In memory of Prof. Akira Ohnishi: Hyperon puzzle of neutron stars examined through heavy-ion collisions and hypernuclei

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in collaboration with

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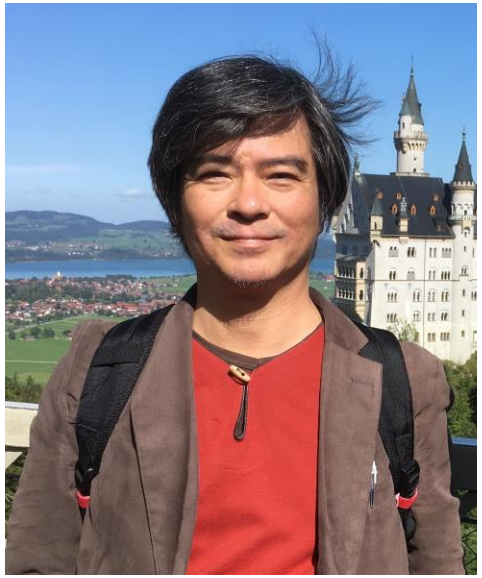
- **Y. Nara, A. Jinno, K. Murase, and A. Ohnishi, Phys. Rev. C 106 (2022) 044902.**
- **A. Jinno, K. Murase, Y. Nara, & A. Ohnishi, PRC 108, 065803 (2023).**
- **+ongoing work**

CSQCD 2024, YITP, Oct. 7-11, 2024.

In memory of Prof. Akira Ohnishi



[Akira Ohnishi: Home Page]

- I had been taught by Ohnishi-san for about one yeah and a half.
- I asked Ohnishi-san to be my supervisor because I was intrigued by his way of talking his physics, with great enthusiasm and full of joy.
- He told me "The master's degree is something your supervisor supports you to be deserved. The PhD degree is something you get by yourself." He have taught me enough to achieve this.
- He connects me with many researchers.
  I am in collaboration with them, and I can continue to carry on the intensive works.

An episode: Drinking

- It was November 2023. I was in my 2nd year of the master's course.
- I experienced the <u>two biggest events</u> on the same day:

1. I was literally "on fire" in my midterm presentation, although I had to submit the thesis in two months.
2. My girlfriend sentenced me to end up with our relation.

- I was completely exhausted and even considered to quit from physics.
- In the next meeting, my supervisor encouraged me, but I could not recover at all.
- He asked me, "How about having a drink and talk about the future?"
- …… We intensively discussed about only physics for two hours.

Hyperon puzzle of neutron stars examined from heavy-ion collisions and hypernuclei

Asanosuke Jinno (Kyoto U., Japan)

Outline

Introduction: Hyperon puzzle of neutron stars and the Λ potential

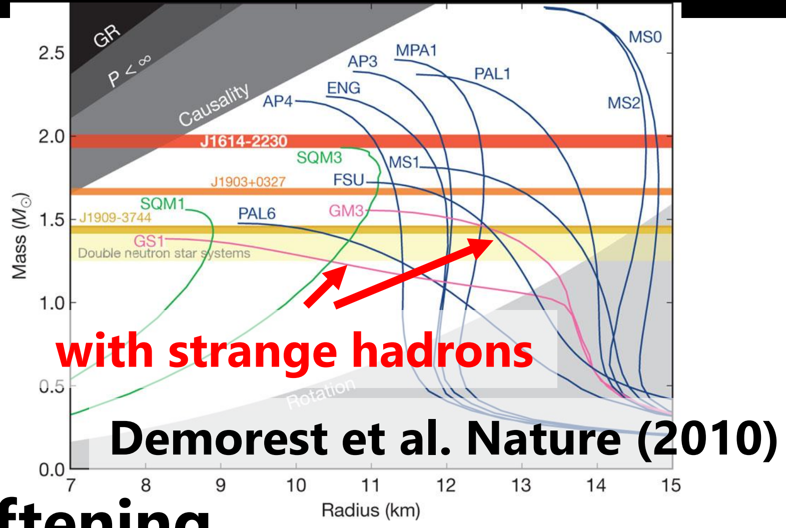
1. Verifying the Λ potential from Λ hypernuclear data

2. Verifying the Λ potential from heavy-ion collision data (Λ directed flow $v1$)

3. How about the Σ potential?

Introduction: Hyperon puzzle of neutron stars and the Λ potential

Hyperon puzzle of neutron stars



- **Most of the equations of state in which hyperons appear become too soft to support the observed massive neutron stars with twice the solar mass.**

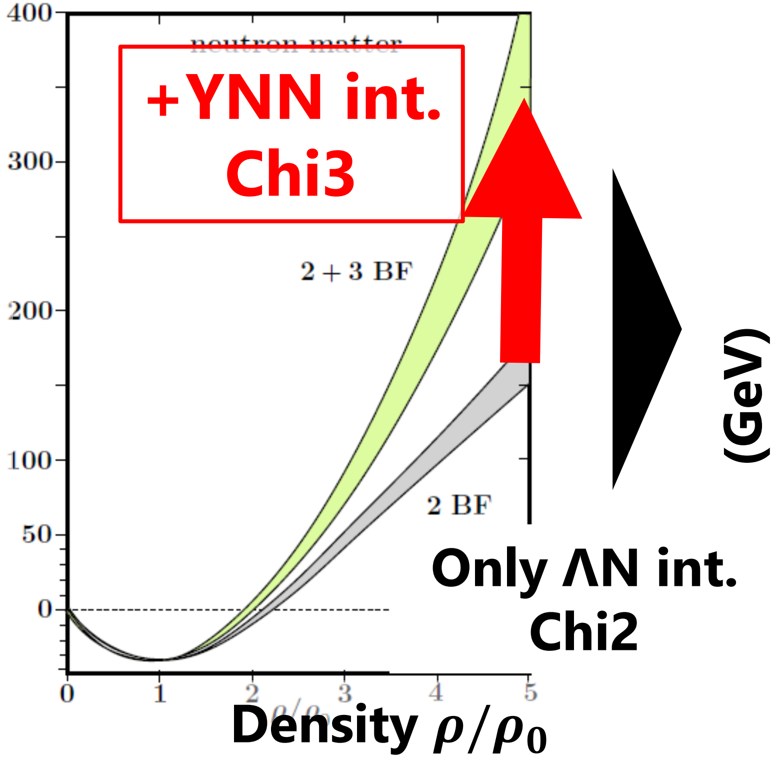
- **Many solutions have been proposed to avoid the softening.**
  - **Many-baryon repulsions (e.g. ΛNN)** e.g. Nishizaki, Yamamoto, & Takatsuka (2002); Gerstung, Kaiser, and Weise (2020); Friedman and Gal (2023).
  - **YY repulsions (e.g. ΛΛ)** e.g. Weissenborn, Chatterjee, Schaffner-Bielich (2012); Fortin, Avancini, Providencia, & Vidana (2017).
  - **Transition to quark matter without phase transition (QH continuity)** e.g. Baym, Hatsuda, Kojo, Powell, Song, & Takatsuka (2018); Minamikawa, Gao, Kojo, and Harada (2023).

(Note) In this talk, only baryonic matter is considered.

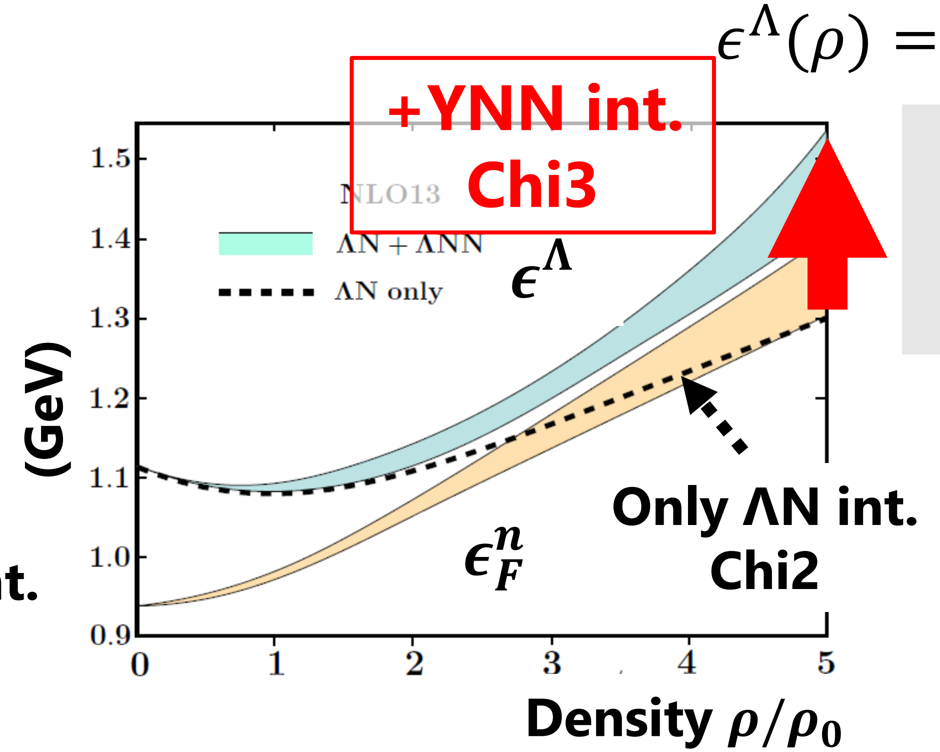
YNN three-body repulsion from Chiral EFT

- **Phenomenological YNN three-body force in dense matter** Nishizaki, Yamamoto, & Takatsuka (2002); Lonardoni et al. (2015); Togashi, Hiyama, Yamamoto, & Takano (2016); Friedman & Gal (2023) etc.
- **Chiral effective field theory (NLO YN + NLO promoted YNN via decuplet saturation)** **Kohno(2018), D. Gerstung, N. Kaiser, and W. Weise (2020)**

Λ potential in nuclear matter U_Λ (MeV)



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



Λ does not appear even at high densities!

Avoiding hyperon puzzle!?

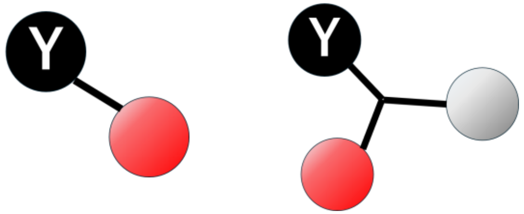
(Note) First order Brückner-Hartree-Fock calculation with continuous choice

Purpose of our study

- Verifying the consistency of the strongly repulsive Λ potential with experiments.
- Examining if the Λ potential can be distinguished from the attractive one.

Chiral EFT

(NLO YN + NLO promoted YNN via decuplet saturation)



+

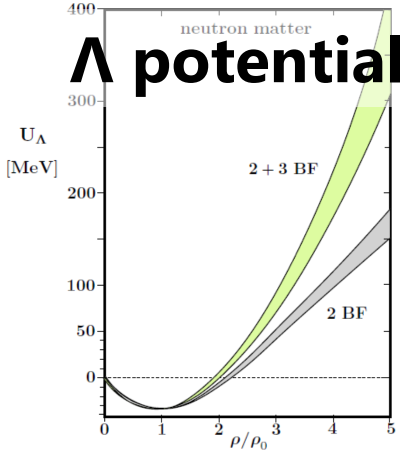
Experiments and observations

YN scatterings ✅,
Neutron stars ✅,
$U_\Lambda(\rho_0) \approx -30\ \text{MeV}$ ✅,
Hypernuclei, Heavy-ion collisions, Σ atoms

→

Λ & Σ single-particle potential

Λ potential



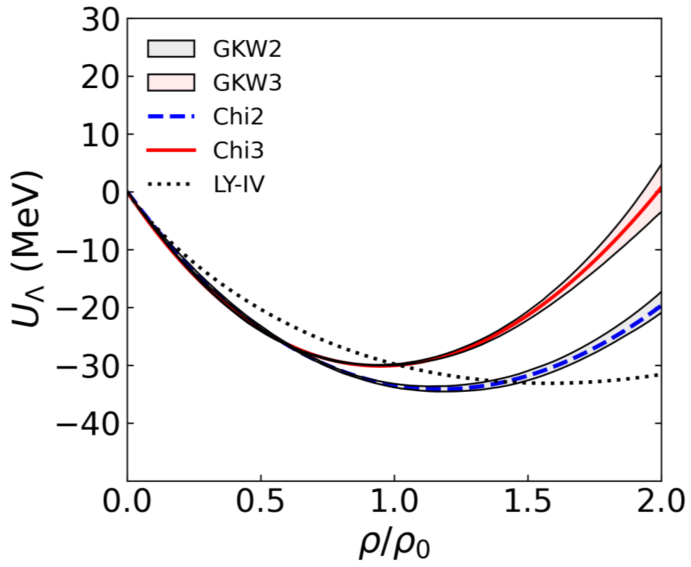
Σ potential

?

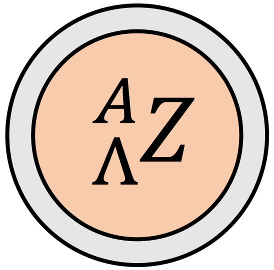
Cf. A recent trend of the nuclear matter studies
(e.g. Drischler, Holt, Wellenhofer, Ann. Rev. Nucl. Part. Sci. 71 (2021) 403;
Rutherford, ..., and Lattimer, Astrophys. J. Lett. 971 (2024) 1, L19.)

Chiral EFT NN + NNN **+** **Experiments and observations** **→** **Nuclear matter EOS**

Verifying the Λ potential from hypernuclear data

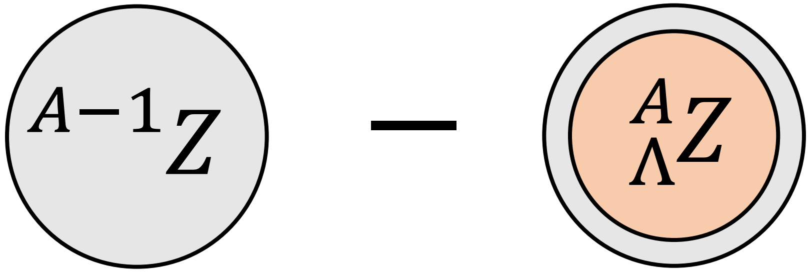


Consistent?

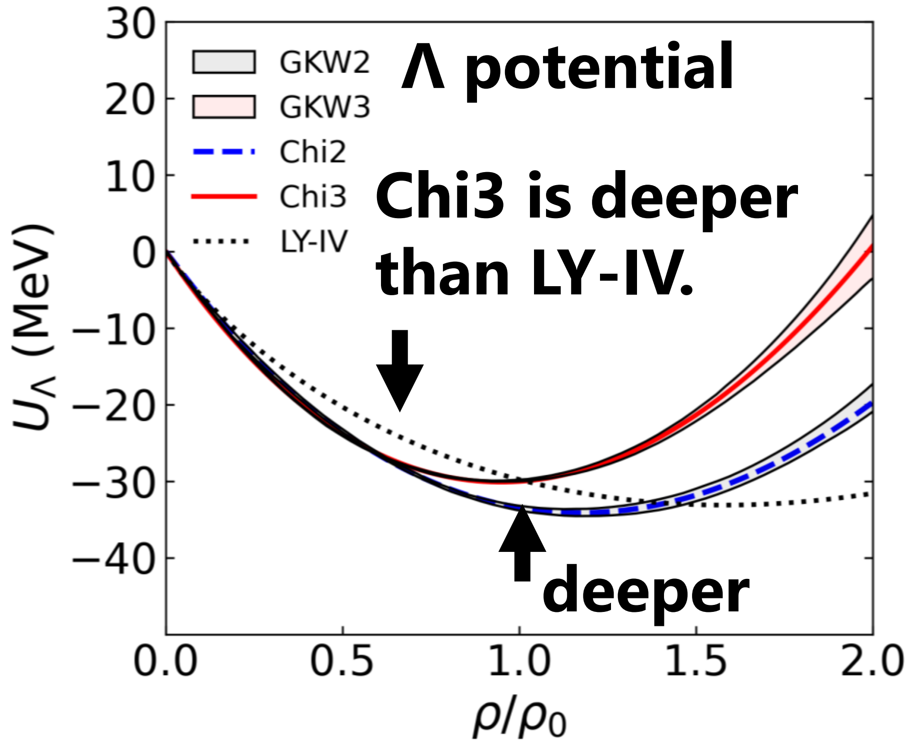


Can the Λ potential reproduce Λ binding energies?

Λ binding energy B_Λ =



Expected to be sensitive to the Λ potential in $\rho \lesssim \rho_0$.



GKW2 (GKW3): Gerstung, Kaiser, and Weise (2020).
Chiral EFT calculation including YN (YN+YNN) interaction.
LY-IV: Lanskoy and Yamamoto (1997).
Skyrme-type Λ potential reproducing Λ binding energies.

- **Can Chi2 and Chi3 reproduce the Λ binding energy data?**
- **If they reproduce the data, how is the level of accuracy compared to a conventional attractive model (LY-IV)?**

Spherical Skyrme-Hartree-Fock method

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

Rayet (1976) & (1981); Lanskoy and Yamamoto (1997); Guleria et al. (2012), Choi, Hiyama et al. (2022) etc.

- Single-particle pot. in nuclear matter

$$U_\Lambda(\rho,k_\Lambda)=a\rho+b\rho^{4/3}+c\rho^{5/3}+a_2^\Lambda k_\Lambda^2\rho+a_3^\Lambda\nabla^2\rho$$

- Effective mass $$\frac{\hbar^2}{2m_\Lambda^*}=\frac{\hbar^2}{2m_\Lambda}+a_2^\Lambda\rho$$

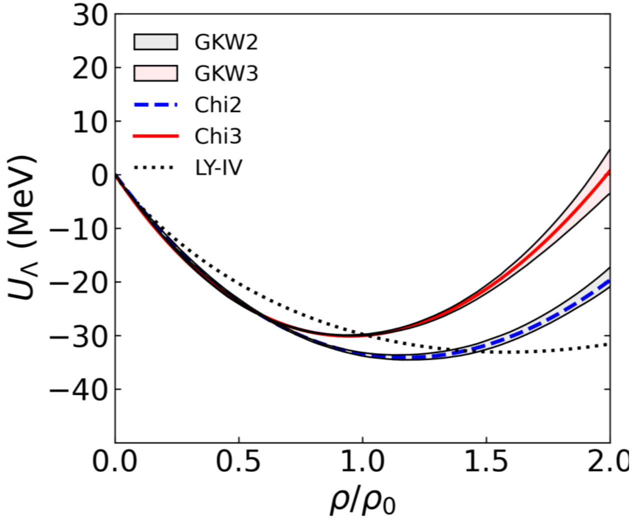
<u>Fitting to the results from chiral EFT</u>

- **a_3^Λ is a fitting parameter to reproduce the exp. data of $^{13}_{\Lambda}$C.**

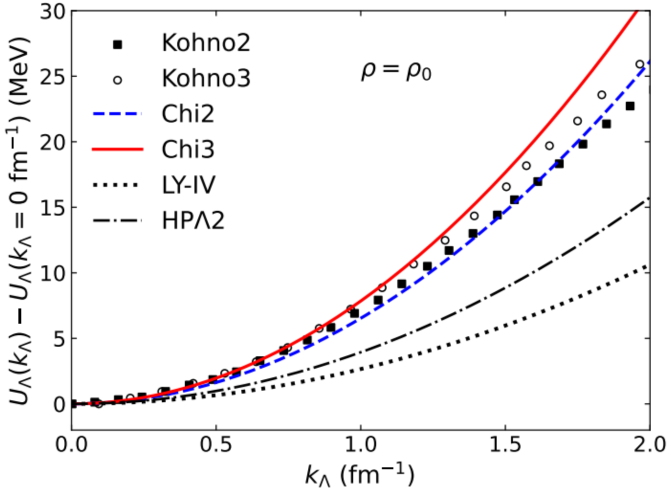
Comparing calculated binding energy $B_\Lambda=\mathcal{E}_{\rm core}-\mathcal{E}_{\rm hyp}$ with exp. data.

* We use SLy4 parameter set for the nucleon interactions.

Density Dependence



Momentum Dependence



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

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

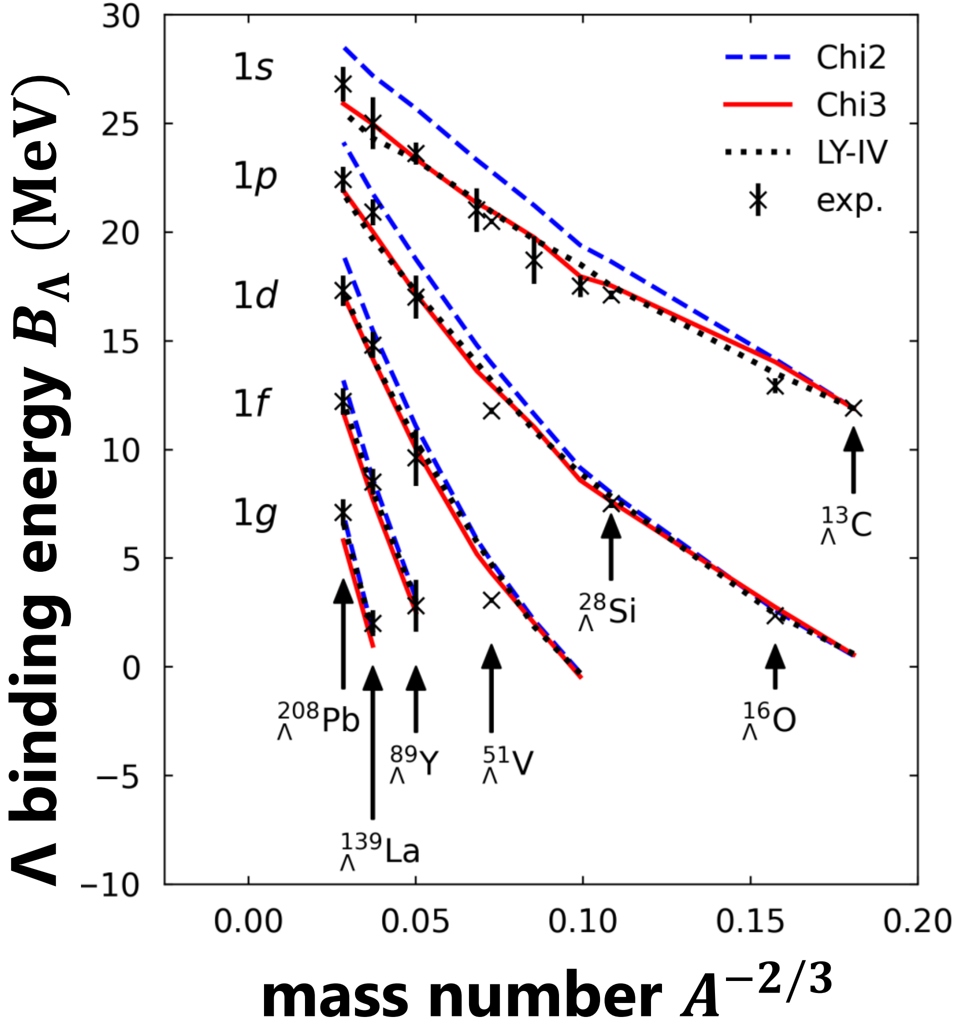
LY-IV: Lanskoy and Yamamoto (1997).

Kohno2 (Kohno3): Kohno (2018)

(Result) Λ binding energies

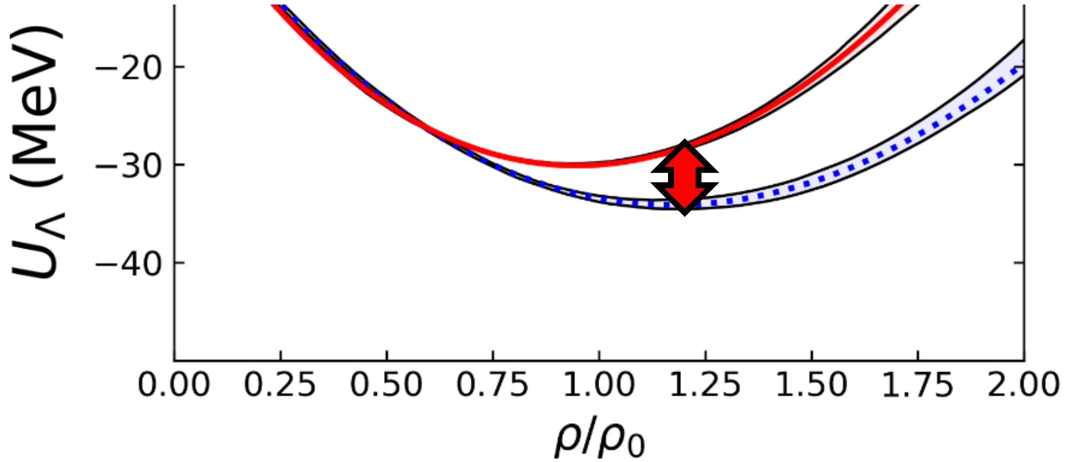
A. Jinno, K. Murase, Y. Nara, & A. Ohnishi, PRC 108, 065803 (2023).

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



- **Chi2 overbounds a few MeV for *s*-wave.**

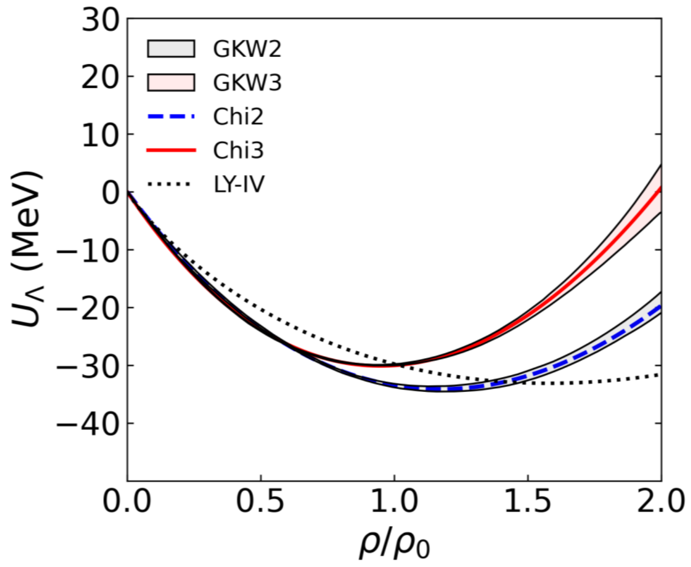
∵ Λ potential depth of Chi2 is too deep.



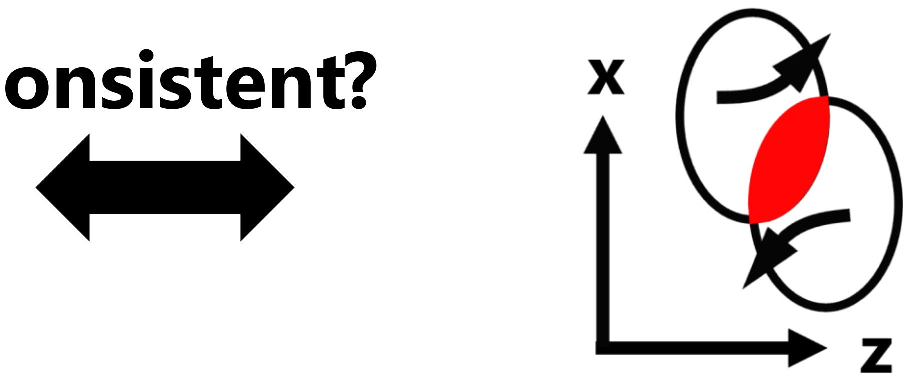
- **Chi3 reproduces the data, at the same level of accuracy as LY-IV.**

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

Verifying Λ potentials from heavy-ion collision data (Λ directed flow v_1)



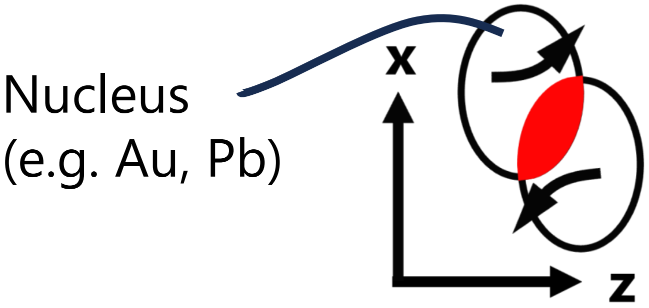
Consistent?



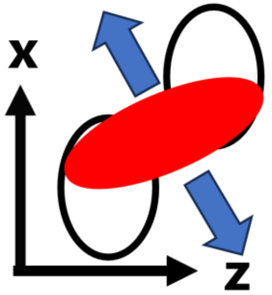
Directed flow v_1

- **The anisotropic collective flow $v_n = \langle \cos n\phi \rangle$** has been extensively investigated to extract the dense matter equation of state (EOS).
  (Recent review: Sorensen et al., Prog. Part. Nucl. Phys. 134 (2024) 104080)

- **Directed flow: $v_1 = \langle \cos\phi \rangle = \langle p_x / p_T \rangle \quad (p_T^2 = p_x^2 + p_y^2)$**



$v_1 > 0$ for $y > 0$



$v_1 < 0$ for $y > 0$

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

- **Collision energy $\sqrt{s_{NN}}$ dependence of proton v_1 is explained** by the Lorentz vector version of the relativistic quantum molecular dynamics **(RQMDv)** model implemented in hadronic transport model **JAM2.** Nara and Ohnishi (2022).

Let's discuss Λ v_1!

JAM2: https://gitlab.com/transportmodel/jam2

Λ potentials $U_\Lambda(\rho, k_\Lambda)$

Using the Λ potentials reproducing the Λ hypernuclear data

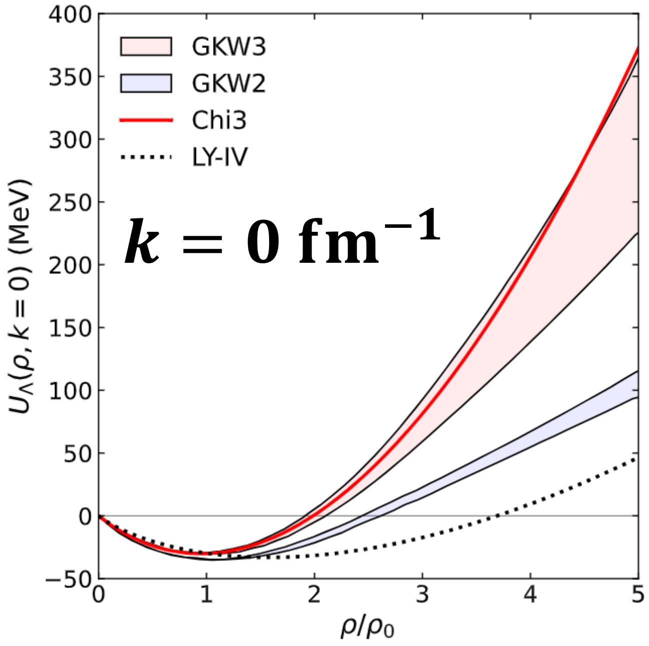
Fitting function: $U_\Lambda^{\rm opt} = \sqrt{m_\Lambda^2 + (\boldsymbol{p} - \boldsymbol{U}_\Lambda)^2} + U_\Lambda^0 - \sqrt{m_\Lambda^2 + \boldsymbol{p}^2}$

with $U_{\rho,\Lambda} = a\frac{\rho}{\rho_0} + b\left(\frac{\rho}{\rho_0}\right)^{4/3} + c\left(\frac{\rho}{\rho_0}\right)^{5/3}$, $U^0_{m,\Lambda} = \frac{C}{\rho_0}\int d^3p' \frac{f(x,p')}{1+[(\boldsymbol{p}-\boldsymbol{p}')/\mu]^2}$

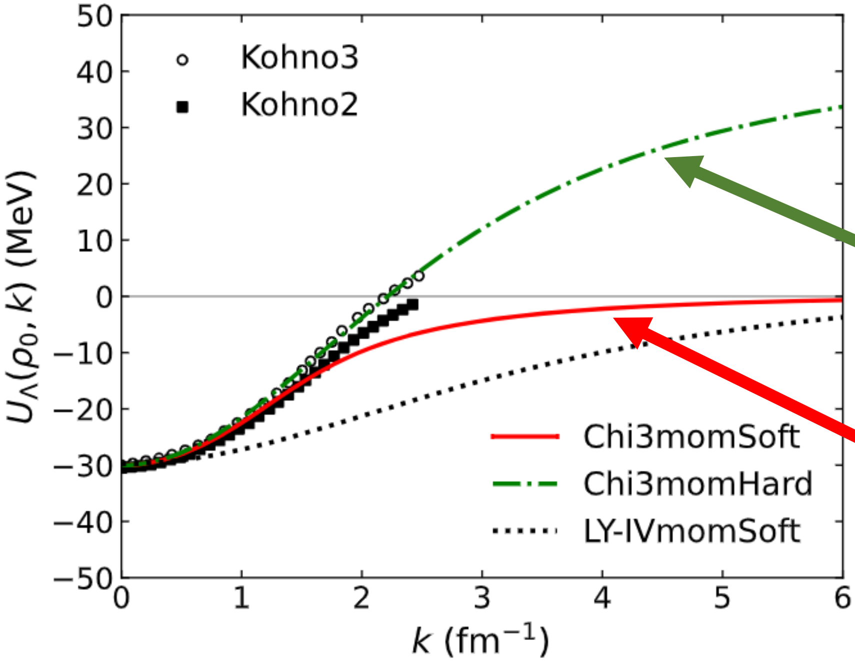
Baryon distribution function

Explicit expression is in Nara, AJ, Murase, and Ohnishi (2023).

Density dependence



Momentum Dependence



cutoff of Kohno3 = 550 MeV

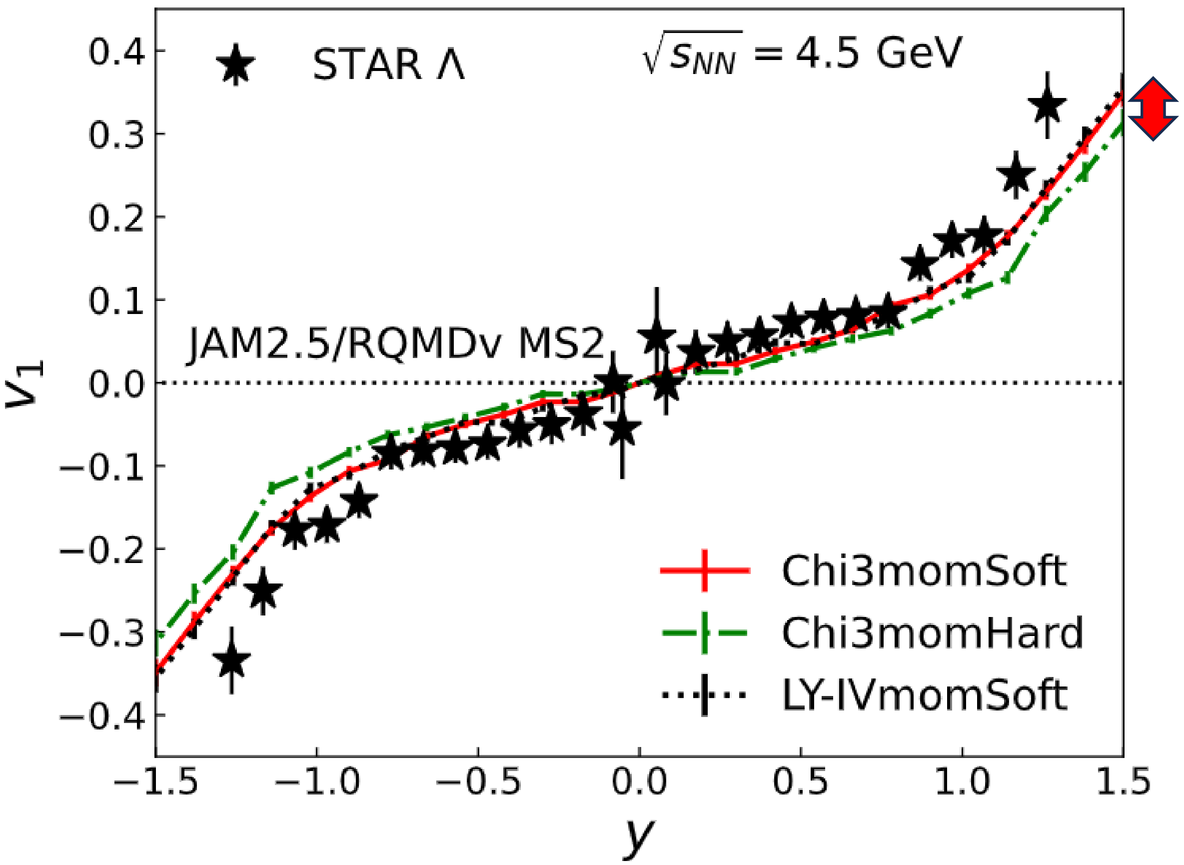
momHard: fit within $k < 2.5\ \mathrm{fm}^{-1} \sim 100\%$ of cutoff

momSoft : fit within $k < 1\ \mathrm{fm}^{-1} \sim 40\%$ of cutoff

Potentials of other hyperons (Σ and Ξ) and resonances are set to be the same as that of Λ.

Λ directed flow v_1

Y. Nara, AJ, K. Murase, & A. Ohnishi, PRC 106, 044902(2022).
(The calculation is performed using the latest version of JAM2.)



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

- **Chi3momSoft reproduces the data!**
- **No difference is found between Chi3momSoft and LY-IVmomSoft.**
- **Difference is found between the Soft and Hard momentum dep.**

(Same trend is observed for $\sqrt{s_{NN}} = 3 - 19.6$ GeV)

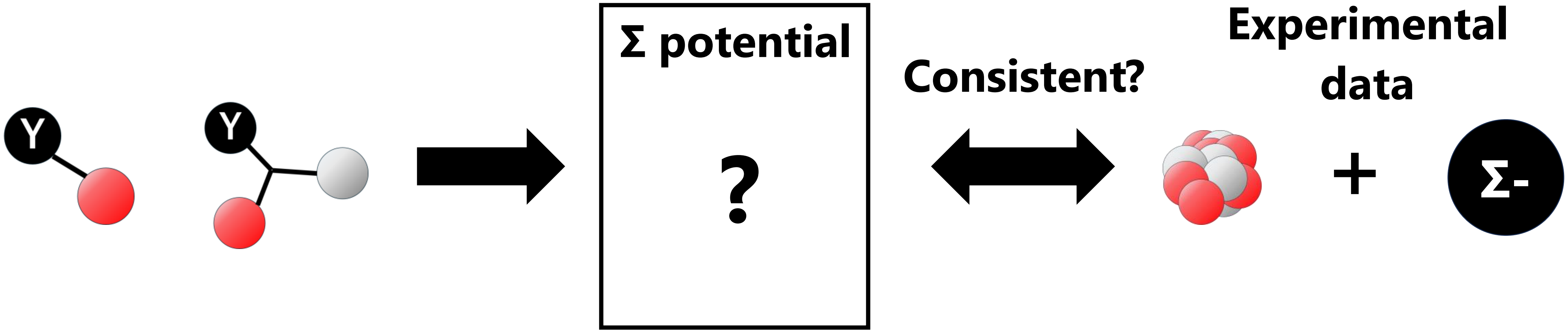
Λ v_1 is sensitive to the momentum dep. of U_Λ rather than the density dep.

Short Summary

- The Λ potential strongly repulsive at high densities that can solve the hyperon puzzle of neutron stars has been calculated from chiral EFT with the YNN force.
- We have examined the consistency of the repulsive Λ potential with experimental data.
- Λ binding energy of Λ hypernuclei:
  - Λ potential with only two-body interaction is excluded due to overbinding.
  - Both the repulsive and attractive Λ potentials are consistent with the data.
- Λ directed flow v_1 of heavy-ion collisions:
  - The repulsive Λ potential is consistent with the data.
  - Λ v_1 is not so sensitive to the density dep. of U_Λ, but rather to momentum dep.
- We still need another data or methods to distinguish between the repulsive and attractive Λ potentials.

How about the Σ potential?

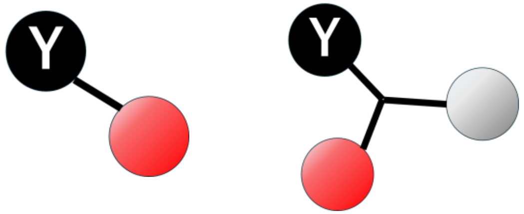
in collaboration with Johann Haidenbauer (FZ Jülich)



The Σ potential

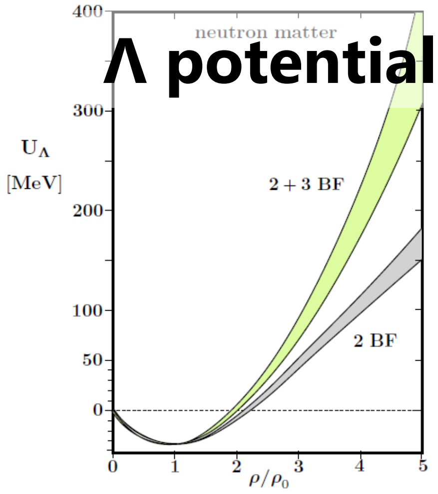
The Σ potential can be calculated by using same YN and YNN interactions as the Λ potential.

Chiral EFT
YN 2BF + YNN 3BF



Matter calculation (Brückner-HF)

Λ potential



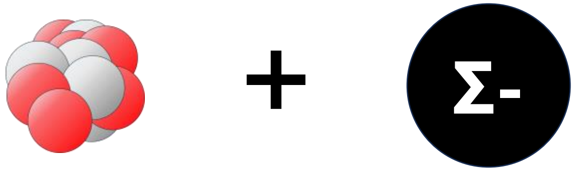
Σ potential

?

Empirical information on the Σ potential:

$U\_\Sigma(\rho_0) = 30 \pm 20$ MeV **(from the Σ^- atomic data)**

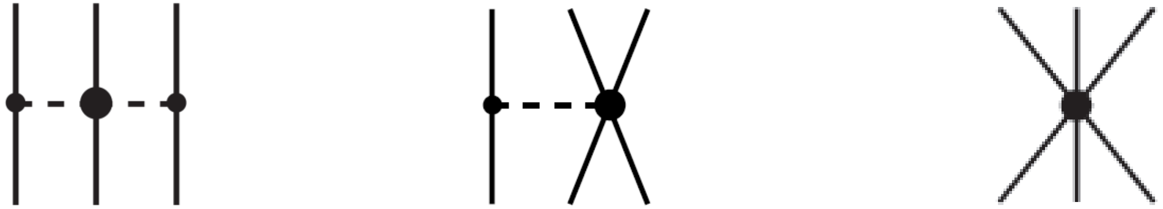
Gal, Hungerford, & Millener (2016).



Consistent when employing the repulsive 3BF?

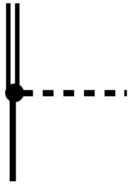
Three-body force from chiral EFT

- **<u>Many</u> low-energy constants (LECs) are involved in the NNLO three-baryon forces.**
  Petschauer, Kaiser, Haidenbauer, Meißner, & Weise (2016)



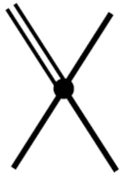
2 LECs in ΛNN-ΛNN | 2 LECs in ΛNN-ΛNN | 3 LECs in ΛNN-ΛNN, 5 LECs in ΣNN-ΣNN, 1 LECs in ΛNN-ΣNN

- **Only <u>3</u> LECs by adopting decuplet saturation (NLO)**
  Petschauer, Haidenbauer, Kaiser, Meißner, & Weise (2017)



$\propto \boldsymbol{C}$

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

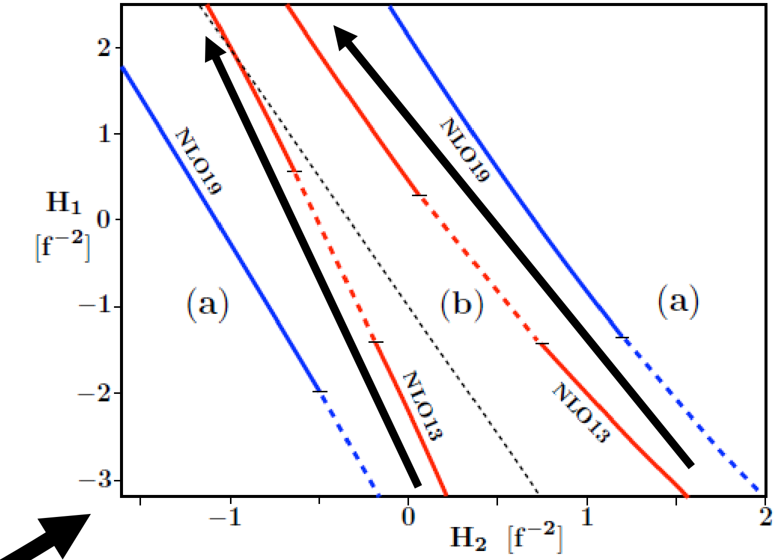


$\propto \boldsymbol{H_1, H_2}$

$U_\Lambda(\rho_0) \approx -30$ MeV

Gerstung, Kaiser, Weise (2020)

LECs H1 and H2 combinations



Gerstung, Kaiser, Weise (2020)

How does $U\_\Sigma(\rho_0)$ behave along lines with $U_\Lambda(\rho_0) = -30$ MeV?

Detailed settings

Gerstung, Kaiser, Weise (2020).

- **NN: N3LO(500)** Entem & Machleidt, PRC 68, 041001(R) (2003).
- **NNN (Density-dependent NN): N2LO(500)**

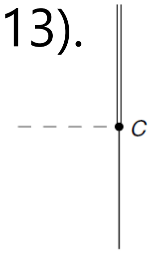
  Holt, Kaiser, and Weise (2009, 2010).

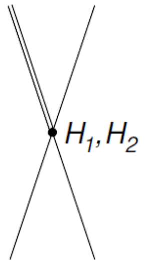
  LECs c_D and c_E are determined from $^3\mathrm{H}$ and $^3\mathrm{He}$ binding energies and the half-life of $^3\mathrm{H}$.

  Gazit, Quaglioni, & Navratil, PRL 103, 102502 (2009).
- **YN: NLO13(500)**

  Haidenbauer, Petschauer, Kaiser, Meißner, Nogga, & Weise, NPA 915, 24 (2013).
- **YNN: NLO promoted from NNLO by decuplet saturation**

  Petschauer, Haidenbauer, Kaiser, Meißner, & Weise (2017).
- **U_Λ and U_Σ calculation method: First order Brückner-Hartree-Fock calculation using the continuous choice of the single-particle potential**

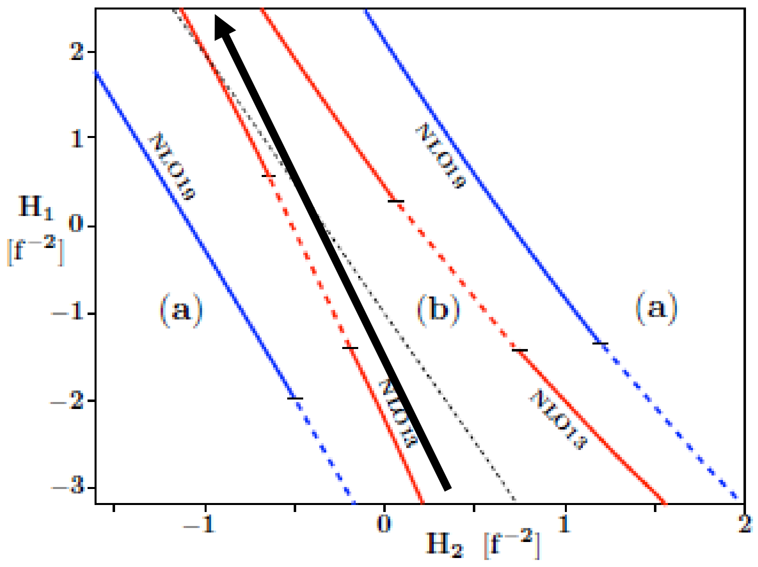




- **C: Decay width of $\Delta \to \pi N$**
- **$U_\Lambda(\rho_0) = -30$ MeV**
- **One undetermined LEC**

Hyperon single-particle potentials with YNN

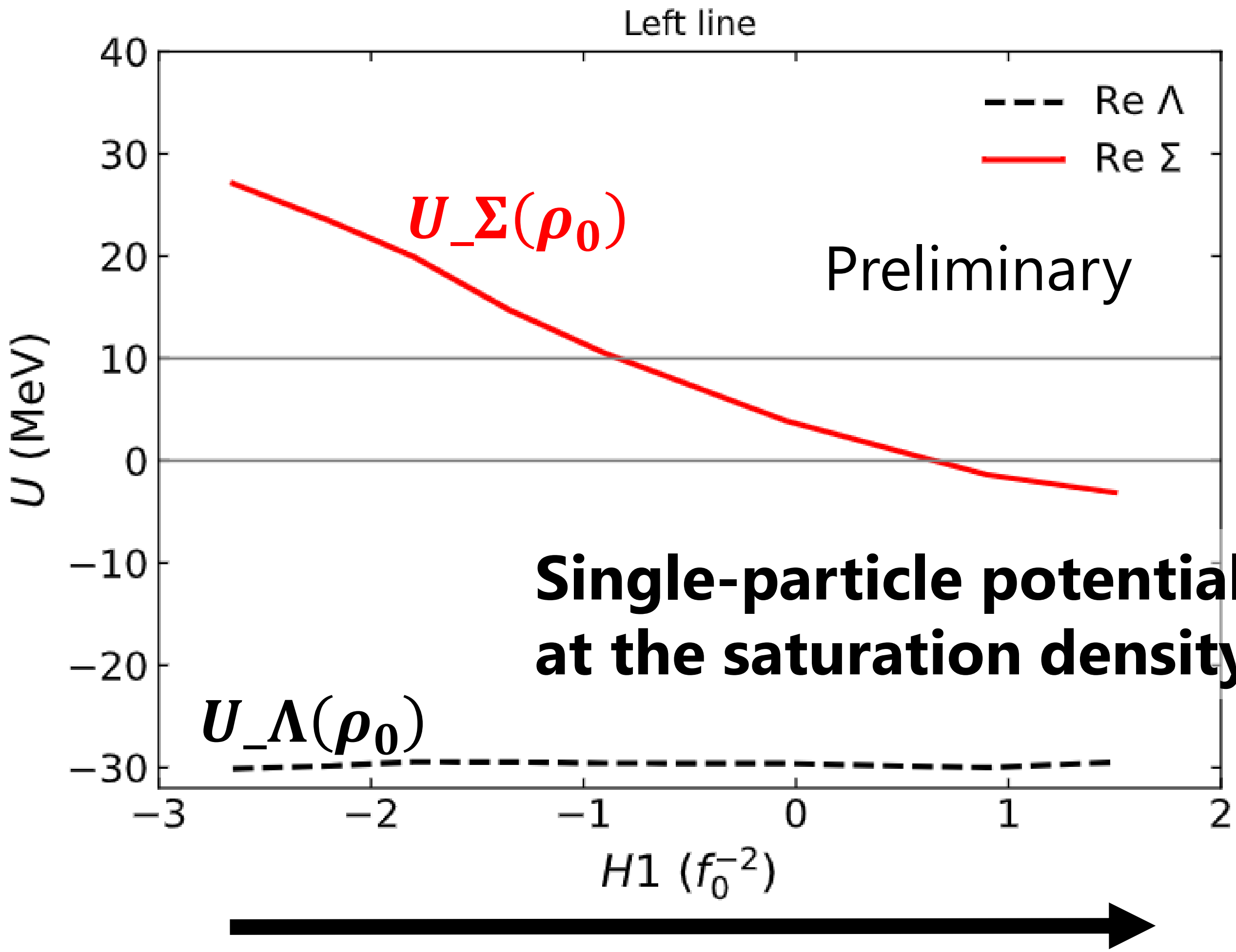
Combinations of LECs H1 and H2 that fulfill $U_\Lambda(\rho_0) = -30$ MeV



Taken from Gerstung, Kaiser, Weise (2020)

(Note) Right line has similar behaviour.

$U\_\Sigma(\rho_0)$ varies from repulsive to attractive.

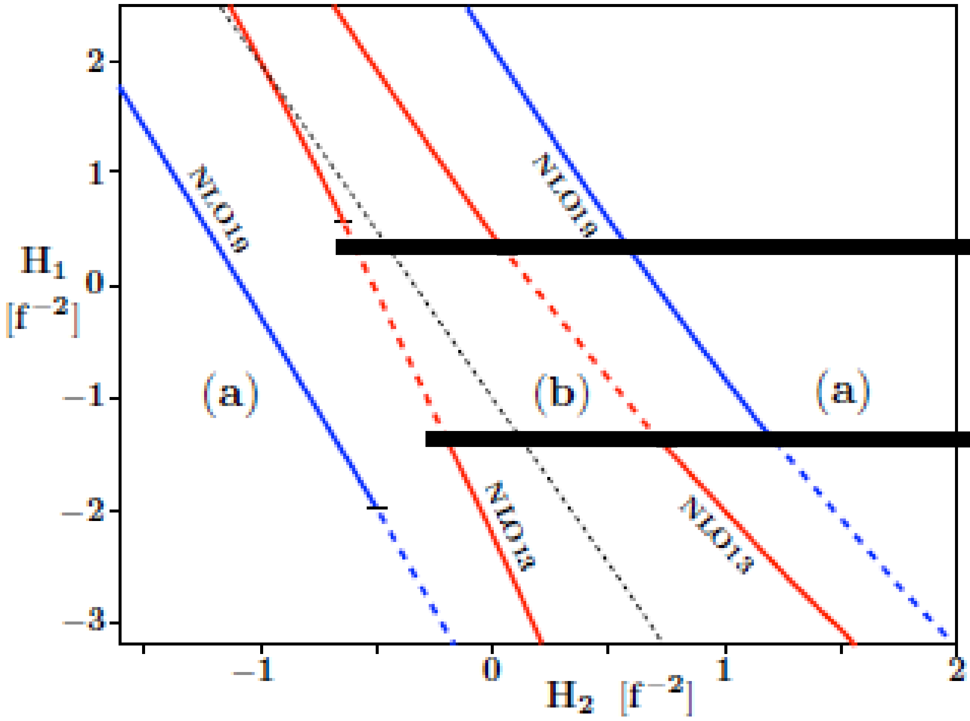


Single-particle potentials at the saturation density

Single-particle potentials with YNN

Empirical value from the Σ atom: $U_\Sigma(\rho_0) = 30 \pm 20$ MeV Gal, Hungerford, & Millener (2016).

Taken from Gerstung, Kaiser, Weise (2020)



- $U_\Sigma(\rho_0) < 0$ ✗

- $15 > U_\Sigma(\rho_0) > 0$ MeV △
- U_Λ is Moderately repulsive at high densities

- $U_\Sigma(\rho_0) > 15$ MeV ✅
- U_Λ is strongly repulsive at high densities*

Low-energy constants can be chosen in such a way that Λ's do not appear in neutron stars and the empirical value of U_Σ is reproduced.

*$U_\Lambda(3\rho_0) > 80$ MeV as discussed in Gerstung, Kaiser, Weise (2020).

Summary

- **Both the repulsive and attractive Λ potentials at high densities are found to reproduce the Λ hypernuclear and heavy-ion collision data.**
- **We have newly investigated the Σ potentials with the YNN interactions that reproduce $U_\Lambda = -30$ MeV.**
- **With chiral NLO YN + YNN interactions, low-energy constants can be chosen in such a way that Λ's do not appear in neutron stars and the empirical value of U_Σ is reproduced.**

Future work

- **Implementing the Λ and Σ potentials consistently in the heavy-ion collision simulator and verifying the consistency with data, e.g. the directed flows of Λ and Σ.**
- **Calculating the hyperon potentials using the up-to-date NNLO chiral YN and YNN forces.**