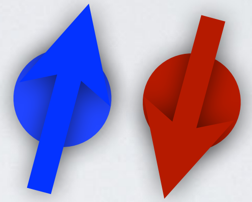
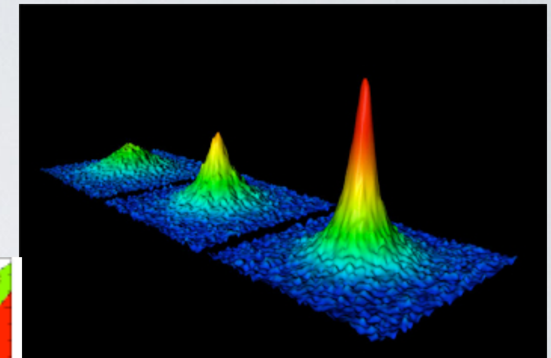
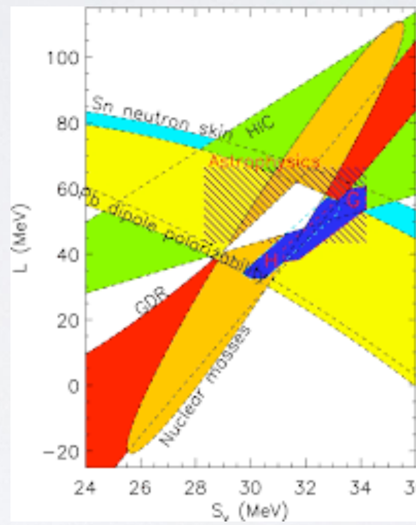
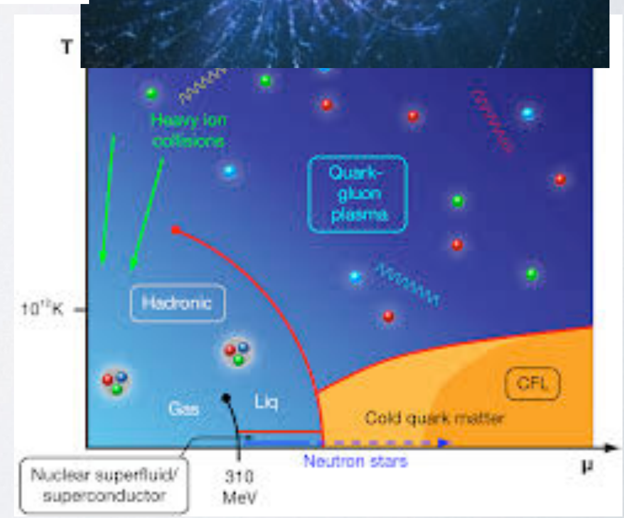
Neutron Matter from Low to High Density

J. Carlson - LANL



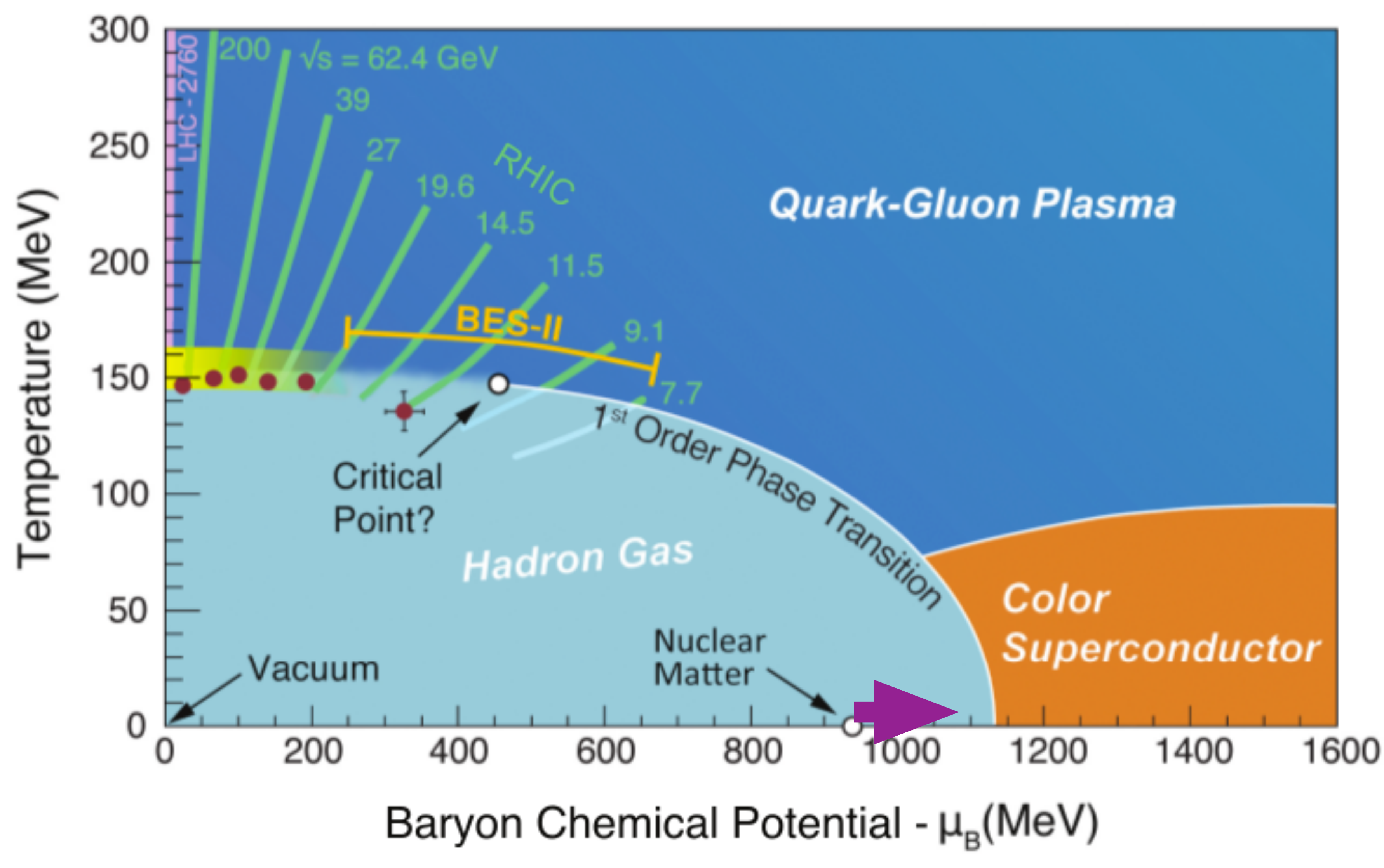




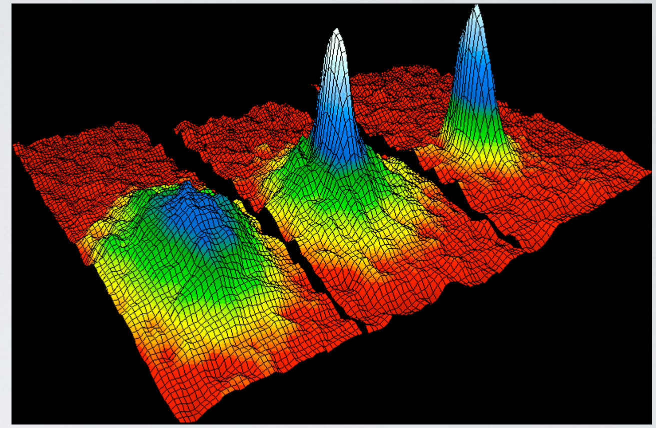


- Very low density:
  relation to cold fermions
- Moderate density:
  nuclear symmetry energy
- 1-2 times saturation density:
  neutron star mass/radius
- Color superconducting quark matter
- Outlook

QCD Phase Diagram



Very Low Density Equation of State



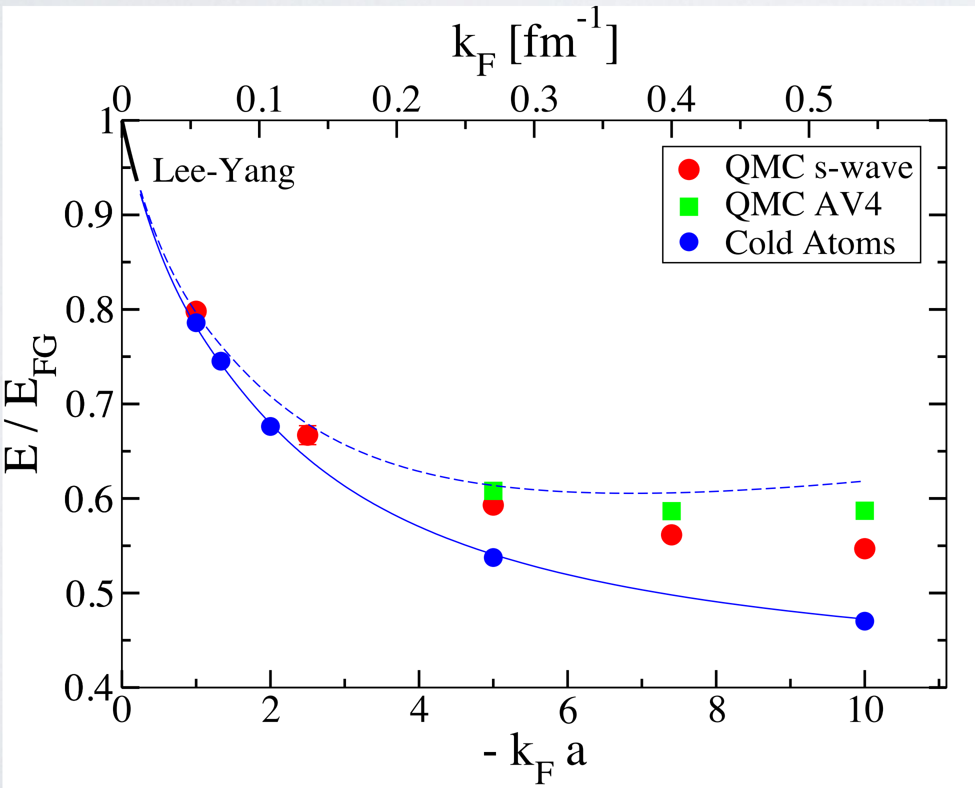
Neutrons:

$$a_{nn} \approx -18 \text{ fm}$$
$$r_e \approx 2.7\text{fm}$$

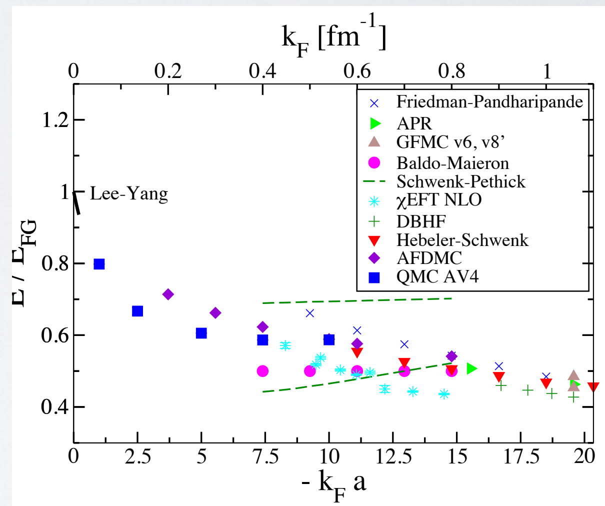
Cold atoms:

$$a \text{ from } 0 \rightarrow \infty \rightarrow 0$$
$$r_e \rightarrow 0$$

BCS → BEC



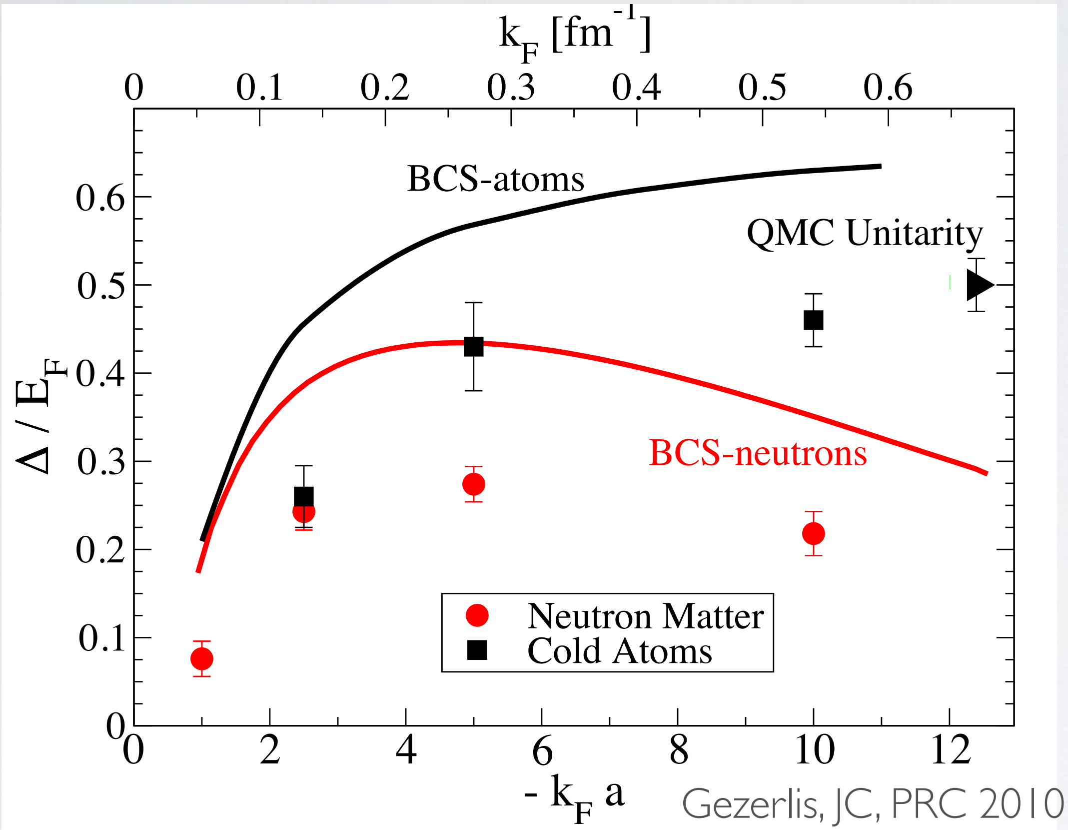
Gezerlis, JC, PRC 2010



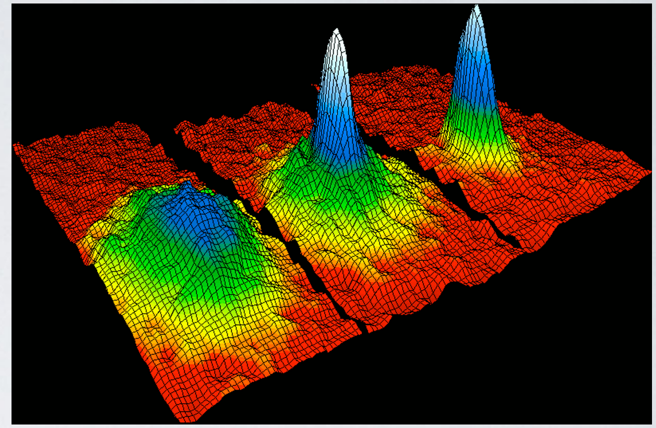
Slightly higher densities

Gandolfi, Gezerlis, JC, ARNPS 2015

Very Low Density Pairing Gap



Gezerlis, JC, PRC 2010

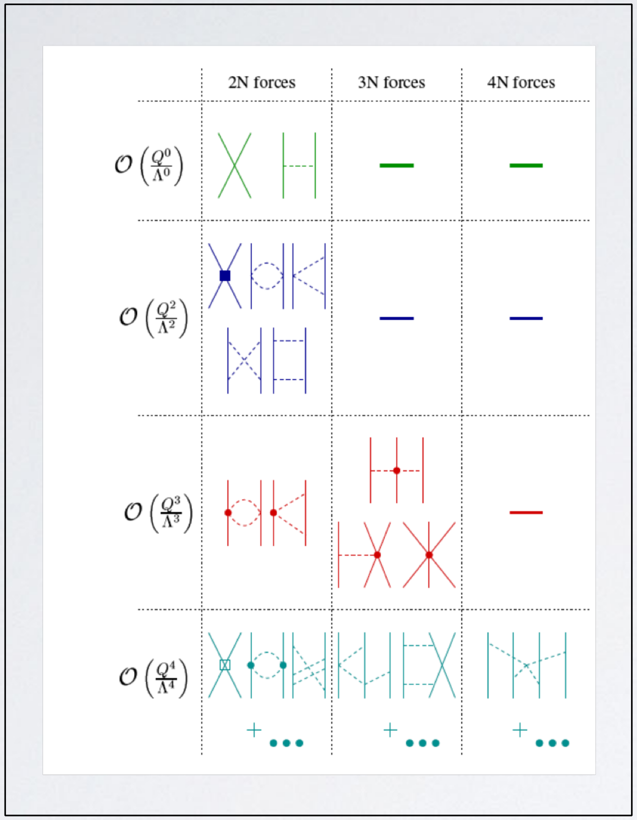


Neutron matter: largest pairing gap in nature : $\Delta / E_F \approx 0.3$

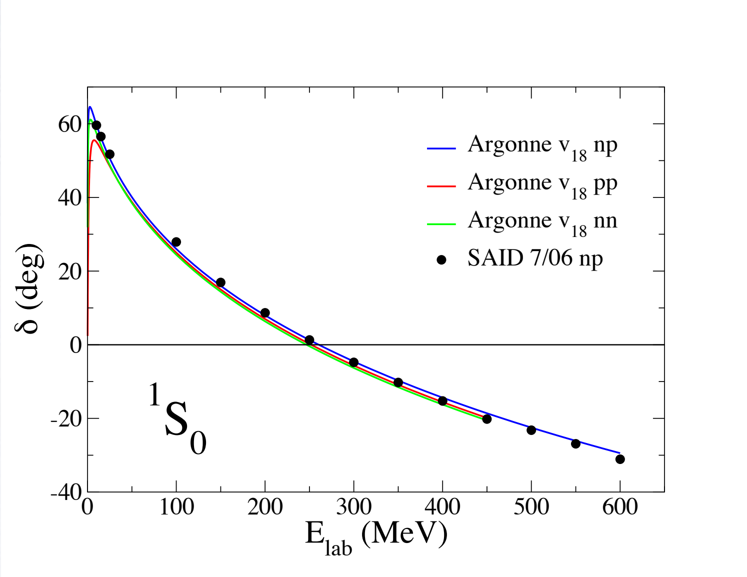
Cold atoms at unitarity : $\Delta / E_F = 0.45(0.05)$

Beyond very low density

Nuclear Interactions



Chiral EFT
and AV18, …



NN interactions fit to huge database
3N interactions fit to nuclei

Beyond very low density

Method: Auxiliary Field Diffusion Monte Carlo

sampling spins/isospins with diffusion for coordinates

introduced by Schmidt and Fantoni

$$\Psi_0 \; = \exp[-H\tau] \; \Psi_T$$

$$|\boldsymbol{R}\,S\rangle = |\boldsymbol{r}_1 s_1\rangle \otimes |\boldsymbol{r}_2 s_2\rangle \cdots \otimes |\boldsymbol{r}_n s_n\rangle\,.$$

$$|s_i\rangle \;\; = \;\; | \begin{array}{c} \cos(\theta_i)\exp[i\phi_i] \\ \sin(\theta_i)\exp[-i\phi_i] \end{array} \rangle$$

and similarly for isospin,

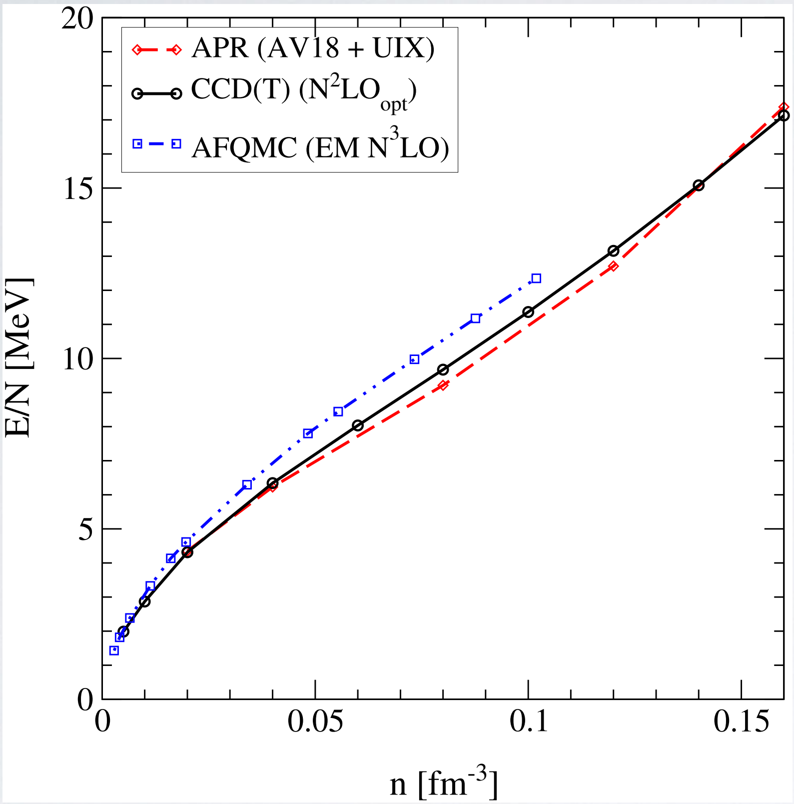
auxiliary fields used to propagate with spin-dependent interaction

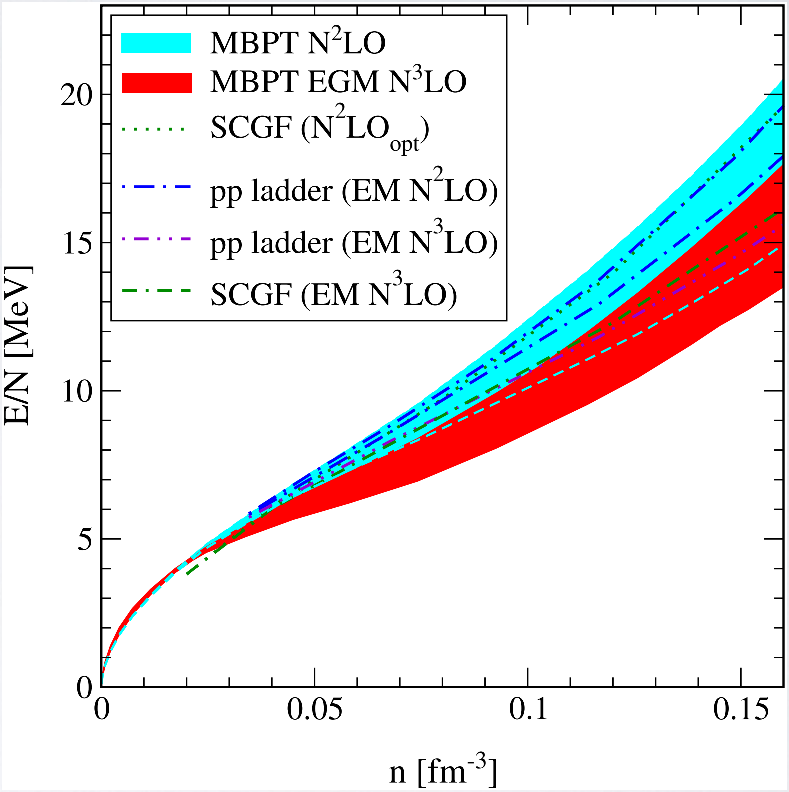
$$\prod_{i<j} e^{-V_{ij}\delta\tau} |\boldsymbol{R}\,S\rangle =$$

$$\prod_n \frac{1}{(2\pi)^{3/2}} \int dx_n e^{-x_n^2/2}\, e^{\sqrt{-\lambda_n \delta\tau} x_n \mathcal{O}_n} |\boldsymbol{R}\,S\rangle = |\boldsymbol{R}\,S'\rangle\,,$$

Lattice methods also used extensively

Moderate Densities



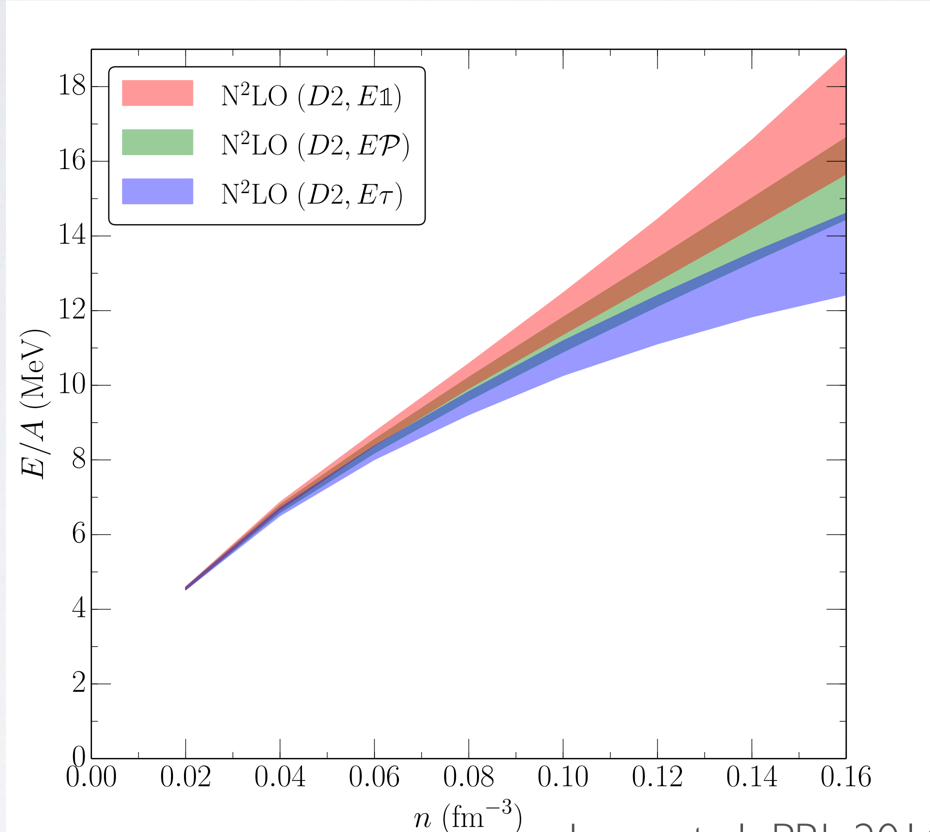


Various approaches agree precisely at low densities,
start to diverge near saturation densities
Symmetry Energy ~ 29-34 MeV

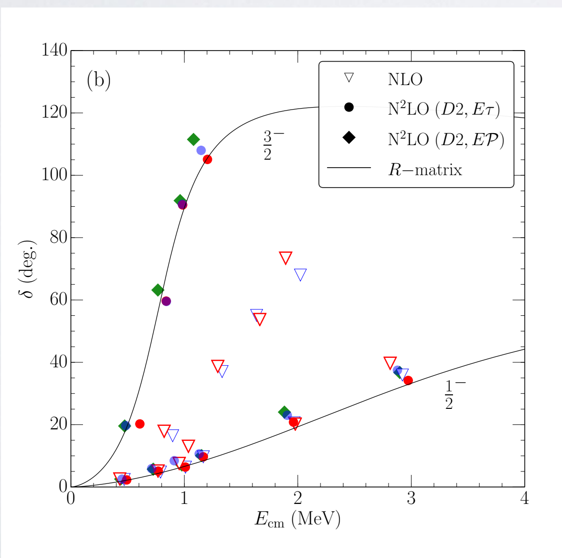
Gandolfi, Gezerlis, JC, ARNPS 2015

Neutron Matter w/ chiral 2N and 3N interactions at N2LO

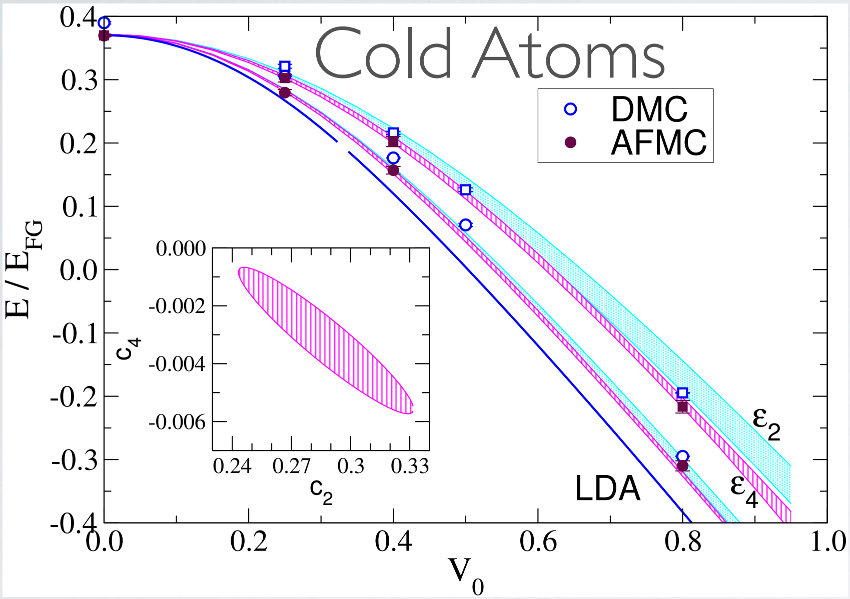
- TNI fit to A=4 binding, n-alpha scattering; A=5 includes T=3/2 triplets
- Significant uncertainties from regulators, Fierz rearrangements, …
- How to reduce uncertainties?

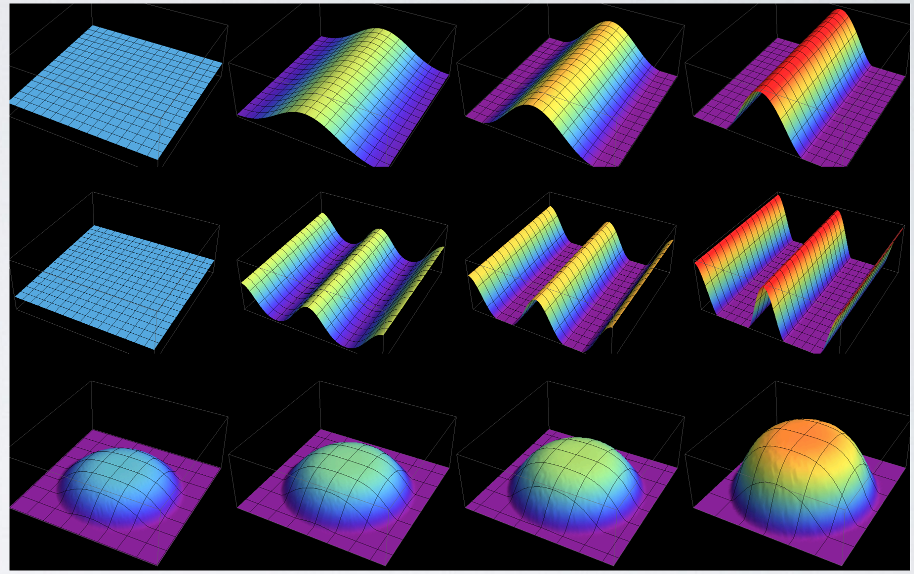


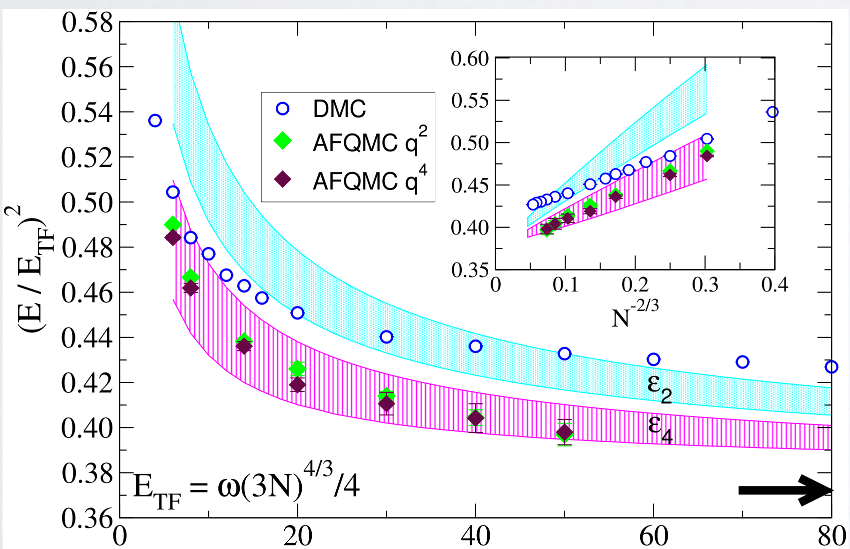
Lynn, et al., PRL 2016



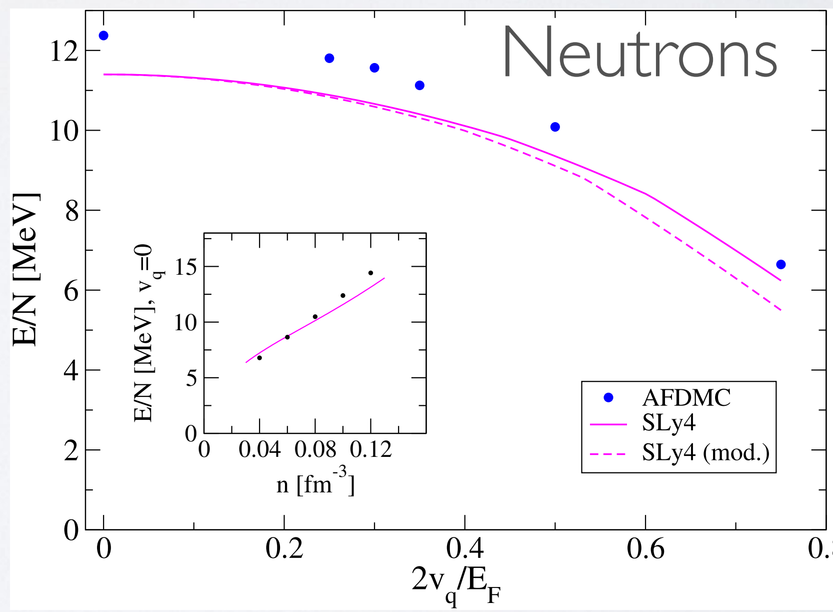
Inhomogeneous Matter







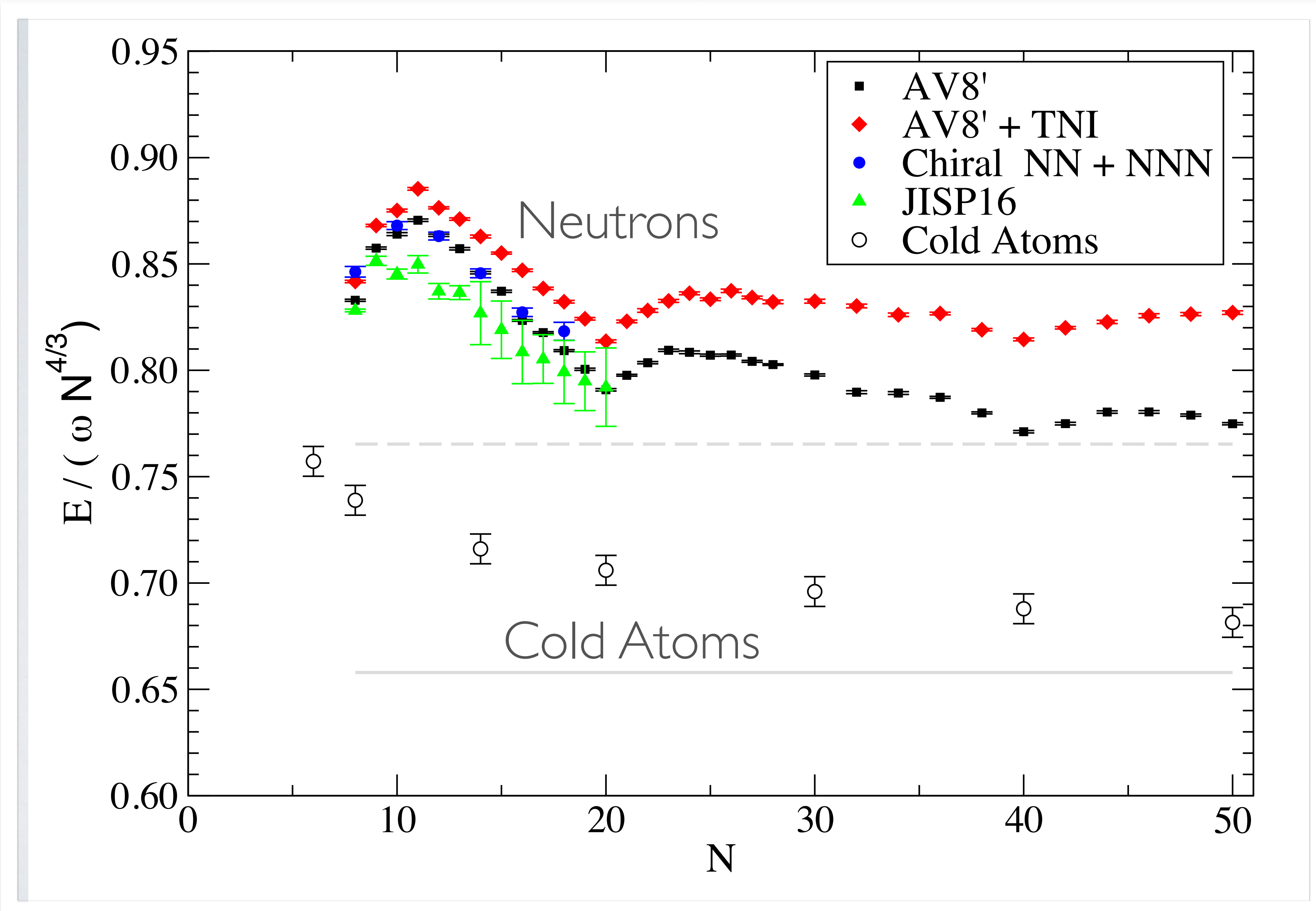
JC, Gandolfi, PRA, 2014



Density functionals and small clusters

Bruaczynski, Gezerlis, PRL 2016

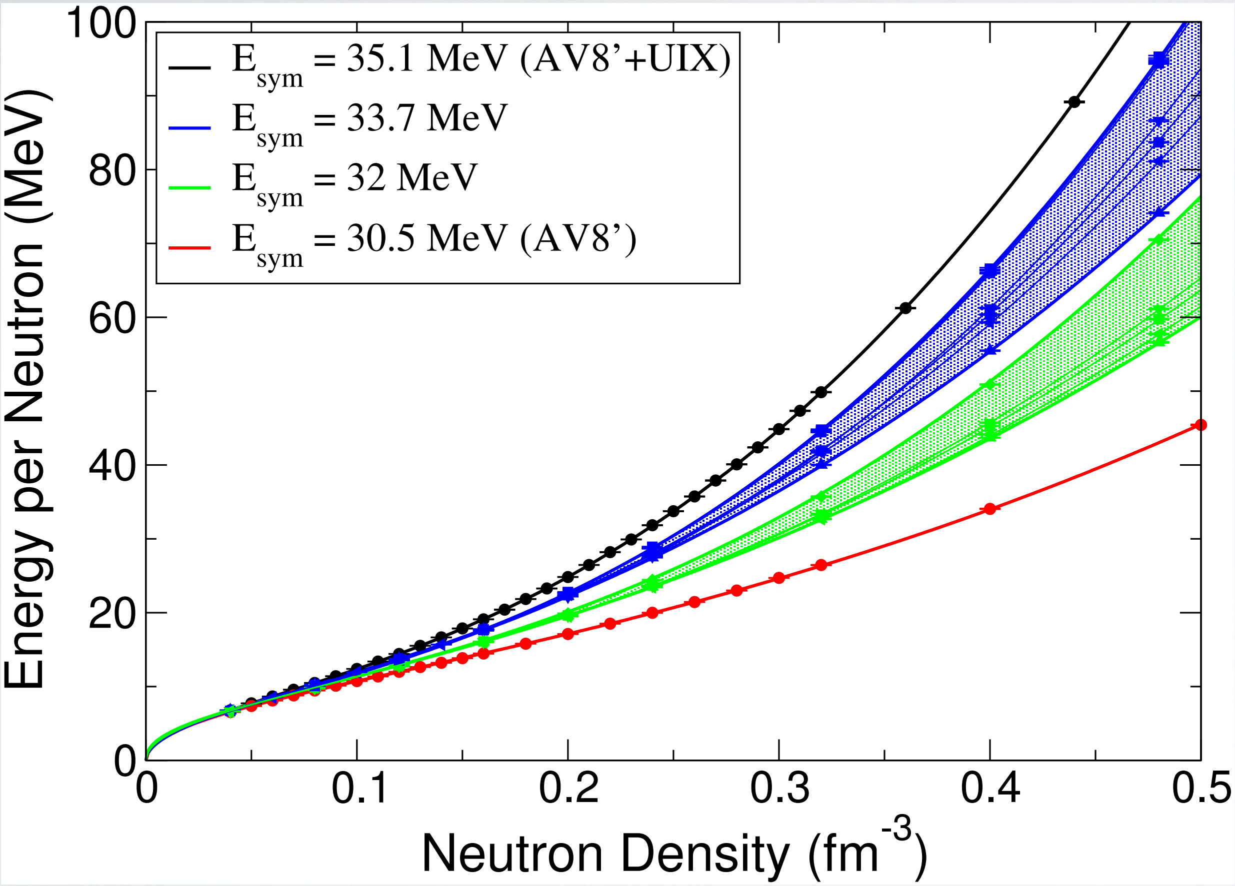
Inhomogeneous Systems: Neutrons vs. Cold Atoms

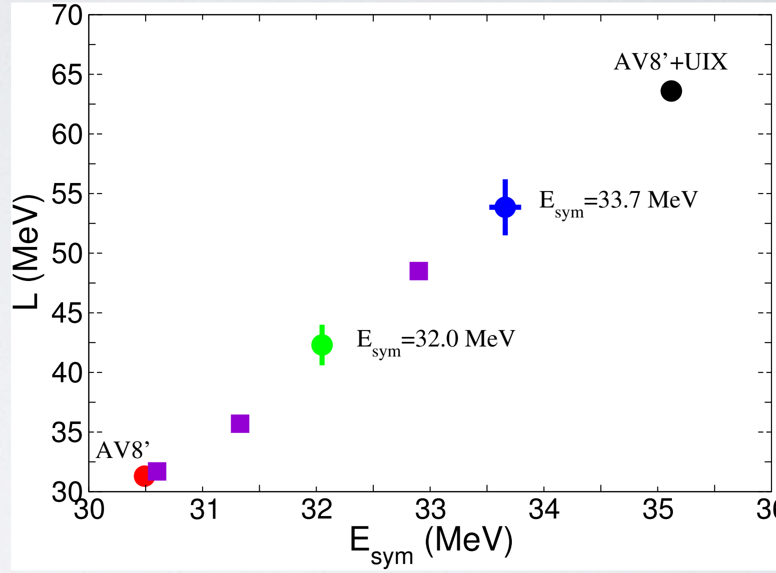


Shell structure very different

Gandolfi, Gezerlis, Carlson; Ann. Rev. Nucl. Part. Sci. 65, 303 (2015)

Higher Density and the Three Neutron Interaction





Gandolfi, JC, and Reddy (2012):
arXiv 1101.1921

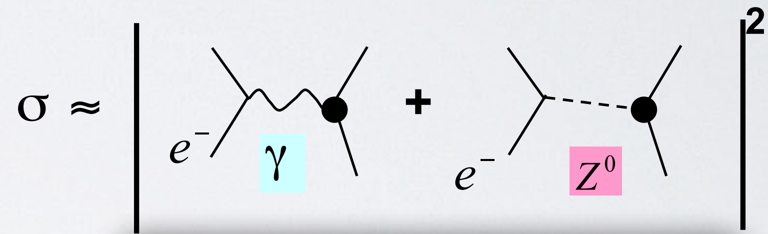
Strong Correlation between S and L (symmetry energy and slope)

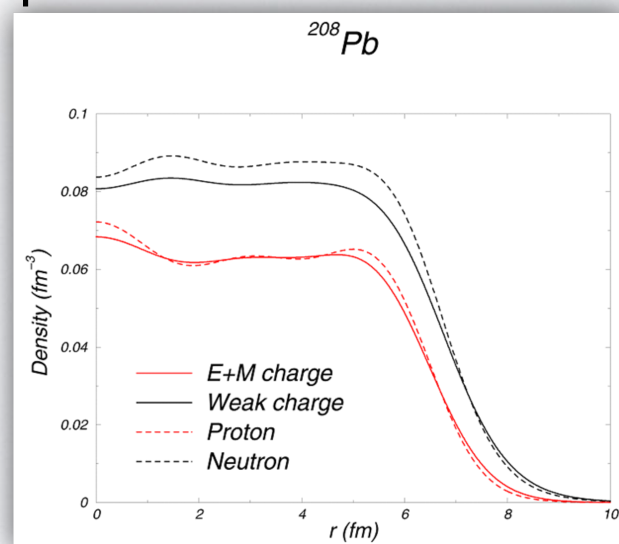
Experimental Constraints near Saturation Density

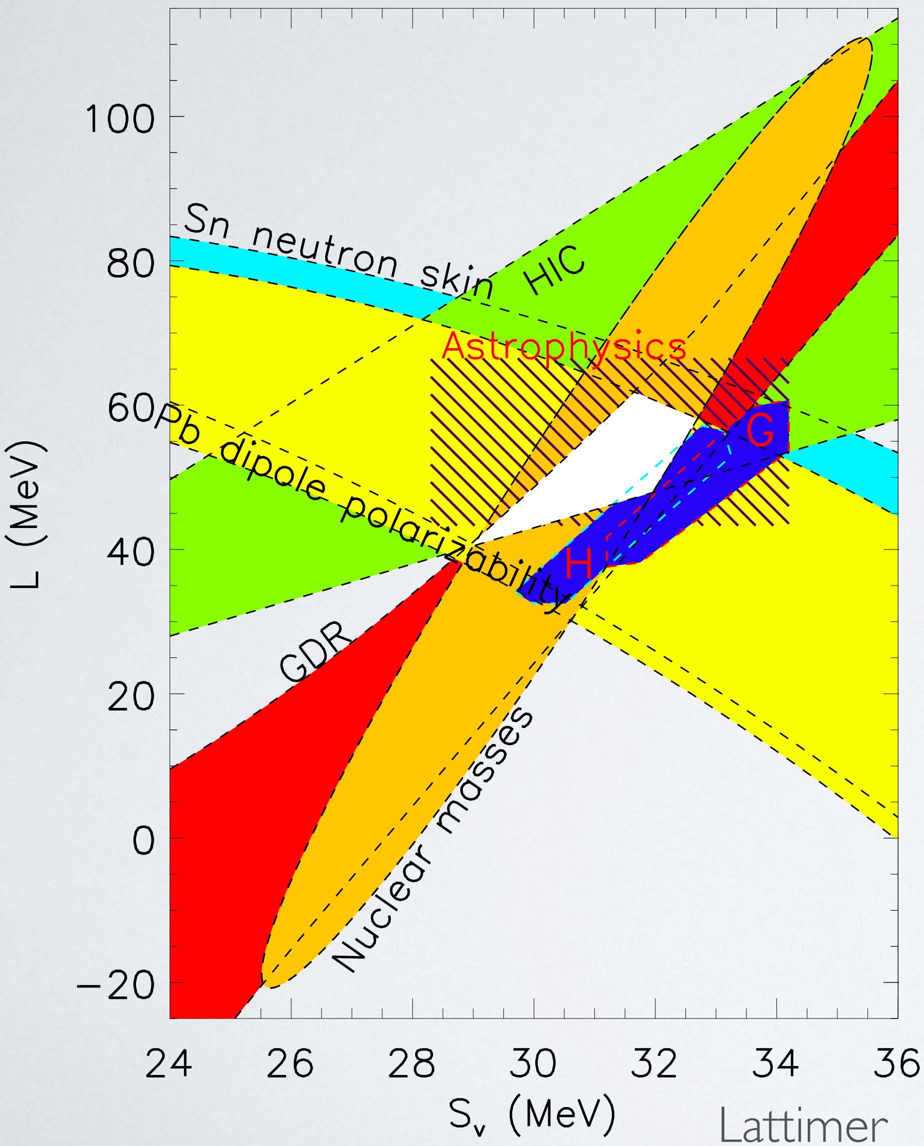
Also parity-violating e scattering:
PREX, CREX: neutron radius
(similar to proton radius from
elastic electron scattering)

PREX and

^{208}Pb ^{48}Ca



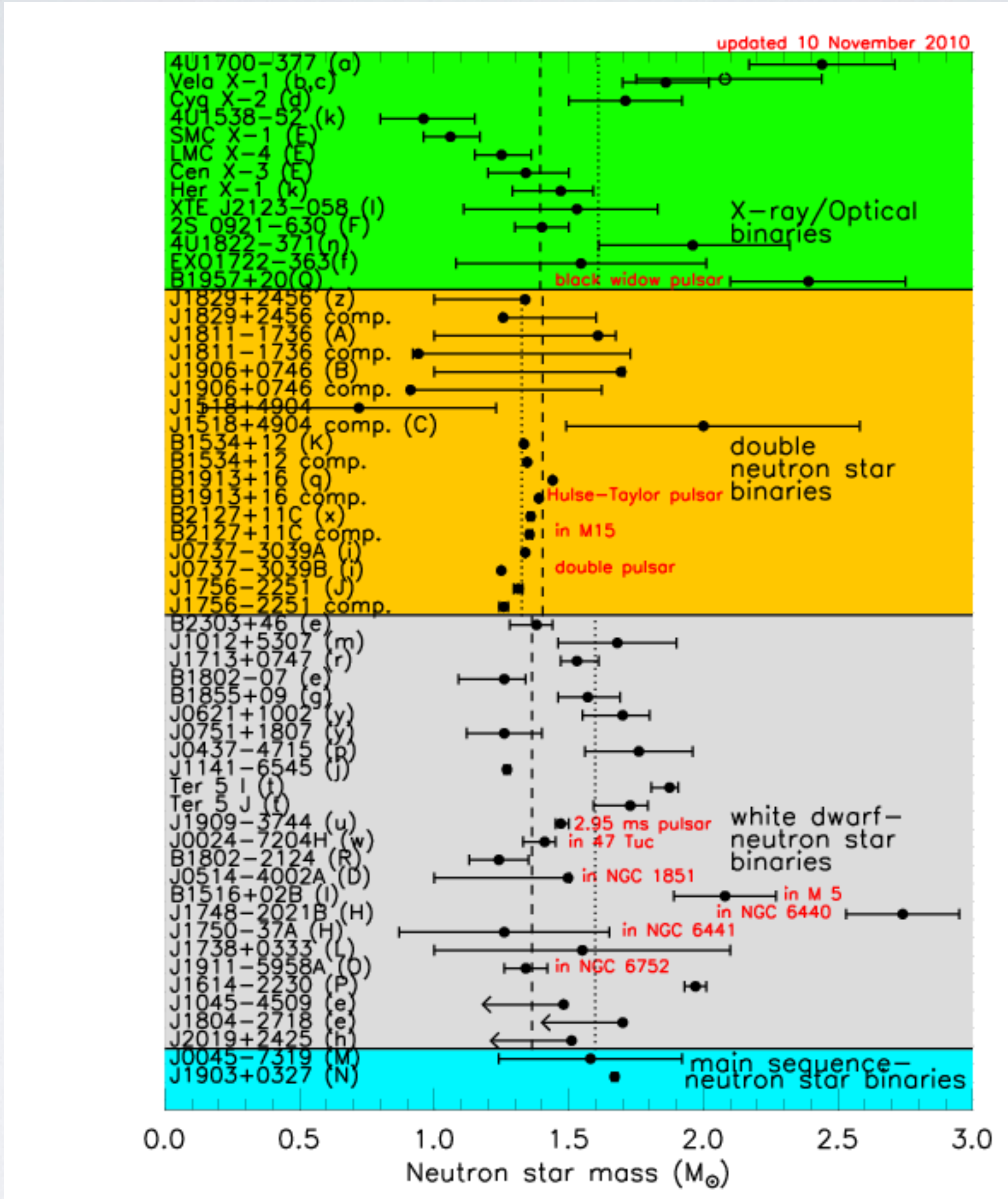




Lattimer

Theory: Schwenk et al., Gandolfi et al.

Observations: Neutron Star Masses

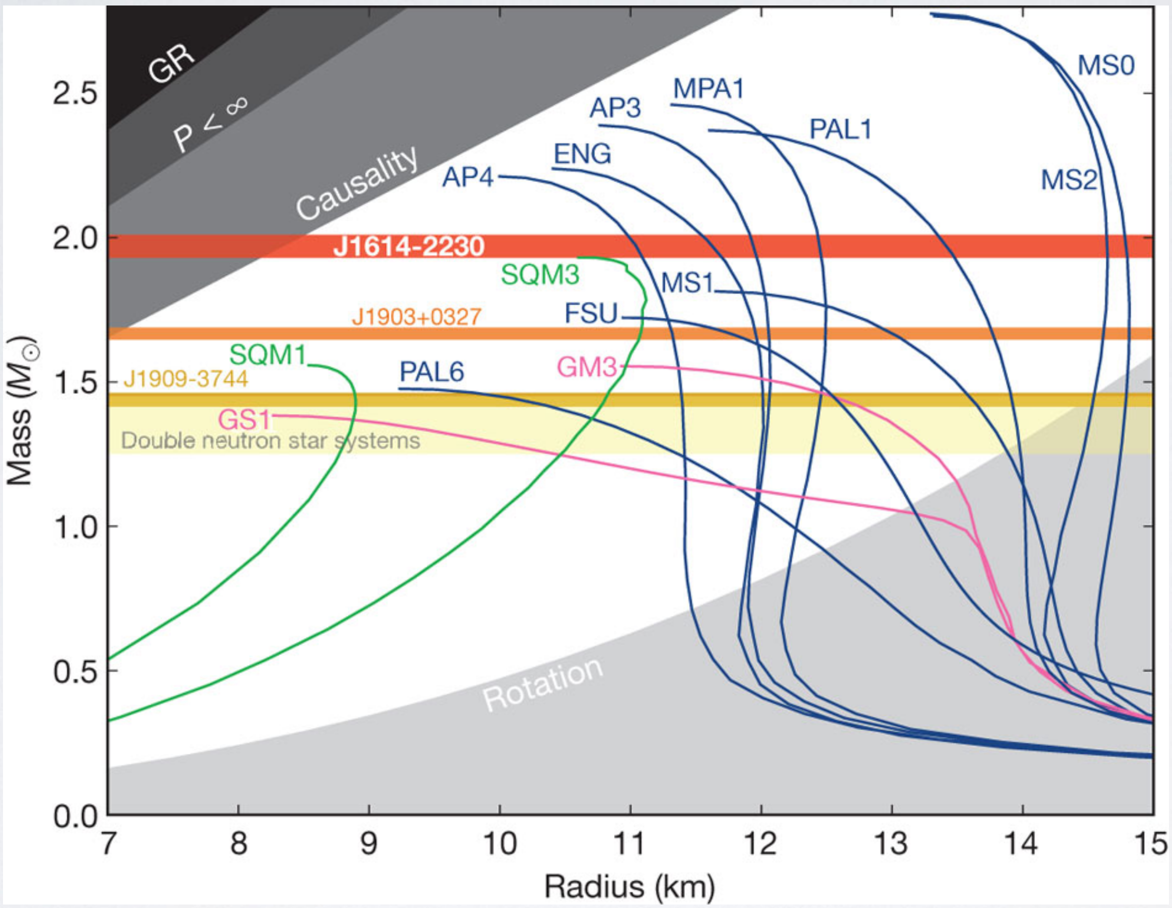


Demorest, et al
Nature 467: 2081 (2010)

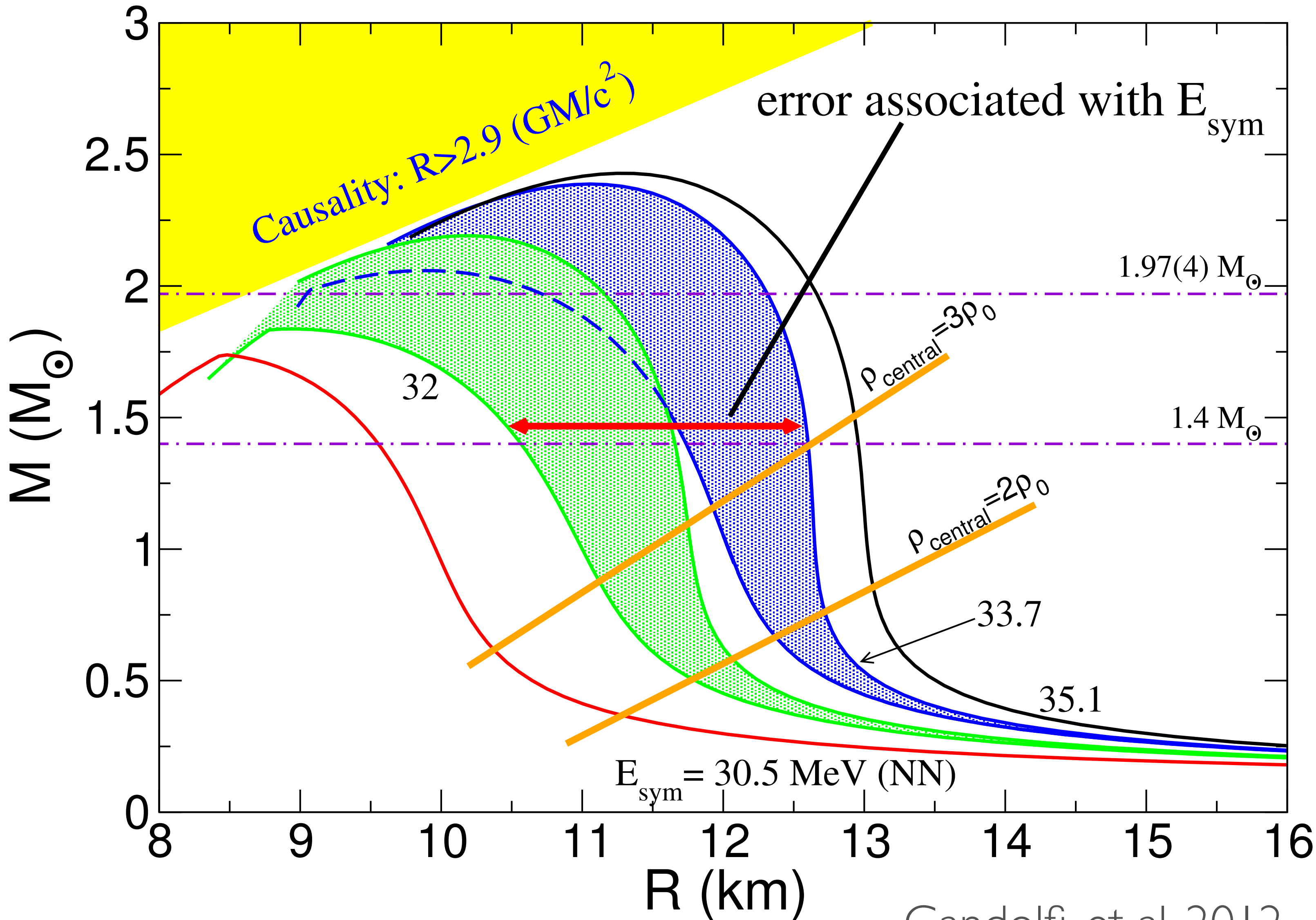
from Lattimer

Neutron Star Mass/Radius Relations: History

For many years only ~1.4-1.5 solar mass neutron stars observed
2010: Two solar mass neutron stars



Mass-Radius Relation for Neutron Stars

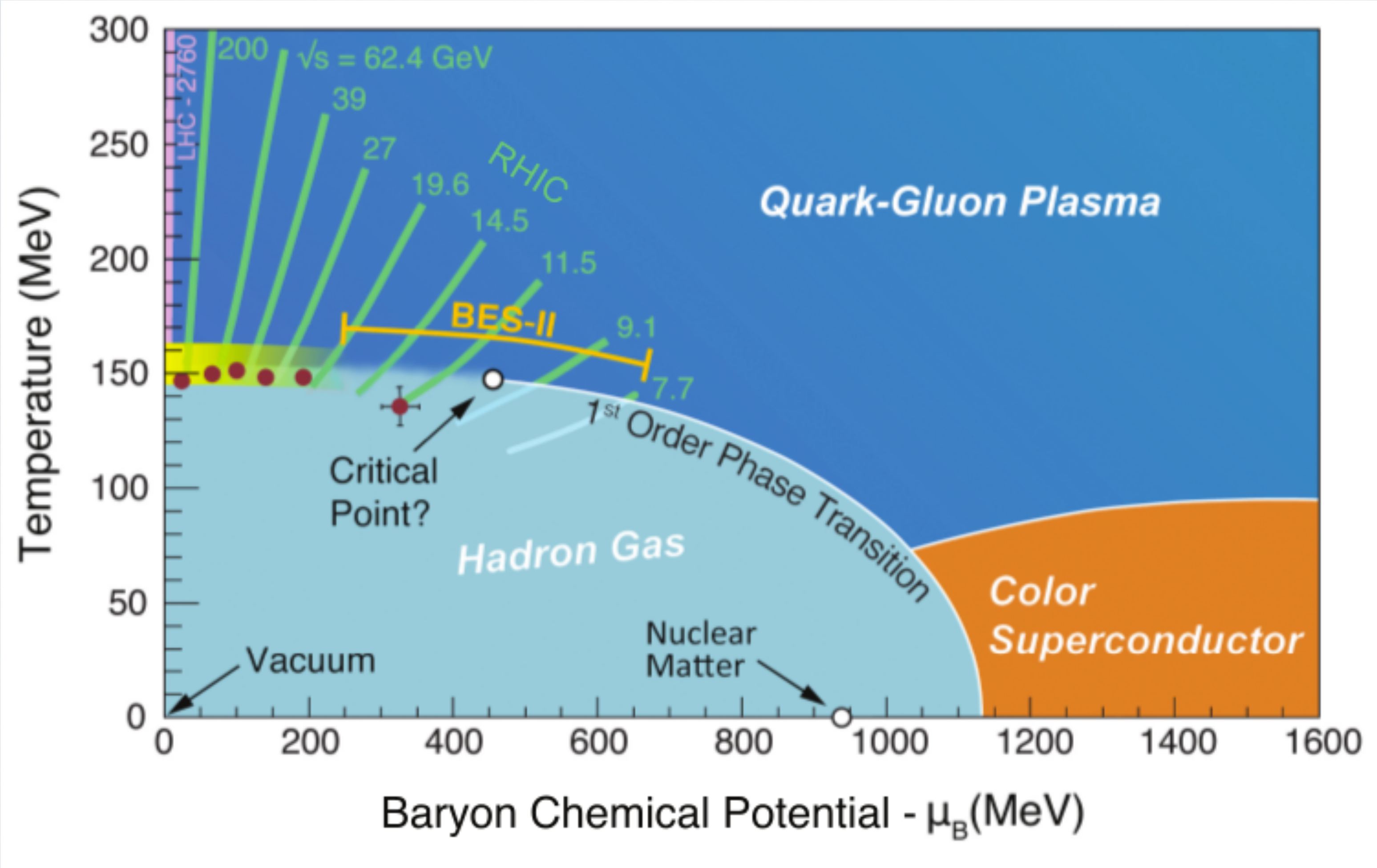


Gandolfi, et al, 2012

Hyperons? see S. Gandolfi's talk

What about QCD ?

from USQCD.org



Impressive lattice QCD at **μ** = 0, and exploratory studies at **μ** > 0

Little work at T ~ 0 for large **μ**

Fermion Sign Problem

Exponential decay in signal to noise for quantum fermi systems
Ubiquitous: electrons, cold atoms, helium, cold atoms, NP, LQCD

Decay proportional to Bose minus Fermi Energy
QCD : A (M_N - (3/2) M)
Nucleons: A x Fermi Energy

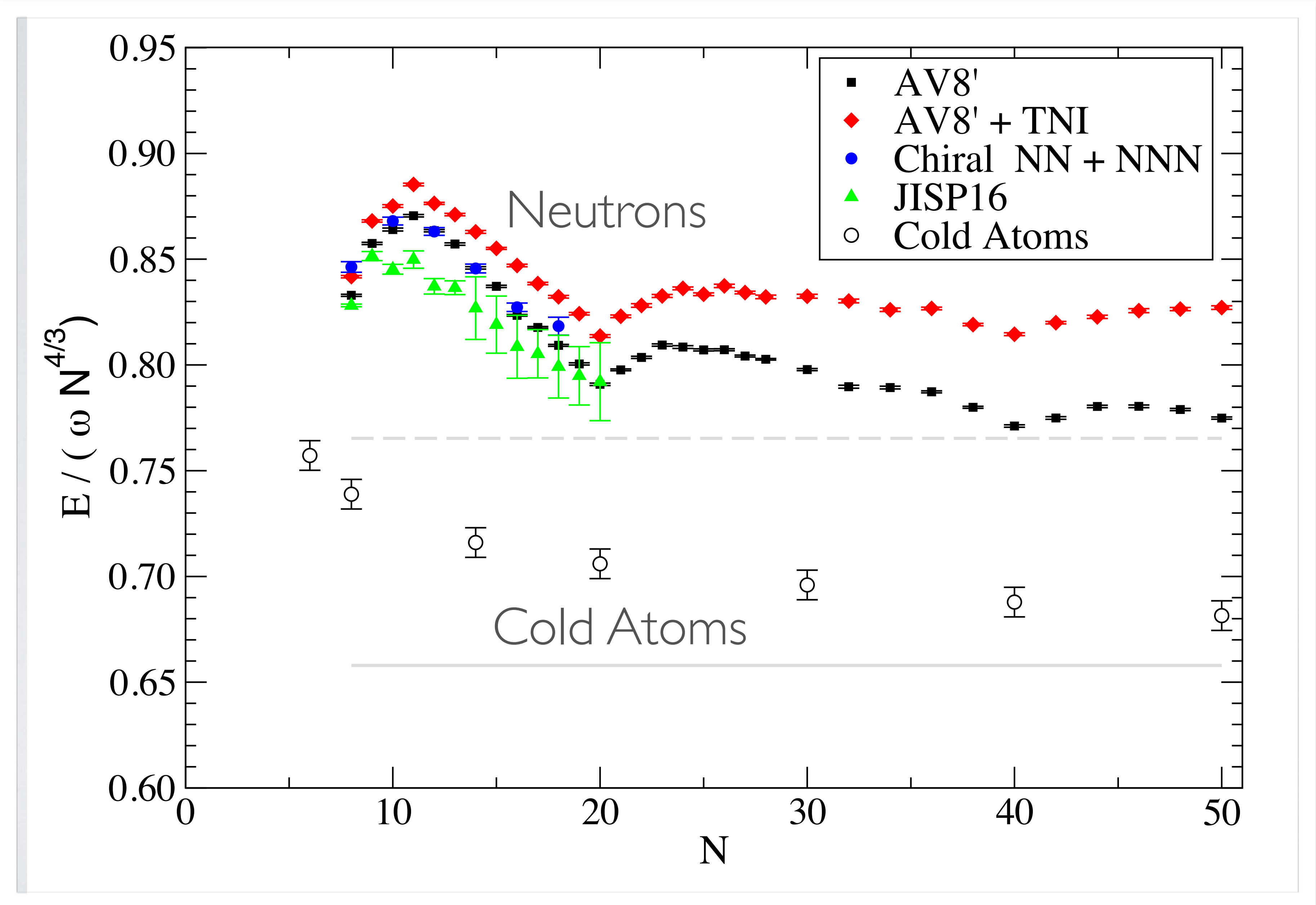
No general solution - exponentially difficult for large systems
- believed to be NP hard

Try small A - make direct comparisons
to lattice at moderate to high densities
not necessary to go through S-matrix

Advantages: small boxes give large gaps, high excitation energies
can probe different N, boundary conditions, quantum numbers,…

Can we calibrate nuclear interactions?
Can we extrapolate to matter?
Can we begin to identify the phase transition?

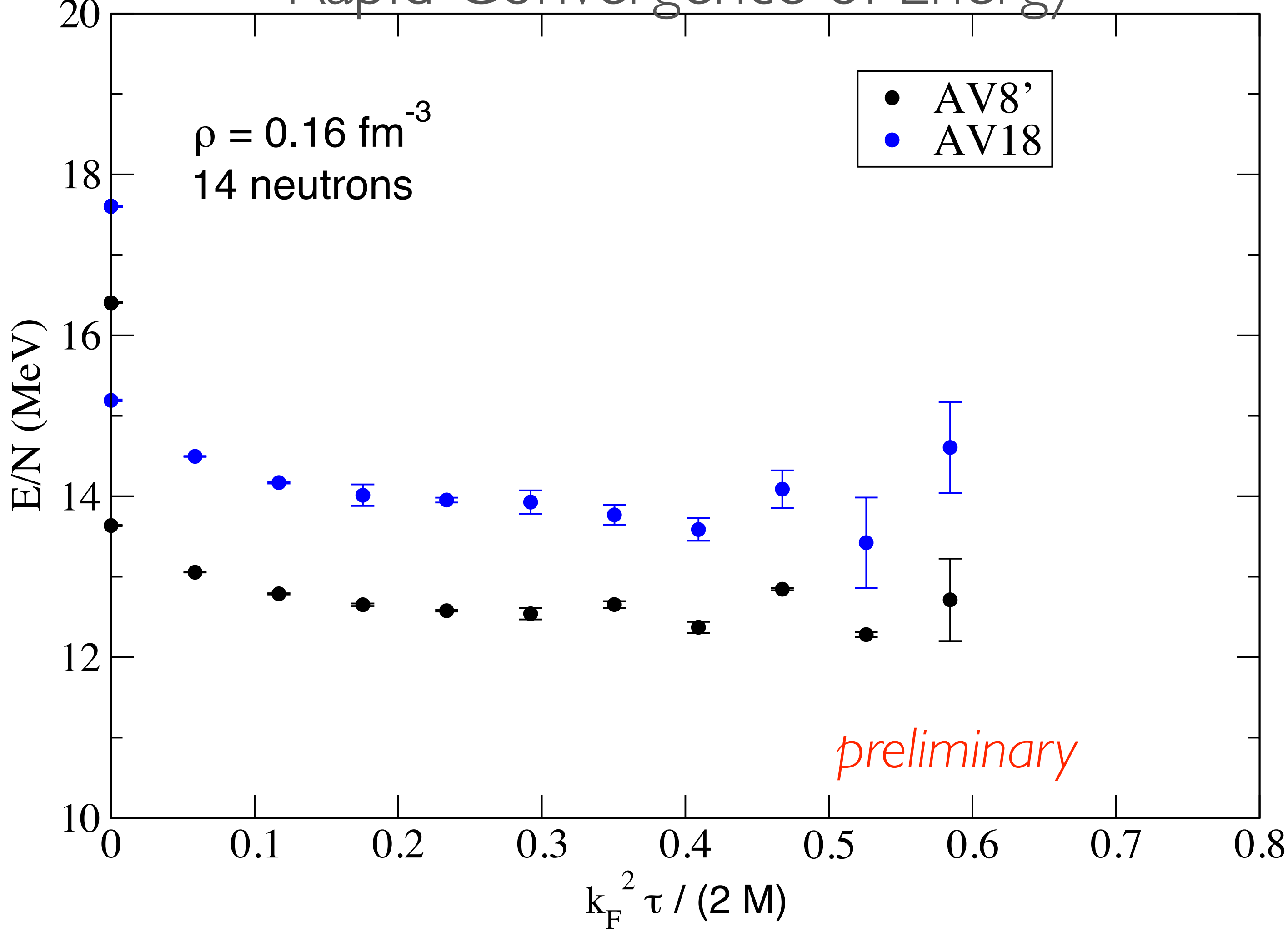
Small quantum systems can identify important degrees of freedom



Gandolfi, Gezerlis, Carlson; Ann. Rev. Nucl. Part. Sci. 65, 303 (2015)

14 Neutrons at Saturation Density w/ PBC:

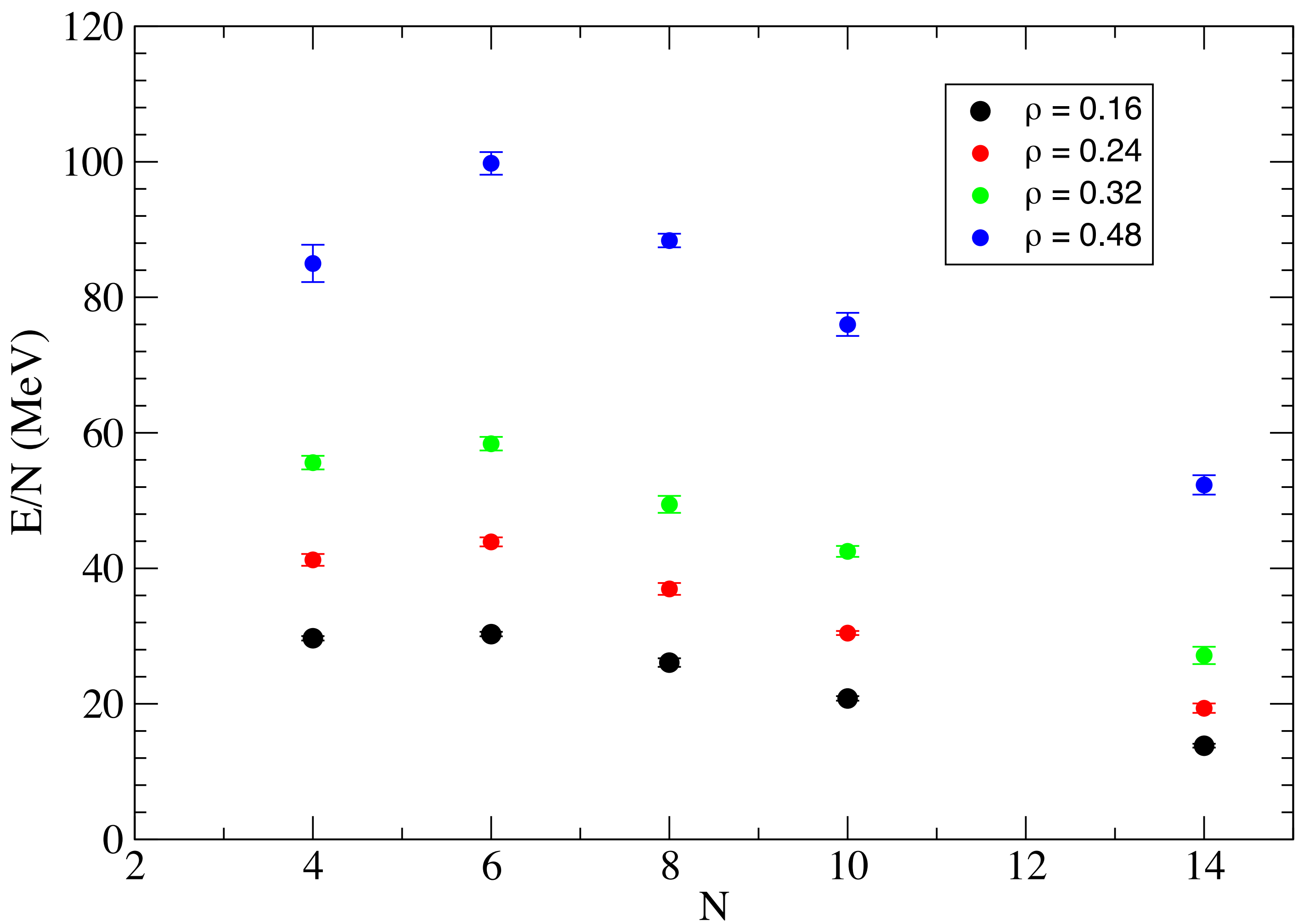
Rapid Convergence of Energy



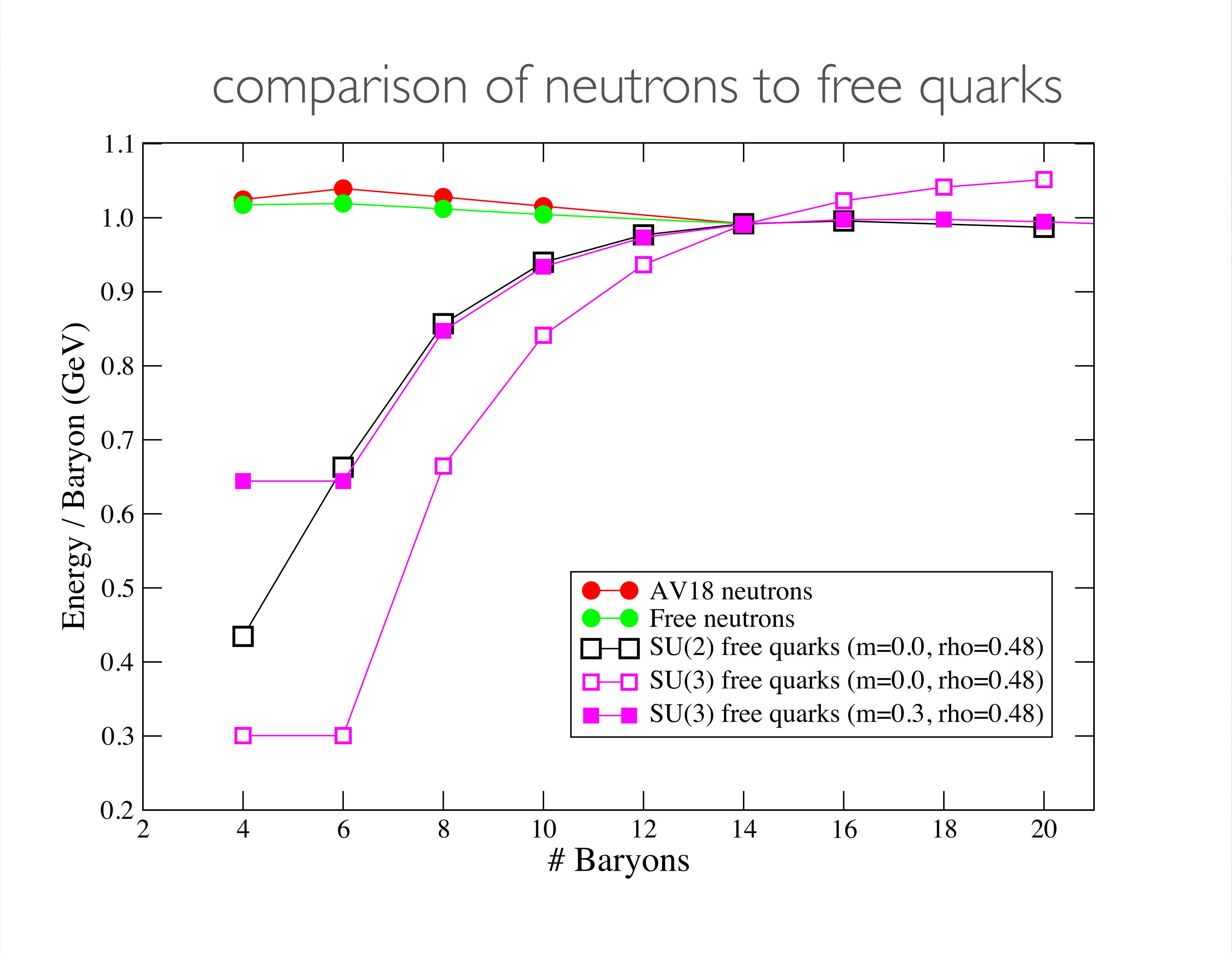
L = 4.4 fm, E_F = 55 MeV, $\Delta \sim 2\ E_F \sim 100$ MeV

Closed shell numbers change with boundary conditions

Neutrons: energies versus N at constant density



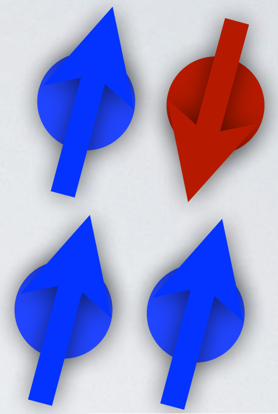
Degrees of freedom can have a huge impact:



P-wave states for N = 4:

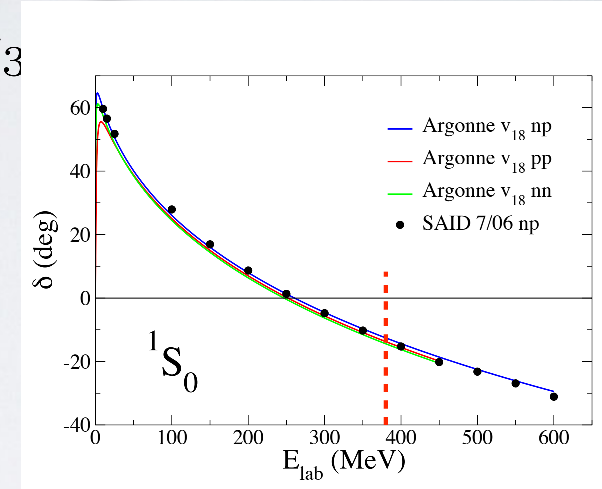
original (BCS s-wave) state:

$$\Phi \;=\; \mathcal{A}\prod[\phi(\mathbf{r}_{ij})(\uparrow_i\downarrow_j - \downarrow_i\uparrow_j)]$$

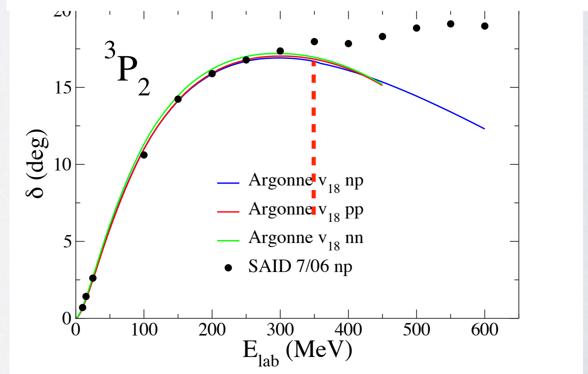


new (p-wave) state:

$$\Phi \;=\; \mathcal{A}[\uparrow_1\downarrow_2\,[\sin[k_x\cdot\mathbf{r}_{34}] + i\sin[k_y\cdot\mathbf{r}_{34}]]\uparrow_3$$



rho	E_s (MeV)	E_p (MeV)
0.08	71.0(.5)	65.0(.5)
0.16	117(2)	92.0(1.2)



25 MeV difference at saturation density

L ~ 3 fm, level spacing ~ 100 MeV

very large energy differences; still exploring other states

Conclusions: Neutron Matter

Want to determine the QCD EOS at high density and low T

Low density regime well constrained

More precise knowledge at saturation density required

Phase transitions - what densities in relation to neutron stars ?

Want to understand properties of neutron stars / supernovae

EOS at zero and finite T

Weak rates and neutron star cooling

Neutrinos in supernovae (quantum coherence /matter)

Critical role of observations:

x-rays

neutrinos

gravitational waves

. . .