A new EOS for nucleonic and hyperonic matter from ChEFT: application to NS structure and BNs merging

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Many of the results I will show today from the collaboration with:

- Ignazio Bombaci (University of Pisa)
- Alejandro Kievsky (INFN Pisa)
- Albino Perego (INFN Parma)
- Isaac Vidana (INFN Catania)
- Bruno Giacomazzo (University of Trento)
- Andrea Endrizzi (University of Trento)
- Riccardo Ciolfi (INAF Padova)
- Wolfgang Kastaun (Max Planck Institute)

Outlook

- The nuclear many-body problem
- Interactions from ChEFT and nuclear matter calculations
- EOS for cold and hot nucleonic matter
- Hyperon-puzzle in neutron stars
- Application to neutron star merging

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

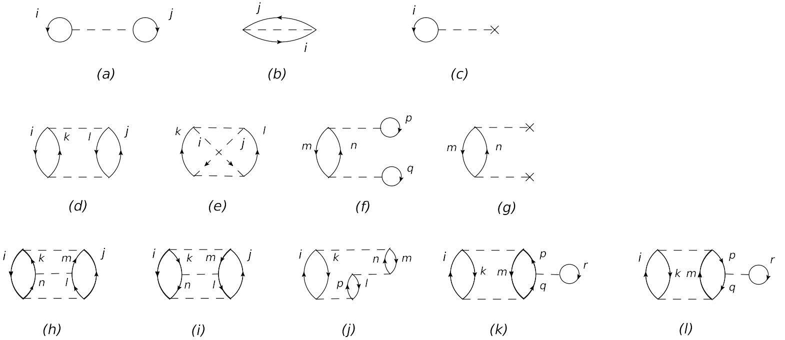
How to study it?

- 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.

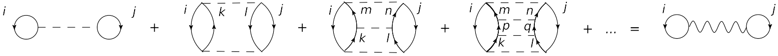
$$H = \sum_{i=1}^{A} T_i + \sum_{i<j}^{A} V_{ij} = H_0 + H_1;$$

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

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



Ladder diagrams summation:



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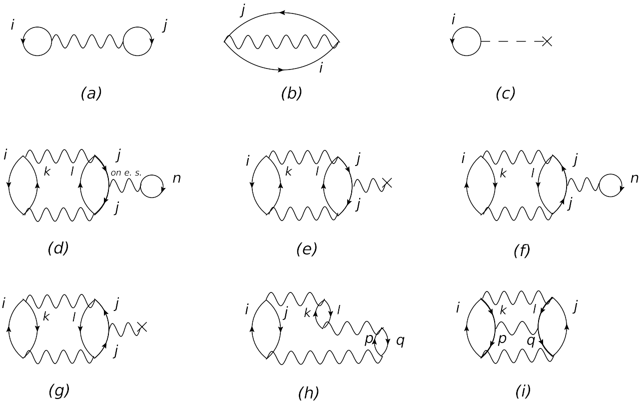


The Brueckner-Hartree-Fock approach

- Starting point: the Bethe-Goldstone equation

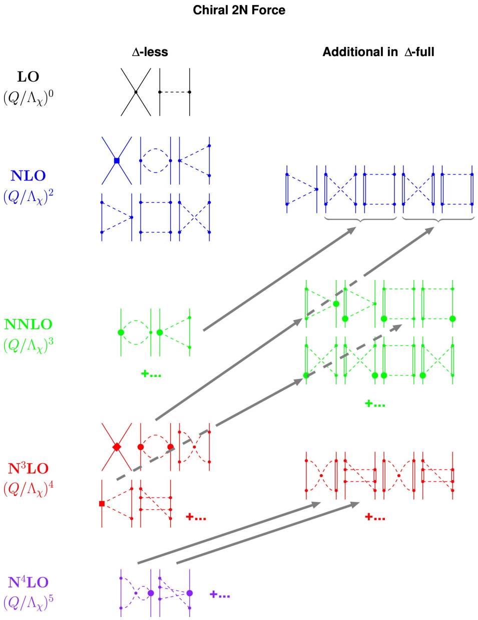
$$G(\omega)_{B_1B_2,B_3B_4} = V_{B_1B_2,B_3B_4} + \sum_{B_iB_j} V_{B_1B_2,B_iB_j} \times \frac{Q_{B_iB_j}}{\omega - E_{B_i} - E_{B_j} + i\eta} G(\omega)_{B_iB_j,B_3B_4}$$

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

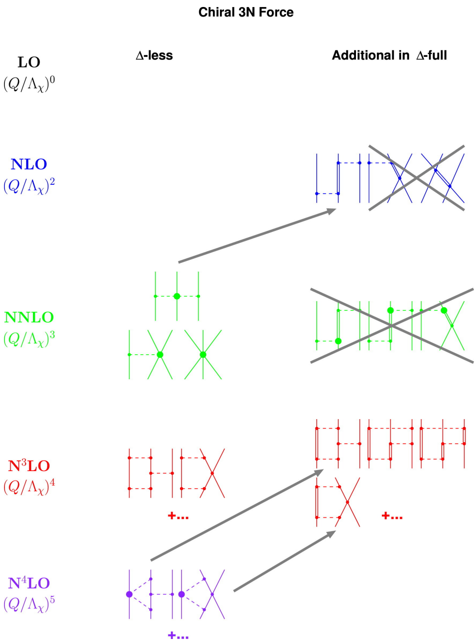
$$E_{B_i}(k) = M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + U_{B_i}(k)$$

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

NN chiral forces



NNN chiral forces



- 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

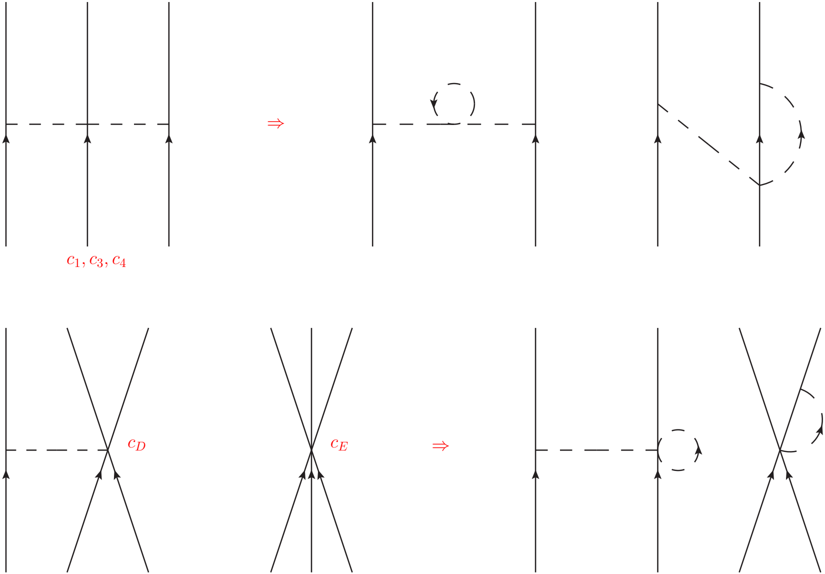
- BHF calculations with NNN forces $\Rightarrow$ very challenging

$$\Downarrow$$

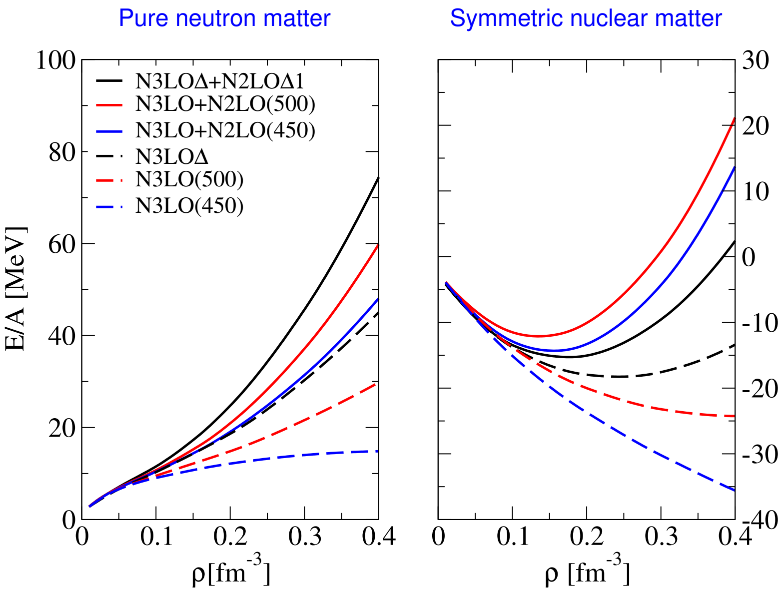
- NNN force is reduced to a NN density dependent one
- In p-space:

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

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



E/A nuclear matter N3LO+N2LO



Logoteta et al. Phys. Rev. C 94, 064001 (2016)

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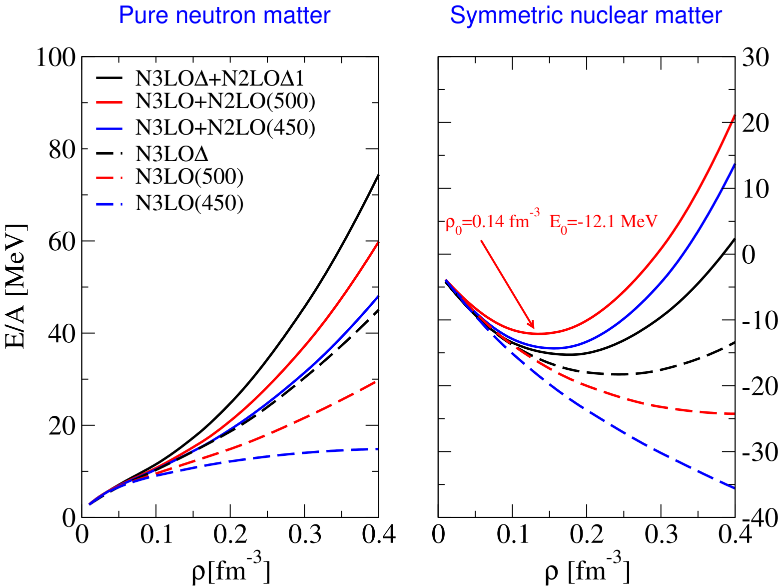

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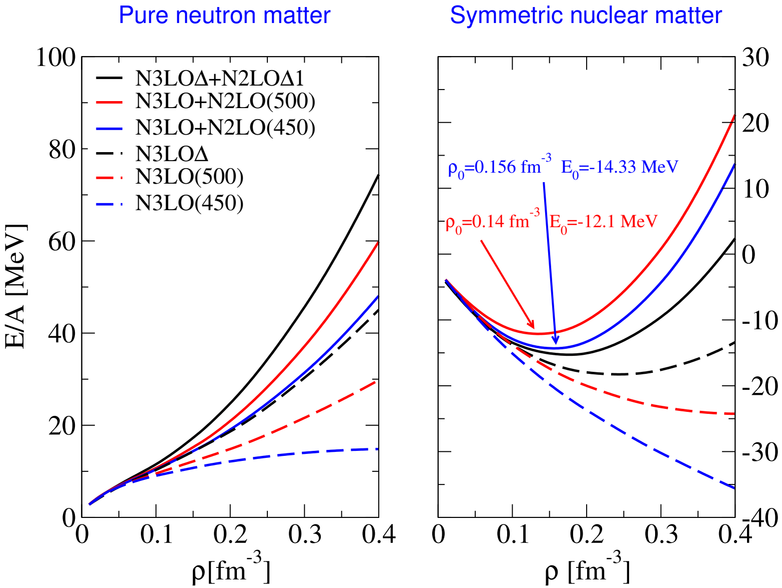

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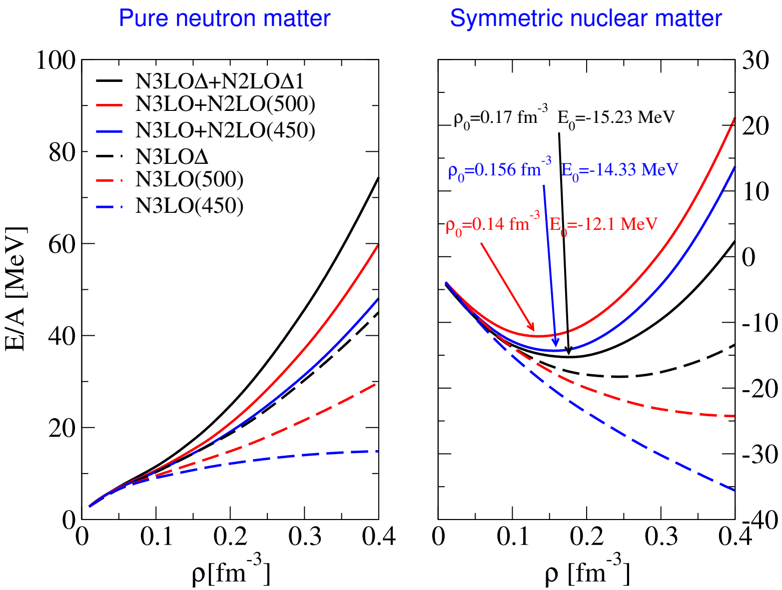

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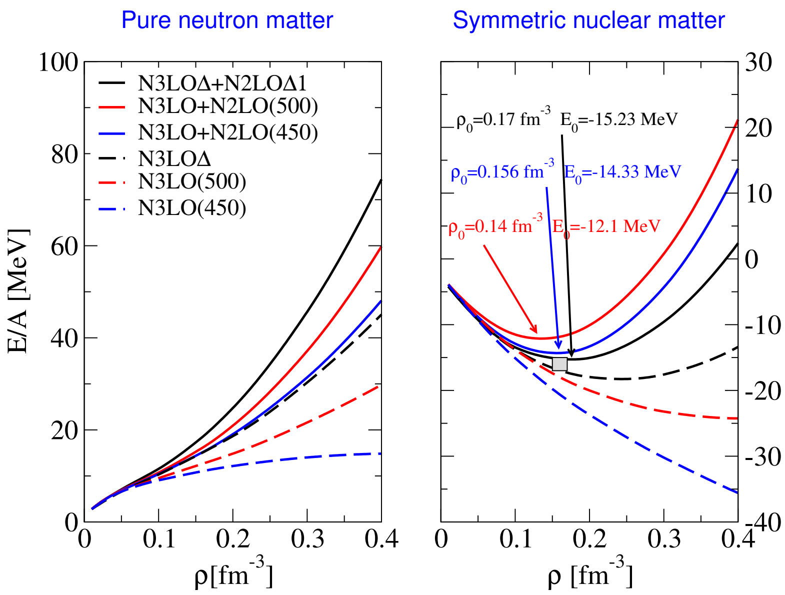
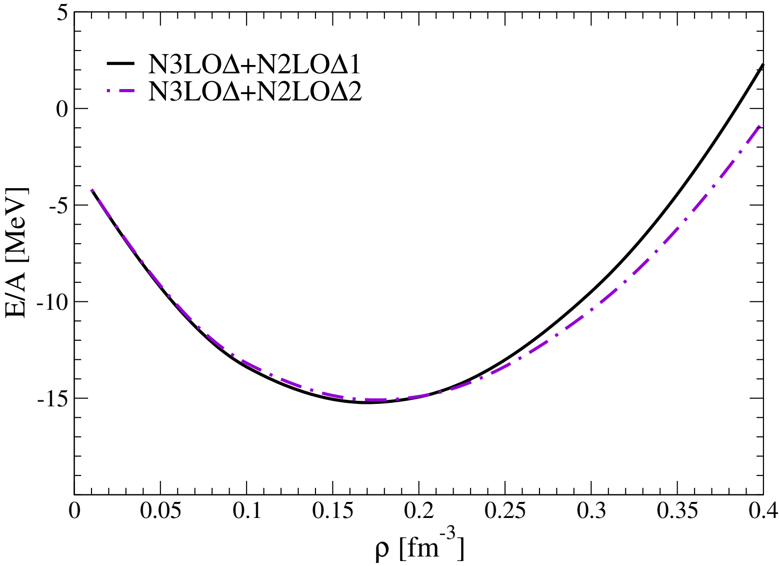


Logoteta et al. Phys. Rev. C 94, 064001 (2016)

Symmetric nuclear matter: comparision between N2LOΔ1 and N2LOΔ2



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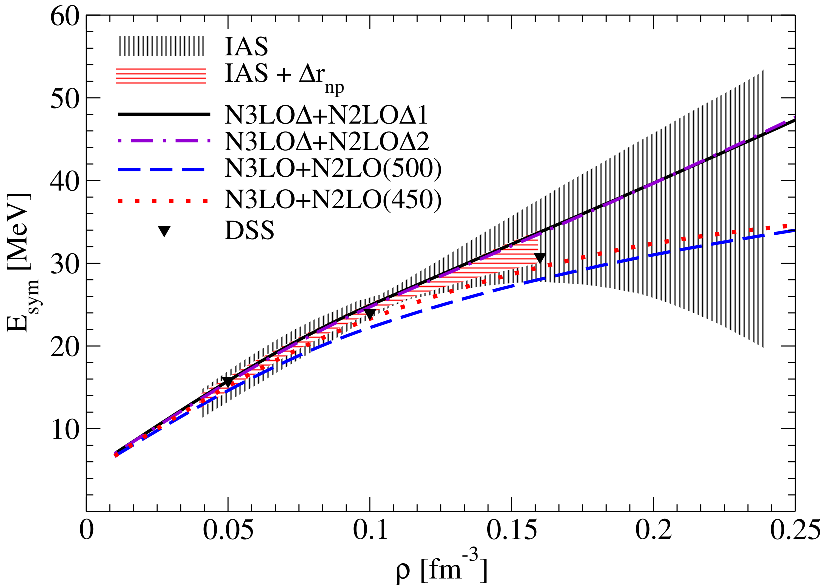
Symmetry energy N3LO+N2LO



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Equation of state for cold neutron stars

- Asymmetric matter ⇒ parabolic approximation:

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

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

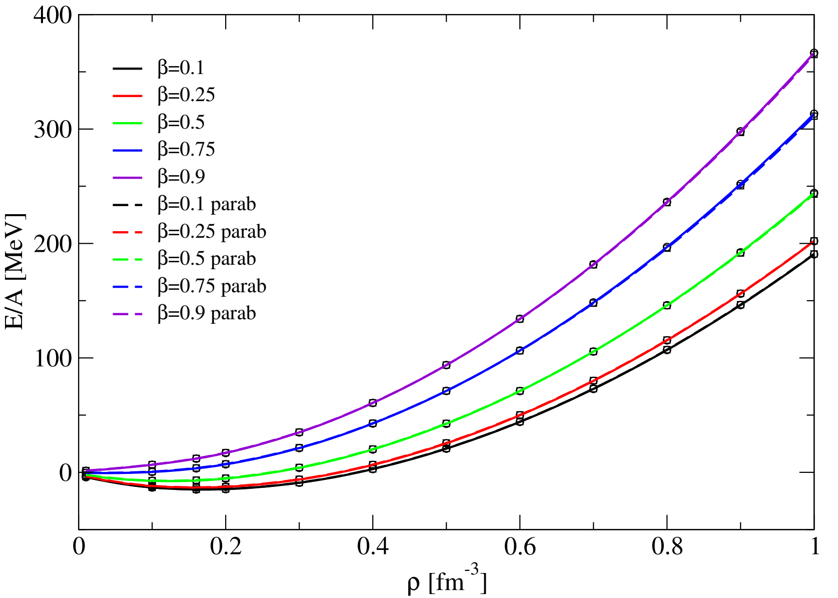
- Chemical equilibrium:

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

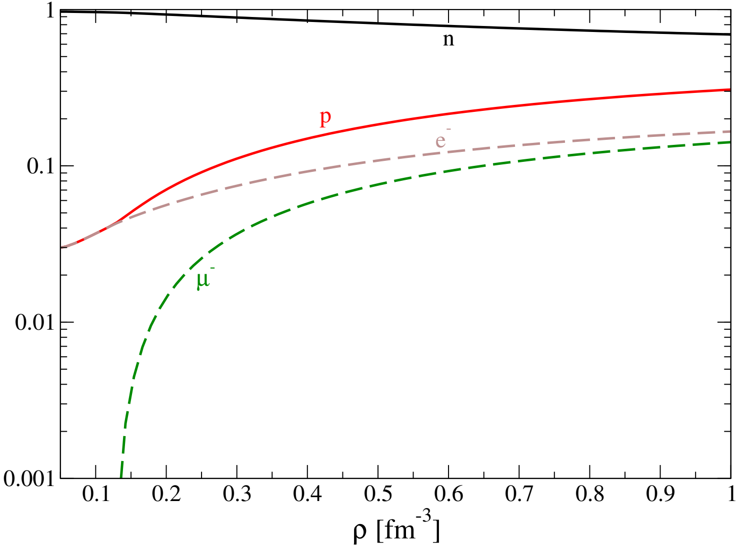
- Charge neutrality:

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

Check parabolic approximation for asymmetric matter

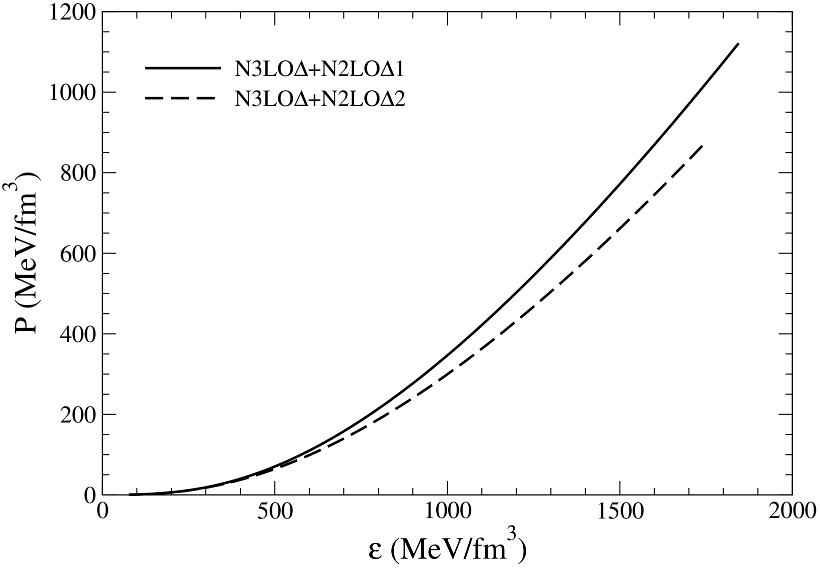


Particle fractions in $\beta-$stable matter N3LOΔ+N2LOΔ



I. Bombaci and D. Logoteta A&A 609, A128 (2018)

EOS $\beta-$stable matter N3LOΔ+N2LOΔ



I. Bombaci and D. Logoteta A&A 609, A128 (2018)

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

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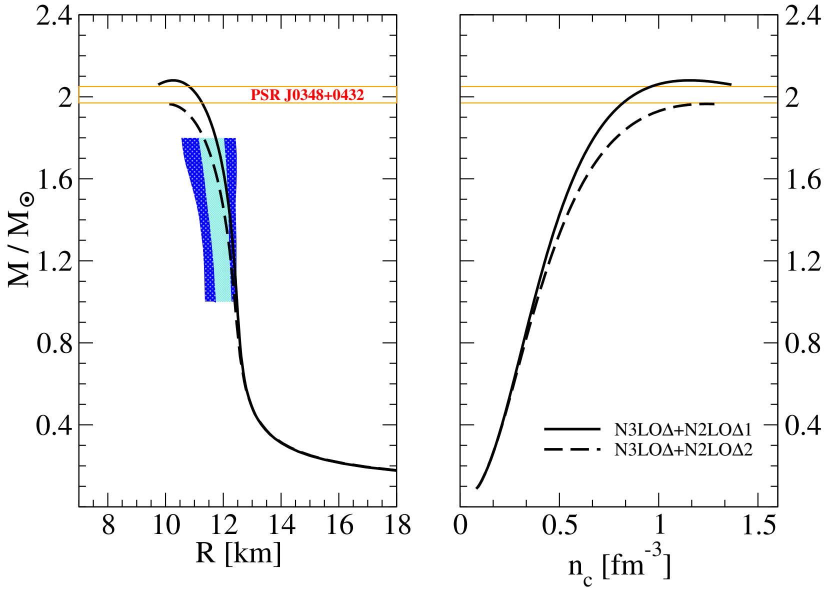
Neutron stars structure $\Rightarrow$ TOV equations

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



I. Bombaci and D. Logoteta A&A 609, A128 (2018)

Extension to finite temperature

- Starting point: the Bethe-Goldstone equation at finite T
- Note $Q_{B_iB_j} \Rightarrow Q_{B_iB_j}(T) = (1 - f_{B_i}) \times (1 - f_{B_j})$

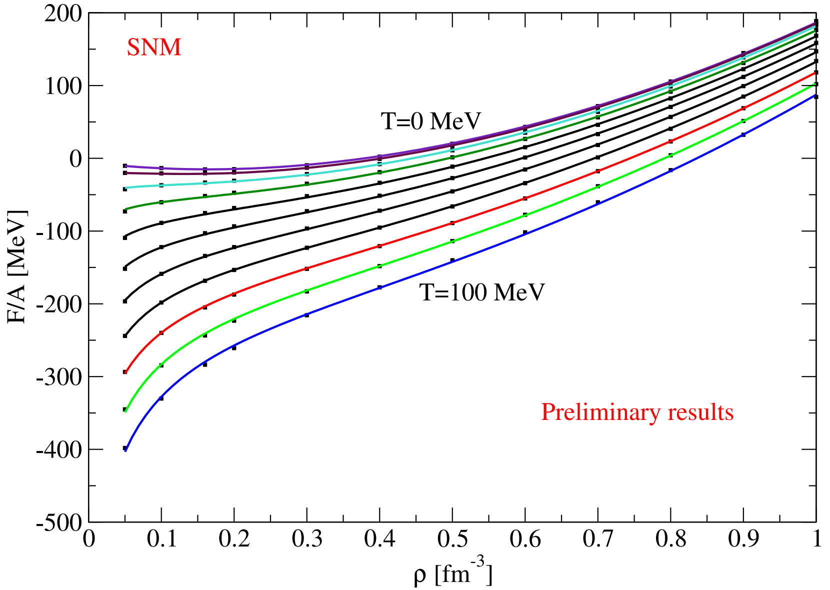
$$G(\omega)_{B_1B_2,B_3B_4} = V_{B_1B_2,B_3B_4} + \sum_{B_iB_j} V_{B_1B_2,B_iB_j} \times \frac{Q_{B_iB_j}}{\omega - E_{B_i} - E_{B_j} + i\eta} G(\omega)_{B_iB_j,B_3B_4}$$

$$U_{B_i}(k) = \sum_{B_j} \sum_{\vec{k'}} \times \langle \vec{k}\vec{k'} | G(E_{B_i}(\vec{k}) + E_{B_j}(\vec{k'}))_{B_iB_j,B_iB_j} | \vec{k}\vec{k'} \rangle_{\mathcal{A}} \; f_{B_j}(\vec{k'}, T)$$

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

$$\epsilon_{BHF} = \frac{1}{V} \sum_{B_i} \sum_{k} \left[M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + \frac{1}{2} U_{B_i}(k) \right] \; f_{B_i}(\vec{k}, T)$$

Analytic fit of F/A(T,ρ) for SNM



In collaboration with A. Perego

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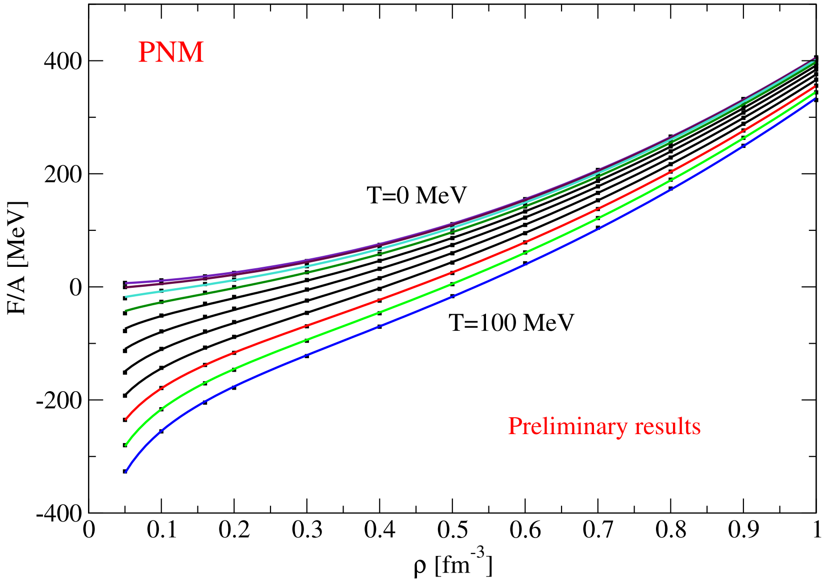

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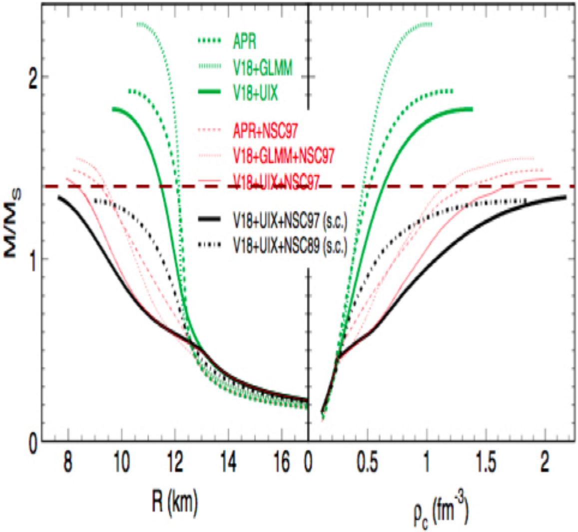
The problem of the maximum mass of neutron stars with microscopic approaches

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



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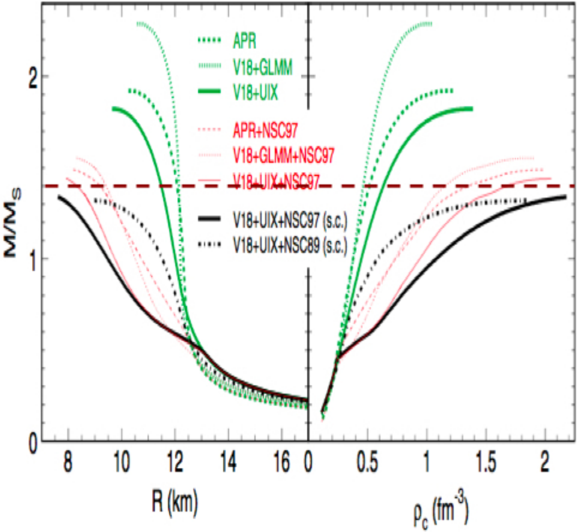

- $n + n \rightarrow n + \Lambda$
- $n + n \rightarrow p + \Sigma^-$
- $p + e^- \rightarrow \Lambda + \nu_{e^-}$
- $n + e^- \rightarrow \Sigma^- + \nu_{e^-}$

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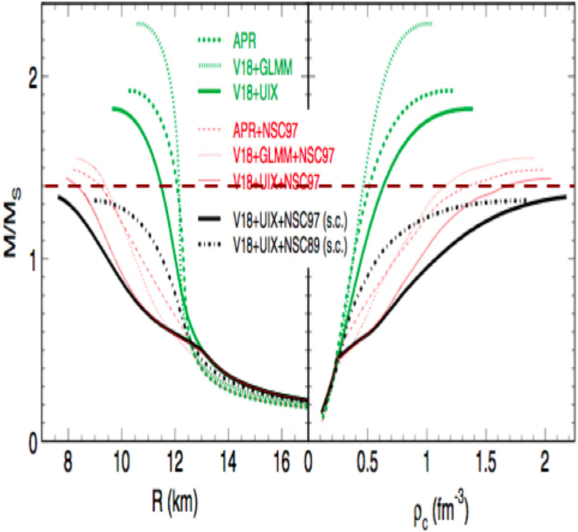

- $n + n \to n + \Lambda$
- $n + n \to p + \Sigma^-$
- $p + e^- \to \Lambda + \nu_{e^-}$
- $n + e^- \to \Sigma^- + \nu_{e^-}$
- Appearance of Hyperons $\Rightarrow$ Fermi pressure relieves
- $M_{max} < 1.44\ M_{\odot}$

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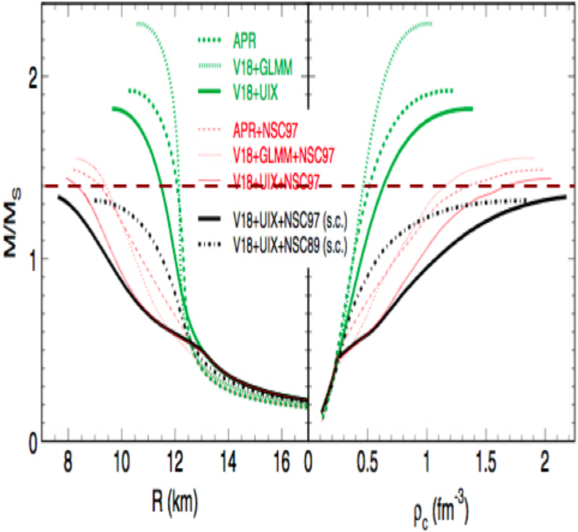

- Recent measurements:
- $M_{PRS}^{J1903+0327} = 1.67\ M_{\odot}$
- $M_{PRS}^{J1614-2230} = 1.97\ M_{\odot}$
- $M_{PRS}^{J0348+0432} = 2.01\ M_{\odot}$

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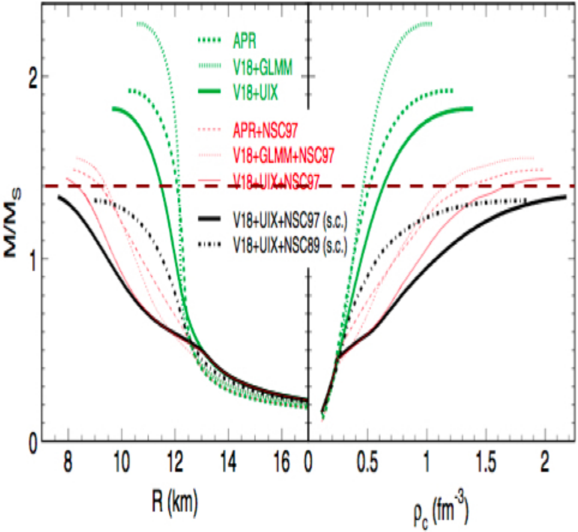

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DRAMMATIC SCENARIO!!

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

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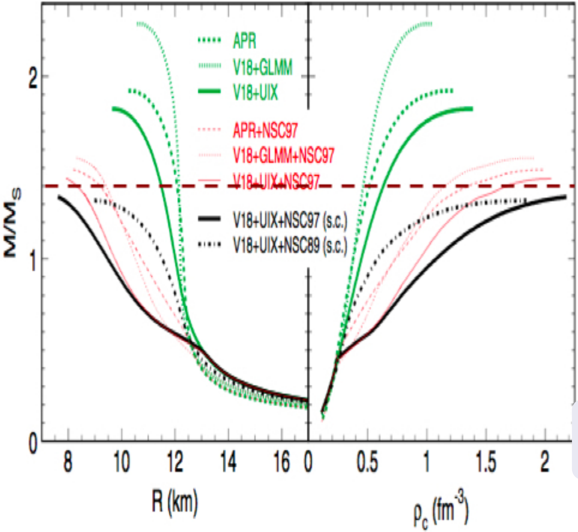

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DRAMMATIC SCENARIO!!

NNY, NYY and YYY may help??

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

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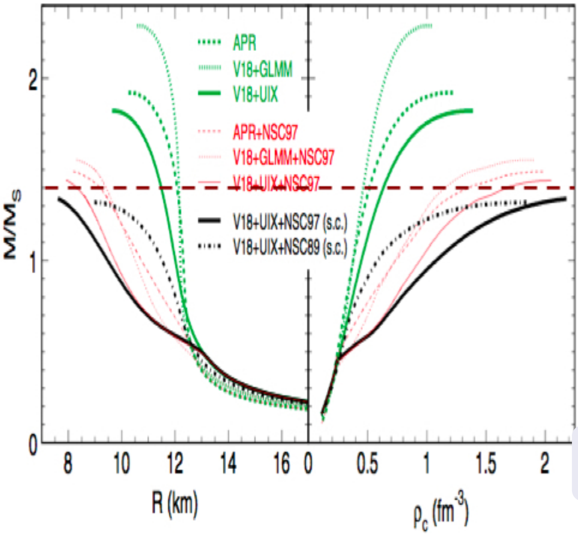

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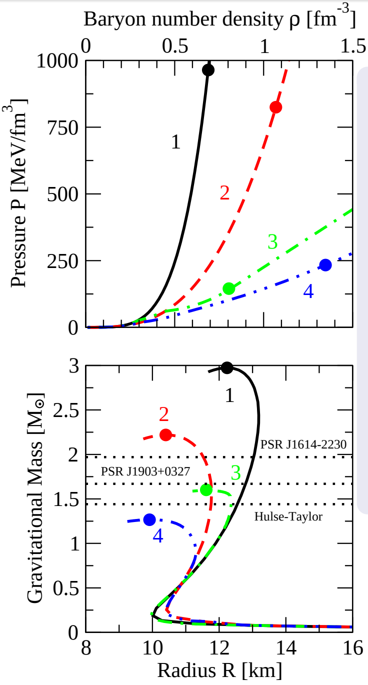
DRAMMATIC SCENARIO!!

We focused on the NNY interactions

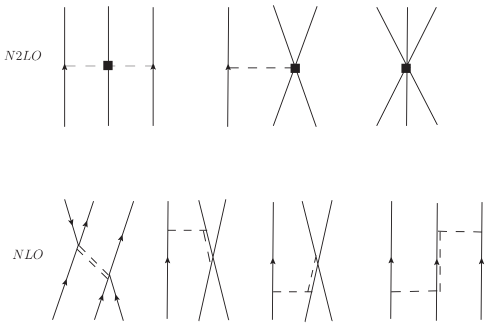


γ_{NN}	x	γ_{YN}	M_{max}
	0	-	1.27 (2.22)
	1/3	1.49	1.33
2	2/3	1.69	1.38
	1	1.77	1.41
	0	-	1.29 (2.46)
	1/3	1.84	1.38
2.5	2/3	2.08	1.44
	1	2.19	1.48
	0	-	1.34 (2.72)
	1/3	2.23	1.45
3	2/3	2.49	1.50
	1	2.62	1.54
	0	-	1.38 (2.97)
	1/3	2.63	1.51
3.5	2/3	2.91	1.56
	1	3.05	1.60

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

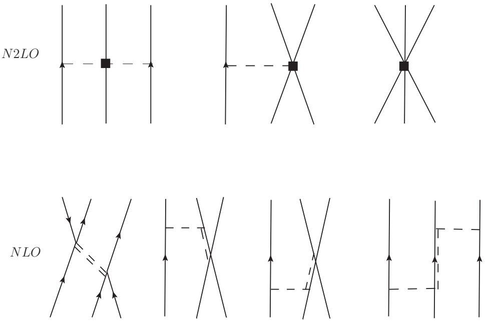
I. Vidaña, D. Logoteta, C. Providência, A. Polls, I. Bombaci EPL 94, 11002 (2011)

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

NNΛ force from ChPT



- Up to N2LO just 1 LEC ⇒ fixed to $U_\Lambda(k=0) = -30$ MeV

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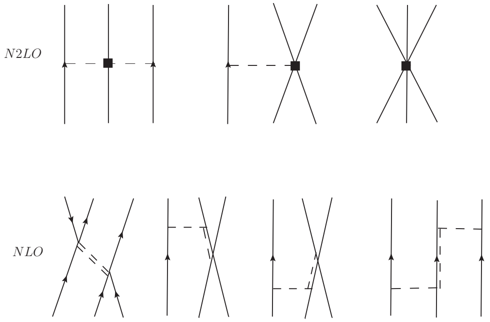

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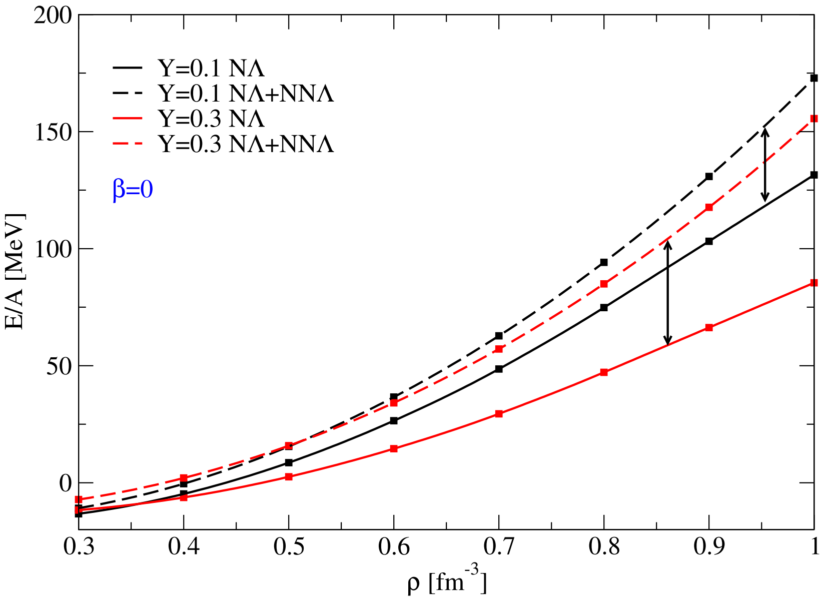
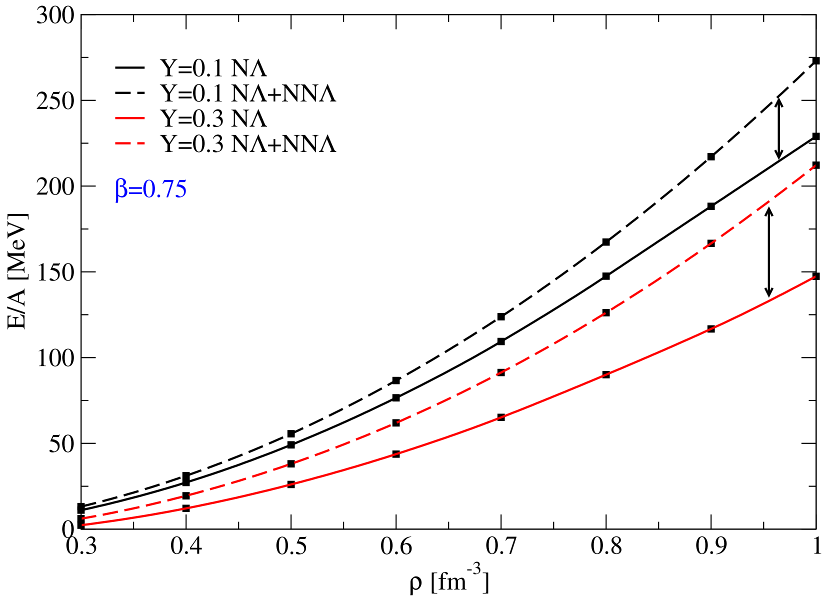
- Up to N2LO just 1 LEC $\Rightarrow$ fixed to $U_\Lambda(k=0) = -30$ MeV
- Note: NNΛ-force strongly improve heavy hypernuclei ($^{208}{}_\Lambda$Pb, $^{89}{}_\Lambda$Zr ,...) description!

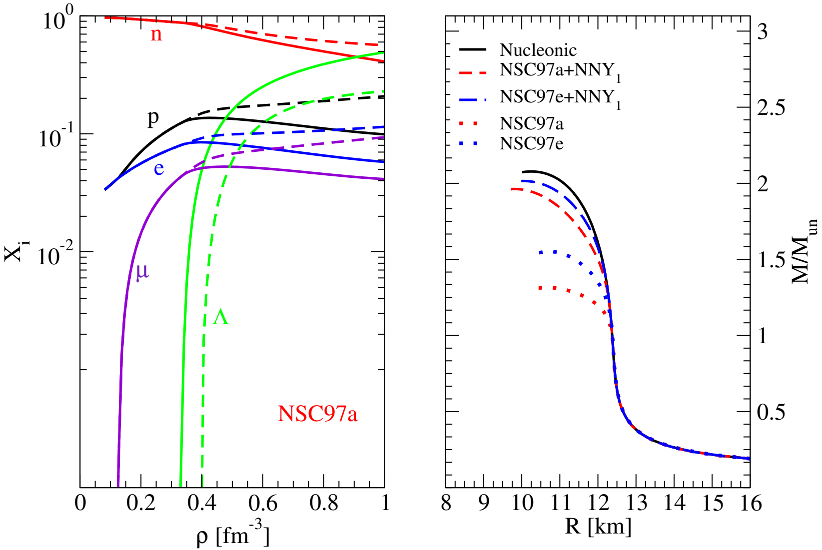
Effect of hyperonic three-body force NNΛ



Effect of hyperonic three-body force NNΛ



Neutron stars structure including Λ-hyperon



Application to binary neutron stars merging

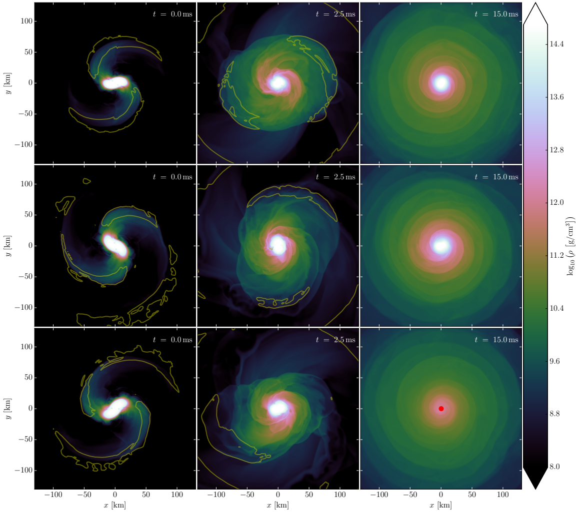
- Numerical simulation of NS($1.35\ M_\odot$)-NS($1.35\ M_\odot$) merging
- T=0 microscopic EOS + Thermal component added via gamma law
- Evolved with Whisky Thermal + Einstein Toolkit
- A new similation with a full T consistent EOS is under consideration
- Comparison: microscopic BL EOS vs EOS from RMF model (GM3) $\Rightarrow$ same M_{max} for both models

Dynamics of merging

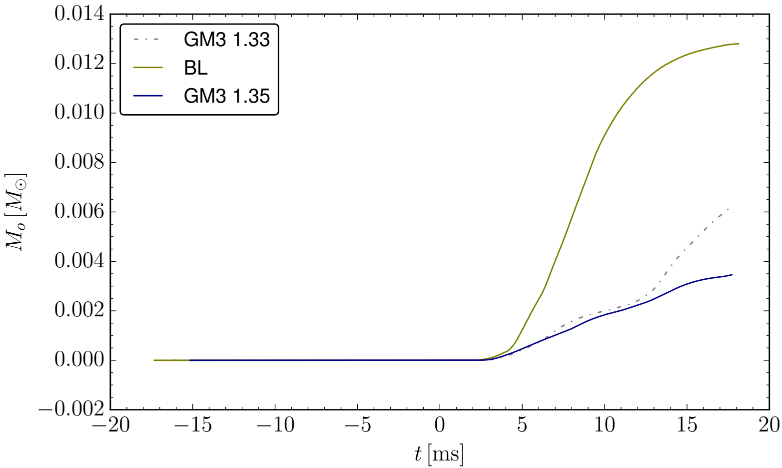
BL($1.35 M_\odot$)

GM3($1.31 M_\odot$)

GM3($1.35 M_\odot$)



A. Endrizzi, D. Logoteta, B. Giacomazzo, I. Bombaci, W. Kastaun and R. Ciolfi, to be submitted to PRD



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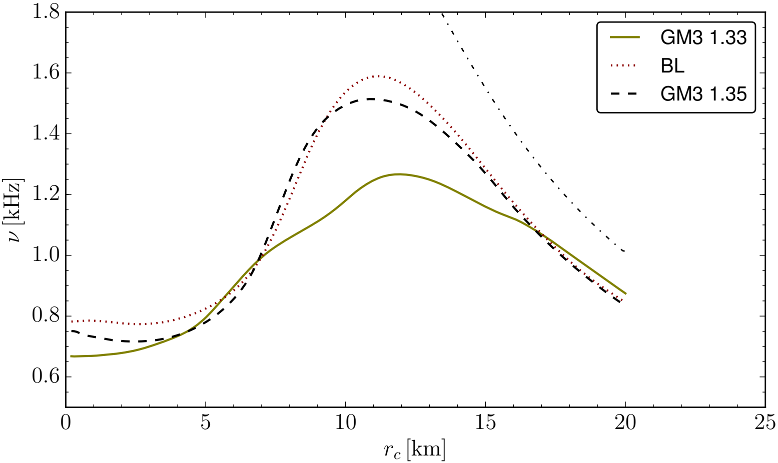
Rotational profile



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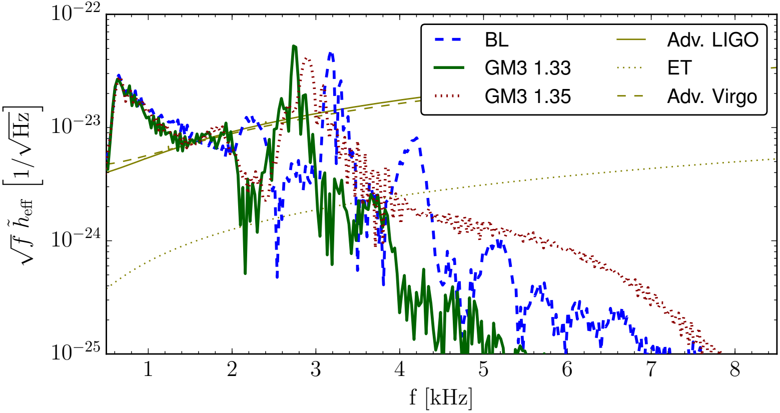

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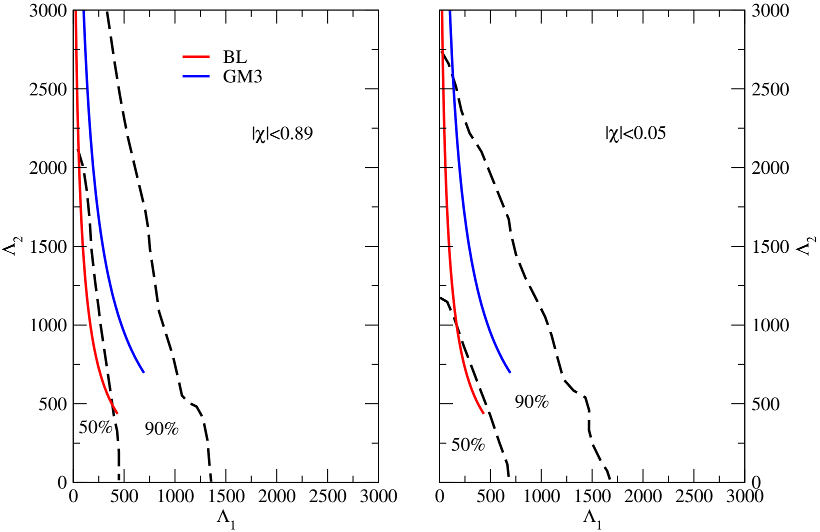
Numerical simulation of BNs merging

Main differences between the BL and GM3 EOSs

- HMNS: GM3 $\Rightarrow$ collapse in ~ 14 *ms* after merging; BL survives at least 5 *ms* more
- BL EOS ejects 6 times more mass than GM3 EOS (different compactness??)
- Main post-merger frequency 10% higher for BL than GM3
- Detecting the postmerger signal it would be possible to distinguish between the two EOSs!

- A reasonable description of nuclear matter and NSs based on ChEFT is possible
- A more in deep study of β-stable hyperonic matter based on NY, NNY chiral forces is under development... NOTE: the hyperon puzzle is still far to be solved but...we try to do the best!
- EOSs derived from ChEFT can consistently bridge together a lot of different physics: nuclei, nuclear matter, neutron stars, NSs-merging...CCS
- Future: new simulation with a hot EOS from ChEFT
- Future: new simulation with an hyperonic EOS from ChEFT

Thank you!


3000
2500
2000
1500
1000
500
0
Λ_2
BL
GM3
|χ|<0.89
50%
90%
0 500 1000 1500 2000 2500 3000
Λ_1
|χ|<0.05
90%
50%
0 500 1000 1500 2000 2500 3000
Λ_1
3000
2500
2000
1500
1000
500
0
Λ_2