Impact of chiral hyperonic three-body forces on neutron stars

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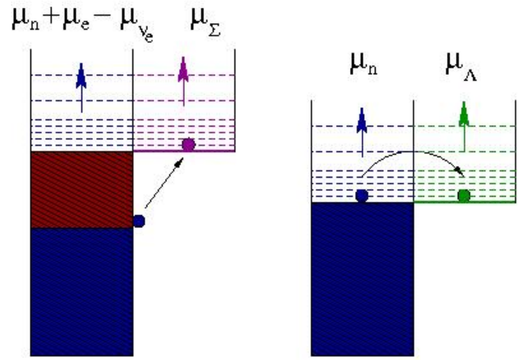
3rd EMMI Workshop: Anti-matter, hyper-matter & exotica production at the LHC

2-5 December 2019, Wroclaw (Poland)

The Hyperon Puzzle: An Open Problem

Hyperons are expected to appear in the core of neutron stars at $\rho \sim (2\text{-}3)\rho_0$ when μ_N is large enough to make the conversion of N into Y energetically favorable.

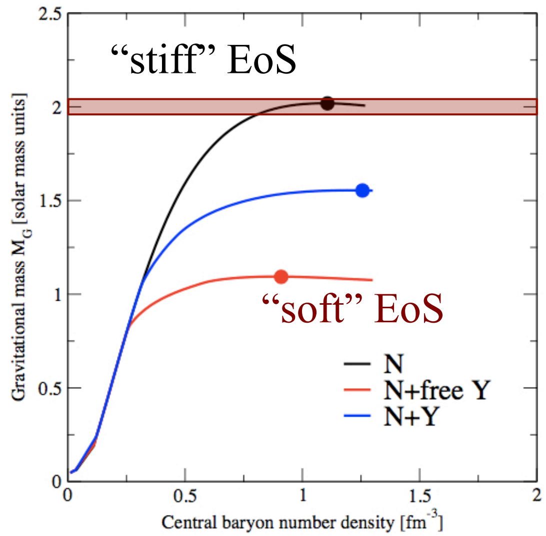


But

The relieve of Fermi pressure due to its appearance → EoS softer → reduction of the mass to values incompatible with observation

Observation of $\sim 2\,M_\odot$ NS → Any reliable EoS of dense matter should predict $M_{\max}[EoS] > 2M_\odot$

Can hyperons be present in the interior of neutron stars in view of this new constraint ?



Possible Solutions to the Hyperon Puzzle

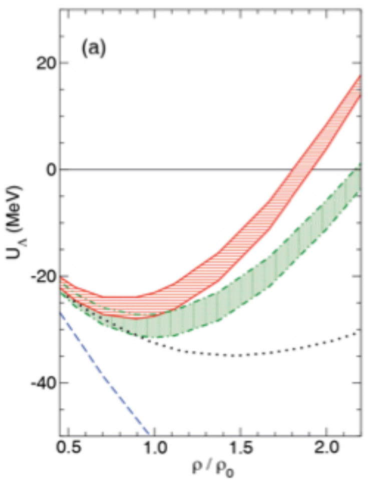
YN & YY

- YY vector meson repulsion

  ϕ meson coupled only to hyperons yielding strong repulsion at high ρ

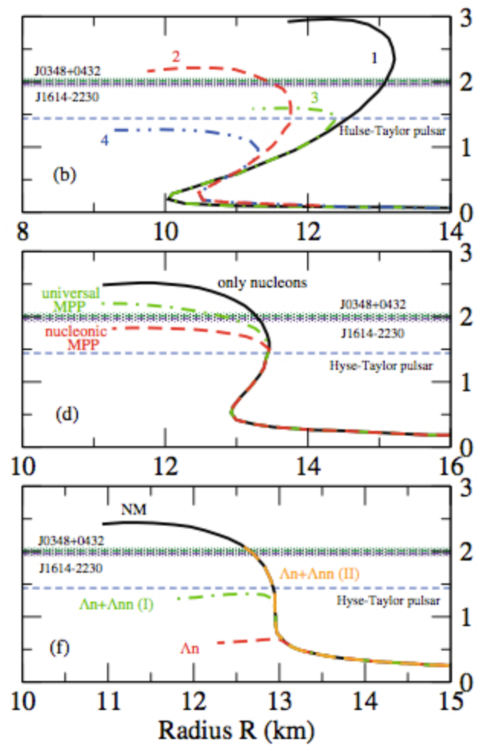
- Chiral forces

  YN from χEFT predicts Λ s.p. potential more repulsive than those from meson exchange



Hyperonic TBF

Natural solution based on the known importance of 3N forces in nuclear physics



Quark Matter

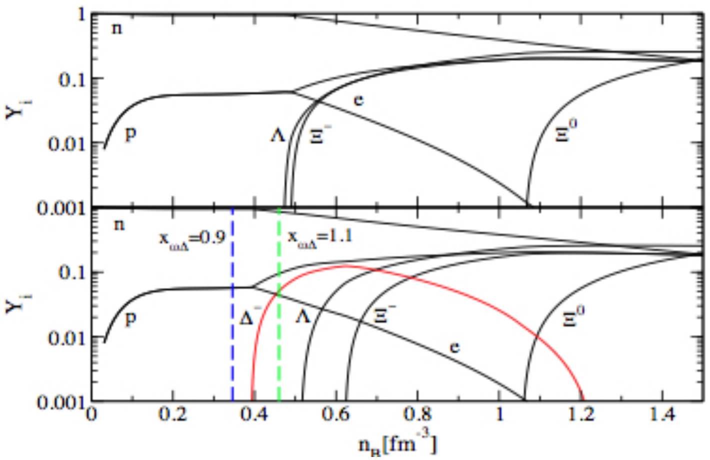
Phase transition to deconfined QM at densities lower that hyperon threshold

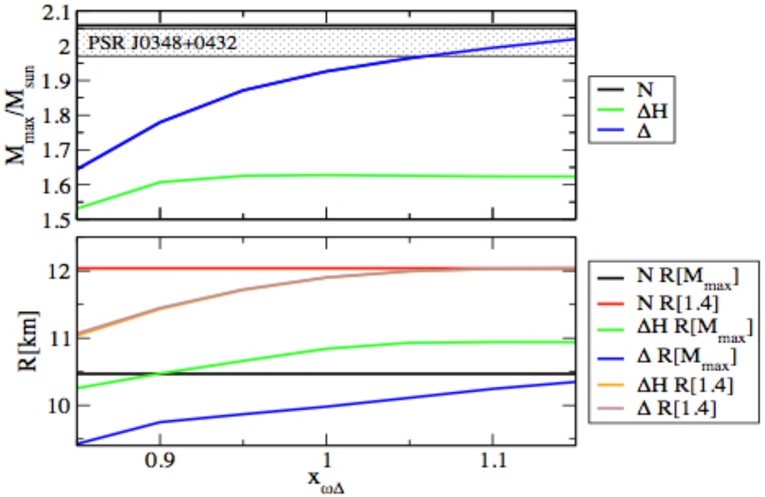
To yield $M_{max} > 2M_{\odot}$ QM should be

- significantly repulsive to guarantee a stiff EoS
- attractive enough to avoid reconfinement

Is there also a Δ isobar puzzle ?

Drago et al. (2014) & other authors have studied in the context of RMF models the role of the Δ isobar in neutron star matter & its interplay with hyperons





- ❖ Constraints from L indicate an early appearance of Δ isobars in neutron stars matter at ~ 2-3 ρ_0 (same range as hyperons)
- ❖ Appearance of Δ isobars modify the composition & structure of hadronic stars
- ❖ M_{max} is dramatically afected by the presence of Δ isobars

If Δ potential is close to that indicated by π−, e-nucleus or photoabsortion nuclear reactions then EoS is too soft ⟶ Δ puzzle similar to the hyperon one

Short Summary of the Talk

✧ Study of the effects of NNΛ force on neutron stars

To such end EoS & NS structure derived within the BHF approach using:

- NN at N^3LO in χEFT including Δ isobar in intermediate states of NN scattering
- NNN at N^2LO in χEFT
- NΛ from meson-exchange (Nijmegen group). Weak point of the work
- NNΛ derived by the Juelich-Munich-Bonn group in χEFT at N^2LO

✧ Inclusion of NNΛ force improves description of heavy hypernuclei

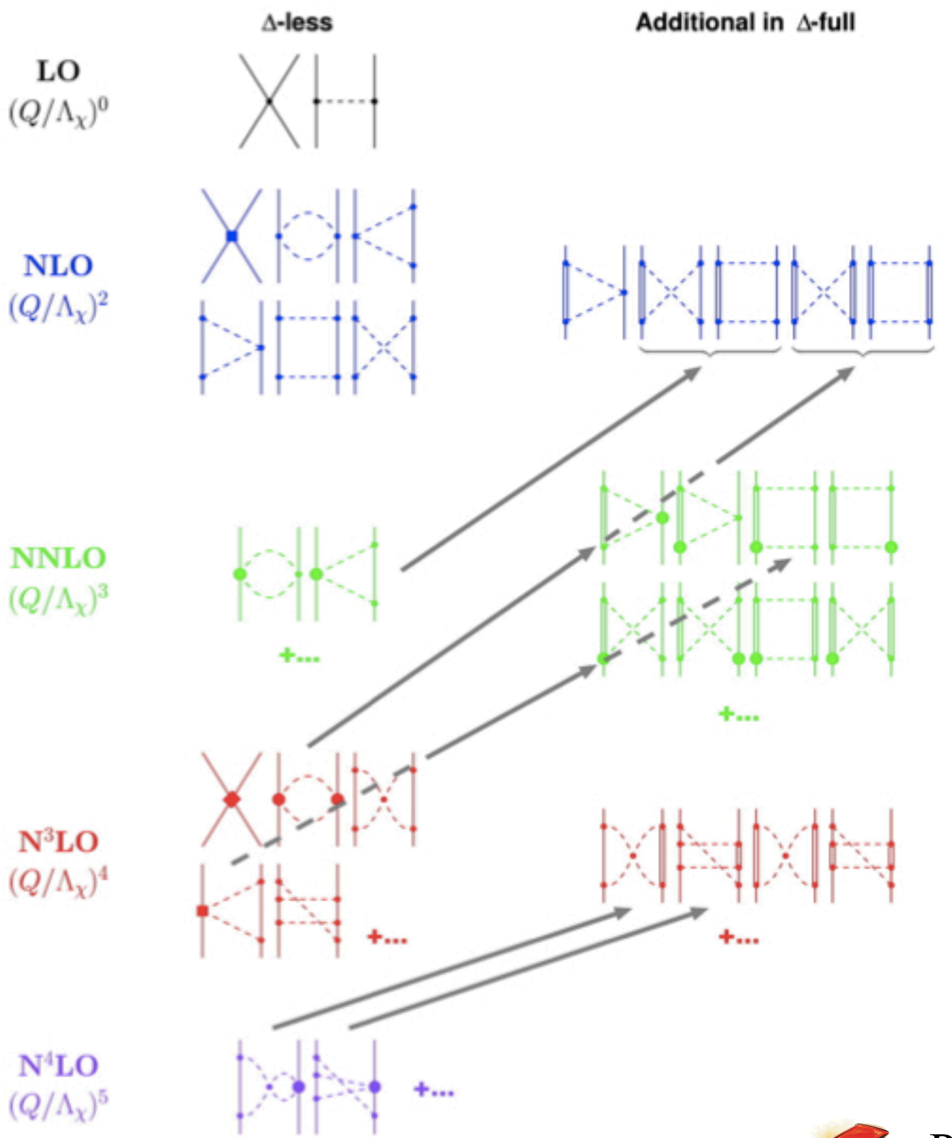
✧ Inclusion of NNΛ force leads to an EoS stiff enough such that he resulting NS maximum mass is compatible with current observations **but the model contains only N, leptons & Λ's**

✧ We have **NOT SOLVED** the hyperon puzzle **but have taken an additional step towards its solution**

In collaboration with: D. Logoteta & I. Bombaci (University of Pisa)

For details see:  EPJA 55, 207 (2019)

NN interaction



- ✧ Local chiral potential derived in coordinate space
- ✧ Δ isobar included in intermediate NN scattering
- ✧ A gaussian regulator for short range contributions

$$\frac{1}{\pi^{3/2}R_s^3}\exp\left[-r^2/R_s^2\right],\quad R_S=0.7\,fm$$

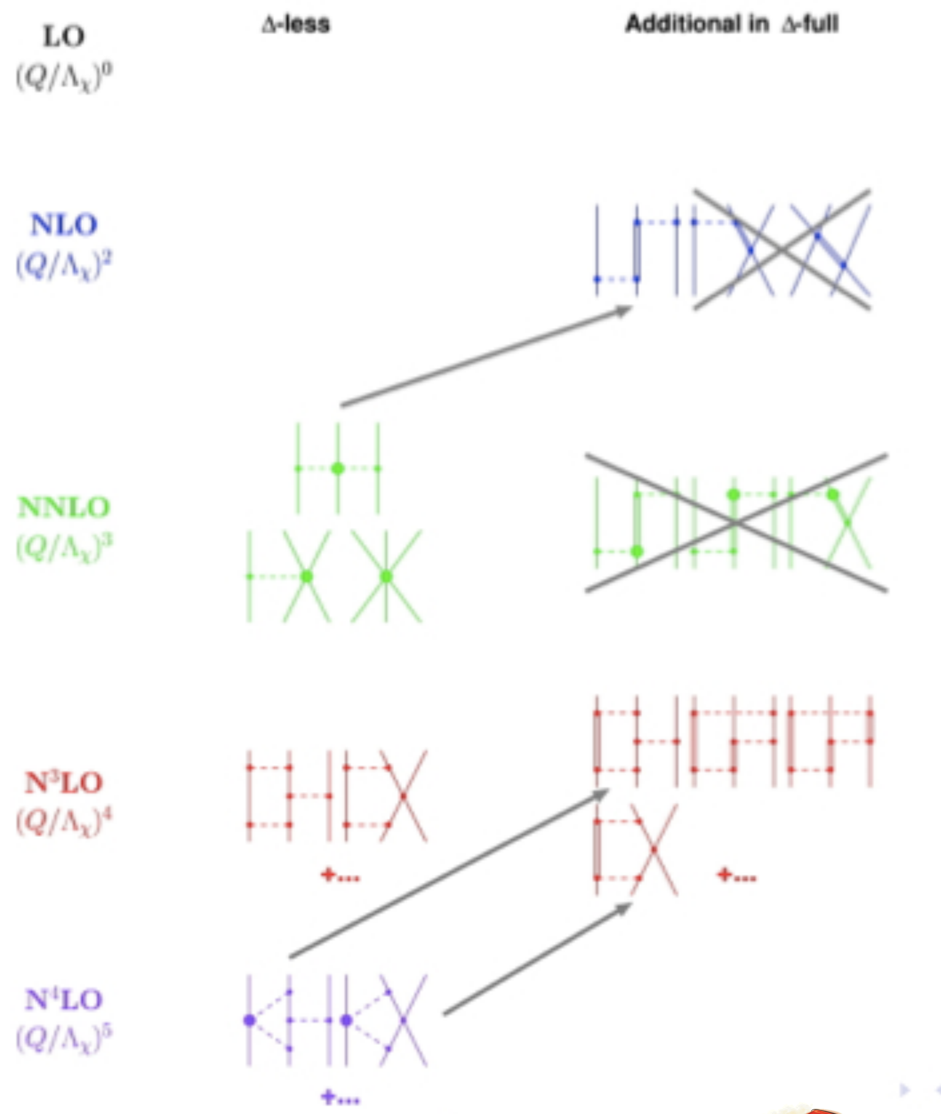
- ✧ Long range contributions regularized with

$$1-\left(\left(\frac{r}{R}\right)^6\exp\left(\frac{2r}{R_l}-2\right)+1\right)^{-1},\quad R_l=1\,fm$$

- ✧ Operatorial structure similar to the Av18 (but not the same)

Piraulli et al., PRC 94, 054007 (2016)

NNN interaction



- First TNF contribution at NLO
- Δ isobar included
- Gaussian regulator used

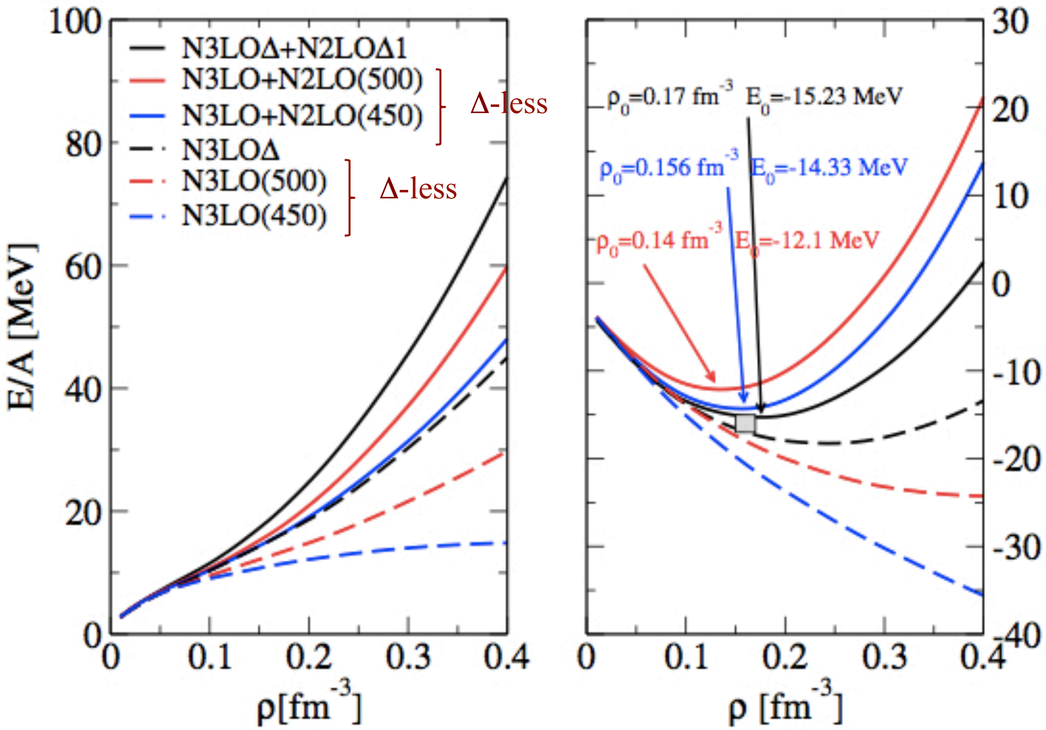
$$\frac{1}{\pi^{3/2}R_s^3}\exp\left[-r^2\Big/R_s^2\right],\quad R_S = 0.7\,fm$$

- 5 LEC:
  - c_1, c_3, c_4 fixed from the two-body interaction
  - c_E & c_D fixed from observables of few body nuclear systems (^3H) or to reproduce the saturation point (this work)

Piraulli et al., PRC 94, 054007 (2016)

Nuclear Matter EoS

PNM SNM



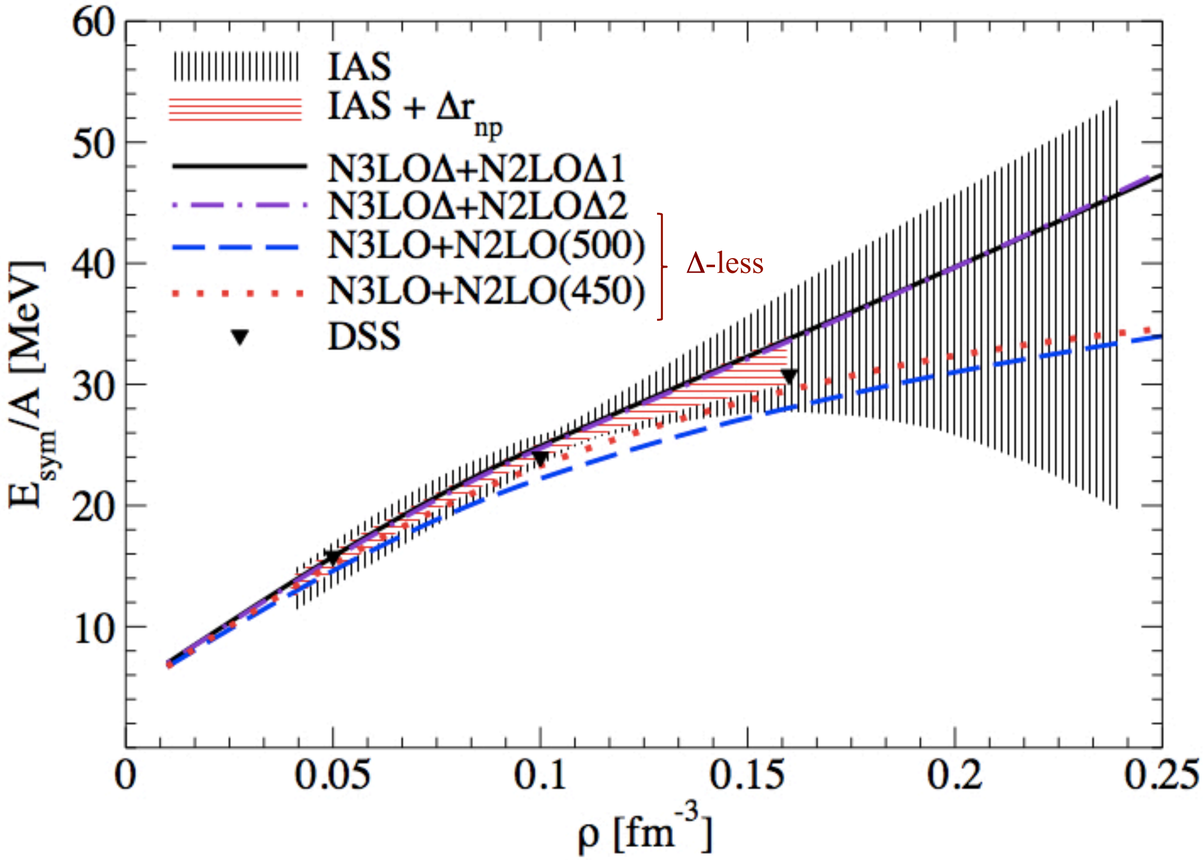
- ✧ Significant improvement of SNM saturation point due to TNF
- ✧ Explicit inclusion of the Δ isobar diminishes the strength of the TNF needed to obtain a good saturation point

Nuclear Matter Properties at Saturation

	Model	ρ_0(fm^{-3})	E/A (MeV)	E_{sym} (MeV)	L (MeV)	K_∞ (MeV)
	N3LOΔ+N2LOΔ1	0.171	-15.23	35.39	76.0	190
	N3LOΔ+N2LOΔ2	0.176	-15.09	36.00	79.8	176
Δ-less	N3LO+N2LO(500)	0.135	-12.12	25.89	38.3	153
Δ-less	N3LO+N2LO(450)	0.156	-14.32	29.20	39.8	205

Logoteta et al., PRC 94, 064001 (2016)

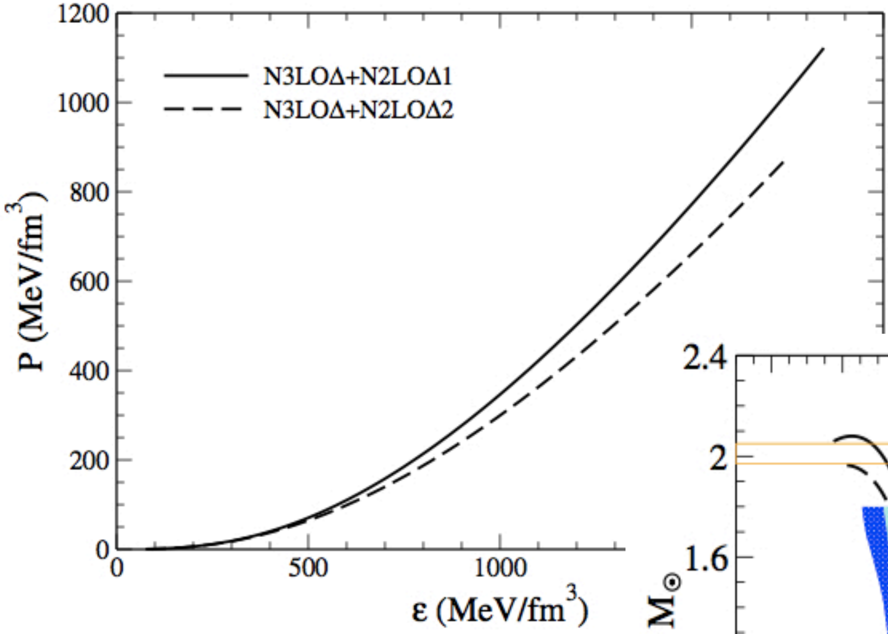
Nuclear Symmetry Energy

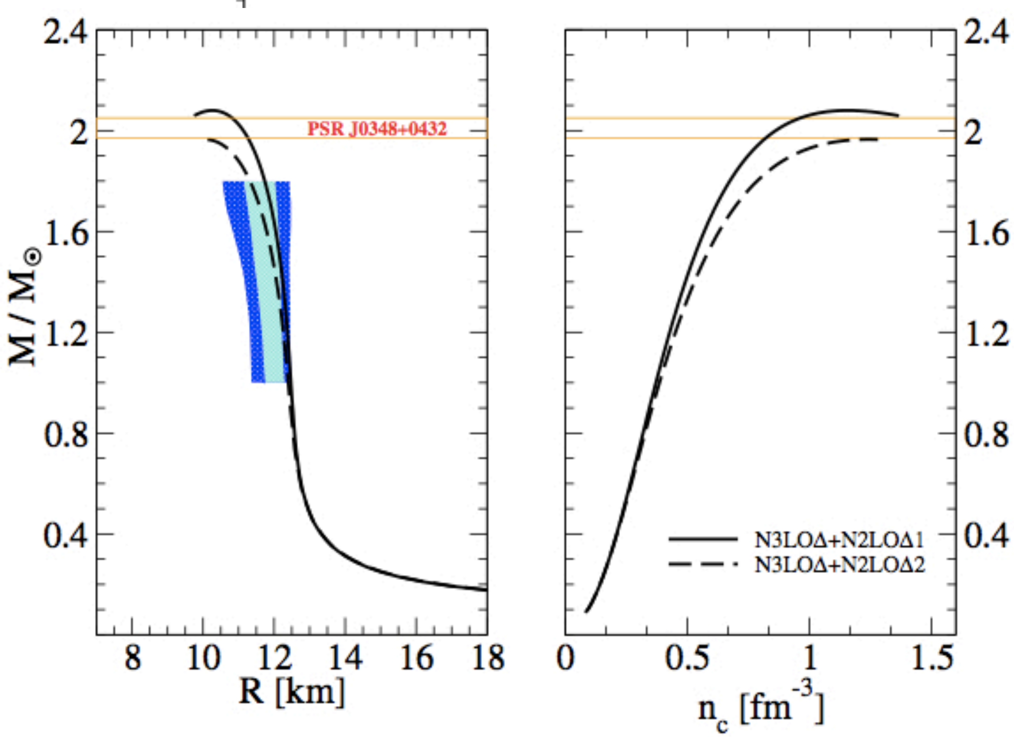


Good agreement with experimental constraints from Isobaric Analog States & neutron skin thinkness

Logoteta et al., PRC 94, 064001 (2016)

NS EoS & Structure at $N^3LO\Delta+N^2LO\Delta$





Good agreement with with recent observations of $2M_\odot$ NS

Logoteta et al., A&A 609, A128 (2018)

NΛ interaction

✧ NY & YY interactions in χEFT derived by the Juelich-Bonn-Munich group

- NY at

  LO: Polinder et al., NPA 779, 244 (2006)

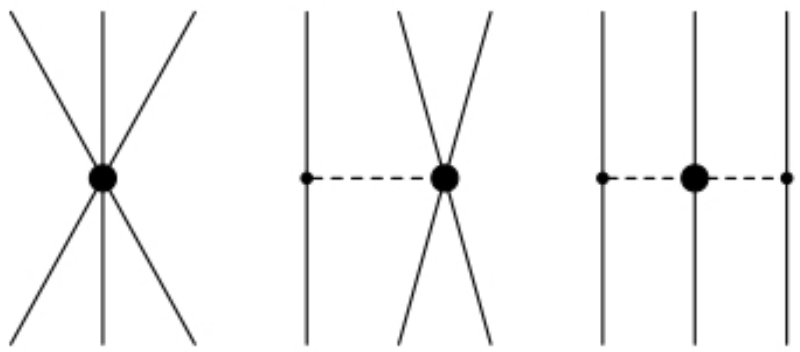
  NLO: Haidenbauer et al., NPA 915, 24 (2013)

  Haidenbauer et al., arXiv:1906.11681

- YY at NLO: Haidenbauer et al., NPA 954, 273 (2016)

WEAK POINT OF THE PRESENT WORK: unfortunately at the time this work was done we did not have at our disposal this interaction and, therefore, instead we used a NY meson-exchange interaction from the Nijmegen group (NSC97a & NSC97f)

NNΛ interaction



(π exchange expected to be dominant, heavy meson (K,η) exchange absorbed into contact terms)

- ✧ First contributions to NNY appear in χEFT at N^2LO
- ✧ Leading terms at N^2LO
  - ✓ Three-baryon contact terms
  - ✓ One & two-meson exchange

- ✧ LEC estimated through decouplet saturation. Only one LEC H' remains a free parameter. A value of $H'=\pm 1/f_\pi$ where $f_\pi=93$ MeV has been considered by Petschauer et al.

- ✧ In this work $H'=\beta/f^2_\pi$ with β a parameter fixed to reproduce $U_\Lambda(k=0) \sim -28 - 30$ MeV in SNM at saturation ⟶ Models $NN\Lambda_1$ & $NN\Lambda_2$

- ✧ A non-local regulator $\exp(-(p^4+p'^4)/\Lambda^4)$ with $\Lambda=500$ MeV is used

Petschauer et al., PRC93, 014001 (2016)

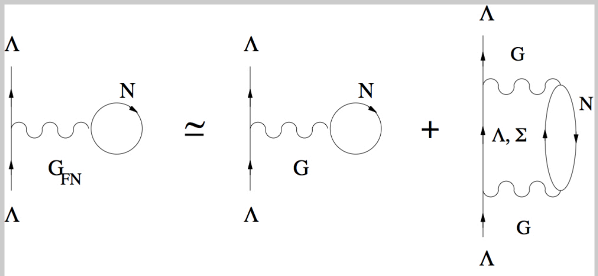
Effect of NNΛ interaction on hypernuclei

Before analyzing the effect of NNΛ interaction on NS we consider its role on hypernuclear strucure. To such end

A perturbative many-body approach is employed to obtain the Λ self-energy in finite nuclei from which the Λ s.p. bound states can be obtained

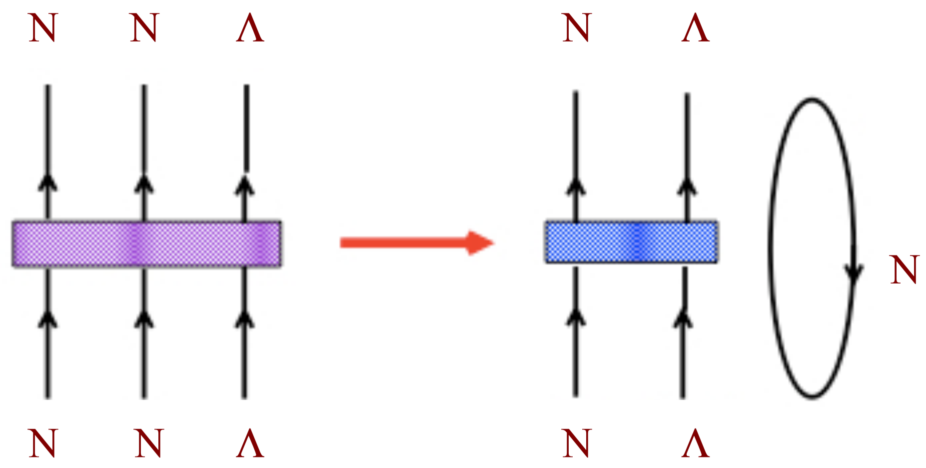
$$G_{NM} = V + V\left(\frac{Q}{E}\right)_{NM} G_{NM} \longrightarrow G_{FN} = G_{NM} + G_{NM}\left[\left(\frac{Q}{E}\right)_{FN} - \left(\frac{Q}{E}\right)_{NM}\right] G_{FN}$$

BHF approximation to the Λ irreducible self-energy in finite nuclei



NNΛ interaction within the BHF approach

The NNΛ interaction can be introduced in our BHF approach by adding an effective density-dependent NΛ force to the NΛ two-body one when solving the Bethe-Goldstone equation



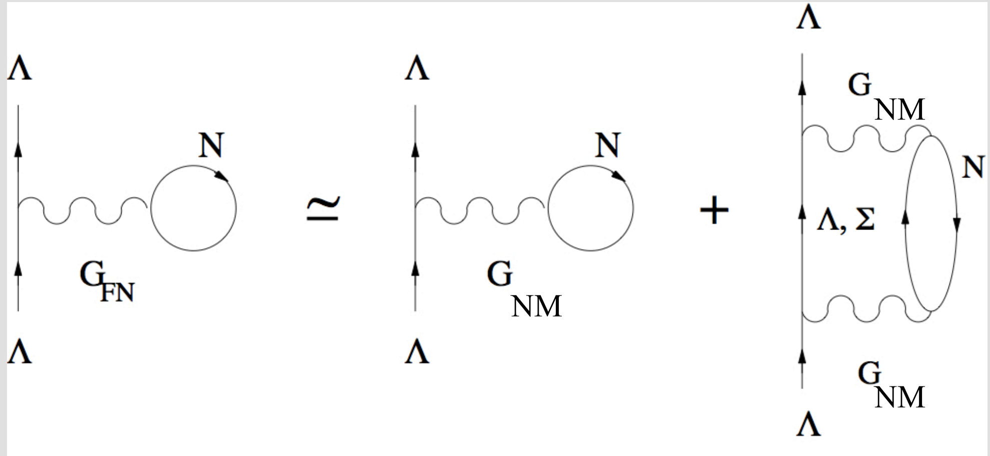
$$W_{B_iB_j}\left(\vec{r}_{ij}\right)=Tr_{(\tau_k,\sigma_k)}\int W_3\left(\vec{r}_i,\vec{r}_j,\vec{r}_k\right)n\left(\vec{r}_i,\vec{r}_j,\vec{r}_k\right)d^3\vec{r}_k$$

$W_3\left(\vec{r}_i,\vec{r}_j,\vec{r}_k\right)$: genuine TBF $\quad$ $n\left(\vec{r}_i,\vec{r}_j,\vec{r}_k\right)$: three-body correlation function

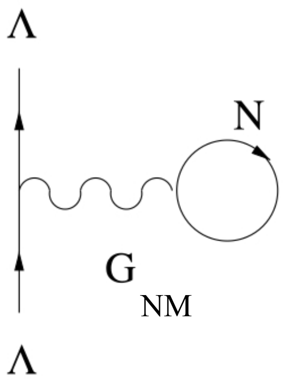
N.B.: Petschauer et al., have derived this effective density-dependent NΛ force allowing a straightforward inclusion of the NNL force in our BHF approach

Finite nucleus Λ self-energy in the BHF approximation

Using G_{FN} as an effective YN interaction, the finite nucleus Λ self-energy is given as sum of a 1st order term & a 2p1h correction



✧ 1st order term



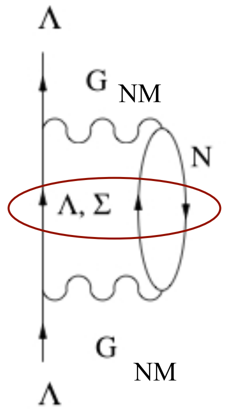
$$\mathcal{V}_1(k_\Lambda, k'_\Lambda, l_\Lambda, j_\Lambda) = \frac{1}{2j_\Lambda + 1} \sum_{\mathcal{J}} \sum_{n_h l_h j_h t_{z_h}} (2\mathcal{J}+1) \times \langle (k'_\Lambda l_\Lambda j_\Lambda)(n_h l_h j_h t_{z_h})\mathcal{J} | G | (k_\Lambda l_\Lambda j_\Lambda)(n_h l_h j_h t_{z_h})\mathcal{J} \rangle$$

This contribution is real & energy-independent

N.B.: most of the effort is on the basis transformation $\left|(k_\Lambda l_\Lambda j_\Lambda)(n_h l_h j_h t_{z_h})J\right\rangle \rightarrow \left|KLqLSJTM_T\right\rangle$

✧ 2p1h correction

This contribution is the sum of two terms:



$$\left[\left(\frac{Q}{E}\right)_{FN}-\left(\frac{Q}{E}\right)_{NM}\right]$$

- The first, due to the piece $G_{NM}(Q/E)_{FN}G_{NM}$, gives rise to an imaginary energy-dependent part in the Λ self-energy

$$\begin{aligned}
&\mathcal{W}_{2p1h}(k_\Lambda, k'_\Lambda, l_\Lambda, j_\Lambda, \omega) \\
&\quad = -\frac{\pi}{2j_\Lambda+1}\sum_{n_h l_h j_h t_{z_h}}\sum_{\mathcal{L}LSJ\mathcal{J}}\sum_{Y'=\Lambda\Sigma}\int dq q^2\int dK K^2(2\mathcal{J}+1) \\
&\quad \times \langle (k'_\Lambda l_\Lambda j_\Lambda)(n_h l_h j_h t_{z_h})\mathcal{J}|G|K\mathcal{L}qLSJ\mathcal{J}TM_T\rangle \\
&\quad \times \langle K\mathcal{L}qLSJ\mathcal{J}TM_T|G|(k_\Lambda l_\Lambda j_\Lambda)(n_h l_h j_h t_{z_h})\mathcal{J}\rangle \\
&\quad \times \delta\left(\omega+\varepsilon_h-\frac{\hbar^2K^2}{2(m_N+m_{Y'})}-\frac{\hbar^2q^2(m_N+m_{Y'})}{2m_N m_{Y'}}-m_{Y'}+m_\Lambda\right)
\end{aligned}$$

From which can be obtained the contribution to the real part of the self-energy through a dispersion relation

$$\mathcal{V}^{(1)}_{2p1h}(k_\Lambda, k'_\Lambda, l_\Lambda, j_\Lambda, \omega)=\frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty}d\omega'\frac{\mathcal{W}_{2p1h}(k_\Lambda, k'_\Lambda, l_\Lambda, j_\Lambda, \omega')}{\omega'-\omega}$$

- The second, due to the piece $G_{NM}(Q/E)_{NM}G_{NM}$, gives also a real & energy-independent contribution to the Λ self-energy and avoids double counting of Y'N states

$$
\begin{aligned}
&\mathcal{V}^{(2)}_{2p1h}(k_\Lambda, k'_\Lambda, l_\Lambda, j_\Lambda) \\
&= \frac{1}{2j_\Lambda+1} \sum_{n_h l_h j_h t_{z_h}} \sum_{\mathcal{L}LSJ\mathcal{J}} \sum_{Y'=\Lambda\Sigma} \int dq q^2 \int dK K^2 (2\mathcal{J}+1) \\
&\times \langle (k'_\Lambda l_\Lambda j_\Lambda)(n_h l_h j_h t_{z_h})\mathcal{J}|G|K\mathcal{L}qLSJ\mathcal{J}TM_T\rangle \\
&\times \langle K\mathcal{L}qLSJ\mathcal{J}TM_T|G|(k_\Lambda l_\Lambda j_\Lambda)(n_h l_h j_h t_{z_h})\mathcal{J}\rangle \\
&\times Q_{Y'N}\left(\Omega - \frac{\hbar^2 K^2}{2(m_N+m_{Y'})} - \frac{\hbar^2 q^2 (m_N+m_{Y'})}{2m_N m_{Y'}} - m_{Y'} + m_\Lambda\right)^{-1}
\end{aligned}
$$

Summarizing, in the BHF approximation the finite nucleus Λ self-energy is given by:

$$\Sigma_{l_\Lambda j_\Lambda}(k_\Lambda, k'_\Lambda, \omega) = \mathcal{V}_{l_\Lambda j_\Lambda}(k_\Lambda, k'_\Lambda, \omega) + i\mathcal{W}_{l_\Lambda j_\Lambda}(k_\Lambda, k'_\Lambda, \omega)$$

with

$$\mathcal{V}_{l_\Lambda j_\Lambda}(k_\Lambda, k'_\Lambda, \omega) = \mathcal{V}_1(k_\Lambda, k'_\Lambda, l_\Lambda, j_\Lambda) + \mathcal{V}^{(1)}_{2p1h}(k_\Lambda, k'_\Lambda, l_\Lambda, j_\Lambda, \omega) - \mathcal{V}^{(2)}_{2p1h}(k_\Lambda, k'_\Lambda, l_\Lambda, j_\Lambda)$$

$$\mathcal{W}_{l_\Lambda j_\Lambda}(k_\Lambda, k'_\Lambda, \omega) = \mathcal{W}_{2p1h}(k_\Lambda, k'_\Lambda, l_\Lambda, j_\Lambda, \omega)$$

Λ single-particle bound states

Λ s.p. bound states can be obtained using the real part of the Λ self-energy as an effective hyperon-nucleus potential in the Schoedinger equation

$$\sum_{i=1}^{N_{max}} \left[\frac{\hbar^2 k_i^2}{2m_\Lambda} + \mathcal{V}_{l_\Lambda j_\Lambda}(k_n, k_i, \omega = \varepsilon_{l_\Lambda j_\Lambda}) \right] \Psi_{i l_\Lambda j_\Lambda m_{j_\Lambda}} = \varepsilon_{l_\Lambda j_\Lambda} \Psi_{n l_\Lambda j_\Lambda m_{j_\Lambda}}$$

solved by diagonalizing the Hamiltonian in a complete & orthonormal set of regular basis functions within a spherical box of radius R_{box}

$$\Phi_{n l_\Lambda j_\Lambda m_{j_\Lambda}}(\vec{r}) = \langle \vec{r} | k_n l_\Lambda j_\Lambda m_{j_\Lambda} \rangle = N_{n l_\Lambda} \, j_{l_\Lambda}(k_n r) \psi_{l_\Lambda j_\Lambda m_{j_\Lambda}}(\theta, \phi)$$

- $N_{nl\Lambda}$ $\longrightarrow$ normalization constant
- N_{max} $\longrightarrow$ maximum number of basis states in the box
- $j_{j\Lambda}(k_n r)$ $\longrightarrow$ Bessel functions for discrete momenta ($j_{j\Lambda}(k_n R_{box})=0$)
- $\psi_{l\Lambda j\Lambda mj\Lambda}(\theta,\phi)$ $\longrightarrow$ spherical harmonics the including spin d.o.f.
- $\Psi_{nl\Lambda j\Lambda mj\Lambda} = \langle k_n l_\Lambda j_\Lambda m_{j\Lambda} | \Psi \rangle$ $\longrightarrow$ projection of the state $|\Psi\rangle$ on the basis $|k_n l_\Lambda j_\Lambda m_{j\Lambda}\rangle$

N.B.: a self-consistent procedure is required for each eigenvalue

Effect of NNΛ interaction on hypernuclei

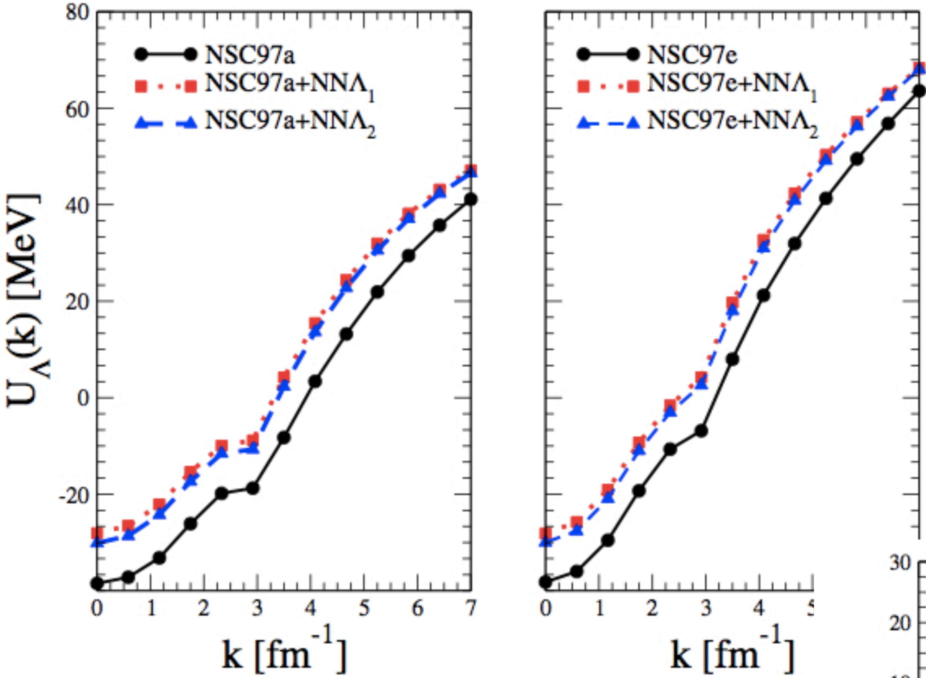
Λ separation energy in $^{41}_{\Lambda}$Ca, $^{91}_{\Lambda}$Zr & $^{209}_{\Lambda}$Pb

	$^{41}_{\Lambda}$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)

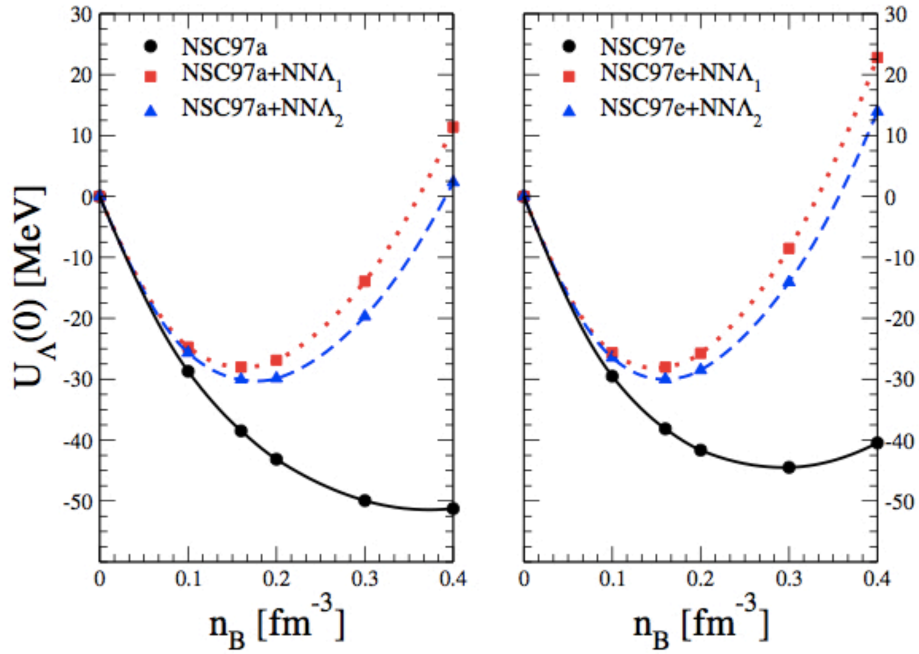
- ✧ We consider only hypernuclei described as a closed shell nuclear core + a Λ sitting in a s.p. state. Comparison with the closest hypernucleus for which exp. data is available
- ✧ Inclusion of NNΛ improves the agreement with data for $^{91}_{\Lambda}$Zr & $^{209}_{\Lambda}$Pb.
- ✧ NNΛ predict too much repulsion in the case $^{41}_{\Lambda}$Ca & lighter hypernuclei
- ✧ No refit of any parameter has been done to perform these calculations

* Taken from Pile et al., PRL 66, 2585 (1991). Not included in the recent Gal et al., RMP 88, 035004 (2016)

Λ BHF single-particle potential in SNM at ρ_0

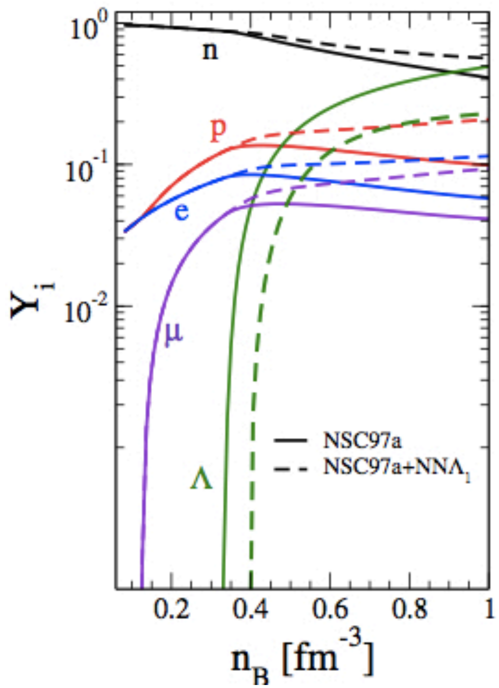


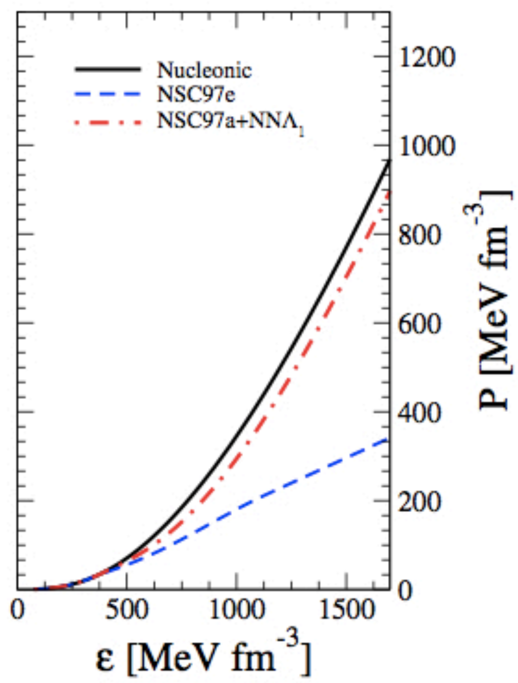
- ✧ NSC97a & NSC97e (with no NNΛ) predict $U_\Lambda(0) \sim$ -40 MeV.
- ✧ NSC97a predict more attraction than NSC97e even when NNΛ is included
- ✧ NNΛ induces as expected repulsion



- ✧ $U_\Lambda(0)$ very deep when only two-body forces are considered
- ✧ NNΛ induces repulsion for densities larger than ~0.1 fm^{-3} & shift the minimum to ~0.16 fm^{-3}
- ✧ NNΛ negligible in the low density region

Neutron star matter EoS & Composition





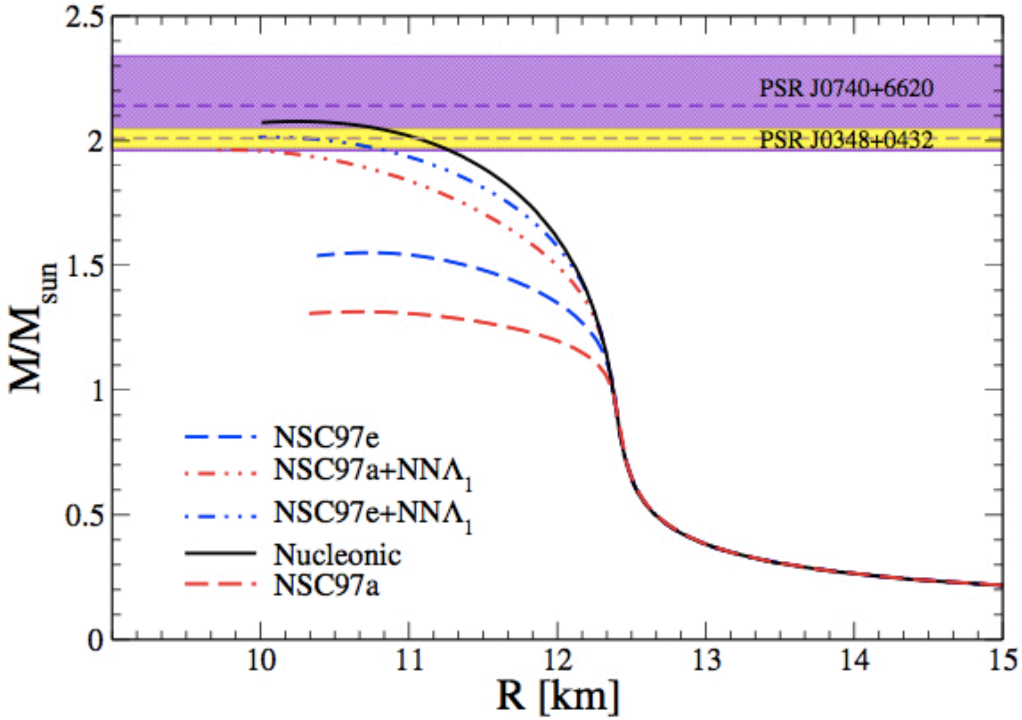
Only n, p, e^-, μ^- & Λ included

- ✓ First exploratory work. We are interested on the role of NNΛ
- ✓ More complete study requires the inclusion of other hyperons (work on progress)

✧ The effect of NNΛ interaction is twofold:

- ✓ Shift the onset of the Λ to slighly larger baryon density
- ✓ Strong reduction of the amount of Λ's at large baryon densities with the consequent stiffening of the EoS compared to the case in which the NNΛ is not included ⟶ important consequences for NS mass (M_{max} increases)

Neuron star Properties



	$M_{max}(M_\odot)$	R (km)	n_c (fm^{-3})
Nucleonic	2.08	10.26	1.15
NSC97a	1.31	10.60	1.40
NSC97a+NNΛ$_1$	1.96	9.80	1.30
NSC97a+NNΛ$_2$	1.97	9.87	1.28
NSC97e	1.54	10.81	1.18
NSC97e+NNΛ$_1$	2.01	10.10	1.20
NSC97e+NNΛ$_2$	2.02	10.15	1.19

NS M_{max} compatible with the largest NS observed

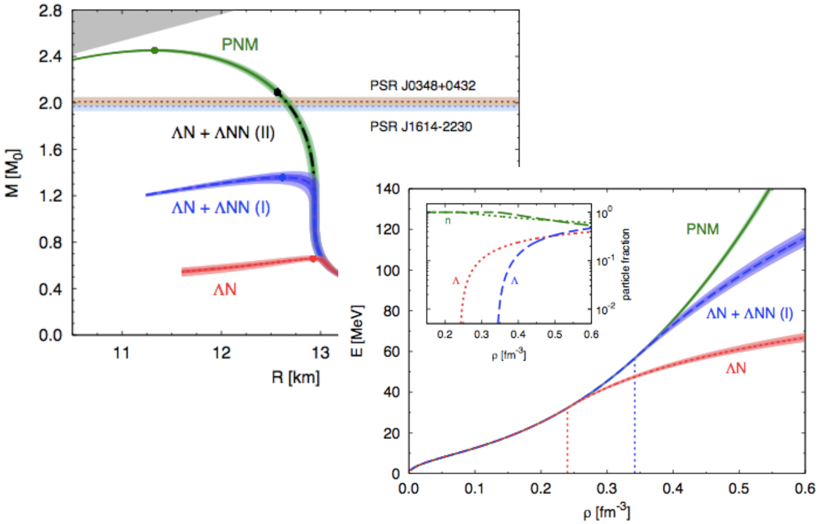
But

- ✓ We have ignored the presence of other hyperons in the NS interior that could change this conclusion
- ✓ Hypothetical repulsive NNY, NYY & YYY forces could lead to a similar conclusion

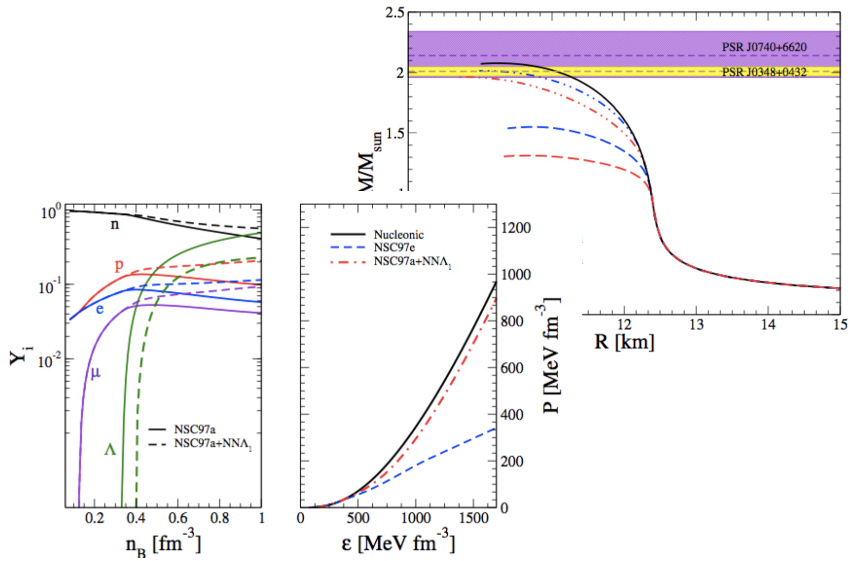
In view of this we CANNOT say that we have solved the hyperon puzzle

A comparison with QMC calculations

Lonardoni et al., PRL 114, 092301 (2016)



This work



- ✧ NS matter described as mixture of neutrons & Λ's in β-equilibrium
- ✧ Simple interaction models: Av8'+UIX (nn,nnn) & Bodmer-Usmani (NΛ) potential, NNΛ (2π exchange + phenomenological repulsive term)
- ✧ The only NNΛ able to give $2M_\odot$ lead to the total disappearance of Λ in NS , but this in in fact just pure neutron matter

- ✧ NS matter described as a mixture of n, p, e^-, μ^- & Λ's in β-equilibrium
- ✧ χEFT (NN, NNN, NNΛ) + meson-exchange (NY)
- ✧ Even if the concentration of Λ's is strongly reduced they are still present in the interior of a $2M_\odot$ NS

Summary & Conclusions (again)

✧ Study of the effects of NNΛ force on neutron stars

To such end EoS & NS structure derived within the BHF approach using:

- NN at N^3LO in χEFT including Δ isobar in intermediate states of NN scattering
- NNN at N^2LO in χEFT
- NΛ from meson-exchange (Nijmegen group). Weak point of the work
- NNΛ derived by the Juelich-Munich-Bonn group in χEFT at N^2LO

✧ Inclusion of NNΛ force improves description of heavy hypernuclei

✧ Inclusion of NNΛ force leads to an EoS stiff enough such that he resulting NS maximum mass is compatible with current observations **but the model contains only N, leptons & Λ's**

✧ We have **NOT SOLVED** the hyperon puzzle **but have taken an additional step towards its solution**

- ✧ You for your time & attention
- ✧ Benjamin, Stefania, Krysztof, Juergen & Ludwik for their invitation