Electric Conductivity of QCD Matter in High-Energy Heavy-Ion Collisions

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Octover 16, 2024@

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  - Electromagnetic fields in high-energy heavy-ion collisions
- **Electric conductivity of QCD matter in high-energy heavy-ion collisions**
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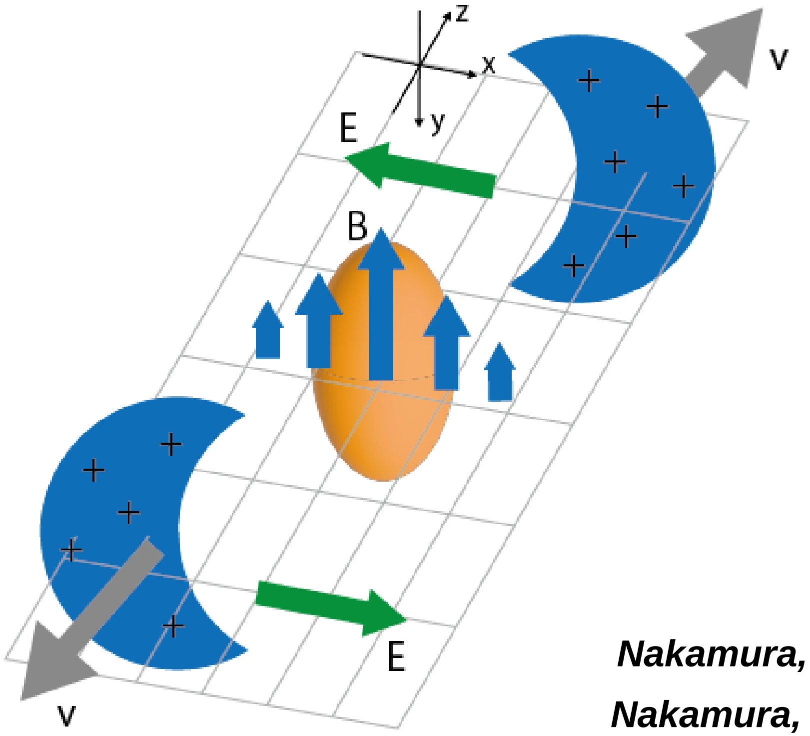
  - Elliptic flow of photons
- **Summary**

Electromagnetic Field in Heavy Ion Collisions

- **Strong Electromagnetic field ?**
  - Au + Au ($\sqrt{s_{NN}} = 200$ GeV) : 10^{14} T ~10 m_π^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

Electromagnetic Field in Heavy-Ion Collisions

■Electromagnetic field in heavy-ion collisions

➢ **Production of strong magnetic field**

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

Not observed

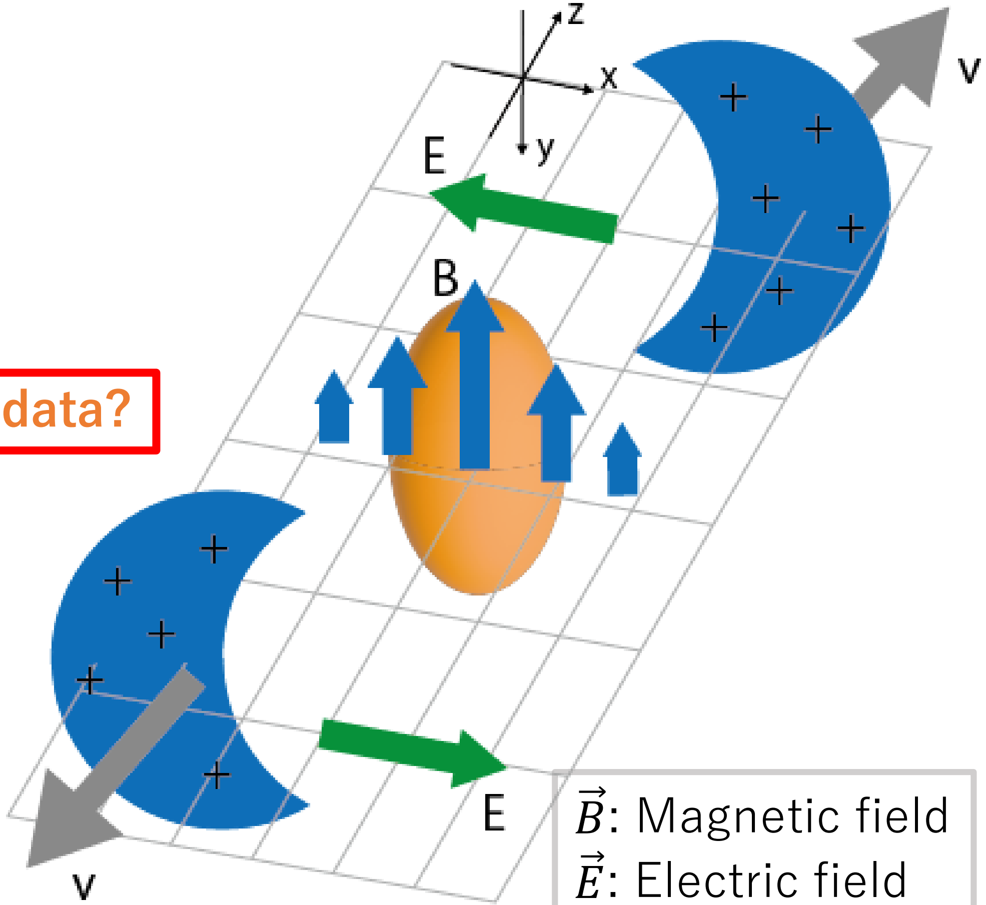
■Response to electromagnetic field

- Electric conductivity

Experimental data?

- Lattice QCD: $\sigma \sim 0.023$ fm^{-1} @ $T \sim 250$ MeV

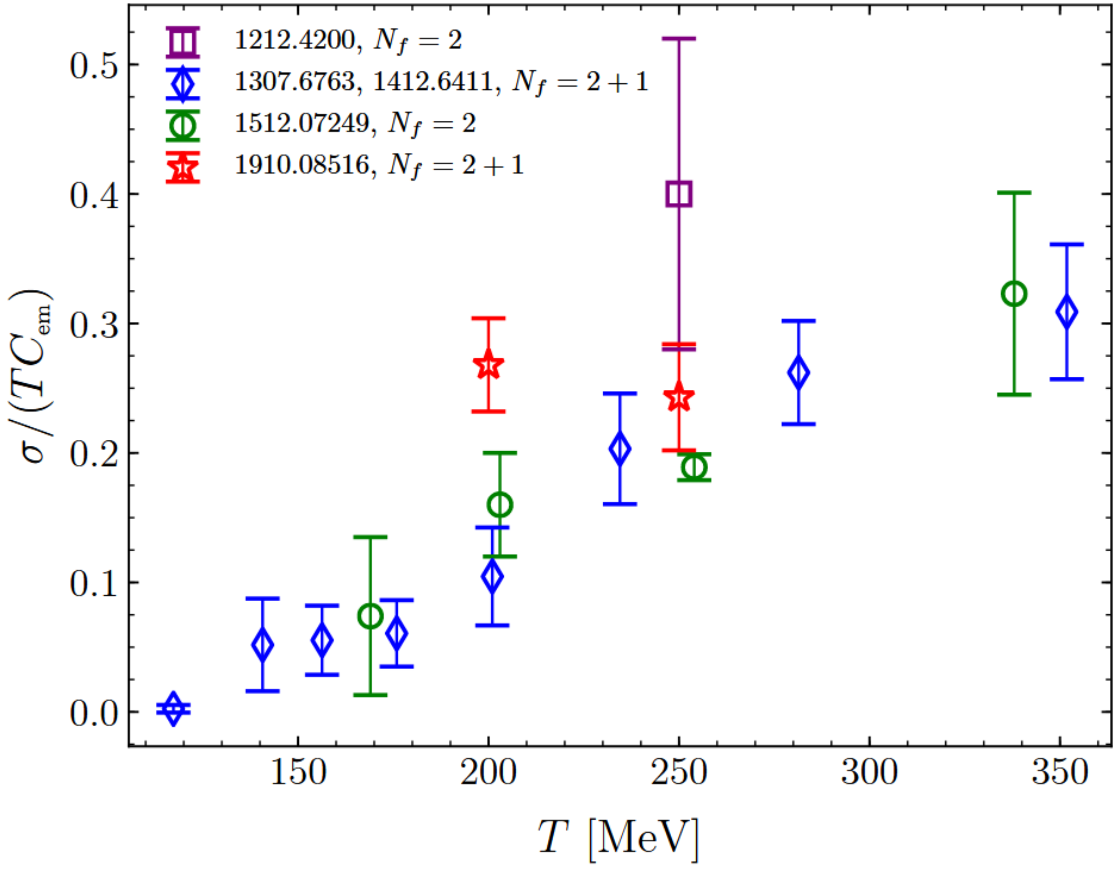
Gert Aarts, et al.
Phys. Rev. Lett., 99:022002, 2007.



$\vec{B}$: Magnetic field
$\vec{E}$: Electric field
v: velocity

Electric Conductivity of QCD Matter

- **Lattice QCD**



Aarts, Nikolaev, EPJ.A 57, 118 (2021); 2008.12326 [hep-lat]

Electric Conductivity on the Lattice

$$\sigma = \frac{1}{6}\frac{\partial}{\omega}\left(\int d^4x e^{i\omega t}\langle[j_\mu^{\rm em}(t,x), j_\mu^{\rm em}(0,0)]\rangle\right)|_{\omega=0}$$

Uses linear-response theory (Kubo formula)
Low energy limit of the electromagnetic spectral function

- Does not include external magnetic field effects
- Uses approximately realistic pion mass
- General agreement among results using a variety of methods and parameters

Electromagnetic Field in Heavy-Ion Collisions

■Electromagnetic field in heavy ion collisions

➢ **Production of strong magnetic field**

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

Not observed

■Response to electromagnetic field

- **Electric conductivity from lattice QCD**

Experimental data?

- $\sigma \sim 0.023$ fm^{-1} @ $T \sim 250$ MeV

Gert Aarts, et al.
Phys. Rev. Lett., 99:022002, 2007.

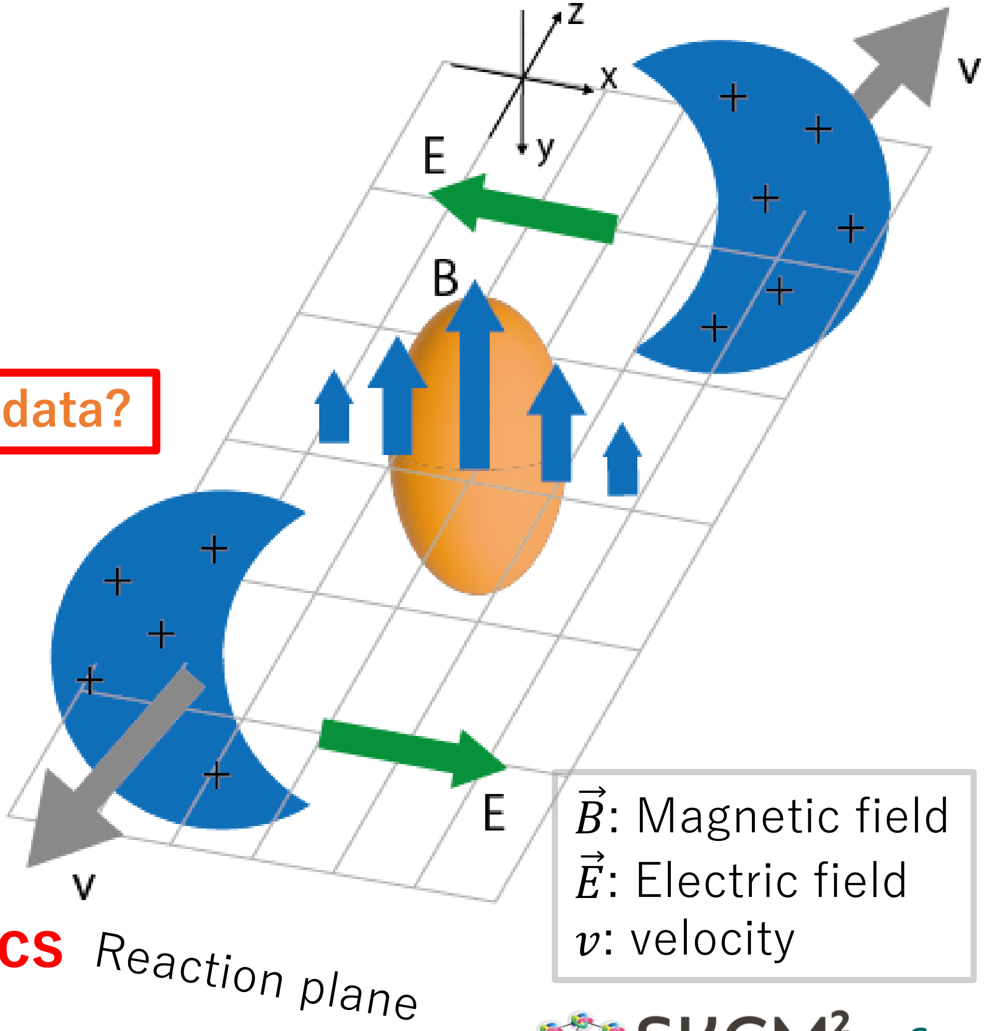
➢ **Magnetohydrodynamics** ($\sigma \to \infty$)

Inghirami, et al, Eur. Phys. J. C (2020) 80:293

- Focus only on magnetic field
- **Quantitative analysis on electric conductivity**

Electric conductivity ⟷ **experimental data**

Relativistic Resistive Magnetohydrodynamics



$\vec{B}$: Magnetic field
$\vec{E}$: Electric field
v: velocity

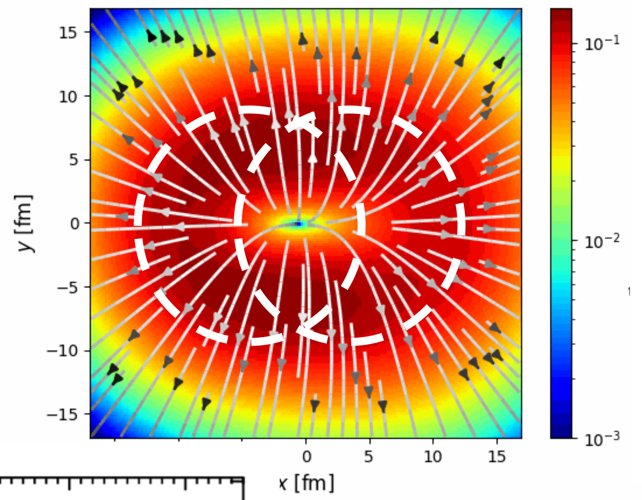
Electromagnetic Fields and Property of QGP

- **Electric Conductivity**
  - **Dissipation of electric field**
    - Ampere's law： $\partial_t \vec{E} - \nabla \times \vec{B} = -\vec{j}$

$\vec{B}$: magnetic field
$\vec{E}$: electric field

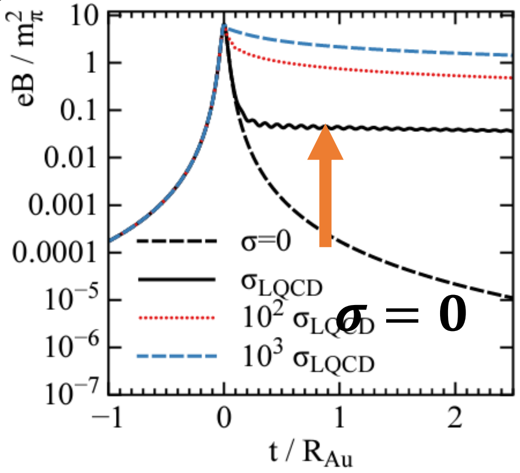
Ohm's law makes electric field dissipate
➡Dissipated energy to fluid

Electric field



  - **Charge is induced.**
    - Charge is induced by electric field.
    - Induced charge depends on charge conductivity
  - **Dissipation of magnetic field**

Magnetic field



$\boldsymbol{\sigma} \neq \mathbf{0}$

Suppresses of dissipation

Electric field is dissipated.

L. McLerran and V. Skokov, Nucl. Phys. A 929 (2014), 184-190

Charge conductivity of QGP

⬅ dissipation of electromagnetic fields and charge distribution QGP

Understanding of QGP Property

Charge conductivity of QGP from analysis of high-energy heavy-ion collisions

Physical property	Observables	Quantitative analysis
Charge conductivity	?	×
Shear viscosity	Azumithal anisotoropy v_n	○
Bulk viscosity	P_T distributions	○
Diffusion coefficient	Jet energy loss	○

Charge dependent directed flow
Asymmetic collisions → i.e., Hirono, Hongo, and Hirano, PRC 90, 021903 (2014).
Symmetric collisions

Proposed EM observables
Dileptons → i.e., Akamatsu, Hamagaki, Hatsuda, and Hirano, PRC 85, 054903 (2012).
Photons → i.e., Sun and Yan, PRC 109, 034917 (2024).

Understanding of QGP Property

Charge conductivity of QGP from analysis of high-energy heavy-ion collisions

↓

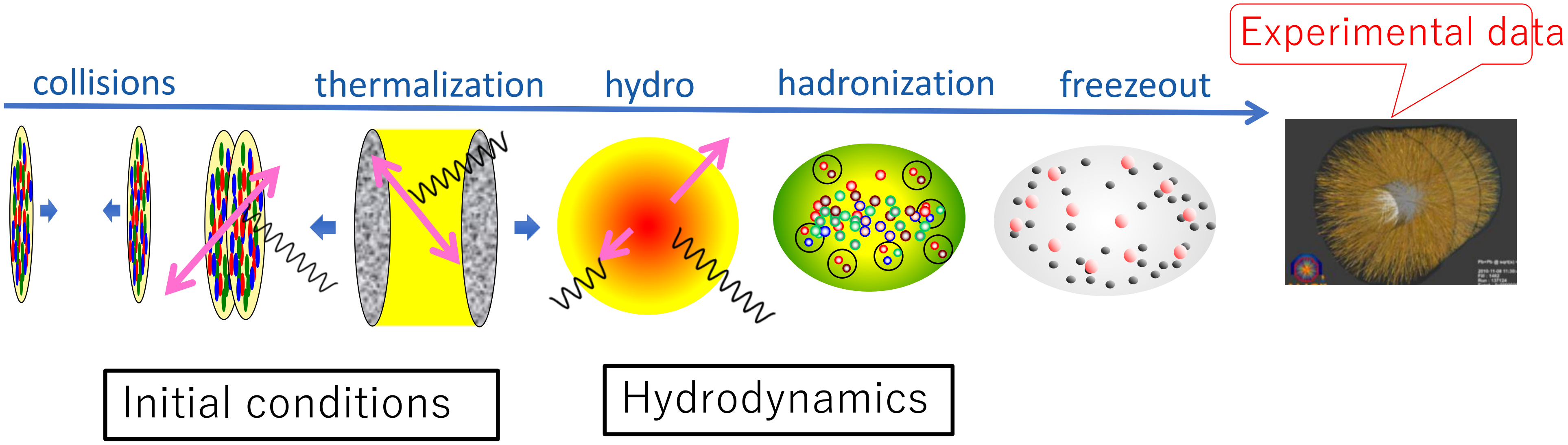
Construction of relativistic resistive magnetohydrodynamics

Physical property	Observables	Quantitative analysis
Charge conductivity	?	×
Shear viscosity	Azumithal anisotoropy v_n	○
Bulk viscosity	P_T distributions	○
Diffusion coefficient	Jet energy loss	○

Relativistic Resistive Magnetohydrodynamics

Relativistic Resistive Magneto-Hydrodynamics (RRMHD)

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



Glauber model
+approximate solutions of Maxwell eq.

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

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

Relativistic Resistive Magneto-Hydrodynamics (RRMHD)

Nakamura, Miyoshi, CN 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

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

Ampere's law

$$\partial_t \vec{E} - \nabla \times \vec{B} = -\vec{J} \rightarrow \begin{cases} \partial_t \vec{E} - \nabla \times \vec{B} = q\vec{v} \\ \partial_t \vec{E} = \vec{J}_c \end{cases}$$

operator splitting

- Integration with quasi-analytic solutions

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

Komissarov, Mon. Not. R. Astron. Soc. 382, 995-1004 (2007)

RRMHD Equation in Milne Coordinates

New

- **Milne coordinates**
  - **Expanding systems in the longitudinal direction (τ, x, y, η_s)**
    - Strong expansion in the longitudinal direction is effectively included.
    - Number of grid of fluid is saved.

$$\tau = \sqrt{t^2 - z^2}$$
$$\eta_s = \frac{1}{2}\ln\frac{t+z}{t-z}$$

RRMHD Equation

$$\partial_\tau(\tau U) + \partial_i(\tau F^i) = \tau S$$

$$U = \begin{pmatrix} D \\ m_j \\ \varepsilon \\ B^j \\ E^j \\ q \end{pmatrix}, \mathrm{F}^{\mathrm{i}} = \begin{pmatrix} Dv^i \\ \Pi^{ji} \\ m^i \\ \varepsilon^{jik}E_k \\ \varepsilon^{jik}B_k \\ J^i \end{pmatrix}, S = \begin{pmatrix} 0 \\ \frac{1}{2}T^{ik}\partial_j g_{ik} \\ -\frac{1}{2}T^{ik}\partial_0 g_{ik} \\ 0 \\ J_c^i \\ 0 \end{pmatrix}$$

The first RRMHD code in Milne coordinates

Validation of the Code

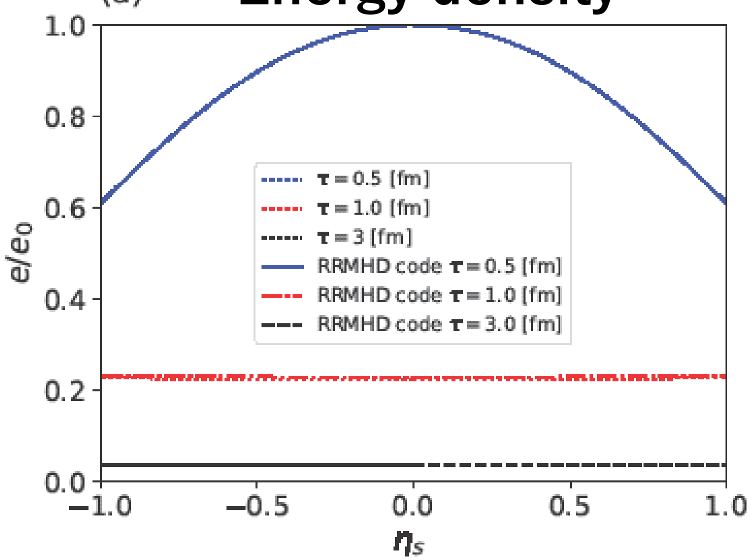
- **RRMHD in the Milne coordinates**

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

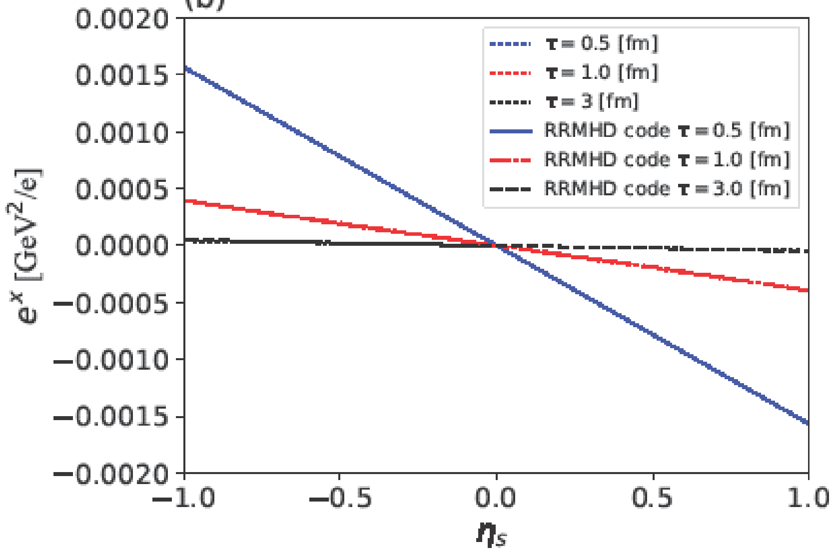
New Test Problem

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

Energy density



Electric field



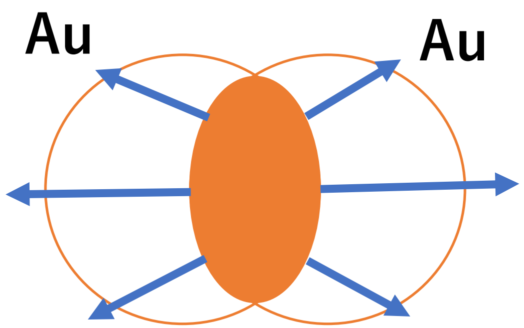
Solid line : RRMHD code
Dashed line: quasi-analytical solution

➡ **Application to Heavy Ion Collisions**

Symmetric and Asymmetric Systems

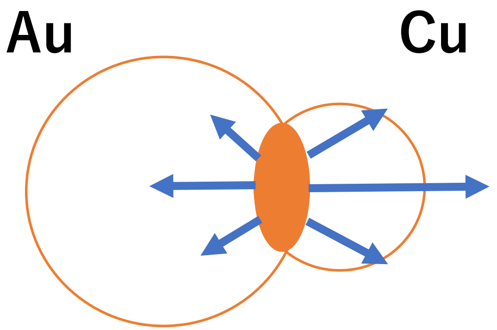
RHIC $\sqrt{s_{NN}} = 200\ \text{GeV}$

■**Au-Au collisions**



- ➢ Symmetric pressure gradient
- ➢ Almond-shaped medium

■**Cu-Au collisions**



- ➢ Asymmetric pressure gradient
- ➢ Distorted Almond-shaped medium

Hirono, Hongo, Hirano

Analysis on High-Energy Heavy-Ion Collisions

- **Directed flow v_1**

$\langle \cdot \rangle$: average over yield

$$v_1 := \langle \cos(\phi - \Psi_1) \rangle \sim \langle \frac{p_x}{\sqrt{p_x^2 + p_y^2}} \rangle$$

Ψ_1 :angle between $\vec{b}$ and x axis

- **Elliptic flow v_2**

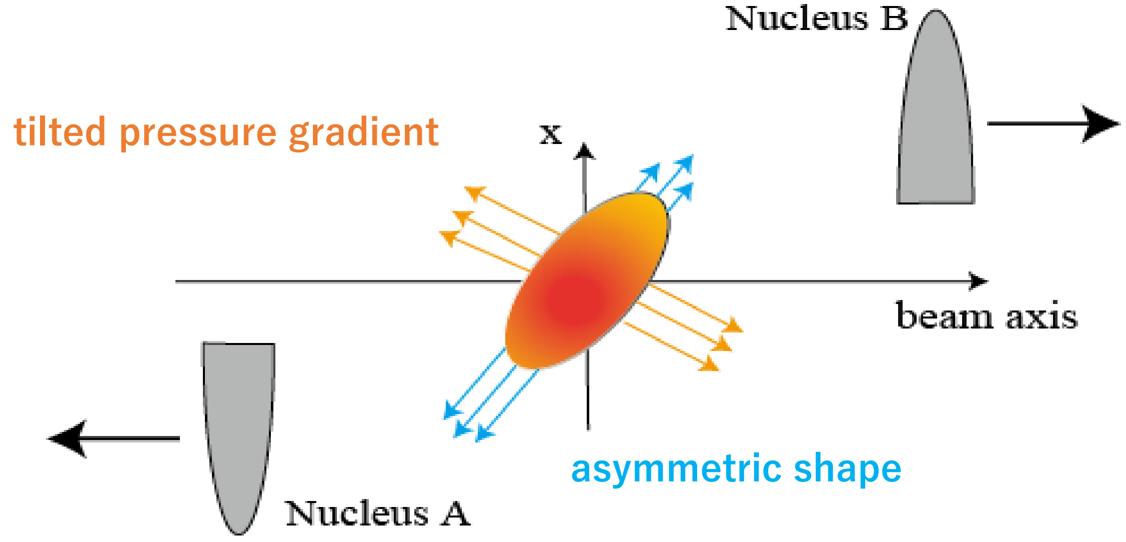
$$v_2 := \langle \cos(2\phi - \Psi_2) \rangle \sim \langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \rangle$$

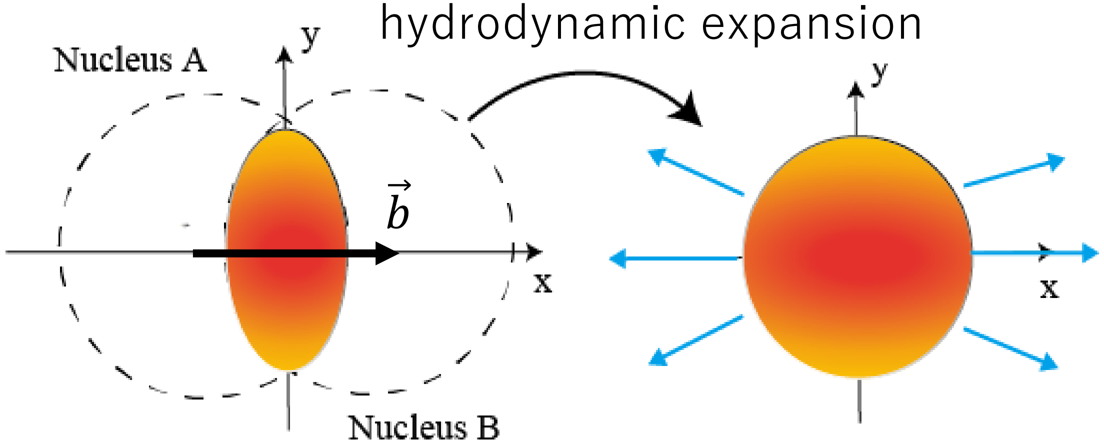
Ψ_2 :angle between $\vec{b}$ and x axis

- **Charge dependence**

$$\Delta v_1 = v_1^{\pi^+} - v_1^{\pi^-}$$

$$\Delta v_2 = v_2^{\pi^+} - v_2^{\pi^-}$$





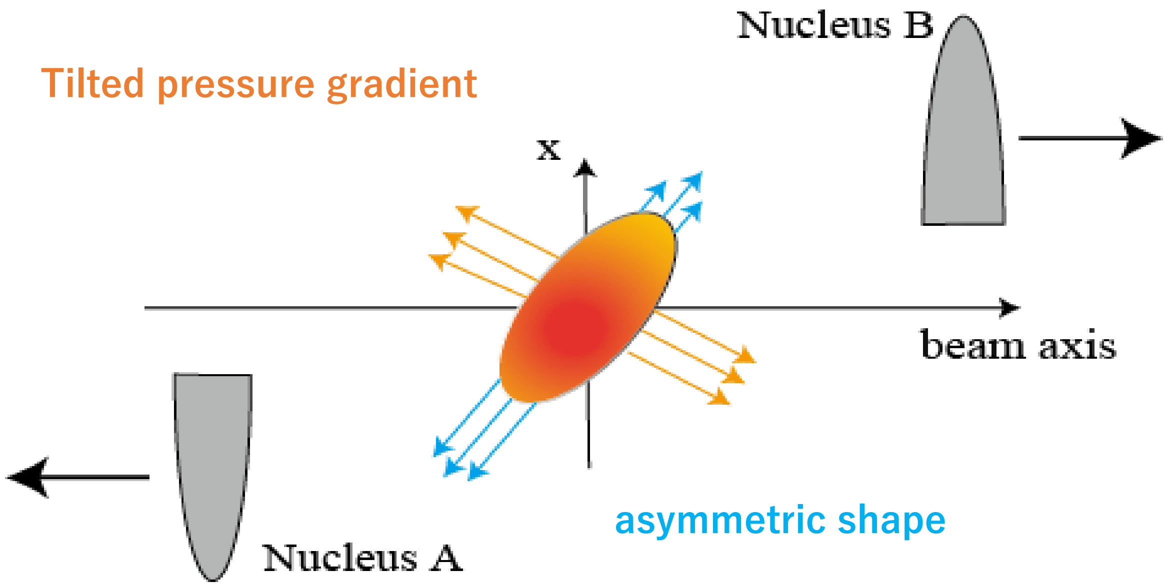
Initial Condition：QGP Medium

■ Tilted Glauber model

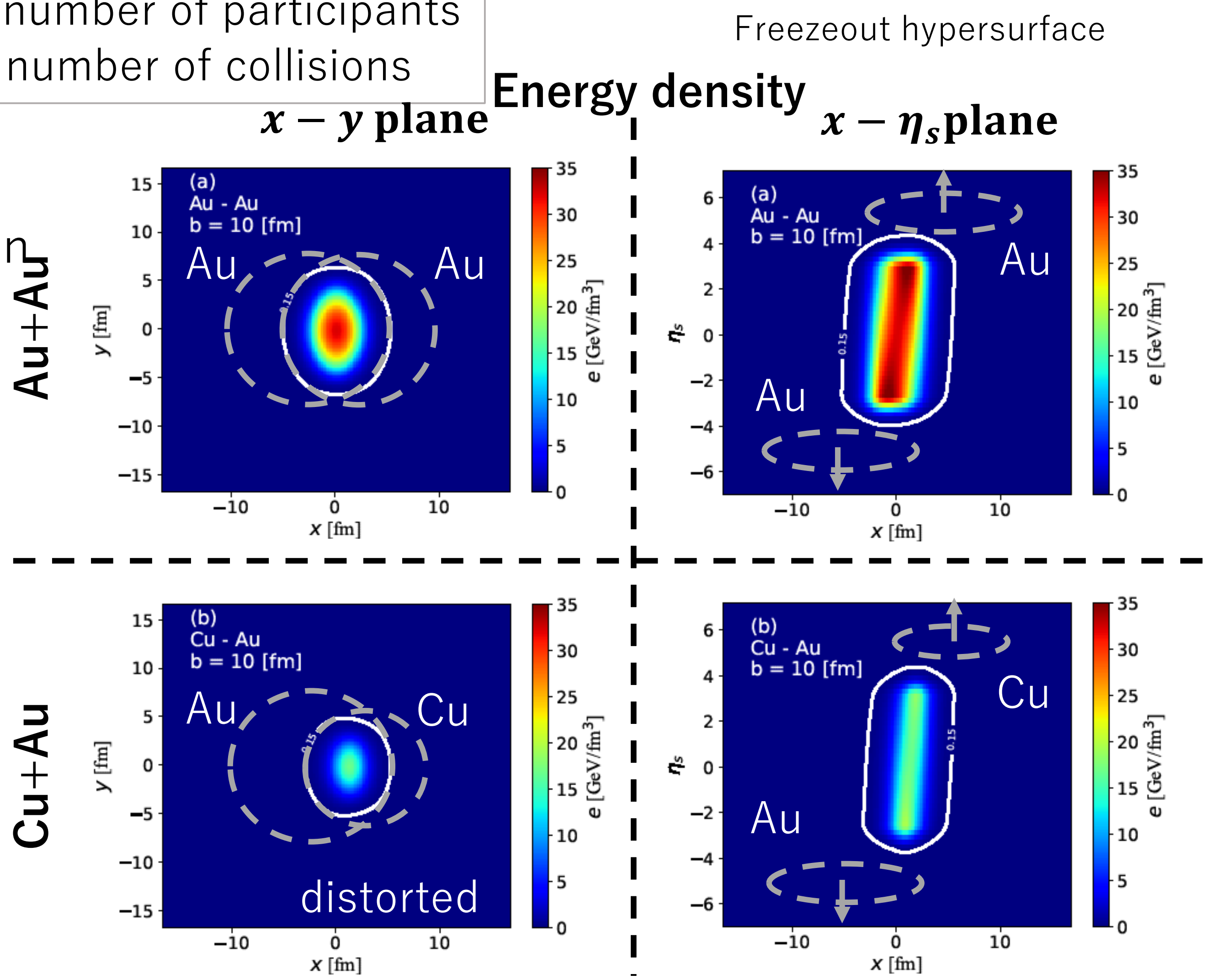
n_p : number of participants
n_c : number of collisions

- Energy density is scaled by n_p and n_c
- Tilted distribution in the longitudinal direction

For directed flow v_1



Bozek, et al, Phys. Rev. C 81, 054902(2010)



Initial Condition：Electromagnetic Fields

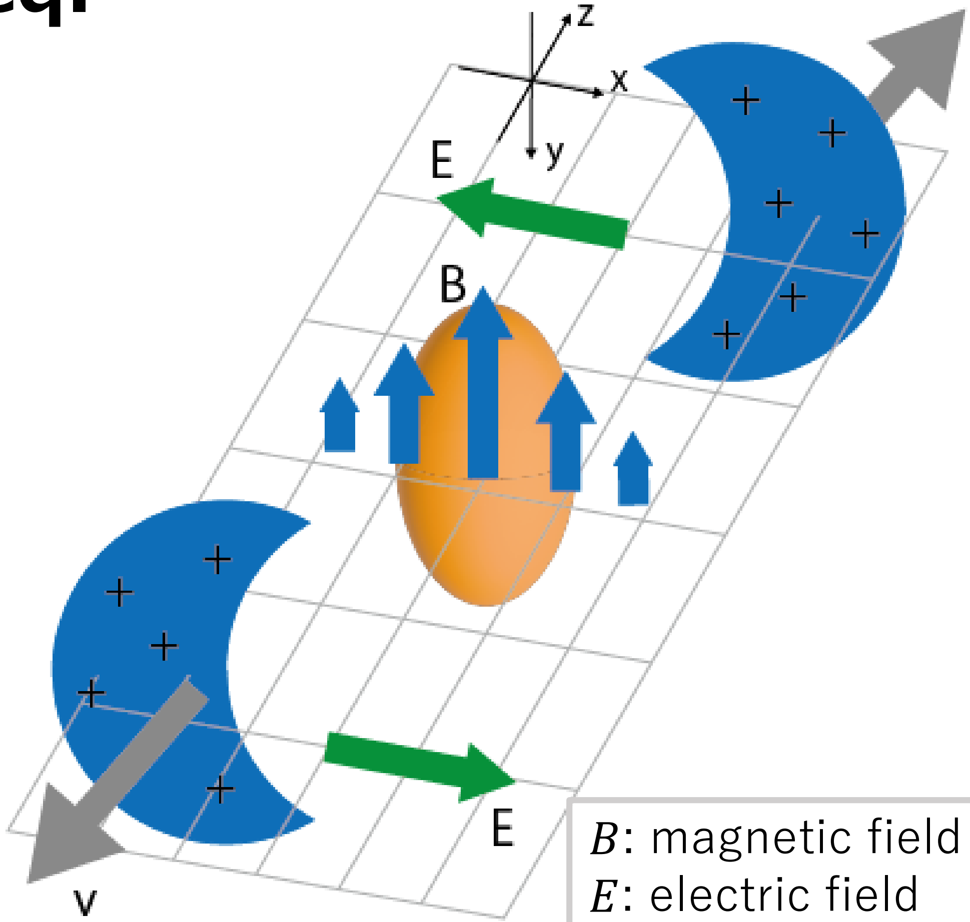
Tuchin, *Phys.Rev.C88,024911(2013)*

■Asymptotic solution of Maxwell eq.

- ➢Electromagnetic field made by point charge moving in the longitudinal axis
  - Proton distribution in nucleus : uniform sphere
  - Constant charge conductivity ($\sigma = 0.023\ \mathrm{fm}^{-1}$)

$$\nabla \cdot \boldsymbol{B} = 0, \quad \nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t},$$
$$\nabla \cdot \boldsymbol{D} = e\delta(z - vt)\delta(\boldsymbol{b}),$$
$$\nabla \times \boldsymbol{H} = \frac{\partial \boldsymbol{D}}{\partial t} + \sigma \boldsymbol{E} + ev\hat{z}\delta(z - vt)\delta(\boldsymbol{b})$$

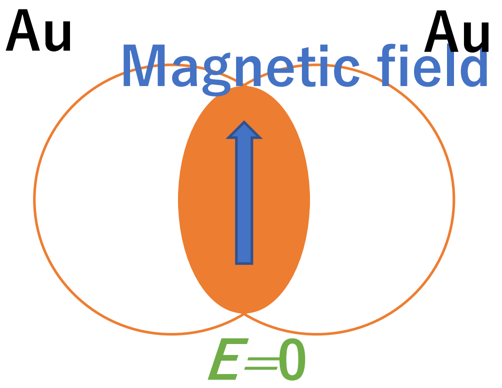
Integration of the asymptotic solutions over the charge distribution inside of nucleus



B: magnetic field
E: electric field
v: velocity of heavy ion

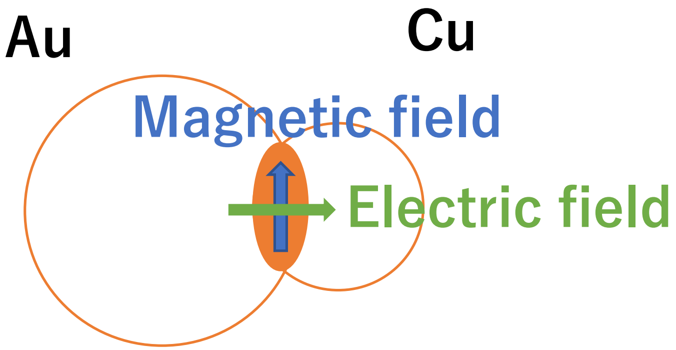
Electromagnetic Field in Symmetric and Asymmetric Systems

■**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

Initial Condition：Electromagnetic Fields ($\eta_s = 0$)

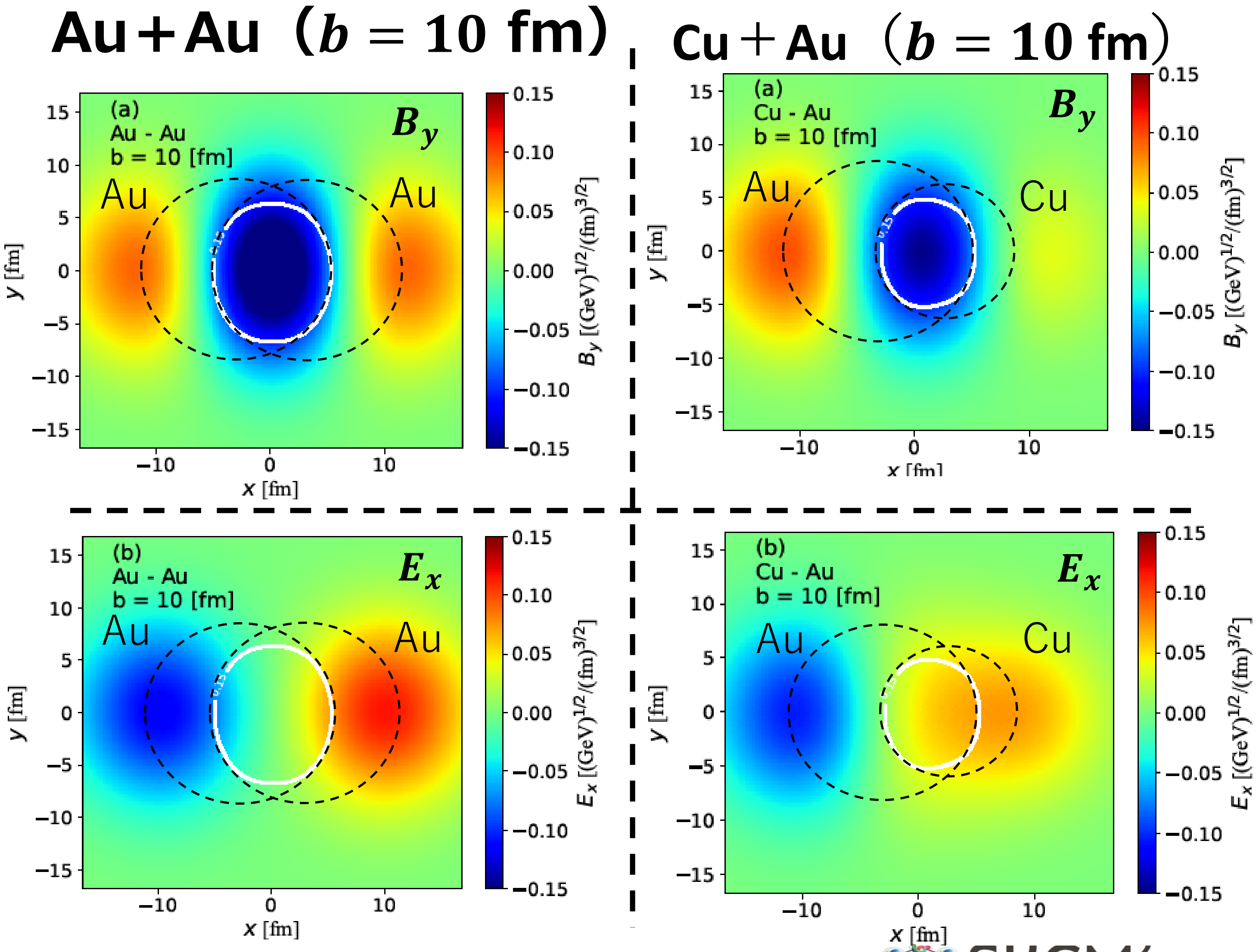
Tuchin, Phys.Rev.C88,024911(2013)

■Au+Au

- ➢Strong magnetic fields in QGP
- ➢Electric field ～0 in QGP

■Cu+Au

- ➢Strong magnetic field in QGP
- ➢Finite electric field in QGP

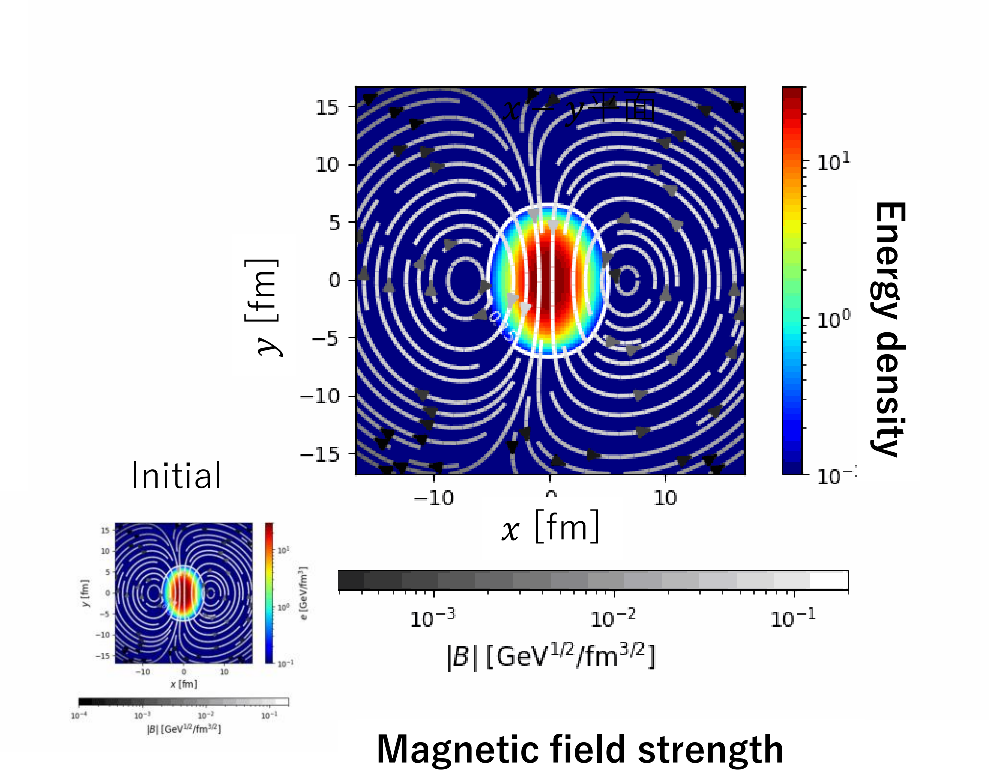


Freezeout hypersurface

Space-time Evolution

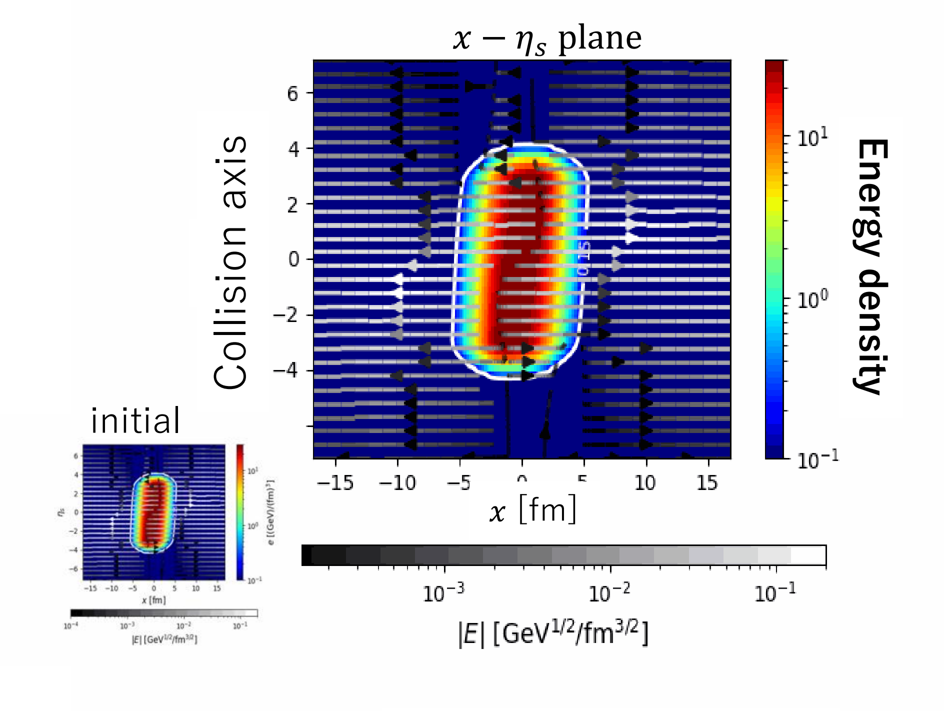
Nakamura, Miyoshi, CN and Takahashi, PRC 107, no.1, 014901 (2023)

Au+Au collision system



Magnetic field strength

First calculation in HIC with RRMHD code



Electric field strength

Analysis of Heavy Ion Collisions

Charge Dependent Flow

Directed Flow

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

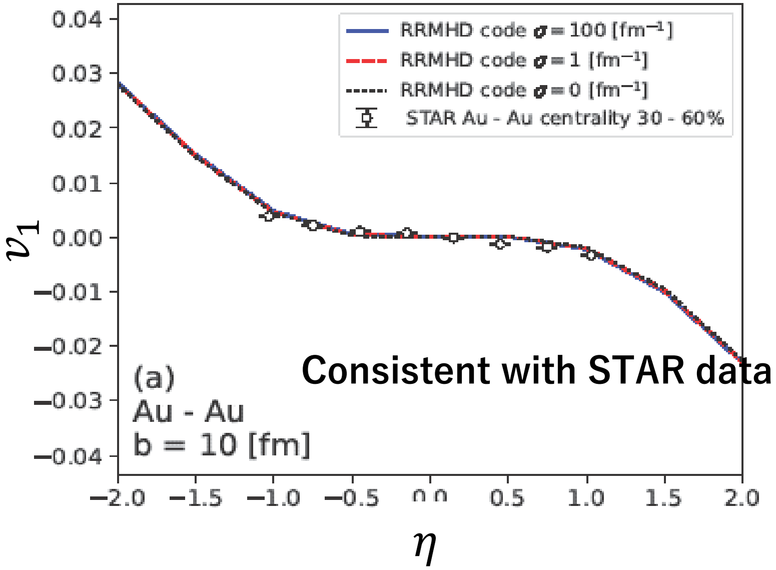
Nakamura, Miyoshi, CN and Takahashi, PRC 107, no.1, 014901 (2023)

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

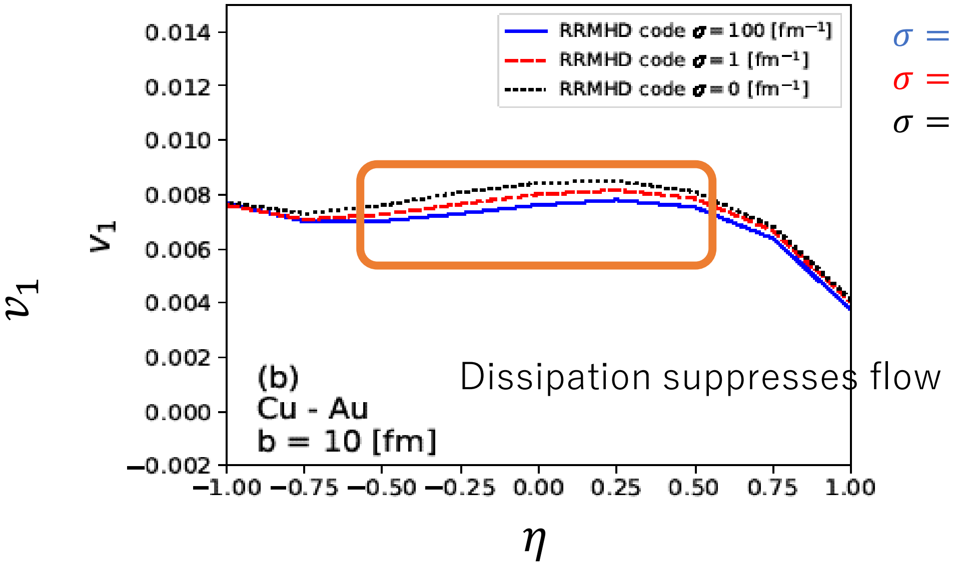
➢ Au-Au collisions （$\sqrt{s_{NN}} = 200\ \text{GeV}$）
- Parameter fixed in initial condition from comparison with STAR data

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

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



$\sigma = 100\ \text{fm}^{-1}$
$\sigma = 1\ \text{fm}^{-1}$
$\sigma = 0\ \text{fm}^{-1}$
○ : STAR



$\sigma = 100\ \text{fm}^{-1}$
$\sigma = 1\ \text{fm}^{-1}$
$\sigma = 0\ \text{fm}^{-1}$

Energy Transfer by Ohm Dissipation

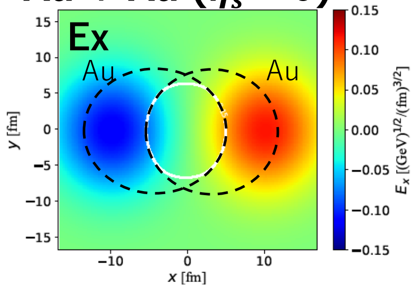
Nakamura, Miyoshi, CN and Takahashi, PRC 107, no.1, 014901 (2023)

- **Energy Transfer**

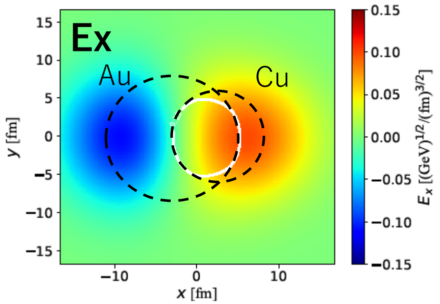
$$\boldsymbol{D(u) \coloneqq j^{\mu} e_{\mu} = \gamma[j \cdot (E + v \times B) - q(v \cdot E)]}$$

energy of the electromagnetic field → { **Thermal energy**, **Kinetic energy** }

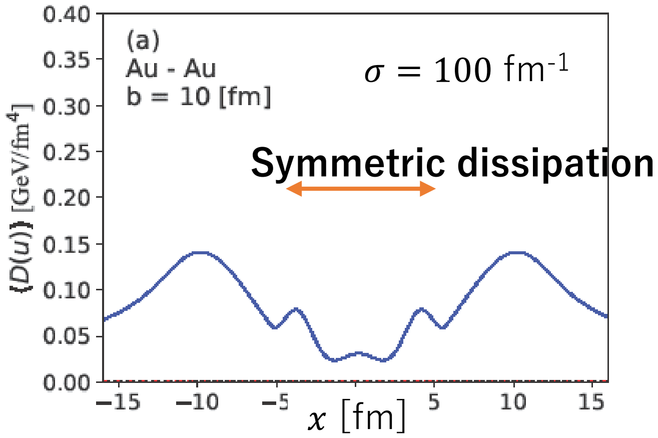
Au + Au ($\eta_s = 0$)



Cu + Au ($\eta_s = 0$)

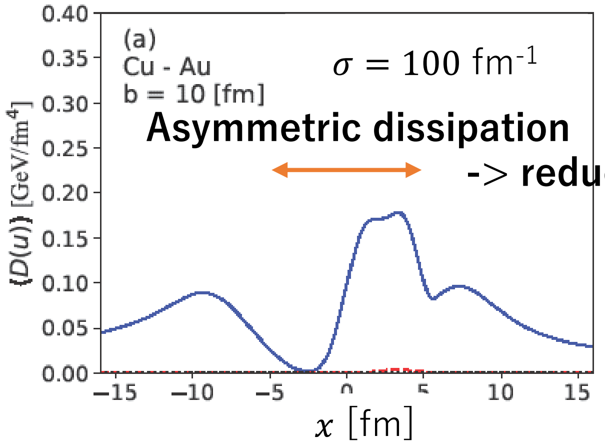


Au+Au collisions



no contribution to $\boldsymbol{v_1}$

Cu+Au collisions



-> reduces pressures gradient

contribution to $\boldsymbol{v_1}$

Directed Flow

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

Nakamura, Miyoshi, CN and Takahashi, PRC 107, no.1, 014901 (2023)

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

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

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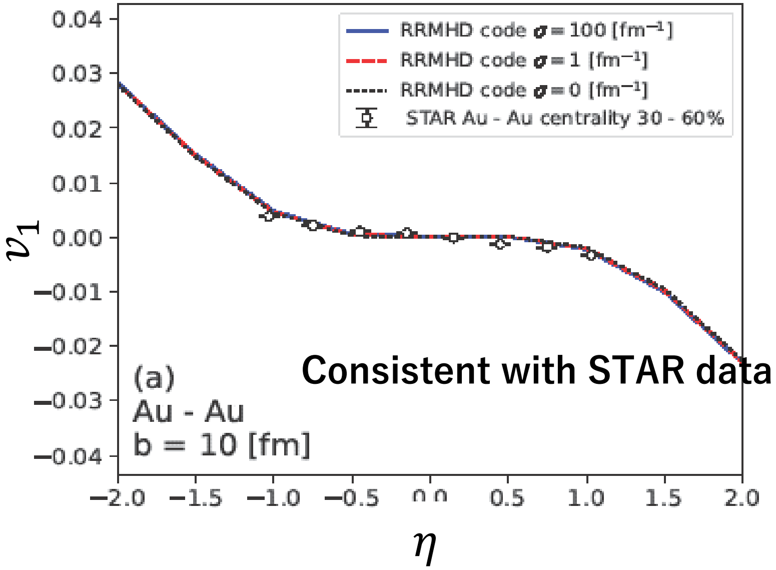
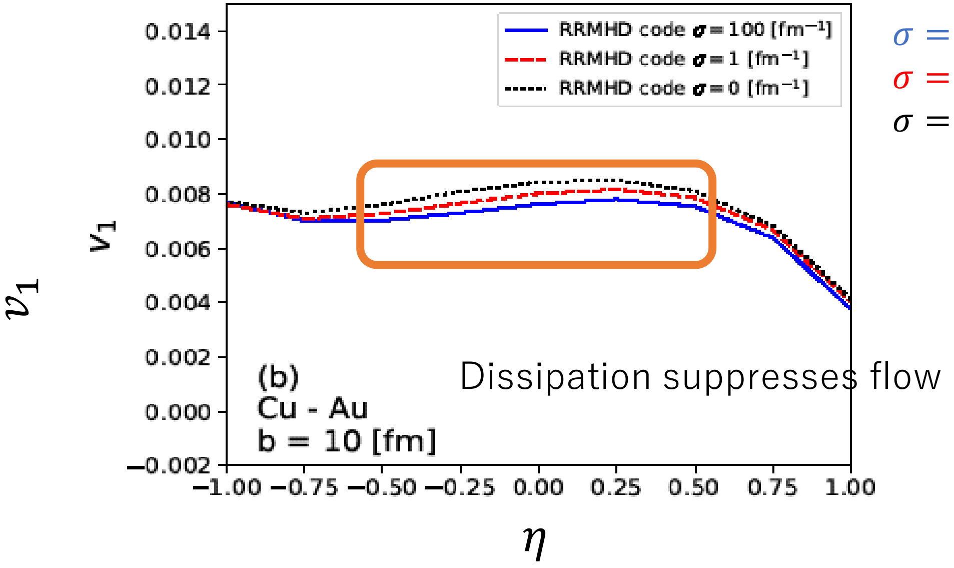


σ =100 fm^{-1}
σ = 1 fm^{-1}
σ = 0 fm^{-1}
○ : STAR

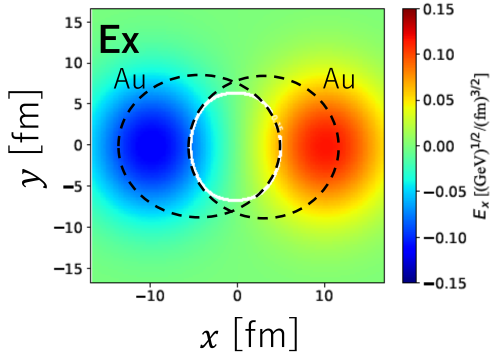


σ =100 fm^{-1}
σ = 1 fm^{-1}
σ = 0 fm^{-1}

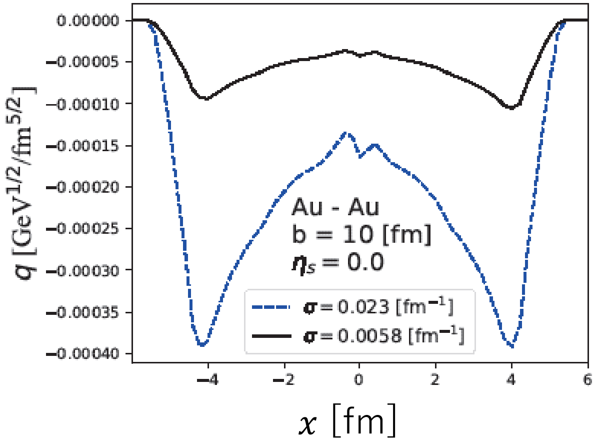
Charge Dependence of Δv_2 : Au + Au

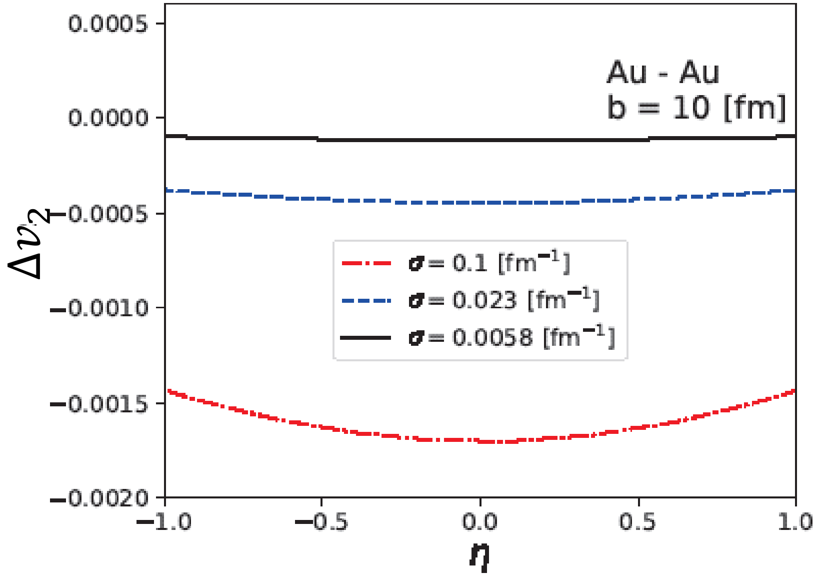
Nakamura, Miyoshi, CN and Takahashi, PRC 107, no.1, 014901 (2023)

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



Charge distribution on freezeout hypersurface





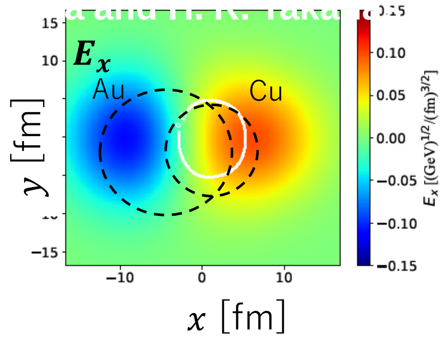
$\sigma = 0.1$ fm^{-1}
$\sigma = 0.023$ fm^{-1}
$\sigma = 0.0058$ fm^{-1}

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

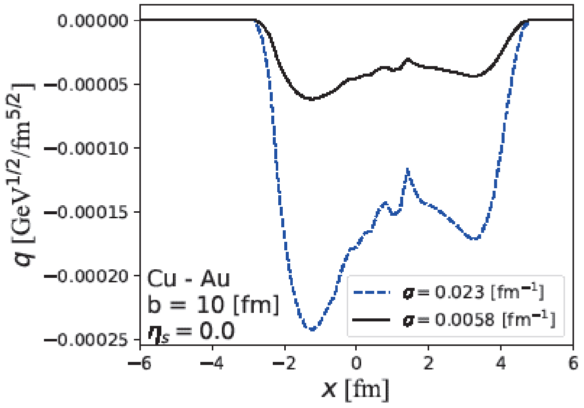
Charge Dependence of Δv_2 ：Cu＋Au

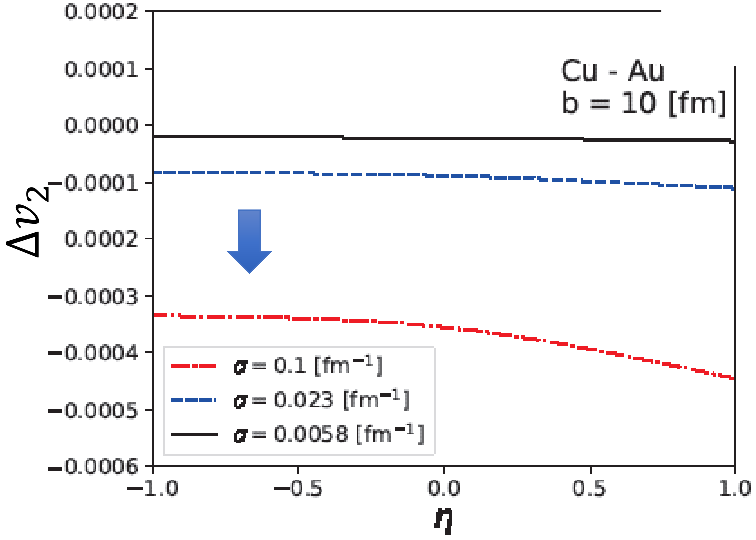
Nakamura, Miyoshi, CN and Takahashi, PRC 107, no.1, 014901 (2023)

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



Charge distribution on freezeout hypersurface





$\sigma = 0.1$ fm^{-1}
$\sigma = 0.023$ fm^{-1}
$\sigma = 0.0058$ fm^{-1}

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

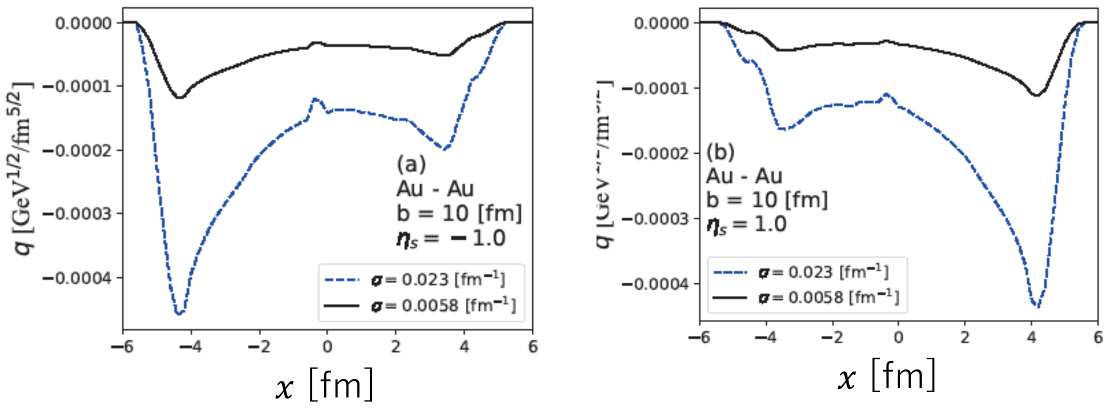
Δv_2: initial electromagnetic field distribution electrical conductivity

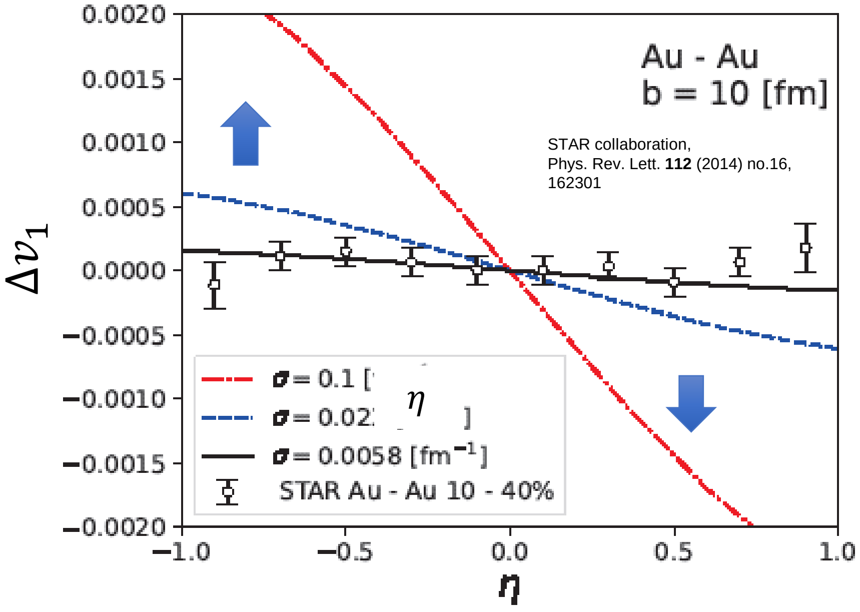
Charge Dependence of Δv_1 : Au + Au

- $\Delta v_1 = v_1^{\pi^+}(\eta) - v_1^{\pi^-}(\eta)$
  - 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
    - $\sigma = 0.0058\ \mathrm{fm}^{-1}$
      ex. $\sigma_{LQCD} = 0.023\ \mathrm{fm}^{-1}$
      from lattice QCD
      Gert Aarts, et al.
      Phys. Rev. Lett., 99:022002, 2007.

✓ **QGP electrical conductivity from high-precision measurement of Δv_1**

Charge distribution on freezeout hypersurface





$\sigma = 0.1$ fm^{-1}
$\sigma = 0.023$ fm^{-1}
$\sigma = 0.0058$ fm^{-1}
○ : STAR data

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

Charge Dependence of Δv_1 ： Cu + Au

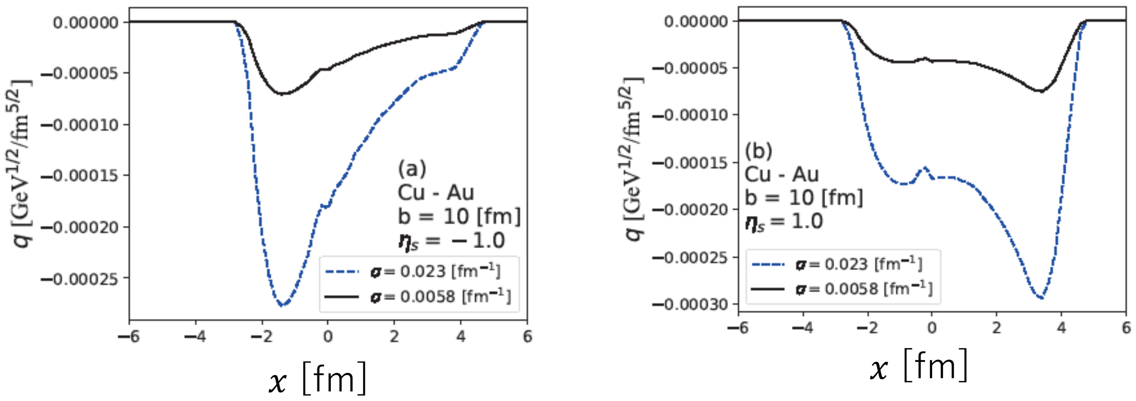
Nakamura, Miyoshi, CN and Takahashi, Phys. Rev. C 107 (2023) 3, 034912

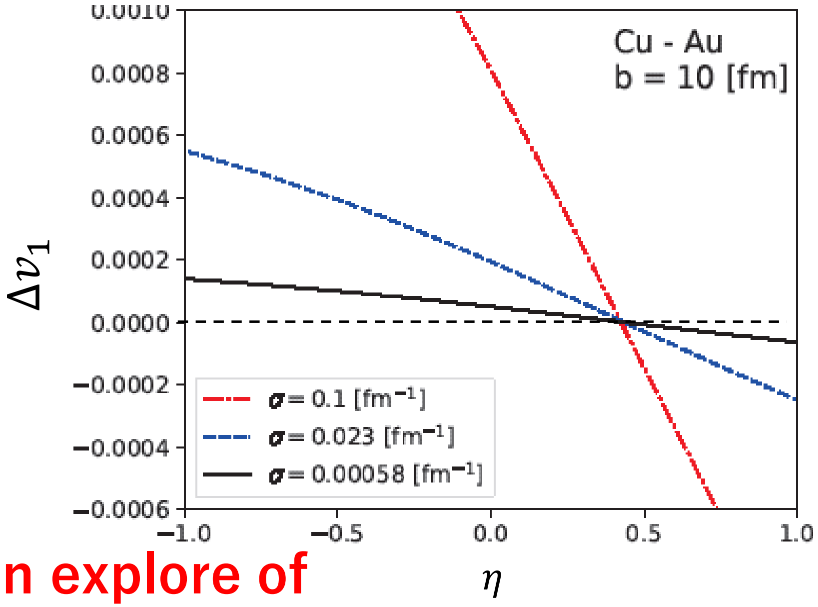
- $\boldsymbol{\Delta v_1 = v_1^{\pi^+}(\eta) - v_1^{\pi^-}(\eta)}$
  - **Electric field created by initial condition**
    - Δv_1 is finite at $\eta = 0$
    - Asymmetry structure to $\eta = 0$
  - **Proportion to electric conductivity**
    - Δv_1 vanishes at $\eta = 0.5$.

✓ **Electrical conductivity <- Δv_1 at $\eta = 0$**

✓ **Initial electrical field from η dependence of Δv_1**

Charge distribution on freezeout hypersurface





$\sigma = 0.1$ fm^{-1}
$\sigma = 0.023$ fm^{-1}
$\sigma = 0.0058$ fm^{-1}

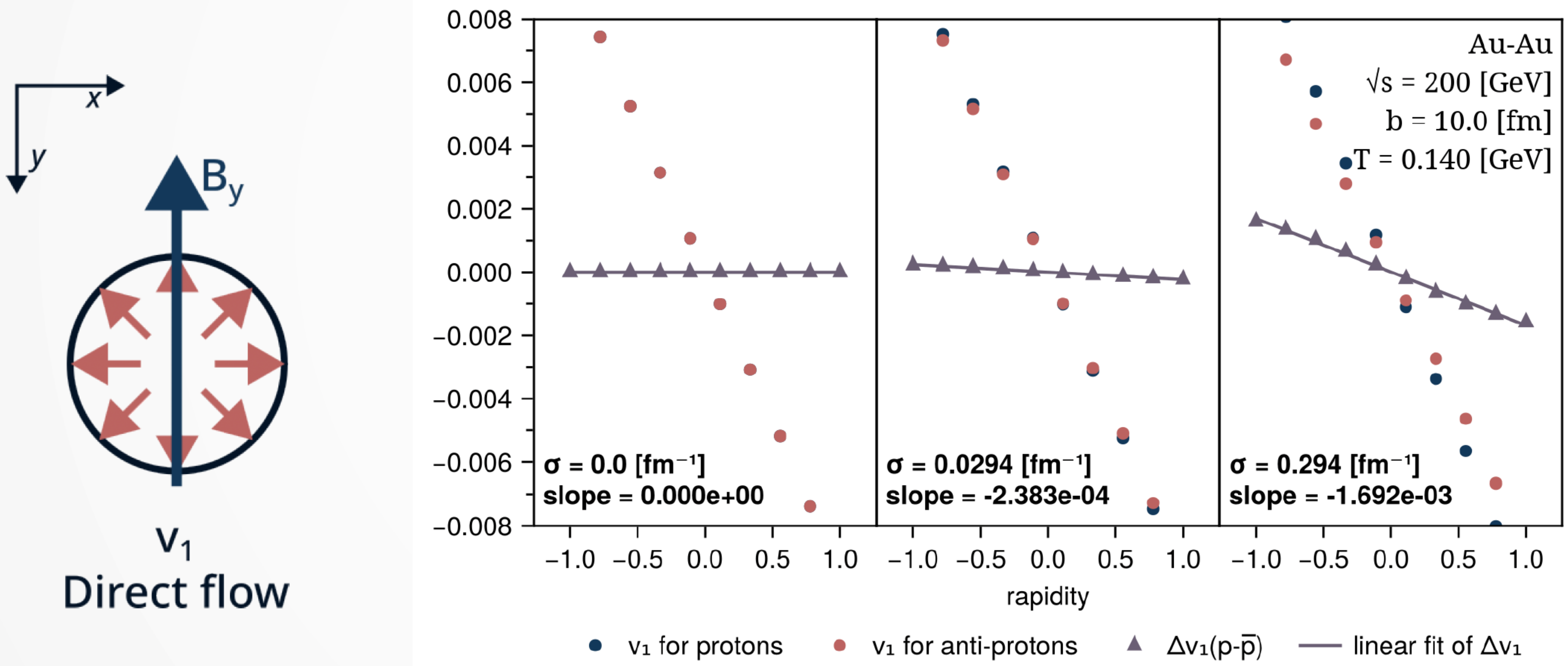
Asymmetric system has advantage in explore of QGP electrical conductivity.

Comparison with STAR Data

Benoit ,Miyoshi, CN , Sakai and Takahashi, in preparation

What RRMHD says about recent experimental result

- Our RRMHD model can reproduce the STAR experiment behavior



By courtesy of Benoit

Photon

Benoit ,Miyoshi, CN , Sakai and Takahashi, in preparation

Nicholas J. Benoit

Electromagnetic Dissipation for QGP Photon

Benoit

- **Electromagnetic fields inside QGP**
  - EM fields penetrating QGP drive charge carriers out-of-equilibrium

$$J^\mu = q u^\mu + \sigma F^{\mu\nu} u_\nu$$

First order dissipation from the EM fields

  - Taking the Boltzmann equation in the relaxation time application

$$k^\mu \partial_\mu f_a + eQ_a F^{\mu\nu} k_\mu \frac{\partial f_a}{\partial k^\nu} = -\frac{k^\mu u_\mu}{\tau_R} \delta f^{(n)}_{a,EM}$$

Sun and Yan, PRC 109, 034917 (2024).

Vlasov term for the external EM fields

Order "n" corrections
to the quark distribution function

Electromagnetic Dissipation for QGP Photon

Benoit

- **Electromagnetic fields inside QGP**
  - 1st order corrections

$$k^\mu \partial_\mu f_a + eQ_a F^{\mu\nu} k_\mu \frac{\partial f_a}{\partial k^\nu} = -\frac{k^\mu u_\mu}{\tau_R} \delta f^{(n)}_{a,EM}$$

Sun and Yan, PRC 109, 034917 (2024).

$$f_a = f_{a,eq} + \delta f^{(1)}_{a,EM} + \delta f^{(2)}_{a,EM} + \delta f^{(3)}_{a,EM} + \cdots$$

$$\delta f^{(1)}_{a,EM}(X,k) = -\frac{-f_{a,eq}(1-f_{a,eq})}{T\chi_{el} k^\mu u_\mu} e\sigma Q_a e^\mu k_\mu$$

Electric conductivity of QGP from Landau matching with the current

EM fields in the fluid rest frame

$$e^\mu = (\gamma v_k E^k, \gamma E^i + \gamma \epsilon^{ijk} v_j B_k)$$

Electromagnetic Dissipation for QGP Photon

Benoit

- **Electromagnetic fields inside QGP**
  - The fluid + EM field contributions from hydrodynamics

Temperature and four velocity

$$\delta f^{(1)}_{a,EM}(X,k) = -\frac{-f_{a,eq}(1-f_{a,eq})}{T\chi_{el}k^\mu u_\mu} e\sigma Q_a e^\mu k_\mu$$

Electric susceptibility of QGP

$$\chi_{a,el} = -\frac{1}{3}\int \frac{d\vec{p}}{(2\pi)^3 E_p}(p^\sigma p^\nu \Delta_{\sigma\nu})\frac{-f_{a,eq}(1-f_{a,eq})}{p^\mu u_\mu}$$

Spacetime dependent EM fields in QGP medium

$$e^\mu = (\gamma v_k E^k, \gamma E^i + \gamma \epsilon^{ijk} v_j B_k)$$

Electromagnetic Dissipation for QGP Photon

Benoit

- **Electromagnetic fields inside QGP**
  - The fluid + EM field contributions from hydrodynamics
  - All of those values can be calculated self-consistently using relativistic resistive magneto-hydrodynamics (RRHMD)

Temperature and four velocity

$$\delta f^{(1)}_{a,EM}(X,k) = -\frac{-f_{a,eq}(1-f_{a,eq})}{T\chi_{el}k^\mu u_\mu} e\underline{\sigma} Q_a \underline{e^\mu} k_\mu$$

Electric susceptibility of QGP

$$\chi_{a,el} = -\frac{1}{3}\int \frac{d\vec{p}}{(2\pi)^3 E_p}(p^\sigma p^\nu \Delta_{\sigma\nu})\frac{-f_{a,eq}(1-f_{a,eq})}{p^\mu u_\mu}$$

Spacetime dependent EM fields in QGP medium

$$e^\mu = (\gamma v_k E^k, \gamma E^i + \gamma \epsilon^{ijk} v_j B_k)$$

Photon production from QGP and EM fields

- **Rate of QGP photon production should be increased by the EM fields**

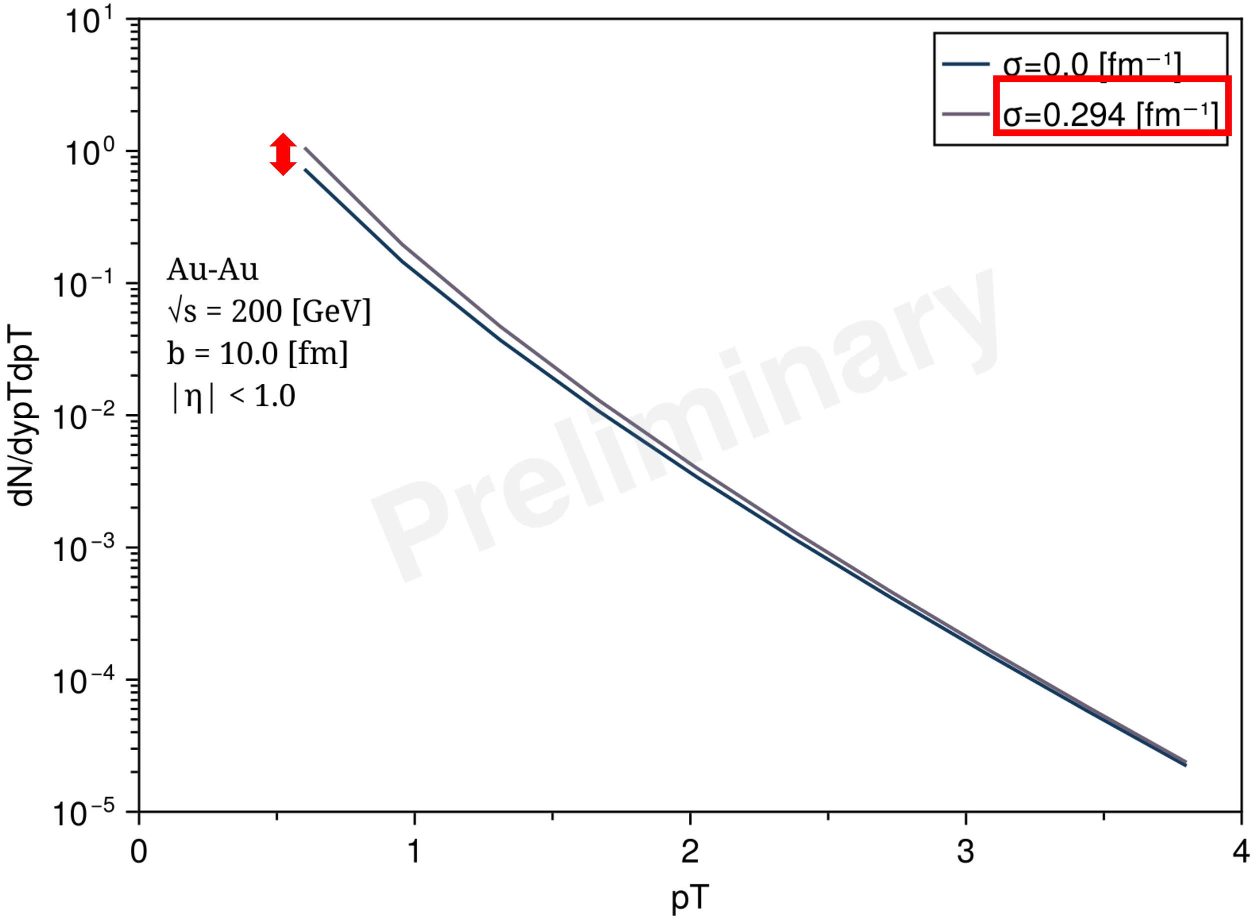
$$E_k \frac{d\mathcal{R}}{d^3\vec{k}} = E_k \frac{d\mathcal{R}}{d^3\vec{k}}^{\text{QGP}} + E_k \frac{d\mathcal{R}}{d^3\vec{k}}^{\text{EM}}$$

$$E_k \frac{d\mathcal{R}}{d^3\vec{k}}^{\text{EM}} \sim C\alpha_s \alpha_{\text{EM}} \mathcal{I}\mathcal{L}_c \sum_a \delta f^{(1)}_{a,\text{EM}}(X,k)$$

We focus on effect of EM dissipation

We neglect viscous dissipation effect

P_T Spectra of Direct Photon



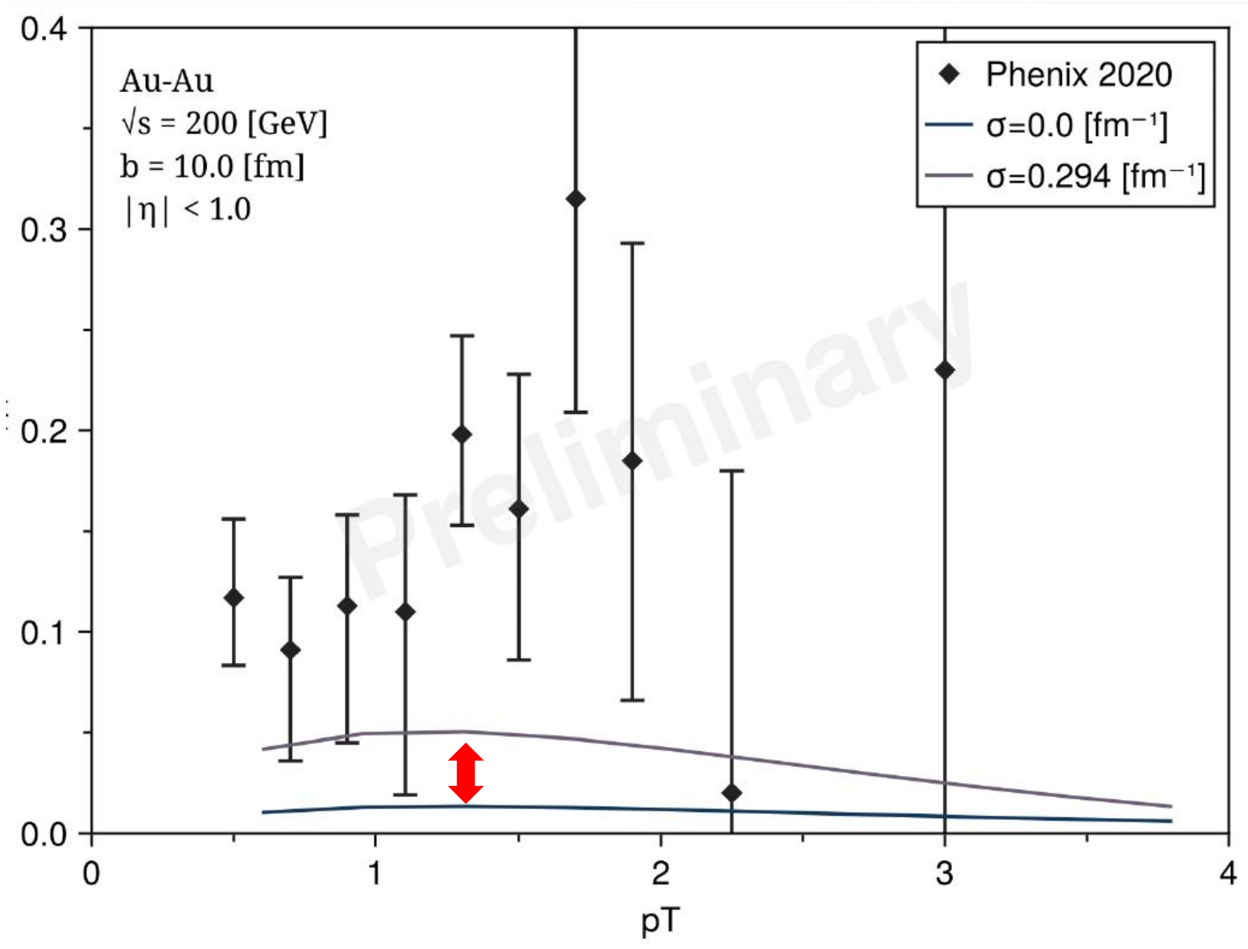
$$E_k \frac{d\mathcal{R}}{d^3\vec{k}}^{\mathrm{EM}} \sim C\alpha_s\alpha_{\mathrm{EM}}\mathcal{I}\mathcal{L}_c \sum_a \delta f^{(1)}_{a,\mathrm{EM}}(X,k)$$

From Lattice QCD

$\sigma = 0.029$ [fm^{-1}]

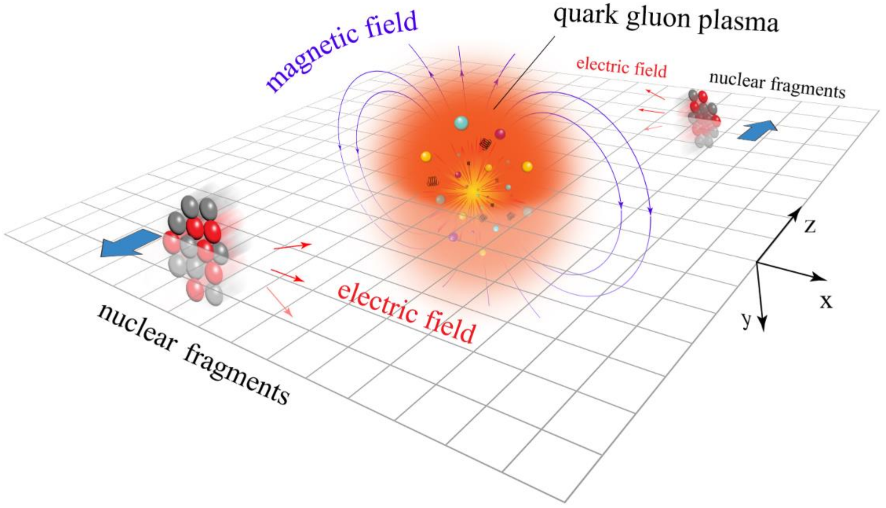
Small contribution to P_T spectra

Elliptic Flow of Direct Photon



Large enhancement is observed.

$$v_2(\gamma) \equiv \frac{v_0 v_2 + v_0^{\mathrm{EM}} v_2^{\mathrm{EM}}}{v_0 + v_0^{\mathrm{EM}}}$$

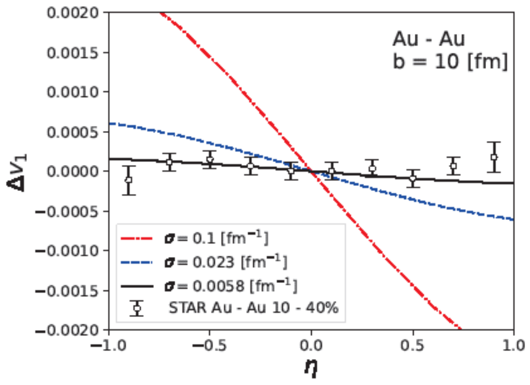


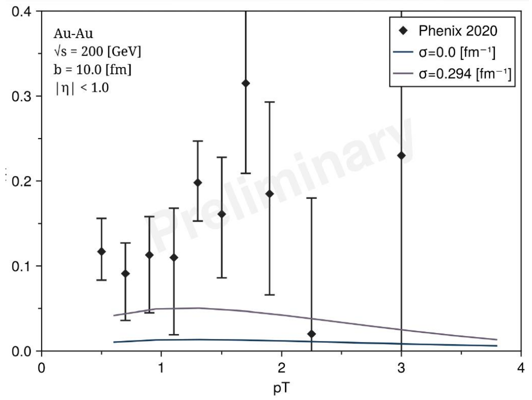
Since largest magnetic field has an elliptic orientation, a larger impact from the EM corrections on elliptic flow appears.

Summary

Electric conductivity of QCD Matter

- **Construction of RRMHD code in the Milne coordinate**
  - Test calculation in the 1+1 expanding system
- **Application to high-energy heavy-ion collisions**
  - Charge dependent flow
    - Au+Au and Au+Cu systems at RHIC energy
  - Elliptic flow of photons





Future work:

Event-by-event fluctuation
Finite density
Nuclear structure Ru+Ru, Zr+Zr
Vortex
Chiral magnetohydrodynamics
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