Early time nonequilibrium heavy quark diffusion and energy loss

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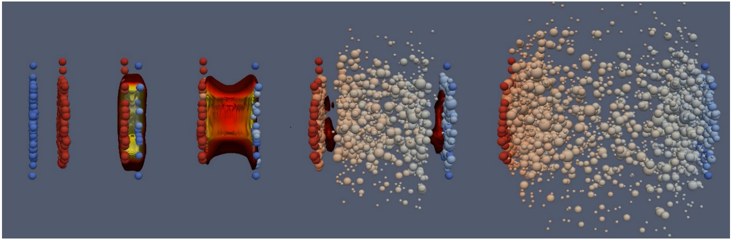
Stages in heavy-ion collisions



MADAI collaboration

- High-energy collisions ⇒ **QGP** created
- Cooling during evolution, go through different **phases**
  ⇒ pre-equilibrium QGP (initial stages) → fluid QGP → hadrons
- **Pre-equilibrium QGP:** testing the very nature of quantum physics
  ⇒ Gluons first as (classical) waves → scatterings of (quasi-)particles

Goals

Learn about **real-time** properties of QCD in **extreme conditions**

Research questions

Non-equilibrium QCD

What are the initial stages of the quark-gluon plasma (QGP)?

- Significant progress from QCD calculations over the past decade(s)
- Interplay of different methods and models

Experimental traces

How can we probe them experimentally? What are their signatures?

- What are the medium properties of the pre-equilibrium QGP?
- How do they affect hard probes? What do we learn?

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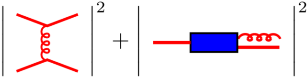
Pre-equilibrium QGP: descriptions (for couplings $g^2 \ll 1$)

- initially: classical-statistical simulations, 'Glasma'
  - $\Rightarrow$ large gluon fields $A \sim 1/g$, full initial conditions
  - $\Rightarrow$ nonlinear dynamics of interacting classical waves
  - $\Rightarrow$ Valid while occupancies large $f(t,p) \approx \langle AA \rangle p \gg 1$

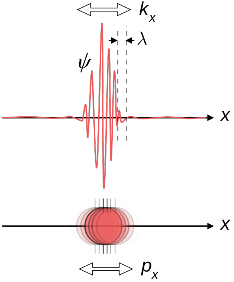
- then, as energy decreases (dilution): kinetic theory
  - $\Rightarrow$ Boltzmann equation for f

$(\partial_t + \boldsymbol{v} \cdot \boldsymbol{\nabla}) f =$



$$\frac{\partial f_{\vec{p}}}{\partial \tau} - \frac{p_z}{\tau} \frac{\partial f_{\vec{p}}}{\partial p_z} = -\mathcal{C}^{2\leftrightarrow 2}[f_{\vec{p}}] - \mathcal{C}^{1\leftrightarrow 2}[f_{\vec{p}}]$$

Arnold, Moore, Yaffe, JHEP 01, 030 (2003)



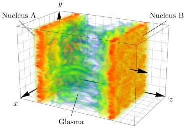
Quantum wave particle duality, approximative descriptions

classical fields $A(t,\vec{x})$ ('waves') $\rightarrow$ interacting particle distribution $f(t,\vec{p})$

Strong initial fields: classical-statistical lattice simulations

- Initial state: Glasma – large longitudinal fields

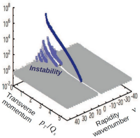
  McLerran, Venugopalan (1999); Krasnitz, Venugopalan (1999, 2000, 2001); Krasnitz, Nara, Venugopalan (2001, 2003); Lappi (2003, 2006, 2011); Lappi, McLerran (2006); Schenke, Tribedy, Venugopalan (2012); Gelfand, Ipp, Müller (2016, 2017); ...



Ipp, Müller (2017)

- Plasma instabilities – from boost-invariant Glasma to highly occupied (mainly gluonic) plasma

  Mrowczynski (1993); Arnold, Lenaghan, Moore (2003); Romatschke, Strickland (2003); Romatschke, Venugopalan (2006); Attems, Rebhan, Strickland (2012); Fukushima, Gelis (2012); Berges, KB, Schlichting, (2012, 2013); Epelbaum, Gelis (2013); ...

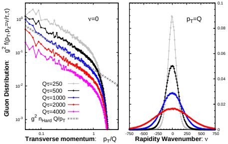


Berges, Schenke, Schlichting, Venugopalan (2014)

- Classical self-similar attractor far from equilibrium – universal dynamics of over-occupied plasma
  - ⇒ agrees with 1. stage of 'bottom-up' scenario

    Berges, KB, Schlichting, Venugopalan (2013, 2014); Kurkela, Zhu (2015); ...
  - ⇒ Far-from-equilibrium universality class with scalars

    Berges, KB, Schlichting, Venugopalan (2015); ...



Berges, KB, Schlichting, Venugopalan (2013)

Bottom-up thermalization: QCD kinetic theory

- When quasiparticles have formed:
  Kinetic theory becomes applicable

  Note: Assumes narrow excitations in spectral functions, which may not be true at low momenta for strong anisotropy
  KB, Kurkela, Lappi, Peuron (2018, 2019, 2021)

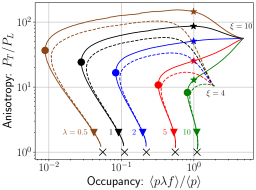
- Bottom-up thermalization: Baier, Mueller, Schiff, Son (2001)
  1. Classical attractor (see above)
  2. Anisotropy freezes
  3. Radiational breakup

- QCD effective kinetic theory (EKT) simulations
  Arnold, Moore, Yaffe (2003); Kurkela, Zhu (2015); Kurkela, Mazeliauskas (2019);

$$-\frac{\partial f_{\vec{p}}}{\partial \tau} = \mathcal{C}^{1\leftrightarrow 2}[f_{\vec{p}}] + \mathcal{C}^{2\leftrightarrow 2}[f_{\vec{p}}] - \frac{p_z}{\tau}\frac{\partial f_{\vec{p}}}{\partial p_z}$$

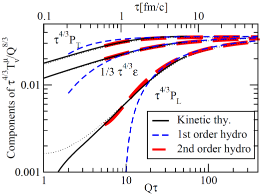
- EKT: smooth transition to hydrodynamics;
  KoMPoST: EKT + $\delta T^{\mu\nu}(\tau, \vec{x})$ perturbations
  Kurkela, Zhu (2015); Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney (2018)

Bottom-up evolution



Kurkela, Zhu (2015); KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

Onset of hydro

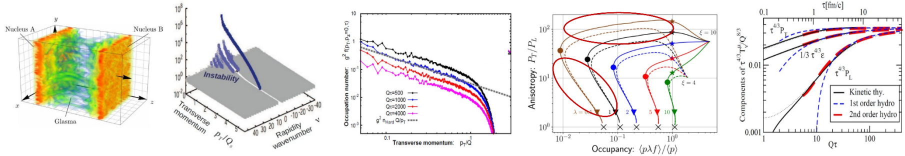


Kurkela, Zhu (2015)

⇒ Talk by G. Denicol

Initial stages in heavy-ion collisions (weak-g^2 perspective)

$Q_s\tau = 0^+$ $\quad$ $Q_s\tau = \ln^2(\alpha_s^{-1})$ $\quad$ $Q_s\tau = \alpha_s^{-3/2}$ $\quad$ $Q_s\tau = \alpha_s^{-13/5}$



Glasma | Instabilities | Bottom-up stage 1 | Bottom-up stages 2 and 3 | Onset of hydrodynamics

$$\underbrace{D_\mu F^{\mu\nu} = J^\nu}_{\text{classical-statistical simulations}}$$

$$\underbrace{-\frac{\partial f_{\vec{p}}}{\partial \tau} = \mathcal{C}^{1\leftrightarrow 2}[f_{\vec{p}}] + \mathcal{C}^{2\leftrightarrow 2}[f_{\vec{p}}] - \frac{p_z}{\tau}\frac{\partial f_{\vec{p}}}{\partial p_z}}_{\text{QCD effective kinetic theory simulations}}$$

$$\underbrace{\qquad\qquad}_{\text{hydrodynamics ...}}$$

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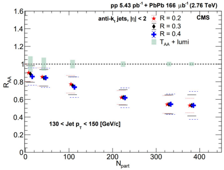
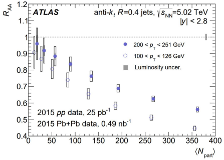
Hard probes show signatures of QGP

Hard probes are modified while traversing the QGP

Examples: heavy quarks, quarkonia ($q\bar{q}$), jets ($p \gg T$)

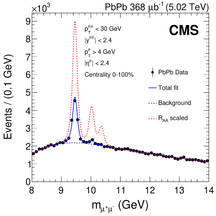
Jet energy loss / suppression

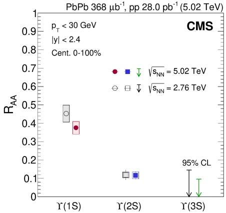




CMS Collaboration, PRC (2017) ; ATLAS Collaboration, PLB (2019)

Bottomonium suppression



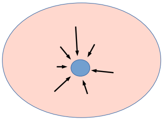


Transport coefficients from pre-equilibrium QGP

Jets, heavy (c, b) quarks: potential for signatures of initial stages

medium interactions $\Rightarrow$ QGP properties encoded in observables

- Quarks/jets get 'kicks' $\dot{p}_i(\tau) = \mathcal{F}_i(\tau)$



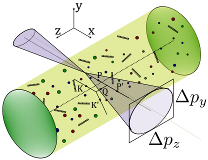
- Heavy-quark diffusion coefficient $\kappa_i = \frac{\mathrm{d}}{\mathrm{d}\tau}\langle p_i^2 \rangle$
  $\Rightarrow$ heavy quark (c, b), small momentum $p \ll M$

- κ enters Lindblad eq. for quarkonium dynamics

  Brambilla, Escobedo, [Soto], [Strickland], Vairo, [v.d. Griend, Weber] (2016, 2021)

  $\Rightarrow$ describe suppression of bottomonium ($b\bar{b}$ states)

- Jet quenching parameter $\hat{q}_i = \frac{\mathrm{d}}{\mathrm{d}\tau}\langle p_{\perp,i}^2 \rangle$
  $\Rightarrow$ jet with high momentum $p \gg Q_s$, T



KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

- They encode also pre-equilibrium dynamics

Impact of initial stages on hard probes

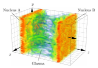
Transport coefficients encode pre-equilibrium dynamics

- Impact on jet energy loss, substructure? ⇒ Talk by Joao Barata
- Pheno. impact of $\kappa_i(\tau)$ on heavy quarks? ⇒ Talk by Pooja

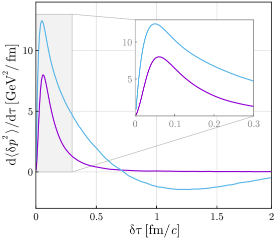
Some recent studies:
Transport coefficients during initial stages + impact on hard probes

Mrowczynski (2018); Ruggieri, Das (2018); Sun, Coci, Das, Plumari, Ruggieri, Greco (2019); Ipp, Müller, Schuh (2020); KB, Kurkela, Lappi, Peuron (2020); Khowal, Das, Oliva, Ruggieri (2022); Carrington, Czajka, Mrowczynski (2020, 2022); Avramescu, Baran, Greco, Ipp, Müller, Ruggieri (2023); KB, Kurkela, Lappi, Lindenbauer, Peuron (2023); Du (2023); Barata, Sadofyev, Wang (2023); Andres, Apolinário, Dominguez, Martinez, Salgado (2023); Pandey, Schlichting, Sharma (2024); Zhou, Brewer, Mazeliauskas (2024); Barata, Hauksson, Lopez, Sadofyev (2024); Priyam Adhya, Tywoniuk (2024); ...

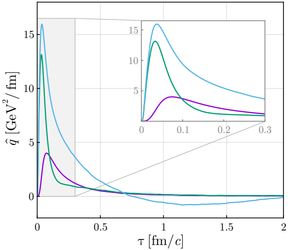
κ and $\hat{q}$ during Glasma phase



κ_i of beauty quarks

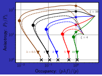


$\hat{q}_i$ of jets

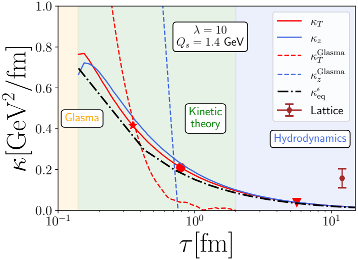


Avramescu, Baran, Greco, Ipp, Müller, Ruggieri PRD 107, 114021 (2023); 2307.07999

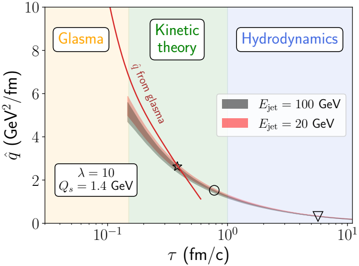
- Classical-statistical simulations of hard probes in the **Glasma** phase
  - Extraction of κ_i and $\hat{q}_i$
    Ipp, Müller, Schuh (2020); KB, Kurkela, Lappi, Peuron (2020); Carrington, Czajka, Mrowczynski (2022); Khowal, Das, Oliva, Ruggieri (2022); Avramescu et al. (2023); Pandey, Schlichting, Sharma (2024); ...
  - Often using $\kappa, \hat{q} \sim \int \mathrm{d}\tau \langle \mathcal{F}\mathcal{F} \rangle$, here via particle-in-cell method
  - Large values, anisotropic $\kappa_z > \kappa_T$ and $\hat{q}_z > \hat{q}_y$ (z is beam direction)
  - Why are they large? Why do κ_z and $\hat{q}_z$ become negative?



κ of heavy quarks



$\hat{q}$ for jet quenching

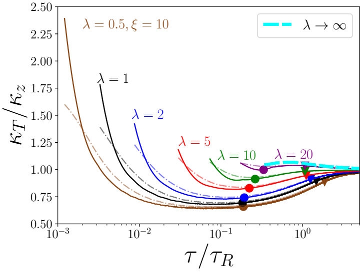


KB, Kurkela, Lappi, Lindenbauer, Peuron, for κ PRD [2303.12520];
for $\hat{q}$: Phys. Lett. B (2024) [2303.12595], PRD [2312.00447]

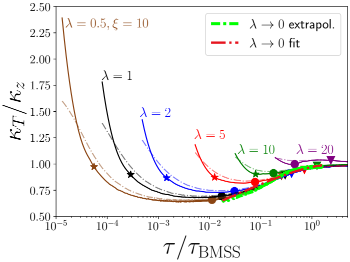
- $\hat{q}$ smoothly connects Glasma and hydro, κ not so much
- Mostly the same ordering $\kappa_z > \kappa_T$ and $\hat{q}_z > \hat{q}_y$
- Evolution in kinetic regime understood, what about Glasma? (later)

Limiting attractors

Rescaling with $\tau_R = \frac{4\pi\,\eta/s(\alpha_s)}{T_\epsilon(\tau)}$



Rescaling with $\tau_{\text{BMSS}} = \alpha_s^{-13/5}/Q$



KB, Kurkela, Lappi, Lindenbauer, Peuron, Phys. Lett. B (2024) [2312.11252]

- Limiting attractors from extrapolating coupling $\lambda = 4\pi N_c \alpha_s$
- Hydrodynamic lim. attr. ($\lambda \to \infty$): very good description of P_L/P_T
- Bottom-up lim. attr. ($\lambda \to 0$): early description of $\hat{q}^{yy}/\hat{q}^{zz}$, κ_T/κ_z

$\Rightarrow$ some 'ratios' better described with bottom-up even at $\lambda \sim \mathcal{O}(10)$

- Also: HQ drag and diffusion coeff. scale at hydro attractor (Du, PRC (2024))

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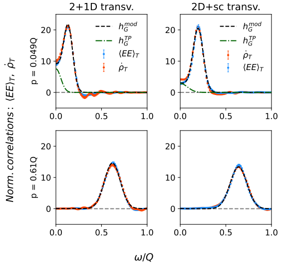
Towards understanding κ_i in the Glasma

L. Backfried, KB, P. Hotzy, 2408.12646

Connect to collective excitations in the pre-equilibrium QGP

- *Spectral functions* $\rho(t, \omega, p) \sim \langle[\hat{A}, \hat{A}]\rangle$ encode excitation spectrum!
- Compute $\langle EE \rangle$ in class.-stat. + algorithm for ρ (KB, Kurkela, Lappi, Peuron (2018))

Transv. polarization (w.r.t. $\vec{p}$)



Models (non-exp. geometry)

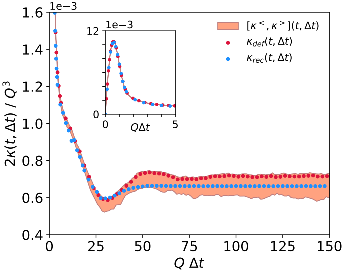
- 2+1D: Yang-Mills $S_{\mathrm{YM}}^{\mathrm{2D}}$
- 2D+sc: $S_{\mathrm{YM}}^{\mathrm{2D}}$ + adj. scalar A_z

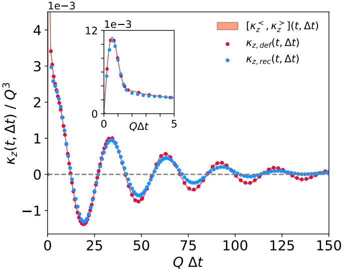
$\Rightarrow$ Glasma-like but at classical attractor + Minkowski

extending [KB, Kurkela, Lappi, Peuron (2019, 2021)]

- HTL perturbation theory breaks down $\Rightarrow$ broad Gaussian excitations
- New transport peak h_G^{TP} at $\omega = 0$ for $p \lesssim m_D$ $\Rightarrow$ nonperturbative!

Heavy-quark diffusion coefficients in 2+1D plasmas

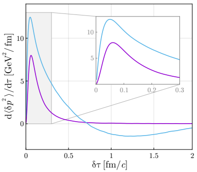




$$2\kappa(t,\Delta t) \approx \frac{g^2}{N_c}\int_t^{t+\Delta t} \mathrm{d}t'\,\langle EE\rangle(t,t',\Delta\vec{x}{=}0)\,,\qquad \Rightarrow \text{gauge invariant}$$

$$\approx \frac{g^2}{N_c}\int_{\vec{p}}\int_{-\infty}^{\infty}\frac{\mathrm{d}\omega}{2\pi}\frac{\sin(\omega\Delta t)}{\omega}\sum_{\alpha=T,L}\langle EE\rangle_\alpha(t,\omega,p)$$

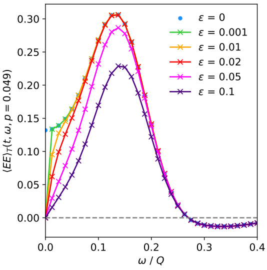
Glasma reminder



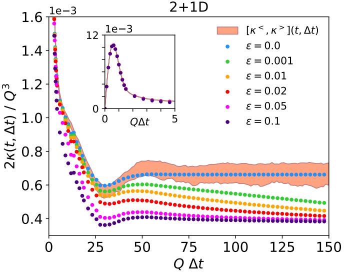
- Initial linear rise $\kappa_i \sim \Delta t\,\langle EE\rangle_i(t,t)$ (KB, Kurkela, Lappi, Peuron ('20))
- Qualitatively similar to Glasma: 2κ finite (diffusive), κ_z around 0
- Gauge-fixed correlators $\langle EE\rangle_\alpha(t,\omega,p)$ reconstruct evolution

Manipulate correlations ⇒ study impact

Suppress low ω of $\langle EE \rangle_T$



2+1D gluonic 2κ



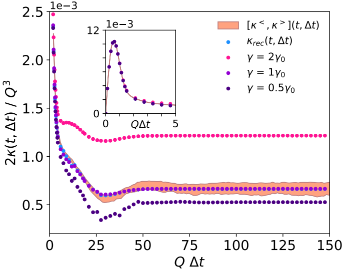
$$2\kappa(t, \Delta t) \approx \frac{g^2}{N_c} \int_{\vec{p}} \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi} \frac{\sin(\omega \Delta t)}{\omega} \sum_{\alpha = T, L} \langle EE \rangle_\alpha(t, \omega, p)$$

- Significant impact on late-Δt evolution
  - ⇒ Evidence of a new transport peak in Glasma-like systems!

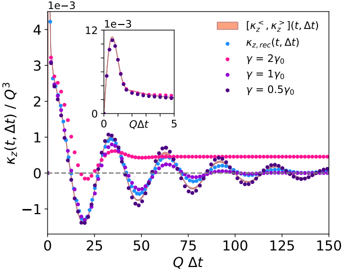
- Preliminary: transport peak also in Glasma (KB, Hotzy, Müller, *in progress*)
  - ⇒ Enhanced transport coefficients, relevance for initial stages?

Manipulate correlations $\Rightarrow$ study impact II

2+1D gluonic 2κ



Glasma-like scalar κ_z



$$2\kappa(t,\Delta t) \approx \frac{g^2}{N_c} \int_{\vec{p}} \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi} \frac{\sin(\omega \Delta t)}{\omega} \sum_{\alpha=T,L} \langle EE \rangle_\alpha(t,\omega,p)$$

- Change peak width $\gamma \Rightarrow$ mismatch with simulations
  $\Rightarrow$ 2κ requires broad $\langle EE \rangle_T$ and κ_z narrow $\langle EE \rangle_z$
- We also demonstrate: scalars are enhanced at low $p \lesssim m_D$ (Backup)

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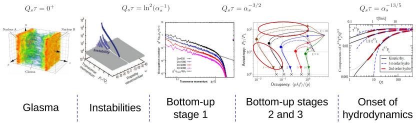
Conclusion



- Initial stages of the QGP
  - $\Rightarrow$ waves vs. particles

- Hard probes (jets, heavy quarks, quarkonia): medium interactions
  - $\Rightarrow$ Coefficients κ, $\hat{q}$ in Glasma and bottom-up $\to$ large, anisotropic
  - $\Rightarrow$ Kinetics: hydrodynamic and limiting attractors useful
  - $\Rightarrow$ Phenomenology: Impact/signatures of pre-equilibrium dynamics?

- Collective excitations of pre-equilibrium QGP influence hard probes
  - $\Rightarrow$ Evidence of new tranport peak in Glasma-like plasmas
  - $\Rightarrow$ Significant impact on transport coefficients

Thank you for your attention!

Backup slides

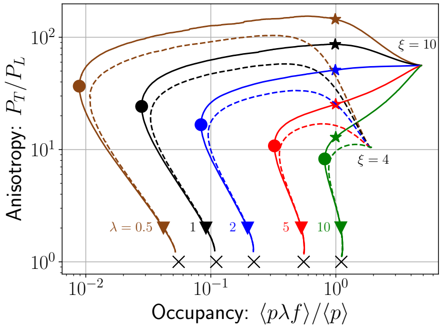
Kinetic theory ⇒ Bottom-up thermalization scenario

- Bottom-up scenario

  Baier, Mueller, Schiff, Son, PLB (2001)

- Consists of three stages
  1. Classical attractor
  2. Anisotropy freezes
  3. Radiational breakup

- Different bottom-up stages separated by markers ($\lambda = g^2 N_c$)
  - ★ large pressure anisotropy $P_T \gg P_L$, occupancy $f \sim 1/\lambda$
  - • minimum (mean) occupancy f
  - ▽ close to isotropic $P_T/P_L = 2$



Kurkela, Zhu (2015); *version from:* KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

- Pressure $P_{T,L} \sim \int d^3p \frac{p^2_{\perp,z}}{p} f$
- Mean $\langle O\rangle = \int d^3p\, f(p)\, O(p)$

- Thermalization time scale $\tau_{\rm BMSS} = \alpha_s^{-13/5}/Q_s$, initial momentum Q_s

QGP description: effective kinetic theory (EKT)

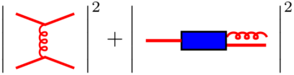
- When quasiparticles have formed: Kinetic theory applicable

  Note: Assumes narrow excitations in spectral functions, which may not be true at low momenta for strong anisotropy (Backup in 'ρ': 'Gluonic 2+1D')

  KB, Kurkela, Lappi, Peuron (2018, 2019, 2021)

- Time evolution described by Boltzmann equation at LO

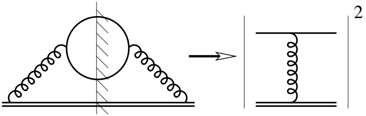
$$(\partial_t + \boldsymbol{v} \cdot \boldsymbol{\nabla}) f =$$



$$\frac{\partial f_{\vec{p}}}{\partial \tau} - \frac{p_z}{\tau} \frac{\partial f_{\vec{p}}}{\partial p_z} = -\mathcal{C}^{2\leftrightarrow 2}[f_{\vec{p}}] - \mathcal{C}^{1\leftrightarrow 2}[f_{\vec{p}}]$$

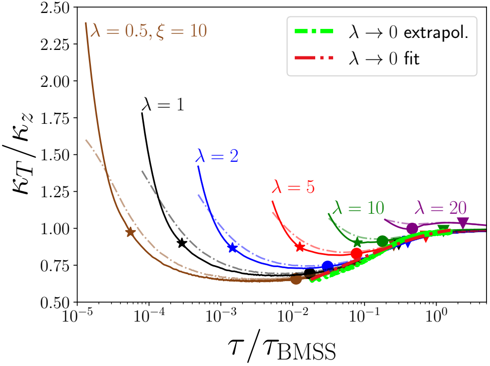
Arnold, Moore, Yaffe, JHEP 01, 030 (2003)

- Heavy-quark coefficient κ_i: Moore, Teaney (2005); Caron-Huot, Moore (2008)



Transverse vs. longitudinal diffusion

KB, Kurkela, Lappi, Lindenbauer, Peuron, 2303.12520



- $\kappa_T > \kappa_z$ during over-occupied stage   (z is longitudinal/beam axis)
- $\kappa_T < \kappa_z$ after $\star$ due to momentum anisotropy and low occupancy
- Most of the time $\kappa_T < \kappa_z$, anisotropy larger at weak coupling

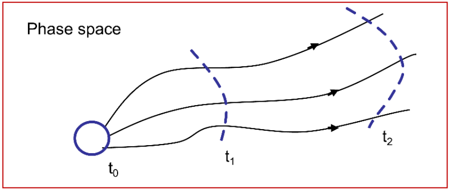
Classical-statistical simulations

- At initial time t_0 set (quantum) initial conditions (IC):

$\Rightarrow$ Choose $\langle AA \rangle$, $\langle EE \rangle$ in x or p space

- Approximate quantum dynamics with classical EOMs $D_\mu F^{\mu\nu} = 0$
  - $\Rightarrow$ Gauge co-variant lattice formulation using links $U_j(x) = e^{ig\, a_j\, A_j(x)}$

- Obtain observables at t by averaging over trajectories (same IC)

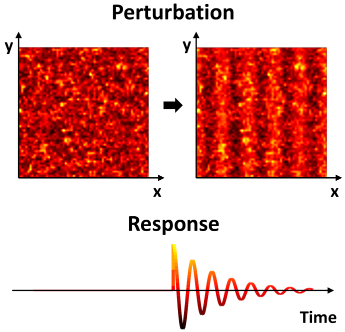


- Valid if occupancies large $f(t,p) \approx \langle AA \rangle p \approx \langle EE \rangle / p \gg 1$
- Applicability limited to earliest times!

Quasiparticles? Extract gluon spectral function ρ

Classical-statistical $\mathrm{SU}(N_c)$ simulations + linear response theory

KB, Kurkela, Lappi, Peuron, *PRD 98, 014006 (2018)*



- Similar algorithm for fermions
- Split $A(t,\vec{x}) \mapsto A(t,\vec{x}) + \delta A(t,\vec{x})$ at t, perturb with plane wave $j_0(\vec{p})\,\delta\,(t'-t)$
- Response $\langle \delta A(t',\vec{p})\rangle = G_R(t',t,\vec{p})\, j_0(\vec{p})$
- Linearized EOM for $\delta A(t,\vec{x})$ such that Gauss law conserved (also in gauge-cov. formulation)

  Kurkela, Lappi, Peuron, *EUJC 76 (2016) 688*
- $\theta(t'-t)\ \boxed{\rho(t',t,p)} = G_R(t',t,p)$
- Fourier transform $\rho(\bar{t},\omega,p)$ $\quad (\bar{t} = \frac{1}{2}(t+t'))$

Very similar methods for scalars:

Aarts (2001); Piñeiro Orioli, Berges (2019); Schlichting, Smith, von Smekal (2020); KB, Piñeiro Orioli (2020); ...

Spectral and statistical correlation functions

- Equal-time correlator $\langle\{\hat{E}(t), \hat{E}(t)\}\rangle \propto f(t,p)$ is distribution
  $\Rightarrow$ But what are the relevant excitations?
- Knowledge of spectral function needed ($\dot{\rho} = \partial_t \rho,\ E = \partial_t A$)

$$\dot{\rho}(x,x') = \frac{i}{N_c^2 - 1} \left\langle \left[\hat{E}(x), \hat{A}(x')\right] \right\rangle$$

- Statistical correlator $\langle EE \rangle$ ($\equiv \ddot{F}$) in general independent of $\dot{\rho}$

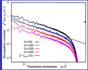
$$\langle EE \rangle(x,x') = \frac{1}{2(N_c^2 - 1)} \left\langle \left\{\hat{E}(x), \hat{E}(x')\right\} \right\rangle$$

- Fourier transf. in $t - t'$ and $\vec{x} - \vec{x}'$ to frequency ω and momentum $\vec{p}$
  Approximation: normally at fixed $\bar{t} = \frac{1}{2}(t + t')$, we hold $t \approx \bar{t}$
- In classical-statistical simulations

$$\langle EE \rangle(t,t',p) = \frac{1}{N_c^2 - 1} \left\langle E(t,\vec{p}) E^*(t',\vec{p}) \right\rangle$$

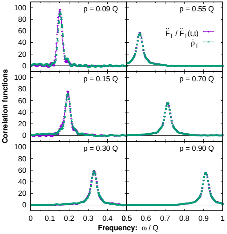
- Gauge: temporal $A_0 = 0$ + Coulomb-type $\partial^j A_j \big|_t = 0$

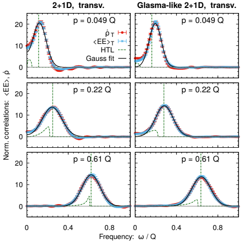
What excitations drive the dynamics in the QGP?

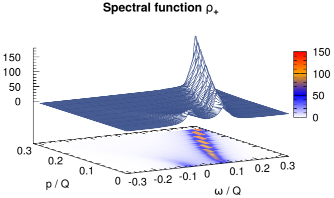


Study microscopics of the Quark-Gluon plasma

- *Spectral functions* $\rho(t, \omega, p) \sim \langle [\hat{A}, \hat{A}] \rangle$ encode excitation spectrum!
- Compute $\langle EE \rangle$ in class.-stat. + algorithm for ρ (KB, Kurkela, Lappi, Peuron (2018))
- Generalized FDR observed $\langle EE \rangle \sim \omega \rho$







Gluonic 3+1D

Gluonic 2+1D

Fermionic 3+1D

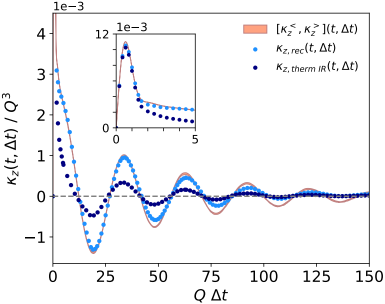
KB, Kurkela, Lappi, Peuron (2018, 2019, 2021)

KB, Lappi, Mace, Schlichting (2022)

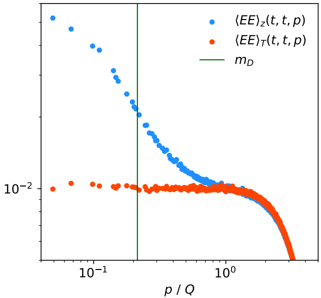
- Gauge fixed: temporal $A_0 = 0$ + Coulomb-type $\partial^j A_j \big|_t = 0$

2+1D: Manipulate correlations ⇒ study impact III

Glasma-like scalar κ_z



Equal-time correlators $\langle EE \rangle_\alpha(t, t, p)$



$$\kappa_z(t, \Delta t) \approx \frac{g^2}{N_c} \int_{\vec{p}} \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi} \frac{\sin(\omega \Delta t)}{\omega} \langle EE \rangle_z(t, t, p) \frac{\dot{\rho}_z(t, \omega, p)}{\dot{\rho}_z(t, t, p)}$$

- If no infrared excess of scalars, smaller oscillations
  ⇒ evidence of infrared enhancement!