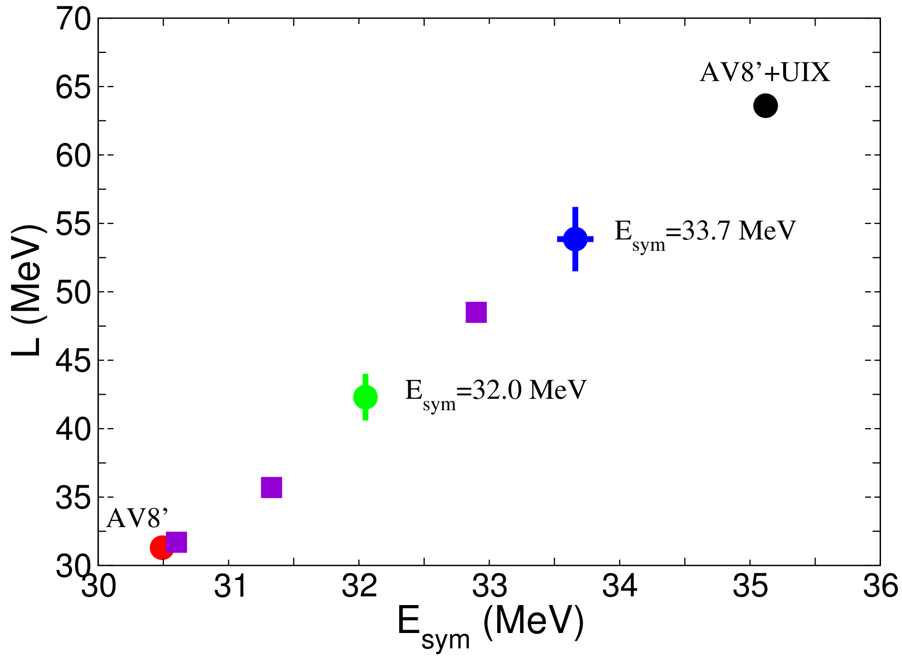
- $V_{2\pi} + \alpha V_R$
- $V_{2\pi} + \alpha V_R^{\mu}$ (several μ)
- $V_{2\pi} + \alpha \tilde{V}_R$
- $V_{3\pi} + \alpha V_R$

Equations of state with a fixed symmetry energy



Gandolfi, Carlson, Reddy 2012

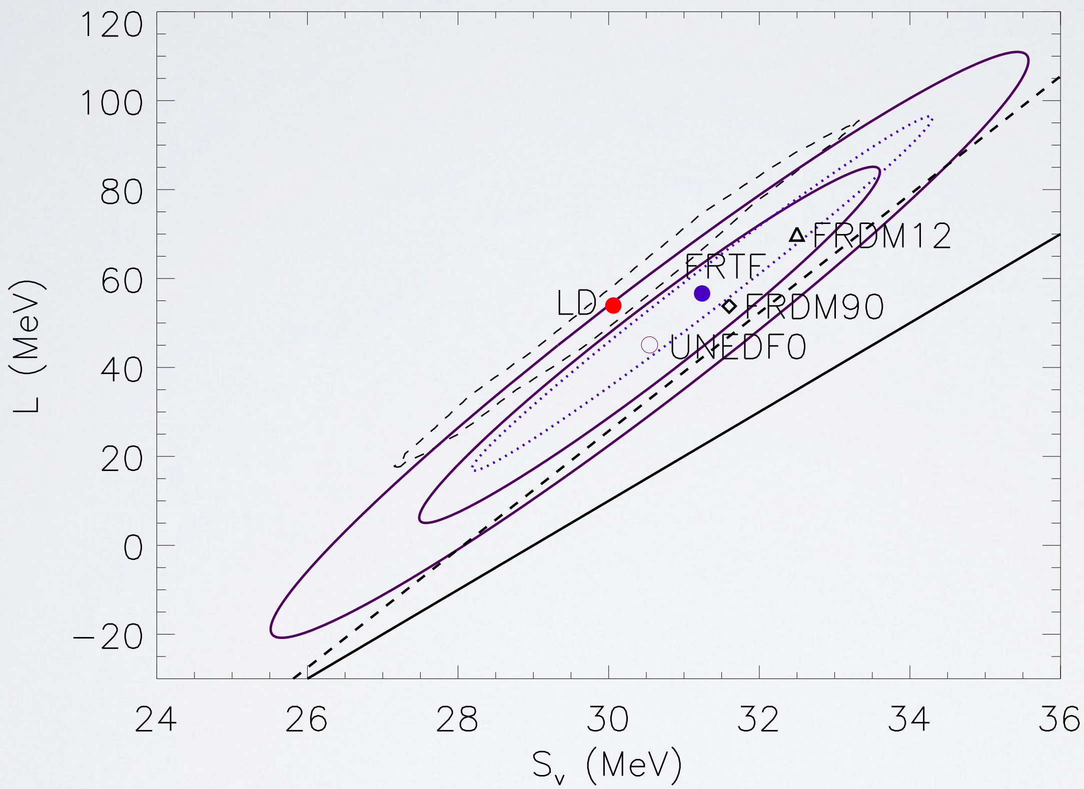
Strong Correlation between Symmetry Energy and its Derivative



Gandolfi *et al.*, EPJ (2014)

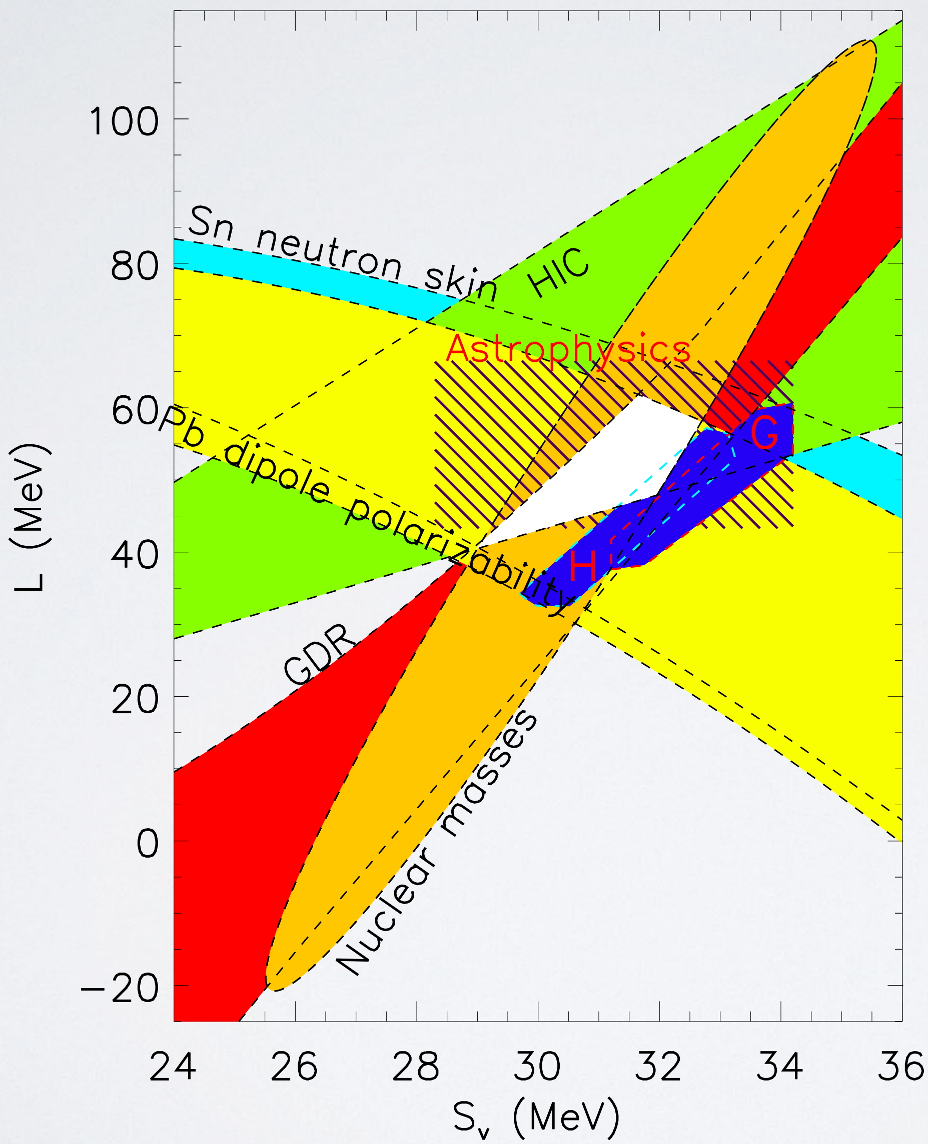
New chiral interaction models give very similar results

Fits to nuclear masses



Lattimer and Lim, ApJ 2013

Variety of Experimental Constraints

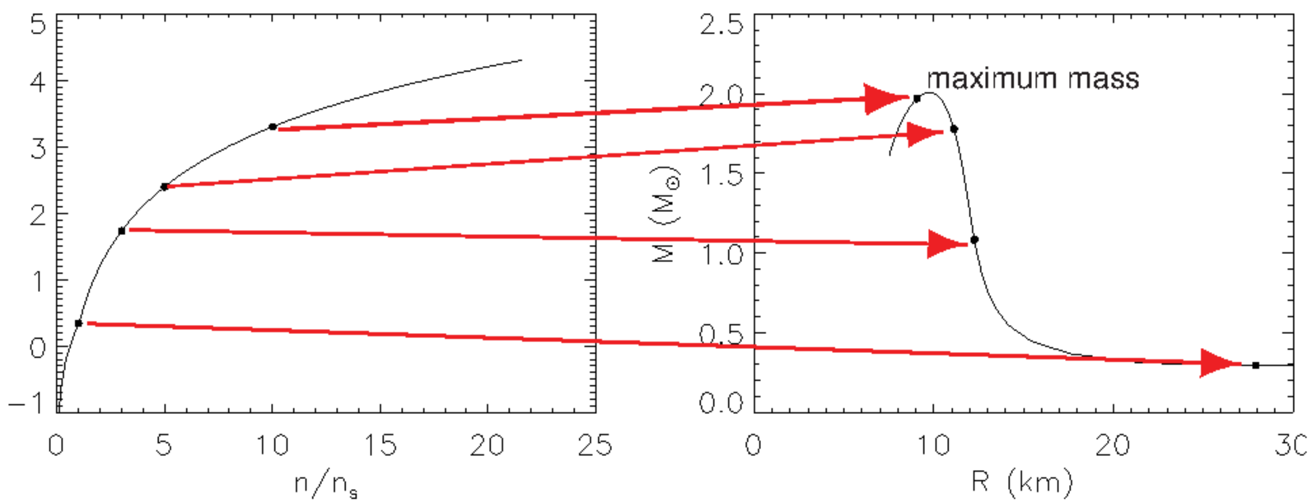


Equation of State to Mass / Radius

TOV equations:

$$\frac{dP}{dr} = -\frac{G[m(r) + 4\pi r^3 P/c^2][\epsilon + P/c^2]}{r[r - 2Gm(r)/c^2]} ,$$

$$\frac{dm(r)}{dr} = 4\pi\epsilon r^2 ,$$



from Lattimer

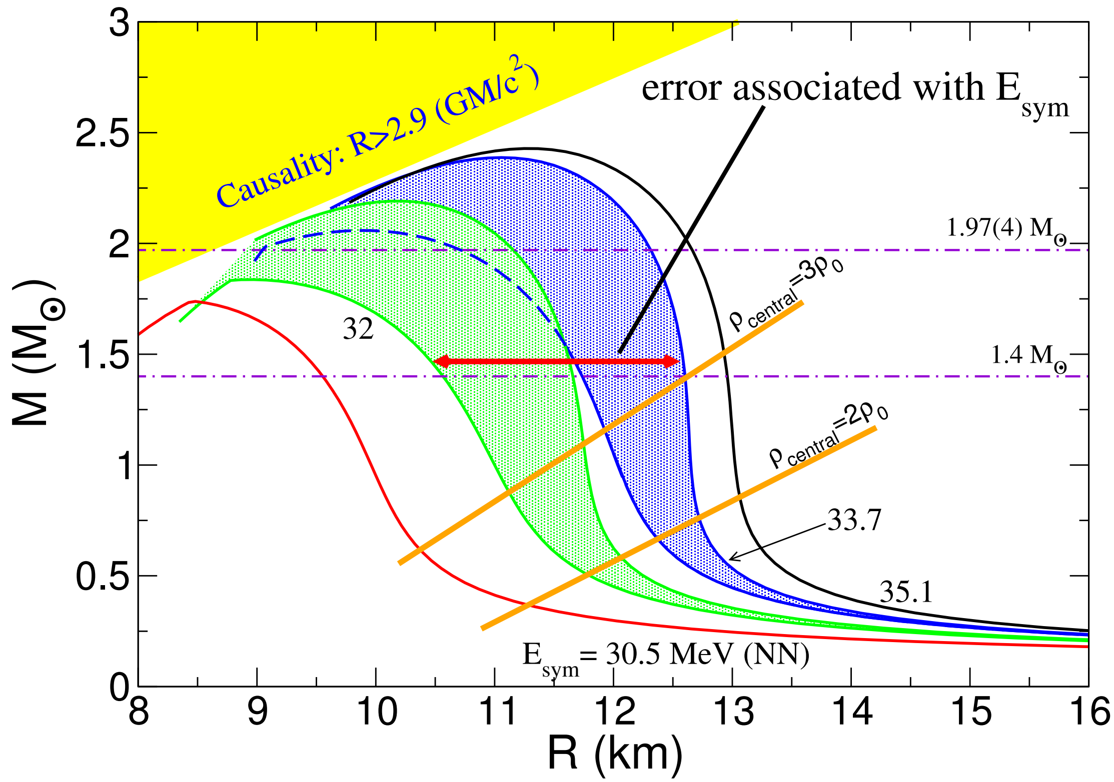
Tolman Oppenheimer Volkov equations: 1939

used free neutron gas to estimate upper bound of 0.7 solar masses

see Silbar and Reddy: arXiv:nucl-th/0309041 for an introduction

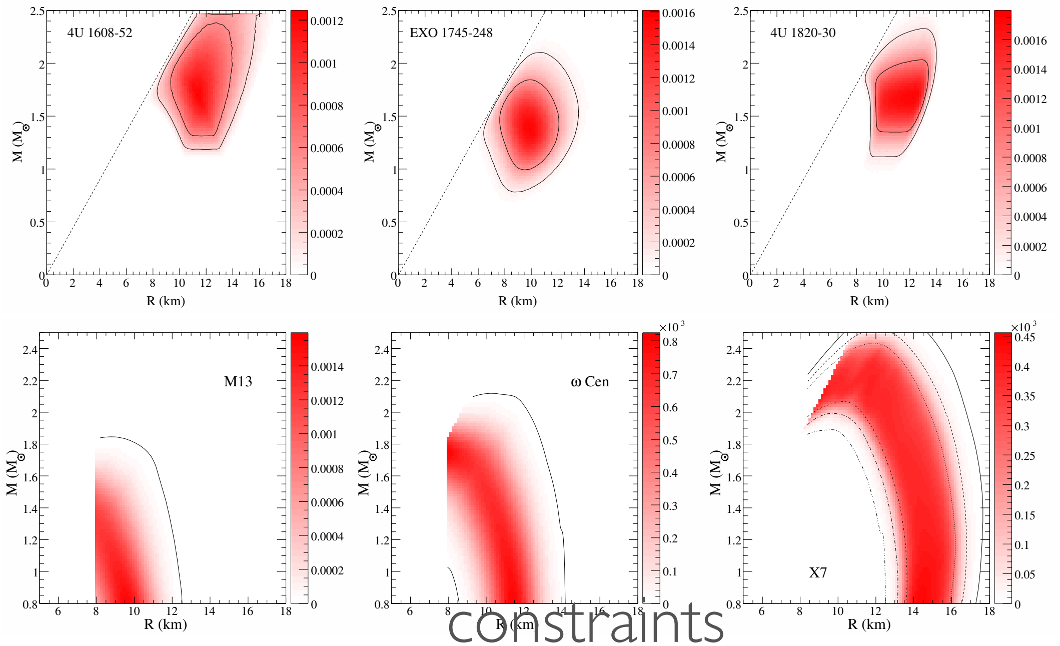
Neutron Star Mass/Radius: Calculations

EOS used to solve the TOV equations.



Gandolfi, Carlson, Reddy, PRC (2012).

Observations - still controversial

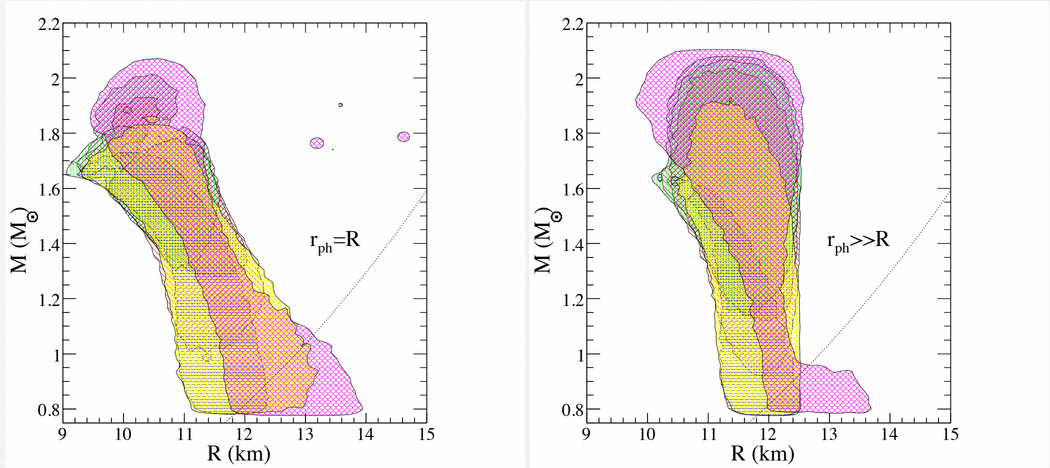


constraints

Steiner, Lattimer, Brown, ApJ (2010)

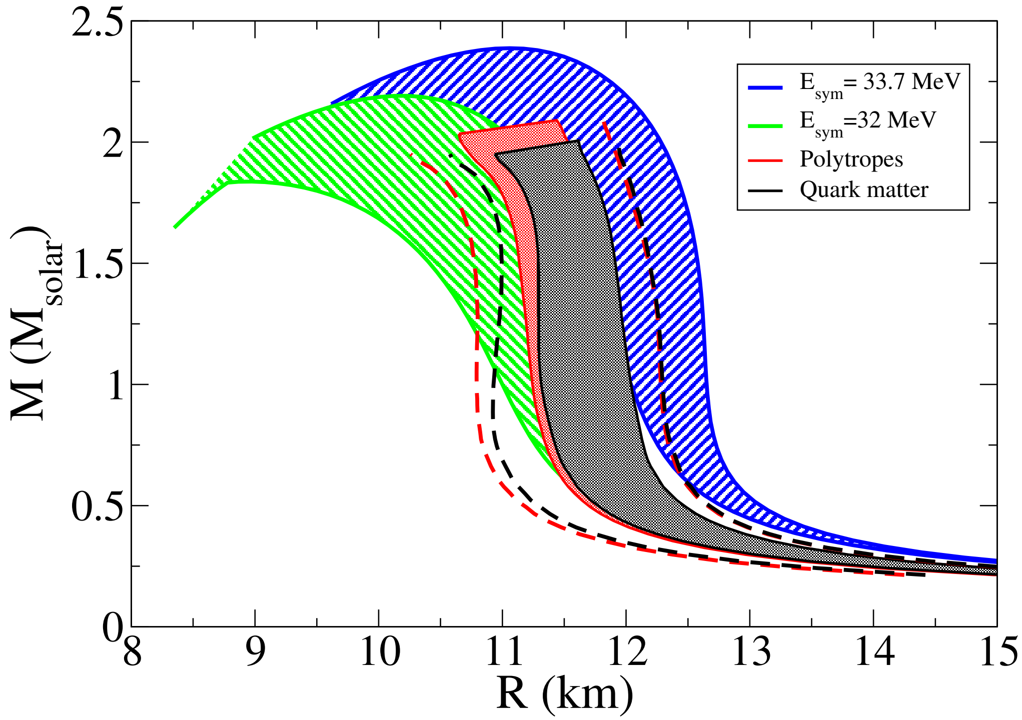
constraints from individual stars

observations from
3 X-ray bursars
plus 3 low-mass X-ray binaries



Mass radius constraints
subject to assumptions

Comparison of theory and observations



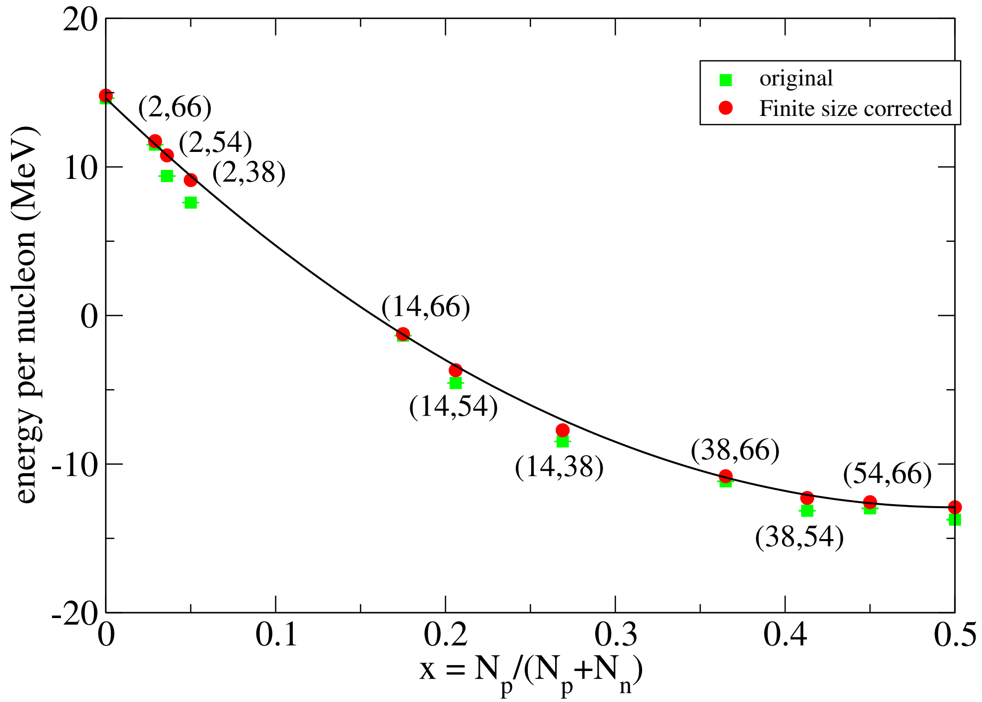
$32 < E_{sym} < 34\,MeV,\ 43 < L < 52\,MeV$

Steiner, Gandolfi, PRL (2012).

What about other particles? protons

Quadratic dependence of E versus n/p imablance

Asymmetric nuclear matter $E(\rho, x) = E_{SNM}(\rho) + E_{sym}^{(2)}(\rho)(1-2x)^2$ -

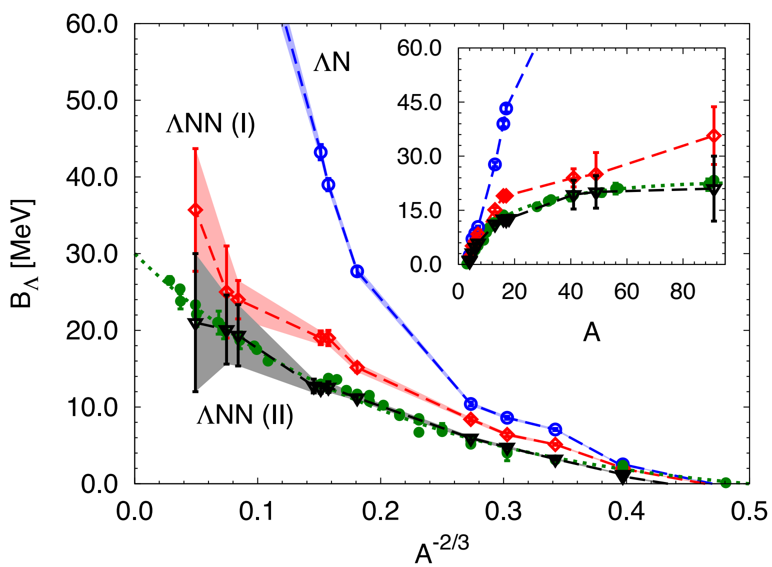


Gandolfi, Lovato, Carlson, Schmidt, arXiv:1406.3388

proton fraction also important for neutrino processes

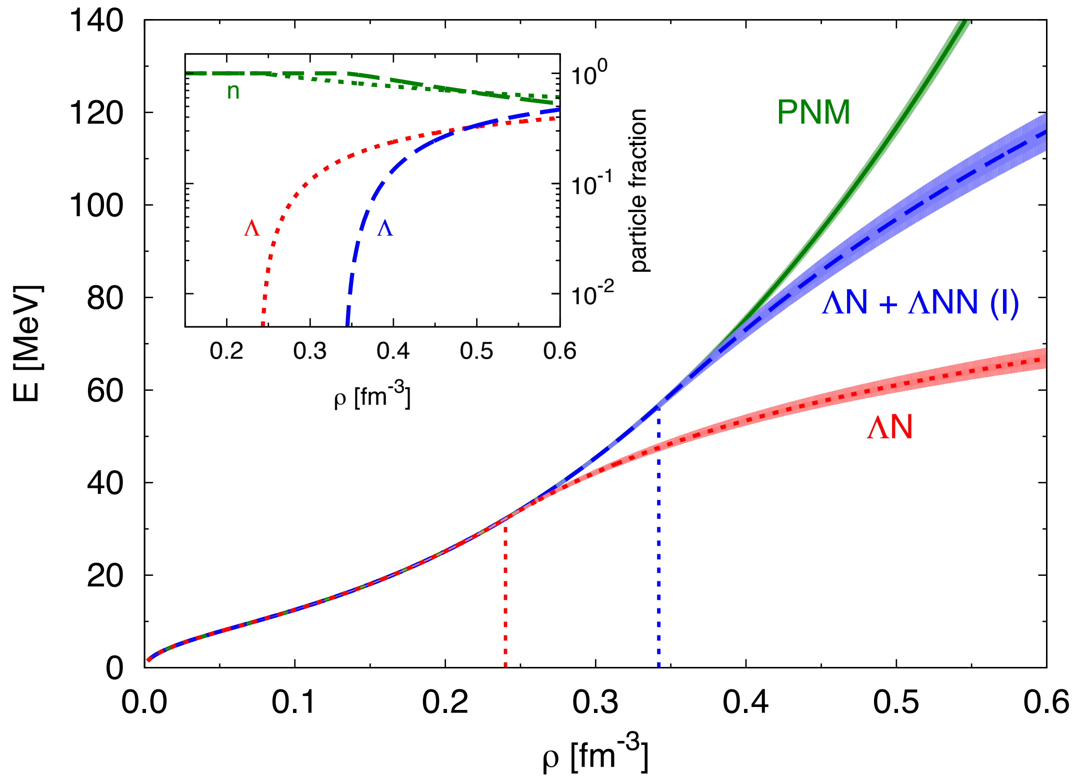
What about other particles? hyperons, …

Hyperons are bound in nuclei by ~ 30 MeV.
What happens in dense matter?



Lonardoni, Pederiva, SG, PRC (2013) and PRC (2014).

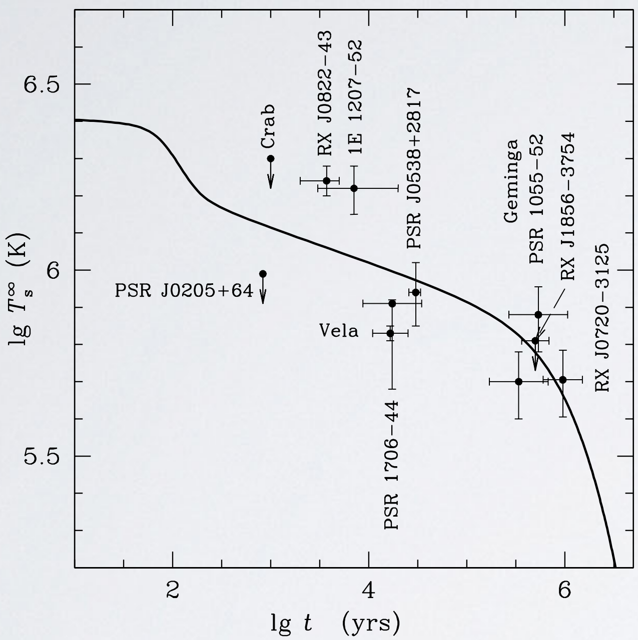
Hyperons in Neutron Matter

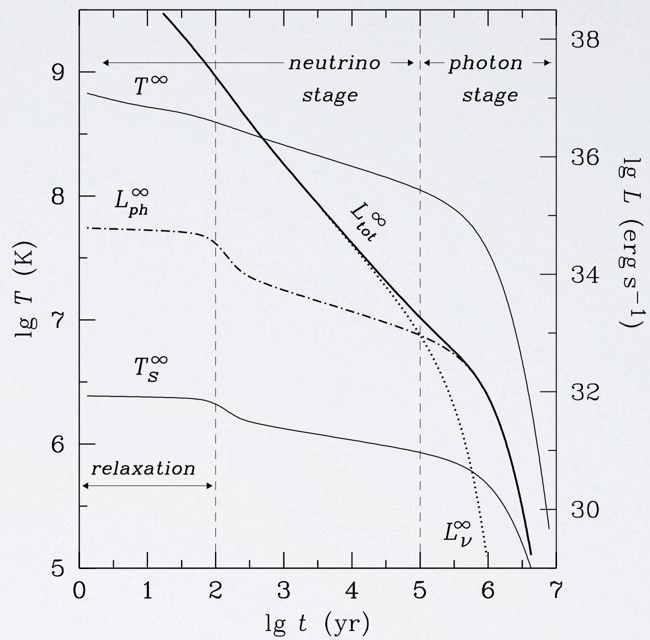


Lonardoni, Lovato, Gandolfi, Pederiva, arXiv:1407.4448 (2014)

Best model gives no hyperons
up to 3-4 x saturation density

Neutrinos in
neutron stars and proto-neutron stars



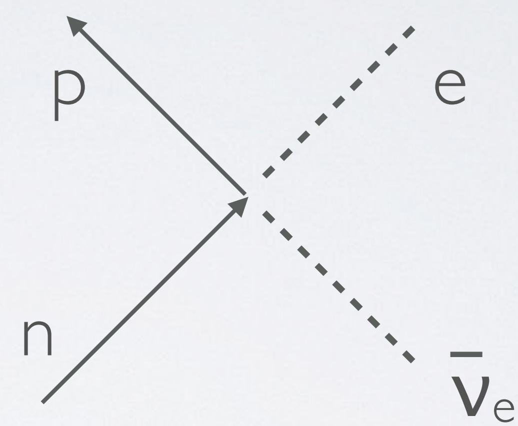


Yakovlev 2004

Neutron Star Cooling Introduction

Sensitive to:
- Equation of state
- Neutrino Emission
- Superfluidity
- Magnetic Fields
- Surface

Direct Urva:
Lattimer, Pethick, Prakash, Haensel (1991)



$$n \to p + e + \bar{\nu}_e$$
$$p + e \to n + \nu_e$$

threshold associated with Fermi surfaces limit this to $\rho > 2\,\rho_0$
Requires ~ 15% proton fraction
to satisfy energy and momentum conservation

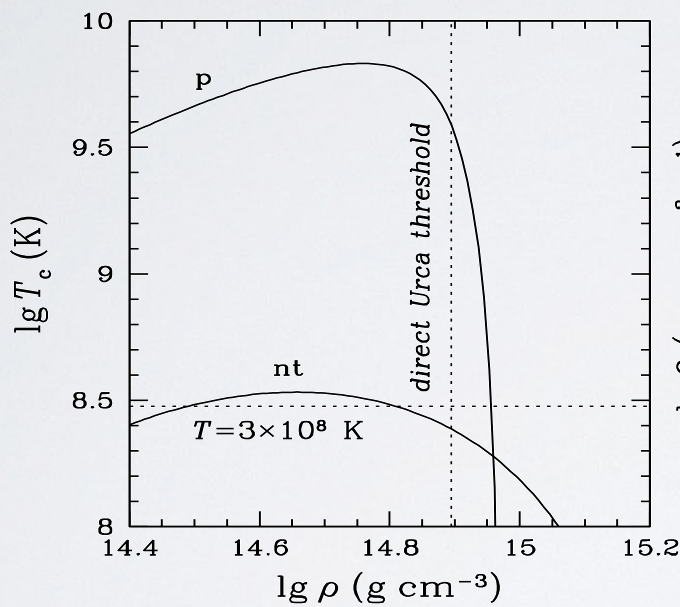
modified Urca works throughout the core

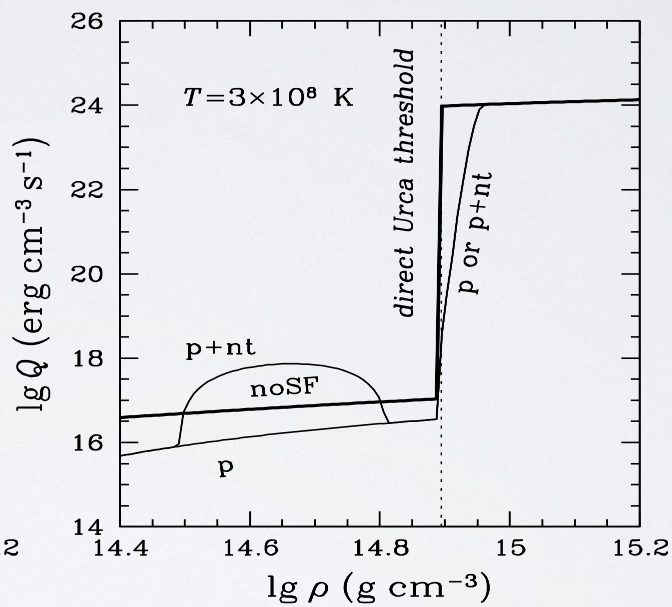
$$n + N \to p + e + N + \bar{\nu}_e$$

much slower

Superfluidity

suppresses familiar neutrino processes
creates new process: production through Cooper pairing
3P2 - 3F2 pairing particularly important but not well constrained





3×10^8 K ~ .026 MeV
typical s-wave pairing gaps ~ 1 MeV
angle average 3P2 ~ .01 MeV
log(nuclear saturation density in g/cm^3) ~ 14.4

Yakovlev, et al, 2004
also see Gezerlis, Pethick, Schwenk arXiv:1406.6109

Neutron and Proto-Neutron Star Cooling

Neutron star cooling depends upon

- Equation of State
- Neutrino Emission and Propagation
- Neutron (and proton) Superfluidity
- + …

Supernovae neutrino emission also depends upon

- weak response of matter
- interesting regime at low densities (0.1 ρ_0)
- and moderate temperatures (non-degenerate matter)

Rapid progress in theory and observations

Summary/ Outlook

Rapid progress in our understanding of cold dense matter

Excellent connections to
- Theory of strongly-correlated matter
- Experiments in cold atom physics
- Astrophysical observations
- Future measurements of gravitational waves
- Supernovae physics and neutrino physics