

Charge-dependent Anisotropic Flow in Relativistic Resistive Magneto-hydrodynamic Expansion

Department of physics, Hiroshima University

International Institute for Sustainability with Knotted Chiral Meta Matter / SKCM².

Hiroshima University

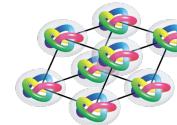
Kobayashi Maskawa Institute, Nagoya University

Department of Physics, Nagoya University



Chiho NONAKA

In collaboration with **Kouki Nakamura**,
Takahiro Miyoshi and Hiroyuki Takahashi, and Nicholas J. Benoit



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Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

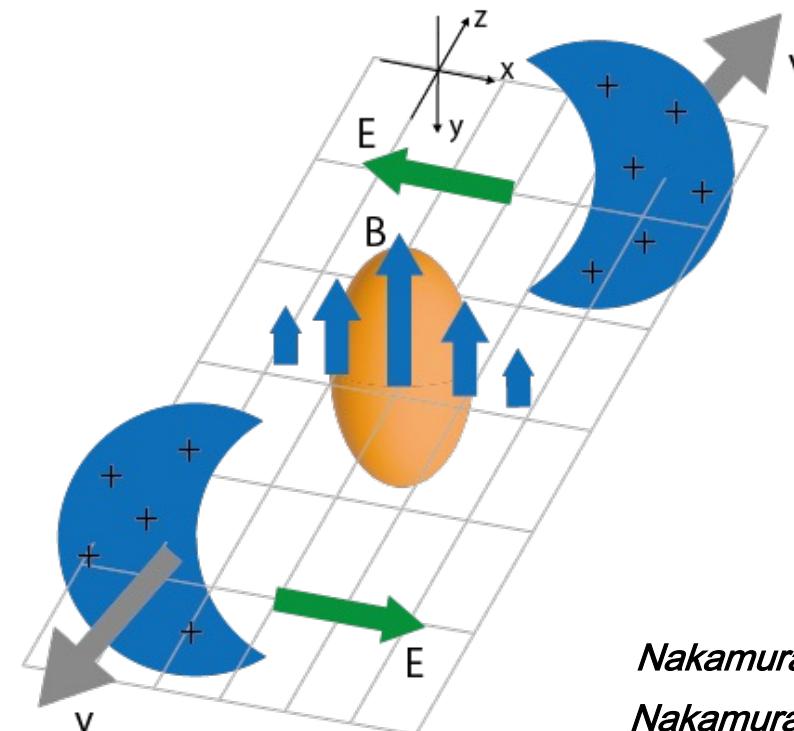
September 6, 2023@QM2023

Electromagnetic Field in Heavy Ion Collisions



- **Strong Electromagnetic field ?**

- Au + Au ($\sqrt{s_{NN}} = 200$ GeV) : 10^{14} T $\sim 10 m_\pi^2$
- Pb + Pb ($\sqrt{s_{NN}} = 2.76$ TeV) : 10^{15} T



Nakamura, Miyoshi, C. N. and Takahashi, Phys. Rev. C 107, (2023) 014901

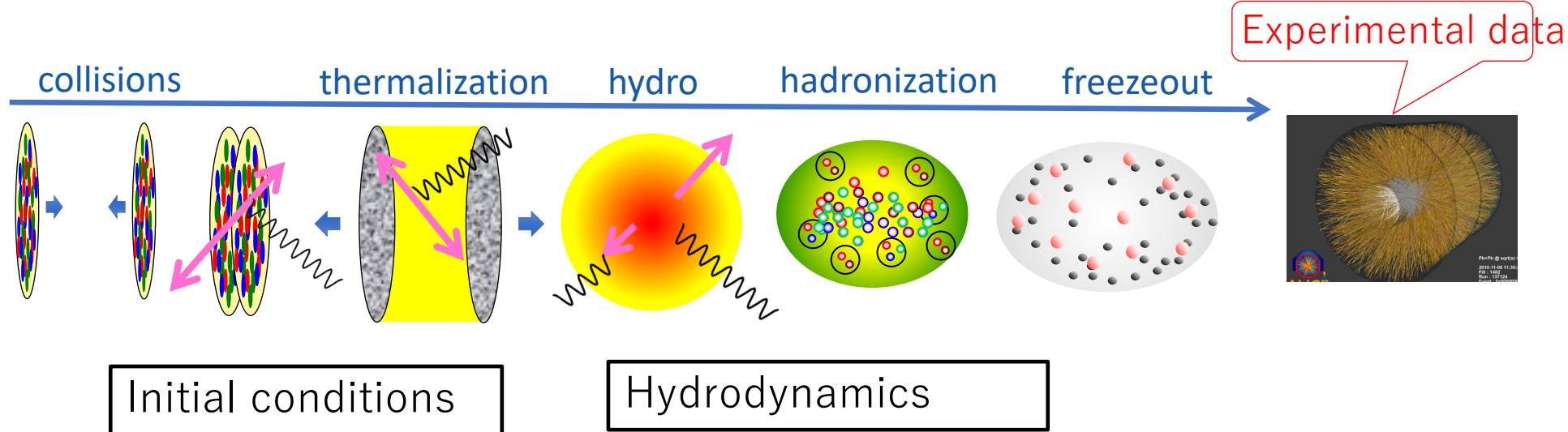
Nakamura, Miyoshi, C. N. and Takahashi, Eur.Phys.J.C 83 (2023) 3, 229.

Nakamura, Miyoshi, C. N. and Takahashi, Phys. Rev. C 107 (2023) 3, 034912

Relativistic Resistive Magneto-Hydrodynamics (RRMHD)



Nakamura, Miyoshi, C. N. and Takahashi, PRC107, no. 1, 014901 (2023)



Glauber model
+approximate solutions of Maxwell eq.

Hydrodynamic eq. + Maxwell eq. + Ohm's law

$$\partial_\mu T^{\mu\nu} = F^{\nu\lambda} J_\lambda \quad J^\mu = \sigma e^\mu$$

Relativistic Resistive Magneto-Hydrodynamics (RRMHD)



Nakamura, Miyoshi, C. N. and Takahashi, PRC107, no. 1, 014901 (2023)

■ RRMHD equation

➤ Conservation law + Maxwell eq. + Ohm's law

$$\partial_\mu T^{\mu\nu} = F^{\nu\lambda} J_\lambda$$

$$J^\mu = J_c^\mu + q u^\mu$$

e : energy density

p : pressure

$$p_{em} = (E^2 + B^2)/2$$

$$\varepsilon = (e + p)\gamma^2 - p + p_{em}$$

$$m^i = (e + p)\gamma^2 v^i + \epsilon^{ijk} B_j E_k$$

$$\Pi^{ij} = (e + p)\gamma^2 v^i v^j + (p + p_{em})g^{ij} - E^i E^j - B^i B^j$$



Energy Conservation

$$\partial_t \varepsilon + \nabla \cdot m = 0$$

Momentum conservation

$$\partial_t m^i + \nabla \cdot \Pi^i = 0$$

Faraday's law

$$\partial_t \vec{B} + \nabla \times \vec{E} = 0$$

Ohm's law

$$\vec{J} = q \vec{v} + \sigma \gamma [\vec{E} + \vec{v} \times \vec{B} - (\vec{v} \cdot \vec{E}) \vec{v}]$$

Ampere's law

$$\partial_t \vec{E} - \nabla \times \vec{B} = -\vec{J}$$

- Integration with quasi-analytic solutions

$$\vec{E}_\perp = -\vec{v} \times \vec{B} + (E_\perp^0 + \vec{v} \times \vec{B}) \exp(-\sigma \gamma t)$$

$$\vec{E}_\parallel = E_\parallel^0 \exp(-\sigma t/\gamma)$$





Validation of the Code

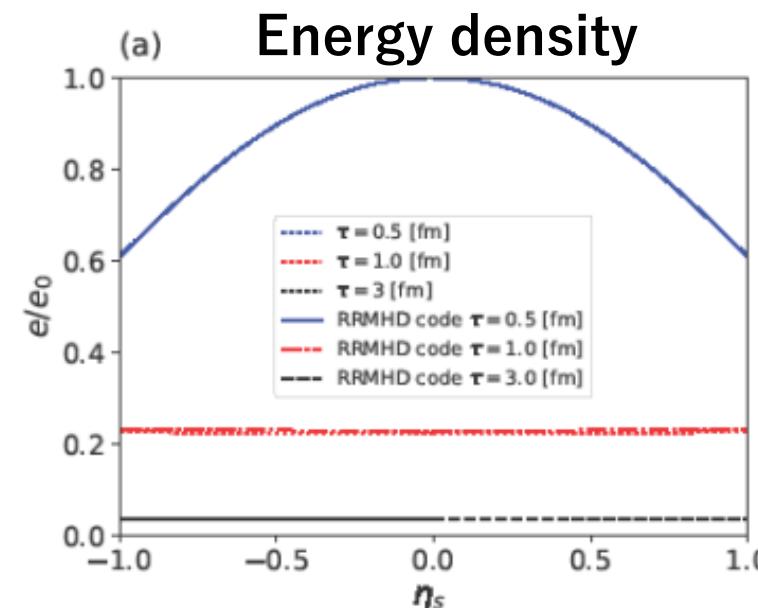


- RRMHD in the Milne coordinates

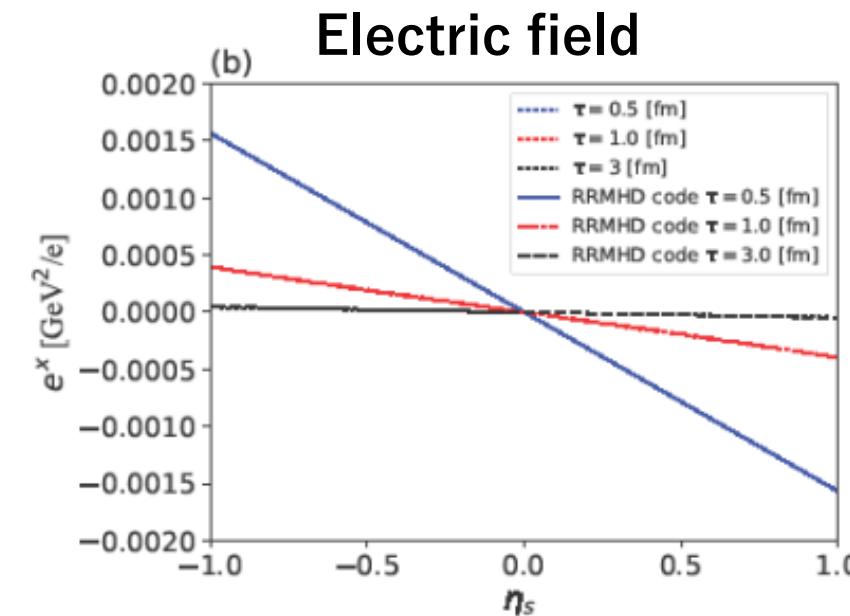
Nakamura, Miyoshi, C. N. and Takahashi, Eur.Phys.J.C 83 (2023) 3, 229.

New Test Problem

- (1+1) dimensional expansion system $u^\mu = (\cosh Y, 0, 0, \sinh Y)$
 - Comparison between quasi-analytical solution and RRMHD simulation



Solid line : RRMHD code
Dashed line: quasi-analytical solution



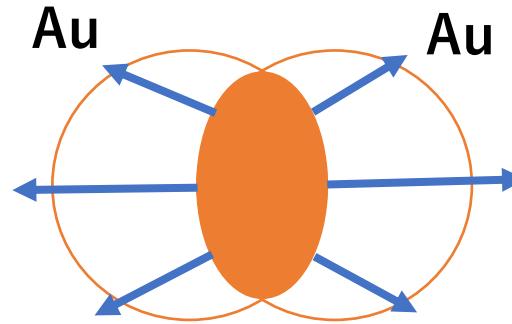
→ Application to Heavy Ion Collisions

Symmetric and Asymmetric Systems



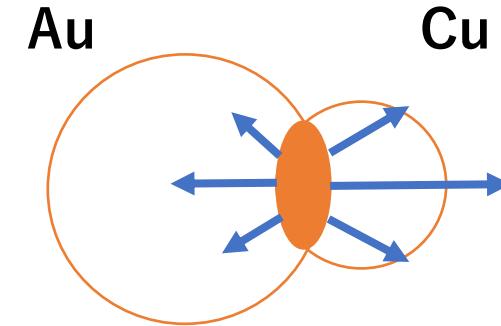
RHIC $\sqrt{s_{NN}} = 200 \text{ GeV}$

■ Au-Au collisions



- Symmetric pressure gradient
- Almond-shaped medium

■ Cu-Au collisions



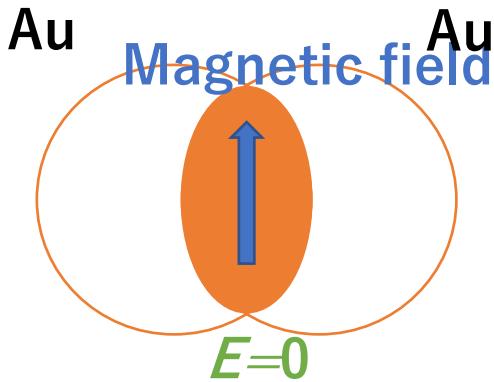
- Asymmetric pressure gradient
- Distorted Almond-shaped medium

Hirono, Hongo, Hirano

Electromagnetic Field in Symmetric and Asymmetric Systems

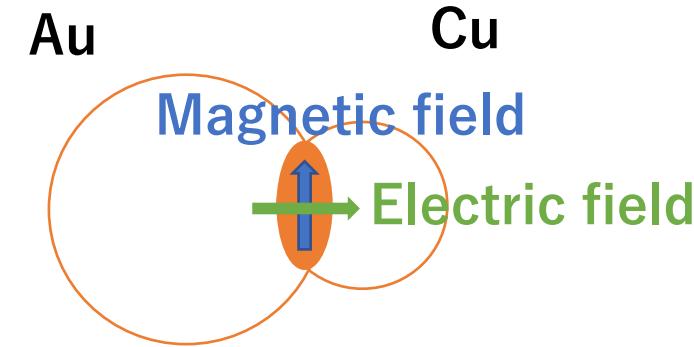


■Au-Au collisions



- Magnetic field
 - Strong magnetic field
- Electric field
 - No electric field

■Cu-Au collisions



- Magnetic field
 - Strong magnetic field
- Electric field
 - $E \neq 0$ due to the asymmetry of the charge distribution

Hirono, Hongo, Hirano



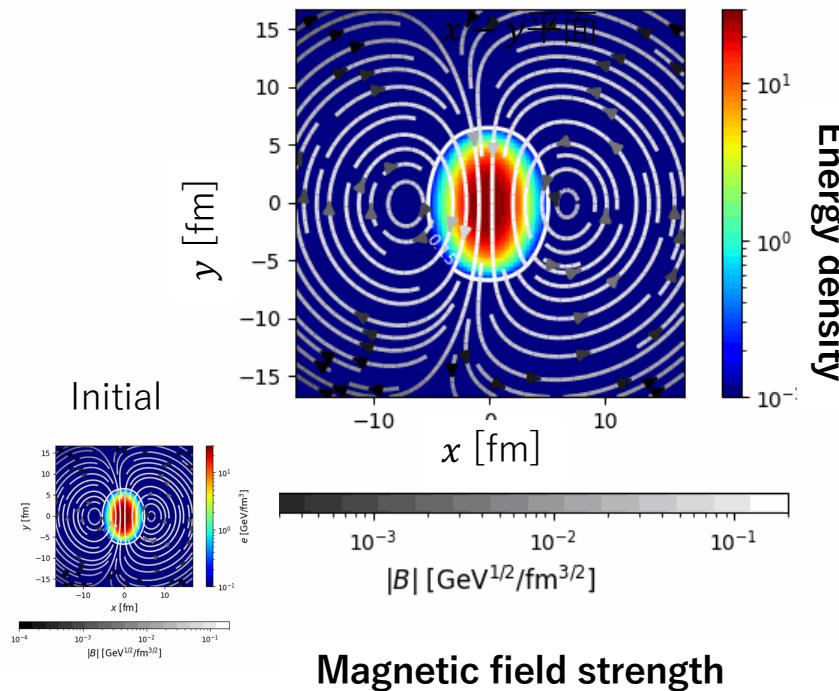
C. NONAKA

Space-time Evolution



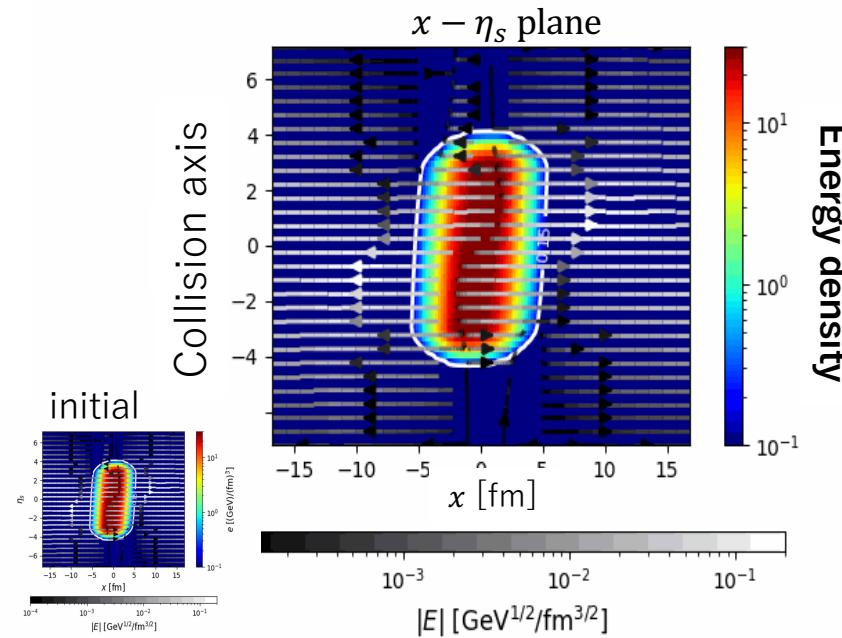
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Au+Au collision system



Magnetic field strength

First calculation in HIC with RRMHD code



Electric field strength

Analysis of Heavy Ion Collisions



Directed Flow



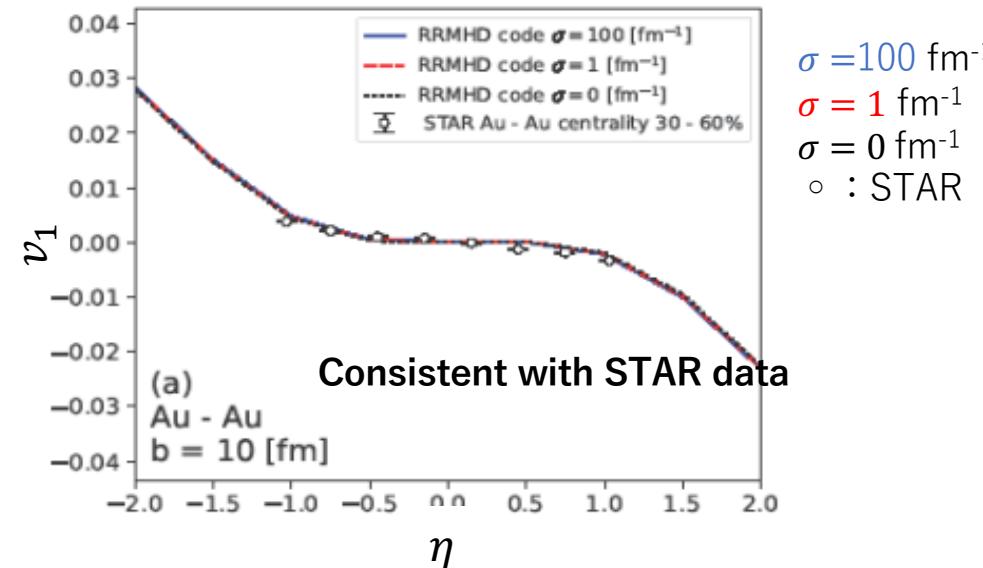
- $v_1 := \langle \cos(\phi - \Psi_1) \rangle \sim \langle \frac{p_x}{p_T} \rangle$

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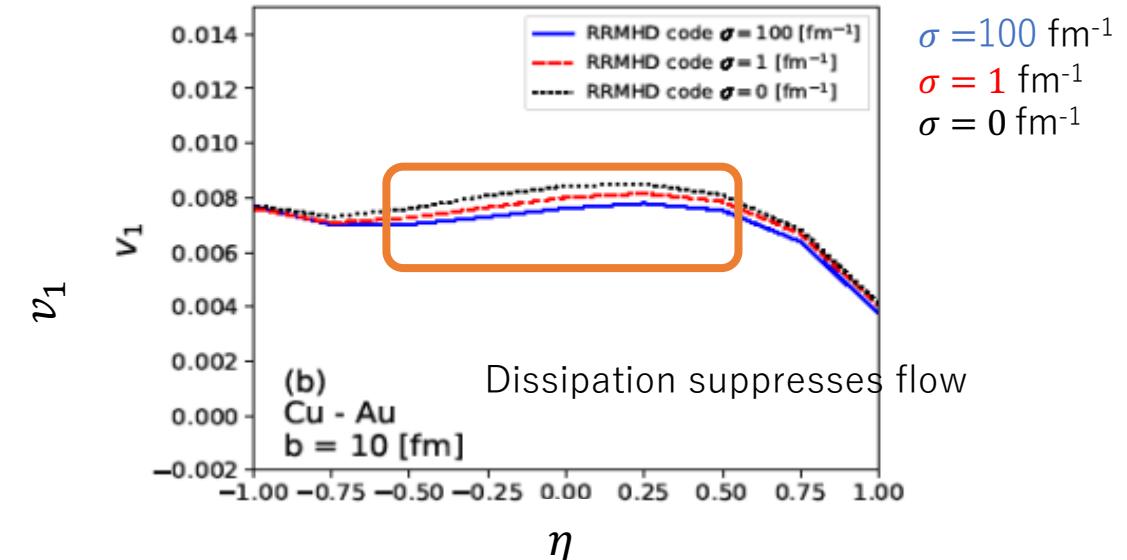
$$\eta = \frac{1}{2} \ln \frac{|p| + p_z}{|p| - p_z}$$

- Au-Au collisions ($\sqrt{s_{NN}} = 200$ GeV)
 - Parameter fixed in initial condition from comparison with STAR data

STAR Collaboration, Phys. Rev. Lett. **101** (2008), 252301



- Cu-Au collisions ($\sqrt{s_{NN}} = 200$ GeV)
 - Decreases with conductivity
 - Dissipation suppresses flow in the Cu direction



Energy Transfer by Ohm Dissipation



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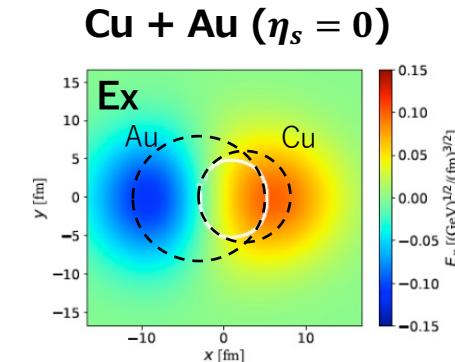
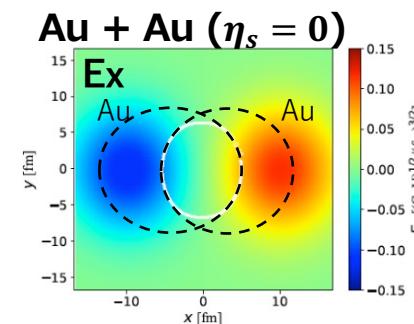


• Energy Transfer

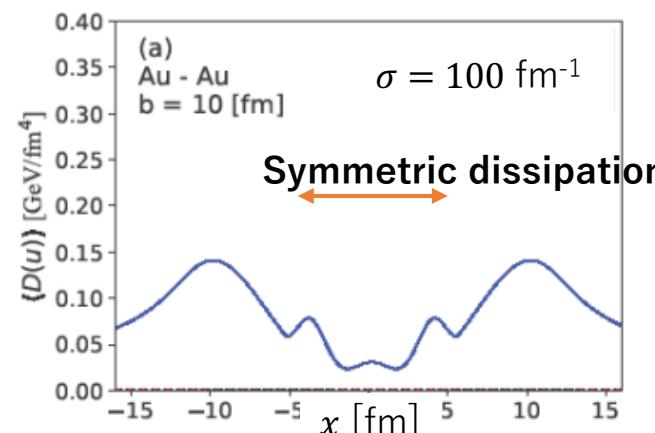
$$D(u) := j^\mu e_\mu = \gamma [j \cdot (E + v \times B) - q(v \cdot E)]$$

energy of
the electromagnetic field

Thermal energy
Kinetic energy

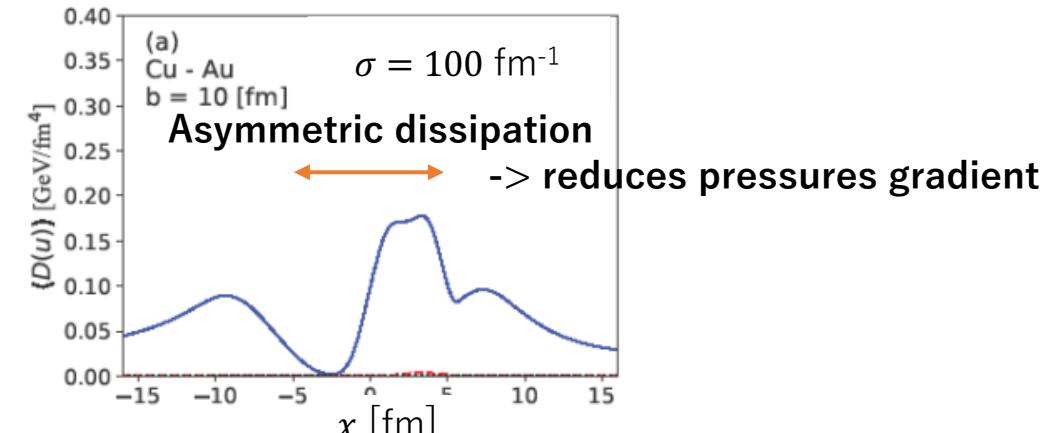


Au+Au collisions



no contribution to v_1

Cu+Au collisions



contribution to v_1

Directed Flow



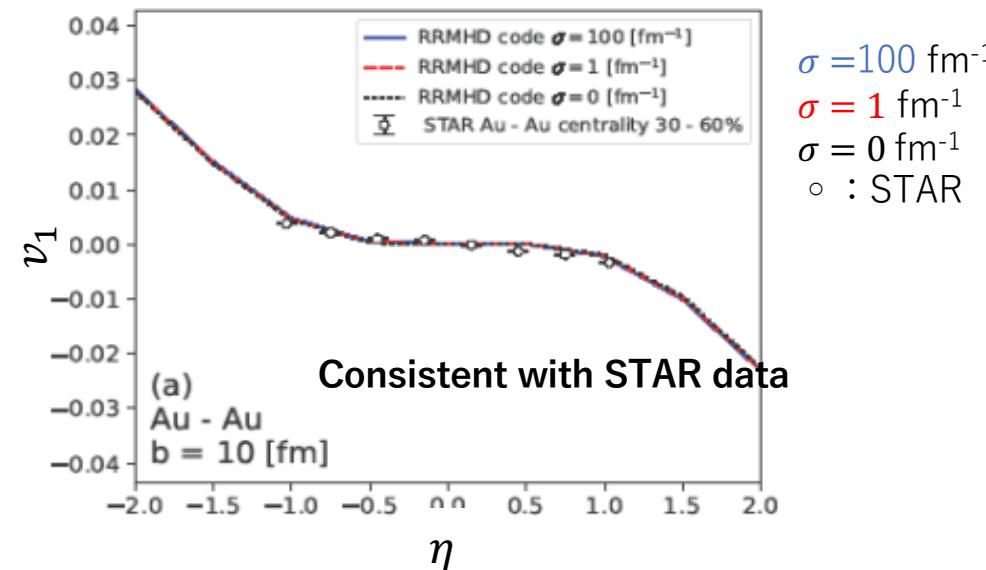
- $v_1 := \langle \cos(\phi - \Psi_1) \rangle \sim \langle \frac{p_x}{p_T} \rangle$

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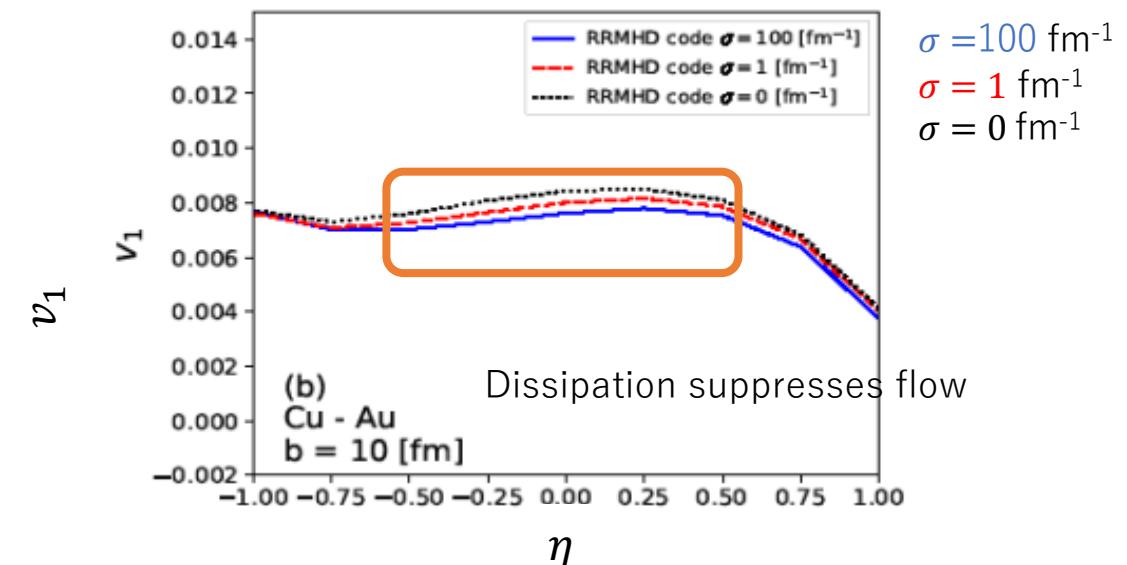
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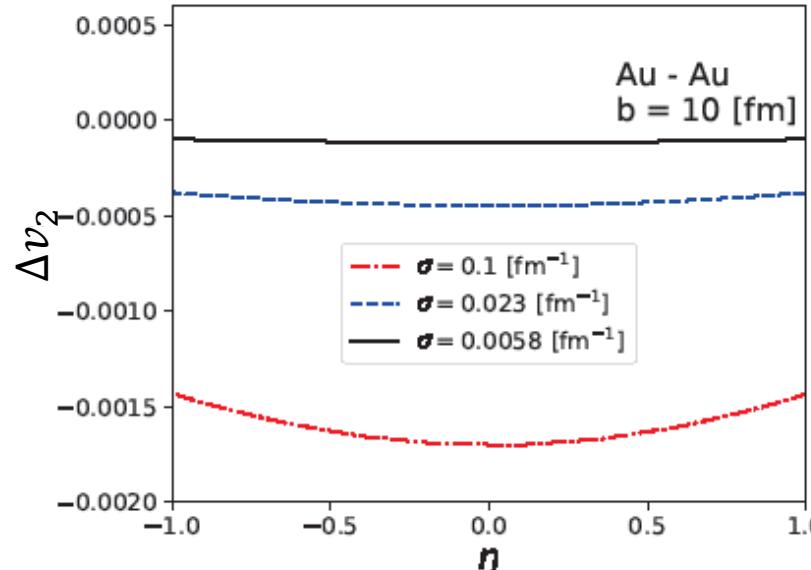
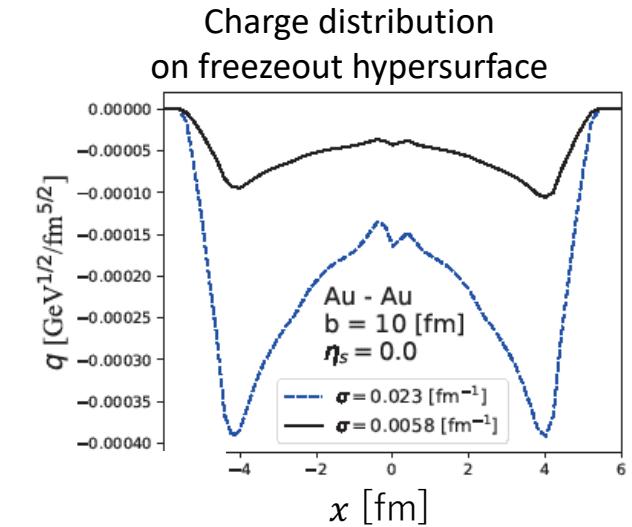
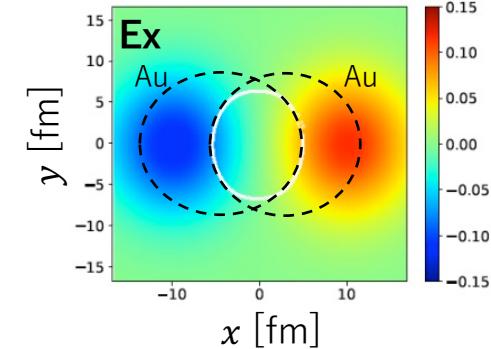


Charge Dependence of Δv_2 : Au + Au



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- $\Delta v_2 = v_2^{\pi^+}(\eta) - v_2^{\pi^-}(\eta)$
 - **Negative Elliptic Flow**
 - Contribution of negative charge on freezeout hypersurface
 - Symmetric structure: initial electric field to the collision axis
 - **Electric conductivity dependence is observed even in the symmetry system.**



$$\eta = \frac{1}{2} \ln \frac{|p| + p_z}{|p| - p_z}$$





Charge Dependence of Δv_2 : Cu + Au



- $\Delta v_2 = v_2^{\pi^+}(\eta) - v_2^{\pi^-}(\eta)$

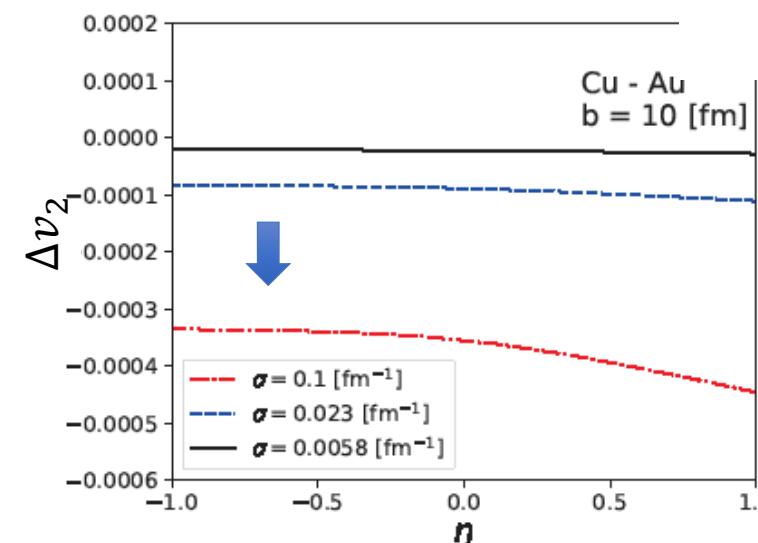
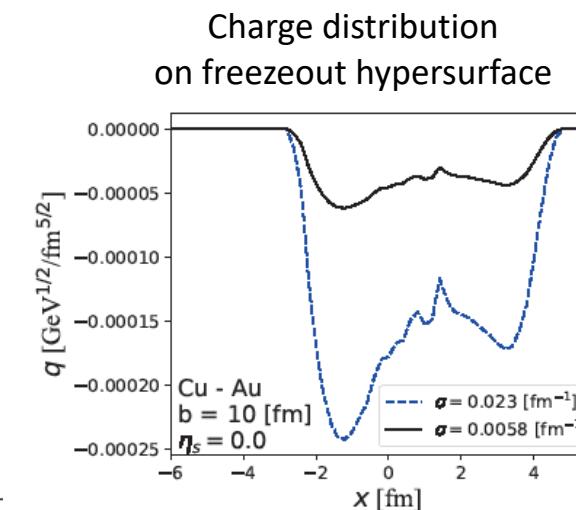
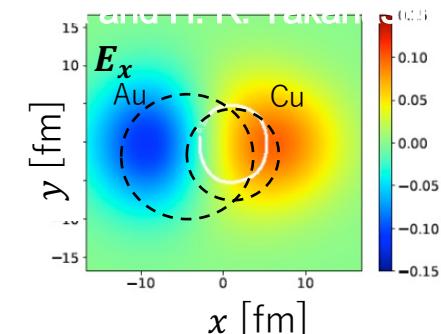
- Negative Elliptic Flow

- Contribution of negative charge on freezeout hypersurface

- Asymmetric structure: initial electric field to the collision axis

- Electric conductivity dependence is observed.

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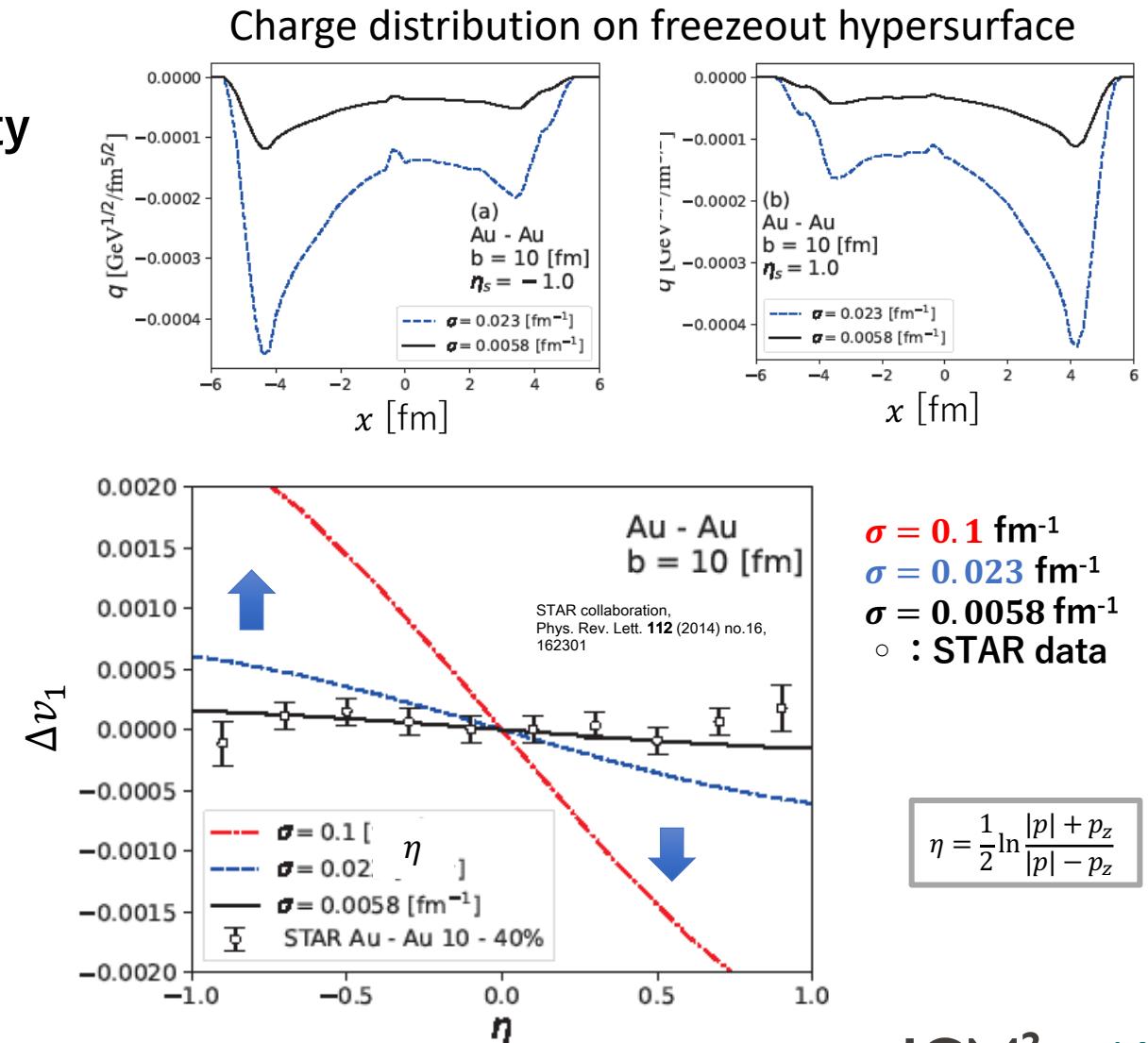
$$\eta = \frac{1}{2} \ln \frac{|p| + p_z}{|p| - p_z}$$

Δv_2 : initial electromagnetic field distribution
electrical conductivity

Charge Dependence of Δv_1 : Au + Au



- $\Delta v_1 = v_1^{\pi^+}(\eta) - v_1^{\pi^-}(\eta)$
 - Clear dependence of charge conductivity
 - Proportion to electric conductivity
 - Negative charge induced in the opposite direction of fluid flow
suppression of v_1 of negative charge
 - Δv_1 with finite σ is consistent with STAR data
 - $\sigma = 0.0058 \text{ fm}^{-1}$
ex. $\sigma_{LQCD} = 0.023 \text{ fm}^{-1}$
from lattice QCD
Gert Aarts, et al.
Phys. Rev. Lett., 99:022002, 2007.
- ✓ QGP electrical conductivity from high-precision measurement of Δv_1

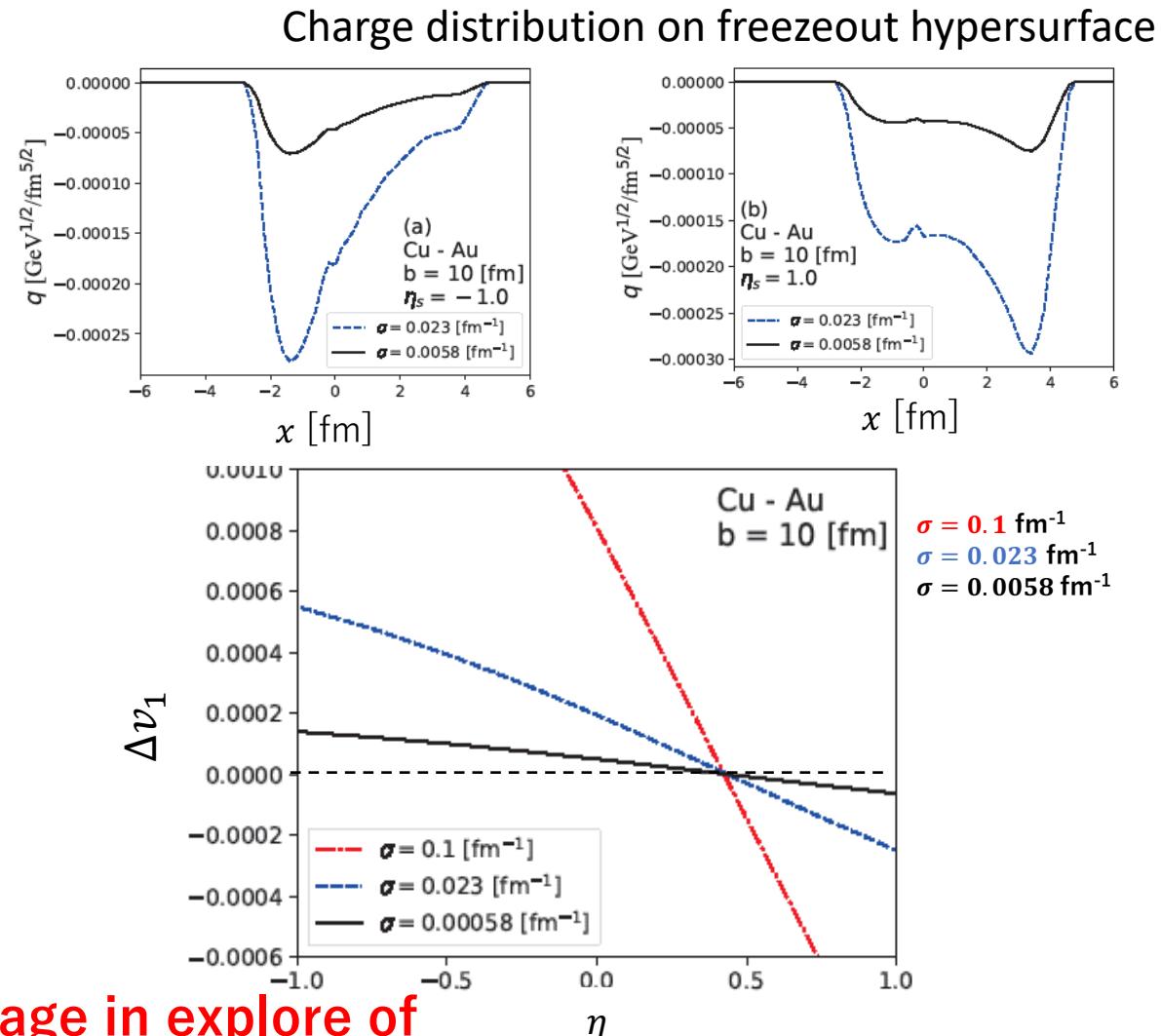


Charge Dependence of Δv_1 : Cu + Au



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- $\Delta v_1 = v_1^{\pi^+}(\eta) - v_1^{\pi^-}(\eta)$
 - Electric field created by initial condition
 - Δv_1 is finite at $\eta = 0$
 - Asymmetry structure to $\eta = 0$
 - Proportion to electric conductivity
 - Δv_1 vanishes at $\eta = 0.5$.
- ✓ Electrical conductivity $< \Delta v_1$ at $\eta = 0$
- ✓ Initial electrical field from η dependence of Δv_1



Asymmetric system has advantage in explore of QGP electrical conductivity.



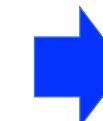
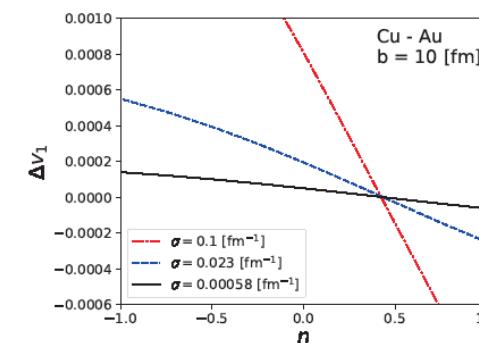
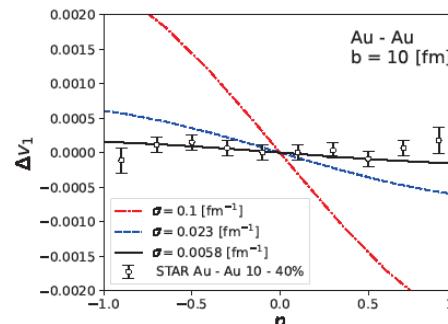


Summary



Relativistic Resistive Magnetohydrodynamic Model

- RRMHD code in the Milne coordinate
 - Test calculation in the 1+1 expanding system
- Application to high-energy heavy-ion collisions
 - Au+Au and Au+Cu systems at RHIC energy
 - Directed flow
 - Cu+Au: suppression of v_1 due to dissipation of electric field
 - Charge dependence of Δv_1 and Δv_2
 - electric conductivity from Δv_1



Future work:
Event-by-event fluctuation
Finite density
Vortex
Chiral magnetohydrodynamics

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