Microscopic Equation of State: From In-Medium Hyperon Potentials to Neutron Star Matter

Mahboubeh Shahrbaf

Institute of Theoretical Physics, University of Wrocław
Visiting Researcher, FBSP Laboratory, RIKEN

NFQCD2026, YITP, Kyoto

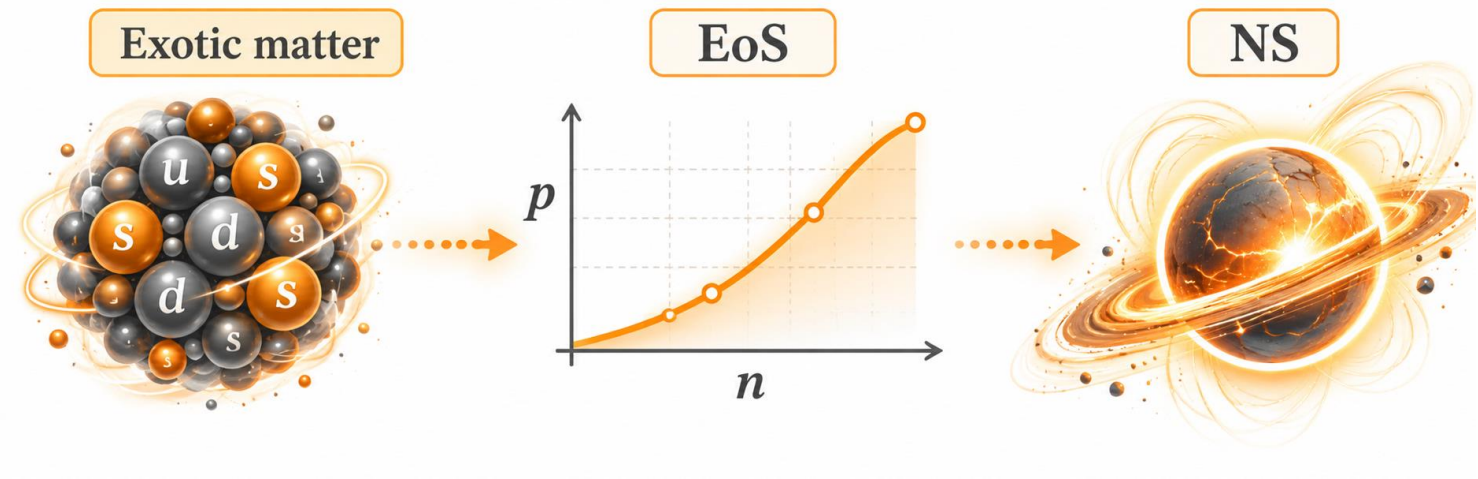
Third week: YKIS Symposium

29 October 2026

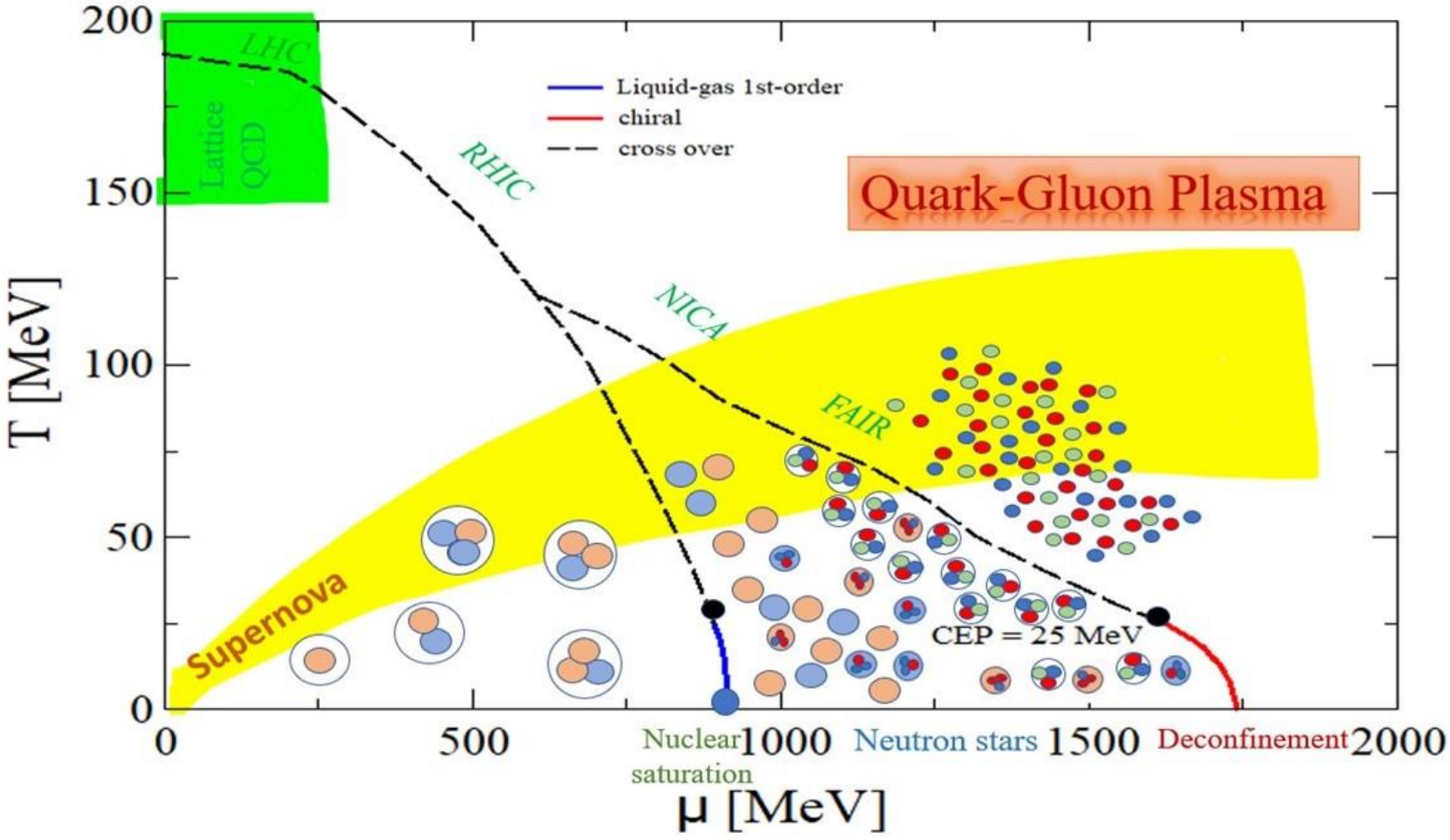
SONATINA 7, Grant No.2023/48/C/ST2/00297

Key Questions

- What is the equation of state (EoS) of dense matter?
- Can exotic forms of strange matter exist beyond conventional nuclear matter?
- Why are neutron stars (NSs) natural laboratories for dense matter physics?



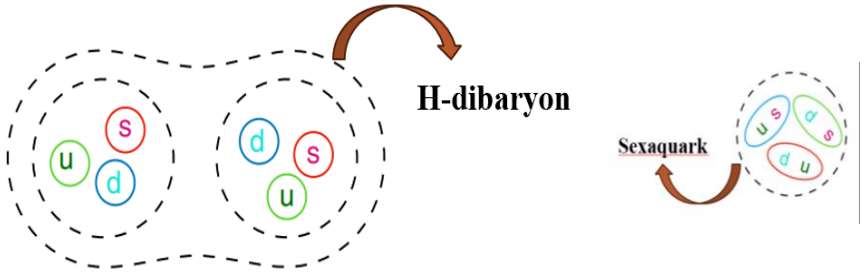
QCD phase diagram of strongly interacting matter
(within parity doublet model)



M. Shahrbaf, [arXiv:2303.03030 [nucl-th]]

Forms of strangeness-bearing matter considered in EoS

- Hyperonic matter
- Kaon-condensed matter
- Strange quark matter
- Color-superconducting strange quark matter (color-flavor-locked (CFL) matter)
- Hyperonic superfluids and paired hyperon phases
- H-dibaryon and Sexaquark



- Strangeon matter (spatially localized multiquark clusters)

Research Overview: Strangeness in Dense Matter

- Hyperonic matter

M. S. and H. R. Moshfegh, Annals Phys. **402**, 66-77 (2019)

M. S., H. R. Moshfegh and M. Modarres, Phys. Rev. C **100**, no.4, 044314 (2019)

A. M. A. Looee, **M. S.** and H. R. Moshfegh, Astrophys. J. **997**, no.1, 26 (2026)

M. S., [arXiv:2609.00851 [nucl-th]] ⟷ The results presented in this talk are based on the EOS derived in this work.

- Color-superconducting strange quark matter (color-flavor-locked (CFL) matter)

Work in preparation: Hyperonic Effects on the Oscillation Signatures of Hybrid Neutron Stars

- H-dibaryon and Sexaquark

M. S., D. Blaschke, S. Typel, G. R. Farrar and D. E. Alvarez-Castillo, Phys. Rev. D **105**, no.10, 103005 (2022)

M. S., J. Phys. Conf. Ser. **2536**, no.1, 012001 (2023)

M. S., D. R. Karkevandi, A. Ayriyan and S. Typel, Astron. Astrophys. **706**, A203 (2026)

M. S., P. Thakur and D. Rafiei Karkevandi, JCAP **03**, 017 (2026)

M. S. and Makoto Oka, [arXiv:2609.17117 [nucl-th]]

The Main Goals of Hypernuclear Physics

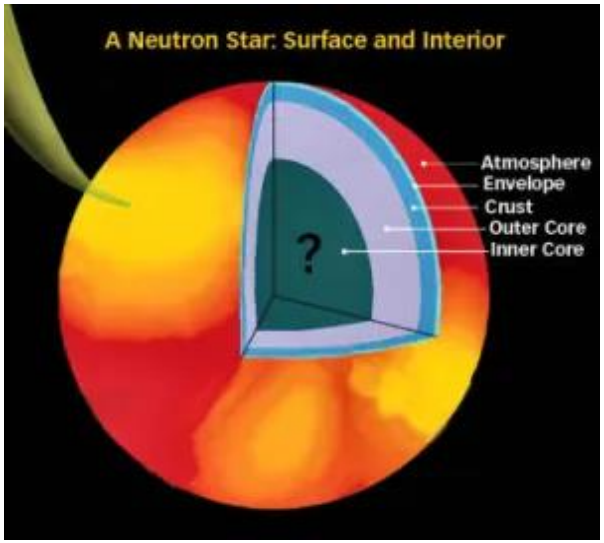
➢ Understanding baryon-baryon interactions

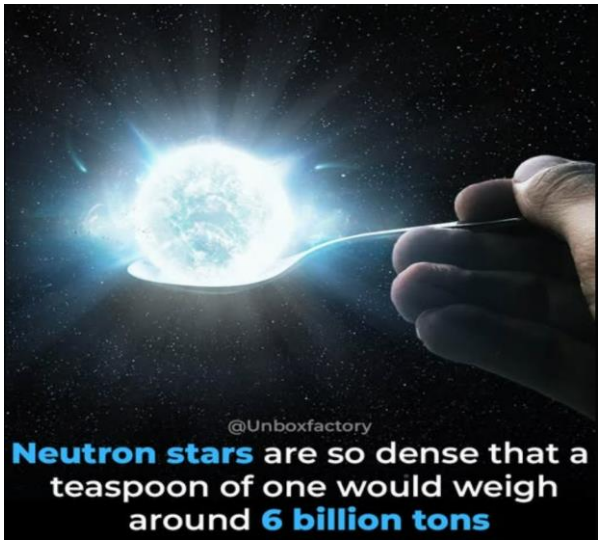
- Total number of N-N scattering data **> 5000 (precise)**
- Total number of differential cross section Y-N data: **about 200 (with large error bars)** Including J-PARC E40 for $\Sigma^{\mp}p$ scattering
- **No direct** Y-Y scattering data

NY and YY potential so far proposed (e.g. Nijmegen and Julich, HAL) have significant ambiguity.

$U_{\Lambda} \approx -28\ MeV$ (Friedman, E., & Gal, A. 2025a)
$U_{\Xi} \approx -21\ MeV$ (Friedman, E., & Gal, A. 2025b)
$U_{\Sigma} \approx +30 \pm 20\ MeV$ (Jinno, A., Murase, K., & Nara, Y. 2025)

Neutron Stars: Natural Laboratories for Dense Matter





NSs: $M \sim 2M_{\odot}$, $R \sim 12$ km

$n \sim (4-8)n_0 \sim (4-8) \times 10^{17} \frac{kg}{m^3}$

$n_0 = 0.16 \frac{1}{fm^3}$

Density in HADES:

$n \sim (2-3)n_0$ for $10^{-23}s$

Composition of the core:

- Nucleons and leptons
- Hyperons?
- Deltas?
- Hexaquark ($d^*(2380)$) (uuuddd)?
- Sexaquark (uuddss)?
- kaon/pion condensates?
- Quarkyonic Matter?
- Deconfined quark matter?
- Dark matter? …

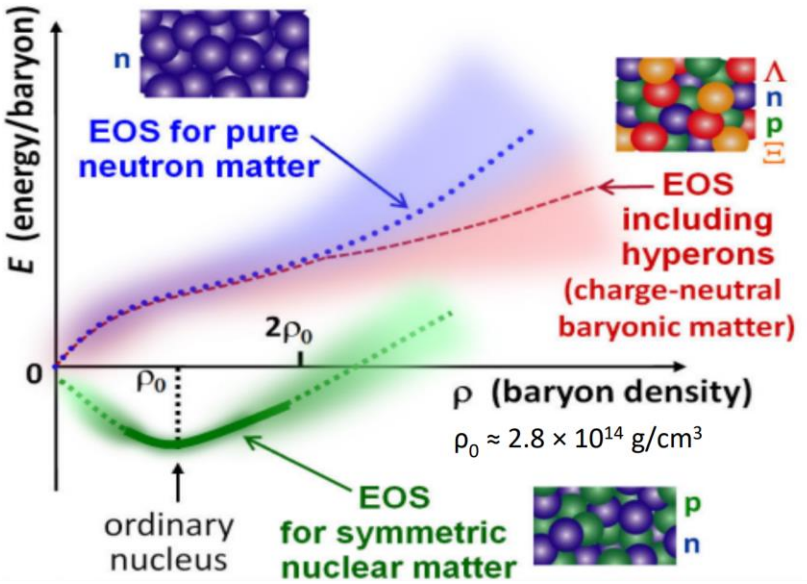
Hyperons in NSs first suggested by Ambartsumyan & Saakyan (1960)

The Most Robust Observational Inputs for the EOS

- Maximum mass of pulsars
- NICER mass-radius measurements
- Gravitational waves detected by LIGO-VIRGO-KAGRA

  mass-radius

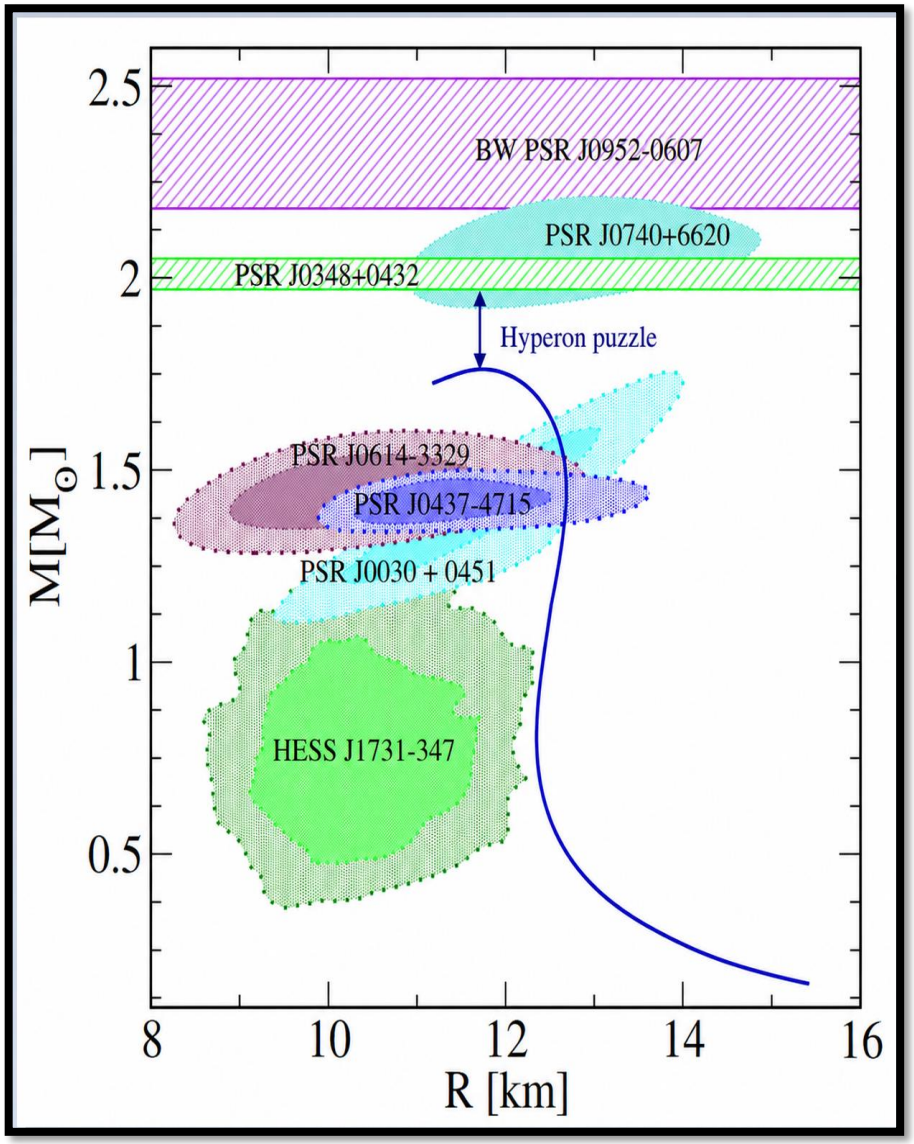
  Tidal Deformability
- Cooling and thermal evolution



➢ **The most important check with hyperons** H.Tamura, JPS Conf. Proc. , 011003 (2014)

Including hyperon ⟶ Softening the EOS ⟶ $M_{max} < 2M_{\odot}$

Hyperon Puzzle



Solutions:

- Changing the composition of the matter: quark matter or parity doublets

G. Baym et al. Rept. Prog. Phys. 81 no.5, (2018)
B. Gao, Phys. Rev. D, 113 no.8, (2026)
M.S. et al. *Phys.Rev.C* 101 no.2, (2020)
M.S. et al. *J.Phys.G* 47 no.11 (2020)
M.S. et al., *Phys.Rev.D* 105 no. 10 (2022)

- Additional repulsive effects in the EOS (e.g., ΛΛ interaction, three-body forces or any kind of universal many-body repulsions)

I. Vidana et al. 2011,
Y. Yamamoto et al. 2014,
H. Togashi et al. 2016,
H. Tong et al. 2025c
A. M. A. Looee, **M.S.** et al. 2026

- Modified gravity frameworks

A. V. Astashenok et al. 2014

Lowest Order Constrained Variational (LOCV) method

Pandharipande & Bethe, 1973; Modarres & Irvine, 1979

- Variational many-body approach with correlated wavefunctions:

$$\Psi(1 \ldots A) = F(1 \ldots A)\Phi(1 \ldots A); \qquad F = S\prod_{i>j} f(ij)$$

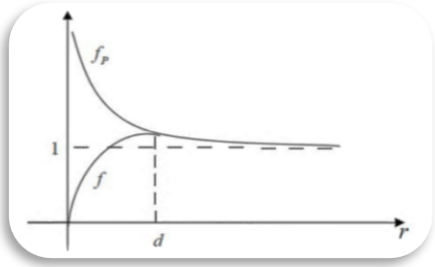
- Two-body cluster truncation:

$$E = \langle H \rangle = \frac{1}{N}\frac{\langle \Psi|H|\Psi\rangle}{\langle \Psi|\Psi\rangle} = E_1 + E_{MB} \cong E_1 + E_2$$

- Correlation function F optimized via Euler–Lagrange equations

$$\langle \Psi\,|\Psi\,\rangle = 1 - \sum_{ij}\langle ij\left|F_p^2 - F^2\right|ij - ji\rangle$$

$$\chi = \frac{1}{N}\sum_{ij}\langle ij\left|F_p^2 - F^2\right|ij - ji\rangle = 0$$



$$E_2 = \frac{1}{2N}\sum_{ij}\left\langle ij\left|\frac{\hbar^2}{m}\left[f(12),\left[\nabla_{12}^2, f(12)\right]\right] + f(12)V(12)f(12)\right|ij - ji\right\rangle$$

$$S = 0,1 \;\; \& \vec{J} = \vec{L} + \vec{S} \;(\vec{J}_{\max} = 2\,)$$

$$^1S_0\,,\; ^3S_1\,,\; ^1P_1\,,\; ^3P_0\,,\; ^3P_1\,,\; ^3P_2\,,\; ^1D_2\,,\; ^3D_1\,,\; ^3D_2\,,\; ^3F_2$$

Input Interactions

- NN: AV18 + **Urbana IX**

$$\begin{aligned}
\text{AV18} &= \sum_{i<j} v_c(r_{ij}) + v_\tau(r_{ij})(\tau_i.\tau_j) + v_\sigma(r_{ij})(\sigma_i.\sigma_j) + v_{\sigma\tau}(r_{ij})(\sigma_i.\sigma_j)(\tau_i.\tau_j) \\
&+ v_t(r_{ij})S_{ij} + v_{t\tau}(r_{ij})S_{ij}(\tau_i.\tau_j) + v_{ls}(r_{ij})\mathbf{L}.\mathbf{S} + v_{ls\tau}(r_{ij})\mathbf{L}.\mathbf{S}(\tau_i.\tau_j) + v_{l2}(r_{ij})L^2 \\
&+ v_{l2\tau}(r_{ij})L^2(\tau_i.\tau_j) + v_{l2\sigma}(r_{ij})L^2(\sigma_i.\sigma_j) + v_{l2\sigma\tau}(r_{ij})L^2(\sigma_i.\sigma_j)(\tau_i.\tau_j) \\
&+ v_{ls2}(r_{ij})(\mathbf{L}.\mathbf{S})^2 + v_{ls2\tau}(r_{ij})(\mathbf{L}.\mathbf{S})^2(\tau_i.\tau_j) + v_T(r_{ij})T_{ij} + v_{\sigma T}(r_{ij})(\sigma_i.\sigma_j)T_{ij} \\
&+ v_{tT}(r_{ij})S_{ij}T_{ij} + v_{\tau z}(r_{ij})(\tau_{zi} + \tau_{zj}),
\end{aligned}$$

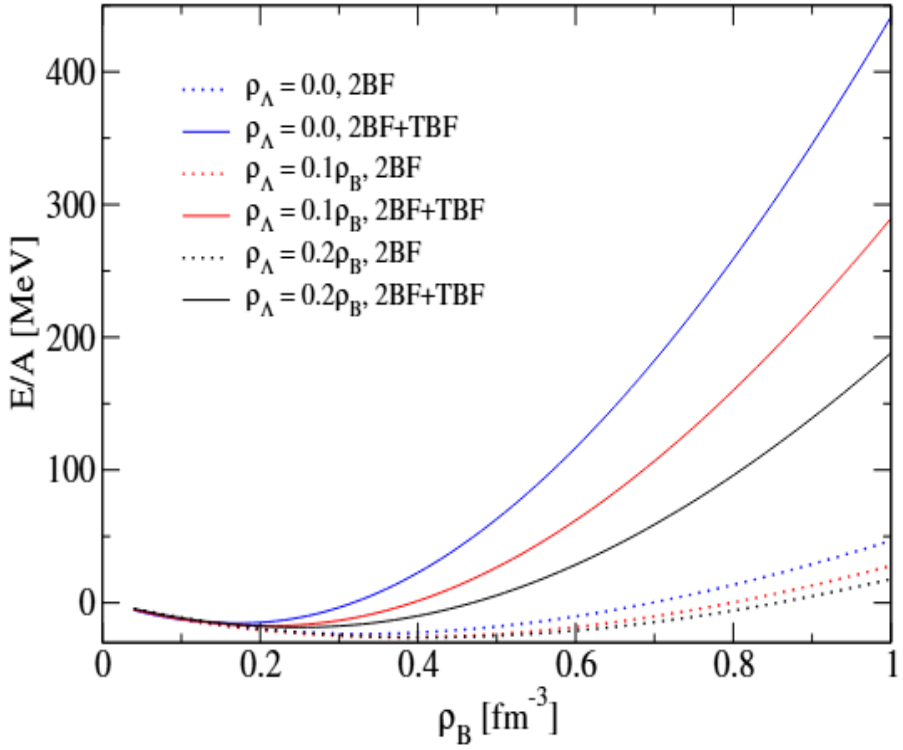
- ΛN: fitted to hypernuclear data (E. Hiyama, et al., Phys. Rev. C 74, 054312 (2006))

$$V_{\Lambda N}^{(c)}(r) = \sum_{\alpha}\sum_{i=1}^{3}\nu_i^{\alpha} exp[-(r/\beta_i)^2]. \qquad \alpha \equiv 1E, 3E, 1O, 3O$$

- ΛΛ: constrained by double-Λ hypernuclei (E. Hiyama, et al., Phys. Rev. C 66, 024007 (2002))

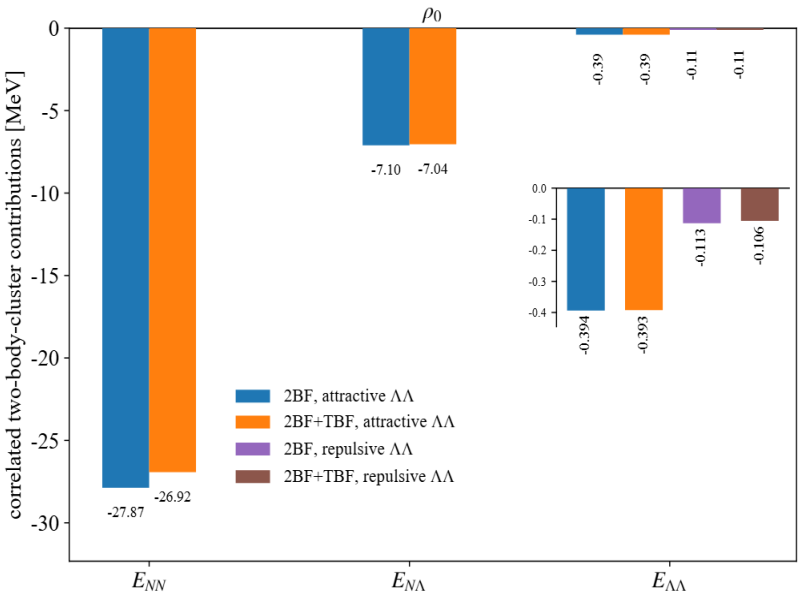
$$V_{12}^{\Lambda\Lambda,even} = \sum_{i=1}^{3}(\nu_i^{even} + \nu_i^{\sigma,even}\sigma_1.\sigma_2)exp[-\mu_i^{even}{r_{12}}^2] \quad V_{12}^{\Lambda\Lambda,odd} = \sum_{i=1}^{3}(\nu_i^{odd} + \nu_i^{\sigma,odd}\sigma_1.\sigma_2)exp[-\mu_i^{odd}{r_{12}}^2].$$

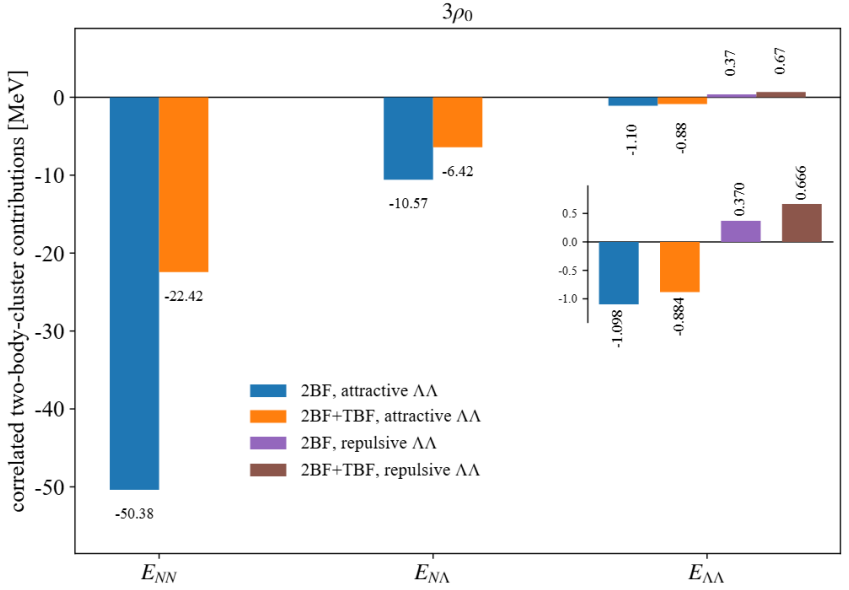
EoS for isospin symmetric hypernuclear matter

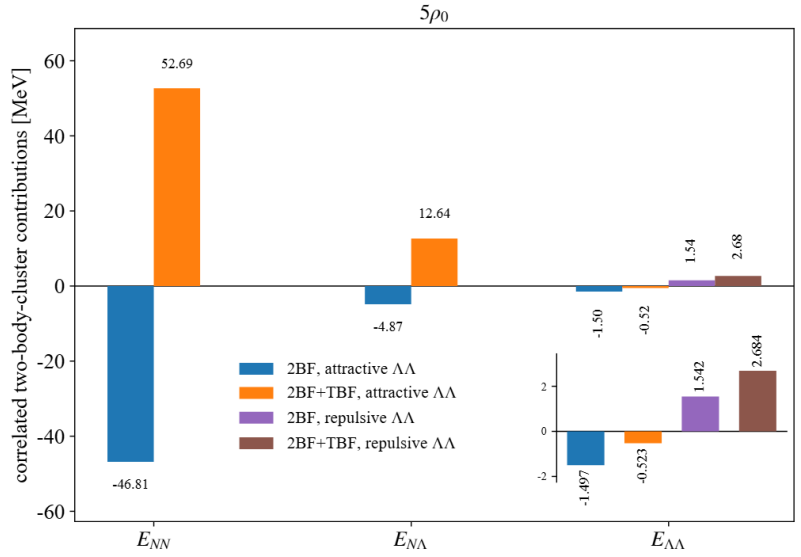


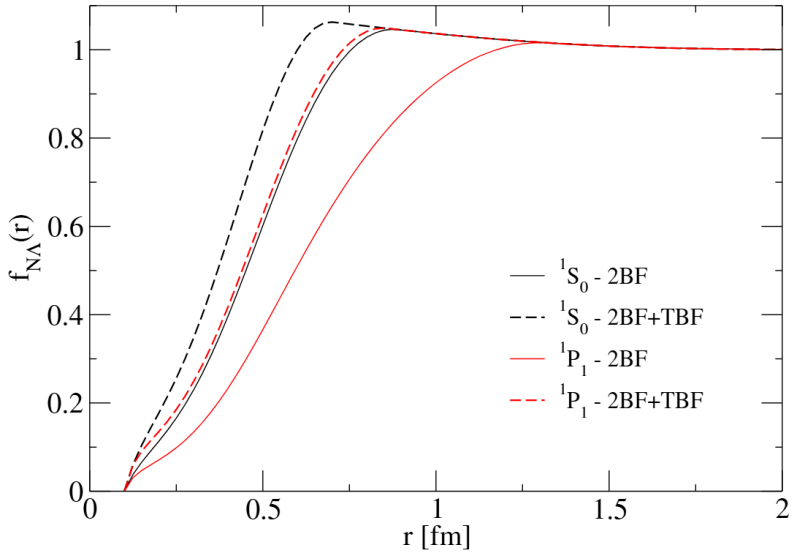
Quantity	LOCV 2BF	LOCV 2BF+UIX	Reference constraint
ρ_{sat} (fm^{-3})	0.32743(10)	0.170286(28)	0.157 ± 0.010
E_{sat} (MeV)	$-23.3729(4)$	$-15.4965(4)$	-15.97 ± 0.40
K_{sat} (MeV)	368(14)	345.6(28)	230 ± 30
Q_{sat} (MeV)	460(910)	340(120)	poorly constrained
J (MeV)	38.025(8)	31.992(4)	32.0 ± 1.1
L (MeV)	75.14(50)	61.81(53)	52.6 ± 8.1
K_{sym} (MeV)	$-30(26)$	$-319.7(55)$	poorly constrained

Microscopic decomposition of the energy





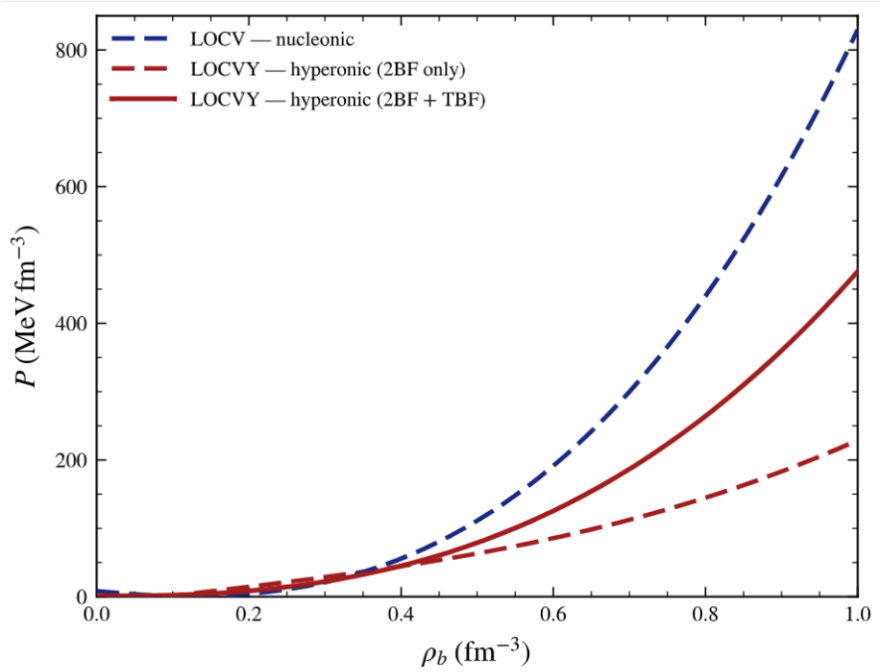


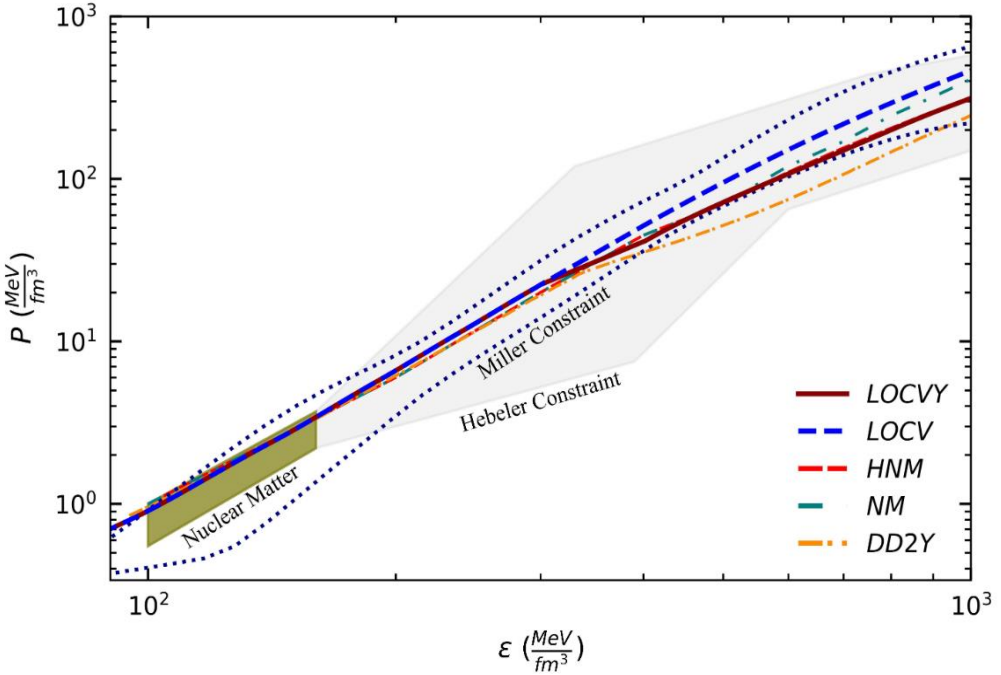


EoS for β-stable matter

$\varepsilon_{TBF} = C_3 n_\Lambda^2 n_N^\gamma, \qquad n_N = n_n + n_p,$ Density-dependent hyperonic TBF

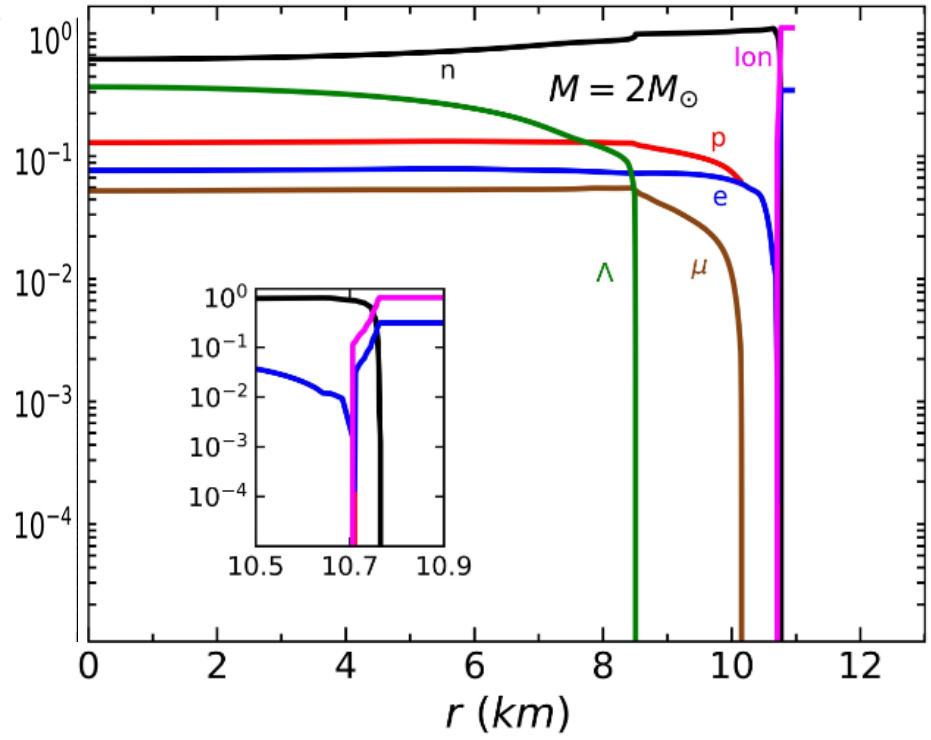
Lee, T., Nam, Y., & Sekizawa, K. 2026, arXiv: 2605.28727



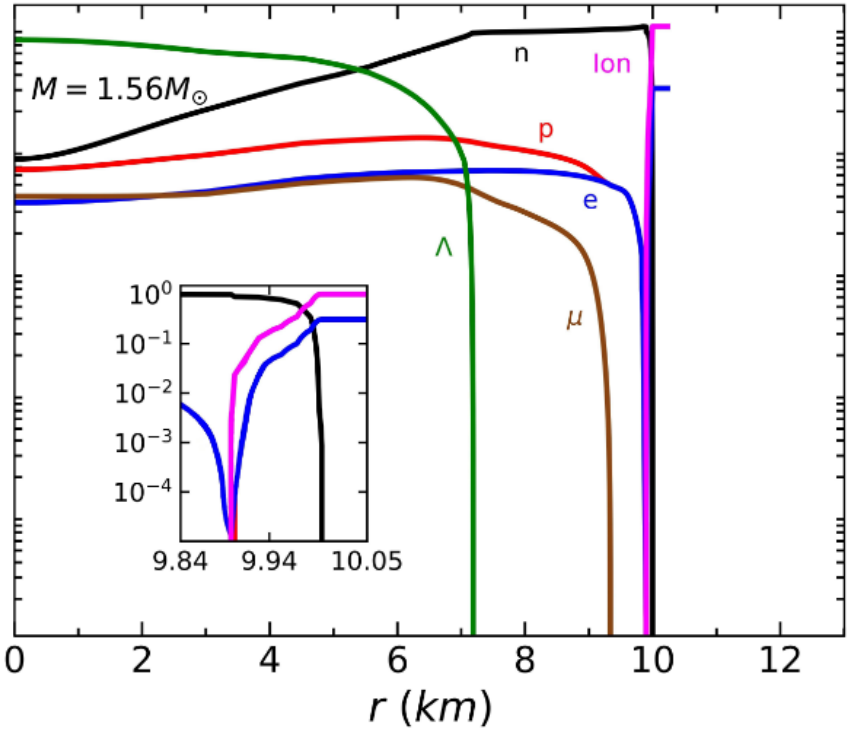


LOCVY with TBF remains compatible with empirical and theoretical constraints derived from chiral EFT and astrophysical observations

Profile of stars with different masses

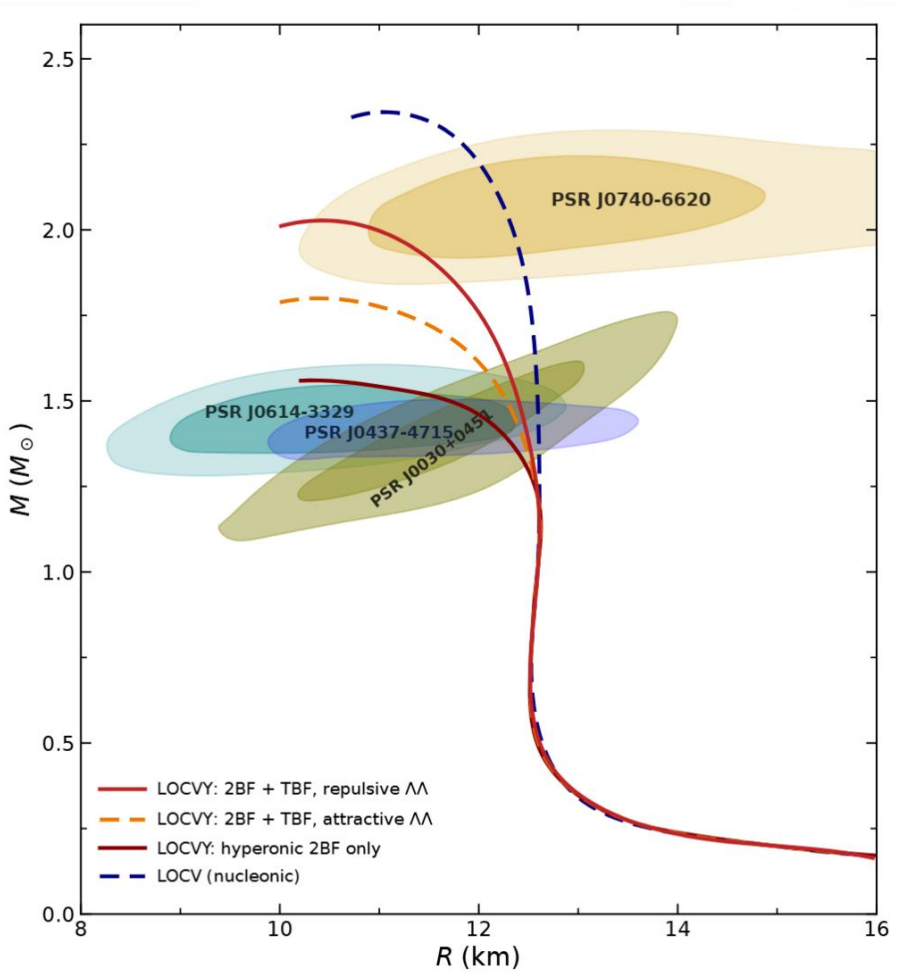


With hyperonic three-body force



Without hyperonic three-body force

Mass-Radius relation



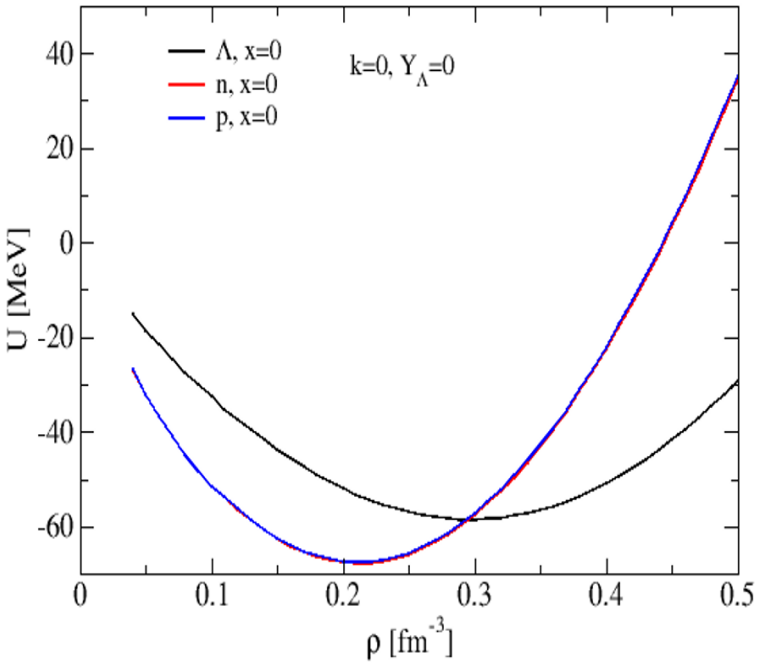
Model	$M_{\max}/M_{\odot}$
LOCV – nucleonic	2.34
LOCVY – hyperonic 2BF only	1.56
LOCVY – 2BF + TBF, attractive ΛΛ	1.81
LOCVY – 2BF + TBF, repulsive ΛΛ	2.03

Switching from repulsive to attractive ΛΛ interactions slightly changes the symmetric-matter EOS but reduces the maximum neutron-star mass by 10–11%.

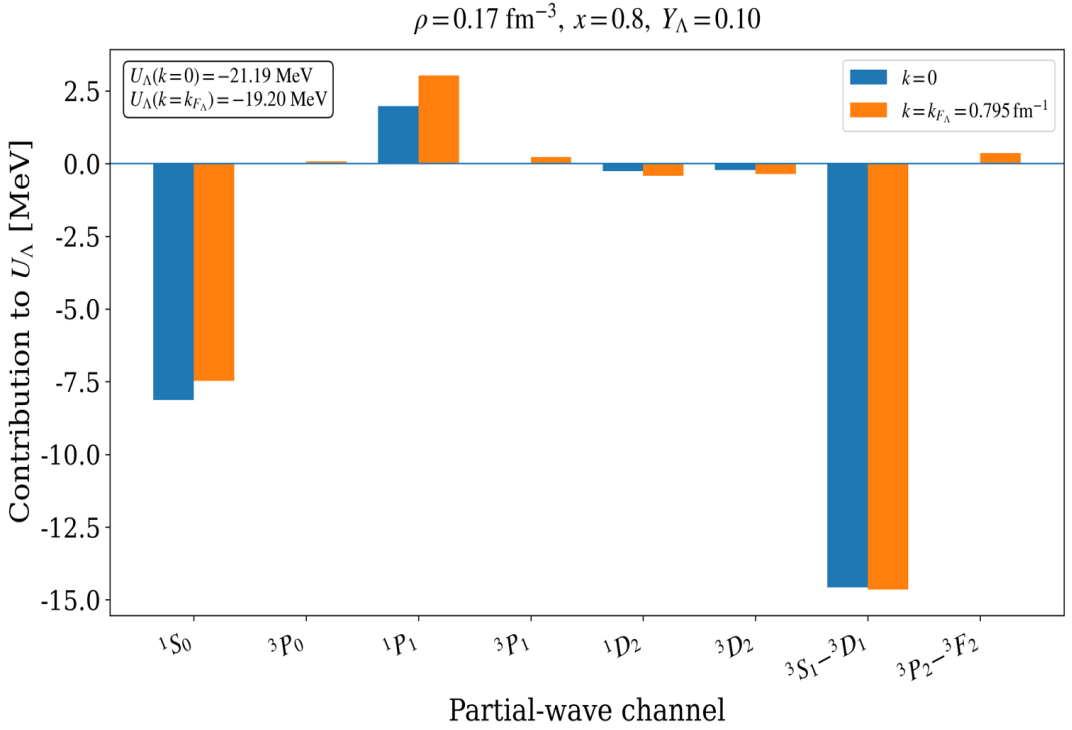
Toward a finite-temperature LOCVY EoS

Preliminary results

Nucleon and Λ Single-Particle Potential

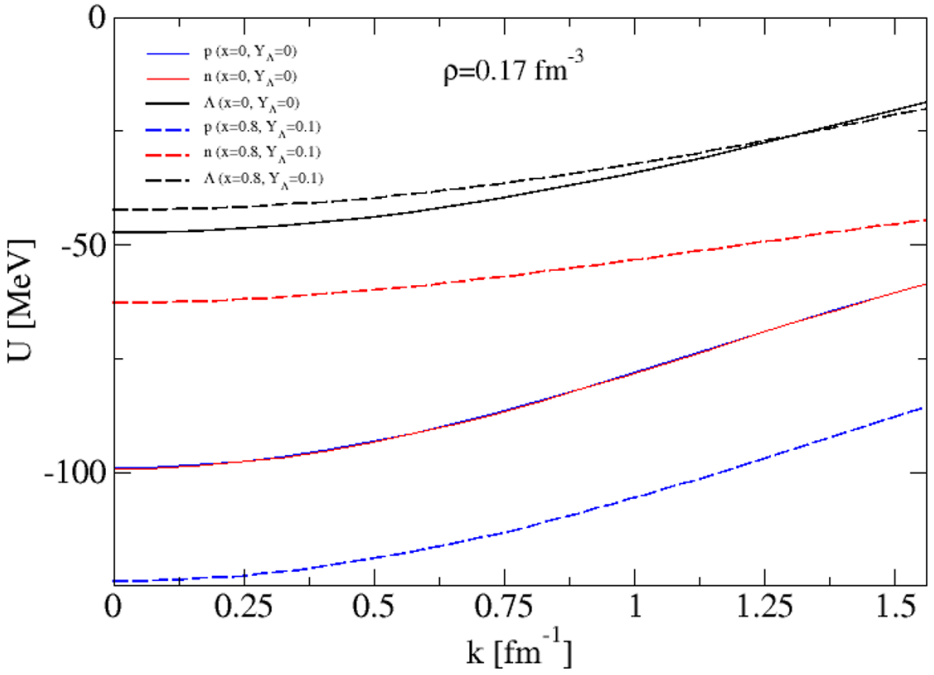


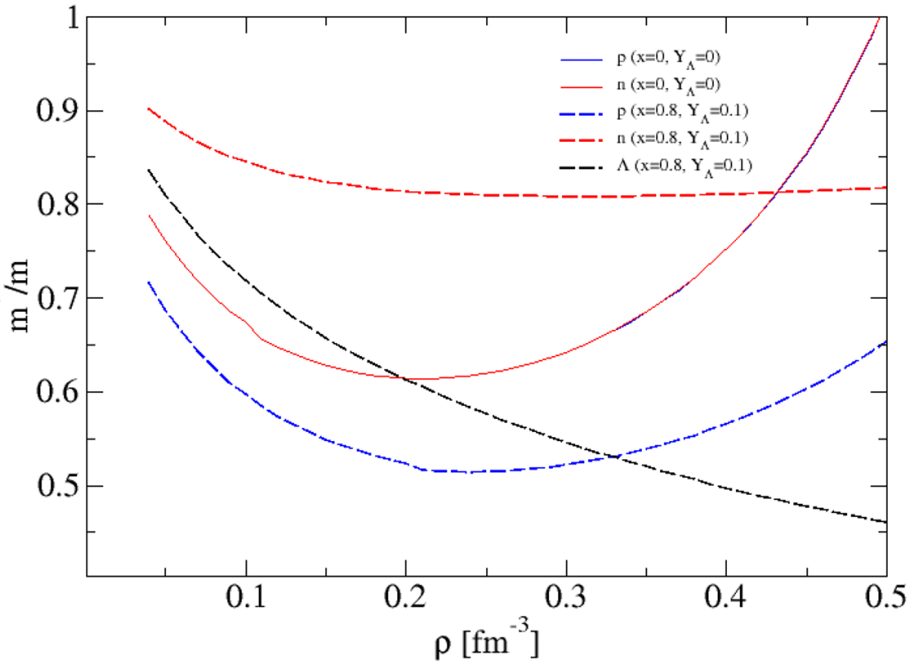
Isospin symmetric matter



Neutron-rich matter

Estimated effective mass of nucleons and Λ hyperon within LOCVY method





Model	x	Y_Λ	m_n^*/m_n	m_p^*/m_p	m_Λ^*/m_Λ
LOCVY (2BF)	0	0	0.89	0.89	–
LOCVY (2BF + TBF)	0	0	0.62	0.62	–
LOCVY (2BF)	0.8	0.1	0.93	0.86	0.88
LOCVY (2BF + TBF)	0.8	0.1	0.82	0.54	0.64

Conclusions

- ✓ Three-body force counteracts hyperonic softening
- ✓ Additional hyperonic repulsion supports $\approx 2M_{\odot}$ stars within a microscopic approach
- ❖ Next: use microscopic potentials and effective masses to extend LOCVY to finite temperature.


سپاسگزارم
ngiyabonga
მადლობა
danke
謝謝
teşekkür ederim
спасибо
thank you
gracias
dank je
tapadh leat
mochchakkeram
bedankt
hvala
mauruuru
dziękuję
go raibh maith agat
obrigado
sukriya
kop khun krap
taiku
arigatō
takk
dakujem
grazie
terima kasih
мерси
شكرا
감사합니다
Շնորհակալություն
merci