

Hyperons in neutron stars

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Fundamental Physics at the strangeness Frontier at DAFNE

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UNIVERSITÀ DI PISA

Results in collaboration with:

Ignazio Bombaci (University of Pisa)

Isaac Vidaña (INFN Catania)

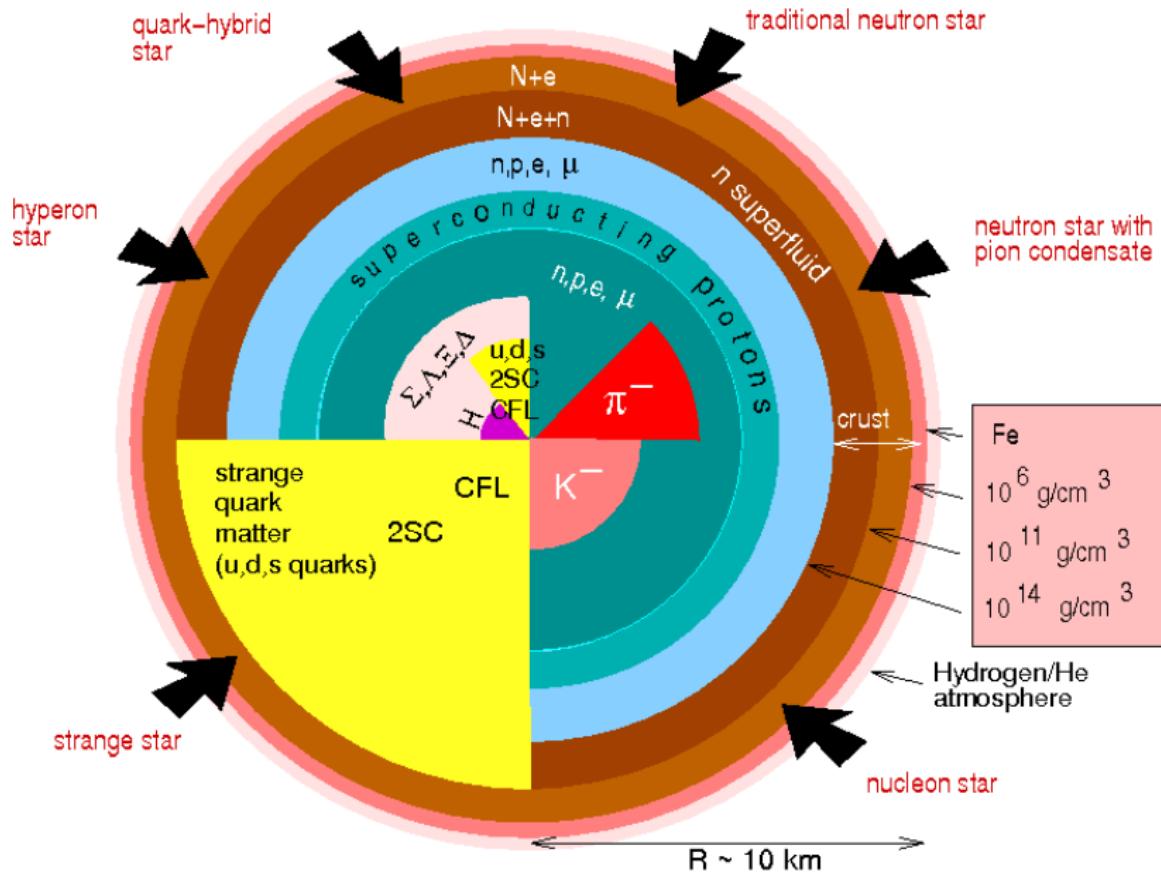
Very soon: results from the collaboration with the Ferrara group!

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

- What do we mean by EOS?
- A relation between: $(n_B, T, P, \epsilon, \{X_i\})$
- n_B : baryonic density
- T : temperature
- P : pressure
- ϵ : energy density
- $\{X_i\}$: composition

- What do we mean by EOS of neutron star matter?
- A relation between: $(n_B, T, P, \epsilon, \{X_i\})$
- n_B : range: $(10^{-13} - 1.5) \text{ fm}^{-3}$
- T : range: $(0 - 100) \text{ MeV}$
- P : range: $(\sim 0 - 10^{38}) \text{ dyne cm}^{-2}$
- ϵ : range: $(1 - 10^{17}) \text{ g cm}^{-3}$
- $\{X_i\}$: n, p, e^- , μ^- , hyperons(?), quarks(?)

Neutron star interior



Which tools do we need?

- A many-body method for low density matter: currently only phenomenological approaches are available: Skyrme, Relativistic mean field (RMF) or Density functional methods
- A many-body method for high density matter: Microscopic approaches or phenomenological approaches
- Our choice for low density matter: RMF
- Our choice for high density matter: Microscopic Brueckner-Hartree-Fock (BHF) approach
- BHF approach: required just the knowledge of the interactions between particles \Rightarrow NO FREE PARAMETERS

- First task: anchor the EOS to what we know... (not so much unfortunately...)

- $\frac{E}{A}(n_0, \beta = 0) = (-16 \pm 1) \text{ MeV}$

- $n_0 = (0.16 \pm 0.01) \text{ fm}^{-3}$ $\beta = \frac{n_n - n_p}{n_n + n_p}$

- $E_{sym}(n_0) = \frac{1}{2} \frac{\partial^2 E/A}{\partial \beta^2} = (33 \pm 3) \text{ MeV}$

- $K_\infty(n_0) = \frac{1}{2} \frac{\partial^2 E/A}{\partial n^2} = (220 \pm 30) \text{ MeV}$

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- How to derive these properties within a microscopic framework?
- May we use a perturbation theory?

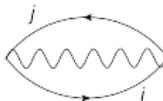
Ladder diagrams summation:

$$i \circlearrowleft \cdots \circlearrowleft j + i \circlearrowleft \bar{k} \bar{l} \bar{j} \circlearrowright + i \circlearrowleft \bar{m} \bar{n} \bar{j} \circlearrowright + i \circlearrowleft \bar{p} \bar{q} \bar{j} \circlearrowright + \dots = i \circlearrowleft \text{wavy line} \circlearrowright j$$

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



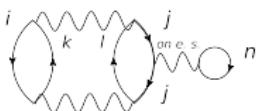
(a)



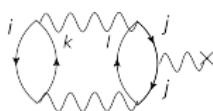
(b)



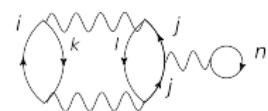
(c)



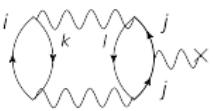
(d)



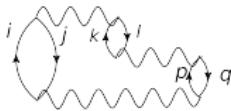
(e)



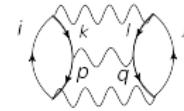
(f)



(g)



(h)



(i)

The Brueckner-Hartree-Fock approach

- Starting point: the Bethe-Goldstone equation

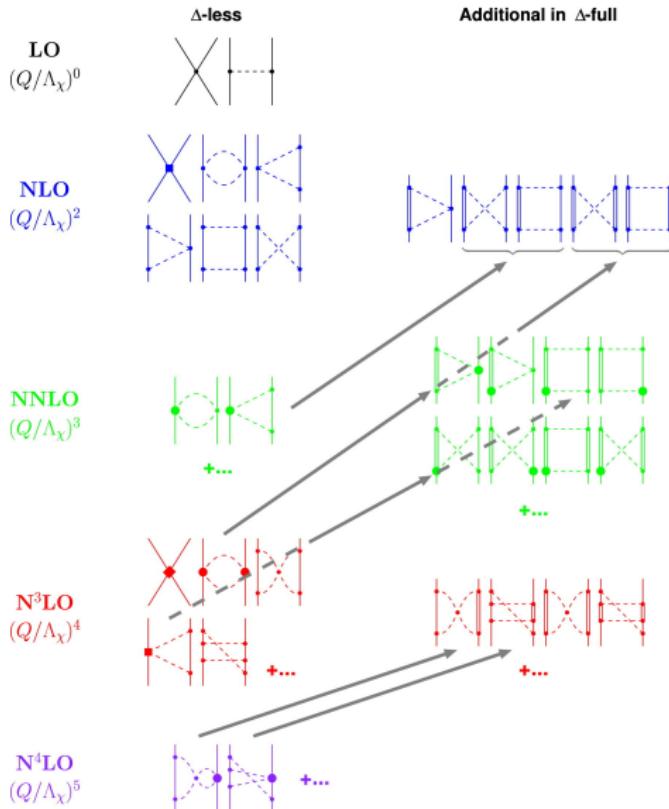
$$G(\omega)_{B_1 B_2, B_3 B_4} = V_{B_1 B_2, B_3 B_4} + \sum_{B_i B_j} V_{B_1 B_2, B_i B_j} \times \frac{Q_{B_i B_j}}{\omega - E_{B_i} - E_{B_j} + i\eta} G(\omega)_{B_i B_j, B_3 B_4}$$

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

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

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

Chiral 2N Force



Chiral 3N Force

LO
 $(Q/\Lambda_\chi)^0$

Δ -less

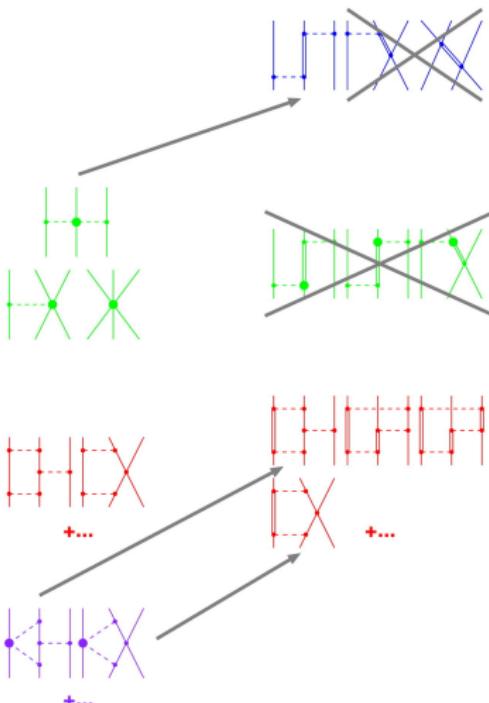
Additional in Δ -full

NLO
 $(Q/\Lambda_\chi)^2$

NNLO
 $(Q/\Lambda_\chi)^3$

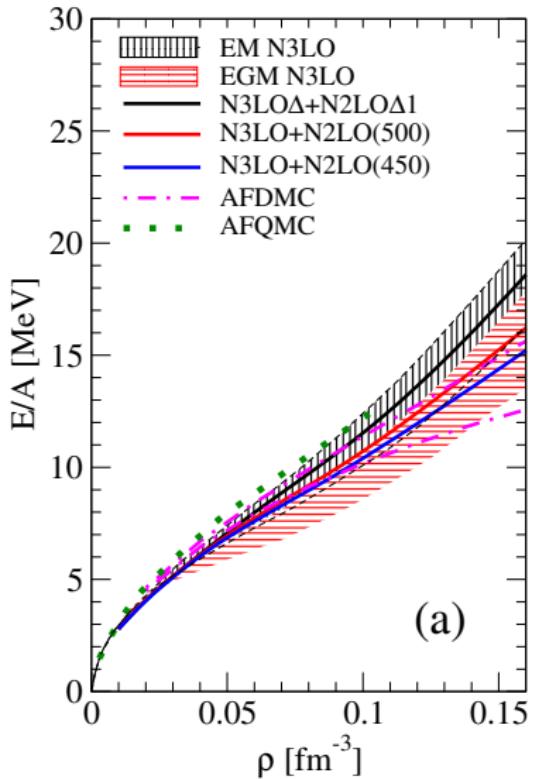
N^3LO
 $(Q/\Lambda_\chi)^4$

N^4LO
 $(Q/\Lambda_\chi)^5$

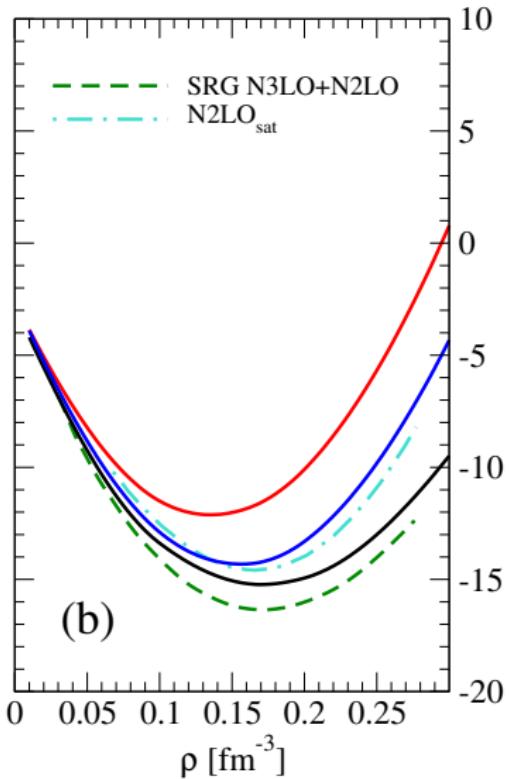


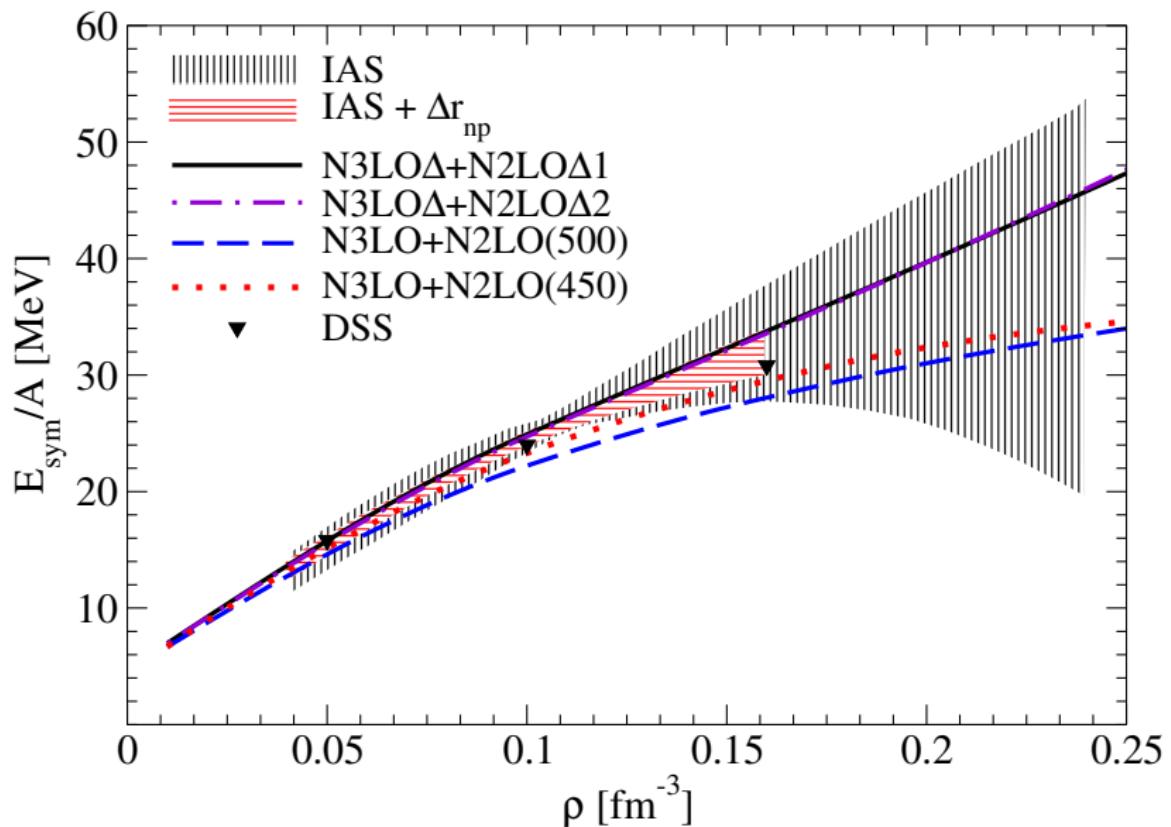
E/A nuclear matter N3LO+N2LO

Pure neutron matter $\beta = 1$



Symmetric nuclear matter $\beta = 0$





Equation of state for cold neutron stars (T=0)

$$E/A(\beta, n_B) = E/A_{snm}(n_B) + E_{sym}(n_B)\beta^2 \quad \beta = \frac{n_n - n_p}{n_n + n_p}$$

$$E_{sym}(n_B) = E/A_{pnm}(n_B) - E/A_{snm}(n_B)$$

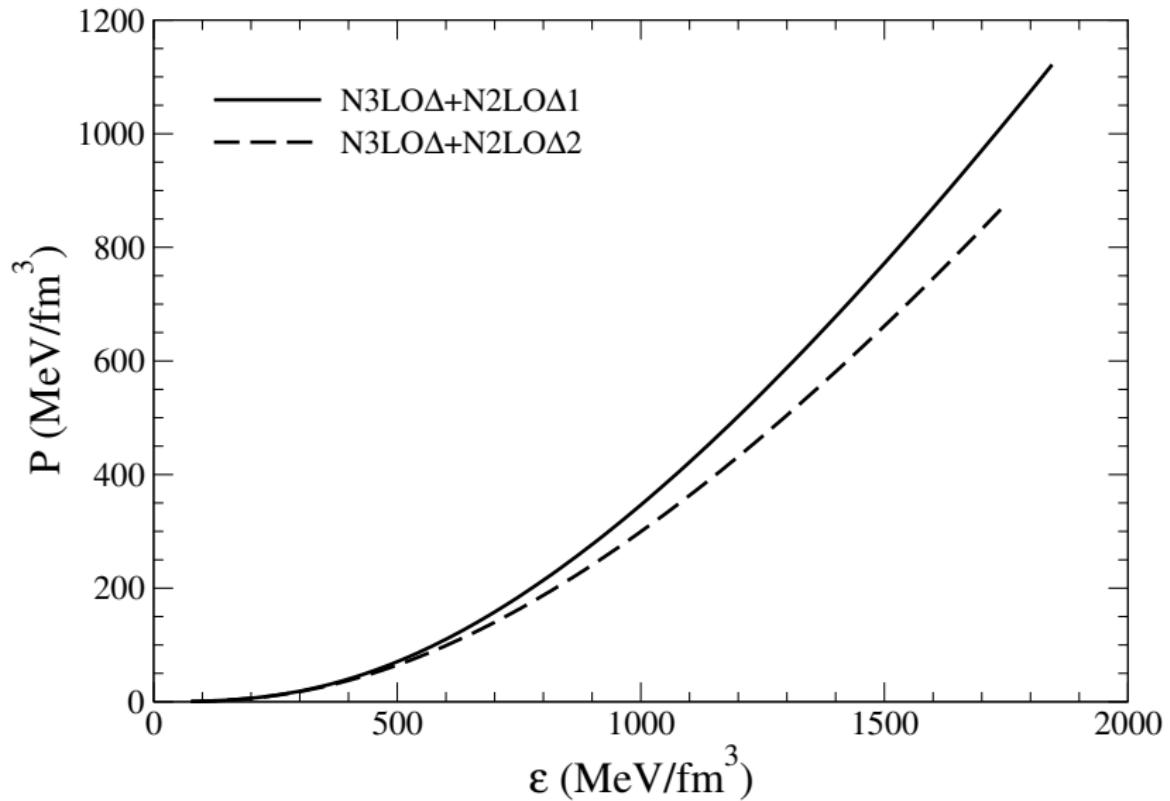
$$\mu_i = \frac{\partial(n_B E/A(\beta, n_B))}{\partial n_i} \quad n_B = n_n + n_p$$

- Chemical equilibrium:

$$\mu_n - \mu_p = \mu_e \quad \mu_e = \mu_\mu$$

- Charge neutrality:

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

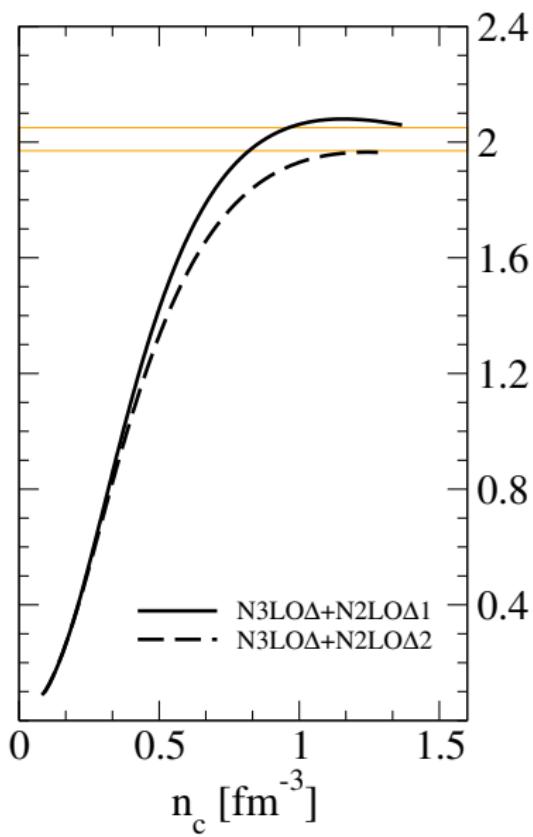
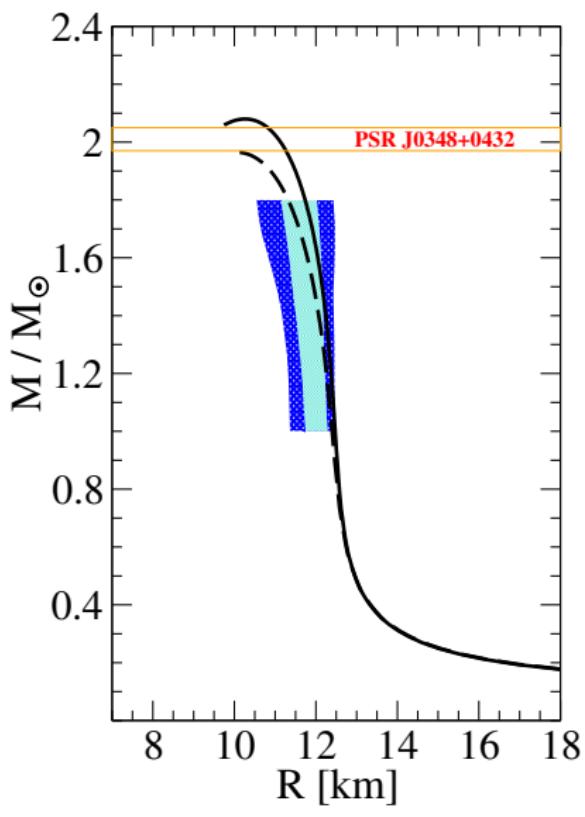


- Neutron stars have a very strong gravitational field \Rightarrow their structure is described by General theory of relativity.
- Equations of hydrostatic equilibrium in general relativity of Tolman-Oppenheimer-Volkoff (TOV):

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

- Fixed an EOS and a value of the central pressure value P_c TOV equations are solved numerically.
- Output $\Rightarrow M_G(R)$, $M_G(P_c)$ (or $M_G(M_B)$)
- $M_B = m_u \int n_B(r)dV$, $m_u = (m_n + m_p)/2$

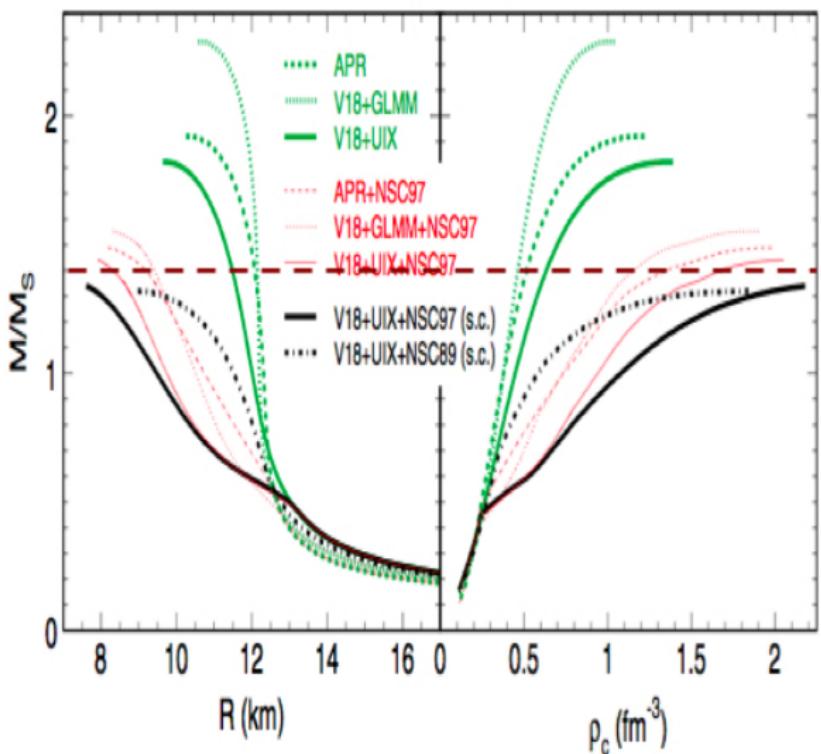
Neutron stars based on N3LO Δ +N2LO Δ (case of nucleonic matter)



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

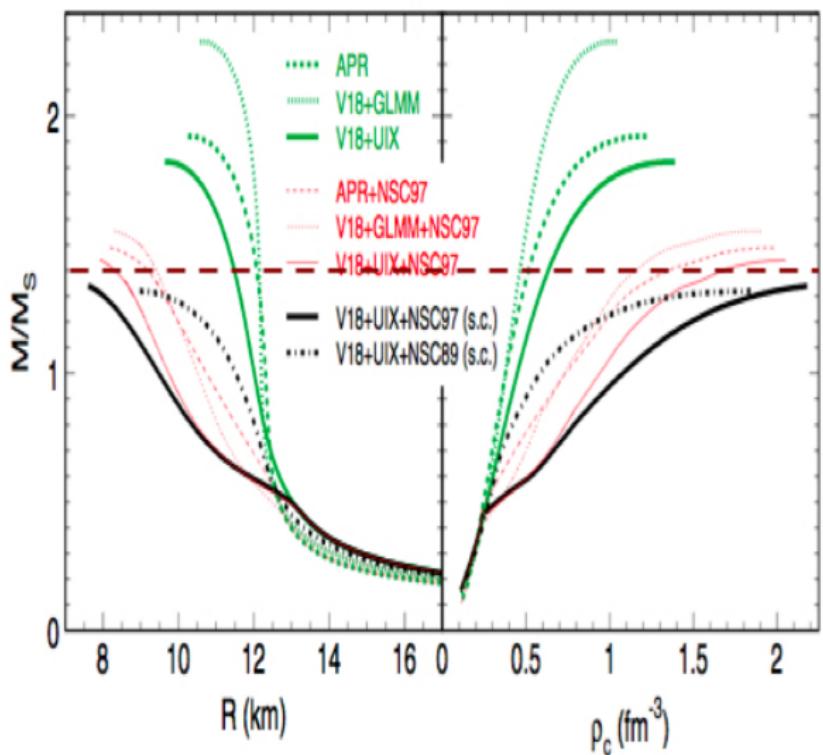
The problem of the maximum mass of neutron stars with microscopic approaches

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



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

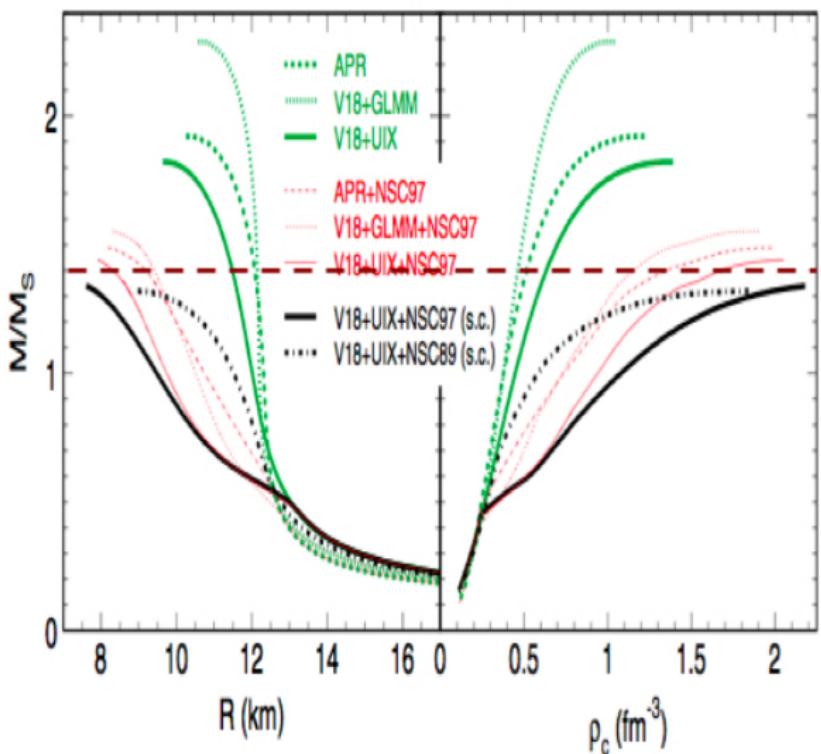
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- $n + n \rightarrow n + \Lambda$
- $n + n \rightarrow p + \Sigma^-$
- $p + e^- \rightarrow \Lambda + \nu_{e^-}$
- $n + e^- \rightarrow \Sigma^- + \nu_{e^-}$

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

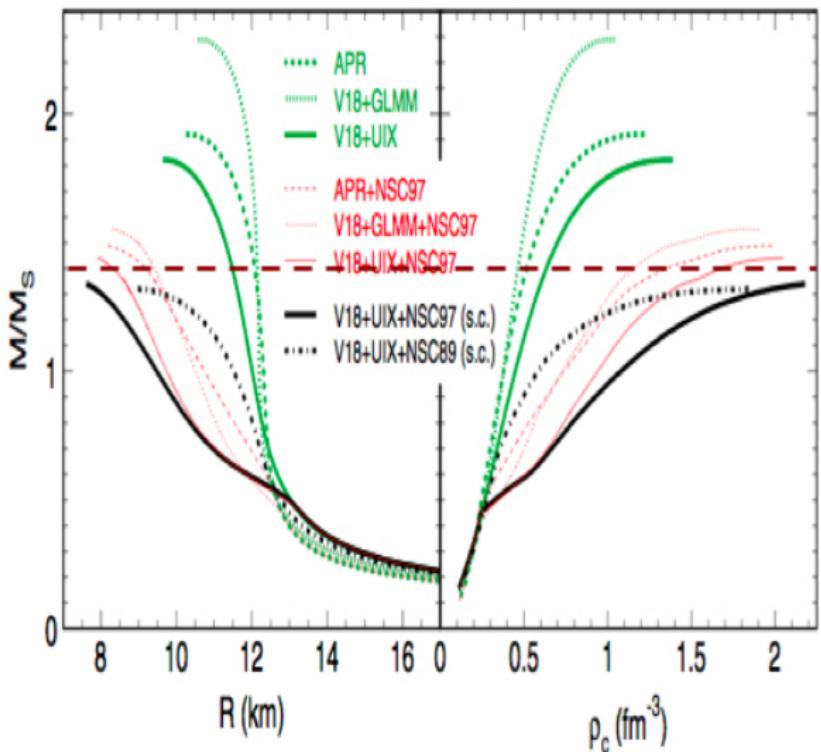
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- $p + e^- \rightarrow \Lambda + \nu_{e^-}$
- $n + e^- \rightarrow \Sigma^- + \nu_{e^-}$
- Appearance of Hyperons \Rightarrow Fermi pressure relieves
- $M_{max} < 1.44 M_{\odot}$

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

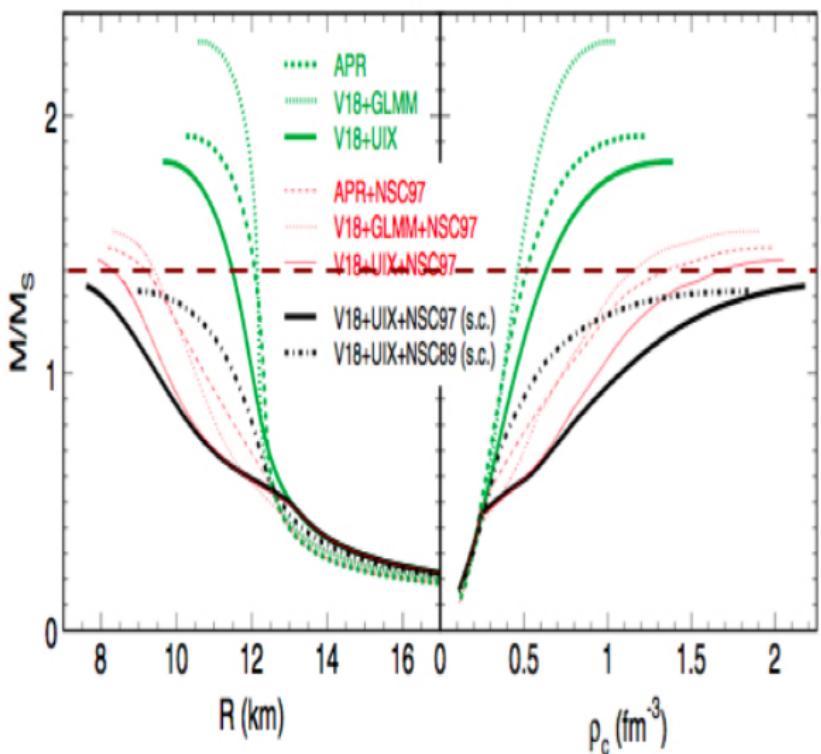
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- Recent measurements:
- $M^{J1614-2230} = 1.97 \pm 0.04 M_{\odot}$
- $M^{J0348+0432} = 2.01 \pm 0.04 M_{\odot}$
- $M^{J0740+6620} = 2.14^{+0.20}_{-0.18} M_{\odot}$

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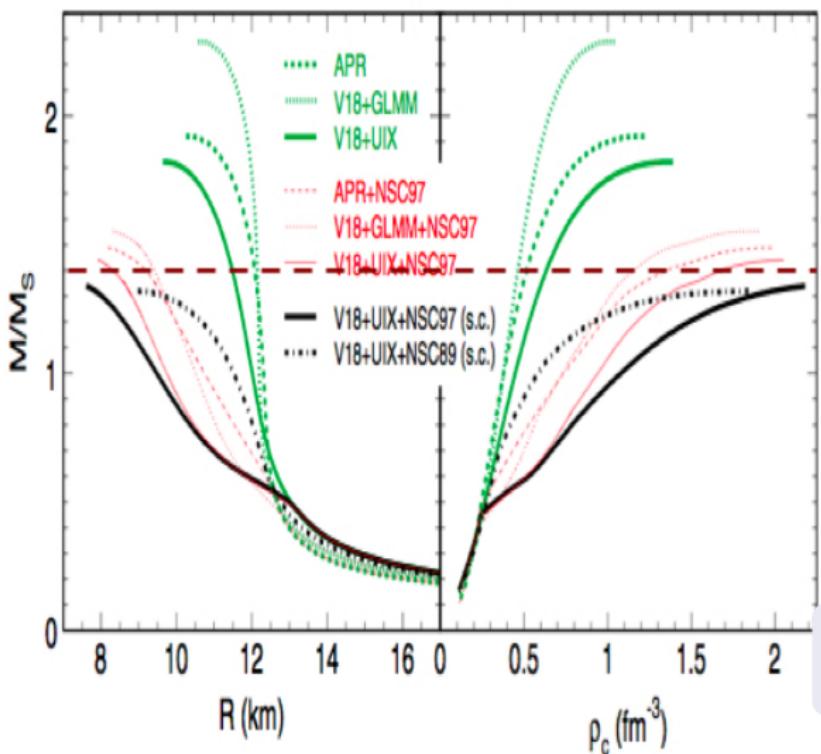
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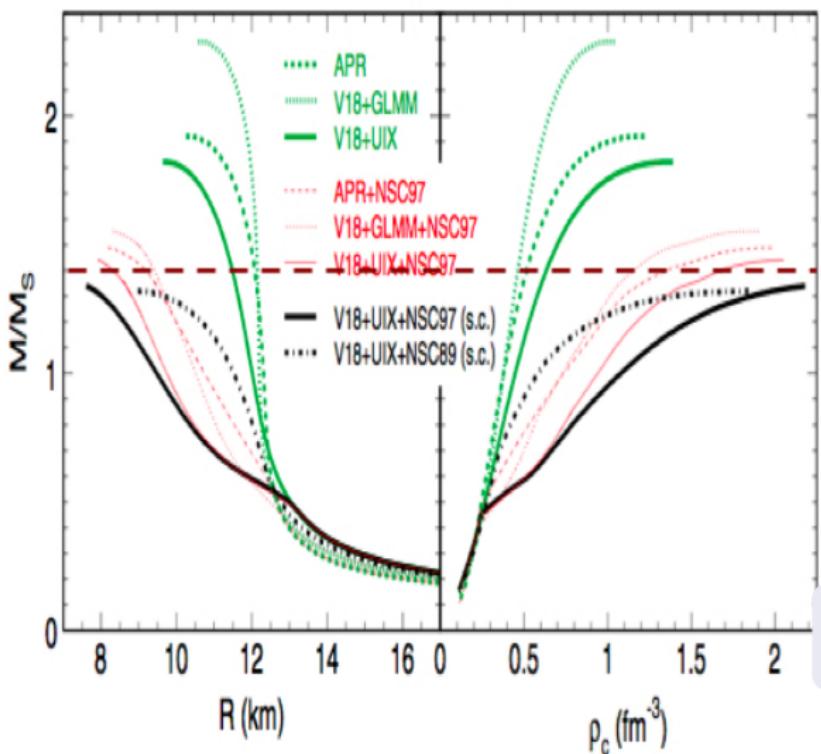


DRAMMATIC SCENARIO!!

NNY, NYY and YYY may help??

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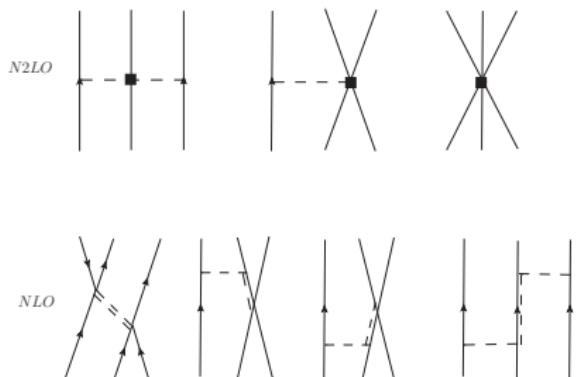


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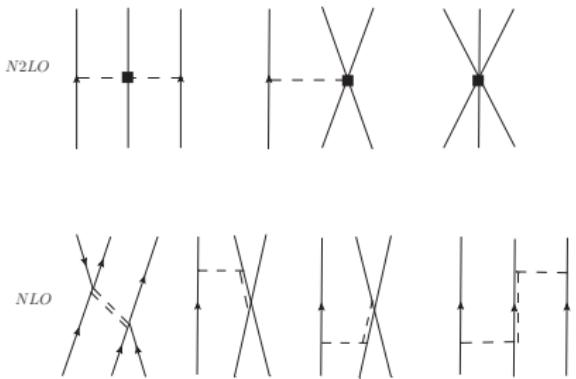
DRAMMATIC SCENARIO!!

We focused on the NNA interactions



- Up to N2LO just 1 LEC \Rightarrow 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 NNΛ interaction from bare NNΛ force
- Low energy constants estimated from decuplet saturation



- Up to N2LO just 1 LEC \Rightarrow fixed to $U_\Lambda(k=0) = (-28, -30)$ MeV
- Separation energies of heavy hypernuclei improve!

- 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 NN Λ interaction from bare NN Λ force
- Low energy constants estimated from decuplet saturation

- Asymmetric matter:

$E/A(\beta, \rho)$ calculated for several values of $\beta = \frac{n_n - n_p}{n_n + n_p}$

$$\mu_i = \frac{\partial(n_B E/A(\beta, n_B))}{\partial n_i} \quad n_B = n_n + n_p + n_\Lambda$$

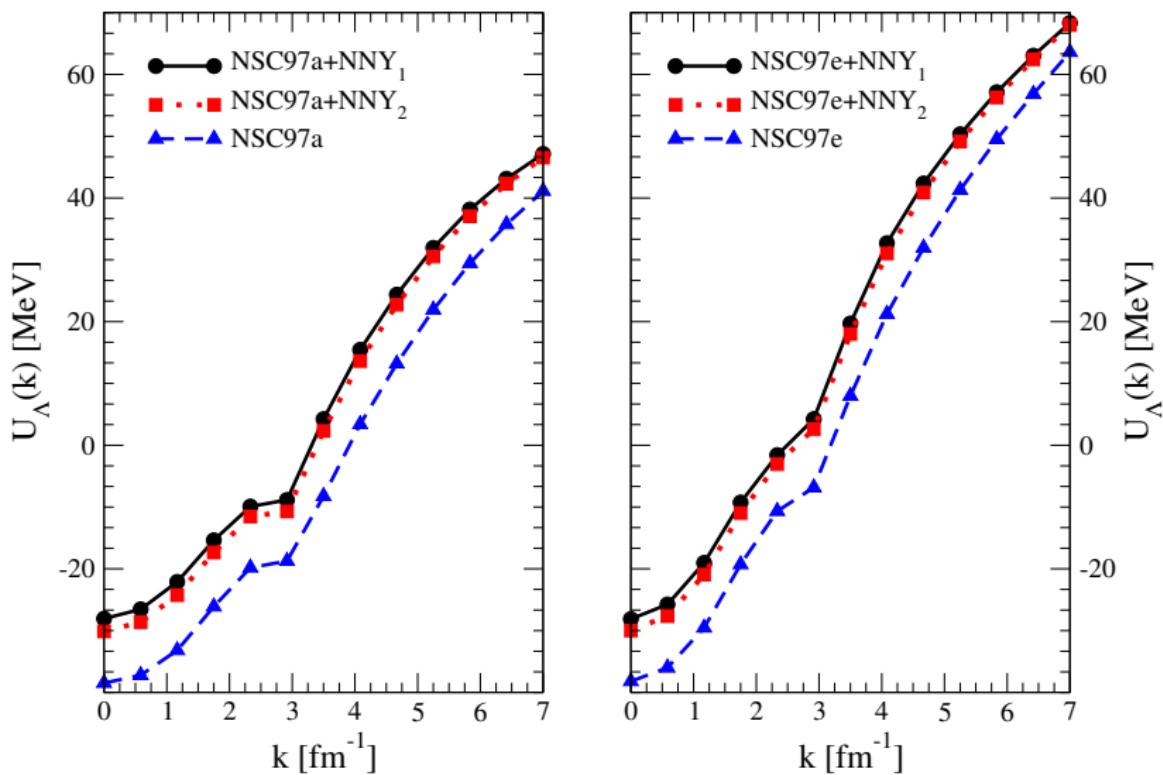
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$$\mu_n - \mu_p = \mu_e \quad \mu_e = \mu_\mu \quad \mu_n = \mu_\Lambda$$

- Charge neutrality:

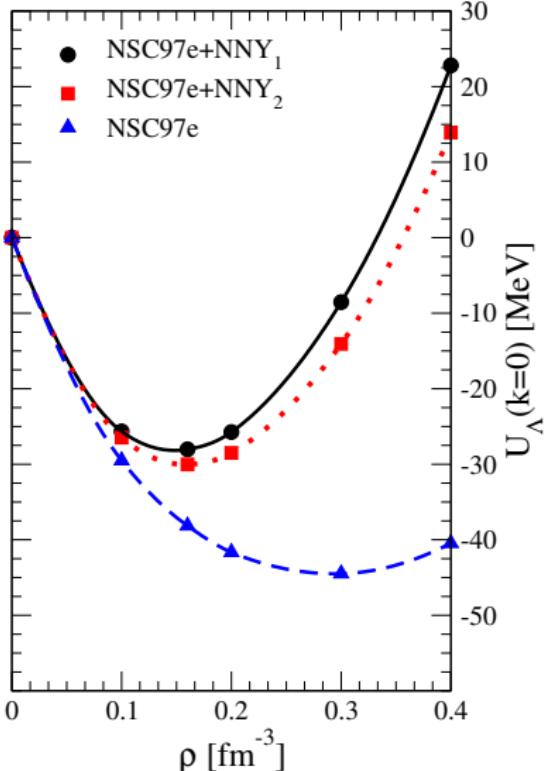
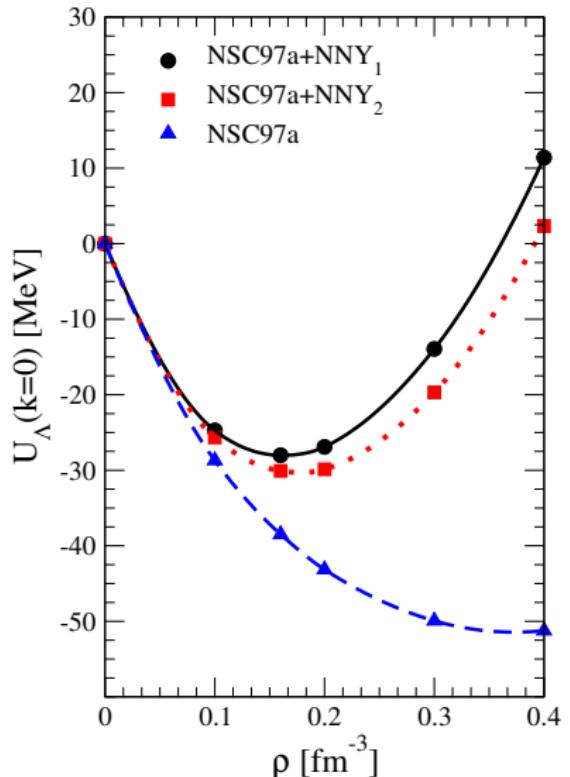
$$n_p - n_\mu - n_e = 0.$$

Λ -single particle potential



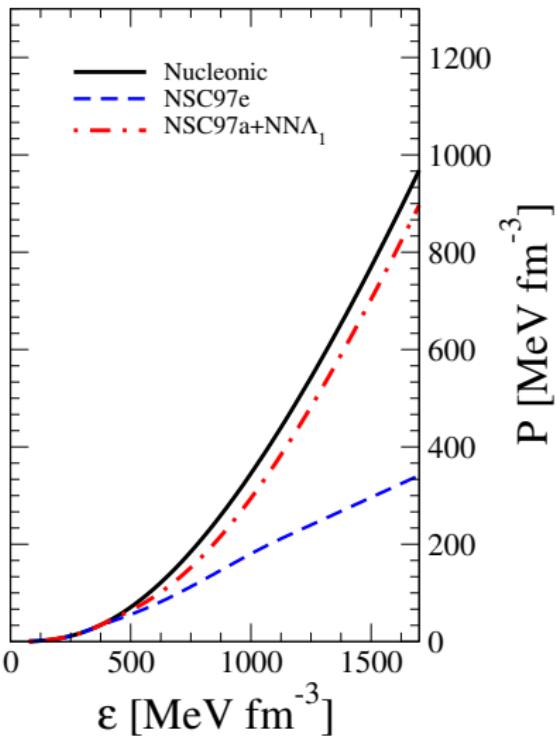
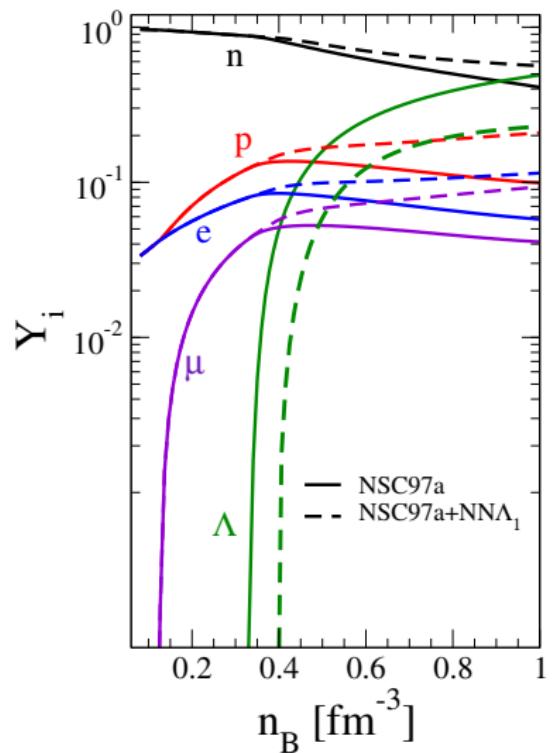
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$U_\Lambda(k=0)$ as function of baryonic density



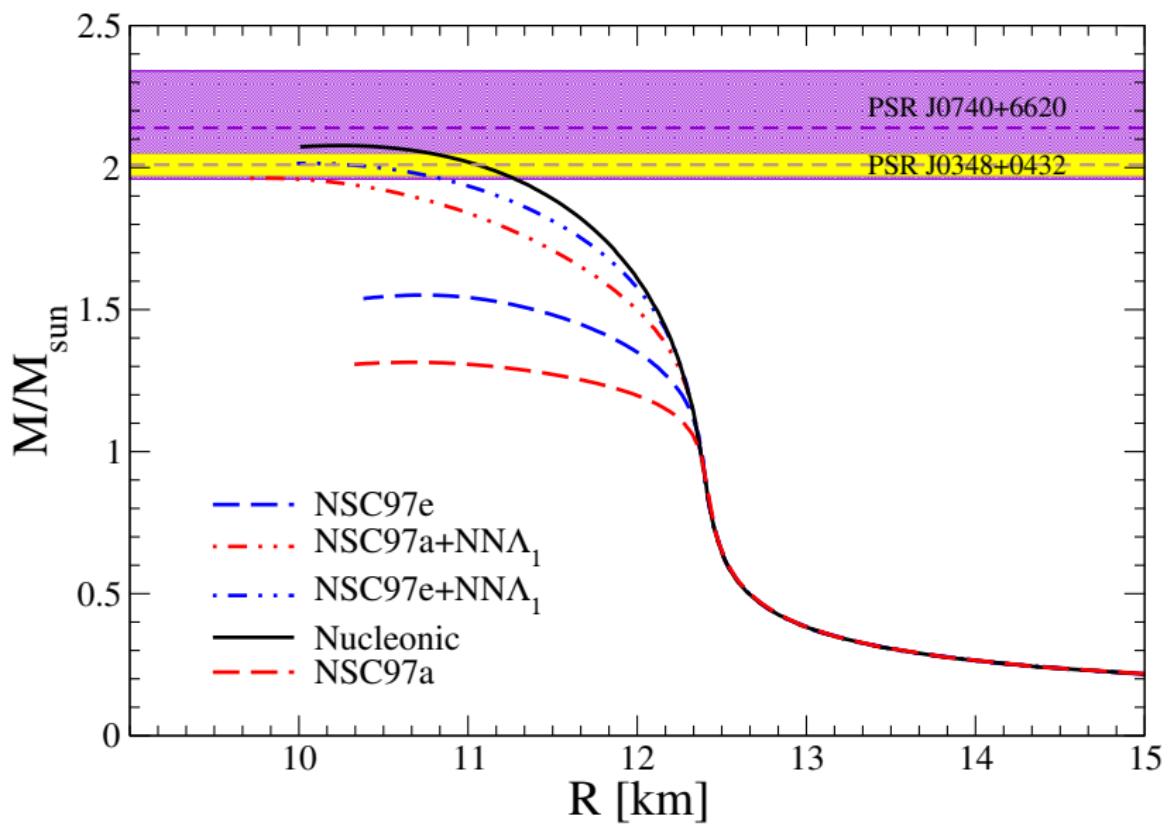
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Composition of hyperonic matter



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Neutron stars structure including Λ -hyperon



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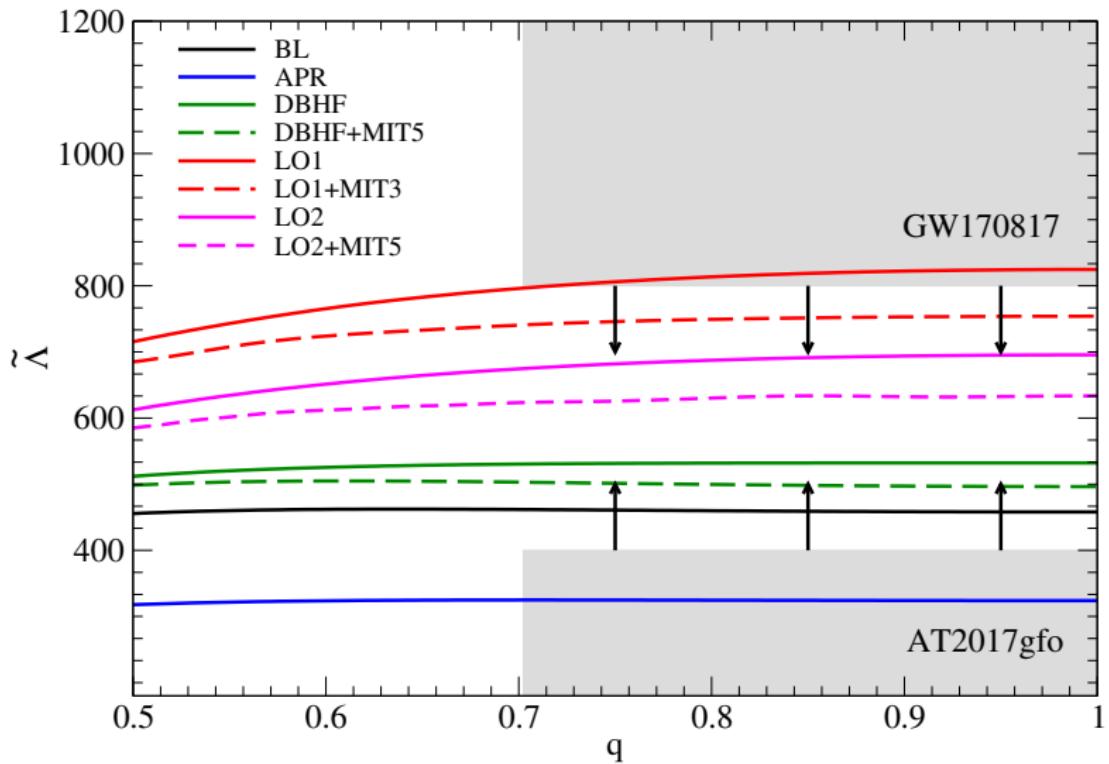
- A reasonable description of nuclear matter and NSs based on ChEFT is possible
- From a microscopic point of view the hyperon puzzle is still far to be completely solved ... but some step forward has been made
- NOTE: if the light mass in GW190814 is a neutron star \Rightarrow very unlikely to be a hyperonic star (see Talk by Alessandro Drago)
- We would like to make a full self-consistent calculation based on NY based on ChEFT...
- ...but VERY IMPORTANT: more experimental efforts are required to improve the quality of NY interactions!!!

Improved description of the separation energies of Λ -hypernuclei

	$^{41}\Lambda\text{Ca}$	$^{91}\Lambda\text{Zr}$	$^{209}\Lambda\text{Pb}$
NSC97a	23.0	31.3	38.8
NSC97a+NN Λ_1	14.9	21.1	26.8
NSC97a+NN Λ_2	13.3	19.3	24.7
NSC97e	24.2	32.3	39.5
NSC97e+NN Λ_1	16.1	22.3	27.9
NSC97e+NN Λ_2	14.7	20.7	26.1
Exp.	18.7(1.1)	23.6(5)	26.9(8)

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Tidal polarizability



D. Logoteta, Eur. Phys. J. A 55, 133 (2019)