Λ directed flow for validating the Λ potential from chiral EFT: Bridging heavy-ion collisions, hypernuclei, and neutron stars

Asanosuke Jinno (Kyoto Univ.)

in collaboration with Koichi Murase (Tokyo Metropolitan Univ.)

Yasushi Nara (Akita International Univ.)

- **Introduction: Nuclear matter EOS and the Λ potential**
- **Λ directed flow to validate the Λ potential**

Y. Nara, A. Jinno, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).
A. Jinno, K. Murase, Y. Nara, & A. Ohnishi, PRC 108, 065803 (2023).
ATHIC2025, Gopalpur, India, Jan. 13-16, 2025

Nuclear matter EOS: An ultimate goal

■ **Nuclear matter Equation of state, EOS:**

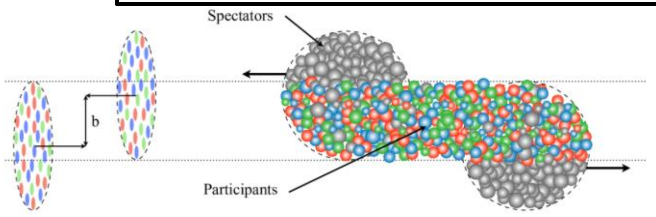
Pressure as a function of the energy density, temperature, etc.

EOS of dense nuclear matter plays an important role in various physics!

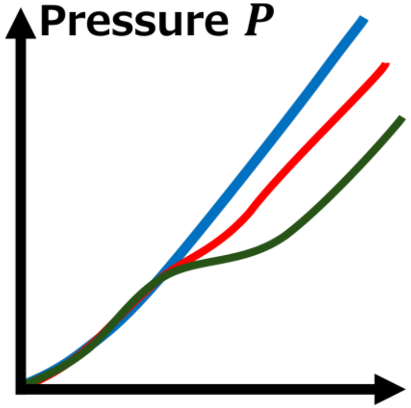
EOS of nuclear (neutron star) matter

(Hyper) Nuclear structures & reactions

Heavy-ion collisions



CERN

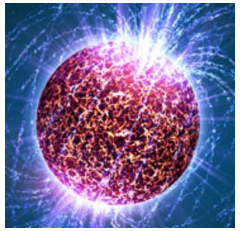


Energy density ϵ

△ (sign problem)

Lattice QCD

Neutron stars



LIGO

Supernovae

EOS models ⇄ **Experiments and Observations**

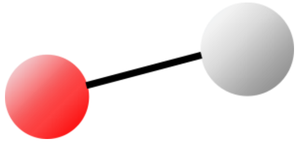
Unified approach for EOS

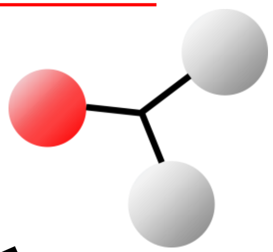
A unified approach provides a strong constraint on EOS, $P = P(\epsilon)$.

e.g. S. Huth et al., Nature 606 (2022) 276.; N. Rutherford et al., Astrophys. J. Lett. 971 (2024)

Low density region ($\rho < 2\rho_0$)

Modern NN + NNN forces based on chiral EFT

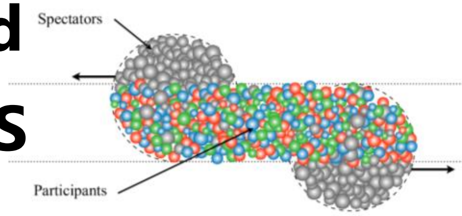


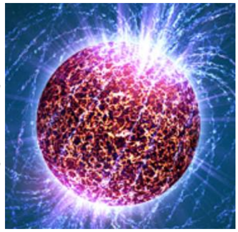


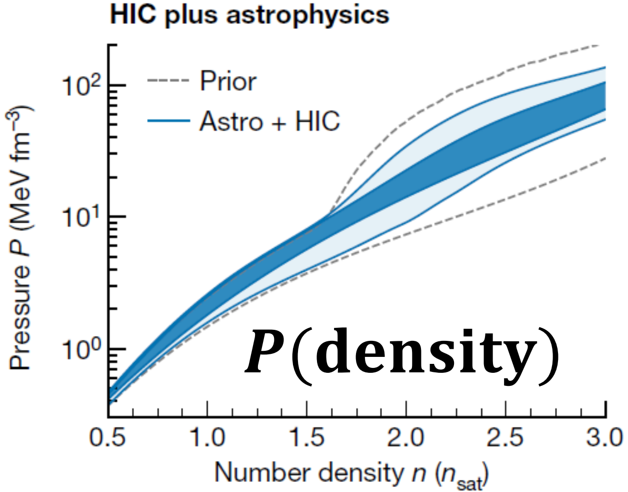
High density region ($\rho > 2\rho_0$)

Constrained by data (via model calculation)

e.g. Anisotropic collective flow (v_1, v_2), Mass-radius relation and tidal deformability of NS







S. Huth et al., Nature 606 (2022) 276.

Hyperon composition is important!

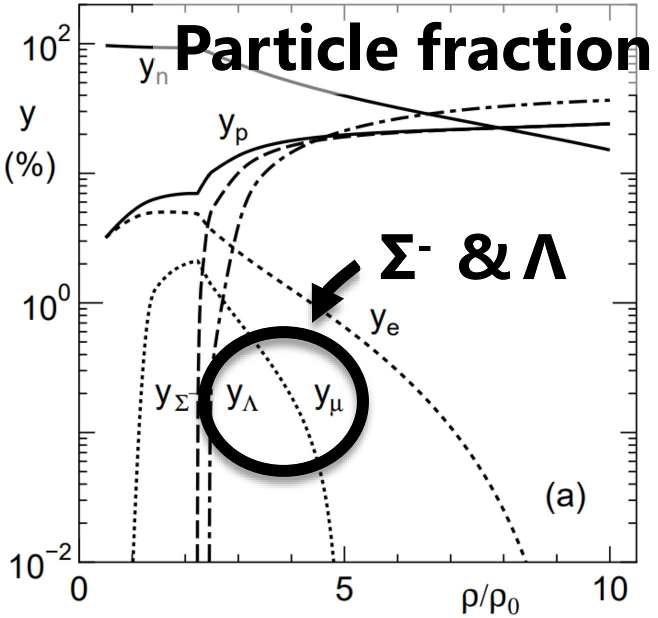
Such an approach does not tell us the detailed properties of EOS.

Given ρ: **Proton ?? %** **Neutron ?? %** **Hyperon ?? %**

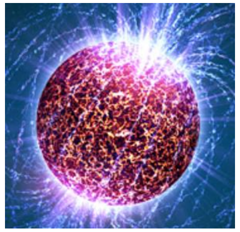
Appearance of hyperons in nuclear matter significantly changes the EOS!

(1990-) Hyperon appears at $2-4\,\rho_0$ in NS matter.

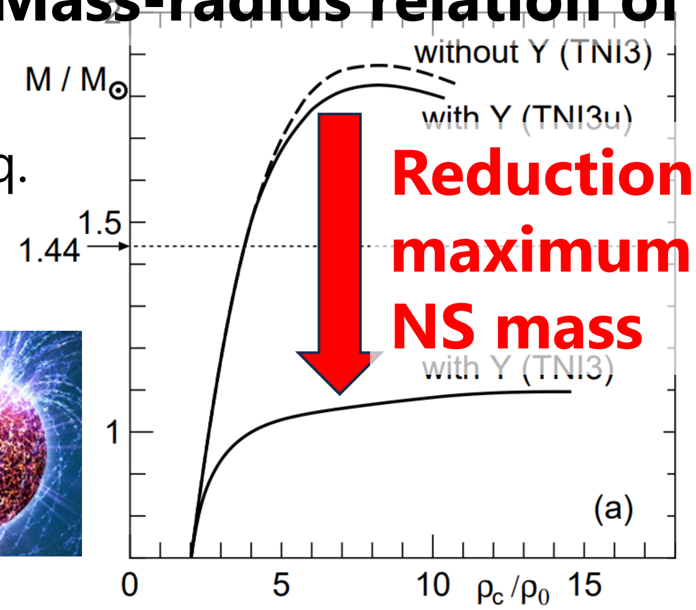
e.g. S. Nishizaki, T. Takatsuka, and Y. Yamamoto, Prog. Theor. Phys. 108 (2002) 703.



TOV eq.



Mass-radius relation of NS



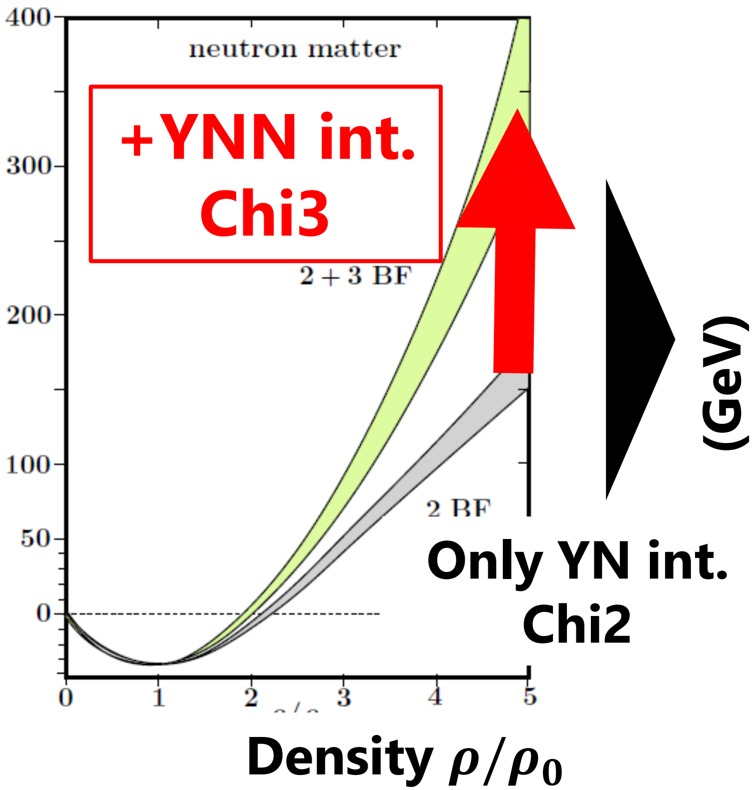
cf. Hyperon puzzle of neutron stars, Demorest et al. Nature (2010).

The Λ single-particle potential U_Λ

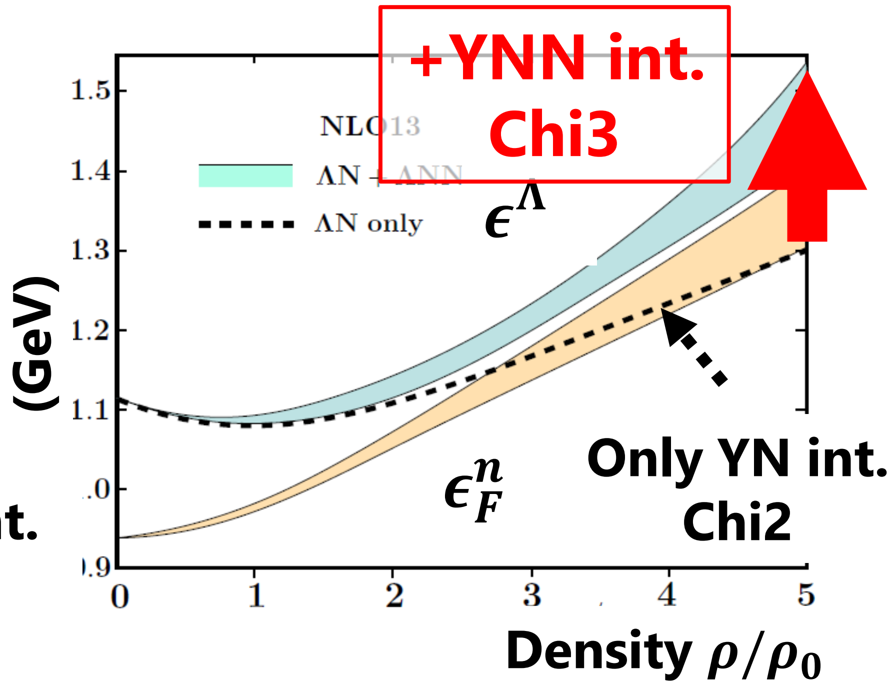
- The Λ potential is important whether Λ can appear in neutron stars.
- **Recently, YN + YNN forces from chiral EFT are used to calculate U_Λ!**

  Kohno(2018), D. Gerstung, N. Kaiser, and W. Weise (2020)

Λ potential in symmetric nuclear matter U_Λ (MeV)



$$\epsilon^\Lambda(\rho) = m_\Lambda + U_\Lambda(\rho)$$

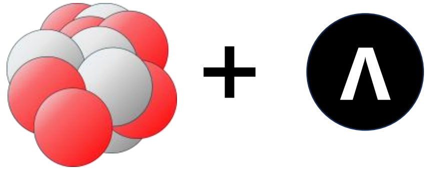


Λ does not appear even in high density region?!

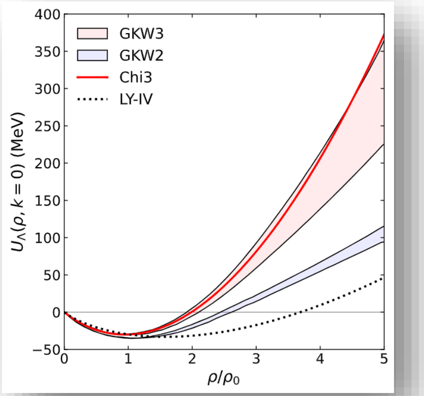
Our study on the Λ hypernuclei

AJ, K. Murase, Y. Nara, & A. Ohnishi, PRC 108, 065803 (2023).

We have verified that the Λ potential repulsive at high densities is consistent with the Λ hypernuclear spectroscopy.

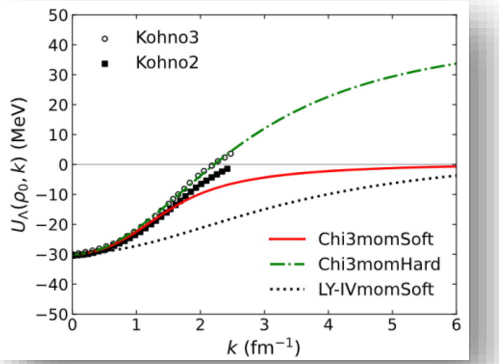


U_Λ Density dep.



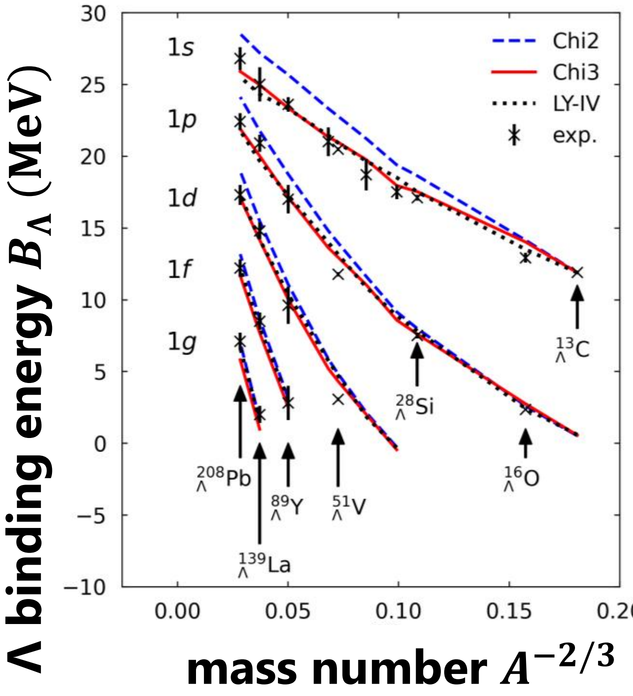
GKW2 (GKW3): Gerstung, Kaiser, and Weise (2020).
Kohno2 (Kohno3): M. Kohno (2018).
Chiral EFT calculation with YN (YN+YNN) interaction.

U_Λ Momentum dep.



LY-IV: Lanskoy and Yamamoto (1997).
Skyrme-type Λ potential reproducing Λ binding energies.

Skyrme-HF



At the same time, more attractive Λ potentials (conventional Skyrme-HF model) at high densities are also consistent with the data.

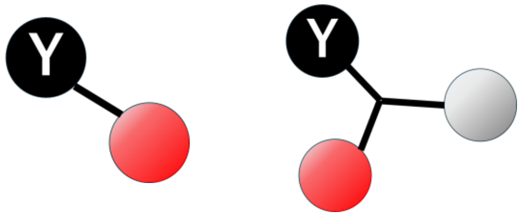
We need other strategy to distinguish the repulsive and attractive Λ potentials.

Purpose of our study

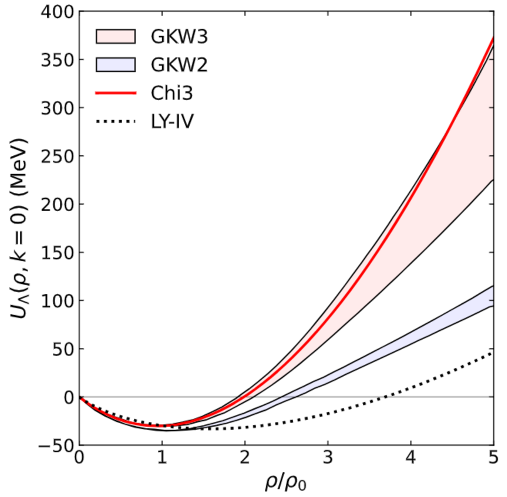
Check the consistency of the repulsive Λ potential with the heavy-ion collision observable (Λ directed flow v_1).

Chiral EFT

(NLO YN + YNN via decuplet saturation)

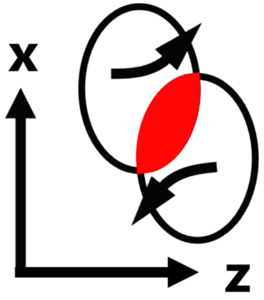


Λ single-particle potential



Experiments and observations

YN scatterings ✅,
Neutron stars ✅,
Λ Hypernuclei ✅,
Heavy-ion collisions



Feedback!

Evaluate!

Λ directed flow to validate the Λ potential

Directed flow v_1 ($\sqrt{s_{NN}} \approx 3-5$ GeV)

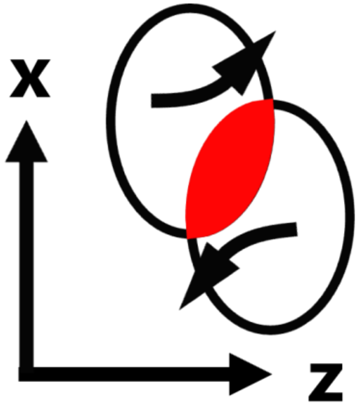
- **The anisotropic collective flow $v_n = \langle \cos n\phi \rangle$ has been extensively investigated to extract the properties of dense matter equation of state (EOS).**

  (Recent review: A. Sorensen, Prog. Part. Nucl. Phys. 134 (2024) 104080)

- **Directed flow: $v_1 = \langle \cos\phi \rangle = \langle p_x/p_T \rangle$ as a function of rapidity $y = \tanh^{-1}\left(\frac{p_z}{E}\right)$**

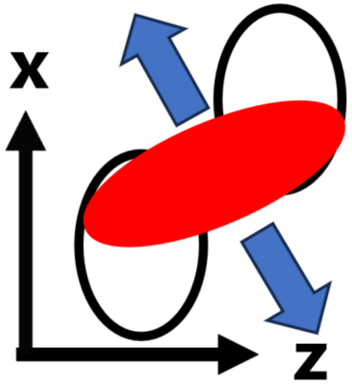
  $(p_T^2 = p_x^2 + p_y^2)$

Early (compression) stage



$v_1 > 0$ **for**
$y > 0$

Later (expansion) stage



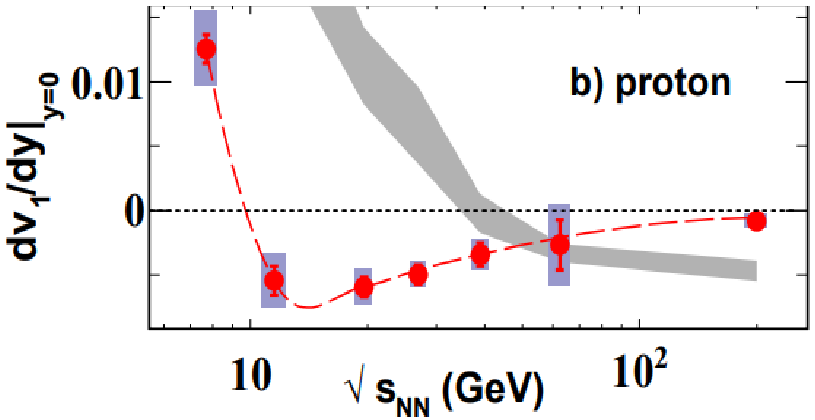
$v_1 < 0$ **for**
$y > 0$

v_1 has a non-trivial dependence on EOS.

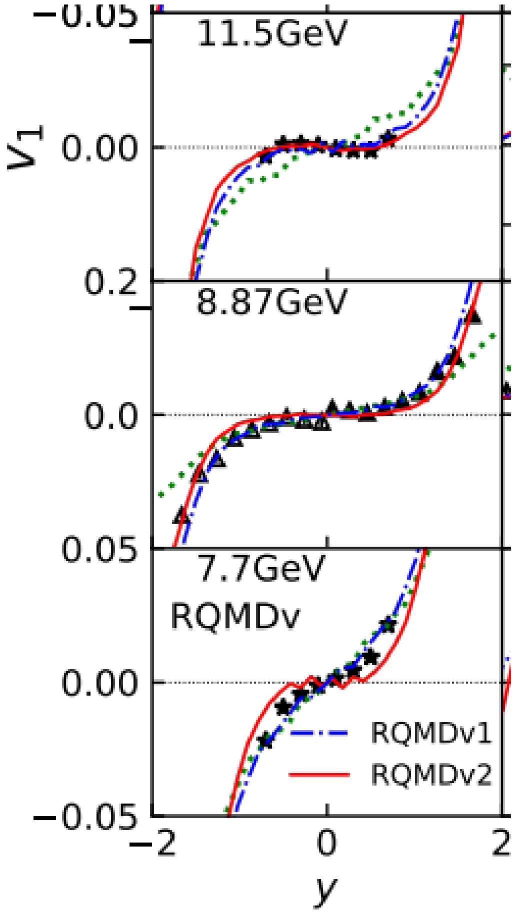
Proton directed flow v_1

- Proton directed flow slope dv_1/dy shows sign change at $\sqrt{s_{NN}} = 11.5$ GeV.

STAR Collaboration, Phys. Rev. Lett. 112 (2014) 162301.



Signal of the 1st order phase transition?



- In 2022, it is shown $\sqrt{s_{NN}}$ dependence of proton $v1$ can be <u>explained without phase transition</u> by the relativistic quantum molecular dynamics model with the Lorentz-vector potential (RQMDv) implemented in JAM2.

Nara and Ohnishi (2022)

➡ Let's discuss Λ v_1!

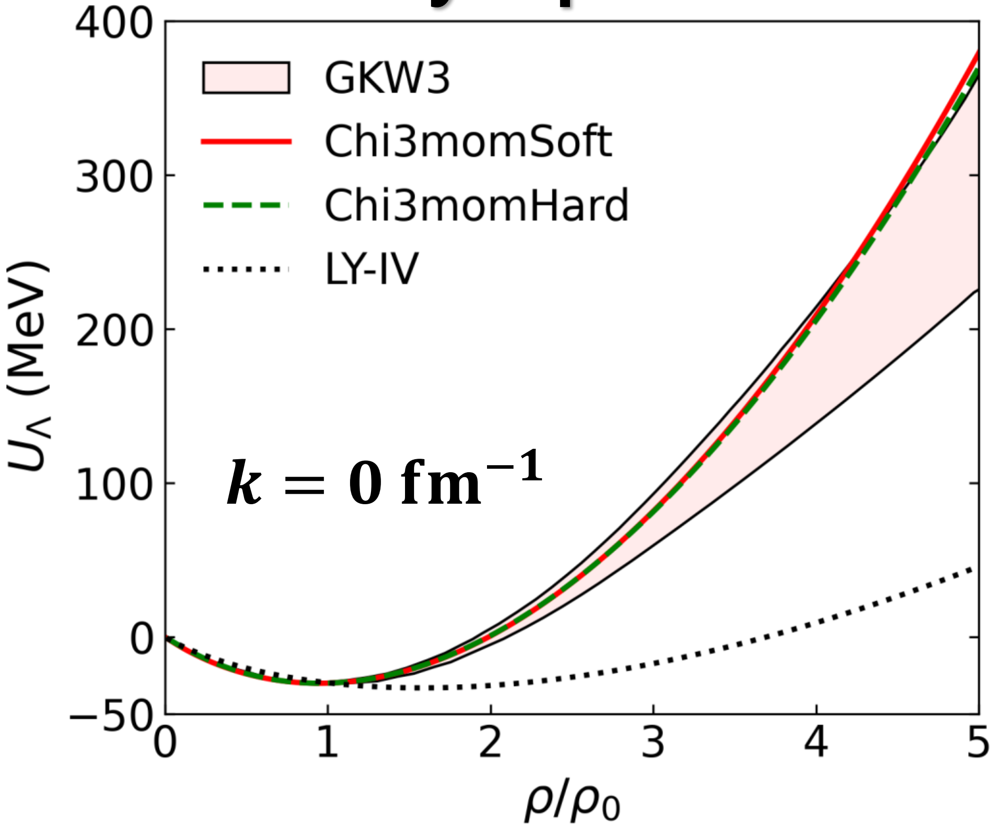
https://gitlab.com/transportmodel/jam2

Employed Λ potentials

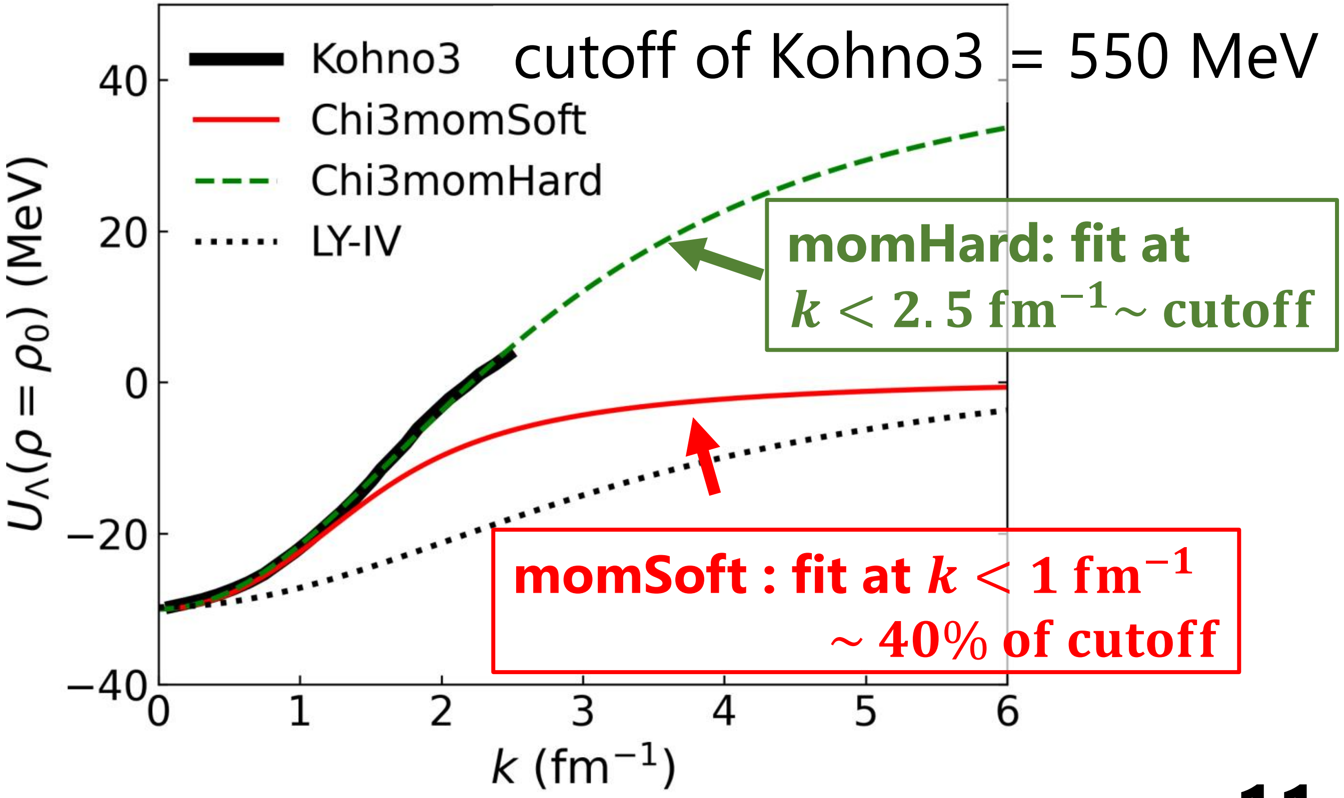
<u>**Using Λ potentials reproducing the Λ hypernuclear data**</u>

Since the momentum dependence has uncertainty in large k (fm^{-1}),
we compare two types of the momentum dependence.

Density dependence

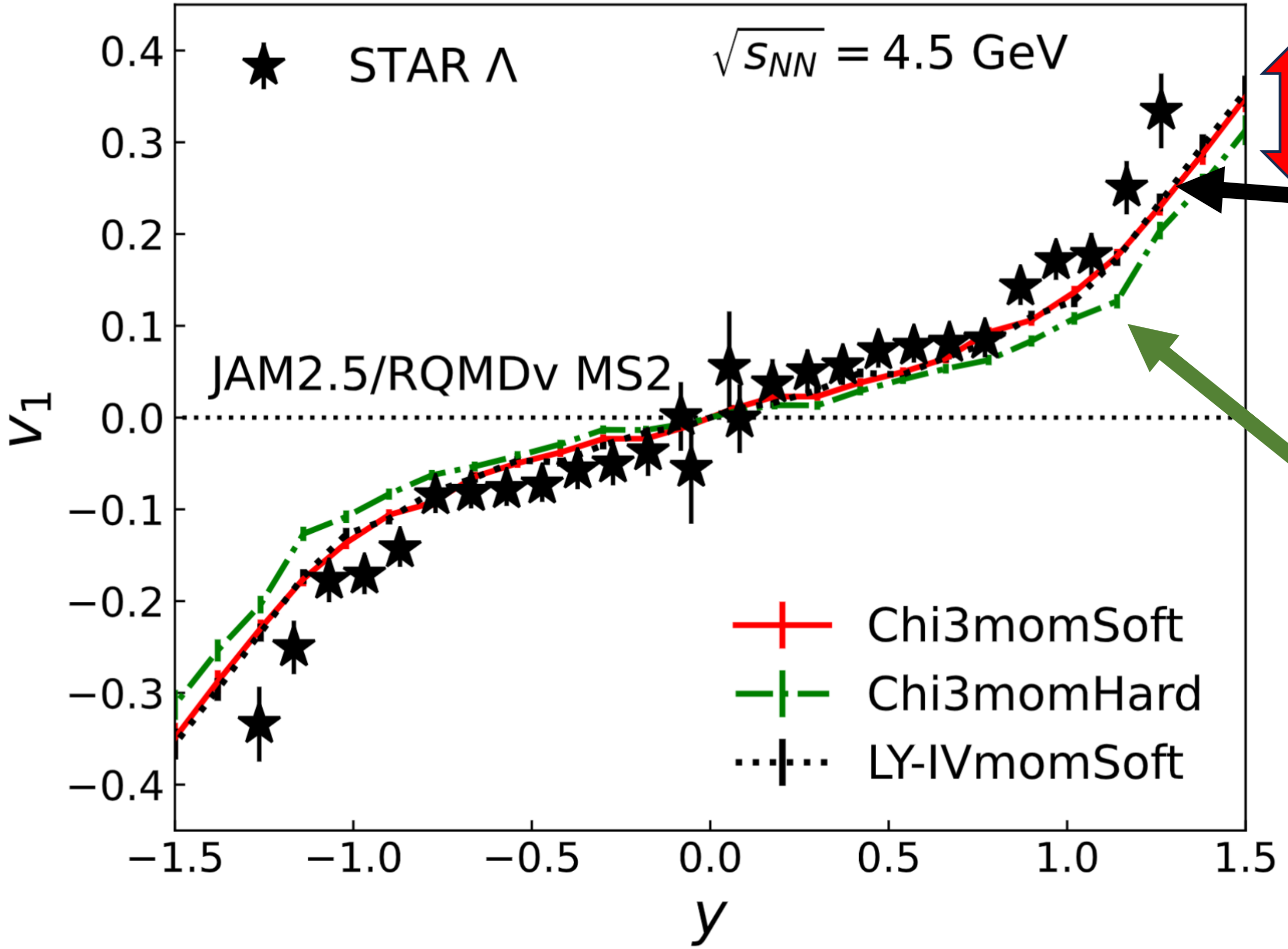


Momentum Dependence



Λ directed flow v_1 ($\sqrt{s_{NN}} = 4.5$ GeV)

Y. Nara, A. Jinno, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).
(Calculation is done by using latest version of JAM2)



STAR Λ: Phys. Rev. C 103, 034908 (2021).

- **Chi3momSoft reproduces the data!**
- **(Repulsive) Chi3momSoft & (Attractive) LY-IVmomSoft: No difference is found.**
- **Difference is found between the Soft and hard momentum dependencies.**

Λ v_1 is sensitive to the momentum dependence, rather than the density dependence.

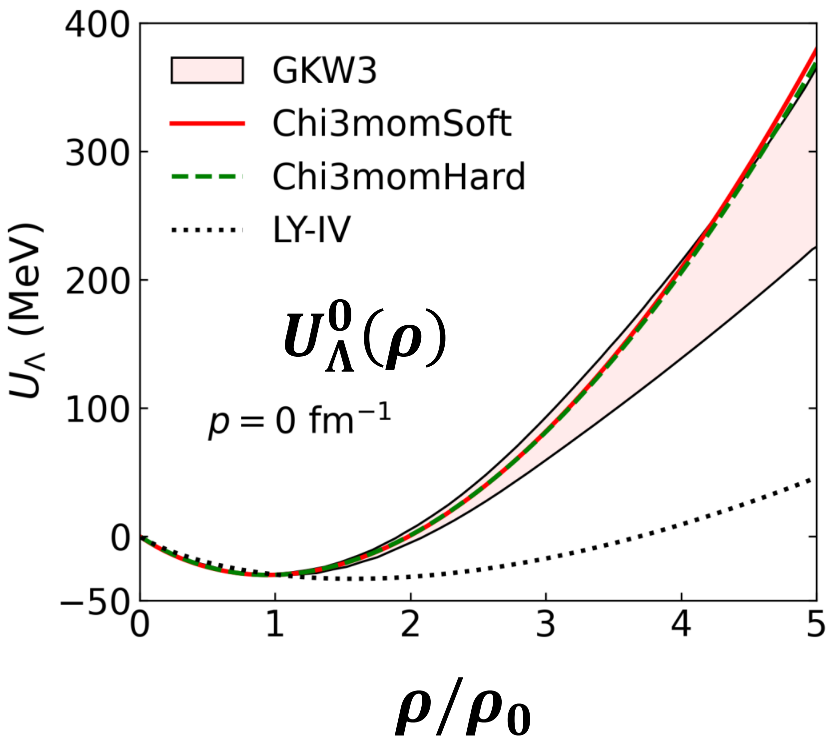
Why?

Repulsion is enhanced by mom. dep.

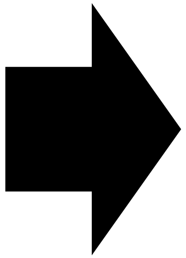
The density dependence gets more repulsion with the harder momentum dependence.

$$U_\Lambda^0(\rho, k=0) = U_\rho^0 + U_m^0 =$$

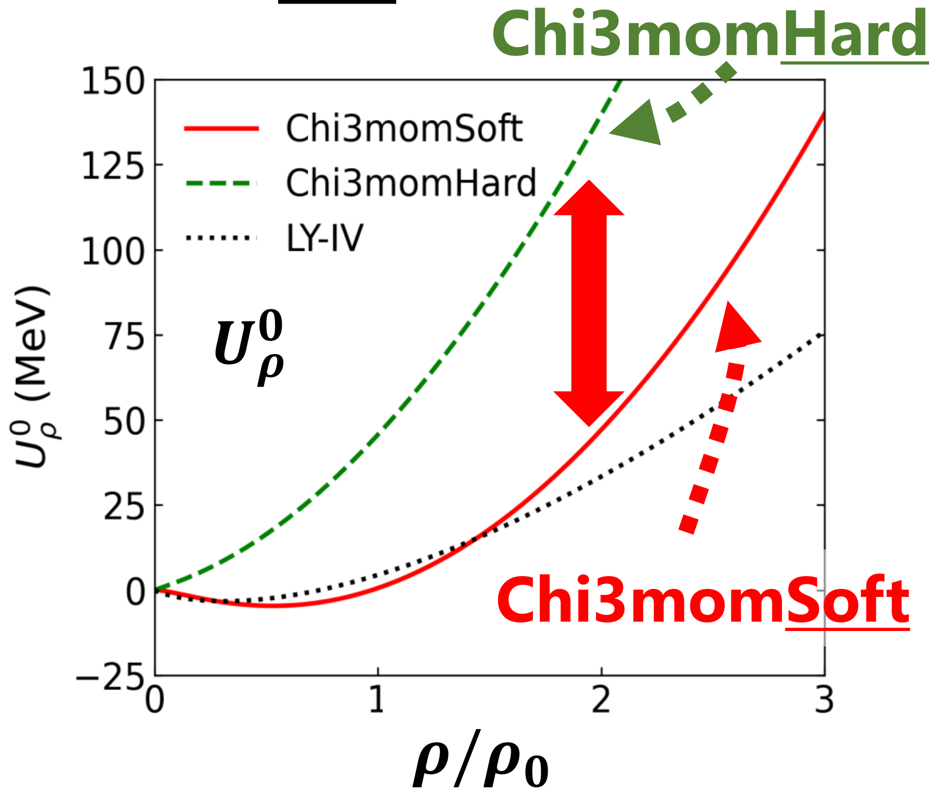
$$a\left(\frac{\rho}{\rho_0}\right) + b\left(\frac{\rho}{\rho_0}\right)^{4/3} + c\left(\frac{\rho}{\rho_0}\right)^{5/3} + \frac{2C\mu^3}{\pi^2\rho_0}\left(\frac{p_f}{\mu} - \arctan\left(\frac{p_f}{\mu}\right)\right)$$



C, μ: fitting parameter for mom. dep.
p_f: fermi momentum



$$U^0 = U_\rho^0 + U_m^0$$



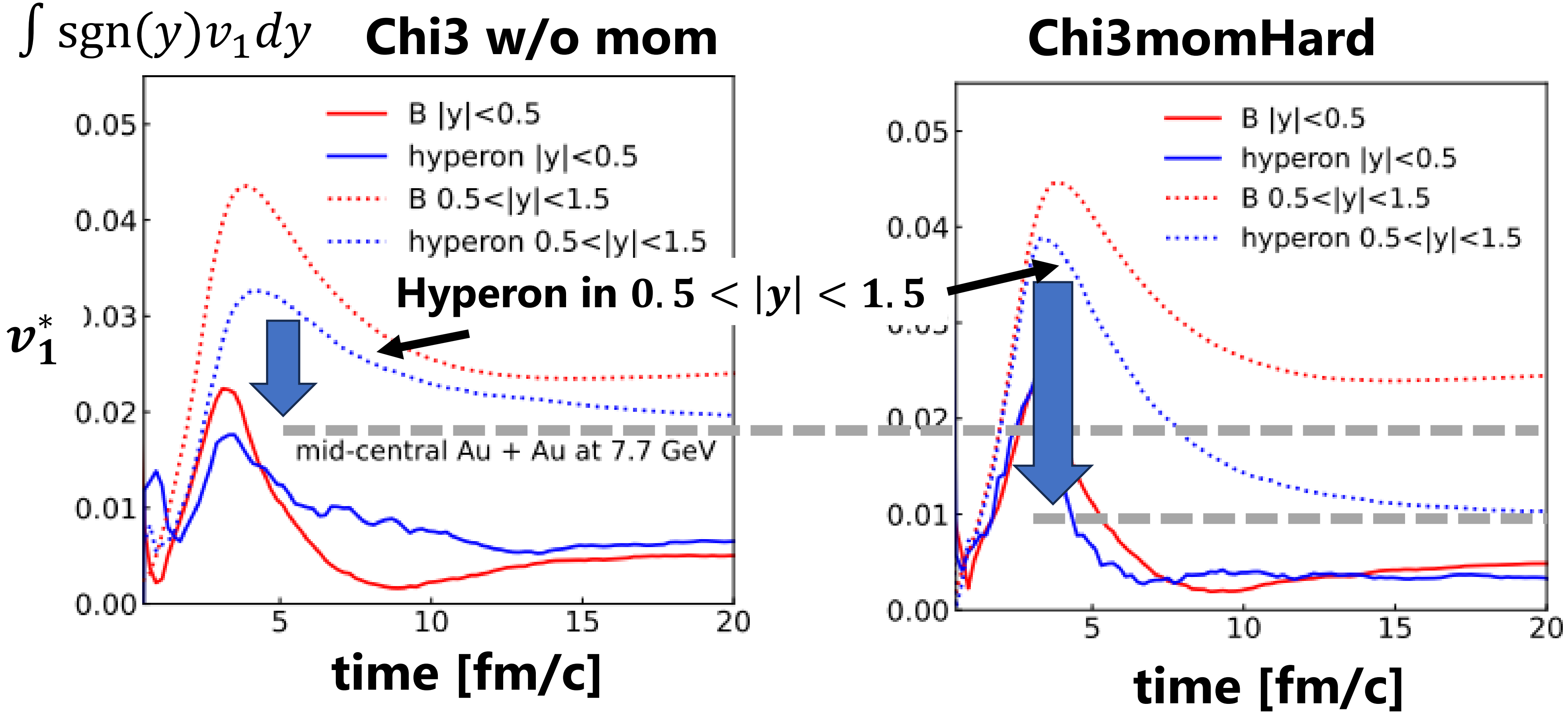
v_1 with and without momentum dependence

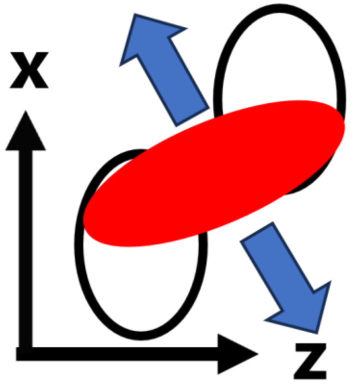
Y. Nara, A. Jinno, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).

In the expansion stage, v_1 of Λ is much suppressed with momentum dependence.

The momentum dependence enhances the repulsion.

$v_1^* = \int \mathrm{sgn}(y) v_1 dy$



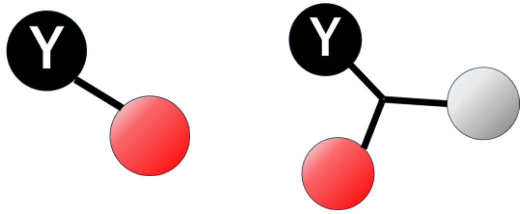


[Ad] Ongoing works to be given in QM2025

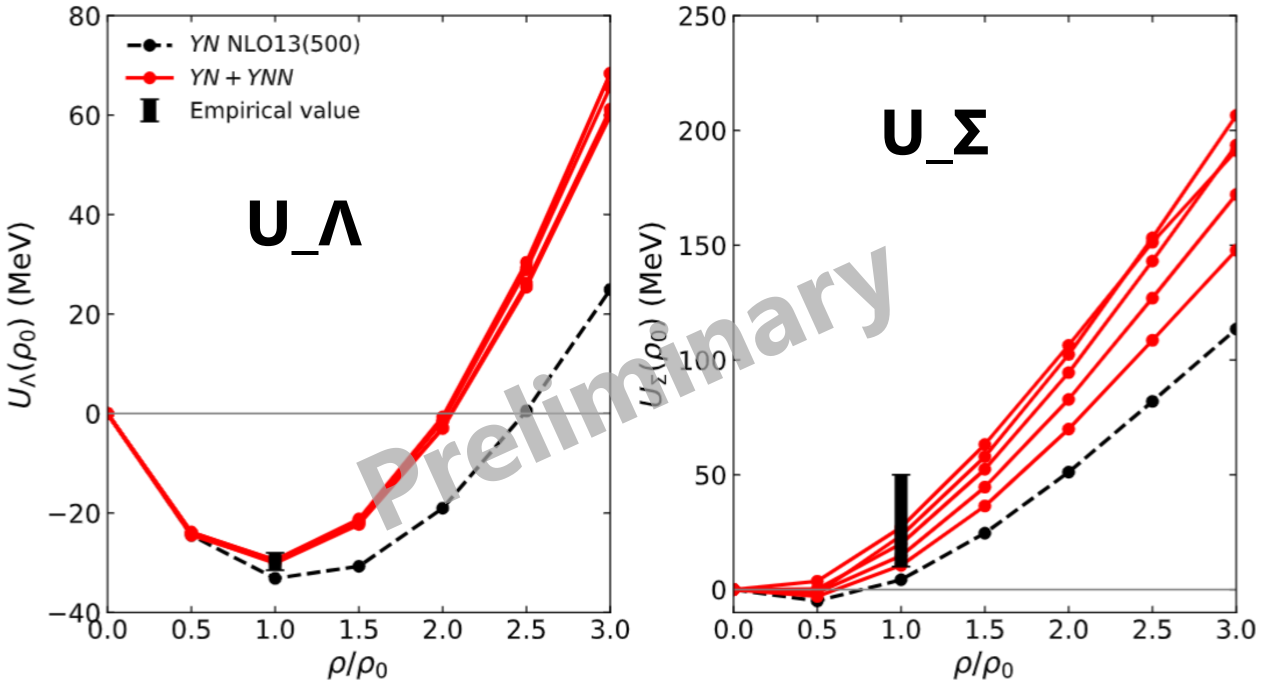
- **Improving the formalism of RQMD simulation with a better approximation.**
  Y. Nara, AJ, and K. Murase, in preparation. (Poster in QM 2025)
- **Implementing the Σ potential consistently calculated as the Λ potential.**
  AJ, J. Haidenbauer, K. Murase, Y. Nara, on working (Oral talk in QM 2025)

(Note) v_1 of Λ is here calculated as v_1 of Σ0+Λ. cf. $\Sigma^0 \to \Lambda + \gamma$

Chiral EFT
YN 2BF + YNN 3BF



Matter calculation (Brückner-HF)



AJ and Johann Haidenbauer, on working.

Summary

We have examined the scenario which hyperon does not appear in neutron stars using the Λ directed flow v_1 created in the heavy-ion collision.

- **<u>The chiral EFT model is consistent with the experimental data!</u>**
- **Λ v_1 is not so sensitive to the density dependence of the Λ potential but is <u>sensitive to the momentum dependence</u>.**
- **With the momentum dependence, the repulsion felt by Λ is enhanced.**
- **The Λ optical potential from e.g. Λ-A scattering may be useful to constrain it.**

Ongoing work

- **Constructing the Σ potential based on chiral EFT**
- **Implementing the Λ and Σ potentials consistently in the event generator JAM2**