Repulsive Λ potential at high densities examined from heavy-ion collision and hypernuclear data

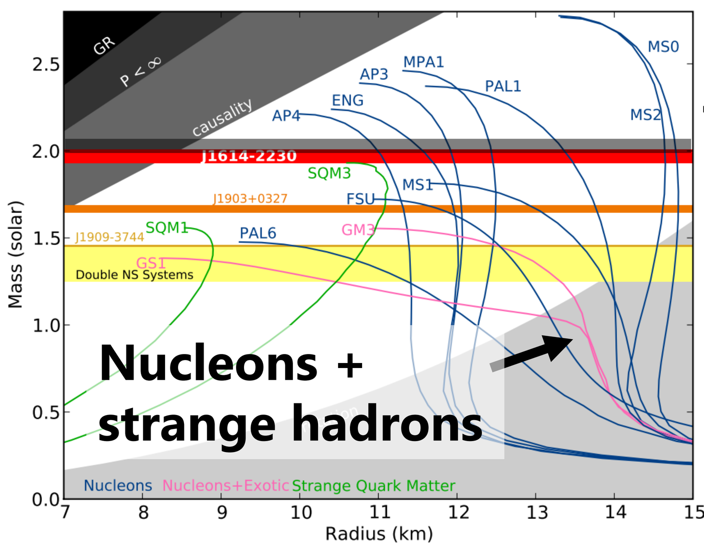
Asanosuke Jinno[1], Koichi Murase[2], Yasushi Nara[3], and Akira Ohnishi[2]

1. Dept. Phys. Kyoto U.
2. YITP, Kyoto U.
3. Akita International U.

Background

Hyperon Puzzle

Many equations of state with hyperons are too soft to support the massive neutron stars.



J0740+6620 (2.08±0.07)$M_\odot$ Miller et al.(2021)

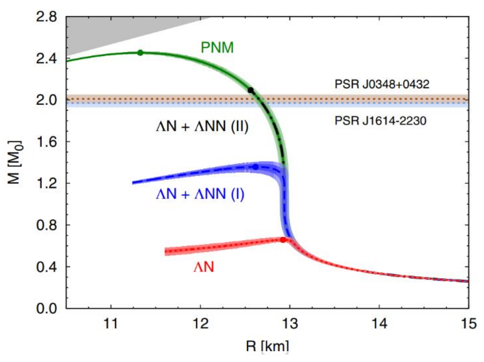
Demorest et al. (2010)

Many-body int. may solve the puzzle?!

By including many-body interaction (e.g. ΛNN), some models can support the 2$M_\odot$ neutron star, but some cannot.

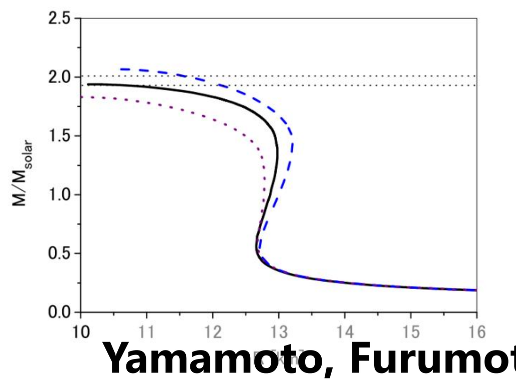
We have no definitive conclusion whether hyperon can appear in neutron stars.

Quantum Monte Carlo



Lonardoni et al. (2015)

Multi-Pomeron exch. pot.



Yamamoto, Furumoto, Yasutake, Rijken (2016)

Λ potential at high densities

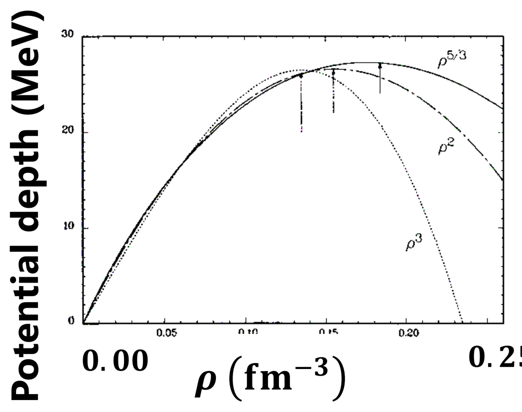
Λ potential U_Λ is a key ingredient in discussing the admixture of Λ in NS!

Λ appears in NS when condition $\mu_n(\rho) > \mu_\Lambda^0(\rho) = m_\Lambda c^2 + U_\Lambda(\rho)$ is satisfied.

μ_n: neutron chemical potential

Old hypernuclear data could not constrain U_Λ at $\rho > \rho_0$.

Millner, Dover, and Gal (1988).



Purpose

To examine the possibility to constraint Λ potential at high densities from heavy-ion collision data and future high resolution Λ hypernuclear data measured at J-PARC.

Λ binding energy B_Λ of Λ hypernuclei

AJ, K. Murase, Y. Nara, and A. Ohnishi, arXiv:2306.17452 [nucl-th].

Skyrme-Hartree-Fock method with spherical symmetry

Rayet (1981); Lansky and Yamamoto (1997); Choi, Hiyama et al. (2022)

Skyrme-Hartree-Fock eq.

$$\left[-\nabla\cdot\left(\frac{\hbar^2}{2m_B^*}\nabla\right)+U_B-iW_B\cdot(\nabla\times\sigma)\right]\psi_{B,i}=\epsilon_{B,i}\psi_{B,i}$$

$$\frac{\hbar^2}{2m_\Lambda^*}=\frac{\hbar^2}{2m_\Lambda}+a_2^\Lambda\rho_N \qquad U_\Lambda(\rho_N)=a_1^\Lambda\rho_N+a_2^\Lambda\tau_N-a_3^\Lambda\Delta\rho_N+a_4^\Lambda\rho_N^{4/3}+a_5^\Lambda\rho_N^{5/3}$$

*We take $W_\Lambda = 0$ because the spin-orbit potential of Λ is small.

$$\rho_N=\sum_{B=p,n}\sum_i|\psi_{B,i}|^2 \quad \tau_N=\sum_{B=p,n}\sum_i|\nabla\psi_{B,i}|^2 \quad \tau_\Lambda=|\nabla\psi_\Lambda|^2$$

Obtain Λ binding energy $B_\Lambda = -(E_{\rm HYP} - E_{\rm Core})$ for a given set of a_i^Λ, and then compare with the exp. data using RMSD.

$$\Delta B_\Lambda = \sqrt{\sum\left(B_\Lambda^{\rm exp} - B_\Lambda^{\rm cal}\right)^2/N}$$

Method

Λ & $^3_\Lambda$H directed flow of heavy-ion collision

Y. Nara, AJ, K. Murase, and A. Ohnishi, Phys. Rev. C 106, 044902 (2022).
AJ, K. Murase, and Y. Nara, work in progress.

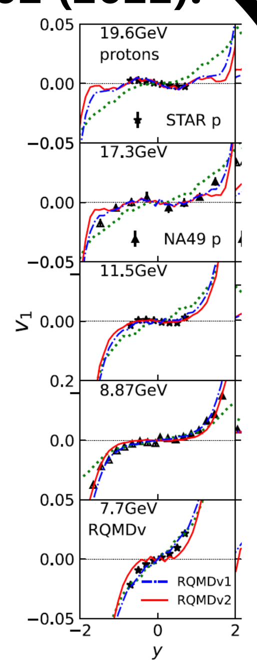
directed flow $v_1 = \langle p_x/p_T\rangle = \left\langle p_x/\sqrt{p_x^2+p_y^2}\right\rangle$

Microscopic transport model JAM2

Relativistic Quantum Molecular Dynamics mode using Lorentz-vector type potential **RQMDv**

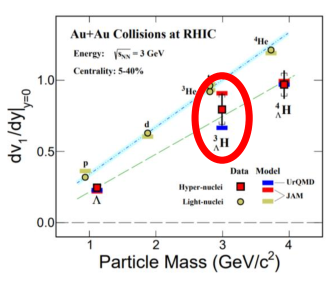
$\sqrt{s_{NN}}$ dependence of proton v_1 is explained.

Nara and Ohnishi (2022)



Also, hypertriton $^3_\Lambda$H v_1 is recently measured at STAR, and old JAM + coalescence overestimates the data.

STAR, Phys. Rev. Lett. 130, 212301 (2023).



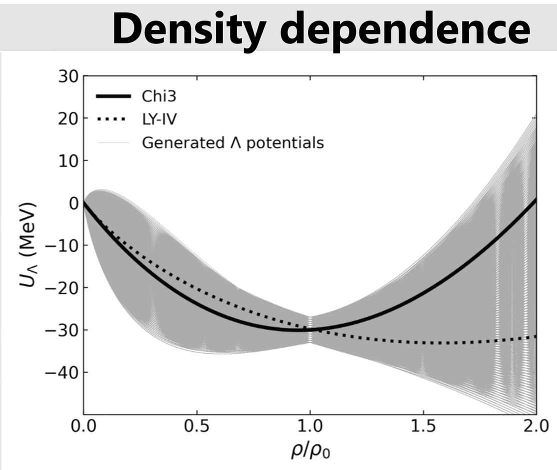
Let's discuss Λ and $^3_\Lambda$H v_1 by JAM2!

Λ potentials

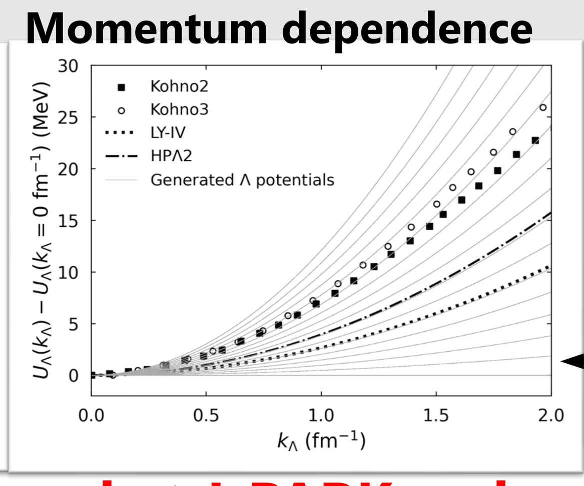
Generate Λ potentials of different $a_i^\Lambda (i = 1, 2, 4, 5)$.

*a_3^Λ is determined to reproduce the $^{13}_\Lambda$C data.

Density dependence

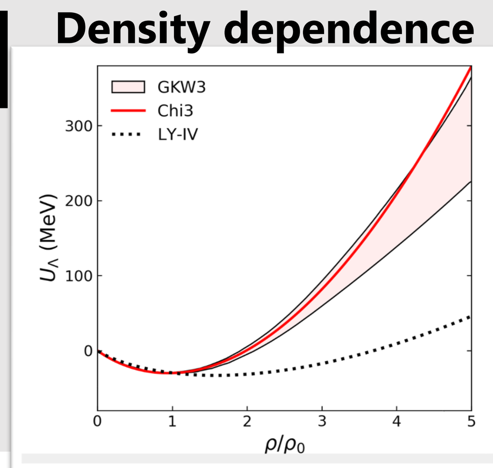


Momentum dependence

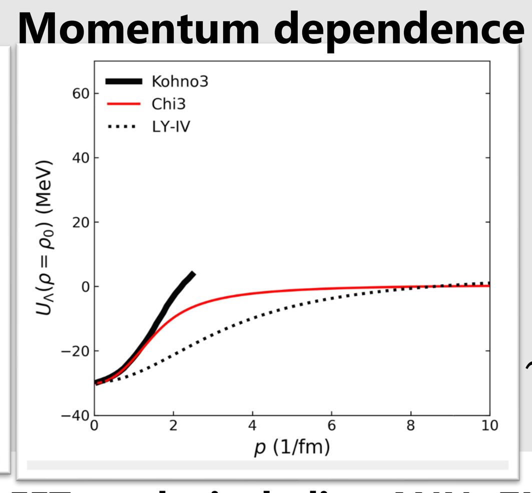


$U_\Lambda(\rho_0, k_\Lambda) - U_\Lambda(\rho_0, k_\Lambda = 0) = a_2^\Lambda \rho_0 k_\Lambda^2$

Density dependence



Momentum dependence



$$U_\Lambda(k_\Lambda) \approx \frac{C}{\rho_0}\int d^3k'_\Lambda \frac{f(x,k'_\Lambda)}{1+[(\boldsymbol{k}_\Lambda-\boldsymbol{k}'_\Lambda)/\mu]^2}$$

The explicit expression is in Nara and Ohnishi (2022).

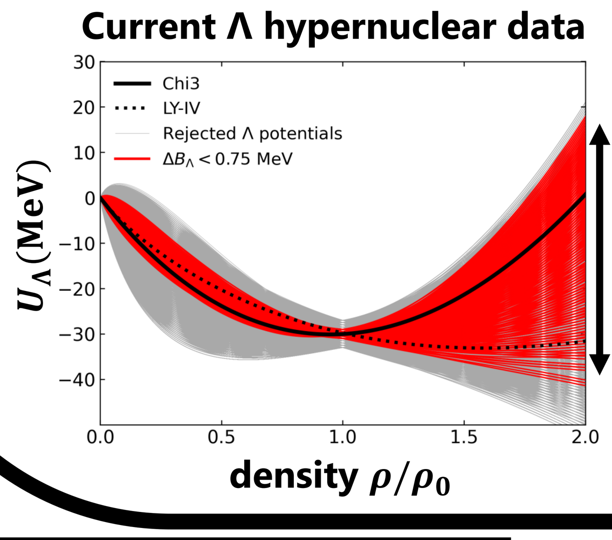
fit up to $p < 1.0$ fm^{-1} ~ 40% of cutoff (550 MeV)

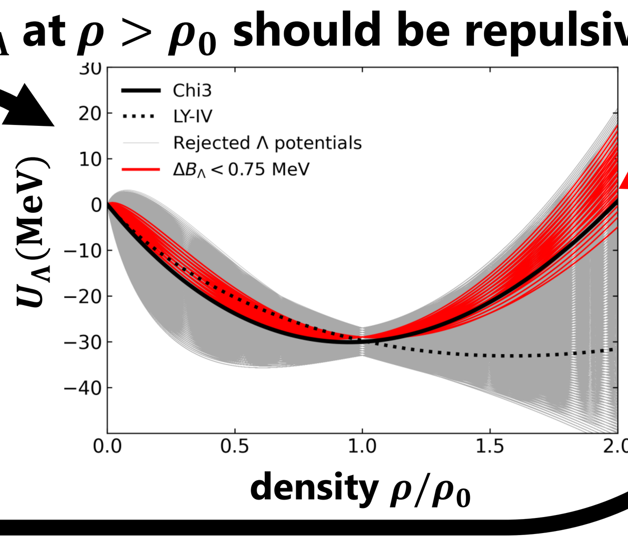
Results

Future high-resolution data measured at J-PARK and JLab have a possibility to constrain U_Λ at $\rho > \rho_0$!

If the depth of the Λ potential $U_\Lambda(\rho_0)$ is larger, U_Λ at $\rho > \rho_0$ should be repulsive!

Current Λ hypernuclear data

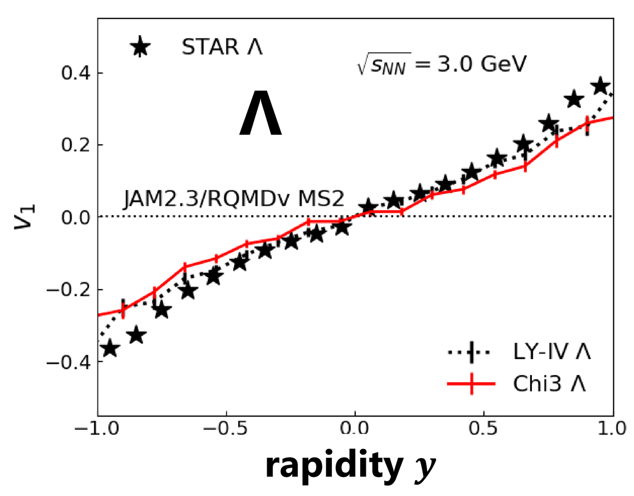


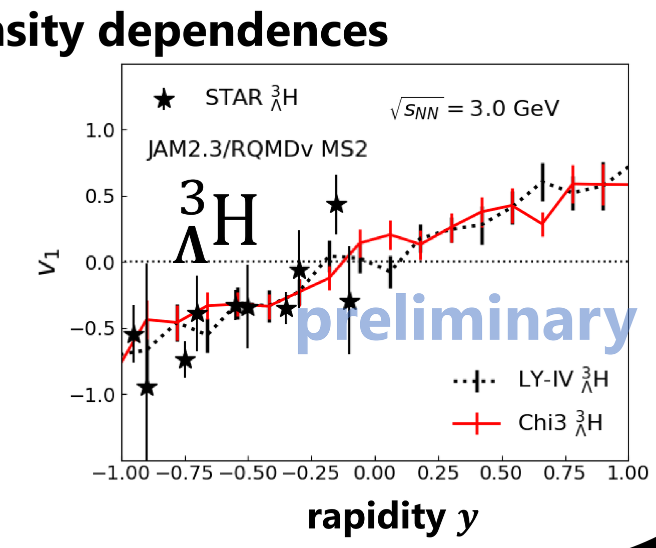


Chi3: Fitted to Chiral EFT results including ΛNN+ΣNN.
(GKW3) Gerstung, Kaiser, and Weise (2020); (Kohno3) Kohno (2018).
LY-IV: Skyrme-type Λ potential reproducing Λ binding energy data, Lanskoy and Yamamoto (1998).

Both Chi3 and LY-IV reproduce the data.

Insensitive to the density dependences





Summary

- We have examined the possibility to constraint the Λ potential at high-densities from Λ hypernuclear and heavy-ion collision data.
- Future high-resolution hypernuclear data measured at J-PARC and JLab have a possibility to constrain the Λ potential at $\rho > \rho_0$!
- Both repulsive and attractive Λ potentials at high densities reproduce the Λ and $^3_\Lambda$H directed flow, but they are not sensitive to the density dependence of the Λ potential. Why?

Future work

- Investigating the Λ production mechanism in heavy-ion collision to
  - elucidate why Λ and $^3_\Lambda$H directed flow are not sensitive to the density dependence of the Λ potential.
  - search for the channels sensitive to the density dependence of the Λ potential.