Nuclear matter calculations with new chiral interactions

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Pisa

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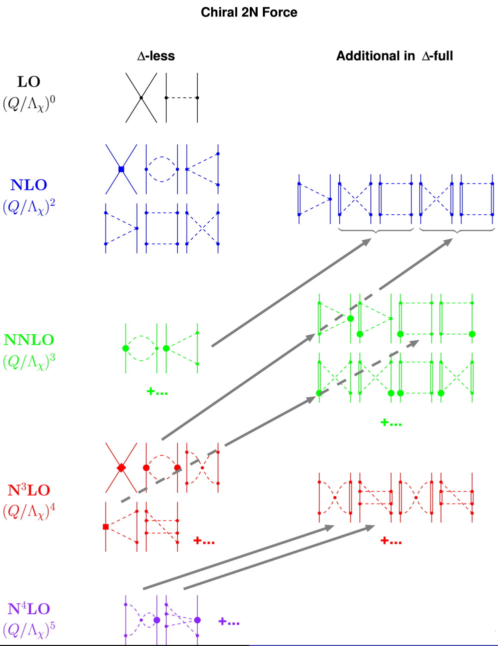
Outline

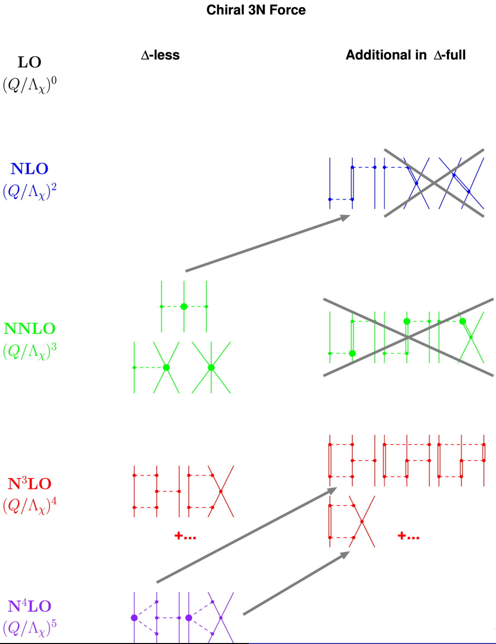
- Chiral interactions
- The Brueckner-Hartree-Fock approach in nuclear matter
- Conclusions

- V_{lowk}-approach:
  K. Hebeler and A. Schwenk, Phys. Rev. C **82**, 014314 (2010).
  K. Hebeler, S. K. Bogner, R. J. Furnstahl, A. Nogga and A. Schwenk, Phys. Rev. C **83**, (2011) 031301(R).
- Green's function:
  A. Carbone, A. Polls and A. Rios Phys. Rev. C **88**, (2013) 044302.
- Monte Carlo:
  S. Gandolfi, A. Lovato, J. Carlson, Kevin E. Schmidt, Phys. Rev. C **90**, 061306 (2014).
- Brueckner-Hartree-Fock:
  L. Coraggio, J. W. Holt, N. Itaco, R. Machleidt, L. E. Marcucci and F. Sammarruca, Phys Rev. C **89**, (2014) 044321.
  M. Kohno, Phys. Rev. C **88**, 064005 (2013).
  F. Sammarruca, L. Coraggio, J.W. Holt, N. Itaco, R. Machleidt, L. E. Marcucci, Phys. Rev. C **91**, 054311 (2015).
  D. Logoteta, I. Vidaña, I. Bombaci and A. Kievsky Phys. Rev. C 91, 064001 (2015).
  D. Logoteta, I. Bombaci and A. Kievsky PoS (CD15) 111 (2016).
  D. Logoteta, I. Bombaci and A. Kievsky submitted to PLB.

Chiral forces NN



Chiral forces NNN



- 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 $\mathcal{L}$ included N, π and Δ
- Optimized N2LO (N2LO$_{sat}$) (A. Ekstrom 2015) $\Rightarrow$ global fit including: NN scattering data, B. E. and radii of light nuclei and selected isotopes of oxygen and carbon
- NNN potential: local N2LO (P. Navratil 2007) and non local (E. Epelbaum 2002)
- When possible, parameters of NNN force fixed in few-body calculations of light nuclei $\Rightarrow$ no free parameters

The Brueckner-Hartree-Fock approach

- Starting point: the Bethe-Goldstone equation

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

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

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

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

- BHF calculations with NNN forces

NNN forces in the BHF-approach

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

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$$\Downarrow$$

- NNN force is reduced to a NN density dependent one

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$\Downarrow$

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

$$W_{eff}(1,2) = Tr_{\sigma_3\tau_3} \int dx_3 \sum_{cyc} W(1,2,3)\, n(1,2,3)(1-P_{13}-P_{23}) \;\; (A.\ Lovato\ 2011)$$

- In p-space:

$$W_{eff}(1,2) = Tr_{\sigma_3\tau_3} \int dp_3 \sum_{cyc} W(1,2,3)\, n(1,2,3)(1-P_{13}-P_{23}) \;\; (M.\ Holt\ 2010)$$

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

$$\Downarrow$$

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

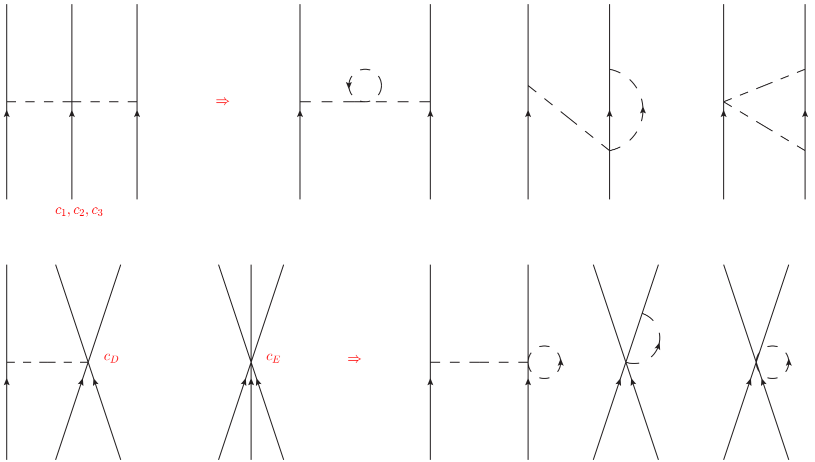
$$W_{eff}(1,2) = Tr_{\sigma_3 \tau_3} \int dx_3 \sum_{cyc} W(1,2,3)\, \eta(1,2,3)(1-P_{13}-P_{23}) \;\; (A.\ Lovato\ 2011)$$

- In p-space:

$$W_{eff}(1,2) = Tr_{\sigma_3 \tau_3} \int dp_3 \sum_{cyc} W(1,2,3)\, n(3)(1-P_{13}-P_{23}) \;\; (M.\ Holt\ 2010)$$

- Usually for $p-$space average $\Rightarrow$ non local cutoff:
  $F_{\Lambda}(p,q) = exp\left(-\frac{4p^2+3q^2}{4\Lambda^2}\right)^n \rightarrow p, q$ Jacobi momenta

Momentum space average of N2LO TBF



Choice of parameters

- Following: L. E. Marcucci, A. Kievsky, S. Rosati, R. Schiavilla and M. Viviani Phys. Rev. Lett. **108**, (2012) 052502.
  L. Coraggio, J. W. Holt, N. Itaco, R. Machleidt, L. E. Marcucci and F. Sammarruca, Phys Rev. C **89**, (2014) 044321.

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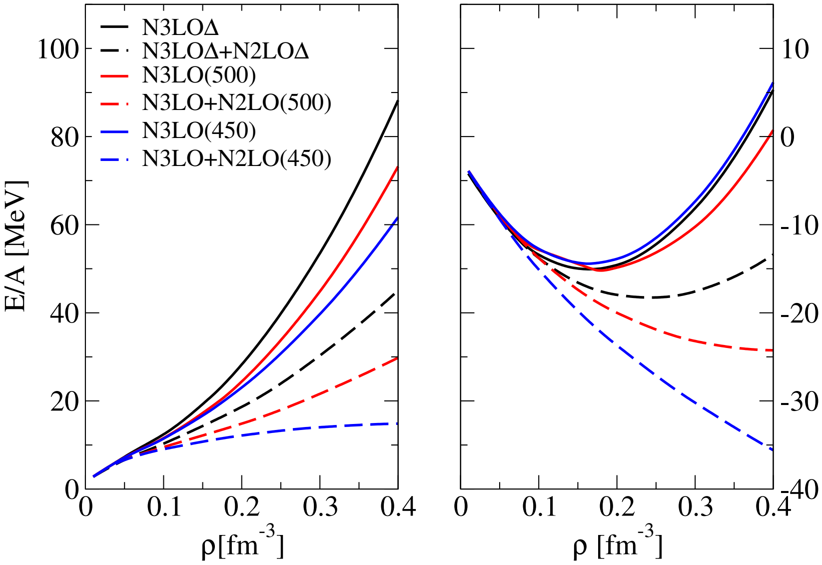
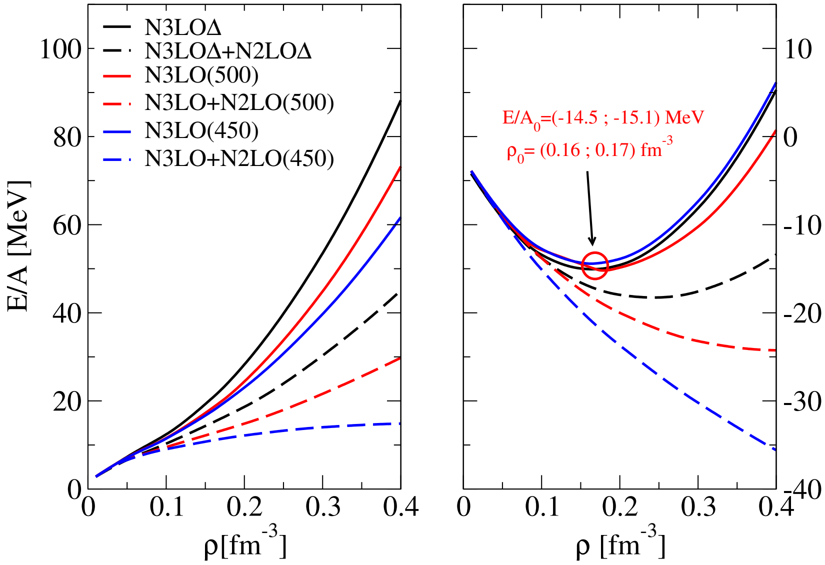
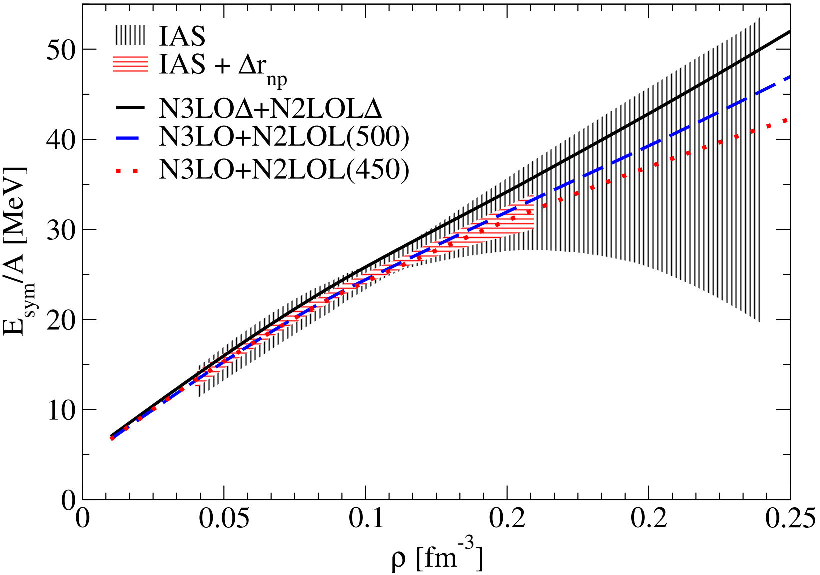
- Low energy constants (c_D, c_E) fixed to reproduce the ^{3}H binding energy + (^{3}H-^{3}He) *GT* transition matrix element.
- In our many-body calculations we use the same cutoff $F_\Lambda(q^2) = e^{-q^4/\Lambda^4}$ (q is the exchanged momentum!) employed in the few-body ones $\Rightarrow$ "almost" fully consistent calculation.
- N3LOΔ+N2LOΔ $\Rightarrow$ still no calculation in light nuclei $\Rightarrow$ fitted to reproduce $(\rho_0, E/A_0)$
- N3LO+N2LO(500) $\Rightarrow$ too attractive in nuclear matter $\Rightarrow$ refitted to reproduce $(\rho_0, E/A_0)$
- N3LO+N2LO(450) $\Rightarrow$ reproduces the ^{3}H binding energy but not (^{3}H-^{3}He) *GT* $\Rightarrow$ provides realistical description of nuclear matter!

E/A nuclear matter N3LO+N2LO

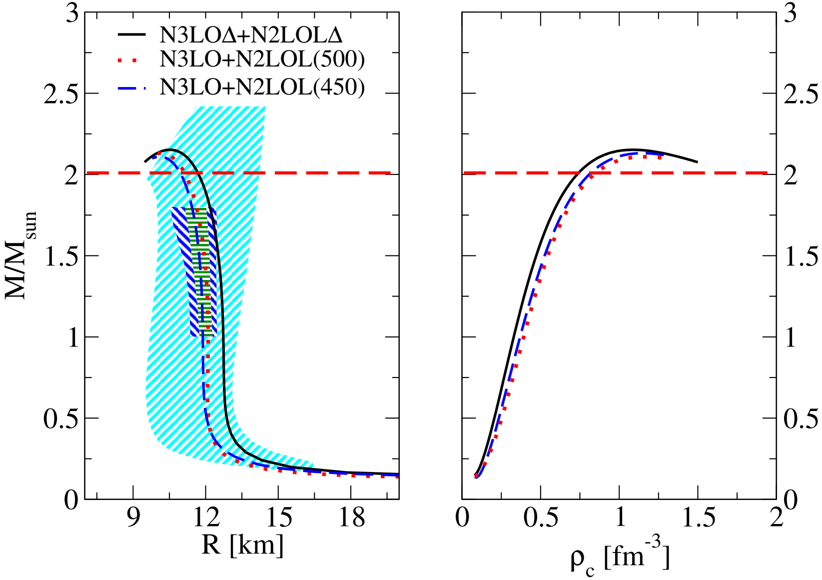



N3LOΔ
N3LOΔ+N2LOΔ
N3LO(500)
N3LO+N2LO(500)
N3LO(450)
N3LO+N2LO(450)
E/A [MeV]
ρ[fm^-3]
E/A_0=(-14.5 ; -15.1) MeV
ρ_0= (0.16 ; 0.17) fm^-3
ρ [fm^-3]

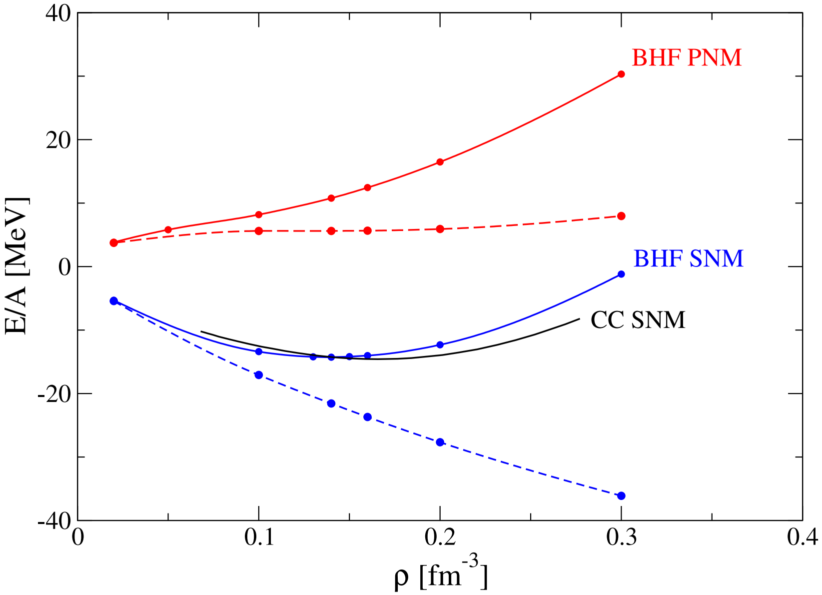
Symmetry energy N3LO+N2LO

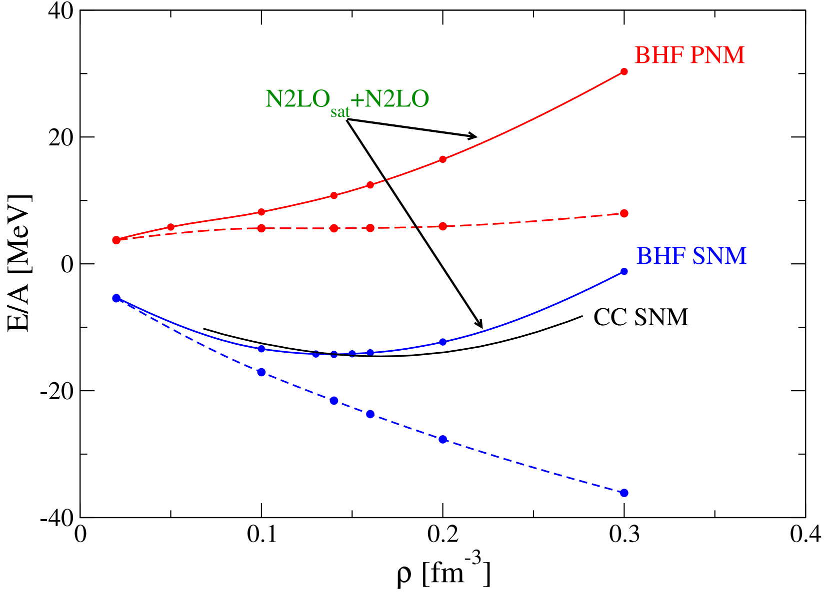


Neutron stars based on N3LO+N2LO

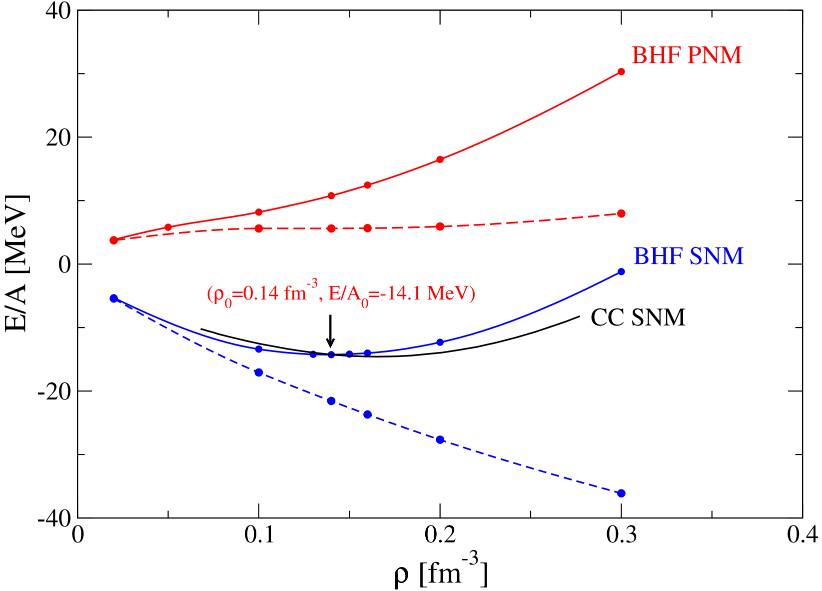


E/A nuclear matter N2LO$_{sat}$+N2LO




BHF PNM
N2LO$_{sat}$+N2LO
BHF SNM
CC SNM
E/A [MeV]
ρ [fm^{-3}]
40
20
0
-20
-40
0
0.1
0.2
0.3
0.4

E/A nuclear matter N2LO$_{sat}$+N2LO



- 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.
- ...however...we have to improve the average procedure
- ...what is the three-hole-lines contribution considering chiral interactions?
- ...then $\Rightarrow$ study of asymmetric and hyperonic matter based on chiral forces.

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- Problem of maximum mass of neutron stars with hyperons.