The earliest phase of relativistic heavy-ion collisions

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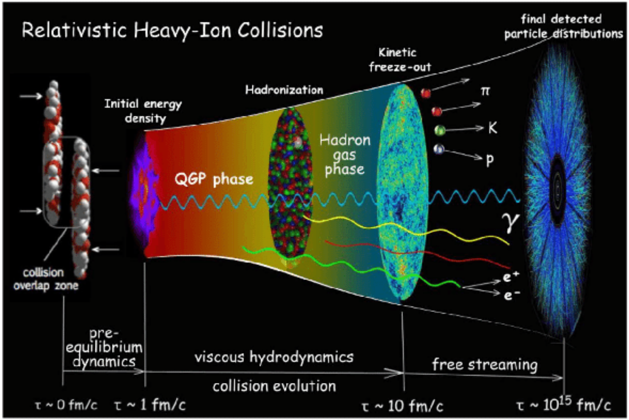
arXiv:2012.03042
arXiv:2105:05327
arXiv:2112:06812

Introduction

- properties of a many-body system governed by strong interactions
  $\rightarrow$ **relativistic heavy-ion collisions at RHIC and the LHC**
- evolution of strongly interacting matter
  $\rightarrow$ **many models/approaches needed**



Motivation

INITIAL PHASE - highly anisotropic system made mostly of gluon fields

→ the least understood phase of the collision
→ lack of a direct experimental access to it
→ initial conditions for subsequent hydrodynamic evolution

- transition between early-time dynamics and hydrodynamics

early-time dynamics	hydrodynamics
- microscopic theory of non-Abelian gauge fields - out-of-equilibrium	- macroscopic effective theory based on universal conservation laws - close to equilibrium

two possible strategies:

  * hydrodynamics → initial dynamics
  * initial dynamics → hydrodynamics

- impact of pre-equilibrium phase on hard probes

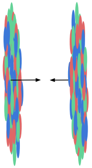
  * hard probes - produced in the earliest phase through hard scatterings
  * influence of initial dynamics on hard probes ignored for a long time

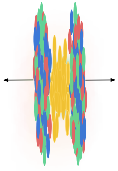
IN THIS TALK: analytical purely classical approach to the initial state

→ insight into macroscopic properties of the nuclear matter soon after the collision
→ impact of the initial phase on energy losses of hard probes
→ consistency and reliability of the approach

Relativistic heavy-ion collision

Color Glass Condensate (CGC) - effective theory to describe a nucleus in terms of QCD quanta





before the collision (MV model)

- large-x partons:
  valence quarks, source partons $\rho(x^-, \vec{x}_\perp)$
- small-x partons:
  soft gluon fields $\beta^\mu(x^-, \vec{x}_\perp)$
- classical Yang-Mills equations:
  $[D_\mu, F^{\mu\nu}] = J^\nu$
- solution:

$\beta^-(x^-, \vec{x}_\perp) = 0$

$\beta^i(x^-, \vec{x}_\perp) = \theta(x^-)\frac{i}{g}U(\vec{x}_\perp)\partial^i U^\dagger(\vec{x}_\perp)$

- saturation scale Q_s - UV regulator
- $m \sim \Lambda_{QCD}$ - IR regulator

after the collision (glasma)

- valence quarks fly away
- glasma fields $\alpha(\tau, \vec{x}_\perp)$ and $\alpha^i_\perp(\tau, \vec{x}_\perp)$
- glasma fields evolve in τ according to source-less classical YM equations
- current dependence enters through boundary conditions at $\tau = 0$:

$\alpha^i_\perp = \beta^i_1 + \beta^i_2, \qquad \alpha = -\frac{ig}{2}[\beta^i_1, \beta^i_2]$

- general solutions to CYM eqs. not known
- expansion of the glasma fields in τ:

$\alpha^i_\perp(\tau, \vec{x}_\perp) = \sum_{n=0}^{\infty} \tau^n \alpha^i_{\perp(n)}(\vec{x}_\perp)$

$\alpha(\tau, \vec{x}_\perp) = \sum_{n=0}^{\infty} \tau^n \alpha_{(n)}(\vec{x}_\perp)$

- solutions of CYM eqs. found recursively
- 0th order coefficients = boundary conditions

Correlators of gauge potentials

- colour charge distributions within a nucleus not known
- key assumption of MV model - Gaussian averaging

$$\langle \rho_a(x^-, \vec{x}_\perp)\rho_b(y^-, \vec{y}_\perp)\rangle = g^2\delta_{ab}\lambda(x^-, \vec{x}_\perp)\delta(x^- - y^-)\delta^2(\vec{x}_\perp - \vec{y}_\perp)$$

$\lambda(x^-, \vec{x}_\perp)$ - volume density of sources

- potentials of different nuclei are uncorrelated: $\langle \beta^i_{1a}\beta^j_{2b}\rangle = 0$

Basic building block: 2-point correlator (with Wick's theorem)

$$\delta_{ab}B^{ij}_n(\vec{x}_\perp, \vec{y}_\perp) \equiv \lim_{\mathrm{w}\to 0}\langle \beta^i_{n\,a}(x^\mp, \vec{x}_\perp)\beta^j_{n\,b}(y^\mp, \vec{y}_\perp)\rangle$$

$$B^{ij}_n(\vec{x}_\perp, \vec{y}_\perp) = \frac{2}{g^2 N_c \tilde{\Gamma}_n(\vec{x}_\perp, \vec{y}_\perp)}\left[\exp\left(\frac{g^4 N_c}{2}\,\tilde{\Gamma}_n(\vec{x}_\perp, \vec{y}_\perp)\right) - 1\right]\partial^i_x\partial^j_y\tilde{\gamma}_n(\vec{x}_\perp, \vec{y}_\perp)$$

$\tilde{\Gamma}_n(\vec{x}_\perp, \vec{y}_\perp)$ and $\tilde{\gamma}_n(\vec{x}_\perp, \vec{y}_\perp)$ - determined by modified Bessel functions

* geometry of the collision enters via the impact parameter $\vec{b}$ and the surface charge density $\mu(\vec{x}_\perp)$ (uniform or Woods-Saxon distribution)
* IR and UV regulators: $m \sim \Lambda_{\mathrm{QCD}} = 200$ MeV and $Q_s = 2$ GeV

→ 1-point correlators (when $\vec{x}_\perp \to \vec{y}_\perp$) determine quantities in $T^{\mu\nu}$
→ 2-point correlators determine glasma interaction with hard probes

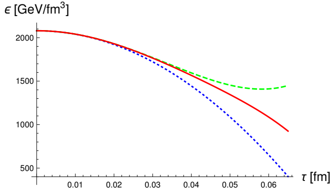
Energy density and pressure

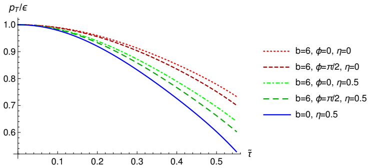
Energy-momentum tensor:

$$T^{\mu\nu} = 2\mathrm{Tr}\left[F^{\mu\lambda}F_{\lambda}{}^{\nu} + \frac{1}{4}g^{\mu\nu}F^{\alpha\beta}F_{\alpha\beta}\right], \qquad F_{\mu\nu} = \frac{i}{g}[D_\mu, D_\nu]$$

- $T^{\mu\nu}$ was found in powers of τ up to τ^6 order
- various profiles of $\mathcal{E}$, p_T, and p_L for different geometries of the collision and different charge densities were studied

* left: energy density as a function of τ at $\eta = 0$ for uniform $\bar{\mu}$ (blue=τ^2, green=τ^4, red=τ^6)
* right: transverse pressure as a function of $\tilde{\tau} = \tau Q_s$ for Woods-Saxon distribution





→ **proper time expansion works reasonably well for times $\tilde{\tau} \sim 0.5$ (or $\tau \sim 0.05$ fm)**
→ **$\mathcal{E}$, p_T, and p_L are smooth functions in time and space**
→ **sensitivity to the geometry of the collision**
→ **dependence on azimuthal angle and rapidity emerges → anisotropies**

Anisotropy of p_L and p_T

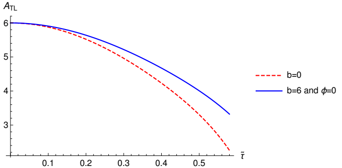
- longitudinal and transverse pressure components

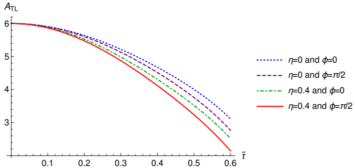
$$\frac{p_L}{\mathcal{E}} = \frac{T^{11}}{T^{00}} \qquad \frac{p_T}{\mathcal{E}} = \frac{1}{2}\frac{(T^{22}+T^{33})}{T^{00}}$$

- anisotropy of the pressure components

$$A_{TL} \equiv \frac{3(p_T - p_L)}{2p_T + p_L}$$

- $A_{TL} = 6$ at $\tau = 0$ and $A_{TL} = 0$ in isotropic plasma





$\rightarrow$ **approach to isotropy faster for central collisions**

$\rightarrow$ **approach to isotropy faster at space points within the reaction plane than perpendicular to it**

$\rightarrow$ **approach to isotropy faster for larger rapidities**

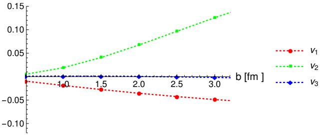
Azimuthal flow

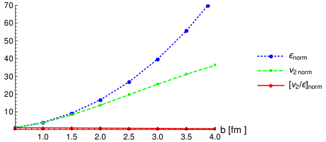
- Fourier coefficients of the momentum azimuthal flow

$$v_n = \int_0^{2\pi} d\phi \, \cos(n\phi) \, P(\phi)$$

distribution $P(\phi)$ defined as: $P(\phi) \equiv \frac{1}{\Omega} \int d^2\vec{x}_\perp \, \delta(\phi - \varphi(\vec{x}_\perp)) \, W(\vec{x}_\perp)$ with $W(\vec{x}_\perp) \equiv \sqrt{(T^{0x}(\vec{x}_\perp))^2 + (T^{0y}(\vec{x}_\perp))^2}$ and $\varphi(\vec{x}_\perp) = \cos^{-1}\left(\frac{T^{0x}(\vec{x}_\perp)}{W(\vec{x}_\perp)}\right)$

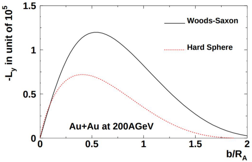
- Fourier coefficients v_1, v_2 and v_3 calculated as a function of impact parameter (at fixed $\eta = 0.1$)
- Eccentricity ϵ_n determines spatial deviations from the azimuthal symmetry: we calculated ϵ_2 and its correlation with v_2

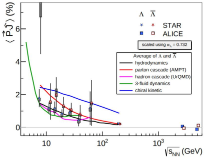


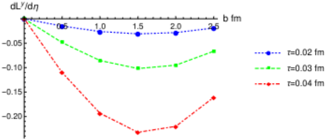


→ **v_2 and v_3 are of the same order as experimental values**
→ **$|v_1|$ is bigger than expected**
→ **correlation of eccentricity ϵ_2 and v_2 → usually treated as a indication of onset of hydrodynamic behaviour**

Angular momentum of glasma







- angular momentum at RHIC energies
  - **large angular momentum in non-central collisions**
  - **spin-orbit coupling $\rightarrow$ global polarization of hyperons**
  - **QGP is rapidly rotating system**

- angular momentum at higher energies, where the glasma description is valid (LHC energies)
  - **the shape and the position of the peak similar**
  - **the result at RHIC energies $\sim 10^5$ bigger than our results**
  - **most of the momentum of the incoming nuclei is NOT transmitted to the glasma**
  - **small angular momentum of the glasma $\rightarrow$ no polarization effect at highest collision energies**

Hard probes in glasma

Fokker-Planck equation - evolution equation on the distribution function n(t,**x**,**p**) of hard probes interacting with a medium
→ usually applied to probes moving through QGP in equilibrium

- equilibrated QGP - a collection of fast-moving particles
- hard probe - Brownian particle:

  p (probe's momentum) $\gg q$ (momentum transfer)

Fokker-Planck equation for hard probes interacting with glasma:

$$\Big(D - \nabla_p^i X^{ij}(\mathbf{v})\nabla_p^j - \nabla_p^i Y^i(\mathbf{v})\Big) n(t,\mathbf{x},\mathbf{p}) = 0$$

Collision terms:

$$X^{ij}(\mathbf{v}) = \frac{1}{2N_c}\int_0^t dt' \langle F_a^i(t,\mathbf{x}) F_a^j(t',\mathbf{x}-\mathbf{v}(t-t'))\rangle, \qquad Y^i(\mathbf{v}) = X^{ij}(\mathbf{v})\frac{v^j}{T}$$

color Lorentz force: $\mathbf{F}(t,\mathbf{x}) = g(\mathbf{E}(t,\mathbf{x}) + \mathbf{v}\times\mathbf{B}(t,\mathbf{x}))$

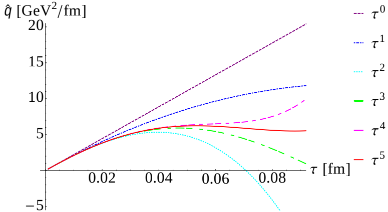
Energy loss and momentum broadening determined through correlators of chromodynamic fields:

$$-\frac{dE}{dx} = \frac{v}{T}\frac{v^i v^j}{v^2} X^{ij}(\mathbf{v}) \qquad \hat{q} = \frac{2}{v}\Big(\delta^{ij} - \frac{v^i v^j}{v^2}\Big) X^{ij}(\mathbf{v})$$

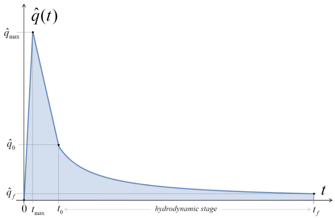
Hard probes in glasma

Experiments focus on probes moving mostly perpendicularly to the beam axis

- $\frac{dE}{dx}$ - collisional energy loss - does not play a role in this domain
- $\hat{q}$ - transverse momentum broadening - determines radiative energy loss



$\hat{q}$ of hard probes in glasma calculated at τ^5 order for $v = v_\perp = 1$



schematic picture of $\hat{q}$ of hard probes moving through non-equilibrium and then equilibrium QGP

radiative energy loss:

$$\Delta p_T^2 \equiv \int_{t_i}^{t_f} dt\, \hat{q}(t), \qquad \frac{\Delta p_T^2\big|^{\text{neq}}}{\Delta p_T^2\big|^{\text{eq}}} = 0.9$$

→ **pre-equilibrium phase gives a similar contribution to the radiative energy loss as the equilibrium one**

→ the ratio is weakly sensitive to the choice of parameters

Summary and conclusions

- Glasma dynamics studied in the proper time expansion
- Convergence of the proper time expansion tested
- Many physical characteristics of glasma dynamics calculated

- Proper time expansion can be trusted to about $\tau = 0.05$ fm; glasma moves towards equilibrium within this time
- Onset of hydrodynamic-like behaviour in the glasma phase
- Angular momentum of glasma is found to be small
- Large value of the momentum broadening coefficient $\rightarrow$ significant impact of the glasma on jet quenching