Relativistic Resistive Magneto-Hydrodynamics in High-Energy Heavy-Ion Collisions: ~Hadron distribution and Flow~

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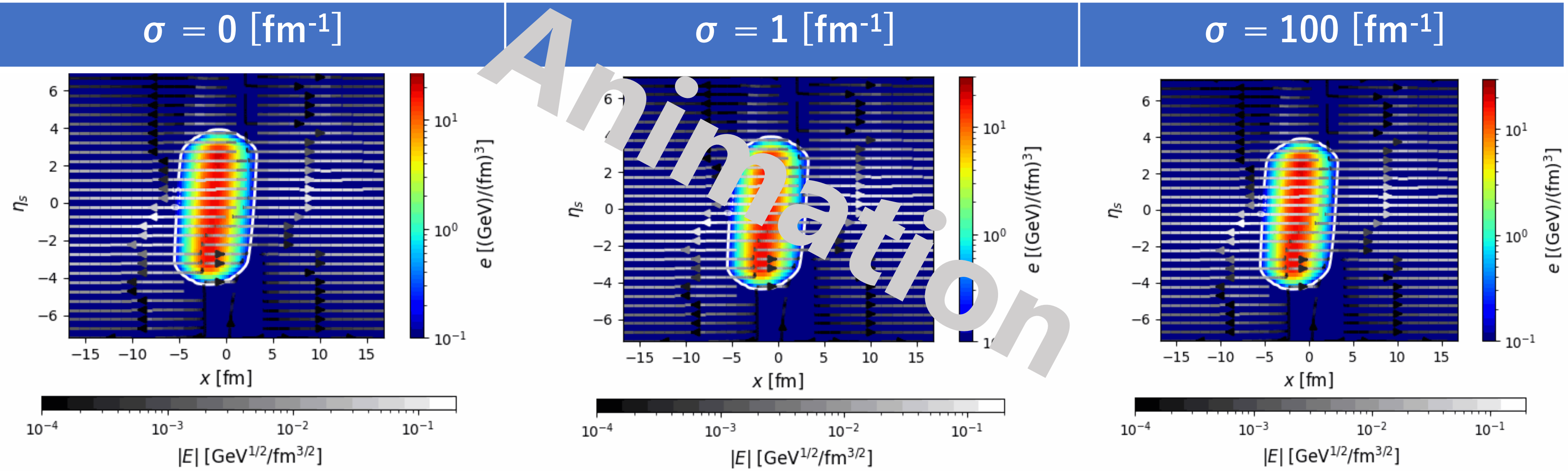
$\sigma = 0$ [fm^{-1}]	$\sigma = 1$ [fm^{-1}]	$\sigma = 100$ [fm^{-1}]

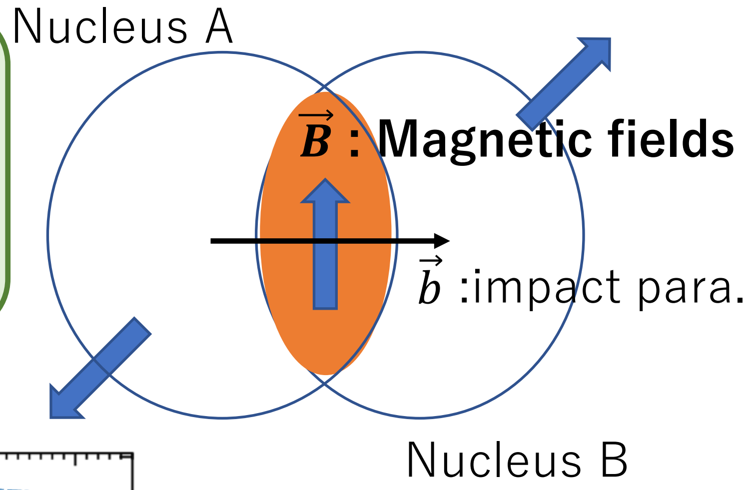


Why is Resistivity considered?

No hydrodynamic calculation with electrical conductivity

Electrical conductivity ⟺ ? ⟺ particle distributions

Direct simulation: Relativistic Resistive Magneto-hydrodynamics



■ Strong Magnetic fields produced by Spectators inside of Nuclei

- Au - Au collision ($\sqrt{s_{NN}} = 200$ GeV) : 10^{14} T
- Pb – Pb collision ($\sqrt{s_{NN}} = 2.76$ TeV) : 10^{15} T

■ Quark-Gluon Plasma and EM fields

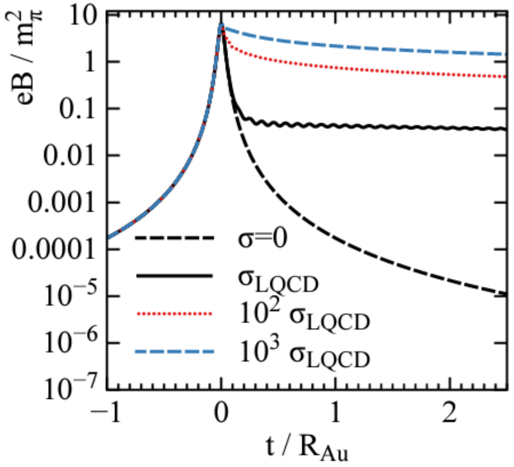
- Dynamics of EM Fields: Electrical conductivity dependence
  - ✓ Instantaneously decay in vacuum
  - ✓ Longer lifetime in **the conductive medium**

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

- Relativistic **ideal** ($\sigma \to \infty$) magneto-hydrodynamics

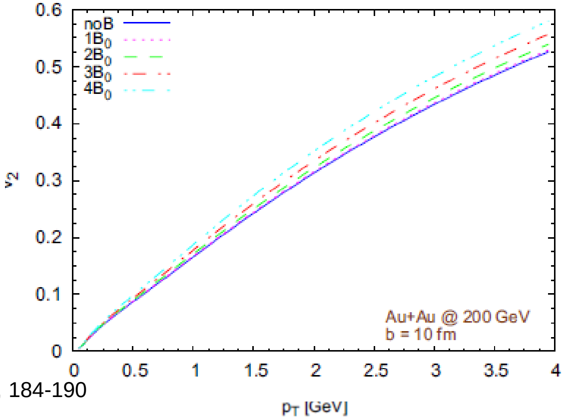
Inghirami, et al, Eur. Phys. J. C (2020) 80:293

  - ✓ Infinite electrical conductivity ($\sigma \to \infty$)
  - ✓ Effects of the magnetic field are very small
  - ✓ **Initial Electric fields are ignored!! → we need RRMHD simulations in order to consider the initial electric fields**



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

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



In the asymmetric system, initial electric fields are important!

Relativistic Resistive Magneto-hydrodynamics(R2MHD)

■R2MHD model

- ➢ Initial condition
  - ✓ Glauber model with tilted source
  - ✓ EM fields: produced by protons inside nuclei
    - Cu - Au Collision ($\sqrt{s_{NN}}$ = 200 GeV) (Asymmetric systems)

Bozek, et al, Phys. Rev. C 81, 054902(2010)
Tuchin, Phys.Rev.C88,024911(2013)

- ➢ **R2MHD simulation code**
  - ✓ **Relativistic hydrodynamic eq. + Maxwell eq.**

$$\partial_\mu T_m^{\mu\nu} = F^{\nu\lambda} j_\lambda$$

  - ✓ **Ohm's law**

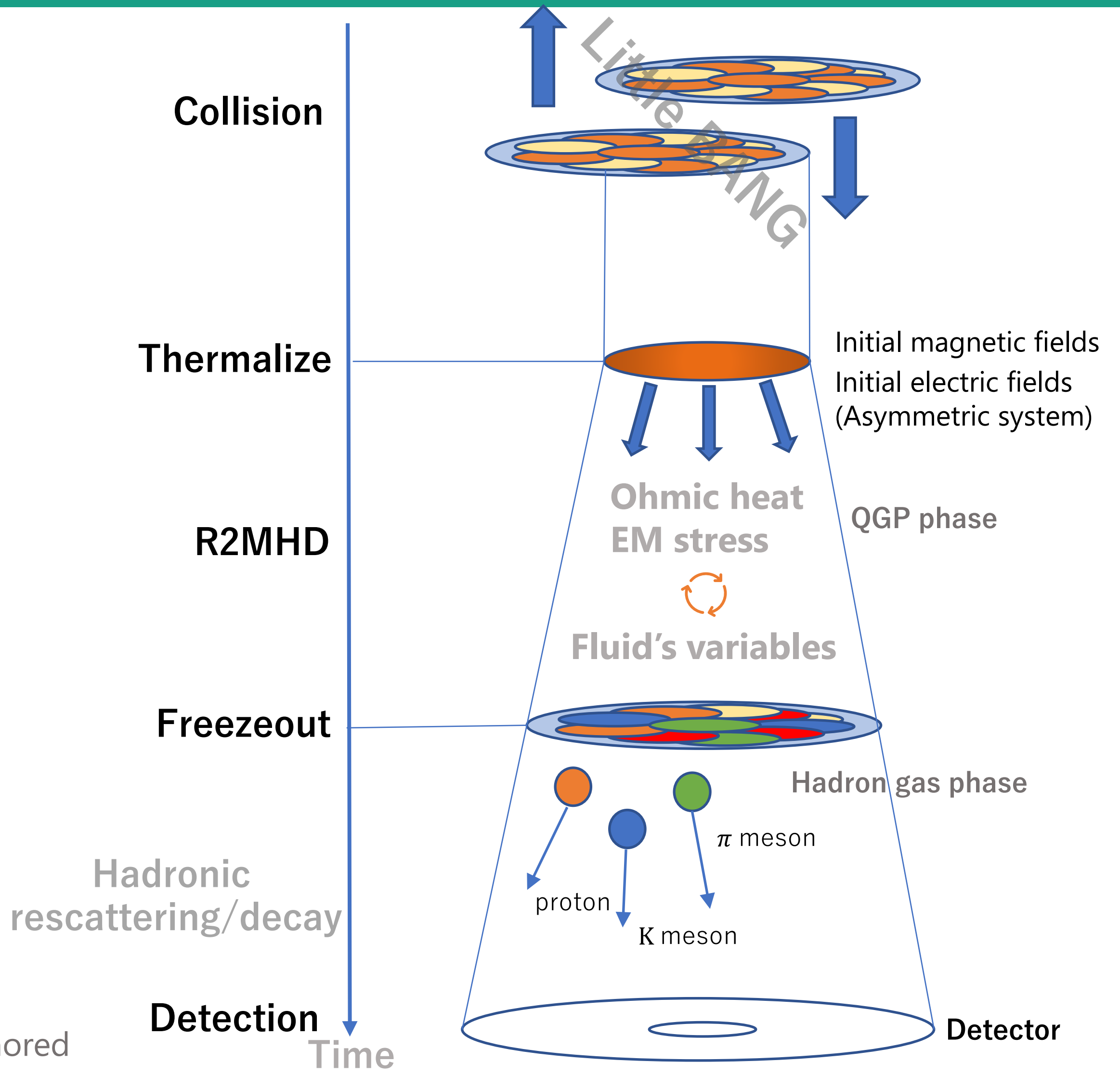
$$\vec{j} = \sigma\gamma\left[\vec{E} + \vec{v}\times\vec{B} - (\vec{v}\cdot\vec{E})\vec{v}\right] + q\vec{v}$$

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

- ➢ Freezeout
  - ✓ Fluid picture → particle picture (energy density: 150 MeV/fm^3)

$$E\frac{d^3N}{dp^3} = \frac{g_i}{2\pi^3}\int_\Sigma \frac{p^\mu d^3\Sigma_\mu}{\exp(p^\mu u_\mu) - 1}$$

Hadronic rescattrering and decay are ignored



Asymmetric Collision System: Cu – Au

■Cu – Au Collision ($\sqrt{s_{NN}} = 200$ GeV)

- **Asymmetric charge distribution** along with the impact parameter
- **Initial Electric fields are non-zero** in QGP medium

Ohmic heating occurs!

■Asymmetric Ohmic heating and EM stress

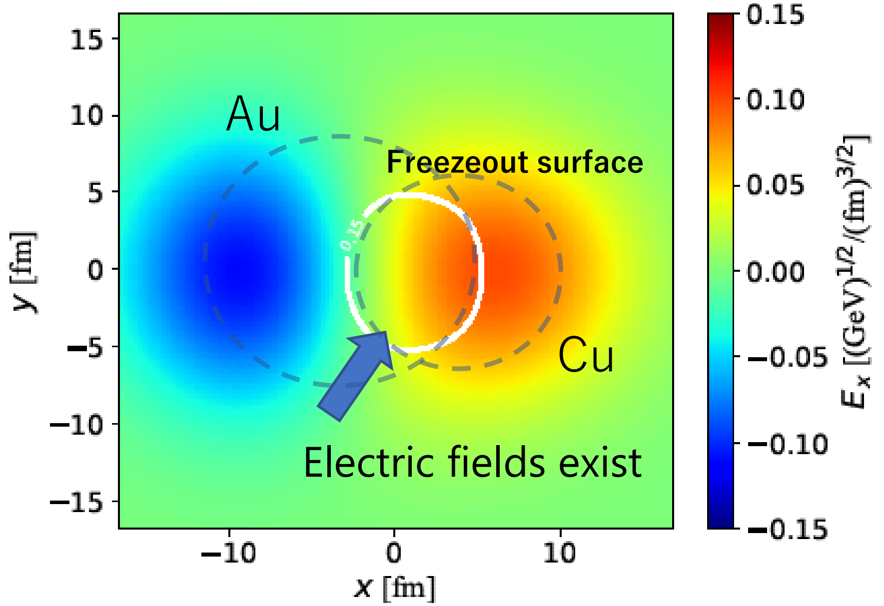
- Electromagnetic energy converts to thermal or kinetic energy

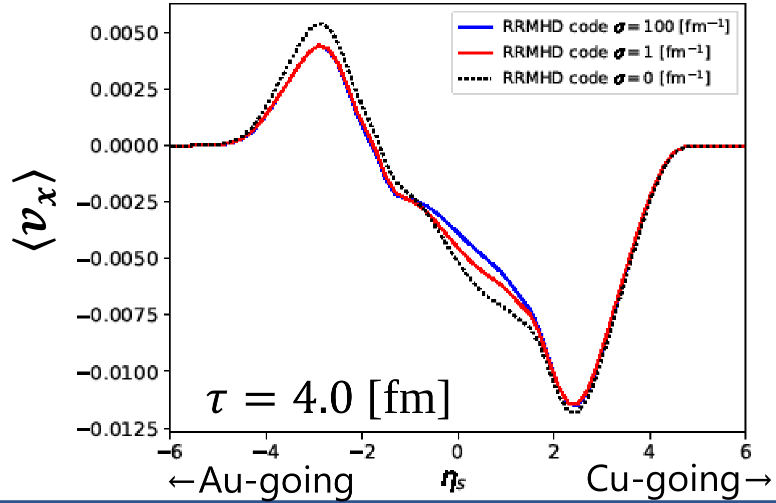
  ➡ It changes fluid's velocity along with impact param.
- The weighted average of fluid's velocity along with impact param.

$$\langle v_x \rangle(\eta_s) = \frac{\int v_x(x, y, \eta_s)\gamma e dx dy}{\int \gamma e dx dy}$$

  ✓ EM fields suppress fluid's velocity in direction of impact param.

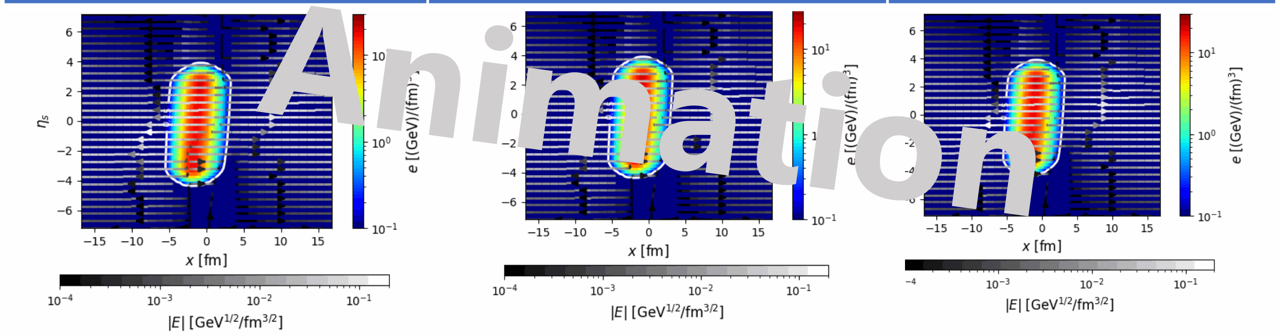
- **Directed flow v_1** is good probe such phenomena





Directed flow v_1: Cu - Au （$b = 8$ fm）

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



■ $v_1 - \eta$

➢ $v_1 \sim \langle \frac{p_x}{p_T} \rangle$

$$E\frac{d^3N}{dp^3} = \frac{dN}{p_T dp_T d\eta}(1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \cdots)$$

- $v_1 > 0$: particles flow positive x (**Cu**) direction
- $v_1 < 0$: particles flow negative x (**Au**) direction

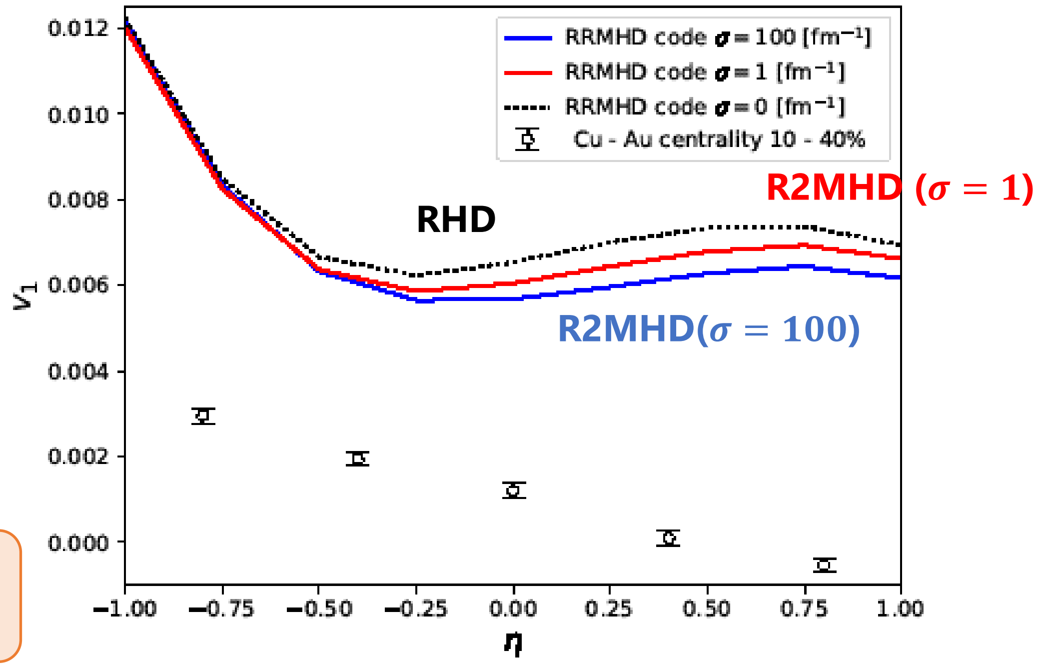
➢ **Electrical conductivity dependence is observed at $(-1 < \eta < 1)$**
- **Ohmic heating/Electric current**
- **Maxwell's stress**

It makes v_1 small
Suppress the flow in **Cu direction**

Deference of the integrated v_1 [%] ($|\eta| < 1.0$)

Star	RHD - R2MHD $\sigma = 1$ (black - red)	RHD – R2MHD $\sigma = 100$ (black - blue)
0.12	0.042	0.09

It is not negligible effect!!
The Deference is same order of STAR data



Summary

Construction of new Relativistic Resistive Magneto-Hydrodynamic model

■Investigating electrical conductivity dependence on hadron distribution and flow using RRMHD model

- ➢Ohmic heating and Maxwell's stress affect the fluid's velocity along with the impact parameter.
- ➢Directed flow v_1 is sensitive to the Ohmic heating and Maxwell's stress in the Asymmetric system

■Future works

- ➢Charge dependent flow
- ➢Electromagnetic probe(photon, dilepton)
- ➢Rotating system
  - ✓Magneto-rotational instability may be probed.
- ➢Chiral Magnetic effects
  - ✓Introduce chiral current and chiral electrical conductivity