Heavy quark momentum diffusion coefficient during the hydrodynamization in heavy-ion collisions

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Work in progress

Ultrarelativistic heavy ion collisions & heavy quarks, why?

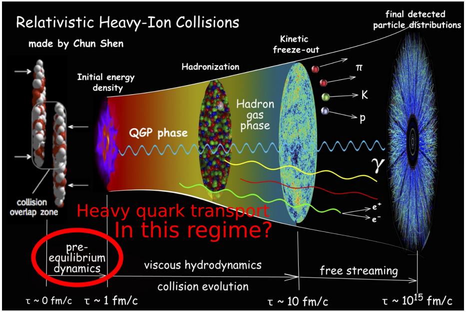


Figure: Fig: Chun Shen

- Short formation time & no pair production/annihilation → entire history of the medium
- Assume $M \gg T, Q$.

First principle description of URHIC from QCD?

Observation:

- Emergence of hydrodynamics after $\tau \sim 1\text{fm}/c \rightarrow$ approx. local equilibrium, how?

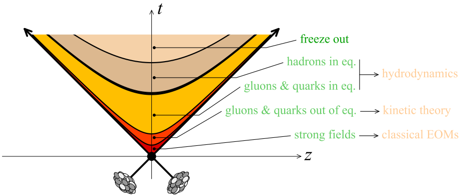


Figure: Fig: E. Iancu, arXiv:1105.0751 [hep-ph].

Solution (?):

- $Q_s = \alpha_s N_c \dfrac{1}{\pi R_A}\dfrac{\mathrm{d}N}{\mathrm{d}y}$, at high energy $Q_s \gg \Lambda_{QCD} \rightarrow \alpha_s(Q_s) \ll 1$
- $\dfrac{\mathrm{d}N}{\mathrm{d}y} \sim 1/\alpha_s \gg 1$ Large occupation number $\rightarrow$ classical field $(gA = const, g \rightarrow 0)$.
- Later stage $\rightarrow$ gas of partons described by kinetic theory which equilibrates.

Descriptions of pre-equilibrium: Classical fields & EKT

- Classical description, CYM (applicability: $f \gg 1$ Initially: $A \sim 1/g$)

$$[D^{\mu}, F^{\mu\nu}] = 0 \tag{1}$$

- EKT: Boltzman equation (applicability: $f \ll 1/g^2$)

$$-\frac{\mathrm{d}f}{\mathrm{d}\tau} + \frac{p_z}{\tau}\partial_{p_z} f = C_{1\leftrightarrow 2}[f] + C_{2\leftrightarrow 2}[f] \tag{2}$$

- Overlapping range of validity when $1/\alpha_s \gg f \gg 1$.
- Collision terms C involve matrix elements describing scattering processes among quarks and gluons. Computed in thermal field theory.
- This talk: effective kinetic theory description. For heavy quarks in classical setup, see: JHEP 09 (2020) 077.

Isotropization in the kinetic theory stage: "Bottom-up"

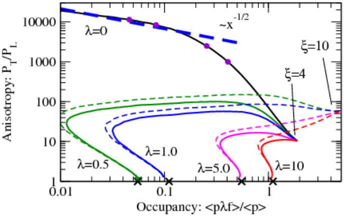


Figure: Kurkela & Zhu, Phys.Rev.Lett. 115 (2015) 18, 182301

Isotropization in 3 stages:

- Stage 1: competition of momentum diffusion and expansion, expansion wins → anisotropy grows.
- Stage 2: Soft thermal bath starts to form, momentum diffusion and expansion roughly equal → constant anisotropy.
- Stage 3: Soft thermal bath formed, energy cascades from hard particles to the thermal bath.

Originally proposed in: Baier et. al. PLB 502 (2001) 51-58.

Extracting the diffusion coefficient (PRC 71 (2005) 064904)

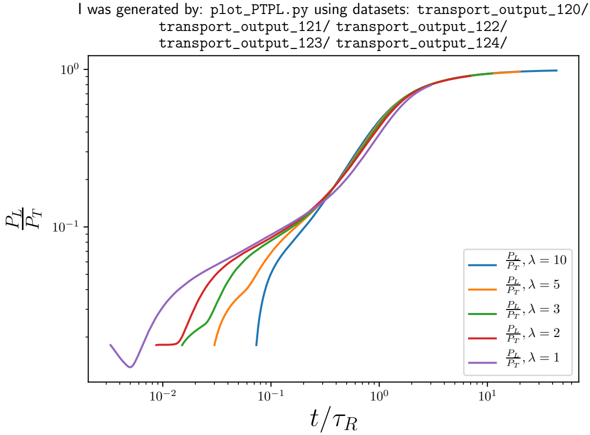
In the kinetic theory framework κ is given by ($gq \to gq$, t-channel gluon exchange)

$$\kappa = \frac{\langle \Delta k^2 \rangle}{\Delta t} = \frac{1}{6M} \int \frac{\mathrm{d}^3\boldsymbol{k}\,\mathrm{d}^3\boldsymbol{q}}{(2\pi)^6\, 8|\boldsymbol{k}||\boldsymbol{k}+\boldsymbol{q}|M} 2\pi\delta(|\boldsymbol{k}+\boldsymbol{q}| - |\boldsymbol{k}|) \times \boldsymbol{q}^2 |\mathcal{M}|^2_{\mathrm{gluon}} f(k)(1 + f(|\boldsymbol{k}+\boldsymbol{q}|)) \tag{3}$$

k and k' gluon momenta, $q = k - k'$, p and p' incoming and outgoing heavy quark momenta.

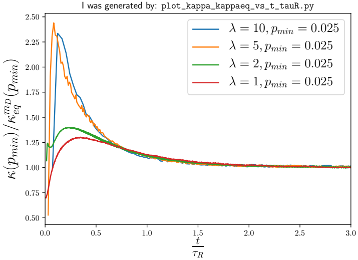
$$|\mathcal{M}|^2_{\mathrm{gluon}} = \left[N_c C_H g^4\right] \frac{16M^2k^2\left(1+\cos^2\theta_{\boldsymbol{k}\boldsymbol{k}'}\right)}{(q^2+m_D^2)^2} \tag{4}$$

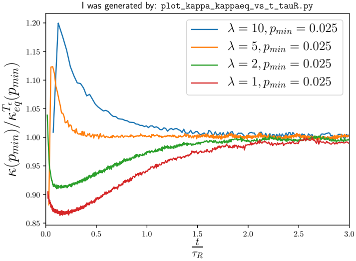
Pressure isotropization

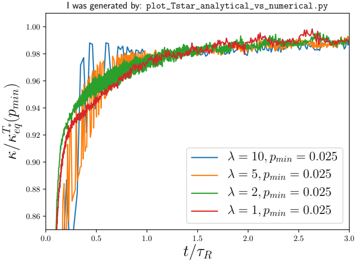


- System is fairly isotropic at $t \approx \tau_R$
- $\tau_R = \dfrac{4\pi\eta/s(\lambda)}{T}$

Diffusion coefficient: approach to thermal







- κ_{eq} computed using BE distribution (thermal).
- Match same ϵ, m_D, T_*?
- Winner: T_*!

Conclusions

We have:

- κ during bottom-up isotropization (EKT): no large deviations from thermal. Best match achieved when compare these with the same IR temperature.

Future plans:

- Precision comparison of EKT and CYM?
- Possibly other transport coefficients such as $\hat{q}$ using CYM/EKT.

Isotropization of heavy quarks: how to compare to thermal?

- Comparison not unambiguous! Same ϵ, m_D, T? T as an integral moment of particle distribution:

$$T_* = \frac{2\lambda \int \frac{\mathrm{d}^3 p}{(2\pi)^3} f(p)(1+f(p))}{m_D^2}, \tag{5}$$

- Discretization effects: $\epsilon \sim \int \mathrm{d}^3 p p f(p) \to \int_{p_{\min}}^{\infty} \mathrm{d}^3 p p f(p)$