Transport coefficients in the pre-equilibrium stage

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Exploring Quark-Gluon Plasma through soft and hard probes,
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Outline

- Bottom-up thermalization,
- QCD kinetic theory
- Jet momentum broadening $\hat{q}$
- Heavy quark diffusion κ

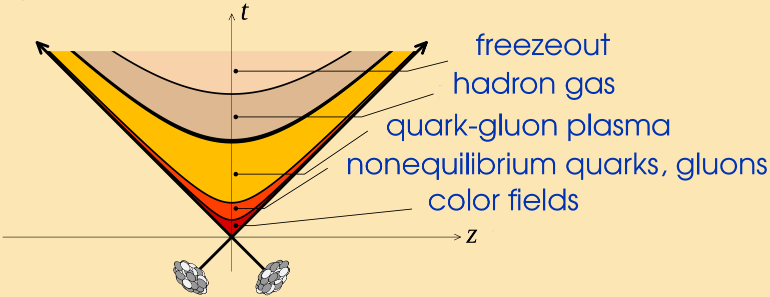
This talk:

- Heavy quark diffusion coefficient in heavy-ion collisions via kinetic theory,
  K. Boguslavski, A. Kurkela, T. L., F. Lindenbauer, J. Peuron, `arXiv:2303.12520 [hep-ph]`
- Jet momentum broadening during initial stages in heavy-ion collisions,
  K. Boguslavski, A. Kurkela, T.L., F. Lindenbauer, J. Peuron, `arXiv:2303.12595 [hep-ph]`
- 1+1D boost invariant expansion

Goal: calculate transport coefficients $\hat{q}$ and κ in pre-equilibrium phase

Heavy ion collision in spacetime

Stages of a heavy ion collision



- Timescales for hard $M \sim m_c, p_T$ probes:

$$1/M \ll 1/Q_s \ll t_{\text{therm}}$$

- Hard probes $M \sim m_c, p_T$ created first $\Longrightarrow$ cannot neglect pre-equilibrium
- Even if thermalization is quick, pre-equilibrium is hot, dense $\Longrightarrow$ large effect

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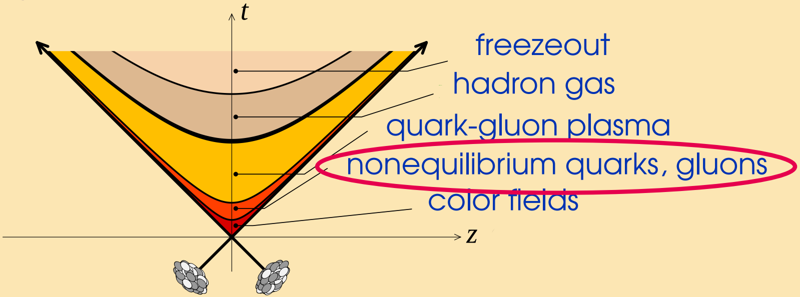

freezeout

hadron gas

quark-gluon plasma

nonequilibrium quarks, gluons

color fields

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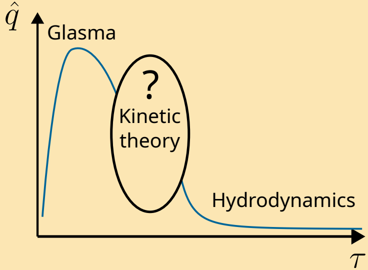
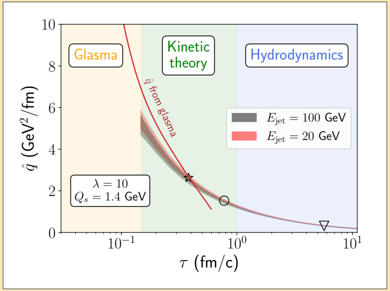
Transport coefficients pre-equilibrium

$$\left.\begin{array}{c}\hat{q}\\ \kappa\end{array}\right\} = \frac{d\left\langle q_\perp^2\right\rangle}{dt}\quad\left\{\begin{array}{l}\text{jet } (p=\infty)\\ \text{H.Q. } (m=\infty)\end{array}\right.$$

- Standard for a long time:
  $\hat{q}$, κ in thermal system
  $\Longrightarrow$ Input for jet quenching, H.Q. diffusion
- Recent interest: glasma phase
  E.g. A. Ipp et al `2001.10001`, `2009.14206`
  Avramescu et al `2303.05599`
  Carrington et al `2112.06812`, `2202.00357`, `2304.03241`, `2001.05074`
  P. Khowal et al `2110.14610`
  M. Ruggieri et al `2203.06712`
  Y. Sun et al. `1902.06254`
  K. Boguslavski et al `2005.02418`
- Aim: complete the picture
  from the glasma to hydrodynamics





Bottom-up thermalization

Baier, Mueller, Schiff, Son `hep-ph/0009237`

3 stages of bottom-up thermalization

1. Classical field stage $(0 \to \star)$:
   growing anisotropy of hard $\sim Q_s$ modes
2. Bath of soft particles develops $(\star \to \bullet)$
3. Radiative breakup of hard particles $(\bullet \to \blacktriangledown)$

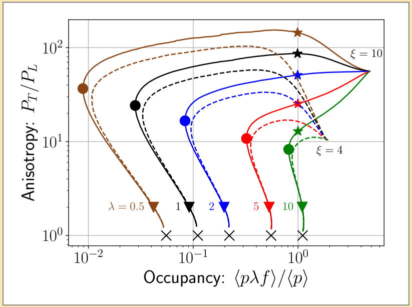
$$\tau_{\mathrm{BMSS}} = \alpha_s^{-13/5} Q_s^{-1}$$

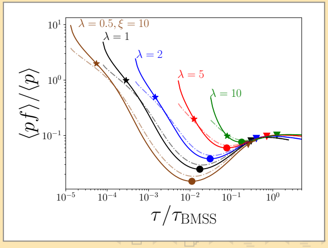
Can be tracked with AMY kinetic theory:

$$-\frac{\mathrm{d}}{\mathrm{d}\tau} f_{\mathbf{p}} = \mathcal{C}^{2\leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}^{1\leftrightarrow 2}[f_{\mathbf{p}}] + \mathcal{C}^{\mathrm{exp}}[f_{\mathbf{p}}].$$

Attractor: different initial conditions converge

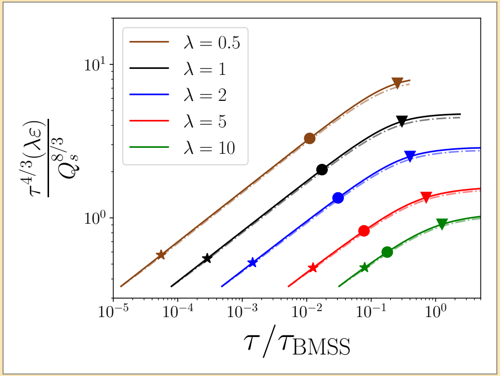
(ξ: initial anisotropy, $\lambda = 4\pi N_c \alpha_s$)

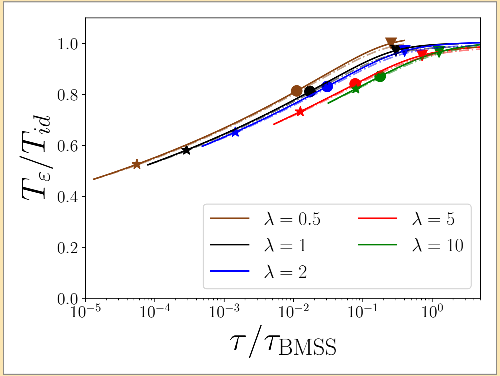




Convergence to hydro

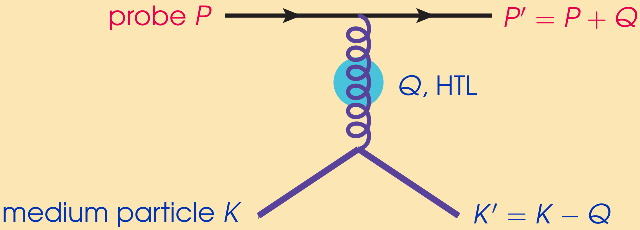
Most of pre-equilibrium: $\varepsilon \sim 1/\tau$





T_{id}= bwd extrapolated ideal hydro
$T_\varepsilon \sim \sqrt[4]{\varepsilon}$

Calculating transport coefficients



Momentum broadening from interactions with medium particles:

$$\begin{matrix}\hat{\mathrm{q}}\\ \kappa\end{matrix} \sim \int_{\mathbf{k}\mathbf{k}'\mathbf{p}'} \frac{q_T^2}{E_{\mathbf{p}}} (2\pi)^4 \delta^4(P + K - P' - K')\, |\mathcal{M}|^2\, f(\mathbf{k})\, (1 + f(\mathbf{k}'))\,,$$

- κ: heavy quark $P = (M, \mathbf{0})$, $M \to \infty$
- $\hat{\mathrm{q}}$: energetic jet $P^2 = 0, p \to \infty$ (need cutoff $\hat{\mathrm{q}} \sim \ln \Lambda_\perp$)

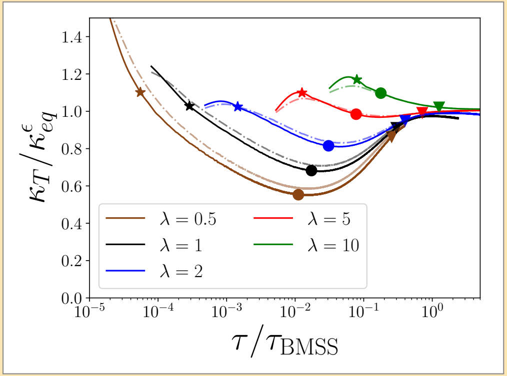
These limits: **medium properties**, not probe

Result: κ

Compare to thermal system with same ε
(Landau matching,

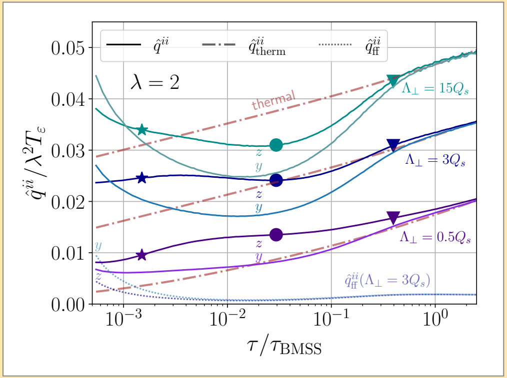
thermal with same m_D or T_* is much further)

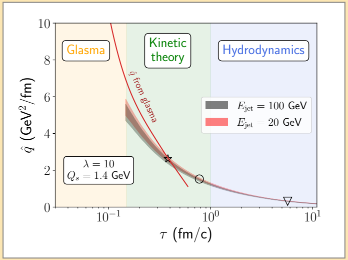
- Enhancement first (overoccupied)
- Then suppression (underoccupied)
- Larger $\lambda = 4\pi N_c \alpha_s$:
  behavior smoothed out



Result: $\hat{q}$

- Large cutoff $\Lambda_\perp$:
  Enhancement first, then suppression
- Smaller $\Lambda_\perp$:
  smoother, overall enhancement

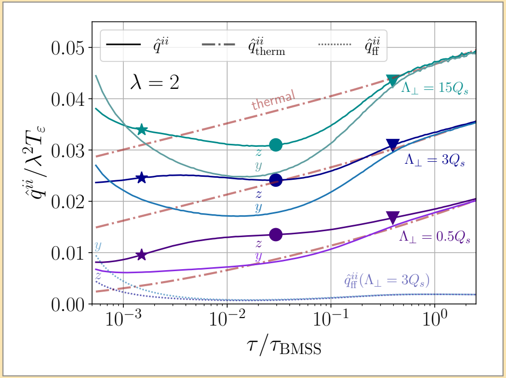


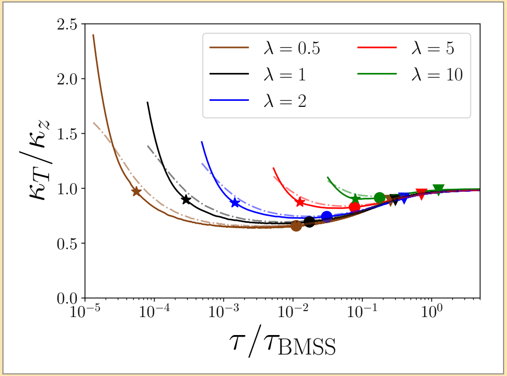


- $\varepsilon \sim 1/\tau$ large
- At ▼ $\hat{q}$ value ≈ JETSCAPE estimate (choose $\Lambda_\perp$)

Anisotropy

- Inital overoccupied: $\kappa_T > \kappa_L$, $\hat{\mathrm{q}}_T > \hat{\mathrm{q}}_L$ $\Longrightarrow$ Bose enhancement, Glasma
- Then underoccupied $\kappa_T < \kappa_L$, $\hat{\mathrm{q}}_T < \hat{\mathrm{q}}_L$ $\Longrightarrow$ Anisotropy of f





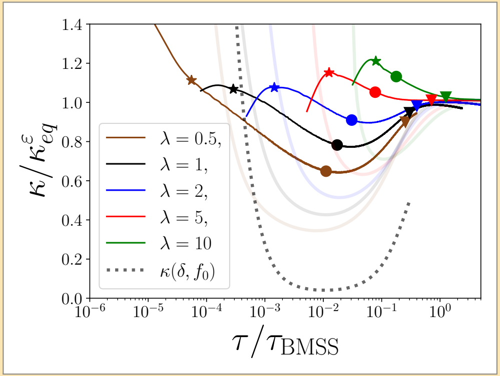
Relevant microscopic scales

- Occupation number f
- Coupling α_s
- Anisotropy $\delta \sim \sqrt{\frac{\langle p_z^2 \rangle}{\langle p_T^2 \rangle}}$
- Hard scale $p_T^2 \sim Q_s^2$

From these estimate

- Energy density $\varepsilon \sim \delta Q_s^4 f$
- Debye scale $m_D^2 \sim \alpha_s \delta\, Q_s^2 f$
- Soft mode eff. temperature $T_* \sim Q_s(f+1)$
- $\kappa \sim m_D^2 T_*$

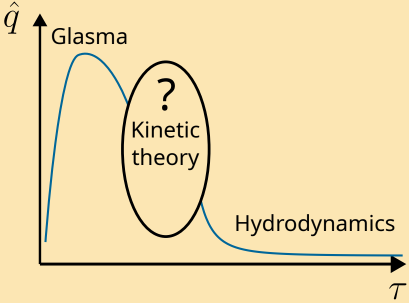
Understanding the systematics



(Light: T_*, m_D from EKT, dashed: f, δ from EKT)

Conclusions

- Pre-equilibrium stage short, but hot
  $\Longrightarrow$ Significant effect on hard observables
- QCD kinetic theory:
  trace system from glasma to hydro
  — and calculate transport coefficients
- First estimate: $\hat{\mathrm{q}}, \kappa$ within $\sim$ 30% of thermal system **@ same energy density**
  — and pre-equilibrium ε
- Qualitative features, anisotropy understood from microscopic quantities m_D, T_*



$\hat{\mathrm{q}}$ parametrizations available in `2303.12595`, κ upon request