Lambda potential in dense nuclear matter from chiral EFT: Bridging heavy-ion collisions, hypernuclei, and neutron stars

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in collaboration with

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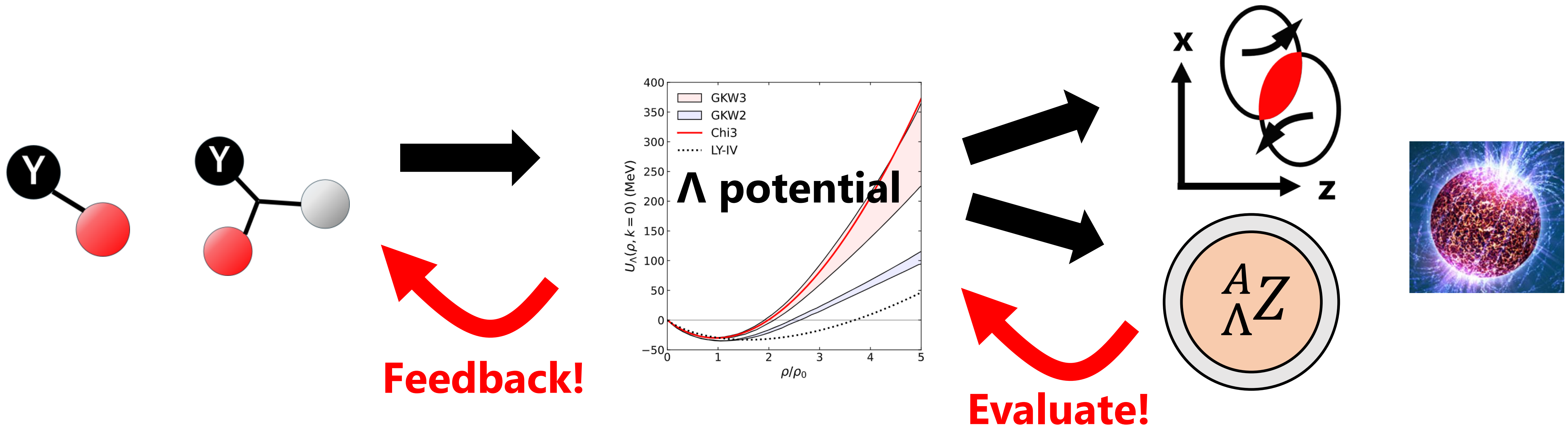
Y. Nara, AJ, K. Murase, and A. Ohnishi, Phys. Rev. C 106 (2022) 044902.
AJ, K. Murase, Y. Nara, and A. Ohnishi, Phys. Rev. C 108 (2023) 065803.
AJ, K. Murase, and Y. Nara, arXiv:2501.09881 (2025) (Proceeding for EXA/LEAP2024)
+ ongoing work

JLab Hypernuclear Collaboration Meeting 2025, 16 May, 2025

- **Neutron star matter EOS study and Λ potential**
- **Evaluation of the Λ potential/YN+YNN forces from chiral EFT**

1. Λ hypernuclear spectroscopy

2. Λ directed flow v_1 of heavy-ion collisions

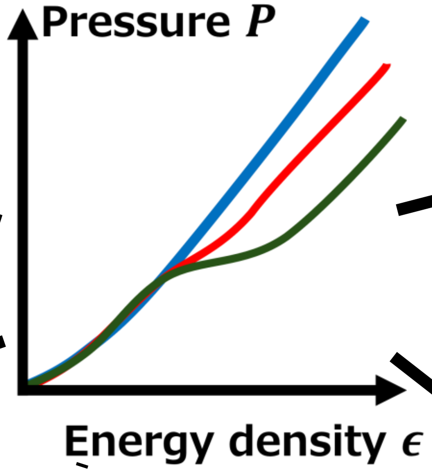


Nuclear matter EOS

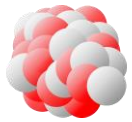
■ (Nuclear matter) Equation Of State, EOS, $P(\epsilon, T, \mathrm{etc.})$:

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

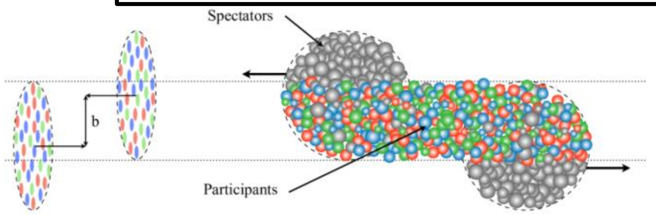
EOS of dense nuclear matter plays an important role in various physics!



(Hyper) Nuclear structures & reactions



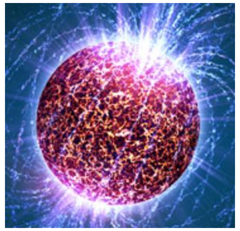
Heavy-ion collisions



CERN

Lattice QCD △ (sign problem)

Neutron stars



LIGO

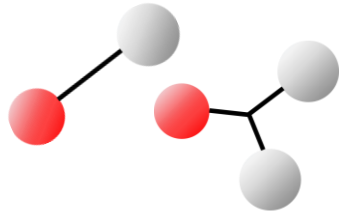
Supernovae

EOS models ⇄ Experiments and observations

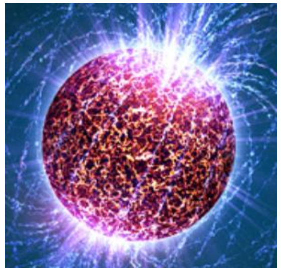
Unified approach for neutron star EOS

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

- **Lower density:** based on **NN + NNN int. from chiral EFT**, or well constrained **mean field model**

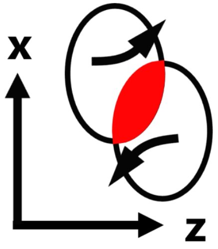


- **Higher density**: combining many observational/experimental information



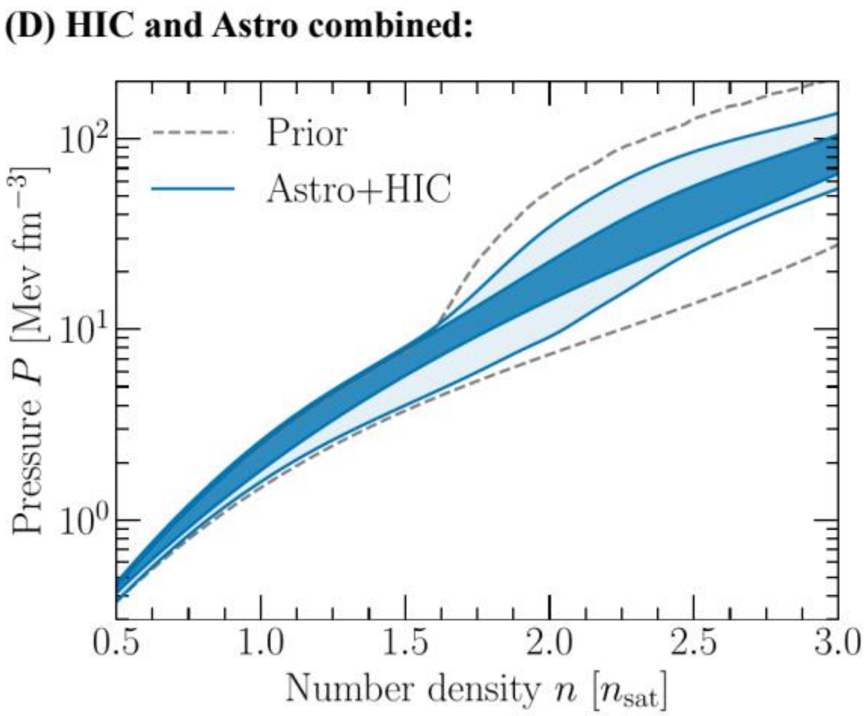
Neutron star observation

e.g. E. Annala et al., Nature Phys. 16, 907 (2020); Y. Fujimoto, K. Fukushima, & K. Murase, PRD 101, 054016 (2020), L. Brandes, Weise, Kaiser, PRD 108, 094104 (2023).



Neutron star observation + heavy ion (collective flow)

e.g. S. Huth et al., Nature 606 (2022) 276.; N. Rutherford et al.; Astrophys. J. Lett. 971 (2024) L19.



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

Hyperon composition is important!

Such an approach does <u>not</u> tell us the <u>detailed properties</u> of EOS.

Given density ρ: **Proton ?? %** **Neutron ?? %** **<u>Hyperon</u> <u>?? %</u>**

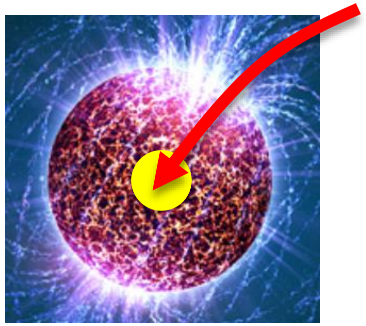
Microscopic description would give more insight to hadron-quark phase transition and guide to construct finite temperature EOS.

Appearance of <u>hyperons significantly changes the EOS!</u>

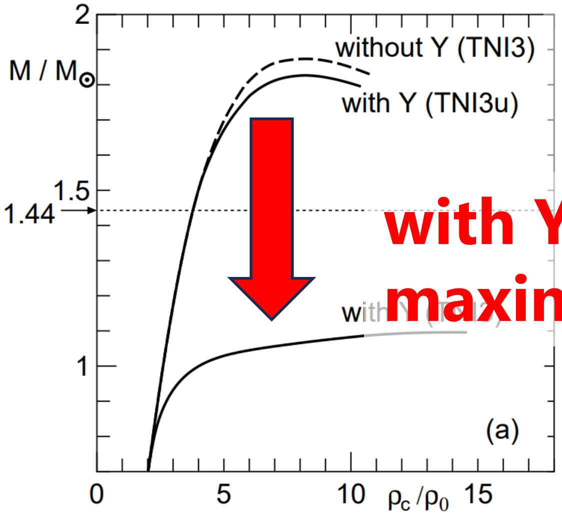
cf. Hyperon puzzle of neutron stars, Demorest et al. Nature (2010).

(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.



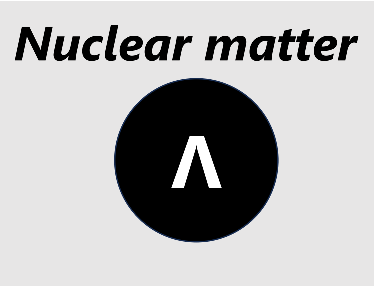
Λ, Σ-



Mass-radius relation of NS

with Y: Reduction of maximum NS mass

Λ potential in nuclear matter

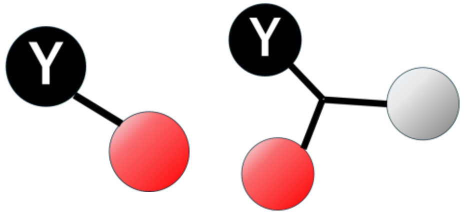


An important quantity: **Λ single-particle potential (Λ potential)**

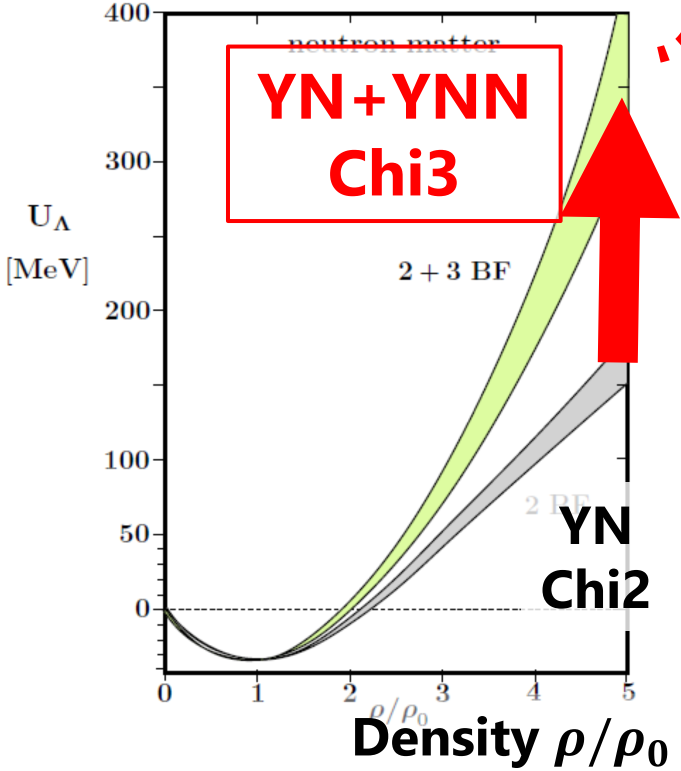
~ average repulsion and attraction Λ feels in nuclear matter

E.g.: D. Gerstung, N. Kaiser, and W. Weise, EPJA 56, 175 (2020)

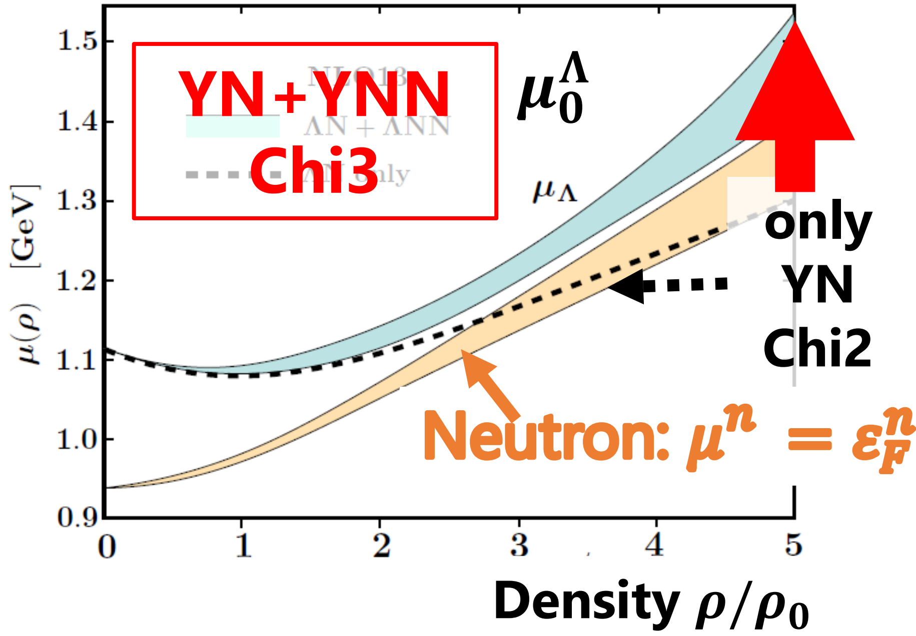
SU(3) Chiral EFT



Matter calculation (BHF)

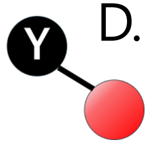


$$\mu_0^\Lambda(\rho) = m_\Lambda + U_\Lambda(\rho)$$



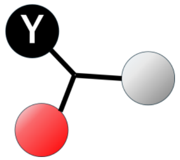
Λ does not appear even at high densities!
Can we avoid the hyperon puzzle...?

Construction of the Λ potential



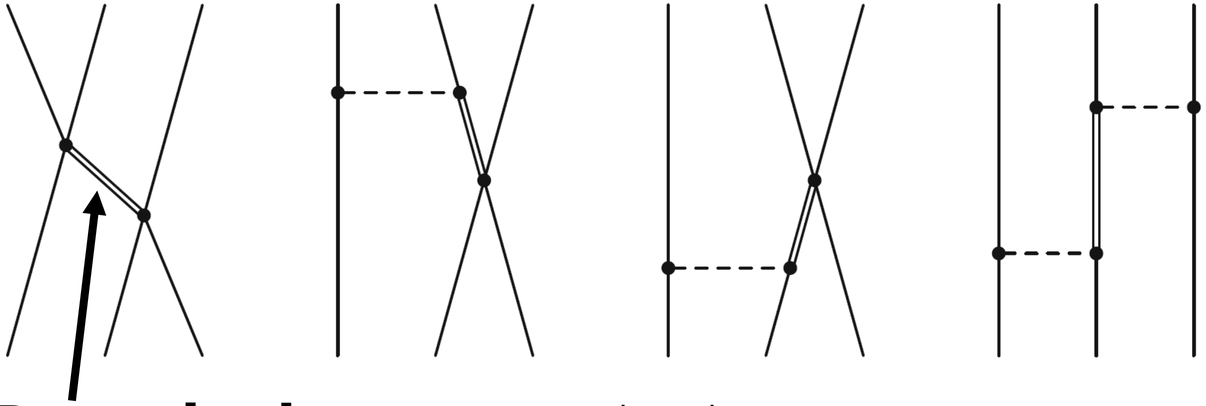
D. Gerstung, N. Kaiser, & W. Weise (2020).

NLO13(500) J. Haidenbauer et al., Nucl. Phys. A 915, 24 (2013).

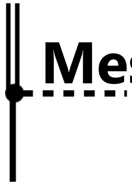


Decuplet saturated three-body forces: Only 3 LECs

Low-energy constants

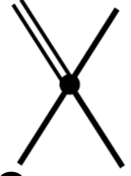


Decuplet baryon $\Delta, \Sigma^*, \Lambda^*$

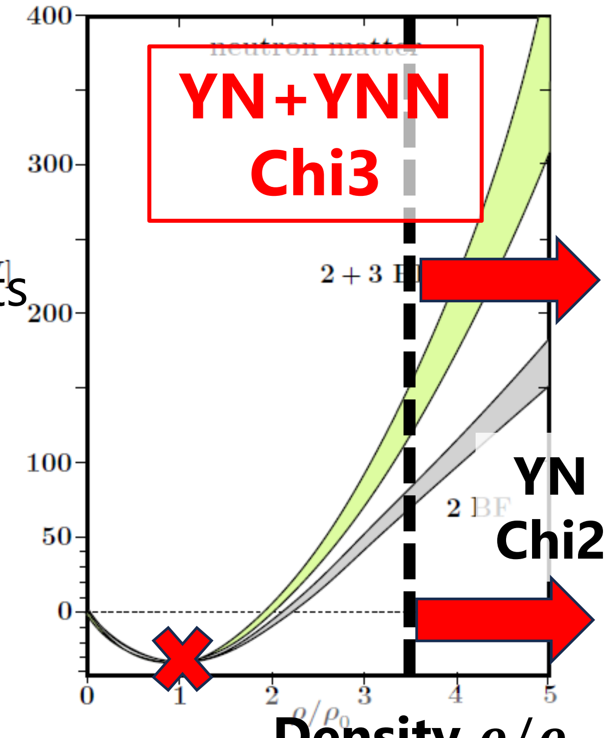


$\propto C$

Determined from $\Delta \to \pi N$ transition



$\propto H_1, H_2$



- **Empirical value based on Λ hypernuclei $U_\Lambda(\rho_0) \approx -30$ MeV is fitted**
- **$\rho \gtrsim 3.5\rho_0$ is extrapolated by using the anzats**

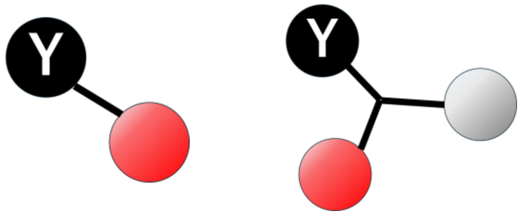
$$U_\Lambda(\rho) = u_0 + u_1\left(\frac{\rho}{\rho_0} - 1\right) + u_2\left(\frac{\rho}{\rho_0} - 1\right)^2 .$$

Validity of the Λ potential in $\rho < \rho_0$ and $\rho > \rho_0$ should be evaluated!

Purpose of this research

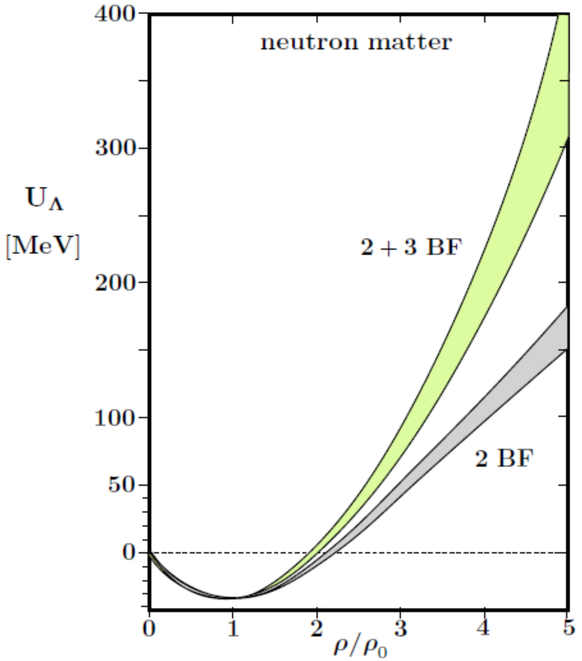
Evaluating the validity of the strongly repulsive Λ potential based on chiral EFT by using the heavy-ion collision and hypernuclear data.

YN + YNN forces from Chiral EFT



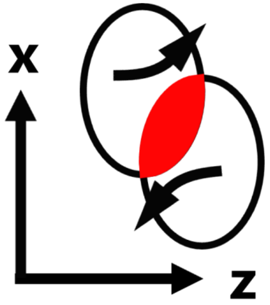
Feedback!

Λ (+Σ) single-particle potential



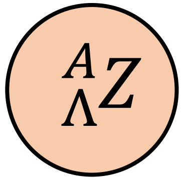
JAM2

Λ+Σ0 directed flow



Skryme-HF

Λ hypernuclei

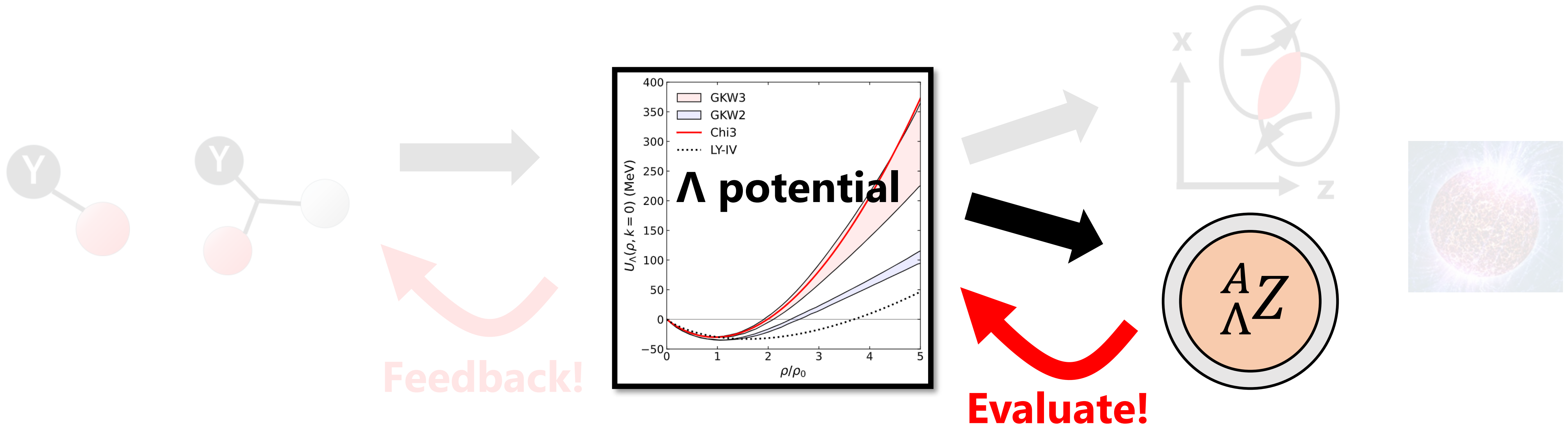


Evaluate!

Unified approach for the Λ potential!

- **Neutron star matter EOS study and Λ potential**
- **Evaluation of the Λ potential/YN+YNN forces from chiral EFT**

  1. ***Λ hypernuclear spectroscopy***
  2. **Λ directed flow v_1 of heavy-ion collisions**

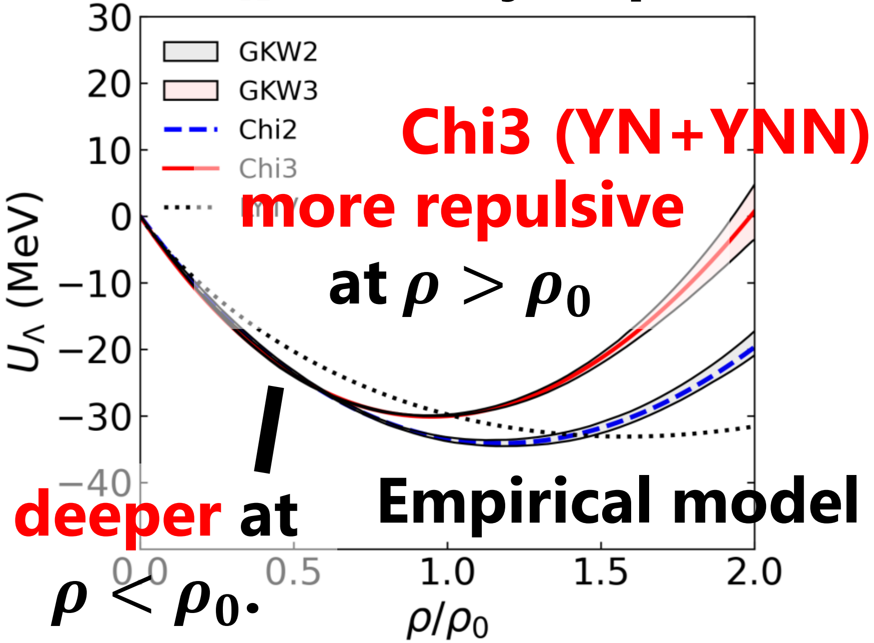


Motivations of using Λ binding energy

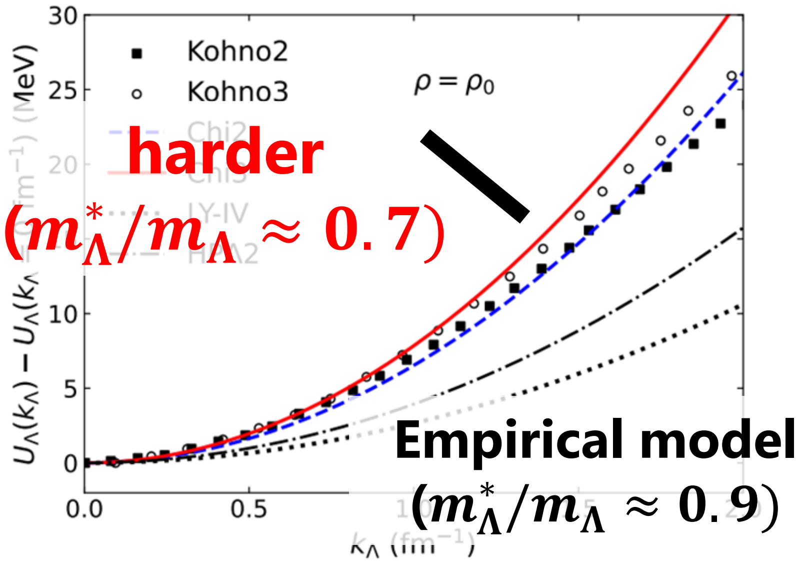
Λ binding energy B_Λ = ${}^{A-1}Z$ — ${}^{A}_{\Lambda}Z$

Behaving differently from the empirical Λ potentials used in Skyrme-Hartree-Fock method. e.g. LY-IV: Lanskoy and Yamamoto (1997)

U_Λ: Density dep.



U_Λ: Momentum dep.



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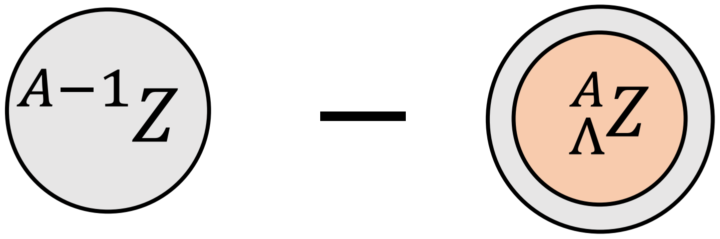
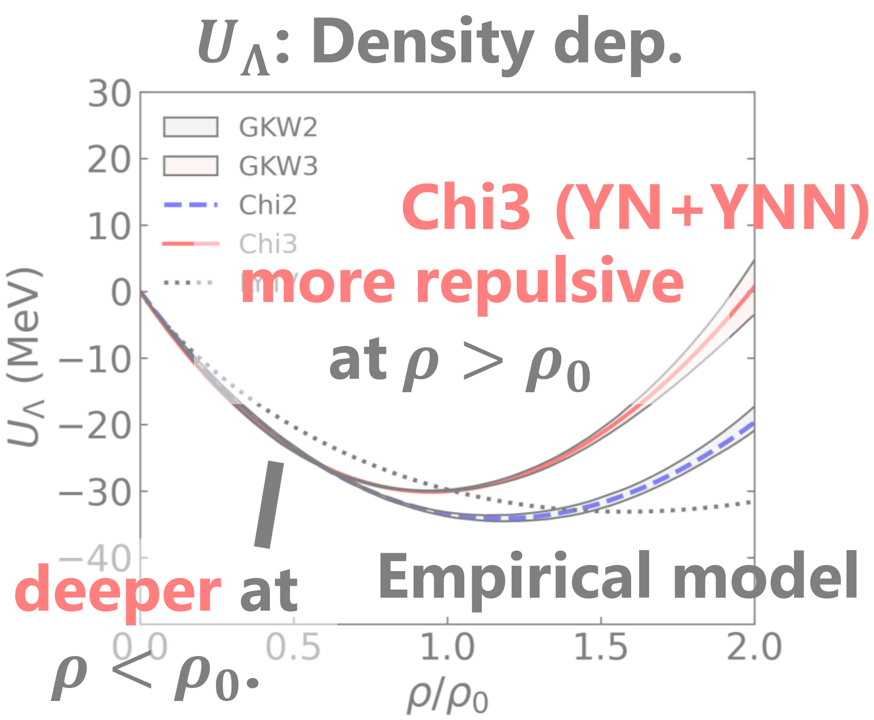
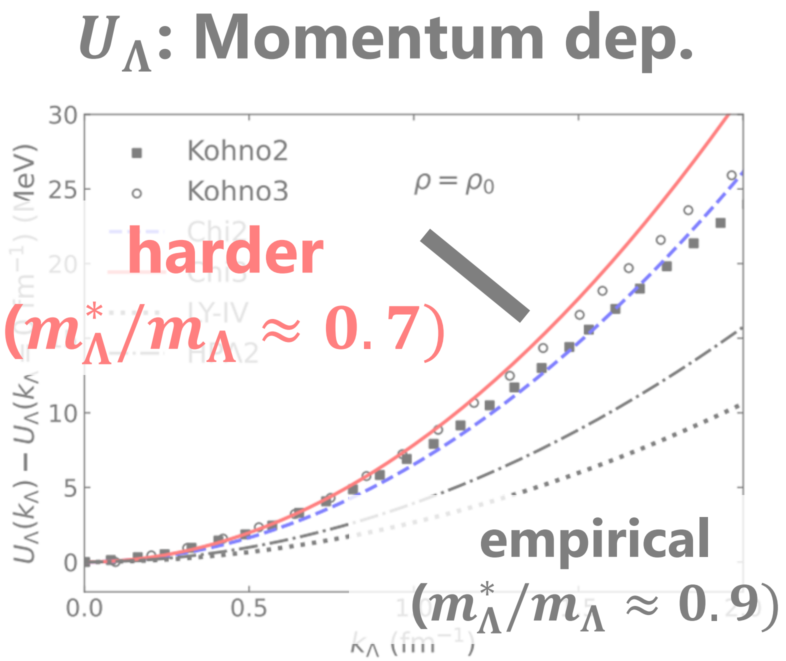
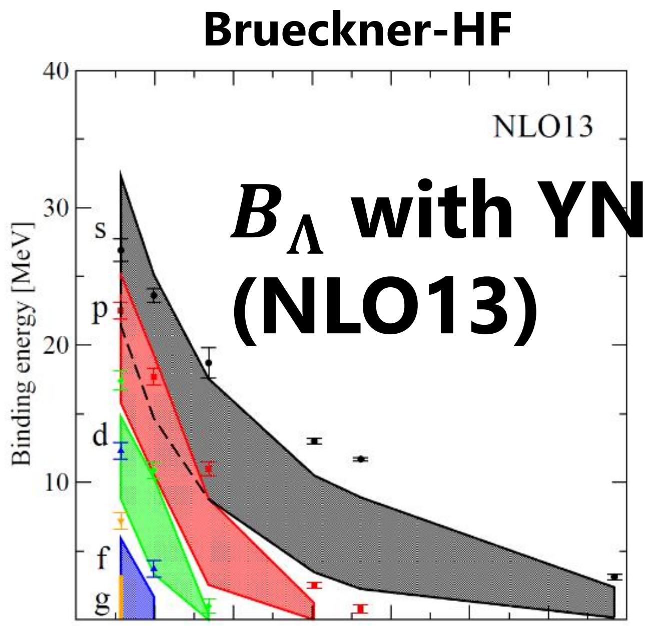


NLO result has been tested but does not explain the data well.

Haidenbauer and Vidaña (2021) **How about including ΛNN int.?**







Haidenbauer and Vidaña (2021)

Spherical Skyrme-Hartree-Fock for Λ hypernuclei

Skyrme-Hartree-Fock eq.

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

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

For Λ, ignore $i\boldsymbol{W}_B\cdot(\nabla\times\sigma)$
(∵Spin-orbit potential for Λ is small.)

effective mass $$\frac{\hbar^2}{2m_\Lambda^*}=\frac{\hbar^2}{2m_\Lambda}+a_2^\Lambda\rho_N$$

single-particle potential $$U_\Lambda=a_1^\Lambda\rho_N+a_2^\Lambda\tau_N-a_3^\Lambda\Delta\rho_N+a_4^\Lambda\rho_N^{4/3}+a_5^\Lambda\rho_N^{5/3}$$

Self-consistent calculation

Λ binding energy $B_\Lambda=-(E_{\mathrm{Hyper}}-E_{\mathrm{Core}})$

density $\rho_N=\sum_{B=p,n}\sum_i|\psi_{B,i}|^2$

kinetic density $\tau_N=\sum_{B=p,n}\sum_i|\nabla\psi_{B,i}|^2$

Λ kinetic density $\tau_\Lambda=|\nabla\psi_\Lambda|^2$

(Note) For neutron and proton, we use SLy4 (Chabanat et al. (1998)).
(Note2) CSB, pair correlation, and deformation are neglected.

Fitting of the Λ potential from chiral EFT

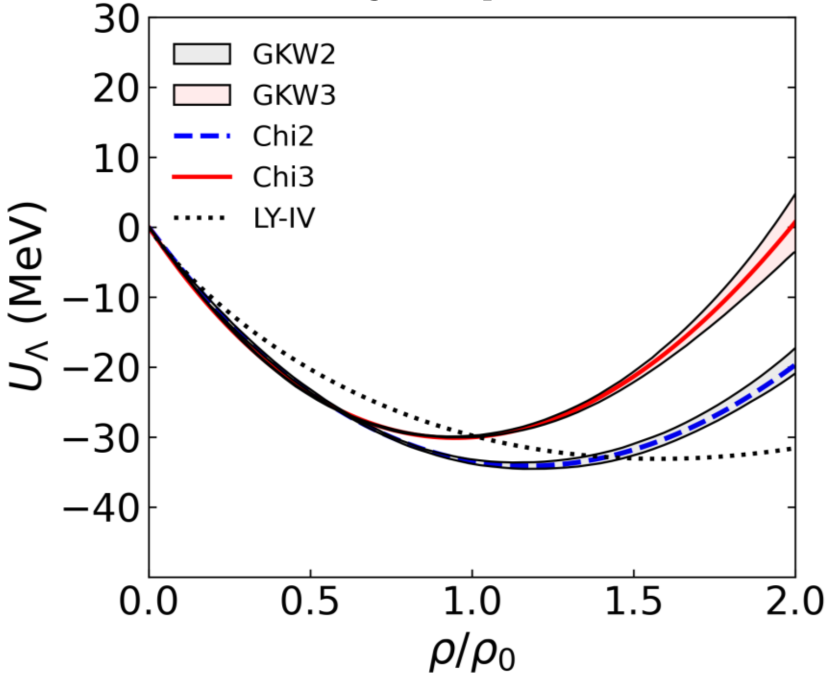
Skyrme-type mom. dep. Λ potential in uniform matter

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

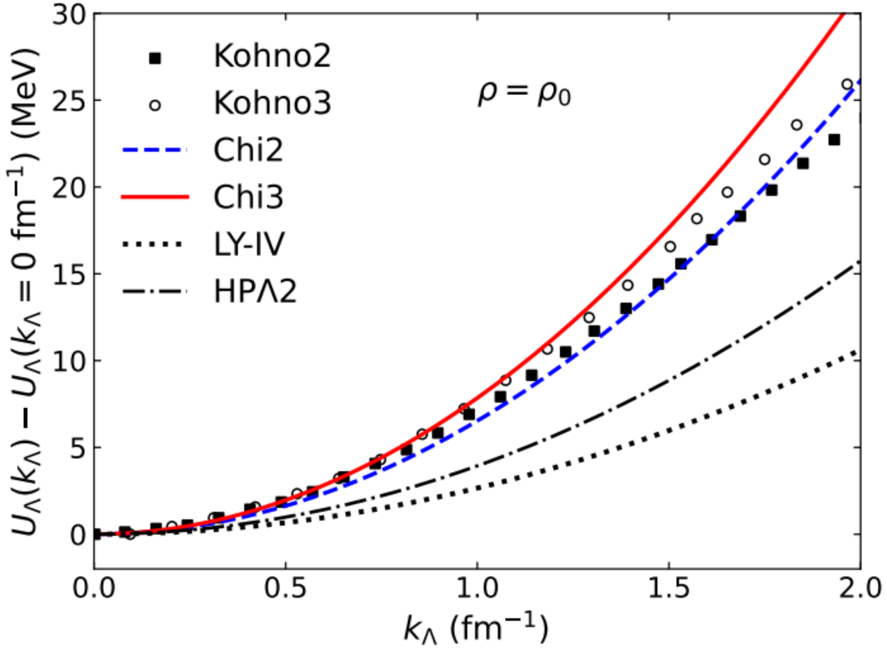
$$U_\Lambda = a_1^\Lambda \rho_N + \underline{a_2^\Lambda (k_\Lambda^2} \rho_N + \tau_N) - a_3^\Lambda \Delta\rho_N + a_4^\Lambda \rho_N^{4/3} + a_5^\Lambda \rho_N^{5/3}$$

Λ kinetic density $\tau_\Lambda = |\nabla\psi_\Lambda|^2$

Density Dependence



Momentum Dependence



Fit to the results from chiral EFT

GKW2 (GKW3): Gerstung, Kaiser, and Weise (2020).

LY-IV: Lanskoy and Yammoto (1997).

Kohno2 (Kohno3): Kohno (2018)

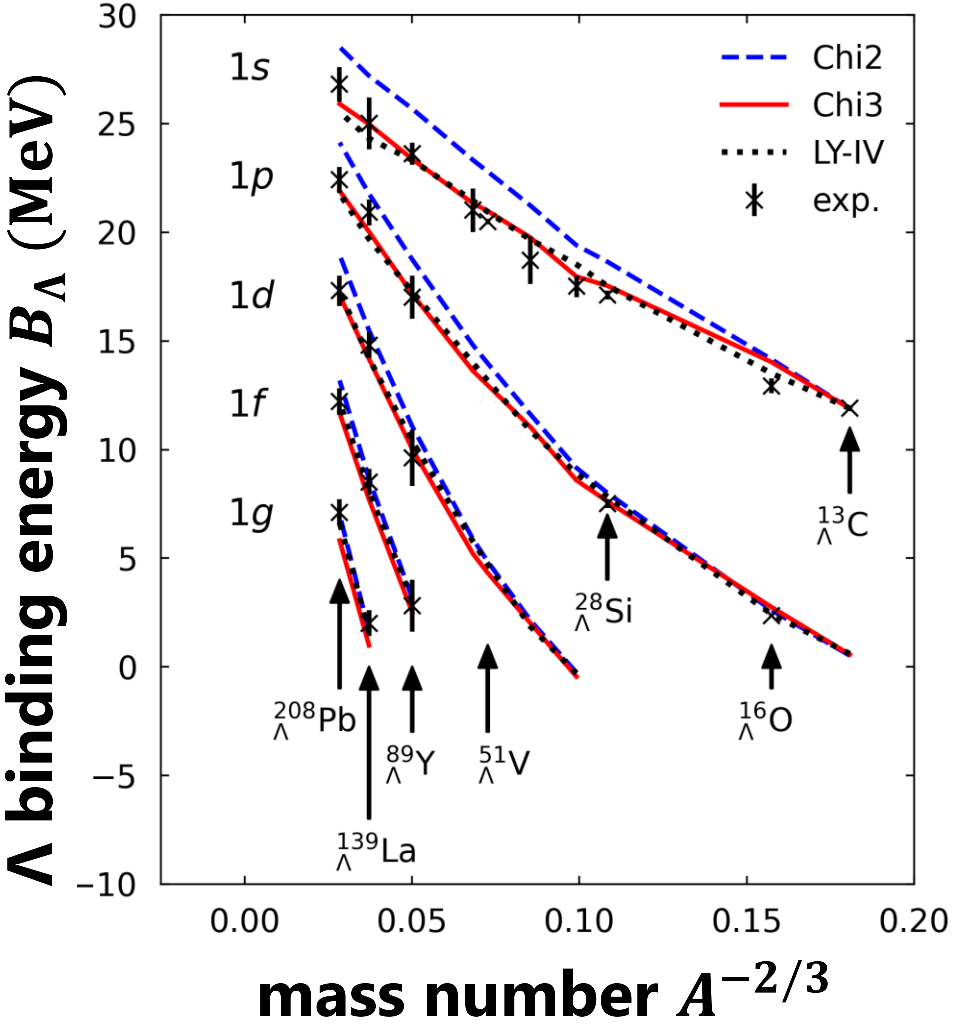
* The value of a_3^Λ is determined to reproduce the Λ binding energy of ${}^{13}_{\Lambda}\mathrm{C}$ (11.88 MeV).

(∵ Surface terms have a large effect. even-even nuclei)

Λ binding energies

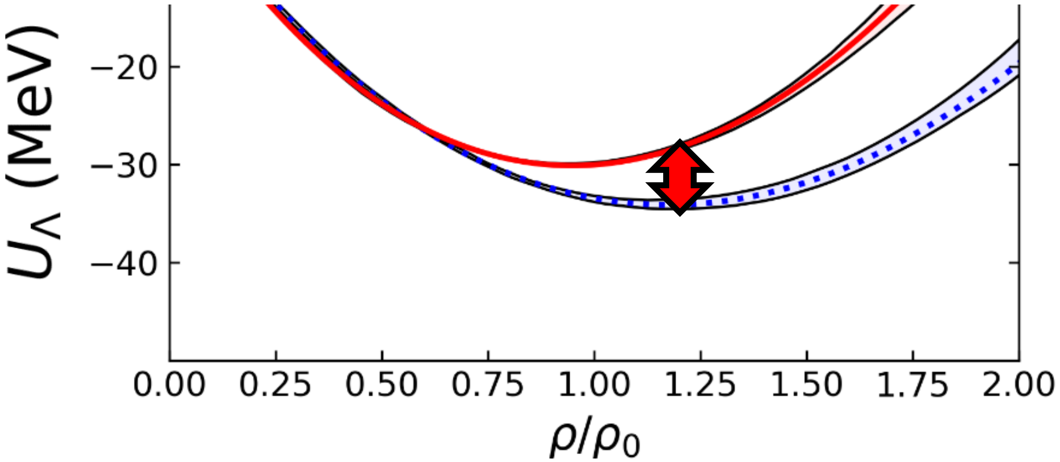
AJ, K. Murase, Y. Nara, & A. Ohnishi, PRC 108, 065803 (2023).

(a_3^Λ in LY-IV model is also tuned to reproduce ${}^{13}_{\Lambda}\mathrm{C}$ data)



- **Chi2 (chiral YN) overbounds a few MeV for *s*-wave.**

  ∵ Λ potential depth of Chi2 is too deep.



- **Chi3 reproduces the data, at the same level of accuracy as LY-IV.**

Both the repulsive and attractive Λ potentials are consistent with the data.

Constraints on U_Λ from Λ hypernuclei

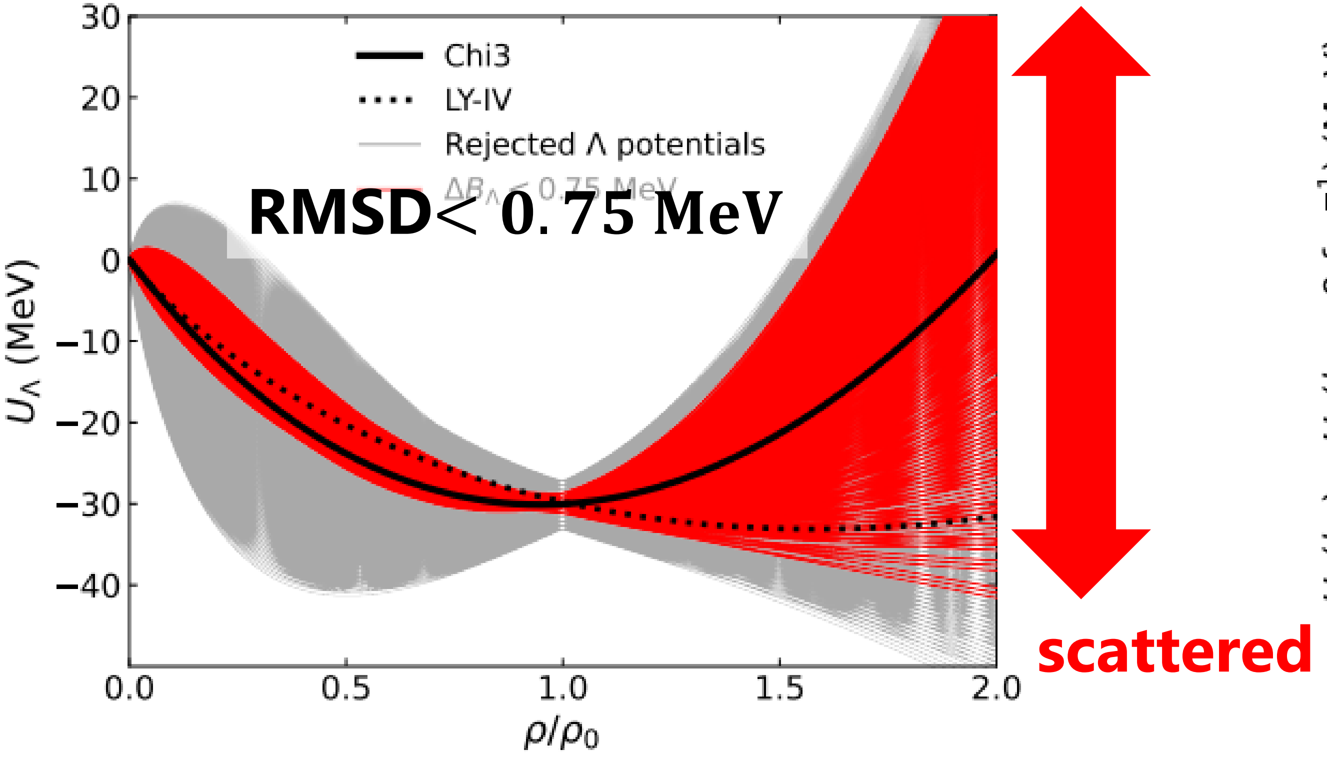
AJ, K. Murase, Y. Nara, & A. Ohnishi, PRC 108, 065803 (2023).

Generating Λ potentials and choose ones well reproduces the experimental data.

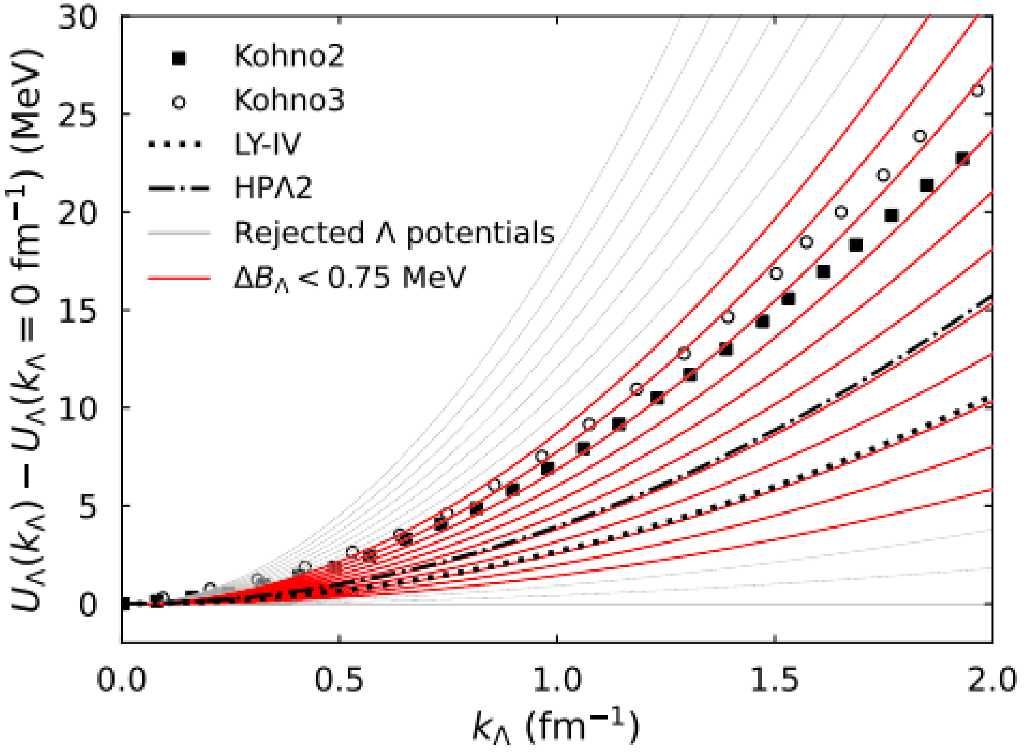
$U_\Lambda(\rho \leq \rho_0)$ and m^*_Λ are constrained to some extent, while

$U_\Lambda(\rho > \rho_0)$ is scattered! We need other data to constrain $U_\Lambda(\rho > \rho_0)$!

Density dependence



Momentum dependence



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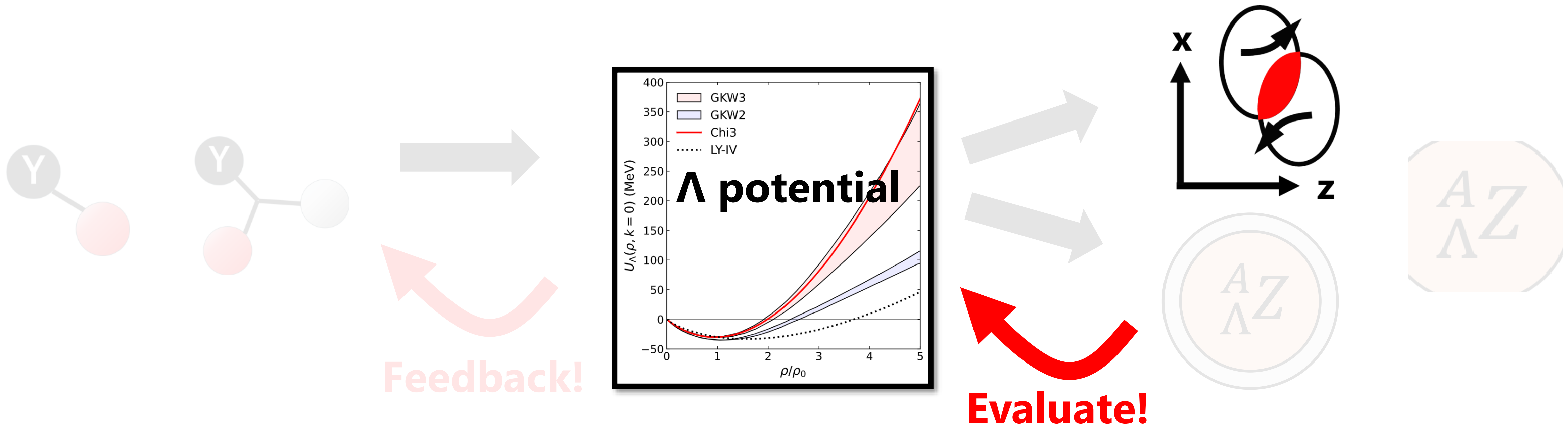
2. Λ directed flow v_1 of heavy-ion collisions



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

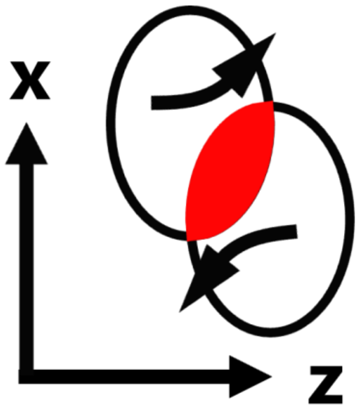
- **The anisotropic collective flow $v_n = \langle \cos n\phi \rangle$ has been extensively investigated to extract the properties of dense matter equation of states.**

  Recent review: A. Sorensen et al., 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 the rapidity $y = \tanh^{-1}\left(\frac{p_z}{E}\right)$**

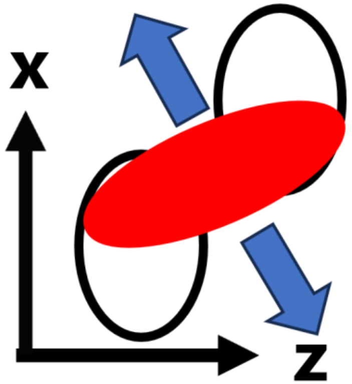
  $(p_T^2 = p_x^2 + p_y^2)$

Early (compression) stage



$v_1 > 0$ for $y > 0$

Later (expansion) stage



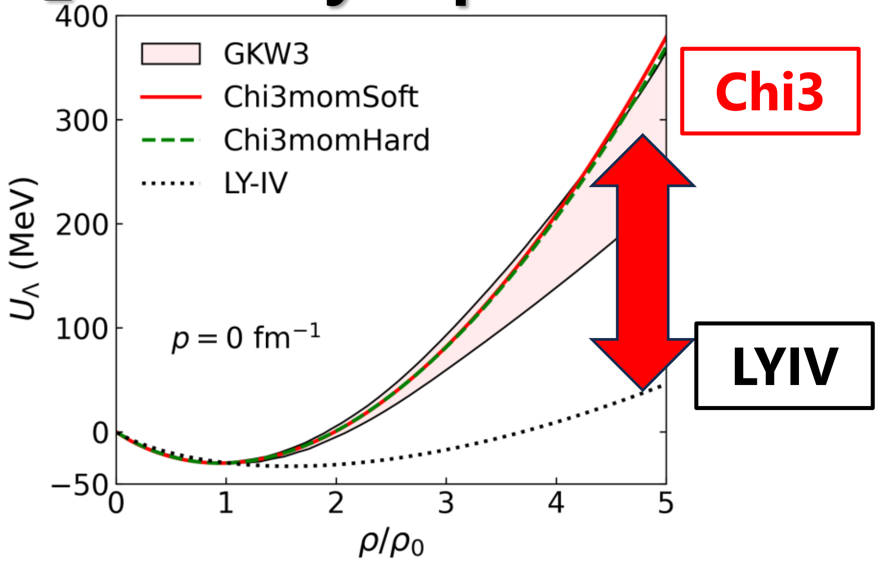
$v_1 < 0$ for $y > 0$

v_1 has a non-trivial dependence on EOS.

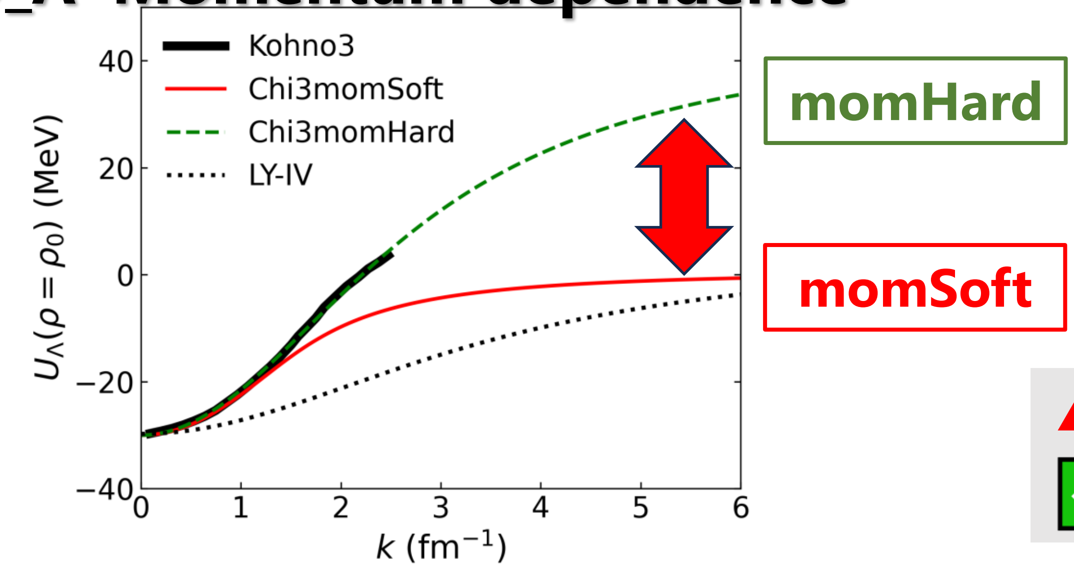
Our previous result in Nara et al. (2022)

Y. Nara, AJ, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).
Updated figures: AJ, K. Murase, and Y. Nara, arXiv:2501.09881 (2025) (Proceeding for EXA/LEAP2024)

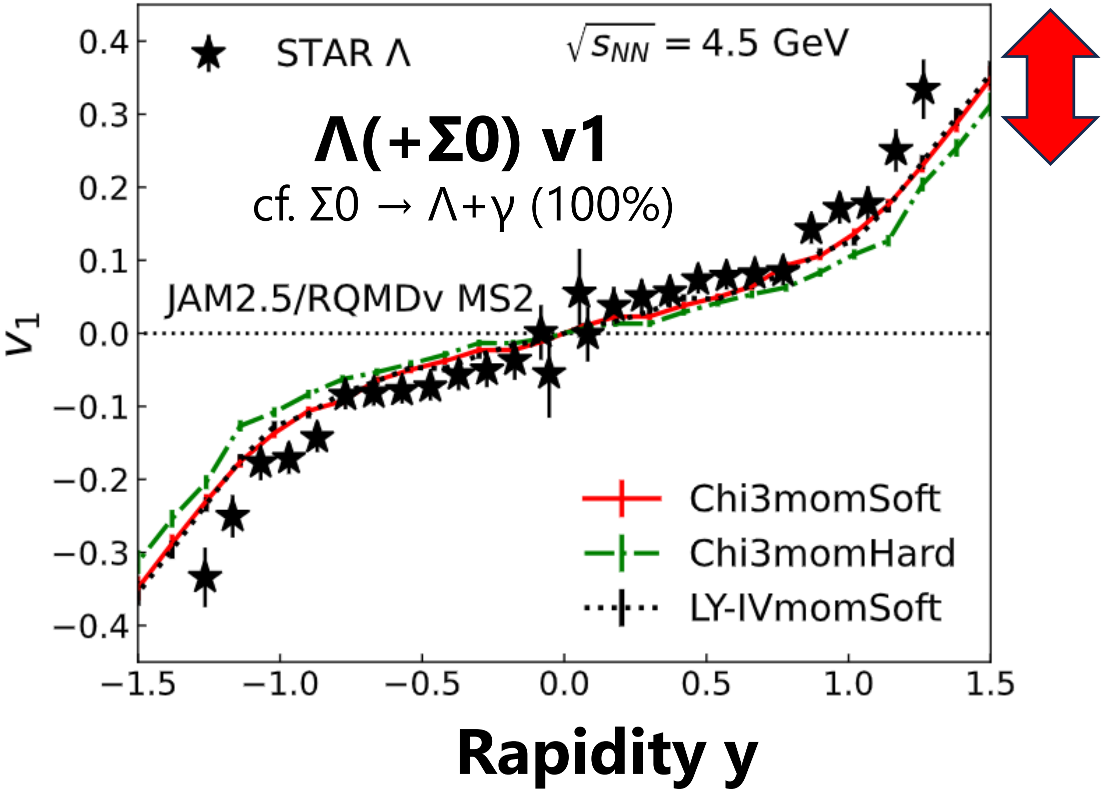
U_Λ Density dependence



U_Λ Momentum dependence



JAM2 RQMDv

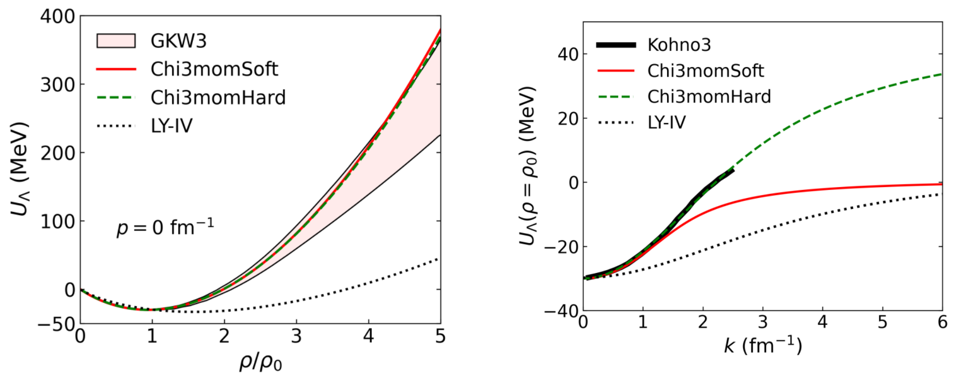


▲ **Insensitive to the density dep. of U_Λ.**

✅ **Sensitive to the momentum dep. of U_Λ.**

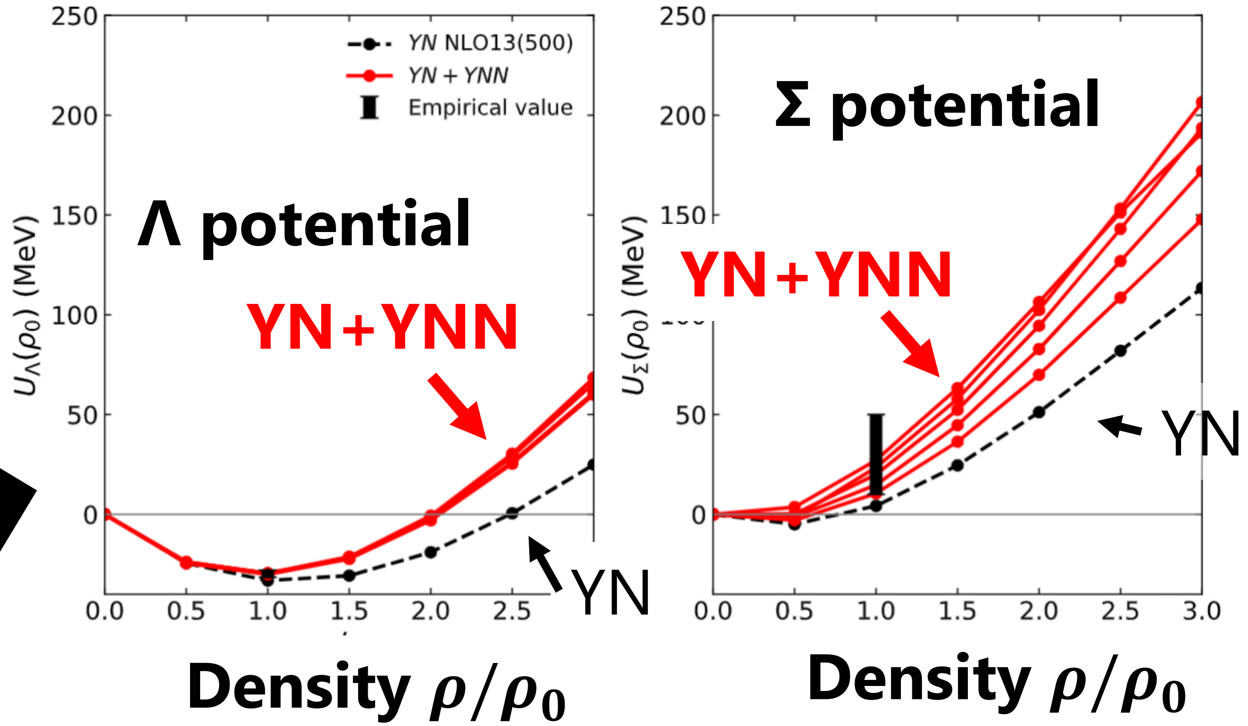
(Extension) Σ potential

- **Previous work: Λ potentials for all hyperons** Y. Nara, AJ, K. Murase, & A. Ohnishi, PRC 106, 044902(2022)
- **Σ potential may affect the Λ+Σ⁰ dynamics in heavy-ion collisions and can be constrained by data!** AJ, K. Murase, and Y. Nara, arXiv:2501.09881 (2025) (Proceeding for EXA/LEAP2024)

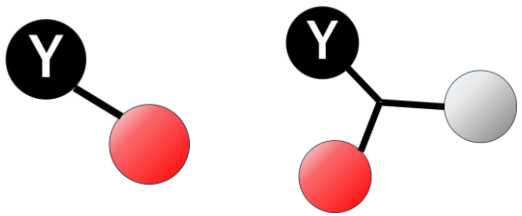


→ Λ, Σ, Ξ, Y*

Symmetric nuclear matter



SU(3) Chiral EFT



Extensions in JAM2 after Nara et al. (2022)

Several (minor) extensions have been made after the Λ v1 paper: Y. Nara, AJ, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).

Λ+Σ0 v1 is still similar.

- **New covariant RQMD model (RQMDv2)**
  Y. Nara, AJ, K. Murase, in preparation. QM2025 Poster
- **Covariant collision term**
  Y. Nara, AJ, T. Maruyama, K. Murase, and A. Ohnishi, Phys. Rev. C 108, 024910 (2023).
- **YN cross section by chiral N2LO**

Action for new RQMD

Motivated by the time-dependent variational principle: $S = \int dt \langle \Phi | i\hbar \frac{\partial}{\partial t} - \hat{H} | \Phi \rangle$

$$S = S_{\rm part} + S_{\rm field} \qquad S_{field} = \int d^4x \mathcal{L}_{\rm field}$$

$$S_{part} = \sum_{i=1}^{N} \int p_i \cdot dx_i - \int d^4x d^4p\, W(x,p) f(x,p)$$

Generalized potential: $W(x,p) = \frac{p^{*2}(x,p) - m^{*2}(x,p)}{2}$

Potential contribution: $p^{*\mu} = p^\mu - U^\mu, \quad m^* = m + U_s$

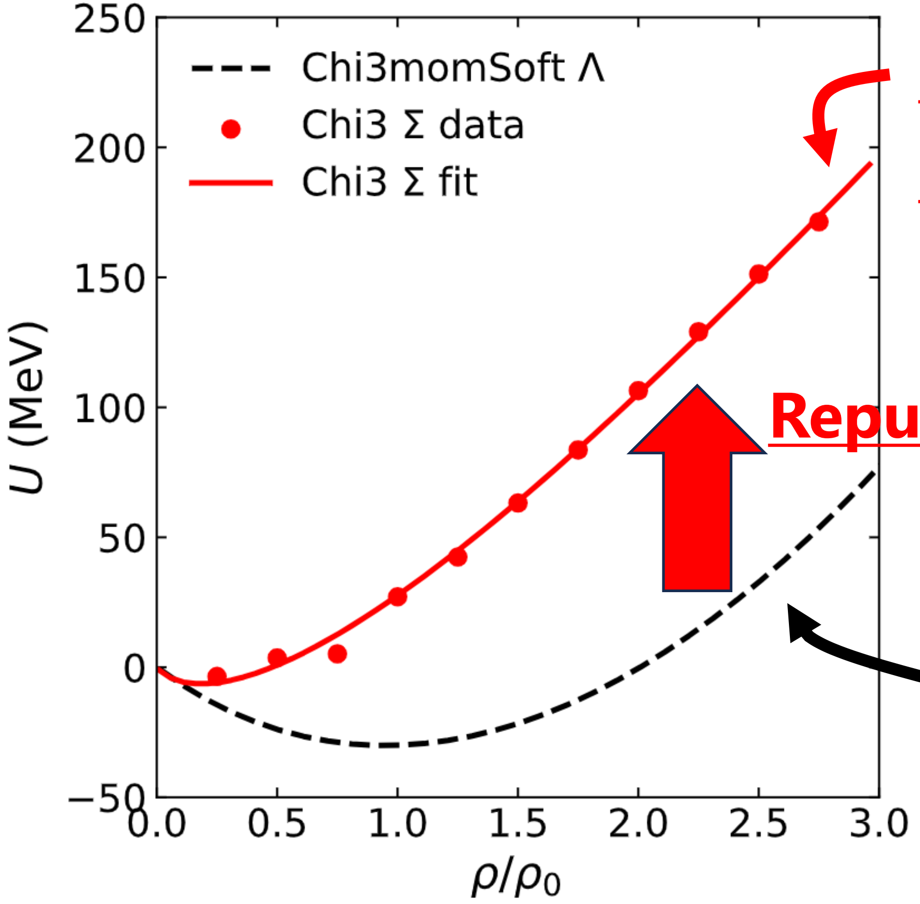
$$f(x,p) = \sum_{i=1}^{N} f_i(x,p) = \sum_{i=1}^{N} \int ds \lambda_i(s) \delta((x - x_i(s)) \cdot \hat{a})) g(x,p; x_i(s), p_i(s))$$

$\lambda_i(s)$ is a Lagrange multiplier and g is a Gaussian profile.

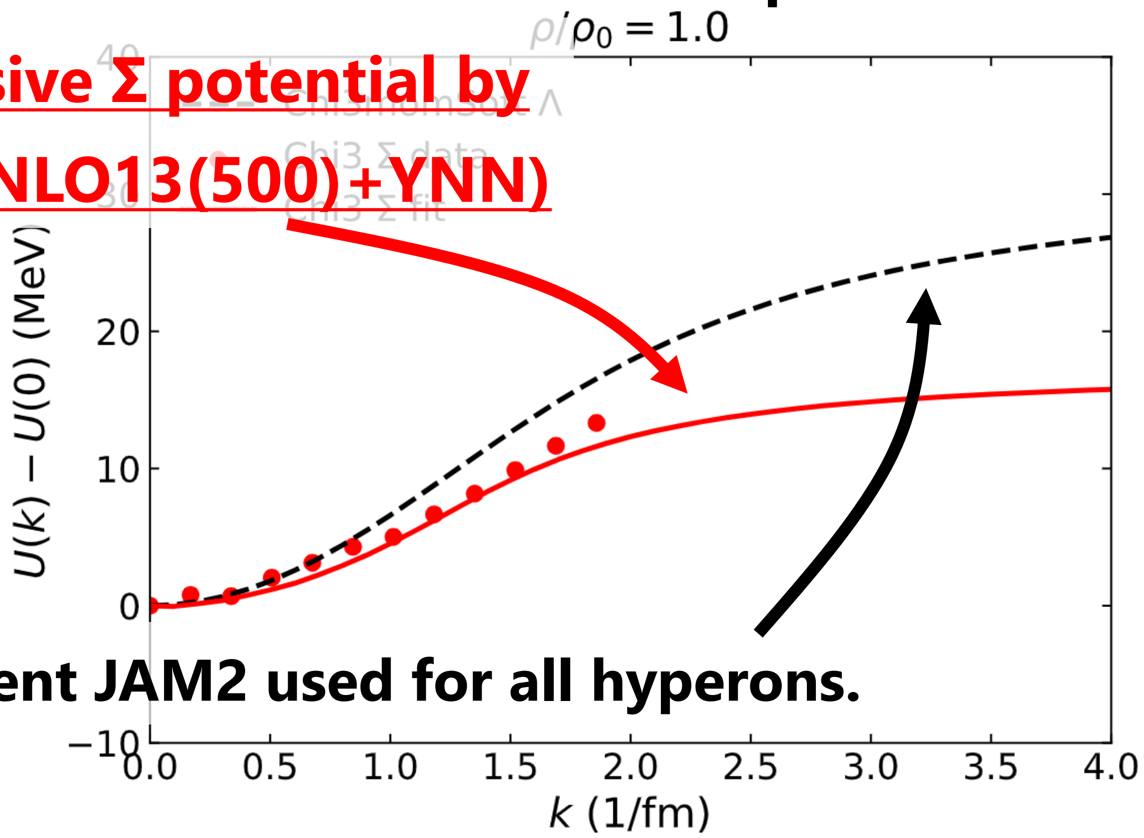
Σ single-particle potentials

For fitting procedure, see Y. Nara, AJ, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).

Density dependence



Momentum dependence



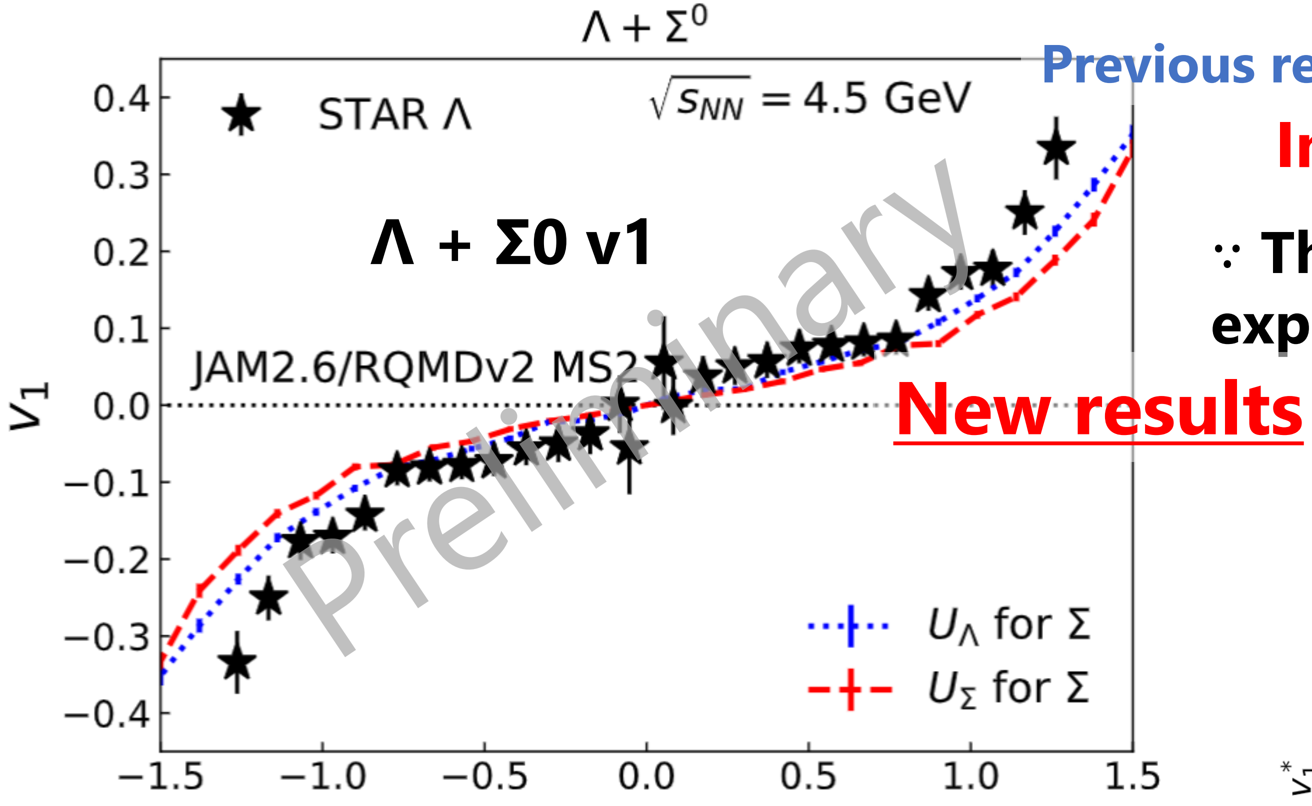
Most repulsive Σ potential by chiral EFT (NLO13(500)+YNN)

U_Λ: Current JAM2 used for all hyperons.

Note: Symmetry energy is not neglected.

Can this difference be found in hyperon directed flows?

$\Lambda+\Sigma 0$ v1 at $\sqrt{s_{NN}}=4.5$ GeV

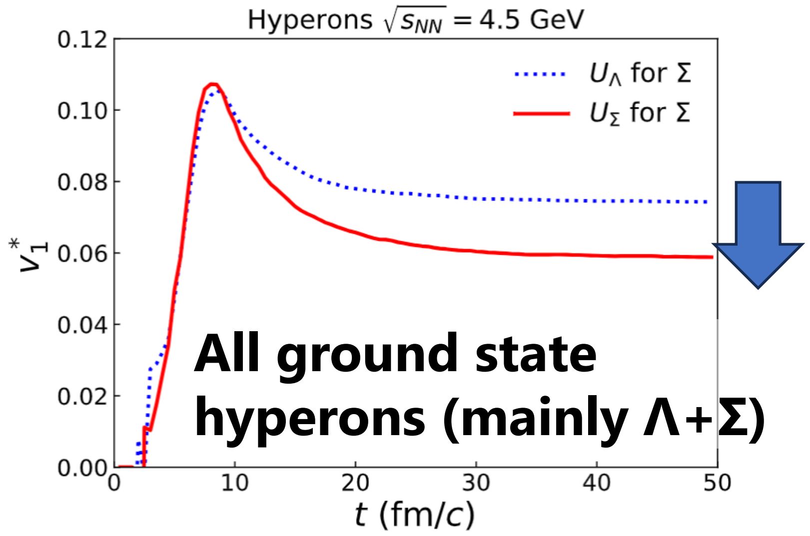


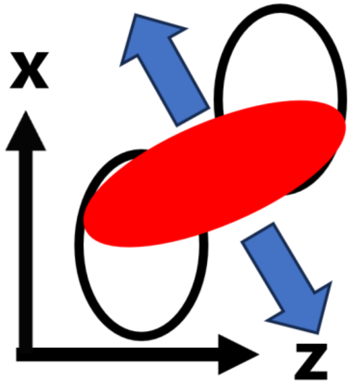
Rapidity $y = \tanh^{-1}\left(\frac{p_z}{E}\right)$

Inclusion of Σ potential decreases v1.

∵ **The Σ repulsion suppresses v1 in the expansion stage by forming the tilted matter.**

$$v_1^* = \int_{-1}^{1} \mathrm{sgn}(y) v_1(y) dy$$

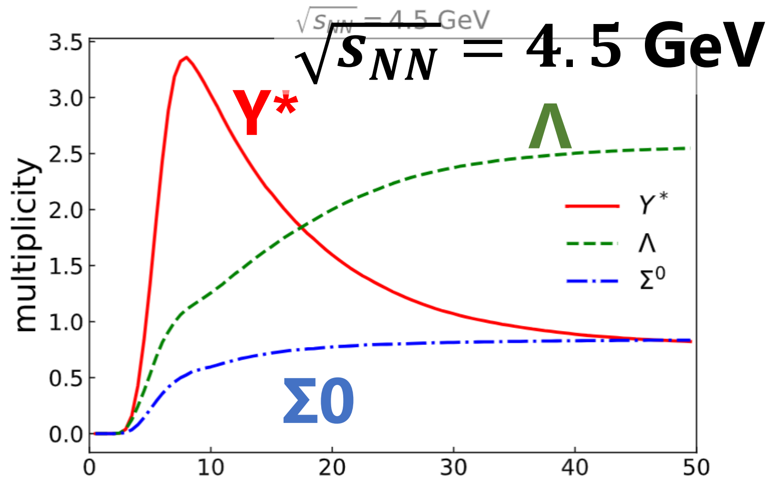




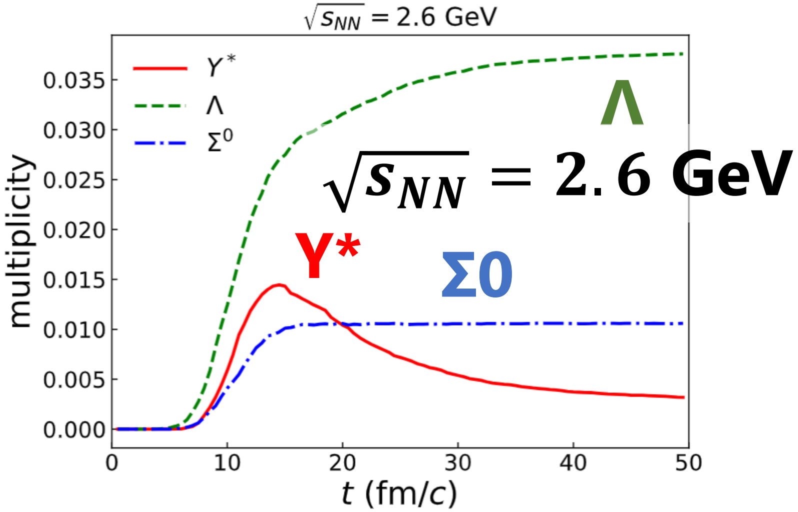
WIP projects for more quantitative modeling

- **Calculating hyperon potentials with <u>chiral N2LO YN+YNN</u>**
  YN: J. Haidenbauer, U.-G. Meißner, A. Nogga, & H. Le, Eur. Phys. J. A 59 (2023) 3, 63.
  YNN: **working with Johann Haidenbauer.**

- **Implementing potentials of hyperon resonances (Y*) by employing the parity doublet model with Y. Nara and K. Murase**



- **To avoid the uncertainty in Y*, lower collision energy (HADES energy) may be preferred.**

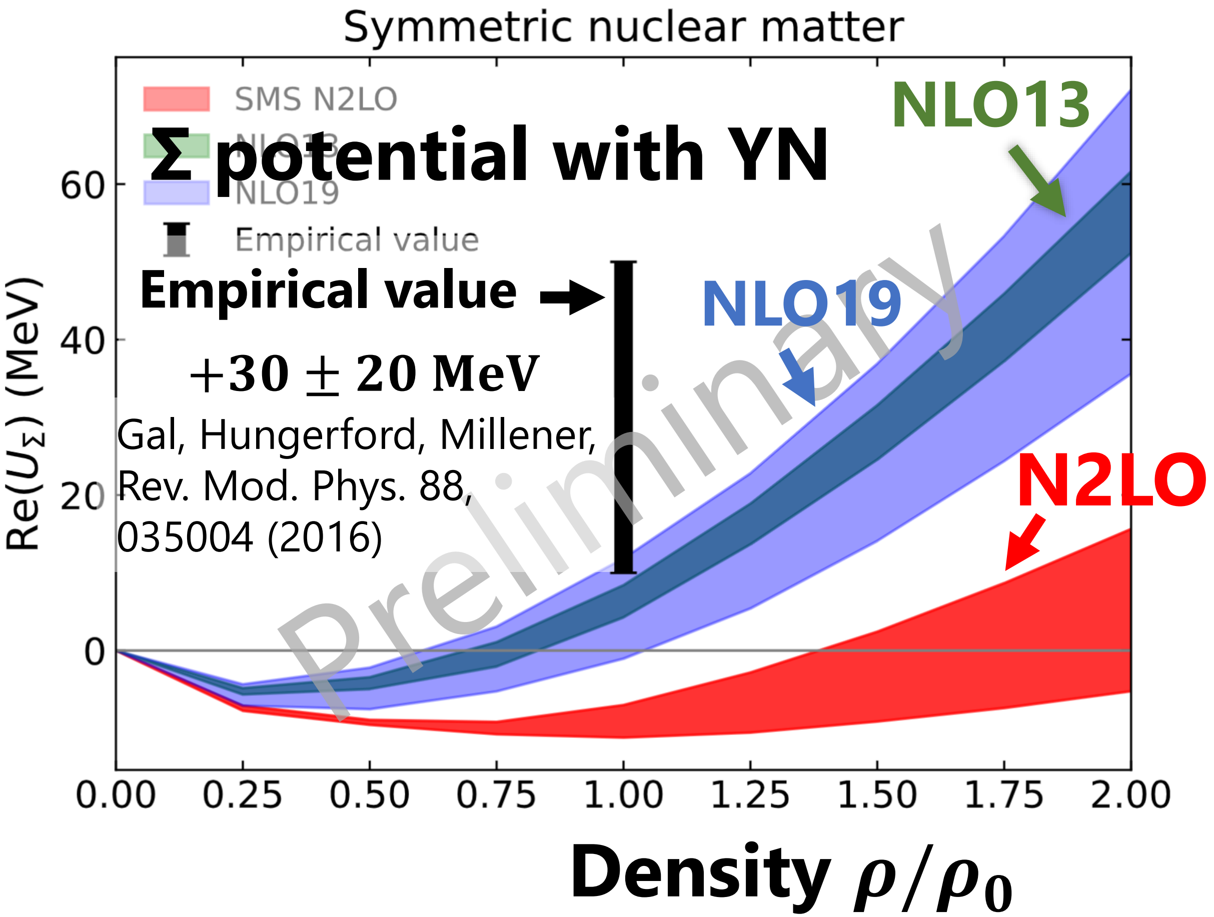


Interactions including resonance hyperon could affect the dynamics.

Σ potential is interesting.

- **Σ potential has large uncertainty:** $U_{\Sigma}(\rho_0) = 30 \pm 20$ MeV
  based on Σ^- atom data and (π^+, K^+) inclusive spectra
  A. Gal, E. V. Hungerford, & D. J. Millener (2016).
- **New nice measurements:**
  - **Differential cross section of Σp (J-PARC E40)**
    $\Sigma^+ p$: T. Nanamura et al., PTEP 2022, 093D01 (2022).
    $\Sigma^- p$: K. Miwa et al., PRC 104, 045204 (2021).
    →More attractive Σ potential
  - **Femtoscopy of Σ^+p**
    B. Heybeck (ALICE) talk at QM2025
  - **Formation of ${}^{5}_{\Sigma}\mathrm{He}$...? inferred from ${}^{5}_{\Lambda}\mathrm{He}$ yield**
    Yingjie Zhou (STAR) talk at QM 2025

A. Jinno and J. Haidenbauer, wip.

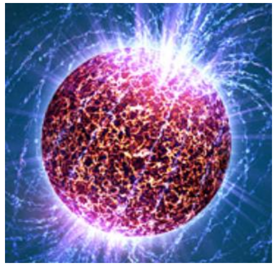


Summary

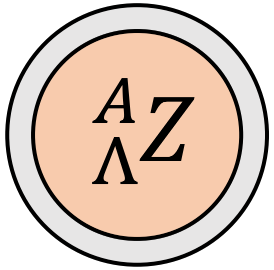
- **<u>NLO13(500) YN + YNN</u> via decuplet saturation:**

  The strongly repulsive Λ potential is obtained and is found consistent with

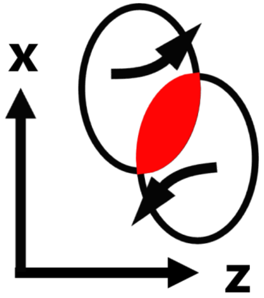
$2M_{\odot}$ NS
(No Λ in NS)



Λ binding energy



Λ directed flow



- **We still need other strategy to distinguish between the repulsive and attractive Λ potentials.**
- **The <u>Λ+Σ0 flow</u> is sensitive to the momentum dependence of the hyperon potentials and the <u>density dependence of the Σ potential</u>.**
- **Σ potential can be a key to pin down YN and YNN interaction.**