Infinite and Finite Nuclear Matter (INFINUM-2023)

Hyperonic interactions and charge symmetry breaking in neutron stars

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Introduction

- Neutron stars are hydrostatically equilibrium stars, the matter of which consists mainly of neutrons and has a density of the order of the nuclear one
- Mostly observed as radiopulsars (> 2500)
- Masses are measured in binary systems (10%)
- According to the latest data (J0740+6620, M = 2.14 +- 0.2 Ms) mass M > 2Ms must be reached in theoretical models
- First registration of gravitational waves from the merger of two neutron stars (GW170817)
- Studying of neutron stars can be promising for understanding the properties of hyperonic interactions

Neutron stars matter

Energy and energy density

$$E = \langle \phi | T + V | \phi \rangle = \sum_i \langle i | T_i | i \rangle + \frac{1}{2} \sum_{i,j} \langle ij | V_{ij} | ij \rangle + \frac{1}{6} \sum_{i,j,k} \langle ijk | V_{ijk} | ijk \rangle = \int H dr$$

Energy per nucleon

$$\varepsilon(Y_p, n) = \frac{E}{A} = \frac{H}{n}$$

Pressure

$$p = n^2 \frac{d\varepsilon}{dn}$$

Incompressibility (K_{inf})

$$K_{inf} = 9n^2 \frac{\partial^2 \varepsilon}{\partial n^2}$$

β-equilibrium matter

$$\begin{cases} \mu_p(Y_p, Y_\Lambda) + \mu_e(Y_e) = \mu_n(Y_p, Y_\Lambda) \\ \mu_\mu(Y_p, Y_e) = \mu_e(Y_e) \\ \mu_\Lambda(Y_p, Y_\Lambda) + m_\Lambda = \mu_n(Y_p, Y_\Lambda) + m_n \end{cases}$$

$$n \Longrightarrow p + e^- + \bar{\nu}_e; \; p + e^- \Longrightarrow n + \nu_e$$

$$n \Longrightarrow p + \mu^- + \bar{\nu}_\mu; \; p + \mu^- \Longrightarrow n + \nu_\mu$$

$$n + n \Longleftrightarrow n + \Lambda$$

Chemical potentials

$$\mu_i = \frac{\partial H}{\partial n_i}$$

$$\mu_e = \sqrt{m_e{}^2 + (3\pi^2 Y_e n)^{2/3}}$$

$$\mu_\mu = \sqrt{m_\mu{}^2 + (3\pi^2 Y_\mu n)^{2/3}}$$

Skyrme interaction

$$V_{NN}(\vec{r_1}, \vec{r_2}) = t_0(1 + x_0 P_\sigma)\delta(\vec{r_1} - \vec{r_2})$$
$$+ \frac{1}{2}t_1(1 + x_1 P_\sigma)[\vec{P}'^2\delta(\vec{r_1} - \vec{r_2}) + \delta(\vec{r_1} - \vec{r_2})\vec{P}^2]$$
$$+ t_2(1 + x_2 P_\sigma)\vec{P}'\delta(\vec{r_1} - \vec{r_2})\vec{P}$$
$$+ iW_0\vec{\sigma}[\vec{P}' \times \delta(\vec{r_1} - \vec{r_2})\vec{P}]$$

$$V_{\Lambda N}(\vec{r_\Lambda}, \vec{r_N}) = u_0(1 + \xi_0 P_\sigma)\delta(\vec{r_\Lambda} - \vec{r_N})$$
$$+ \frac{1}{2}u_1(1 + \xi_1 P_\sigma)[\vec{P}'^2\delta(\vec{r_\Lambda} - \vec{r_N}) + \delta(\vec{r_\Lambda} - \vec{r_N})\vec{P}^2]$$
$$+ u_2\vec{P}'\delta(\vec{r_\Lambda} - \vec{r_N})\vec{P}$$
$$+ iW_0^\Lambda\vec{P}'\delta(\vec{r_\Lambda} - \vec{r_N})[\vec{\sigma} \times \vec{P}]$$

$$V_{\Lambda\Lambda}(\vec{r_1}, \vec{r_2}) = \lambda_0\delta(\vec{r_1} - \vec{r_2})$$
$$+ \frac{1}{2}\lambda_1[\vec{P}'^2\delta(\vec{r_1} - \vec{r_2}) + \delta(\vec{r_1} - \vec{r_2})\vec{P}^2]$$

Density dependence and three-body forces

$$V_3 = V_{\Lambda NN}(\overrightarrow{r_\Lambda}, \overrightarrow{r_{N1}}, \overrightarrow{r_{N2}}) = t_3\delta(\overrightarrow{r_\Lambda} - \overrightarrow{r_{N1}})\delta(\overrightarrow{r_\Lambda} - \overrightarrow{r_{N2}})$$

$$V_3 = V_{\Lambda N}(\overrightarrow{r_\Lambda}, \overrightarrow{r_N}, \rho) = \frac{3}{8}t_3(1 + x_3 P_\sigma)\delta(\overrightarrow{r_\Lambda} - \overrightarrow{r_N})\rho^\gamma(\frac{\overrightarrow{r_\Lambda} + \overrightarrow{r_N}}{2})$$

Parameters

Parametrizations	γ
YBZ6	1
YBZ2	1
SLL4'	1
LYI	1/3
YMR	1/8

Neutron stars

Tolman Oppenheimer Volkov equation

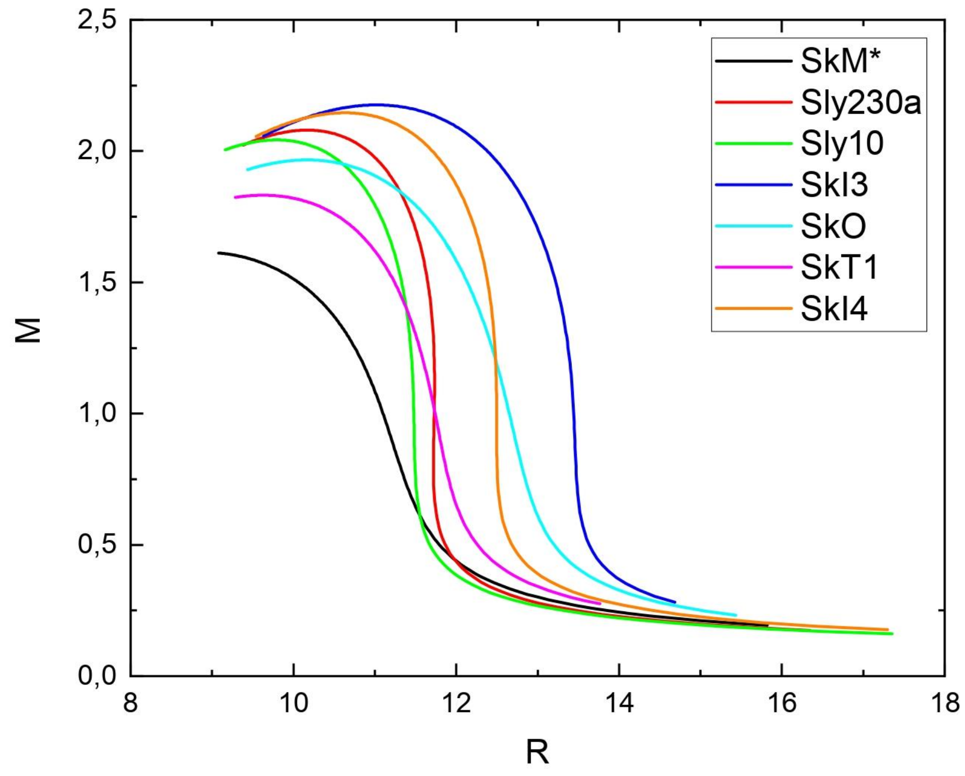
$$\frac{dP}{dr} = \frac{G}{r^2}\frac{[\rho(r) + P(r)/c^2][m(r) + (4\pi r^3 P(r)/c^2)]}{1 - (2Gm(r)/rc^2)}$$

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

$$M = \int_0^R 4\pi r^2 \rho dr$$

$\rho(0)$ ⟶ M,R

Sequence $\rho(0)$ ⟶ M(R)



Tidal deformability

Tidal deformability coefficient

$$Q_{ij} = -\lambda \varepsilon_{ij}$$

$$\Lambda = \frac{\lambda}{M^5}$$

Theoretical calculation

$$\mathrm{r}\frac{dy(r)}{dr} + y(r)^2 + y(r)F(r) + r^2 Q(r) = 0$$

$$F(r) = \frac{r - 4\pi r^3[\epsilon(r) - p(r)]}{r - 2m(r)}$$

$$Q(r) = \frac{4\pi r\left[5\epsilon(r) + 9p(r) + \frac{\epsilon(r) + p(r)}{\partial p(r)/\partial\epsilon(r)} - \frac{6}{4\pi r^2}\right]}{r - 2m(r)} - 4\left[\frac{m(r) + 4\pi r^3 p(r)}{r^2[1 - 2m(r)/r]}\right]$$

$$y_R \equiv y(R), \qquad C \equiv m/R$$

$$k_2 = f(y_R, C)$$

$$\lambda = \frac{2}{3} k_2 R^5$$

[1]Tuhin Malik, Phys. Rev. C 98 035804 (2018)

Tidal deformability. experiment

GW170817

$$M_{chirp} = 1.186^{+0.001}_{-0.001} \qquad M_{chirp} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$\bar{\Lambda} \leq 900 \qquad \bar{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$$

$$m_1 = 1.4\mathrm{M}_\odot \rightarrow \Lambda = 70 - 580$$

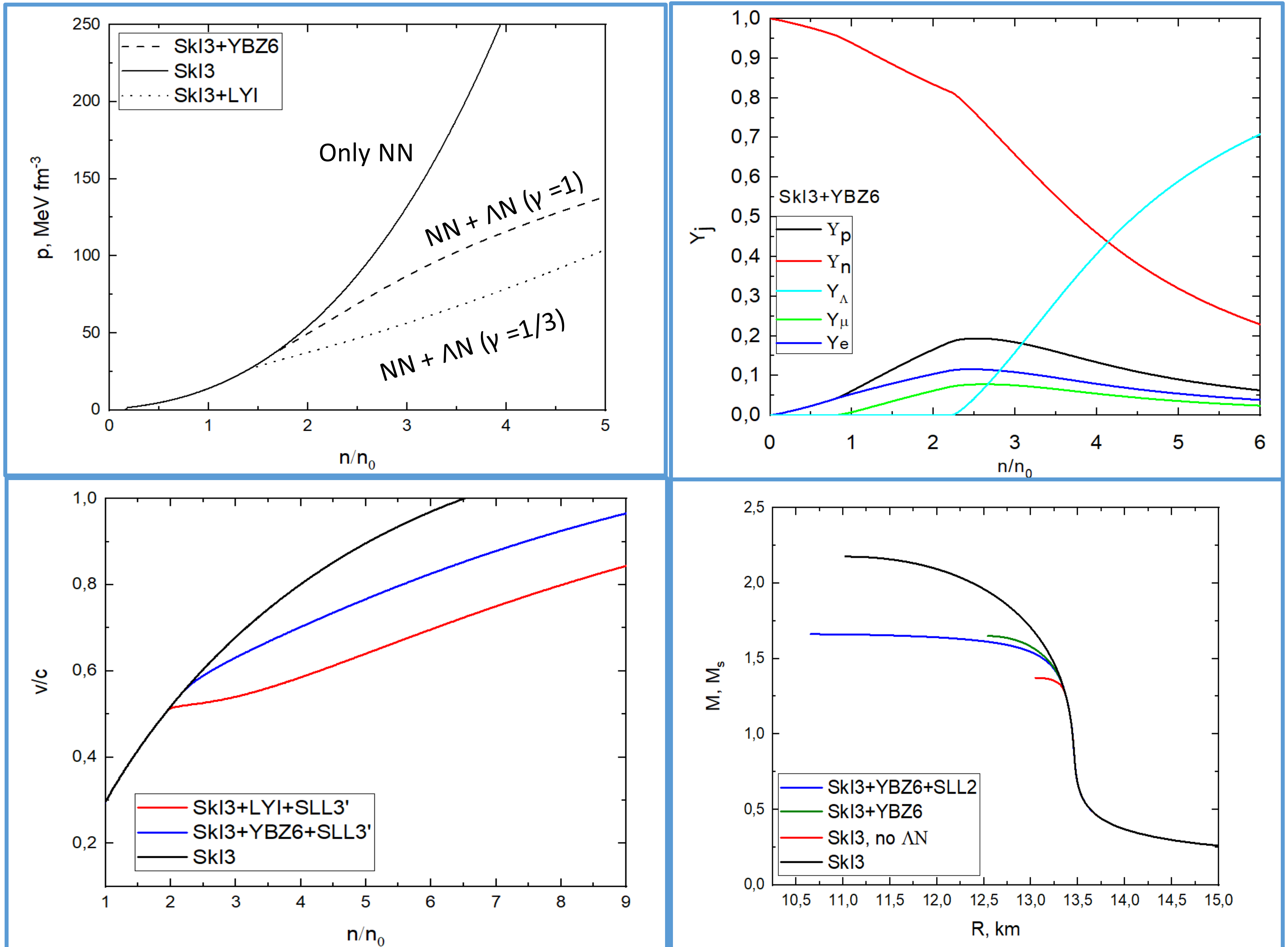
$$R = 10.5 - 13.3 \text{ км } [1,2,3]$$

[1] B. Abbott et al. (LIGO Scientific and Virgo Collaboration), Phys. Rev. Lett. 119, 161101 (2017)

[2] B. Abbott et al. (LIGO Scientific and Virgo Collaboration), Phys. Rev. Lett. 121, 161101 (2018)

[3] B. Abbott et al. (LIGO Scientific and Virgo Collaboration), Phys. Rev. X 9(1) 011001 (2019).

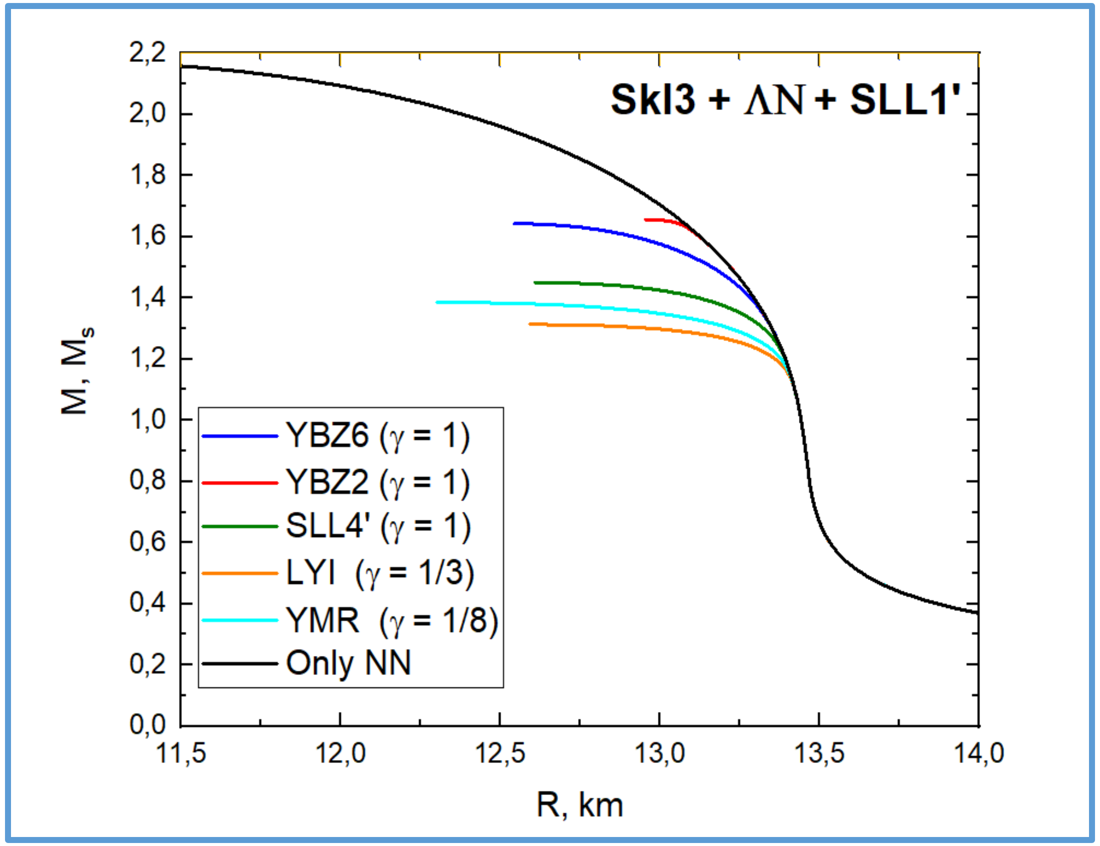
Hyperon puzzle

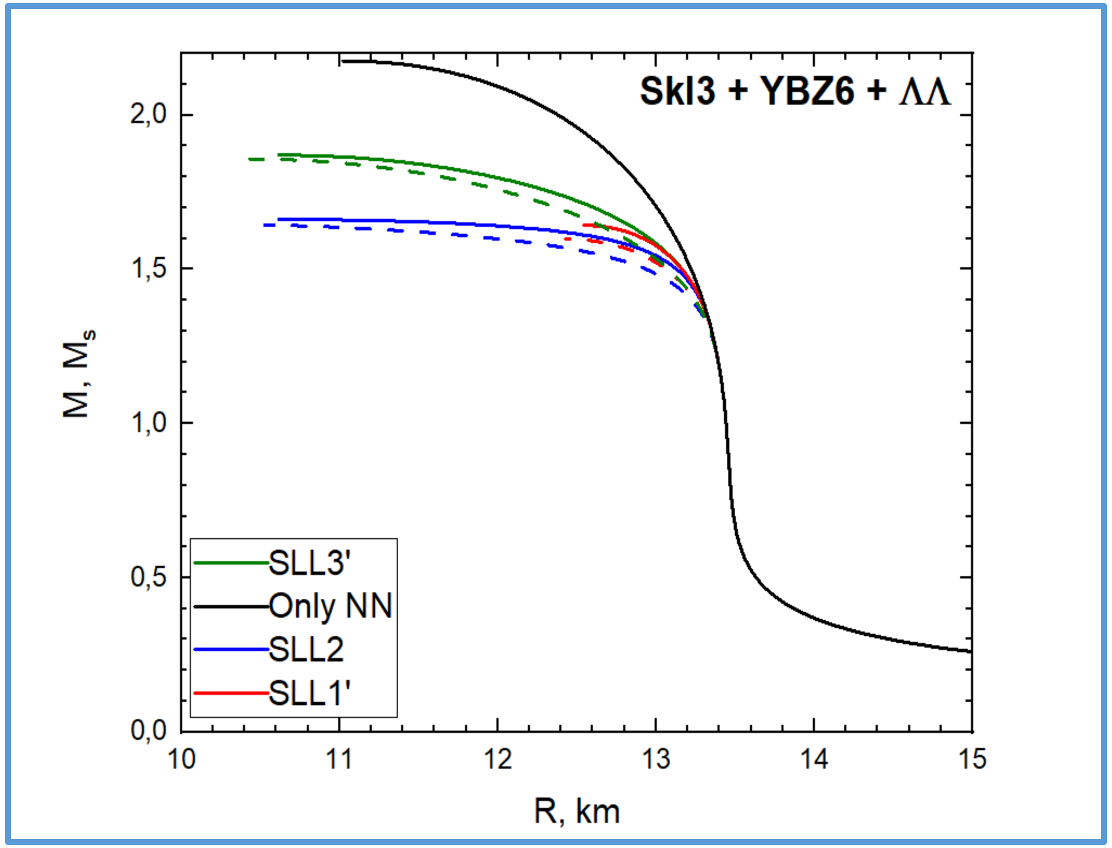


Masses and radii in neutron stars with hyperons

$$V_3 = V_{\Lambda NN}(\overrightarrow{r_\Lambda}, \overrightarrow{r_{N1}}, \overrightarrow{r_{N2}}) = t_3 \delta(\overrightarrow{r_\Lambda} - \overrightarrow{r_{N1}}) \delta(\overrightarrow{r_\Lambda} - \overrightarrow{r_{N2}})$$

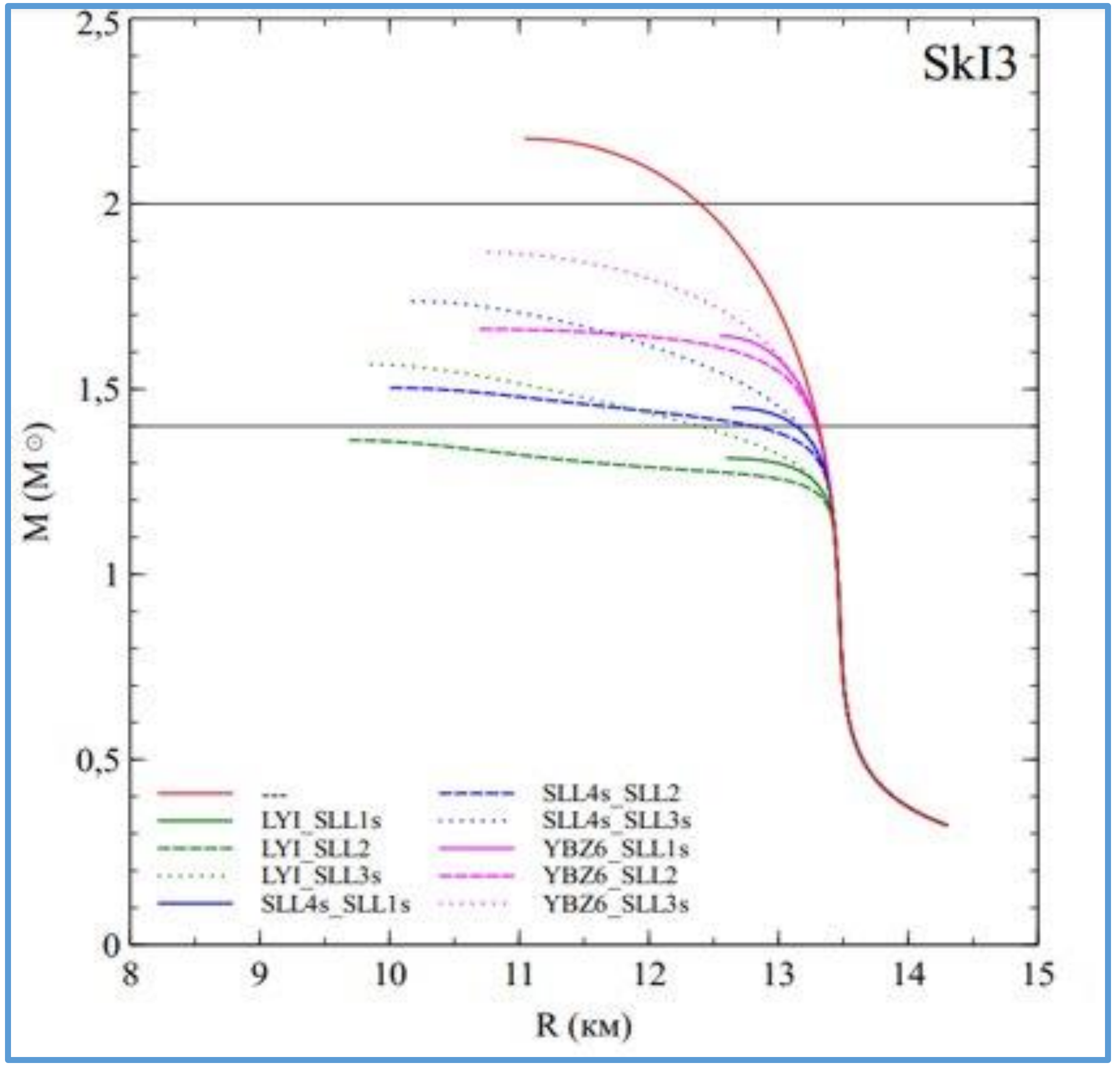
$$V_3 = V_{\Lambda N}(\overrightarrow{r_\Lambda}, \overrightarrow{r_N}, \rho) = \frac{3}{8} t_3 (1 + x_3 P_\sigma) \delta(\overrightarrow{r_\Lambda} - \overrightarrow{r_N}) \rho^\gamma \left(\frac{\overrightarrow{r_\Lambda} + \overrightarrow{r_N}}{2}\right)$$

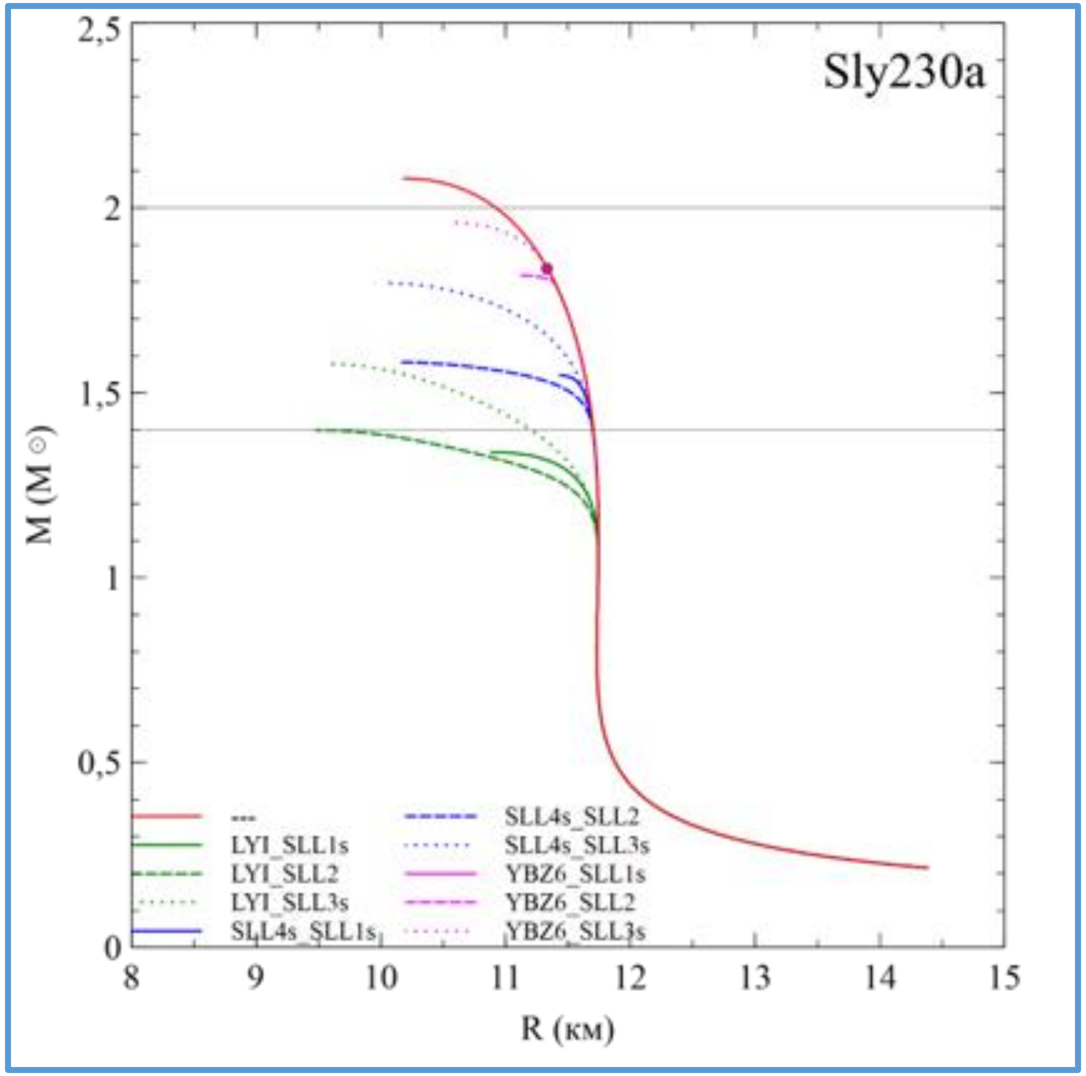




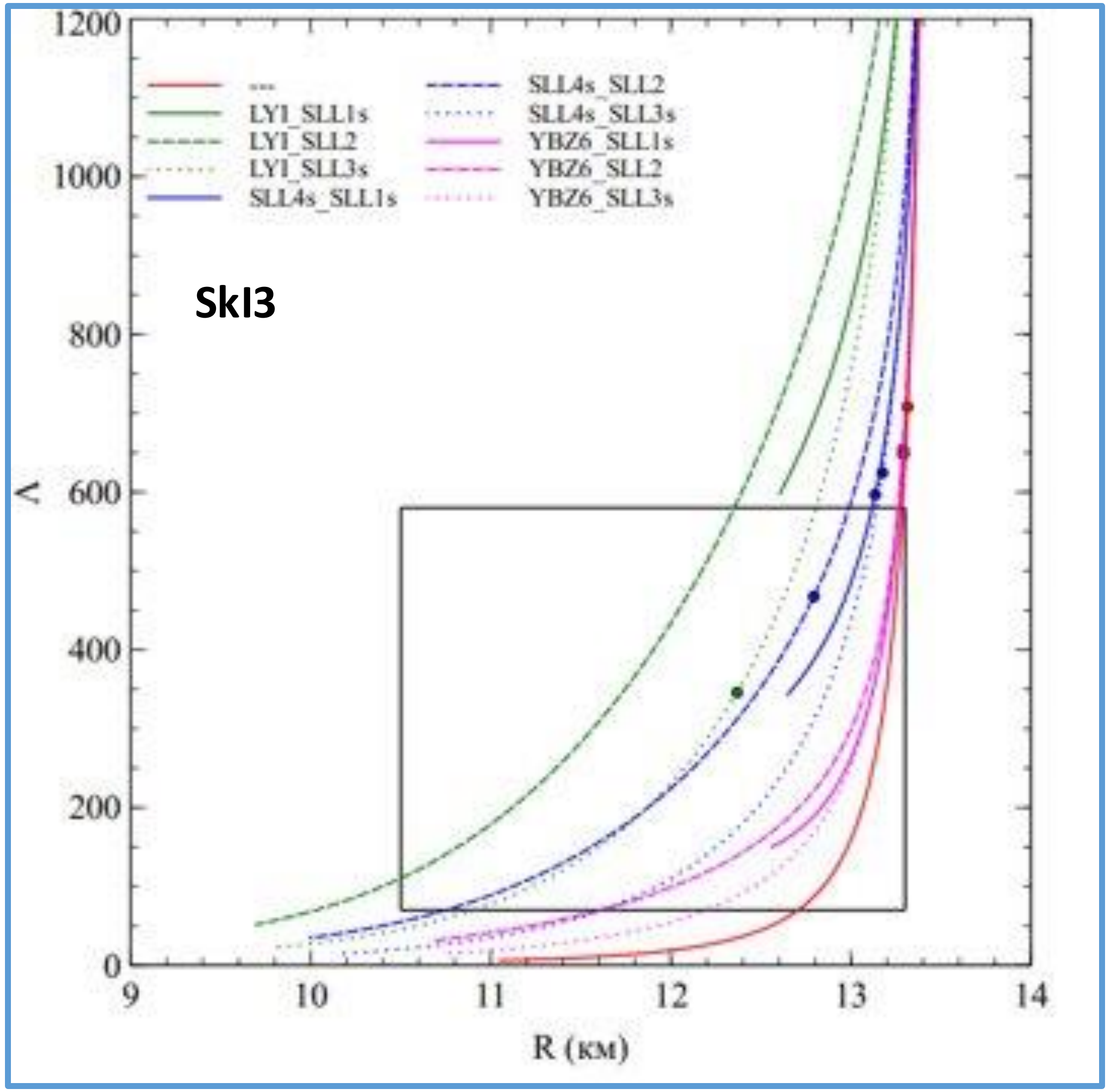
Solid lines - density dependence, dotted lines - three-body forces

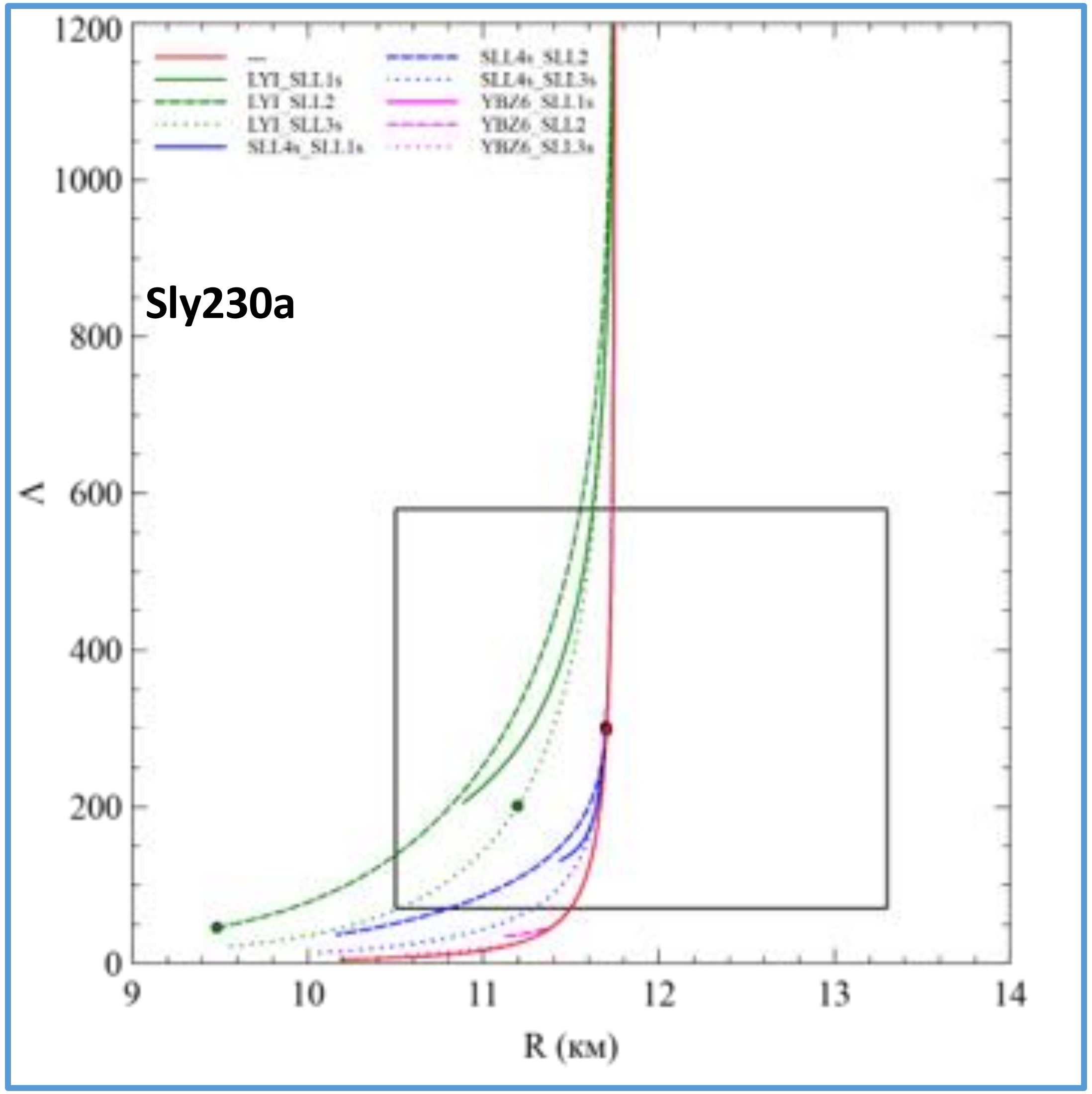
Masses and radii in neutron stars with hyperons





Dependence of tidal deformability on radius in neutron stars with hyperons



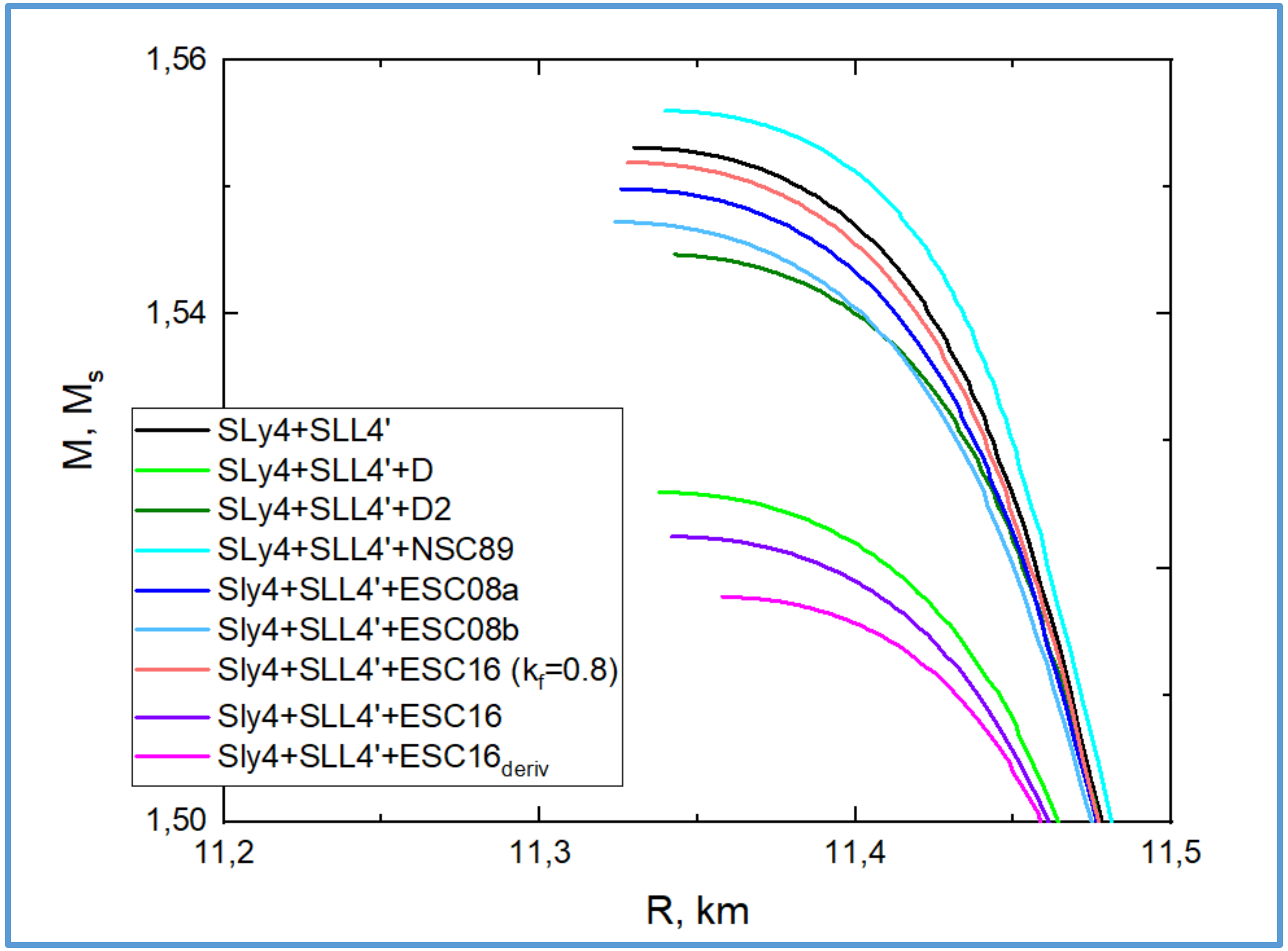


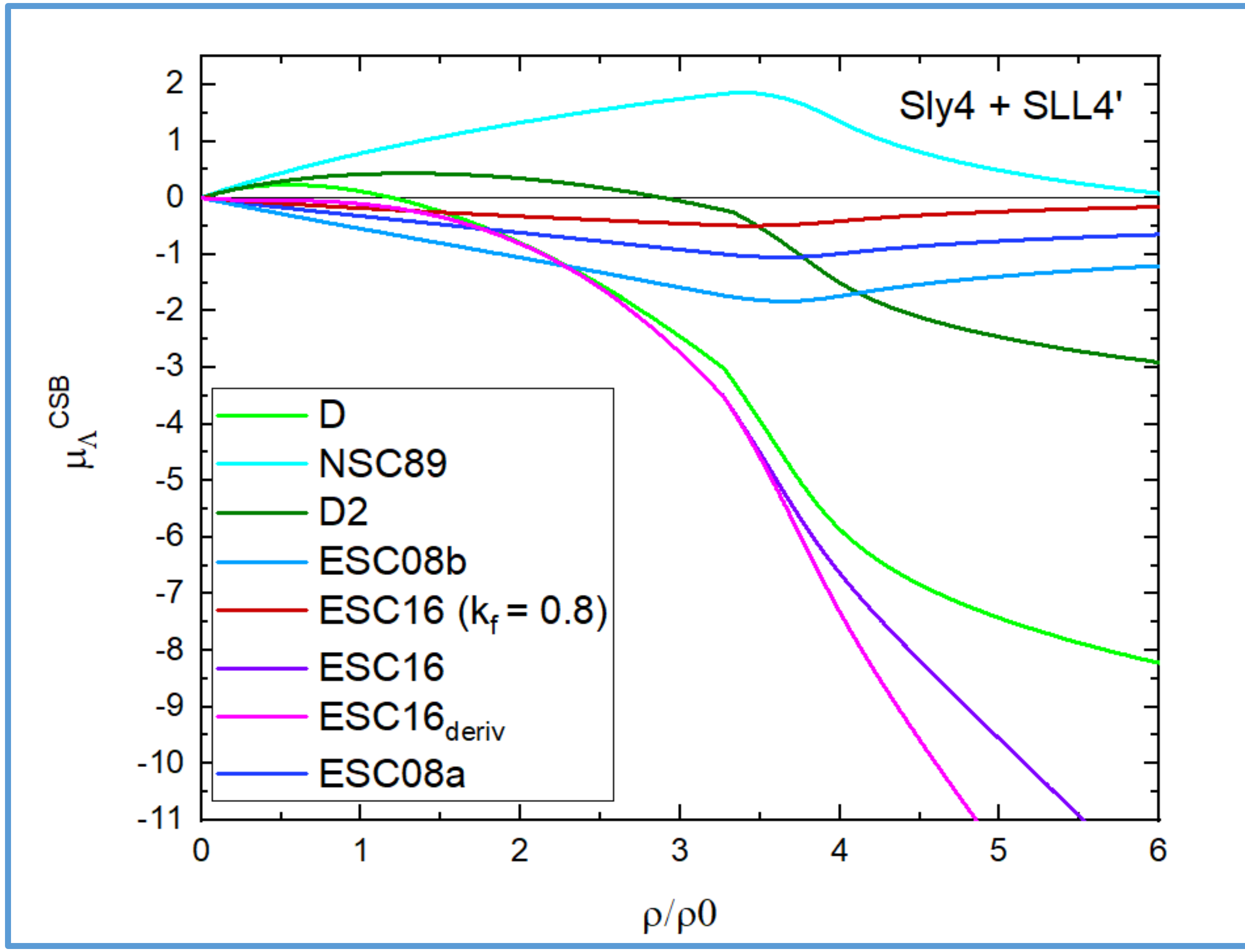
Charge symmetry breaking

Charge symmetry breaking (CSB) – effect of breaking isospin symmetry because of electromagnetic interaction

Model	a_0^{CSB}, Mev·fm³	a_1^{CSB}, Mev·fm³	$B_\Lambda(^9_\Lambda C)$, Mev	$B_\Lambda(^{13}_\Lambda C)$, Mev	$B_\Lambda(^{23}_\Lambda C)$, Mev
Without CSB	0	0	7,74	11,79	15,86
ESC08a	2,2660	-0,0092	7,68	11,80	15,92
ESC08b	3,7649	0,0776	7,64	11,80	16,00
D2	-5,6105	3,6480	7,83	11,79	15,73
NSC89	-6,5946	1,4628	7,89	11,79	15,64
D [16]	-6,8277	8,1513	7,80	11,79	15,77
ESC16 [17] with k_F=0,8 fm^{-1}	1,4423	-0,2061	7,70	11,79	15,91
ESC16 [17] with k_F=1,3 fm^{-1}	0,5204	0,1242	7,73	11,79	15,87

CSB in neutron stars



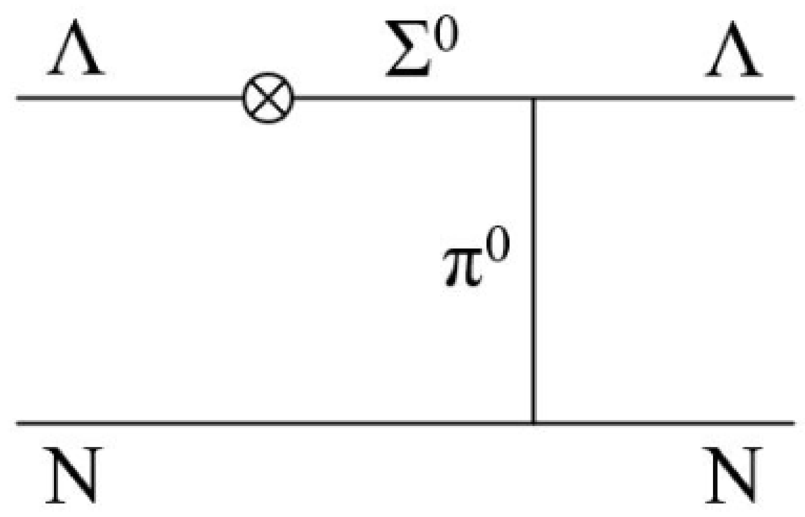


Conclusion

- We considered two alternative ways to describe nonlinear effects in ΛN-interaction: dependence on nucleon density (ρ^{α}) and three-body ΛNN force, and investigated the difference between them in neutron stars.
- It was found that Skyrme parameterizations of ΛN-interaction with $\alpha = 1$ are the most suitable for describing neutron stars.
- New combinations of parametrizations of NN- and ΛN-interactions were found, leading to the values of the maximum mass close to two solar masses.
- CSB effect affect neutron stars, and some characteristics, such as chemical potential of Λ-hyperon, can change its behavior at high densities

THANK YOU FOR ATTENTION

Extra slides



$$\mathcal{E}_{N\Lambda} = u_0\left(1+\frac{y_0}{2}\right)\rho_\Lambda\rho_N + a_0^{CSB}\rho_\Lambda\rho_- + \frac{3}{8}u_3\left(1+\frac{y_3}{2}\right)\rho_\Lambda\rho_N^{\beta+1} + \frac{1}{4}\left[u_1\left(1+\frac{y_1}{2}\right)+u_2\left(1+\frac{y_2}{2}\right)\right](\tau_\Lambda\rho_N+\tau_N\rho_\Lambda) + \frac{1}{4}(a_1^{CSB}+a_2^{CSB})(\tau_\Lambda\rho_- + \tau_-\rho_\Lambda),$$

$$V_{CSB} = -0{,}0297\tau_{Nz}\cdot\frac{1}{\sqrt{3}}V(\Lambda N \leftrightarrow \Sigma N).$$

$$V(\Lambda N \leftrightarrow \Sigma N) = \sum_{i=1}^{3} v_i \exp(-(r/\beta_i)^2),$$

$$V(\Lambda N \leftrightarrow \Sigma N) = \sum_{i=1}^{3}(a_i + b_i k_F + c_i k_F^2)\exp(-(r/\beta_i)^2),$$

Laplass method

$$t_0^{s/t} = \pi^{3/2}\sum v_i^{s/t}\beta_i^3,$$
$$t_1^{s/t} = -\frac{1}{2}\pi^{3/2}\sum v_i^{s/t}\beta_i^5,$$

$$t_i^{CSB} = \frac{t_i^t + t_i^s}{2},$$
$$x_i^{CSB} = \frac{t_i^t - t_i^s}{t_i^t + t_i^s},$$
$$a_i^{CSB} = -\frac{0{,}0297}{\sqrt{3}}t_i^{CSB}(1 + x_i^{CSB}/2).$$