Nuclear matter calculations with modern chiral interactions

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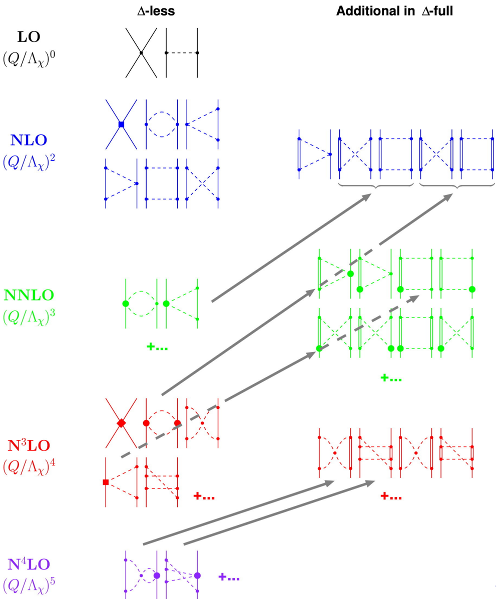
- Chiral interactions
- The Brueckner-Hartree-Fock approach in nuclear matter
- Nuclear matter calculations
- Applications to neutron stars
- Conclusions

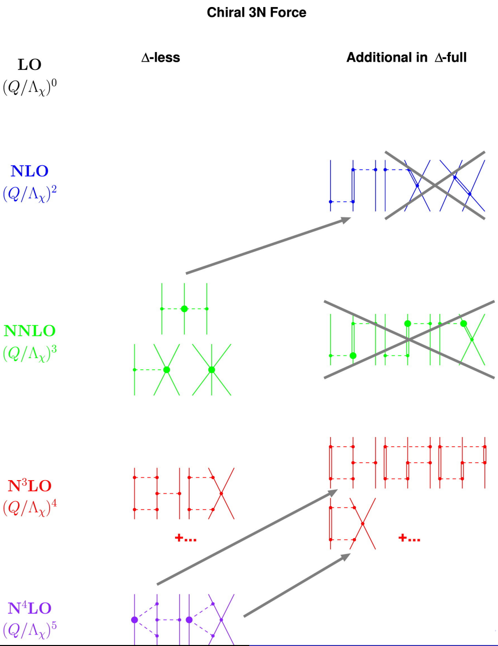
Literature

- Many-body perturbation theory-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:
  F. Sammarruca, L. Coraggio, J.W. Holt, N. Itaco, R. Machleidt, L. E. Marcucci, Phys. Rev. C **91**, 054311 (2015).
  Z. H. Li and H.-J. Schulze, Phys. Rev. C 85, (2012) 064002.
  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 to be published in PLB (2016).

Chiral 2N Force



Chiral forces NNN



- NN potentials: non local N3LO (Idaho-2003), minimal non 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
- 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

- Starting point: the Bethe-Goldstone equation

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

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

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

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

NNN forces in the BHF-approach

- BHF calculations with NNN forces

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

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

NNN forces in the BHF-approach

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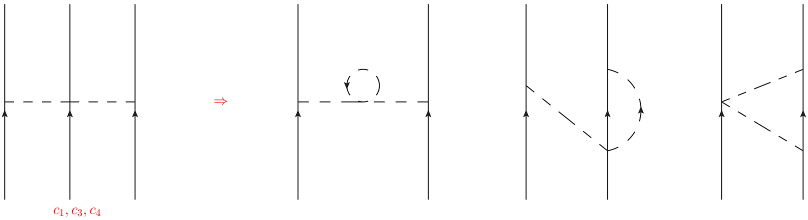
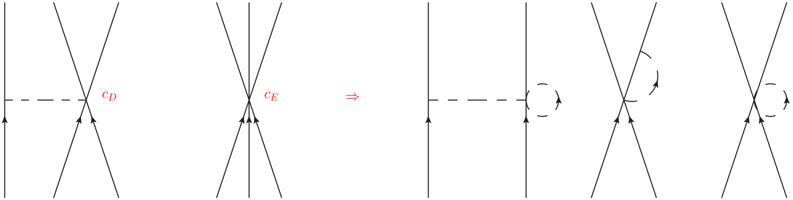
$$W_{eff}(1,2) = Tr_{\sigma_3 \tau_3} \int dp_3 \sum_{cyc} W(1,2,3)\; n(3)(1 - P_{13} - P_{23})$$

- 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





- 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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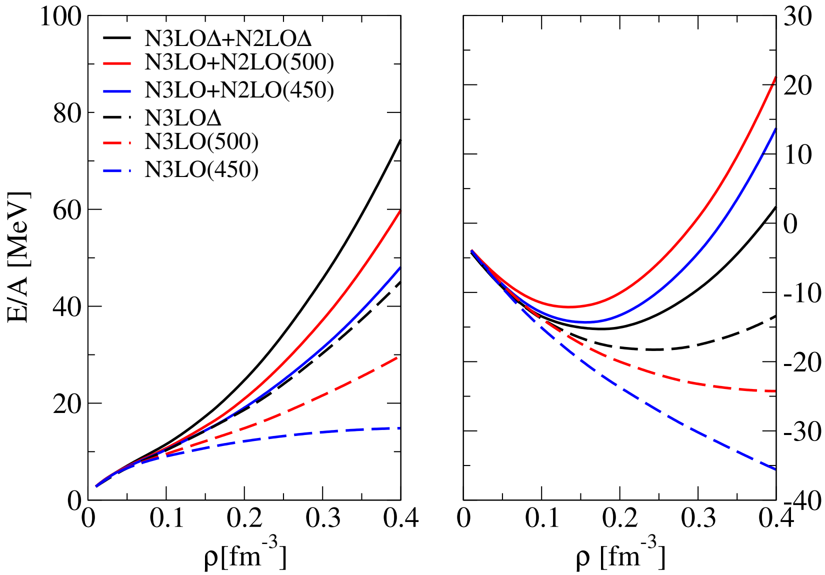
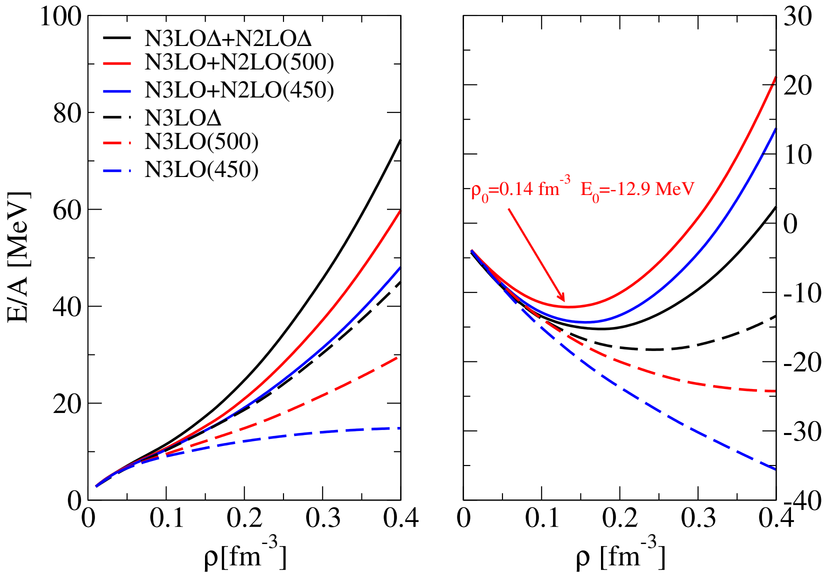
- Low energy constants (c_D, c_E) fixed to reproduce the ^{3}H binding energy + (^{3}H-^{3}He) *GT* transition matrix element.
- In our many-body calculations we use the same cutoff employed in the few-body ones $\Rightarrow$ "almost" fully consistent calculation.
- N3LOΔ+N2LOΔ $\Rightarrow$ still no calculation in light nuclei $\Rightarrow$ fitted to reproduce $(\rho_0, E/A_0)$
- N3LO+N2LO(500) $\Rightarrow$ reproduces the ^{3}H binding energy and a_{nd} scattering length (A. Baroni, 2016)
- N3LO+N2LO(450) $\Rightarrow$ reproduces the ^{3}H binding energy and (^{3}H-^{3}He) *GT* $\Rightarrow$ provides reasonable description of nuclear matter!

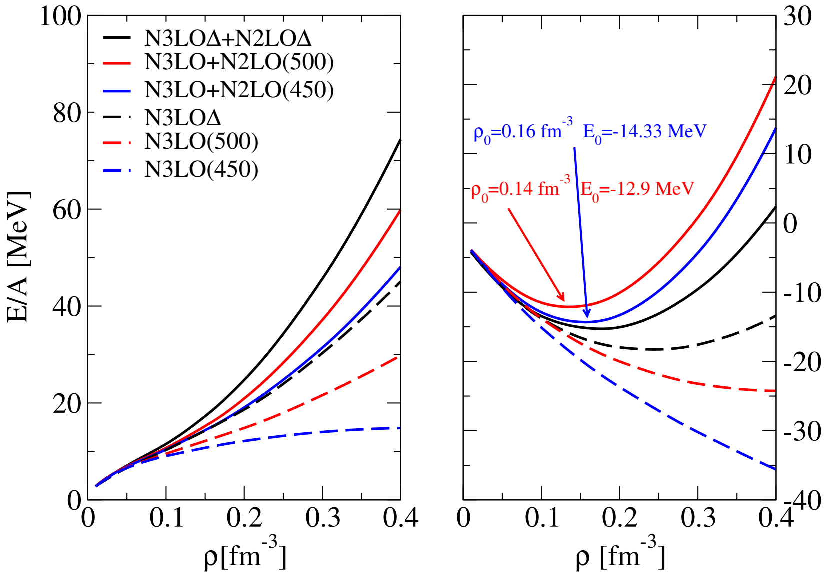
E/A nuclear matter N3LO+N2LO



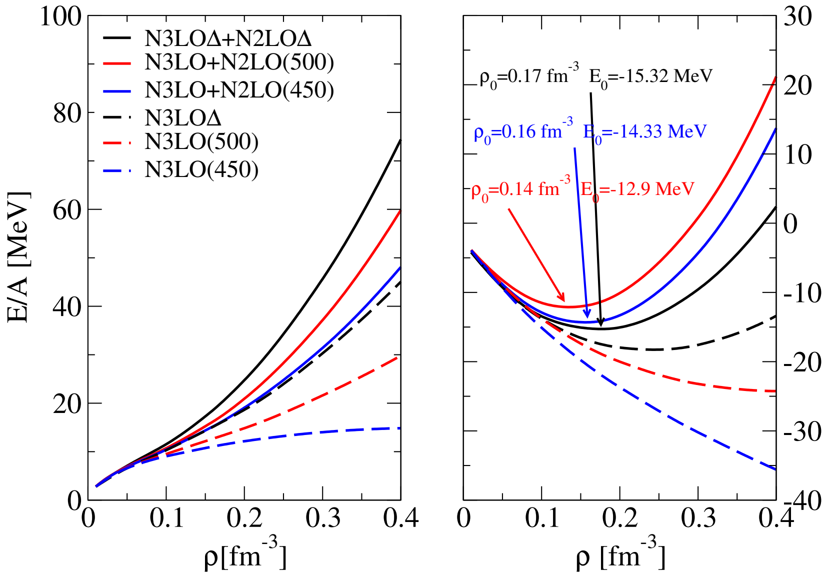
E/A nuclear matter N3LO+N2LO

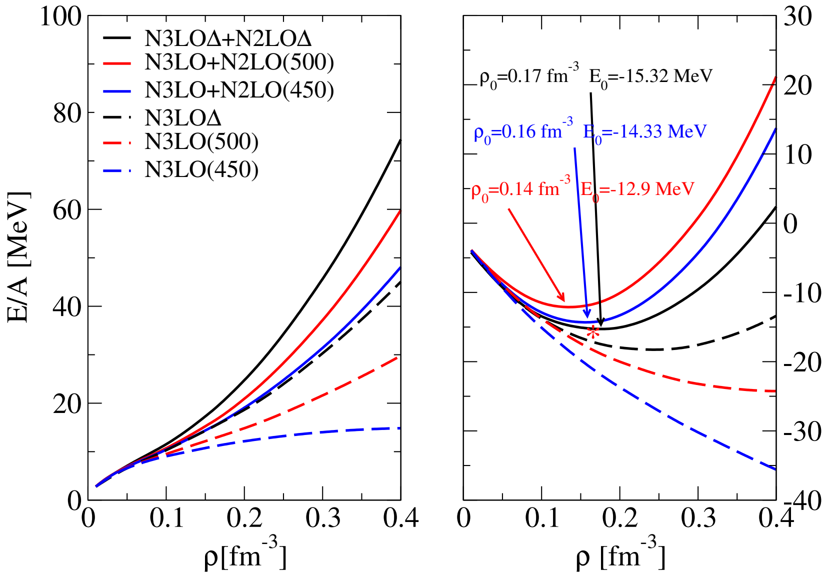


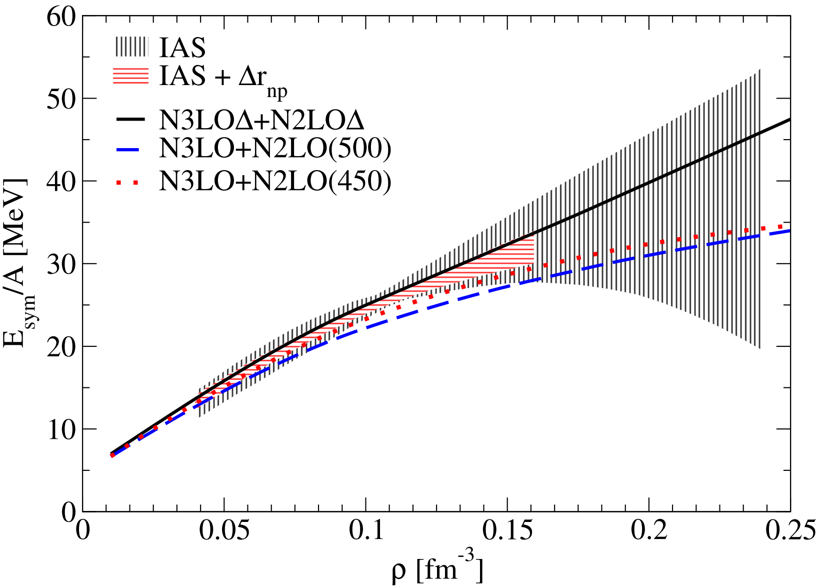
E/A nuclear matter N3LO+N2LO



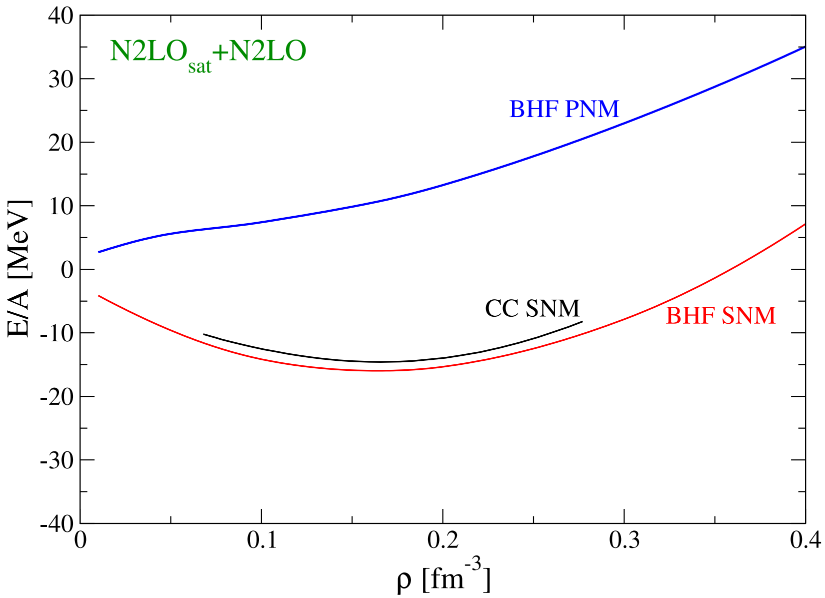
E/A nuclear matter N3LO+N2LO



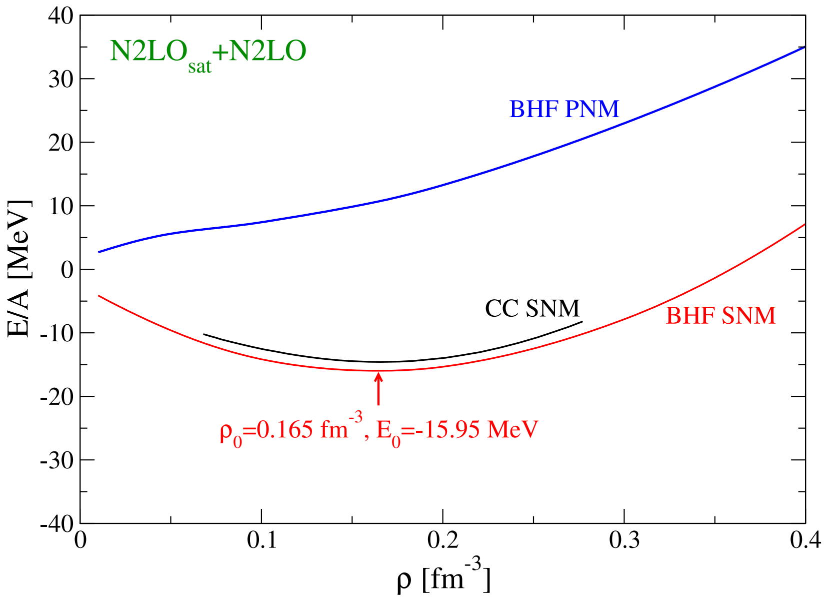

N3LOΔ+N2LOΔ
N3LO+N2LO(500)
N3LO+N2LO(450)
N3LOΔ
N3LO(500)
N3LO(450)
E/A [MeV]
ρ[fm^-3]
ρ0=0.17 fm^-3 E0=-15.32 MeV
ρ0=0.16 fm^-3 E0=-14.33 MeV
ρ0=0.14 fm^-3 E0=-12.9 MeV
ρ [fm^-3]


60
50
40
30
20
10
0
0
0.05
0.1
0.15
0.2
0.25
IAS
IAS + Δr_np
N3LOΔ+N2LOΔ
N3LO+N2LO(500)
N3LO+N2LO(450)
E_sym/A [MeV]
ρ [fm^-3]

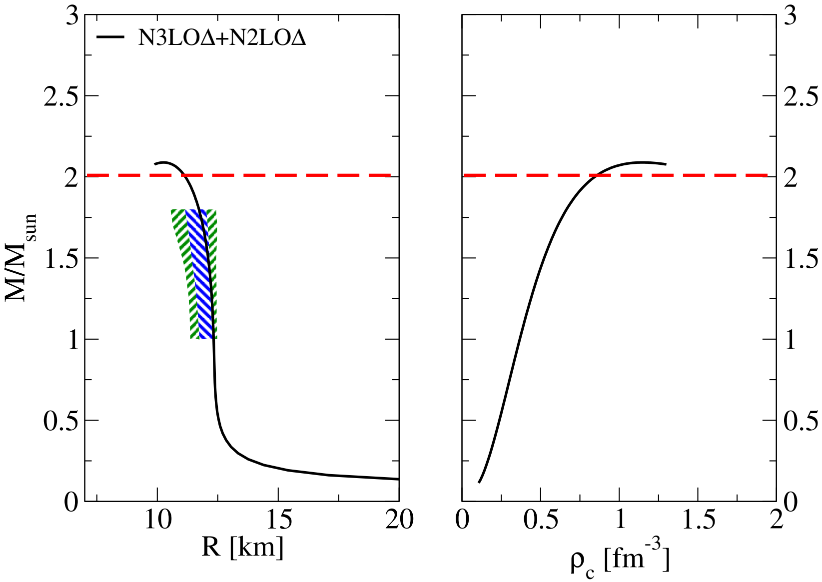
Calculations with N2LO$_{sat}$+N2LO

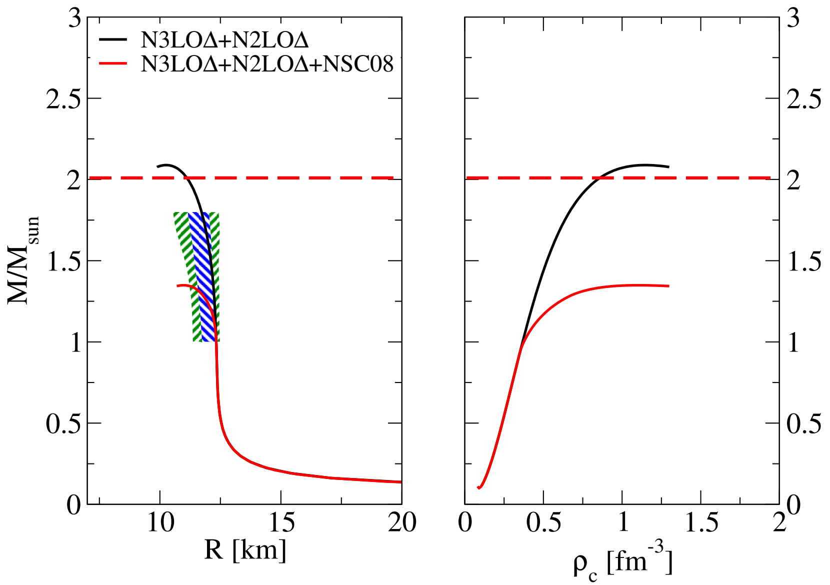


Calculations with N2LO$_{sat}$+N2LO



Neutron stars based on N3LOΔ+N2LOΔ




N3LOΔ+N2LOΔ
N3LOΔ+N2LOΔ+NSC08
M/M_sun
R [km]
ρ_c [fm^-3]
0
0.5
1
1.5
2
2.5
3
10
15
20
0
0.5
1
1.5
2

Conclusions

- 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.

Thank you!