The EOS of neutron matter, symmetry energy, and the effect of Λ hyperons to neutron star structure

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NUCLEI Nuclear Computational Low-Energy Initiative

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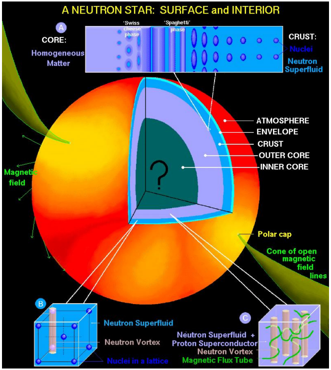
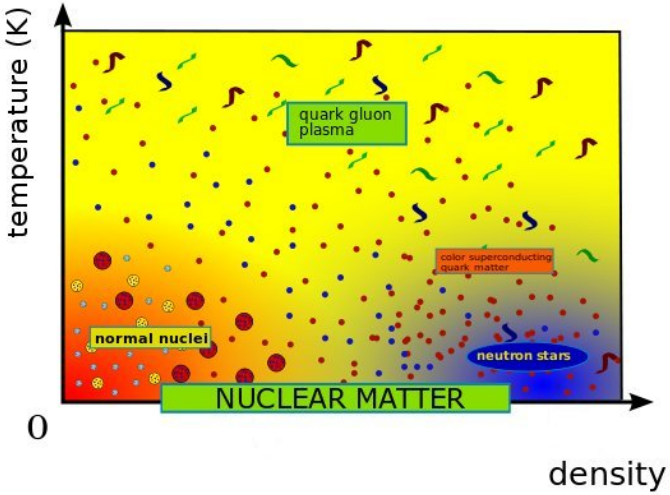
Neutron star is a wonderful natural laboratory



D. Page

- Atmosphere: atomic and plasma physics
- Crust: physics of superfluids (neutrons, vortex), solid state physics (nuclei)
- Inner crust: deformed nuclei, pasta phase
- Outer core: nuclear matter
- Inner core: hyperons? quark matter? π or K condensates?

Homogeneous neutron matter



Outline

- The model and the method
- Equation of state of neutron matter, role of three-neutron force
- Symmetry energy
- Neutron star structure
- Λ-neutron matter
- Conclusions

Nuclear Hamiltonian

Model: non-relativistic nucleons interacting with an effective nucleon-nucleon force (NN) and three-nucleon interaction (TNI).

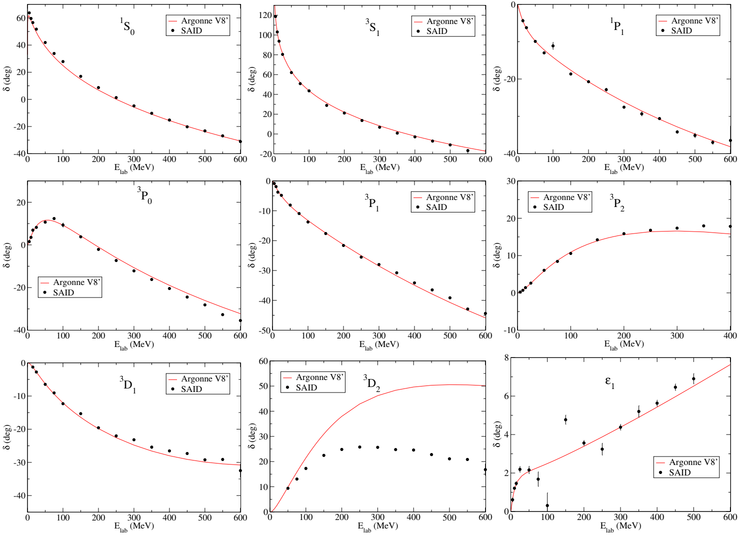
$$H = -\frac{\hbar^2}{2m}\sum_{i=1}^{A}\nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

v_{ij} NN fitted on scattering data. Sum of operators:

$$v_{ij} = \sum O_{ij}^{p=1,8} v^p(r_{ij}) \,, \quad O_{ij}^p = (1, \vec{\sigma}_i \cdot \vec{\sigma}_j, S_{ij}, \vec{L}_{ij} \cdot \vec{S}_{ij}) \times (1, \vec{\tau}_i \cdot \vec{\tau}_j)$$

NN interaction - Argonne AV8'.

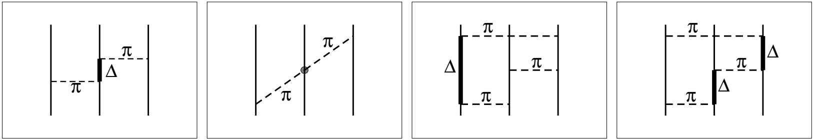
Phase shifts, AV8'



At $\rho = \rho_0$, $k_F \simeq 330$ MeV. Two neutrons have $E_{CM} \simeq 120$ MeV, $E_{LAB} \simeq 240$ MeV. $\rightarrow$ Argonne NN accurate up to (at least) 2-3ρ_0.

Three-body forces

Urbana–Illinois V_{ijk} models processes like



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

Quantum Monte Carlo

$$H\,\psi(\vec{r}_1\ldots\vec{r}_N) = E\,\psi(\vec{r}_1\ldots\vec{r}_N) \qquad \psi(t) = e^{-(H-E_T)t}\psi(0)$$

Ground-state extracted in the limit of $t \to \infty$.

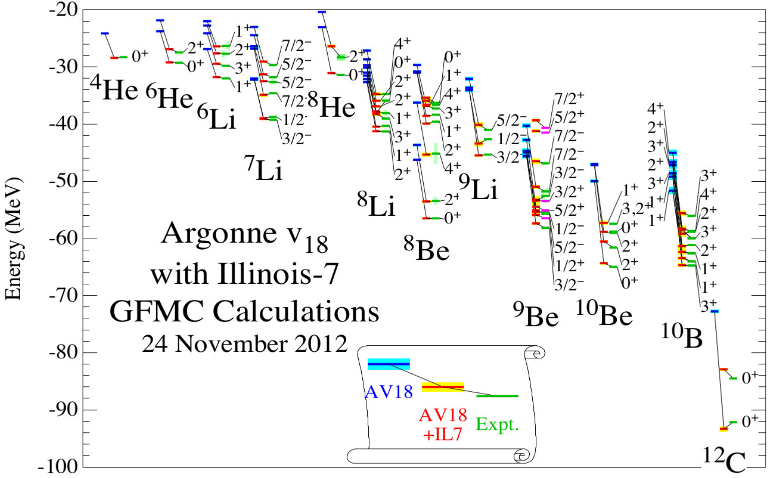
Propagation performed by

$$\psi(R,t) = \langle R|\psi(t)\rangle = \int dR'\,G(R,R',t)\psi(R',0)$$

- Importance sampling: $G(R,R',t) \to G(R,R',t)\,\Psi_I(R')/\Psi_I(R)$
- Constrained-path approximation to control the sign problem.

Ground–state obtained in a **non-perturbative way.** Systematic uncertainties within 1-2 %.

Light nuclei spectrum computed with GFMC



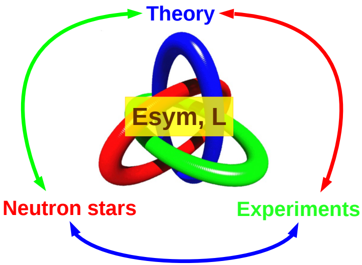
Carlson, Pieper, Wiringa, many papers

Neutron matter equation of state

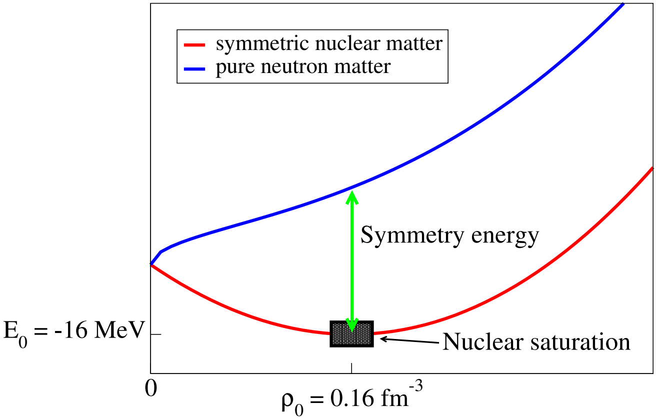
Why to study neutron matter at nuclear densities?

- EOS of neutron matter gives the symmetry energy and its slope.
- The three-neutron force ($T = 3/2$) very weak in light nuclei, while $T = 1/2$ is the dominant part. No direct $T = 3/2$ experiments available.

Why to study symmetry energy?



What is the Symmetry energy?



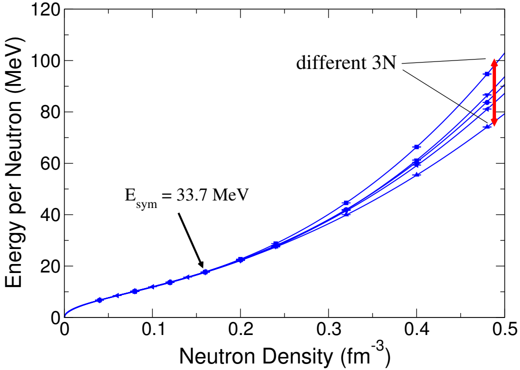
Assumption from experiments:

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

At ρ_0 we access E_{sym} by studying PNM.

Neutron matter

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

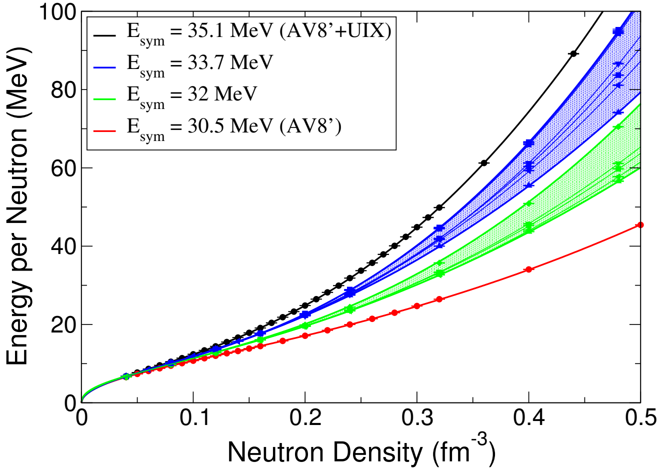


different 3N:

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

Neutron matter

Equation of state of neutron matter using Argonne forces:

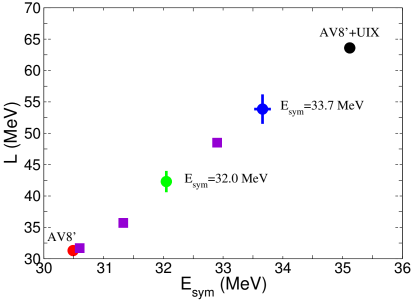


Gandolfi, Carlson, Reddy, PRC (2012)

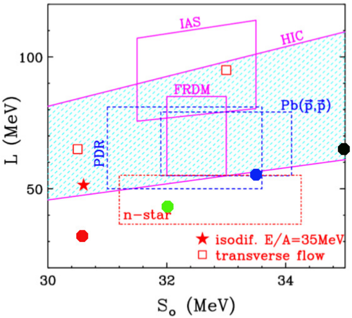
Neutron matter and symmetry energy

From the EOS, we can fit the symmetry energy around ρ_0 using

$$E_{sym}(\rho) = E_{sym} + \frac{L}{3}\frac{\rho - 0.16}{0.16} + \cdots$$



Gandolfi *et al.*, EPJ (2014)

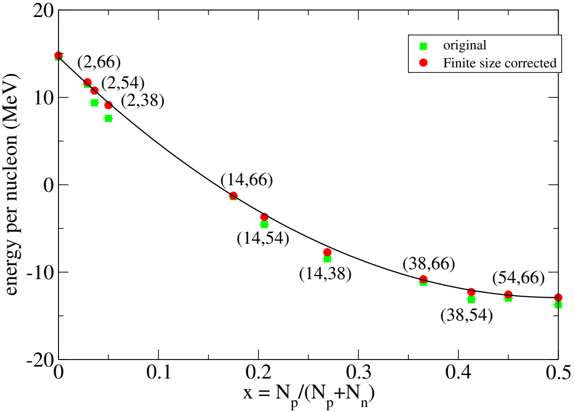


Tsang *et al.*, PRC (2012)

Very weak dependence to the model of 3N force for a given E_{sym}.
Chiral Hamiltonians give compatible results.

Nuclear matter

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



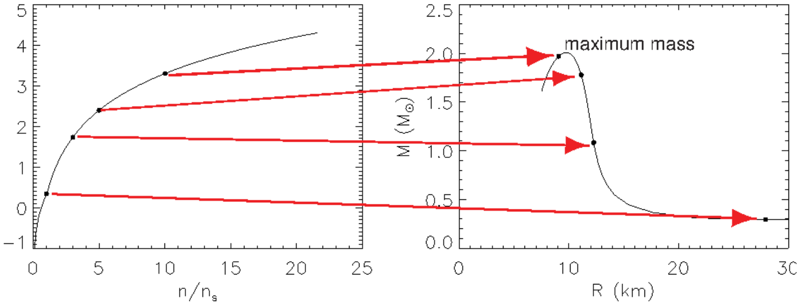
Gandolfi, Lovato, Carlson, Schmidt, arXiv:1406.3388

Quadratic dependence to isospin-asymmetry look fine.

TOV equations:

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

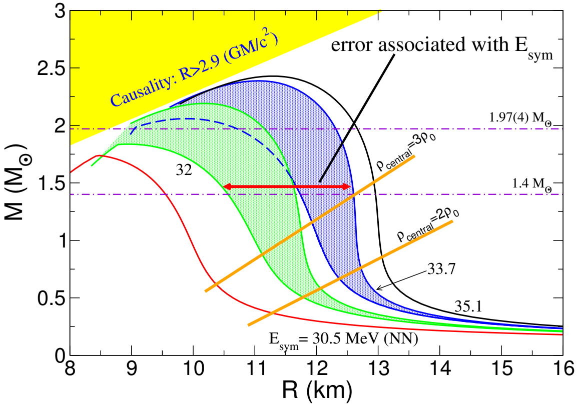
$$\frac{dm(r)}{dr} = 4\pi\epsilon r^2 \,,$$



J. Lattimer

Neutron star structure

EOS used to solve the TOV equations.

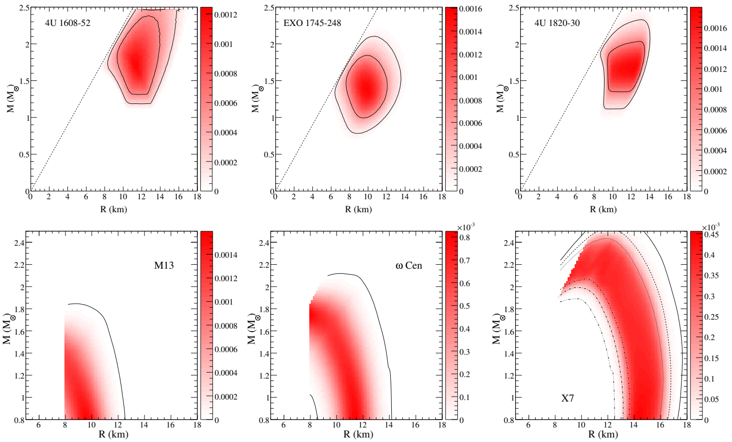


Gandolfi, Carlson, Reddy, PRC (2012).

Accurate measurement of E_{sym} put a constraint to the radius of neutron stars, **OR** observation of M and R would constrain E_{sym}!

Neutron stars

Observations of the mass-radius relation are becoming available:



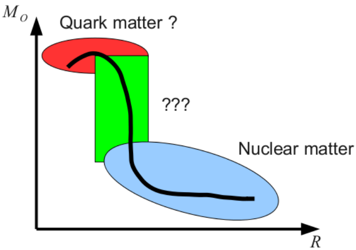
Steiner, Lattimer, Brown, ApJ (2010)

Neutron star observations can be used to 'measure' the EOS and constrain E_{sym} and L.

Neutron star matter

Neutron star matter model:

$$E_{NSM} = a\left(\frac{\rho}{\rho_0}\right)^{\alpha} + b\left(\frac{\rho}{\rho_0}\right)^{\beta}, \quad \rho < \rho_t$$



(form suggested by QMC simulations),

and a high density model for $\rho > \rho_t$

i) two polytropes

ii) polytrope+quark matter model

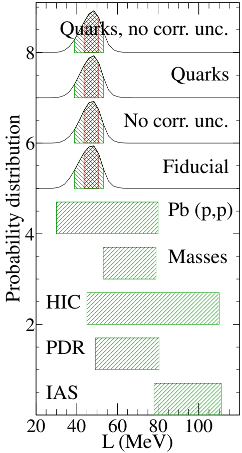
Neutron star radius sensitive to the EOS at nuclear densities!

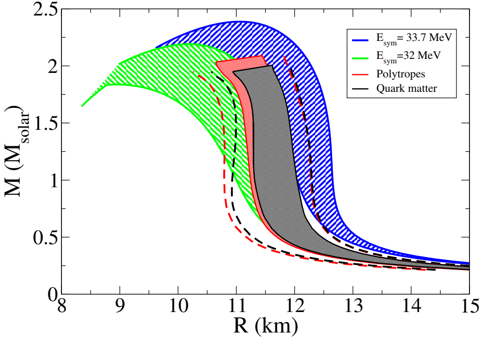
Direct way to extract E_{sym} and L from neutron stars observations:

$$E_{sym} = a + b + 16\,, \quad L = 3(a\alpha + b\beta)$$

Neutron star matter really matters!

Here an 'astrophysical measurement'





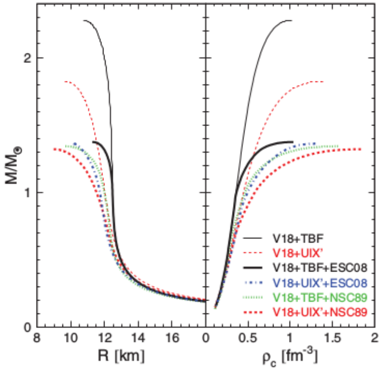
$32 < E_{sym} < 34\ MeV,\ 43 < L < 52\ MeV$

Steiner, Gandolfi, PRL (2012).

High density neutron matter

If chemical potential large enough, heavier particles form, i.e. Λ, Σ, ...

Non-relativistic BHF calculations suggest that none of the available hyperon-nucleon Hamiltonians support an EOS with $M > 2M_\odot$:

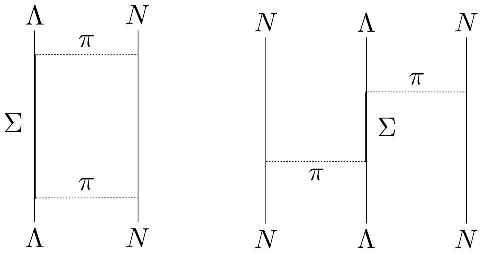


Schulze and Rijken PRC (2011).

(Some) other relativistic model support $2M_\odot$ neutron stars.

ΛN and ΛNN interactions

ΛNN has the same range of ΛN

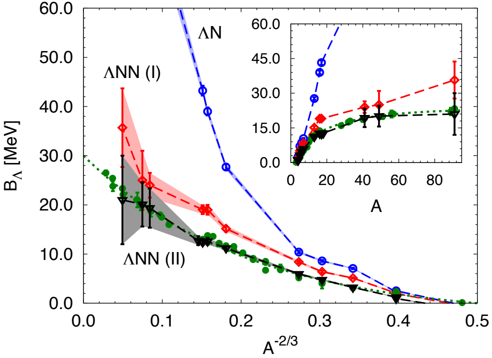


But, three-body interactions are not included in non-relativistic calculations!

Hypernuclei and hypermatter:

$$H = H_N + \frac{\hbar^2}{2m_\Lambda}\sum_{i=1}^{A}\nabla_i^2 + \sum_{i<j} v_{ij}^{\Lambda N} + \sum_{i<j<k} V_{ijk}^{\Lambda NN}$$

$v^{\Lambda N}$ and $V^{\Lambda NN}$ are phenomenological (Usmani).



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

$V^{\Lambda NN}$ (II) is a new form where the parameters have been fine tuned.

As expected, the role of ΛNN is crucial.

Hyper-neutron matter

Neutrons and Λ particles:

$$\rho = \rho_n + \rho_\Lambda \,, \qquad\qquad x = \frac{\rho_\Lambda}{\rho}$$

$$E_{\rm HNM}(\rho,x) = \Big[E_{\rm PNM}((1-x)\rho)+m_n\Big](1-x)+\Big[E_{\rm P\Lambda M}(x\rho)+m_\Lambda\Big]x+f(\rho,x)$$

where $E_{P\Lambda M}$ is the non-interacting energy (no $v_{\Lambda\Lambda}$ interaction),

$$E_{PNM}(\rho) = a\left(\frac{\rho}{\rho_0}\right)^\alpha + b\left(\frac{\rho}{\rho_0}\right)^\beta$$

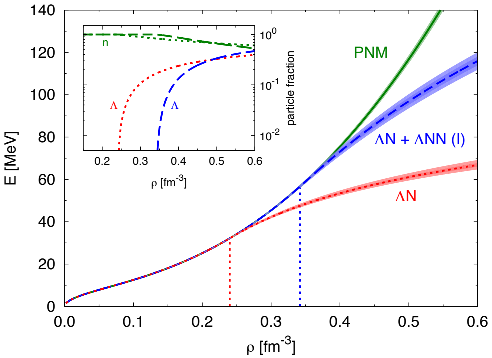
and

$$f(\rho,x) = c_1\frac{x(1-x)\rho}{\rho_0} + c_2\frac{x(1-x)^2\rho^2}{\rho_0^2}$$

All the parameters are fit to AFDMC results.

Λ-neutron matter

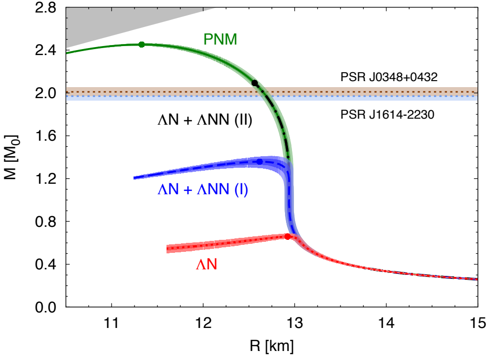
EOS obtained by solving for $\mu_\Lambda(\rho, x) = \mu_n(\rho, x)$



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

No hyperons for ΛNN (II) up to $\rho = 0.5$ fm^{-3}!

Λ-neutron matter



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

Drastic role played by ΛNN. Calculations compatible with neutron star observations.

Note: no $v_{\Lambda\Lambda}$, no protons, and no other hyperons included

Summary

QMC methods useful to study nuclear systems in a coherent framework:

- Three-neutron force is the bridge between E_{sym} and neutron star structure.
- Neutron star observations becoming competitive with experiments.

  Can we use observations with current uncertainties to constrain nuclear interactions?
- Λ-nucleon data very limited. Role of Λ in neutron stars far to be understood. Input from Lattice QCD?

  Conclusion? We cannot conclude anything with present models...

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