CLASH discussion - Theory introduction

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Terminology

- CGC = Color Glass Condensate, description of the incoming nuclei before the collision
- Glasma = matter formed after the collision before the formation of QGP. Combination of glass and plasma.
- Hydrodynamization = onset of applicability of hydrodynamics
- Chemical thermalization = equilibration between quarks and gluons in the glasma/plasma.
- Isotropization = usually refers to pressure anisotropy when monitoring onset of hydrodynamics.
- Thermalization = point at which the system has reached local thermal equilibrium.

Overview of first fm/c

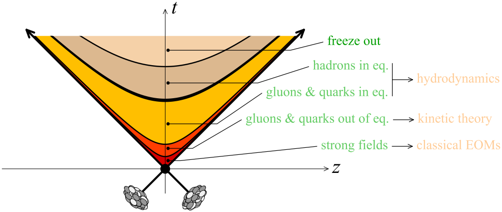


Figure: [1]

- The colliding nuclei described as thin sheets of CGC. The IS is approximately boost invariant.
- Saturated gluon fields reach occupation numbers $f \sim {}^{1}/_{\alpha_s}$. $\rightarrow$ classical fields
- Followed by glasma evolution dominated by overoccupied gluon fields.
- Kinetic theory valid at ranges ${}^{1}/_{\alpha_s} \ll f$.
- Kinetic theory evolution can then be matched to viscous

CGC initial condition [2, 3, 4]

- In regions 1 & 2, one nucleus solutions $\alpha^{1,2} = \frac{1}{ig} U_{1,2} \partial^i U^\dagger_{1,2}$.
- Wilson lines $U_{1,2}$ given by $U_{1,2} = \mathscr{P} \exp\left(-ig \int \mathrm{d}x^\pm \frac{1}{\nabla_\perp^2} \rho_{1,2}(\boldsymbol{x}_\perp, x^\pm) \right)$
- ρ is a stochastic variable $\rho^a_{1,2}(\boldsymbol{x}_\perp, x^\pm) = \delta(x^\pm)\rho^a(\boldsymbol{x}_\perp)$ $\langle \rho^a(\boldsymbol{x}_\perp)\rho^b(\boldsymbol{y}_\perp)\rangle = g^2\mu^2\delta^{ab}\delta^2(\boldsymbol{x}_\perp - \boldsymbol{y}_\perp)$.

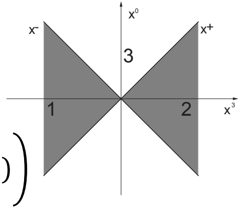


Fig. 1: Regions with different structures of the gauge potential:
In regions 1 and 2 we have the well known one nucleus solutions $\alpha_{1,2}$. While the gauge potential in the backward light cone is vanishing we have a non-trivial solution in the forward lightcone, region 3

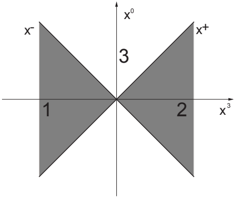
Figure: Sketch of different regions where one needs to know the gauge field configuration Fig. [2]

CGC initial condition [2, 3, 4]

- Solve the Yang-Mills EOMs in region 3 $\left[D^{\mu}, F_{\mu\nu}\right] = 0$
- To the lowest order in τ the solution for $F^{\mu\nu}$ is

$$F_0^{+-} = ig\left[\alpha_1^i, \alpha_2^i\right]$$
$$F_0^{21} = ig\epsilon^{ij}\left[\alpha_1^i, \alpha_2^j\right]$$
$$F_0^{i\pm} = 0$$

- Thus initially $E_z \neq 0, B_z \neq 0$, but $E_\perp = B_\perp = 0$!
- Approximately boost invariant.



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The initial chromoelectric and chromomagnetic fields

- The initial state directly after the collision $\tau = 0$ consists of purely longitudinal fields.
- Similar to Angantyr: string-like structures
- Different from Angantyr: Purely longit. fields initially. The string picture is short lived.

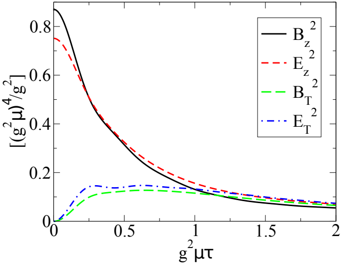


Figure: Chromoelectric and magnetic field energies after the collision [5]

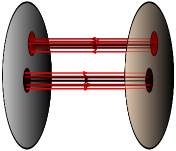
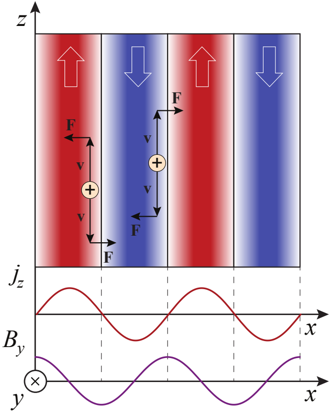


Figure: Cartoon of the fields after the collision [6].

Plasma instabilities - Weibel instability [7]



- Assume a current of the form $\boldsymbol{j}(x) = j\hat{\boldsymbol{e}}_z \cos(k_x x)$
- Generate a magnetic field $\boldsymbol{B}(x) = \frac{j}{k_x}\hat{\boldsymbol{e}}_y \sin(k_x x)$.
- Lorentz force on partons in the x-direction $\boldsymbol{F} = q\boldsymbol{v} \times \boldsymbol{B} = -qv_z \frac{j}{k_x} \sin(k_x x)$.
- Induced force makes particles feed the pre-existing current.

Plasma instabilities [8]

- Boost invariance at the IS needs to be broken for isotropization.
- Invariance broken by: Finite collision energy, quantum corrections & fluctuations, finite nuclear thickness.
- Boost invariant field unstable → Weibel instability.

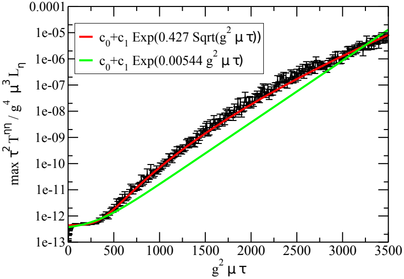


Figure: Maximum Fourier mode amplitude of $\tau^2 T^{\eta\eta}$. Glasma simulation where IS violates boost invariance.

Topological effects - Introduction

- Need to find a way to distinguis between Angantyr/weak coupling thermalization scenario.
- Why I am obsessed about $\boldsymbol{E}\cdot\boldsymbol{B}$:

Angantyr:

- $\boldsymbol{E}\cdot\boldsymbol{B} = 0$
- Axial anomaly only due to quark masses.

Weak coupling scenario:

- 1)$\boldsymbol{E}\cdot\boldsymbol{B} \neq 0$ (at $\tau = 0$)!
- Axial current: $j^5_\mu = \bar{q}\gamma^\mu\gamma_5 q$
- Axial anomaly $\partial_\mu j^\mu_5 = 2m_f\bar{q}\gamma^5 q - \frac{g^2}{16\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu a}$, with $F^a_{\mu\nu}\tilde{F}^{\mu\nu a} \sim \boldsymbol{E}^a\cdot\boldsymbol{B}^a$
- 2) $\boldsymbol{E}\cdot\boldsymbol{B}$ can also change due to sphaleron transitions during the evolution.

Chern-Simons number [10]

Express the axial anomaly in terms of Chern-Simons current

$$K^\mu = \frac{g^2}{32\pi^2}\epsilon^{\mu\nu\rho\sigma}\left(A^a_\nu F^a_{\rho\sigma} - \frac{g}{3}f^{abc}A^a_\nu A^b_\rho A^c_\sigma\right)$$

$$\partial_\mu K^\mu = \frac{g^2}{32\pi^2}F^a_{\mu\nu}\tilde{F}^{\mu\nu a}$$

Define

$$N_{CS}(t) = \int \mathrm{d}^3x K^0(t,x) \quad (1)$$

Change in N_{CS} → change in net axial charge.

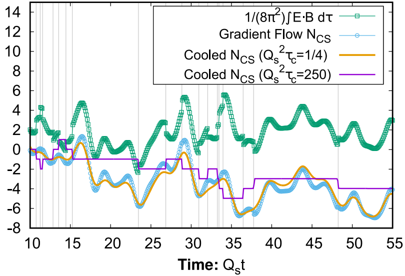


Figure: Fluctuations in Chern-Simons number ∼ axial charge in the glasma (No fermions in this simulation).

Chiral magnetic effect

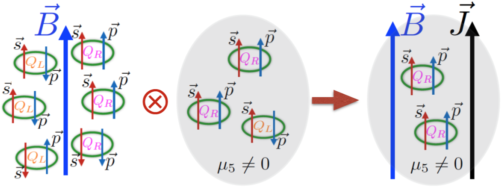


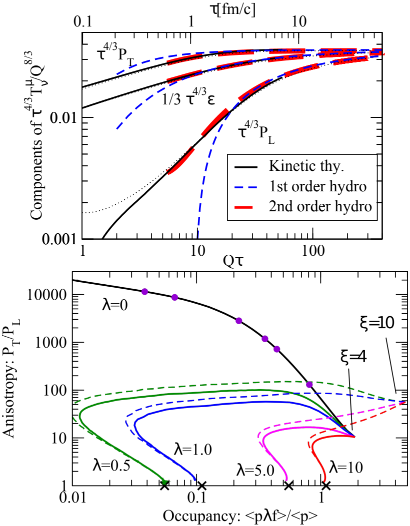
Figure: Fig. [11]

- Medium with chirality imbalance & external magnetic field.
- Magnetic field will polarize the medium.
- Due to the chirality imbalance, more left/right handed fermions than right/left handed fermions.
- Momentum and spin aligned → electric current generated along the external magnetic field.
- Is this generated by Angantyr by any mechanism?

Kinetic theory [12]

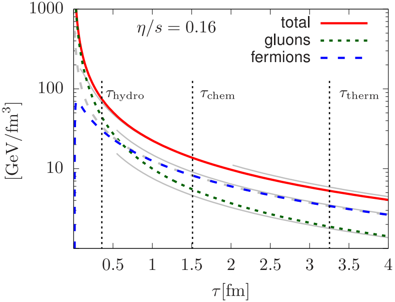
- Quasiparticle description applicable in the perturbative regime $f \ll {}^{1}\!/_{g^2}$.
- Solve Boltzmann equation $(\partial_t + \boldsymbol{v} \cdot \nabla) f = -C[f]$.
- The collision term C describes scattering into and out of the state. Contains scattering matrix elements which are evaluated perturbatively.
- Assume observables dominantly sensitive to hard excitations. (Thermal case: hard T, soft (screening scale) gT, ultrasoft g^2T etc.)

Hydrodynamization in KT framework [13]



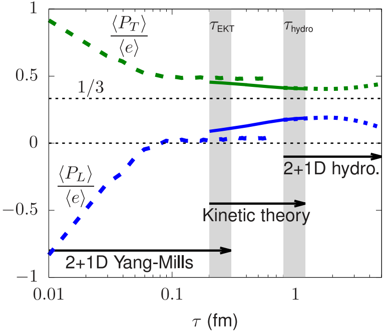
- Simulate glasma with kinetic theory. Match to hydro. ($\lambda = 10 \rightarrow \alpha_s \approx 0.3$.)
- (Top)Observe an agreement with viscous hydro in realistic timescales!
- (Bottom) Trajectory of the system to equilibrium in occupation number-anisotropy plane for different couplings.

Chemical equilibration in KT [14, 15]



- Homogenous, boost-invariant longitudinally expanding system.
- Gluon and fermion contributions to total energy density in KT. Timescales defined with 10% tolerance.

Beyond transverse isotropy - Matching IP glasma + KT + hydro (KoMPoST) [16, 17]



- Expanding, boost-invariant system with transverse anisotropies from the IC.
- In kinetic theory the energy-momentum tensor is computed with non-equilibrium linear response theory.
- Unified framework to propagate IS in the weak coupling framework all the way to the hydro regime.
- Open source: code publicly available!

Conclusions

- Our understanding of the weak coupling equilibration has improved tremendously over the last 5 years. Major pieces of the puzzle are now set.
- Still lot of work needs to be done. For a realistic unified description need to go beyond boost invariant approximation.

Ideas:

- Maybe it's possible to use KoMPoST framework to compare with Angantyr somehow? KoMPoST also includes hadronization implemented with Cooper-Frye procedue.
- Topological effects: can they be used to distinguish the weakly coupled scenario from Angantyr? Or should Angantyr be extended to somehow accomodate for these effects?

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