Physical characteristics of glasma at very early times

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based on: **arXiv:2012.03042**
arXiv:2105:05327

Strong and Electroweak Matter
July 1st, 2021

Outline of the talk

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Introduction & motivation

One of the biggest challenges in the dynamics of heavy-ion collisions is to understand the 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:

- unreasonable effectiveness of hydrodynamics: push hydrodynamics to the limits where it is not expected to be efficient
- work out more constrained frameworks of the initial QGP evolution in quest of the onset of hydrodynamics

Try to answer: how many unique features of fluid dynamics can be found in the initial state made of QCD quanta and to what extent QCD mimics hydrodynamics?

In this talk:

- analytical purely classical approach to the initial state
  $\rightarrow$ to learn what it can offer in understanding of QGP dynamics
  $\rightarrow$ to improve the consistency and reliability of the approach

Before the collision: MV model

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

- MV model - a particular realization of CGC:
  - **large x partons**: valence quarks:

$$J^{\mu}(x^-, \vec{x}_\perp) = \delta^{\mu +}\rho(x^-, \vec{x}_\perp)$$

  - **small x partons**: soft gluon fields $\beta^{\mu}(x)$:

$$F^{\mu\nu} = \frac{i}{g}[D^{\mu}, D^{\nu}], \qquad D^{\mu} = \partial^{\mu} - ig\beta^{\mu}$$

  - **scales**:
    - separation scale between small-x and large-x partons fixed $\rightarrow$ classical description
    - saturation scale Q_s - UV regulator
    - $m \sim \Lambda_{QCD}$ - IR regulator - the effect of valence quarks dies off at the transverse scales larger than $1/\Lambda_{QCD}$
  - **classical Yang-Mills equations**:

$$[D_{\mu}, F^{\mu\nu}] = J^{\nu}$$

solutions: $\beta^-(x^-, \vec{x}_\perp) = 0$ and $\beta^i(x^-, \vec{x}_\perp) = \theta(x^-)\frac{i}{g}U(\vec{x}_\perp)\partial^i U^{\dagger}(\vec{x}_\perp)$
with $U(\vec{x}_\perp)$ - Wilson line

After the collision: Glasma

Glasma:

- valence quarks fly away
- highly energetic and anisotropic medium made of mostly gluon fields (quarks appear at NLO)
- glasma characterised by the fields $\alpha(\tau, \vec{x}_\perp)$ and $\alpha_\perp^i(\tau, \vec{x}_\perp)$ through the ansatz:

$$\alpha^+(x) = x^+\alpha(\tau, \vec{x}_\perp) \qquad \alpha^-(x) = -x^-\alpha(\tau, \vec{x}_\perp) \qquad \alpha^i(x) = \alpha_\perp^i(\tau, \vec{x}_\perp)$$

- glasma fields are boost independent, evolve in $\tau = \sqrt{t^2 - z^2}$ according to sourceless classical Yang-Mills (CYM) equations
- current dependence enters through boundary conditions at $\tau = 0$:

$$\alpha_\perp^i = \beta_1^i + \beta_2^i, \qquad \alpha = -\frac{ig}{2}[\beta_1^i, \beta_2^i]$$

- general solutions to CYM equations not known
- here: temporal evolution of glasma fields studied in the proper time expansion:

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

- solutions of CYM equations found recursively with 0th order coefficients identified with the boundary conditions
Fries, Kapusta, Li, arXiv:0604054
Chen, Fries, Kapusta, Li, Phys. Rev. C 92, 064912 (2015)

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 normalized as $\int dx^-\lambda(x^-,\vec{x}_\perp) = \mu(\vec{x}_\perp)$
- 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)

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

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

$$\tilde{\Gamma}_n(\vec{x}_\perp,\vec{y}_\perp) = 2\tilde{\gamma}_n(\vec{x}_\perp,\vec{y}_\perp) - \tilde{\gamma}_n(\vec{x}_\perp,\vec{x}_\perp) - \tilde{\gamma}_n(\vec{y}_\perp,\vec{y}_\perp)$$

$$\tilde{\gamma}_n(\vec{x}_\perp,\vec{y}_\perp) = \int d^2z_\perp\,\mu_n(\vec{z}_\perp)\,G(\vec{x}_\perp - \vec{z}_\perp)\,G(\vec{y}_\perp - \vec{z}_\perp), \qquad G(\vec{x}_\perp) = \frac{1}{2\pi}K_0(m|\vec{x}_\perp|)$$

* charge density per unit transverse area: $\bar{\mu} = g^{-4}Q_s^2$ (uniform) or Woods-Saxon distribution $\mu(\vec{x}_\perp)$
* IR and UV regulators: $m \sim \Lambda_{QCD} = 200$ MeV and $Q_s = 2$ GeV

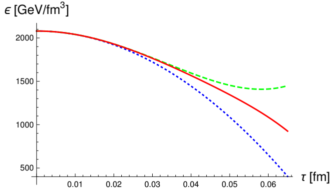
$$\lim_{r\to 0} B^{ij}(\vec{x}_\perp,\vec{y}_\perp) = \delta^{ij}g^2\frac{\bar{\mu}}{8\pi}\left(\ln\left(\frac{Q_s^2}{m^2}+1\right) - \frac{Q_s^2}{Q_s^2+m^2}\right) \quad [+\text{ gradients of }\mu]$$

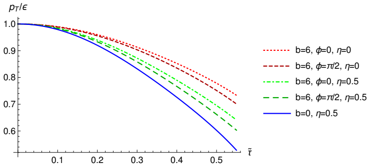
Energy density and pressure

Energy-momentum tensor:

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

- $T^{\mu\nu}$ 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

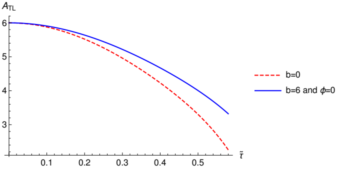
- longitudinal and transverse pressure components

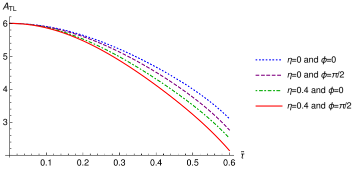
$$\frac{p_L}{\mathcal{E}} = \frac{T^{11}}{T^{00}} \qquad \frac{p_T}{\mathcal{E}} = \frac{1}{2}\frac{(T^{22}+T^{33})}{T^{00}}$$

- 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





→ approach to isotropy faster for central collisions
→ approach to isotropy faster at space points in the reaction plane than perpendicular to it
→ approach to isotropy faster for larger rapidities

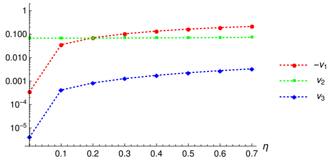
Azimuthal flow

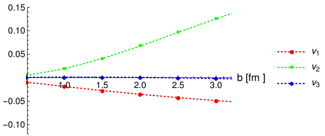
- Fourier coefficients of the momentum azimuthal flow

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

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 rapidity (at fixed $b = 2$ fm) and as a function of impact parameter (at fixed $\eta = 0.1$)





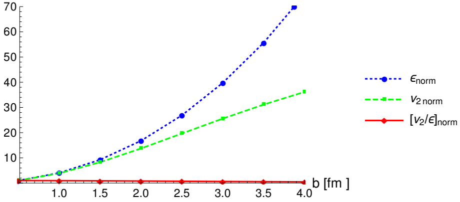
→ **symmetries: n-odd coefficients are rapidity odd and n-even coefficients are rapidity even** (we know the reaction plane and we do not include fluctuations in the positions of participants)
→ v_2 **and** v_3 **are of the same order as experimental values**
→ $|v_1|$ **is bigger than expected**

Eccentricity and elliptic flow coefficient

- eccentricity - spatial deviations from azimuthal symmetry

$$\varepsilon_n = -\frac{\int d^2\vec{R}|\vec{R}|\cos(n\phi)\mathcal{E}(\vec{R})}{\int d^2\vec{R}|\vec{R}|\mathcal{E}(\vec{R})} \qquad \phi = \tan^{-1}(R_y/R_x)$$

- calculated as a function of the impact parameter at $\tau = 0.04$ fm and $\eta = 0$



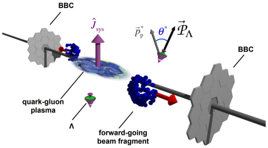
→ **correlation of eccentricity ϵ_2 and v_2 is treated as a indication of onset of hydrodynamic behaviour**

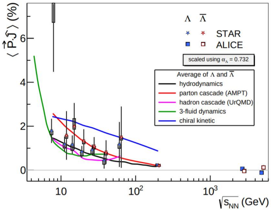
The expected role of angular momentum in HIC

- large angular momentum is expected to be generated in non-central collisions

STAR Collaboration,
Nature 548, 62 (2017)

Becattini and Lisa,
Ann.Rev.Nucl.Part.Sci. 70 (2020) 395-423





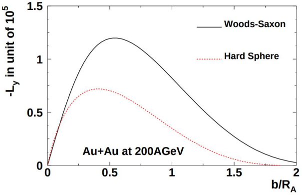
- consequences:
  - ∗ spin-orbit coupling leads to alignment of spins to the direction of the angular momentum → polarization of hyperons and vector mesons
  - ∗ QGP is rapidly-rotating (vortical) system
- many attempts to formulate hydrodynamics with spin

Experimental observations:

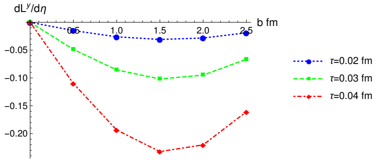
* at RHIC energies polarization of a few percent is seen in non-central AA collisions
* at LHC energies polarization is not observed at all

Angular momentum of glasma

- angular momentum at RHIC energies
  Gao et al, Phys. Rev C 77, 044902 (2008)



- our result: angular momentum as a function of the impact parameter



- **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**

Heavy quarks in glasma

Evolution equation on the distribution function n(t,x,p) of heavy quarks interacting with chromodynamic fields:

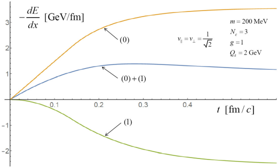
$$\left(D - \nabla_p^i X^{ij}(\mathbf{v})\nabla_p^j - \nabla_p^i Y^i(\mathbf{v})\right) n(t,\mathbf{x},\mathbf{p}) = 0$$

Collision terms:

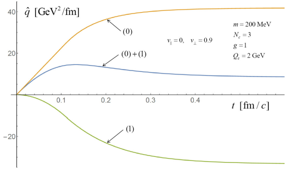
$$X^{ij}(\mathbf{v}) = \frac{1}{2N_c}\int_0^t dt' \langle F_a^i(t,\mathbf{x}) F_a^j(t',\mathbf{x}-\mathbf{v}(t-t'))\rangle, \qquad Y^i(\mathbf{v}) = X^{ij}\frac{v^j}{T}$$

Energy loss and momentum broadening:

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



$v_\parallel = v_\perp = 1/\sqrt{2}$



$v_\parallel = 0, v_\perp = 0.9$

→ **value of $\hat{q}$ comparable to that of equilibrated plasma of the same energy density**

Mrówczyński, Eur. Phys. J, A54 no 3, 43 (2018)
Carrington, Czajka, Mrówczyński, Nucl. Phys. A, 1001 (2020) 121914

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
  - Fourier coefficients of the azimuthal flow relatively large
  - Sizeable correlation of the eccentricity and elliptic flow coefficient
- Angular momentum of glasma is found to be small
  - Need to study the transmission of the momentum from incoming nuclei to the interaction region
  - Glasma is not a rapidly rotating system
  - No polarization effect - in agreement with experimental observations for LHC energies
- Large value of the momentum broadening of heavy quarks glasma $\rightarrow$ significant impact of glasma on jet quenching