Heavy quark momentum diffusion coefficient during hydrodynamization via effective kinetic theory

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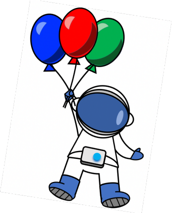
arXiv:2303.12520 [hep-ph]

CoE QM



Transport coefficients in pre-equilibrium vs. equilibrium

- Glasma – transport coefficients large:

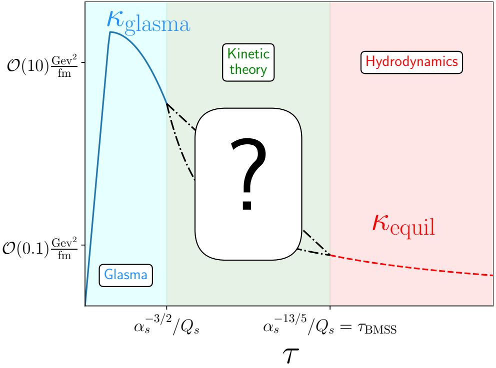
  Czajka et. al: PRC 105, 064910, PLB 834 (2022) 137464, NPA 1001 (2020) 121914, JP et. al: JHEP 09 (2020) 077 , Müller et. al: PLB 810 (2020) 135810, Ruggieri et. al: EPJP 137 (2022) 3, 307, PLB 798 (2019) 134933
- This work: heavy quark momentum diffusion coefficient κ during hydrodynamization.
- Use Effetive Kinetic Theory (EKT)

  Arnold et. al: JHEP 01 (2003) 030

- Glasma: $\kappa \approx \mathscr{O}(10)\frac{\mathrm{Gev}^2}{\mathrm{fm}}$ (larger ϵ)

  Avramescu et. al: PRD 107 (2023) 11, 114021
- Lattice: $\kappa \approx \mathscr{O}(0.1)\frac{\mathrm{Gev}^2}{\mathrm{fm}}$

  Banerjee et. al: PRD 85, 014510



Main research questions of this talk

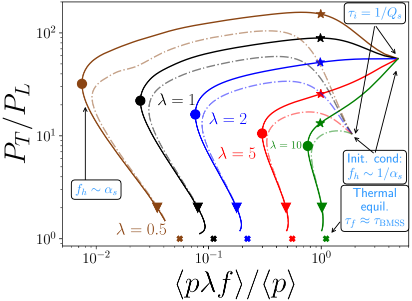
The relevant questions:

1. How large is κ during hydrodynamization?
2. How anisotropic is heavy quark diffusion?

EKT & bottom-up thermalization PLB 502 (2001) 51-58
à la Kurkela & Zhu PRL 115 (2015) 18, 182301

- Dof: gluon phase space density f
- Dynamics: Boltzmann equation

$$\frac{\partial f(\boldsymbol{p})}{\partial \tau} = \mathscr{C}_{1\leftrightarrow 2}[f] \quad + \mathscr{C}_{2\leftrightarrow 2}[f] + \mathscr{C}_{\exp}[f].$$

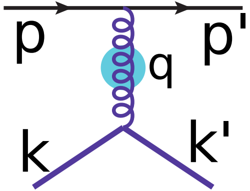


- ⋆ maximum anisotropy / occupancy $f_h \sim 1/\lambda$, $\lambda = g^2 N_c$.
- ∘ minimum occupancy
- ▲ Approx. isotropy $P_T/P_L = 2$.

Heavy quark momentum diffusion coefficient κ PRC 71 (2005) 064904

$$3\kappa = \frac{\langle \Delta k^2 \rangle}{\Delta t} = \frac{1}{2M} \int_{\boldsymbol{k}\boldsymbol{k}'\boldsymbol{p}'} (2\pi)^3 \delta^3 \left(\boldsymbol{p} + \boldsymbol{k} - \boldsymbol{p}' - \boldsymbol{k}'\right)$$

$$\times 2\pi\delta\left(k' - k\right) \boldsymbol{q}^2 \left[|\mathcal{M}_\kappa|^2 f(\boldsymbol{k})(1 + f(\boldsymbol{k}')) \right].$$



Matrix element

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

Out of equilibrium transverse κ_T and longitudinal κ_z coefficients not same:

$$3\kappa = 2\kappa_T + \kappa_z$$

Other relevant observables

Effective temperature:

$$T_* = \frac{4\lambda}{m_D} \int_{\boldsymbol{p}} p f(p)(1 + f(p))$$

Debye screening mass

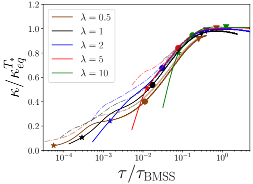
$$m_D^2 = 8 \int_{\boldsymbol{p}} \lambda f(p)$$

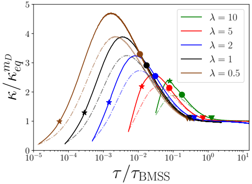
Temperature from energy density

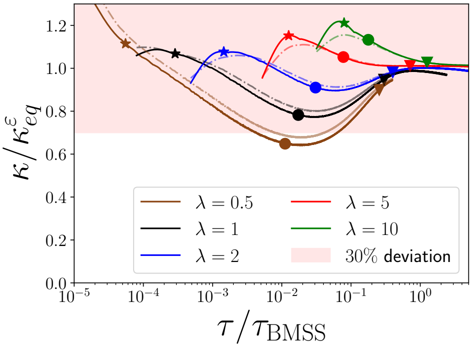
$$T_\epsilon \sim \sqrt[4]{\epsilon}$$

Comparing equilibrium κ to non-equilibrium κ

- Try: compare to the same $T_*(t)$, $m_D(t)$, and $\varepsilon(t)$.
- $\tau_{\text{BMSS}} = \alpha_s^{-13/5}/Q_s$ thermalization timescale Baier et. al: PLB 502 (2001) 51-58.



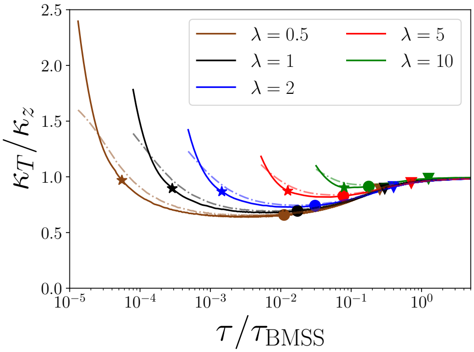




How large is κ during hydrodynamization?

For the same ε (Landau matching) deviation from equilibrium $\sim 30\%$.

Transverse vs. longitudinal (κ_T vs. κ_z, Question 2)

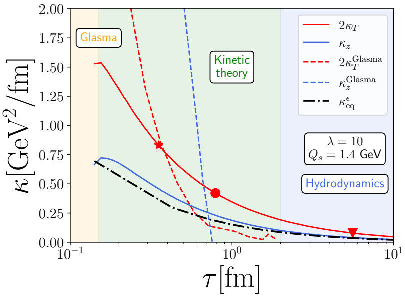


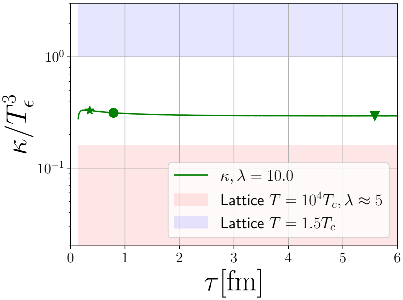
- Initially $\kappa_T/\kappa_z > 1$: Overoccupied, highly anisotropic stage $\rightarrow$ enhanced transverse momentum exchange.
- After $\star$ marker $\kappa_T/\kappa_z < 1$: Results from momentum anisotropy. In line with squeezed thermal distributions: Romatschke: PRC 75 (2007) 014901

How anisotropic is heavy quark diffusion?

Initially transverse diffusion coefficient dominates.
At the underoccupied phase longitudinal coefficient is larger.
Difference factor of 2.

Comparison with lattice & glasma (preliminary)





- EKT, our result: $\kappa/T^3 \approx 0.3$ (at $\blacktriangle, T \approx 300\mathrm{MeV}, \lambda = 10$)
- Lattice Leino et. al: PRD 107 (2023) 5, 054508:
  - $\kappa/T^3 \approx 1-3$ ($T = 1.5T_c$, strong coupling)
  - $\kappa/T^3 \approx 0.02-0.16$ ($T = 10^4 T_c$, corresponds to $\lambda \approx 5$)
- κ_T matches glasma better than κ_z.
  Glasma results much larger for small τ Avramescu et. al: PRD 107 (2023) 11, 114021 .

Conclusions & outlook

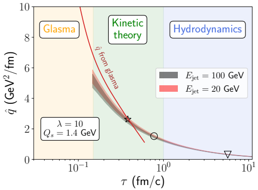
1. How large is κ during hydrodynamization?
   Within 30 % from κ^{eq} for the same ε!
2. How anisotropic is heavy quark diffusion?
   Initially $\kappa_T > \kappa_z$. At underoccupation $\kappa_z > \kappa_T$. Difference factor $\lesssim 2$.

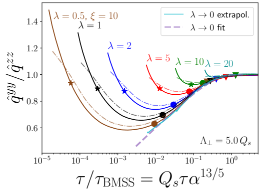
Applications for:

- Phenomenological descriptions of heavy quark diffusion and quarkonium dynamics.

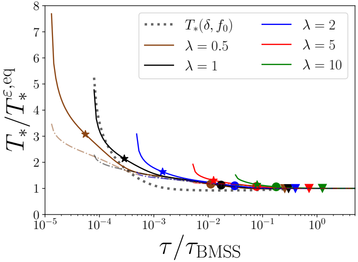
Related talks at QM 2023:

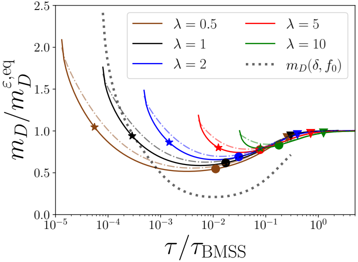
- F. Lindenbauer: limiting attractors (Talk, 15:10, Initial State session) & jet quenching factor $\hat{q}$ (Poster, Initial state) with the same setup





Evolution of m_D and T_*

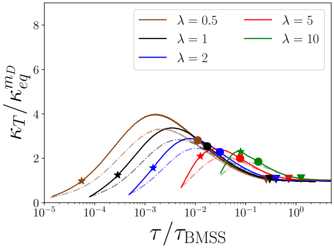


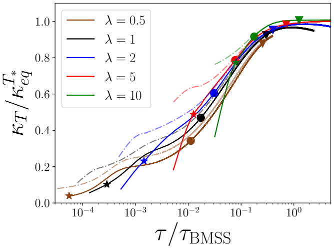


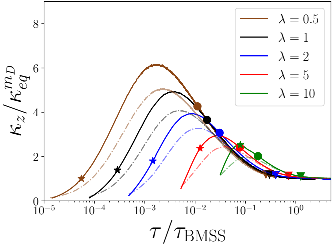
- Initially large $f_0 \rightarrow$ enhancement
- At underoccupation f dominates over $f^2 \rightarrow$ ratio becomes 1.

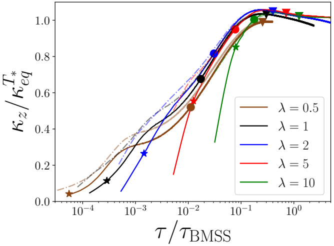
- Initial enhancement due to large occupation number.
- Suppression due to underoccupation.

Transverse and longitudinal κ matched for other quantities



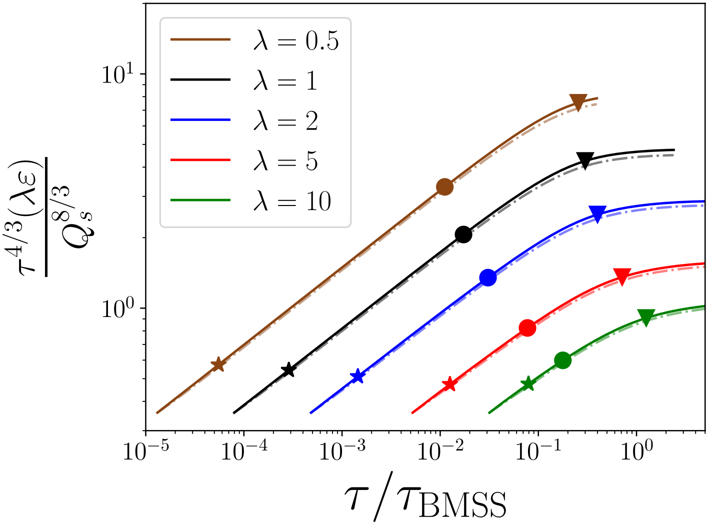






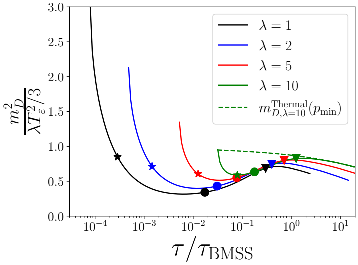
- Similar to the results for the full coefficient

Time-evolution of energy density



Discretization effects

- By far the most important parameter: UV cutoff p_{min}.

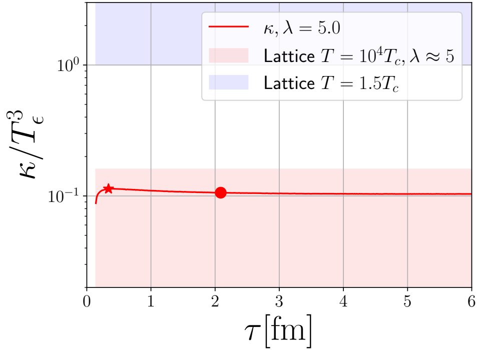


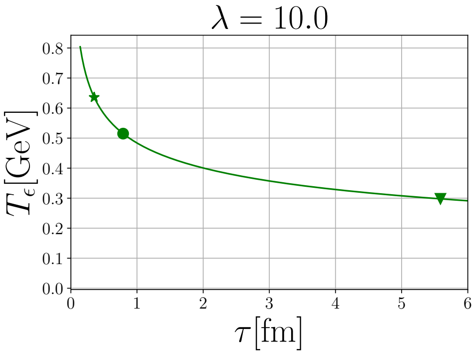
$$m_D^2(p_{\min}) = \frac{8\lambda}{(2\pi)^2} \int_{p_{\min}}^{\infty} \mathrm{d}p\, p f(p)$$

$$= \frac{2\lambda T}{\pi^2}\left(T \,\mathrm{Li}_2\left(e^{-\frac{p_{\min}}{T}}\right) - p_{\min} \log\left(1 - e^{-\frac{p_{\min}}{T}}\right)\right)$$

- Compare non-equilibrium quantities to thermal result, with the same UV cutoff p_{min}.
- Left: Effect illustrated for m_D
- Redefine thermal T_* and κ similarly.
- Residual discretization effects cause ratios to deviate from equilibrium values at late times.

κ/T^3 for $\lambda = 5$ and T_ϵ in GeV





κ_{eq} vs $\kappa_{T,z}$ during hydrodynamization

- $\kappa_{T,z}$ behave qualitatively similarly to κ (except κ_z at early times)
- Small λ → larger deviations (small λ → bottom-up reproduced better).