Effect of hyperonic three-body forces in hadronic matter and neutron stars

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In collaboration with:

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Frascati

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Istituto Nazionale di Fisica Nucleare

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

motivations:

1) Strongly correlated to the physics of hypernuclei

2) Determination of symmetry energy

3) Study of astrophysical systems: neutron stars

- System of $A = N + Z + Y$ hadrons in a volume V
- Thermodynamical limit: $A \rightarrow +\infty$ and $V \rightarrow +\infty$ with $\frac{A}{V} = \rho = const.$
- Asymmetry between number of N and number of $Z \Rightarrow \beta = \frac{N-Z}{N+Z}$, strangeness fraction $y = Y/A$

How to study it?

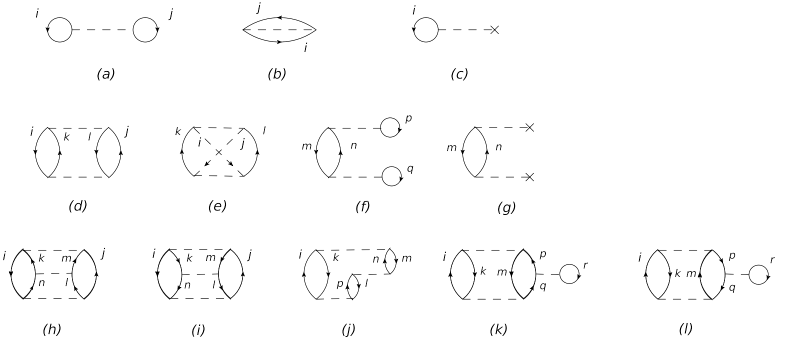
- Relativistic mean field (Hartree) $\Rightarrow \mathcal{L}$ (QFT) $\Rightarrow$ Eulero-Lagrange equations solved in mean field approximation.
- Relativistic mean field (Hartree-Fock) $\Rightarrow \mathcal{L}$ (QFT) $\Rightarrow$ Eulero-Lagrange equations solved in mean field approximation.
- Skyrme models $\Rightarrow$ effective nuclear interaction
- Ab initio approaches $\Rightarrow$ Brueckner-Hartree-Fock, Quantum-Monte-Carlo, Self-consistent Green function $\Rightarrow$ start from microscopic potentials explicitly including many-body forces.

Goldstone expansion up to three-hole-lines

$$H = \sum_{i=1}^{A} T_i + \sum_{i<j}^{A} V_{ij} = H_0 + H_1;$$

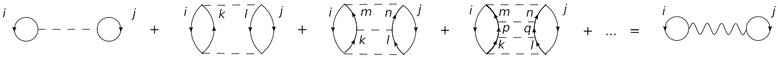
$$H_0 = \sum_{i=1}^{A} T_i + \sum_{i=1}^{A} U_i \qquad H_1 = \sum_{i<j}^{A} V_{ij} - \sum_{i=1}^{A} U_i$$

1st-order, 2nd-order and 3rd-order contributions:



Bethe-Goldstone expansion up to three-hole-lines

Ladder diagrams summation:



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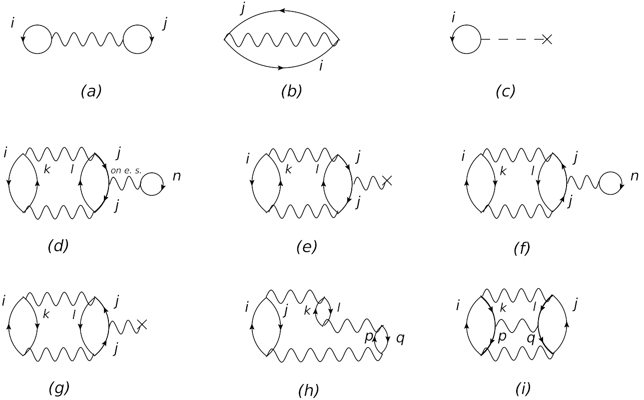


The Brueckner-Hartree-Fock approach

- Starting point: the Bethe-Goldstone equation

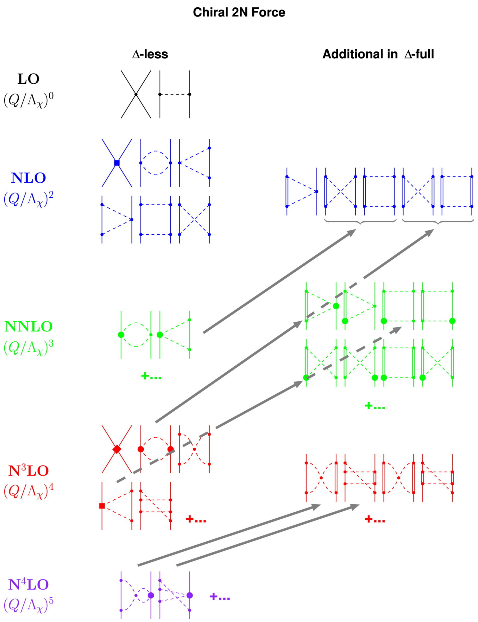
$$G(\omega)_{B_1B_2,B_3B_4} = V_{B_1B_2,B_3B_4} + \sum_{B_iB_j} V_{B_1B_2,B_iB_j} \times \frac{Q_{B_iB_j}}{\omega - E_{B_i} - E_{B_j} + i\eta} G(\omega)_{B_iB_j,B_3B_4}$$

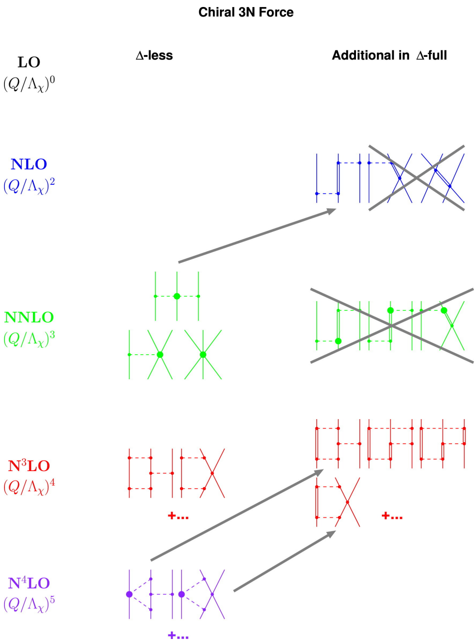
$$U_{B_i}(k) = \sum_{B_j}\sum_{\vec{k'}} n_{B_j}(|\vec{k'}|) \times \langle \vec{k}\vec{k'}|G(E_{B_i}(\vec{k}) + E_{B_j}(\vec{k'}))_{B_iB_j,B_iB_j}|\vec{k}\vec{k'}\rangle_{\mathcal{A}}$$

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

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

- We included the Λ, Σ hyperons in our calculations.


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
$(Q/\Lambda_\chi)^5$
+...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$(Q/\Lambda_\chi)^0$
NLO
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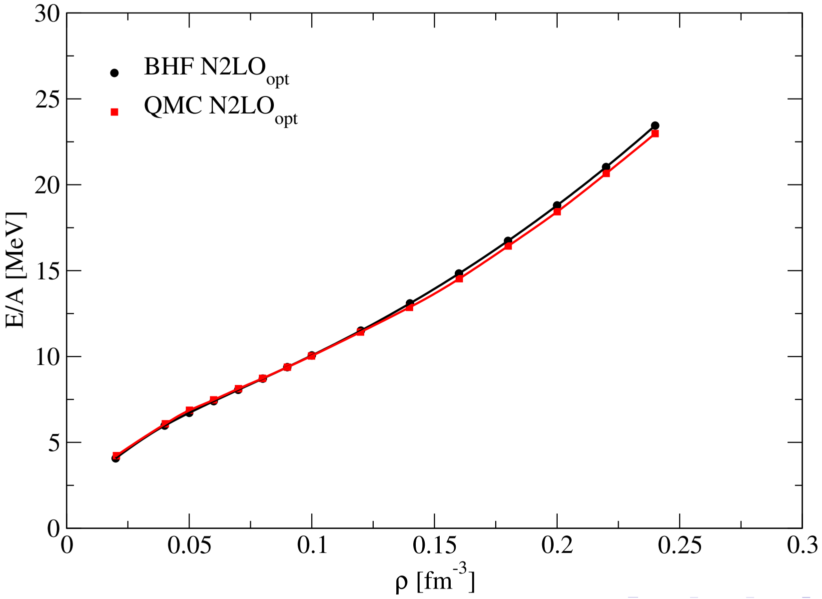
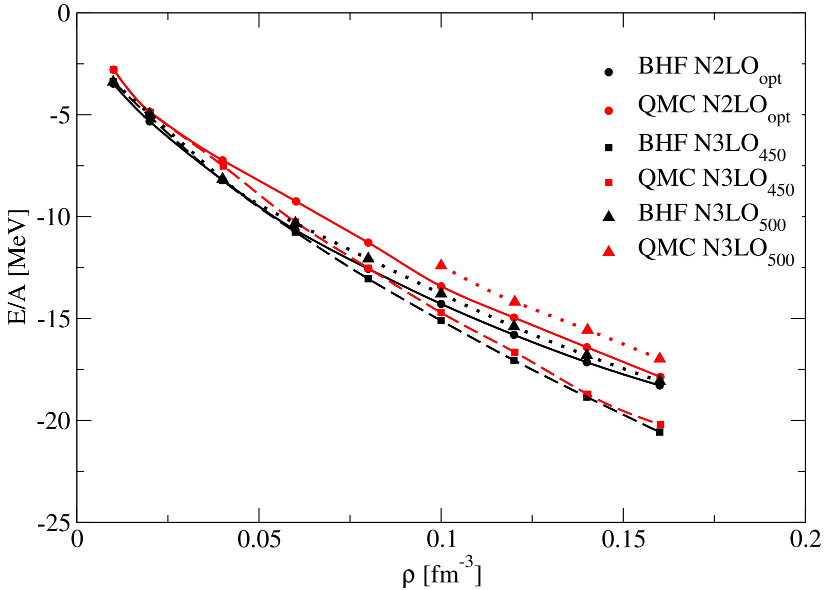
NNLO
$(Q/\Lambda_\chi)^3$
N^{3}LO
$(Q/\Lambda_\chi)^4$
+...
+...
N^{4}LO
$(Q/\Lambda_\chi)^5$
+...

- 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
- Optimized N2LO (N2LO$_{opt}$), 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: N2LO and N2LOΔ

Comparison with momentum-space QMC calculations (PNM) (E. Rrapaj 2016)



Comparison with momentum-space QMC calculations (SNM) (E. Rrapaj 2016)



- BHF calculations with NNN forces $\Rightarrow$ very challenging

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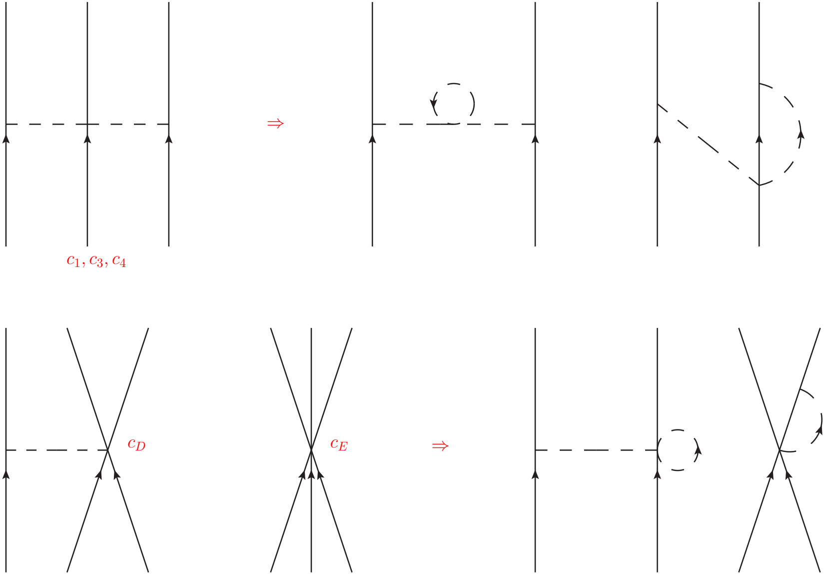
- NNN force is reduced to a NN density dependent one
- In p-space:

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

Momentum space average of N2LO TBF (J. W. Holt et al. 2010)



Setting of low energy constants (c_D, c_E)

- N2LO$_{opt}$: fixed to reproduce the ^{3}H and ^{4}He binding energy in CC calculations

- 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.

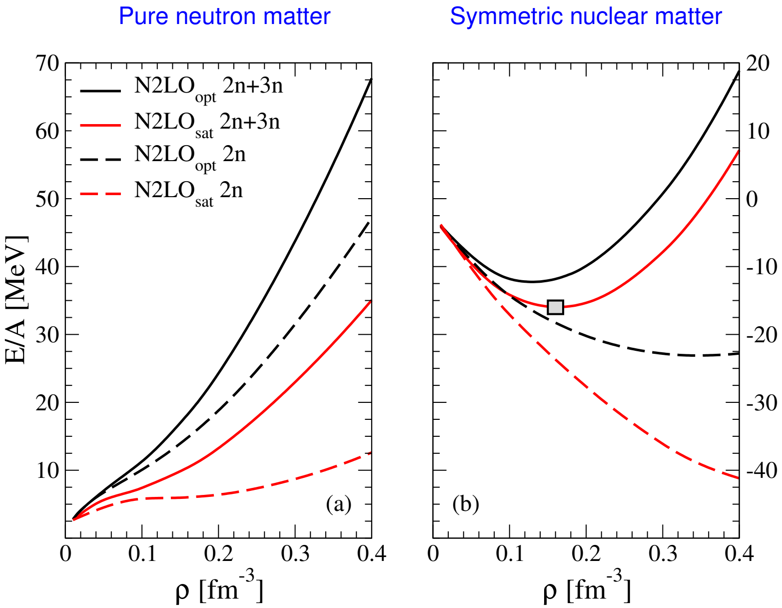
$\Downarrow$

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

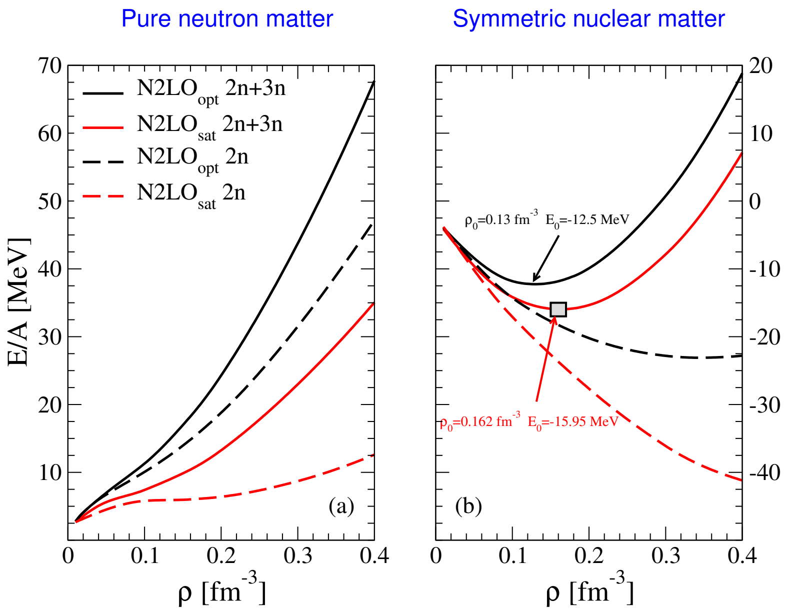
- N3LO+N2LO(450) $\Rightarrow$ reproduces the ^{3}H binding energy and (^{3}H-^{3}He) *GT*

- N3LOΔ+N2LOΔ $\Rightarrow$ parametrization N2LOΔ1 fitted to reproduce (ρ_0, E/A_0); parametrization N2LOΔ2 fitted to reproduce ^{3}H binding energy.

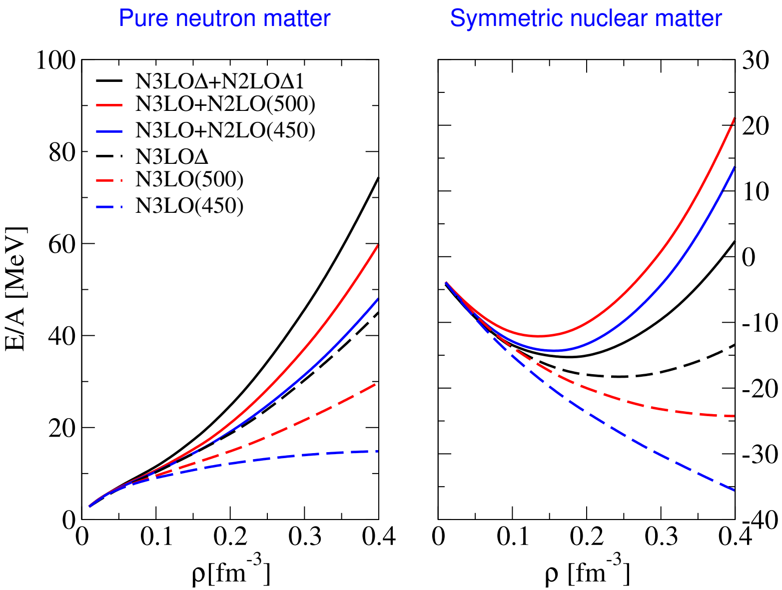
E/A nuclear matter N2LO+N2LO



E/A nuclear matter N2LO+N2LO

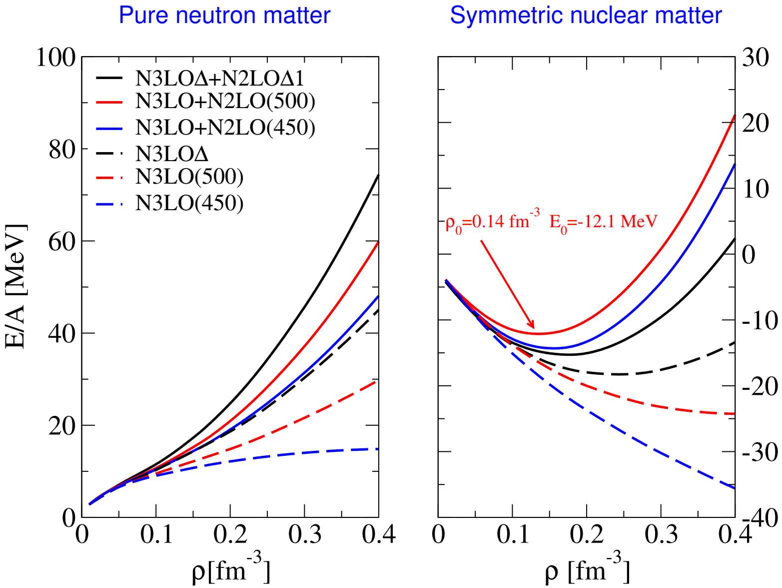


E/A nuclear matter N3LO+N2LO



Logoteta et al. Phys. Rev. C 94, 064001

E/A nuclear matter N3LO+N2LO



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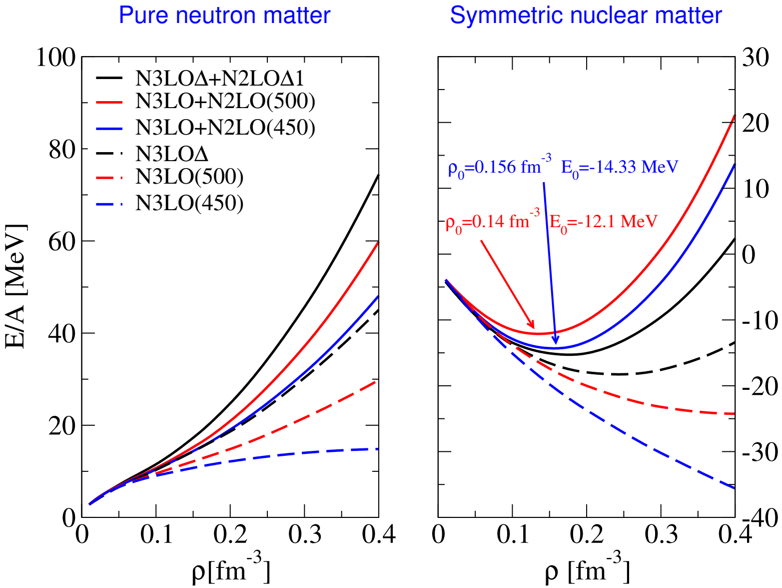
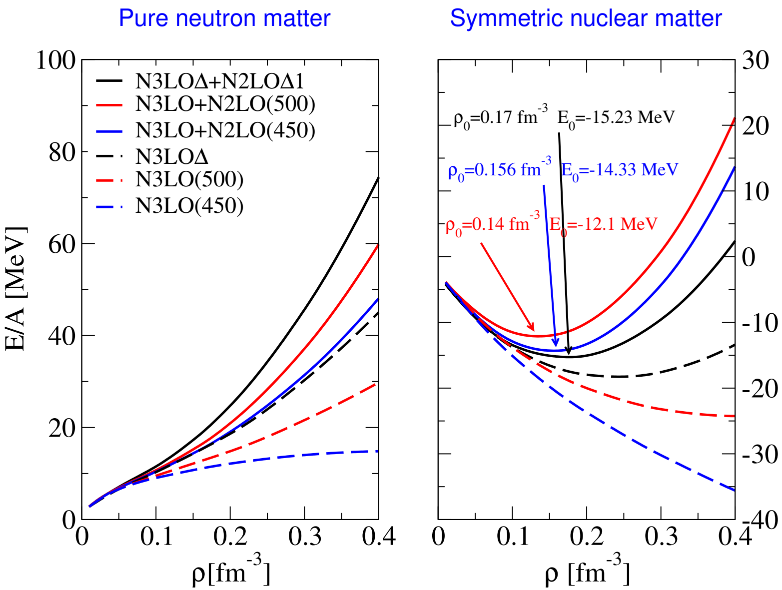
E/A nuclear matter N3LO+N2LO



Logoteta et al. Phys. Rev. C 94, 064001

E/A nuclear matter N3LO+N2LO



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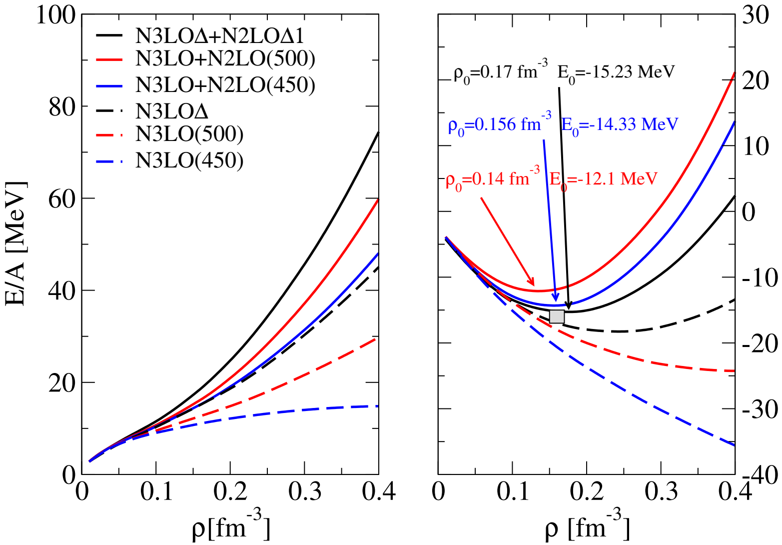
E/A nuclear matter N3LO+N2LO

Pure neutron matter | Symmetric nuclear matter



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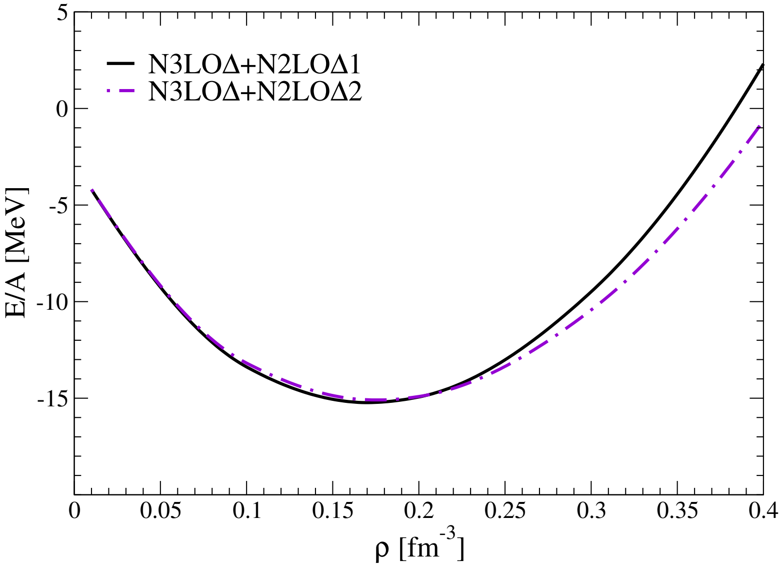
E/A nuclear matter N3LO+N2LO (2)

Symmetric nuclear matter: comparision between N2LOΔ1 and N2LOΔ2



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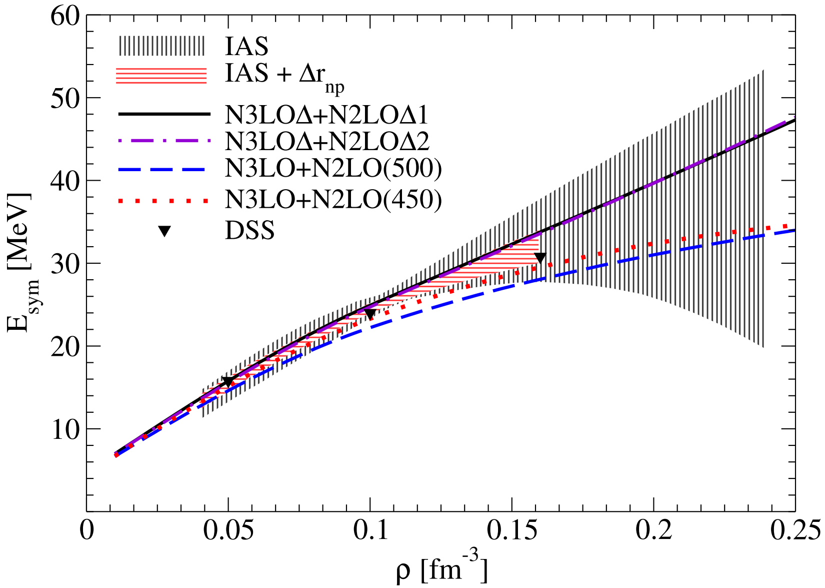
Symmetry energy N3LO+N2LO



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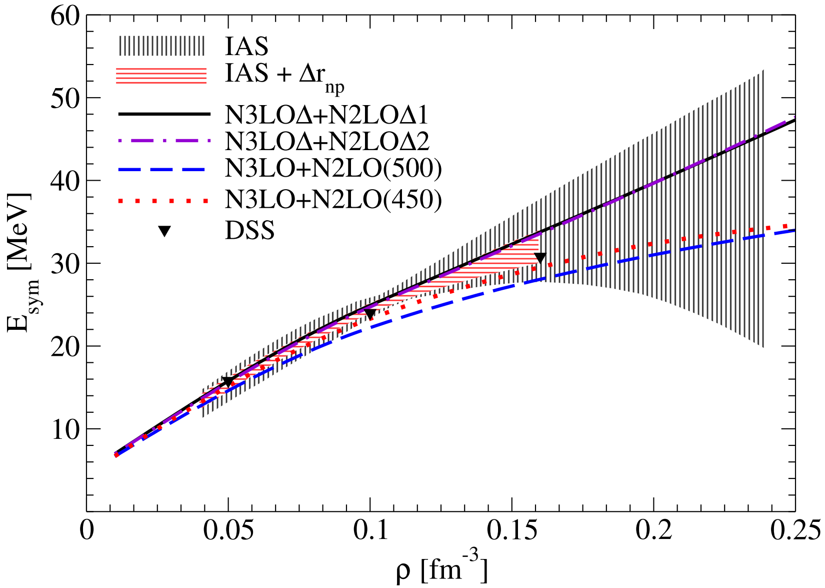


Logoteta et al. Phys. Rev. C 94, 064001

- Asymmetric matter $\Rightarrow$ parabolic approximation:

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

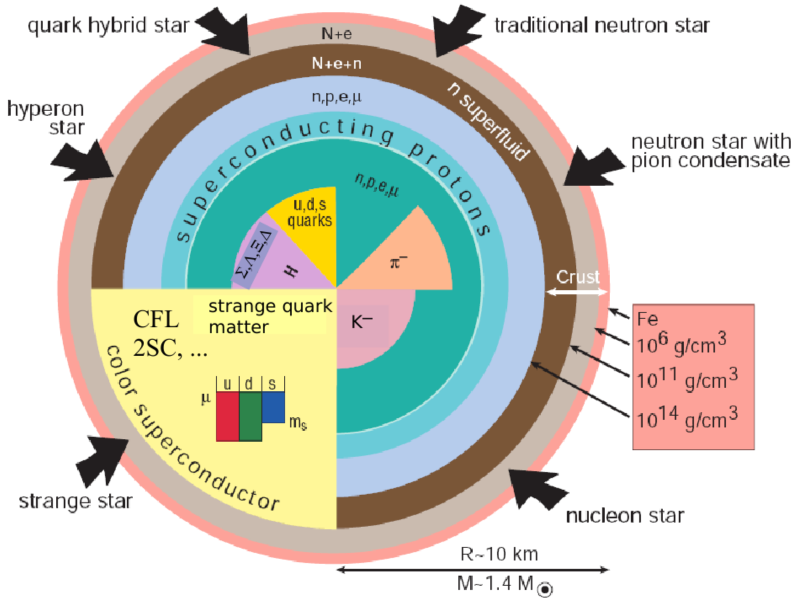
$$\mu_i = \frac{\partial(\rho E/A(\beta,\rho))}{\partial\rho_i} \qquad \rho = \rho_n + \rho_p$$

- Chemical equilibrium:

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

- Charge neutrality:

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


quark hybrid star
traditional neutron star
hyperon star
neutron star with pion condensate
strange star
nucleon star
N+e
N+e+n
n,p,e,μ
n superfluid
superconducting protons
n,p,e,μ
u,d,s quarks
Σ,Λ,Ξ,Δ
H
π⁻
K⁻
Crust
strange quark matter
CFL
2SC, ...
color superconductor
u d s
μ
m_s
Fe
10^6 g/cm^3
10^11 g/cm^3
10^14 g/cm^3
R~10 km
M~1.4 M☉

- For a fixed equation of state (EOS): $P = P(\rho)$ and $P = P(n_B)$

$$\Downarrow$$

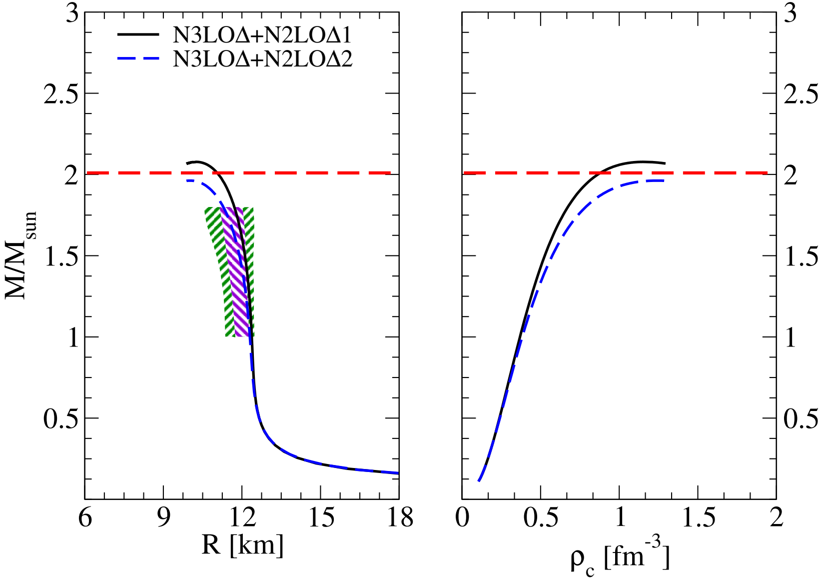
Neutron stars structure $\Rightarrow$ TOV equations

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

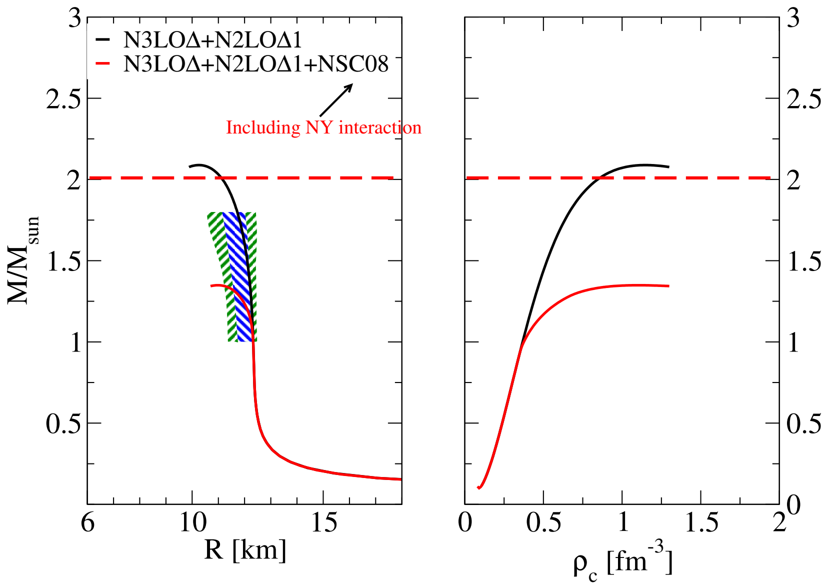
$$\frac{dP}{dr} = -\frac{G\rho m}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi P r^3}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1},$$

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

Neutron stars based on N3LOΔ+N2LOΔ

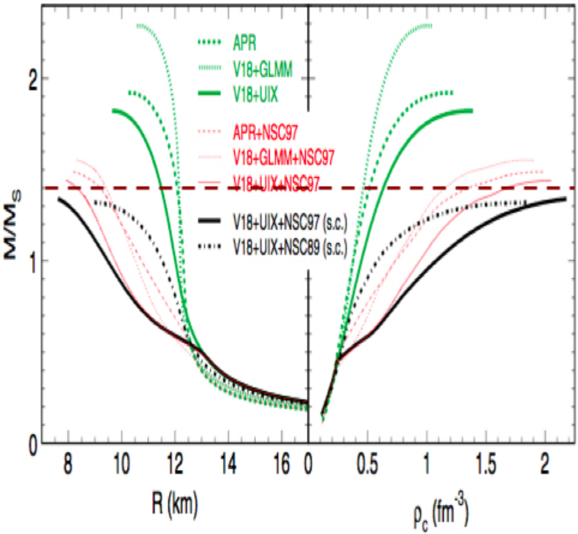


Neutron stars based on N3LOΔ+N2LOΔ+NY



The problem of the maximum mass of neutron stars with microscopic approaches

H.-J. Schulze et al. Phys. Rev. C 73, 058801 (2006)



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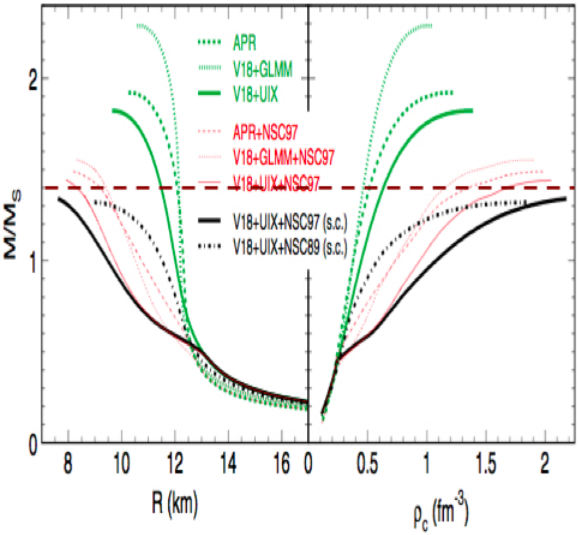

- $n + n \rightarrow n + \Lambda$
- $n + n \rightarrow p + \Sigma^-$
- $p + e^- \rightarrow \Lambda + \nu_{e^-}$
- $n + e^- \rightarrow \Sigma^- + \nu_{e^-}$

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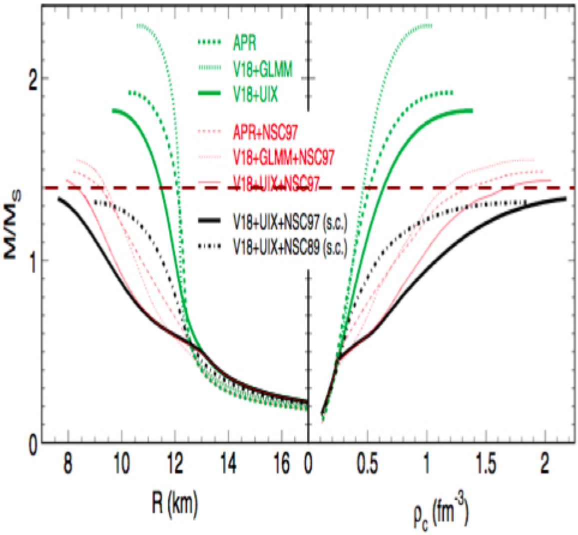
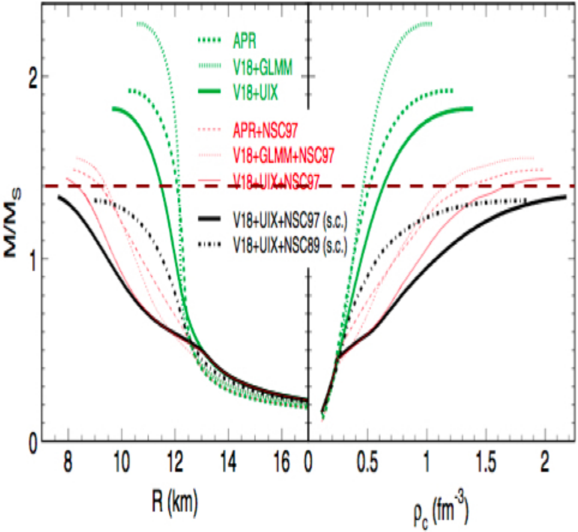


- $n + n \rightarrow n + \Lambda$
- $n + n \rightarrow p + \Sigma^-$
- $p + e^- \rightarrow \Lambda + \nu_{e^-}$
- $n + e^- \rightarrow \Sigma^- + \nu_{e^-}$
- Appearance of Hyperons $\Rightarrow$ Fermi pressure relieves
- $M_{max} < 1.44\ M_{\odot}$

H.-J. Schulze et al. Phys. Rev. C 73, 058801 (2006)



- Recent measurements:
- $M_{PRS}^{J1903+0327} = 1.67\ M_{\odot}$
- $M_{PRS}^{J1614-2230} = 1.97\ M_{\odot}$
- $M_{PRS}^{J0348+0432} = 2.01\ M_{\odot}$

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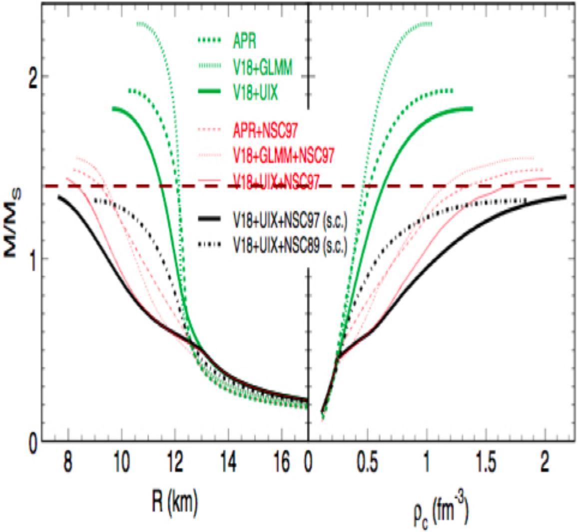

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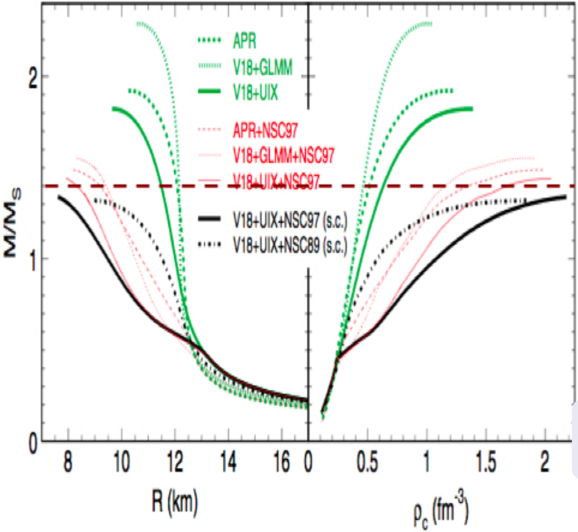
DRAMMATIC SCENARIO!!

H.-J. Schulze et al. Phys. Rev. C 73, 058801 (2006)



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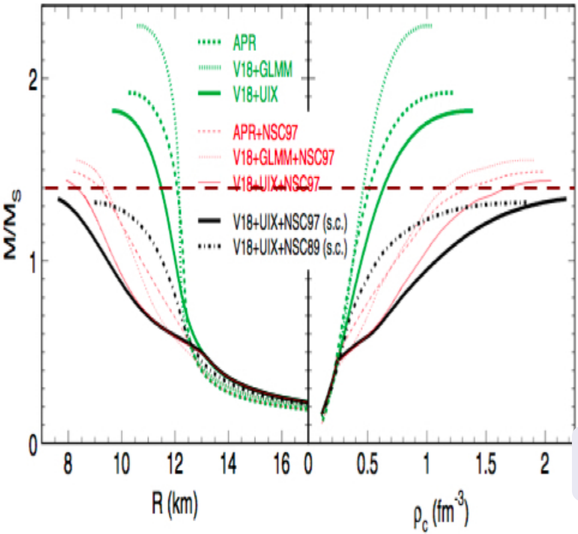
DRAMMATIC SCENARIO!!

NNY, NYY and YYY may help??

H.-J. Schulze et al. Phys. Rev. C 73, 058801 (2006)



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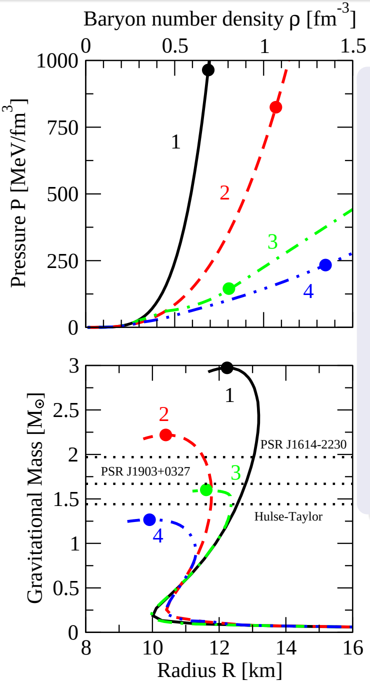
DRAMMATIC SCENARIO!!

We focused on the NNY interactions

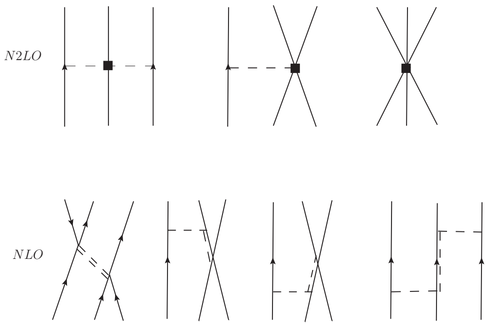


γ_{NN}	x	γ_{YN}	M_{max}
2	0	-	1.27 (2.22)
	1/3	1.49	1.33
	2/3	1.69	1.38
	1	1.77	1.41
2.5	0	-	1.29 (2.46)
	1/3	1.84	1.38
	2/3	2.08	1.44
	1	2.19	1.48
3	0	-	1.34 (2.72)
	1/3	2.23	1.45
	2/3	2.49	1.50
	1	2.62	1.54
3.5	0	-	1.38 (2.97)
	1/3	2.63	1.51
	2/3	2.91	1.56
	1	3.05	1.60

$$1.27\ M_\odot < M_{max} < 1.6\ M_\odot$$

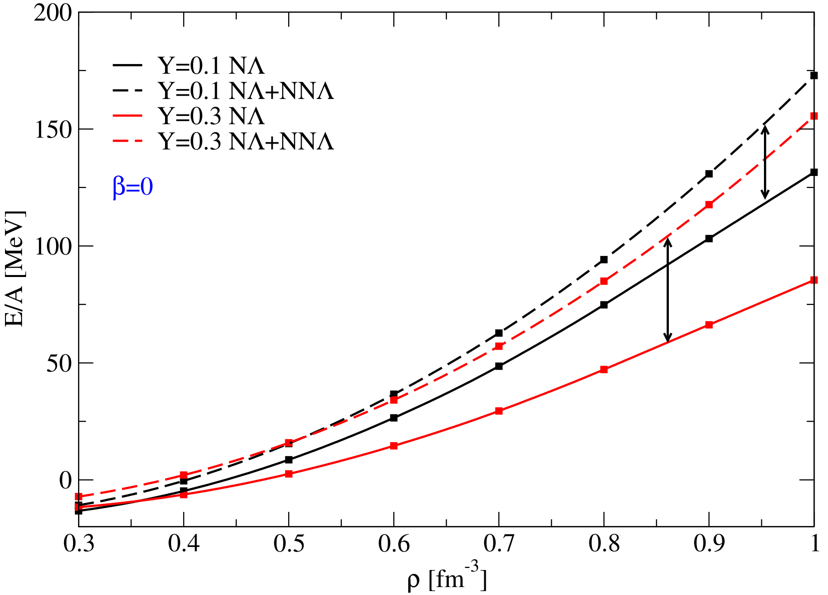
I. Vidana, D. Logoteta, C. Providencia, A. Polls, I. Bombaci EPL 94, 11002 (2011)

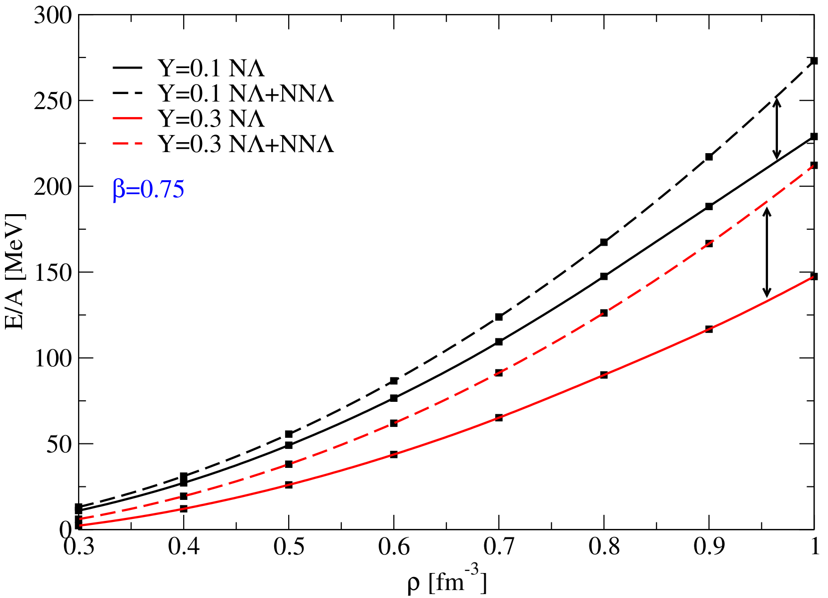
NNΛ force from ChPT



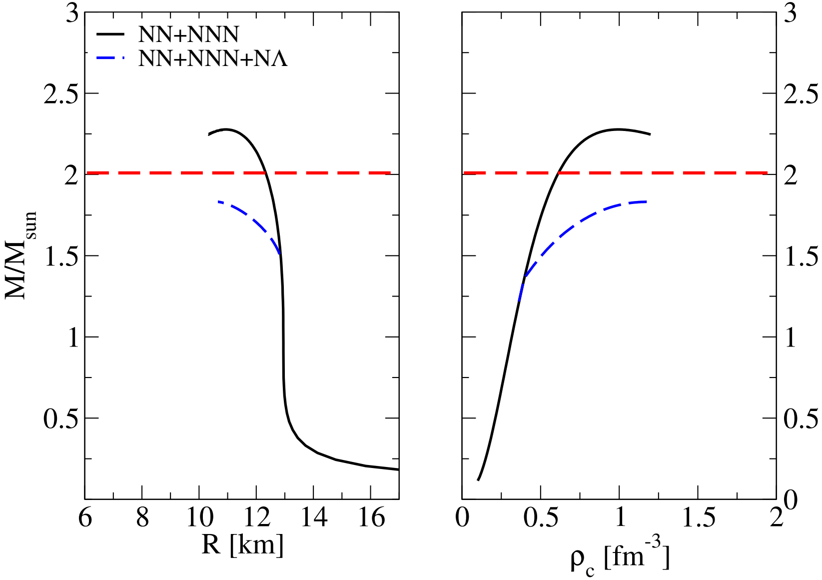
- Following Petschauer (2013)
- Baryonic three-body forces from chiral effective field theory
- Nonvanishing leading order contributions at order NLO and N2LO
- Same strategy used for nuclear matter
- Effective NΛ interaction from bare NNΛ force
- Low energy constants estimated from decuplet saturation

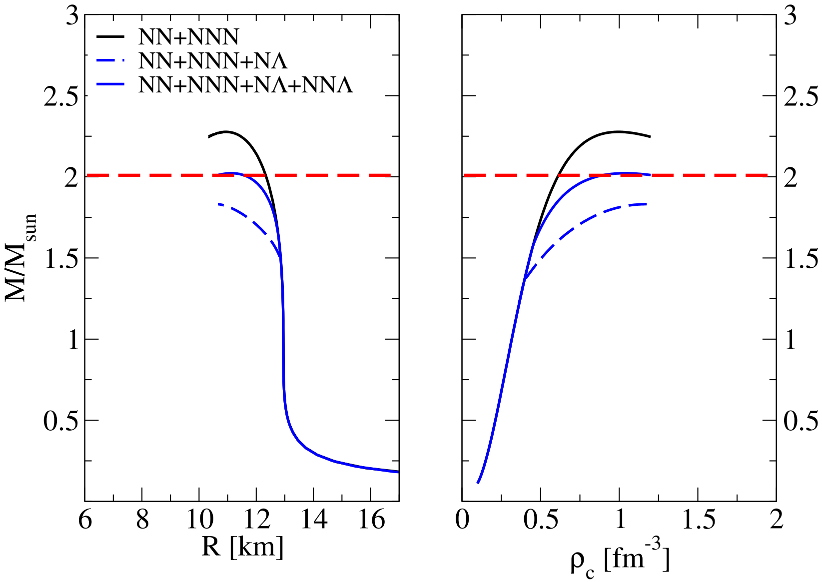
Effect of hyperonic three-body force NNΛ



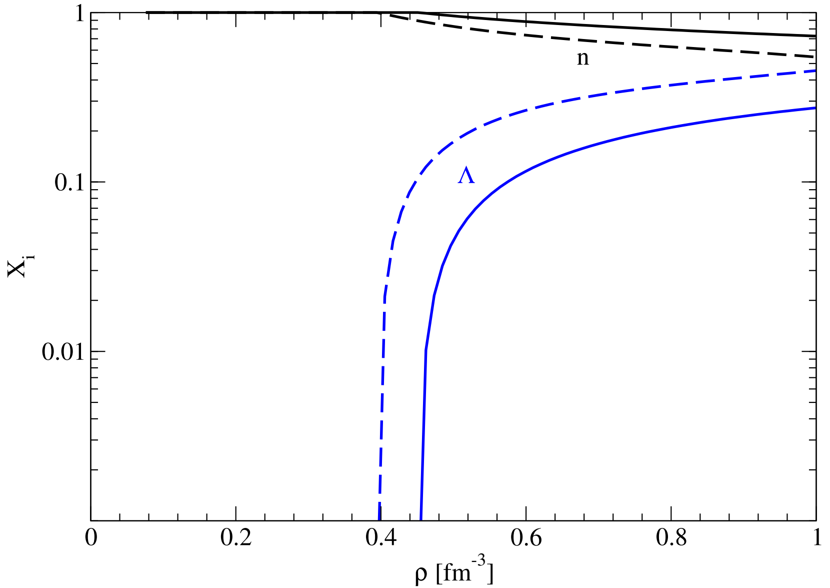

Y=0.1 NΛ
Y=0.1 NΛ+NNΛ
Y=0.3 NΛ
Y=0.3 NΛ+NNΛ
β=0.75
E/A [MeV]
ρ [fm^-3]
0
50
100
150
200
250
300
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

A simplified model of neutrons and Λ's matter...

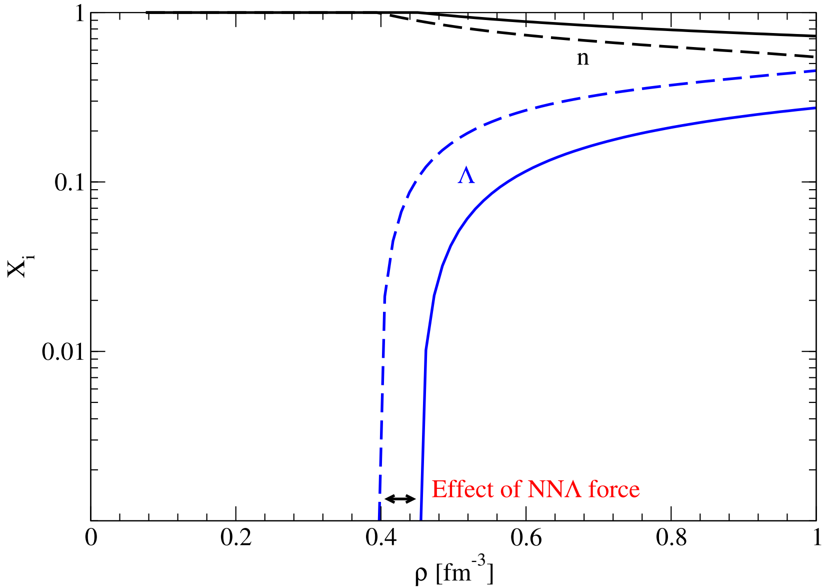



NN+NNN
NN+NNN+NΛ
NN+NNN+NΛ+NNΛ
M/M_sun
R [km]
ρ_c [fm^-3]
0
0.5
1
1.5
2
2.5
3
6
8
10
12
14
16

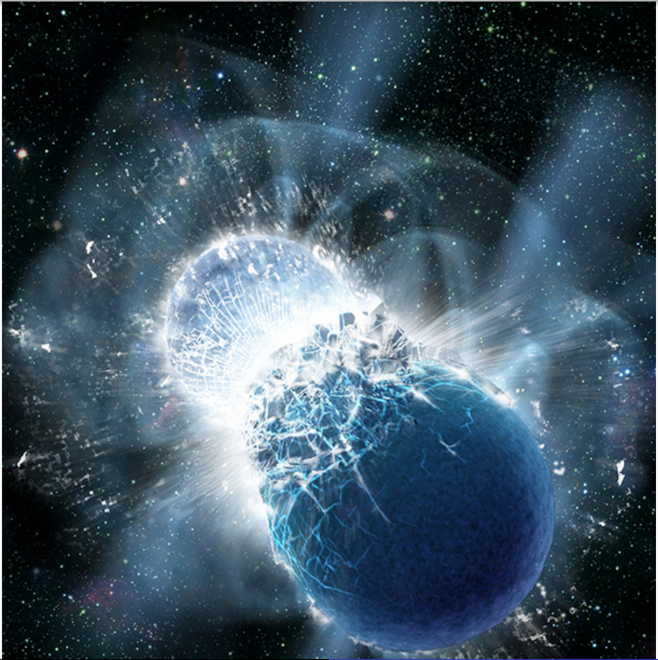
Particle fractions for neutrons and Λ's matter



Particle fractions for neutrons and Λ's matter



Neutron stars merge



Supernova explosions

Conclusions

- New generation of interactions based on chiral perturbation theory provide realistic results in nuclear matter and hadronic matter $\Rightarrow$ interesting connection to neutron stars.
- A combined and reasonable description of light nuclei and nuclear matter is possible
- ...but...how work these interactions in medium mass and heavy nuclei and hypernuclei?
- A study of β-stable hyperonic matter based on NY, NNY chiral forces should be performed.

$$\Downarrow$$

- Problem of maximum mass of neutron stars with hyperons.
- More experimental effort (PLEASE RAFFAELE AND KRISTIAN) is required to improve the quality of NY, YY and NNY interactions!!!

Thank you!