High energy probes of the initial stages

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Together with:

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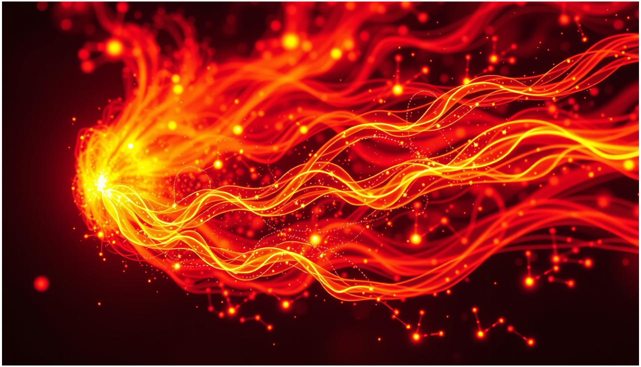
Table of Contents

Table of Contents

Quark-gluon plasma

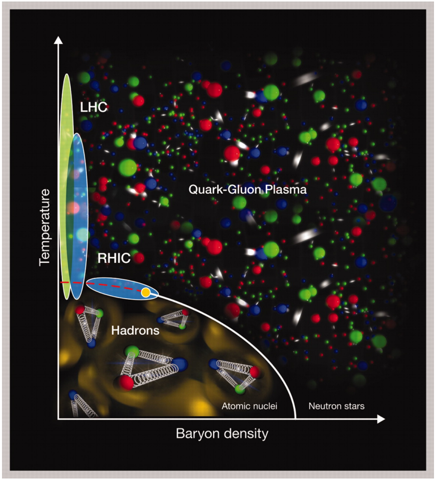
The hottest matter in the world

At 4 trillion °C consisting from elementary particles



QCD phase diagram

- High T or density:
  Quark-Gluon plasma (QGP)
  (Other phases may also be possible)
- Low temperature T: hadrons
- *Early Universe:* High to low T
- *On Earth:* QGP formed in heavy-ion collisions (LHC at CERN, RHIC at BNL)



Jacak, Müller, Science 6092, 310 (2012)

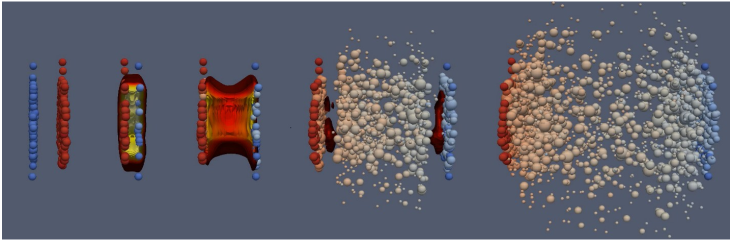
Colliders reproduce QGP from first instants of Early Universe!

Colliders: zooming in on elementary particles

LHC @ CERN (Photo: Maximilen Brice)

- Heavy-ion collider facilities
  - Large Hadron Collider (LHC) at CERN
  - Relativistic Heavy Ion Collider (RHIC) at BNL
  - FAIR particle accelerator facility at GSI
- Many goals, for us essential
  - study QCD under extreme conditions!
  - for us more precisely: QGP in and out of equilibrium

Stages in heavy-ion collisions



MADAI collaboration

- Quark-Gluon plasma created between colliding heavy ions
- Cooling during evolution, go through different **phases**
  $\Rightarrow$ Collision $\rightarrow$ pre-QGP (non-equ.) $\rightarrow$ fluid QGP $\rightarrow$ hadrons $\rightarrow$ detectors
- **Pre-QGP:** testing the very nature of quantum physics
  $\Rightarrow$ Gluons first as (classical) waves $\rightarrow$ scatterings of (quasi-)particles

Goals

Learn about **high-energy** and **real-time** properties of QCD

Some properties of the QGP

- Nearly perfect fluid (small specific shear viscosity η/s)
- *Heavy-ion collisions:* Fast hydrodynamization (~ 1 fm/c $\sim 10^{-24}$ s)

Many current hot topics! Some examples:

- Experiments show flow in pp, pA collisions, also O+O
  $\Rightarrow$ QGP in small systems? Differences to AA collisions?
- What is the correct initial state? Is saturation observable?
- Can we describe and measure the pre-QGP dynamics?
- How are hard probes (jets, Q, $Q\bar{Q}$, ...) influenced by the QGP?
- Does the QCD phase diagram have a critical point? Where?
- Do we really understand the phase transition?
  $\Rightarrow$ Lattice and phenomenological studies may suggest new phase between QGP and hadron gas

Table of Contents

Pre-QGP: classical-statistical description (weak $g^2 \ll 1$)

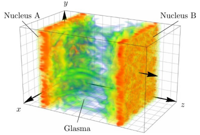
Quantum wave particle duality, approximative descriptions

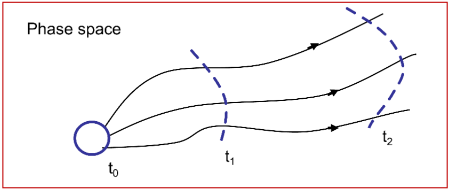
classical fields $A(t, \vec{x})$ ('waves') $\rightarrow$ interacting particle distribution $f(t, \vec{p})$

- initially: classical-statistical simulations
  - $\Rightarrow$ (modeled) quantum initial conditions: **'Glasma', highly-occupied gluonic plasma**
  - $\Rightarrow$ nonlinearly interacting classical waves on a lattice
  - $\Rightarrow$ ('Yang-Mills') generalization of Maxwell's Eqs.

$$D_{\mu,ab} F_b^{\mu\nu} = J_a^\nu$$

  - $\Rightarrow$ justified when gluon fields large $A_{\mu,a} \sim 1/g$





Pre-QGP: QCD kinetic theory (weak $g^2 \ll 1$)

Quantum wave particle duality, approximative descriptions

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- initially: classical-statistical simulations, 'Glasma'
  - $\Rightarrow$ (modeled) quantum initial conditions
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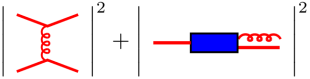
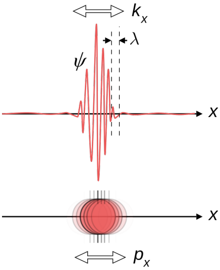
- as T^{00} decreases: QCD eff. kinetic theory (EKT)
  - $\Rightarrow$ Boltzmann equation for f

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





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

Thermalization scenario: Baier, Mueller, Schiff, Son (2001);

QCD EKT: Arnold, Moore, Yaffe, JHEP 01, 030 (2003); Abraao York, Kurkela, Lu, Moore (2014); Kurkela, Zhu (2015)

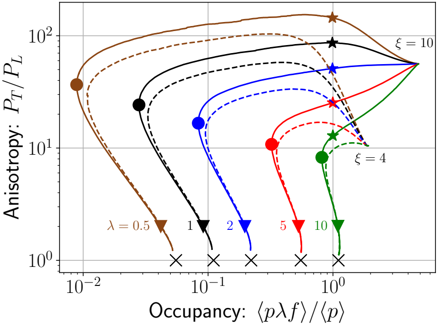
Kinetic theory ⇒ Bottom-up thermalization scenario

- 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 $P_T/P_L = 2$



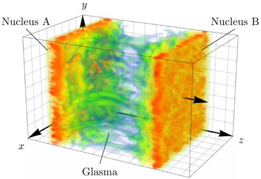
Kurkela, Zhu (2015); *version from:* KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

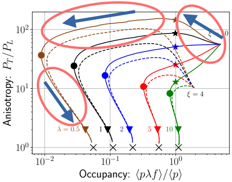
- Pressure $P_{T,L} \sim \int d^3p \frac{p^2_{\perp,z}}{p} f$
- Mean $\langle O\rangle = \int d^3p\, f(p)\, O(p)$

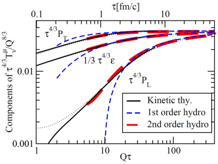
- Thermalization time scale $\tau_{\rm BMSS} = \alpha_s^{-13/5}/Q_s$, initial momentum Q_s

Initial stages of the pre-QGP (weak-g^2 perspective)

Glasma, high occupation | Bottom-up stages | Hydrodynamization







0 fm/c | 0.1 fm/c | 1 fm/c | 10 fm/c

Classical field theory | *QCD kinetic theory* | *Viscous hydrodynamics*

Figures: Ipp, Müller (2017); Kurkela, Zhu (2015) + *adapted by:* KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

- Glasma: Large fields A & occupancies, flux tubes, transv. domains
  [In practice, transition Glasma → kinetic often matched, not smooth]
- Kinetic: Quasiparticles, dense & dilute stages, anisotropies

⇒ **In principle, experimentally testable features!**

- Other approaches: holography (strong-g^2), pQCD transport models, ...

Research on pre-QGP dynamics

Non-equilibrium QCD

Is our thermalization picture complete? Weak vs. strong coupling?

- (Standard) Picture of hydrodynamization (for 5-10 ys, based on weak g^2 QCD)
- Interplay of initial state, classical simulations, kinetic theory

$\Rightarrow$ Saturated initial state? Glasma?

$\Rightarrow$ Practical framework for transition to EKT?

$\Rightarrow$ Do we account for all relevant ingredients, excitations?

$\Rightarrow$ Do we have the right numerical descriptions?

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Towards experimental traces and applications

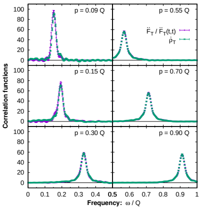
How can we probe pre-QGP experimentally? Signatures? Universality?

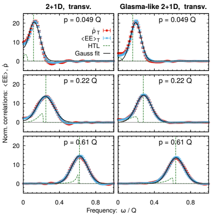
- How does pre-QGP affect hard (QCD) probes?
- What are the right observables?
- Universal attractors: Can we understand and exploit them?

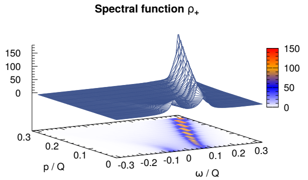
⇒ Hot topics: new properties and opportunities

What excitations drive the dynamics in the pre-QGP?

- Spectral functions $\rho(t,\omega,p) \sim \langle[\hat{A},\hat{A}]\rangle$ encode the excitation spectrum!
- Compute ρ via linear response (Kurkela, Lappi, Peuron (2016); KB, Kurkela, Lappi, Peuron (2018))
- (Nonperturbative) Classical-statistical lattice simulations for ρ and $\langle EE\rangle$







Gluonic 3+1D

Gluonic 2+1D

Fermionic 3+1D

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

KB, Lappi, Mace, Schlichting (2022)

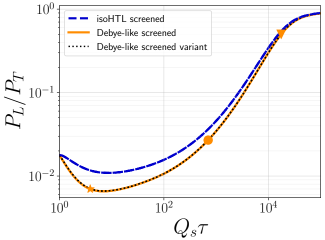
- Accurate perturbative (HTL) description in 3+1D; full p of lifetimes
- Nonperturb. in 2+1D: short lifetimes, new transport peak ($\omega = 0$)
- Impact on transport properties (KB, Kurkela, Lappi, Peuron (2020); Backfried, KB, Hotzy (2024))

Improving QCD kinetic theory

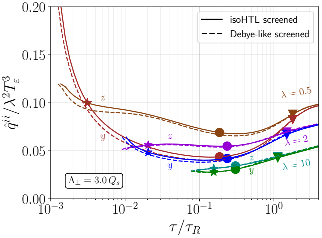
Does soft-gluon exchange matter (improving screening for gluons)?

KB, Lindenbauer, PRD, 2024

Yes, at early times



Not really for $\hat{q}^{ii}$



$$\mathcal{C}^{2\leftrightarrow 2}[f_{\vec{p}}] = \frac{1}{4|\vec{p}|\nu_g}\int_{kp'k'} |\mathcal{M}|^2 (2\pi)^4 \delta^{(4)}(P+K-P'-K')\left(f_{\vec{p}} f_{\vec{k}}(1+f_{\vec{p}'})(1+f_{\vec{k}'}) - f_{\vec{p}'} f_{\vec{k}'}(1+f_{\vec{p}})(1+f_{\vec{k}})\right)$$

- Screening in $\frac{|\mathcal{M}|^2}{4\lambda^2 d_A} = 9 + \frac{(t-s)^2}{\underline{u^2}} + \frac{(s-u)^2}{\underline{t^2}} + \frac{(u-t)^2}{s^2}$ (Arnold, Moore, Yaffe (2003))
- Debye-like: self-energy approx. by m_D; isoHTL: using full (isotropic) HTL

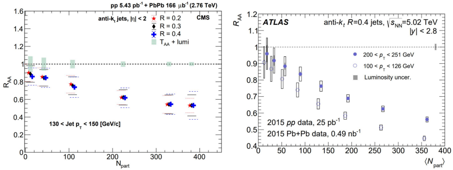
- Screening in full QCD kinetic theory (KB, Lindenbauer, Mazeliauskas, Takacs, Zhou (2025))
- Splitting function with anisotropy (Lindenbauer (2025); Altenburger, KB, Lindenbauer (2025))

Table of Contents

Hard probes are modified while traversing the QGP

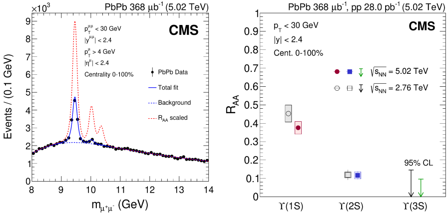
Examples: jets ($p \gg T$), heavy quarks (c, b), quarkonia ($q\bar{q}$)

Jet energy loss / suppression



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

Bottomonium suppression

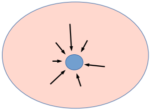


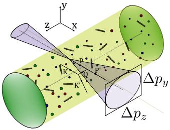
Transport coefficients from (pre-)QGP

Jets, heavy quarks: potential for signatures of initial stages

medium interactions ⇒ QGP properties encoded in observables

- Quarks/jets get 'kicks' $\dot{p}_i(\tau) = \mathcal{F}_i(\tau)$
- Heavy-quark diffusion coefficient $\kappa_i = \frac{\mathrm{d}}{\mathrm{d}\tau}\langle p_i^2 \rangle$
  - ⇒ heavy quark, small momentum $p \ll M$
- κ relevant for quarkonium dynamics
  - ⇒ suppression of bottomonium ($b\bar{b}$ states)
- Jet quenching parameter $\hat{q}_i = \frac{\mathrm{d}}{\mathrm{d}\tau}\langle p_{\perp,i}^2 \rangle$
  - ⇒ jet with high momentum $p \gg Q_s, T$
- They encode also pre-equilibrium dynamics

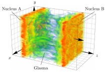




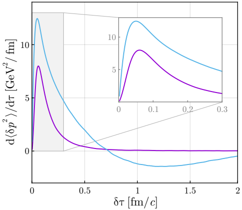
KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

Fochler, Xu, Greiner (2009); 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); Grishmanovskii et al. (2022); Avramescu, Baran, Greco, Ipp, Müller, Ruggieri (2023); KB, Kurkela, Lappi, Lindenbauer, Peuron (2023, 2024); Du (2023); Barata, Sadofyev, Wang (2023); Andres et al. (2023); Pandey, Schlichting, Sharma (2024); Zhou, Brewer, Mazeliauskas (2024); Barata, Hauksson, Lopez, Sadofyev (2024); Priyam Adhya, Tywoniuk (2024); KB, Lindenbauer (2024); Avramescu, Greco, Lappi, Mäntysaari, Müller (2024); ...

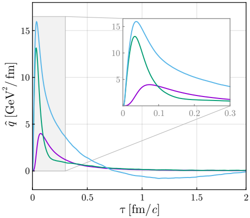
κ and $\hat{q}$ during Glasma phase



κ_i of beauty quarks



$\hat{q}_i$ of jets



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

- Classical-statistical simulations of hard probes in the **Glasma** phase
  - Gauge-invariant extraction of κ_i and $\hat{q}_i$
  - Via $\langle \mathcal{F}\mathcal{F} \rangle$ correlators, particle-in-cell, or linearized perturbations
    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); ...
  - Large values, anisotropic $\kappa_z > \kappa_T$ and $\hat{q}_z > \hat{q}_y$ (z is beam direction)
  - $\kappa_i \sim \tau$ (coherence), $\kappa_z < 0$ (gluon q.p.), large κ_i (transport peak)
    KB, Kurkela, Lappi, Peuron (2020); Backfried, KB, Hotzy (2024)
- What about kinetic regime? $\Rightarrow$ [more details later]

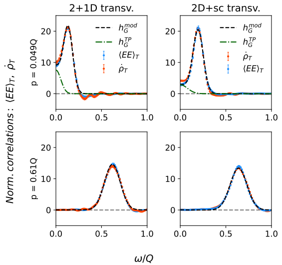
Towards understanding κ_i in the Glasma

L. Backfried, KB, P. Hotzy, PRD (2024)

Connect to collective excitations in the pre-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

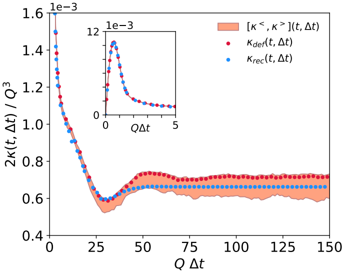
$\Rightarrow$ Glasma-like but at classical attractor + Minkowski

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

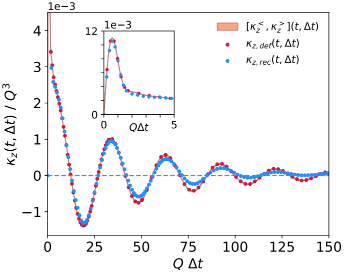
- HTL perturbation theory breaks down $\Rightarrow$ broad Gaussian excitations
- New transport peak h_G^{TP} at $\omega = 0$ for $p \lesssim m_D$ $\Rightarrow$ nonperturbative!

Heavy-quark diffusion coefficients in 2+1D plasmas

2+1D gluonic 2κ



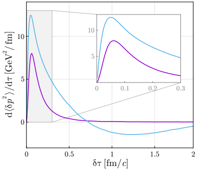
Glasma-like scalar κ_z



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

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

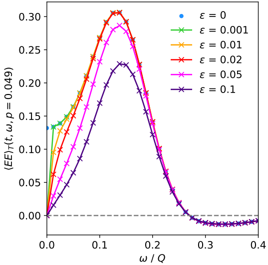
Glasma reminder



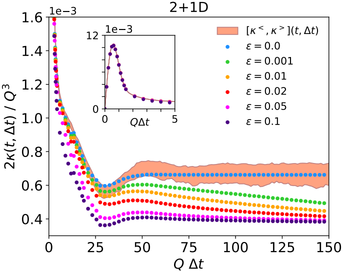
- Initial linear rise $\kappa_i \sim \Delta t\,\langle EE\rangle_i(t,t)$ (KB, Kurkela, Lappi, Peuron ('20))
- Qualitatively similar to Glasma: 2κ finite (diffusive), κ_z around 0
- Gauge-fixed correlators $\langle EE\rangle_\alpha(t,\omega,p)$ reconstruct evolution

Manipulate correlations ⇒ study impact

Suppress low ω of $\langle EE \rangle_T$



2+1D gluonic 2κ

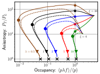


$$2\kappa(t, \Delta t) \approx \frac{g^2}{N_c} \int_{\vec{p}} \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi} \frac{\sin(\omega \Delta t)}{\omega} \sum_{\alpha = T, L} \langle EE \rangle_\alpha(t, \omega, p)$$

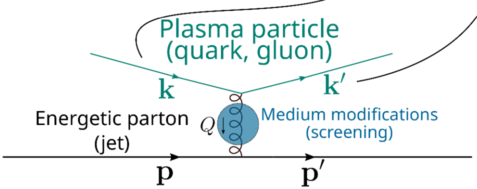
- Significant impact on late-Δt evolution
  ⇒ Evidence of a new transport peak in Glasma-like systems!

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

κ and $\hat{q}$ during kinetic phase



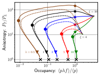
$$\hat{q}^{ij} = \int_{\substack{q_\perp < \Lambda_\perp \\ p \to \infty}} \mathrm{d}\Gamma \, q^i q^j |\mathcal{M}|^2 f(k)(1 + f(k'))$$



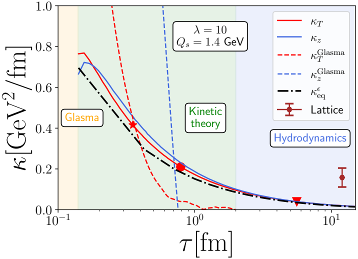
F. Lindenbauer

- Diagrammatic calc. leads to expressions for kinetic-theory
- Similar calculations and expressions for κ_i and other transport coeff.
- From linearization of kinetic theory: corrections (recoiling medium)!
  KB, Lindenbauer, Mazeliauskas, Takacs, Zhou (2025)
- Logarithmic dependence on $q_\perp$ cutoff, $\hat{q}(\Lambda_\perp)$, for $p \to \infty$

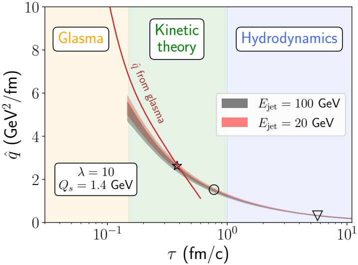
κ and $\hat{q}$ during kinetic phase



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]

- **Kinetic** regime: $\hat{q}$ smoothly connects Glasma and hydro, κ not quite
- Also large values, mostly the same ordering $\kappa_z > \kappa_T$ and $\hat{q}_z > \hat{q}_y$
- Pre-QGP important for HQ broadening $\langle \Delta p^2 \rangle_{\rm neq} \sim \langle \Delta p^2 \rangle_{\rm eq}$

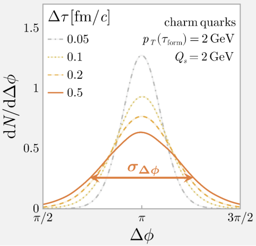
Carrington, Czajka, Mrowczynski (2022); KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

$\Rightarrow$ Impact on (differential) observables? Phenomenological impact?

Anisotropies and pre-QGP lead to azimuthal structures

$c\bar{c}$ pair in Glasma

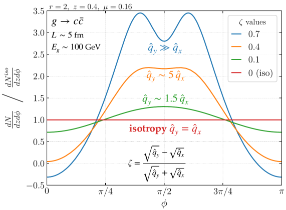
Avramescu et al., PRL (2025)



Correlation remains large

Jet $g \to Q\bar{Q}$ spectrum

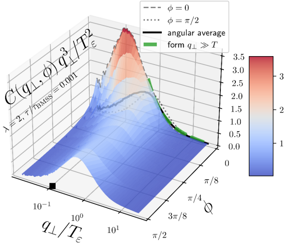
Barata, Salgado, Silva, JHEP (2024)



Effect from anisotropic $\hat{q}_i$

Jet coll. kernel in EKT

Altenburger, KB, Lindenbauer (2025)



From anisotropic dynamics

- Medium anisotropies observable via jet polarization?

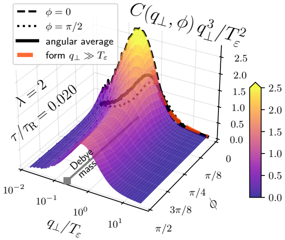
  Hauksson, Iancu (2023); Barata, Salgado, Silva (2024)

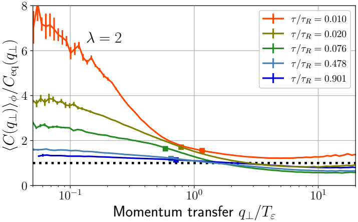
- Or via differential gluon emission spectra, jet substructure?

  Barata, KB, Lindenbauer, Sadofyev (2025)

Jet collision kernel in kinetic theory beyond $\hat{q}$

Altenburger, KB, Lindenbauer (2025)





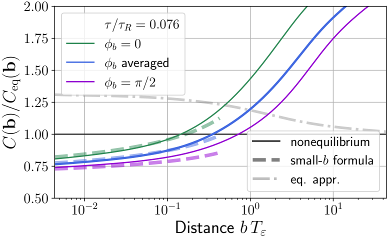
$$C(\vec{q}_\perp) = \int d\Gamma\, |\mathcal{M}|^2 f(\vec{k})(1 + f(\vec{k} - \vec{q}))\,, \qquad \hat{q} = \int \frac{d^2 q_\perp}{(2\pi)^2}\, \vec{q}_\perp^{\,2}\, C(\vec{q}_\perp)$$

- Broadening along ($\phi = 0$) or transverse to ($\phi = \pi/2$) beam axis
- Early times: strong anisotropy, peak shift, enhanced kernel at low $q_\perp$
- Dipole cross section (impact par.): $C(\vec{b}) = \int \frac{d^2 \vec{q}_\perp}{(2\pi)^2} \left(1 - e^{i\vec{b}\cdot\vec{q}_\perp}\right) C(\vec{q}_\perp)$

Dipole cross section beyond harmonic approximation

Altenburger, KB, Lindenbauer (2025)

- Dipole cross section:
  $C(\vec{b}) = \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\left(1 - e^{i\vec{b}\cdot\vec{q}_\perp}\right) C(\vec{q}_\perp)$
- Jet quenching parameter included:
  $\hat{q}^i(\Lambda_\perp,\tau) \approx \hat{q}_0(\tau)\log\frac{\Lambda_\perp}{Q} + c_i(\tau)$



- Generic small-b form of the kernel

$$C(\vec{b},\tau) = \frac{1}{4}\hat{q}_0(\tau)\,\vec{b}^2\left(\log\frac{4}{\vec{b}^2 Q^2} + 2 - 2\gamma_E\right) + \frac{1}{2}b_i^2 c_i(\tau) + \mathcal{O}(b^4)$$

$$\approx \frac{1}{4}\hat{q}_0(\tau)\,\vec{b}^2\log\frac{1}{\vec{b}^2{\mu_*}^2(\tau)} \qquad \text{(for isotropic case)}$$

- Harmonic approximation requires cutoff scale, can be problematic:

$$C(\vec{b},\tau) \approx \frac{1}{4}\hat{q}(\Lambda_\perp,\tau)\,\vec{b}^2$$

Jet quenching in out-of-equilibrium QCD matter

$\Rightarrow$ Differential single gluon emission spectrum and jet substructure

Barata, KB, Lindenbauer, Sadofyev (2025)

- Strategy: use $\hat{q}_0(\tau)$ and $\mu_*(\tau)$ in Improved Opacity Expansion (OPE)
- Compute medium-induced spectrum ("medium - vacuum"): $\frac{dI}{d\omega d^2k}$
  - Compare to "static brick" approximation of $\hat{q}(\tau)$
  - Compare to corresponding Landau-matched thermal evolution
- Compute substructure observables or simply maximum

$$\chi_m = \frac{\text{Maximum spectrum nonequ.}}{\text{Maximum spectrum equ.}}$$

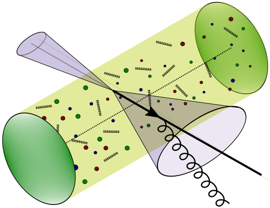
Related studies

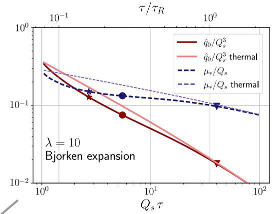
- Medium-induced radiation in Glasma model (Barata, Hauksson, Mayo López, Sadofyev (2024))
- Sensitivity of jet quenching to the initial state in heavy-ion collisions (Adhya, Tywoniuk (2025))

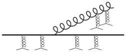
Jet quenching in out-of-equilibrium QCD matter

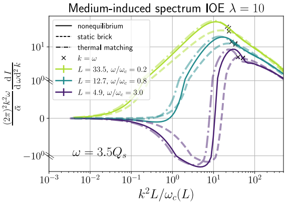
⇒ Differential single gluon emission spectrum in pre-QGP kinetic regime

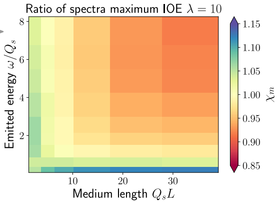
Barata, KB, Lindenbauer, Sadofyev (2025)







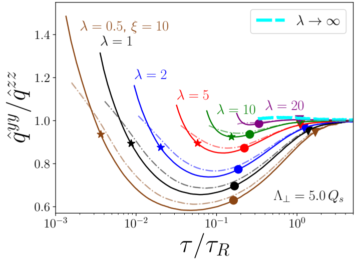




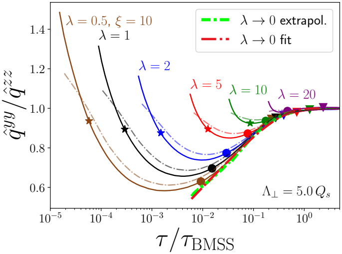
⇒ Changes due to pre-QGP dynamics remain at late times (large L)!

Limiting attractors

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



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



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

- 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
- Limiting attractors even in energy loss due to single gluon emission
  KB, Hörl, Lindenbauer (2026)

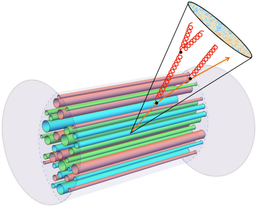
⇒ Attractors useful concept to study pre-QGP efects!

“Probing the early stages with jets”

Upcoming EMMI workshop @ GSI, Germany, 13.-17.07.26

Organizers: L. Apolinário, J. Barata, KB, L. Cunqueiro, T. Lappi

Registration: https://indico.gsi.de/event/24197/



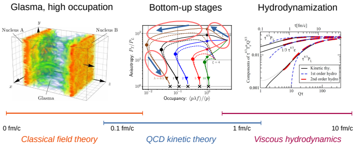
- **Focus:** intersection between jets and initial stages
- **Opportunities** for HL-LHC Runs 4 & 5, small systems, FAIR

Theory Institute, 2025 @ CERN: High energy probes of the initial stages

Organizers: J. Barata, KB, S.K. Das, C.A. Salgado, U.A. Wiedemann, K. Zapp

Table of Contents

Conclusion



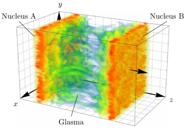
- QGP dynamics: many hot topics
- Initial stages of pre-QGP
  - ⇒ Classical waves vs. particles
- Pre-QGP dynamics is a central research area
  - ⇒ Well understood? Excitations and ingredients?
  - ⇒ Traces in small systems? Universal dynamics?
- Probing the pre-equilibrium medium evolution
  - ⇒ Hard probes (EM, jets, heavy quarks) access of early stages?
  - ⇒ Impact on transport coefficients, broadening, correlations, spectra, . . .
- High energy probes of the pre-QGP dynamics
  - ⇒ Workshops at CERN (2025) and at GSI (upcoming in 2026)
  - ⇒ Exciting opportunities, towards synergies with experiment

Thank you for your attention!

Backup slides

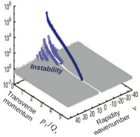
Strong initial fields: classical-statistical lattice simulations

- Glasma – large longitudinal fields, $D_\mu F^{\mu\nu} = J^\nu$
  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); ...



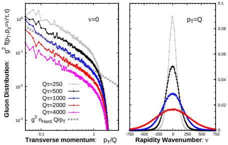
Ipp, Müller (2017)

- Plasma instabilities – from boost-invariant Glasma ($p_z \approx 0$) to highly occupied plasma ($|p_z| \gtrsim 0$)
  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, prescaling – universal dynamics of over-occupied plasma
  - $\Rightarrow$ agrees with 1. stage of 'bottom-up' scenario
    Berges, KB, Schlichting, Venugopalan (2013, 2014); Kurkela, Zhu (2015); Mazeliauskas, Berges (2019); Heller, Mazeliauskas, Preis (2024); ...
  - $\Rightarrow$ Far-from-equilibrium universality class with scalars
    Berges, KB, Schlichting, Venugopalan (2014, 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)

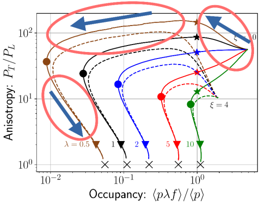
- Bottom-up thermalization: Baier, Mueller, Schiff, Son (2001)
  1. Classical attractor (see above)
  2. Anisotropy freezes
  3. Radiational breakup

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

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

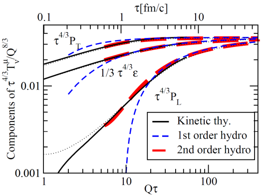
- EKT: smooth transition to hydrodynamics; hydrodynamic & limiting attractors
  A. Soloviev (2022); …; KB, Kurkela, Lappi, Lindenbauer, Peuron (2024)

Bottom-up evolution



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

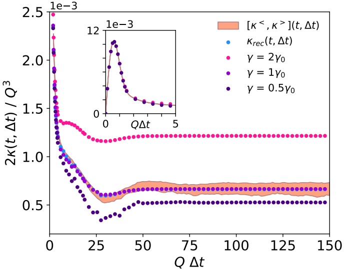
Onset of hydro



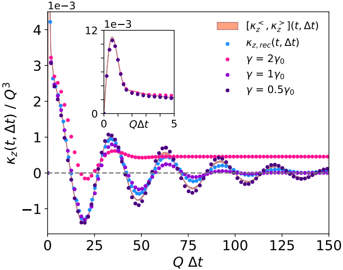
Kurkela, Zhu (2015)

Manipulate correlations ⇒ study impact on κ_i II

2+1D gluonic 2κ



Glasma-like scalar κ_z

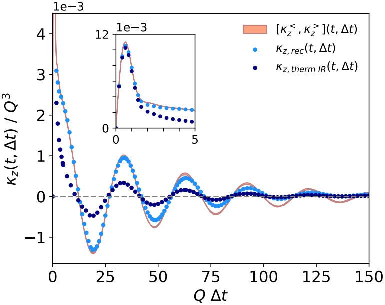


$$2\kappa(t,\Delta t) \approx \frac{g^2}{N_c} \int_{\vec{p}} \int_{-\infty}^{\infty} \frac{\mathrm{d}\omega}{2\pi} \frac{\sin(\omega \Delta t)}{\omega} \sum_{\alpha=T,L} \langle EE \rangle_\alpha(t,\omega,p)$$

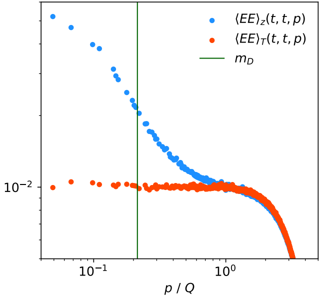
- Change peak width γ ⇒ mismatch with simulations
  ⇒ 2κ requires broad $\langle EE \rangle_T$ and κ_z narrow $\langle EE \rangle_z$
- We also demonstrate: scalars are enhanced at low $p \lesssim m_D$

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!

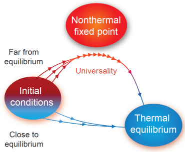
What is universal about initial stages?

Stage 1 in bottom-up scenario

Nonthermal fixed point, links to different systems (e.g., cold atoms)

Universality: Berges, Rothkopf, Schmidt (2008); Piñeiro Orioli, KB, Berges (2015); Berges, KB, Schlichting, Venugopalan (2015); Walz, KB, Berges (2017); Chantesana, Piñeiro Orioli, Gasenzer (2018); KB, Piñerio Orioli (2020); . . .

Cold-atom exp.: Prüfer et al., Nature (2018); Erne et al., Nature (2018); Glidden et al., Nature Phys. (2021); Gazo et al. (2023)



★ Initial over-occupancy ⇒ may approach attractor

★ System 'forgets' initial conditions

★ Self-similar universal dynamics

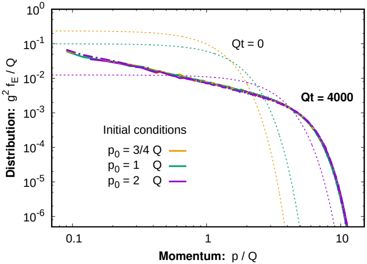
$$f(t,p) = t^{\alpha} f_s(t^{\beta} p)$$

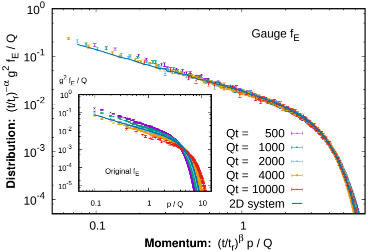
Recent developments on universality

- Prescaling (Schmied, Mikheev, Gasenzer (2019); Mazeliauskas, Berges (2019); Heller, Mazel., Preis (2024))
- Adiabatic hydrodyn. (Brewer, Yan, Yin (2019); Rajagopal, Scheihing-Hitschfeld, Steinhorst (2024))
- Hydrodynamic attractors (M. Heller's talk; **Limiting:** KB, Kurkela, Lappi, Lindenbauer, Peuron ('23))
- Gauge inv. condens. (Berges, KB, Mace, Pawlowski ('20); Berges, KB, Butler, de Bruin, Pawlowski ('24))

Example: gluon plasmas (isotropic)

Figures: attractor in 2+1D; KB, Kurkela, Lappi, Peuron, PRD 100, 094022 (2019)





- Gluonic initial $f_g(t{=}0, p \lesssim Q) \sim \frac{1}{g^2} \gg 1$ often approach attractors

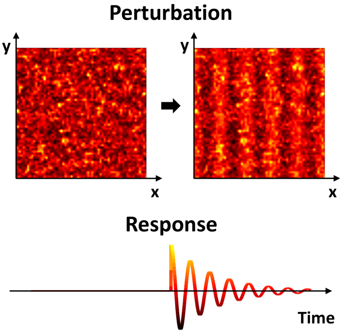
$$f(t,p) = (Qt)^{\alpha} f_s\left((Qt)^{\beta} p\right)$$

- Universal exponents insensitive to details of initial conditions
  - ✓ 2+1D: $\beta = -1/5,\ \alpha = 3\beta,$ KB, Kurkela, Lappi, Peuron (2019)
  - ✓ 3+1D: $\beta = -1/7,\ \alpha = 4\beta,$ Berges, Scheffler, Sexty (2009); Kurkela, Moore (2011, 2012); Berges, Schlichting, Sexty (2012); Schlichting (2012); Berges, KB, Schlichting, Venugopalan (2014); ...
- Great control ⇒ attractors useful to understand dynamical properties

Quasiparticles? Extract gluon spectral function ρ

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

KB, Kurkela, Lappi, Peuron, PRD 98, 014006 (2018), Editors' suggestion



- 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 $\partial^j A_j\big|_t = 0$

Perturbative computation: HTL results

- Hard loop (HTL) framework applicable for $m_D/\Lambda \ll 1$;
  in thermal equ. for $g \sim m_D/T \ll 1$, Braaten, Pisarski (1990); Blaizot, Iancu (2002); ...
- In 3+1D $m_D^2 = 4N_c \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{g^2 f(t,p)}{p} \sim g^2 f\,\Lambda^2 \Rightarrow$ HTL applicable
- In 2+1D soft-soft interactions important

$$m_D^2 \approx d_{\mathrm{pol}} N_{\mathrm{c}} \int \frac{\mathrm{d}^2 p}{(2\pi)^2} \frac{g^2 f(t,p)}{\sqrt{m^2 + p^2}} \sim g^2 f\,\Lambda \ln\left(\frac{\Lambda}{m_D}\right)$$

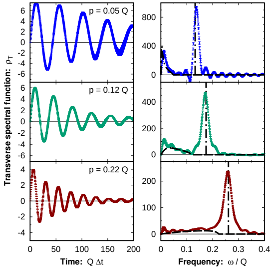
$\Rightarrow$ HTL breaks down already at soft scale $p \sim m_D$

- Comparison to HTL still useful to extract nonperturbative features
- Quasiparticles in $\rho^{\mathrm{HTL}}(\omega, p)$ as $\sim \delta\big(\omega - \omega_\alpha^{\mathrm{HTL}}(p)\big)$
- All expressions depend only on m_D, computed consistently in HTL

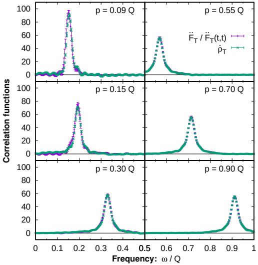
Gluon ρ in 3+1D: compare with HTL perturbation theory

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

$\rho_T(\omega, p)$



$\dot{\rho}_T(\omega, p) \approx \omega \rho_T(\omega, p)$



- Narrow Lorentzian q.p. peaks (position $\omega(p)$, width $\gamma(p)$)
- HTL at LO (black dashed) describes main features well
- Landau cut ($\omega < p$) and q.p. peak distinguishable

- Generalized fluctuation dissipation relation (FDR)

$$\frac{\langle EE\rangle_\alpha(t,\omega,p)}{\langle EE\rangle_\alpha(t,\Delta t{=}0,p)} \approx \frac{\dot{\rho}_\alpha(t,\omega,p)}{\dot{\rho}_\alpha(t,\Delta t{=}0,p)}$$

$\ddot{F} \equiv \langle EE\rangle$, $\alpha = T, L$ polarizations