Equation of state of hadronic matter and application to merging of neutron stars

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Collaborators

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

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

- 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: $A \rightarrow +\infty$ 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 $y = Y/A$

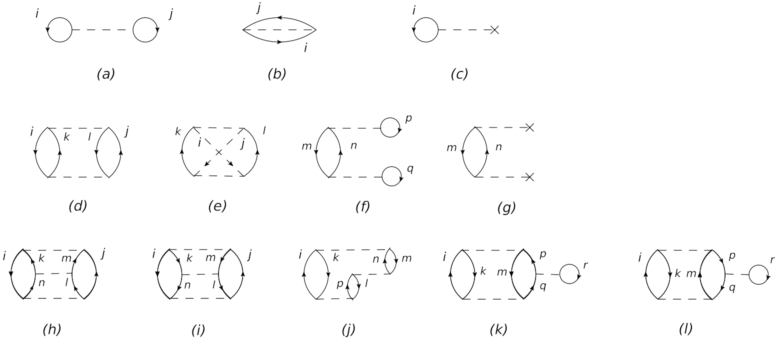
Several ways for studying this system...

- 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.

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

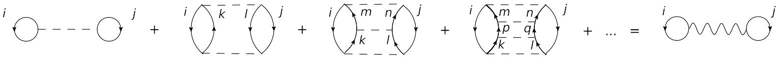
$$H_0 = \sum_{i=1}^{A} T_i + \sum_{i=1}^{A} U_i \qquad H_1 = \sum_{i<j}^{A} V_{ij} - \sum_{i=1}^{A} U_i$$

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



Bethe-Goldstone expansion up to three-hole-lines

Ladder diagrams summation:



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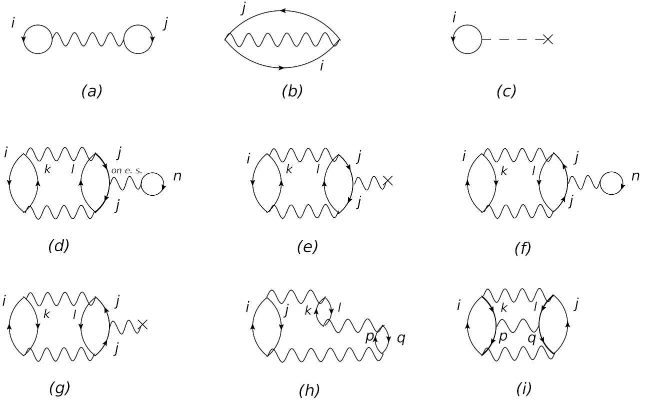


- Starting point: the Bethe-Goldstone equation

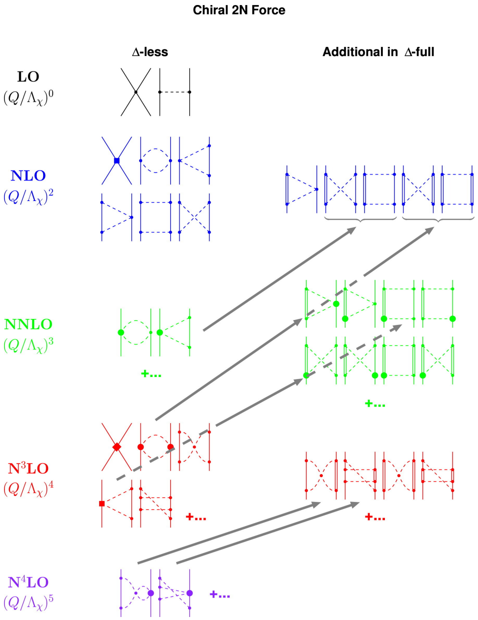
$$G(\omega)_{B_1B_2,B_3B_4} = V_{B_1B_2,B_3B_4} + \sum_{B_iB_j} V_{B_1B_2,B_iB_j} \times \frac{Q_{B_iB_j}}{\omega - E_{B_i} - E_{B_j} + i\eta} G(\omega)_{B_iB_j,B_3B_4}$$

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

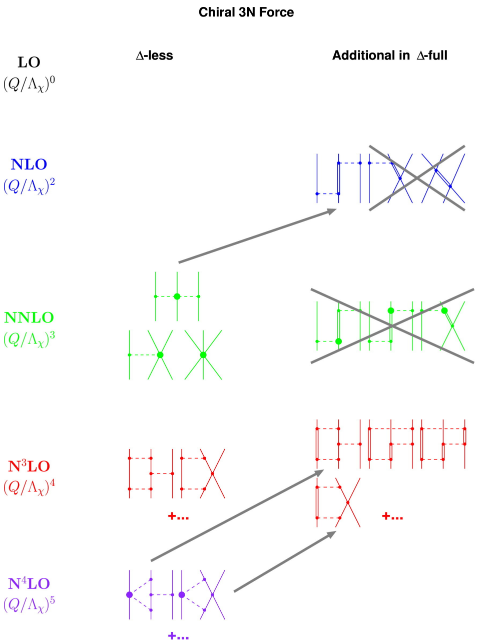
$$E_{B_i}(k) = M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + U_{B_i}(k)$$

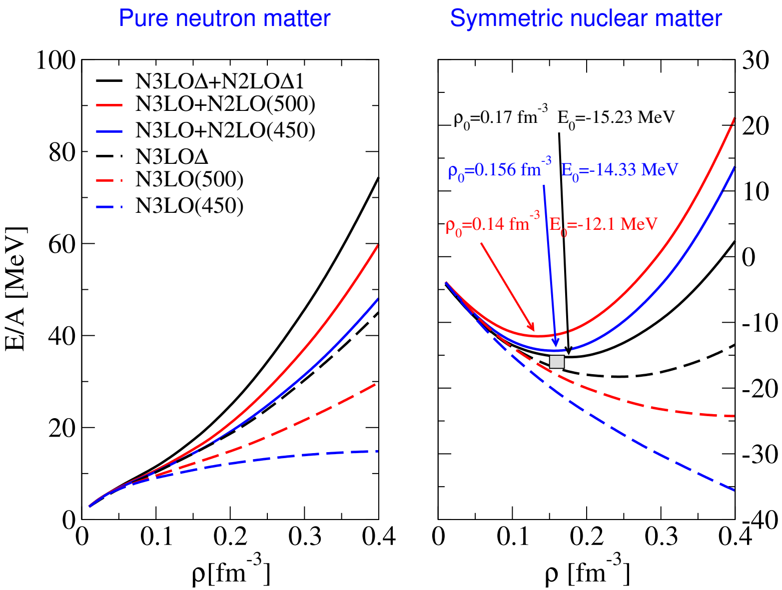
$$\epsilon_{BHF} = \frac{1}{V} \sum_{B_i} \sum_{k \leq k_{F_i}} \left[M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + \frac{1}{2} U_{B_i}(k) \right]$$

NN chiral forces



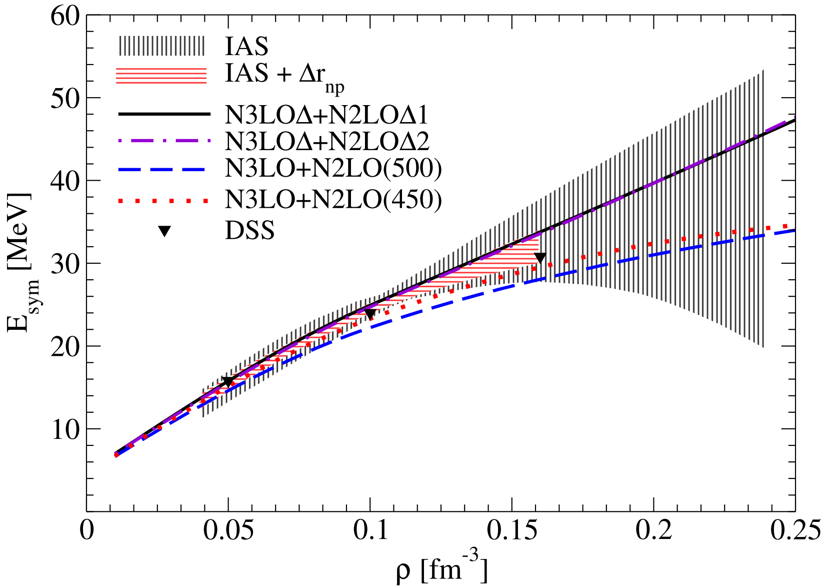
NNN chiral forces





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

Symmetry energy N3LO+N2LO



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

- Asymmetric matter $\Rightarrow$ parabolic approximation:

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

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

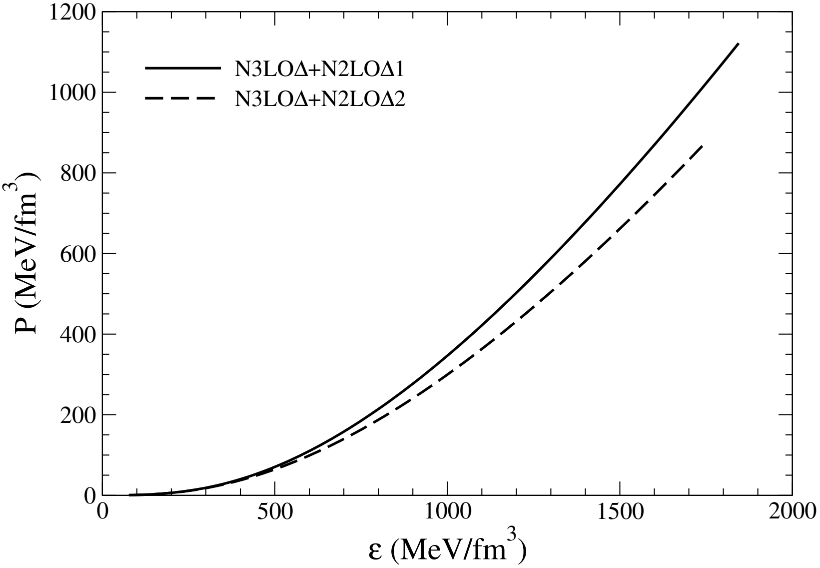
- Chemical equilibrium:

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

- Charge neutrality:

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

EOS $\beta-$stable matter N3LOΔ+N2LOΔ



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

- For NS: $\frac{GM}{Rc^2} \sim 10^{-1}$ $\Rightarrow$ GR is required!
- For a fixed equation of state (EOS): $P = P(\epsilon)$ and $P = P(\rho)$

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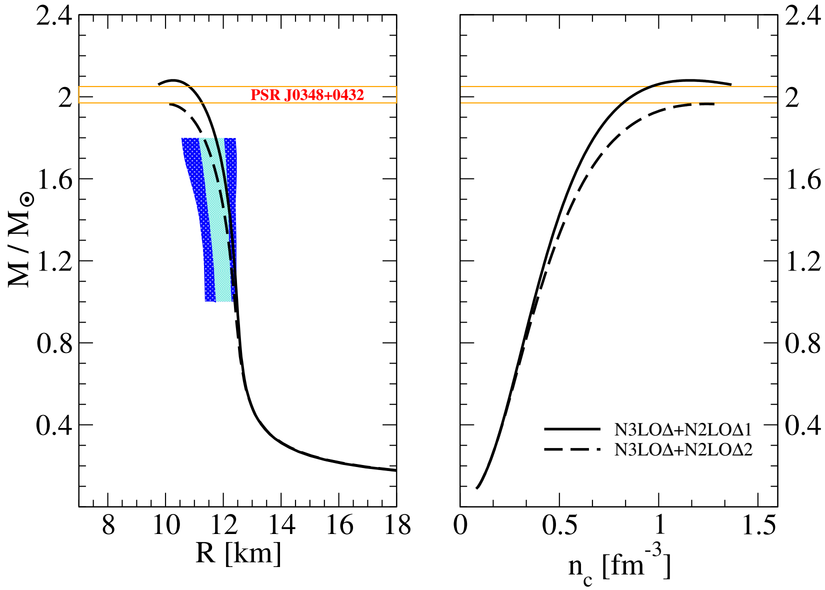
Neutron stars structure $\Rightarrow$ TOV equations

Equations of hydrostatic equilibrium in general relativity

Tolman-Oppenheimer-Volkoff (TOV):

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

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



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Extension to finite temperature

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

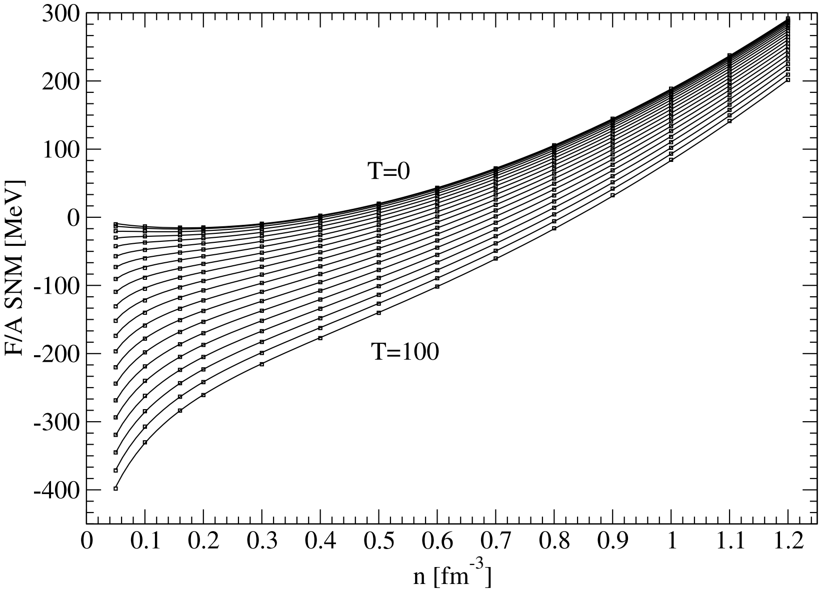
$$G(\omega)_{B_1B_2,B_3B_4} = V_{B_1B_2,B_3B_4} + \sum_{B_iB_j} V_{B_1B_2,B_iB_j} \times \frac{Q_{B_iB_j}}{\omega - E_{B_i} - E_{B_j} + i\eta} G(\omega)_{B_iB_j,B_3B_4}$$

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

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

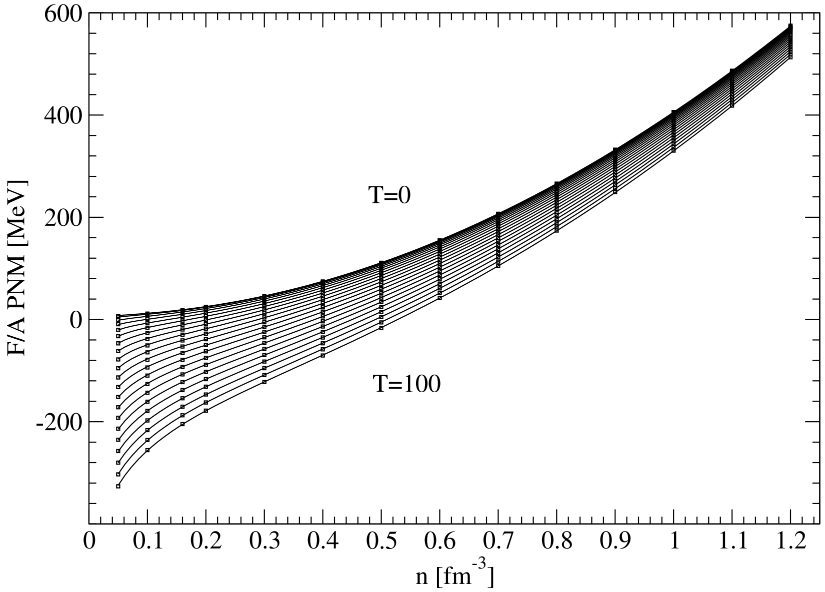
$$\epsilon_{BHF} = \frac{1}{V} \sum_{B_i} \sum_{k} \left[M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + \frac{1}{2} U_{B_i}(k) \right] \, f_{B_i}(\vec{k}, T)$$

Analytic fit of F/A(T,ρ) for SNM



Low density part: EOSs from RMF and/or skyrme models

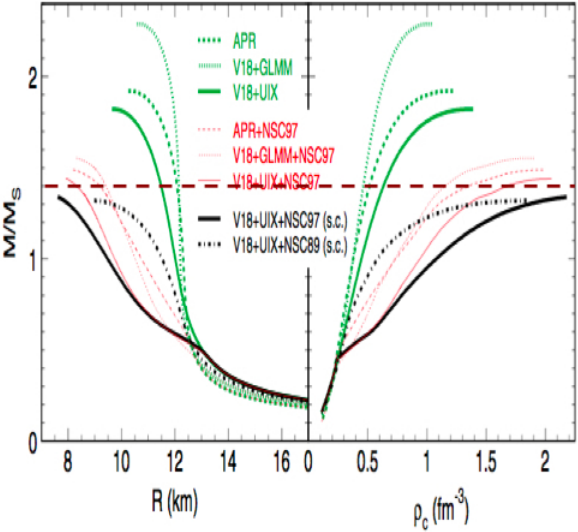
Analytic fit of F/A(T,ρ) for PNM



Low density part: EOSs from RMF and/or skyrme models

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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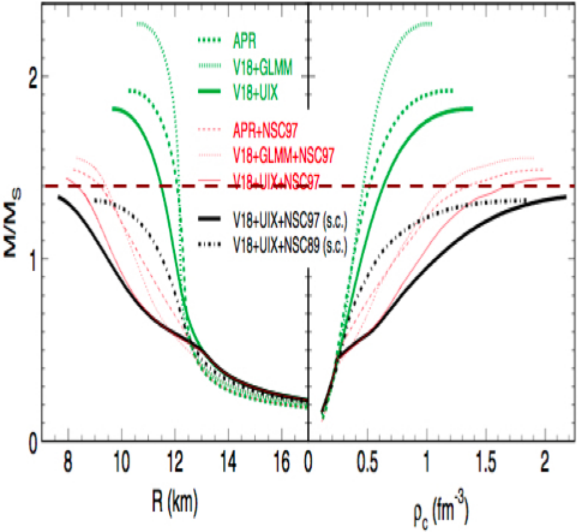

- $n + n \rightarrow n + \Lambda$
- $n + n \rightarrow p + \Sigma^-$
- $p + e^- \rightarrow \Lambda + \nu_{e^-}$
- $n + e^- \rightarrow \Sigma^- + \nu_{e^-}$

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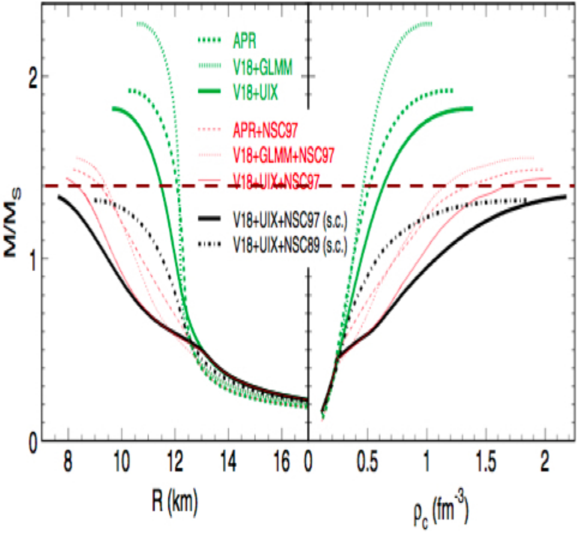

- $n + n \rightarrow n + \Lambda$
- $n + n \rightarrow p + \Sigma^-$
- $p + e^- \rightarrow \Lambda + \nu_{e^-}$
- $n + e^- \rightarrow \Sigma^- + \nu_{e^-}$
- Appearance of Hyperons $\Rightarrow$ Fermi pressure relieves
- $M_{max} < 1.44\ M_\odot$

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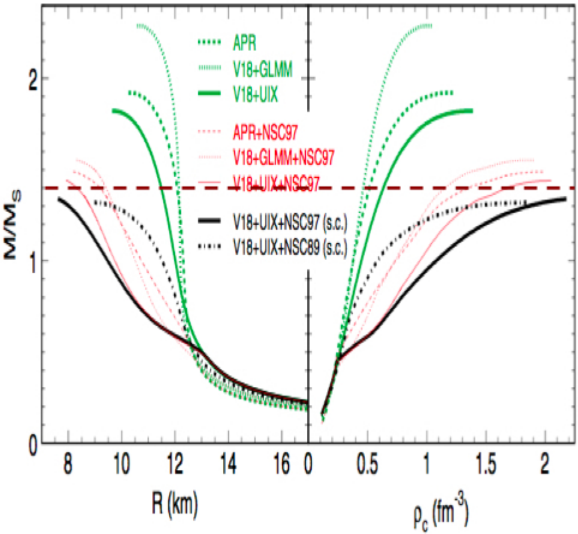

- Recent measurements:
- $M_{PRS}^{J1903+0327} = 1.67\ M_\odot$
- $M_{PRS}^{J1614-2230} = 1.97\ M_\odot$
- $M_{PRS}^{J0348+0432} = 2.01\ M_\odot$

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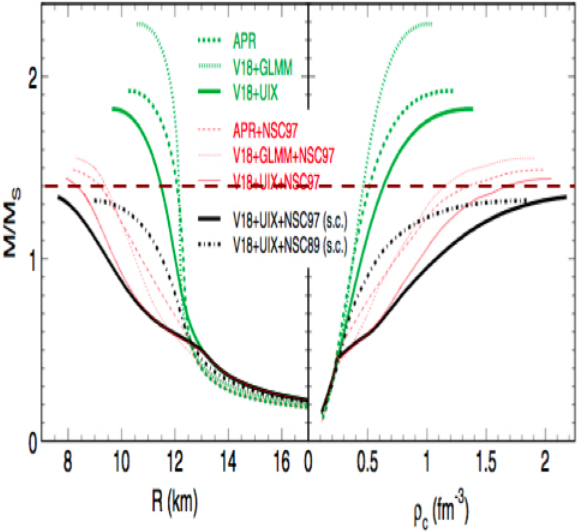

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DRAMMATIC SCENARIO!!

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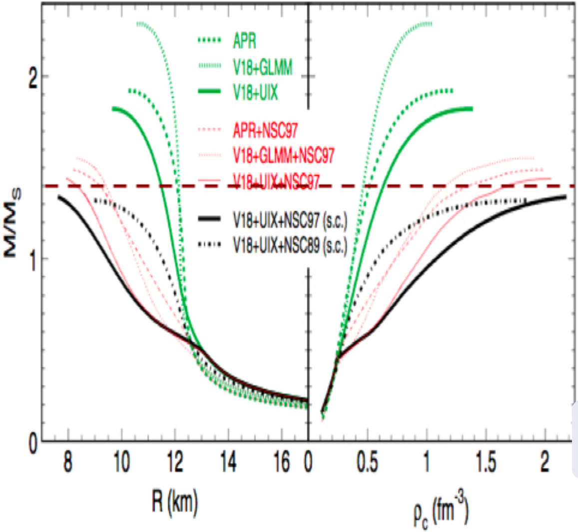

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DRAMMATIC SCENARIO!!

NNY, NYY and YYY may help??

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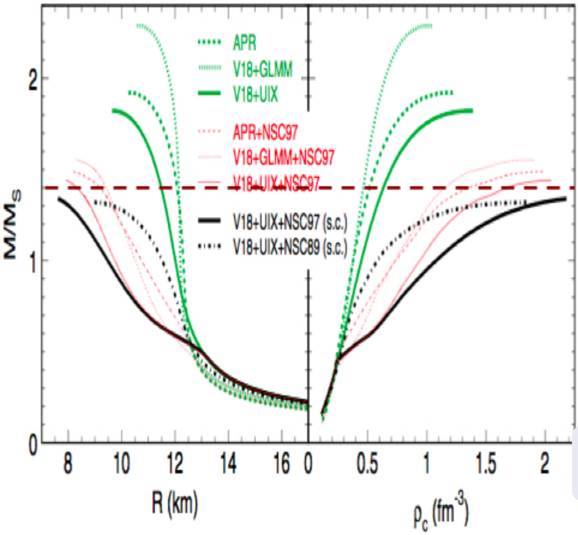

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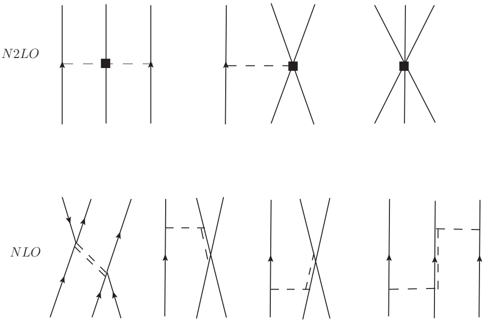
DRAMMATIC SCENARIO!!

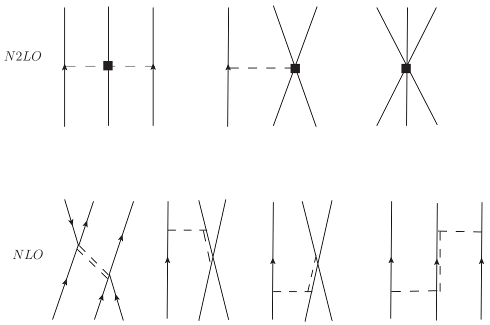
We focused on the NNY interactions

NNΛ force from ChPT



- Up to N2LO just 1 LEC ⇒ fixed to $U_\Lambda(k=0) = (-28,\ -30)$ MeV

- 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



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- Up to N2LO just 1 LEC $\Rightarrow$ fixed to $U_\Lambda(k=0) = (-28,\ -30)$ MeV
- Note: NNΛ-force strongly improve heavy hypernuclei ($^{208}{}_\Lambda$Pb, $^{89}{}_\Lambda$Zr ,...) description!

- Improvement in the separation energies of Λ-hypernuclei

	${}^{41}_{\Lambda}$Ca	${}^{91}_{\Lambda}$Zr	${}^{209}_{\Lambda}$Pb
NSC97a	23.0	31.3	38.8
NSC97a+NNΛ_1	14.9	21.1	26.8
NSC97a+NNΛ_2	13.3	19.3	24.7
NSC97e	24.2	32.3	39.5
NSC97e+NNΛ_1	16.1	22.3	27.9
NSC97e+NNΛ_2	14.7	20.7	26.1
Exp.	20.0	23.0	27.0

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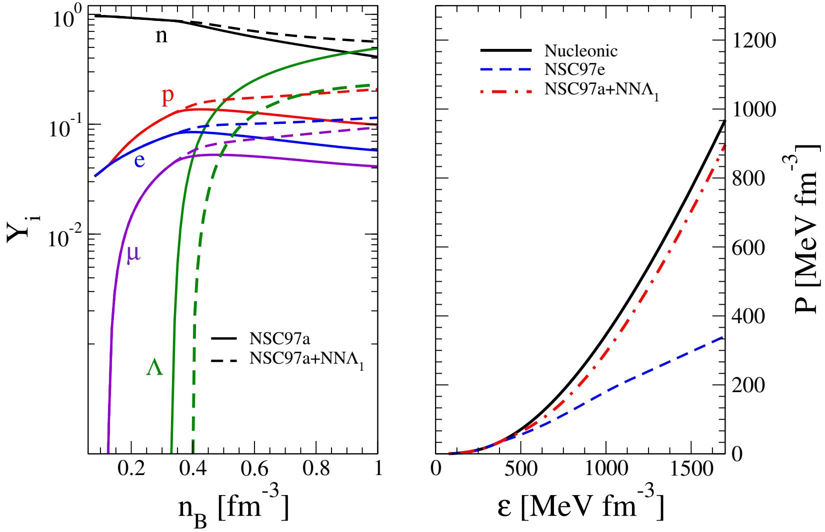
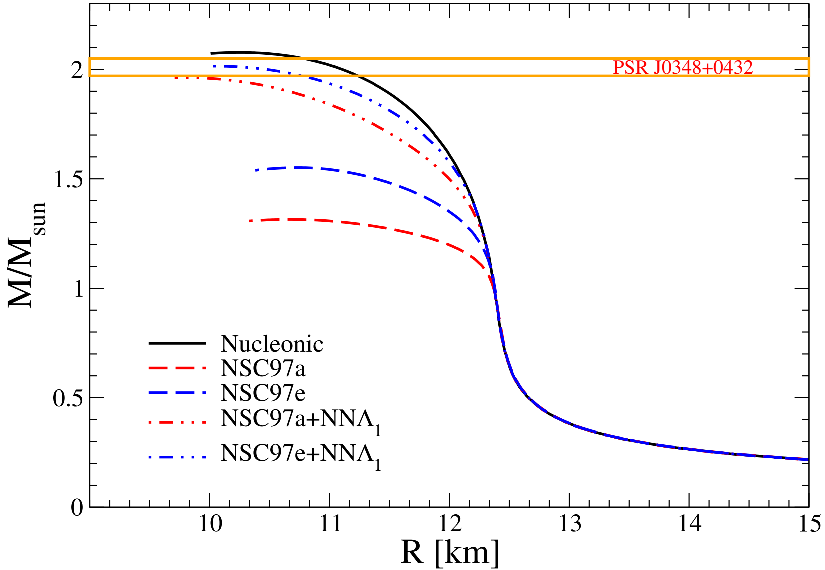
NOTE: experimental SE relative to: ${}^{40}_{\Lambda}$Ca, ${}^{89}_{\Lambda}$Y and ${}^{208}_{\Lambda}$Pb

Composition of hyperonic matter



D. Logoteta, I. Vidaña and I. Bombaci accepted for publication in EPJA Lett.

Neutron stars structure including Λ-hyperon



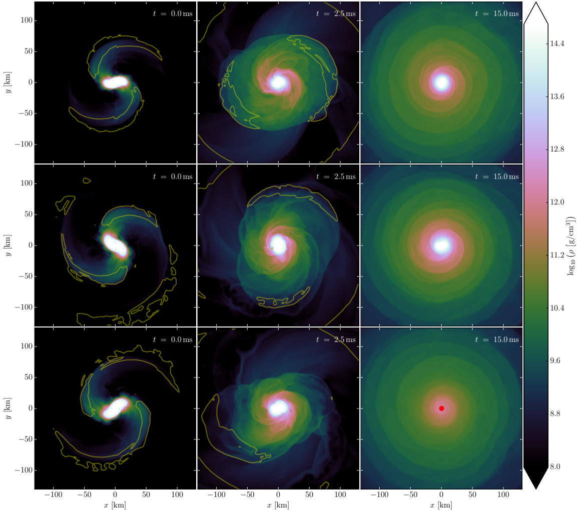
D. Logoteta, I. Vidaña and I. Bombaci accepted for publication in EPJA Lett.

- 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

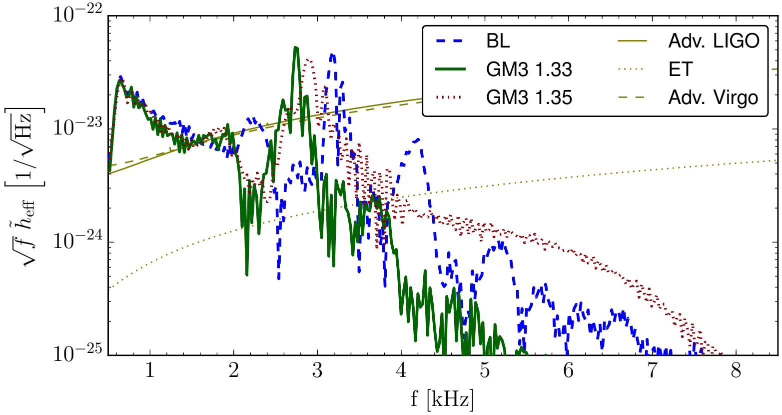
BL($1.35 M_\odot$)

GM3($1.31 M_\odot$)

GM3($1.35 M_\odot$)



A. Endrizzi, D. Logoteta, B. Giacomazzo, I. Bombaci, W. Kastaun and R. Ciolfi, Phys. Rev. D 98, 043015 (2018)



A. Endrizzi, D. Logoteta, B. Giacomazzo, I. Bombaci, W. Kastaun and R. Ciolfi, Phys. Rev. D 98, 043015 (2018)

Numerical simulation of BNs merging using a finite temperature EOS

- 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: from a microscopic point of view the hyperon puzzle is still far to be solved but we are improving our understanding...
- Future: new simulations with hot EOSs are running (in collaboration also with S. Bernuzzi and D. Radice)
- Future: new simulations with a quark-matter phase transition under considerations