From nuclear interactions to binary neutron star mergers

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QFC2022- Quantum gases, fundamental interactions and cosmology

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UNIVERSITÀ DI PISA

Results in collaboration with:

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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
- Nuclear interactions and nuclear matter calculations
- The nuclear many-body problem
- EOS for cold nucleonic and hyperonic matter
- Open problems: Hyperon-puzzle in neutron stars and connection with hypernuclei
- Applications to 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(?)

Brute force lattice QCD calculation

- In principle the best way ⇒ really ab-initio
- Problems:
- ⇒ no unique way to define a "potential"
- ⇒ extremely challenging from a computational point of view

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Phenomenological interactions

- Describe very well NN-phase shifts and several nuclear observables
- "Problems":
- $\Rightarrow$ Phenomenological...not very satisfactory from a theoretical point of view
- $\Rightarrow$ Many-body forces "seem" included just as a way to improve models

Derivation of nuclear interaction

Brute force lattice QCD calculation: HAL QCD

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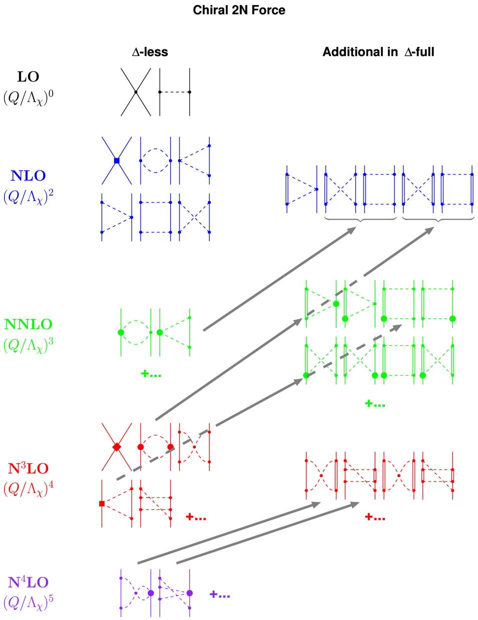
Phenomenological interactions

- Describe very well NN-phase shifts and several nuclear observables
- "Problems":
- ⇒ Phenomenological or based on one meson exchange...not very satisfactory from a theoretical point of view
- ⇒ Many-body forces "seem" included just as a way to improve models

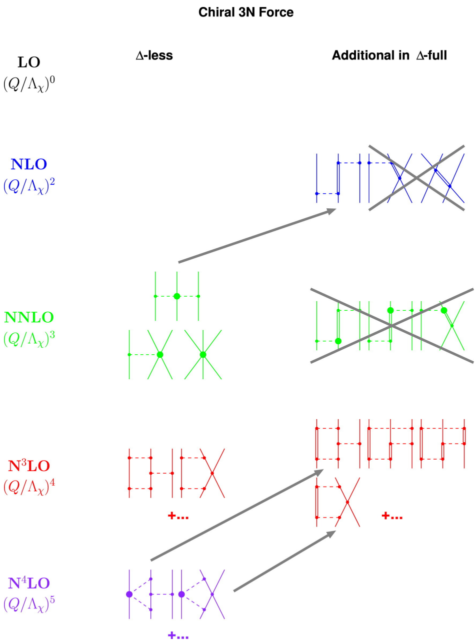
Interactons from ChEFT

- Developed on a well defined theoretical framework
- Many-body forces appear naturally in the theory
- "Problems":
- ⇒ Treatment of many-body forces quite involving
- ⇒ Issues about renormalization of the theory...

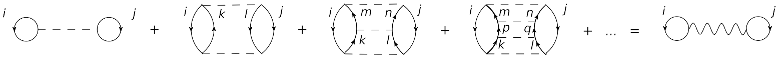
NN chiral forces



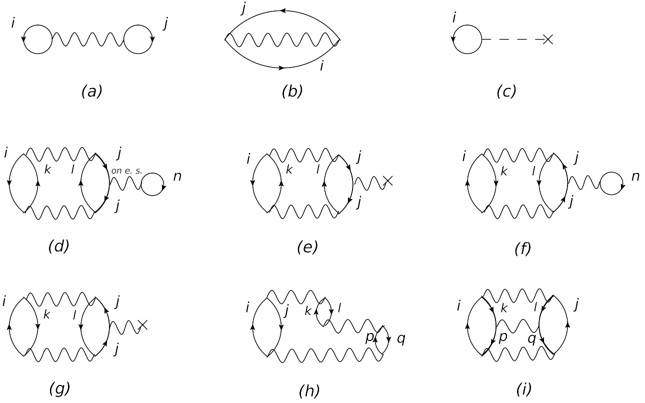
NNN chiral forces



Ladder diagrams summation:



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



- Starting point: the Bethe-Goldstone equation

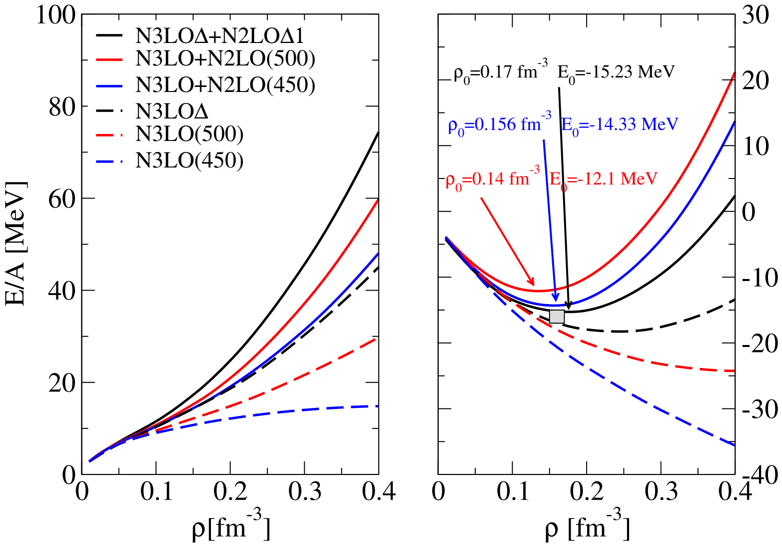
$$G(\omega)_{B_1B_2,B_3B_4} = V_{B_1B_2,B_3B_4} + \sum_{B_iB_j} V_{B_1B_2,B_iB_j} \times \frac{Q_{B_iB_j}}{\omega - E_{B_i} - E_{B_j} + i\eta} G(\omega)_{B_iB_j,B_3B_4}$$

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

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

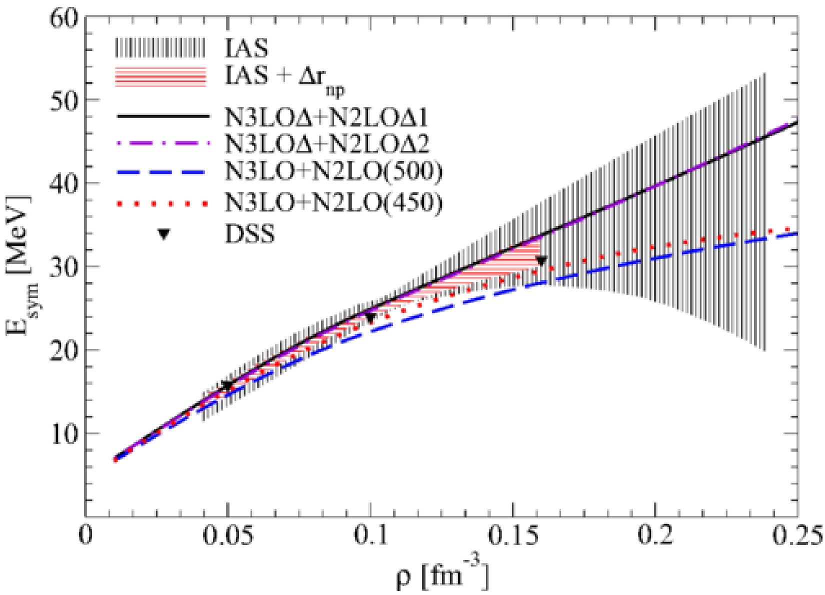
$$\frac{E}{A}_{BHF} = \frac{1}{AV} \sum_{B_i} \sum_{k \leq k_{F_i}} \left[M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + \frac{1}{2} Re[U_{B_i}(k)] \right]$$

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)

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

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

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

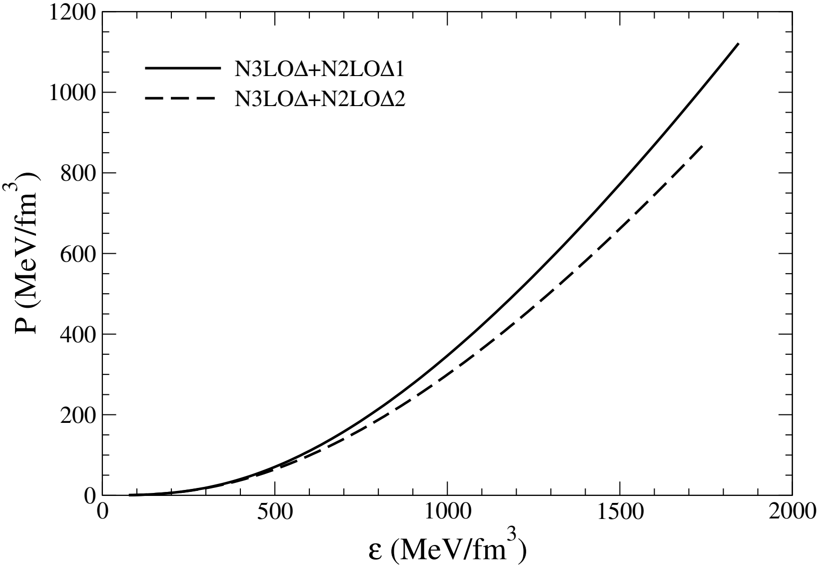
- Chemical equilibrium:

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

- 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):

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

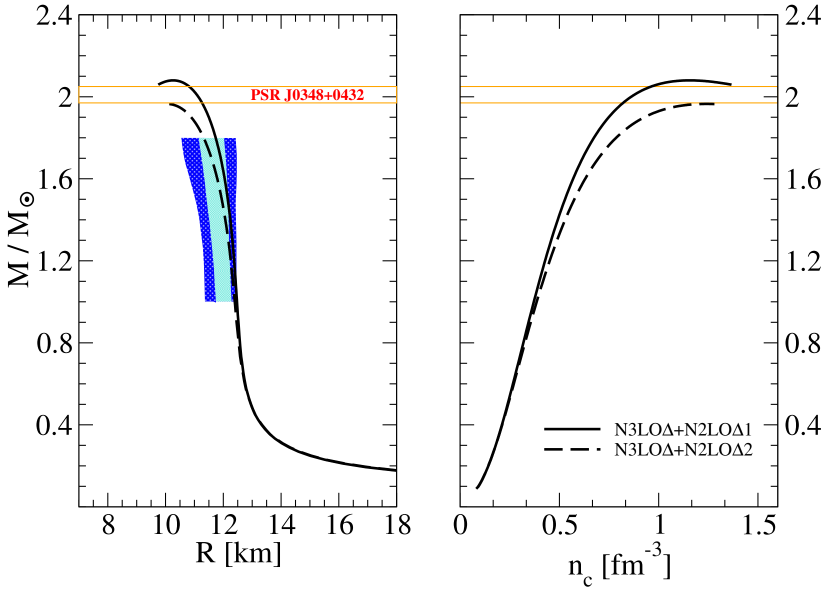
$$\frac{dm(r)}{dr} = 4\pi r^2 \rho\,.$$

- 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)



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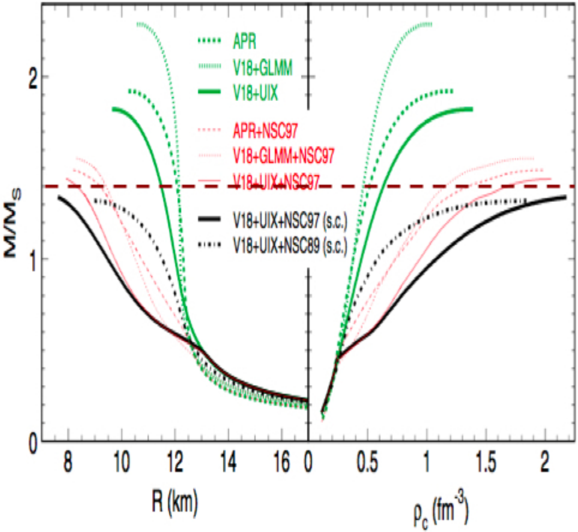
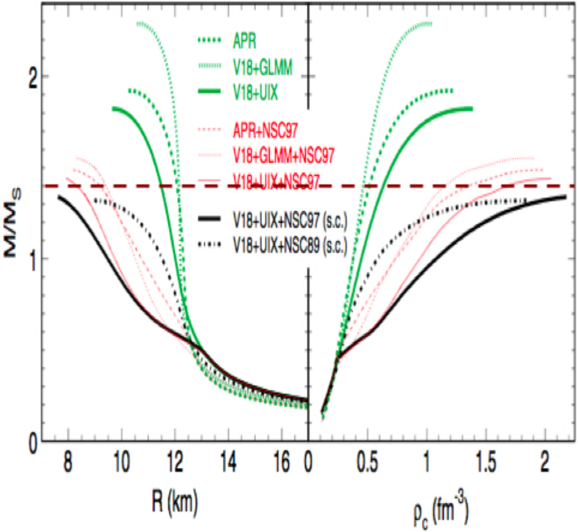
H.-J. Schulze et al. Phys. Rev. C 73, 058801 (2006)



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

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



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

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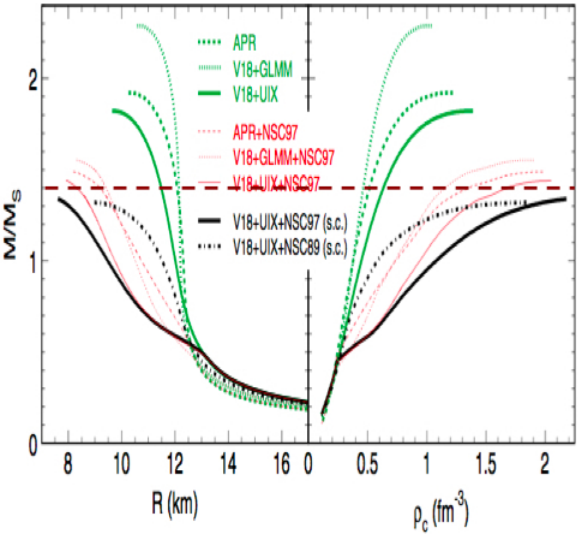

- Recent measurements:
- $M^{J1614-2230} = 1.97 \pm 0.04\ M_\odot$
- $M^{J0348+0432} = 2.01 \pm 0.04\ M_\odot$
- $M^{J0740+6620} = 2.14^{+0.20}_{-0.18}\ M_\odot$

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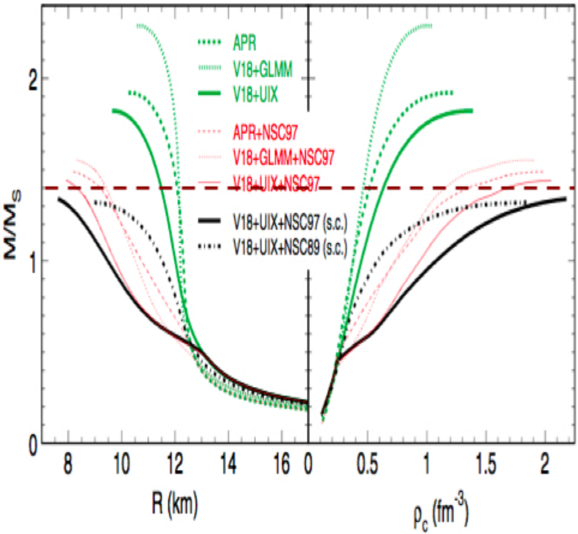

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DRAMMATIC SCENARIO!!

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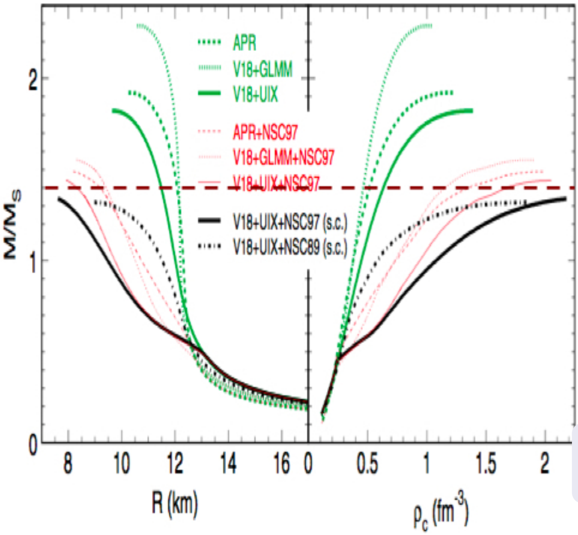

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DRAMMATIC SCENARIO!!

NNY, NYY and YYY may help??

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

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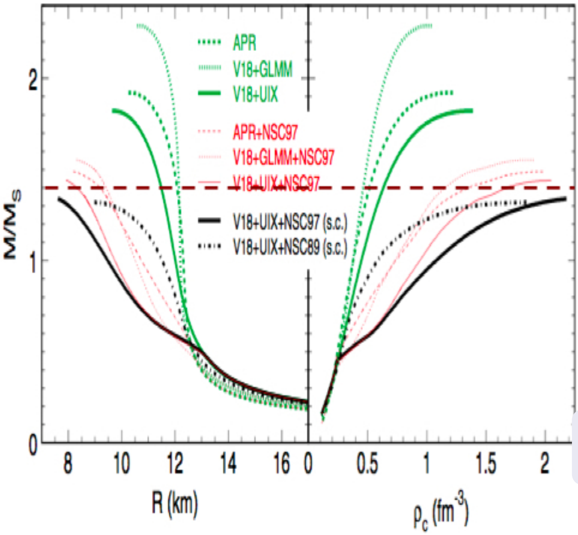

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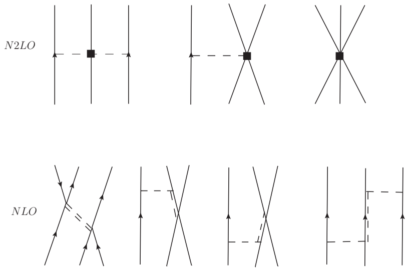
$\Downarrow$

DRAMMATIC SCENARIO!!

We focused on the NNΛ interactions

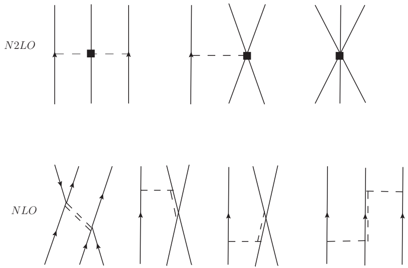
NNΛ force from ChPT



- Up to N2LO just 1 LEC ⇒ 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:

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

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

- Chemical equilibrium:

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

- Charge neutrality:

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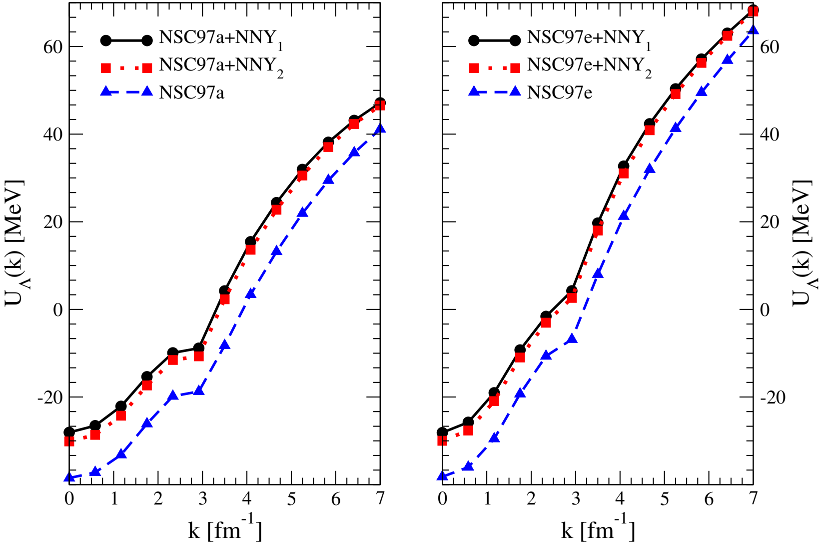
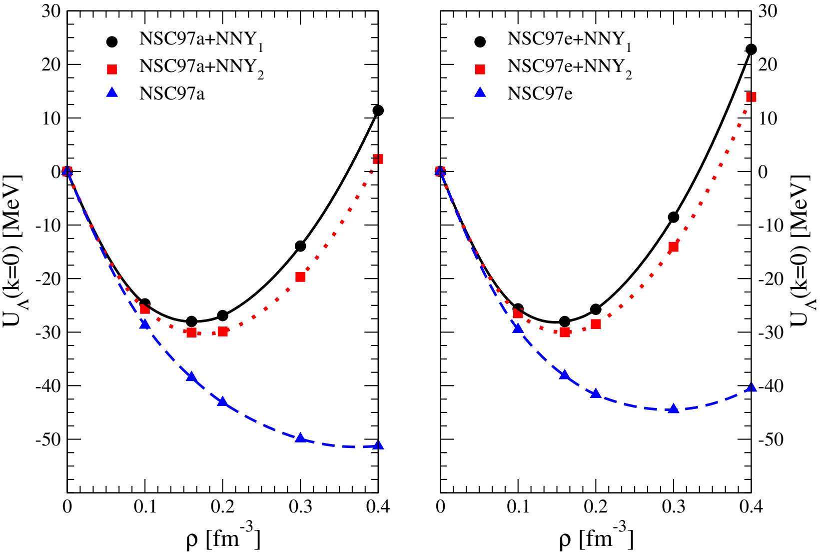
Λ-single particle potential



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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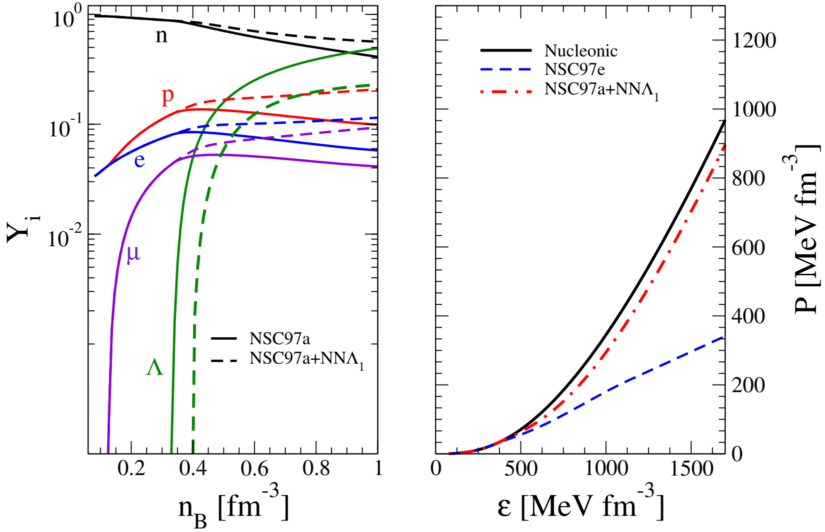
Composition of hyperonic matter



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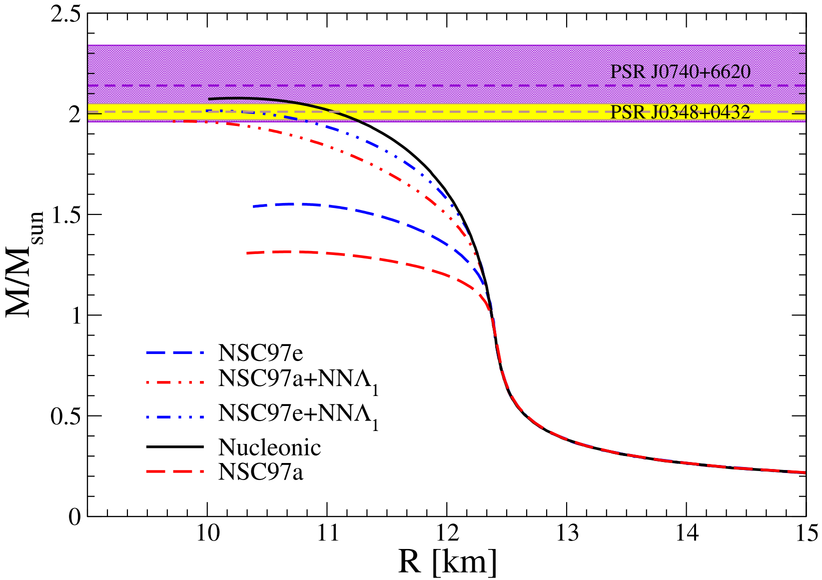

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Improved description of the separation energies of Λ-hypernuclei

	${}^{41}_{\Lambda}$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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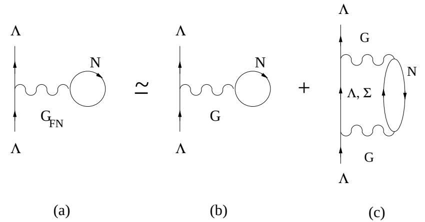
Λ separation energies in hypernuclei



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Numerical setup of BNSM simulations

- 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

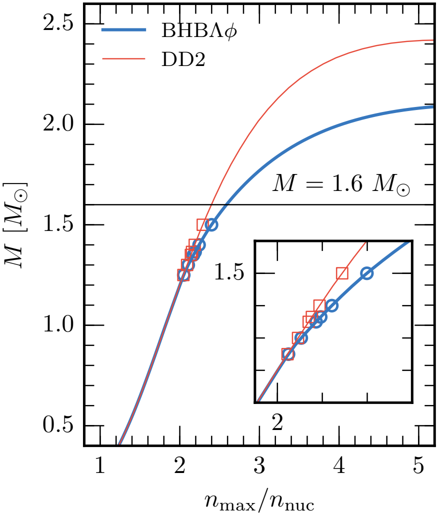
Once all these stuff is done...(thousand of CPU hours)

Output:

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

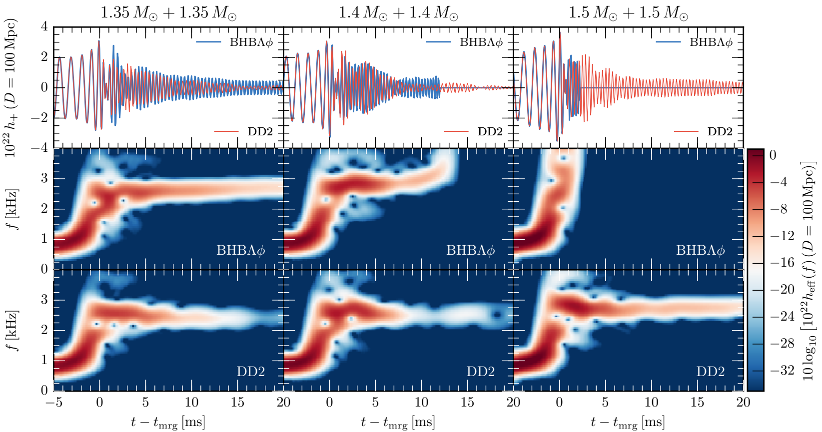
...and very important:

Constraints on the EOS of neutron star matter



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

GWs spectrum with hyperons and without



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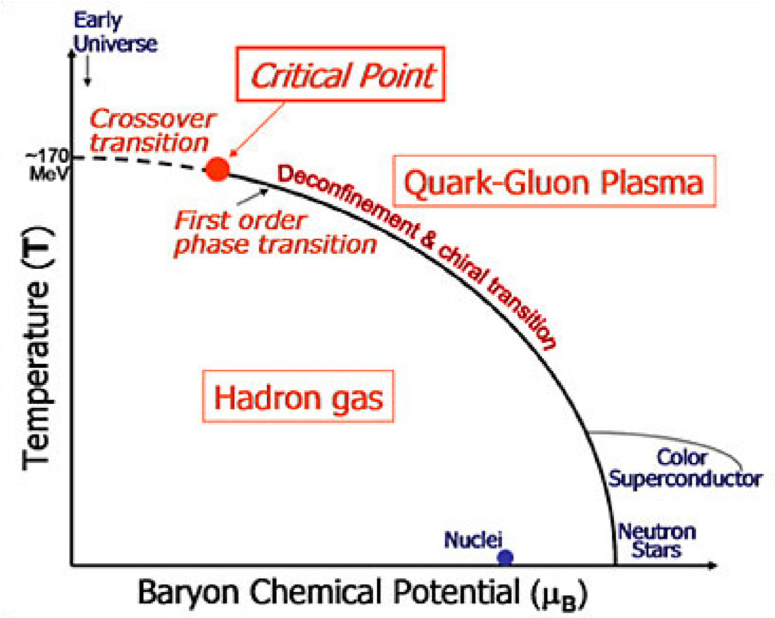
Quark matter?



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:

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

Quarks in neutron stars: BLh vs BLh+eMIT 1.3 $M_\odot$-1.3 $M_\odot$

placeholder box

A. Prakash, D. Radice, D. Logoteta, A. Perego, V. Nedora, I. Bombaci, R. Kashyap, S. Bernuzzi, and A. Endrizzi Phys. Rev. D 104, 083029 (2021)

placeholder box

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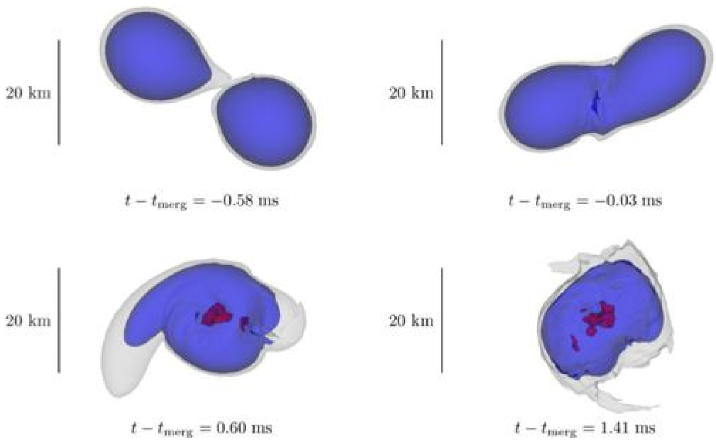
Snapshots of the merger



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Choose your favourite EOS, fix M_1, M_2

$$M_{tot} = M_1 + M_2$$
$$q = M_1 / M_2$$

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Possible scenarios:

- Long lived
- Short lived (delayed collapse)
- Prompt collapse (PC)

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Questions:

- Can we relate this behavior to some specific properties of the EOS?
- For fixed q, is there a threshold value of M_{tot} (M_{th}) to get a PC?

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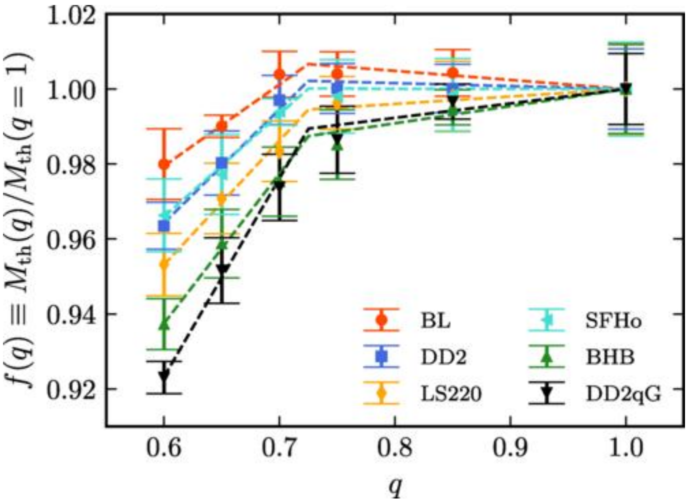
Key quantity

$$K^{\infty}(n_B^{max}) = 9(n_B^{max})^2 \frac{\partial^2 E/A}{\partial n_B^2}\Big|_{n_B^{max}}$$



A. Perego, D. Logoteta, D. Radice, S. Bernuzzi, R. Kashyap, A. Das, S. Padamata, and A. Prakash Phys. Rev. Lett. 129, 032701 (2022)

- Taking into account the correct degrees of freedom 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