Magnetohydrodynamics, charged currents and directed flow in heavy ion collisions

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with D. Kharzeev and K. Rajagopal
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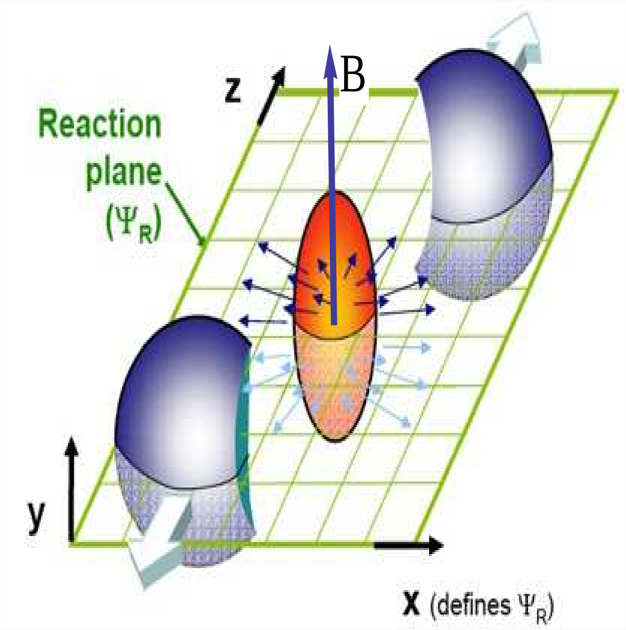
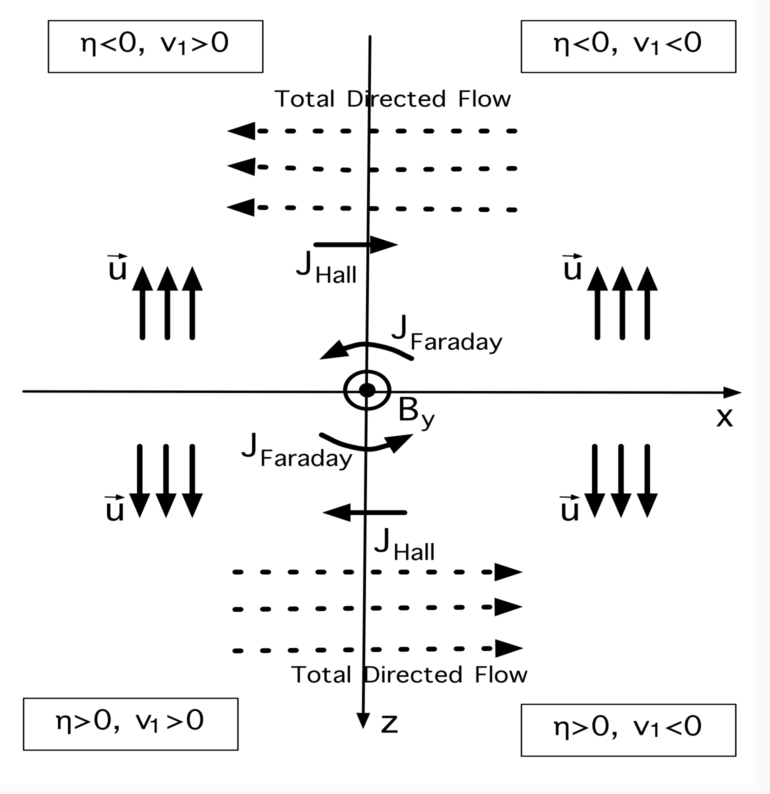
Heavy ion collisions and magnetic fields



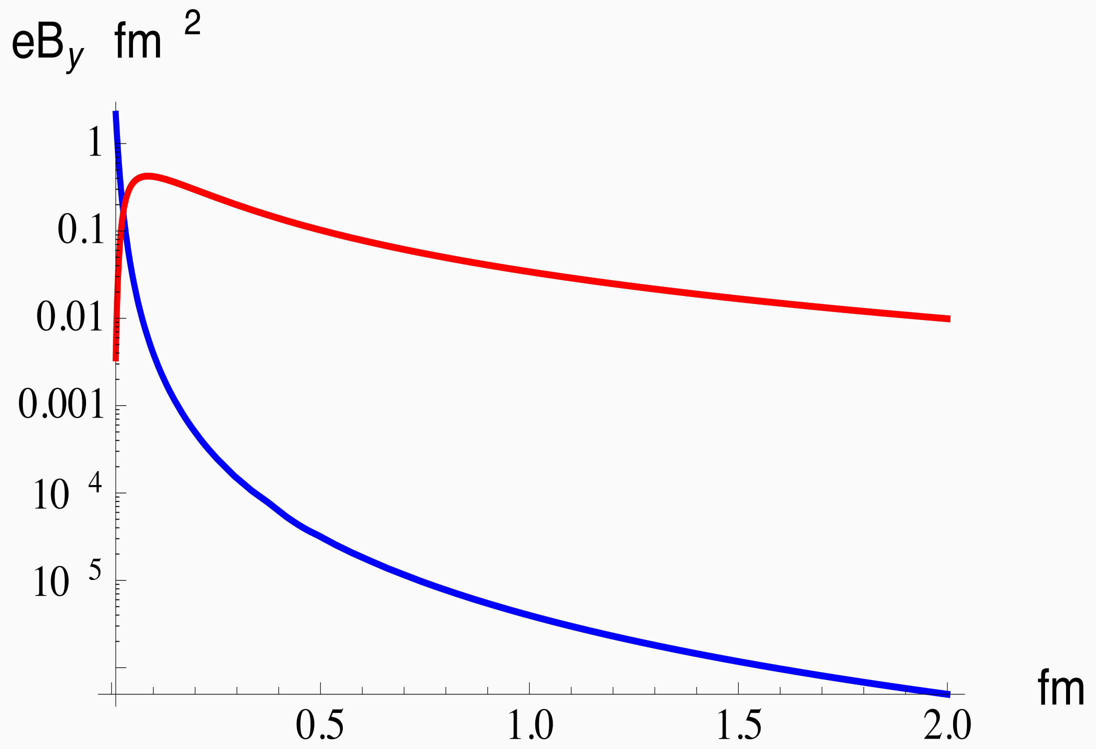
- Initial magnitude of B
- Bio-Savart: $B_0 \sim \gamma Z e \frac{b}{R^3} \Rightarrow$ $eB \approx 5 - 15 \times m_\pi^2$ at RHIC (LHC).
- In this talk $b = 7\text{fm}$ and $R = 7\text{fm}$.
- Motivation: find observables that are directly tied to the presence of B



"Classical" currents in charged and expanding medium:

- Faraday currents $\vec{J}_F \sim \sigma \vec{E}_F$ with $\nabla \times \vec{E}_F = -\frac{\partial \vec{B}}{\partial t}$
- Hall currents $\vec{J}_H \sim \sigma \vec{E}_H$ with $\vec{E}_H = \vec{u} \times \vec{B}$
- Also a "quantum" current $\vec{J}_{CME} \sim \mu_5 \vec{B}$, not considered here.

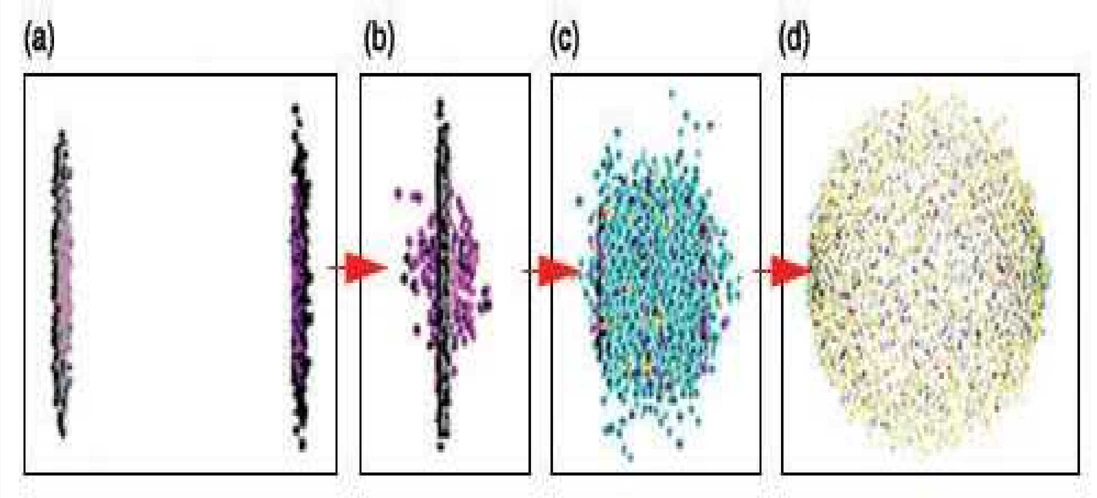
Time profile of B at LHC



with $\sigma = 0.023\text{fm}^{-1}$ and with $\sigma = 0$

- Simplifying assumption hard-sphere distribution for spectators and participants
- For participants empirical distribution over Y: Kharzeev et al. 2007
  $f(Y_b) = (4\sinh(Y_0/2))^{-1}\, e^{Y_b/2}, \qquad -Y_0 \le Y_b \le Y_0$

Strategy



- Suppose $u^\mu(x)$ for expanding QGP is given.
- Calculate stationary velocity v_B:
  $m\frac{d\langle \vec{v'_B}\rangle}{dt} = q\langle \vec{v'_B}\rangle \times \vec{B}' + q\vec{E}' - \mu m\langle \vec{v'_B}\rangle = 0\,,$ with
  $\mu m = \frac{\pi\sqrt{\lambda}}{2}T^2$ from AdS/CFT.
- Add the induced velocity v_B to $u^\mu(x)$, assuming $|\vec{v}_B| \ll |\vec{u}|$
- Total 4-velocity $V^\mu \sim u^\mu + v_B^\mu$: contains all observable information.
- Apply Cooper-Frye to calculate v_1.

Constructing u^μ for the expanding fluid

- Start from the Bjorken flow: Bjorken ’83
  1. Boost invariance along z: $\xi = z\partial_t + t\partial_x$
  2. Rotation around z: $\xi = x\partial_y - y\partial_x$
  3. Translations in transverse plane: $\xi = \partial_x$ and $\xi = \partial_y$
- Solution to $[\xi, u] = 0$ is $u = \partial_\tau$ $(ds^2 = -d\tau^2 + \tau^2 d\eta^2 + dx_\perp^2 + x_\perp^2 d\phi^2)$
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- Gubser's flow Gubser '10
- Replace $\xi = \partial_x,\ \partial_y$ with $\xi_i = \partial_i + q^2\left[2x^i x^\mu \partial_\mu - x^\mu x_\mu \partial_i\right]$
- Solution to $[\xi, u] = 0$ is $u = \cosh\kappa\partial_\tau + \sinh\kappa\partial_\perp$ with $\kappa = \frac{2q^2\tau x_\perp}{1+q^2\tau^2+q^2x_\perp^2}$
- Solution to Hydrodynamics: $\nabla_\mu T^{\mu\nu} = 0$ with $\epsilon = \frac{\hat{\epsilon}_0}{\tau^{4/3}} \frac{(2q)^{8/3}}{\left[1+2q^2(\tau^2+x_\perp^2)+q^4(\tau^2-x_\perp^2)^2\right]^{4/3}}$

Cooper-Frye and parameter fixing

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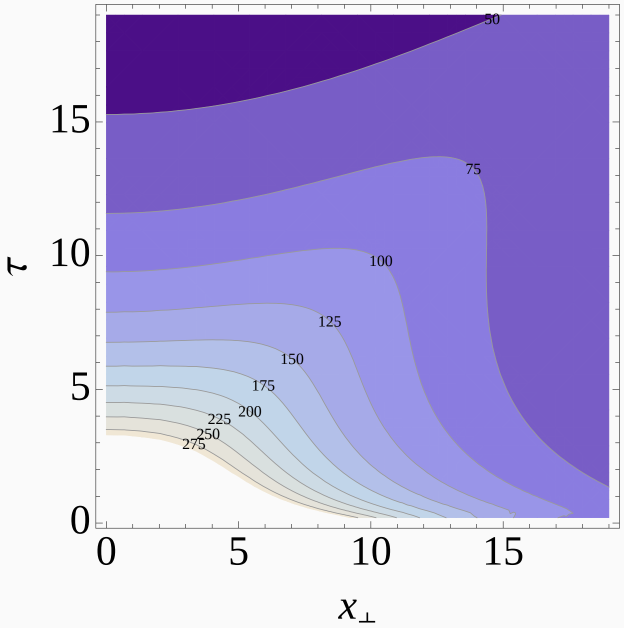
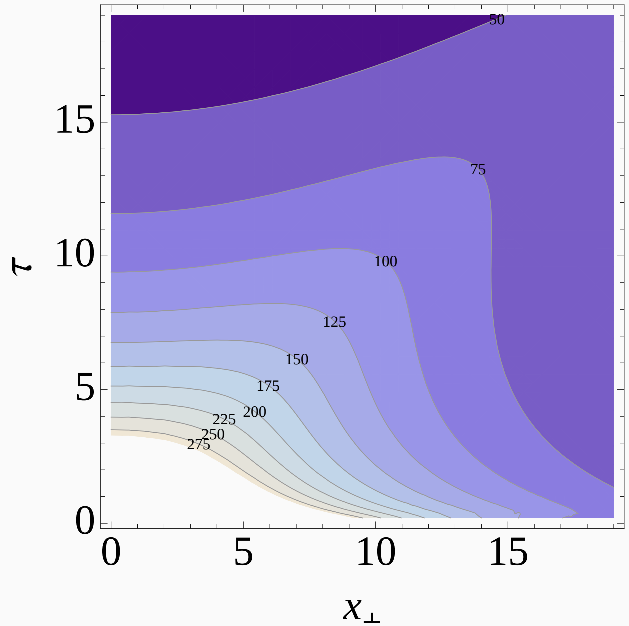
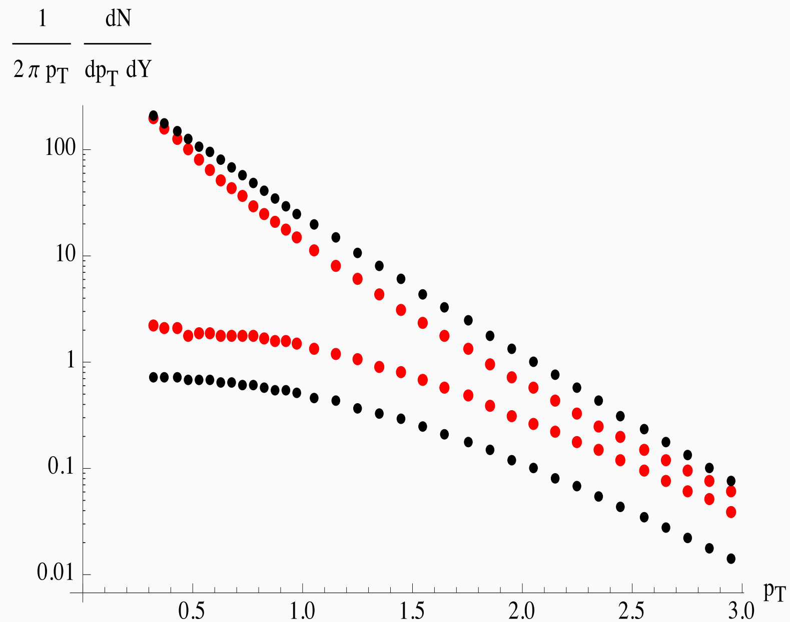


- Cooper-Frye analysis at isothermal surfaces. $T_f \approx 130$ MeV

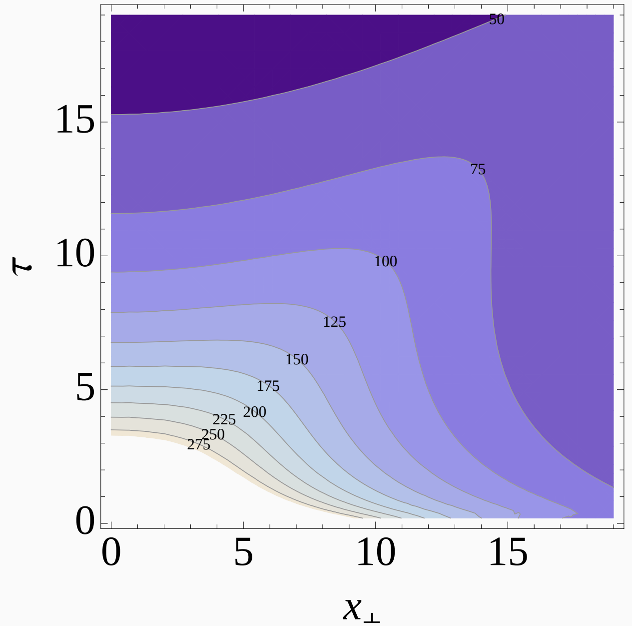
Cooper-Frye and parameter fixing

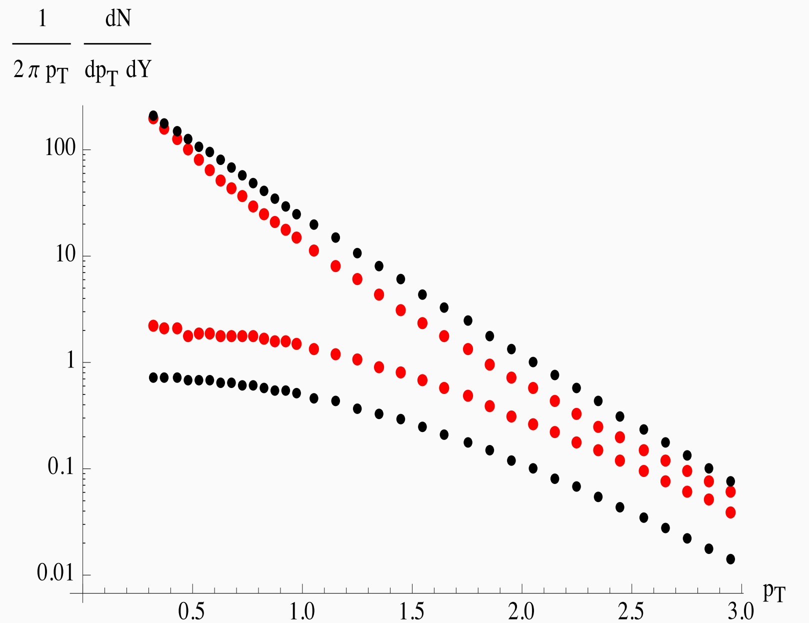




- Cooper-Frye analysis at isothermal surfaces. $T_f \approx 130$ MeV
- Demand realistic comparison with ALICE data for pions and protons and reasonable hydronization temperature $T_h \approx 400 - 550$ MeV
- Optimal solution $q^{-1} = 6.5$ fm and $\hat{\epsilon}_0 = (8.7)^4$.

Cooper-Frye and parameter fixing





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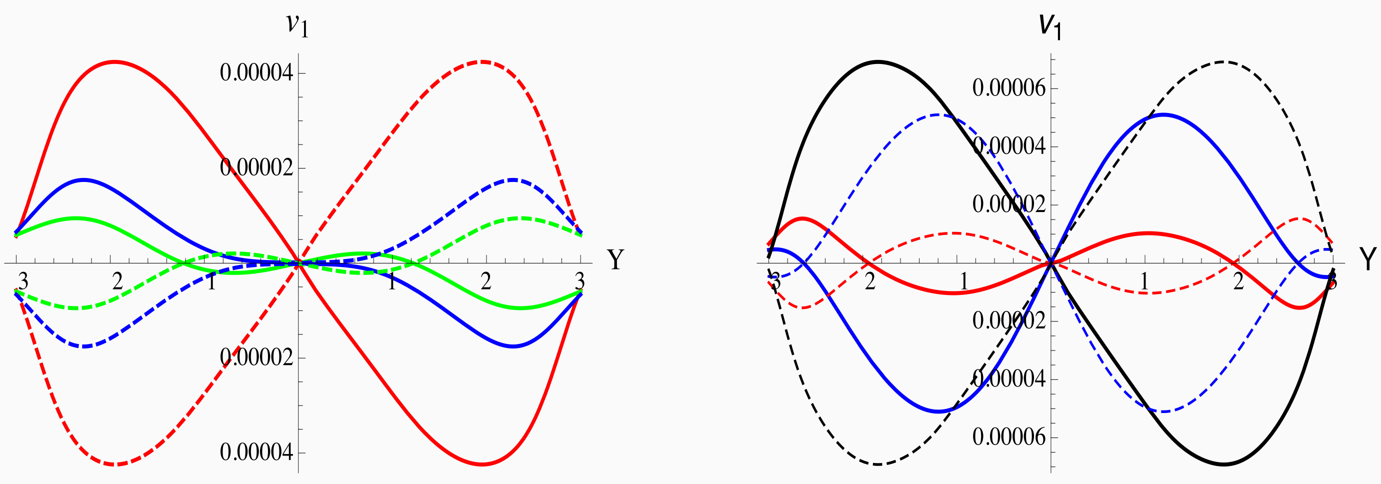
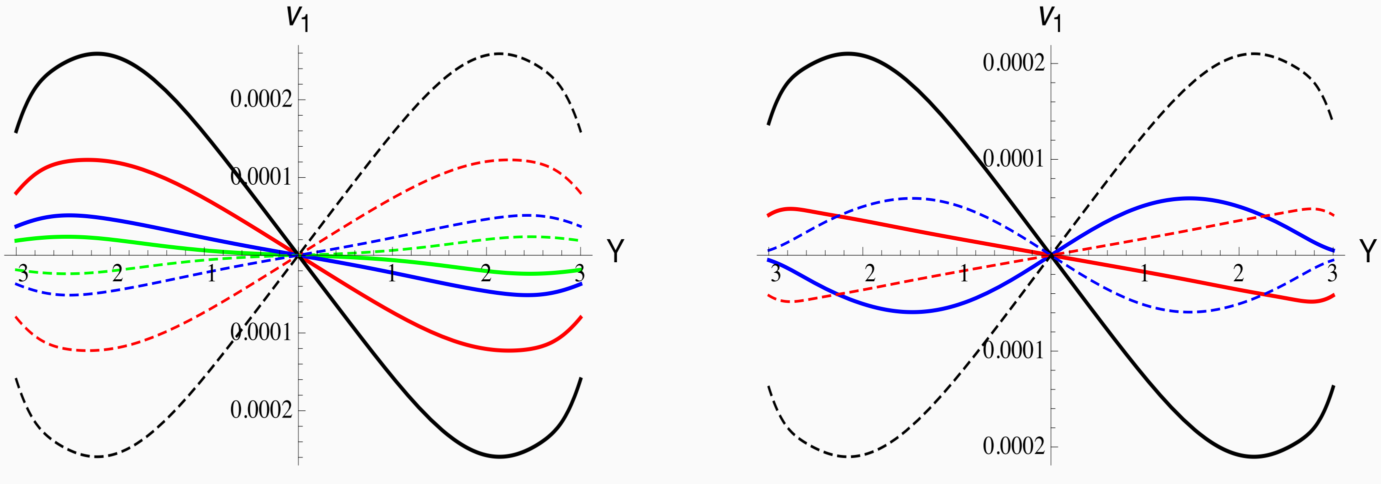
- Spectra from Gubser flow independent of Φ_p and Y

Predictions for charge identified v_1

- Pions and protons at LHC



- Pions and protons at RHIC



Proposal for observables

- Define $A_1^{+-}(Y_1, Y_2) = v_1^+(Y_1) - v_1^-(Y_2)$,
  $A_1^{++}(Y_1, Y_2) = v_1^+(Y_1) - v_1^+(Y_2)$, etc.
  to eliminate charge independent contributions to v_1 produced in event-by-event fluctuations
- Look at quadratic observables
  $C_1^{+-,+-}(Y, Y) = \langle A_1^{+-}(Y, Y) A_1^{+-}(Y, Y) \rangle = 4\langle v_1^+(Y) v_1^+(Y) \rangle$
  to eliminate event-by-event fluctuations in direction of B.
- To be compared with data ...

- Summary:
  - Calculated the contribution of the time-varying B in an expanding plasma, using a perturbative approach to magnetohydrodynamics.
  - Effect odd under charge and rapidity.
  - Competition between Faraday and “Hall” effects.
  - However the magnitude is small.

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  - Effect odd under charge and rapidity.
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  - However the magnitude is small.
- Outlook:
  - Time dependence of σ, μ, T etc.
  - More realistic hydrodyamics.
  - Backreaction of EM on hydro $\Rightarrow$ full magnetohydrodynamics
  - More realistic distributions for the sources

THANK YOU !