Directed flow of Λ from heavy-ion collisions and hyperon puzzle of neutron stars

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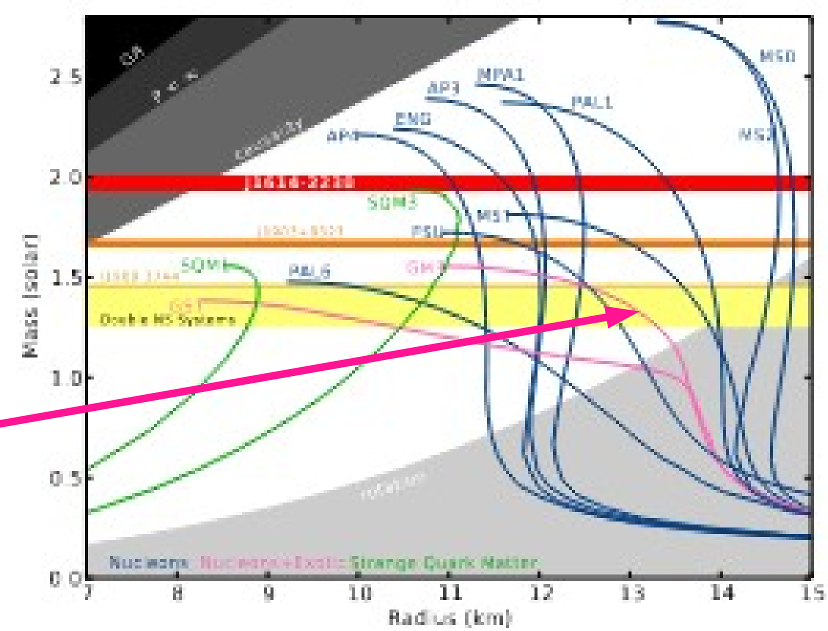
- **Introduction – Hyperon puzzle**
- **Λ potential from chiral effective field theory (chiral EFT)**
- **Balance energy of proton directed flow slope**
- **Λ directed flow**
- **Summary**

Y.Nara, A. Jinno, K. Murase, AO, in prep.

Hyperon Puzzle of Neutron Stars

- **Observation of massive neutron stars rules out hyperonic EOS ?**
  - **Attractive $U_\Lambda(\rho)$ causes hyperon mixing in NS at $(2\text{-}4)\rho_0$, softens the EOS, and reduces $M_{max} = (1.3\text{-}1.6)\ M_\odot$**
- **Proposed solutions**
  - **Three-body ΛNN repulsion → repulsive $U_\Lambda(\rho)$ at high density**
  - **Transition to quark matter before Λ appears**
  - **General relativity → Modified gravity**

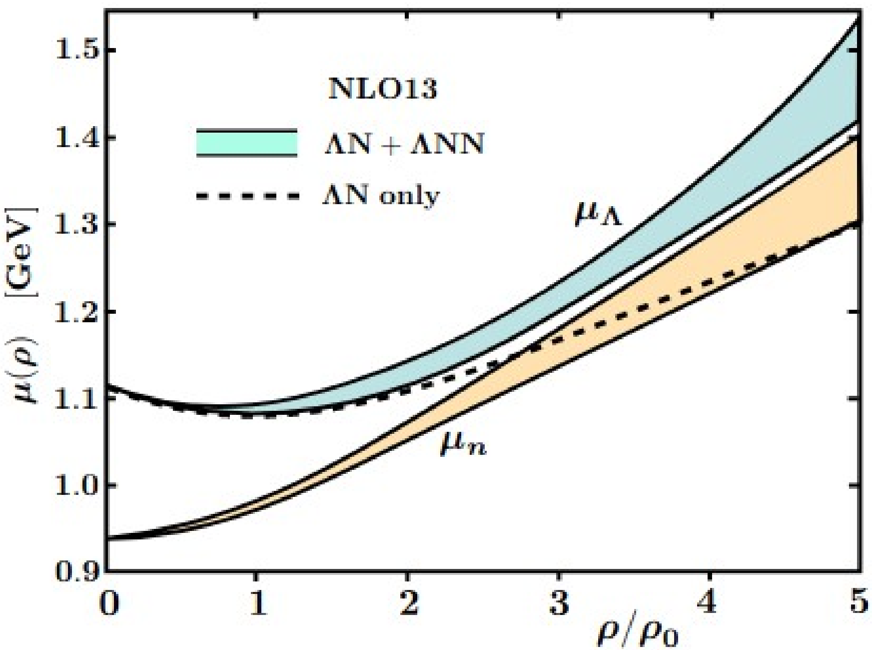
Hyperons



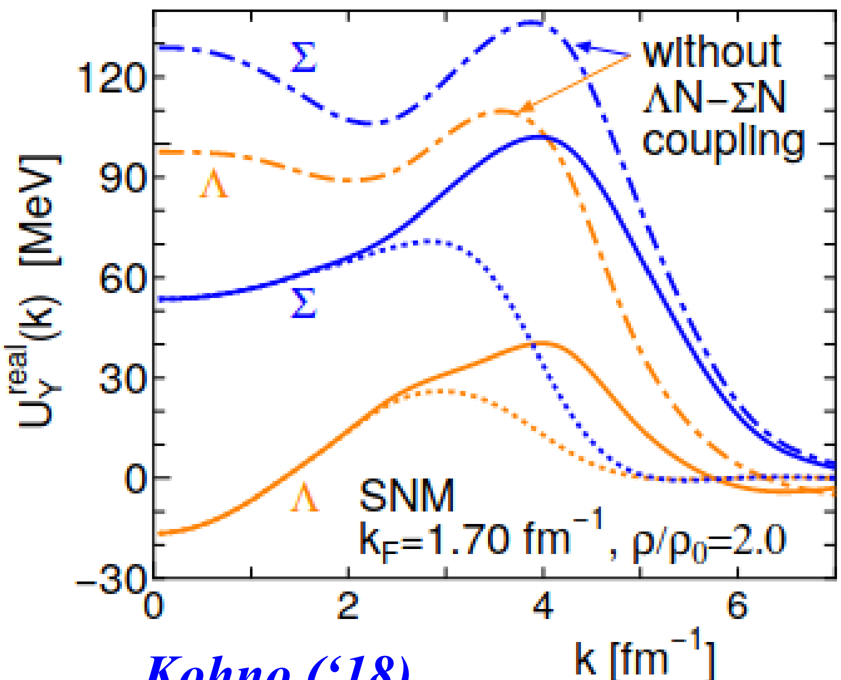
Demorest+(1010.5788)

Repulsive $U_\Lambda(\rho)$ at high density in chiral EFT

- **Chiral effective field theory (chiral EFT) may cause repulsive Λ potential at high densities**
  Gerstung, Kaiser, Weise (2001.10563), Kohno (1802.05388)
- **Yet unknown parameters are tuned to support 2 $M_\odot$ neutron stars.**
  → Repulsion at high densities needs to be verified !
  → Directed flow in HIC



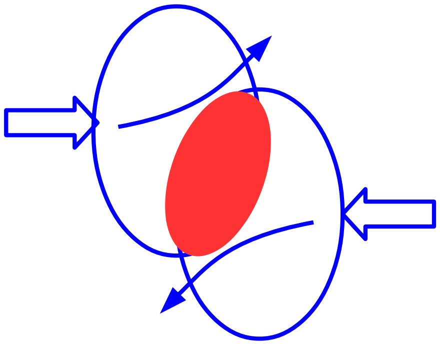
Gerstung+('20)



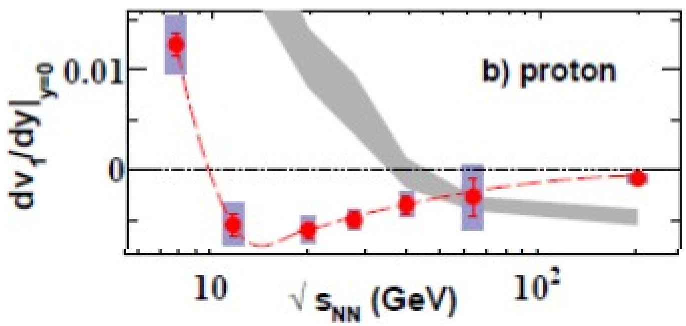
Kohno ('18)

Directed flow (v_1)

- **Directed flow (v_1 or <p_x>) has been utilized to constrain EOS**
  E.g. Sahu, Cassing, Mosel, AO (nucl-th/9907002), Snellings+(nucl-ex/9908001)

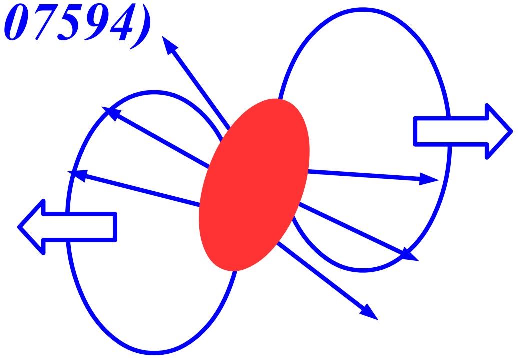


- **Proton v_1 slope problem** *STAR (1401.3043)*
  - **Non-monotonic beam E. dep. of v_1 slope**
  - **Sign change of v_1 slope at $\sqrt{s_{NN}} \sim 10$ GeV**
  - **None of fluid and hybrid models explain the colliding energy dependence using a single EOS**
    Nara+(JAM, 1601.07692, 1611.08023, 1708.05617), Ivanov+(3FD, 1412.1669, 1601.03902), Konchakovski+ (PHSD, 1404.2765)



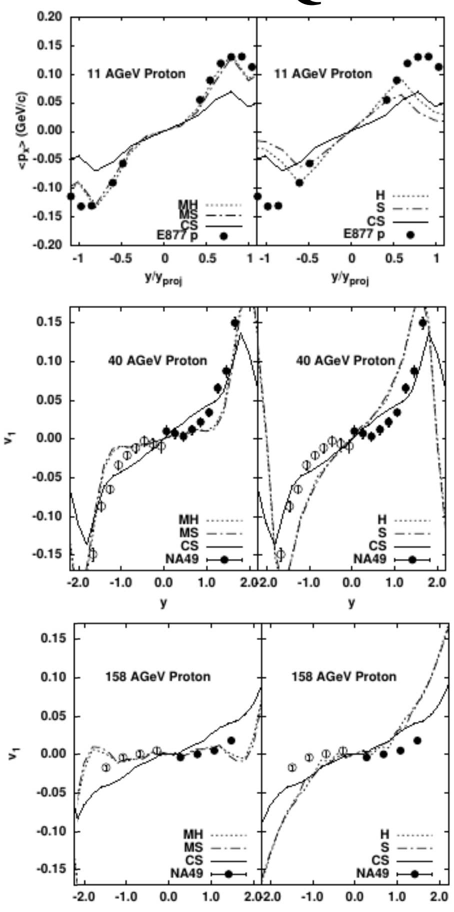
STAR, PRL112('14)162301 (1401.3043)

- **An answer has been found !** *Nara, AO (PRC'('22), 2109.07594)*
  - **Repulsion during compression → positive**
  - **Expansion of tilted matter → negative**
  - **Balance of two causes non-monotonic behavior**



Past tries

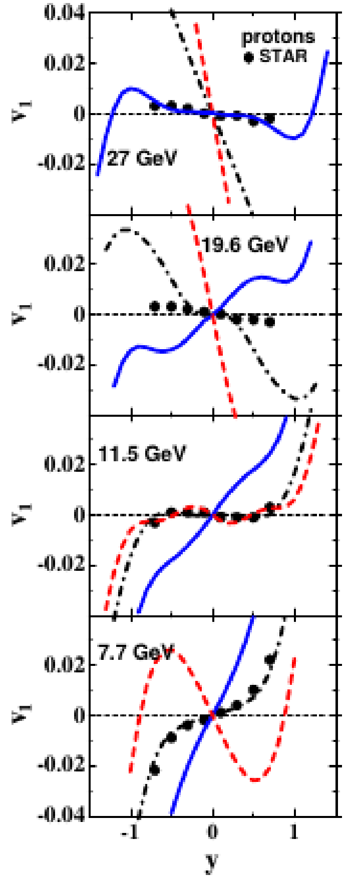
JAM-RQMD



p-dep. p-indep.

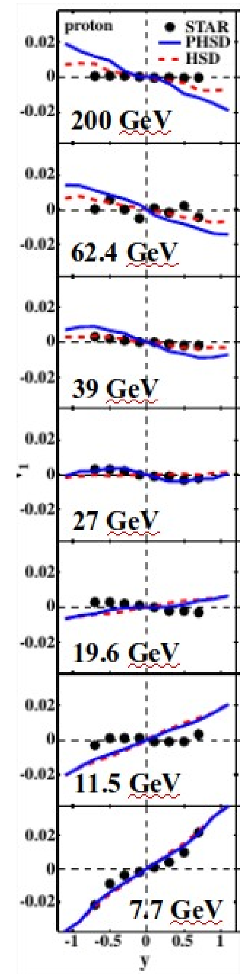
M.Isse, AO, N.Otuka, P.K.Sahu, Y.Nara, PRC72('05)064908 (There was a mistake...)

3FD



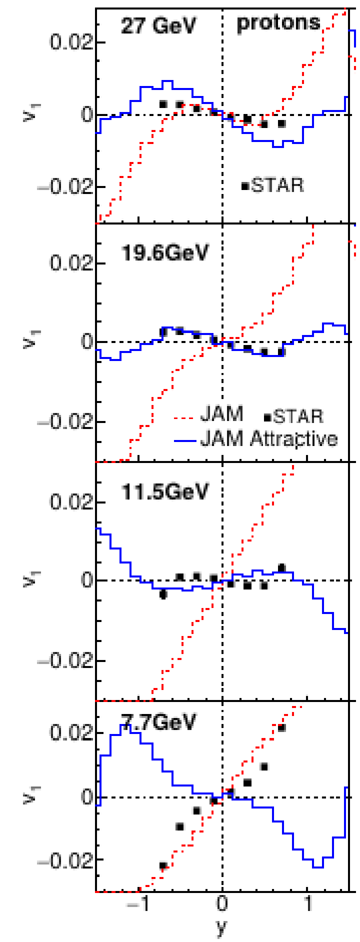
Y.B.Ivanov, A.A.Soldatov, PRC91('15) 024915

HSD/PHSD



V.P.Konchakovski, W.Cassing, Y.B.Ivanov, V. D. Toneev, PRC90('14)014903

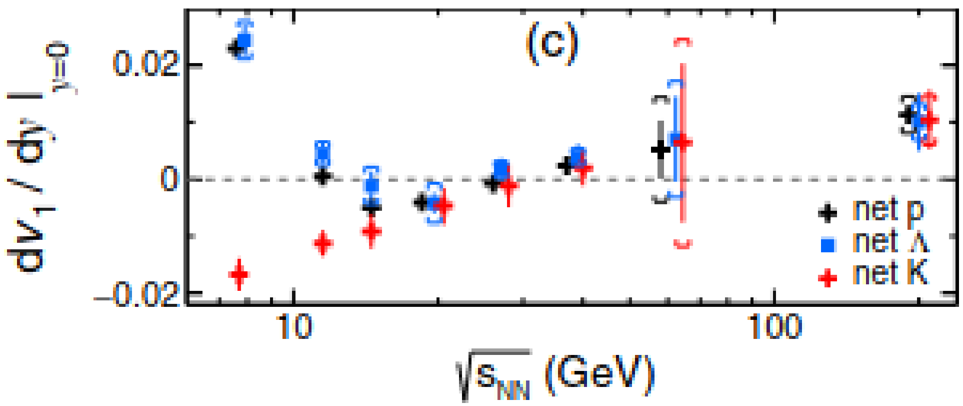
JAM+Att.



Y.Nara, H.Niemi, AO, H.Stoecker, PRC94 ('16)034906

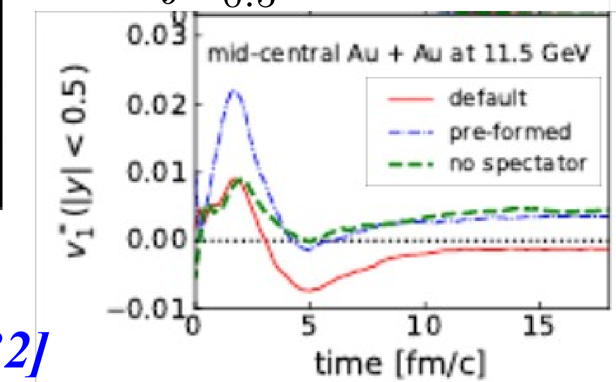
Why Directed flow (v_1) of Λ

- **Directed flow of Λ**
  - **In the compression+tilted expansion mechanism, directed flow of Λ should be smaller than p.**
  - **Data show $v_1(\Lambda) \sim v_1(p)$** ***STAR (1708.07132)***
    → Stronger repulsion for Λ at high densities ?

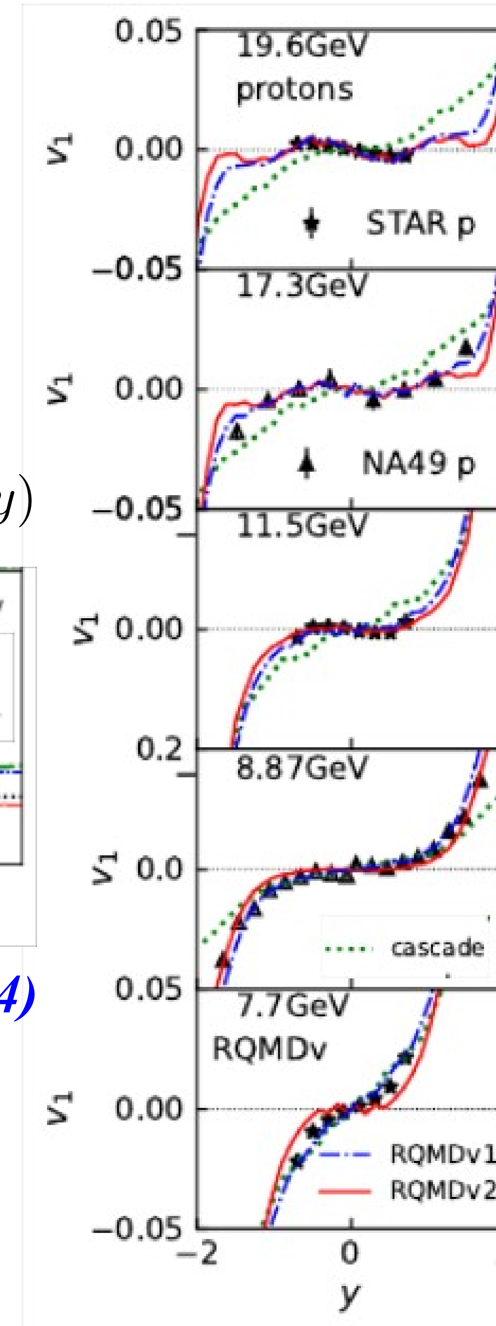


STAR, PRL120 ('18),062301 [1708.07132]

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



Y. Nara, AO (2109.07594)



Let us examine Λ directed flow using $U_\Lambda(\rho)$ from chiral EFT !

JAM2/RQMDv+chiral EFT U_Λ

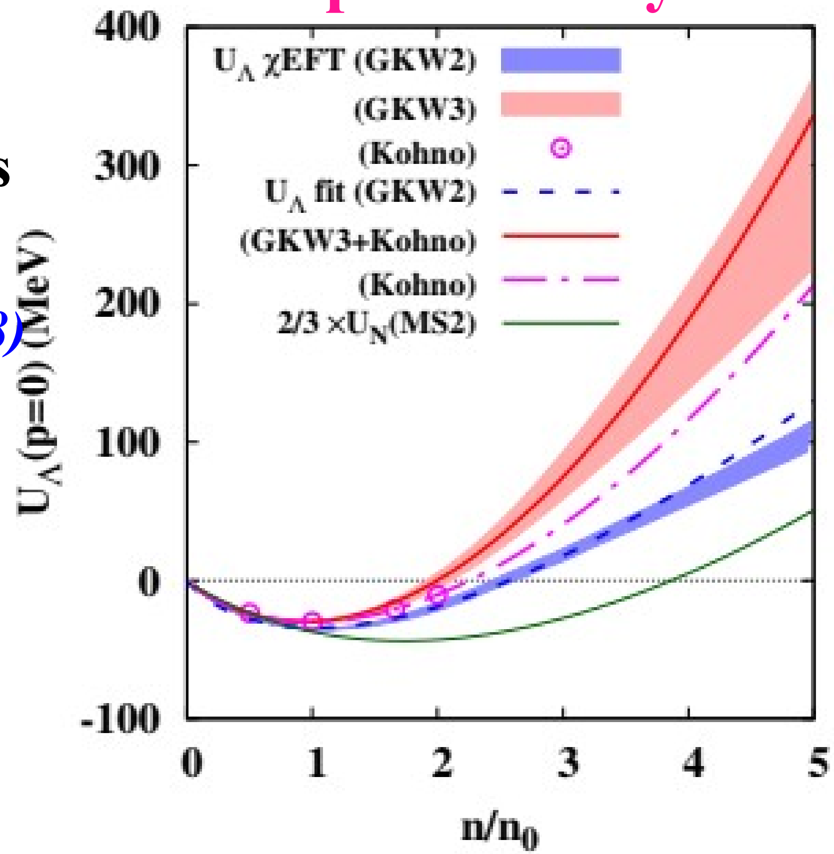
- **JAM2/RQMDv**
  - **JAM2 = Update of JAM1 (fortran → C++, pythia6 → pythia8)**
    + improvement of resonance exc. cross sections
    + expanding box to reduce the CPU time
  - **JAM2/RQMDv** *Nara+(2109.07594)*
    - **Lorentz vector type implementation of ρ- and p-dep. potential, which operates also on high p particles**
- **U_Λ from chiral EFT**
  Gerstung+(2001.10563)(GKW), Kohno (1802.05388)
  - **ρ-dep. potential using Fermi mom. expansion** *Tews+(1611.07133)*

$$U_{\rm sk}(\rho) = a(\rho/\rho_0) + b(\rho/\rho_0)^{4/3} + c(\rho/\rho_0)^{5/3}$$

  - **Momentum dep. fit to** *Kohno('18)*

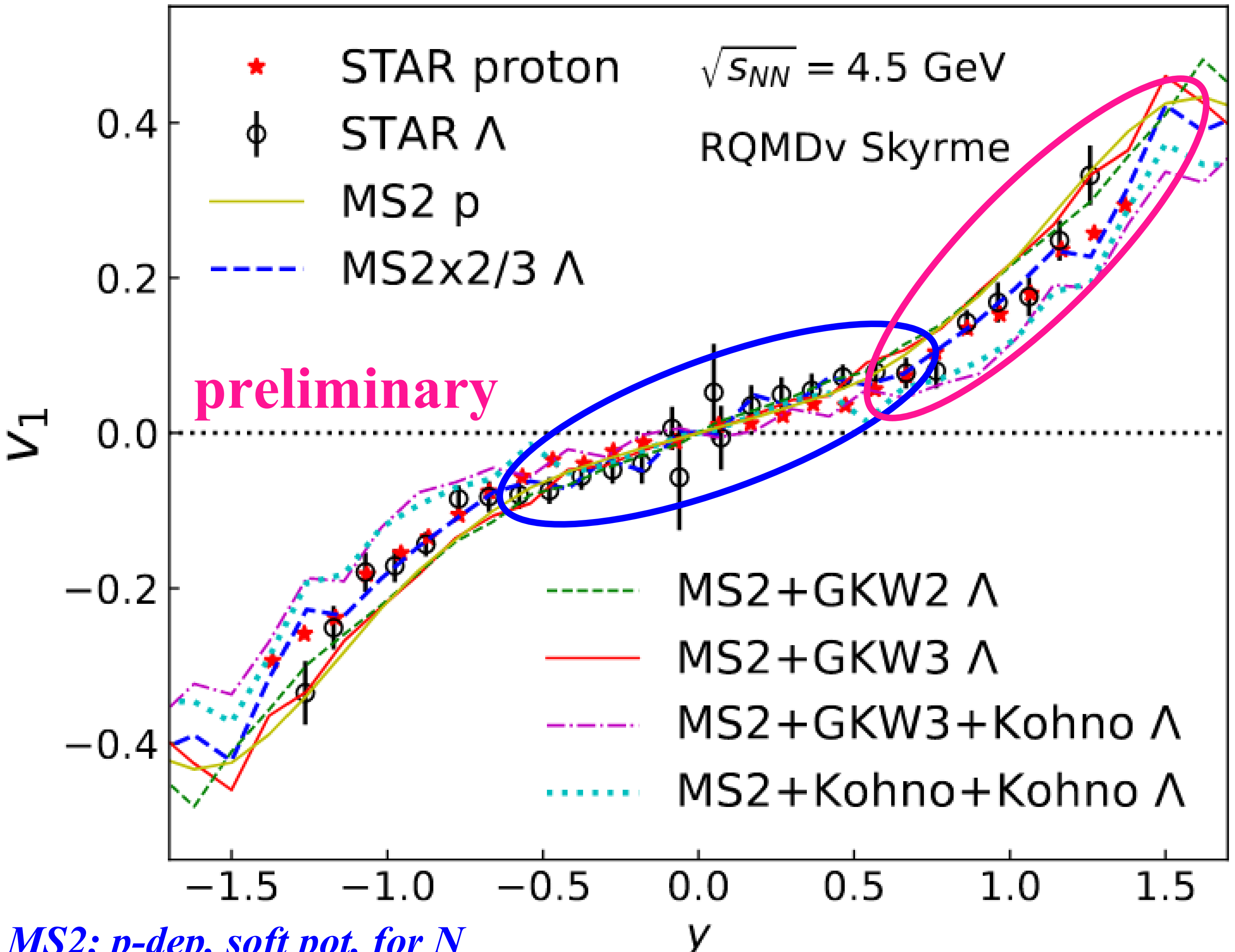
$$U^0_{\rm m}(\boldsymbol{p}) = \frac{C}{\rho_0}\int \frac{d\boldsymbol{p}'}{(2\pi)^3}\frac{f(\boldsymbol{r},\boldsymbol{p}')}{1+(\boldsymbol{p}-\boldsymbol{p}')^2/\mu^2}$$

preliminary



Nara, Jinno, Murase, AO, in prep.

$\sqrt{s_{NN}}$=4.5 GeV

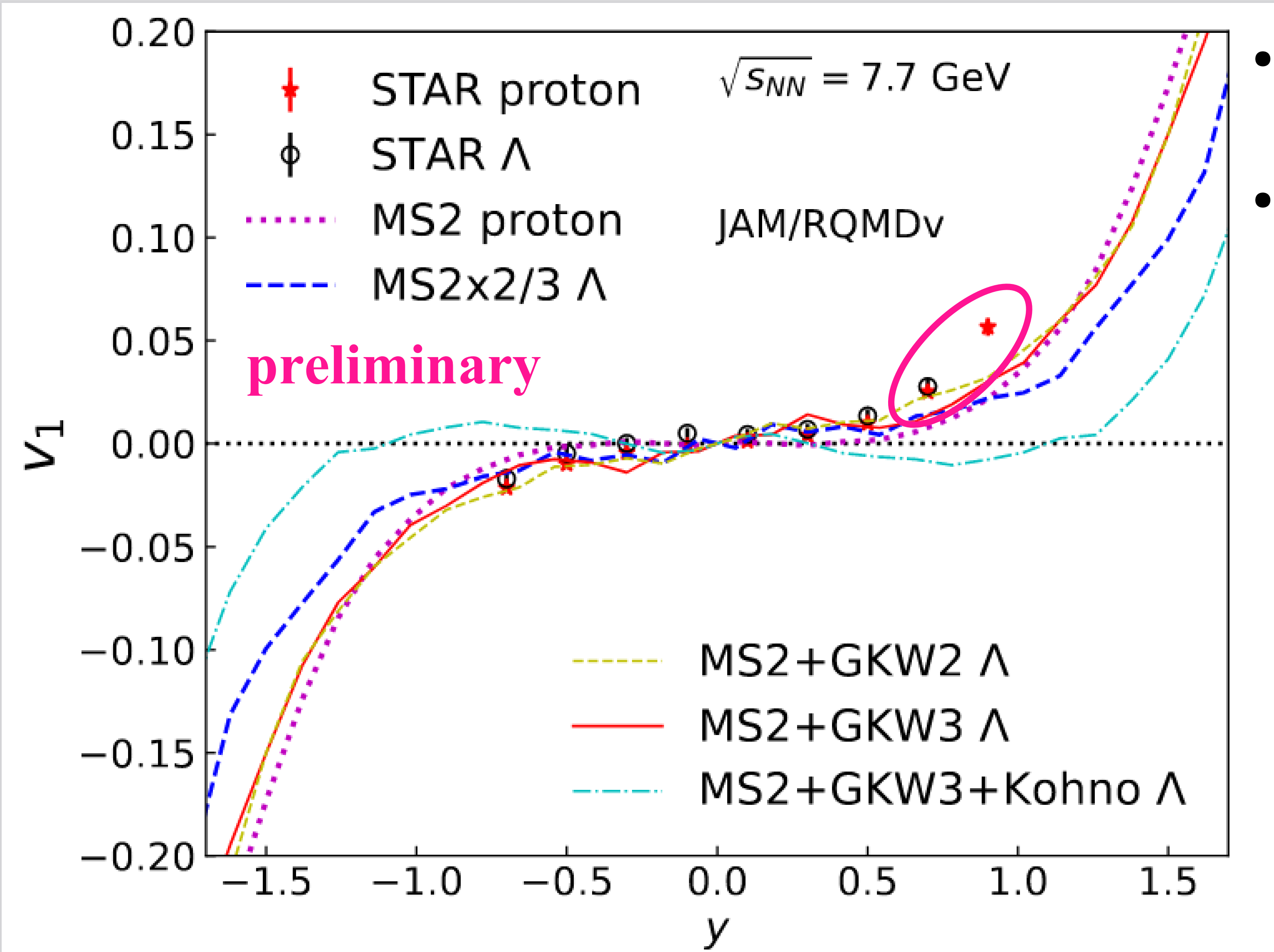


- **Slope (y=0) is OK with**
  - **chiral EFT U_Λ (p-indep.)**
  - **U_Λ = 2/3 U_N**
- **v_1 at large |y| needs stiffer U_Λ**
  - **chiral EFT (p-indep.)**
- **p-dep. U_Λ seems to underestimate v_1**

MS2: p-dep. soft pot. for N
GKW2: chiral EFT with 2-body int.
GKW3: chiral EFT with 2+3 body int.
GKW3+Kohno: GKW3 with p-dep. from Kohno
Kohno+Kohno: ρ- and p-dep. from Kohno

Nara, Jinno, Murase, AO, in prep.

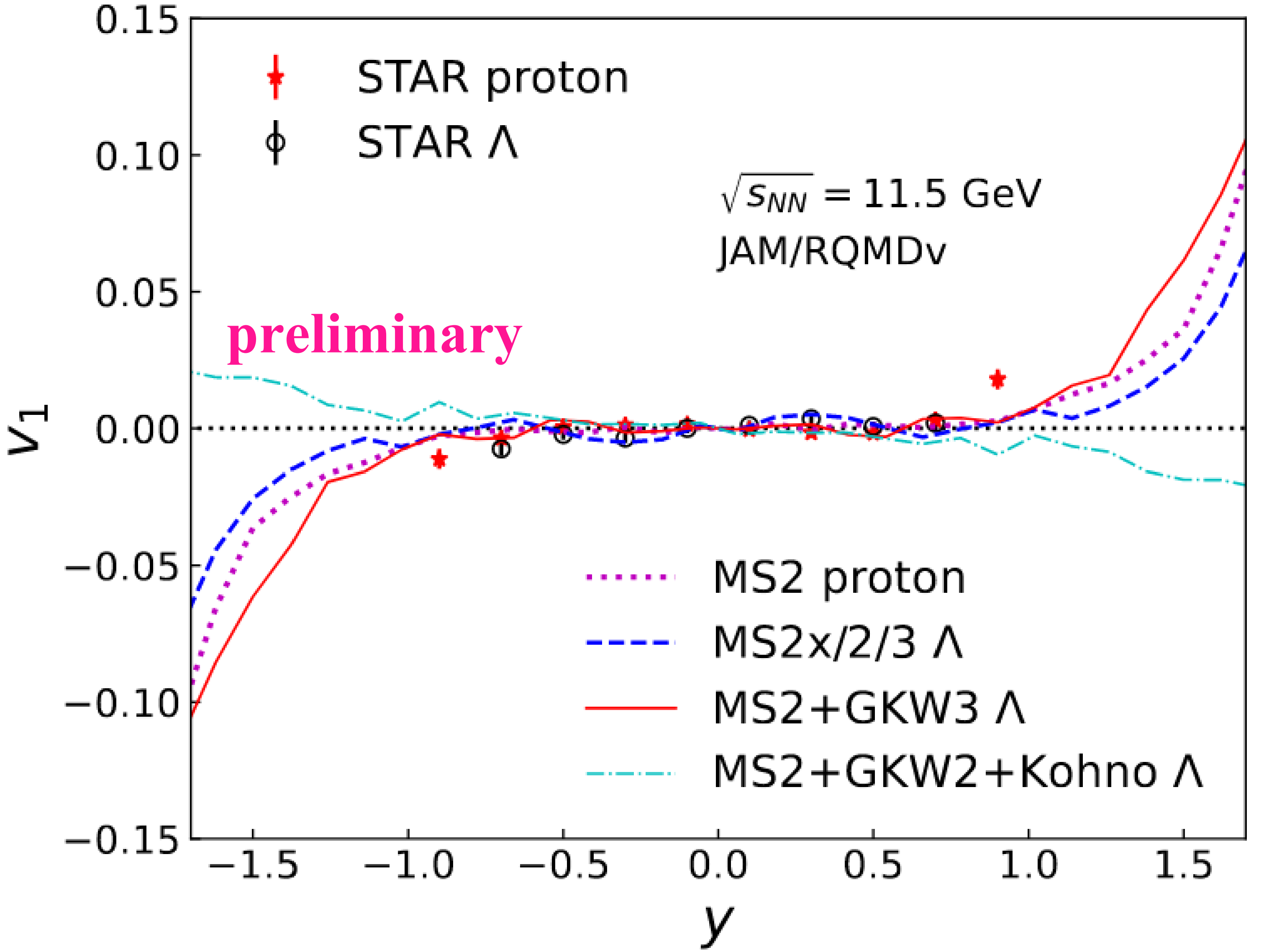
$\sqrt{s_{NN}}$=7.7 GeV



- v_1 at large |y| is underestimated
- chiral EFT U_Λs (p-indep.) are closer

Nara, Jinno, Murase, AO, in prep.

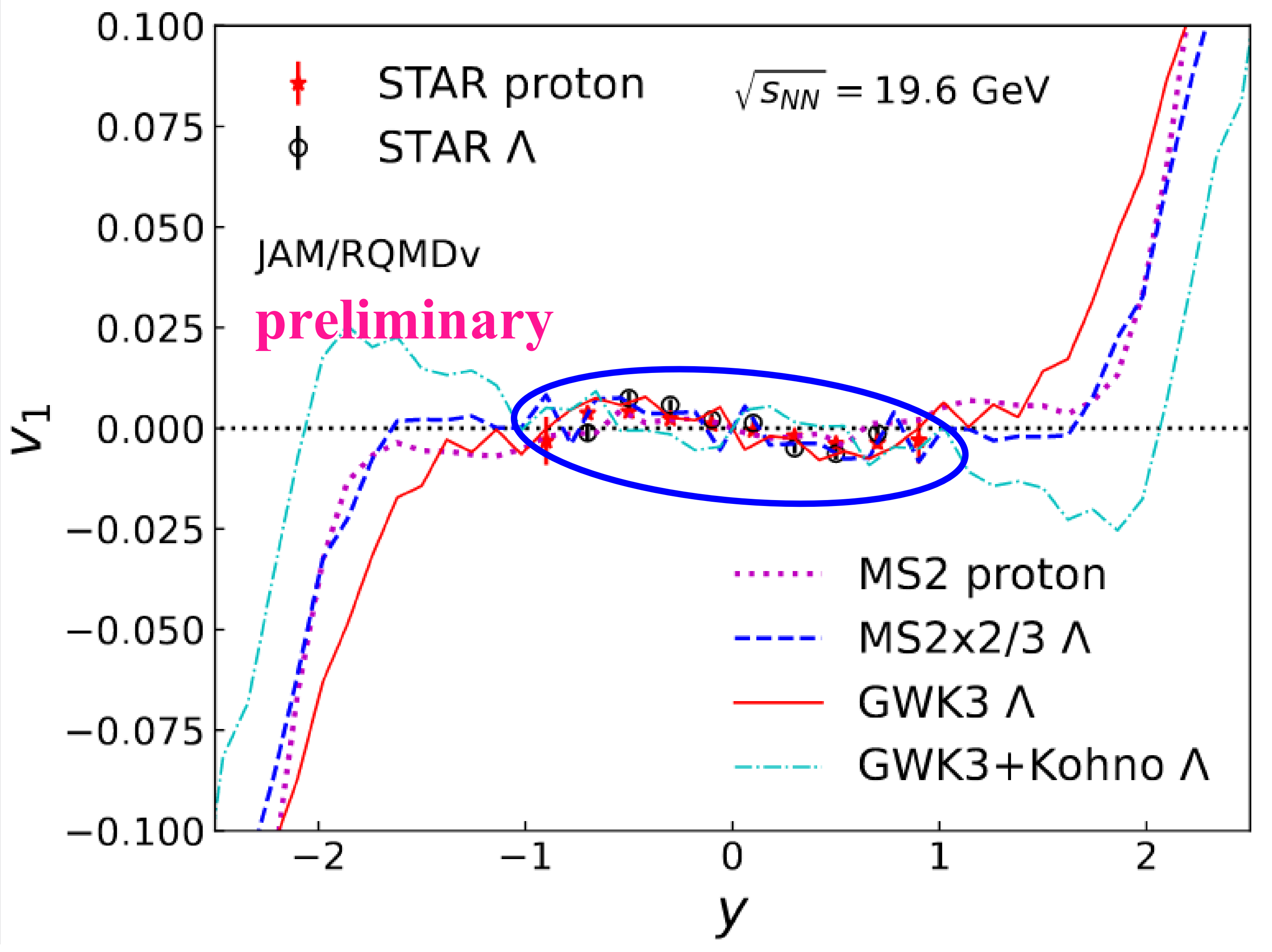
$\sqrt{s_{NN}}$=11.5 GeV



- **$\sqrt{s_{NN}}$=11.5 GeV is around the "balance energy" (slope changes sign)**

Nara, Jinno, Murase, AO, in prep.

$\sqrt{s_{NN}}$=19.6 GeV



- **Negative dv_1/dy at $y \sim 0$**

Nara, Jinno, Murase, AO, in prep.

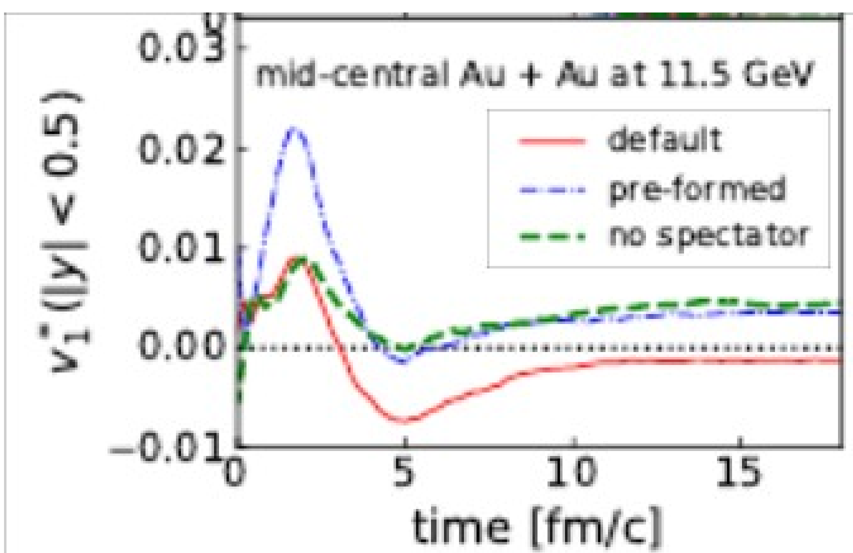
Summary

- **The directed flow (v_1) of Λ from HICs at $\sqrt{s_{NN}}$=(4.5-19.6) GeV is studied by using the Λ potential from chiral EFT.**
  - **U_Λ from chiral EFT contains strong repulsion from the 3-body interactions and suppresses Λ to appear in neutron stars.**
  - **The Λ v_1 slopes at midrapidity are roughly explained by the Λ potentials having ρ-dep. from the chiral EFT with 2+3 body int.**
    [Similar results for <px> at √sNN=3.0 GeVare obtained by D.C. Zhang+ (2107.00277)]
  - **U_Λ = 2/3 U_N and U_Λ from 2-body chiral EFT also explains the slopes. (Strong repulsion in U_Λ at high densities is not verified yet.)**
  - **The p-dep. of U_Λ seems to reduce the slopes significantly. While the p-dep. of U_Λ enhances the slope in the compression stage, it reduces the slope in the tilted matter expansion stage. (The simultaneous fit to ρ- and p-dep. would be necessary.)**
  - **The forward and backward v_1 values seem to be sensitive to the Λ potential at high densities.**

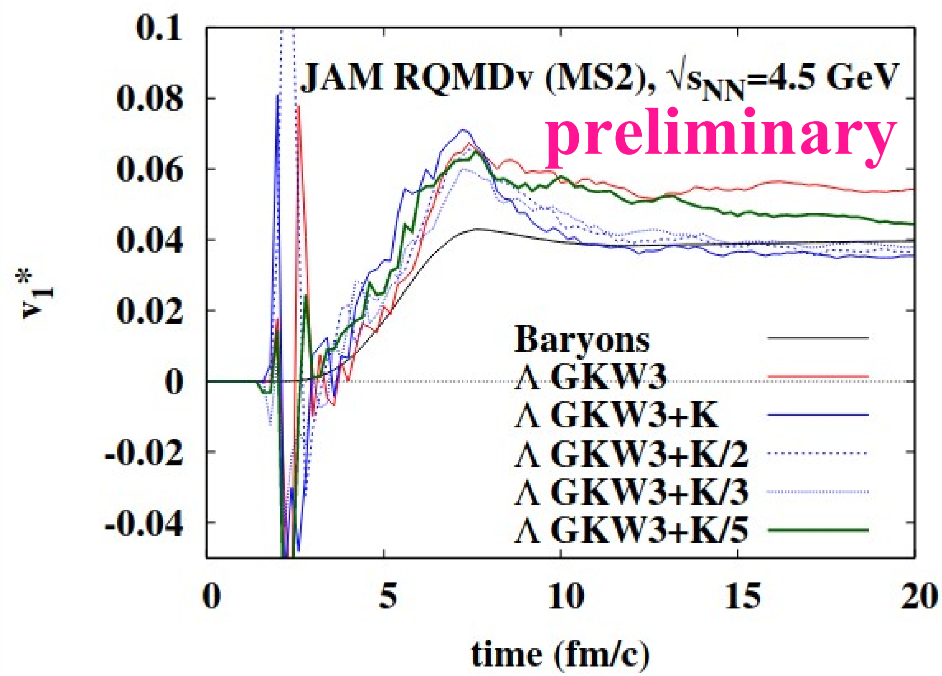
Nara, Jinno, Murase, AO, in prep.

p-dep. potential works on the way and back

- **Momentum dependent potential works repulsively to high-momentum particles even at low densities.**
  (p-indep. potential is attractive at $\rho < 2\,\rho_0$)
  → It increases v1 slope in the compression stage more strongly, but it also strongly reduces the slope in the tilted matter expansion stage.



Y. Nara, AO (2109.07594)



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Thank you for your attention !

Short (5 slide-)version follows.

Directed flow of Λ from HICs and hyperon puzzle of NSs

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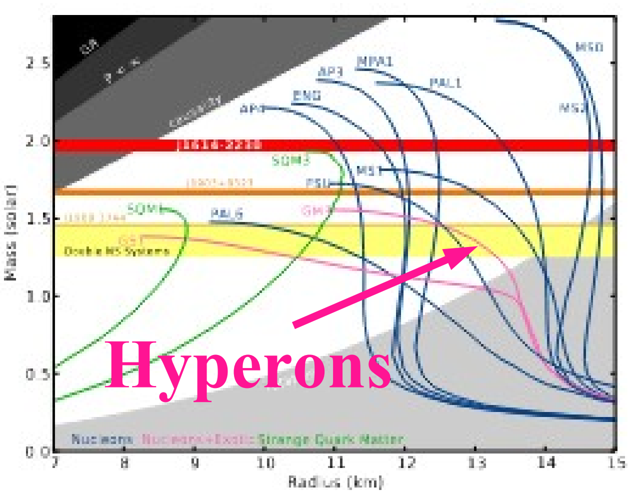
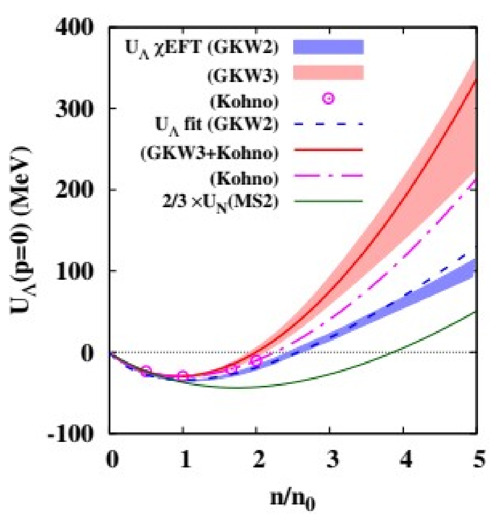
- **Does three-body ΛNN repulsion solve the hyperon puzzle ?**
  - **E.g. Chiral EFT w/ 2+3-body int. can give repulsive potential.**
    Gerstung, Kaiser, Weise (2001.10563)(GKW), Kohno (1802.05388)
- **Examination of U_Λ via directed flow (v_1) of Λ** *Data: STAR (1708.07132)*
  - **Studied in JAM2/RQMDv (explains v_1 of p) + U_Λ from chiral EFT**

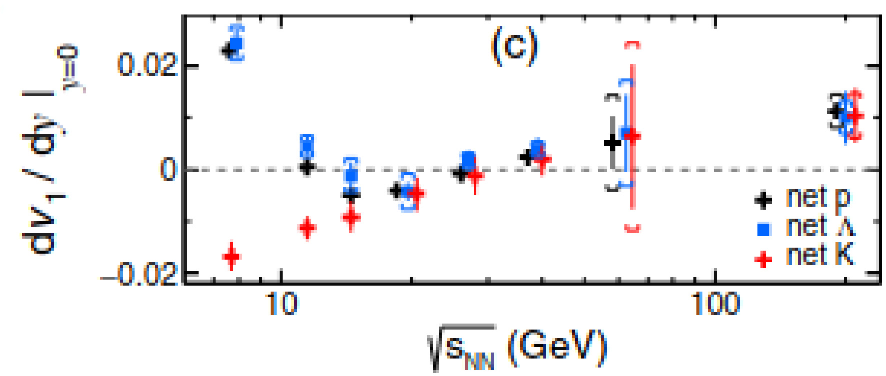
$$U_{\rm sk}(\rho) = a(\rho/\rho_0) + b(\rho/\rho_0)^{4/3} + c(\rho/\rho_0)^{5/3} \qquad U^0_{\rm m}(\boldsymbol{p}) = \frac{C}{\rho_0}\int \frac{d\boldsymbol{p}'}{(2\pi)^3}\frac{f(\boldsymbol{r},\boldsymbol{p}')}{1+(\boldsymbol{p}-\boldsymbol{p}')^2/\mu^2}$$



Demorest+(1010.5788)



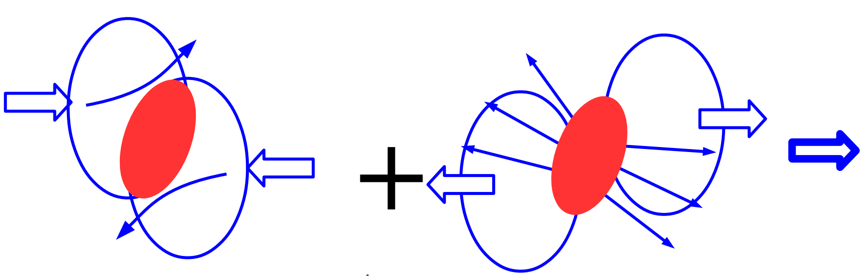
Nara+(in prep.)

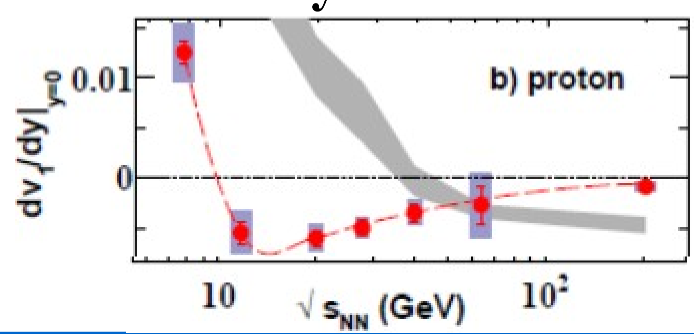


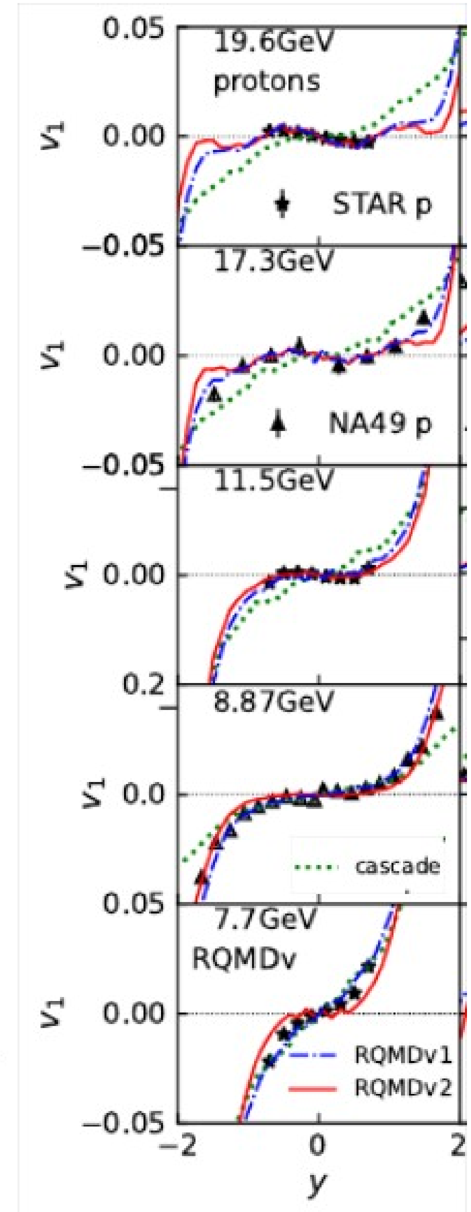
STAR, PRL('18) [1708.07132]

Directed flow (v_1) of protons

- **Directed flow (v_1 or $<p_x>$) has been utilized to constrain EOS**
  E.g. Sahu, Cassing, Mosel, AO (nucl-th/9907002), Snellings+(nucl-ex/9908001)
- **Proton v_1 slope** *STAR (1401.3043), Nara+(2109.07594)*
  - **Non-monotonic beam E. dep. of v_1 slope**
  - **Sign change of v_1 slope at $\sqrt{s_{NN}} \sim 10$ GeV**
  - **None of fluid and hybrid models explain the colliding energy dependence using a single EOS**
  - **An answer** *Nara, AO (PRC'('22), 2109.07594)*
    - **Compression (positive) and expansion (negative) contributions cause non-monotonicity.**

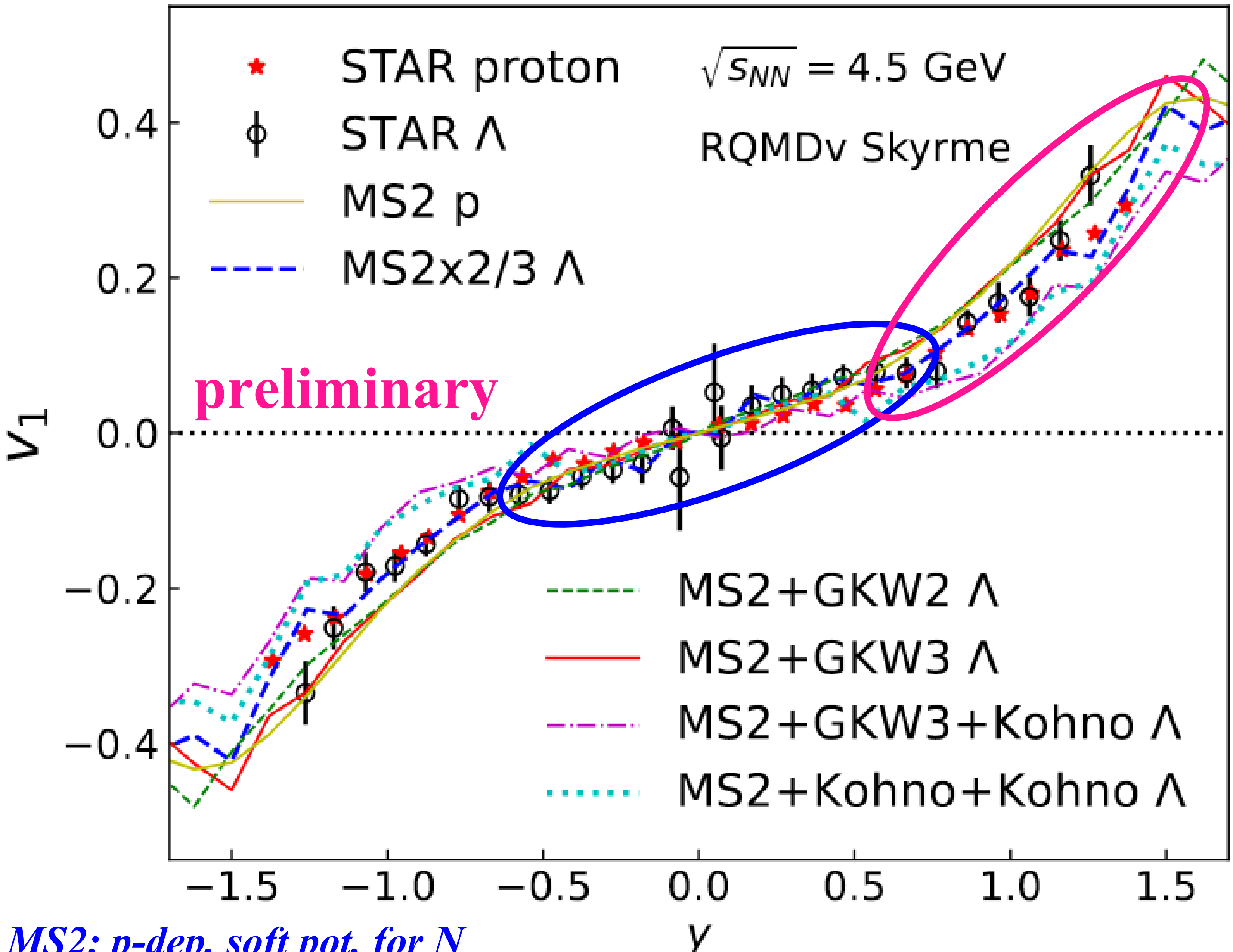






STAR, PRL112('14) 162301 (1401.3043)

Directed flow (v_1) of Λ at $\sqrt{s_{NN}}$=4.5 GeV



Calculation with JAM2/RQMDv

- **Slope (y=0) is OK with**
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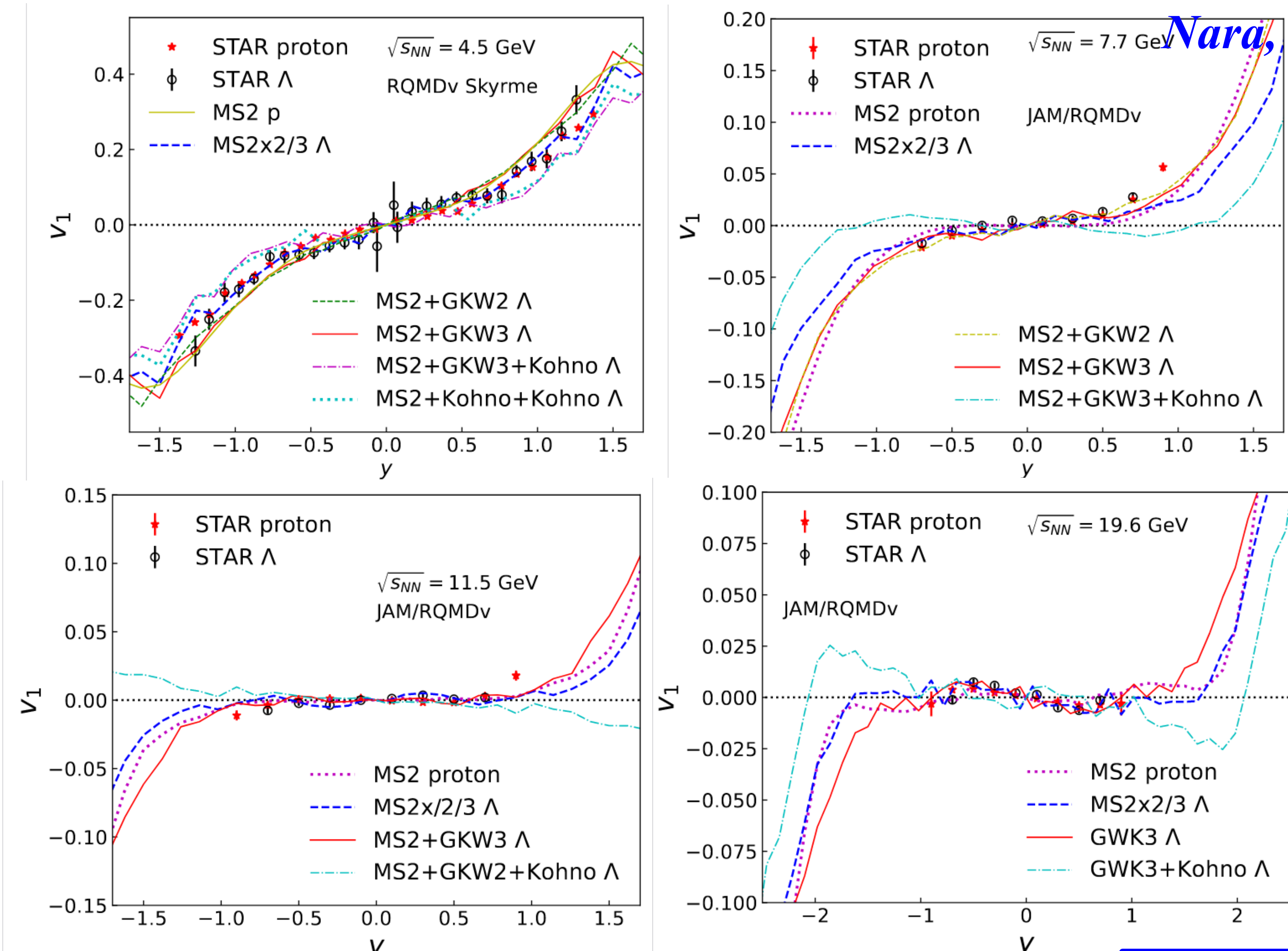
Nara, Jinno, Murase, AO, in prep.

Directed flow of Λ at $\sqrt{s_{NN}}$=(4.5-19.6) GeV

Nara, Jinno, Murase, AO, in prep.



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Kohno+Kohno: ρ- and p-dep. from Kohno

> ***U_Λ having the ρ-dep. in chiral EFT roughly explains the v_1 slopes.***

Summary

- The directed flow (v_1) of Λ from HICs at $\sqrt{s_{NN}}$=(4.5-19.6) GeV is studied by using the Λ potential from chiral EFT.
  - U_Λ from chiral EFT contains strong repulsion from the 3-body interactions and suppresses Λ to appear in neutron stars.
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