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Diffusion of heavy quarks in the early stages of high-energy nuclear collisions

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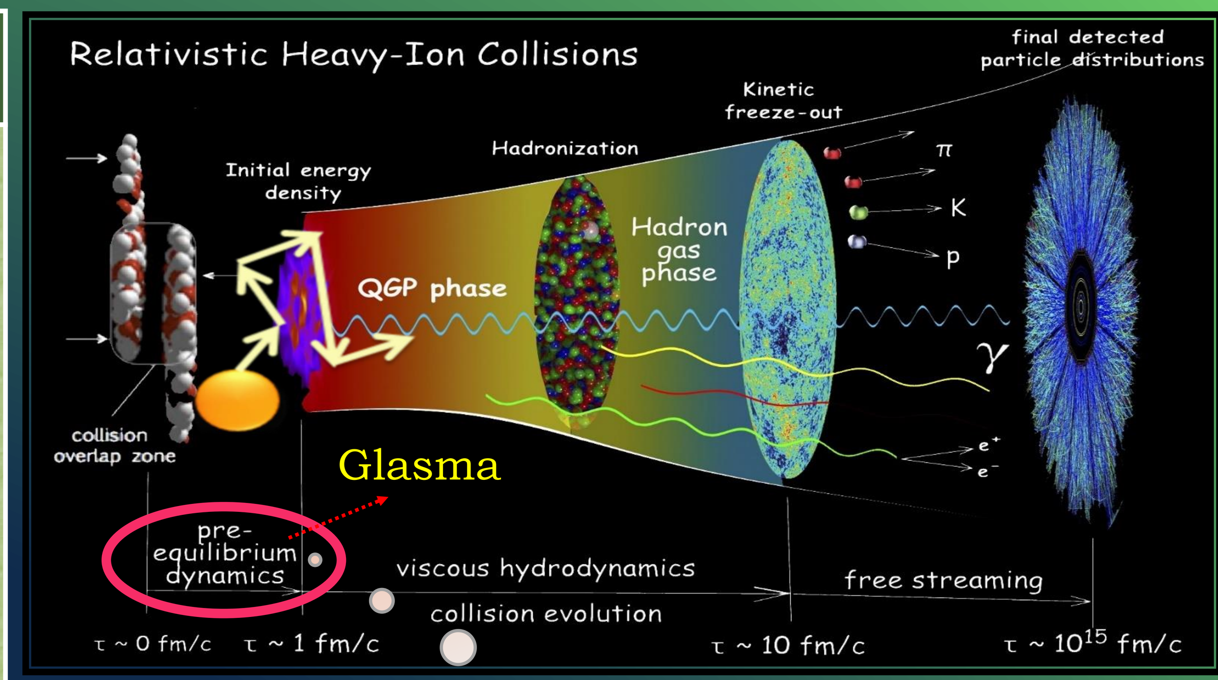
Introduction

- Heavy quarks (HQs) are considered potential probes of the QCD matter produced in high-energy heavy-ion collisions.
- In the pre-equilibrium stage of relativistic heavy-ion collisions, strong quasi-classical gluon fields emerge at approximately $\tau_0 = 0.08$ fm/c which evolves according to the classical Yang-Mills (CYM) equations. This set of classical fields is known as **Glasma**.
- We study the diffusion of the heavy quarks in the early stage of heavy-ion collisions. The diffusion HQs in the evolving Glasma fields is compared with that of the Markovian-Brownian motion in a thermalized medium.

Motivation

Just after the big-bang, just for a few millionth of a second, the universe had extreme temperature, pressure and density conditions. To recreate conditions similar to those of very early universe, physicists do a mini-bang. They use powerful accelerators such as RHIC, LHC to collide massive ions such as gold, lead nuclei at relativistic velocities. Quark-Gluon Plasma (QGP) is formed in the early stage of high-energy nuclear collisions where Glasma serves as the pre-equilibrium condition.



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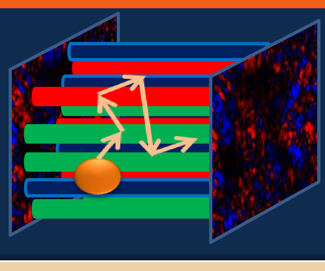
Pre-equilibrium dynamics
- Strong longitudinal color fields
- Glasma to Plasma conversion

Heavy quark : An efficient probe

Heavy quark : probe for evolving Glasma



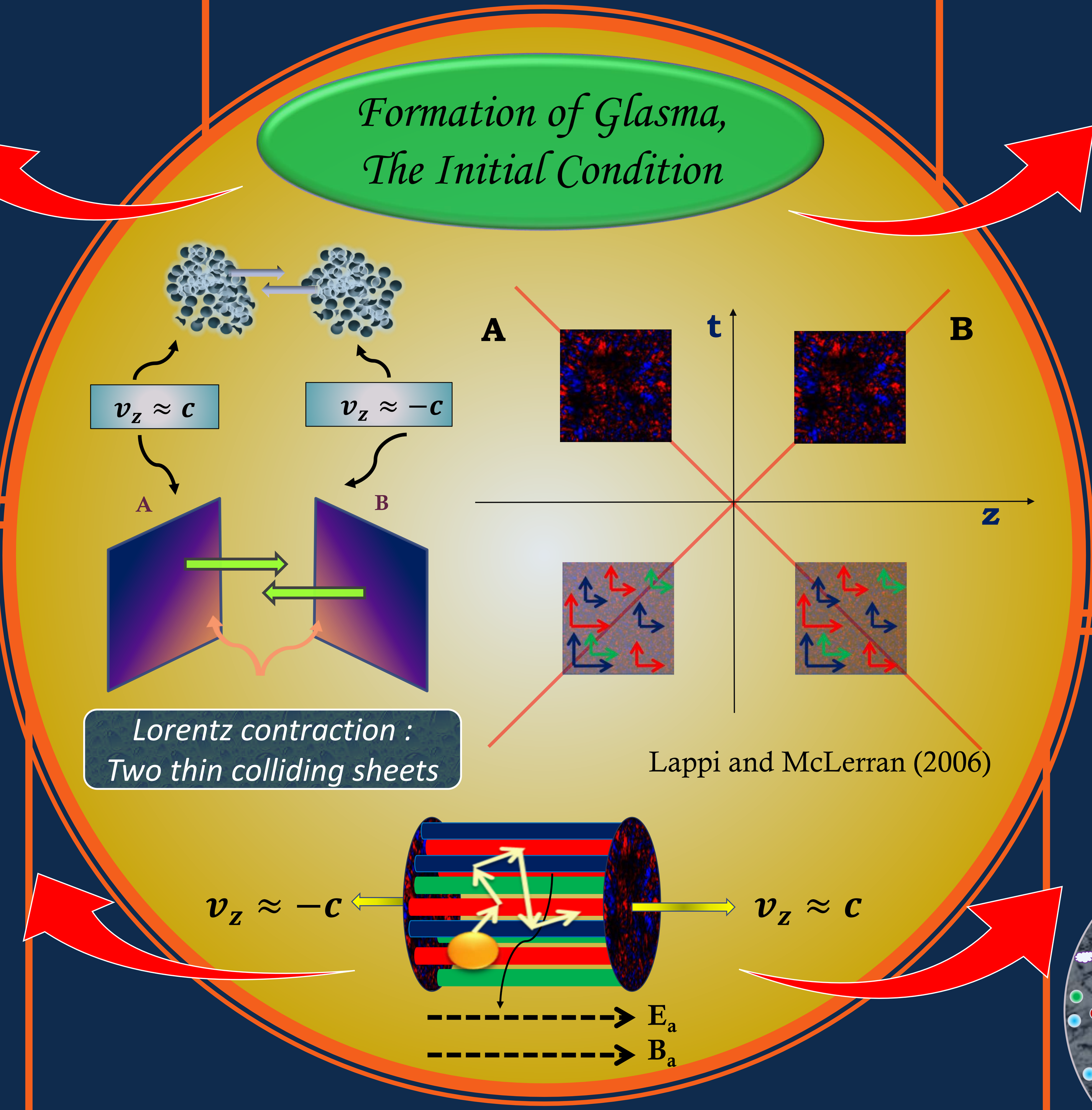
Kinetic equations of motion for heavy quarks in EvGlasma

$$\frac{dp^i}{dt} = \frac{g}{m} Q_a F_a^{i\nu} p_\nu - \frac{g}{m} Q_a (\mathcal{D}^i B_a^j) S^j$$

$$\frac{dQ_a}{dt} = \frac{g}{m} f_{abc} A_b^\mu p_\mu Q_c + \frac{g}{m} f_{abc} S^i B_b^i Q_c$$

$$\frac{ds^i}{dt} = -\frac{g}{m} Q_a F_a^{ij} S^j, \quad \frac{dL^i}{dt} = \epsilon_{ijk} x^j \frac{dp^k}{dt}$$

Formation of Glasma, The Initial Condition



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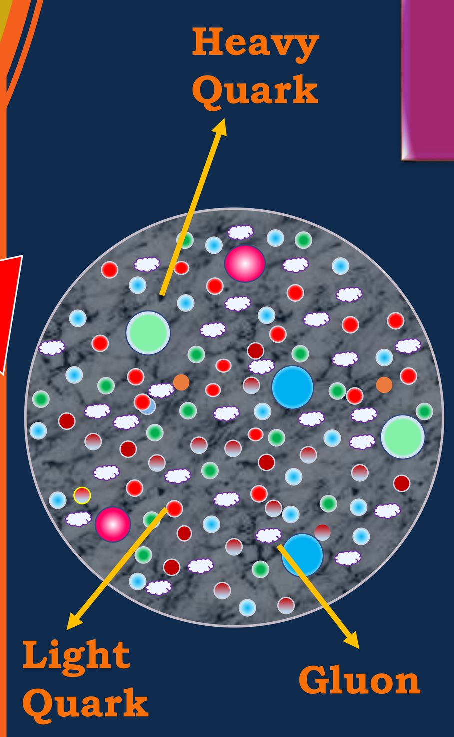
CYM Equations

$$\frac{dA_i^a}{dt} = E_i^a$$

$$\frac{dE_i^a}{dt} = \partial_j F_{ji}^a + g f^{abc} A_j^b F_{ji}^c$$

$$F_{ij}^a = \partial_i A_j^a - \partial_j A_i^a + g f^{abc} A_i^b A_j^c$$

Heavy quark : probe for evolving Plasma



Langevin Equations

$$\frac{dx^i}{dt} = \frac{p^i}{E}$$

$$\frac{dp^i}{dt} = -\gamma p^i + \xi^i(t)$$

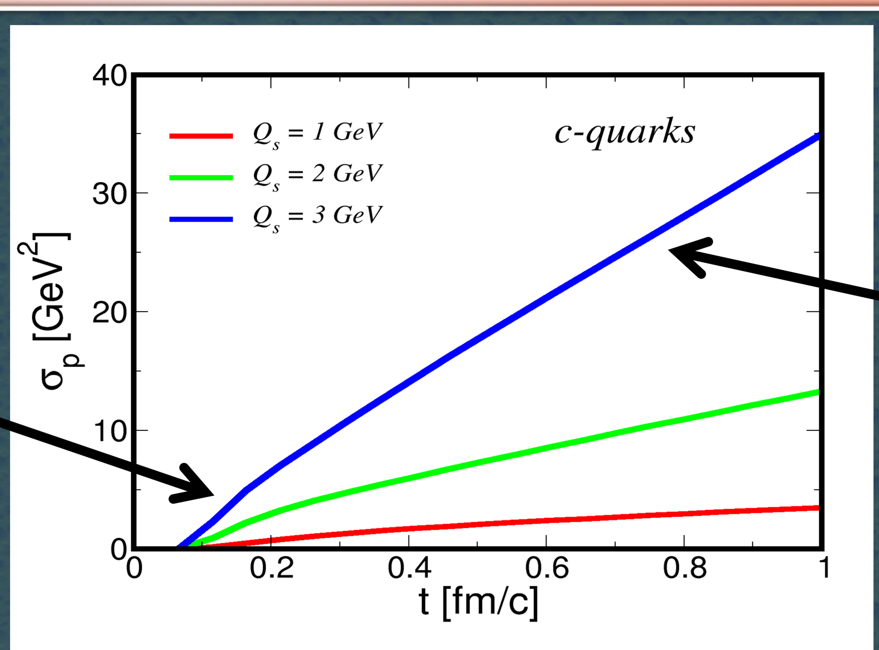
RESULTS

Transverse Momentum Broadening :

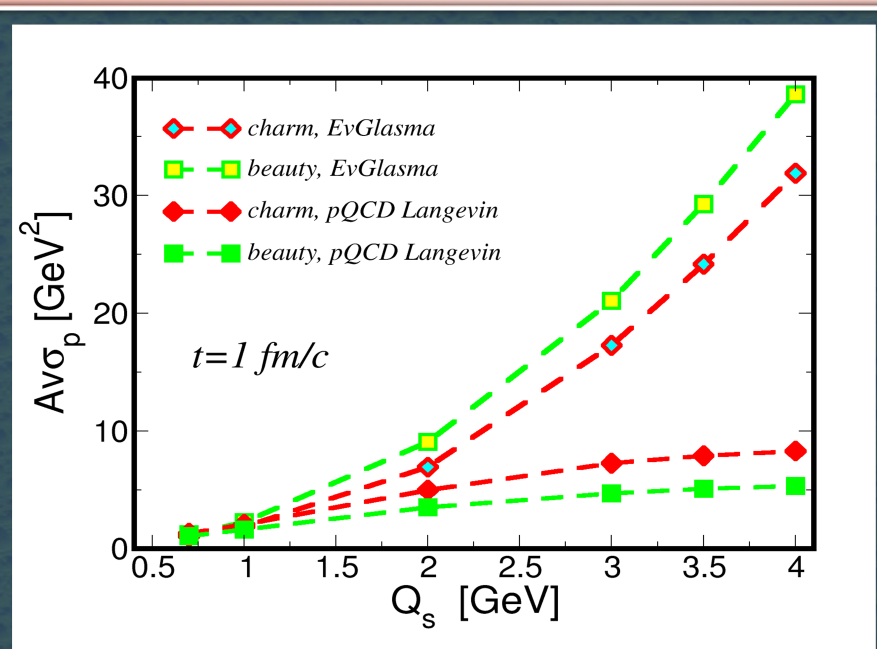
$$\sigma_p = \frac{1}{2} < (p_x(t) - p_{ox})^2 + (p_y(t) - p_{oy})^2 >$$

We prepare a bath of gluons at temperature T, with the same energy density that of the EvGlasma, and study the diffusion of HQs in this bath with Langevin equation.

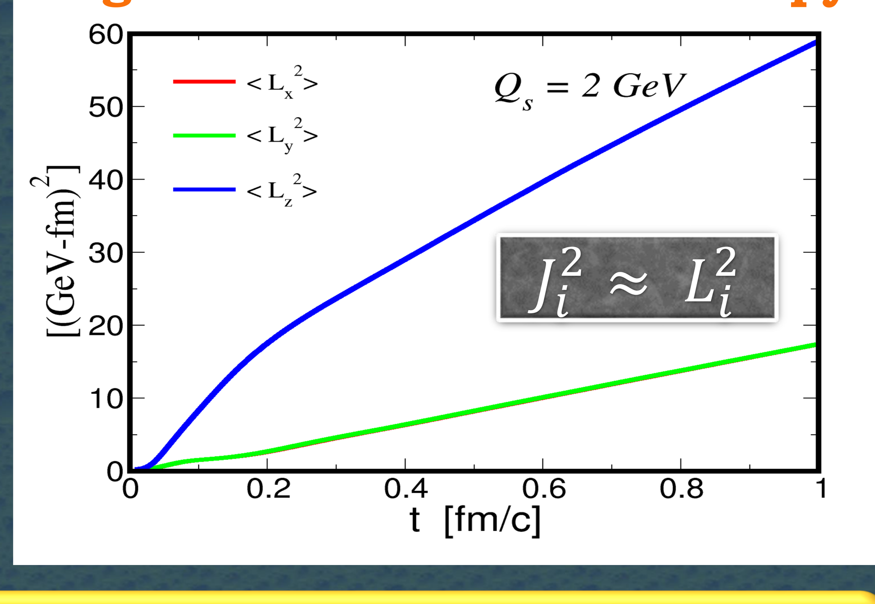
Diffusion in a filament $\sigma_p \propto t^2$



Diffusion in a random medium $\sigma_p \propto t$



Angular momentum anisotropy



At early time : $\sigma_p \approx \frac{Dt^2}{\tau_{mem}}$

At later time : $\sigma_p \approx 2Dt$

Energy density : $\varepsilon = 2(N_c^2 - 1) \int \frac{d^3p}{(2\pi)^3} \frac{p}{e^{\beta p} - 1} = \frac{(N_c^2-1)\pi^2 T^4}{15}$

Conclusions and Outlook

- The diffusion of HQs in the early stage of high energy collisions is charaterized by $\sigma_p \propto t^2$, following $\sigma_p \propto t$ at a later stage.
- Average momentum broadening (Av σ_p) of HQs in the EvGlasma is in agreement with the standard pQCD-Langevin for small values of Q_s, while differs significantly for larger Q_s.
- The fluctuations of the angular momentum, $\boldsymbol{L}$, of HQs are anisotropic, whereas we found no sign of anisotropy in the fluctuations of the spin angular momentum, $\mathbf{S}$. Moreover, $\langle J_i^2 \rangle \approx \langle L_i^2 \rangle$.

Acknowledgements

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References

[1] P. Khowal, S. K. Das, L. Oliva , M. Ruggieri, *Eur. Phys. J. Plus 137* (2022) 3, 307
[2] Pooja, S. K. Das, M. Ruggieri, V. Greco, *Eur. Phys. J. Plus* 138 (2023) 4, 313

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