Equation of state for neutron stars and binary neutron star mergers

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EXOTICO: EXOTIc atoms meet nuclear COllisions for a new frontier precision era in low-energy strangeness nuclear physics

20 ottobre 2022

UNIVERSITÀ DI PISA

Results in collaboration with:

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I. Bombaci (University of Pisa)
A. Perego (University of Trento)
D. Radice (Penn State University)
S. Bernuzzi (Jena University)
A. Prakash (Penn State University)

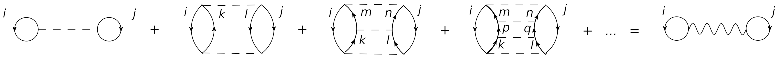
Hopefully very soon: results from new collaborations...

- 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 and connection with hypernuclei
- Strangeness in binary netron star mergers

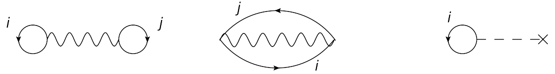
- What do we mean by EOS?
- A relation between: $(n_B, T, P, \epsilon, \{X_i\})$
- n_B: baryonic density
- T: temperature
- P: pressure
- ϵ: energy density
- $\{X_i\}$: composition

- 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(?)

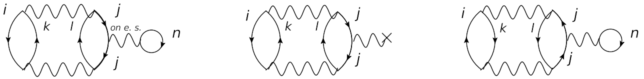
Ladder diagrams summation:



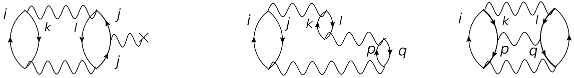
1st-order, 2nd-order and 3rd-order contributions:



(a) (b) (c)



(d) (e) (f)



(g) (h) (i)

- Starting point: the Bethe-Goldstone equation

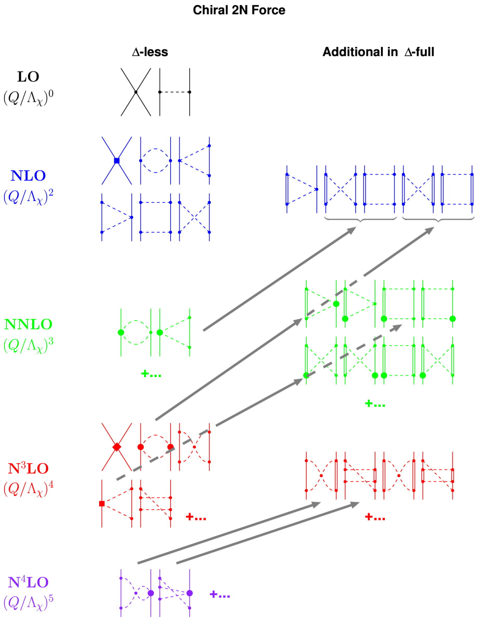
$$G(\omega)_{B_1B_2,B_3B_4} = V_{B_1B_2,B_3B_4} + \sum_{B_iB_j} V_{B_1B_2,B_iB_j} \times \frac{Q_{B_iB_j}}{\omega - E_{B_i} - E_{B_j} + i\eta} G(\omega)_{B_iB_j,B_3B_4}$$

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

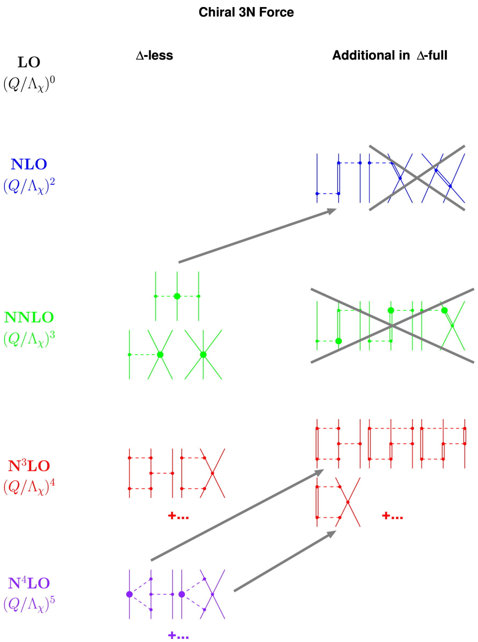
$$E_{B_i}(k) = M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + Re[U_{B_i}(k)]$$

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

NN chiral forces

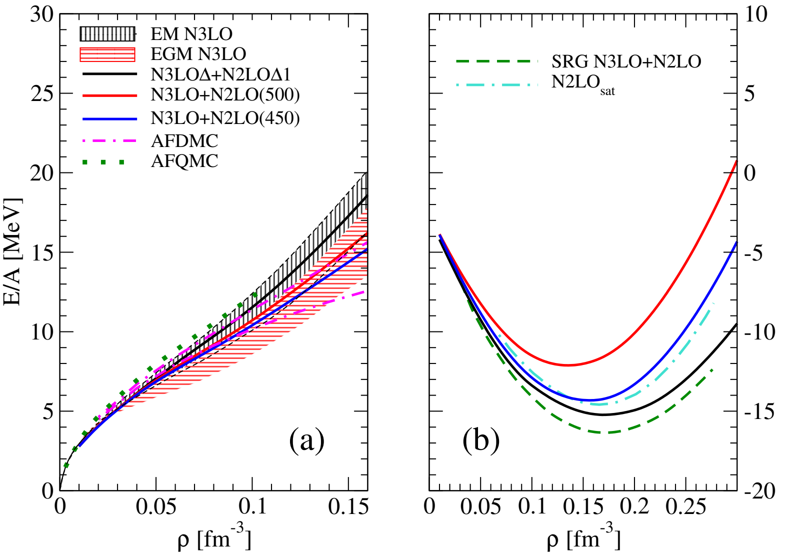


NNN chiral forces



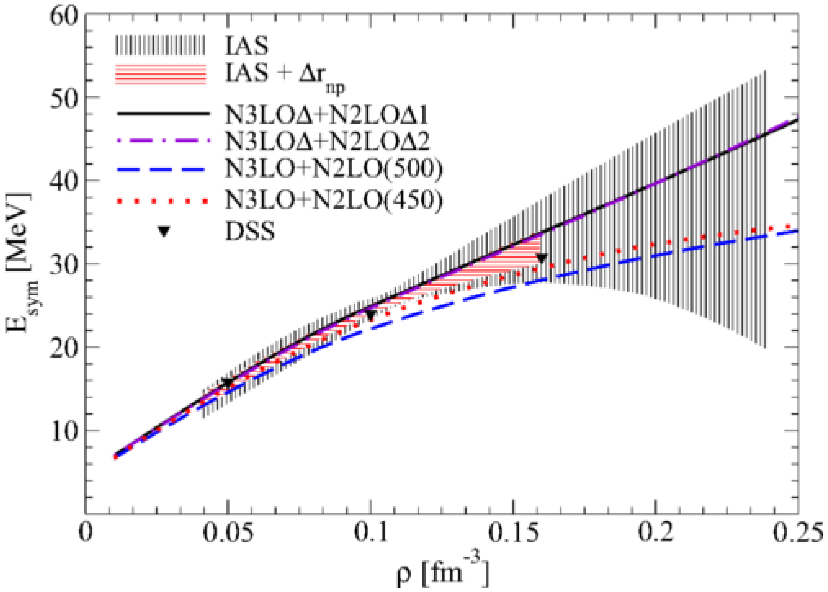
E/A nuclear matter N3LO+N2LO

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



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

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

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

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

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

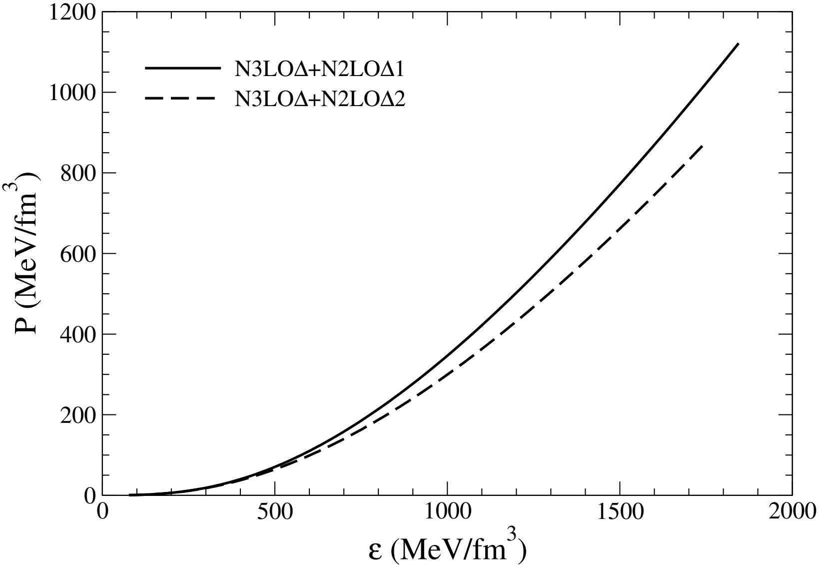
- Chemical equilibrium:

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

- 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)

- 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):

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

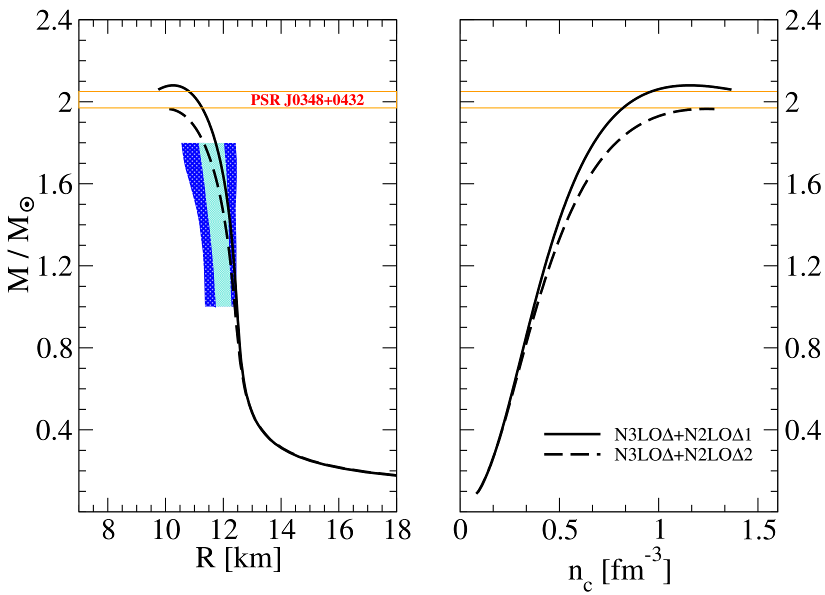
$$\frac{dm(r)}{dr} = 4\pi r^2 \rho \,.$$

- 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 $M_G(M_B)$)

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

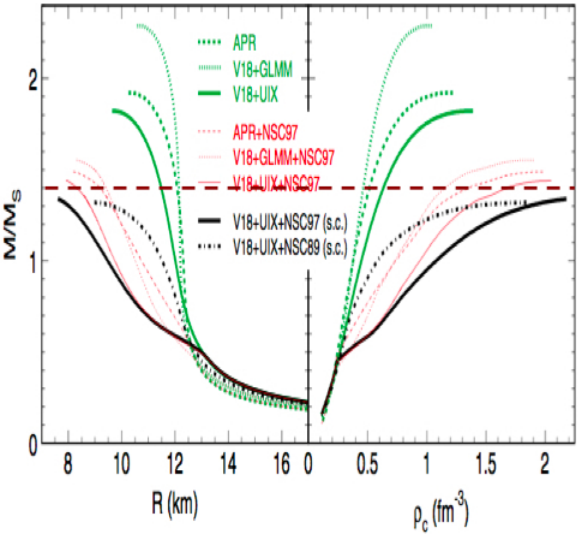
Neutron stars based on N3LOΔ+N2LOΔ (case of nucleonic matter)



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)



- 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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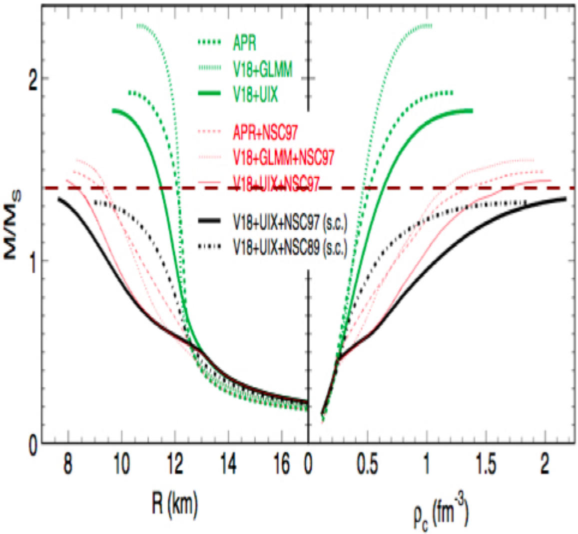

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$\Downarrow$

DRAMMATIC SCENARIO!!

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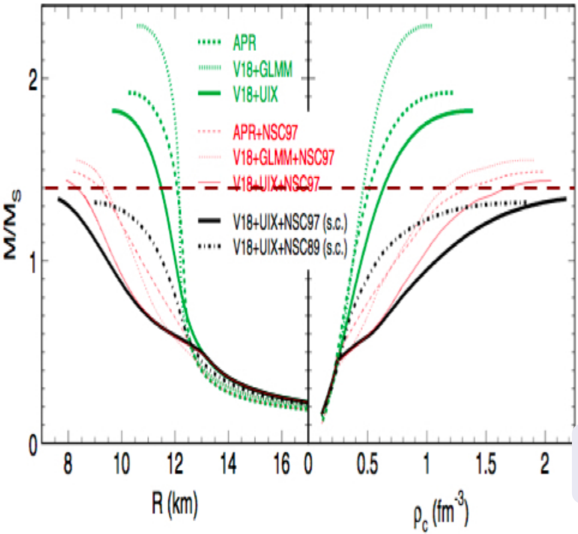

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$\Downarrow$

DRAMMATIC SCENARIO!!

NNY, NYY and YYY may help??

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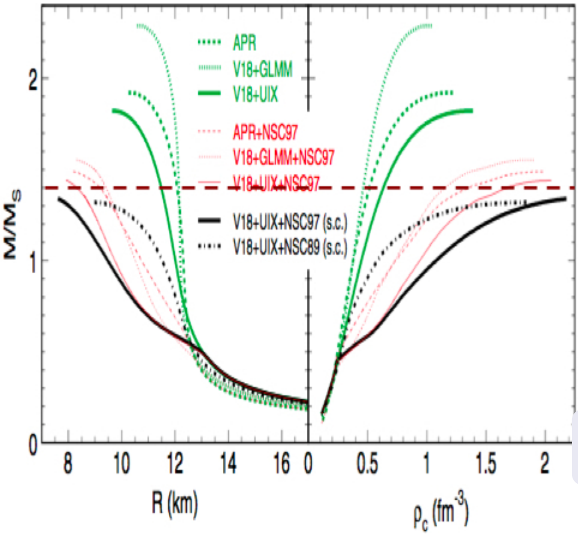

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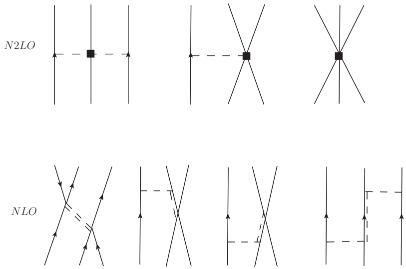
$\Downarrow$

DRAMMATIC SCENARIO!!

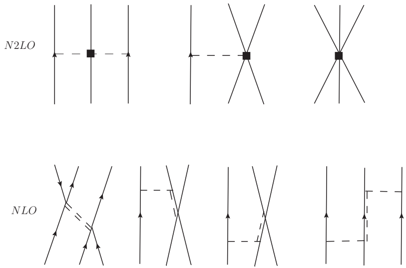
We focused on the NNΛ interactions



- 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

NNΛ force from ChPT



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

- Asymmetric matter:

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

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

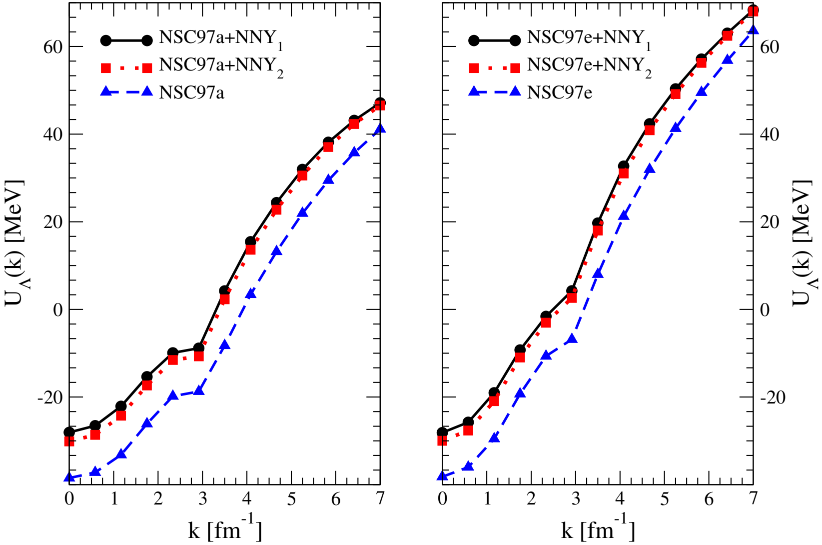
- Chemical equilibrium:

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

- Charge neutrality:

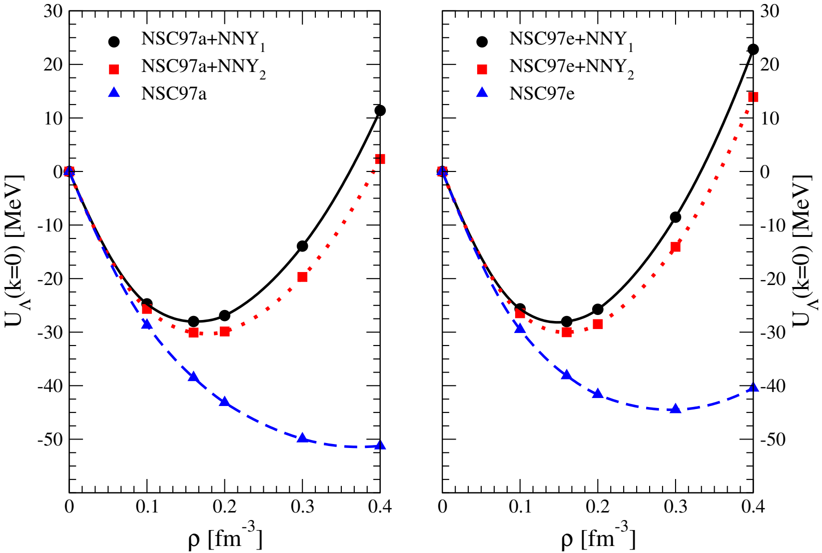
$$n_p - n_\mu - n_e = 0\,.$$

Λ-single particle potential



D. Logoteta, I. Vidaña and I. Bombaci Eur. Phys. J. A, 55 11 (2019) 207

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



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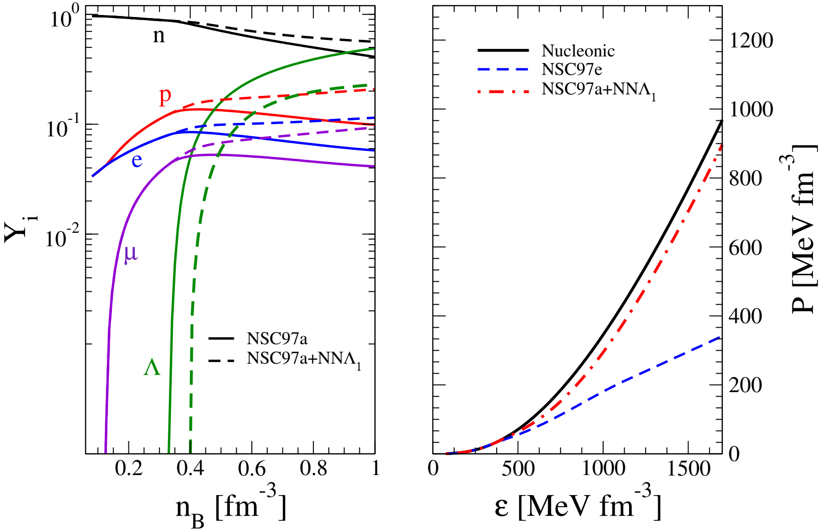
Composition of hyperonic matter



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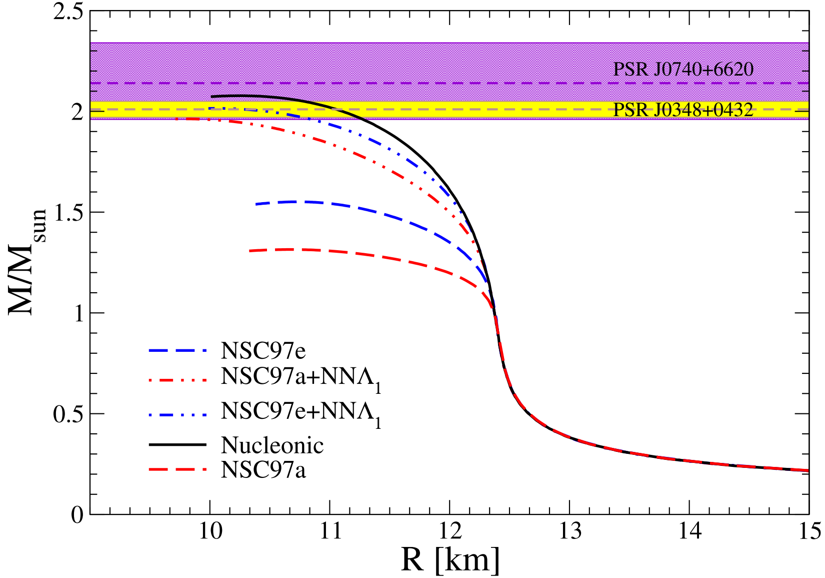
Neutron stars structure including Λ-hyperon



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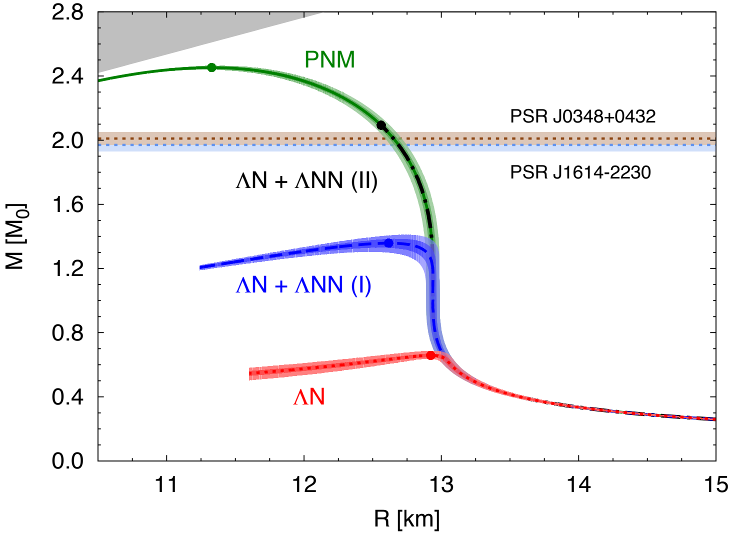
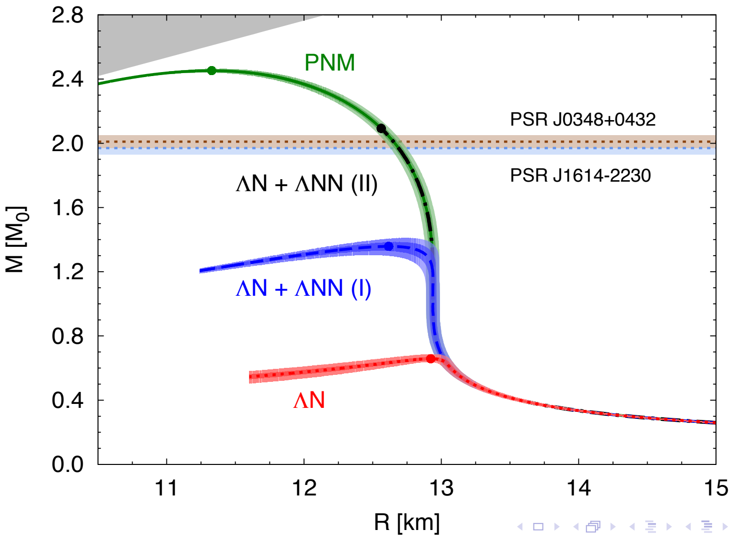
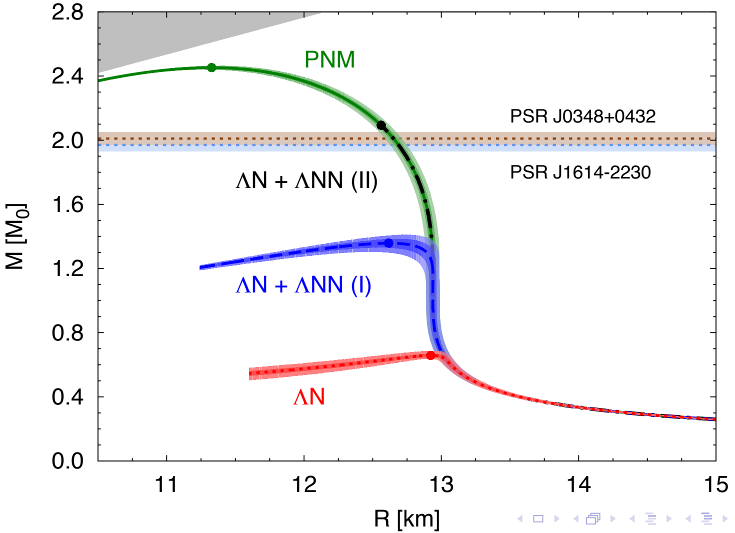


Lonardoni D. et al. Phys. Rev. Lett. 114, 092301 (2015)

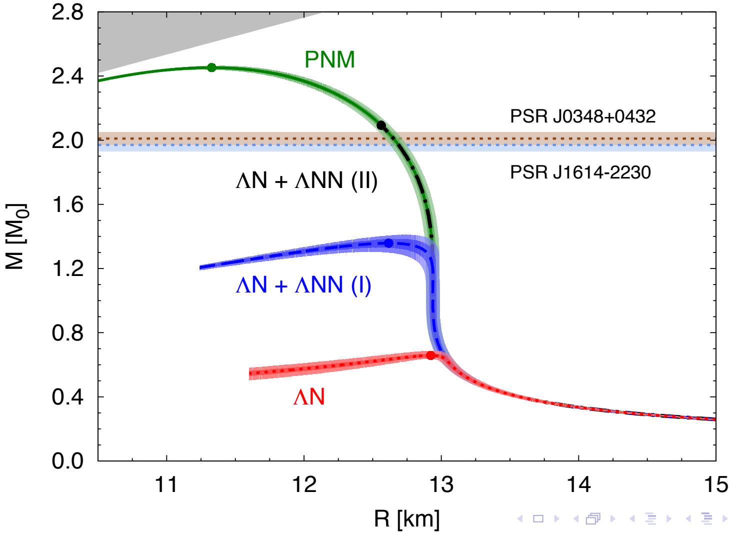
Similar result but several differences...



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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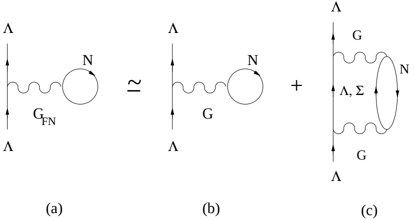
Λ separation energies in hypernuclei



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- EOS $\Rightarrow P, \varepsilon, T, n_B, X_i$
- TOV $\Rightarrow$ gravitational masses M_1 and M_2 you want to use in your simulation
- Initial data: LORENE $\Rightarrow$ solves problem of the two (M_1 and M_2) NSs orbiting $\sim$ 45 km away in quasicircular orbit
- Evolution: Whisky THC $\Rightarrow$ describes temporal evolution of the system: solves Einstein equations coupled to hydrodynamics

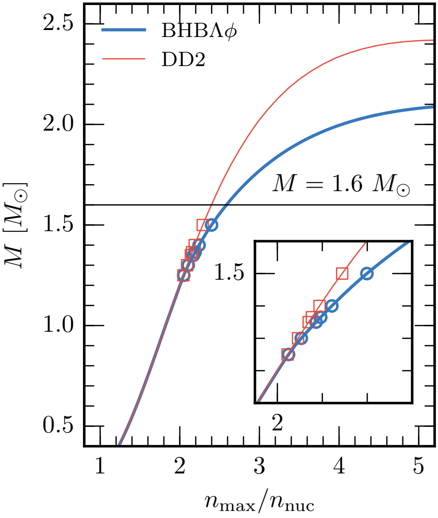
Once all these stuff is done...

Output:

Extraction of GWs signal, mass ejected, nucleosynthesis ...

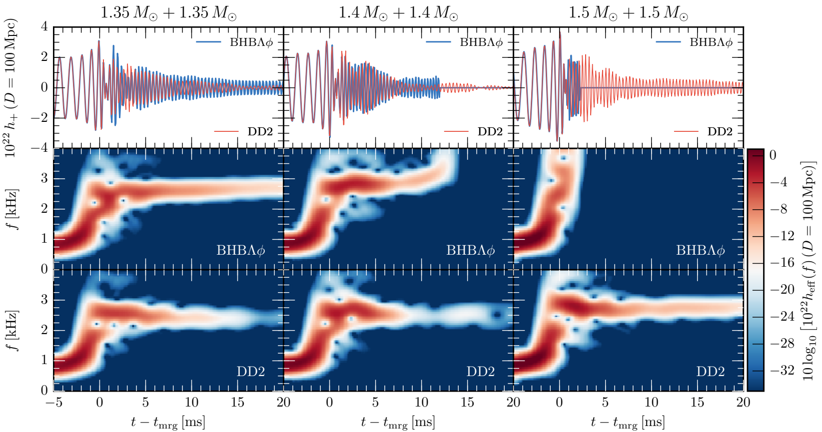
...and very important:

Constraints on the EOS of neutron star matter



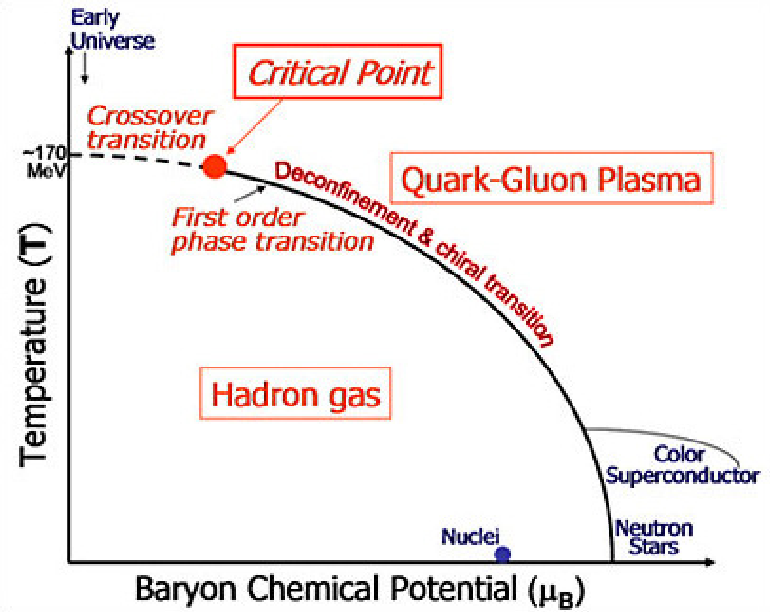
D. Radice et al. ApJL 842 L10 (2017)

GWs spectrum with hyperons and without



D. Radice et al. ApJL 842 L10 (2017)

Quark matter?



Construction of the EOS

- Gibbs conditions for phase coexistence:

$$\mu_H(P_H, T_H) = \mu_Q(P_Q, T_Q), \quad T_H = T_Q, \quad P_H(\mu_H, T) = P_Q(\mu_Q, T) = P_T.$$

- Charge neutrality is not imposed locally but globally.
- Hadronic and quark phase are not separately neutral.
- The whole system satisfies:

$$\chi\rho_c^Q + (1-\chi)\rho_c^H + \rho_c^l = 0\,.$$

- Energy density and baryonic density in the mixed phase read:

$$< \epsilon >= (1-\chi)\,\epsilon_H - \chi\,\epsilon_Q\,,$$
$$< n >= (1-\chi)\,n_H - \chi\,n_Q\,.$$

placeholder box

Aviral Prakash, David Radice, Domenico Logoteta, Albino Perego, Vsevolod Nedora, Ignazio Bombaci, Rahul Kashyap, Sebastiano Bernuzzi, and Andrea Endrizzi Phys. Rev. D 104, 083029 (2021) placeholder box

Aviral Prakash, David Radice, Domenico Logoteta, Albino Perego, Vsevolod Nedora, Ignazio Bombaci, Rahul Kashyap, Sebastiano Bernuzzi, and Andrea Endrizzi Phys. Rev. D 104, 083029 (2021)

Conclusions

- The physics of hyperons and more in general of matter with strangeness is crucial for a realistic description of astrophysical system like NSs, BNSM and CCSNe
- Future GW detectors (ET, KAGRA, LISA) will provide the chance to observe the postmerger GW signal $\Rightarrow$ strong constraints on the EOS of dense hadronic matter
- We need finite temperature microscopic EOSs with hyperons based on realistic interactions between nucleons and hyperons (and/or quarks)
- EQUALLY IMPORTANT: strong experimental efforts are required to improve the quality of NY, YY and many-body hyperonic interactions