Directed flow of $\Lambda$ from heavy-ion collisions and hyperon puzzle of neutron stars

Akira Ohnishi $^1$, A. Jinno $^2$, K. Murase $^1$, Y. Nara $^3$

1. YITP, Kyoto U., 2. Dept. Phys., Kyoto U., 3. Akita International U.

Introduction – Hyperon puzzle
Directed flow of protons
Directed flow of $\Lambda$ using $U_\Lambda$ from chiral EFT
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 $(2-4)\rho_0$, softens the EOS, and reduces $M_{\text{max}} = (1.3-1.6)M_\odot$

- Proposed solutions
  - Three-body $\Lambda NN$ repulsion $\rightarrow$ repulsive $U_\Lambda(\rho)$ at high density
  - Transition to quark matter before $\Lambda$ appears
  - General relativity $\rightarrow$ Modified gravity

Challenging Subject in Mean Field Dynamics
Chiral effective field theory (chiral EFT) may cause repulsive $\Lambda$ 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!
→ E.g. Collective flows in heavy-ion collisions

Gerstung+ (‘20)  
Kohno (‘18)
Semi-Classical Nuclear Transport Theories

- Wigner(-Weyl) transform of TDHF = Vlasov equation
  - Wigner transform of density matrix = Wigner fn. (phase space dist.)
  - Wigner transform of commutator $\sim i\hbar \times$ Poisson bracket
    \[
    i\hbar \frac{d\rho}{dt} = [\hbar, \rho] \rightarrow \frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \nabla U \cdot \nabla_p f = 0
    \]
    \[
    [f = \rho_W, [A, B]_W = i\hbar \{A_W, B_W\}_{PB} + \mathcal{O}(\hbar^2)]
    \]
- Test particle solution of the Vlasov equation $\rightarrow$ Classical EOM
  \[
  f(r, p) = \frac{(2\pi)^3}{N} \sum_{i=1, NA} \delta(r - r_i)\delta(p - p_i)
  \]
  \[
  \rightarrow \frac{dr_i}{dt} = \frac{\partial h}{\partial p} \bigg|_{p=p_i} = \frac{p}{m} + \frac{\partial U}{\partial p} \bigg|_{p=p_i}, \quad \frac{dp_i}{dt} = -\frac{\partial U}{\partial r} \bigg|_{r=r_i}
  \]
- Relativistic Quantum Molecular Dynamics
  - Transport model applicable to high energies
    Sorge, Stoecker, Greiner (‘89); Maruyama et al. (‘96)
  - Stronger potential effects are necessary $\rightarrow$ Vector potential
    Nara et al. (‘20), Nara, AO (‘21)
  - Stochastic collisions are also included
Transport models and then (High-Energy) Heavy-Ion Collisions are RELEVANT to Mean Field Dynamics.

Let us Examine the Effects of $U_\wedge$ at High Densities via Collective Flow(s) in Heavy-Ion Collisions!
Directed flow of protons
Directed flow ($v_1$)

- Directed flow ($v_1$ or $\langle p_x \rangle$) 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)*

\[ v_1 = \langle \cos \phi \rangle \]
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

A. Ohnishi @ MCD 2022, June 8, 2022, Hybrid (YITP, Kyoto, Japan / Online)
An Explanation is found

Beam energy dependence of $dv_1/dy$ can be explained with JAM2 in the RQMDv mode. 
\textit{Nara+('16,'17,'18); Y. Nara, AO, arXiv:2109.07594}

Origin of Positive & Negative Flow Components

- Compression stage $\rightarrow$ repulsive pot. at high $\rho$ $\rightarrow$ positive flow ($dv_1/dy > 0$)
- Expansion stage $\rightarrow$ tilted matter formation $\rightarrow$ negative flow ($dv_1/dy < 0$)
\textit{(E.g. 3FD, Tonnev+('03)}

Balance of two contributions may cause non-monotonic colliding energy dep. of $v_1$ slope

18 GeV, 3-fluid \textit{Toneev et al. ('03)} \textit{Nara, AO (PRC’(’22), 2109.07594)
Positive and Negative Contributions

\[ \sqrt{S_{NN}} = 4.86 \text{ GeV} \ b=6 \text{ fm} \]

JAM2

\[ \sqrt{S_{NN}} = 11.5 \text{ GeV} \ b=6 \text{ fm} \]

JAM2

Nara, AO (PRC’(’22), 2109.07594)
Can we access EOS by using flows?

- EOS from Flow is a Notorious problem!
  - Momentum-dependent potential can simulate stiff EOS, and then we cannot extract stiffness. (1980s ~)
  - Directed flow value depends on the details of the theoretical treatment.

- A New (?) Hope (Episode IV)
  - After fixing momentum-dependent pot. from pA scattering data and explaining $v_1$ data, EOS dependence of $v_2$ (elliptic flow) remains! (Global analysis of multiple observables will help.)

- How about $\Lambda$?

_Nara, AO (PRC’(’22), 2109.07594)_
Directed flow of $\Lambda$ using $U_\Lambda$ from chiral EFT
Why Directed flow ($v_1$) of $p$ and $\Lambda$

Directed flow of $\Lambda$

- In the compression+tilted expansion mechanism, directed flow of $\Lambda$ is expected to be smaller than $p$ ($\Lambda$s are produced during the compression stage).
- Data show $v_1(\Lambda) \sim v_1(p)$ *STAR, PRL120 (‘18),062301 (1708.07132)*
  - Stronger repulsion for $\Lambda$ at high densities?

Let us examine $\Lambda$ directed flow using $U_\Lambda(\rho)$ from chiral EFT!
Chiral EFT with 3BF and hyperons

Gerstung+(2001.10563)(GKW, decouplet saturation model), Kohno (1802.05388)

- ρ-dep. potential using Fermi mom. expansion Tews+(1611.07133)

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

Momentum dep. fit to Kohno('18)

\[ U^{0}_m(p) = \frac{C}{\rho_0} \int \frac{dp'}{(2\pi)^3} \frac{f(r, p')}{1 + (p - p')^2/\mu^2} \]

preliminary

Nara, Jinno, Murase, AO, in prep.
$\sqrt{s_{NN}} = 4.5 \text{ GeV}$

- Slope ($y=0$) is OK with
  - chiral EFT $U_\Lambda$ (p-indep.)
    - $U_\Lambda = 2/3 \ U_N$
  - $v_1$ at large $|y|$ needs stiffer $U_\Lambda$
  - chiral EFT (p-indep.)
  - p-dep. $U_\Lambda$ 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: $\rho$- and p-dep. from Kohno

Nara, Jinno, Murase, AO, in prep.
Can we rely on $U_\Lambda$ up to 2 GeV/c?

- The cutoff is 550 MeV/c $\sim 2.75$ fm$^{-1}$ in Kohno (‘18)
- Quark model YN interaction gives weaker p-dep.
- Chiral EFT results at $k < 1$ fm$^{-1}$ are fitted and used (Kohno low-k)

Fujiwara, Suzuki, Nakamoto, PPNP 58 (‘07) 439 (nucl-th/0607013)
Chiral EFT at low momentum seems to be consistent with the $\Lambda$ directed flow.
Summary

- The directed flow ($v_1$) of $\Lambda$ from HIC is studied by using the $\Lambda$ potential from chiral EFT with 3-body potential, which can support 2 solar mass neutron stars.
  - $U_\Lambda$ from chiral EFT is not inconsistent with the directed flow data from heavy-ion collisions.
  - [Similar results for $<px>$ at $\sqrt{s_{NN}}=3.0$ GeV are obtained by D.C. Zhang+ (2107.00277)]
- Momentum dependence may be weaker than the explicit results. (We should not rely on results at $k > \Lambda/2$)
- $v_1(\Lambda)$ is not very sensitive to the density dep. of $U_\Lambda$.
  - ($\Lambda$ produced from $N$ in the compression stage succeeds the $v_1$ of $N$)
- The forward and backward $v_1$ values seem to be sensitive to the $\Lambda$ potential at high densities and/or high momentum.
- How can we pin down $U_\Lambda$ at high densities?
  - $\Lambda$-nucleus scattering (Emulsion or Femtoscopy) $\rightarrow$ mom. dep.
  - Elliptic flow ($v_2$) and other observables
  - Hypernuclear spectroscopy

Nara, Jinno, Murase, AO, in prep.
Thank you for your attention!
Directed flow of $\Lambda$ at $\sqrt{s_{NN}} = (4.5-19.6)$ GeV

$U_\Lambda$ having the $p$-dep. in chiral EFT roughly explains the $v_1$ slopes.

**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**: $\rho$- and $p$-dep. from Kohno

Nara, Jinno, Murase, AO, in prep.
Time dependence of $v_1$

Courtesy of Y. Nara
Lambda position: 11.5GeV 20 events

Red: nucleons
Blue: Lambda + Sigma0

\( \sqrt{s_{NN}} = 11.5 \text{ GeV} b=6 \text{ fm} \)

Courtesy of Y. Nara
Collision order = collision time
= \frac{(t_1 + t_2)}{2}, \quad L = 0.5 \text{ fm}^2

\begin{align*}
\text{CO} &= \text{CT} = \min(t_1, t_2), \quad L = 1.0 \text{ fm}^2
\end{align*}

Courtesy of Y. Nara