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HYPERONS IN NEUTRON STARS

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Neutron stars

Neutron star structure

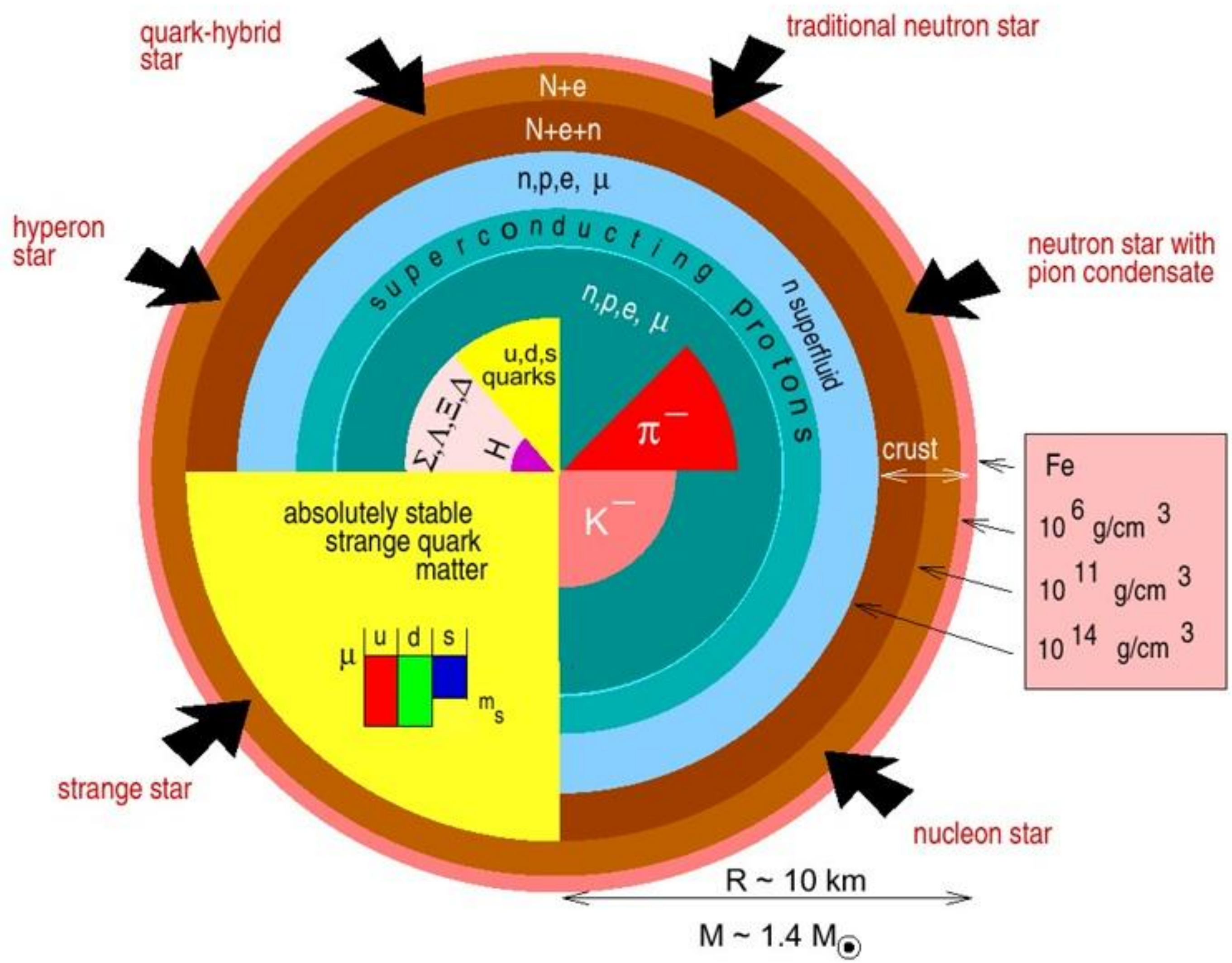
•Mass:
M ~ 1 - 2 M_S

•Radius:
R ~ 10 - 12 km

•Density:
~ 10^{14} - 10^{15} g/cm^3

•Mass number:
A ~ 10^{57} ("giant nucleus")

•Number in the Galaxy
~ 10^8 – 10^9 NS



Masses of neutron stars

- The most accurate mass measurements are for stars in binary systems (~1%)
- Maximum mass

  PSR J0348+0432: $M = 2.01 \pm 0.04\ M_S$
  [Antoniadis et al. 2013]

  J0740+6620: $M = 2.14 \pm 0.10\ M_S$
  [Cromartie et al. 2020]

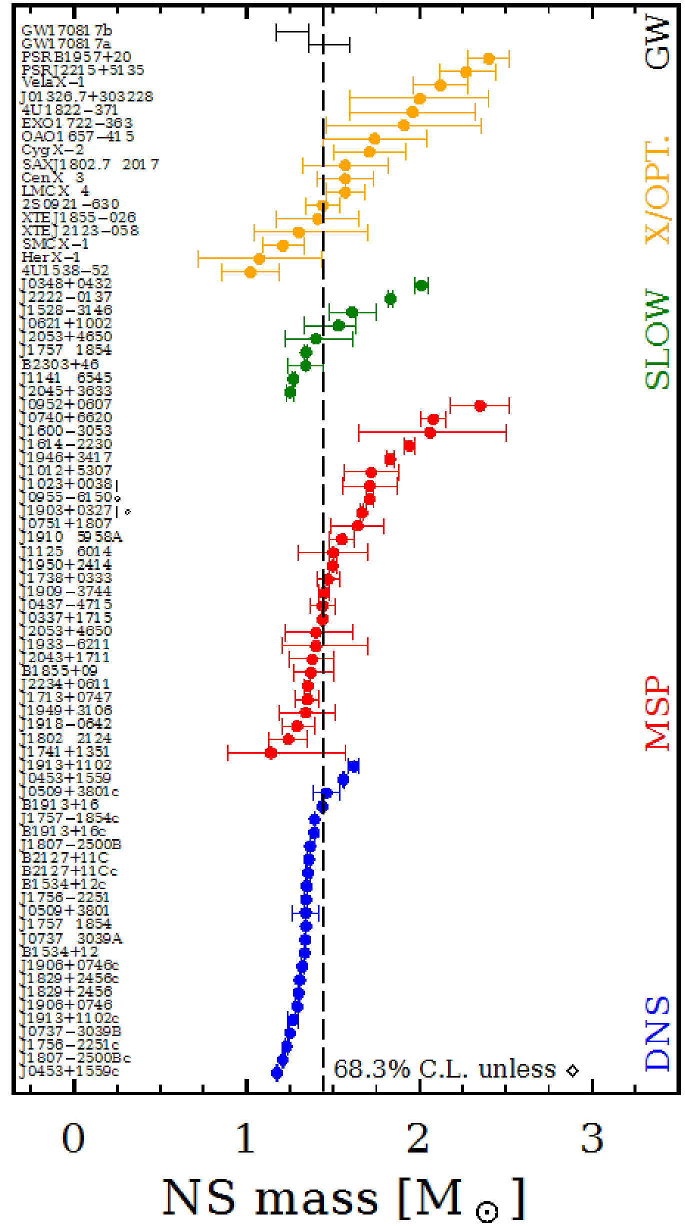
  PSR J0952-0607: **$M = 2.35 \pm 0.17\ M_S$**
  [Romani et al. 2022]

  PSR J0740+6620:
  $M = 2.027 \pm 0.067\ M_S$; $R = 12.39 \pm 1.14$ km
  [Riley et al. 2021]

- Minimum mass

  HESS J1731-347: $M = 0.8 \pm 0.2\ M_S$
  [Doroshenko et al. 2022]

Any consistent calculation must provide **$M > 2M_s$**



Suleiman et al 2021

Radii of neutron stars

X-Ray Observations

R = 9–14 km	$M \sim 1.4\, M_S$	[Lattimer 2012; Özel & Freire 2016]
R = 10–14 km	$M \sim 1.4\, M_S$	[Steiner et al. 2016, 2018]

The Neutron Star Interior Composition ExploreR (NICER)

PSR J0740+6620:

$M = 2.027 \pm 0.067\, M_S$; $R = 12.39 \pm 1.14$ km

[Riley et al. 2021]

PSR J0030+0451:

$M = 1.34 \pm 0.16\, M_S$; $R = 12.7 \pm 1.2$ km

[Riley et al. 2019]

GW 170817

$M = 1.186 \pm 0.001\, M_S$ (average);

$R = 11.9 \pm 1.4$ km (average)

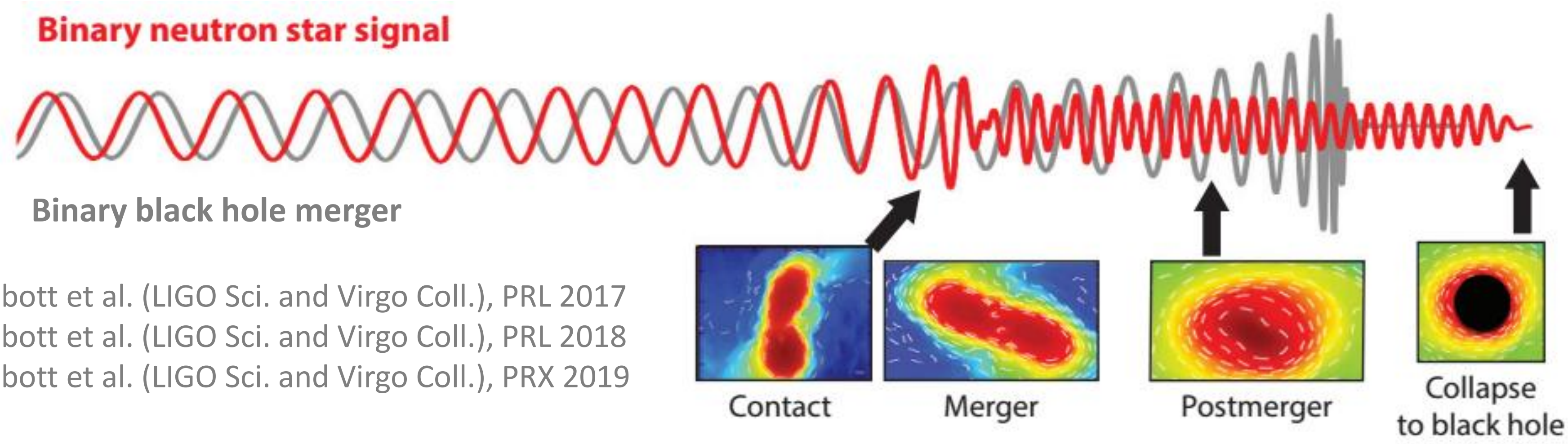
[Abbott et al. 2018]

Compact Star Mergers

17/08/17 – multimessenger signal
(gravitational waves, gamma-ray burst, optical, X-ray, UV, IR)
GW170817 LIGO Virgo, **GRB170817A** Fermi, INTEGRAL

Maximum mass **$M=2.16\pm 0.17\ M_S$** [Rezzolla ApJL 2018]
Radii **$11.82 < R_{1.4} < 13.72$ km**
Tidal deformability coefficient λ: $Q_{ij} = -\lambda\varepsilon_{ij}$ (Q_{ij} – NS quadrupole moment)
Dimensionless coefficient: $\Lambda = \lambda/M^5$

$$m_1 = 1.4\ \mathrm{M}_{\odot} \rightarrow \ \Lambda = 70 - 580; R = 10.5 - 13.3\ \mathrm{km}$$



Abbott et al. (LIGO Sci. and Virgo Coll.), PRL 2017
Abbott et al. (LIGO Sci. and Virgo Coll.), PRL 2018
Abbott et al. (LIGO Sci. and Virgo Coll.), PRX 2019

Baryonic Matter in Neutron Stars

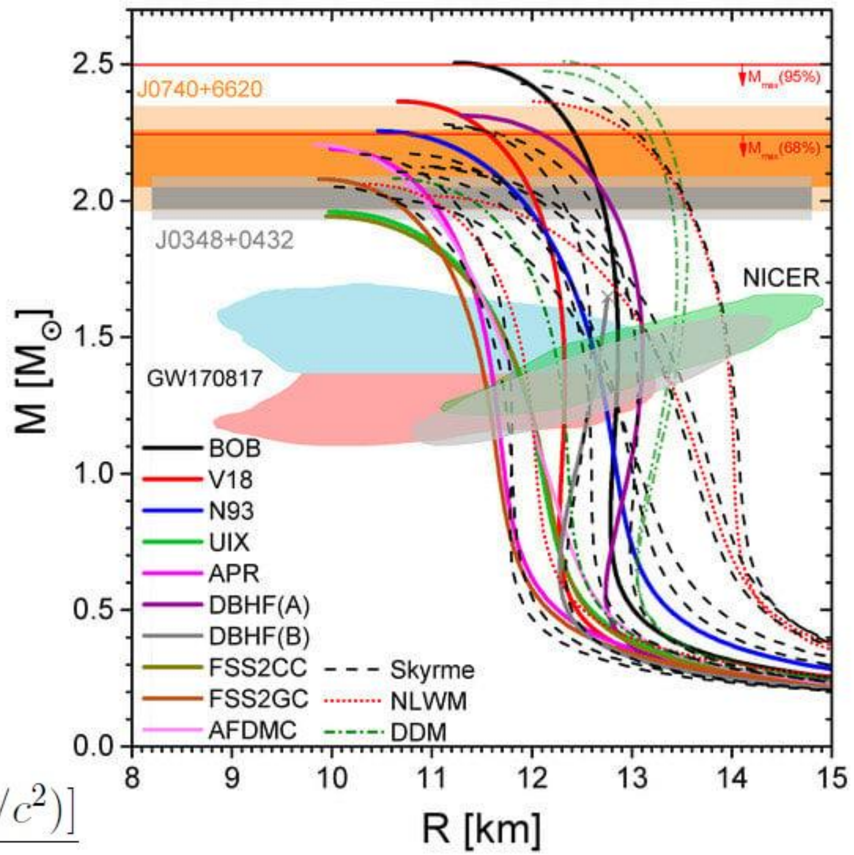
Chemical equilibrium

$\mu_p + \mu_e = \mu_n$

$\mu_\mu = \mu_e$

$\mu_\Lambda + m_\Lambda = \mu_n + m_n$

$\mu_{\Xi^-} + m_{\Xi^-} + \mu_p + m_p = 2\mu_\Lambda + 2m_\Lambda$



Burgio et al. 2021

Tolman-Oppenheimer-Volkov equation

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

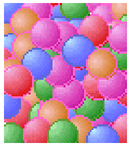
$$\frac{dm}{dr} = 4\pi r^2 \rho(r)$$

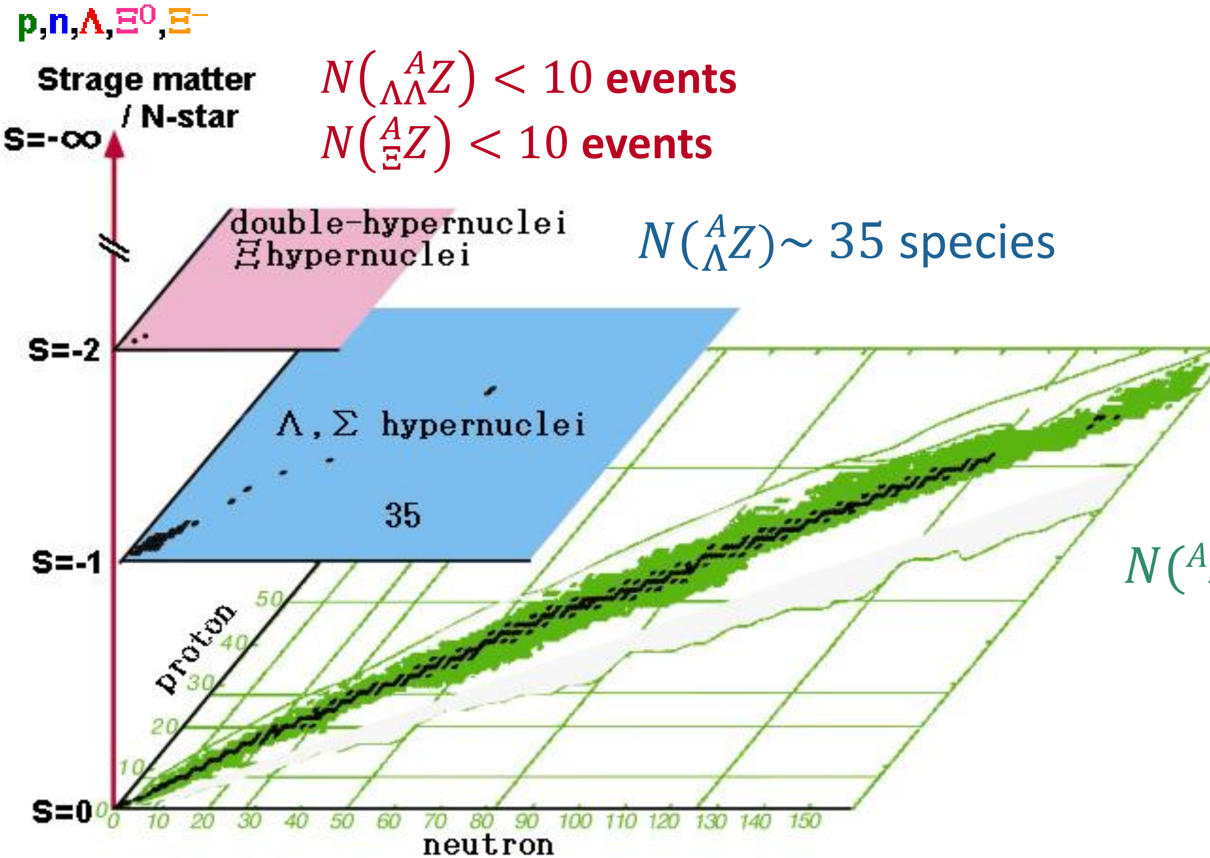
$$M = \int_0^R 4\pi r^2 \rho dr$$

Hyperonic interactions

Baryonic systems with strangeness (hypernuclei)

N(u) ~ N(d) ~ N(s)





$N({}^{A}_{\Lambda\Lambda}Z) < 10$ **events**

$N({}^{A}_{\Xi}Z) < 10$ **events**

$N({}^{A}_{\Lambda}Z) \sim 35$ species

$N({}^{A}Z) > 2500$

$$\Lambda \to \pi N \ (\sim 40 \text{ MeV})$$
$$\Lambda N \to NN \ (176 \text{ MeV})$$
$$\tau \sim 10^{-10} \text{ s}$$

$$\Sigma N \to \Lambda N$$
$$\Xi N \to \Lambda\Lambda$$
$$\tau \sim 10^{-23} \text{ s}$$

Λ-hypernuclei

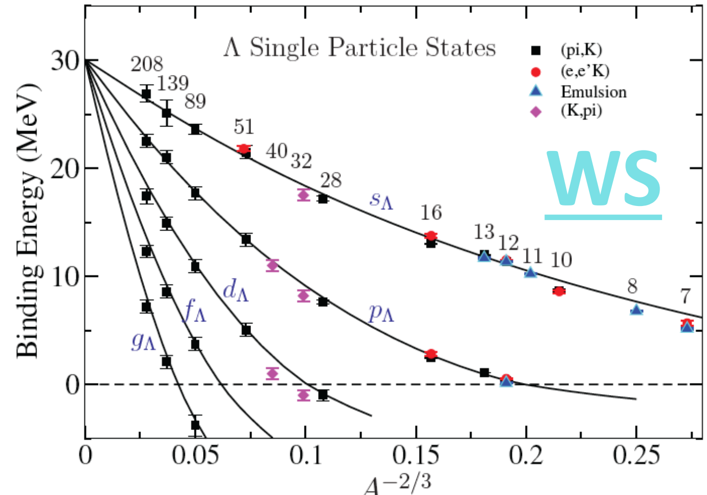
Λ separation energies

$$B_\Lambda\left({}^{A}_{\Lambda}Z\right) = B\left({}^{A}_{\Lambda}Z\right) - B\left({}^{A-1}Z\right)$$

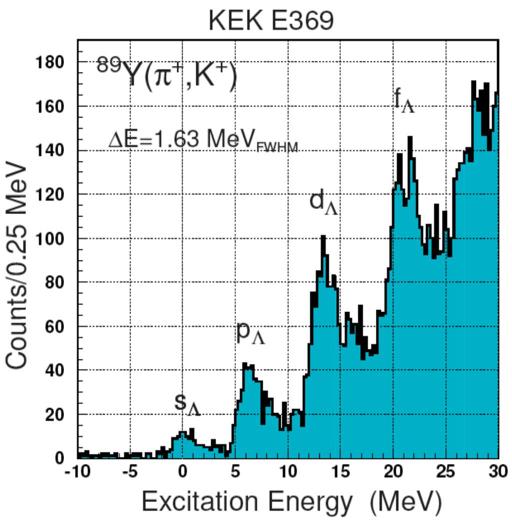
$$U_{\Lambda N} = U_0 + U_S(\boldsymbol{s}_N \boldsymbol{s}_\Lambda) + W_{LS}(\boldsymbol{l}\boldsymbol{s}_\Lambda) + \\ + W'_{LS}(\boldsymbol{l}\boldsymbol{s}_N) + TS_{12}$$

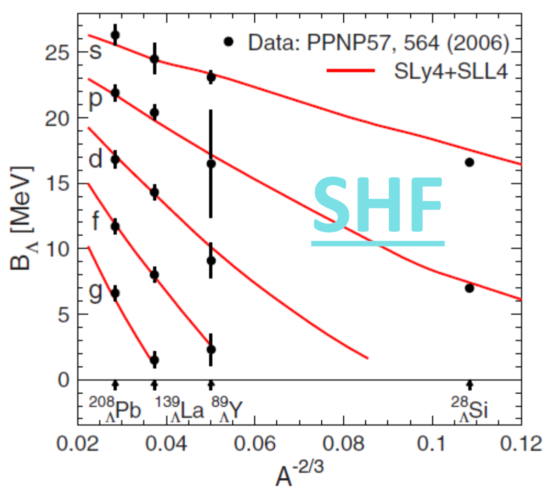
$$B_\Lambda(A \to \infty) = D_\Lambda \approx 28 - 32 \text{ MeV}$$

$$U_S, W_{LS}, W'_{LS}, T - small$$

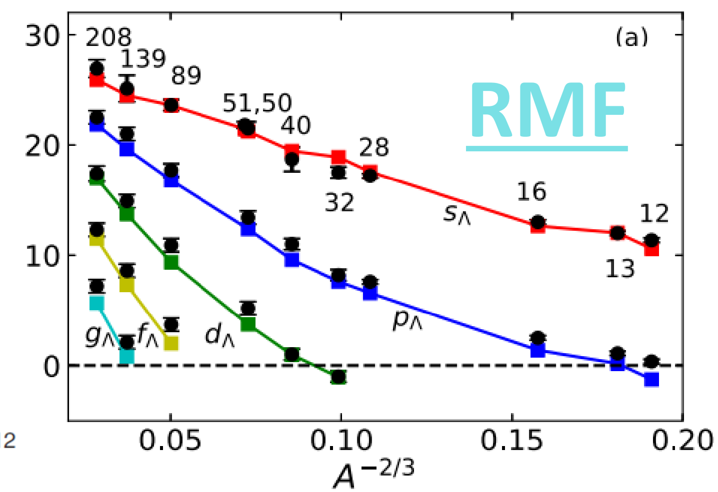


Gal, Hungerford, Millener (2016)





Schulze, Hiyama (2014)



Rong, Tu, Zhou (2021)

Σ-hypernuclei

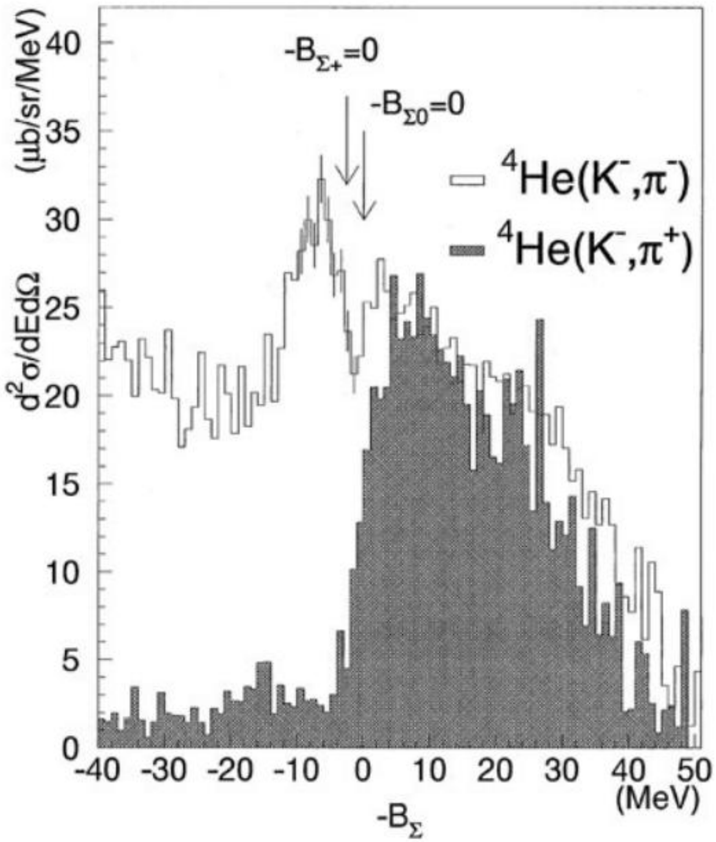
$$\Sigma^{\pm} \to N\pi\ (\sim 113\ \text{MeV})$$
$$\Sigma^{0} \to \Lambda\gamma\ (74\ \text{MeV})$$
$$\Sigma N \to \Lambda N\ (\sim 75\ \text{MeV})$$

From (π⁻, K⁺)

$$U_\Sigma(r) = (U_0 + U_L(\boldsymbol{\tau}_{core}\boldsymbol{\tau}_\Sigma)/A)\frac{\rho(r)}{\rho_0}$$

$$\boldsymbol{U_0 = +30 \pm 20\ \text{MeV}}$$

Lane term $\mathbf{U_L \approx 80\ MeV}$



Excitation energy spectra of ^{4}He(K⁻, π⁻) at 600 MeV/c K⁻ momentum (BNL AGS) [Nagae 1998]

Lane potential

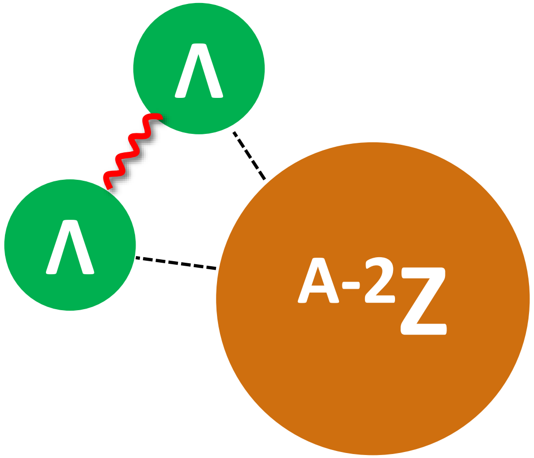
	Σ^-	Σ^0	Σ^+
N > *Z*	repulsion	zero	attraction
N = *Z*	zero	zero	zero
N < *Z*	attraction	zero	repulsion

$$|{}^4_\Sigma\text{He}\rangle = \alpha|\,{}^3\text{H} + \Sigma^+\rangle + \beta|\,{}^3\text{He} + \Sigma^0\rangle$$
$$|{}^4_\Sigma n\rangle = |\,{}^3\text{H} + \Sigma^-\rangle$$

$$B_{\Sigma+}({}^4_\Sigma\text{He}) = 4.4 \pm 0.3 \pm 1\ \text{MeV}$$
$$\Gamma = 7.0 \pm 0.7^{+1.2}_{0.0}\ \text{MeV}$$

Double-strangeness hypernuclei

the unique source of information on baryon interactions in the S=-2 sector



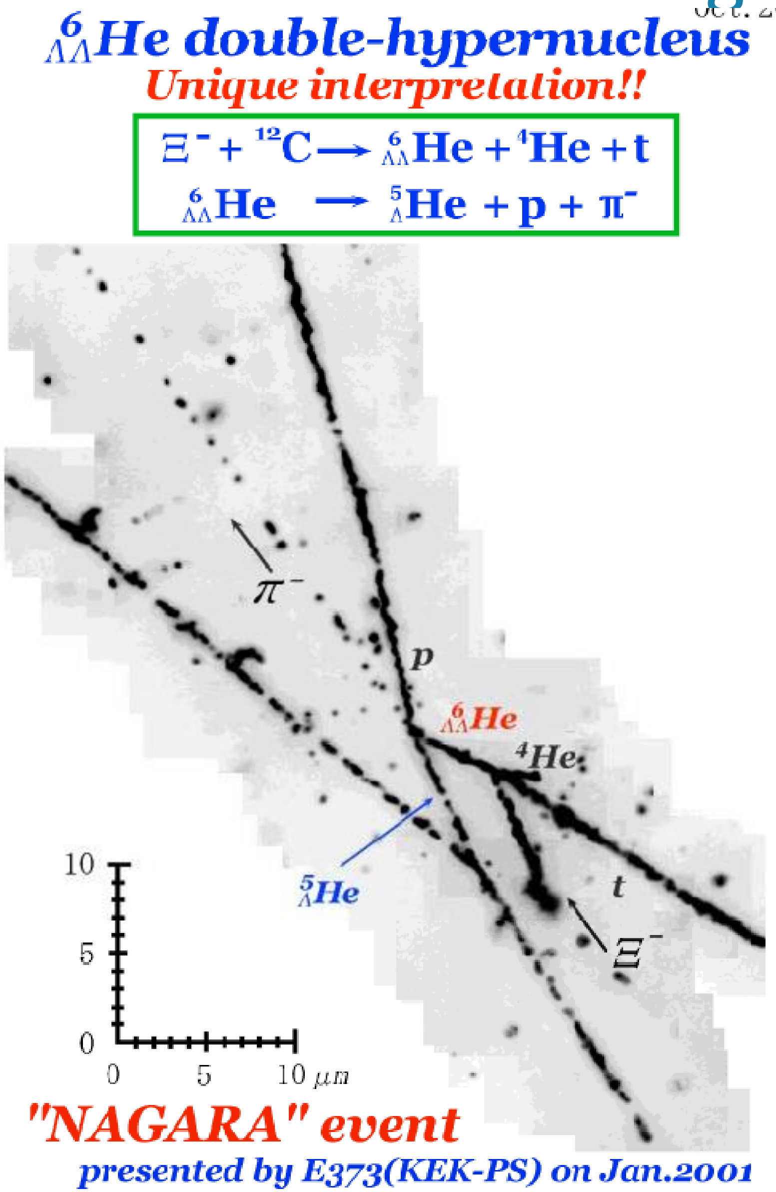
Hyperons binding energy

$$B_{\Lambda\Lambda}\left({}^{A}_{\Lambda\Lambda}Z\right) = B\left({}^{A}_{\Lambda\Lambda}Z\right) - B\left({}^{A-2}Z\right)$$

The interaction energy between two Λ hyperons

$$\Delta B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) = B_{\Lambda\Lambda}({}^{A}_{\Lambda\Lambda}Z) - 2B_{\Lambda}({}^{A-1}_{\Lambda}Z)$$

Double-strangeness hypernuclei



•C(K^-,K^+) reaction to produce Ξ^- then stop it in emulsion
(H. Takahashi et al., PRL87(2001)212502)

•Hyperons binding energy of $^{6}_{\Lambda\Lambda}$He is obtained to be

$B_{\Lambda\Lambda}$ = 6.91±0.17 MeV

• In order to extract $\Lambda\Lambda$ interaction, we take

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda}({}^{5}_{\Lambda}He)$$

=0.67±0.17 MeV

→ weakly attractive

Ahn et al. 2013

Double-strangeness hypernuclei

K. Nakazawa, in HandBook in Nuclear Physics. 2023

Ev. name	Nuclide	Target	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)	Comments
Nagara	${}^{6}_{\Lambda\Lambda}$He	^{12}C	6.91 ± 0.16	0.67 ± 0.17	Uniquely identified
Danysz et al.	${}^{10}_{\Lambda\Lambda}$Be	^{12}C	14.7 ± 0.4	1.3 ± 0.4	${}^{10}_{\Lambda\Lambda}\mathrm{Be} \rightarrow {}^{9}_{\Lambda}\mathrm{Be}^*$ ($Ex. = 3.0$ MeV)
E176	${}^{13}_{\Lambda\Lambda}$B	^{14}N	23.3 ± 0.7	0.6 ± 0.8	${}^{13}_{\Lambda\Lambda}\mathrm{B} \rightarrow {}^{13}_{\Lambda}\mathrm{C}^*$ ($Ex. = 4.9$ MeV)
Demachi-Yanagi	${}^{10}_{\Lambda\Lambda}$Be*	^{12}C	11.90 ± 0.13	-1.52 ± 0.15	Most probable (topology) $Ex. \approx 2.8$ MeV for ${}^{10}_{\Lambda\Lambda}$Be*
Mikage	${}^{6}_{\Lambda\Lambda}$He	^{12}C	10.01 ± 1.71	3.77 ± 1.71	Most probable (mesonic decay)
	${}^{11}_{\Lambda\Lambda}$Be	^{12}C	22.15 ± 2.94	3.95 ± 3.00	
	${}^{11}_{\Lambda\Lambda}$Be	^{14}N	23.05 ± 2.59	4.85 ± 2.63	
Hida	${}^{11}_{\Lambda\Lambda}$Be	^{12}C	20.83 ± 1.27	2.61 ± 1.34	
	${}^{12}_{\Lambda\Lambda}$Be	^{14}N	20.48 ± 1.21	(2.00 ± 1.21)	Assumed 10.24 MeV for $B_{\Lambda}({}^{11}_{\Lambda}\mathrm{Be})$
Mino	${}^{10}_{\Lambda\Lambda}$Be	^{16}O	15.05 ± 0.11	1.63 ± 0.14	
	${}^{11}_{\Lambda\Lambda}$Be	^{16}O	19.07 ± 0.11	1.87 ± 0.37	Most probable (χ^2 minimum)
	${}^{12}_{\Lambda\Lambda}$Be	^{16}O	13.68 ± 0.11	-2.7 ± 1.0	
D001	${}^{8}_{\Lambda\Lambda}$Li	^{12}C	17.50 ± 1.46	6.34 ± 1.46	
	${}^{10}_{\Lambda\Lambda}$Be	^{14}N	15.05 ± 2.78	1.63 ± 2.78	Likely by $B_{\Lambda\Lambda}$

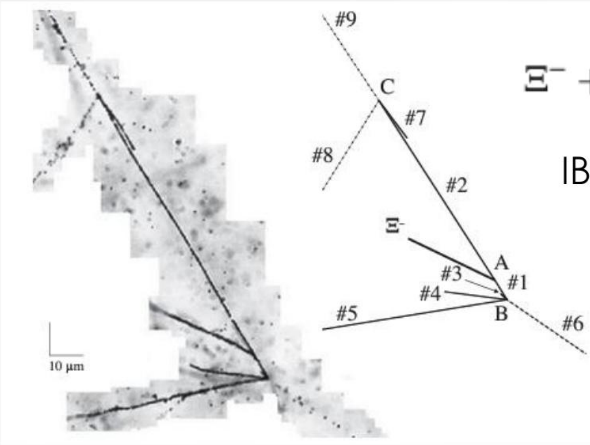
Double-strangeness hypernuclei

Ξ^-–Nuclear Bound States

KEK E373 and **J-PARC E07** experiments

Coulomb-Assisted Ξ^-–^{14}N 1p_Ξ- nuclear bound state

Hayakawa (J-PARC E07), PRL (2021)



$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$$

IBUKI event

Yoshimoto, PTEP (2021)

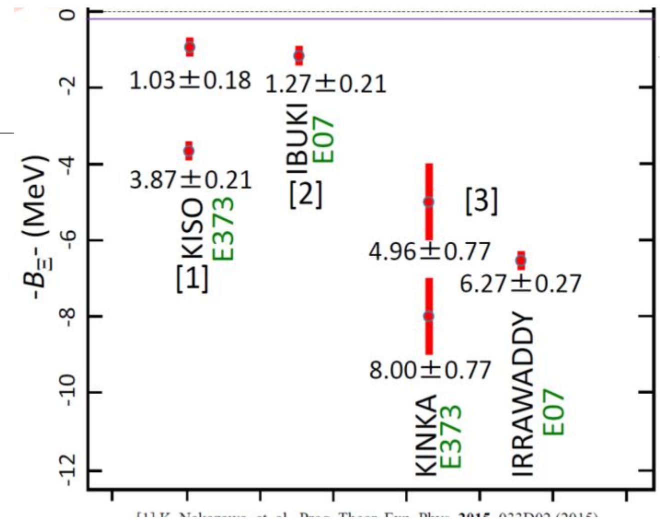
KINKA (E373) $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + n$

IRRAVADDY (E07) $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + {}^{5}_{\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + n$

→ 1s_Ξ- nuclear state

[Nakazawa 2023]

Ξ hypernucleus ($^{15}_{\Xi}$C [Ξ^--^{14}N])



B_Ξ in [Ξ^-–^{12}C] E176 experiment

Cases	10-09-06 ($\chi^2 = 0.4$)	13-11-14 ($\chi^2 = 1.3$)
${}^{4}_{\Lambda}\mathrm{H} + {}^{9}_{\Lambda}\mathrm{Be}$	0.82 ± 0.17	3.89 ± 0.14
${}^{4}_{\Lambda}\mathrm{H}^* + {}^{9}_{\Lambda}\mathrm{Be}$	-0.23 ± 0.17	2.84 ± 0.15
${}^{4}_{\Lambda}\mathrm{H} + {}^{9}_{\Lambda}\mathrm{Be}^*$	–	0.82 ± 0.14
${}^{4}_{\Lambda}\mathrm{H}^* + {}^{9}_{\Lambda}\mathrm{Be}^*$	–	-0.19 ± 0.15

D_Ξ ~ – 14 MeV

Neutron Stars in the Skyrme approach

Skyrme interactions

- **Nucleon-nucleon potential** (Vautherin and Brink, 1972):

$$V_{NN}(\boldsymbol{r_1},\boldsymbol{r_2}) = t_0(1+x_0P_\sigma)\delta(\boldsymbol{r_{12}}) + \frac{1}{2}t_1(1+x_1P_\sigma)\left(\boldsymbol{k}'^2\delta(\boldsymbol{r_{12}}) + \delta(\boldsymbol{r_{12}})\boldsymbol{k}^2\right)$$
$$+t_2(1+x_2P_\sigma)\boldsymbol{k}'\delta(\boldsymbol{r_{12}})\boldsymbol{k} + \frac{1}{6}t_3\rho^\alpha(\boldsymbol{R})(1+x_3P_\sigma)\delta(\boldsymbol{r_{12}}) + iW(\sigma_1+\sigma_2)[\boldsymbol{k}'\times\delta(\boldsymbol{r})\boldsymbol{k}]$$

More than 300 parameterizations

- Hyperon-nucleon potential (Rayet, 1981):

$$V_{YN}(\boldsymbol{r_Y},\boldsymbol{r_q}) = t_0^{\mathrm{Y}}(1+x_0^{\mathrm{Y}}P_\sigma)\delta(\boldsymbol{r_{Yq}}) + \frac{1}{2}t_1^{\mathrm{Y}}\left(\boldsymbol{k}^2\delta(\boldsymbol{r_{Yq}}) + \delta(\boldsymbol{r_{Yq}})\boldsymbol{k}'^2\right)$$
$$+t_2^{\mathrm{Y}}\boldsymbol{k}'\delta(\boldsymbol{r_{Yq}})\boldsymbol{k} + \frac{3}{8}t_3^{\mathrm{Y}}\rho^\gamma(\boldsymbol{R})\delta(\boldsymbol{r_{Yq}})$$

ΛN - ~ 20 parameterizations
ΞN – SL3x (Sun et al 2016)
– GZSx (Guo et al 2021)

- ΛΛ- interaction:

$$V_{\Lambda\Lambda}(\boldsymbol{r_1},\boldsymbol{r_2}) = \lambda_0\delta(\boldsymbol{r_{12}}) + \frac{1}{2}\lambda_1\left(\boldsymbol{k}'^2\delta(\boldsymbol{r_{12}}) + \delta(\boldsymbol{r_{12}})\boldsymbol{k}^2\right) +$$
$$+\lambda_2\boldsymbol{k}'\delta(\boldsymbol{r_{12}})\boldsymbol{k}$$

ΛΛ: SΛΛ1’, SΛΛ2, SΛΛ3’
(Lanskoy, 1998,
Minato and Hagino, 2011)

Nuclear matter in neutron stars

Nuclear matter

Energy per nucleon $\varepsilon = E(Y_p, \rho)/A$

Saturation density $\rho_0 = 0.17 \pm 0.03 \text{ fm}^{-3}$

Symmetric nuclear matter SNM energy per nucleon E_0

$E_0 \sim -16$ MeV

$$E_0 = \left.\frac{E_{SNM}}{A}\right|_{\rho=\rho_0}$$

Nuclear symmetry energy $a_S = S(\rho = \rho_0)$, $Y_p = Z/A$

$a_S = 30–35$ MeV

$$S = \frac{1}{8}\left(\frac{\partial^2 \varepsilon}{\partial Y_p^2}\right)_{N=Z}$$

Symmetry energy first derivative L

$$L = 3\rho_0 \left(\frac{\partial S}{\partial \rho}\right)_{\rho=\rho_0}$$

Symmetry energy second derivative K_{sym}

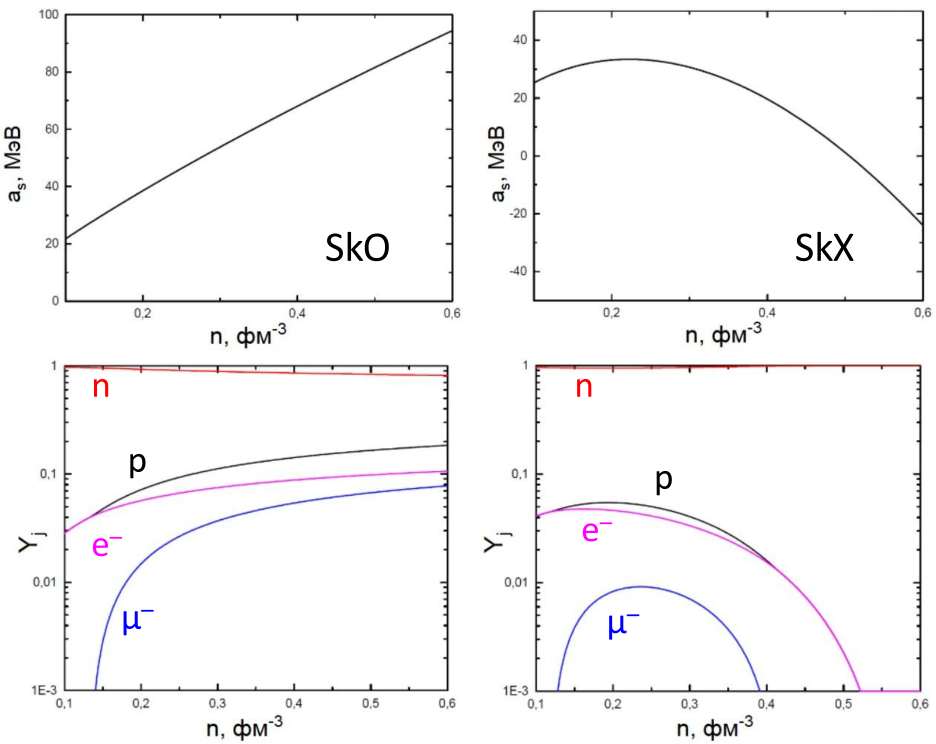
$$K_{sym} = 9\rho_0^2 \left(\frac{\partial^2 S}{\partial \rho^2}\right)_{\rho=\rho_0}$$

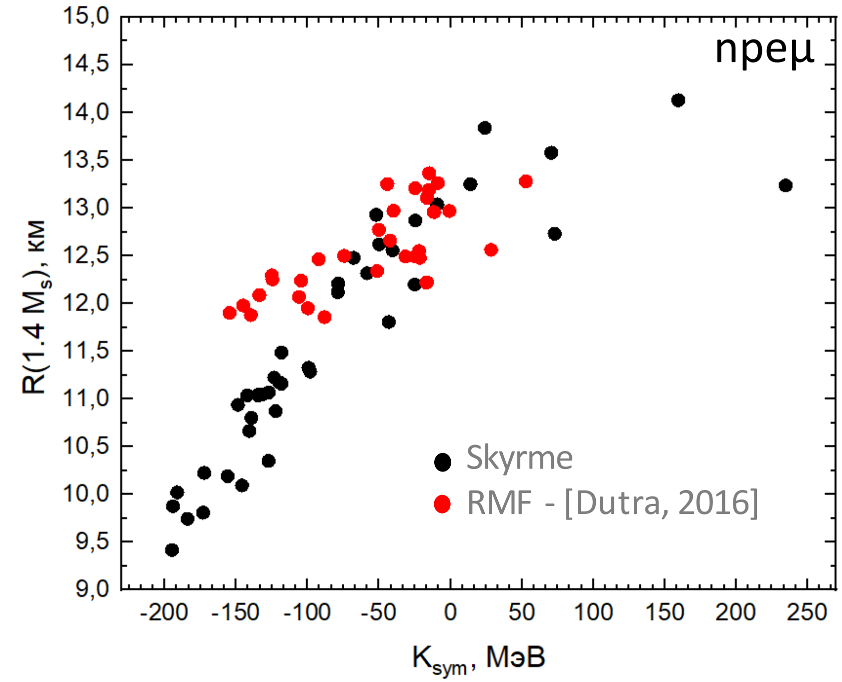
Incompressibility K_{inf}

$$K_{inf} = 9\rho_0^2 \left(\frac{\partial^2 E_{SNM}}{\partial \rho^2}\right)_{\rho=\rho_0}$$

Hadronic matter in neutron stars

Nuclear symmetry energy





The strongest correlations are observed between the characteristics of neutron stars and the properties of matter that depend on isospin asymmetry (**L** and $\mathbf{K_{sym}}$). Significantly smaller correlations for incompressibility $\mathbf{K_{Inf}}$.

Tidal deformability

Coefficient of tidal deformability λ --- proportionality coefficient between the external gravitational field and the quadrupole moment of the star:

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

It is more convenient to describe tidal deformations using a dimensionless coefficient:

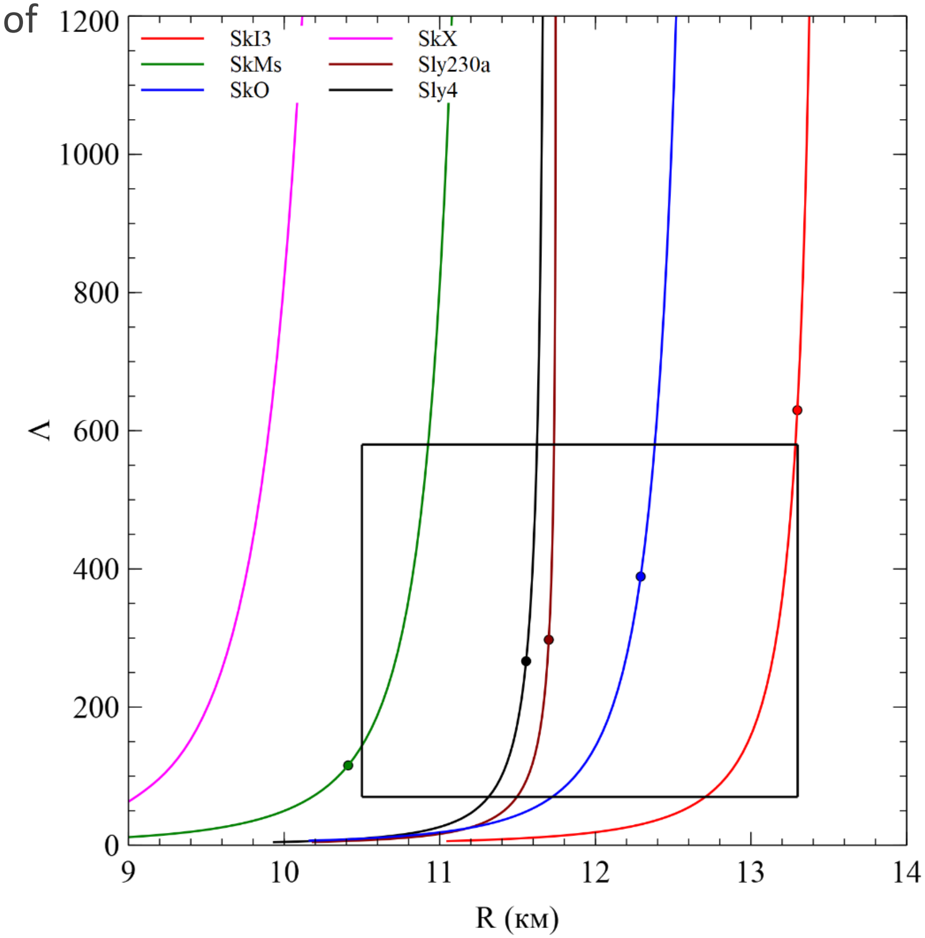
$$\Lambda = \frac{\lambda}{M^5}$$

GW170817

$$m_1 = 1.4\mathrm{M}_\odot \rightarrow \Lambda = 70 - 580$$
$$R = 10.5 - 13.3 \text{ км } [1,2,3]$$

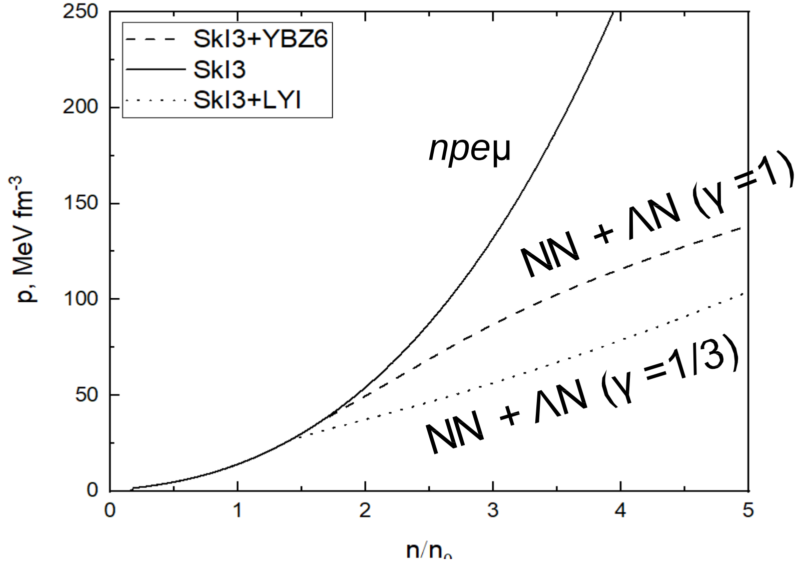
[1] Abbott et al. (LIGO Sci. and Virgo Coll.), PRL 2017
[2] Abbott et al. (LIGO Sci. and Virgo Coll.), PRL 2018
[3] Abbott et al. (LIGO Sci. and Virgo Coll.), PRX 2019

npeμ

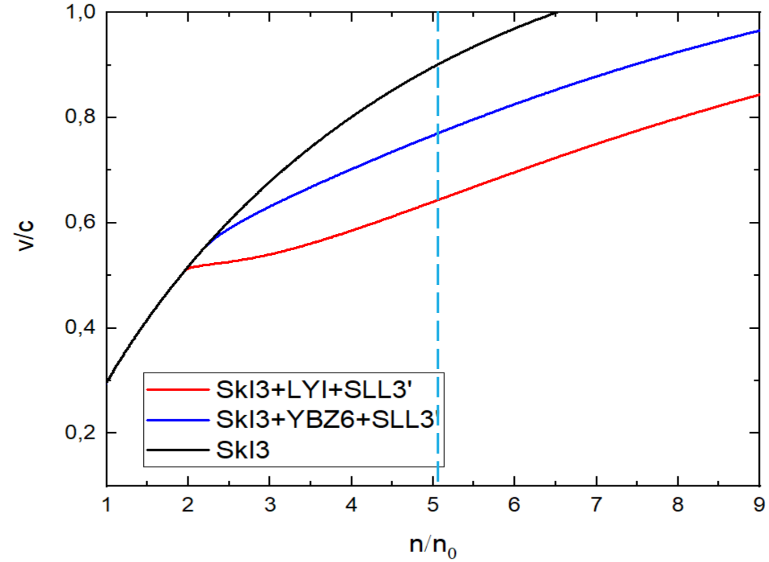


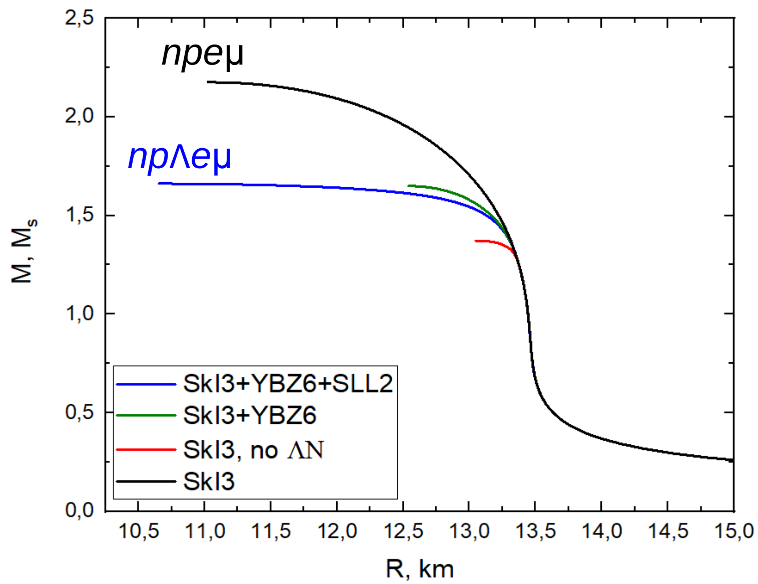
Hyperon puzzle

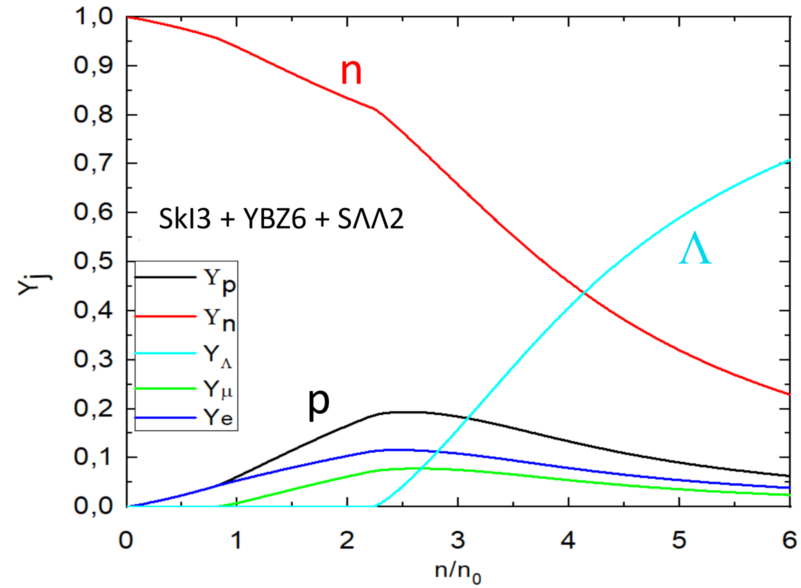
Equation of state EoS



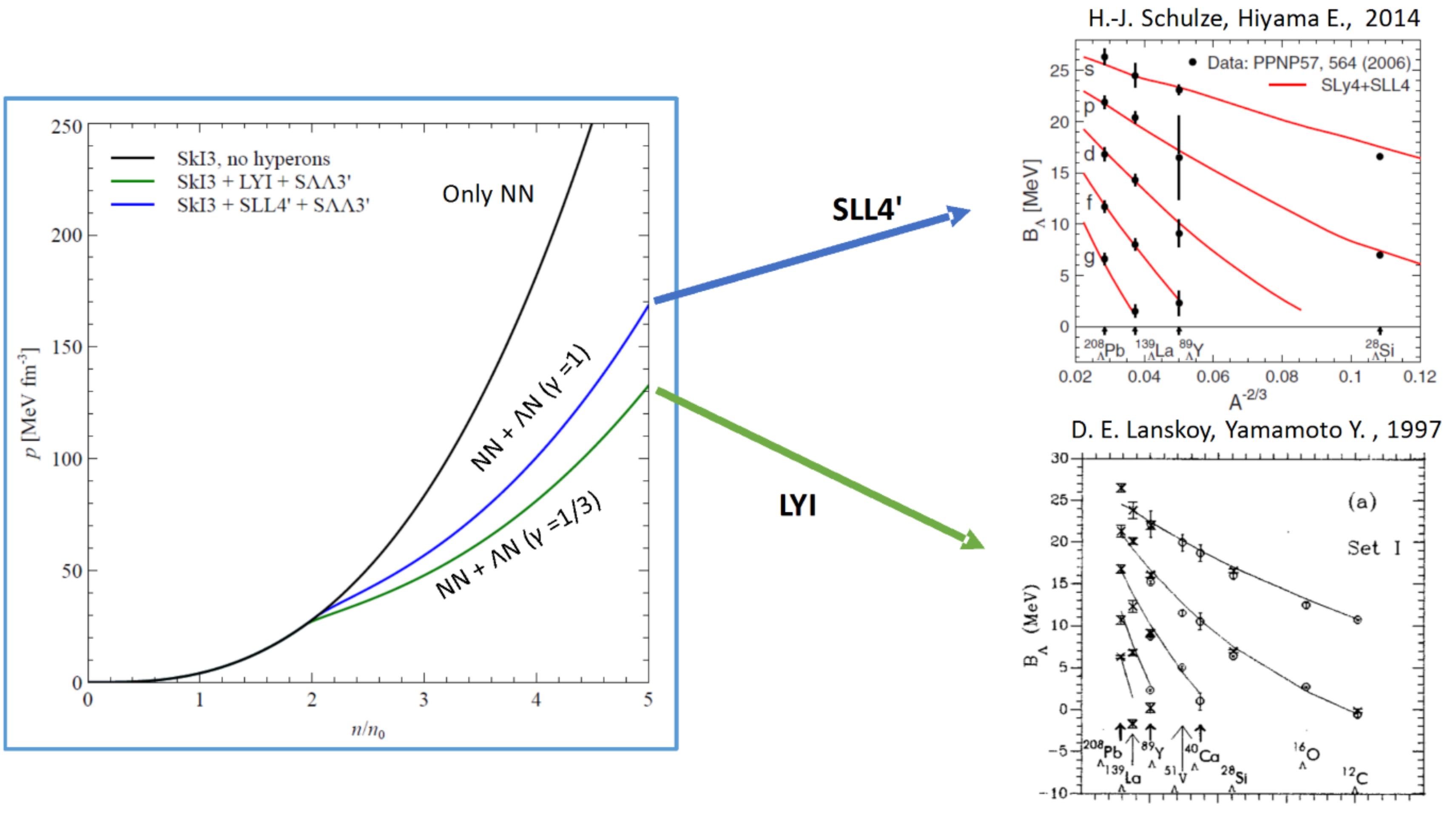
Speed of sound







Hyperon puzzle



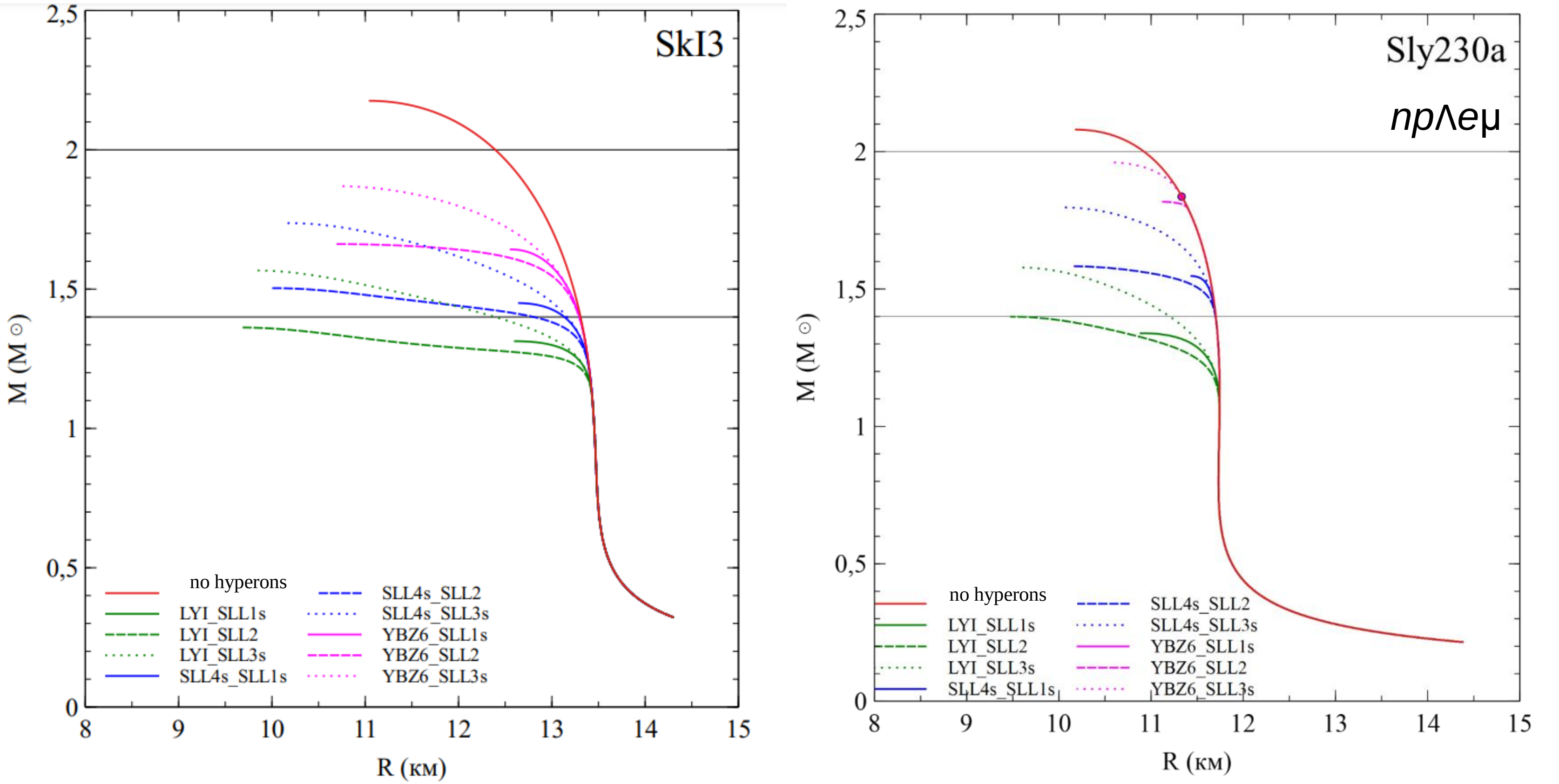
Density dependent term in ΛN-interaction

$$V_{\Lambda N}(\rho_N) = \frac{3}{8} t_3^{\Lambda} \rho^{\gamma}(R) \delta(r_{\Lambda q})$$

S. Mikheev (Thu 3/07 16-20)

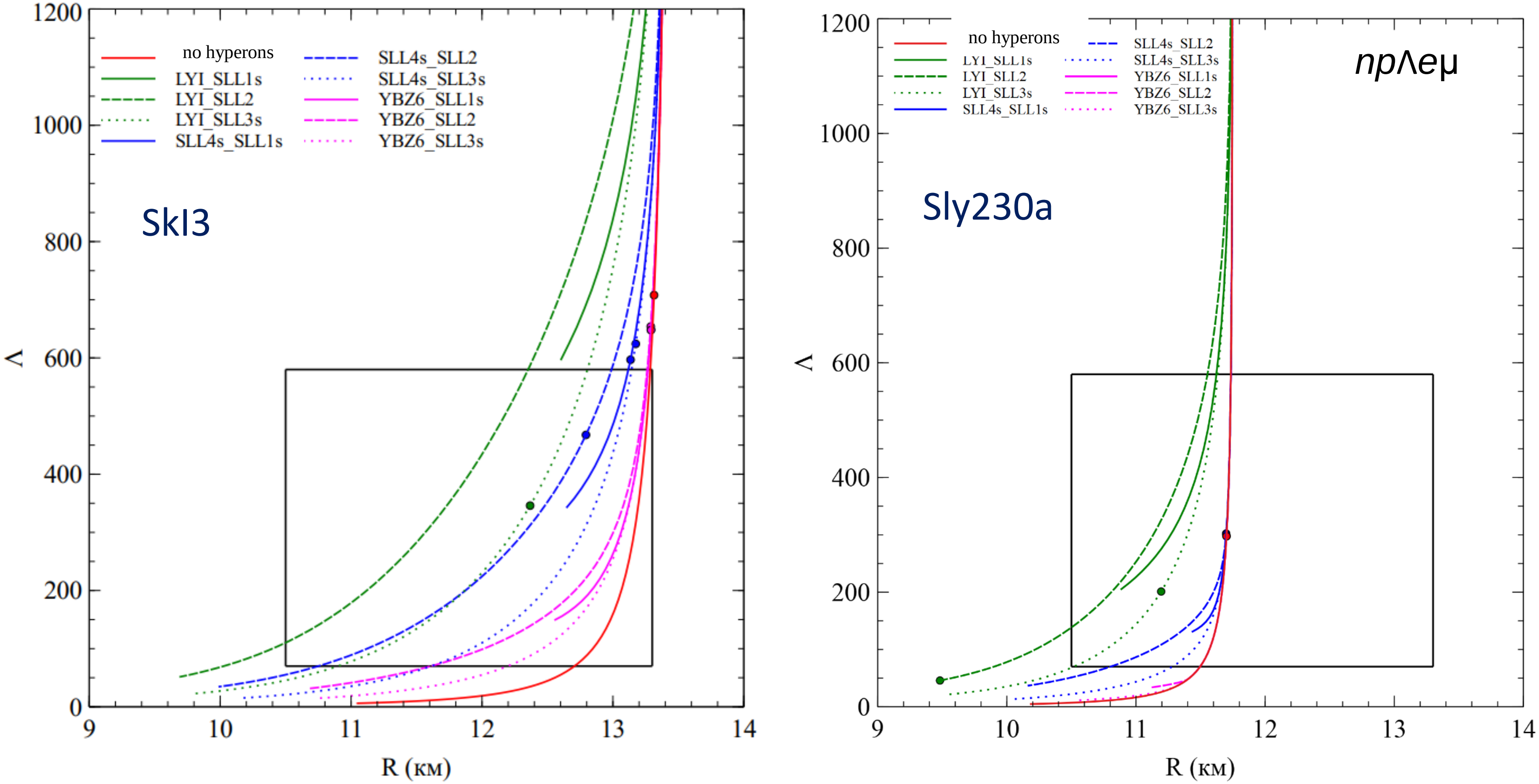
Hadronic matter in neutron stars

NS characteristics
for different Skyrme ΛN and ΛΛ parametrizations



Hadronic matter in neutron stars

Dependence of tidal deformability on the radius of a star for matter including Λ-hyperons



Dots and limits are for $M = 1.4M_S$

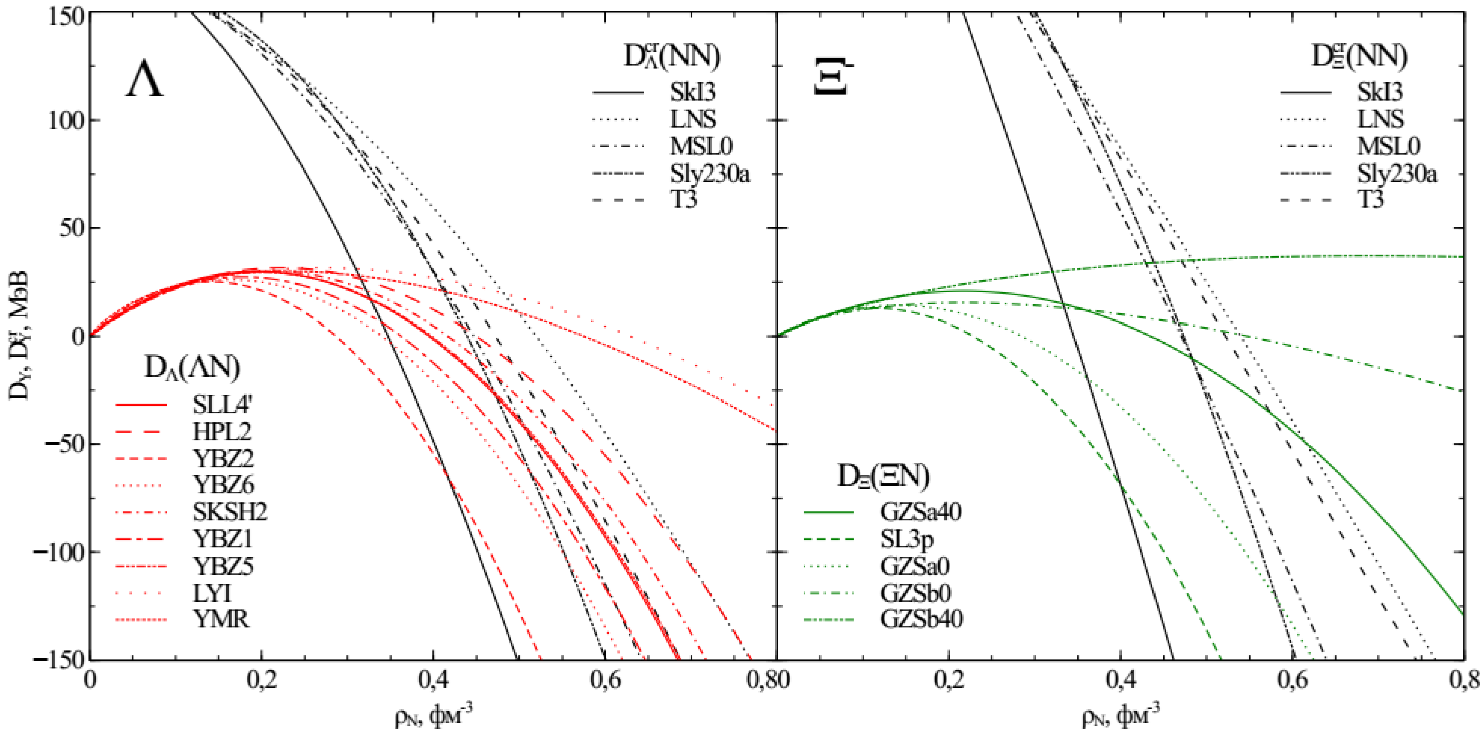
Hyperon appearance in baryonic matter

Hyperon binding energy in nucleonic matter: $D_Y \equiv -\mu_Y$

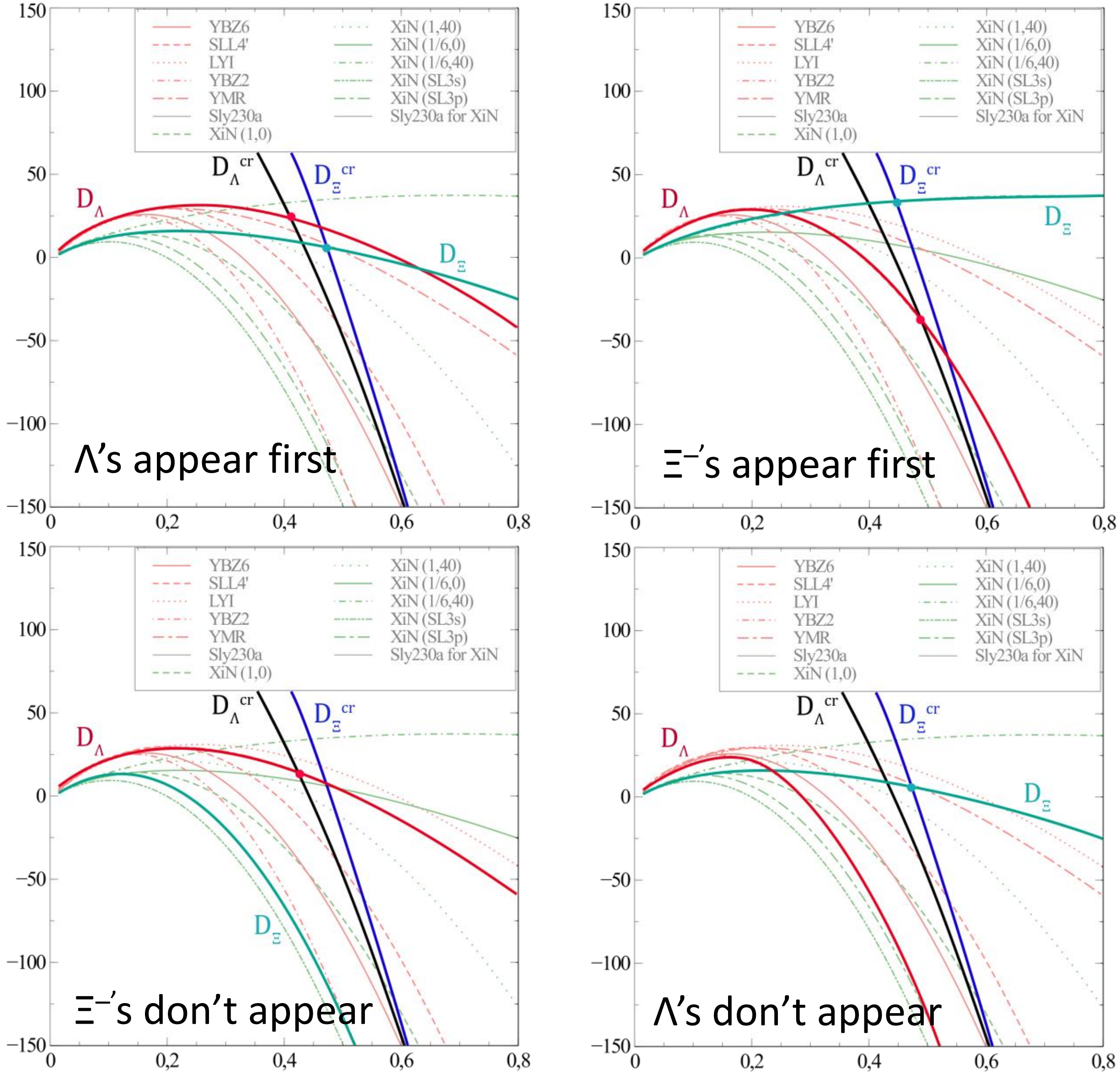
Critical energy of hyperon in baryonic matter: $D_\Lambda^{cr} = m_\Lambda - m_n - \mu_n$

$$D_{\Xi^-}^{cr} = m_{\Xi^-} + m_p + \mu_p - 2m_n - 2\mu_n$$

Condition of hyperon appearance: $D_Y = D_Y^{cr}$



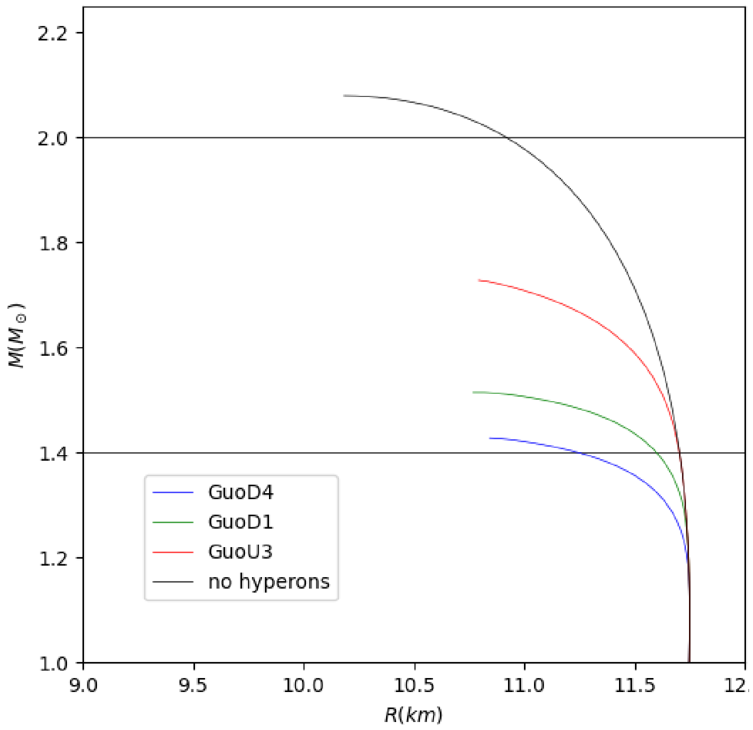
Hyperon appearance in baryonic matter

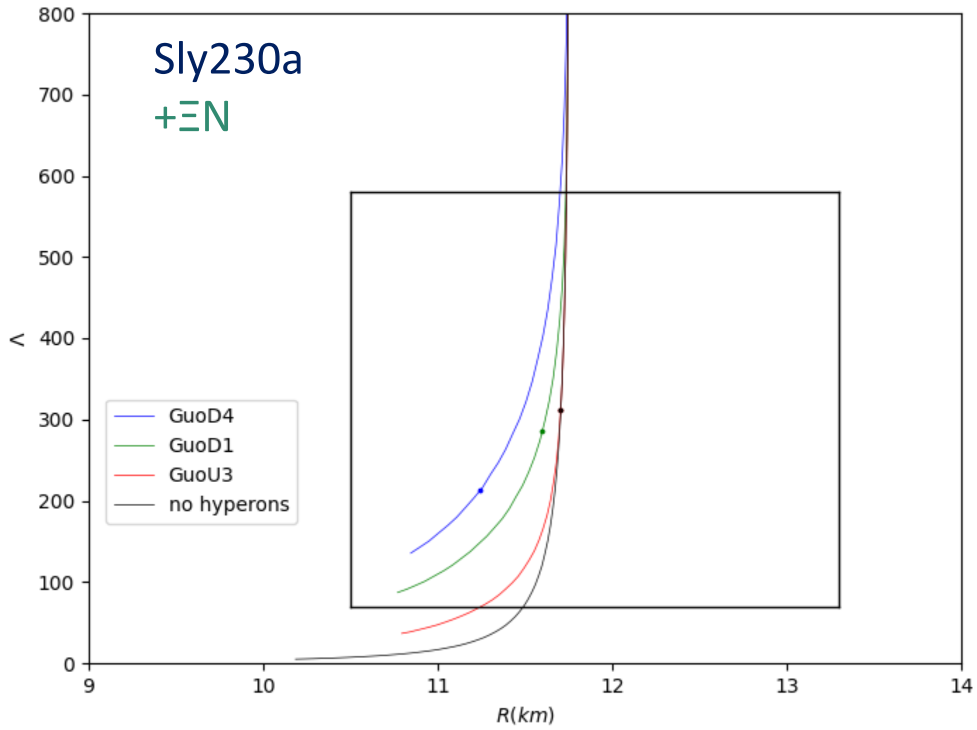


Hadron matter in neutron stars

NS characteristics
for different Skyrme ΞN parametrizations

$np\Xi^- e\mu$

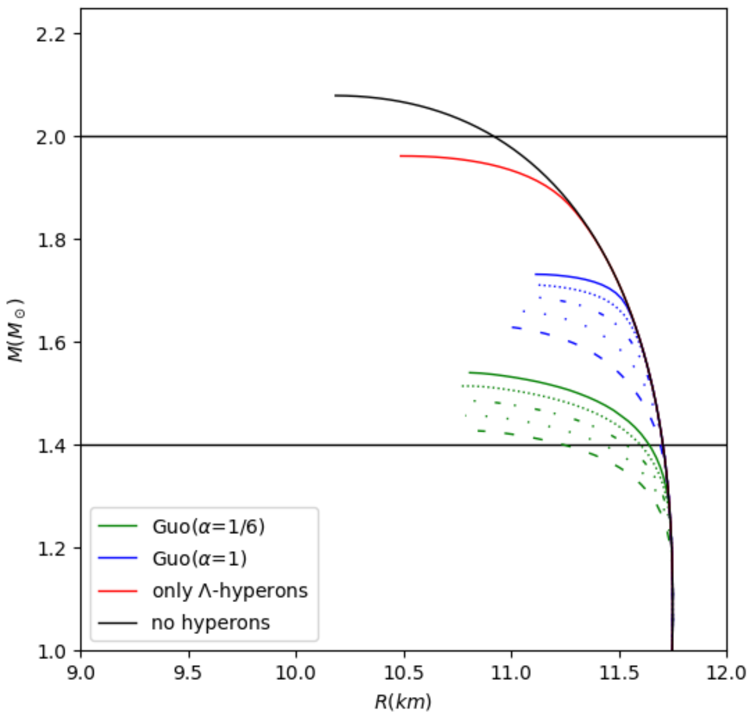


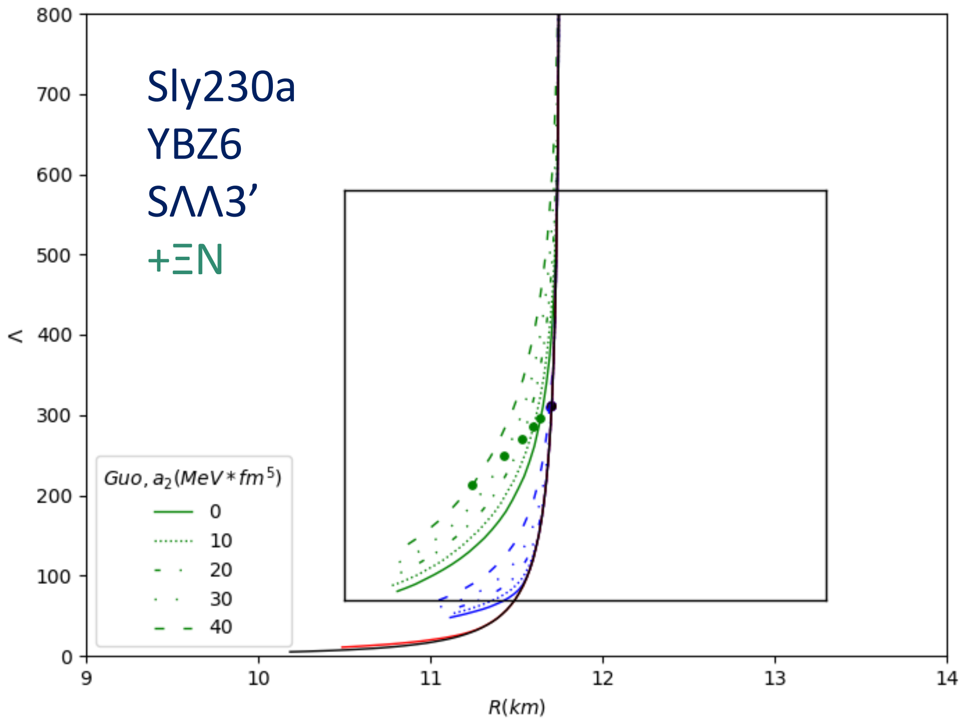


Hadron matter in neutron stars

NS characteristics
for different Skyrme ΞN parametrizations

npΛΞ⁻eμ





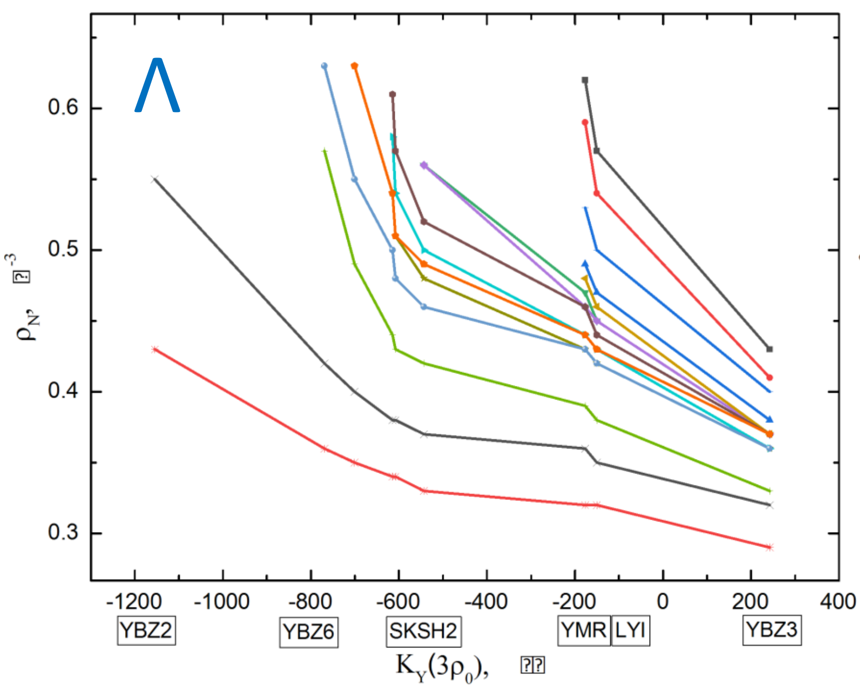
Hyperon appearance in baryonic matter

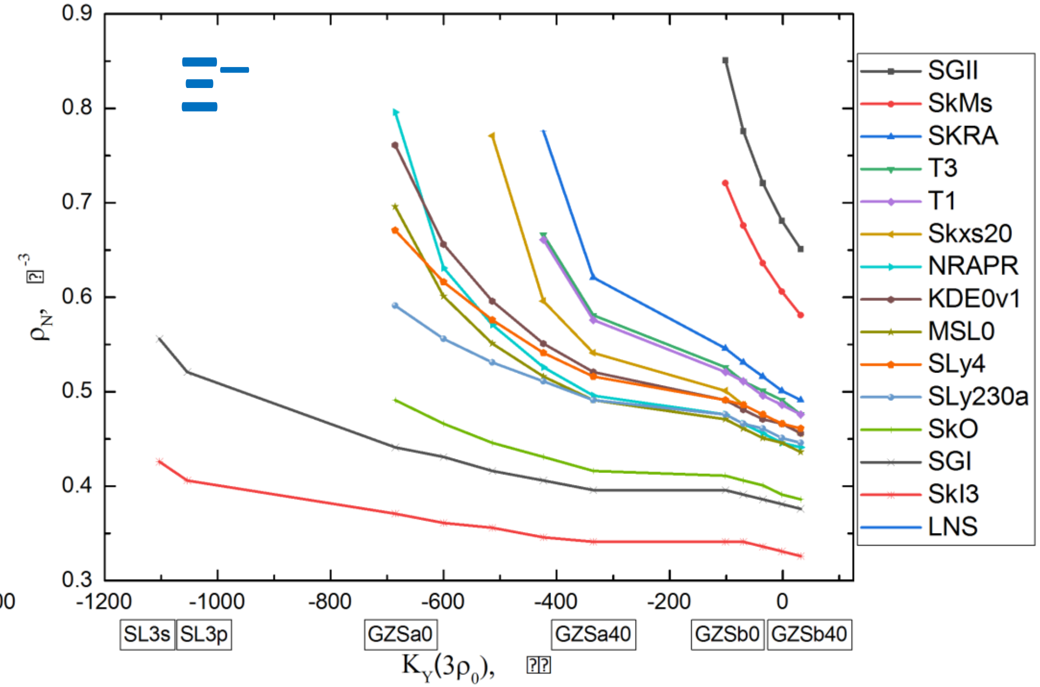
Hypernuclear interaction contracting power K_Y

[Lanskoy, Tretyakova 1989]

$$K_Y(\rho_N) = 3\rho_N \frac{dD_Y}{d\rho_N}$$

Density at the hyperon appearance point versus contracting power of hypernuclear interaction





Hadronic matter in neutron stars

Correlations between NS and baryonic interaction characteristics

Pearson correlation coefficients

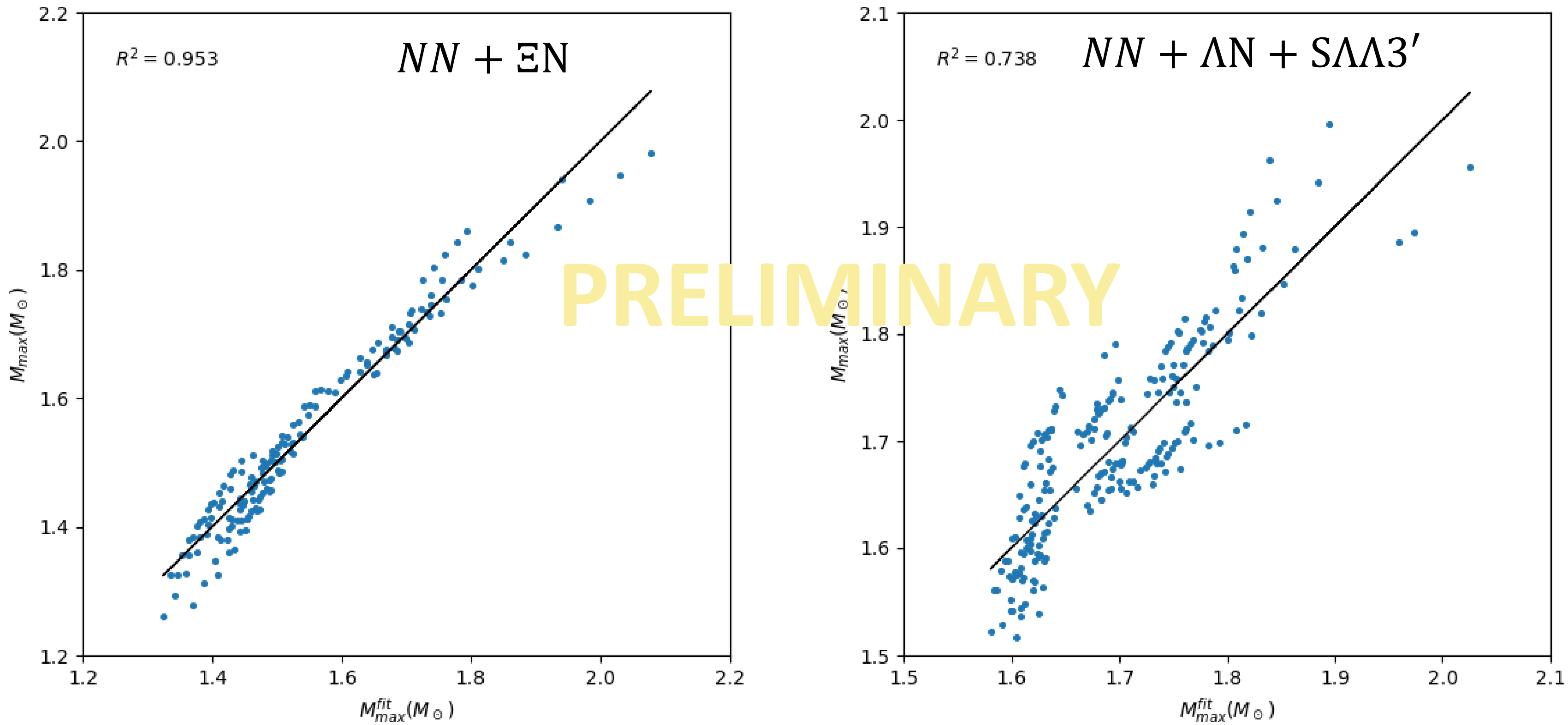
Хар-ка NN	M_{max}		R_{min}		$\Lambda_{1.4}$		$R_{1.4}$	
	no h	Λ	no h	Λ	no h	Λ	no h	Λ
$S(n_0)$	0.16	0.08	0.26	0.15	0.27	0.14	0.29	0.20
$S(3n_0)$	0.59	0.19	0.76	0.56	0.86	0.74	0.82	0.76
$L(n_0)$	0.40	0.07	0.63	0.45	0.77	0.63	0.73	0.65
$L(3n_0)$	0.68	0.24	0.82	0.61	0.90	0.80	0.86	0.80
$K_{sym}(n_0)$	0.67	0.21	0.83	0.62	0.93	0.83	0.87	0.82
$K_{sym}(3n_0)$	0.77	0.34	0.82	0.63	0.84	0.78	0.80	0.77

Хар-ка ΛN	M_{max}	R_{min}	$\Lambda_{1.4}$	$R_{1.4}$
$K_\Lambda(n_0)$	-0.88	-0.89	-0.75	-0.74
$K_\Lambda(2n_0)$	-0.91	-0.91	-0.82	-0.78
$K_\Lambda(3n_0)$	-0.90	-0.90	-0.83	-0.77

Hadronic matter in neutron stars

Correlations between NS and baryonic interaction characteristics

$$M_{\max}^{fit} = aK_0 + bL + cK_Y + d$$



Conclusions

- Hypernuclei remain the main source of information on hyperonic interactions (but: density is close to nuclear one, nuclear cores are near valley of stability). Neutron stars are the additional check-point for hypernuclear interactions features.
- Information on ΛΛ, ΞN and ΣN interactions is very much needed – we are waiting for data on the corresponding hypernuclei.
- Determination of the maximum mass of a neutron star and estimation of tidal deformability place new constraints on the properties of baryon interactions.
- The factors influencing the appearance of Λ and Ξ hyperons in the matter of neutron stars are considered and it is shown that the most important characteristic of YN forces is its contracting power. Various scenarios for the appearance of hyperons in the matter of neutron stars are shown.

THANK YOU FOR YOUR ATTENTION!

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Back-up

Λ-hypernuclei

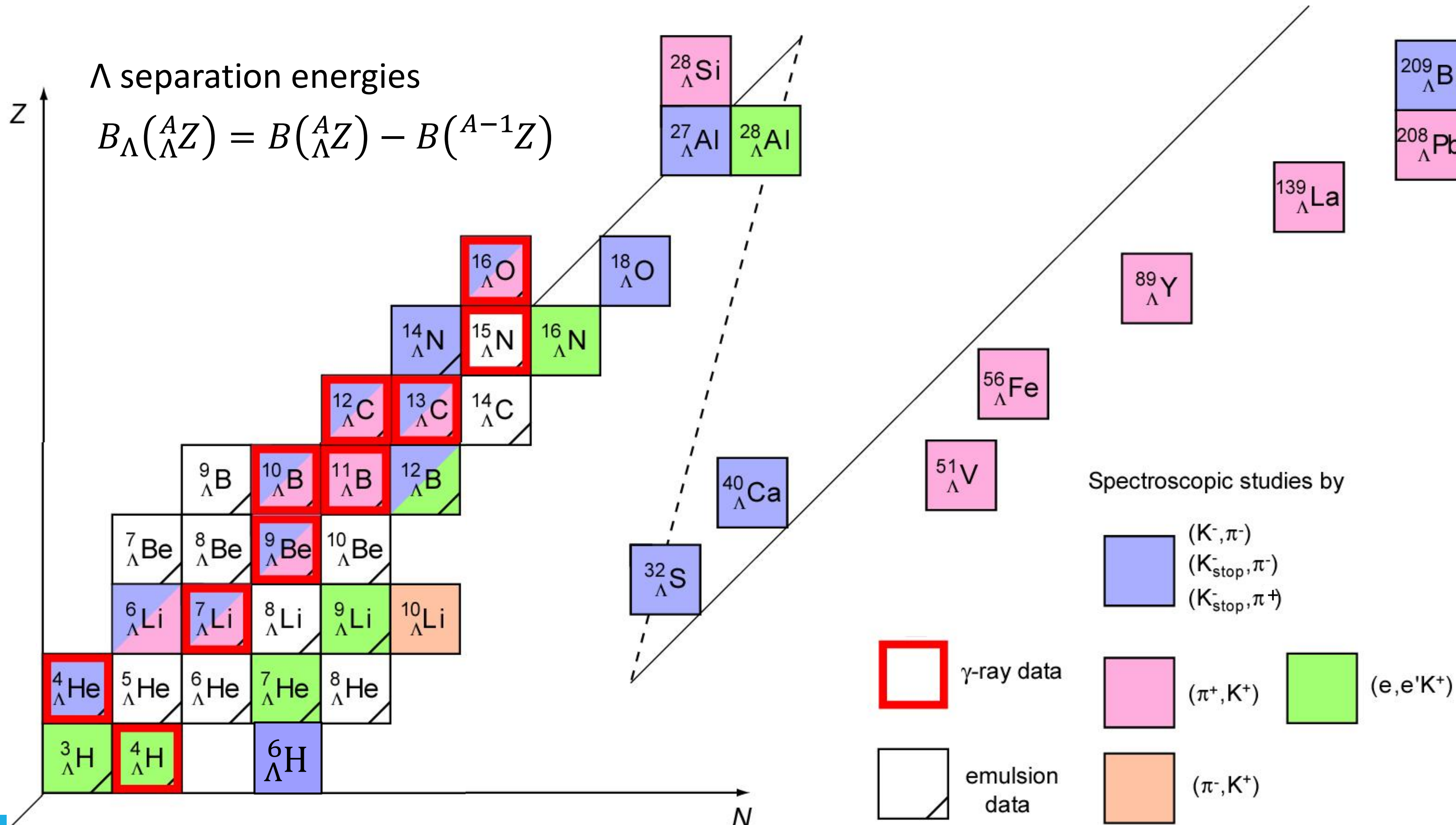
Tamura 2012

<= Few-body / Cluster models

Mean-field models =>

Λ separation energies

$$B_\Lambda({}^A_\Lambda Z) = B({}^A_\Lambda Z) - B({}^{A-1}Z)$$



Updated from: O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. 57 (2006) 564.

Барионная материя в нейтронных звездах

Полная энергия и плотность энергии

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

Энергия на нуклон $\varepsilon(Y_p, n) = \frac{E}{A} = \frac{H}{n}$:

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

Химическое равновесие

$$\nu_\ell + n \rightleftarrows p + \ell^-,$$

$$\bar{\nu}_\ell + p \rightleftarrows n + \ell^+,$$

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

$$\mu_i = \frac{\partial H}{\partial n_i} \qquad i = n,p,\Lambda$$

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

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

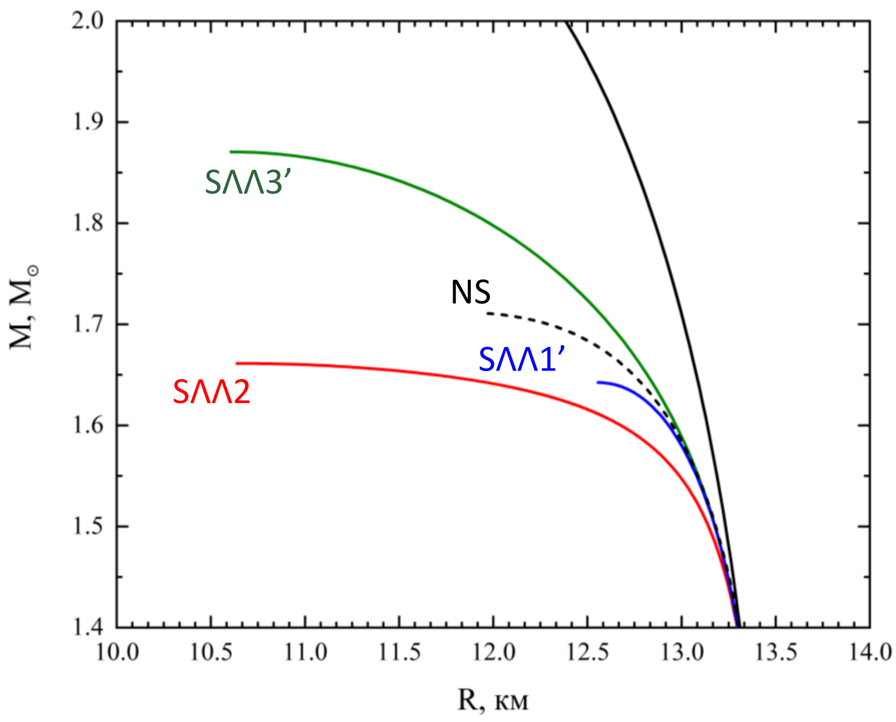
$$\mu_\mu = \sqrt{{m_\mu}^2 + (3\pi^2 Y_\mu n)^{2/3}}$$

ΛΛ – взаимодействие

SΛΛ1’, SΛΛ2, SΛΛ3’
(без зависимости от плотности)

ΛΛ	Радиус взаимодействия
SΛΛ1'	Малый
SΛΛ2	Средний
SΛΛ3'	Большой

NS
(зависимость от плотности)
(Lanskoy, Yamamoto 1997,
Михеев и др. 2025)



Михеев