A real-time lattice simulation of the thermalization of QGP: first results

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HIC for FAIR Helmholtz International Center
H-QM Helmholtz Research School Quark Matter Studies

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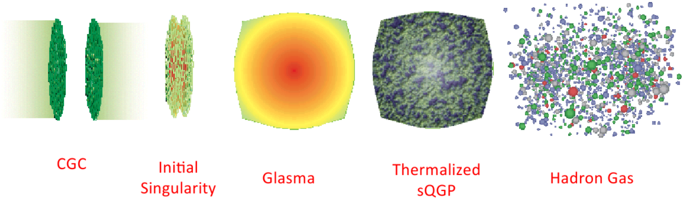
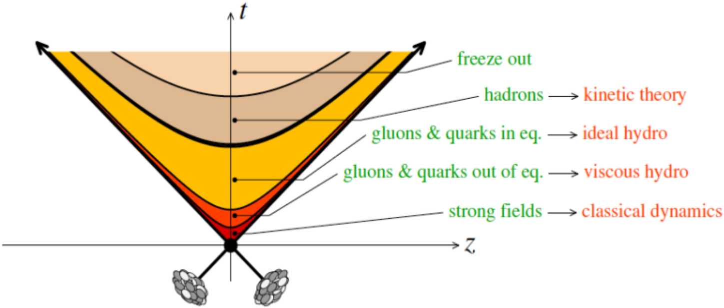
Stages of a heavy ion collision





[Gelis 2006, Bass 2006, McLerran 2012]

Motivation

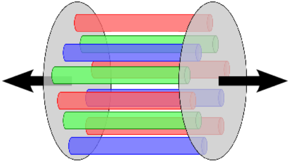
- relativistic hydrodynamics successfully describes the behavior of many observables $\Rightarrow$ how do we reach hydronamization?
- chromo-Weibel instabilities have been proposed to thermalize the non-Abelian plasma
- generalize the work from Fukushima and Gelis from SU(2) to SU(3)
- starting with simulations in a finite box

Semi-classical approach

	classical correlator	Bose-Einstein	Fermi-Dirac
$E \ll T:$	$\sim \frac{T}{E}$	$\sim \frac{T}{E} + \mathcal{O}\left(\frac{E}{T}\right)$	$\sim \mathcal{O}\left(\frac{E}{T}\right)$

- bosonic infrared regime behaves classically at high T
- no classical description for fermions possible
  $\Rightarrow$ "semi-classical"
- YM theory with high occupation of gauge fields
  $\Rightarrow$ statistical fluctuations dominate quantum fluctuations
  $\Rightarrow$ can be treated classically
- non-classical hard modes are excluded by a momentum cutoff
- classical approximation valid even out of equilibrium
  $\Rightarrow$ enables study of early stages of the QGP

Color Glass Condensate



[Fukushima 2011]

- high energies (RHIC, LHC) allow for a consistent description of QCD within the framework of Color Glass Condensate (CGC)
- CGC provides an expansion of inclusive quantities such as the expectation value of $T^{\mu\nu}$ in powers of α_s
- LO is obtained by solving the classical Yang-Mills equations
- we attack this problem with lattice QCD methods

Chromo-magnetic fields

$$J^{\mu,a}(x) = \delta^{\mu+}\rho_1^a(x_\perp)\delta(x^-) + \delta^{\mu-}\rho_2^a(x_\perp)\delta(x^+)$$
$$D_\mu F^{\mu\nu} = J^\nu$$

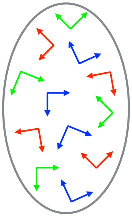
Initial conditions according to McLerran-Venugopalan model:

$$\left\langle \rho_m^a(x_\perp)\rho_n^b(y_\perp) \right\rangle = g^4\mu^2 a_\perp^2 \delta_{mn}\delta^{ab}\delta(x_\perp - y_\perp)$$

- standard deviation $g^2\mu \approx Q_s$
- solve Poisson equation for ρ_m^a
- construct "initial" $U_\perp^{(1),(2)}$, $U_z = 1$
- merge $U^{(1)}$ and $U^{(2)}$ à la Krasnitz, Venugopalan $\Rightarrow$ collective field U

Chromo-electric fields

- $E_\perp = 0,\ E_z = E_z(U_\perp)$
- with this setup no isotropization is reached
- add fluctuations: $E(x) \to E(x) + \delta E(x)$
  $\Rightarrow$ instabilities
  $\Rightarrow$ isotropization
- solve Hamiltonian EOM for U and E



Energy density ϵ

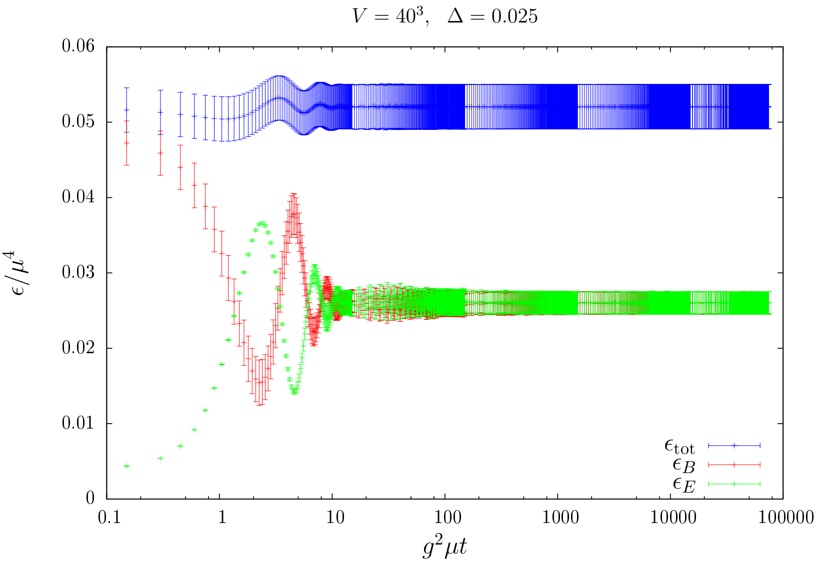
$$H_i^B(t,x) = \frac{2N_c}{g^2} \sum_{\substack{j<k \\ j,k\neq i}} \left[1 - \frac{1}{N_c} \mathrm{ReTr}\, U_{jk}(x) \right]$$

$$H_i^E(t,x) = \frac{1}{g^2} \mathrm{ReTr} \left[E_i(x) E_i(x) \right]$$

Energy density

$$\epsilon_{B/E}(t) = \frac{1}{V} \sum_{\vec{x}} \sum_{i=x,y,z} H_i^{B/E}(x)$$

Energy density ϵ

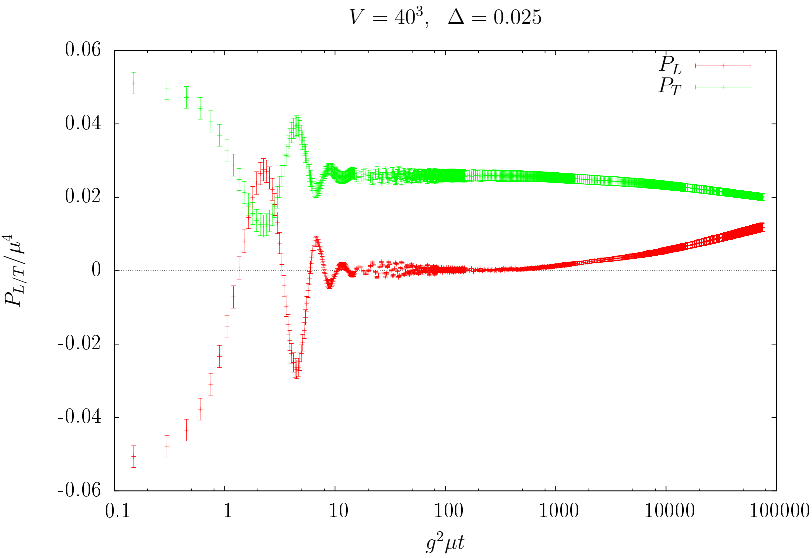


Longitudinal and transverse pressure $P_{L/T}$

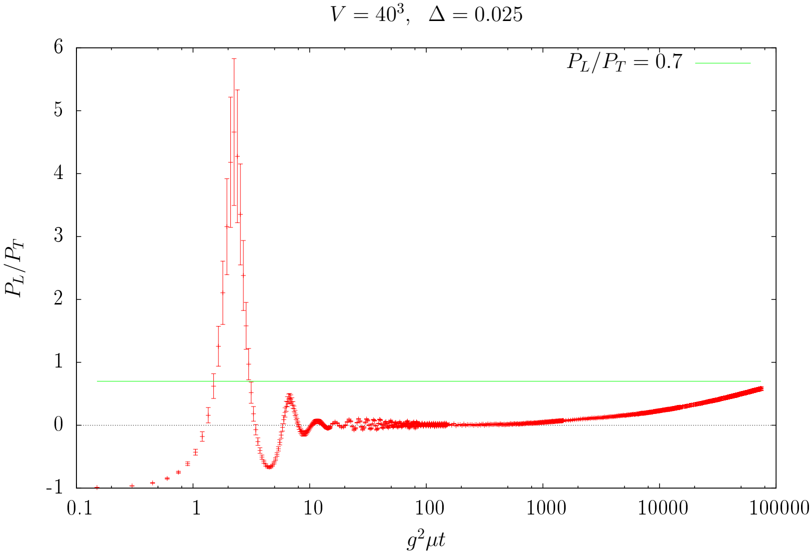
$$P_L(x) = -T_z^z(x) \overset{\text{YMT}}{=} \epsilon_{E_\perp}(t) + \epsilon_{B_\perp}(t) - \epsilon_{E_z}(t) - \epsilon_{B_z}(t)$$

$$P_T(x) = -\frac{1}{2}\left[T_x^x(x) + T_y^y(x)\right] \overset{\text{YMT}}{=} \epsilon_{E_z}(t) + \epsilon_{B_z}(t)$$

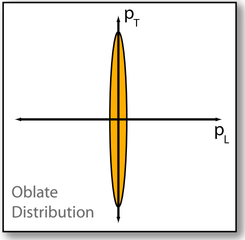
Longitudinal and transverse pressure $P_{L/T}$

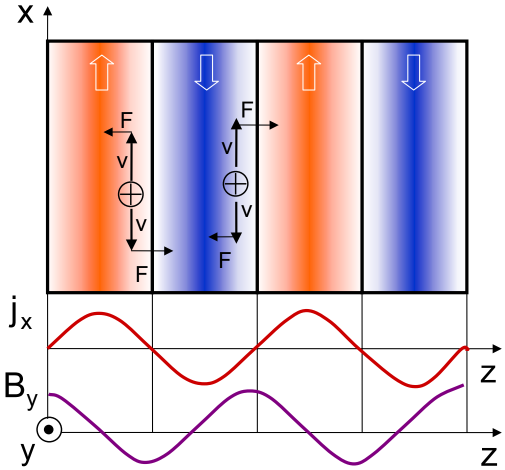


Pressure ratio P_L/P_T



Weibel instabilities (QED)





[Mrówczyński 1993; Strickland 2006]

Chromo-Weibel instabilities (QCD)

[Videos]

Scale setting

- all quantities are expressed in terms of $a_\perp$
- RHIC physics: $\mu \approx 0.5$ GeV, $\alpha_s = \frac{g^2}{4\pi} \approx 0.3$
  $\Rightarrow g^2\mu \approx 2$ GeV
- dimensionless combination to set the scale
  $g^2\mu L_\perp = g^2\mu a_\perp N_\perp$
- using $R_A(\text{Au}) \approx 1.2 \times 197^{1/3}$ fm ≈ 7 fm and $L_\perp^2 = \pi R_A^2$
  $\Rightarrow L_\perp \approx 12$ fm

We set

$$g^2\mu L_\perp = 120 \quad \Longleftrightarrow \quad a_\perp \approx \frac{12}{N_\perp} \text{ fm}$$

Summary

- we presented SU(3) results for the thermalization of QGP via real-time simulations and CGC initial conditions
- we looked at energy densities and the longitudinal to transverse pressure ratio as evidence for thermalization
- we found evidence for the emergence of the chromo-Weibel instability displayed by filaments in the local energy densities

Outlook

- rigorous check of finite size and discretization effects
- compute Wilson loops and the associated real-time static potential in the given framework
- include fermions
- add finite chemical potential
- study expanding systems

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Thank you for your attention!