Nuclear matter calculations with modern microscopic interactions

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Frascati

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- A study of nuclear matter with modern chiral interactions...

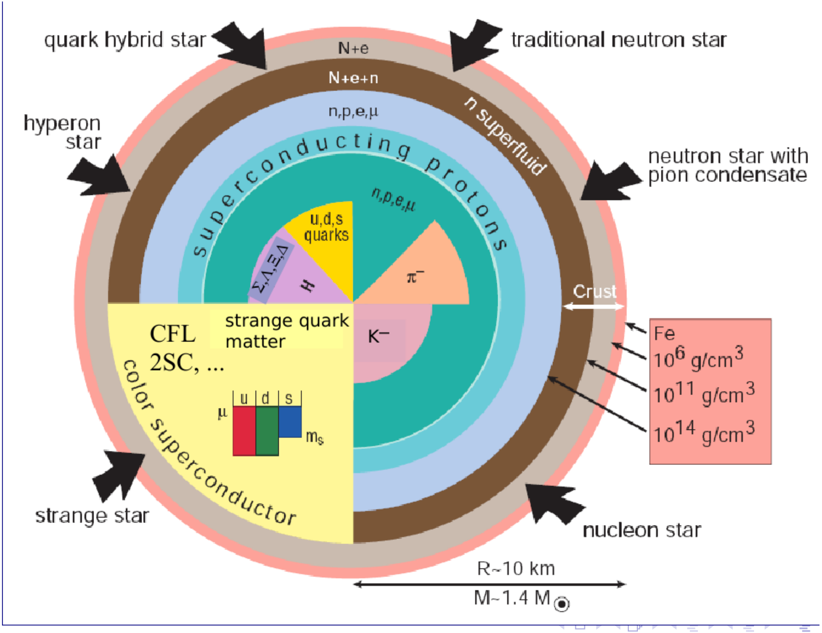
why?

1) Strongly correlated to the physics of neutron reach nuclei

2) Symmetry energy

3) Astrophysical systems: neutron stars

Neutron stars



- We need an equation of state (EOS): $P = P(\rho)$ and $P = P(\epsilon)$

$$\Downarrow$$

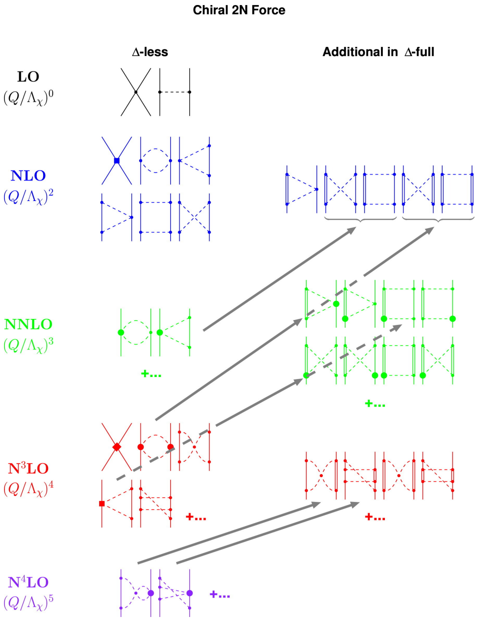
We use the microscopic Brueckner-Hartree-Fock approach
$\Rightarrow$ input: NN and NNN forces (no free parameters)

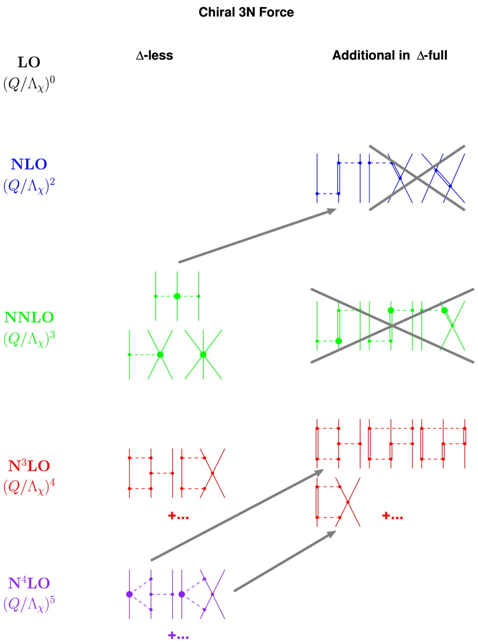
Neutron stars structure $\Rightarrow$ TOV equations

Equations of hydrostatic equilibrium in general relativity of Tolman-Oppenheimer-Volkoff (TOV):

$$\frac{dP}{dr} = -\frac{G\rho m}{r^2}\left(1 + \frac{P}{\rho c^2}\right)\left(1 + \frac{4\pi P r^3}{mc^2}\right)\left(1 - \frac{2Gm}{rc^2}\right)^{-1},$$

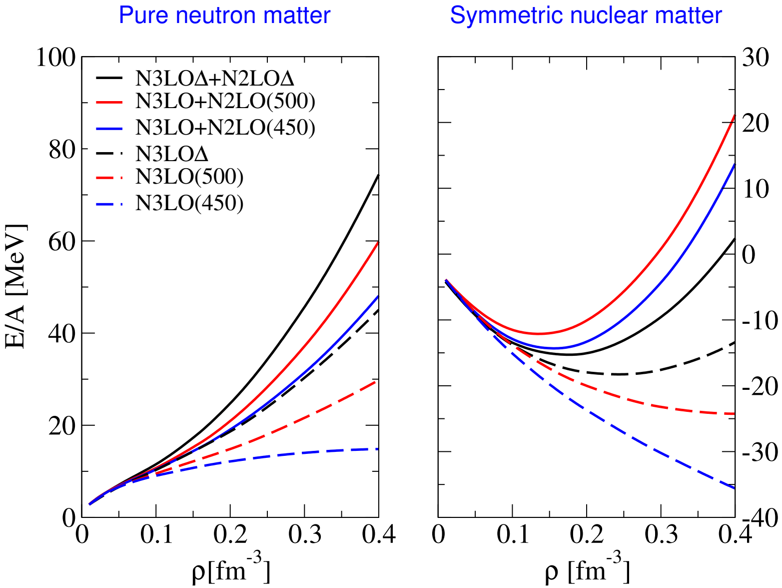
$$\frac{dm(r)}{dr} = 4\pi r^2 \rho \, .$$


Chiral 2N Force
Δ-less
Additional in Δ-full
LO
$(Q/\Lambda_\chi)^0$
NLO
$(Q/\Lambda_\chi)^2$
NNLO
$(Q/\Lambda_\chi)^3$
+...
+...
N^{3}LO
$(Q/\Lambda_\chi)^4$
+...
+...
N^{4}LO
$(Q/\Lambda_\chi)^5$
+...


Chiral 3N Force
Δ-less
Additional in Δ-full
LO
$(Q/\Lambda_\chi)^0$
NLO
$(Q/\Lambda_\chi)^2$
NNLO
$(Q/\Lambda_\chi)^3$
N^3LO
$(Q/\Lambda_\chi)^4$
+...
+...
N^4LO
$(Q/\Lambda_\chi)^5$
+...

- NN potentials: non local N3LO (Idaho-2003), minimal local N3LOΔ (M. Piarulli-2014)
- N3LO (Idaho-2003) $\Rightarrow$ in $\mathcal{L}$ included N, π
- N3LOΔ (M. Piarulli-2014) $\Rightarrow$ in $\mathcal{L}_{eff}$ included N, π and Δ
- NNN potential: N2LO and N2LOΔ (E. Epelbaum 2002)
- When possible, parameters of NNN force fixed in few-body calculations of light nuclei $\Rightarrow$ no free parameters

E/A nuclear matter N3LO+N2LO



Logoteta et al. to be published in Phys. Rev. C

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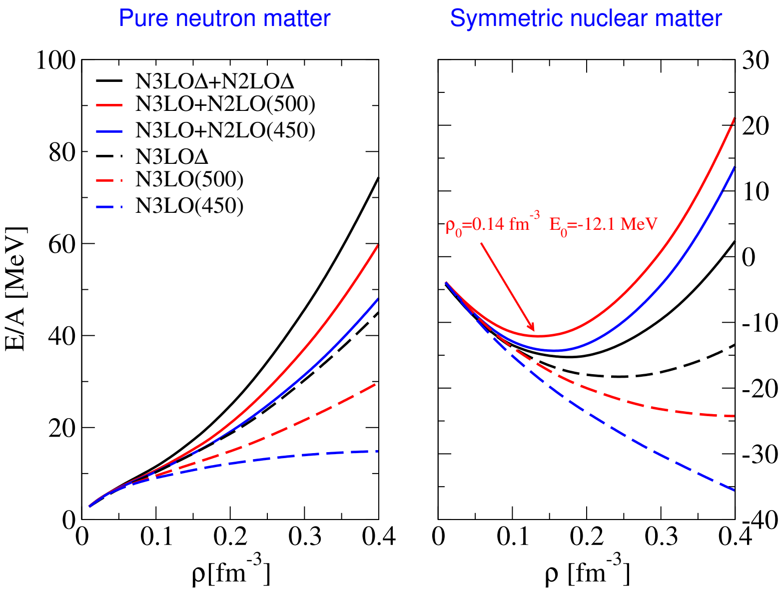

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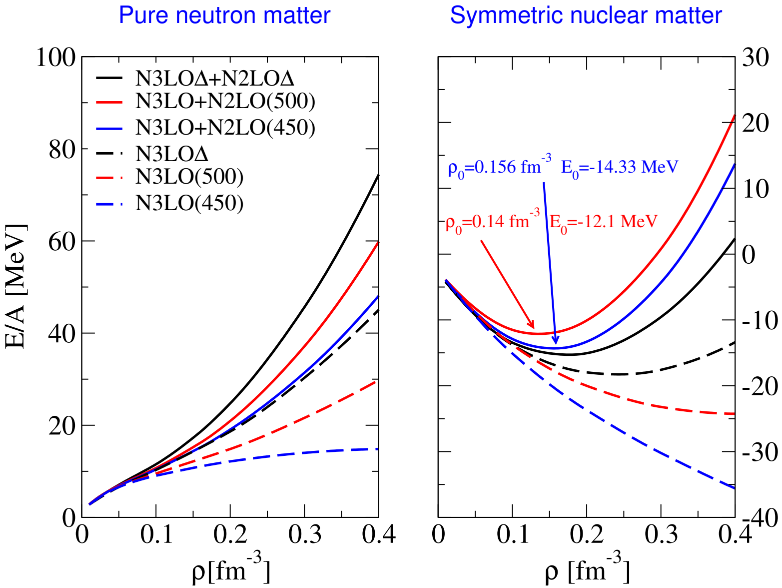

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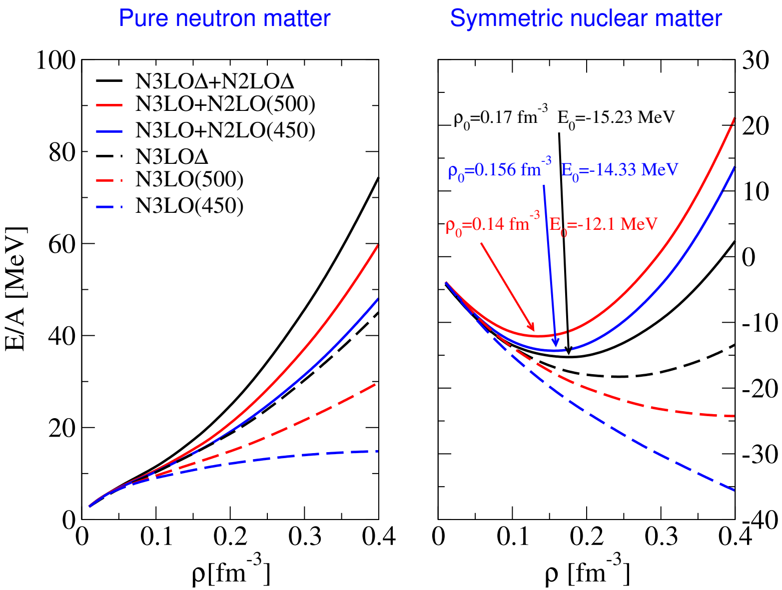

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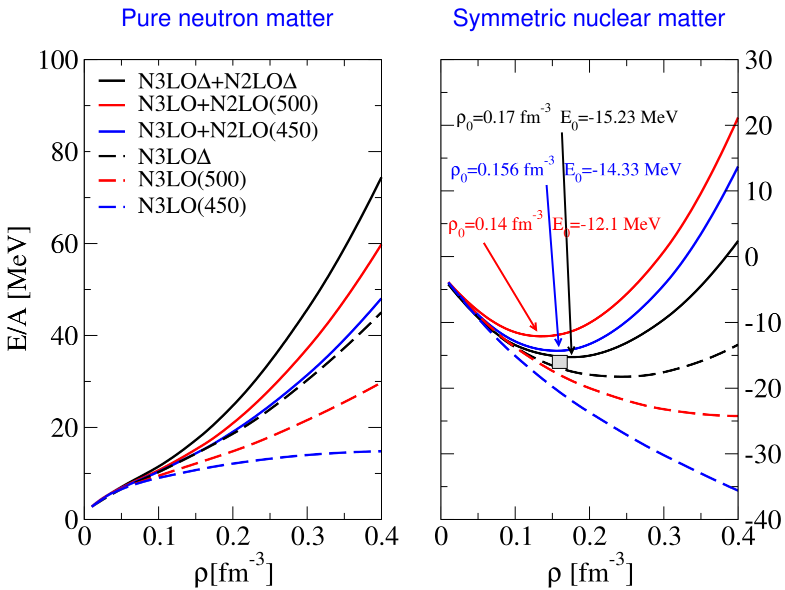

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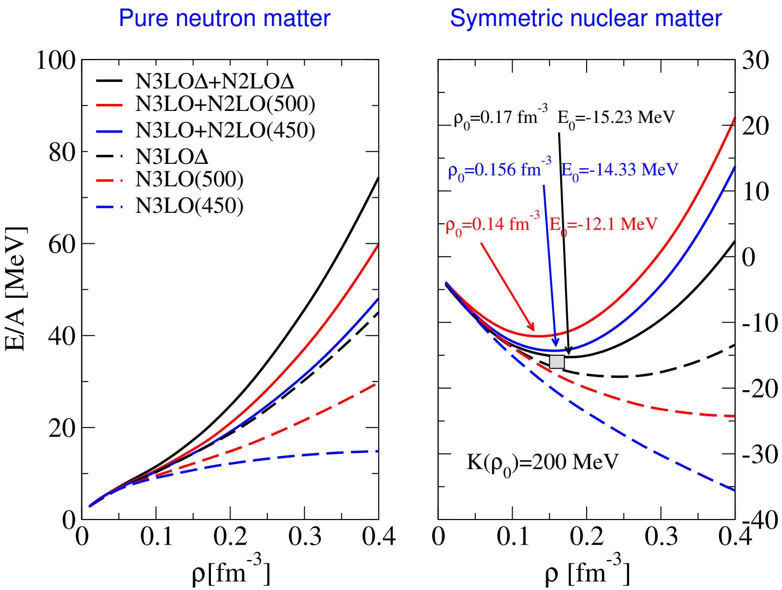

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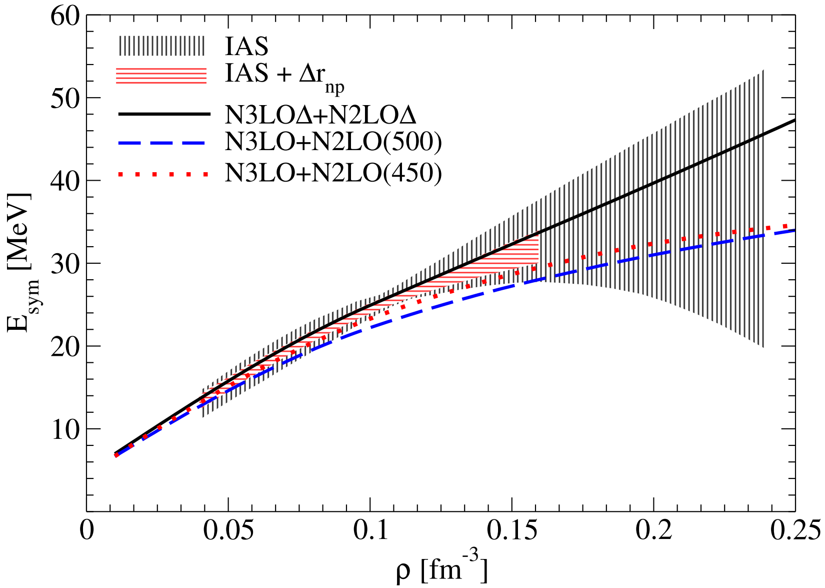
Symmetry energy N3LO+N2LO



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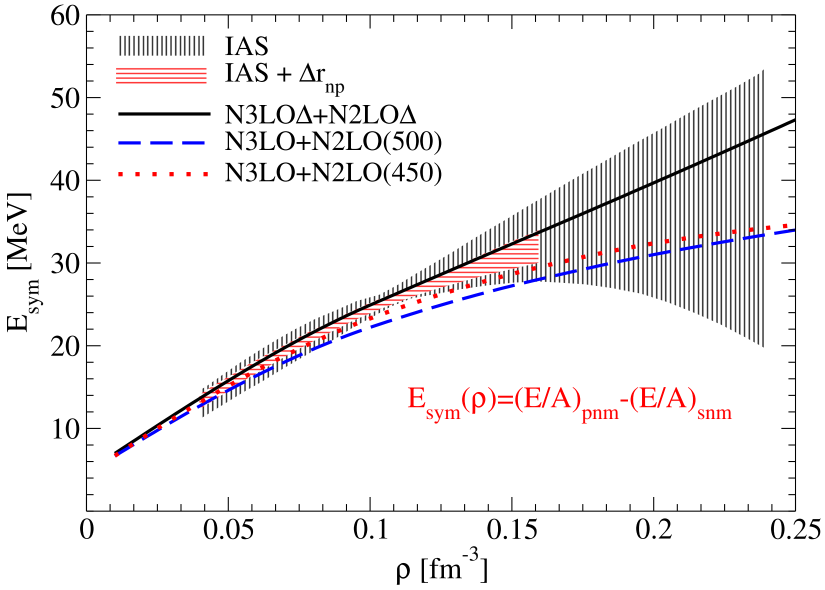
Symmetry energy N3LO+N2LO



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- Asymmetric matter $\Rightarrow$ parabolic approximation:

$$E/A(\beta,\rho) = (E/A(\rho))_{snm} + (E/A(\rho))_{sym}\beta^2 \qquad \beta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

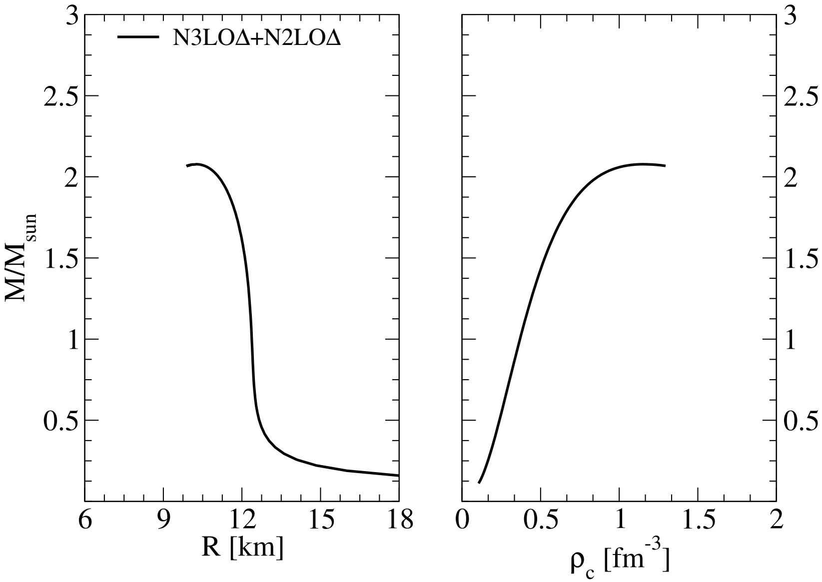
$$\mu_i = \frac{\partial(\rho E/A(\beta,\rho))}{\partial \rho_i} \qquad \rho = \rho_n + \rho_p$$

- Chemical equilibrium:

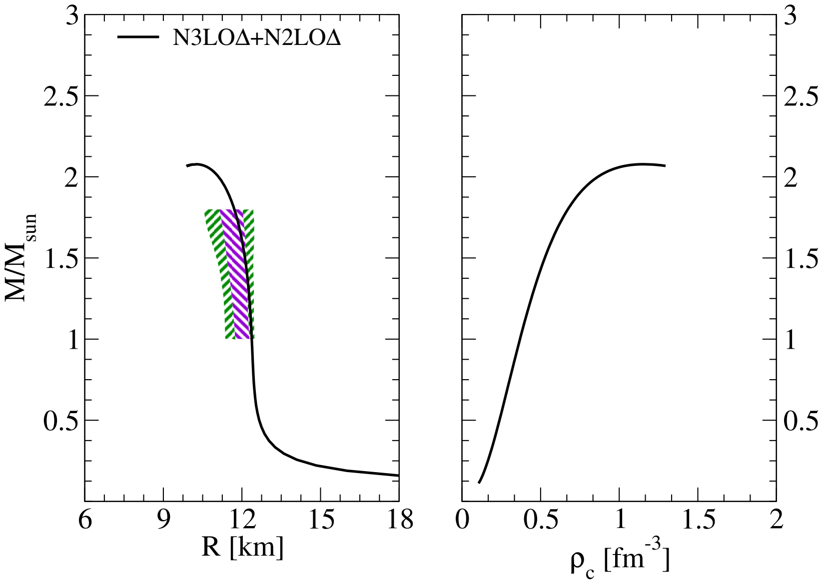
$$\mu_n - \mu_p = \mu_e \qquad \mu_e = \mu_\mu .$$

- Charge neutrality:

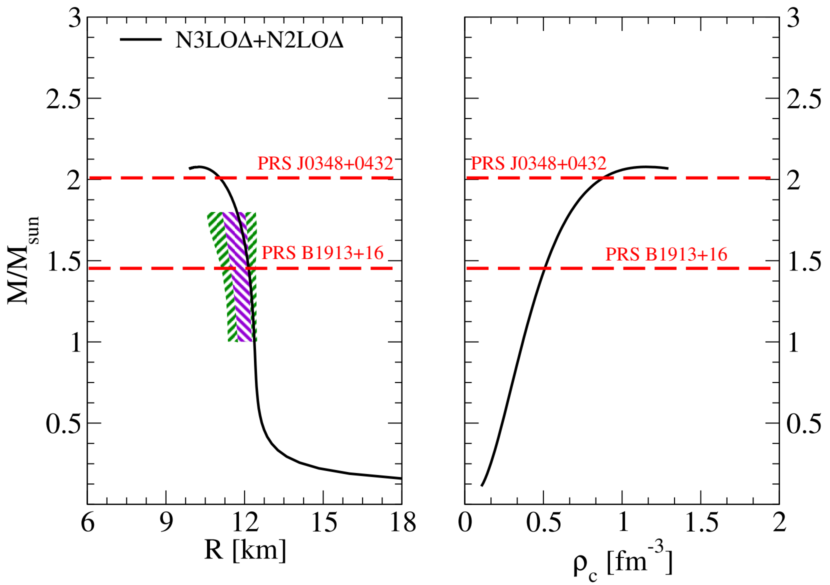
$$n_p - n_\mu - n_e = 0\,.$$


N3LOΔ+N2LOΔ
M/M_sun
R [km]
ρ_c [fm^-3]
0.5
1
1.5
2
2.5
3
6
9
12
15
18
0
0.5
1
1.5
2

Neutron stars based on N3LOΔ+N2LOΔ



Neutron stars based on N3LOΔ+N2LOΔ



- Microscopic calculations of nuclear matter based on realistic interaction can help us to understand discrepancies between many-body and few-body nuclear physics.

- New generation of interactions based on chiral perturbation theory provide realistic results in nuclear matter $\Rightarrow$ interesting connection to neutron stars.

- ...but...what is the three-hole-lines contribution considering chiral interactions?

- ...then $\Rightarrow$ study of hyperonic matter based on chiral forces.

$$\Downarrow$$

- Problem of maximum mass of neutron stars with hyperons.

Thank you!

The Brueckner-Hartree-Fock approach

- Starting point: the Bethe-Goldstone equation

$$G(\omega)_{B_1B_2,B_3B_4} = V_{B_1B_2,B_3B_4} + \sum_{B_iB_j} V_{B_1B_2,B_iB_j} \times \frac{Q_{B_iB_j}}{\omega - E_{B_i} - E_{B_j} + i\eta} G(\omega)_{B_iB_j,B_3B_4}$$

$$U_{B_i}(k) = \sum_{B_j} \sum_{\vec{k'}} n_{B_j}(|\vec{k'}|) \times \langle \vec{k}\vec{k'} | G(E_{B_i}(\vec{k}) + E_{B_j}(\vec{k'}))_{B_iB_j,B_iB_j} | \vec{k}\vec{k'} \rangle_{\mathcal{A}}$$

$$E_{B_i}(k) = M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + U_{B_i}(k)$$

$$\epsilon_{BHF} = \frac{1}{V} \sum_{B_i} \sum_{k \leq k_{F_i}} \left[M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + \frac{1}{2} U_{B_i}(k) \right]$$

- BHF calculations with NNN forces $\Rightarrow$ too complicated

$$\Downarrow$$

- NNN force is reduced to a NN density dependent one
- In p-space:

$$W_{eff}(1,2) = Tr_{\sigma_3 \tau_3} \int dp_3 \sum_{cyc} W(1,2,3)\, n(3)(1 - P_{13} - P_{23})$$

Momentum space average of N2LO TBF