Hydro + Initial State Working Group Plan

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Indiana University, Bloomington, IN

Members (preliminary)

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…?

Initial State Group
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…?

The big picture: Why we are here

- Rigorously extract the equation of state of nuclear matter and determine existence of the critical point
- Quantify the characteristics of the Chiral Magnetic Effect
- This is done by:
  - Developing a comprehensive framework
    - Determine which observables are most sensitive to critical behavior
    - Study dependence on parameters
  - Comparing results to experimental data from BESII

Importance of Hydrodynamics for BEST

- Hydrodynamics will provide underlying framework for all calculations that are to be connected to experimental data:
    - Effects of the equation of state enter through the evolution of the system and its effect on final particle spectra
    - Non-equilibrium evolution of cumulants of critical fluctuations on the hydrodynamic bulk evolution background
      Swagato Mukherjee, Raju Venugopalan, Yi Yin, Phys.Rev. C92 (2015) no.3, 034912
    - Dynamic calculations of the CME are done in an extended hydrodynamic framework
- Initially the hydro group can provide freeze out surfaces / and evolution data. Eventually program packages will be available to the collaboration to download and run.

Current status

3D simulations and tools we have at hand:

- MUSIC: 3+1D viscous relativistic hydrodynamics with shear and bulk viscosities and their non-linear couplings as well as net-baryon current and baryon diffusion
- Simple 3D initial state
  with fluctuating net-baryon and entropy density
- Routines to couple to UrQMD
- Equations of state at finite μ_B constructed from lattice data and hadron gas model
- Ideal hydrodynamics with axial currents
- …

3D initial conditions

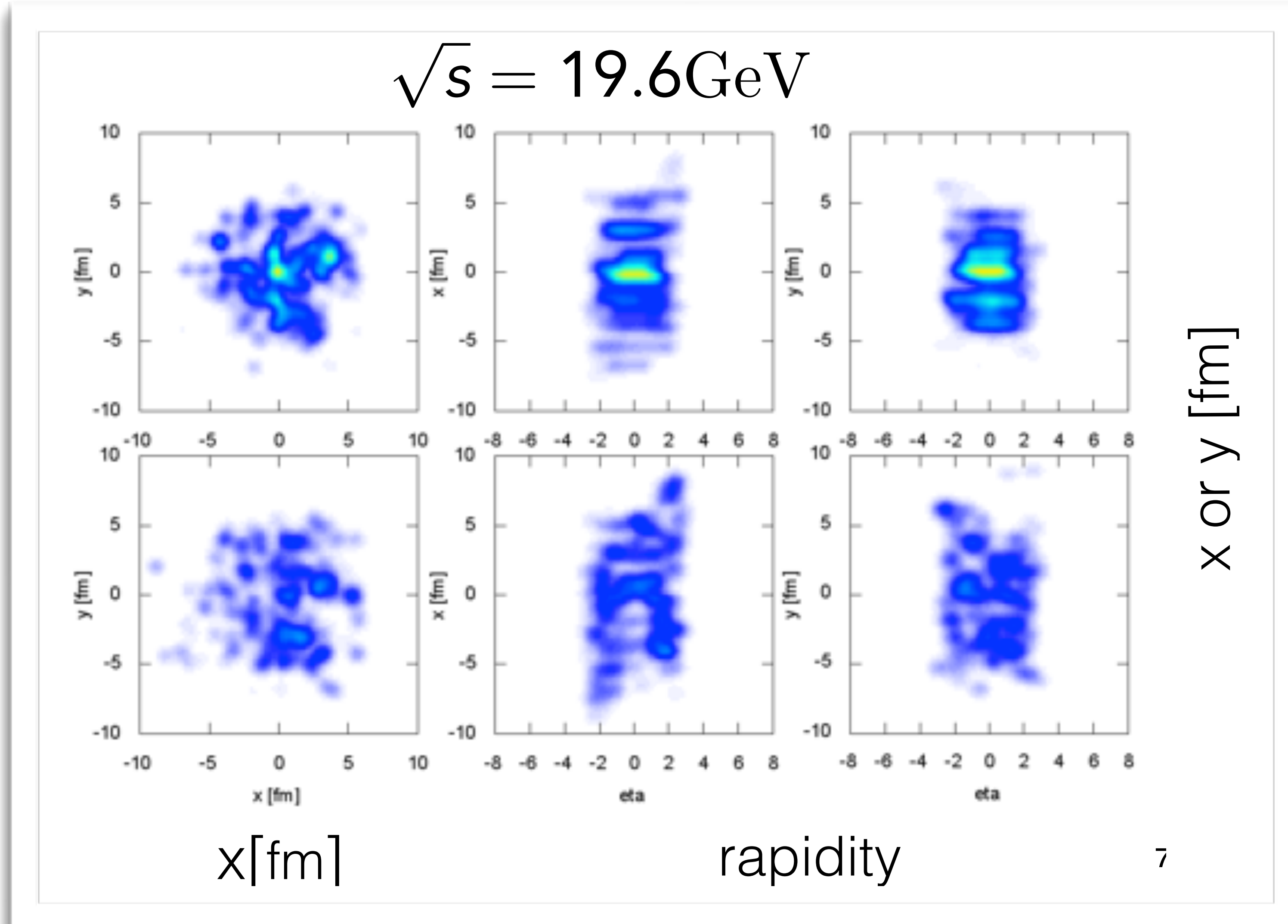
3D initial conditions generated by

- UrQMD, AMPT, EPOS or similar model
- Simple MC-Glauber type model on nucleon or quark level with e.g.
  - Lexus model for the longitudinal fluctuations (Monnai, Schenke)
  - Strings of random longitudinal length (Broniowski, Bozek, …)
- JIMWLK + IP-Glasma (downside: no net baryon density without extension and using high energy limit)
- Strong coupling (van der Schee…)

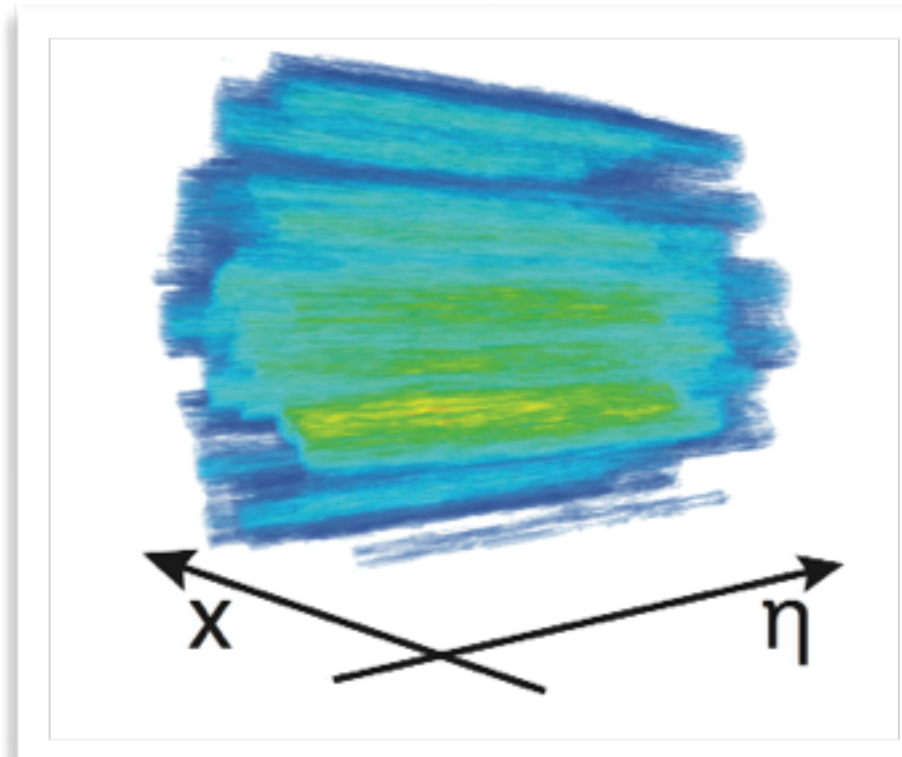
We should employ different initial state models (with different parameter sets) and study the sensitivity of observables

What degree of dynamics will be needed before we start the hydro?

3D initial conditions



Quark 3DMC-Glauber (Monnai, Schenke)



3D-Glasma (Schenke, Schlichting)
(using JIMWLK, coming soon)

Current status

Hydrodynamics

Use the state of the art 3+1D viscous relativistic hydrodynamics **MUSIC** with **shear** and **bulk** viscosity and all nonlinear terms that couple bulk viscous pressure and shear-stress tensor

Solve $\partial_\mu T^{\mu\nu} = 0$ and $\partial_\mu J^\mu_B = 0$ along with

bulk

shear

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}$$

The transport coefficients $\tau_\Pi, \delta_{\Pi\Pi}, \lambda_{\Pi\pi}, \tau_\pi, \delta_{\pi\pi}, \phi_7, \tau_{\pi\pi}, \lambda_{\pi\Pi}$ are fixed using formulas derived from the Boltzmann equation near the conformal limit

G. S. Denicol, S. Jeon and C. Gale, Phys. Rev. C 90, 024912 (2014)
B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys. Rev. Lett. 106, 04230 (2011)

Equation of state

Construct EoS at finite μ_B using Taylor expanded lattice data:

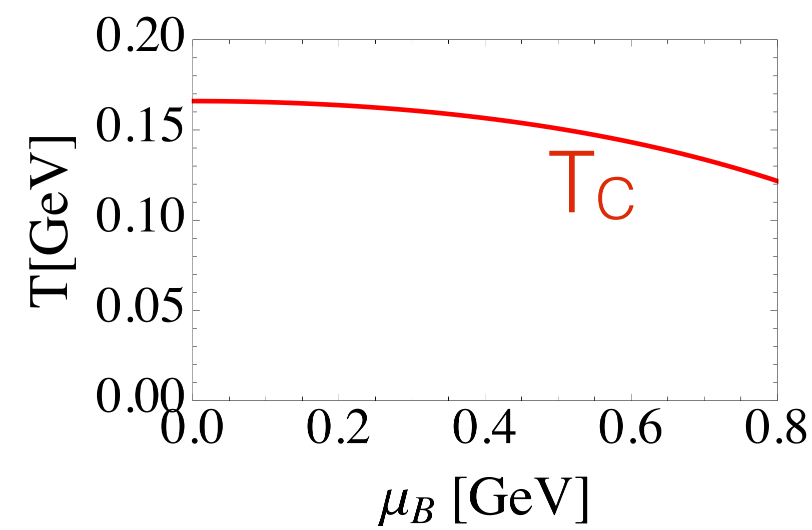
Hadron resonance gas

Lattice QCD

interpolate

connect smoothly at T_C

(**c**onnecting temperature)



$$\frac{P}{T^4} = \frac{P_0}{T^4} + \frac{1}{2}\chi_B^{(2)}\left(\frac{\mu_B}{T}\right)^2 + \frac{1}{4!}\chi_B^{(4)}\left(\frac{\mu_B}{T}\right)^4 + \mathcal{O}\left[\left(\frac{\mu_B}{T}\right)^6\right]$$

Currently using data for parameters P_0^{lat} and $\chi_B^{(2)}$ from:

Borsanyi et al, JHEP1011, 077 (2010); JHEP1201, 138 (2012)

$\chi_B^{(4)}$ from the ratio $\chi_B^{(4)}/\chi_B^{(2)}$ in a HRG and Parton gas model

Also advanced stage development of EoS at University of Houston

Plans

- Make MUSIC ready for the BES:
  - Include transport of strangeness and electric charge
  - Develop and couple to pre-equilibrium evolution models
- Develop 3+1D anisotropic hydrodynamics simulation at non-zero net-baryon chemical potential:
  - Include baryon diffusion and fluctuating initial conditions with pre-equilibrium dynamics
  - Couple to hadronic transport to describe freeze-out dynamics
- Develop chiral magneto-hydrodynamics
  - Match it to gauge fields from classical statistical simulations that generate topological charge
- Compare codes with each other and semi-analytical solutions
- Study hydrodynamic fluctuations

Plans for Year 1

Plans

- Write new 3+1D anisotropic viscous hydrodynamic code (OSU)
- Test the code at zero net-baryon chemical potential (OSU)
- Complete baryon transport treatment in MUSIC (McGill+BNL)
- Study effect of different initial conditions and develop pre-equilibrium evolution models (BNL+OSU+McGill+MIT)
- Construct EoS from lattice data including a critical endpoint (BNL+Houston+OSU+McGill)
- Begin developing Cooper-Frye freeze out interface between anisotropic hydro and hadron cascade (OSU)
- Work on interface with Transport Working Group
- Benchmark and compare the different hydro approaches (BNL+OSU+McGill)
- Construct model of initial conditions that provides axial charge and currents (BNL)

Plans for Year 2

- Include transport of strangeness and electric charge in MUSIC including extended EoS (BNL+McGill+Houston+OSU)
- Complete baryon transport treatment in MUSIC (McGill+BNL)
- Interface anisotropic hydro with pre-equilibrium evolution (OSU)
- Complete developing Cooper-Frye freeze out interface between anisotropic hydro and hadron cascade (OSU)
- Continue benchmarking and comparison of different hydro approaches (BNL+OSU+McGill)
- Develop pre-equilibrium model for axial charge flow (BNL)

Plans

Baryon diffusion (see Chun Shen's talk for details)

Dissipative part:

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{\delta_{\pi\pi}}{\tau_\pi}\pi^{\mu\nu}\theta - \frac{\tau_{\pi\pi}}{\tau_\pi}\pi^{\lambda\langle\mu}\sigma^{\nu\rangle}{}_\lambda + \frac{\phi_7}{\tau_\pi}\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha}$$

$$\Delta^{\mu\nu} Dq_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa\nabla^\mu\frac{\mu_B}{T}\right) - \frac{\delta_{qq}}{\tau_q}q^\mu\theta - \frac{\lambda_{qq}}{\tau_q}q_\nu\sigma^{\mu\nu}$$

$D = u^\mu d_\mu$

$\nabla^\mu = \Delta^{\mu\nu} d_\nu$

$\theta = d_\mu u^\mu$

$$\delta_{qq} = \tau_q \quad \lambda_{qq} = \frac{3}{5}\tau_q$$

In the relaxation time approximation, the net baryon diffusion constant can be related to shear viscosity as,

(in the massless and small μ/T limits)

$$\kappa = \frac{5}{3}\frac{\eta T}{e+\mathcal{P}}\frac{n_B}{\mu_B} = C\frac{n_B}{\mu_B} \qquad \tau_q = \frac{C}{T}$$

Plans

Baryon diffusion (see Chun Shen's talk for details)

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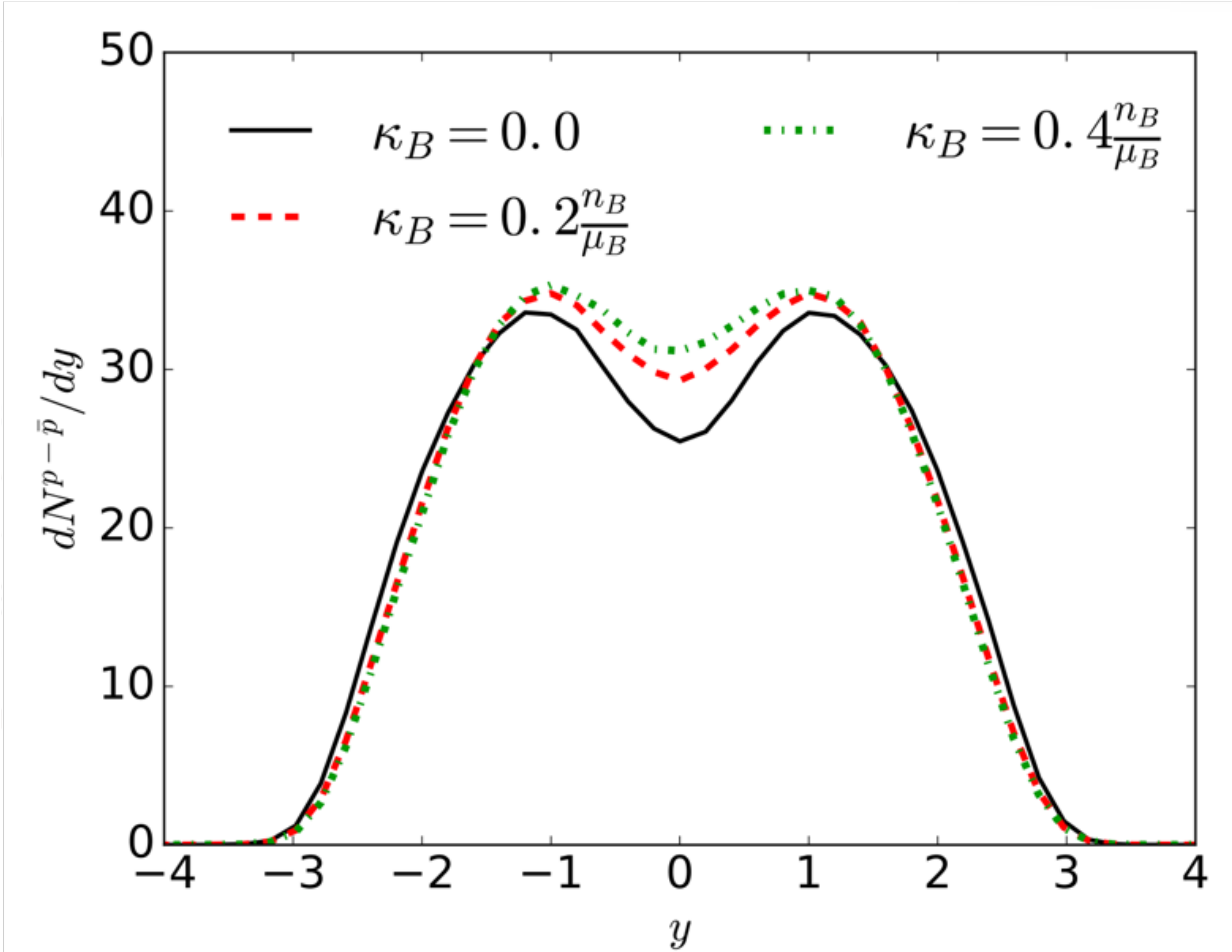

$\nu\rangle\alpha$

$\frac{3}{5}\tau_q$

In th … sion

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Plans

Anisotropic hydrodynamics (see Dennis Bazow's talk for details)

- Idea: Expand around an anisotropic distribution function to accommodate large anisotropy in momentum space:

$$f(x,p) = f_{\rm iso}\left(\frac{\sqrt{E^2+\xi(x)p_z^2}}{\Lambda(x)}\right) + \delta\tilde{f}$$

- The largest dissipative currents are treated nonperturbatively, the rest (from $\delta\tilde{f}$) is treated as in viscous hydrodynamics:

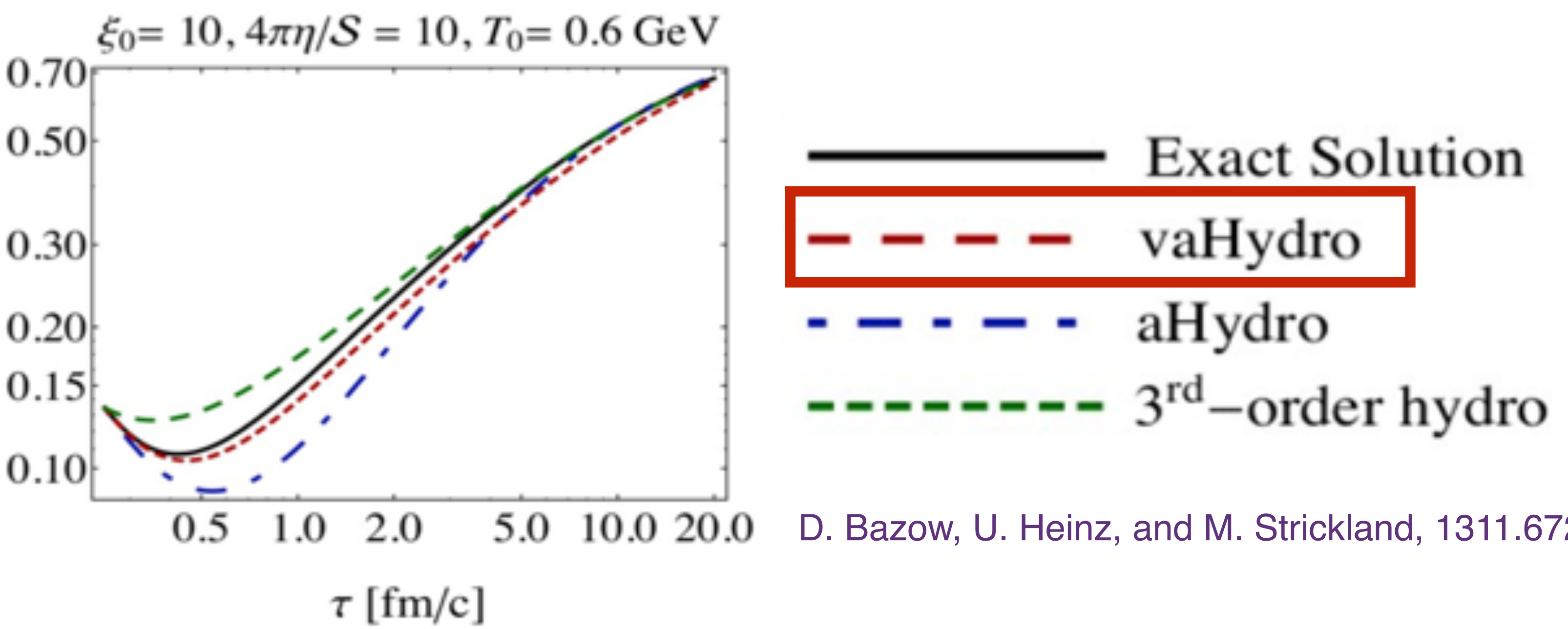
$$J^\mu = \mathcal{N}u^\mu + \tilde{V}^\mu$$

$$T^{\mu\nu} = \mathcal{E}u^\mu u^\nu - (\mathcal{P}_\perp + \tilde{\Pi})\Delta^{\mu\nu} + (\mathcal{P}_{\rm L} - \mathcal{P}_\perp)z^\mu z^\nu + \tilde{\pi}^{\mu\nu}$$

- Requires additional equation of motion for anisotropy param. ξ

Anisotropic hydrodynamics (see Dennis Bazow's talk for details)

- Agrees well with exact sol. of Boltzmann eq. in certain scenarios



D. Bazow, U. Heinz, and M. Strickland, 1311.6720

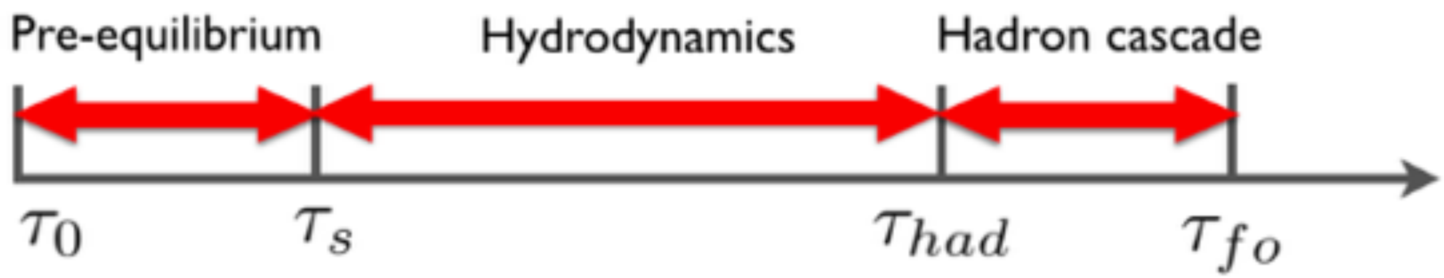
works even for very large viscosity

- Develop 3+1D vaHydro code:
  - Will be built on 3+1D viscous hydro code (KT, on GPUs) that has been developed
  - Include baryon chemical potential
  - Implement Cooper-Frye freeze-out on GPUs (viscous hydro)
  - Then extend Cooper-Frye to anisotropic viscous hydro

Plans

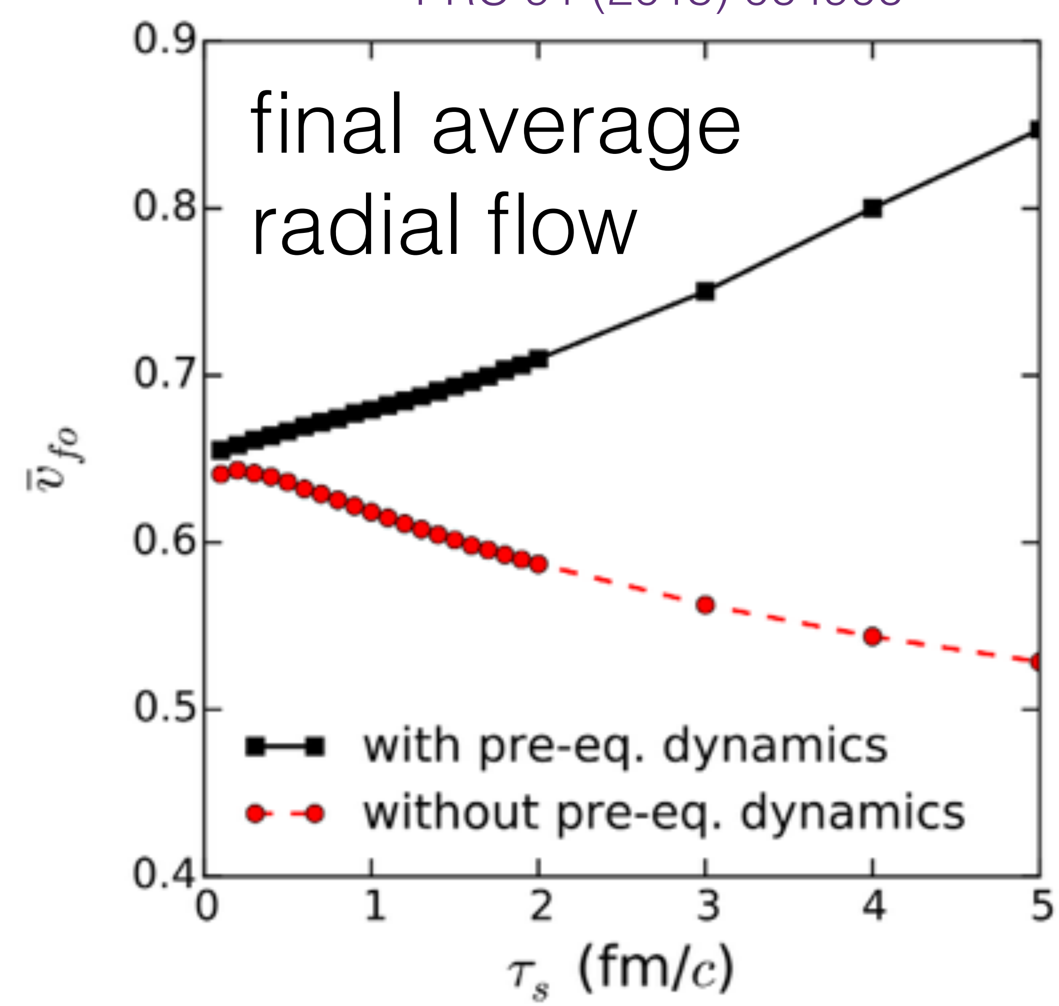
Pre-equilibrium dynamics

- At low energy time for nuclei to pass one another is long >1 fm



- How to describe the system before τ_s?
- One option is free streaming
- More complex models should be investigated
- Yang Mills dynamics at lower energies? Would be needed for axial charge/current anyways

J. Liu, C. Shen and U. Heinz
PRC 91 (2015) 064906



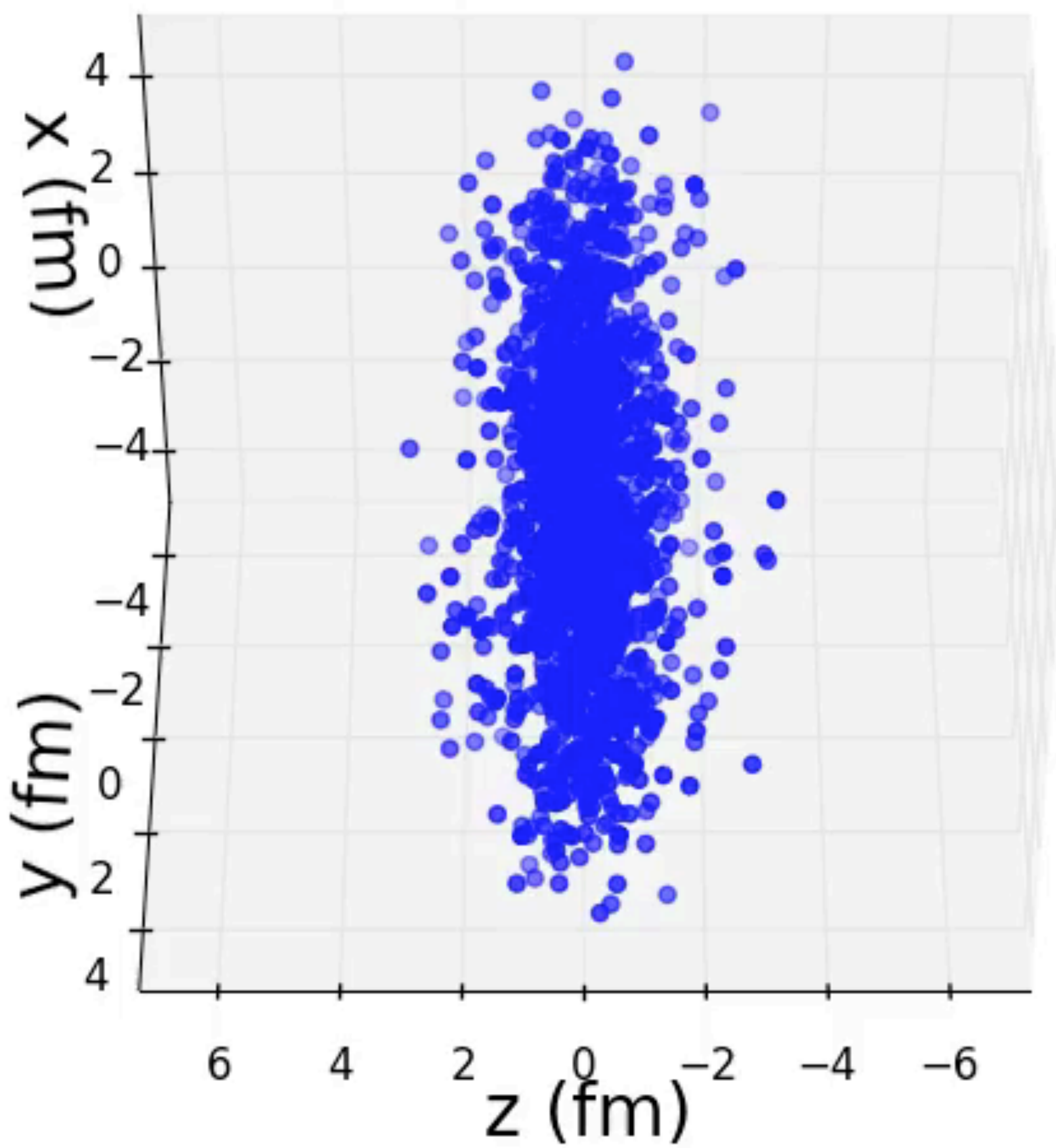
Plans

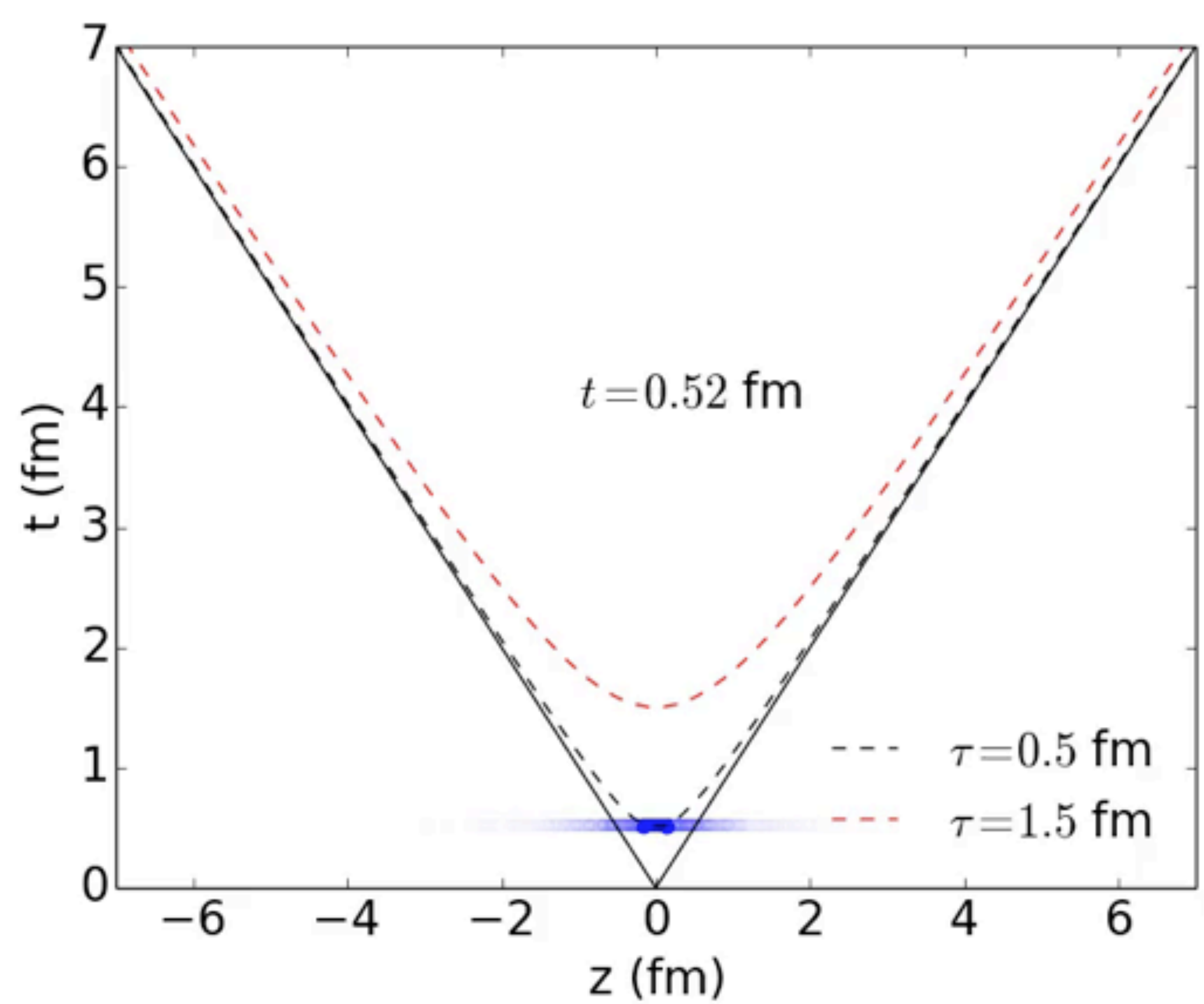
Pre-equilibrium dynamics

- At low energy time for nuclei to pass one another is long >1 fm
- Another simple option: Evolve with elastic scattering

Chun Shen

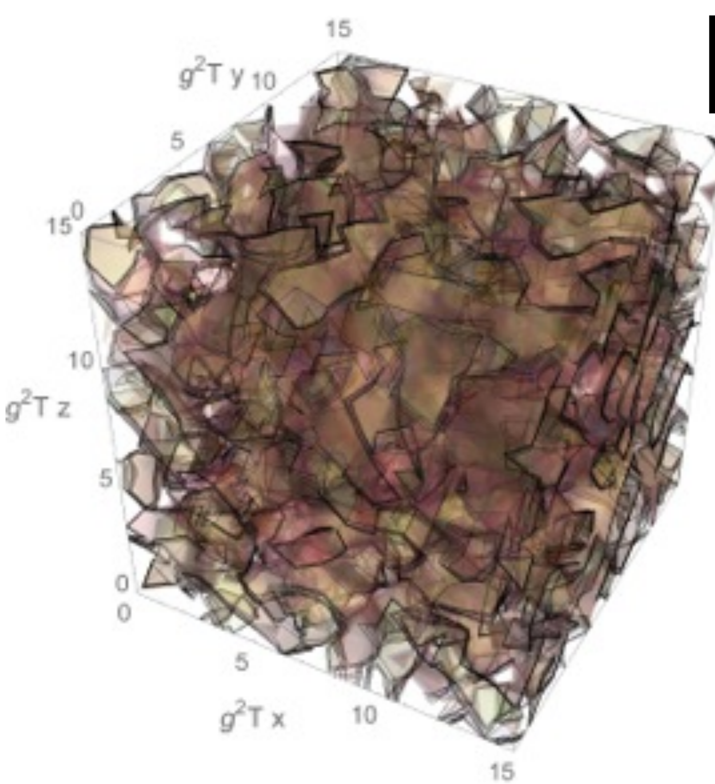
$t = 0.52$ fm



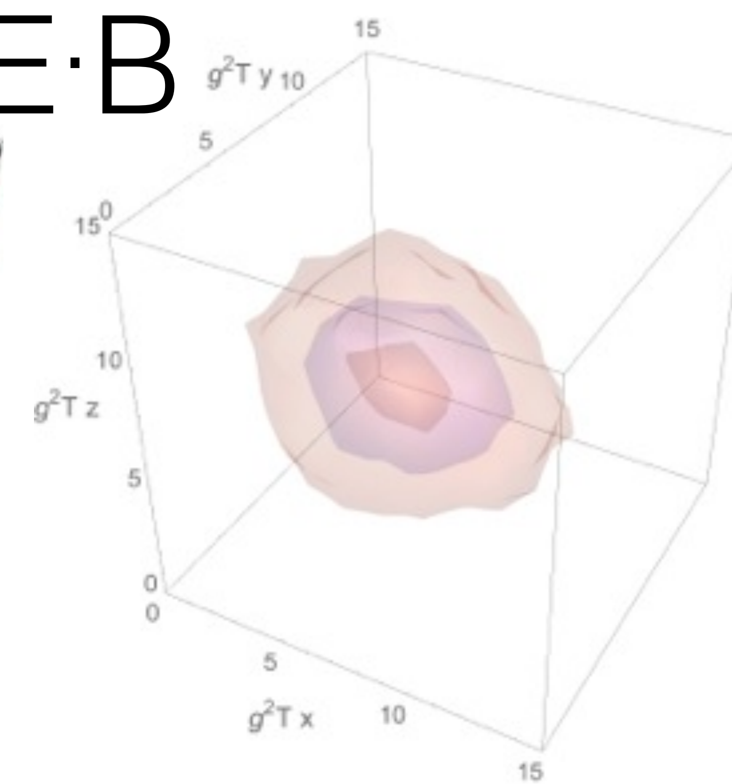


Initial conditions inspired by Glasma simulations

- Axial-charge & currents in the Glasma are an important input for anomalous hydro
- Goal: Use axial charge from Glasma simulation with fermions as an input for anomalous hydro
- For now make use of
$$\partial_\mu j_5^\mu = C E_\mu B^\mu$$
and use E·B from the simulation



E·B



See talks by Yuji and Mark

Conclusions

BEST COLLABORATION

- 3+1D hydrodynamic simulations with bulk and shear viscosity as well as baryon current are ready and well tested
- In the coming year will be working mainly on the following:
  - Explore different treatments of large momentum anisotropies
  - Extensions to include strangeness and electric charge
  - Coupling to transport satisfying all conservation laws
  - Develop proper initial state and pre-equilibrium description
  - Develop and incorporate magneto hydrodynamics