Constraining Lambda potential in dense nuclear matter from the Lambda directed flow

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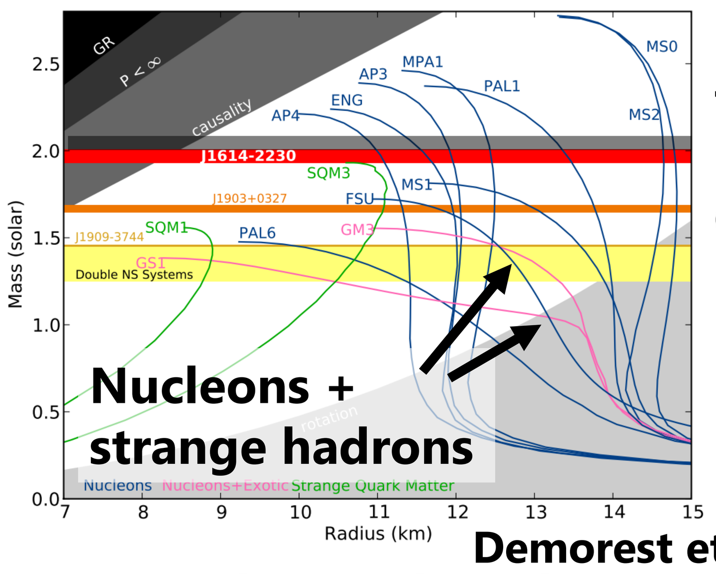
Y. Nara, AJ, K. Murase, and A. Ohnishi, Phys. Rev. C 106, 044902 (2022).
AJ, K. Murase, Y. Nara, and A. Ohnishi, Phys. Rev. C 108, 065803 (2023).

Background

Hyperon puzzle

Most of the 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)

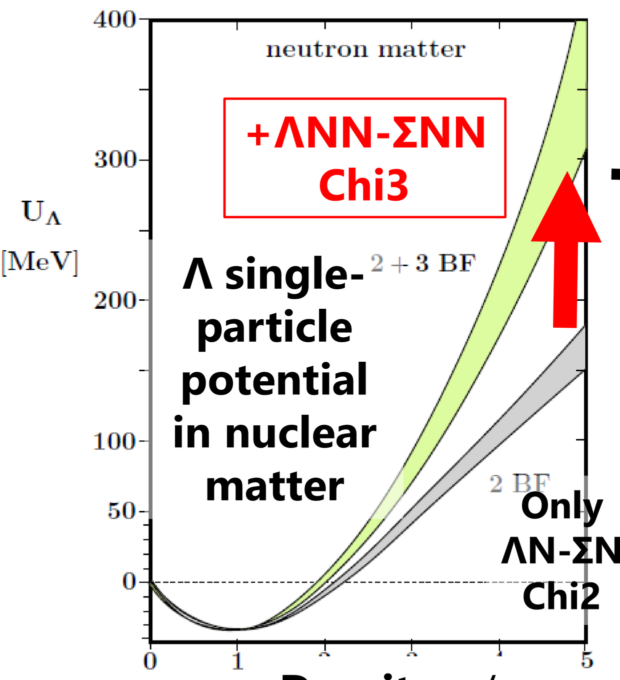
Demorest et al. (2010)

Many solutions have been proposed. Many-baryon repulsions (e.g. ΛNN), YY repulsions (e.g. ΛΛ), transition to quark matter, etc.

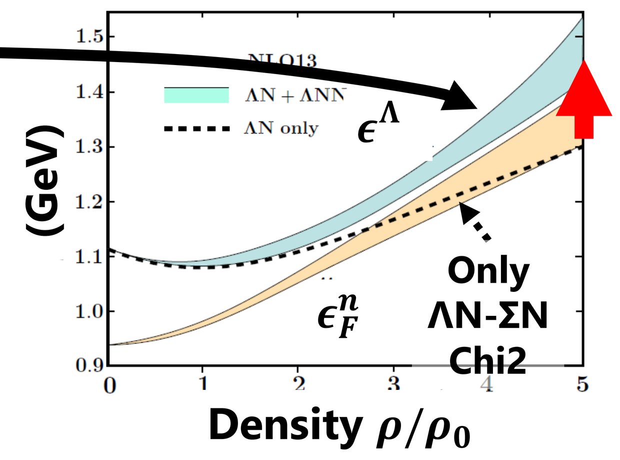
Many-body int. may solve the puzzle?!

YNN three-body force is considered from chiral effective field theory (decuplet saturation model).

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



single-particle energy $\epsilon^\Lambda(\rho) = m_\Lambda + U_\Lambda(\rho)$



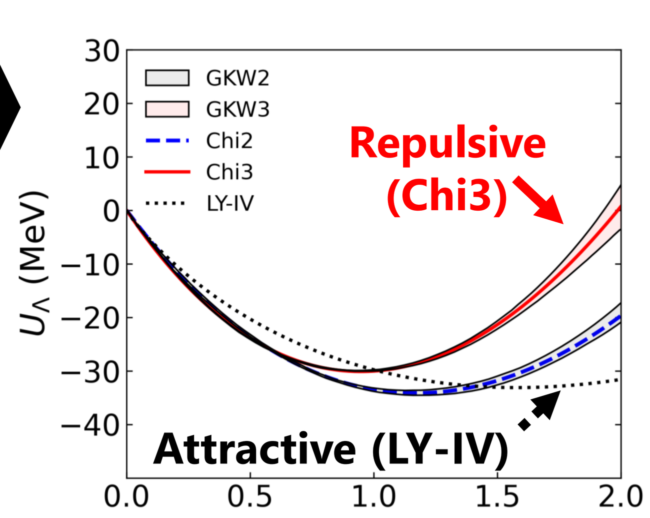
Λ does not appear even at high densities! Hyperon puzzle can be avoided!?

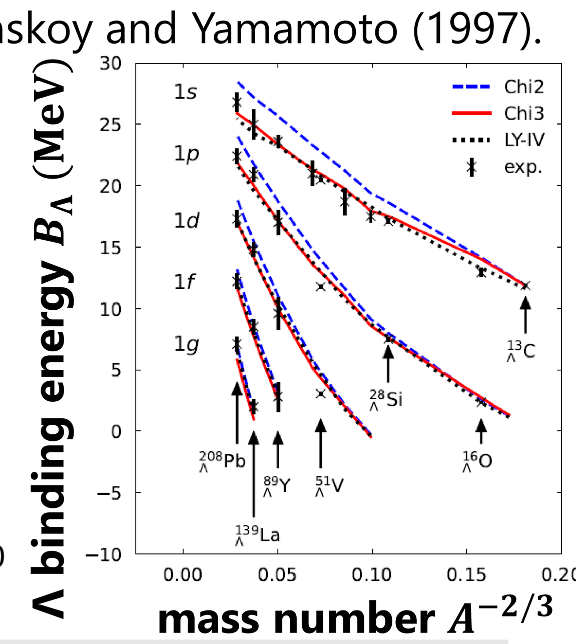
Verification of repulsive Λ potential by Λ hypernuclear data

AJ, K. Murase, Y. Nara, and A. Ohnishi (2023).

- Chi2 overbounds a few MeV for *s*-wave.
- Chi3 reproduces the data, at the same level of accuracy as a more attractive Λ potential.

LY-IV: Lanskoy and Yamamoto (1997).





We need another data to distinguish the repulsive and attractive Λ potentials.

Purpose

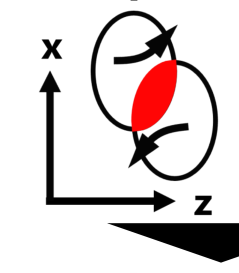
To examine whether the heavy-ion collision data (Λ directed flow v_1) can constrain the Λ potential at high densities.

Methods

Λ directed flow

- Anisotropic collective flow has been widely used to infer the equation of state of dense matter. (e.g. Sorensen et al., Prog. Part. Nucl. Phy 134 (2024) 104080.)
- Directed flow $v_1 = \langle p_x/p_T \rangle = \left\langle p_x/\sqrt{p_x^2+p_y^2} \right\rangle$
- $\sqrt{s_{NN}}$ dependence of proton v_1 is explained by RQMDv implemented in microscopic transport model JAM2. Nara and Ohnishi (2022)

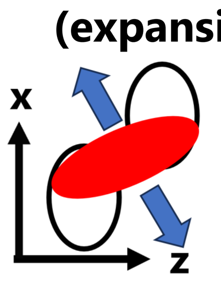
Early time (compression stage)



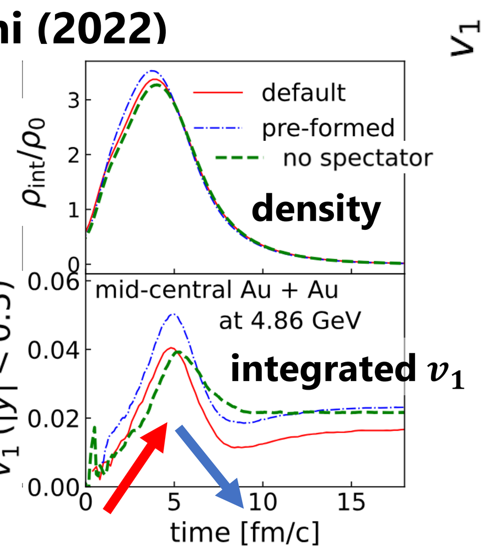
$v_1 > 0$ for $y > 0$

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

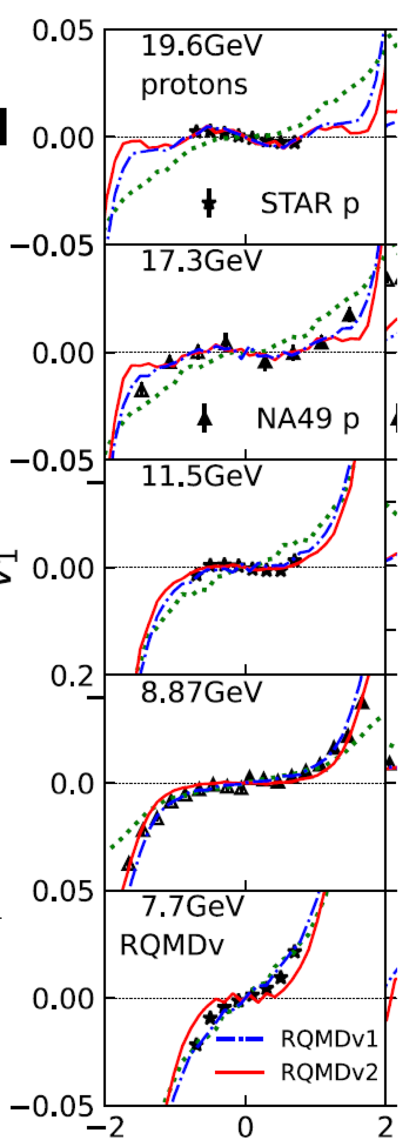
Later time (expansion stage)



$v_1 < 0$ for $y > 0$



$$v_1^* = \int_{-0.5}^{0.5} dy\, v_1(y)\mathrm{sign}(y)$$



Let's discuss Λ v_1 by JAM2!

RQMDv

Relativistic Quantum Molecular Dynamics with Lorentz-vector type potential

Nara and Ohnishi (2022)

Equation of motion

$$\frac{dq_i^\mu}{dt} = v_i^{*\mu} - \sum_j v_j^{*\nu}\frac{\partial V_{j\nu}}{\partial p_{i\mu}}$$

$$\frac{dp_i^\mu}{dt} = \sum_j v_j^{*\nu}\frac{\partial V_{j\nu}}{\partial q_{i\mu}}$$

where $v_i^{*\mu} = \frac{p_i^{*\mu}}{p_i^{*0}}$, $p^{*\mu} = p_i^\mu - V_i^\mu$

V_i^μ: one-particle potential

Total potential: $V^\mu \approx \sum_i V_i^\mu$

Single-particle potential: $U^\mu = \frac{\delta V^\mu}{\delta f}$

where f is phase-space distribution

Λ single-particle potential

$$U_\Lambda^\mu(\rho, p_\Lambda) = \frac{J^\mu}{\rho}U_{\rho\Lambda}(\rho) + U_{m\Lambda}^\mu(\rho, p_\Lambda)$$

$$U_{\rho\Lambda} = a\frac{\rho}{\rho_0} + b\left(\frac{\rho}{\rho_0}\right)^{4/3} + c\left(\frac{\rho}{\rho_0}\right)^{5/3}$$

$$U_{m\Lambda}^\mu = \frac{C}{\rho_0}\int d^3p' \frac{p'^\mu}{p'^0}\frac{f(x,p')}{1+[(p_\Lambda - p')/\mu]^2}$$

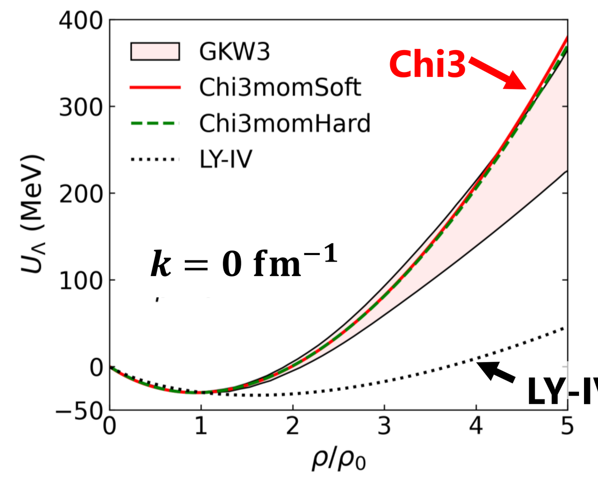
In the simulation, $(p_\Lambda - p')^2$ is replaced the two-body relative momentum squared p_{Rij}^2.

Λ potentials

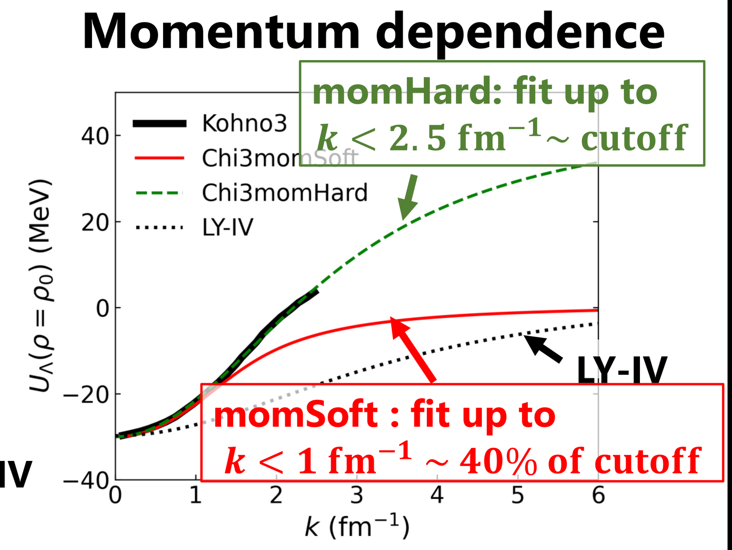
Fitting Λ potentials reproducing hypernuclear data with $U_\Lambda^0 = U_{\rho\Lambda}^0 + U_{m\Lambda}^0$

Chi3: Gerstung, Kaiser, and Weise (2020).
Kohno3 (mom. dep. from chiral EFT with ΛNN-ΣNN coupling)): Kohno (2018).
LY-IV (Skyrme-type Λ potential): Lanskoy and Yamamoto (1998).

Density dependence



Momentum dependence

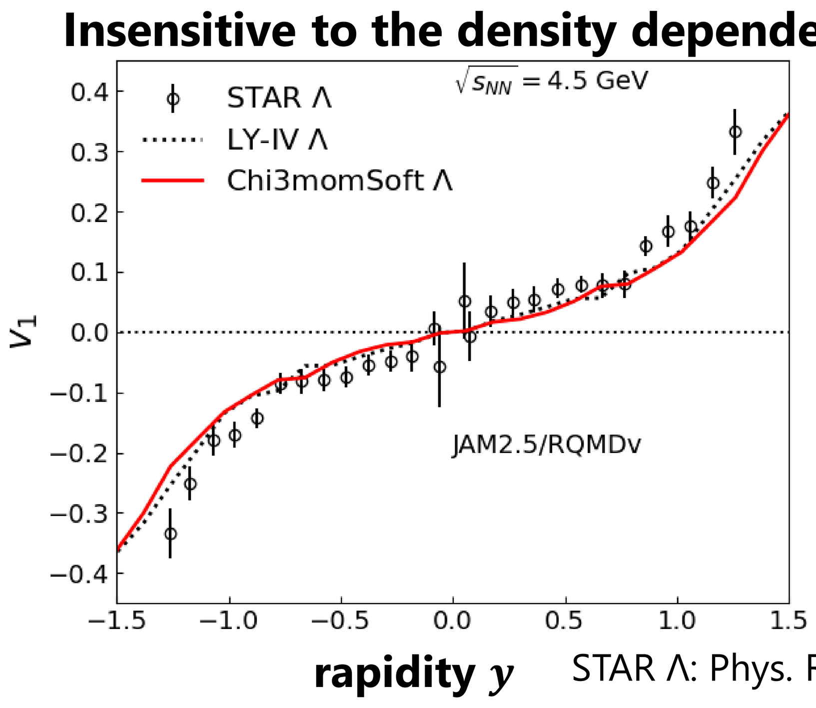


cutoff of Kohno3 = 550 MeV

Results

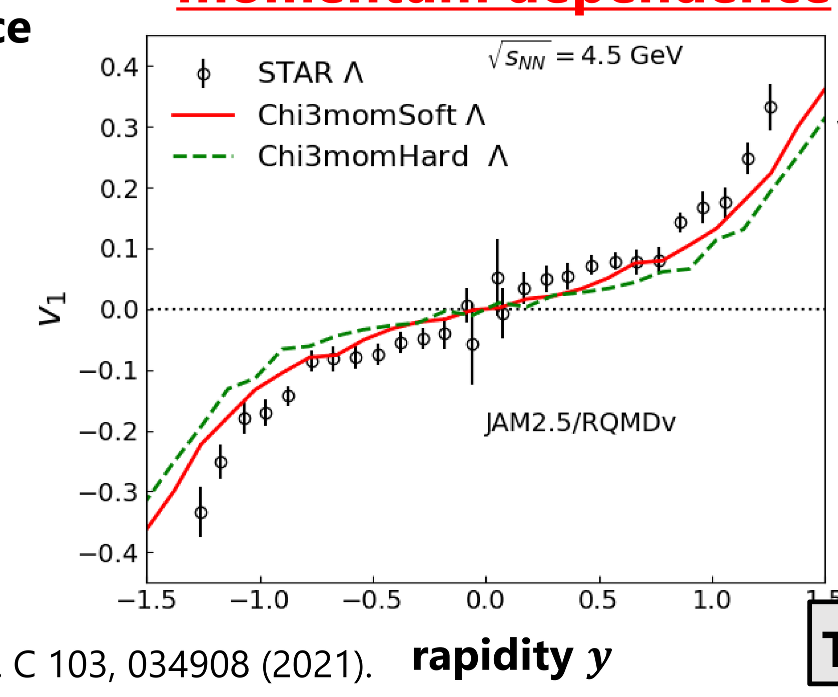
Both Chi3 and LY-IV reproduce the data.

Insensitive to the density dependence



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

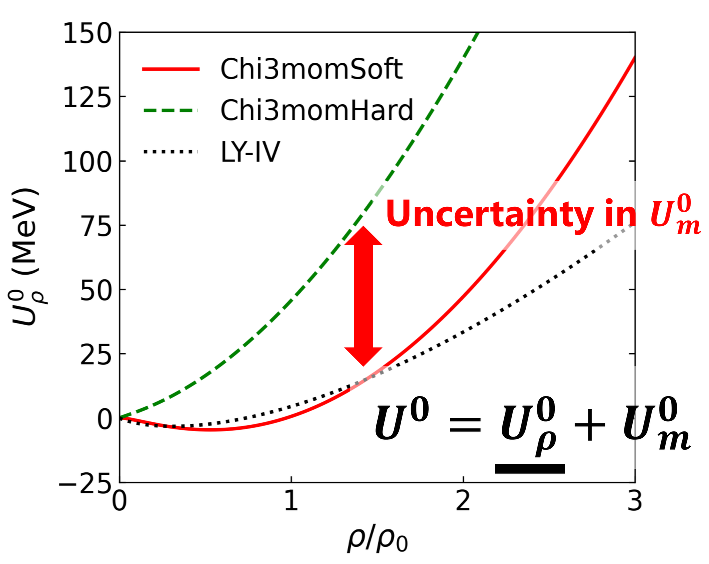
More sensitive to the momentum dependence



rapidity y

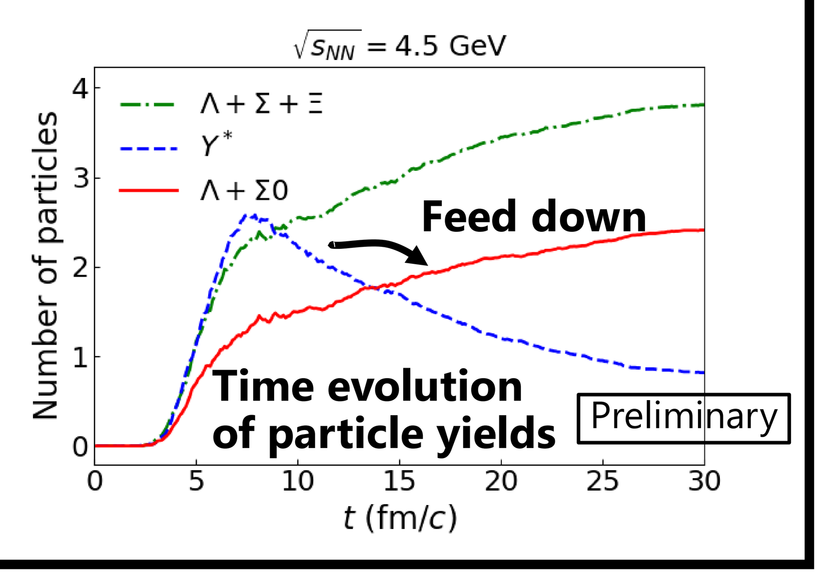
Why?

Large uncertainty in momentum dep. leads to large uncertainty in density dependence.



This difference can be found in Λ v_1.

More rigorous simulations would require Σ and Y* potentials.
(All hyperons currently feel the same as Λ.)
→ e.g. Parity doublet model (ongoing!)
Σ potential from chiral EFT (ongoing!)



Summary

We have examined the possibility to constrain the Λ potential at high densities from Λ directed flow data.

- Λ v_1 is not so sensitive to the density dependence of the Λ potential but is sensitive to the momentum dependence.
  → To pin down both $U_\Lambda(\rho)$ and $U_\Lambda(k_\Lambda)$ is important.
- Y* and Σ are found to be largely produced and their potentials would affect Λ directed flow.

We need further investigation to constrain the Λ potential at high density from Λ directed flow.

Future work

- Implementing both Λ and Σ potentials based on same theory (AJ is working now in Forschungzentrum Jülich)
- Considering the potential of hyperon resonances by e.g. parity doublet model