Early time dynamics and constraints on medium evolution

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2023 HARD PROBES Aschaffenburg

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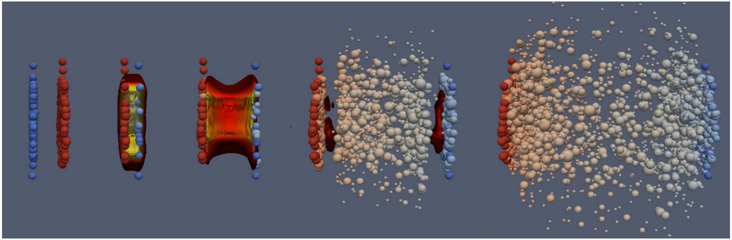
Stages in heavy-ion collisions



MADAI collaboration

- High-energy heavy-ion collisions $\Rightarrow$ quark-gluon plasma (QGP)
- Cooling during evolution, go through different phases
  $\Rightarrow$ pre-equilibrium QGP $\rightarrow$ (viscous) hydrodynamic QGP $\rightarrow$ hadrons
- Many signatures of QGP (elliptic flow, jet quenching, quarkonium suppression,. . .)

Goal

Learn about (high-energy) pre-equilibrium dynamics of QCD

Research questions

Non-equilibrium properties of 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

⇒ HP2023: extending current methods and approaches

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?

⇒ HP2023: new predictions and opportunities

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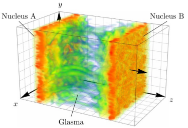
Strong initial fields: classical-statistical lattice simulations

- Initial state: Glasma – large longitudinal fields

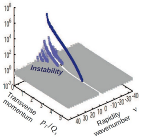
  McLerran, Venugopalan (1999); Krasnitz, Venugopalan (1999, 2000, 2001); Krasnitz, Nara, Venugopalan (2001, 2003); Lappi (2003, 2006, 2011); Lappi, McLerran (2006); Schenke, Tribedy, Venugopalan (2012); Gelfand, Ipp, Müller (2016, 2017); ...



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); ...

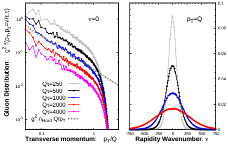


Berges, Schenke, Schlichting, Venugopalan (2014)

- 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

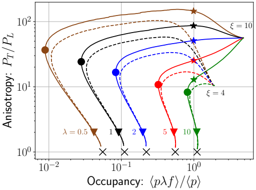
  Arnold, Moore, Yaffe (2003); Kurkela, Zhu (2015); Kurkela, Mazeliauskas (2019);

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

- EKT: smooth transition to hydrodynamics;
  KoMPoST: EKT + $\delta T^{\mu\nu}(\tau, \vec{x})$ perturbations

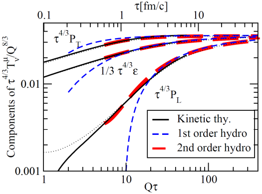
  Kurkela, Zhu (2015); Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney (2018)

Bottom-up evolution



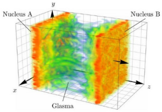
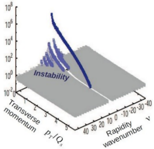
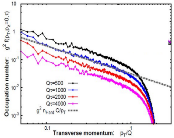
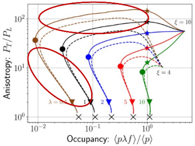
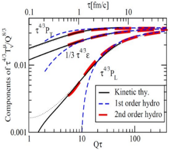
Kurkela, Zhu (2015); KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

Onset of hydro



Kurkela, Zhu (2015)

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

$Q_s\tau = 0^+$	$Q_s\tau = \ln^2(\alpha_s^{-1})$		$Q_s\tau = \alpha_s^{-3/2}$	$Q_s\tau = \alpha_s^{-13/5}$
				
Glasma	Instabilities	Bottom-up stage 1	Bottom-up stages 2 and 3	Onset of hydrodynamics

$$D_\mu F^{\mu\nu} = J^\nu$$

classical-statistical simulations

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

QCD effective kinetic theory simulations

hydrodynamics ...

Further recent approaches to initial stages

- Kinetic KoMPoST framework with quarks $\Rightarrow$ Talk by Travis Dore
- Gauge-inv. condensation in gluon plasmas (large occupancies)
  $\Rightarrow$ Talk by Lillian de Bruin (extending Berges, KB, Mace, Pawlowski [1909.06147])
- Minijets (hard QCD coll.) + hydro framework, modifies fluid QGP
  $\Rightarrow$ Talk by Charles Gale (Pablos, Singh, Gale, Jeon [2202.03414])
- New η-resolved 3+1D initial state models
  - Saturation-based: event-by-event generator based on CGC
    $\Rightarrow$ Talk by Oscar Garcia-Montero
  - Improving Trento initial state model
    $\Rightarrow$ Talk by Govert Nijs (extending Nijs, van der Schee, Gürsoy, Snellings (2020))
- Strong-coupling perspective: holographic QGP (AdS/CFT)
  - far-from-equilibrium definition of shear viscosity, hydro attractor

  $\Rightarrow$ Talk by Matthias Kaminski (Cartwright, Kaminski, Knipfer [2207.02875])
- Towards an ab-initio real-time QCD framework via Complex Langevin
  $\Rightarrow$ Poster by KB (KB, Hotzy, Müller [2212.08602])

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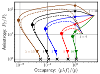
Shape, size and universality

- Impact of the shape and size of colliding nuclei on (flow) observables
  - Small systems at moderate multiplicities

    ⇒ Talk by Wilke van der Schee (using Trajectum: Nijs, van der Schee [2110.13153])
  - Complementing O+O by Ne+Ne collisions (bowling-pin shapes)

    ⇒ Talk by Giuliano Giacalone
  - How important is (kinetic) pre-equilibrium stage?
    - Compare system sizes, viscosities, pre-equ. (kinetic) approaches

    ⇒ Talk by Clemens Werthmann (Werthmann, Schlichting, Ambrus [2211.14356,2211.14379])



- Universal evolution during kinetic stages
  - Universal $\delta T^{\mu\nu}$ (deposited jet energy) in conformal kinetic theories

    ⇒ Talk by Xiaojian Du
  - Far-from-equilibrium and hydro attractors in expanding RTA kinetics
    - Momentum anisotropy studied, slow and fast d.o.f. identified

    ⇒ Talk by Yi Yin (Brewer, Ke, Yan, Yin [2212.00820])
  - *Related:* hydrodynamic attractors (e.g., review: Soloviev (2021))

Hard probes: a window into initial stages

Hard probes have high potential to provide signatures of initial stages

EW probes: early creation; QCD probes: medium interactions

- Direct photons, dileptons: via production rates, spectra, flow, ...
  - Direct photons at RHIC BES energies from hybrid dynamical approach
    - spectra and flow sensitive to early stages $\rightarrow$ constraints on dynamics

    $\Rightarrow$ Talk by Chun Shen (related to Gale, Paquet, Schenke, Shen [2106.11216])
  - Photon production from QCD kinetic theory, compared to thermal

    $\Rightarrow$ Talk by Philip Plaschke
  - Polarized photons emission in anisotropic QGP $\rightarrow$ pressure anisotropy

    $\Rightarrow$ Talk by Sigtryggur Hauksson
  - Dilepton spectra from QCD kinetic theory at $1 < M < 5$ GeV
    - Signal between hydro and Drell-Yan, sensitive to η/s and chemical equ.

    $\Rightarrow$ Talk by Maurice Coquet (Coquet, Du, Ollitrault, Schlichting, Winn [2104.07622])

- Jets, heavy quarks, quarkonia: via transport, spectra, R_{AA}, flow, ...

  $\Rightarrow$ Talks by Dana Avramescu, Marcos Gonzalez Martinez, Jarkko Peuron

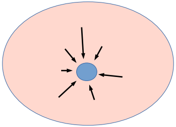
  $\Rightarrow$ *on the following slides*

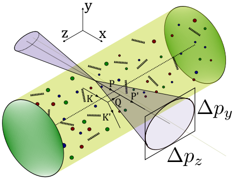
Transport coefficients κ, $\hat{q}$ from pre-equilibrium QGP

QGP properties encoded in observables

Impact of pre-equilibrium QGP on transport coefficients?

- Quantification of momentum broadening
- 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 has small momentum $p \ll M$
- Jet quenching parameter $\hat{q}_i = \frac{\mathrm{d}}{\mathrm{d}\tau}\langle p_{\perp,i}^2 \rangle$
  $\Rightarrow$ jet with high momentum $p \gg Q_s, T$
- Pre-equilibrium dynamics affect jet quenching
  $\Rightarrow$ Talk by Marcos Gonzalez Martinez
  Andres, Apolinário, Dominguez, Gonzalez Martinez, Salgado [2211.10161]

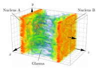




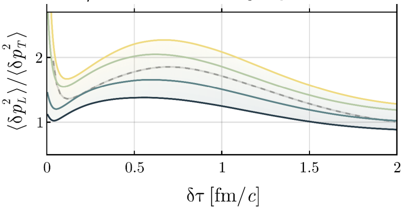
KB, Kurkela, Lappi, Lindenbauer, Peuron (2023)

Sun, Coci, Das, Plumari, Ruggieri, Greco (2019); Ipp, Müller, Schuh (2020); KB, Kurkela, Lappi, Peuron (2020); Carrington, Czajka, Mrowczynski (2022); Avramescu, Baran, Greco, Ipp, Müller, Ruggieri (2023); KB, Kurkela, Lappi, Lindenbauer, Peuron (2023); ...

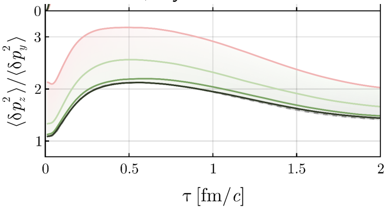
κ and $\hat{q}$ during Glasma phase



κ_z/κ_T of beauty quarks



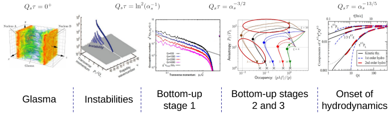
$\hat{q}_z/\hat{q}_y$ of jets



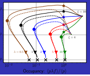
Avramescu, Baran, Greco, Ipp, Müller, Ruggieri [2303.05599]

$\Rightarrow$ Talk by Dana Avramescu

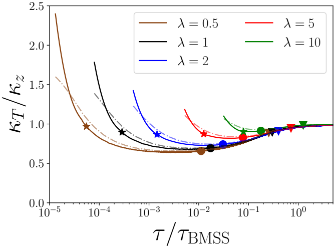
- Simulations of hard probes via Wong's equations in Glasma
  - Extraction of κ_i and $\hat{q}_i$ in Glasma phase extending previous results
    Ipp, Müller, Schuh (2020); Carrington, Czajka, Mrowczynski (2022); Khowal, Das, Oliva, Ruggieri (2022)
  - Large values, anisotropic coefficients $\kappa_z > \kappa_T$ and $\hat{q}_z > \hat{q}_y$
- What about other initial stages?



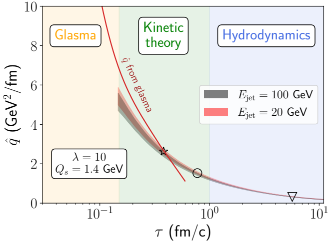
κ and $\hat{q}$ during bottom-up (kinetic evolution)



κ_T/κ_z of heavy quarks



$\hat{q}_z/\hat{q}_y$ of jets



KB, Kurkela, Lappi, Lindenbauer, Peuron; for κ [2303.12520], for $\hat{q}$ [2303.12595]

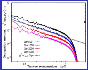
$\Rightarrow$ Talk by Jarkko Peuron

- Close gap in κ and $\hat{q}$ between Glasma and hydrodynamics via EKT
  - $\hat{q}$ smoothly connects Glasma and hydro, little sensitivity to details
  - Mostly same ordering $\kappa_z > \kappa_T$ and $\hat{q}_z > \hat{q}_y$

    $\Rightarrow$ Observable via jet polarisation? (Hauksson, Iancu (2023))

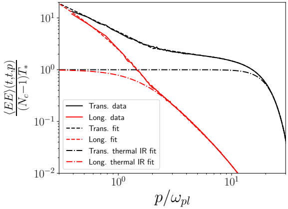
    $\Rightarrow$ Anisotropy affects jet quenching, substructure (talk: Andrey Sadofyev)

Deep IR of gluonic plasmas (at self-sim. attractor)



- Self-similar attractors ($\sim$ bottom-up stage 1): methods overlap
  $\Rightarrow$ Nonperturbative properties revealed from class.-stat. lattice simulations

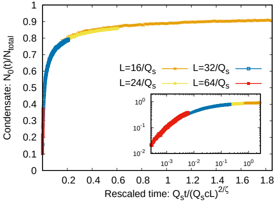
Excess of infrared (IR) modes



KB, Kurkela, Lappi, Peuron (2020)

- Affects gauge-invariant κ evolution
- Observable effect?

Gauge-invariant condensation



Berges, KB, Mace, Pawlowski (2020)

Berges, KB, Butler, de Bruin, Pawlowski, in prep.

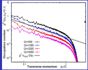
- . . . for different order parameters

  $\Rightarrow$ Talk by Lillian de Bruin

- Their impact on photon/dilepton production, kinetic theory?
- Gauge-inv. cond. similar to Bose cond. in scalars $\Rightarrow$ universality?

Far-from-equ. condensation in scalars: Berges, Sexty (2012); Piñerio Orioli, KB, Berges (2015)

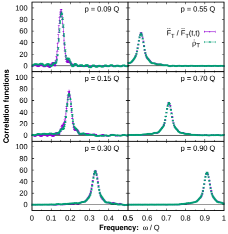
What excitations drive the dynamics in the QGP?



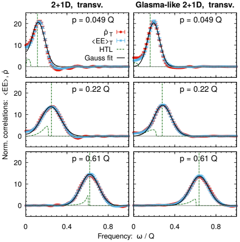
Study microscopics of the Quark-Gluon plasma

Quasiparticles? When is kinetic theory valid?

$\Rightarrow$ *Spectral functions* $\rho(\omega, p) \sim \langle[\hat{A}, \hat{A}]\rangle$ encode full excitation spectrum!

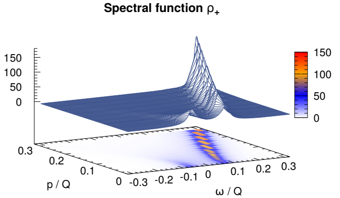


Gluonic 3+1D



Gluonic 2+1D

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



Fermionic 3+1D

KB, Lappi, Mace, Schlichting (2022)

- Impact on hard probes? $\rightarrow$ at least κ affected (KB, Kurkela, Lappi, Peuron (2020))

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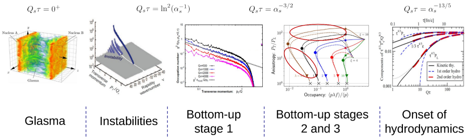
Conclusion

- Initial stages of the QGP
  - ⇒ Further approaches



- Probing the pre-equilibrium medium evolution
  - ⇒ Shape, size and universality of evolution
  - ⇒ EW and QCD probes

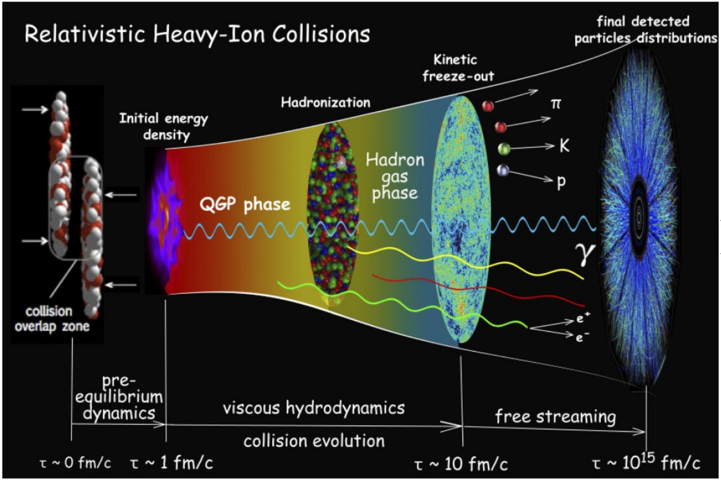
- EW probes (direct photons, dileptons): production, spectra, flow, . . .
  - ⇒ Sensitive to early stages, new calculations

- QCD probes (jets, heavy quarks, quarkonia): medium interactions
  - ⇒ Coefficients κ, $\hat{q}$ in Glasma and bottom-up $\rightarrow$ intriguing anisotropy
  - ⇒ Nonperturbative pre-equ. effects? IR and excitation spectra

Thank you for your attention!

Backup slides

Stages in heavy-ion collisions

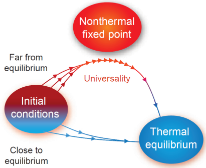


by P. Sorensen and C. Shen

Universal classical attractors: nonthermal fixed points

What is universal about initial stages in heavy-ion collisions?

Stage 1 in bottom-up scenario links different systems

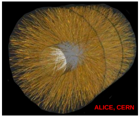


- ★ Initial over-occupancy $\Rightarrow$ may approach attractor
- ★ System ‘forgets’ initial conditions
- ★ Self-similar universal dynamics

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

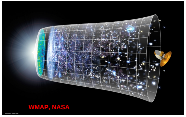
Linking different physical systems

Heavy-ion collisions



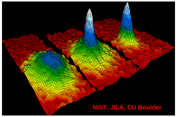
Quark-gluon plasma

Early Universe



Relativistic scalar systems

Ultracold atoms



Nonrelativistic scalar systems

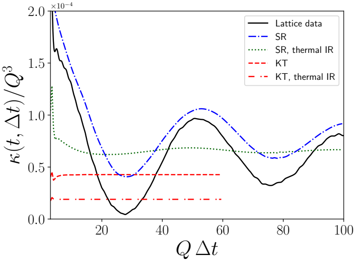
Universality: Berges, KB, Schlichting, Venugopalan (2015); Piñeiro Orioli, KB, Berges (2015); *Experimental observations:* Prüfer et al., Nature 563, 217 (2018); Erne et al., Nature 563, 225 (2018); Glidden et al., Nature Phys. 17, 457 (2021)

Gauge-invariant observation of IR gluon excess in κ

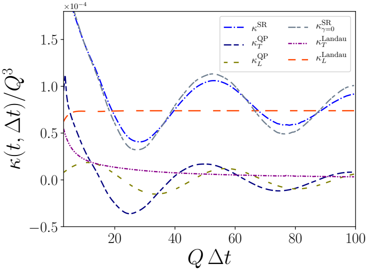
KB, Kurkela, Lappi, Peuron [2005.02418]

$$\kappa\,(t,\Delta t) = \frac{g^2}{2N_c}\int_t^{t+\Delta t}\mathrm{d}t'\int_t^{t+\Delta t}\mathrm{d}t''\,\langle EE\rangle(t',t'')$$
$$\approx \frac{g^2}{3N_c}\int\frac{\mathrm{d}^3p}{(2\pi)^3}\int_{-\infty}^{\infty}\frac{\mathrm{d}\omega}{2\pi}\,\frac{\sin(\omega\,\Delta t)}{\omega}\left[2\langle EE\rangle_T(t,t,p)\,\frac{\dot\rho_T(t,\omega,p)}{\dot\rho_T(t,t,p)}+\langle EE\rangle_L(t,t,p)\,\frac{\dot\rho_L(t,\omega,p)}{\dot\rho_L(t,t,p)}\right]$$

Total $\kappa\,(t,\Delta t) \equiv \sum_i \kappa_i\,(t,\Delta t)$



Components $\kappa_i\,(t,\Delta t)$



- Oscillations with $\omega_{\rm pl}$ due to quasiparticles, sign of IR excess
- Heavy quarks, quarkonia, jets encode nonthermal dynamics of QGP!