

Quark-gluon plasma dynamics in heavy-ion collisions



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Rencontres de Physique des Particules 2026,
Montpellier, 13 March 2026



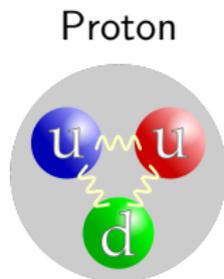
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- 1 Motivation: QCD and heavy-ion collisions
- 2 Pre-QGP dynamics
- 3 Hard probes of the pre-QGP medium
- 4 Conclusion

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Standard model of particle physics



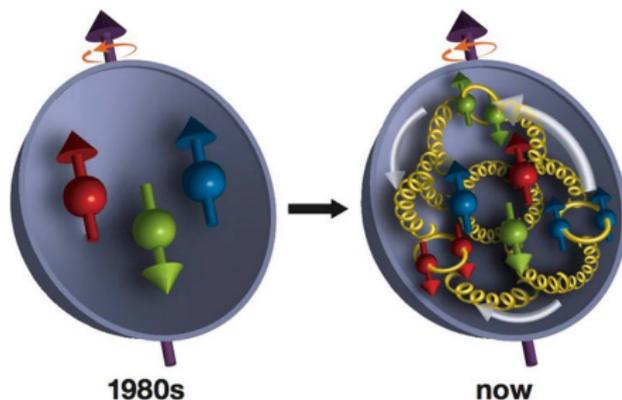
- Hadrons consist of **quarks** (spin 1/2, fermions)
- Glued together by **gluons**
 - ⇒ strong nuclear force
 - ⇒ confined matter
- **Gluons** are exchange particles (spin 1, vector bosons)

Standard Model of Elementary Particles

		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
QUARKS	mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
	charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	1	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		u up	c charm	t top	g gluon	H higgs
		$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
		$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		d down	s strange	b bottom	γ photon	
LEPTONS	mass	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	0	$\approx 91.19 \text{ GeV}/c^2$
	charge	-1	-1	-1	0	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	1
		e electron	μ muon	τ tau	Z Z boson	
		$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.433 \text{ GeV}/c^2$	
		0	0	0	± 1	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

Wikimedia

Quantum Chromodynamics (QCD)

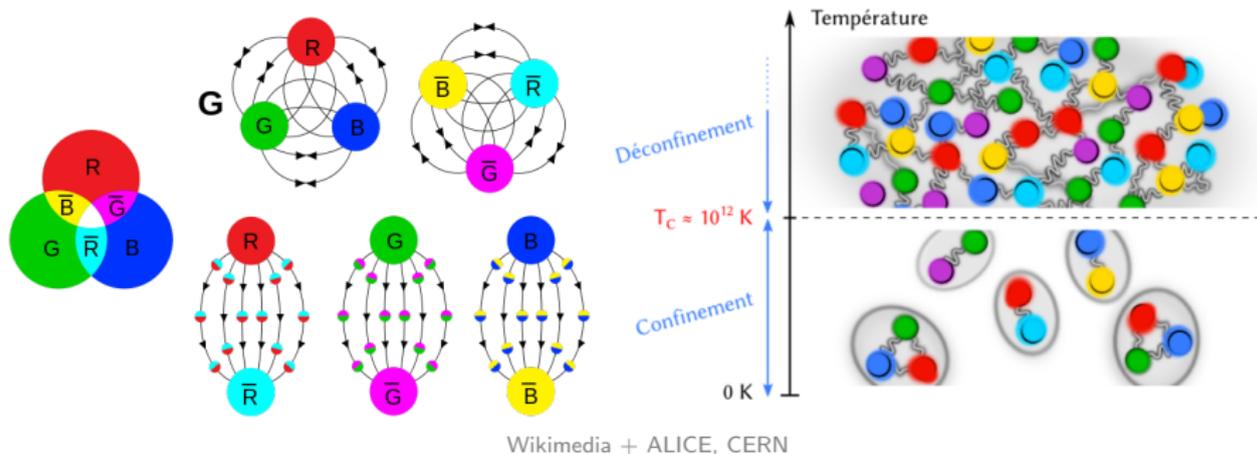


BNL, USA

- 'Strong force': **gluons** interact with **quarks** and with **themselves**
- Theoretically describes by **Quantum Chromodynamics**
 - ⇒ SU(3) gauge theory, $N_c = 3$ colors
- **Asymptotic freedom**
 - ⇒ Interaction vanishes at small distances, increases at large ones
 - ⇒ Confinement: quarks usually confined in observable objects

Confinement vs. deconfinement

- **(Color) confinement:** quarks combine to colorless hadrons
⇒ baryons (rbg \mapsto white) and mesons ($r\bar{r}$ \mapsto white, ...)



- **Deconfined matter:** plasma of quarks and gluons
⇒ plasma screens its color charges, becomes 'white' at a distance

Quark-gluon plasma

The hottest matter in the world!

At 4 trillion °C consisting from elementary particles



Where can we find it?

- In the **Early Universe** shortly after the Big Bang
- In huge **collider facilities** on Earth (Little Bang)



Big Bang (after $\lesssim 1 \mu\text{s}$)

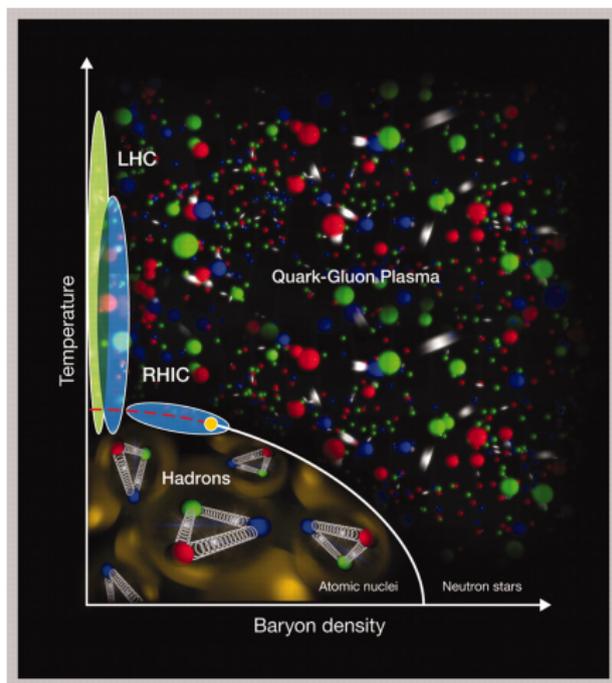


LHC at CERN (after $\sim 10^{-24}$ s)



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!

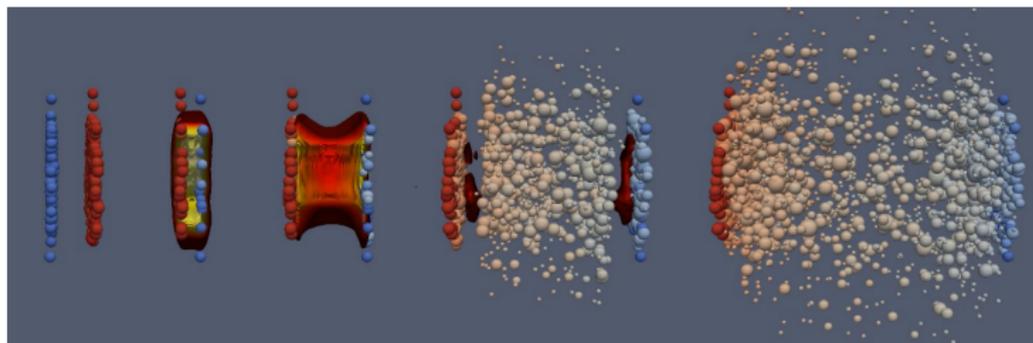
Colliders: zooming in on elementary particles



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**
 - ⇒ Collision → **pre-QGP (non-equ.)** → **fluid QGP** → **hadrons** → detectors
- **Pre-QGP**: testing the very nature of quantum physics
 - ⇒ Gluons first as (classical) waves → 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 ($\sim 1 \text{ fm}/c \sim 10^{-24} \text{ s}$)



Many current hot topics! Some examples:

- Experiments show flow in pp, pA collisions, also O+O
⇒ 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?
⇒ Lattice and phenomenological studies may suggest new phase between QGP and hadron gas

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

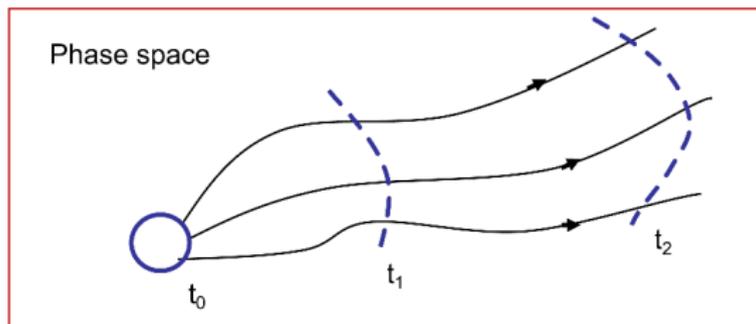
Quantum wave particle duality, approximative descriptions

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

- initially: **classical-statistical simulations**, 'Glasma'
 - \Rightarrow (modeled) quantum initial conditions
 - \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 $g^2 \ll 1$)

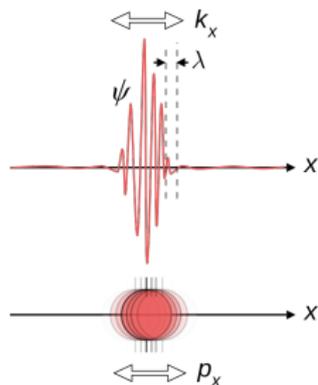
Quantum wave particle duality, approximative descriptions

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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

$$(\partial_t + \mathbf{v} \cdot \nabla) f = \left| \begin{array}{c} \diagup \\ \text{---} \\ \text{---} \\ \diagdown \end{array} \right|^2 + \left| \begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{array} \right|^2$$

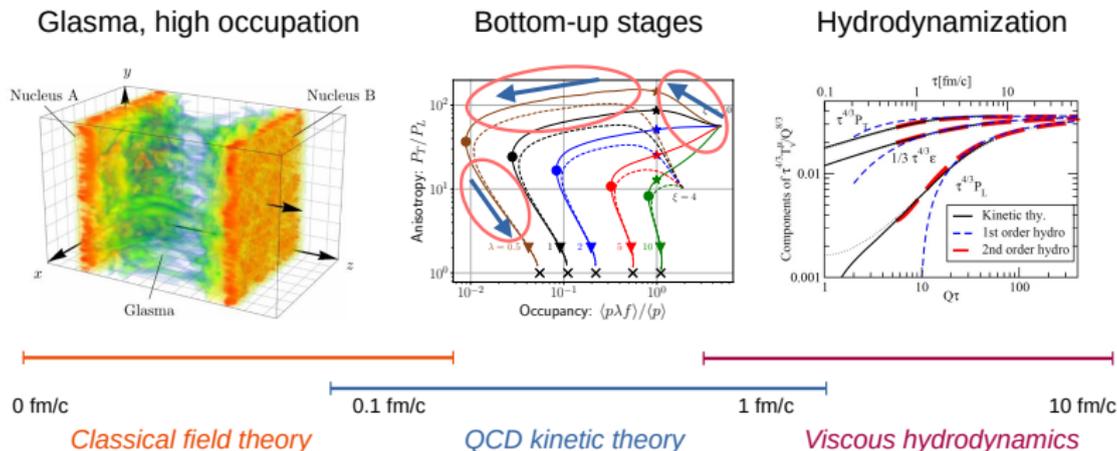
$$\frac{\partial f_{\vec{p}}}{\partial \tau} - \frac{p_z}{\tau} \frac{\partial f_{\vec{p}}}{\partial p_z} = -C^{2 \leftrightarrow 2}[f_{\vec{p}}] - C^{1 \leftrightarrow 2}[f_{\vec{p}}]$$



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)

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



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

- **Glasmata**: Large fields A & occupancies, flux tubes, transv. domains [In practice, transition Glasma \rightarrow kinetic often matched, not smooth]
- **Kinetic**: Quasiparticles, dense & dilute stages, anisotropies
 \Rightarrow **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
- ⇒ Saturated initial state? Glasma?
- ⇒ Practical framework for transition to EKT?
- ⇒ Do we account for all relevant ingredients, excitations? (new phase?)
- ⇒ 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 observables, hard (EM, QCD) probes?
 - Universal attractors? Can we understand and exploit them?
- ⇒ **Hot topics:** new properties and opportunities

Initial stages go spatially 3D, multimessenger

- (Dilute) Glasma in 3D: longitudinal structure
 - ▶ Usually Glasma in 2D (no η dependence)
 - ▶ Incorporate longitudinal structure

Gelfand, Ipp, Müller (2015, 2016);

Ipp, Leuthner, Müller, Schlichting, Schmidt, Singh (2024, 2025); ...

- QCD kinetics in 3+3D via machine learning

Barrera Cabodevila, Kurkela, Lindenbauer (2025)

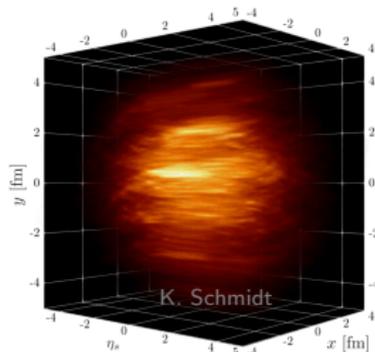
- KoMPoST in 2D and 3D

- ▶ Incorporates energy fluctuations in EKT, before 2D now 3D
- ▶ Multimessenger (McDipper + Kompost-3D + Hydro + SMASH)

Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney (2018);

Garcia-Montero, Elfner, Schlichting (2024); Garcia-Montero, Schlichting, Zhu (2025); ...

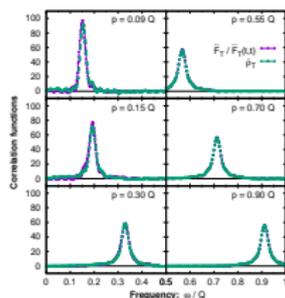
- Much more work on multimessenger frameworks with initial stages (IP-Glasma, EKT, ...)



ϵ_{LRF} for $\sqrt{s_{\text{NN}}} = 200$ GeV Au+Au at $\tau = 0.4$ fm/c with impact param. $b = R$

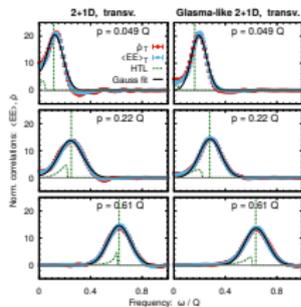
What excitations drive the dynamics in the pre-QGP?

- 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 $\langle EE \rangle$

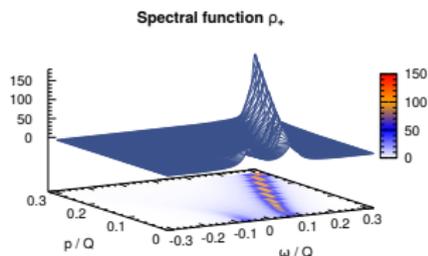


Gluonic 3+1D

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



Gluonic 2+1D



Fermionic 3+1D

KB, Lappi, Mace, Schlichting (2022)

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

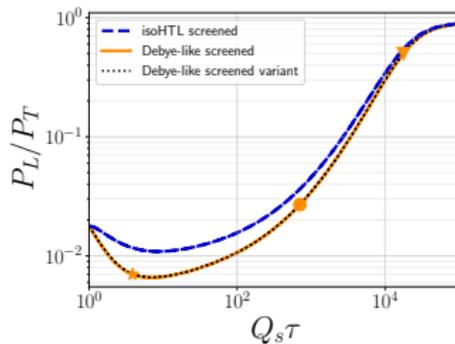
⇒ Excitations just above T_c ? (Cohen, Glzman (2024); Fujimoto, Fukushima, Hidaka, McLerran ('25))

Improving QCD kinetic theory

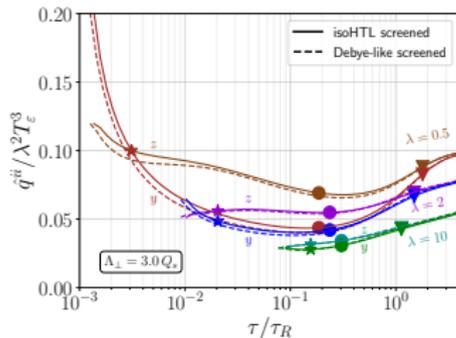
Does **soft-gluon exchange** matter (improving screening for gluons)?

KB, Lindenbauer, PRD, 2024

Yes, at early times



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



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

- Screening in $\frac{|\mathcal{M}|^2}{4\lambda^2 d_A} = 9 + \frac{(t-s)^2}{u^2} + \frac{(s-u)^2}{t^2} + \frac{(u-t)^2}{s^2}$ (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))

Universal attractors of pre-QGP dynamics

★ **Attractor**: system forgets initial details

⇒ Universal time scaling, functions

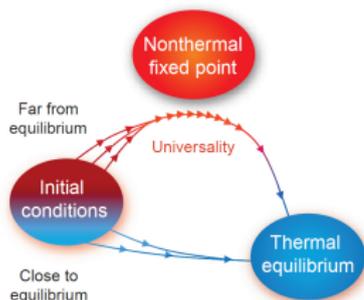
▶ **Hydrodynamic attractors** (A. Soloviev (2022))

▶ **Limiting attractors**

(KB, Kurkela, Lappi, Lindenbauer, Peuron (2024);
KB, Hörll, Lindenbauer (2026))

▶ **Nonthermal fixed points, prescaling**

(Berges, Rothkopf, Schmidt (2008); Piñeiro Orioli, KB,
Berges (2015); Mazeliauskas, Berges (2019), ...)



Berges, KB, Schlichting, Venugopalan (PRL '15)

$$f(\tau, p_T, p_z) = \tau^\alpha f_s(\tau^\beta p_T, \tau^\gamma p_z)$$

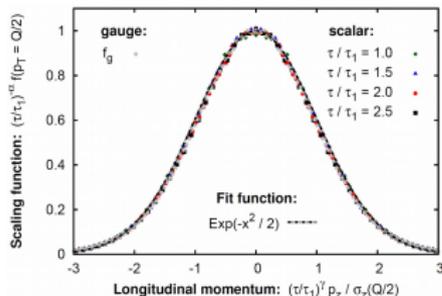
● **NTFP justifies** bottom-up scenario (1. phase) and QCD kinetic theory

(Arnold, Moore, Yaffe, (2003); Baier, Mueller, Schiff, Son (2001))

● Same attractor for scalars and gluons

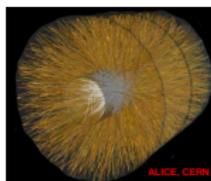
⇒ far-from-equilibrium **universality**

(Berges, KB, Schlichting, Venugopalan (2014, 2015))



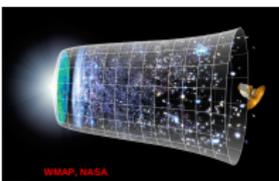
Linking different physical systems

Heavy-ion collisions



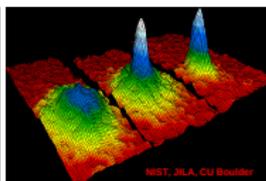
Quark-gluon plasma

Early Universe



Relativistic scalar systems

Ultracold atoms



Nonrelativistic scalar systems

- **Universality classes** in low- p condensation dynamics of scalar systems

Berges, Rothkopf, Schmidt (2008); Piñeiro Orioli, KB, Berges (2015); Berges, KB, Schlichting, Venugopalan (2015); Moore (2016); Karl, Gasenzer (2016); Walz, KB, Berges (2017); Chantesana, Piñeiro Orioli, Gasenzer (2018); ...

- **Classification** of $O(N)$ models: *topology vs. large- N kinetics*

KB, Piñeiro Orioli (2020); Noel, Gasenzer, KB (2025)

- **Experimental observations** of such attractors with ultra-cold atoms

Prüfer et al., Nature (2018); Erne et al., Nature (2018); Glidden et al., Nature Phys. (2021); Gazo et al., Science (2023)

- **Similar condensation in pre-QGP?** (Berges, KB, Butler, de Bruin, Mace, Pawłowski ('20, '23)

- **General classification of far-from-equilibrium universality classes?**

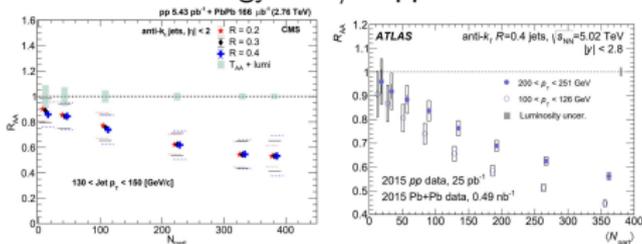
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Hard probes are modified while traversing the QGP

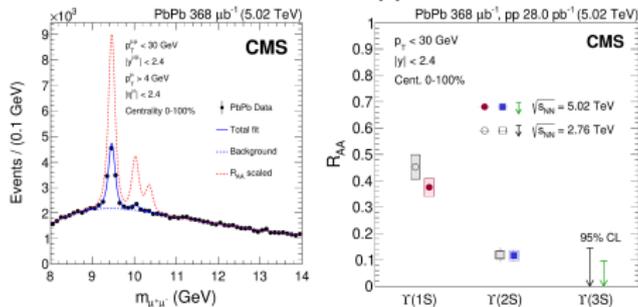
Examples: jets ($p \gg T$), heavy quarks (c, b), quarkonia ($q\bar{q}$)

Jet energy loss / suppression



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

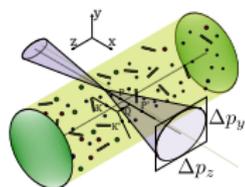
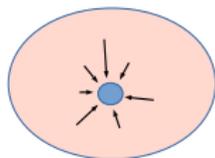
Bottomonium suppression



Transport coefficients from (pre-)QGP

Jets, heavy quarks: potential for signatures of initial stages
medium interactions \Rightarrow QGP properties encoded in observables

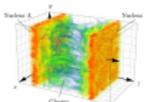
- Quarks/jets get 'kicks' $\dot{p}_i(\tau) = \mathcal{F}_i(\tau)$
- Heavy-quark diffusion coefficient $\kappa_i = \frac{d}{d\tau} \langle p_i^2 \rangle$
 \Rightarrow heavy quark, small momentum $p \ll M$
- κ relevant for quarkonium dynamics
 \Rightarrow suppression of bottomonium ($b\bar{b}$ states)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



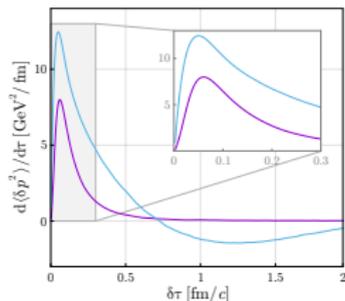
KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

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); ...

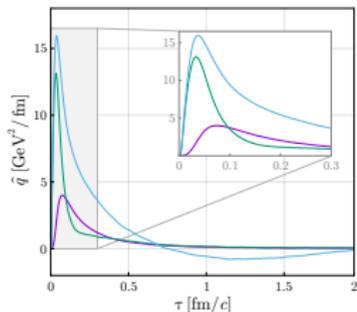
κ and \hat{q} during Glasma phase



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

▶ Extraction of κ_i and \hat{q}_i

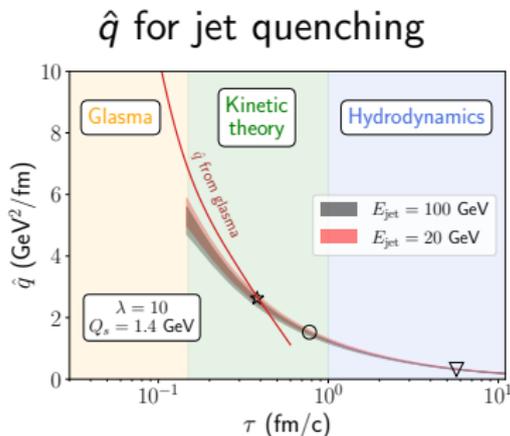
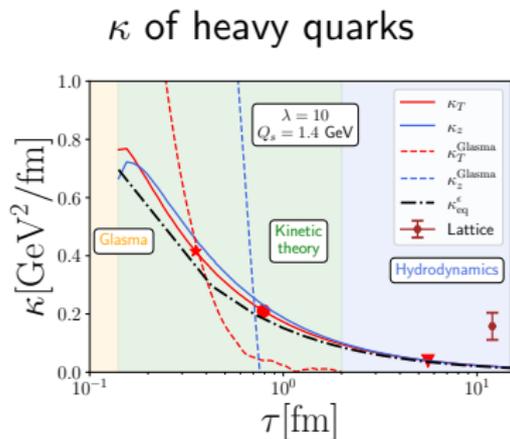
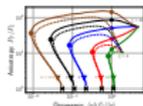
Ipp, Müller, Schuh (2020); KB, Kurkela, Lappi, Peuron (2020); Carrington, Czajka, Mrowczynski (2022); Khowal, Das, Oliva, Ruggieri (2022); Avramescu et al. (2023); Pandey, Schlichting, Sharma (2024); ...

▶ 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) \Rightarrow [Backup]

κ and \hat{q} during kinetic phase



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
- **Pre-QGP important** for HQ broadening $\langle \Delta p^2 \rangle_{\text{neq}} \sim \langle \Delta p^2 \rangle_{\text{eq}}$

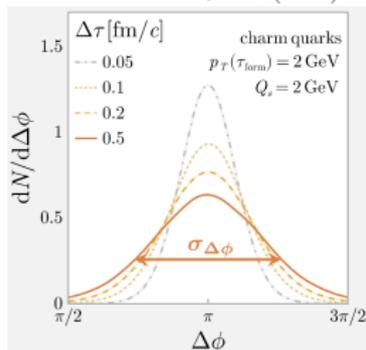
Carrington, Czajka, Mrowczynski (2022); KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

EM probes: direct photons, dileptons (Coquet, Du, Ollitrault, Schlichting, Winn, PRL (2024); ...)

Anisotropies and pre-QGP lead to azimuthal structures

$c\bar{c}$ pair in Glasma

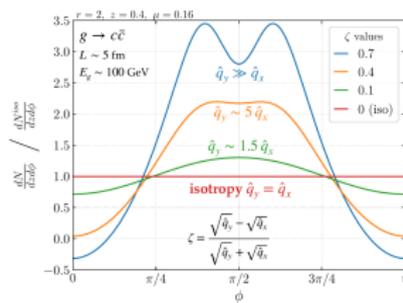
Avramescu et al., PRL (2025)



Correlation remains large

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

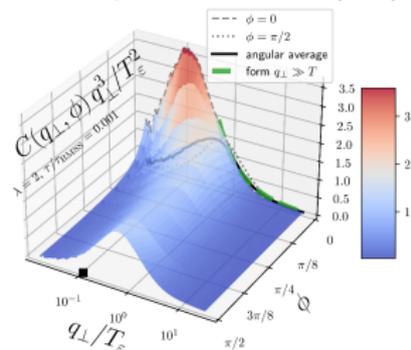
Barata, Salgado, Silva, JHEP (2024)



Effect from anisotropic \hat{q}_i

Jet coll. kernel in EKT

Altenburger, KB, Lindenbauer (2025)



From anisotropic dynamics

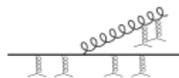
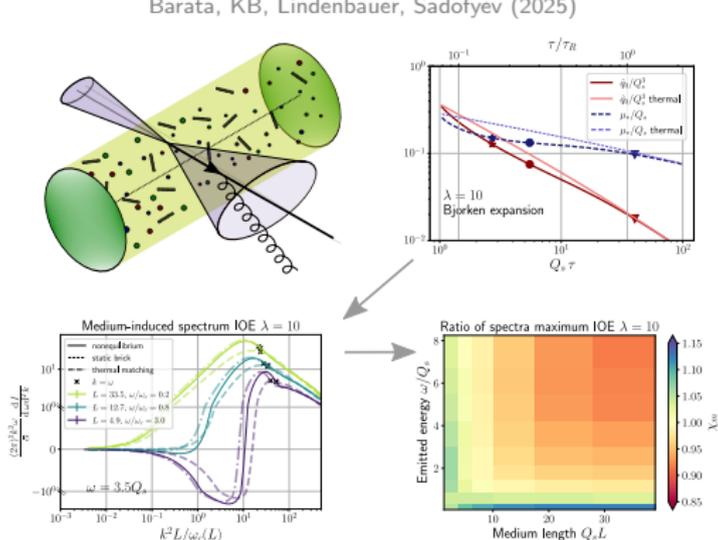
- Medium anisotropies observable via jet polarization?

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

Jet quenching in out-of-equilibrium QCD matter

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

Barata, KB, Lindenbauer, Sadofyev (2025)



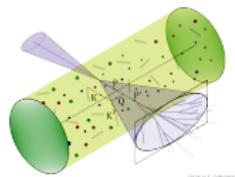
Related studies

- 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))

“High energy probes of the initial stages”

Theory Institute @ CERN, 31.03. - 04.04.2025

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



- Kick-off workshop, **focus:** intersection between **jets** and **initial stages**
- **Long-term goal:** experimental signatures of pre-QGP

EMMI workshop “Probing the early stages with jets” @ GSI, Germany

13.-17.07.26: Opportunities for HL-LHC Runs 4 & 5, small systems, FAIR

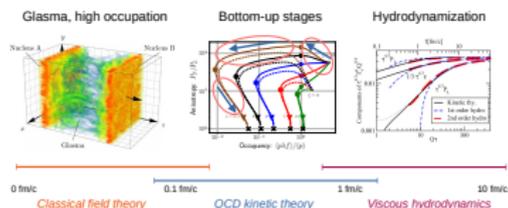
Organizers: L. Apolinário, J. Barata, KB, L. Cunqueiro, T. Lappi

Table of Contents

- 1 Motivation: QCD and heavy-ion collisions
- 2 Pre-QGP dynamics
- 3 Hard probes of the pre-QGP medium
- 4 Conclusion**

Conclusion

- QGP research: 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, ...
- High energy probes of the pre-QGP dynamics
 - ⇒ Workshops at CERN (2025) and at GSI (upcoming in 2026)
 - ⇒ Exciting opportunities, towards synergies with experiment



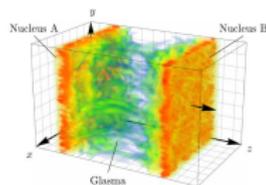
Thank you for your attention!

Backup slides

Strong initial fields: classical-statistical lattice simulations

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

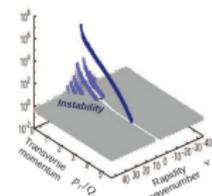
McLerran, Venugopalan (1999); Krasnitz, Venugopalan (1999, 2000, 2001); Krasnitz, Nara, Venugopalan (2001, 2003); Lappi (2003, 2006, 2011); Lappi, McLerran (2006); Schenke, Tribedy, Venugopalan (2012); Gelfand, Ipp, Müller (2016, 2017); ...



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)

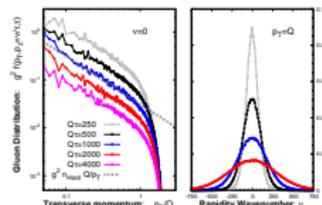
- Classical **self-similar attractor**, prescaling
– universal dynamics of over-occupied plasma

⇒ agrees with 1. stage of 'bottom-up' scenario

Berges, KB, Schlichting, Venugopalan (2013, 2014); Kurkela, Zhu (2015); Mazeliauskas, Berges (2019); Heller, Mazeliauskas, Preis (2024); ...

⇒ 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

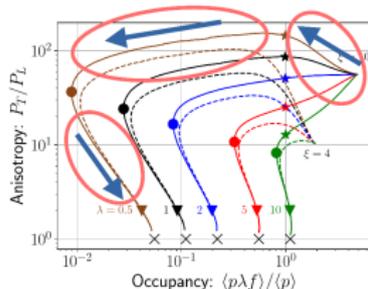
Arnold, Moore, Yaffe (2003); Kurkela, Zhu (2015); Kurkela, Mazeliauskas (2019);

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

- EKT: smooth transition to **hydrodynamics**;
hydrodynamic & limiting attractors

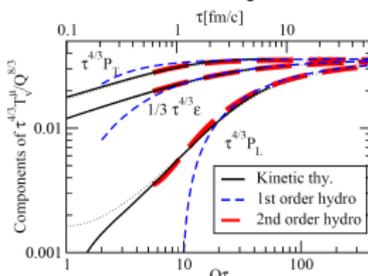
A. Soloviev (2022); ...; KB, Kurkela, Lappi, Lindenbauer, Peuron (2024)

Bottom-up evolution



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

Onset of hydro



Kurkela, Zhu (2015)

Kinetic theory \Rightarrow Bottom-up thermalization scenario

- **Bottom-up scenario**

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

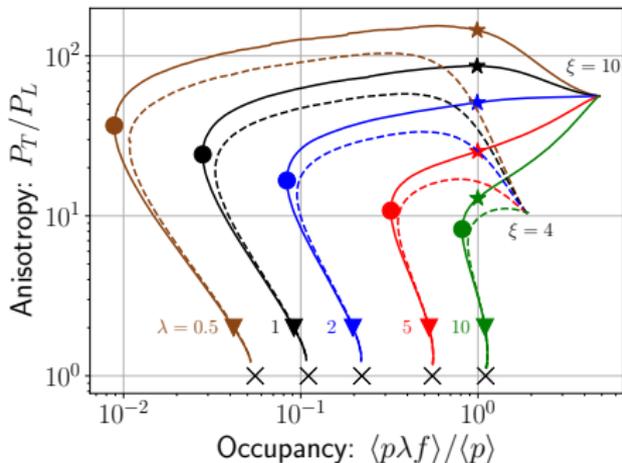
- Consists of **three stages**

- 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 $P_T/P_L = 2$

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



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

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

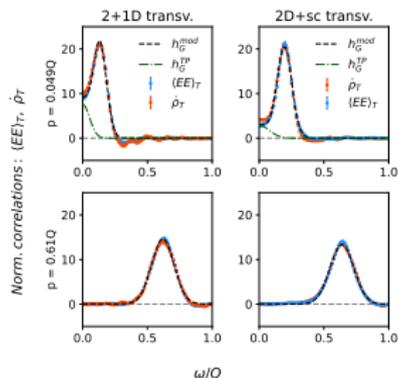
Towards understanding κ_j in the Glasma

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)

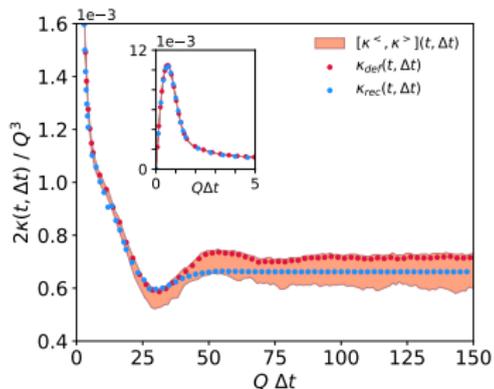
- 2+1D: Yang-Mills S_{YM}^{2D}
 - 2D+sc: $S_{YM}^{2D} + \text{adj. scalar } A_z$
- \Rightarrow Glasma-like but at classical attractor + Minkowski

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

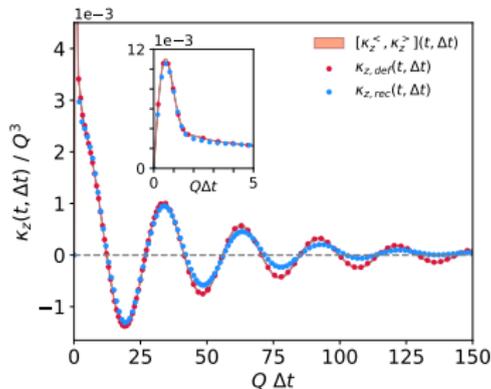
- HTL perturbation theory **breaks down** \Rightarrow broad Gaussian excitations
- New **transport peak** h_G^{TP} at $\omega = 0$ for $p \lesssim m_D \Rightarrow$ nonperturbative!

Heavy-quark diffusion coefficients in 2+1D plasmas

2+1D gluonic 2κ



Glasma-like scalar κ_z

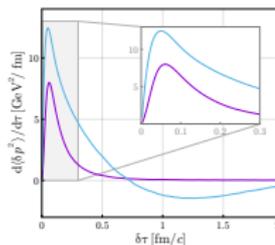


$$2\kappa(t, \Delta t) \approx \frac{g^2}{N_c} \int_t^{t+\Delta t} dt' \langle EE \rangle(t, t', \Delta \vec{x}=0), \quad \Rightarrow \text{gauge invariant}$$

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

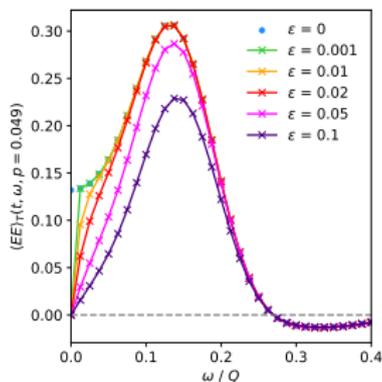
- Initial **linear** rise $\kappa_i \sim \Delta t \langle EE \rangle_i(t, t)$ (KB, Kurkela, Lappi, Peuron ('20))
- Qualitatively **similar to Glasma**: 2κ finite (diffusive), κ_z around 0
- Gauge-fixed **correlators** $\langle EE \rangle_{\alpha}(t, \omega, p)$ reconstruct evolution

Glasma reminder

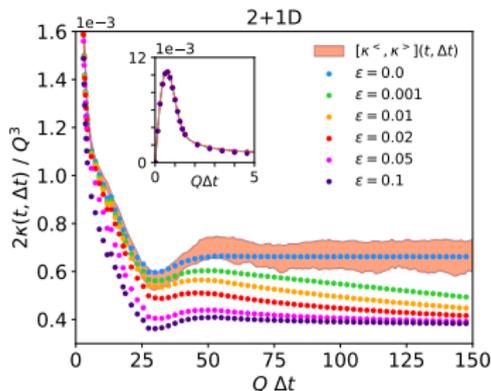


Manipulate correlations \Rightarrow study impact

Suppress low ω of $\langle EE \rangle_T$



2+1D gluonic 2κ

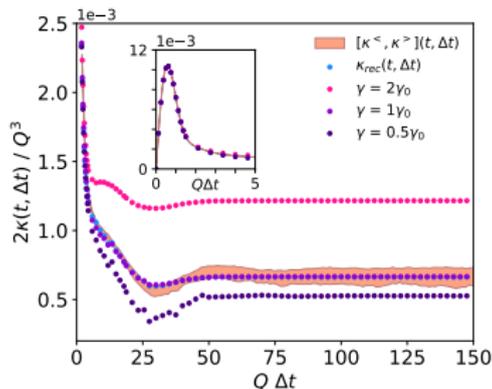


$$2\kappa(t, \Delta t) \approx \frac{g^2}{N_c} \int_{\bar{p}} \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \frac{\sin(\omega \Delta t)}{\omega} \sum_{\alpha=T,L} \langle EE \rangle_{\alpha}(t, \omega, p)$$

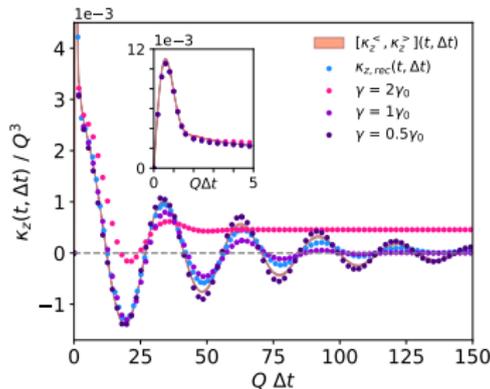
- Significant impact on late- Δt evolution
 - \Rightarrow Evidence of a new transport peak in Glasma-like systems!
- Preliminary: transport peak also in Glasma (KB, Hotzy, Müller, *in progress*)
 - \Rightarrow Enhanced transport coefficients, relevance for initial stages?

Manipulate correlations \Rightarrow study impact II

2+1D gluonic 2κ



Glasma-like scalar κ_z



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

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