Hyperonic three-body forces in hadronic matter

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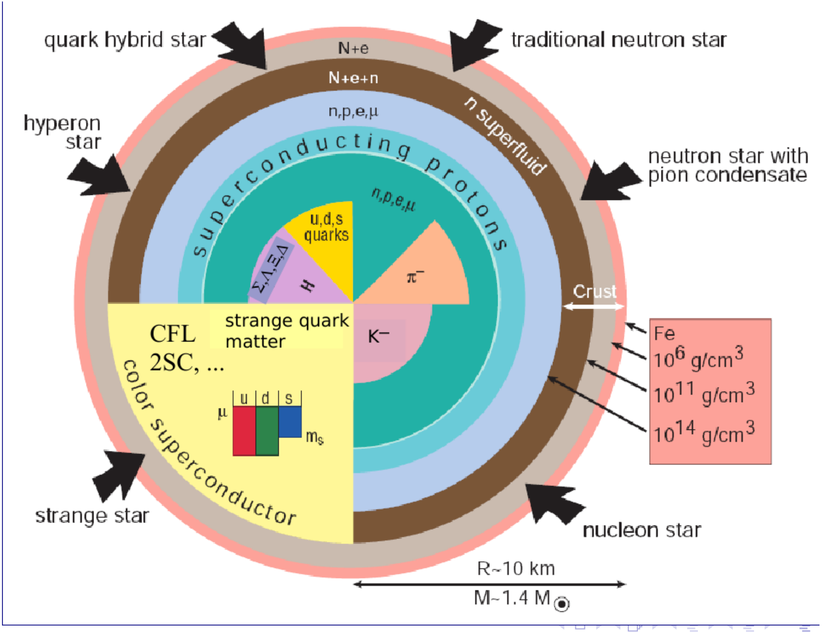
Pisa

20 maggio 2015

- Neutron stars
- The problem of the maximum mass of neutron stars with microscopic approaches
- A possible solution: inclusion of Hyperonic three-body forces



quark hybrid star
traditional neutron star
N+e
N+e+n
n superfluid
n,p,e,μ
hyperon star
superconducting protons
neutron star with pion condensate
n,p,e,μ
u,d,s quarks
Σ,Λ,Ξ,Δ
H
π⁻
Crust
CFL
2SC, ...
strange quark matter
K⁻
Fe
10^6 g/cm^3
10^11 g/cm^3
10^14 g/cm^3
color superconductor
μ
u d s
m_s
strange star
nucleon star
R~10 km
M~1.4 M☉

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):

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

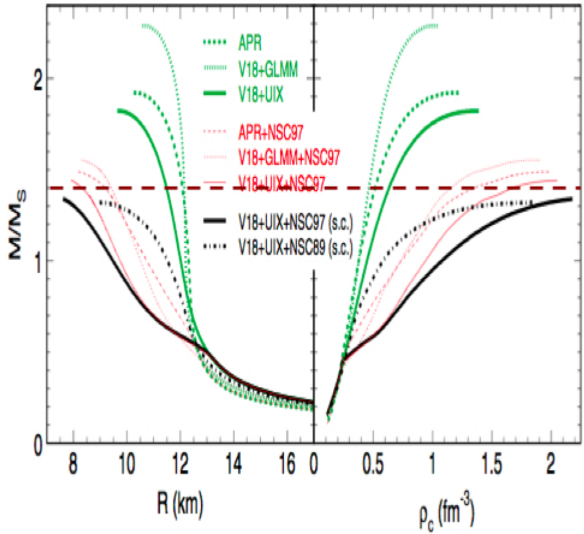
$$\frac{dm(r)}{dr} = 4\pi r^2 \rho\,.$$

- Fixed an EOS ($P(\rho)$) and a value of the central pressure value P_c TOV equations are solved numerically.

- Output $\Longrightarrow$ $M_G(R)$, $M_G(\rho_c)$

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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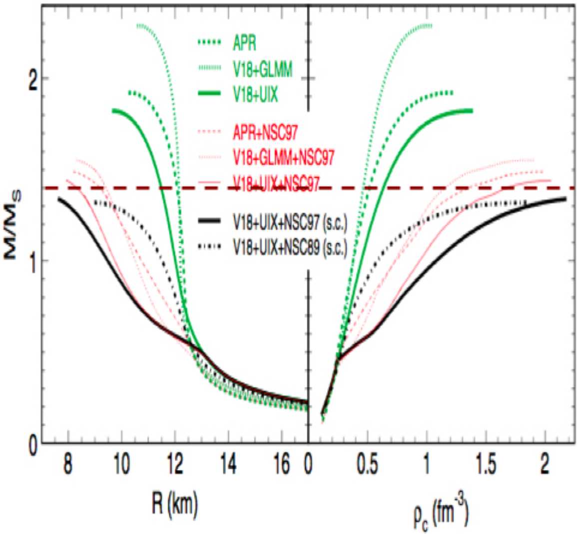

- $n + n \rightarrow n + \Lambda$
- $n + n \rightarrow p + \Sigma^-$
- $p + e^- \rightarrow \Lambda + \nu_{e^-}$
- $n + e^- \rightarrow \Sigma^- + \nu_{e^-}$

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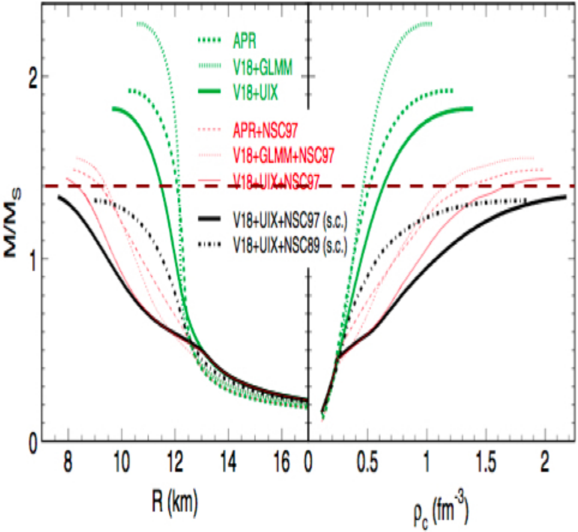

- $n + n \to n + \Lambda$
- $n + n \to p + \Sigma^-$
- $p + e^- \to \Lambda + \nu_{e^-}$
- $n + e^- \to \Sigma^- + \nu_{e^-}$
- Appearance of Hyperons ⇒ Fermi pressure relieves
- $M_{max} < 1.44\ M_\odot$

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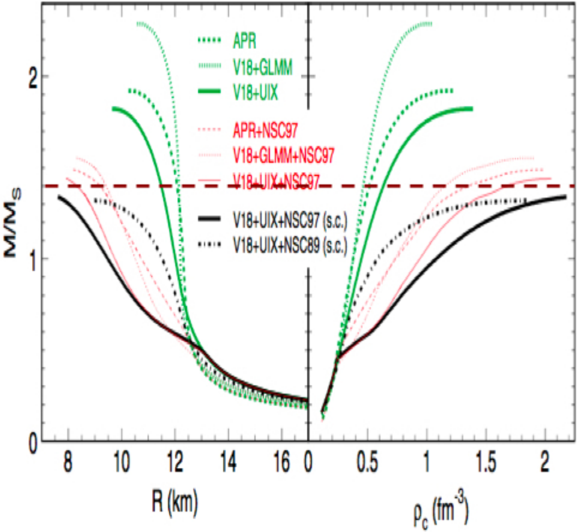

- Recent measurements:
- $M_{PRS}^{J1903+0327} = 1.67\ M_\odot$
- $M_{PRS}^{J1614-2230} = 1.97\ M_\odot$
- $M_{PRS}^{J0348+0432} = 2.01\ M_\odot$

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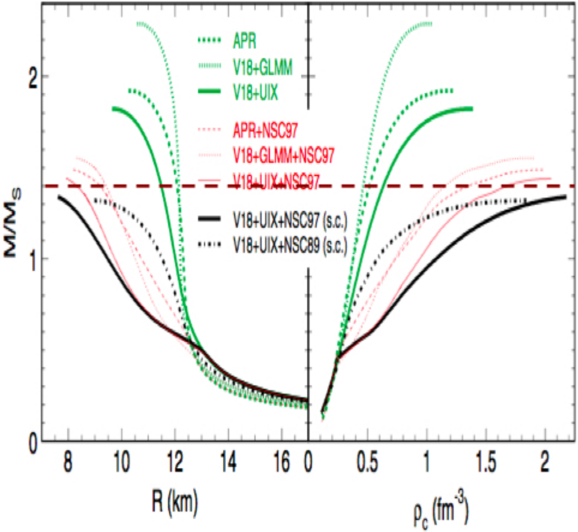

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DRAMMATIC SCENARIO!!

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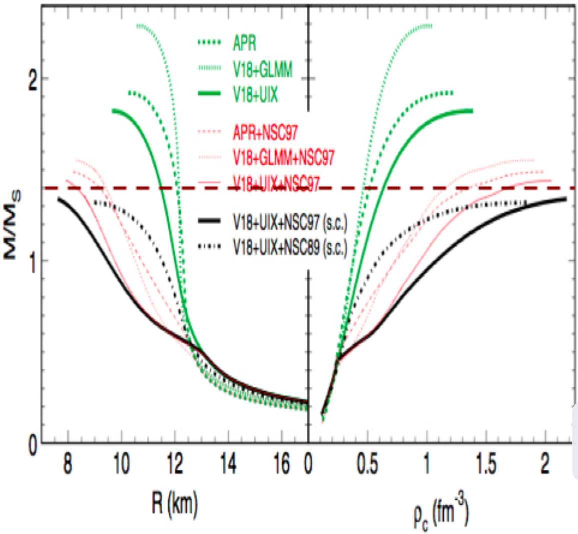

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DRAMMATIC SCENARIO!!

NNY, NYY and YYY may help??

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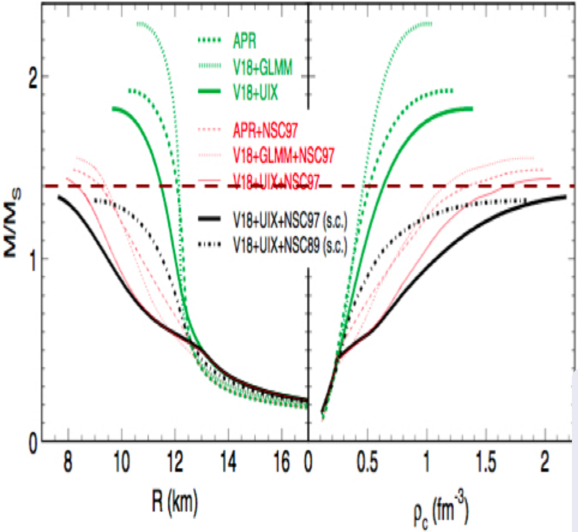

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DRAMMATIC SCENARIO!!

D. Lonardoni et al. PRL 114, 092301 (2015)
D. Lonardoni et al. Phys. Rev. C 87, 041303(R) (2013)

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

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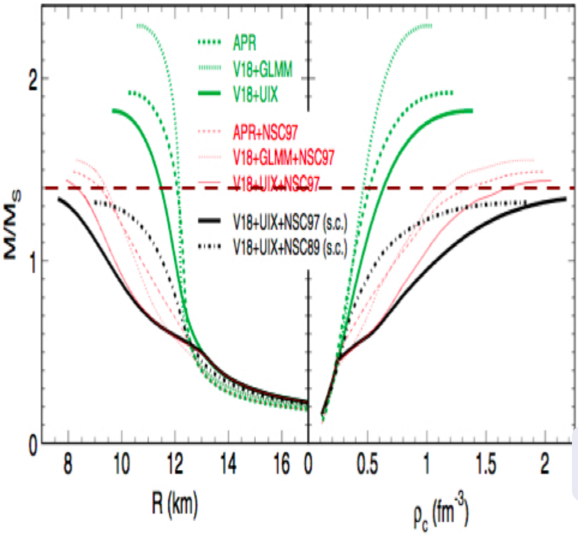

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DRAMMATIC SCENARIO!!

We focused on the NNY interactions

The Brueckner-Hartree-Fock approach

- Starting point: the Bethe-Goldstone equation

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

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

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

$$\epsilon_{BHF} = \frac{1}{V} \sum_{B_i} \sum_{k \le k_{F_i}} \left[M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + \frac{1}{2} U_{B_i}(k) \right]$$

- We included the Λ, Σ hyperons in our calculations.

- Fully two-body BHF calculation AV18+NSC89 + contact terms (CT) corrections from NNN+NNY+NYY forces

$$\epsilon_{CT} = \epsilon_{CT}^{NN} + \epsilon_{CT}^{N\Lambda} + \epsilon_{CT}^{N\Sigma}$$

Nucleonic contribution

$$\epsilon_{CT}^{NN} = a_{NN}\rho_N^2 + b_{NN}\rho_N^{\gamma_{NN}+1} \quad \Rightarrow \quad NNN,\ NNY$$

Hyperonic contribution

$$\epsilon_{CT}^{N\Lambda} = a_{N\Lambda}\rho_\Lambda\rho_N + b_{N\Lambda}\rho_\Lambda\rho_N\left(\frac{\rho_\Lambda^{\gamma_{N\Lambda}} + \rho_N^{\gamma_{N\Lambda}}}{\rho_\Lambda + \rho_N}\right) \quad \Rightarrow \quad NNY,\ NYY$$

$$\epsilon_{CT}^{N\Sigma} = a_{N\Sigma}\rho_\Sigma\rho_N + b_{N\Sigma}\rho_\Sigma\rho_N\left(\frac{\rho_\Sigma^{\gamma_{N\Sigma}} + \rho_N^{\gamma_{N\Sigma}}}{\rho_\Sigma + \rho_N}\right) \quad \Rightarrow \quad NNY,\ NYY$$

- where $\rho_N = \rho_n + \rho_p, \quad \rho_\Sigma = \rho_{\Sigma^0} + \rho_{\Sigma^+} + \rho_{\Sigma^-}$

Choice of parameters

- We fixed a_{NN}, b_{NN} and γ_{NN} in order to fit E/A=-16 MeV at ρ=0.16 fm^{-3} and to produce K_∞=211-285 MeV

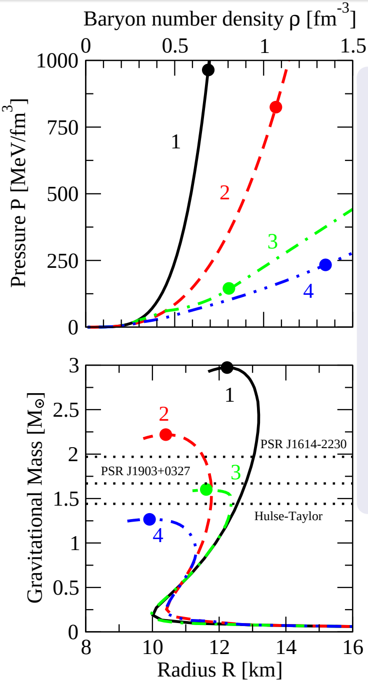
- For semplicity we have chosen: $a_{N\Lambda} = a_{N\Sigma}$, $b_{N\Lambda} = b_{N\Sigma}$ and $\gamma_{N\Lambda} = \gamma_{N\Sigma}$

- We rescaled: $a_{N\Lambda} = x\ a_{NN}$, $b_{N\Lambda} = x\ b_{NN}$, x=0,$\frac{1}{3}$, $\frac{2}{3}$, 1

- The last parameter $\gamma_{N\Lambda}$ has been fixed using the value of -28 MeV of the binding energy of the Λ particle in nuclear matter:

$$\left(\frac{B}{A}\right)_\Lambda = -28\ MeV \ = U_\Lambda(k=0) + a_{NY}\rho_0 + b_{NY}\rho_0^{\gamma_{NY}}$$

- where $U_\Lambda(k=0) = -30.8$ MeV



γ_{NN}	x	γ_{YN}	M_{max}
2	0	-	1.27 (2.22)
	1/3	1.49	1.33
	2/3	1.69	1.38
	1	1.77	1.41
2.5	0	-	1.29 (2.46)
	1/3	1.84	1.38
	2/3	2.08	1.44
	1	2.19	1.48
3	0	-	1.34 (2.72)
	1/3	2.23	1.45
	2/3	2.49	1.50
	1	2.62	1.54
3.5	0	-	1.38 (2.97)
	1/3	2.63	1.51
	2/3	2.91	1.56
	1	3.05	1.60

$$1.27\ M_\odot < M_{max} < 1.6\ M_\odot$$

I. Vidana, D. Logoteta, C. Providencia, A. Polls, I. Bombaci EPL 94, 11002 (2011)

Repulsive value for $\left(\frac{B}{A}\right)_{\Sigma^-}$

$$\left(\frac{B}{A}\right)_{\Sigma^-} = +30 \text{ MeV} = U_{\Sigma^-}(k=0) + a_{NY}\rho_0 + b_{NY}\rho_0^{\gamma_{N\Sigma}}$$

γ_{NN}	x	$\gamma_{N\Lambda}$	$\gamma_{N\Sigma}$	M_{max}	ρ_c
2	1/3	1.49	0.20	1.38	1.00
	2/3	1.69	0.56	1.44	0.99
	1	1.77	0.76	1.48	0.98
2.5	1/3	1.84	0.48	1.46	0.85
	2/3	2.08	0.85	1.52	0.84
	1	2.19	1.05	1.57	0.83
3	1/3	2.23	0.83	1.55	0.77
	2/3	2.49	1.20	1.61	0.76
	1	2.62	1.41	1.66	0.75
3.5	1/3	2.63	1.21	1.63	0.72
	2/3	2.91	1.58	1.70	0.71
	1	3.05	1.79	1.75	0.70

$$1.38\ M_\odot < M_{max} < 1.75\ M_\odot$$

The Brueckner-Hartree-Fock approach

- Starting point: the Bethe-Goldstone equation

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

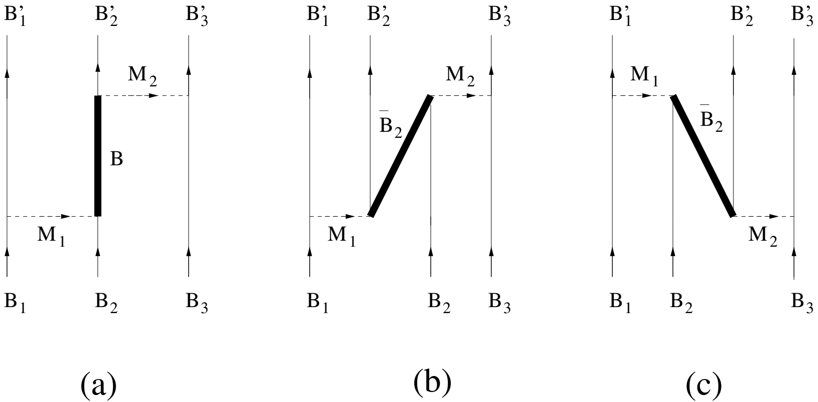
$$U_{B_i}(k) = \sum_{B_j}\sum_{\vec{k'}} n_{B_j}(|\vec{k'}|) \times \langle \vec{k}\vec{k'}|G(E_{B_i}(\vec{k}) + E_{B_j}(\vec{k'}))_{B_iB_j,B_iB_j}|\vec{k}\vec{k'}\rangle_{\mathcal{A}}$$

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

$$\epsilon_{BHF} = \frac{1}{V}\sum_{B_i}\sum_{k\le k_{F_i}}\left[M_{B_i} + \frac{\hbar^2 k^2}{2M_{B_i}} + \frac{1}{2}U_{B_i}(k)\right]$$

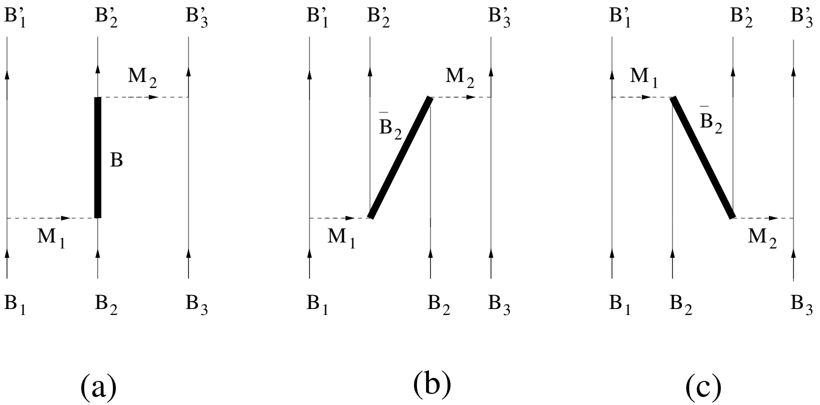
- We included the Λ, Σ hyperons in our calculations.
- We used AV18 NN potential + TM' NNN force and Ju04 NY potential + NNY.

The NNY three-body forces



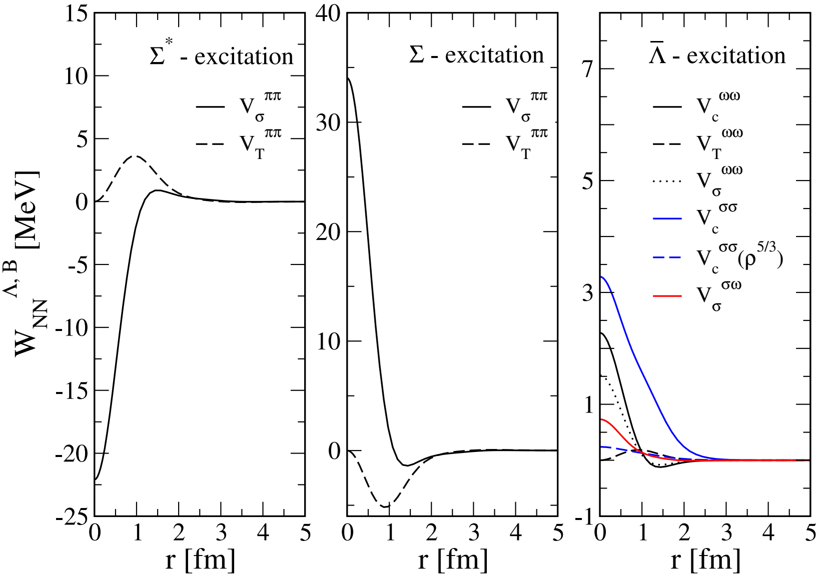
- $B_i = N,\ \Lambda,\ \Sigma$.
- $(M_1,\ M_2) = \pi,\ K,\ \sigma,\ \omega$.
- $B = N,\ \bar{N},\ \Lambda,\ \bar{\Lambda},\ \Sigma,\ \bar{\Sigma},\ \Delta, \Sigma^*$.

The NNY three-body forces

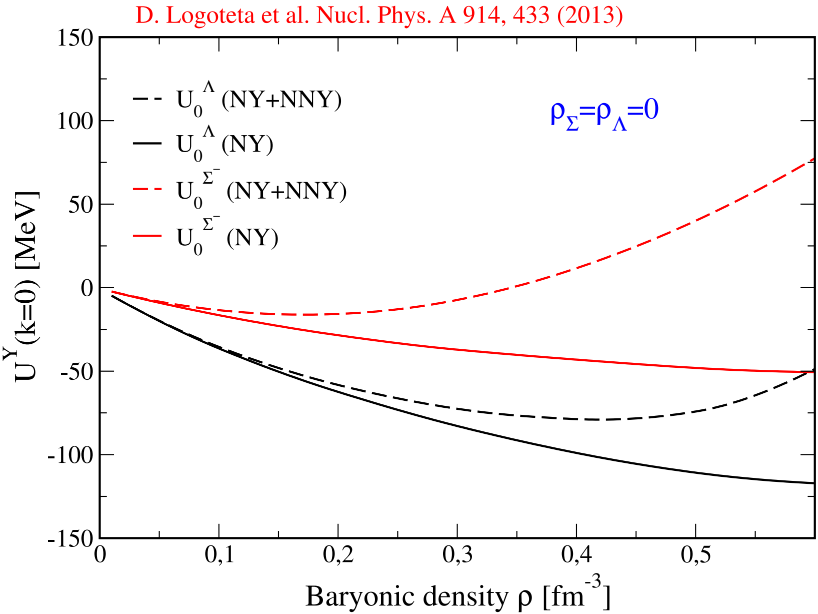


- $B_i = N,\ \Lambda,\ \Sigma.$
- $(M_1,\ M_2) = \pi,\ K,\ \sigma,\ \omega.$ $\Rightarrow W_{NN}(1,2) \sim \int dr_3^Y\ V_{NNY}(1,2,3)$
- $B = N,\ \bar{N},\ \Lambda,\ \bar{\Lambda},\ \Sigma,\ \bar{\Sigma},\ \Delta, \Sigma^*.$ $\Rightarrow W_{NY}(1,2) \sim \int dr_3^N\ V_{NNY}(1,2,3)$

Effective NNΛ forces at $\rho_0 = 0.17\ \mathrm{fm}^{-3}$



Single particle potentials of Λ and Σ^- at $k = 0$ in pure nuclear matter



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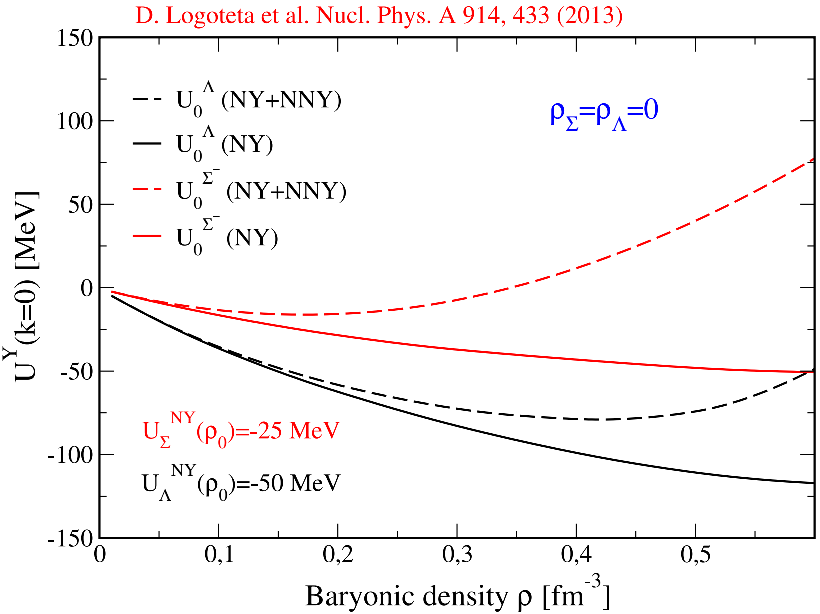
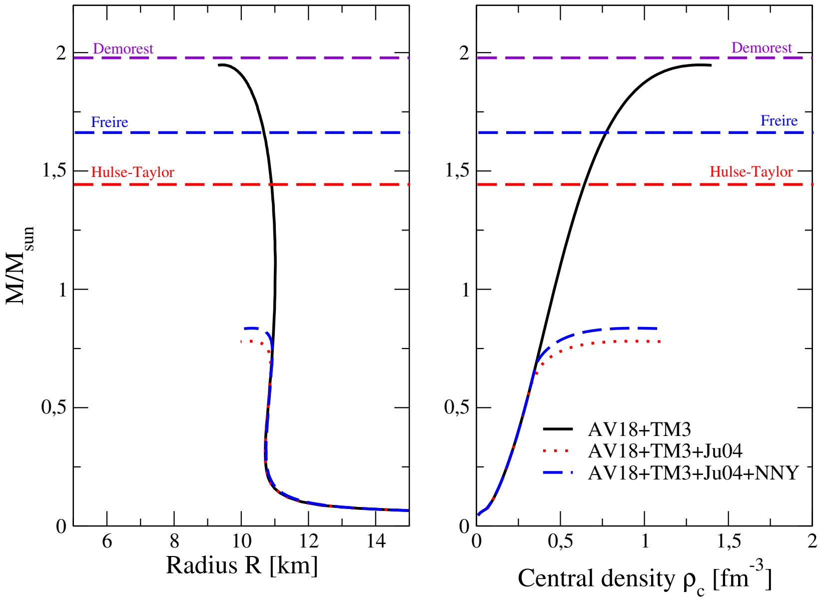


$M(R)$ and $M(\rho_c)$ curves



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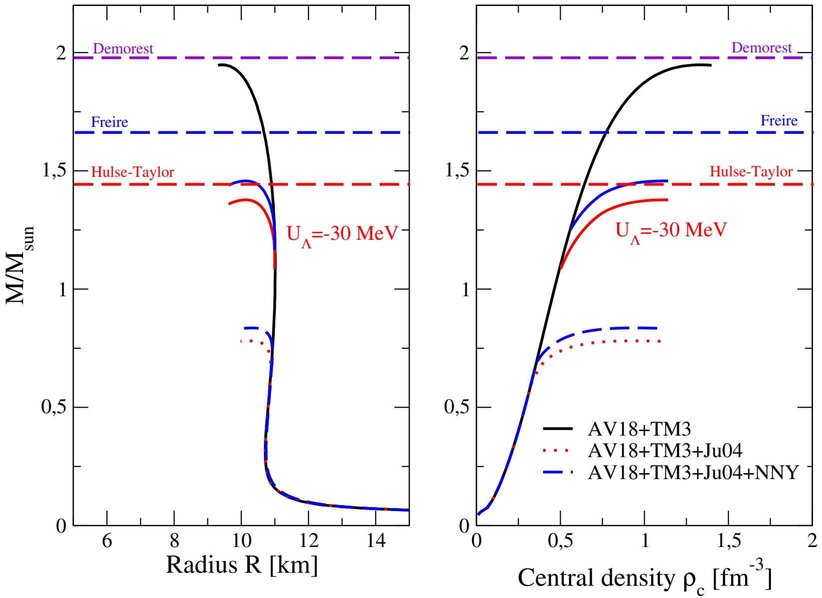

Conclusion

- We have calculated a hyperonic NNY force consistent with Ju04 NY interaction including Λ and Σ hyperons.
- The Ju04 NY potential is too attractive $\Rightarrow$ need to be replaced by some other interaction.
- The total effect of our NNY potential on the EOS is repulsive but...
- ...is not enough to solve the problem of maximum mass of neutron stars.

Thank you