Neutron stars structure with chiral interactions

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Pisa

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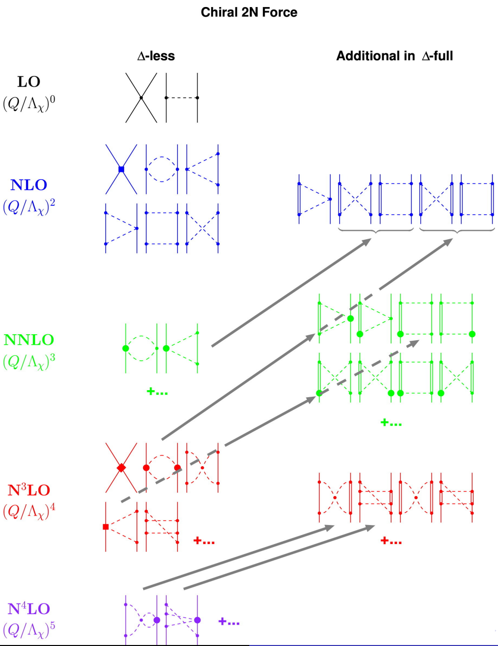
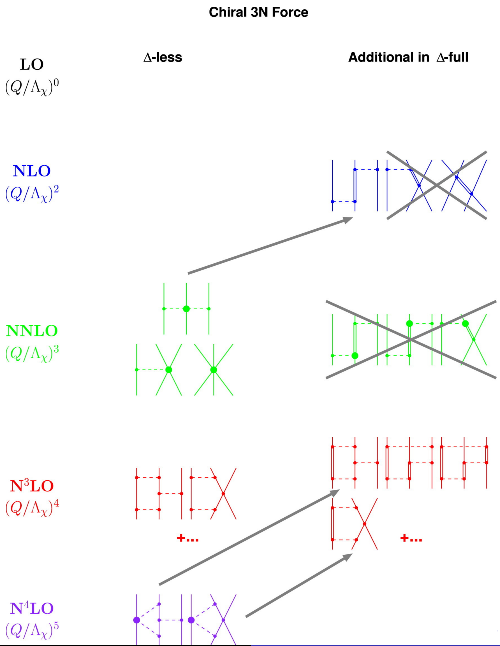
- Chiral interactions
- The Brueckner-Hartree-Fock approach in nuclear matter
- Applications to neutron stars
- Conclusions

Literature

- 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:
  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
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 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
- 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

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

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

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

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

NNN forces in the BHF-approach

- BHF calculations with NNN forces

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$$\Downarrow$$

- NNN force is reduced to a NN density dependent one

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

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

- In p-space:

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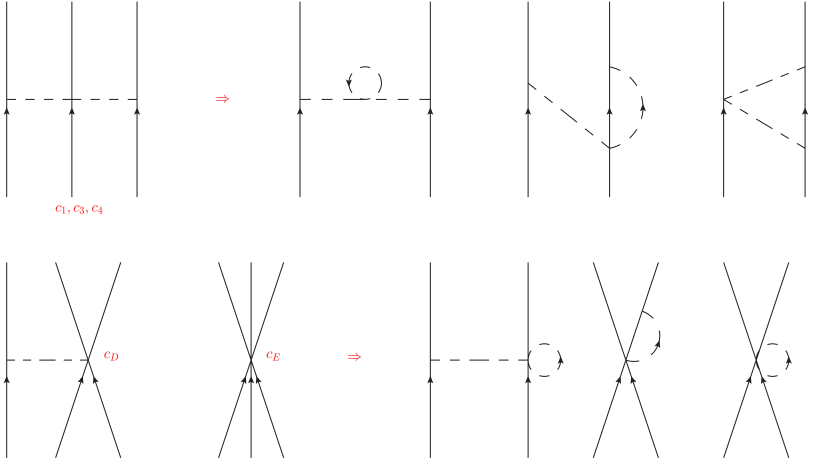
- Usually for $p-$space average $\Rightarrow$ non local cutoff:
  $F_\Lambda(p,q) = exp\left(-\frac{4p^2+3q^2}{4\Lambda^2}\right)^n \rightarrow p, q$ Jacobi momenta

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.

$\Downarrow$

- Low energy constants (c_D, c_E) fixed to reproduce the ^{3}H binding energy + (^{3}H-^{3}He) *GT* transition matrix element.

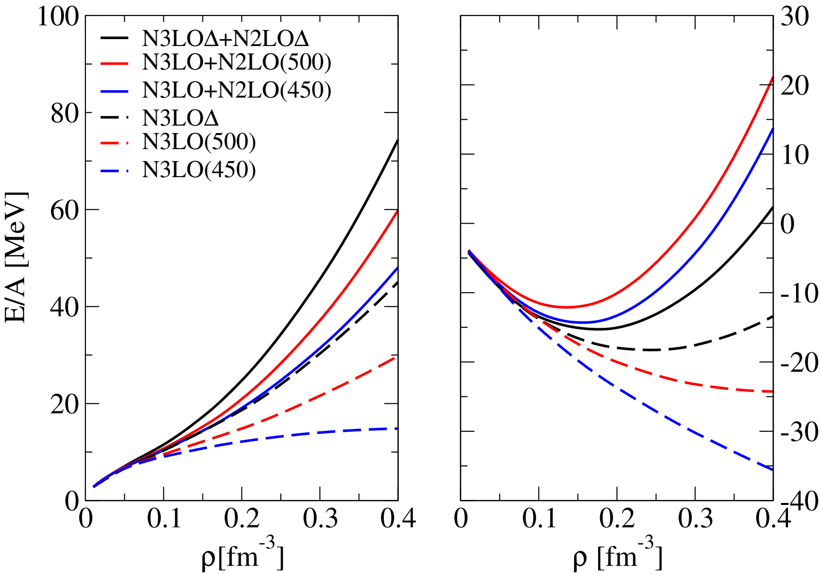
- In our many-body calculations we use the same cutoff $F_\Lambda(q^2) = e^{-q^4/\Lambda^4}$ (q is the exchanged momentum!) employed in the few-body ones $\Rightarrow$ "almost" fully consistent calculation.

- N3LOΔ+N2LOΔ $\Rightarrow$ still no calculation in light nuclei $\Rightarrow$ fitted to reproduce $(\rho_0, E/A_0)$

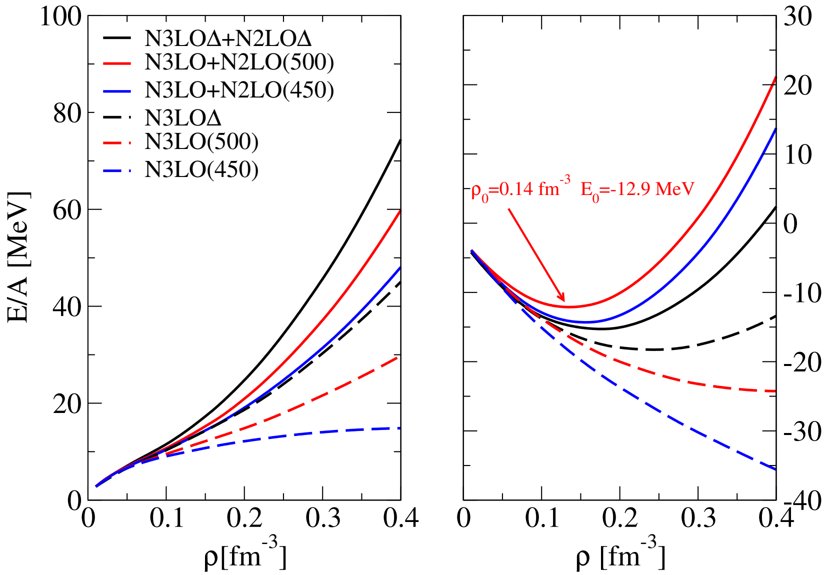
- N3LO+N2LO(500) $\Rightarrow$ reproduces the ^{3}H binding energy and N-d scattering length

- N3LO+N2LO(450) $\Rightarrow$ reproduces the ^{3}H binding energy and (^{3}H-^{3}He) *GT* $\Rightarrow$ provides reasonable description of nuclear matter!

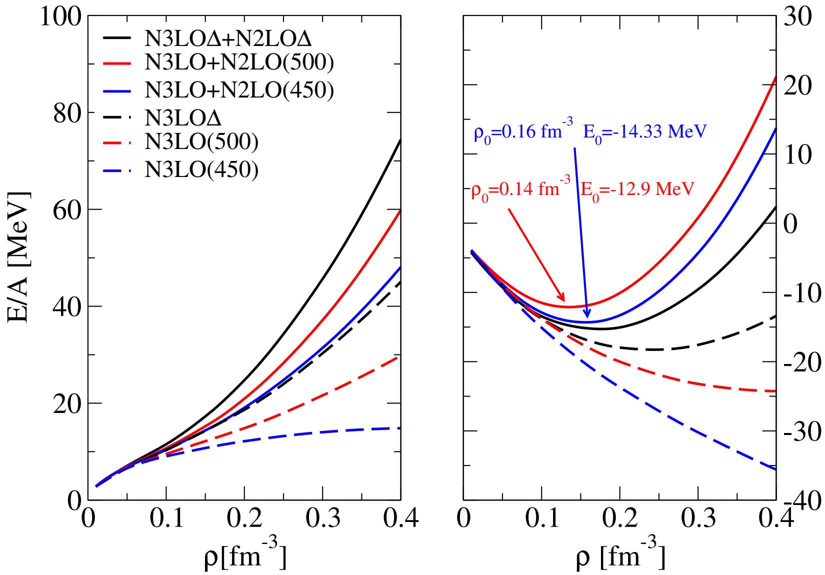
E/A nuclear matter N3LO+N2LO



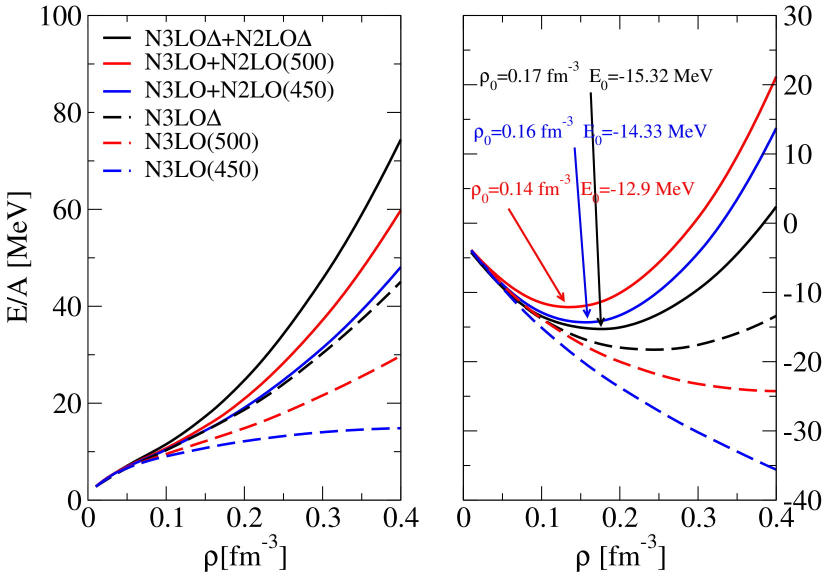
E/A nuclear matter N3LO+N2LO



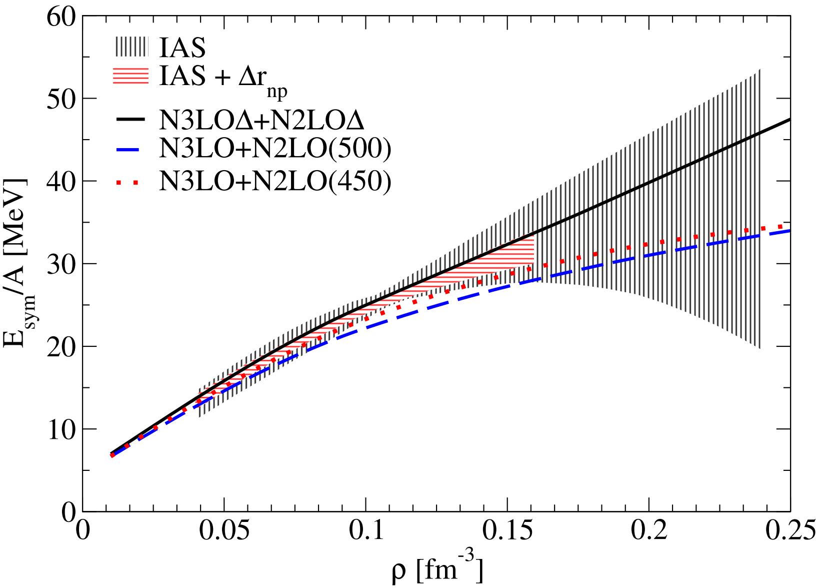
E/A nuclear matter N3LO+N2LO



E/A nuclear matter N3LO+N2LO



Symmetry energy N3LO+N2LO



Application to neutron stars

- Construction of β-stable EoS of nuclear matter $\Rightarrow$ used parabolic approximation for asymmetric nuclear matter.
- Construction of β-stable EoS of quark matter $\Rightarrow$ we consider two popular models FCM and NJL.
- NJL $\Rightarrow$ simple Lagrangian:

$$
\begin{aligned}
\mathcal{L}_{NJL} &= \bar{\psi}(i\gamma^{\mu}\partial_{\mu} - \hat{m})\psi \\
&+ G_S \sum_{a=0}^{8} [(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi}i\gamma_5\lambda_a\psi)^2] \\
&- K \left\{\det{}_f[\bar{\psi}(1+\gamma_5)\psi] + \det{}_f[\bar{\psi}(1-\gamma_5)\psi]\right\} \\
&- G_V \sum_{a=0}^{8} [(\bar{\psi}\gamma_{\mu}\lambda_a\psi)^2 + (\bar{\psi}\gamma_5\gamma_{\mu}\lambda_a\psi)^2]
\end{aligned}
$$

The Field correlator method

Y. A. Simonov, M. A. Trusov JETP Lett. 85, 598 (2007)

- Dynamics of confinement $\Rightarrow D^E(x),\ D_1^E(x),\ D^H(x),\ D_1^H(x)$

$$P_q/T^4 = \frac{1}{\pi^2}[\phi_\nu(\frac{\mu_q - V_1/2}{T}) + \phi_\nu(-\frac{\mu_q + V_1/2}{T})]$$

$$\phi_\nu(a) = \int_0^\infty du \frac{u^4}{\sqrt{u^2+\nu^2}} \frac{1}{\exp[\sqrt{u^2+\nu^2} - a] + 1}\,, \quad \nu = m_q/T$$

$$V_1(T) = \int_0^{1/T} d\tau (1 - \tau T) \int_0^\infty d\chi\, \chi\, D_1^E(\sqrt{\chi^2 + \tau^2})\,.$$

$$D_1^E(x) = D_1^E(0)\exp(-|x|/\lambda), \quad \lambda = 0.34\ fm.$$

$$P_{qg} = P_g + \sum_{u,d,s} P_q - \frac{9}{64} G_2\,.$$

$G_2 = (0.012 \pm 0.006)\ \mathrm{GeV}^4 \Rightarrow$ From QCD sum rules

$V_1(0) = 10 - 100\ \mathrm{MeV} \Rightarrow$ Parameter (M. Baldo et al. Phys. Rev. D **78**, 063009 (2008))

Mixed phase: Gibbs VS Maxwell

- Gibbs conditions for phase coexistence:

$$\mu_H(P_H, T_H) = \mu_Q(P_Q, T_Q), \quad T_H = T_Q, \quad P_H(\mu_H, T) = P_Q(\mu_Q, T) = P_T .$$

- Gibbs construction: Charge neutrality is not imposed locally but globally.

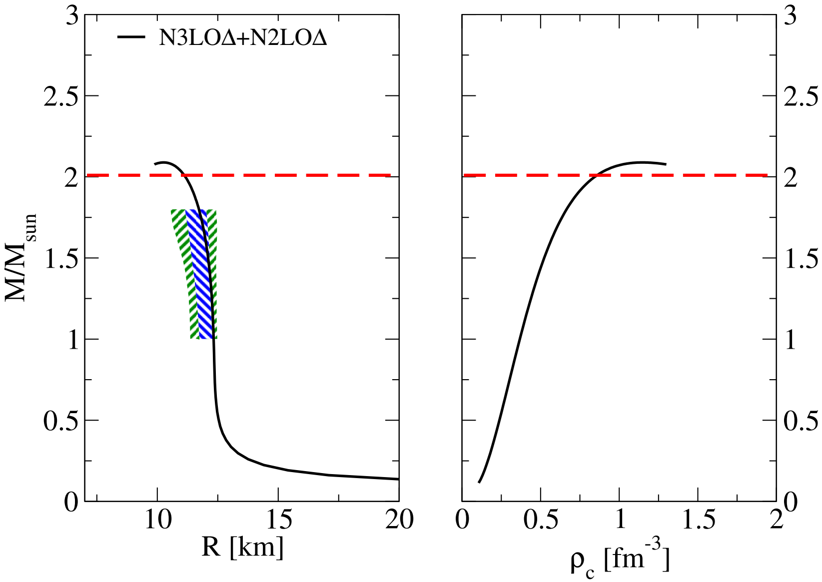
$$\chi \rho_c^Q + (1 - \chi)\rho_c^H + \rho_c^l = 0 .$$

- Energy density and baryonic density in the mixed phase read:

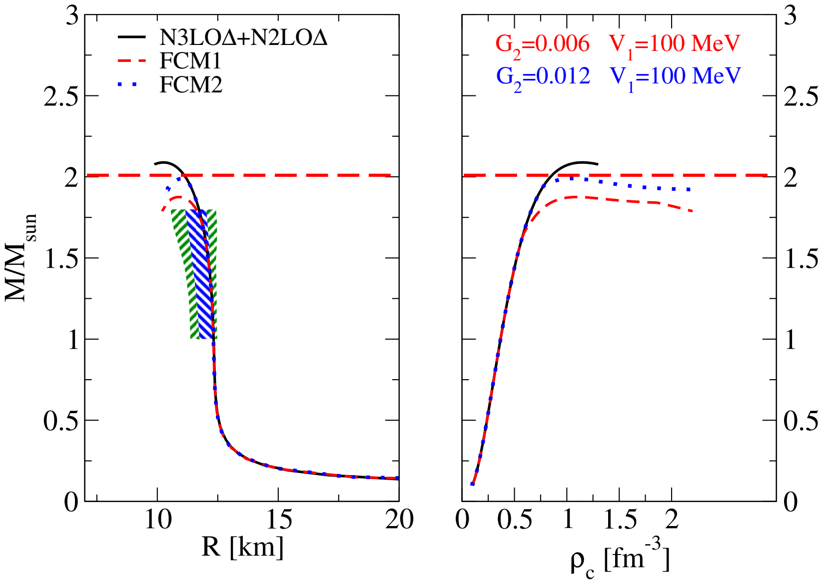
$$< \epsilon >= (1 - \chi)\, \epsilon_H - \chi\, \epsilon_Q ,$$
$$< n >= (1 - \chi)\, n_H - \chi\, n_Q .$$

- Maxwell construction: Charge neutrality is imposed locally!.

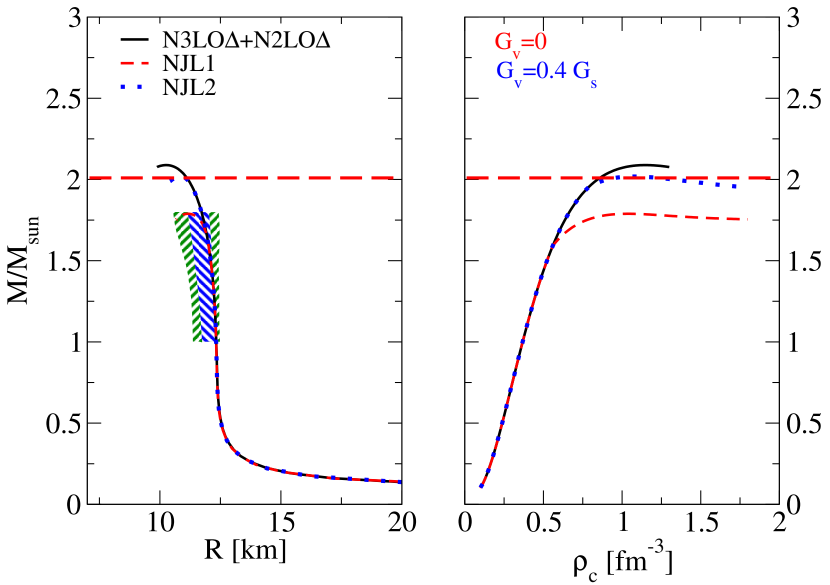
Neutron stars based on N3LOΔ+N2LOΔ



Neutron stars based on N3LOΔ+N2LOΔ+FCM



Neutron stars based on N3LOΔ+N2LOΔ+NJL



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.

$$\Downarrow$$

- Problem of maximum mass of neutron stars with hyperons.

Thank you!

and...thanks to Adelaide for sleeping wednesday in the afternoon...so I could finish my presentation