Equilibration at weak & strong coupling

— Status, Phenomenology & Perspectives

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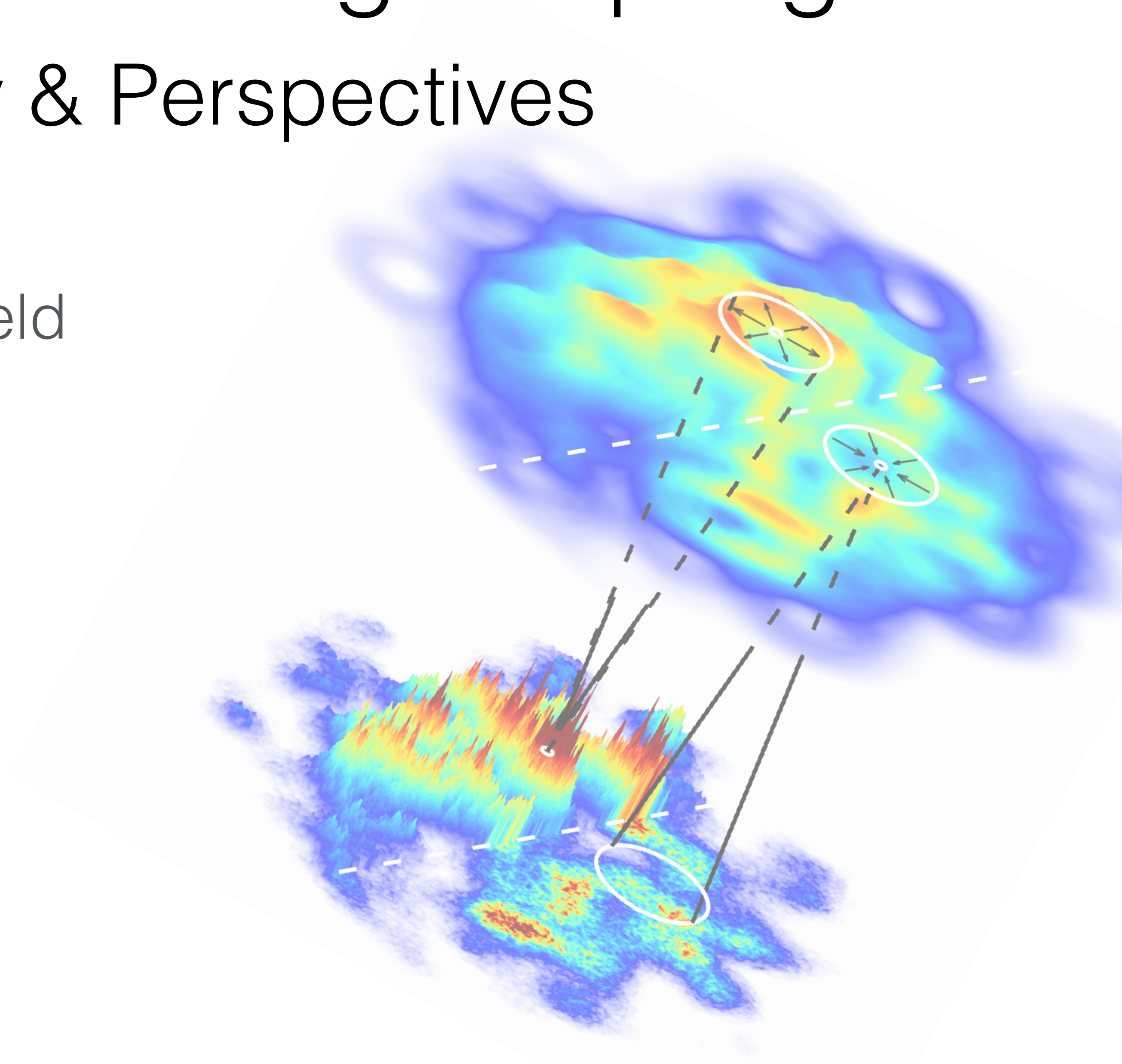

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CRC-TR 211
Strong-interaction matter under extreme conditions

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Outline

Equilibration in Heavy-Ion collisions (HICs)

— Status report

Phenomenology of Pre-Equilibrium phase in HICs

— Entropy production, Electromagnetic probes

Equilibration in Small Systems?

— Non-eq description of flow, (In)applicability of hydrodynamics

Conclusions & Outlook

— Summary & Open questions

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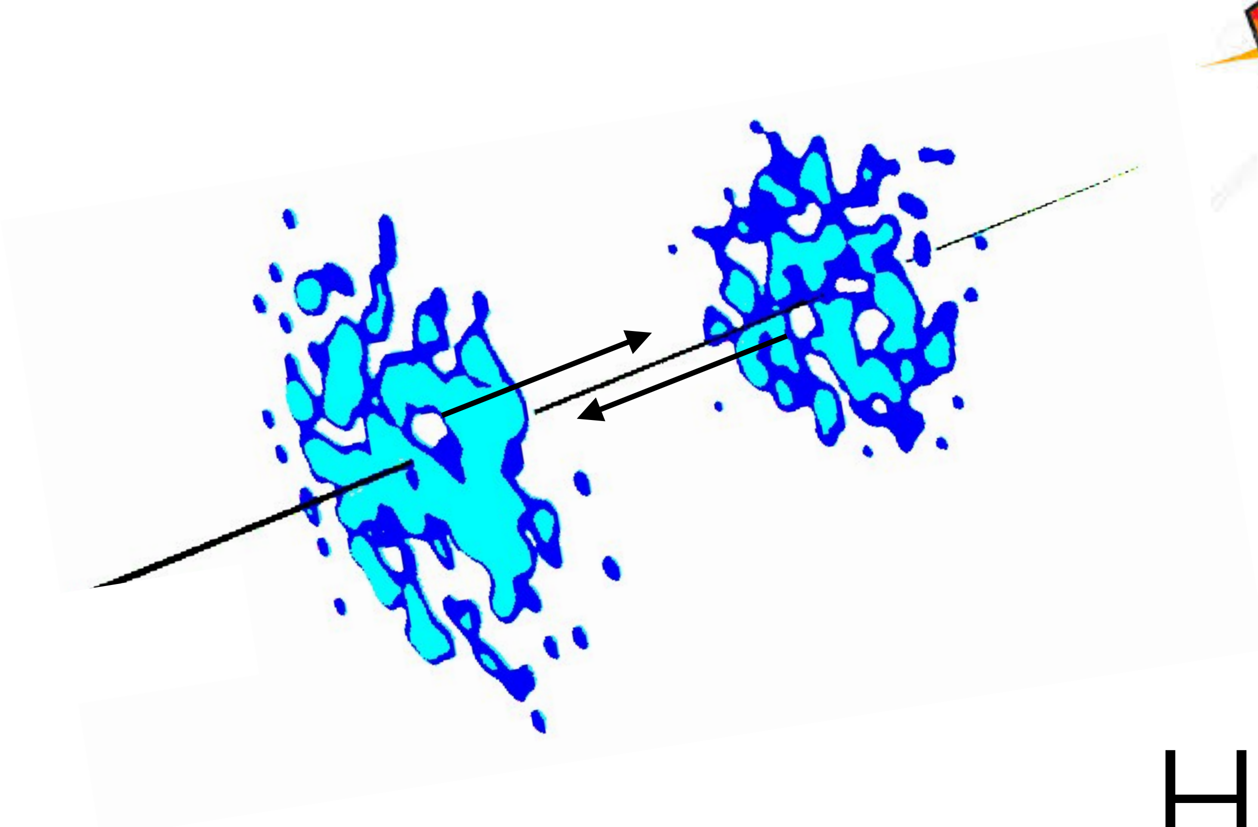
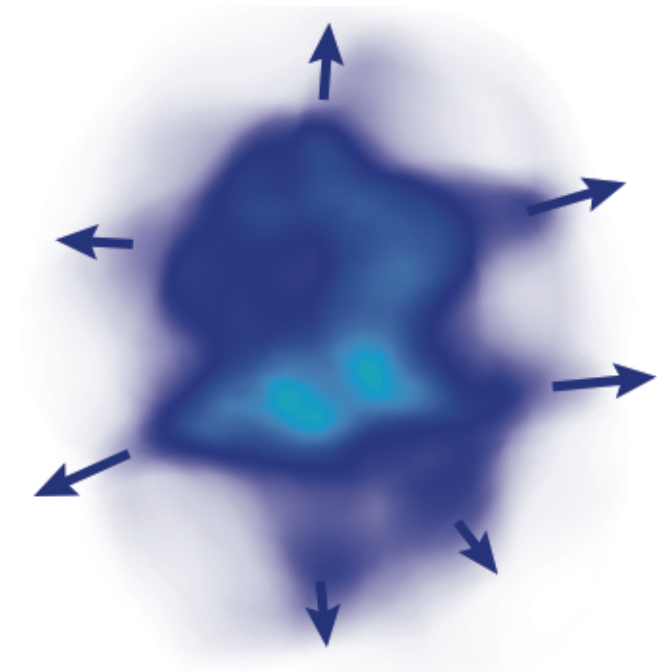


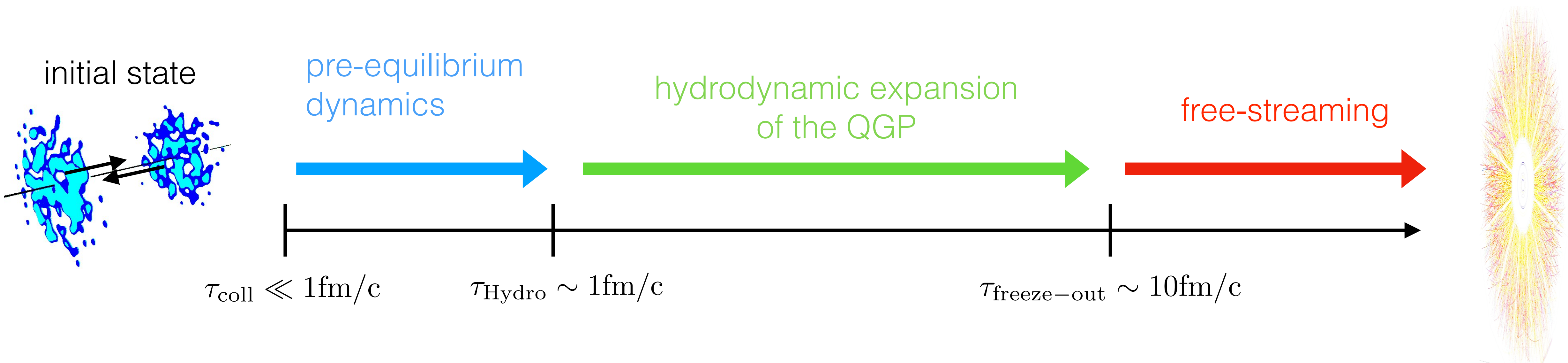


Equilibration in Heavy-Ion Collisions

Heavy-Ion Collisions

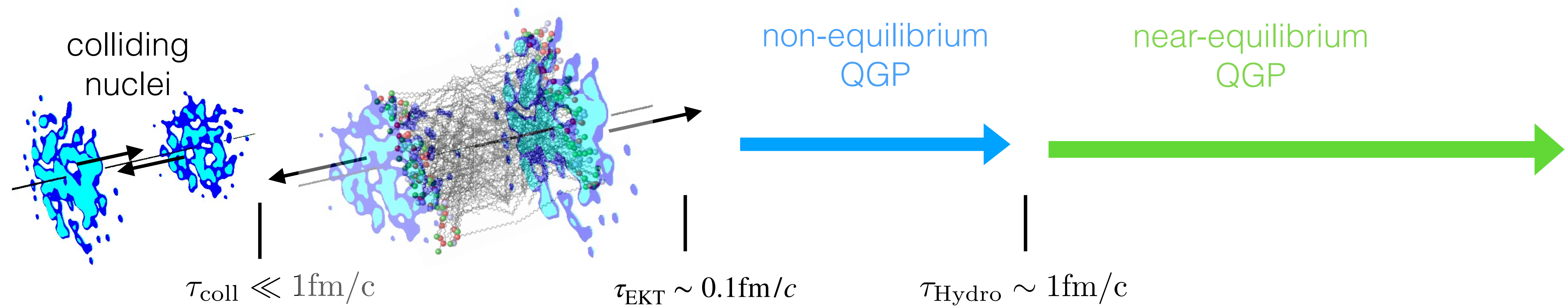
Dynamical description of Heavy-Ion collisions from underlying theory of QCD remains an outstanding challenge

Standard model of nucleus-nucleus (A+A) collisions based on effective descriptions of QCD exploiting clear separation of time scales in the reaction dynamics

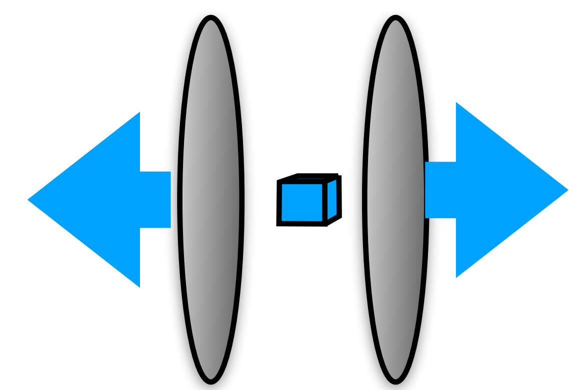


Dynamical description of equilibration process during the pre-equilibrium phase required for continuous description of space-time dynamics

Equilibration of HICs



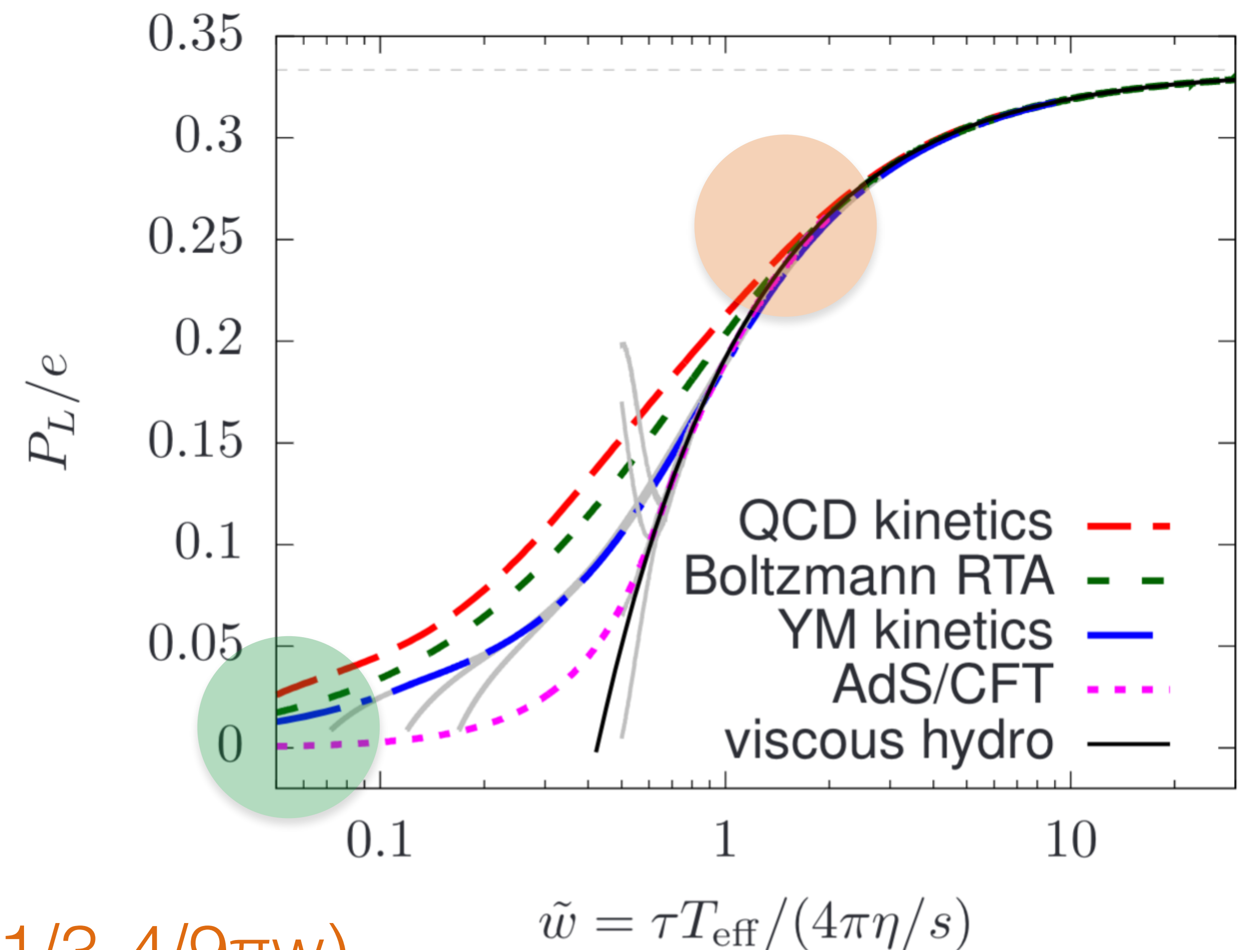
Non-equilibrium QCD plasma created immediately after the collision is expected to be **gluon dominated** and subject to **rapid longitudinal expansion**



Significant progress in understanding **kinetic & chemical equilibration** while **neglecting transverse expansion** over short pre-equilibrium time scale

Kinetic Equilibration — Hydrodynamic attractors

Different microscopic calculations in QCD/YM/RTA Kinetic theory & AdS/CFT show similar results for pressure anisotropy P_L/e



Early times (expansion dominated):

$\tilde{w} \ll 1$ free-streaming ($P_L/e \approx 0$)

Late times (interaction dominated):

$\tilde{w} \gg 1$ visc. hydrodynamics ($P_L/e \approx 1/3 - 4/9\pi w$)

Effective hydrodynamic description applicable on time scales

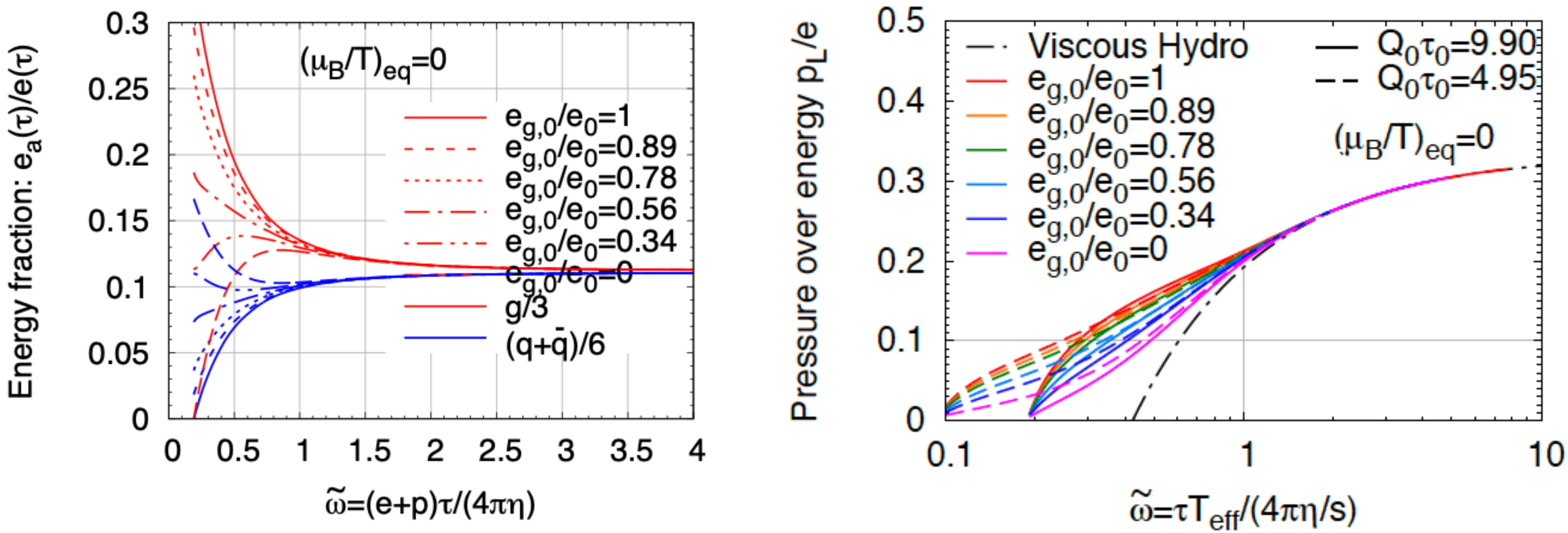
$$\tau_{\mathrm{hydro}} \approx \tau_R^{\mathrm{eq}}(\tau) \qquad \tau_R^{\mathrm{eq}}(\tau) = \frac{4\pi\eta/s}{T_{\mathrm{eff}}(\tau)} \qquad \tau_{\mathrm{hydro}} \approx 1.1\,\mathrm{fm}\left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}}\left(\frac{\langle\tau s\rangle}{4.1\,\mathrm{GeV}^2}\right)^{-1/2}$$

YM: Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910 QCD: Kurkela, Mazeliauskas PRL 122 (2019) 142301; RTA: Strickland JHEP 12 (2018) 128; Kamata, Martinez, Plaschke, Ochsenfeld, SS PRD 102 (2020) 5, 056003 AdS/CFT: Romatschke PRL 120 (2018) no.1, 012301 Hydro vs. RTA: Strickland, Noronha, Denicol, PRD 97 (2018) 3, 036020

Chemical Equilibration

Chemical equilibration in QCD Kinetic Theory proceeds roughly on the same time scale as kinetic equilibration

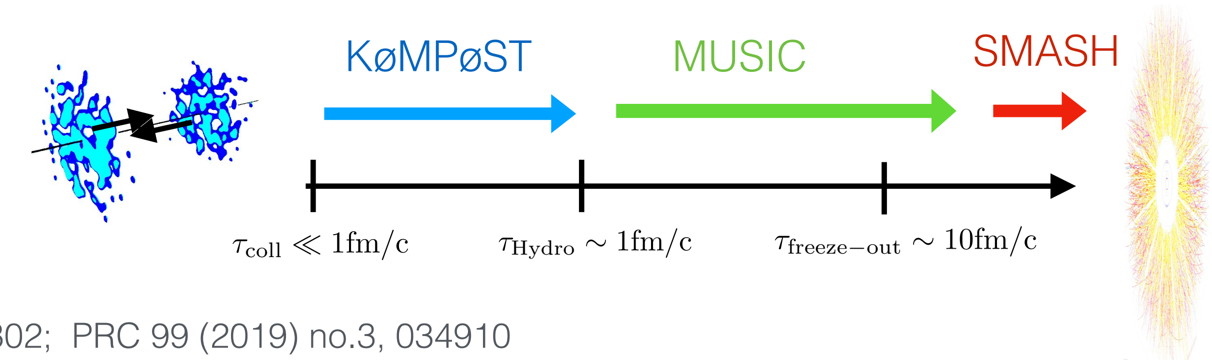
Kurkela, Mazeliauskas PRL 122 (2019) 142301; PRD 99 (2019) 5, 054018; Du,SS *PRL* 127 (2021) 12, 122301; PRD 104 (2021) 5, 054011



Since interaction are required to change QGP chemistry the initial **gluon dominance persist** up to τ_{Hydro} (no early time attractors) and also mildly affects transient pressure equilibration

Event-by-event pre-eq with KoMPoST

Effective macroscopic description of pre-eq dynamics in HICs on event-by-event basis available in KøMPøST



KøMPøST: Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910

Non-equilibrium linear response

$$T^{\mu\nu}(\tau, x) = T^{\mu\nu}_{BG} + \int_\circ G^{\mu\nu}_{\alpha\beta}(\tau_0, \tau, x_0, x)\, \delta T^{\alpha\beta}(\tau_0, x_0)$$

Bjorken flow attractor — Non-Eq Green's functions — Initial state fluctuations

based on input from YM/QCD/RTA Kinetic Theory, still waiting for input from AdS/CFT

New developments:

Extension to include conserved B,Q,S charges — **c.f. talks by P. Carzon, O. Garcia poster by X.Du**

Universality of Non-Eq Green's functions — **c.f. talks by X.Du, Y.Yin, S. Ochsenfeld**

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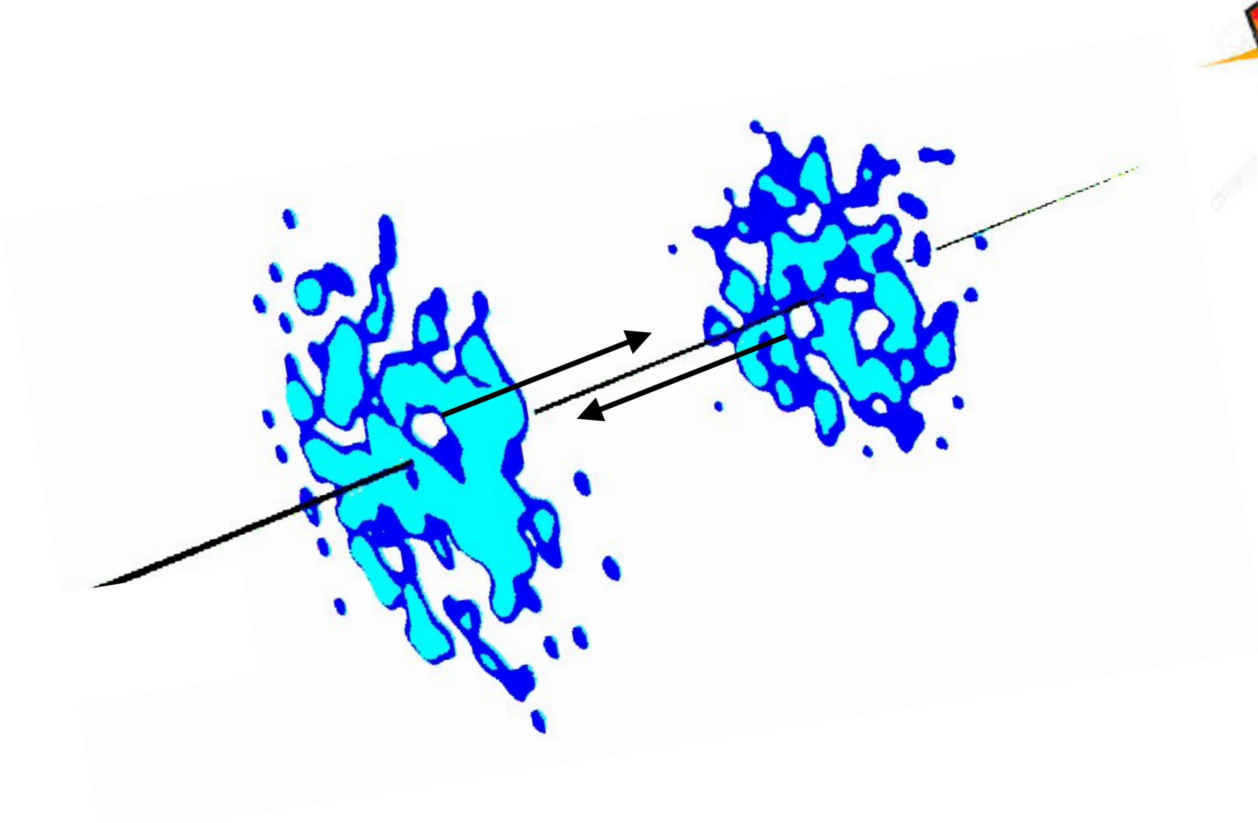
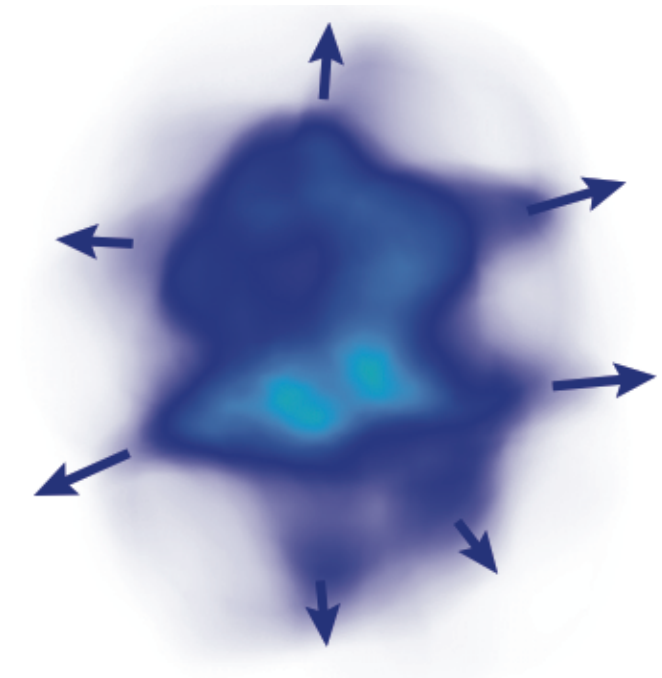




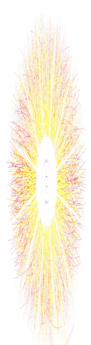
Phenomenology of pre-equilibrium phase in HICs

Entropy production

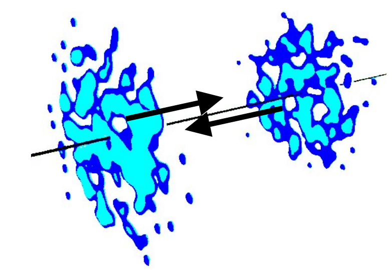
Entropy production occurs pre-dominantly during the pre-equilibrium stage, where QGP is out-of-equilibrium

Experimentally probed in terms of charged particle multipliclicity

Giacalone, Mazeliauskas, SS PRL 123 (2019) 26, 262301; Jankowski, Kamata, Martinez, Spalinski *PRD* 104 (2021) 7, 074012



$$\frac{dN_{\rm ch}}{d\eta} \simeq \frac{4}{3}\left(\frac{N_{\rm ch}}{S}\right) C_\infty^{3/4}\left(4\pi\eta/s\right)^{1/3}\left(\frac{\pi^2}{30}\nu_{\rm eff}\right)^{1/3}\int d^2\mathbf{x}_\perp \left(\frac{dE_\perp^0}{d^2\mathbf{x}_\perp d\eta}\right)^{2/3}$$



Strong sensitivity to shear viscosity **η/s** (determines equilibration time)

Not taken into account in phenomenological inference of QCD transport properties, due to uncertainty in initial state energy density **$dE_0/d^2x_T d\eta$** (typically treated as free parameter)

Significant room for improvement
linking hot QCD and cold QCD properties

Electromagnetic probes (γ)

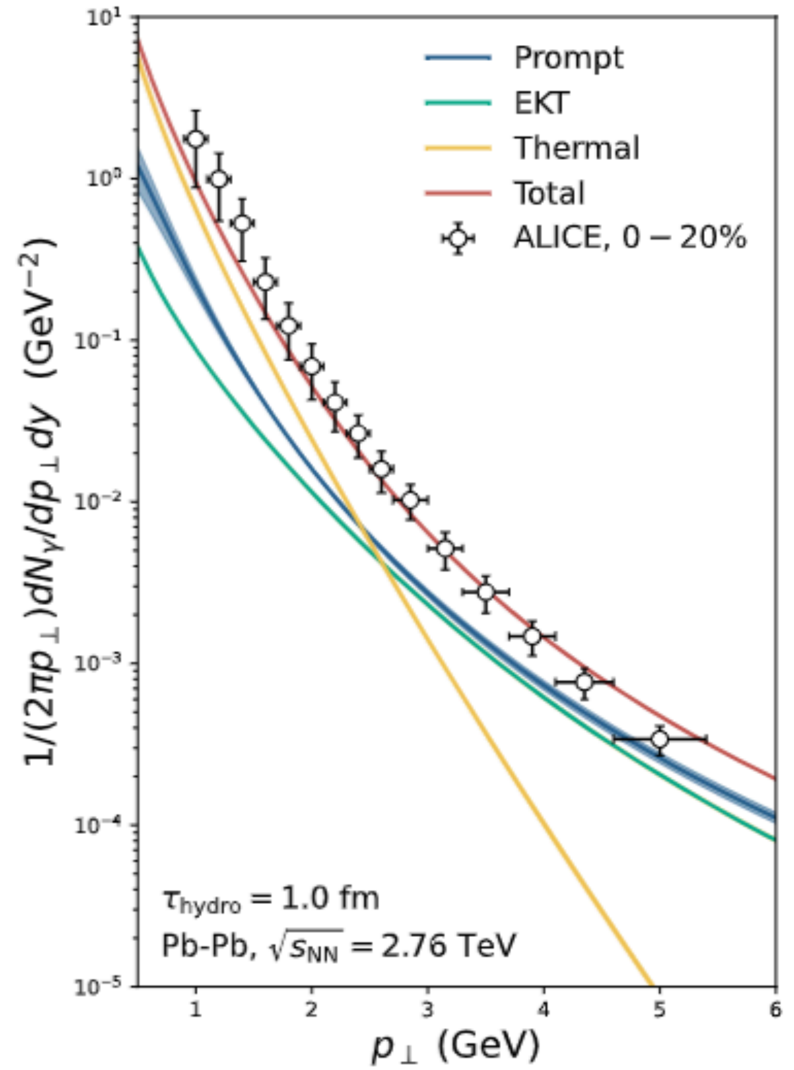
Electromagnetic probes (γ, l^+l^-) produced throughout space-time evolution of HICs escape collision unscathed as they do not interact strongly with the QGP

New calculation of LO pre-eq photon production in QCD Kinetic Theory

c.f. Poster by P.Plaschke

Universal scaling of photon p_T spectrum in terms of shear viscosity η/s and entropy density $dS/d\eta \sim (T\tau^{1/3})^3$

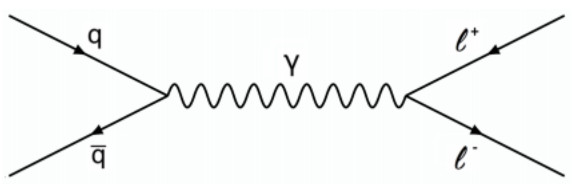
$$\frac{dN}{d^2x_T d^2p_T dy} = (\eta/s)^2 \, \tilde{C}_\gamma^{ideal} \, \mathcal{N}_\gamma\left(\tilde{w}, \sqrt{\eta/s}\, p_T / \left(T\tau^{1/3}\right)_\infty^{3/2}\right)$$

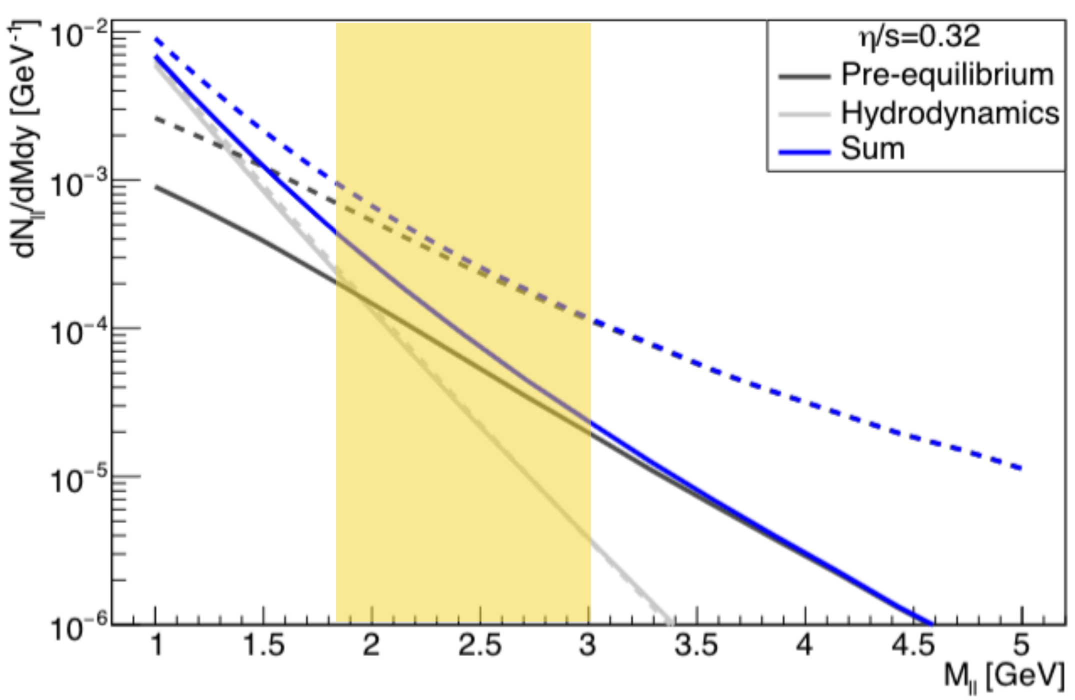


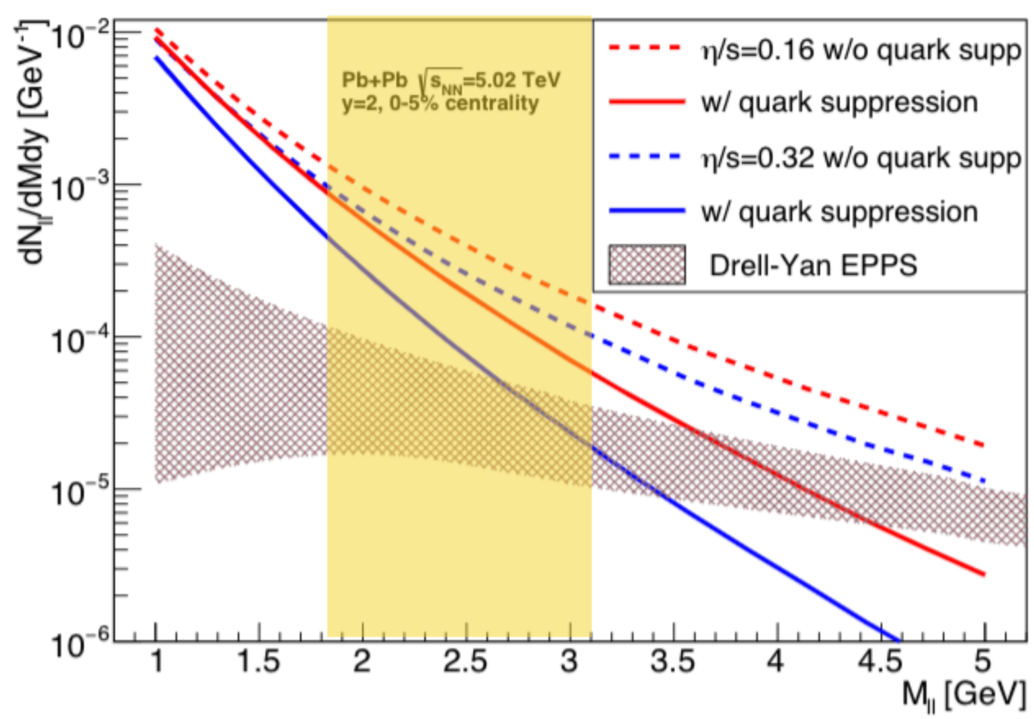
Sizeable pre-eq contribution at p_T>2GeV but not exceeding thermal+prompt contributions

Electromagnetic probes (l^+l^-)

Di-lepton ($e^+e^-/\mu^+\mu^-$) pairs with invariant mass M~GeVs pre-dominantly produced during the initial state as late stage production is suppressed by exp(-M/T)







New window into pre-equilibrium dynamics for 1.5 GeV<M<3GeV
accessible with next generation of heavy-ion detectors (ALICE3,LHCb,…)?

Coquet,Du,Ollitrault,SS,Winn; *PLB* 821 (2021) 136626; *NPA* 1030 (2023) 122579

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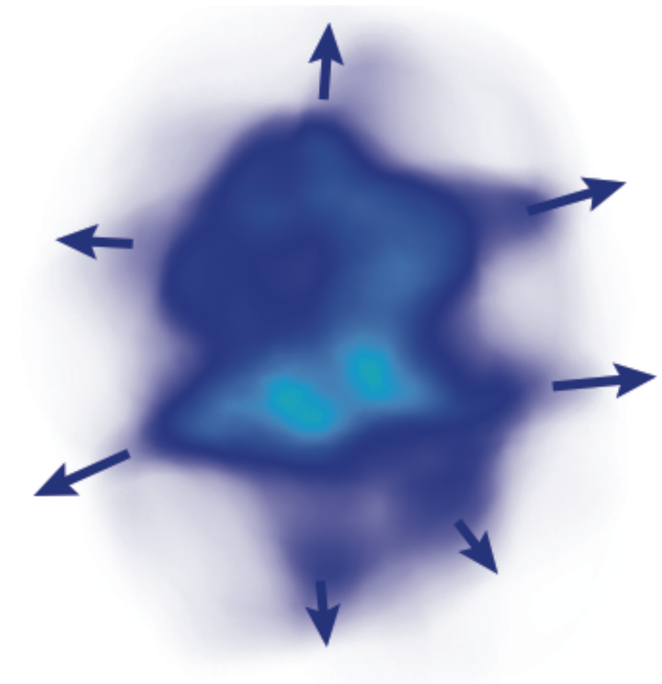
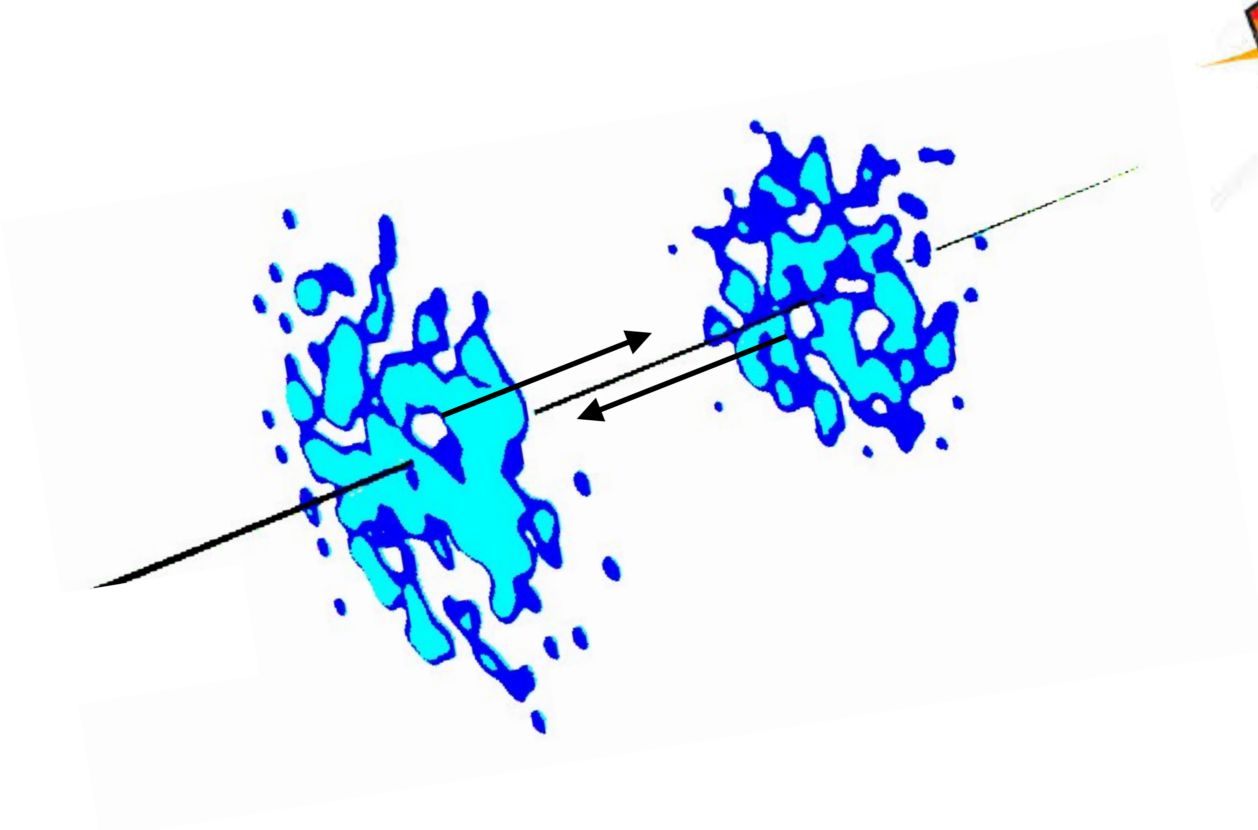


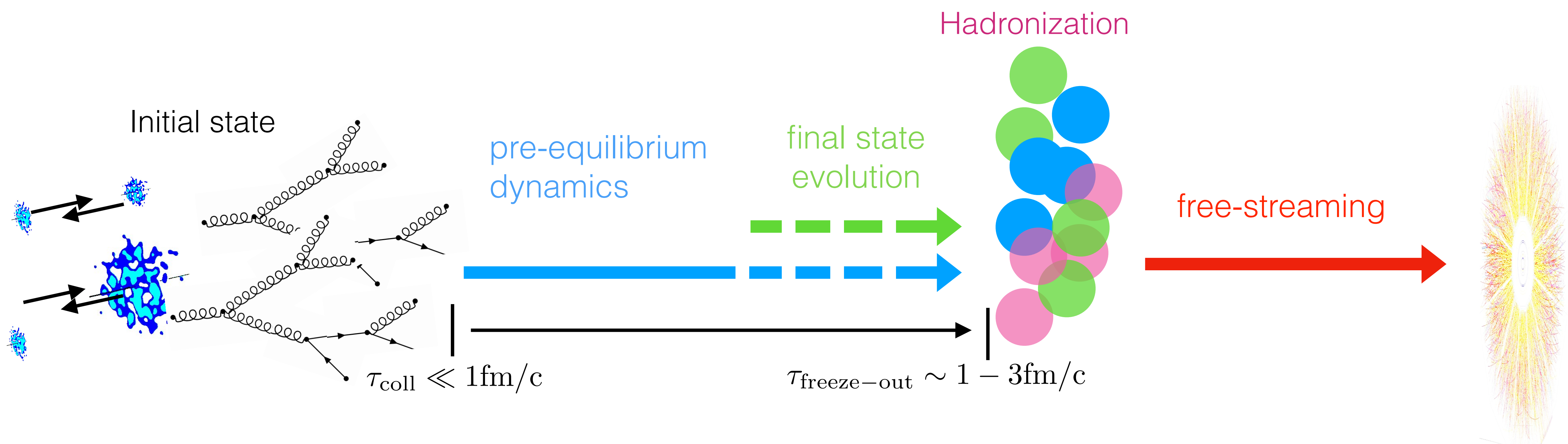


Small system &
development of collective flow

Small systems

Sensitivity to non-equilibrium dynamics enhanced in small systems due to significantly shorter lifetime

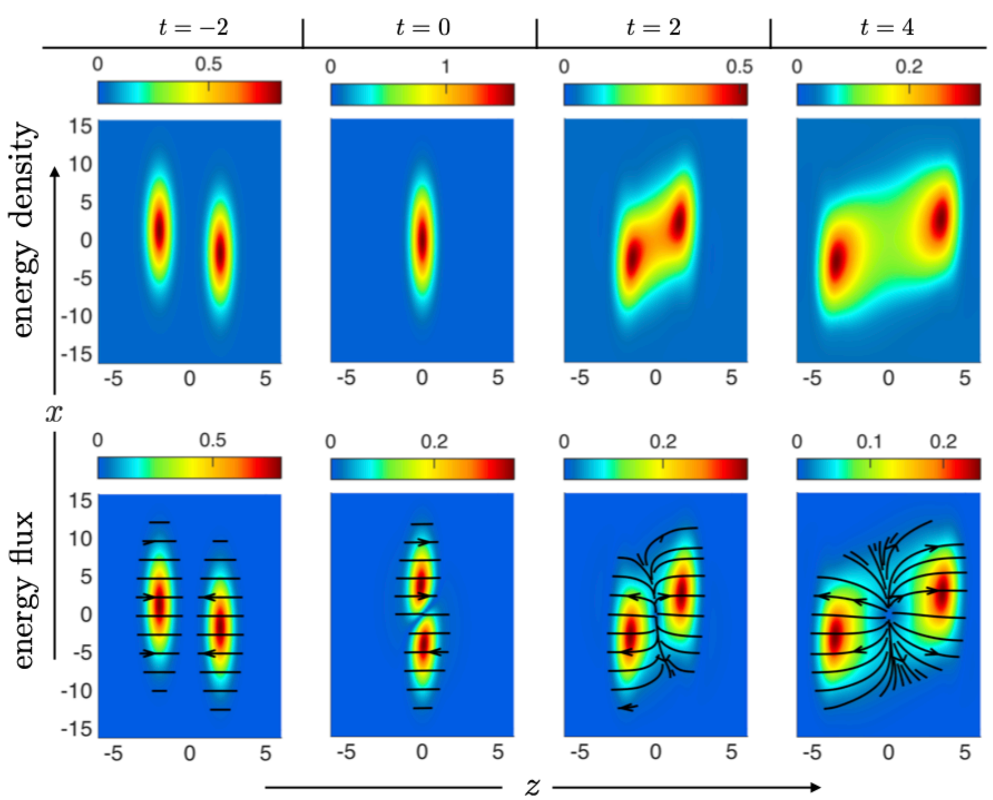
System can fall apart due to transverse expansion before it is sufficiently equilibrated for hydrodynamics to apply



Effect on typical flow observables? What is range of applicability of standard model of HICs applicable? Does it apply to p+p,p/d/He3+A and O+O collisions at RHIC/LHC?

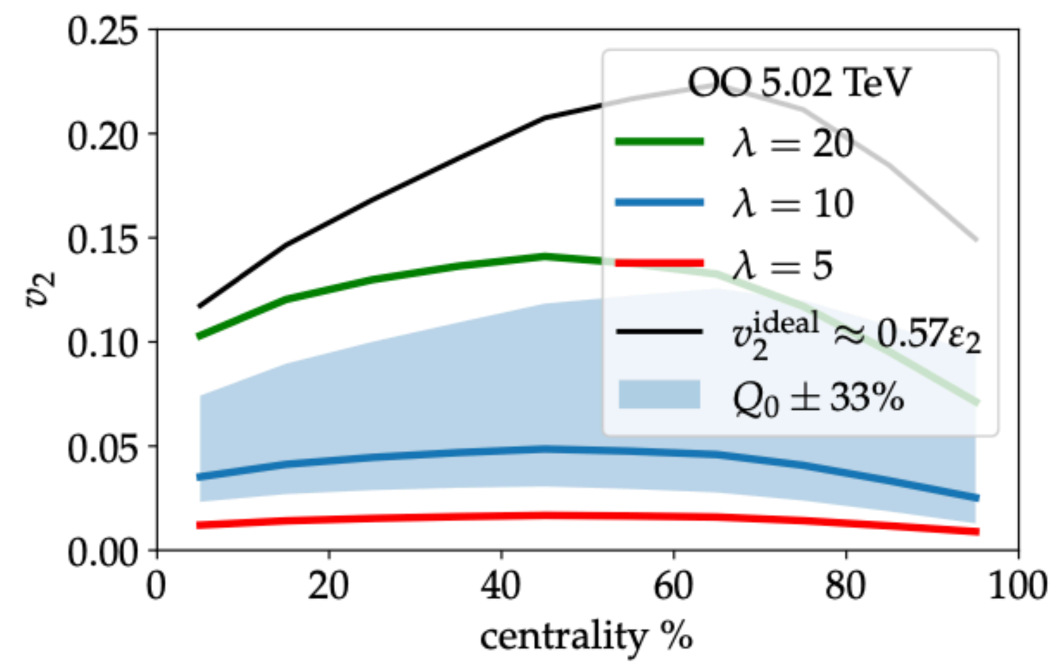
Non-eq description of flow

Challenging to address 2/3+1D space-time dynamics microscopically, but first calculations in the weak & strong coupling limits



holographic calculations
in N=4 SYM

Chesler *PRL* 115 (2015) 24, 241602; Chesler, Yaffe *JHEP* 10 (2015) 070



pure glue QCD Kinetic Theory
in single interaction approximation

Kurkela, Mazeliauskas, Törnkvist *JHEP* 11 (2021) 216

Non-eq description of flow

Development of 2+1D QCD Kinetic Theory simulations in progress

c.f. Talk by R.Törnkvist

meanwhile explored systematically within simplified description in conformal RTA

$$p^\mu \partial_\mu f = -\frac{p \cdot u}{\tau_R}(f - f_{\rm eq}),$$

Due to particular simplicity, all results only depends on initial geometry $e(x_T)$ and one single opacity parameter

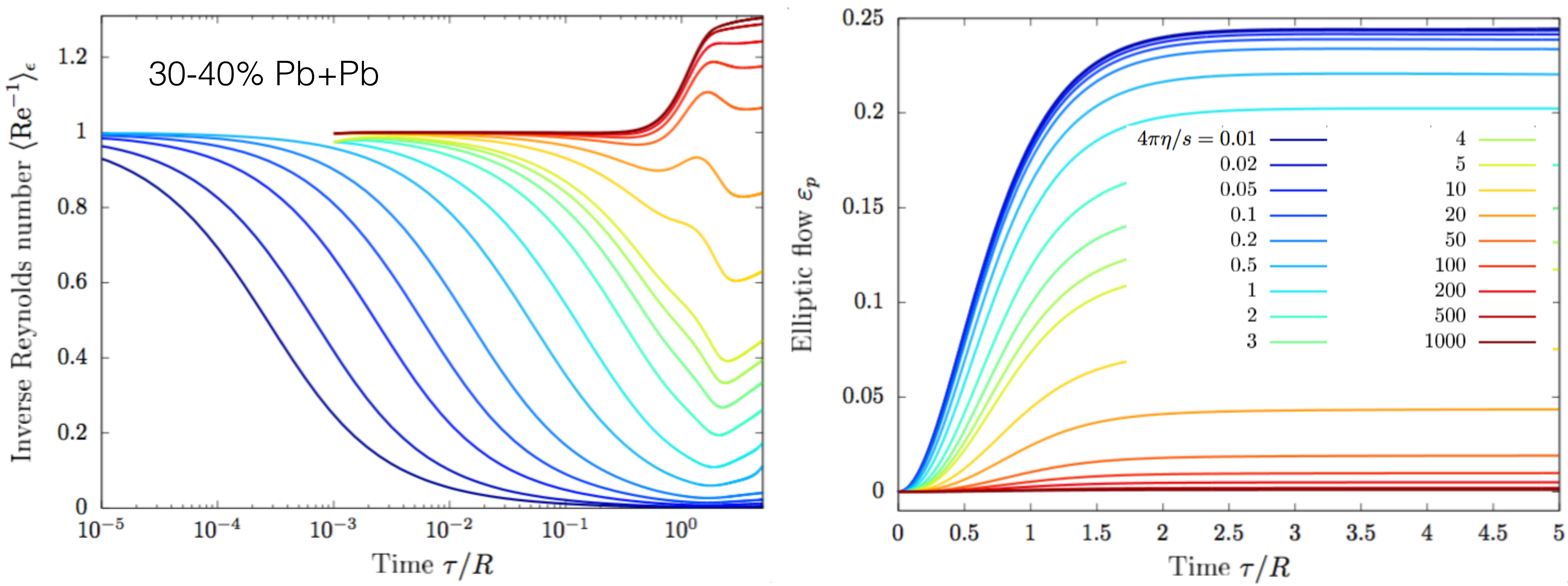
$$\hat{\gamma} = \frac{1}{5\eta/s}\left(\frac{R}{\pi a}\frac{\mathrm{d}E_\perp^0}{\mathrm{d}\eta}\right)^{1/4},$$

encodes dependence on system size, viscosity and collision energy

Ambrus,SS, Werthmann PRL 130 (2023) 15, 152301; PRD 107 (2023) 9, 094013; Kurkela, Taghavi, Wiedemann Wu PLB 811 (2020) 135901; Kurkela, Wiedemann, Wu EPJC 79 (2019) 11, 965; Kurkela, Wiedemann EPJC 79 (2019) 9, 759

Small systems

Degree of equilibration over the course of reaction dynamics strongly depends on opacity



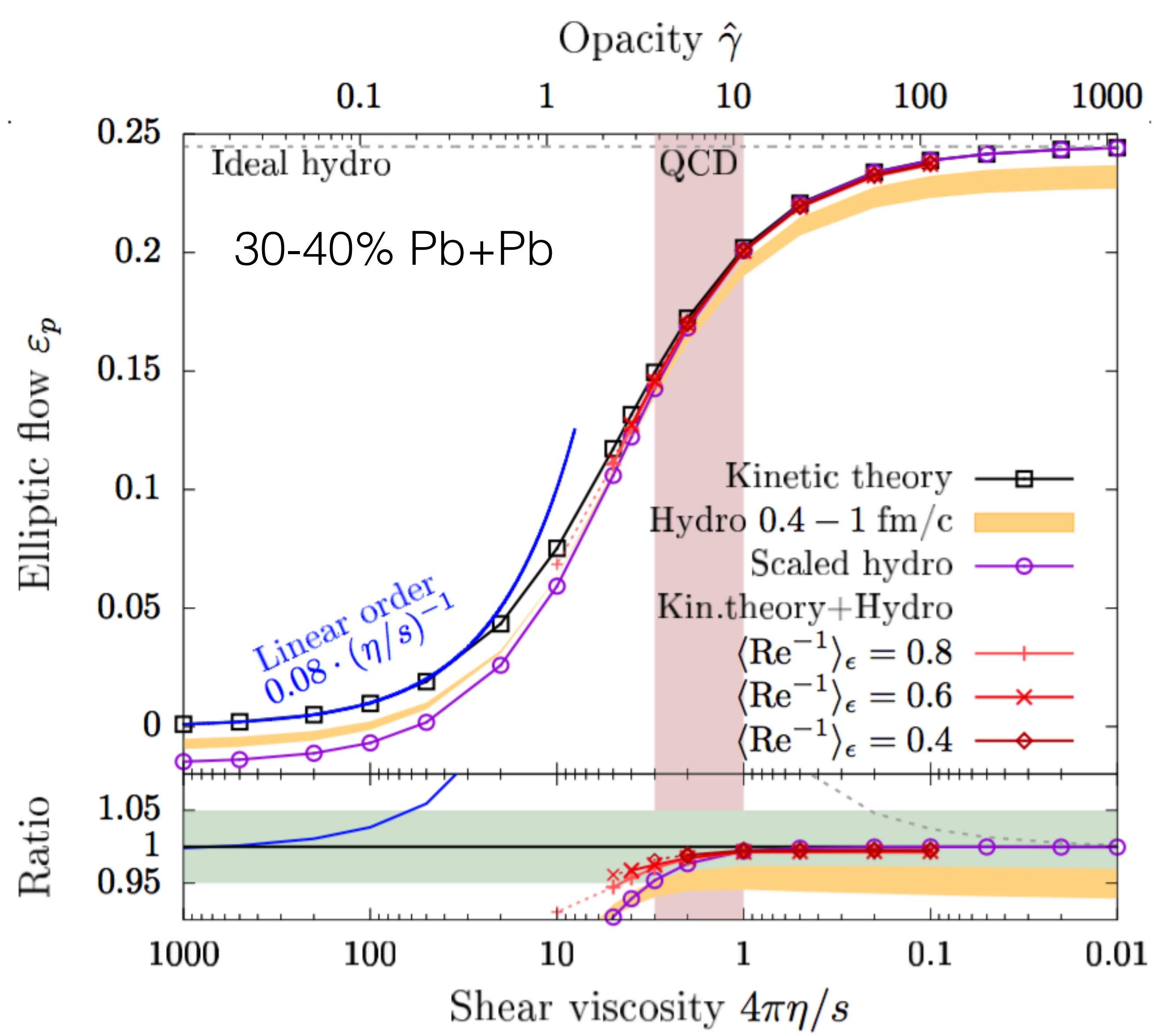
crucial differences in microscopic dynamics during the development of radial and anisotropic transverse flow

c.f. Poster by C.Werthmann

Ambrus,SS, Werthmann PRL 130 (2023) 15, 152301; PRD 107 (2023) 9

Opacity dependence of Flow

Despite microscopic differences, smooth transition from non-interacting (η/s->∞) to strongly interacting limit (η/s->0)



Hydrodynamics accurately describes collective flow in semi-central Pb+Pb collisions at LHC if pre-equilibrium phase is described correctly

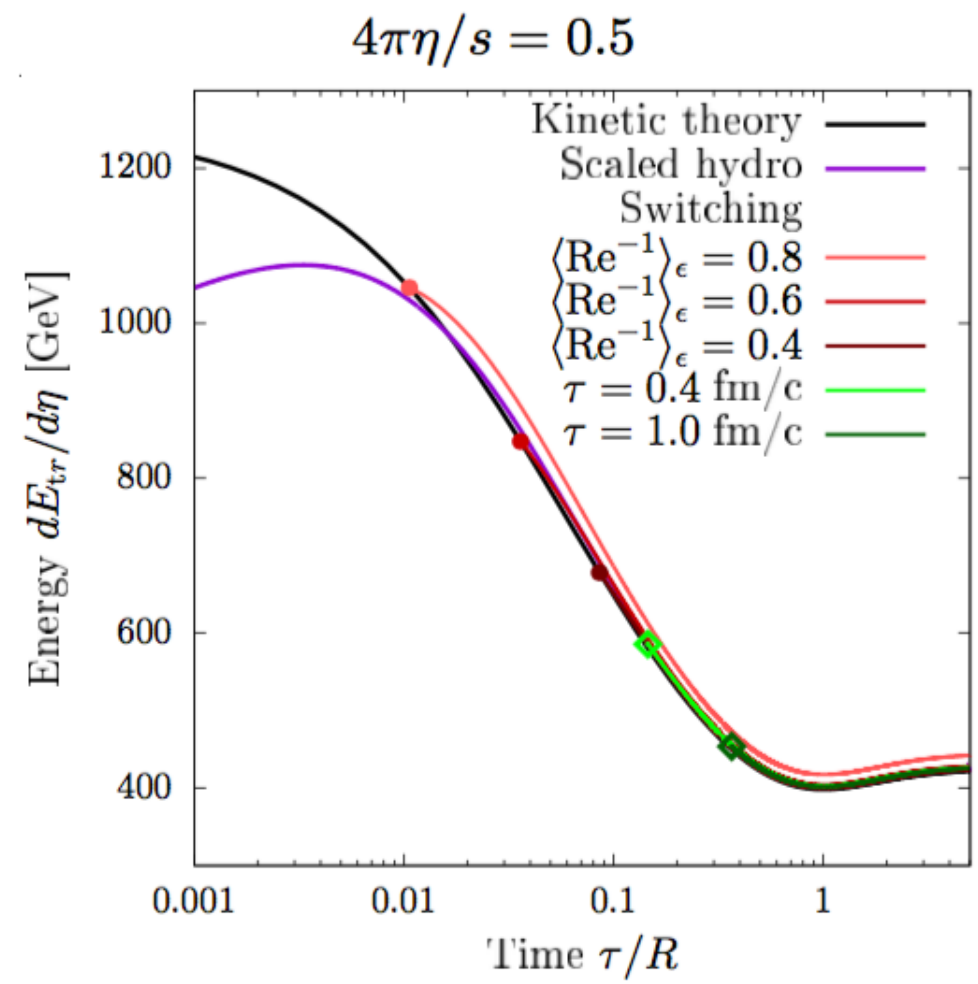
Strong sensitivity of elliptic flow to shear viscosity η/s in the relevant range

c.f. Poster by C.Werthmann

Ambrus,SS, Werthmann PRL 130 (2023) 15, 152301; PRD 107 (2023) 9

Validity of Hydrodynamics

Hydrodynamics does not correctly describe non-equilibrium evolution, but only becomes applicable once/if the system gets sufficiently close to equilibrium



Hydrodynamics applicable below $\mathrm{Re}_c^{-1} \sim 0.75$ across all opacities

$$\mathrm{Re}^{-1} = \left(\frac{6\pi^{\mu\nu}\pi_{\mu\nu}}{\epsilon^2} \right)^{1/2}$$

Since small systems (or large systems with high viscosity) can fall apart before Re_c^{-1} is reached, this yields **bounds on applicability of hydro**

c.f. Poster by C.Werthmann

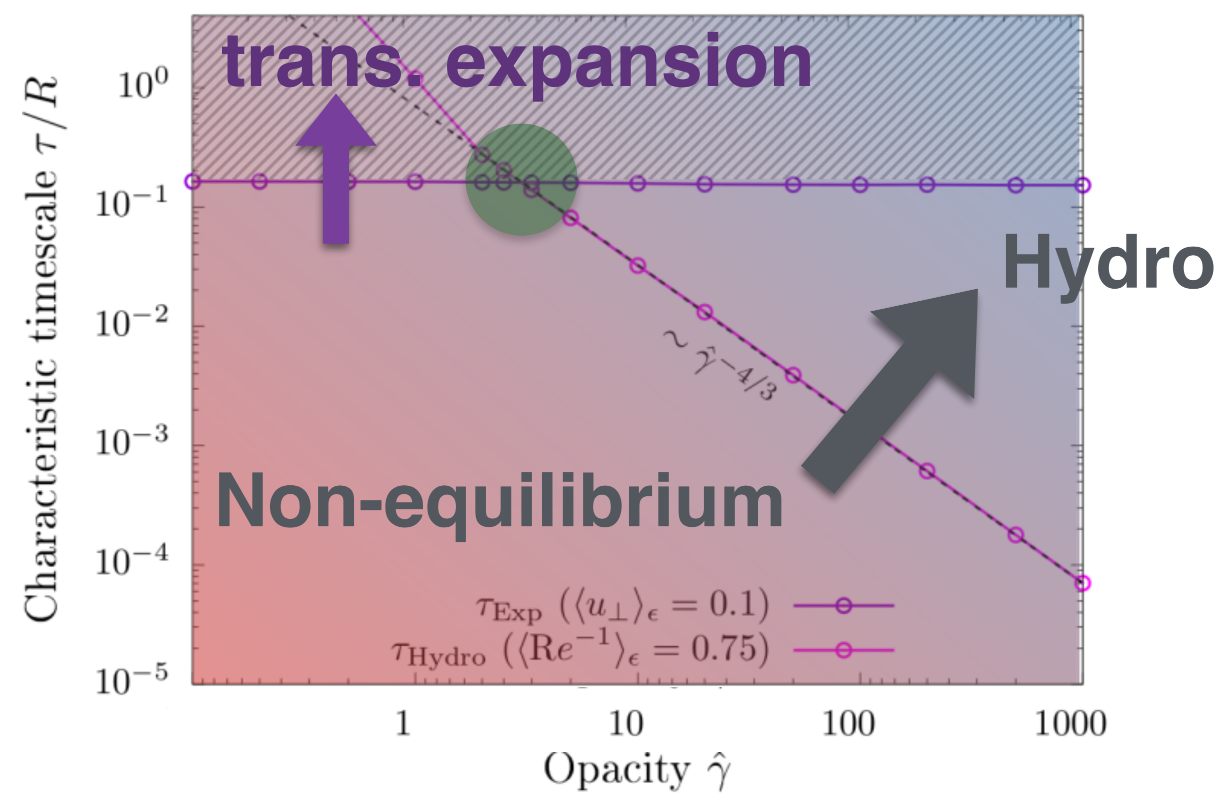
Ambrus,SS, Werthmann PRL 130 (2023) 15, 152301; PRD 107 (2023) 9

Hydrodynamics in small systems?

Development of transverse flow accurately described by hydrodynamics for opacities

$$\hat{\gamma} \gtrsim 3-4$$

Satisfied in central Pb+Pb collisions but questionable in p+p and p+Pb collisions



- pp: $\hat{\gamma} \approx 0.88 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{0.4\,\text{fm}}\right)^{1/4} \left(\frac{dE_\perp^{(0)}/d\eta}{5\,\text{GeV}}\right)^{1/4} \left(\frac{\nu_{\text{eff}}}{40}\right)^{-1/4}$
- PbPb: $\hat{\gamma} \approx 9.2 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{6\,\text{fm}}\right)^{1/4} \left(\frac{dE_\perp^{(0)}/d\eta}{4000\,\text{GeV}}\right)^{1/4} \left(\frac{\nu_{\text{eff}}}{40}\right)^{-1/4}$

Estimate that exciting transition region γ~3 to be probed in future O+O collisions at LHC

Ambrus,SS, Werthmann PRL 130 (2023) 15, 152301; PRD 107 (2023) 9

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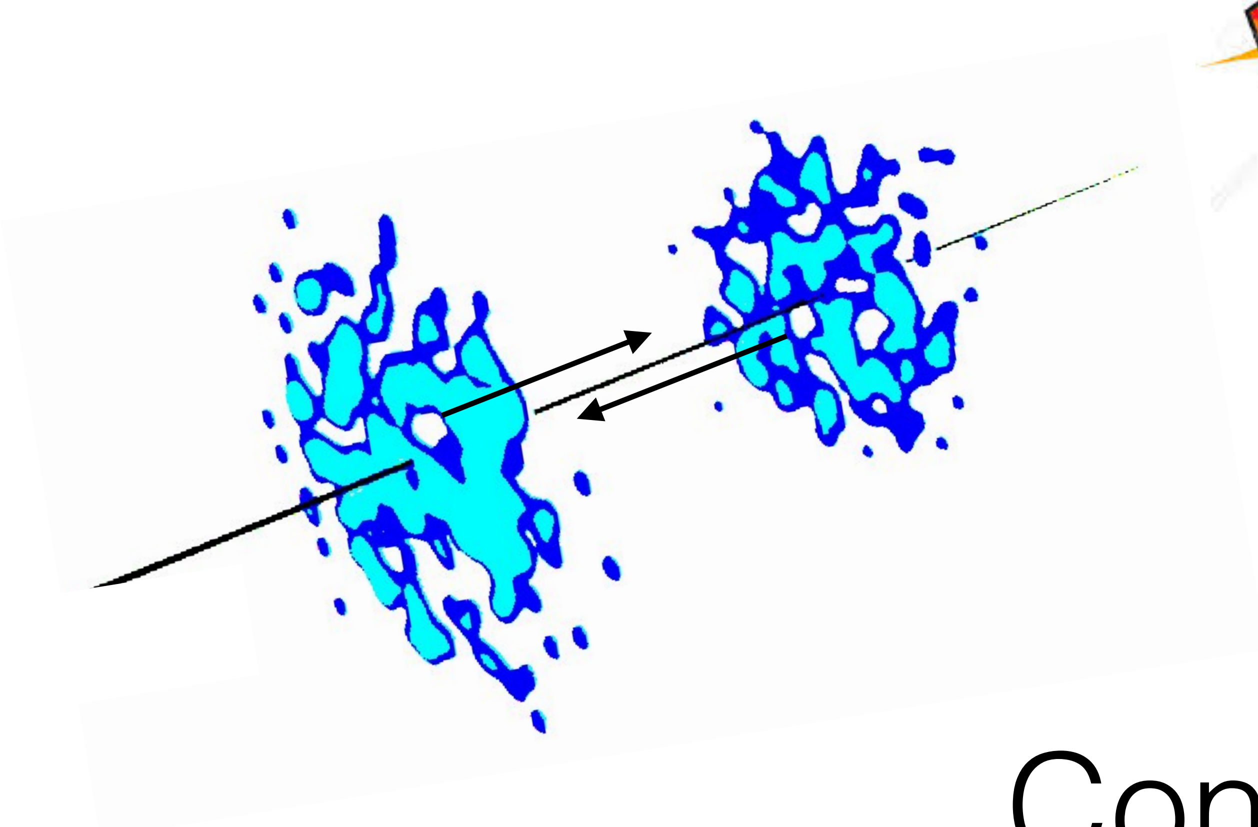
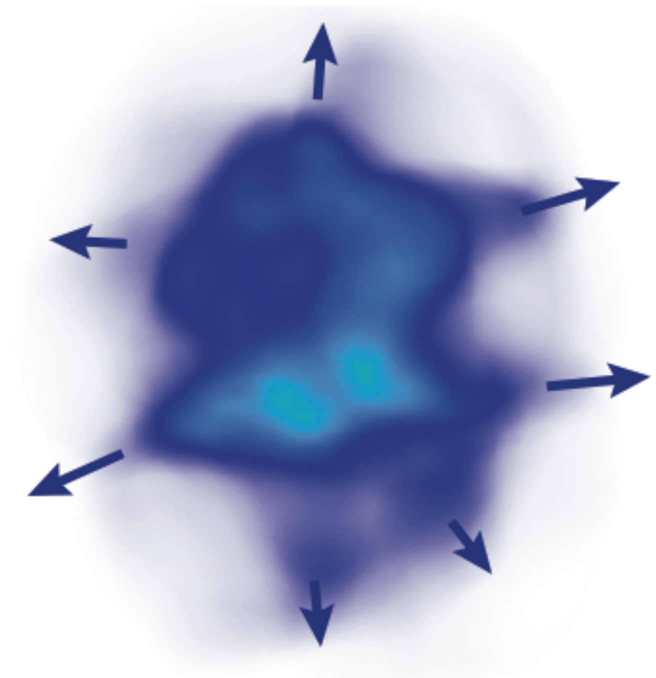




Conclusions & Outlook

Conclusions & Outlook

Solid understanding of equilibration at weak and strong coupling in large systems, where pre-equilibrium is described by (conformal) Bjorken flow

Phenomenology of pre-equilibrium stage in HICs starting to emerge

- Entropy production, E&M Probes, Hard Probes (Jets & Heavy-Flavor),…

Hydrodynamics not applicable in small systems as QGP does not equilibrate to sufficient degree

Open Questions:

Next-to-leading order calculations at weak coupling

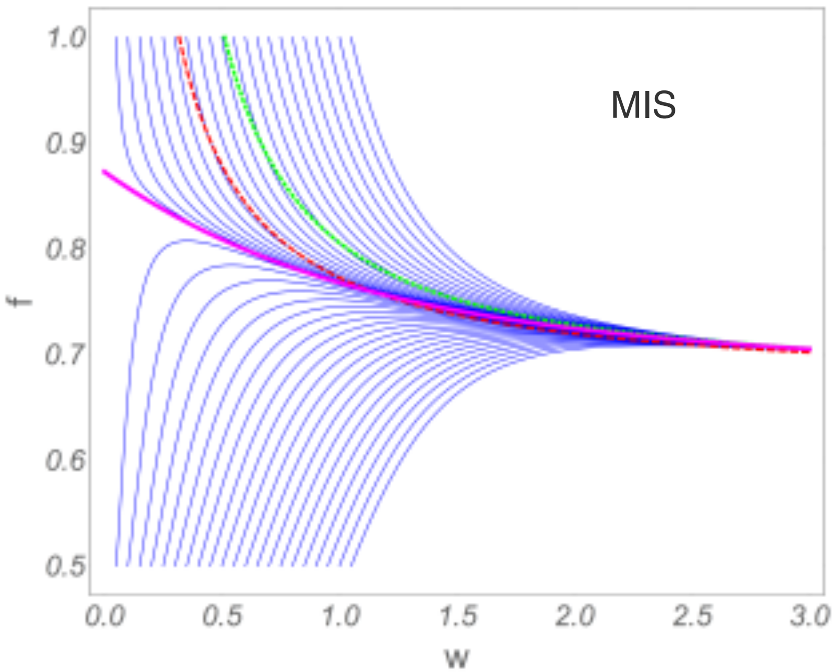
Breaking of conformal invariance -> Non-trivial EoS

Extension to 3+1D long. Dynamics

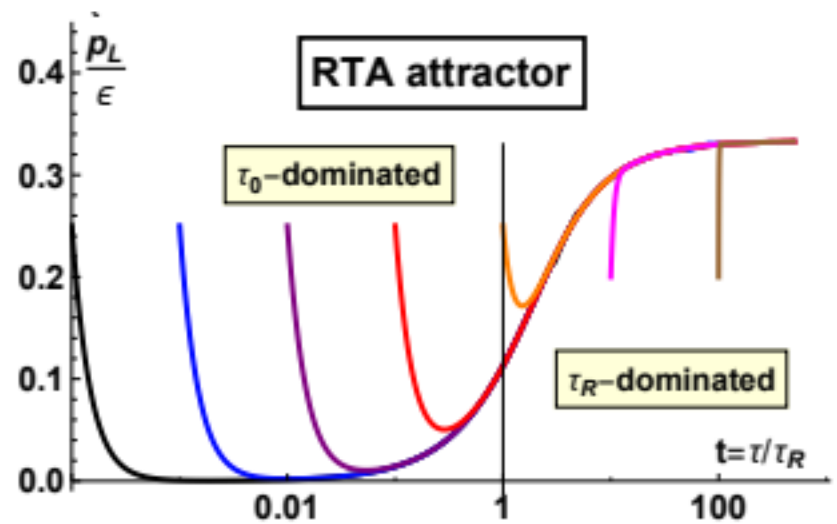
Backup

Sensitivity to initial state

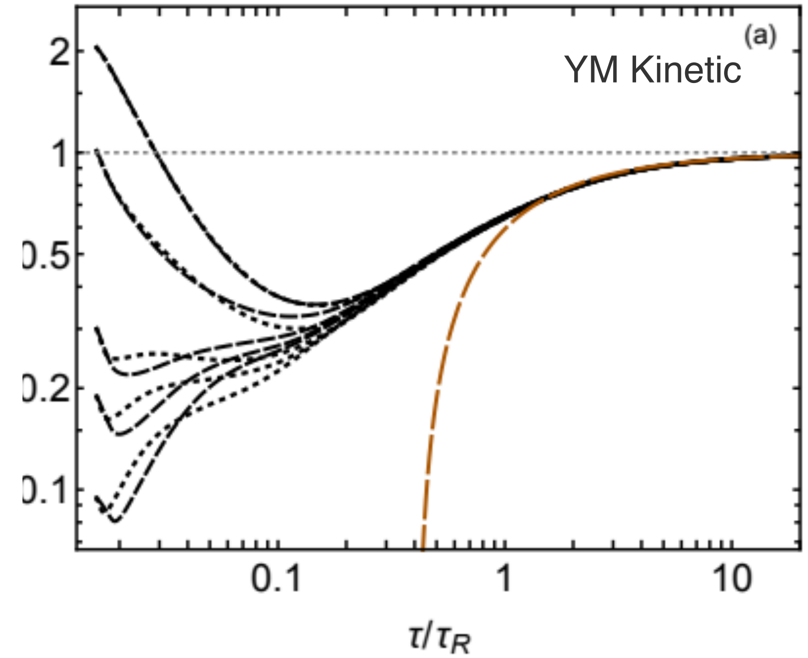
Due to rapid long. expansion at early times initial some details of initial state (e.g. initial momentum anisotropy) quickly become irrelevant



Heller, Spalinski PRL 115 (2015) 7, 072501



Kurkela, vd Schee, Wiedemann
PRL 125 (2020) 12, 122302



Almalool, Kurkela, Strickland
PRL 125 (2020) 12, 122302

``Hydro attractors'' -> Non-equilibrium attractors beyond Hydrodynamics?

Beware of the fact that attractor curve still depends on microscopic theory & symmetries (conformal Bjorken flow) severely constraints evolution