Hyperons: from hypernuclei to neutron stars

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Joint THEIA-STRONG2020 and JAEA/Mainz REIMEI Web-Seminar

7 aprile 2021

UNIVERSITÀ DI PISA

Results in collaboration with:

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Isaac Vidaña (INFN Catania)

Hopefully very soon: results from new collaborations...

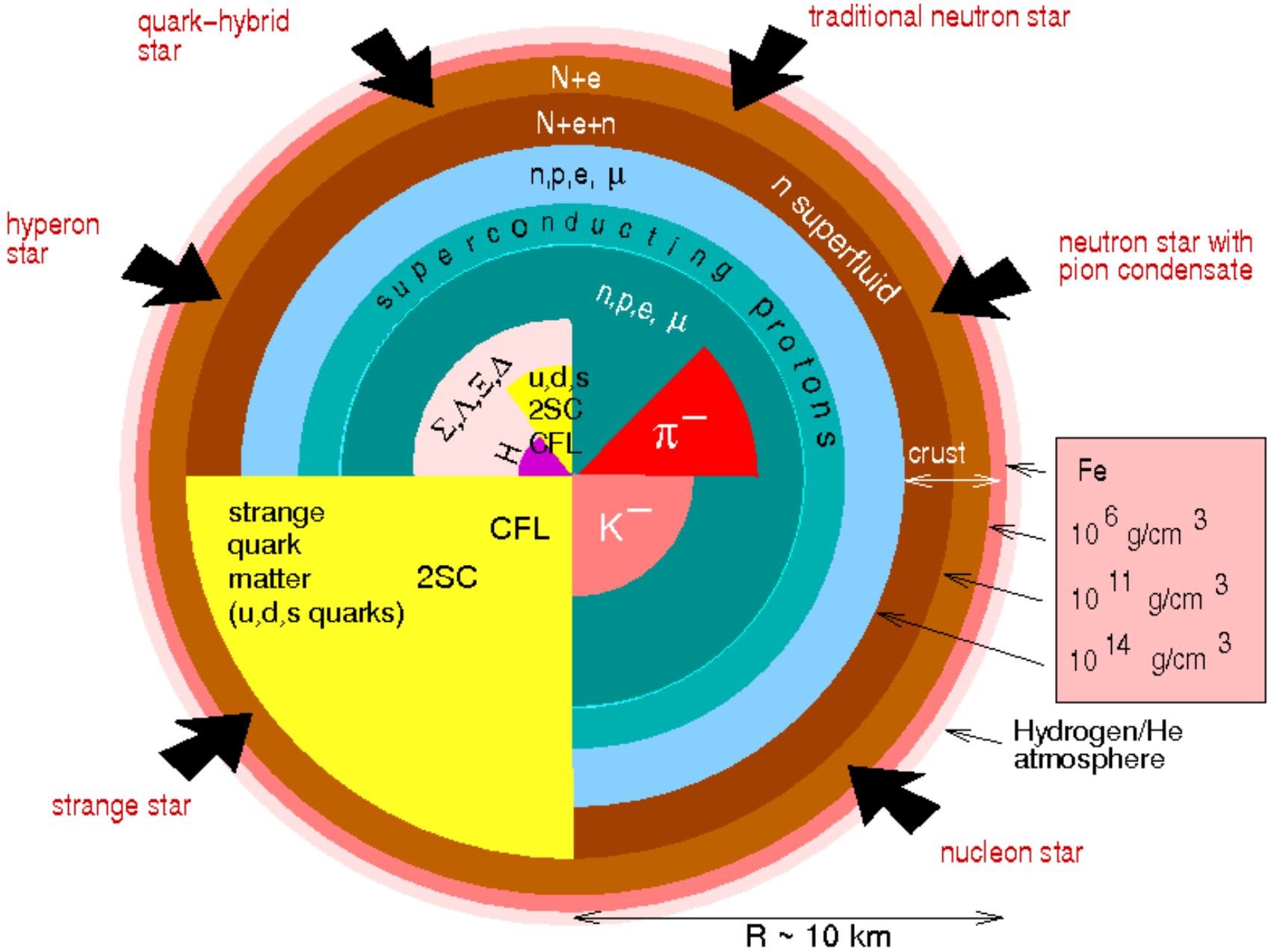
Outlook

- 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
- Hypernuclei

- 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: $(10^{-13} - 1.5)\ fm^{-3}$
- T: range: $(0 - 100)\ MeV$
- P: range: $(\sim 0 - 10^{38})\ dyne\ cm^{-2}$
- ϵ: range: $(1 - 10^{17})\ g\ cm^{-3}$
- $\{X_i\}$: 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...)
- $\frac{E}{A}(n_0, \beta = 0) = (-16 \pm 1)$ MeV
- $n_0 = (0.16 \pm 0.01)\ fm^{-3} \quad \beta = \frac{n_n - n_p}{n_n + n_p}$
- $E_{sym}(n_0) = \frac{1}{2}\frac{\partial^2 E/A}{\partial \beta^2} = (33 \pm 3)$ MeV
- $K_\infty(n_0) = \frac{1}{2}\frac{\partial^2 E/A}{\partial n^2} = (220 \pm 30)$ MeV

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- How to derive these properties within a microscopic framework?

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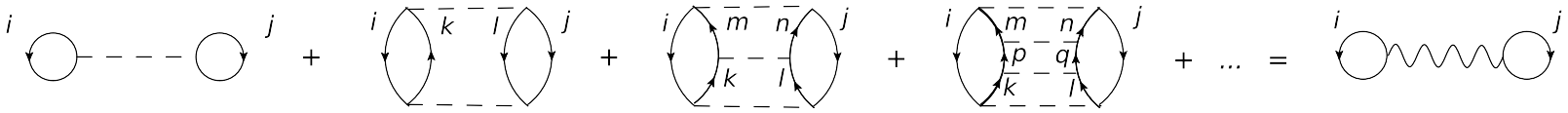
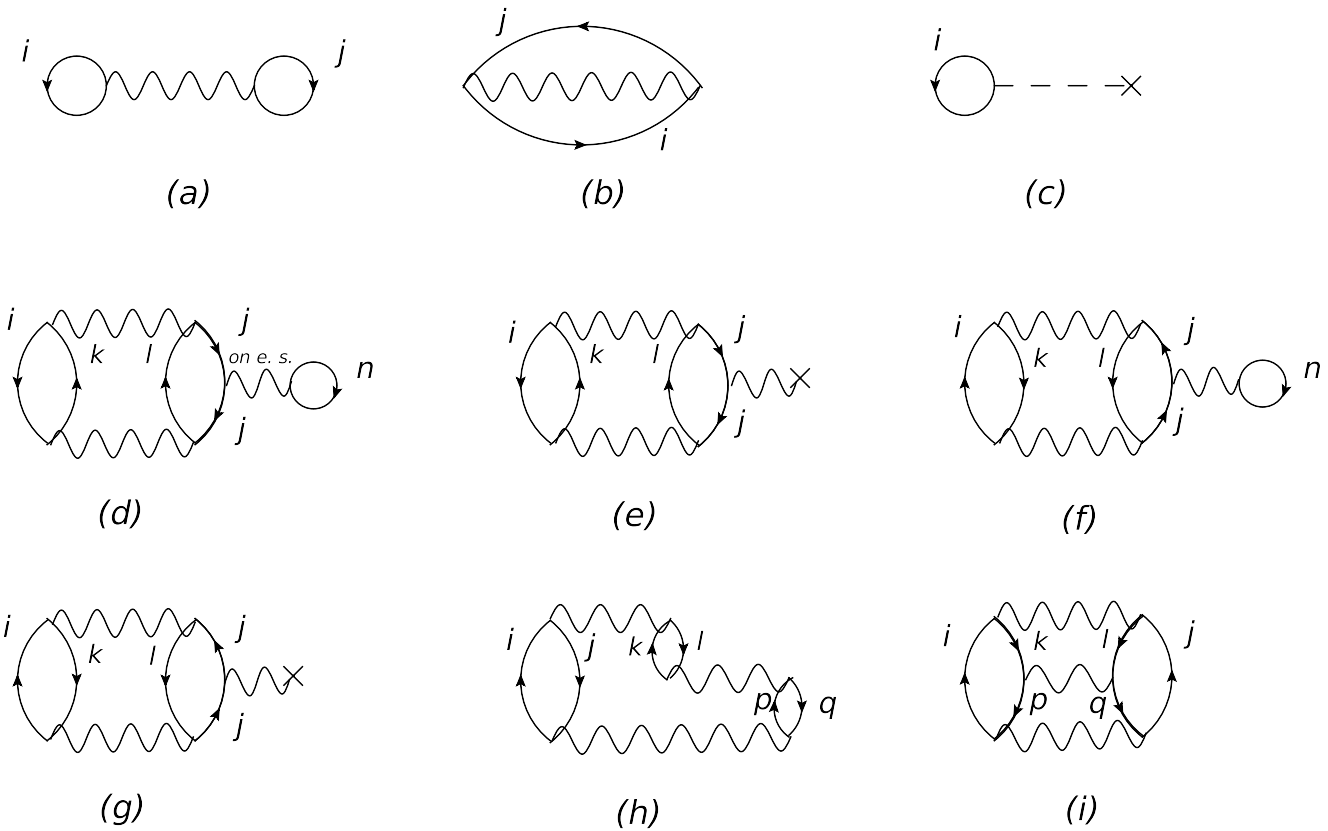
- How to derive these properties within a microscopic framework?
- May we use a perturbation theory?

Bethe-Goldstone expansion up to three-hole-lines

Ladder diagrams summation:



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



- Starting point: the Bethe-Goldstone equation

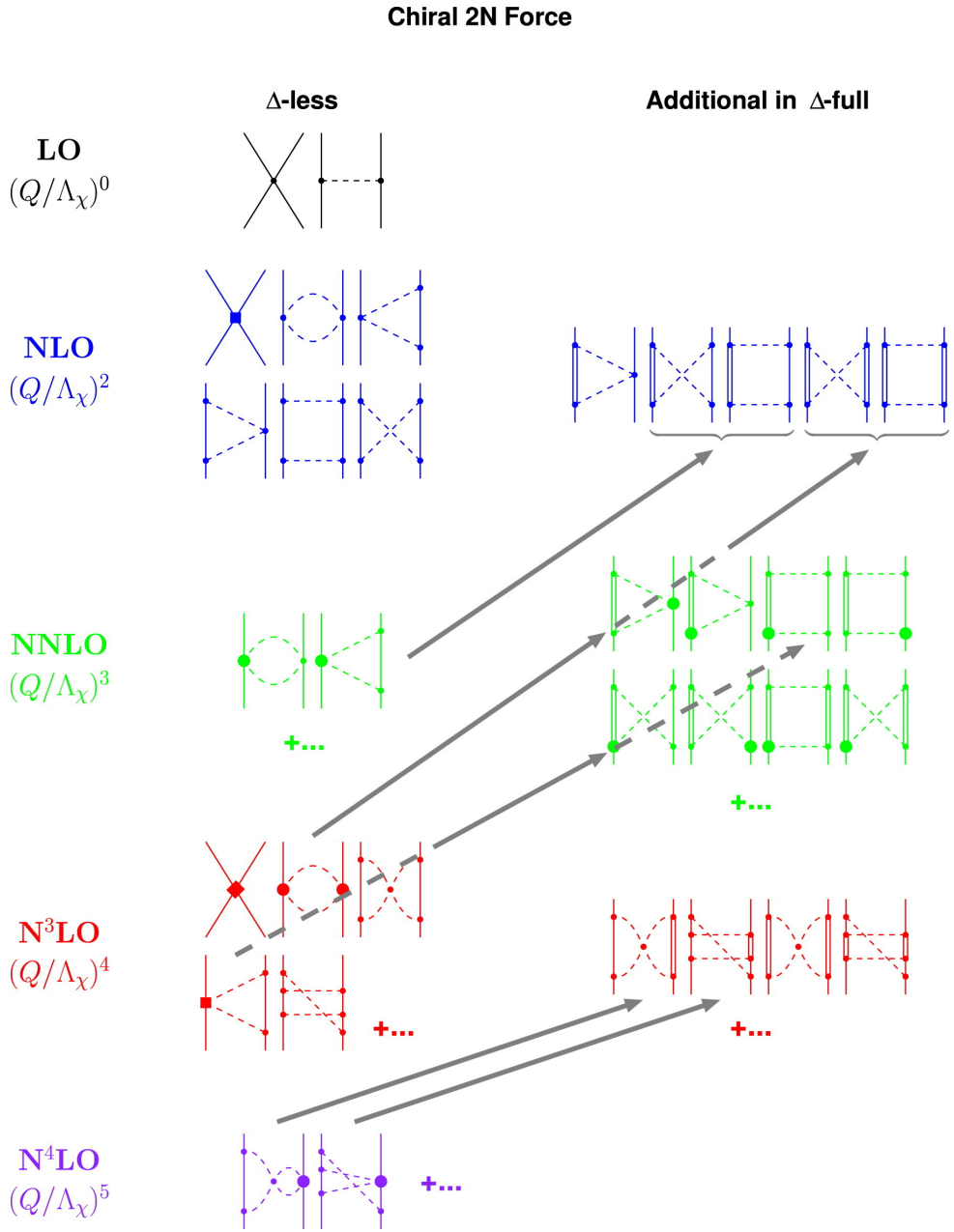
$$G(\omega)_{B_1B_2,B_3B_4} = V_{B_1B_2,B_3B_4} + \sum_{B_iB_j} V_{B_1B_2,B_iB_j} \times \frac{Q_{B_iB_j}}{\omega - E_{B_i} - E_{B_j} + i\eta} G(\omega)_{B_iB_j,B_3B_4}$$

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

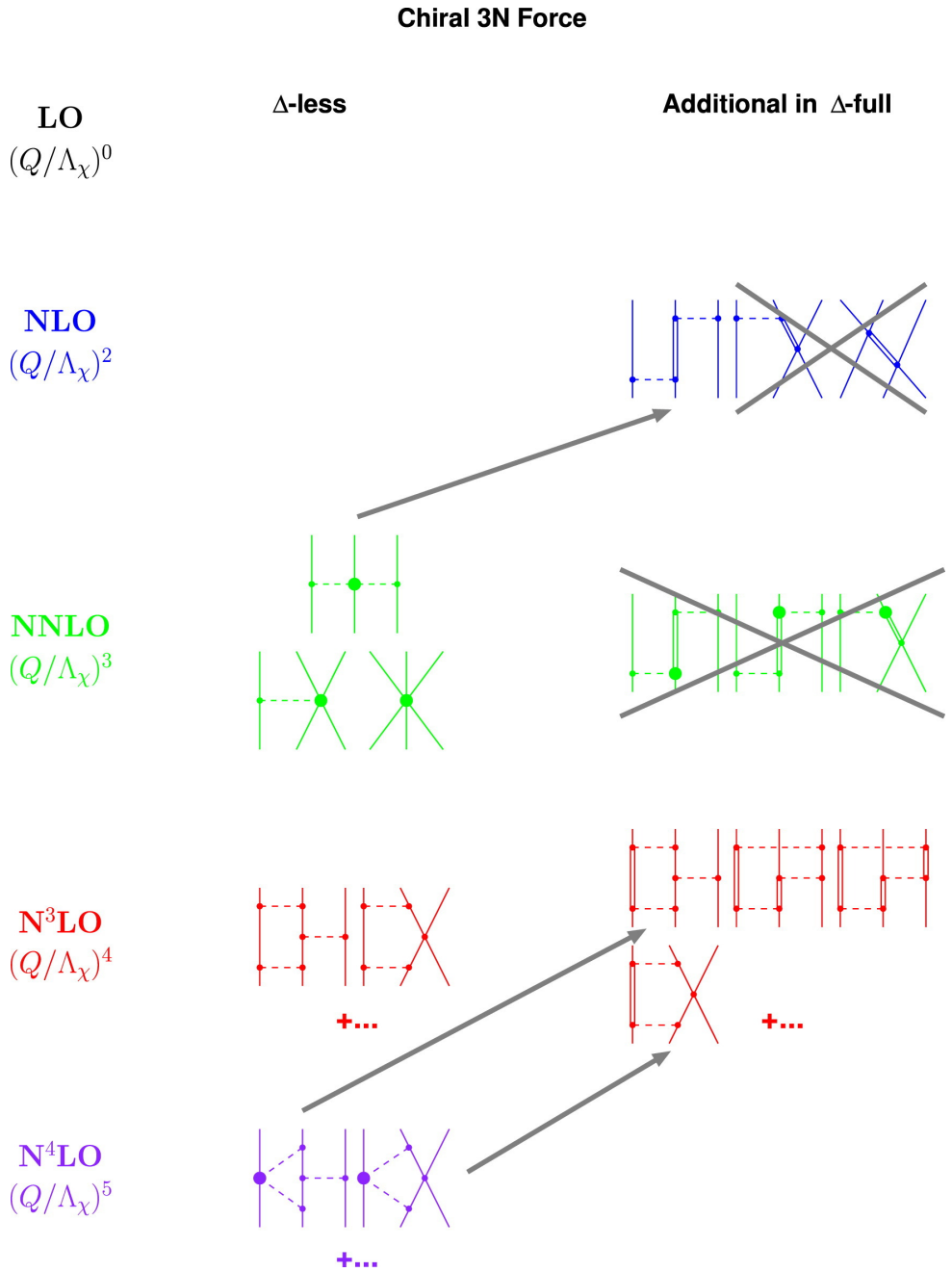
$$E_{B_i}(k) = M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + Re[U_{B_i}(k)]$$

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

NN chiral forces

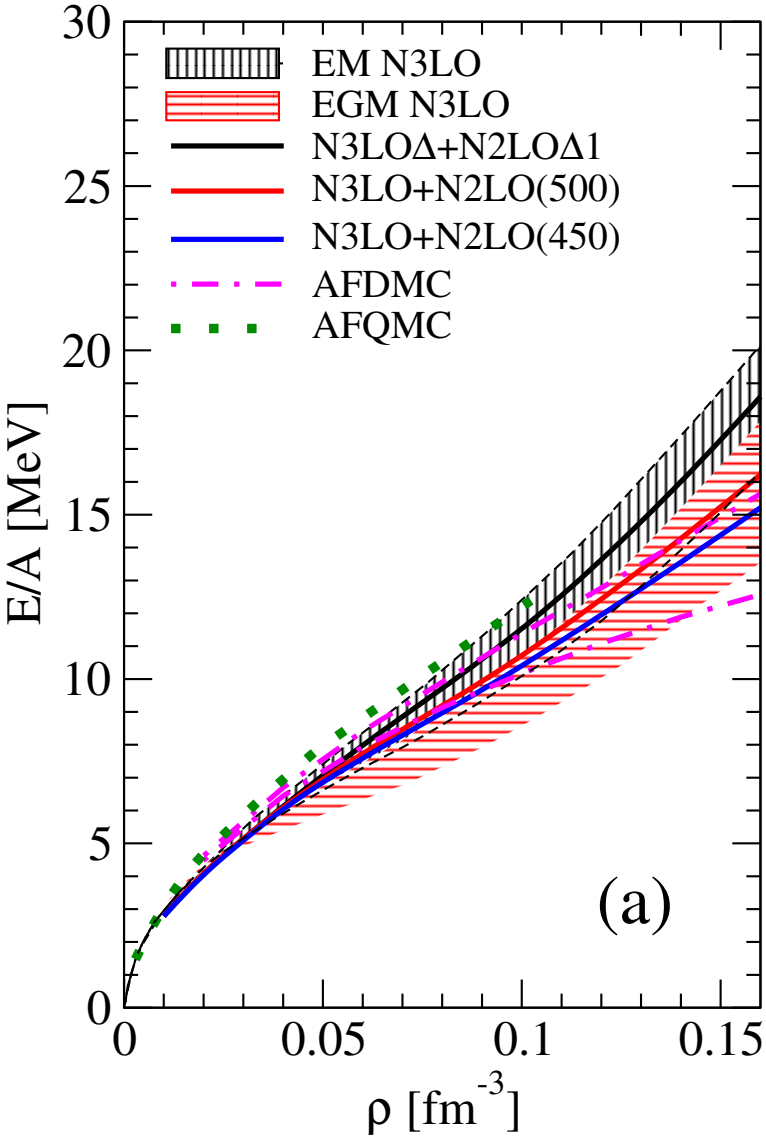


NNN chiral forces

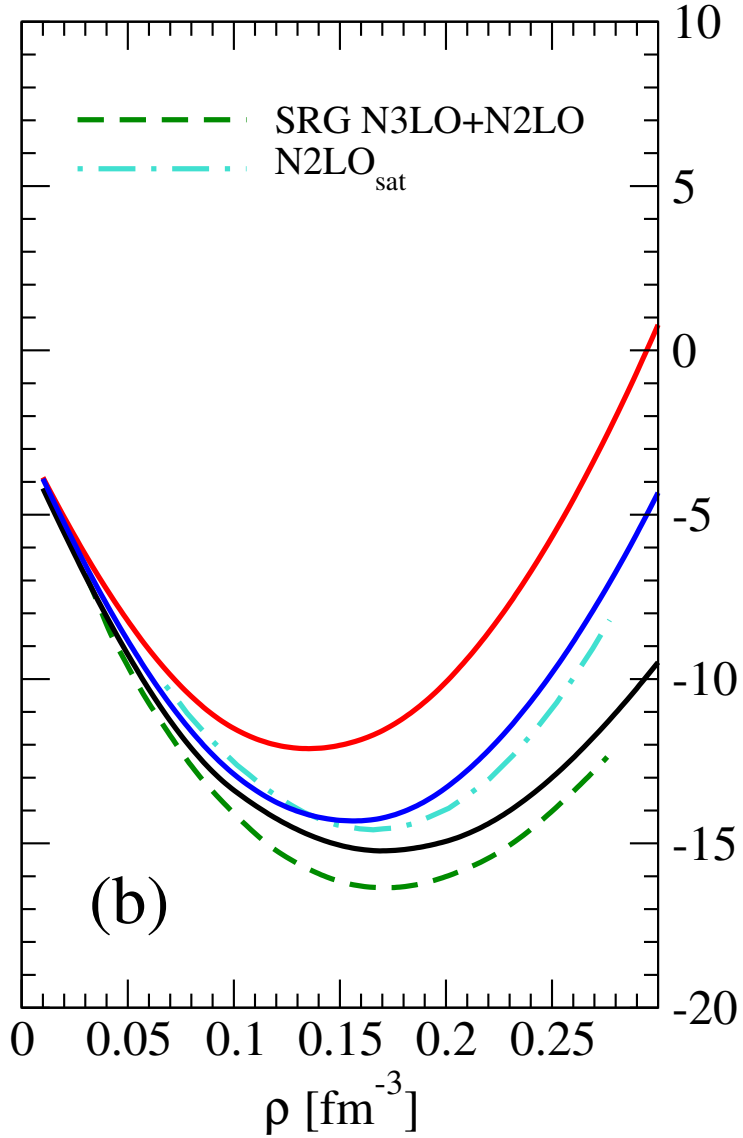


E/A nuclear matter N3LO+N2LO

Pure neutron matter $\beta = 1$

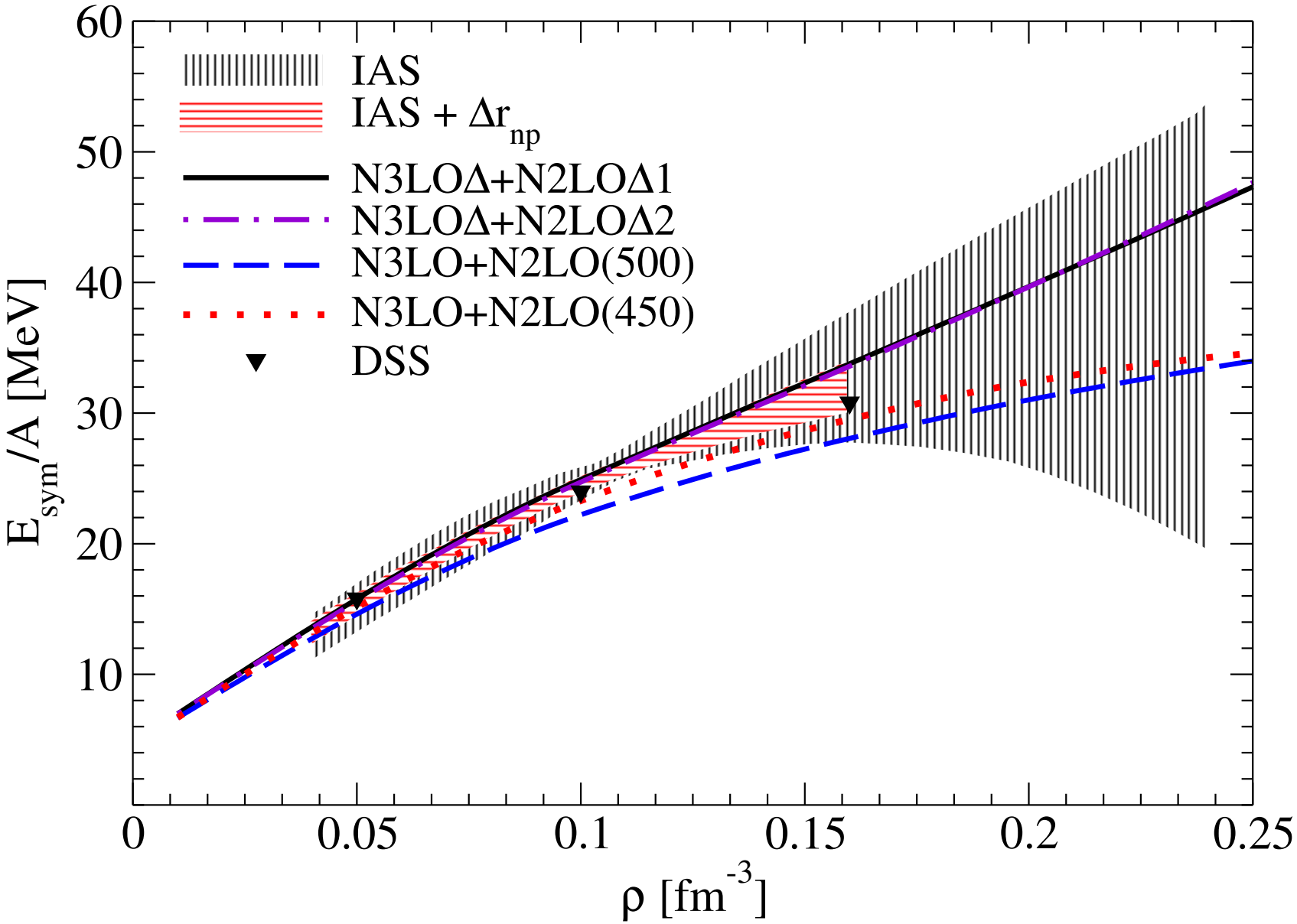


Symmetric nuclear matter $\beta = 0$



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

E_{sym} nuclear matter N3LO+N2LO



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

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

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

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

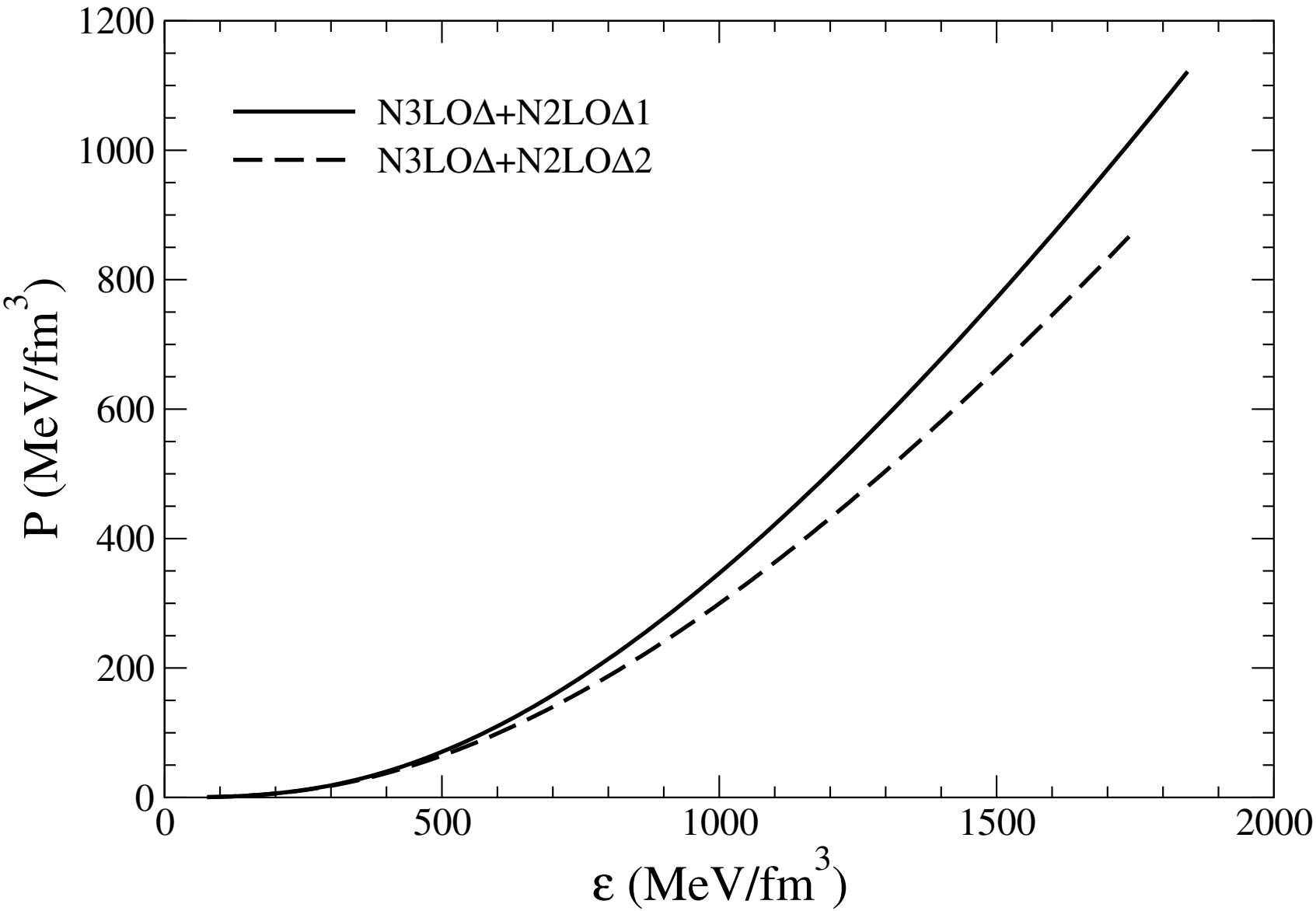
- Chemical equilibrium:

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

- Charge neutrality:

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

EOS $\beta-$stable nucleonic matter N3LOΔ+N2LOΔ



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

Hydrostatic equilibrium

- 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):

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

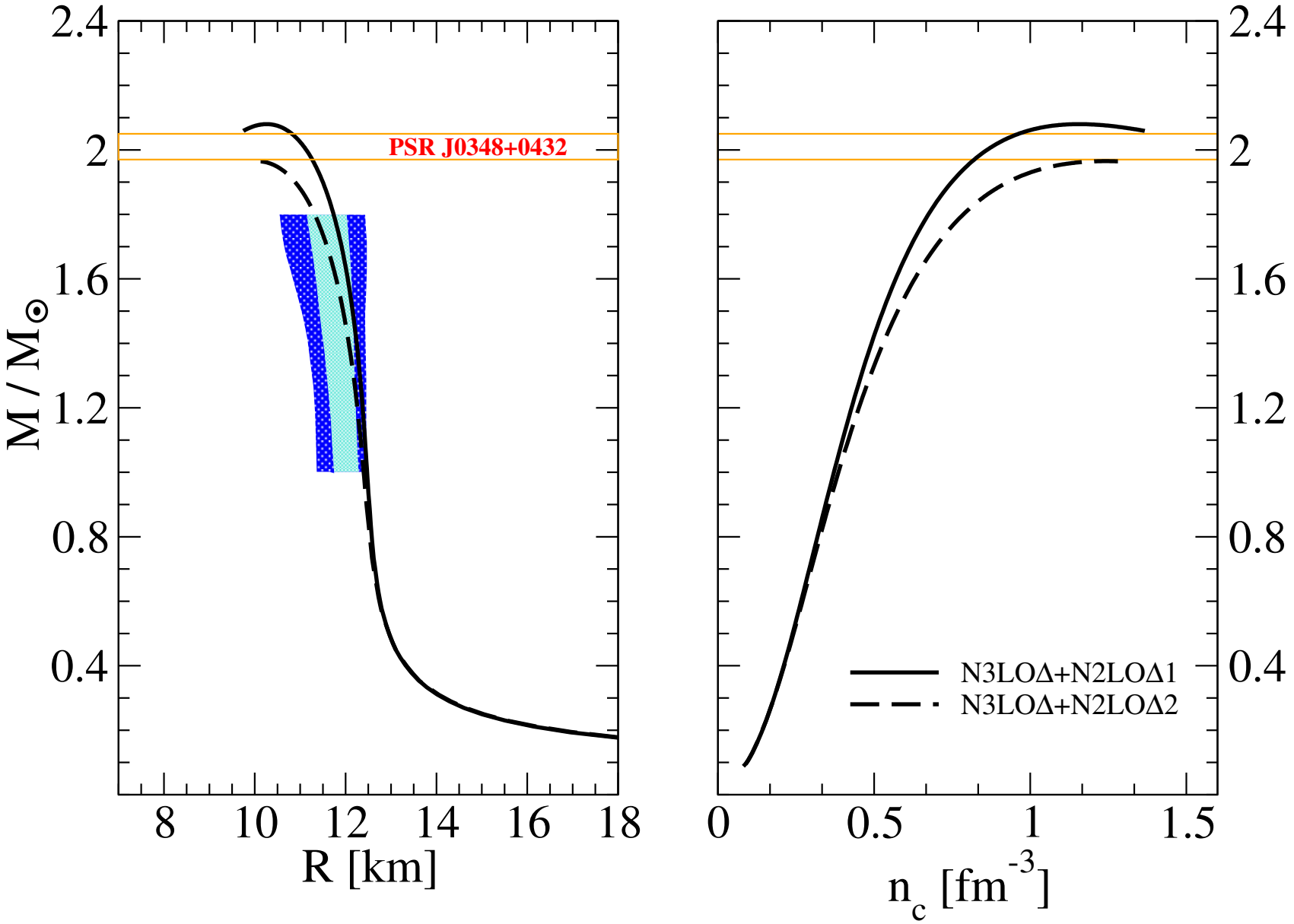
$$\frac{dm(r)}{dr} = 4\pi r^2 \rho\,.$$

- Fixed an EOS and a value of the central pressure value P_c TOV equations are solved numerically.

- Output $\Longrightarrow$ $M_G(R)$, $M_G(P_c)$ (or $M_G(M_B)$)

- $M_B = m_u \int n_B(r) dV, \qquad m_u = (m_n + m_p)/2$

Neutron stars based on N3LOΔ+N2LOΔ (case of nucleonic matter)



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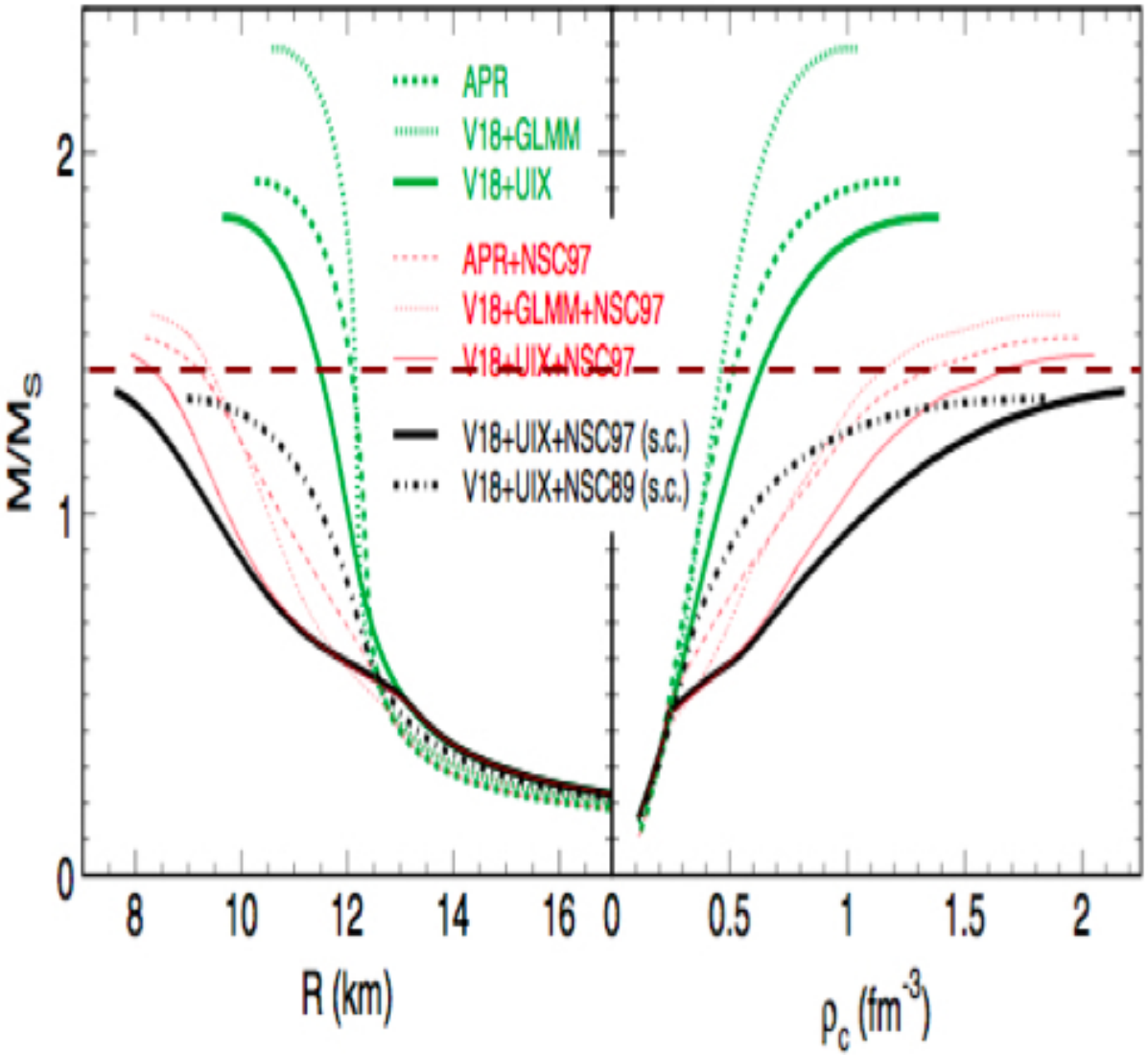
The problem of the maximum mass of neutron stars with microscopic approaches

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



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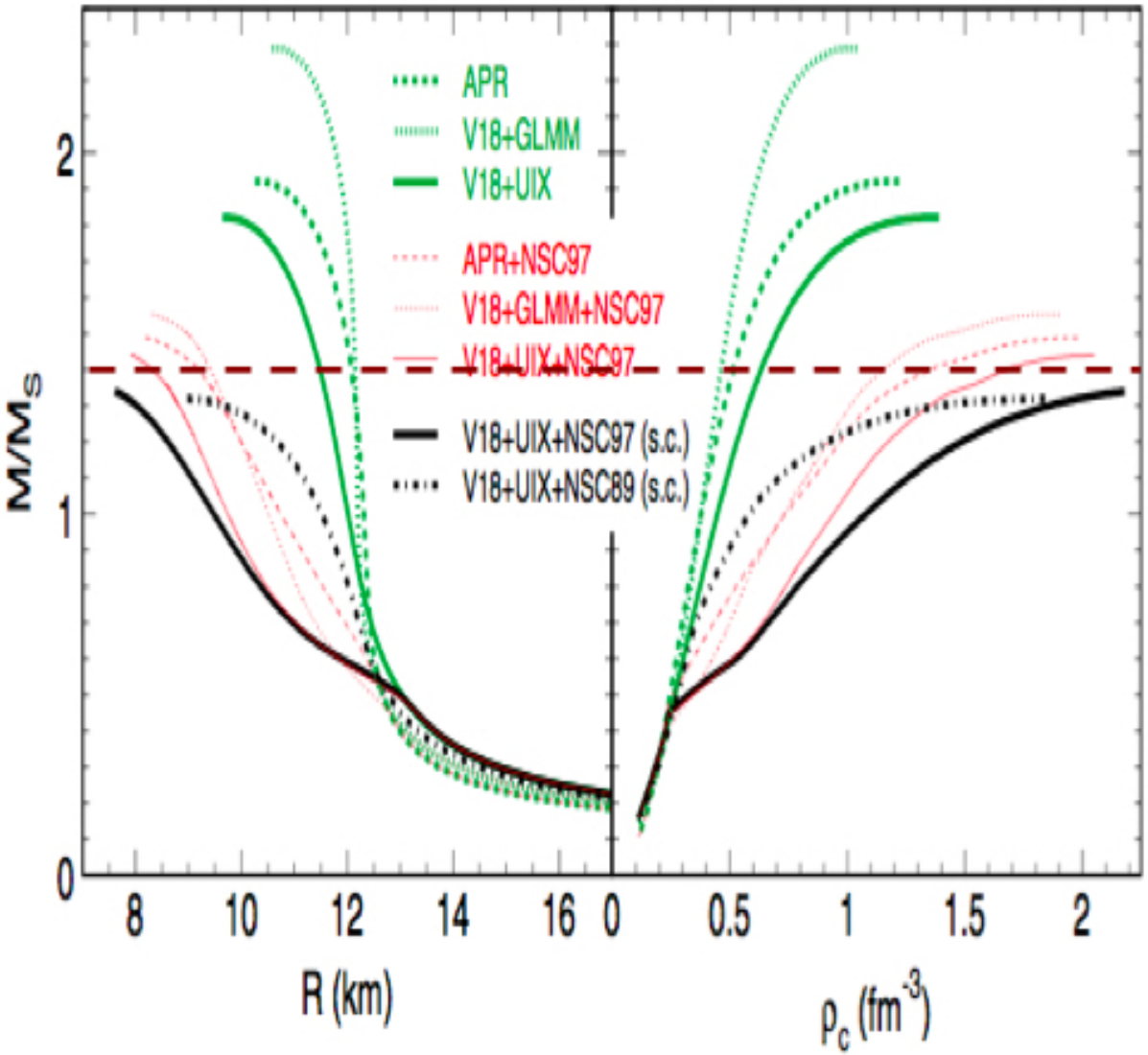

- $n + n \rightarrow n + \Lambda$
- $n + n \rightarrow p + \Sigma^-$
- $p + e^- \rightarrow \Lambda + \nu_{e^-}$
- $n + e^- \rightarrow \Sigma^- + \nu_{e^-}$

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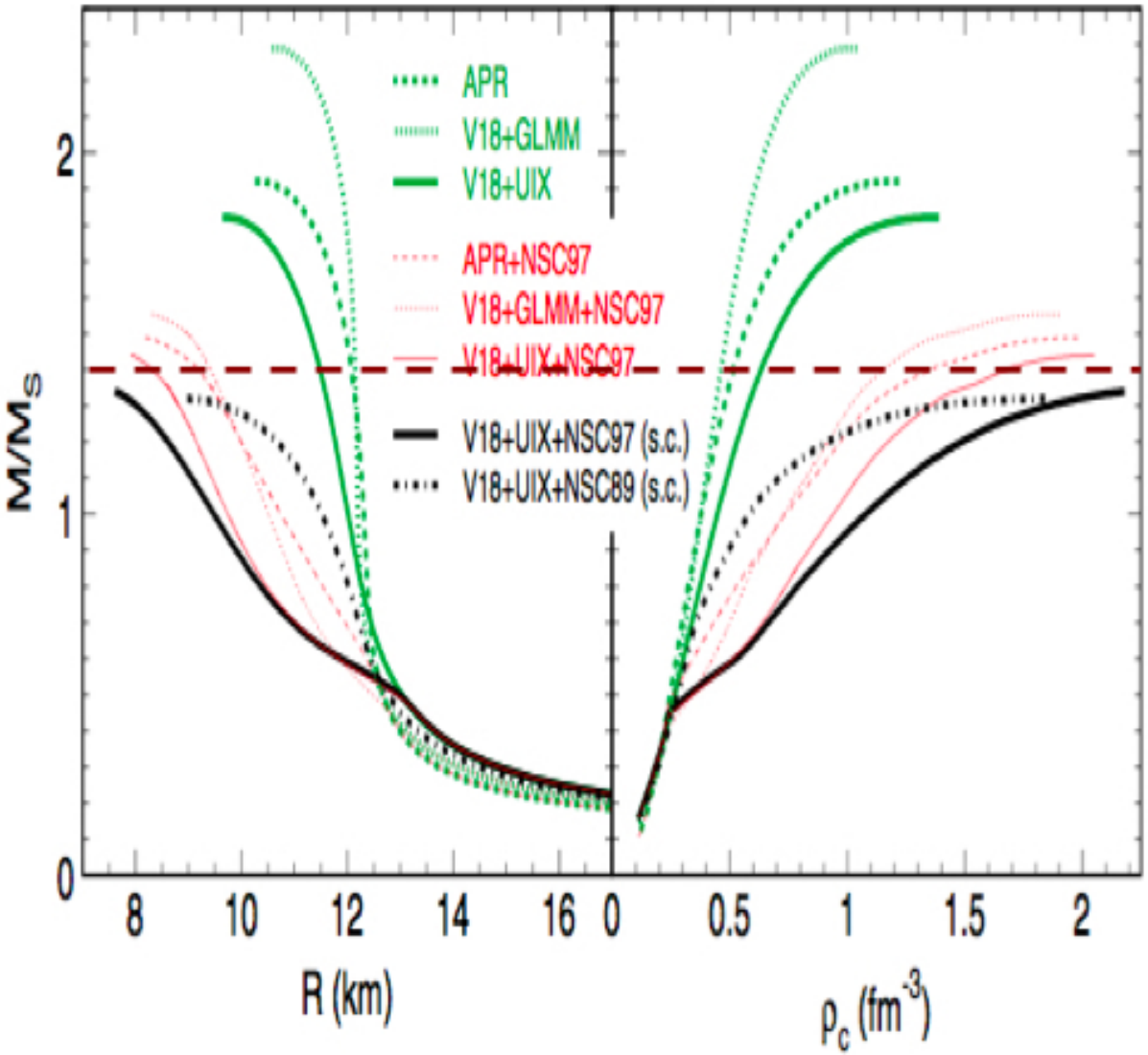

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- $p + e^- \rightarrow \Lambda + \nu_{e^-}$
- $n + e^- \rightarrow \Sigma^- + \nu_{e^-}$
- Appearance of Hyperons $\Rightarrow$ Fermi pressure relieves
- $M_{max} < 1.44\ M_\odot$

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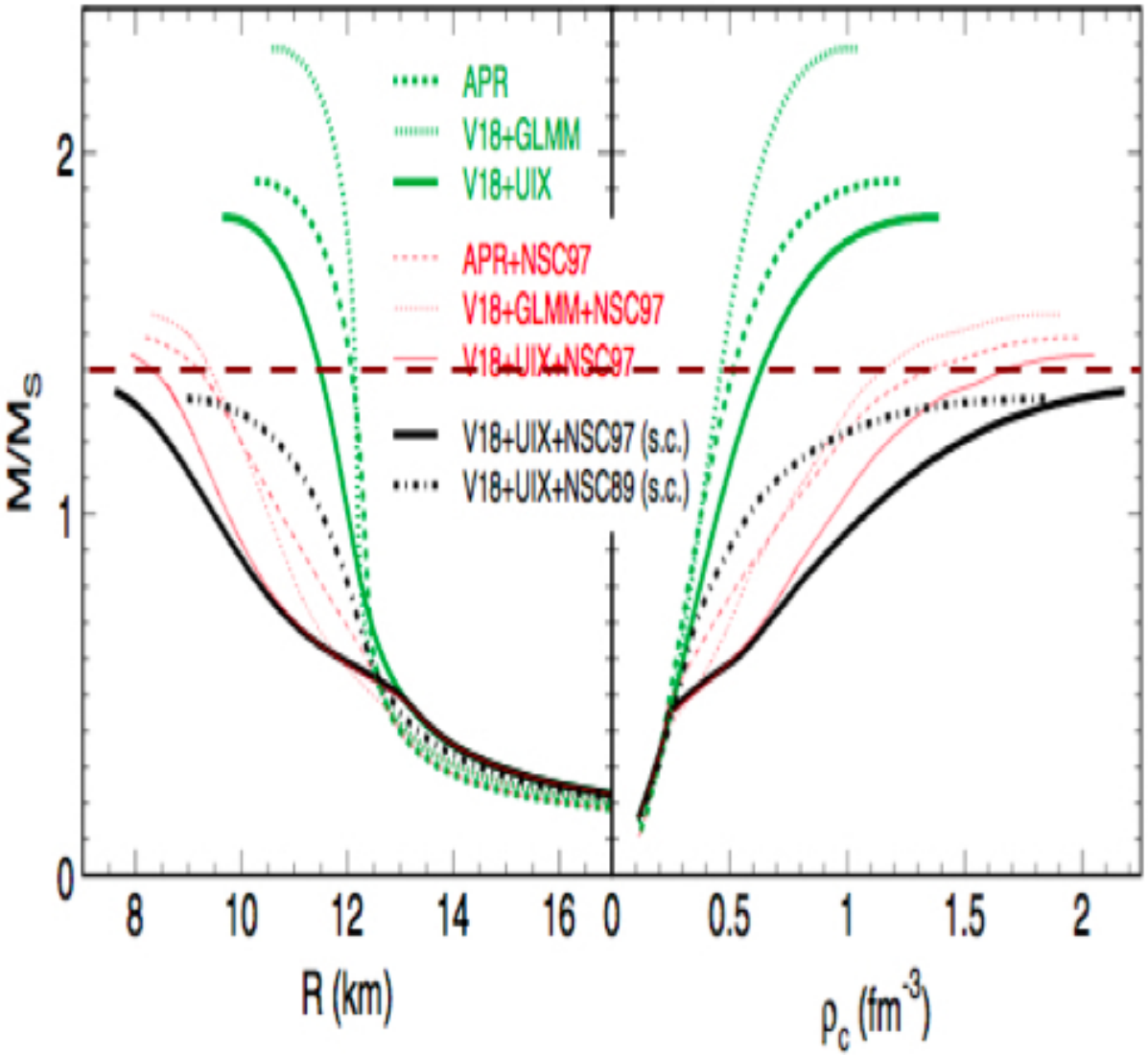

- Recent measurements:
- $M^{J1614-2230} = 1.97 \pm 0.04\ M_\odot$
- $M^{J0348+0432} = 2.01 \pm 0.04\ M_\odot$
- $M^{J0740+6620} = 2.14^{+0.20}_{-0.18}\ M_\odot$

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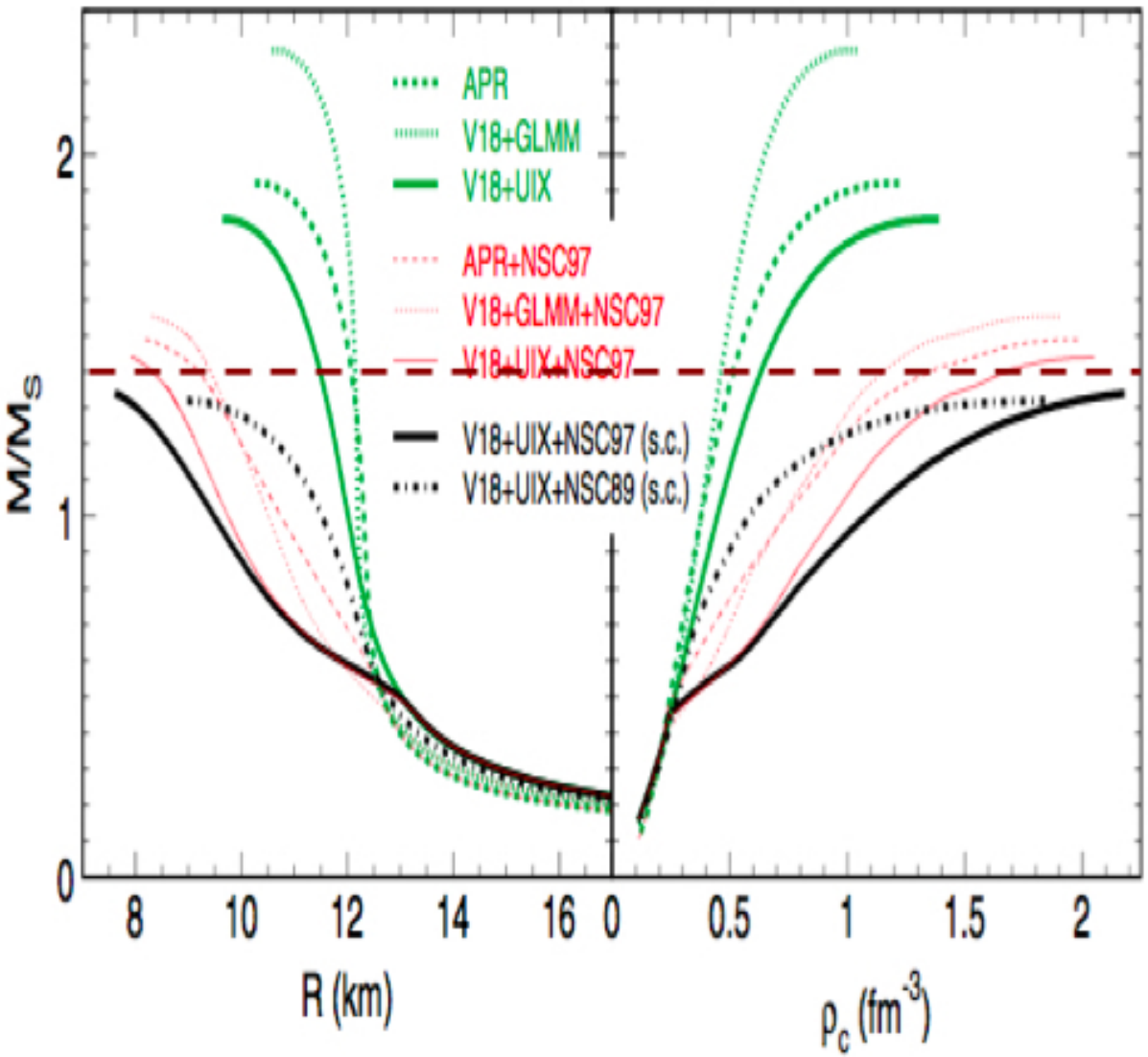

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$\Downarrow$

DRAMMATIC SCENARIO!!

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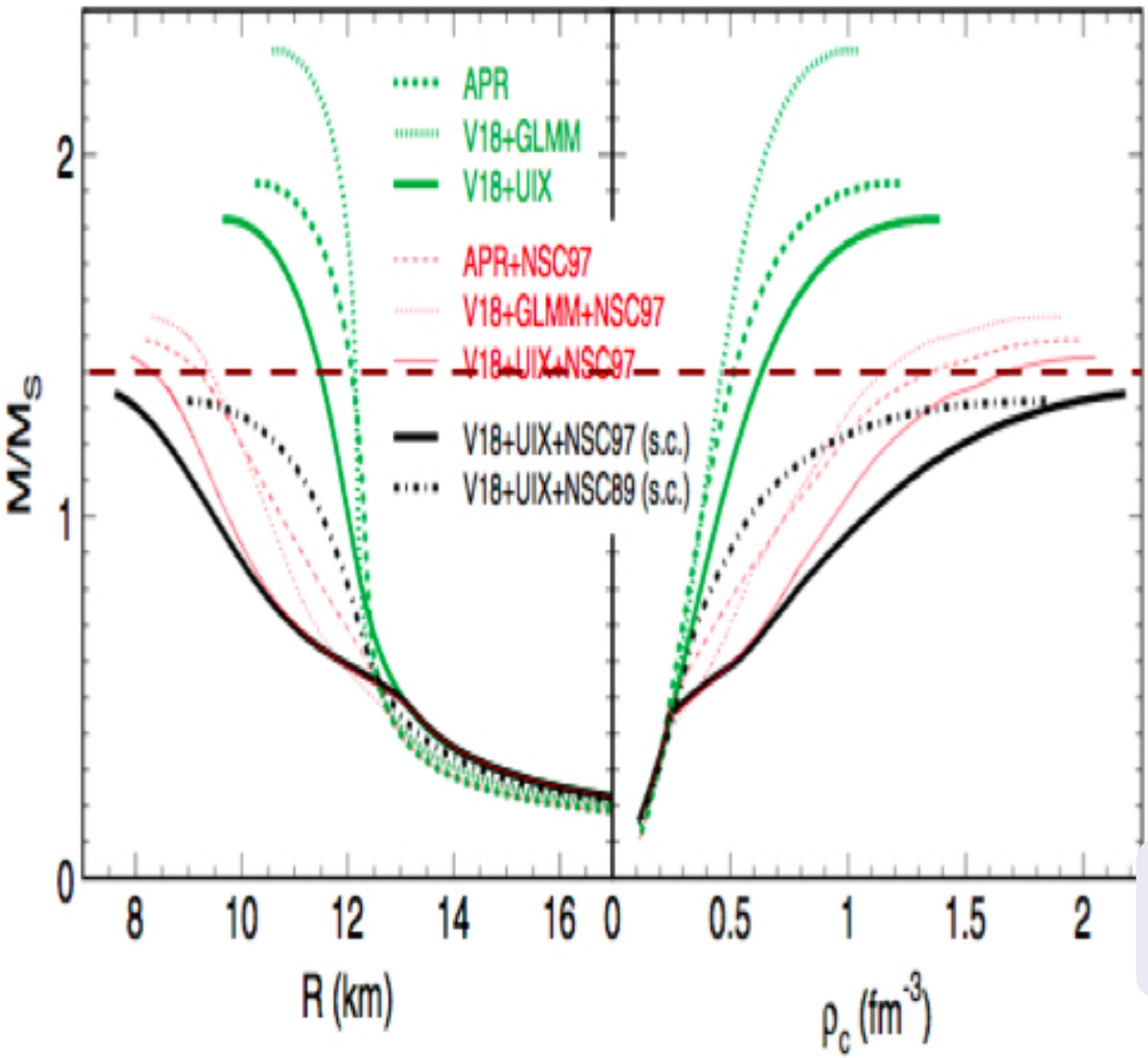

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DRAMMATIC SCENARIO!!

NNY, NYY and YYY may help??

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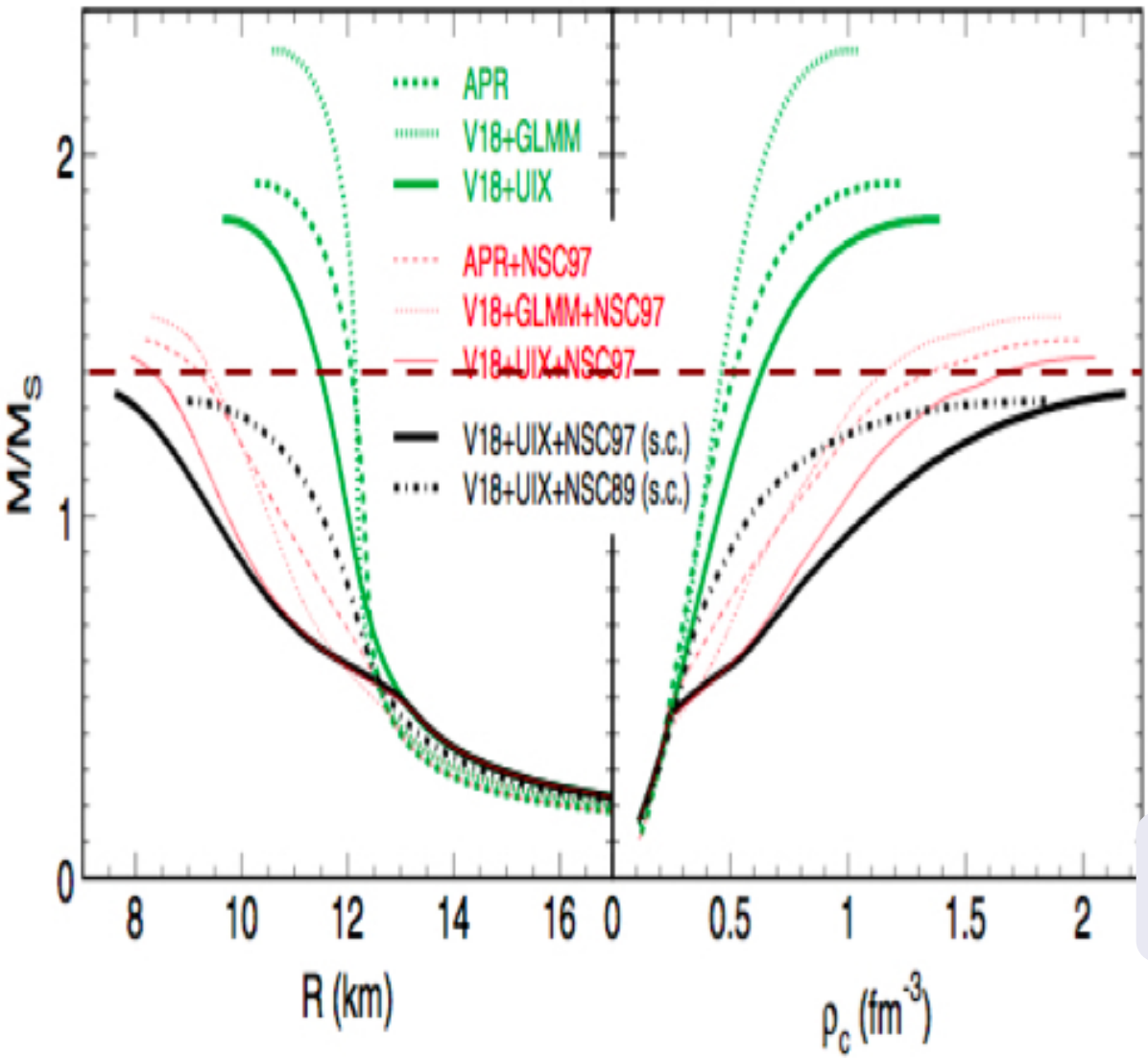

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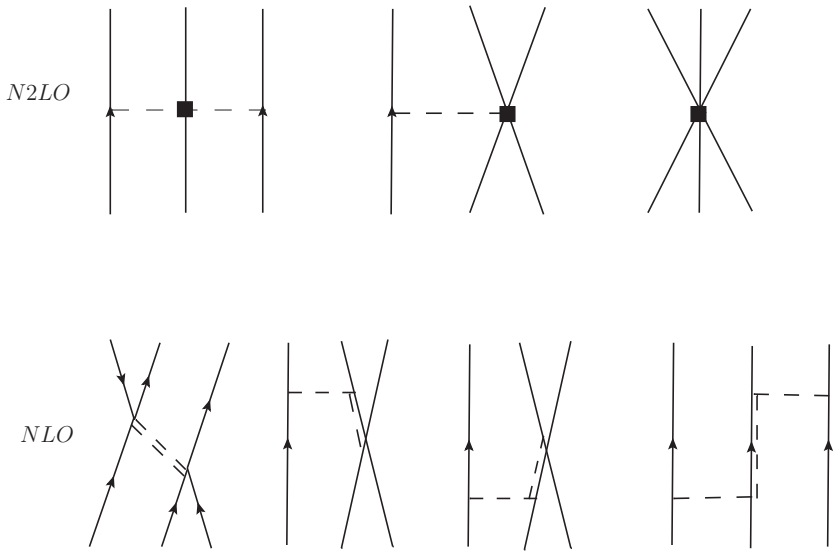
$\Downarrow$

DRAMMATIC SCENARIO!!

We focused on the NNΛ interactions

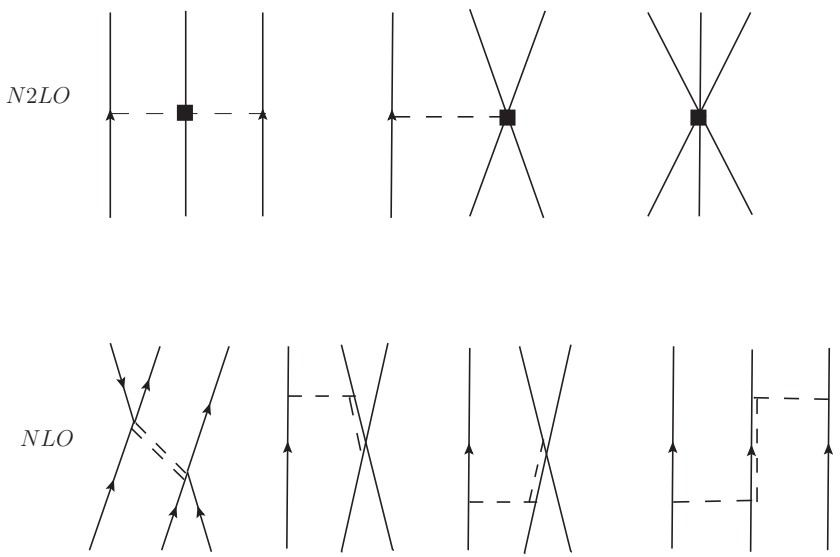
NNΛ force from ChPT



- 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 NΛ interaction from bare NNΛ force
- Low energy constants estimated from decuplet saturation

NNΛ force from ChPT



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

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- Baryonic three-body forces from chiral effective field theory
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- Same strategy used for nuclear matter
- Effective NΛ interaction from bare NNΛ force
- Low energy constants estimated from decuplet saturation

Equation of state for cold neutron stars (case of $\rho_\Lambda \neq 0$)

- Asymmetric matter:

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

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

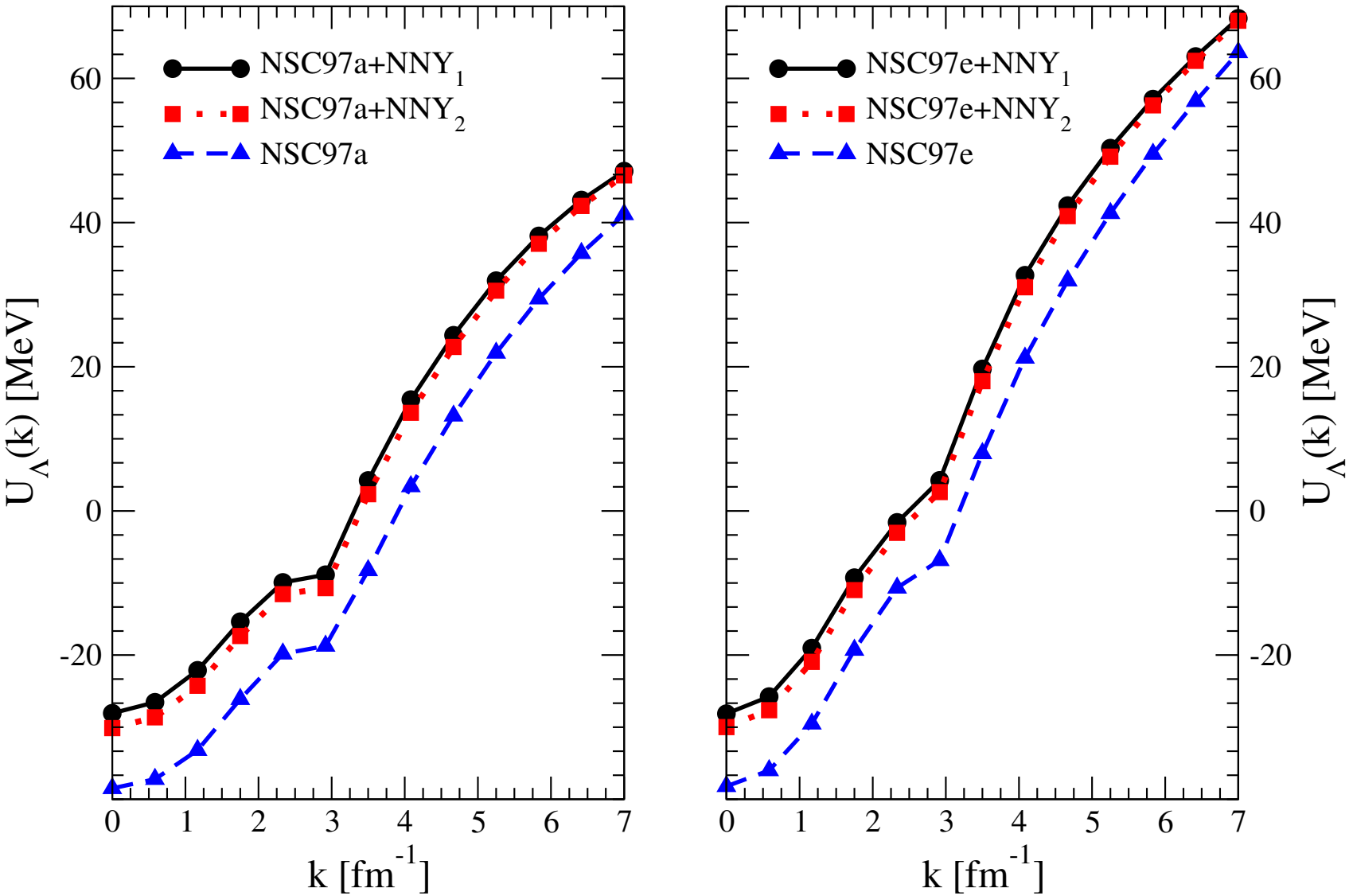
- Chemical equilibrium:

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

- Charge neutrality:

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

Λ-single particle potential



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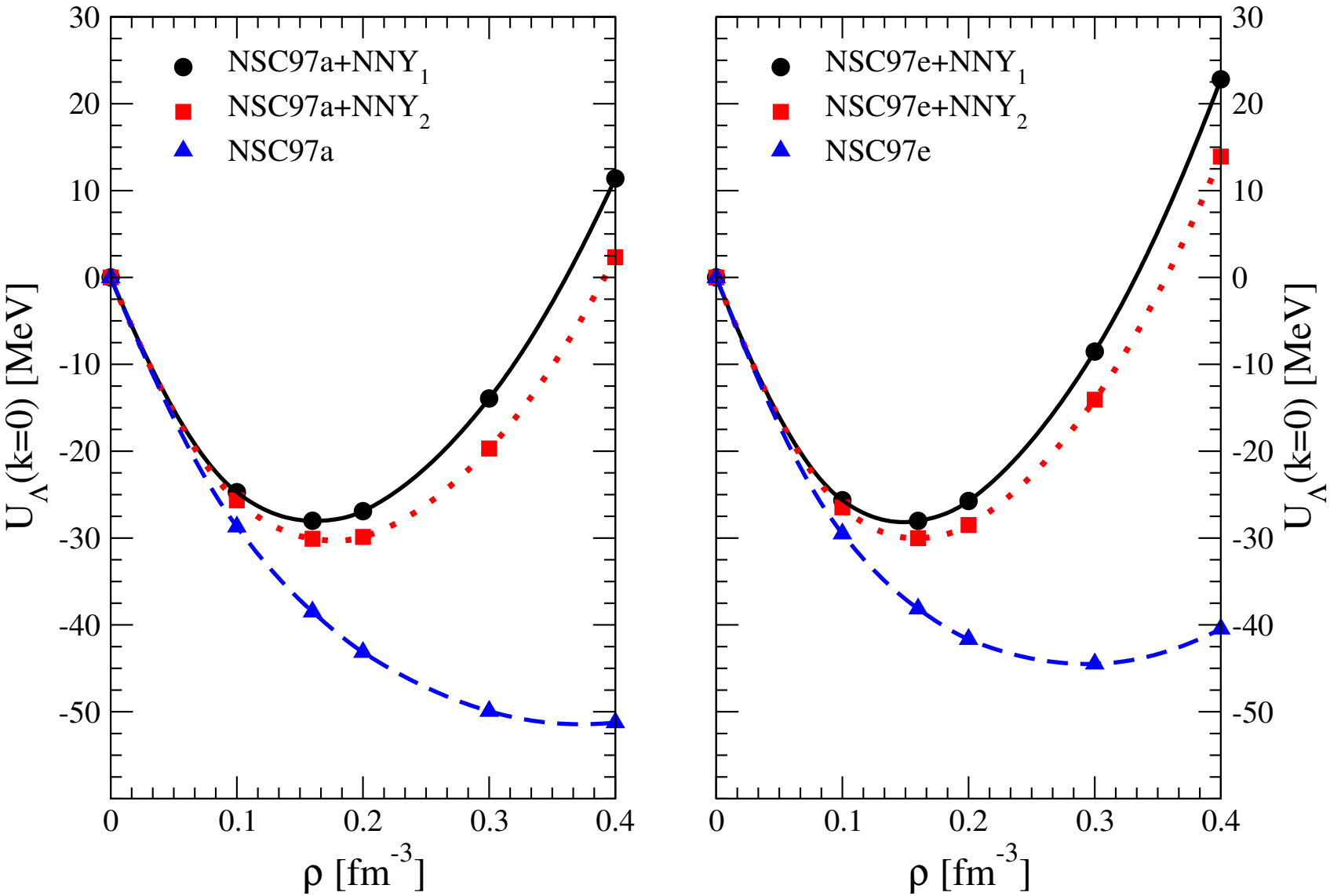
$U_\Lambda(k=0)$ as function of baryonic density



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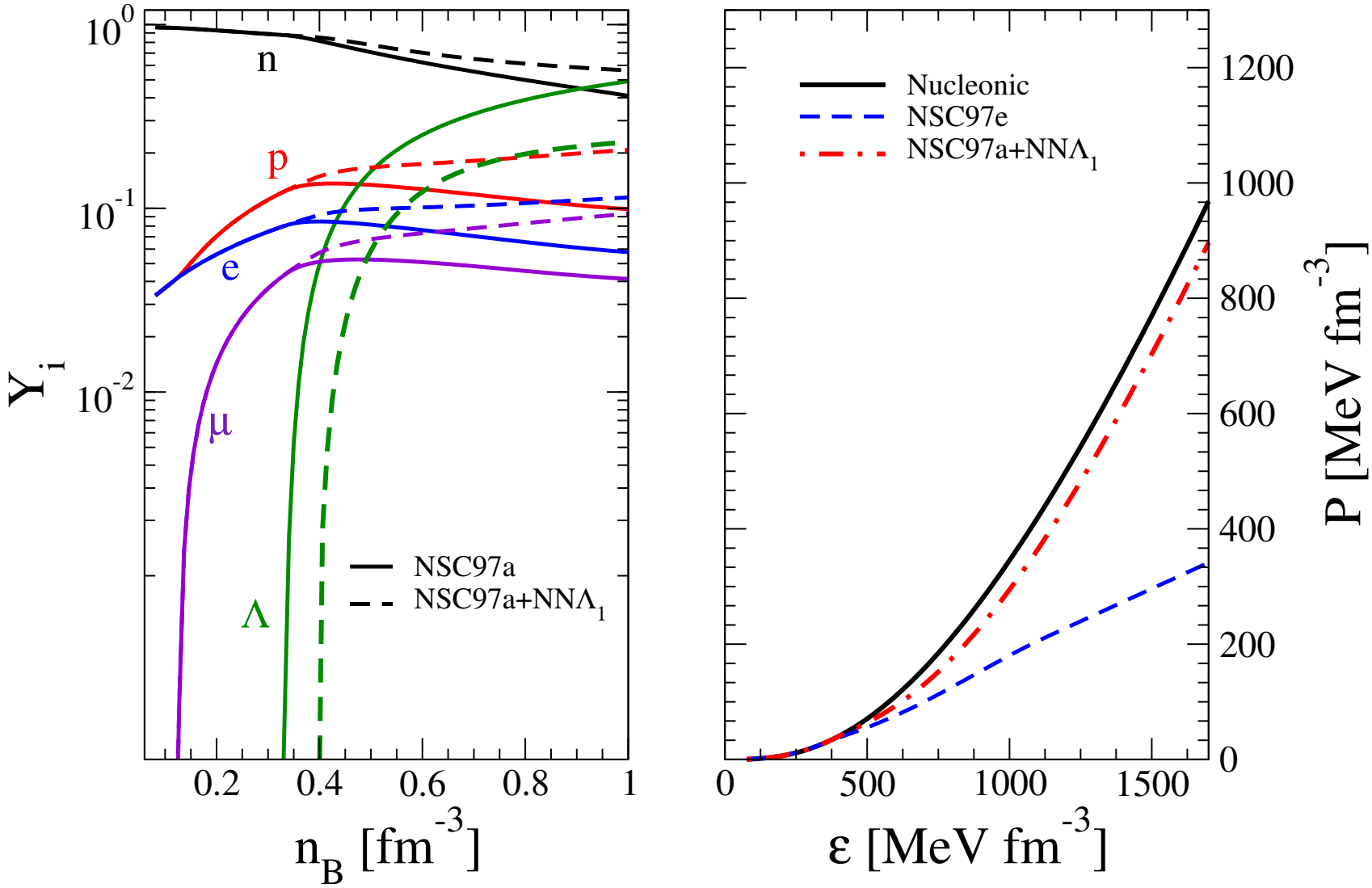
Composition of hyperonic matter



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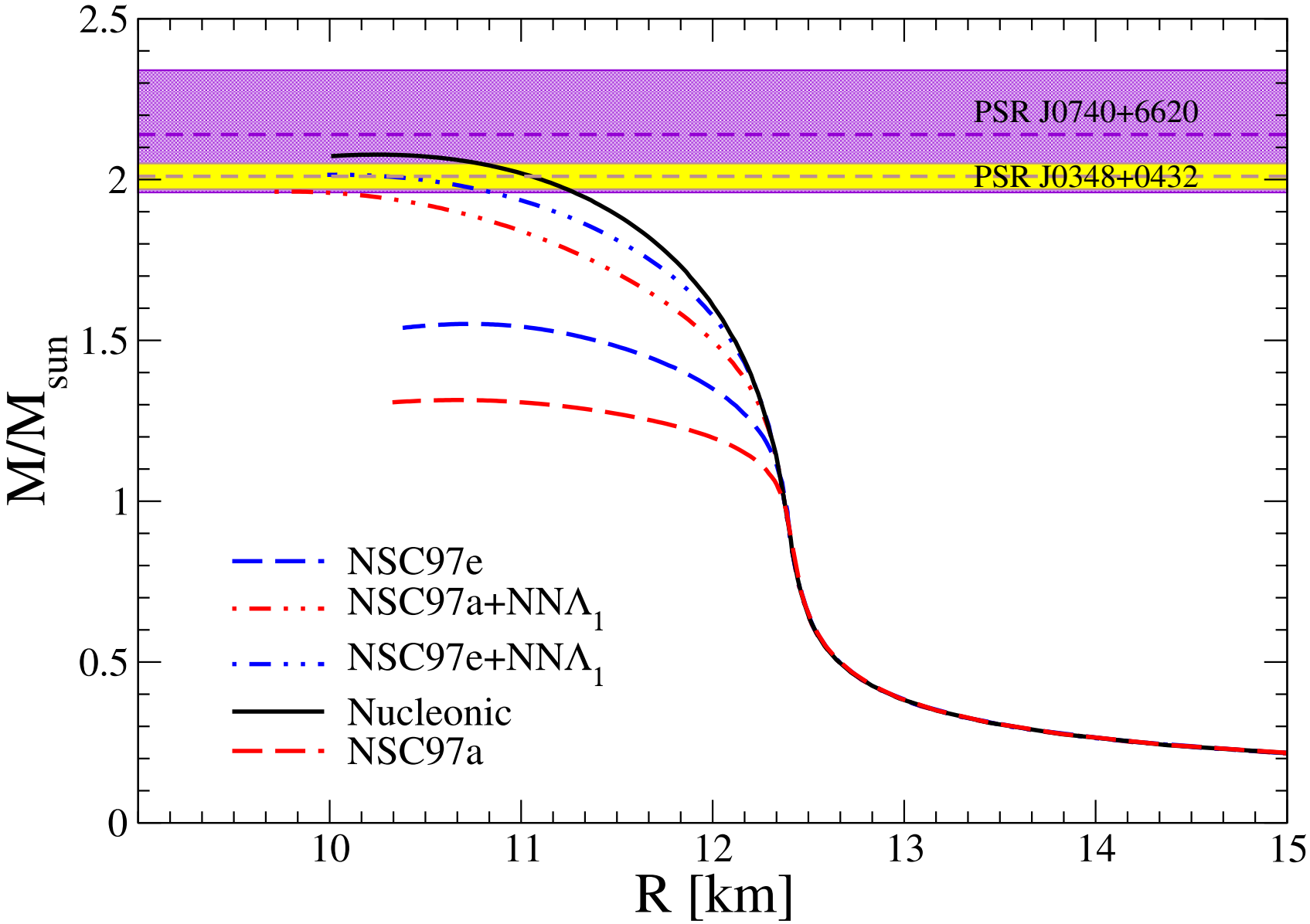
Neutron stars structure including Λ-hyperon



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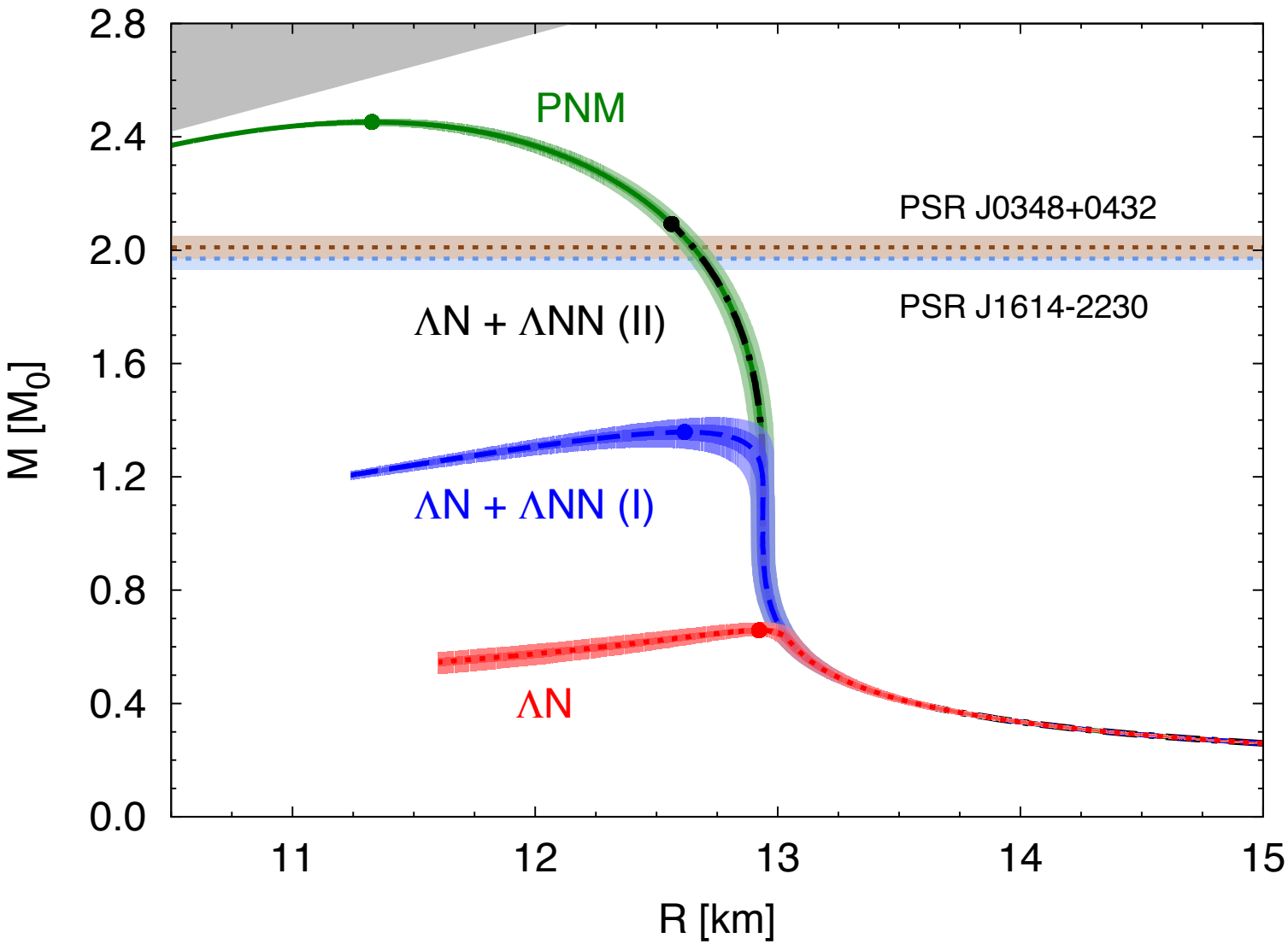
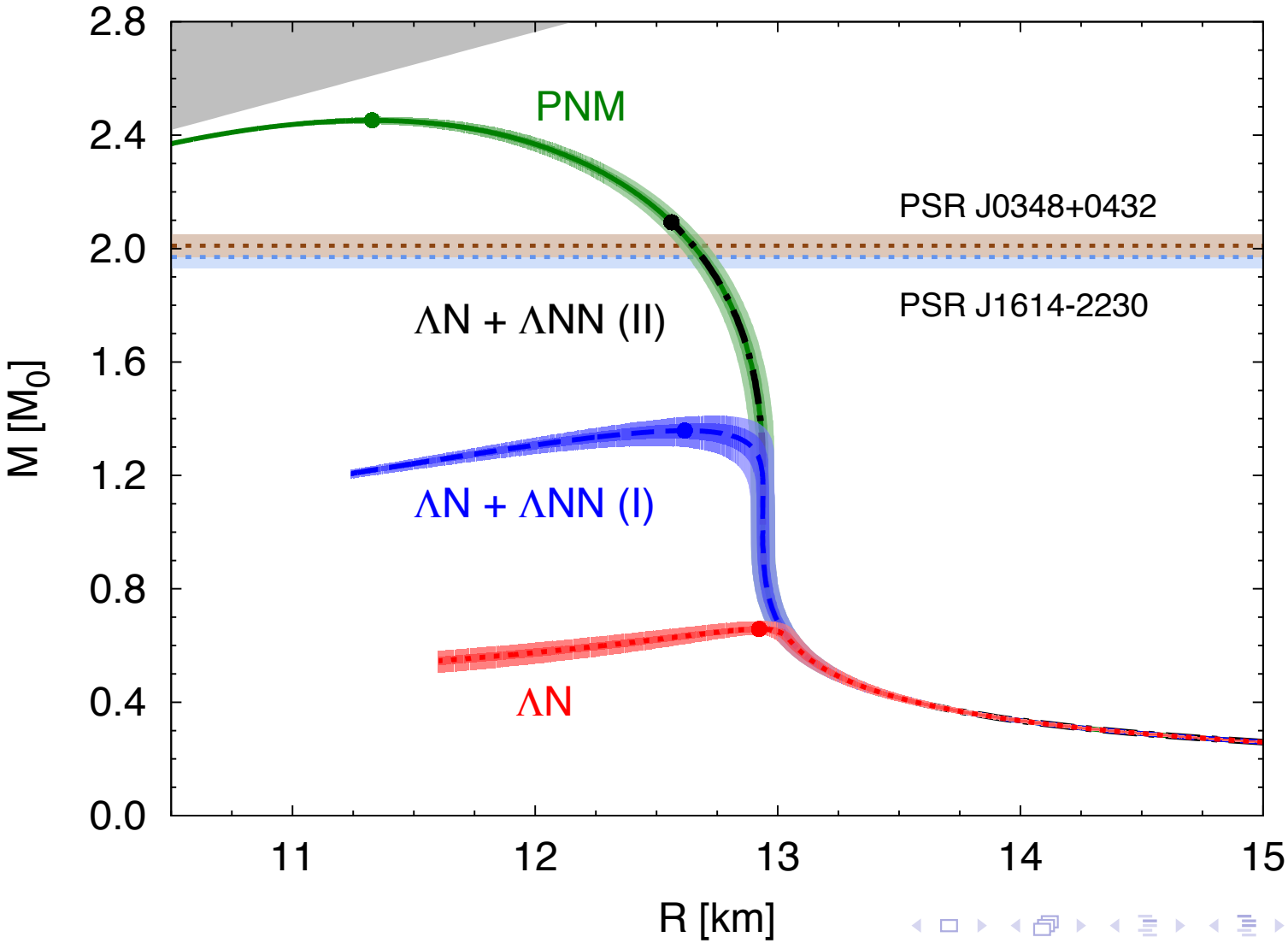


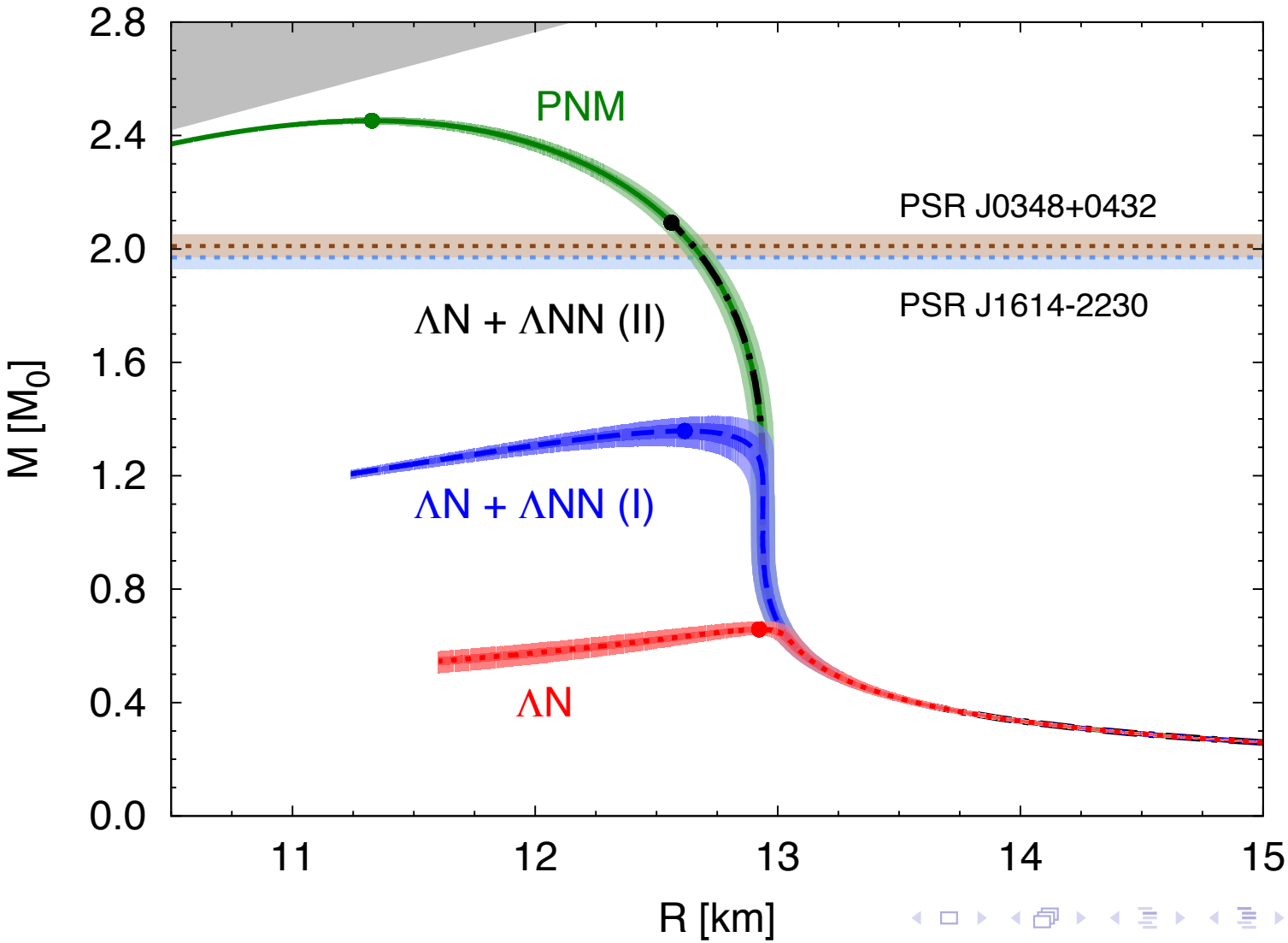
Lonardoni D. et al. Phys. Rev. Lett. 114, 092301 (2015)

Neutron stars structure including Λ-hyperon

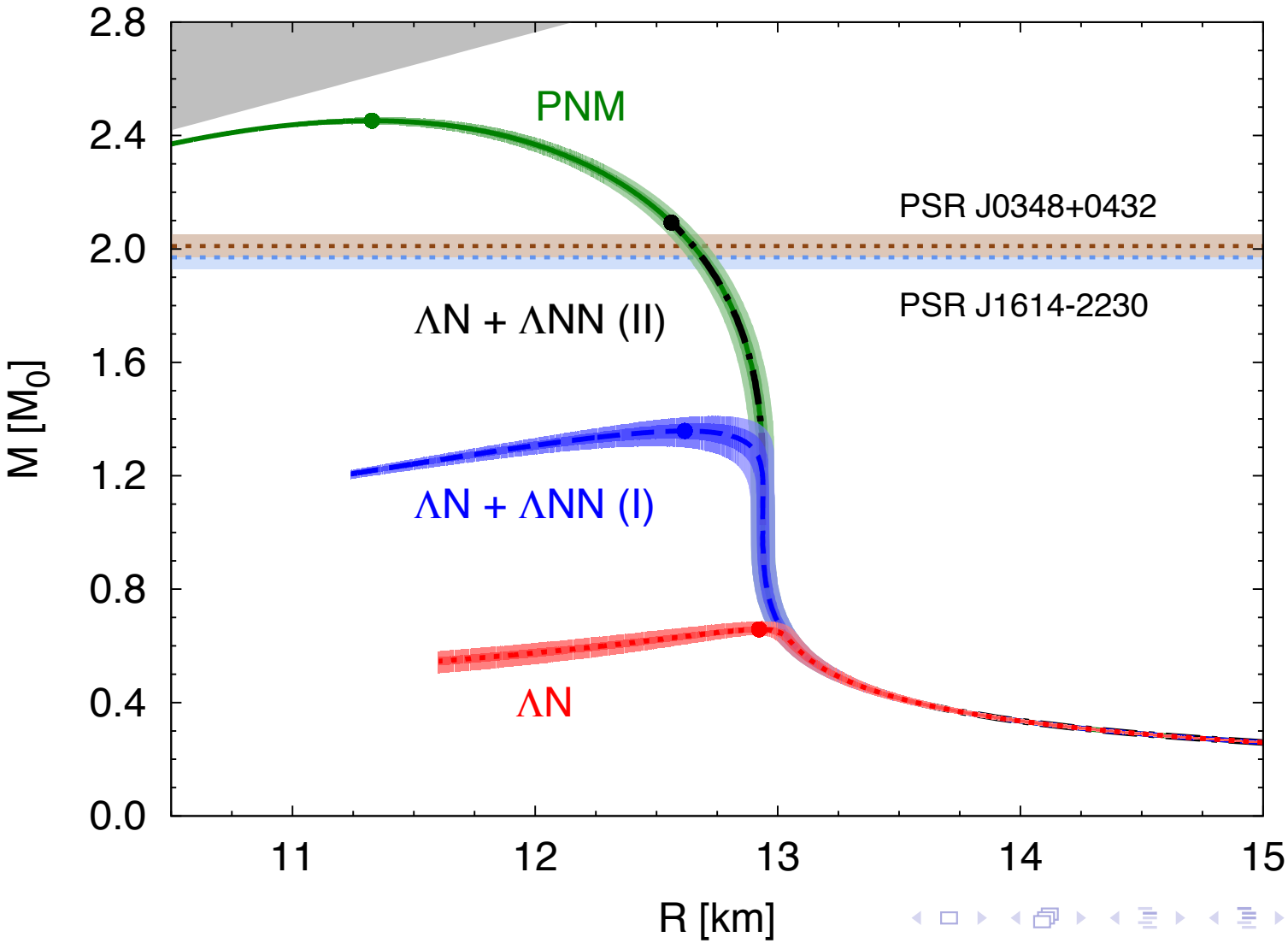
Similar result but several differences...



The main ones: 1) PNM calculation



The main ones: 2) solution of the hyperon puzzle ⇒ no hyperons at all



Improved description of 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.	18.7(1.1)	23.6(5)	26.9(8)

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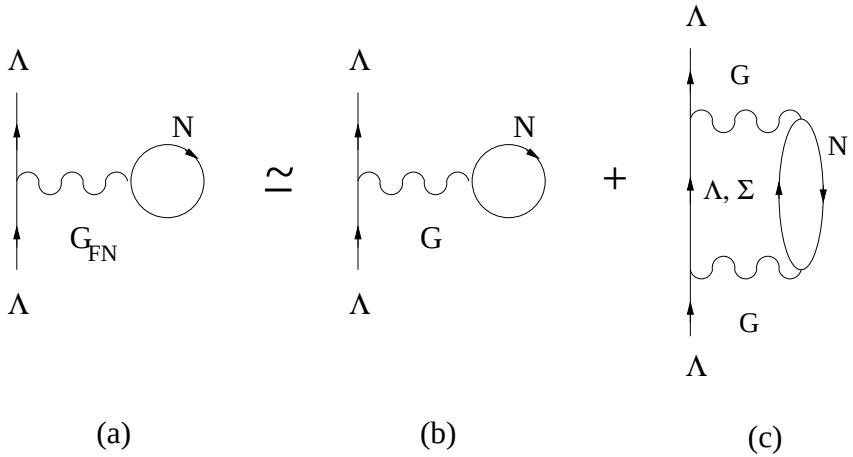
Hypernuclei separation energies



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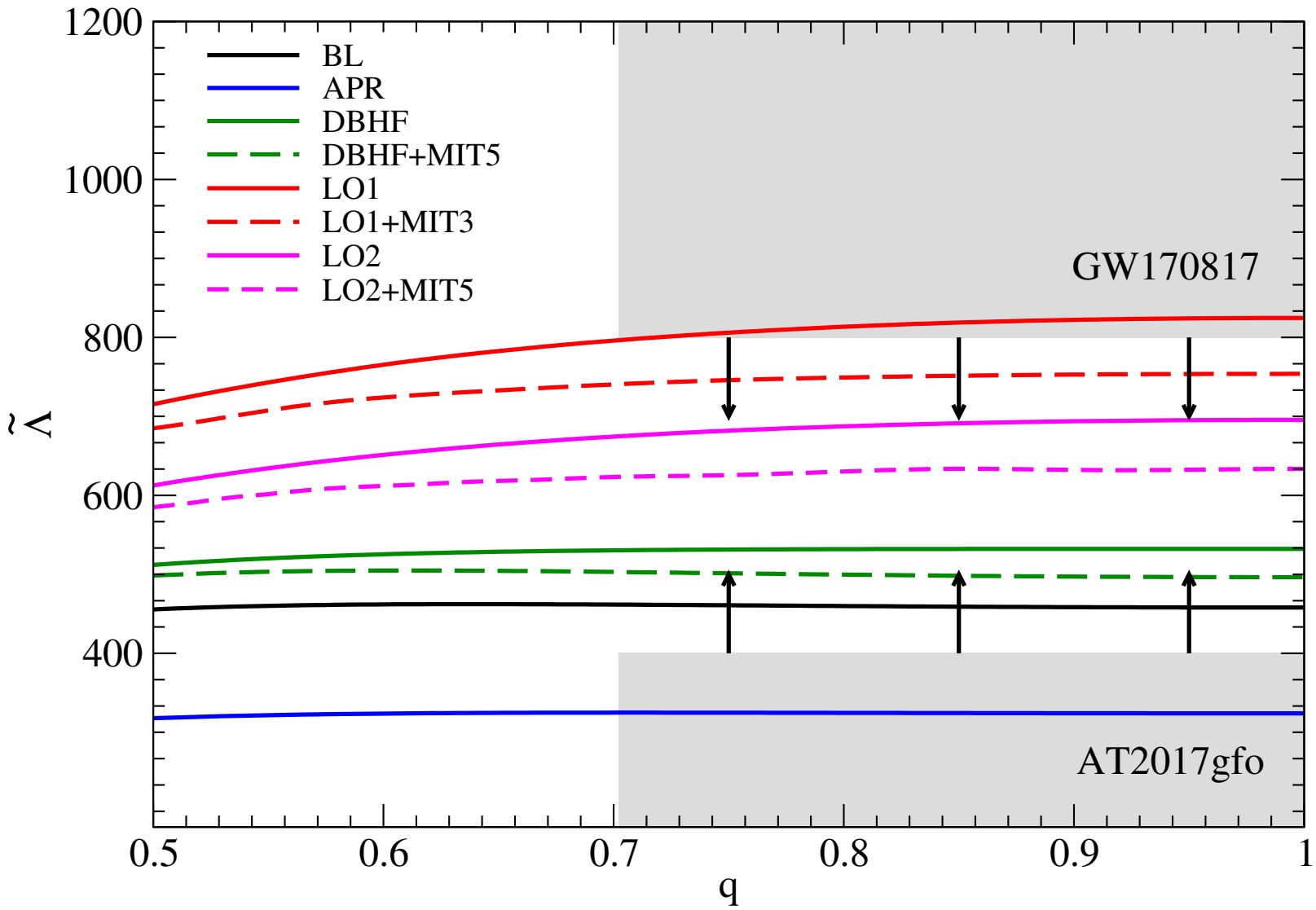
Conclusions

- 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
- 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!!!

Tidal polarizability



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