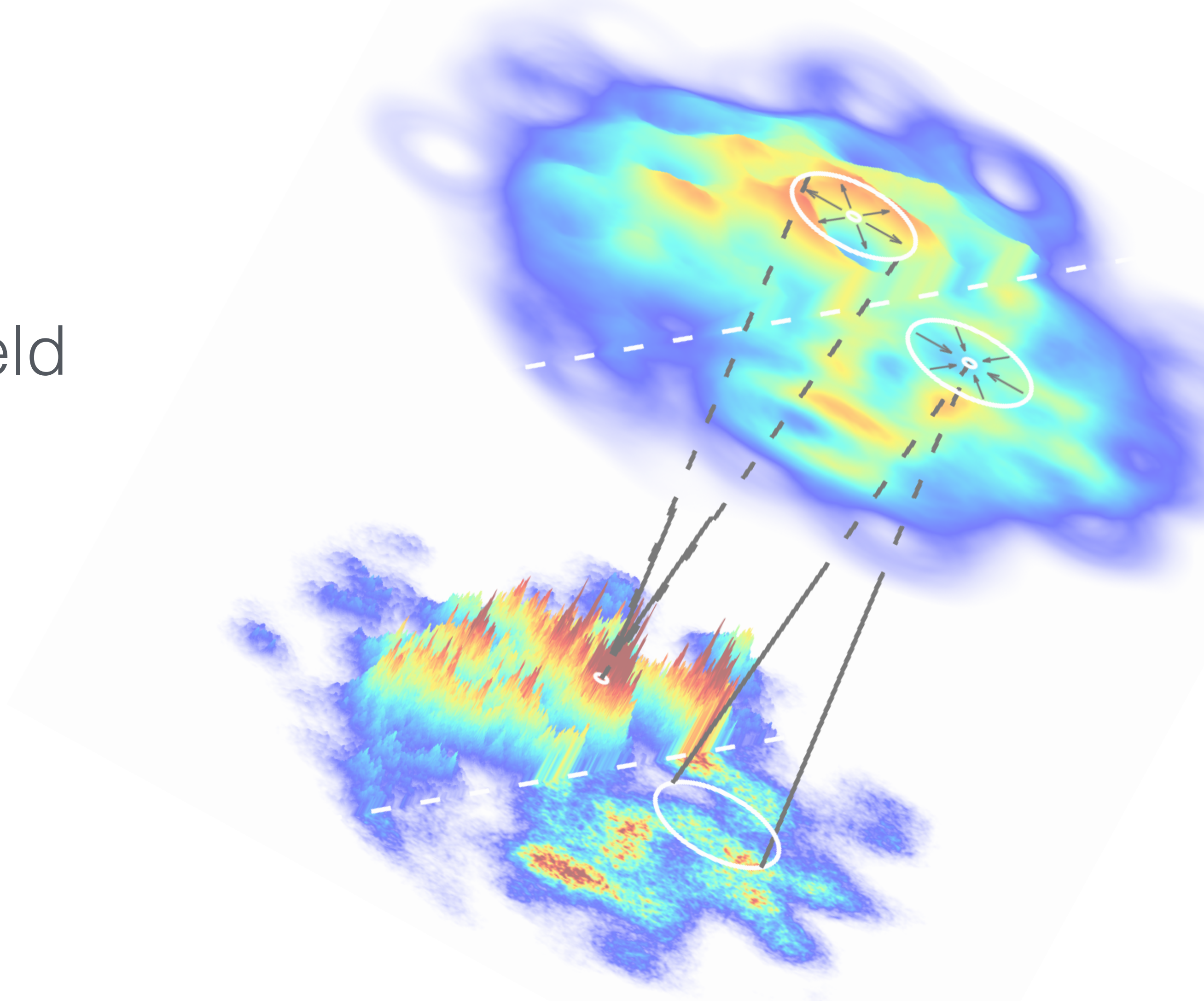
New theoretical developments towards understanding the early stages of HICs



Sören Schlichting | Universität Bielefeld

ICPAQGP
Puri, India
Feb 2023

CRC-TR 211
Strong-interaction matter under extreme conditions

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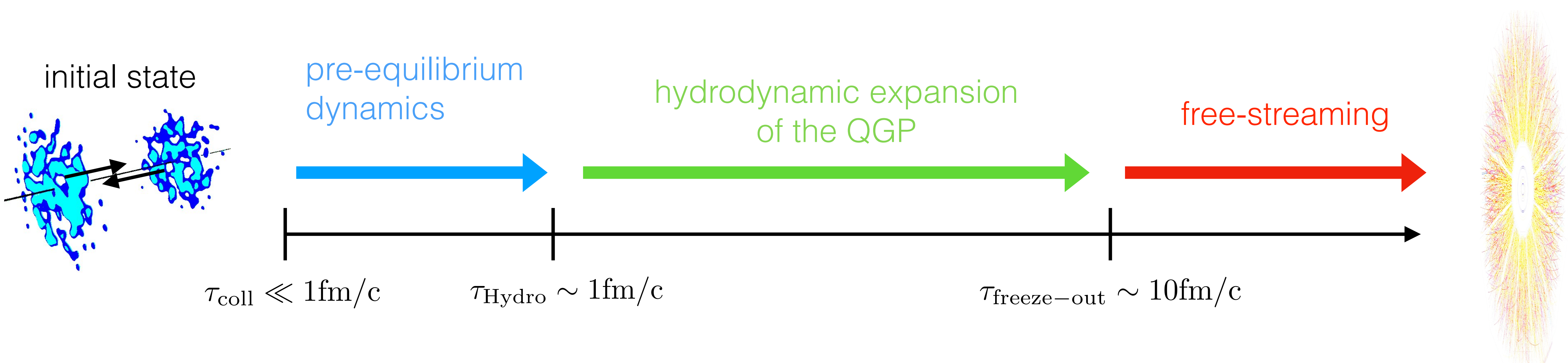
Heavy-Ion Collisions

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



Space-time dynamics (bulk) dominated by hydrodynamics expansion

Viscous Hydrodynamics

Viscous relativistic Hydrodynamics is an effective theory of QCD on large time and distance scales

Based on conservation laws for energy and momentum

$$\partial_\mu T^{\mu\nu} = 0$$

supplemented by hydrodynamic constitutive relations
that are based on an expansion around (local) thermodynamic equilibrium

$$T^{\mu\nu} = T^{\mu\nu}_{\mathrm{eq}}(T, u^\mu) + \pi^{\mu\nu}(\partial T, \partial u^\mu)$$

Since heavy- and in particular light-ion collision produce a small and short lived out-of-equilibrium system, it is by no means clear that such an effective description is applicable

-> Need to establish reason for phenomenological success & quantify range-of-applicability and accuracy

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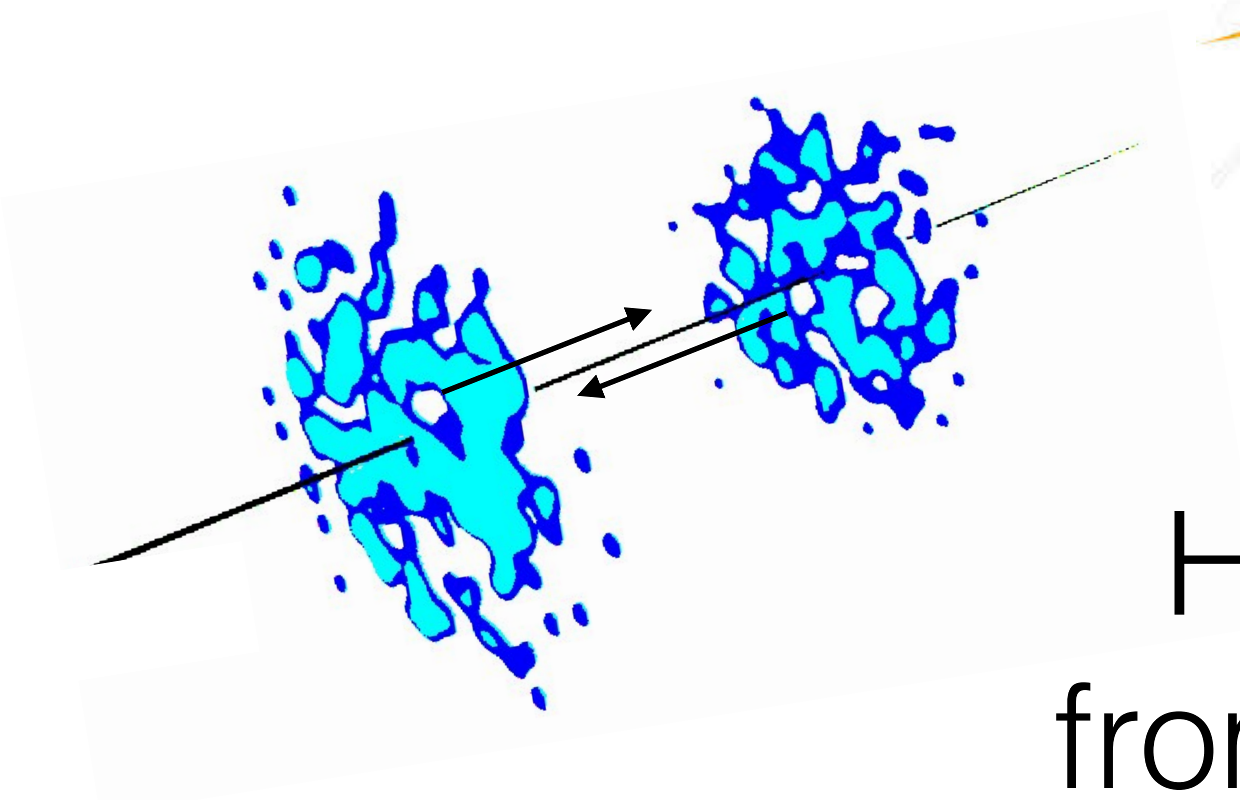
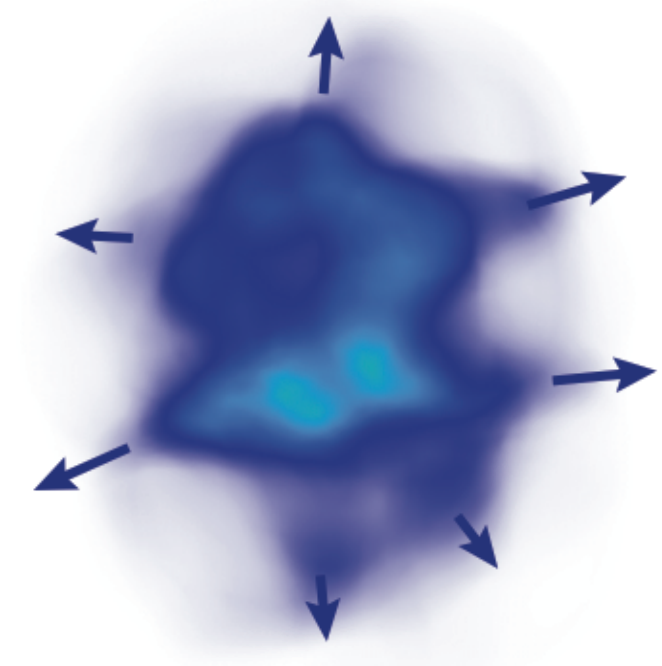
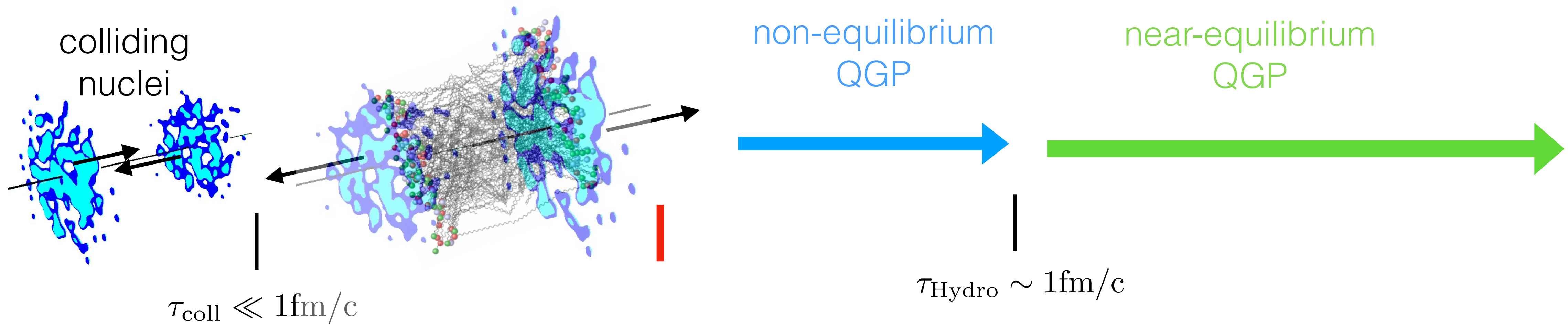




Describing Heavy-Ion Collisions from beginning to end

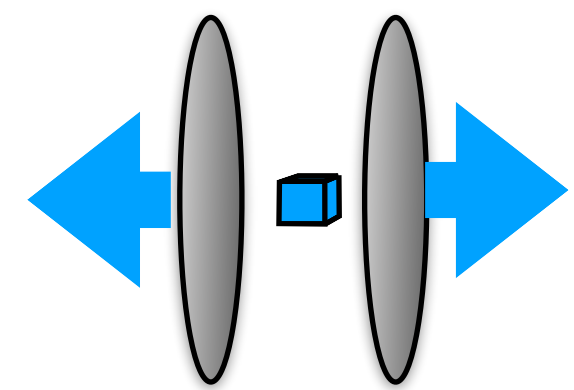
Based on SS, Teaney Ann.Rev.Nucl.Part.Sci. 69 (2019) 447-476
Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12
Coquet,Du,Ollitrault,SS,Winn; *PLB* 821 (2021) 136626

Initial state & Equilibration of HICs



Energy deposition can at least in principle be calculated within an effective theory of high-energy QCD

McLerran, Venugopalan PRD49 (1994) 2233-2241, Kovner, McLerran, Weigert D52 (1995) 6231-6237



-> Gluon dominated initial state far-from equilibrium

c.f. talk by R. Venugopalan

Non-equilibrium QCD plasma created immediately after the collision of heavy nuclei is subject to rapid longitudinal expansion

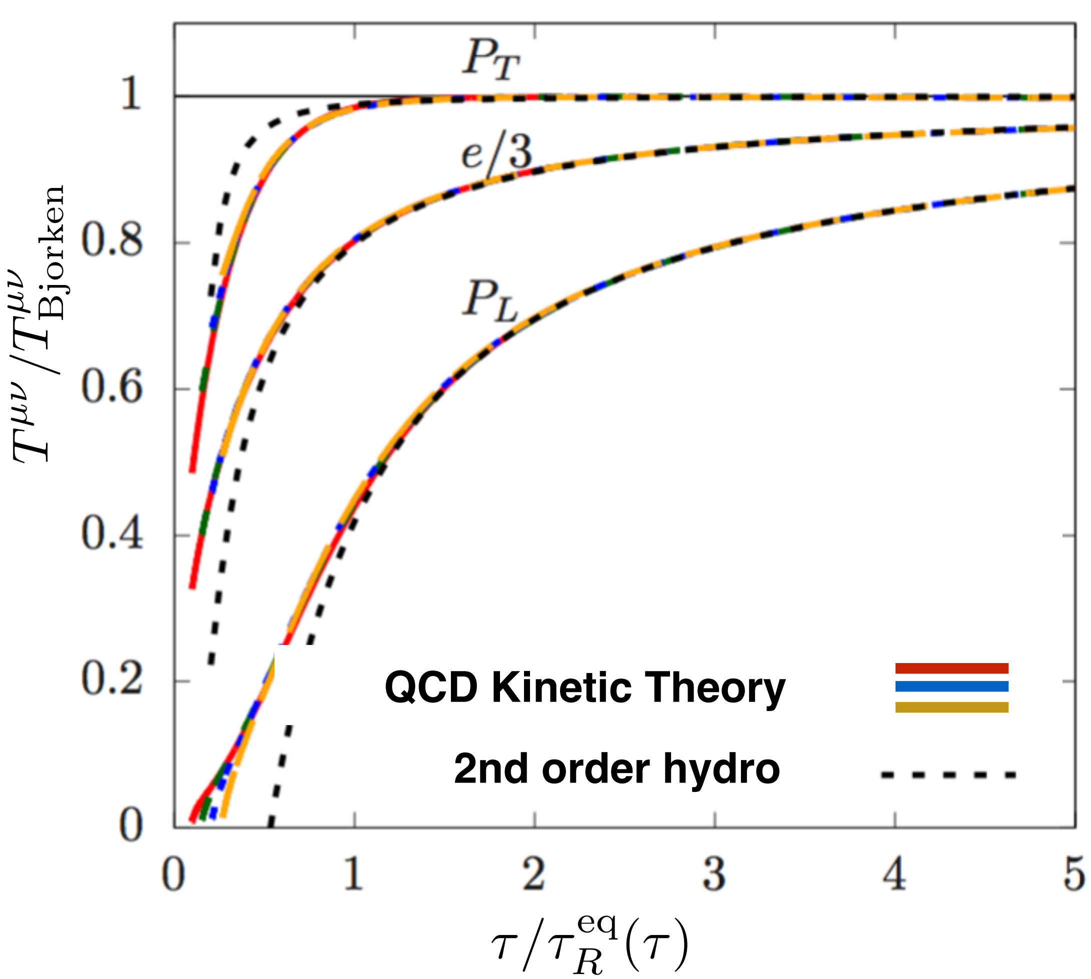
Significant progress in understanding equilibration & onset of hydrodynamic behaviour when neglecting transverse expansion over short pre-equilibrium time scale

Hydrodynamic behavior

Hydrodynamics describes the macroscopic evolution of energy-momentum tensor $T^{\mu\nu}$ based on an expansion around local thermal equilibrium

$$Kn \sim \lambda_{micro}/L_{macro} \qquad Re^{-1} \sim \delta T^{\mu\nu}_{\rm non-eq}/T^{\mu\nu}_{\rm eq}$$

Since the system is highly anisotropic at early times ($P_L \ll P_T$), key question is to understand evolution of $T^{\mu\nu}$ towards local equilibrium ($P_L = P_T$)



Studies in QCD Kinetic theory indicate that equilibration of macroscopic quantities controlled by a single equilibrium relaxation rate

$$\tau_R^{\rm eq}(\tau) = \frac{4\pi\eta/s}{T_{\rm eff}(\tau)}$$

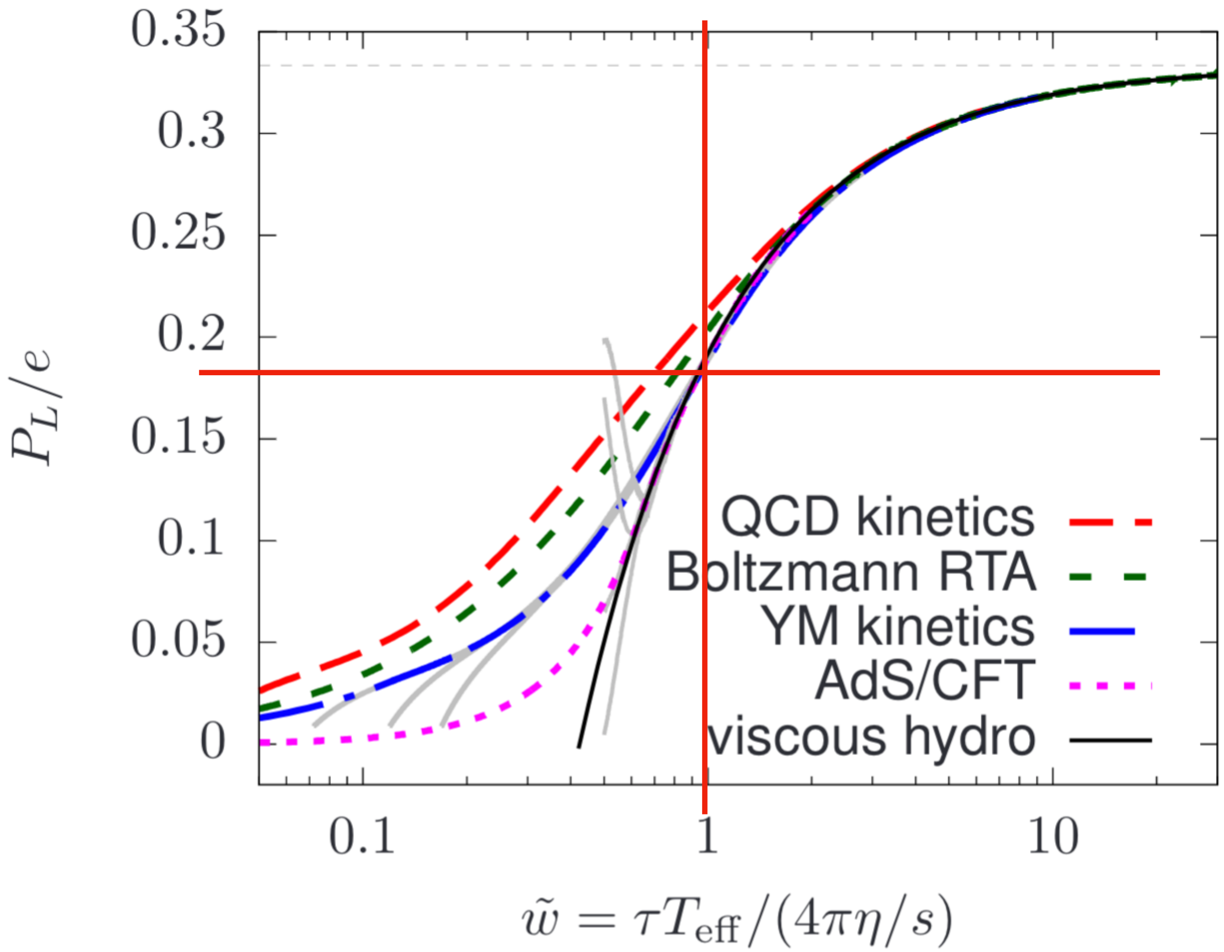
results at different coupling strength indicate small sensitivity to α_s when compared in units of $\tau_R^{\rm eq}$

Kurkela, Zhu PRL 115 (2015) 182301
Kurkela, Mazeliauskas, Paquet, SS, Teaney 1805.01604; 1805.00961

Hydrodynamic behavior

Effective description in viscous hydrodynamics becomes applicable on time scales Kurkela, Mazeliauskas, Paquet, SS, Teaney 1805.01604; 1805.00961

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



when the QGP is significantly out-of-equilibrium

$$Re^{-1} \sim 3(P_L/e - 1/3) \sim 1$$

Surprising effectiveness of viscous fluid dynamics also in a variety of different microscopic theories

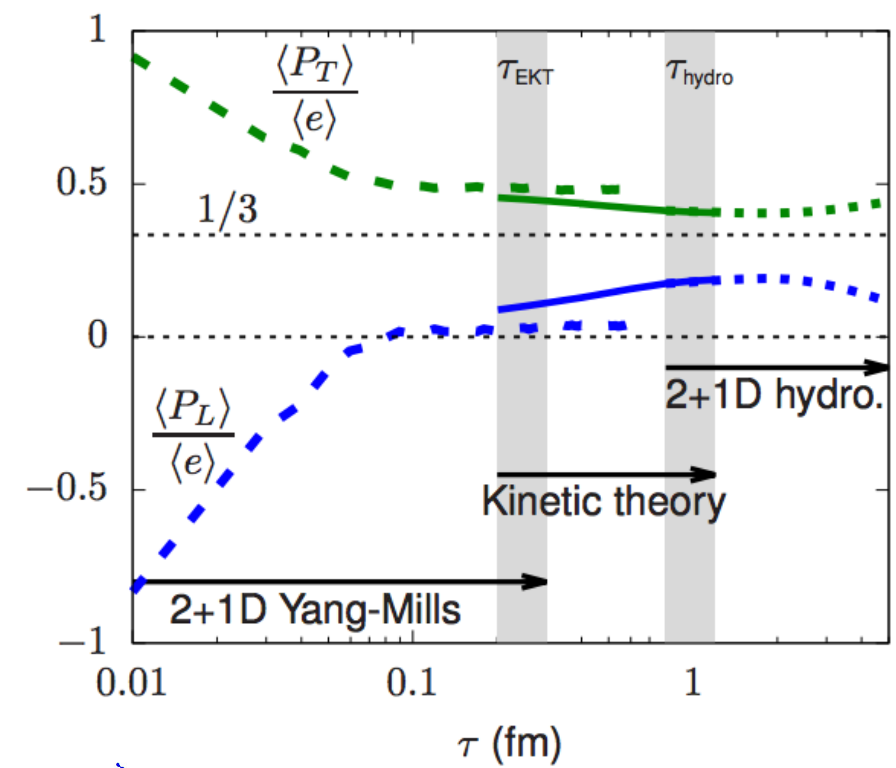
BUT beware of high degree of symmetry in theor. calculations (conformal, no transverse expansion)

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

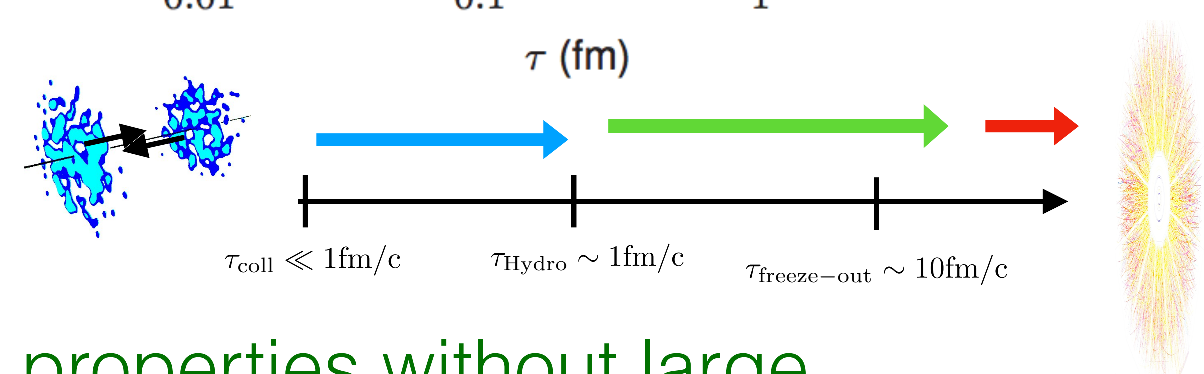
Dynamics of HICs

Based on progress in understanding early time dynamics & equilibration can now describe HIC from beginning to end by matching different effective descriptions of QCD

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



Effects of including pre-equilibrium phase on expansion dynamics/ experimental observables small



Controlled extraction of QGP transport properties without large uncertainties from early times

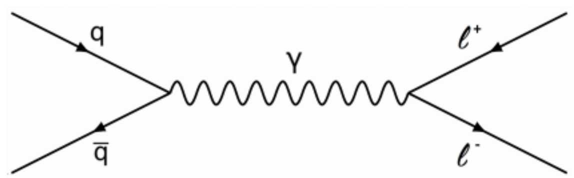
Difficult to gain experimental access to early time non-equilibrium dynamics in heavy-ion collisions

but theoretically important to link cold QCD to hot QCD properties

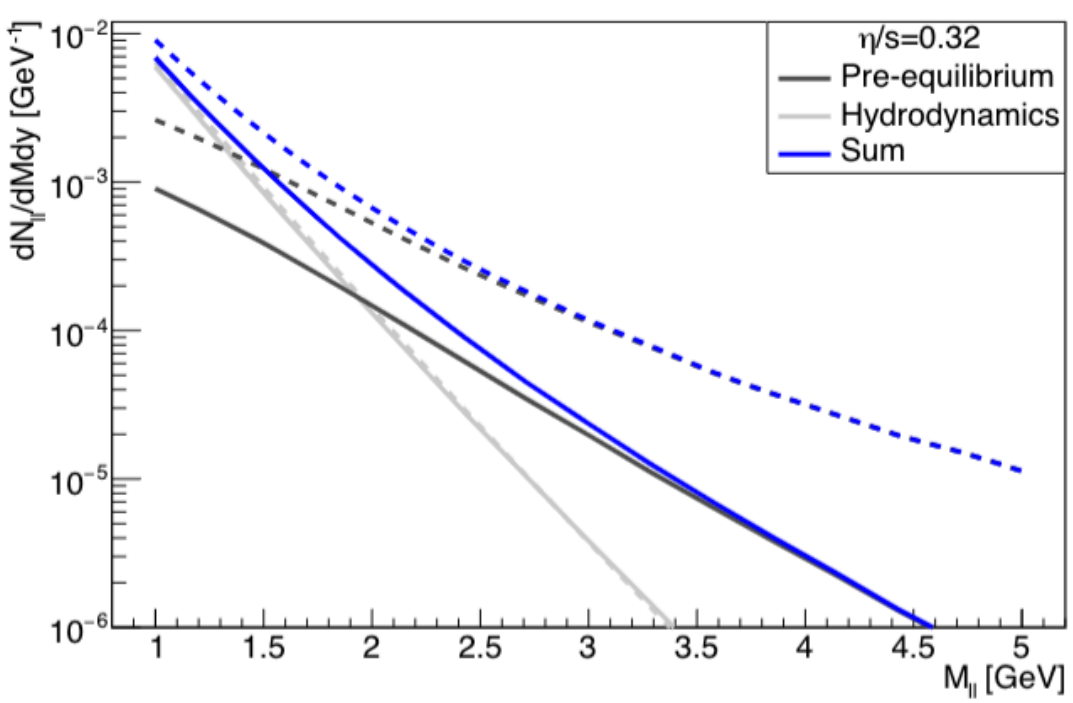
Electromagnetic probes of pre-eq stage

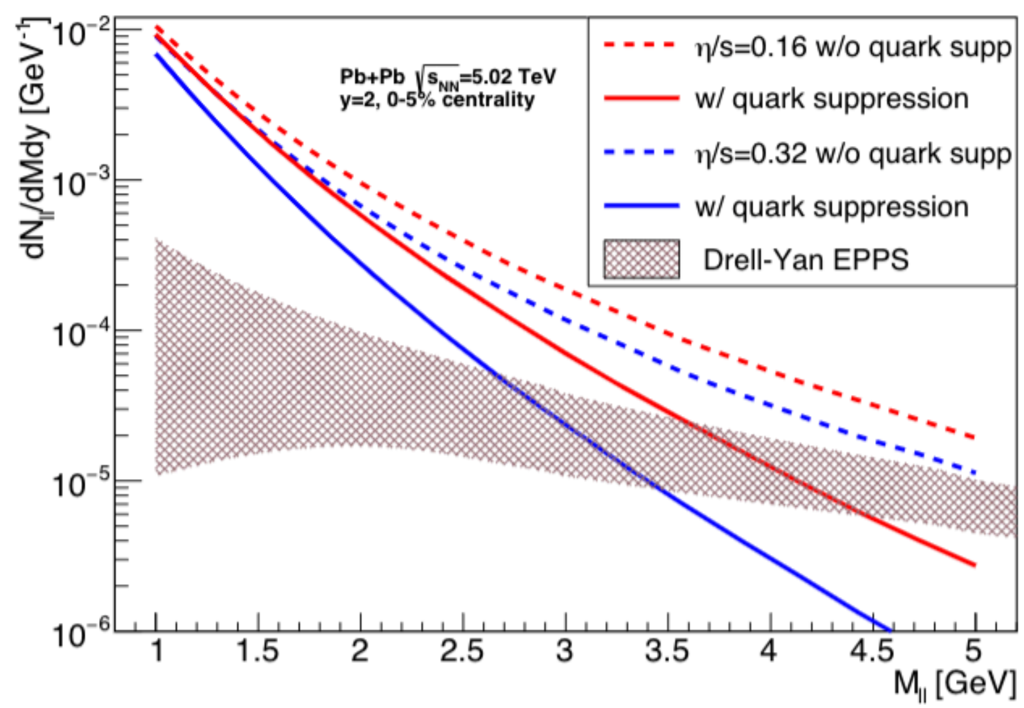
Electromagnetic probes produced throughout space-time evolution of HICs; escape collision unscathed as they do not interact strongly with the QGP

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)



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





New window into pre-equilibrium dynamics for 1GeV<M<3GeV accessible with next generation of heavy-ion detectors (ALICE3,LHCb)

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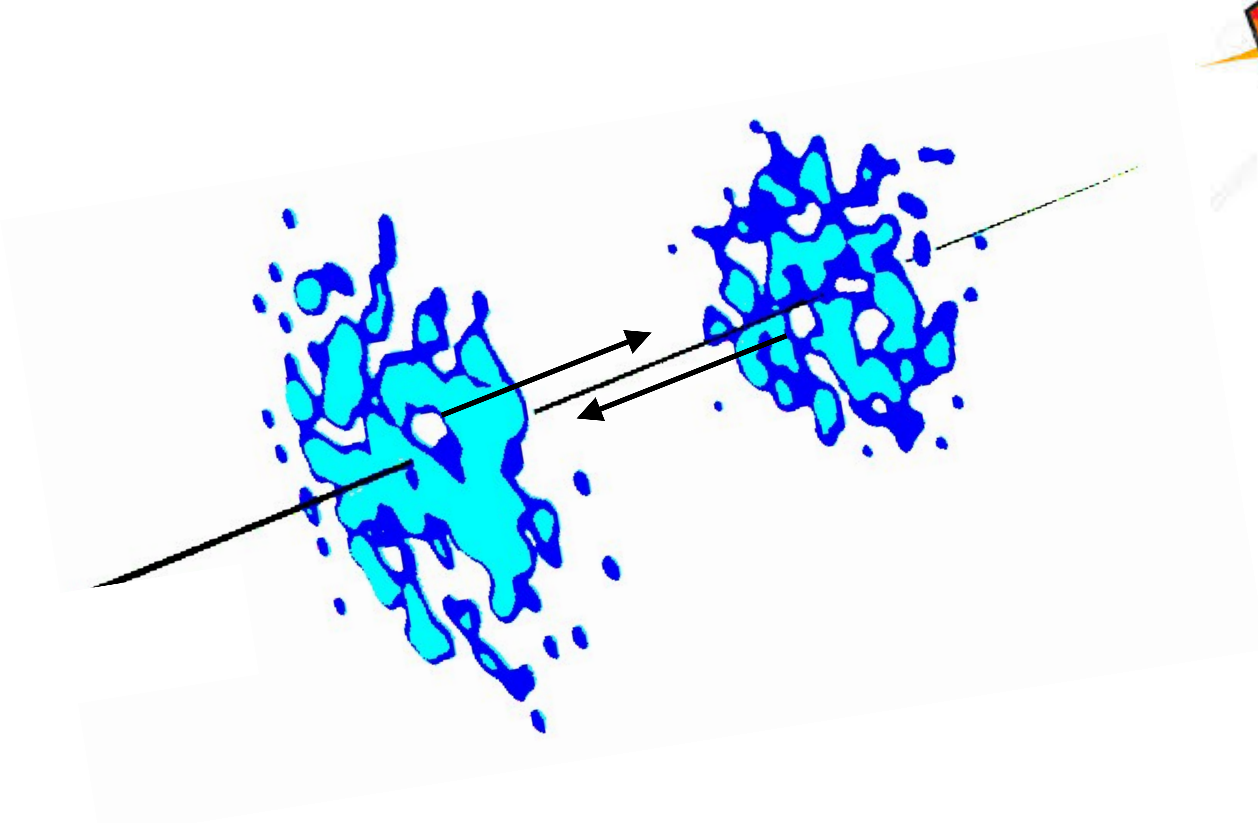
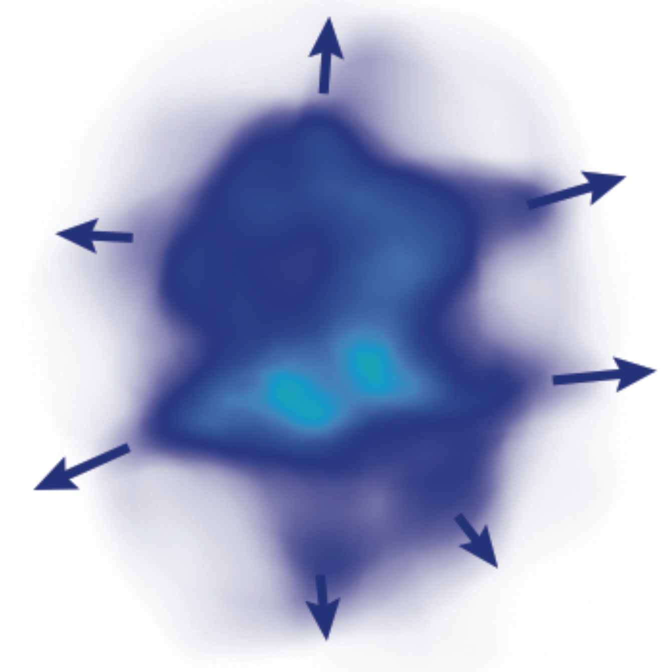




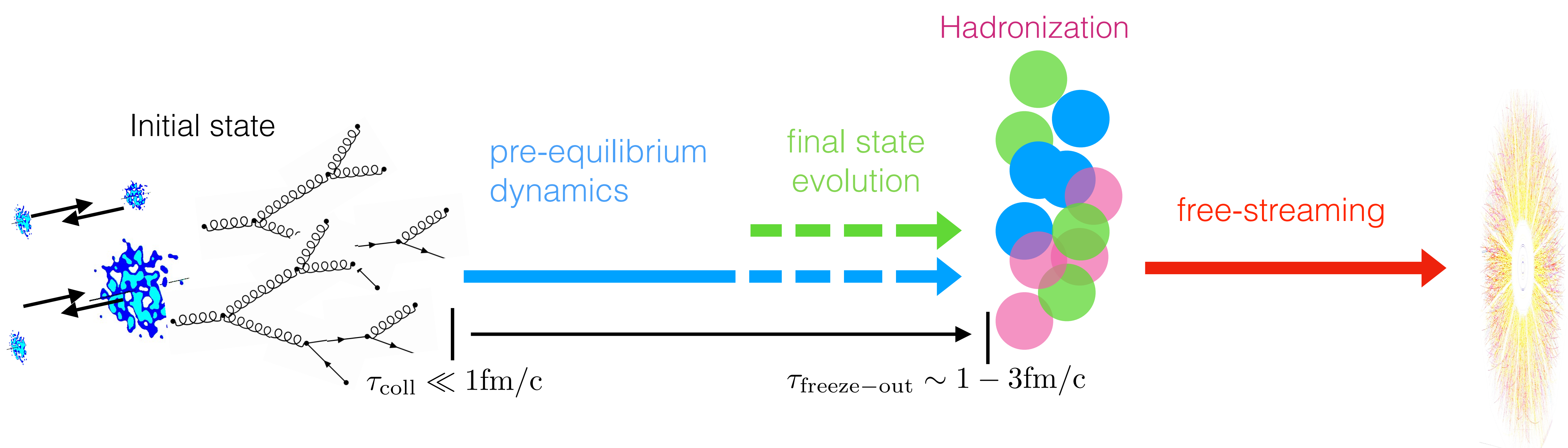
Small system & development of collective flow

Based on Ambrus, SS, Werthmann, arXiv:2211.14356 arXiv:2211.14379

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/Pb collisions at RHIC/LHC?

Small systems

Explore within 2+1D effective kinetic description in conformal RTA

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

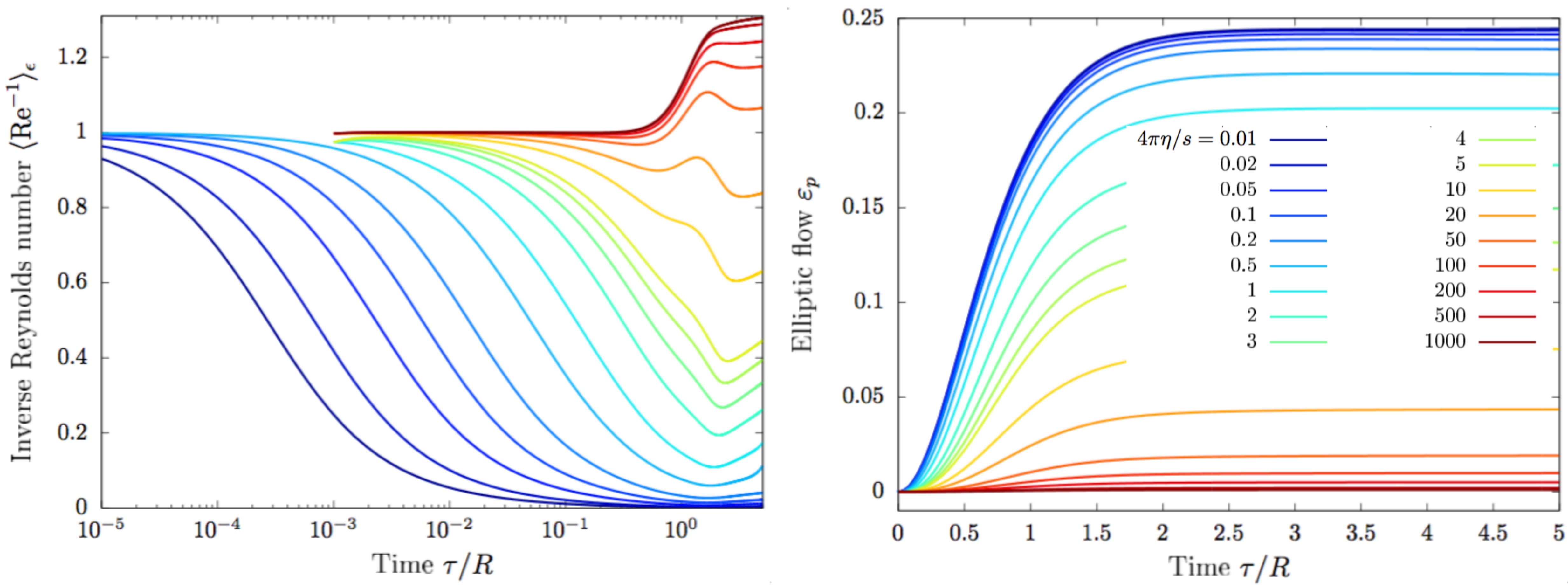
Due to particular simplicity, all results only depends on initial geometry $e(x_T)$ and one single opacity parameter

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

Since opacity encodes system size, viscosity and energy dependence can study effects in Pb+Pb collisions as fct of viscosity η/s and centrality while retaining well defined collision geometry

Small systems

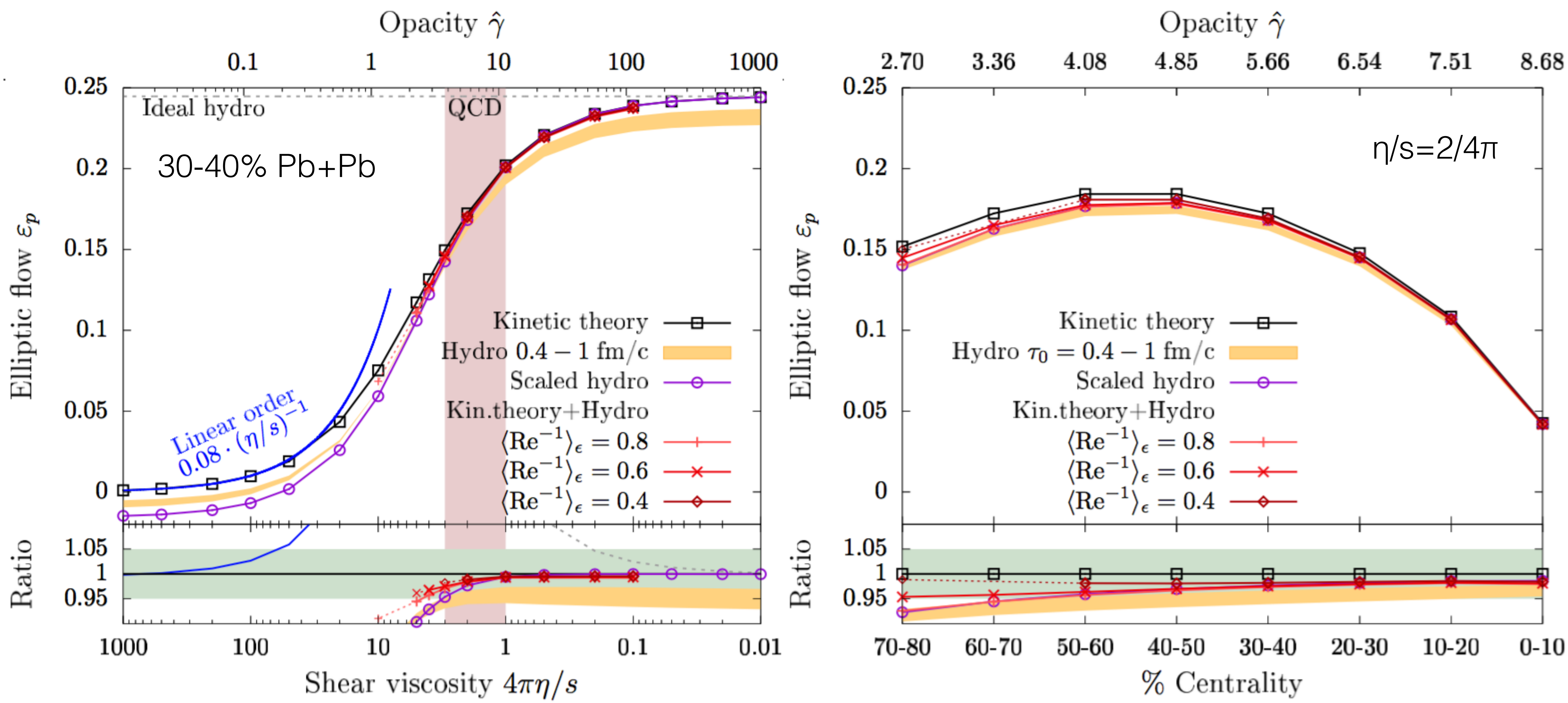
Degree of equilibration over the course of reaction dynamics strongly depends on opacity



Crucial differences in microscopic dynamics during the development of (anisotropic) transverse flow

Opacity dependence of Flow

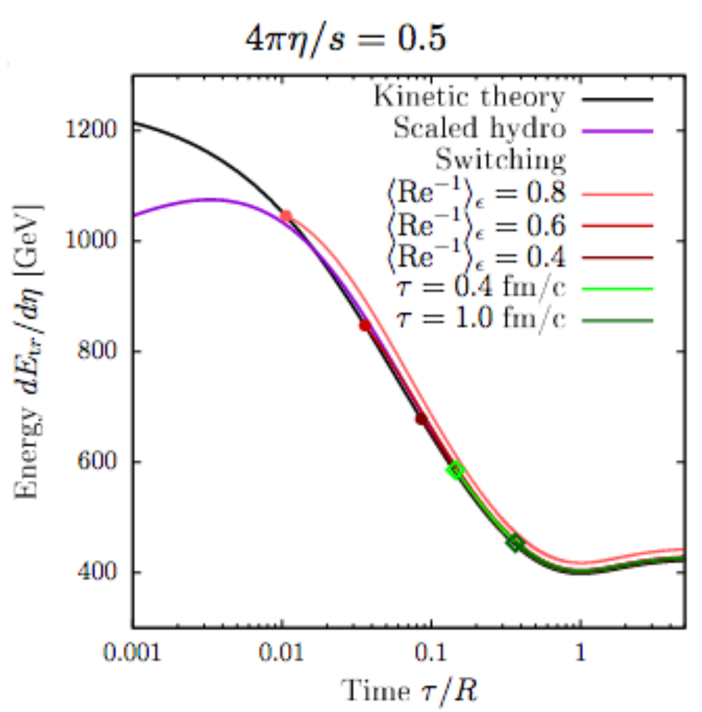
Despite microscopic differences, smooth transition from non-interacting (η/s->∞) to strongly interacting limit (η/s->0)

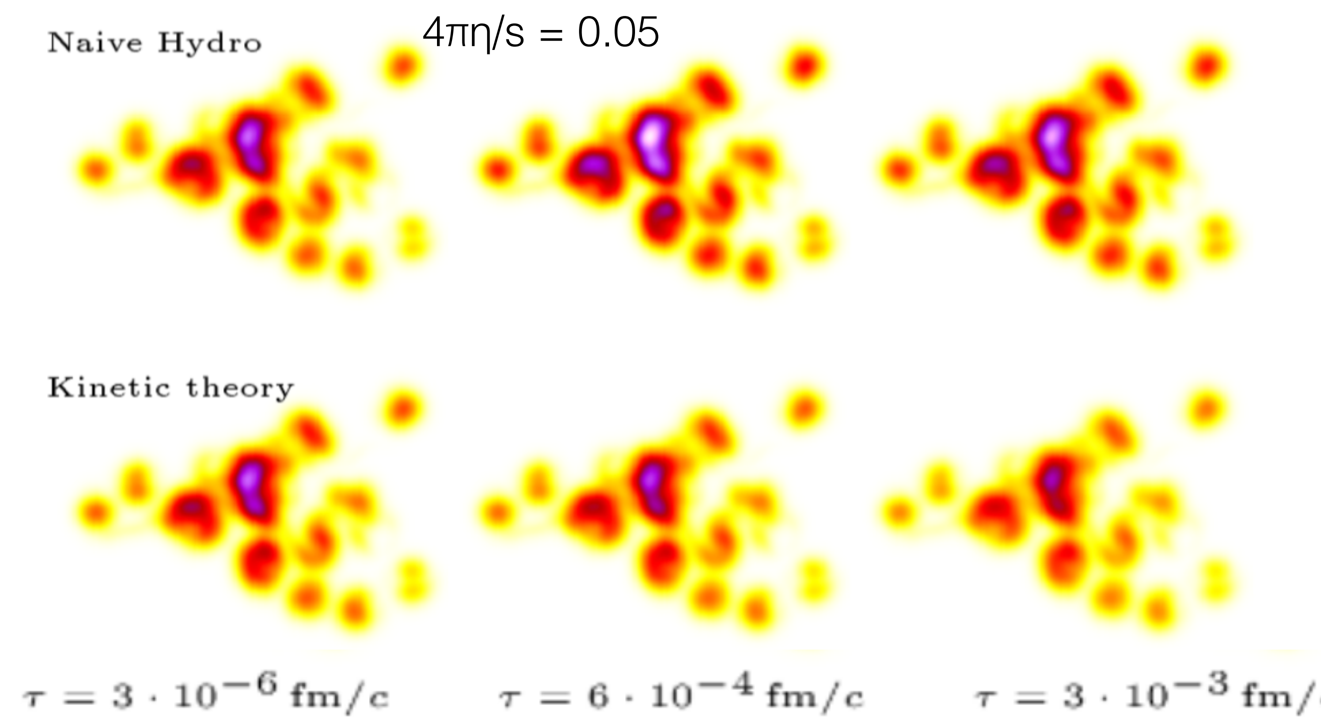


Hydrodynamics applicable for semi-central Pb+Pb collisions at LHC iff sufficient care is taken

Effects of pre-equilibrium phase

Even in the limit of infinite opacity naive hydrodynamics and kinetic theory do not agree due to differences in the early time dynamics



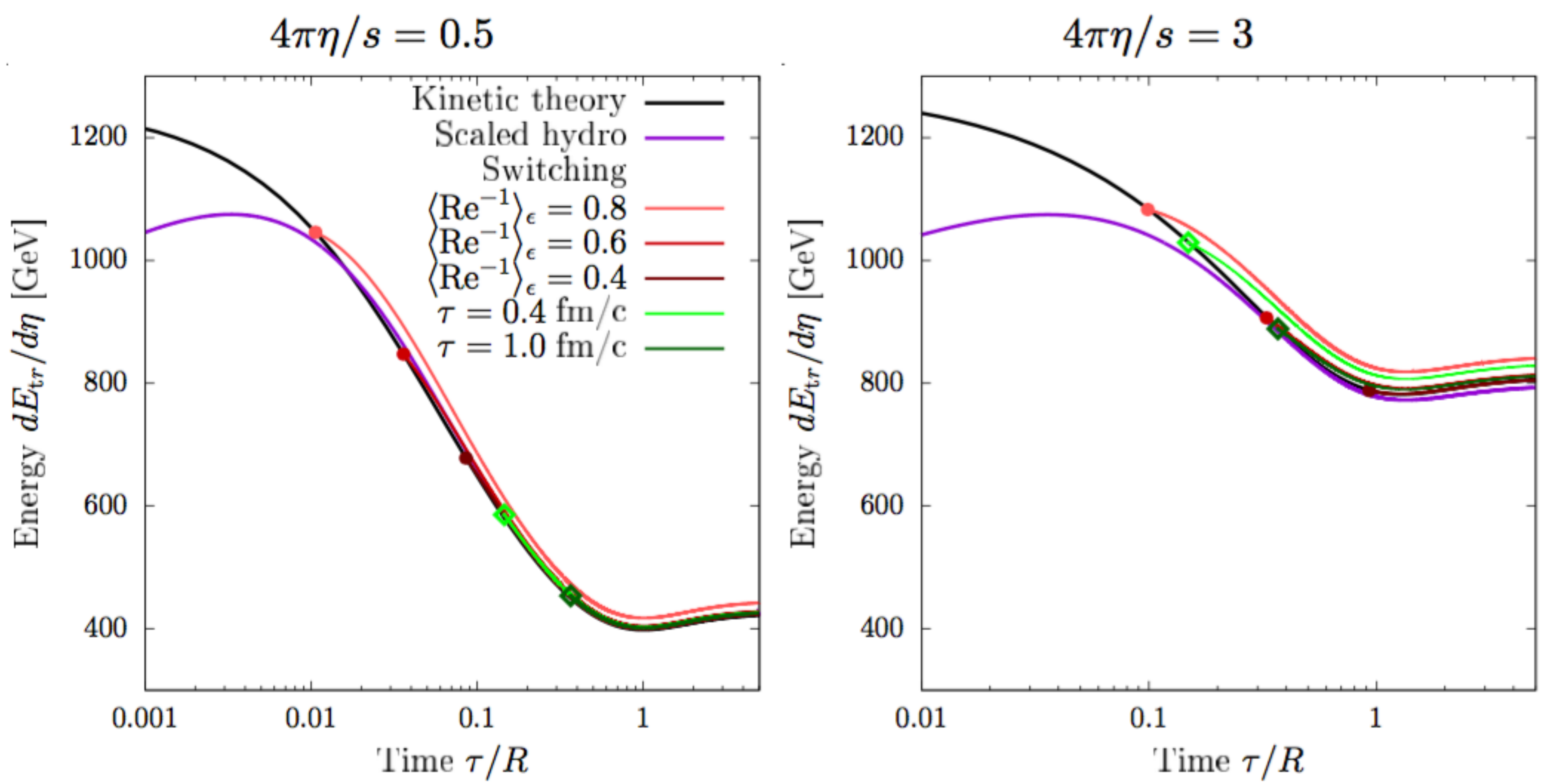


Non-trivial effect of pre-equilibrium dynamics on transverse flow due to inhomogeneous long. cooling Ambrus, SS, Werthmann PRD105 (2022) 1, 014031

Early pre-equilibrium phase is essential to properly map initial state geometry to final state collective flow

Hydrodynamics in small systems?

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

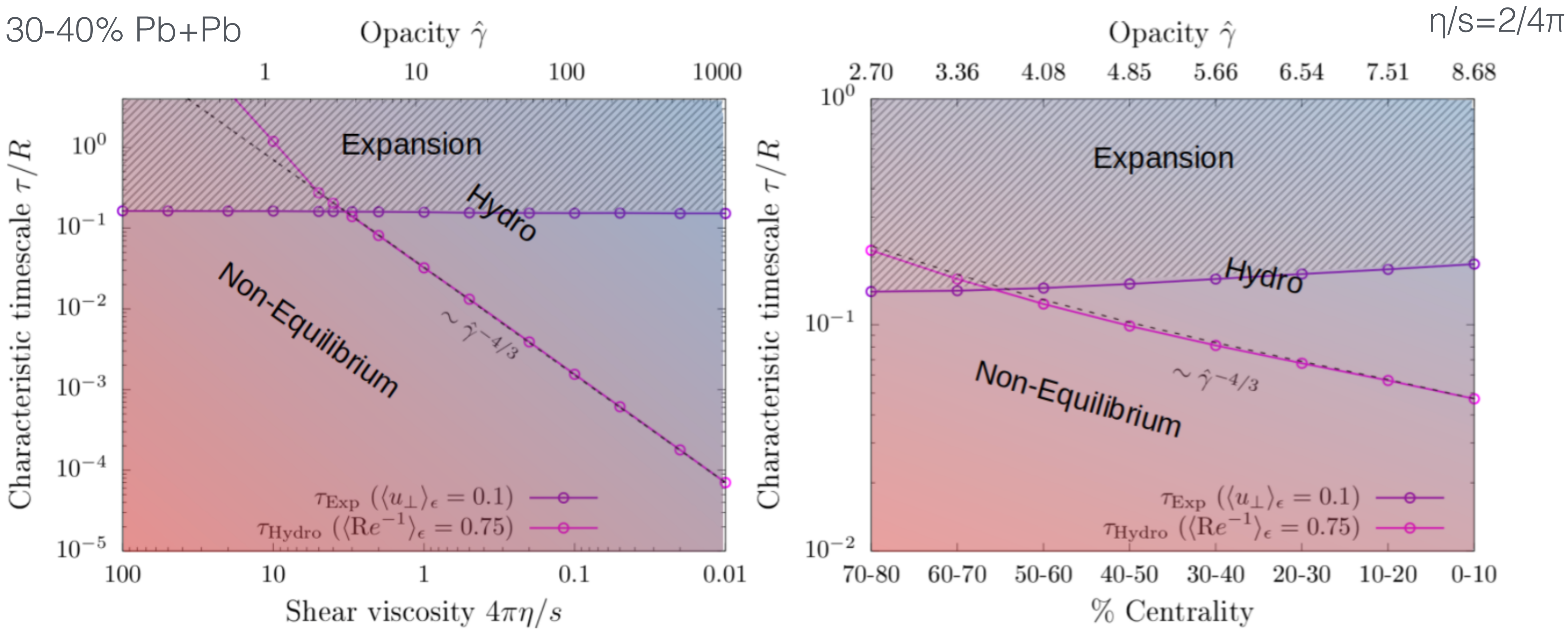


Hydrodynamics applicable below Re_c^{-1}~0.75 across different centralities & viscosities

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

Hydrodynamics in small systems?

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



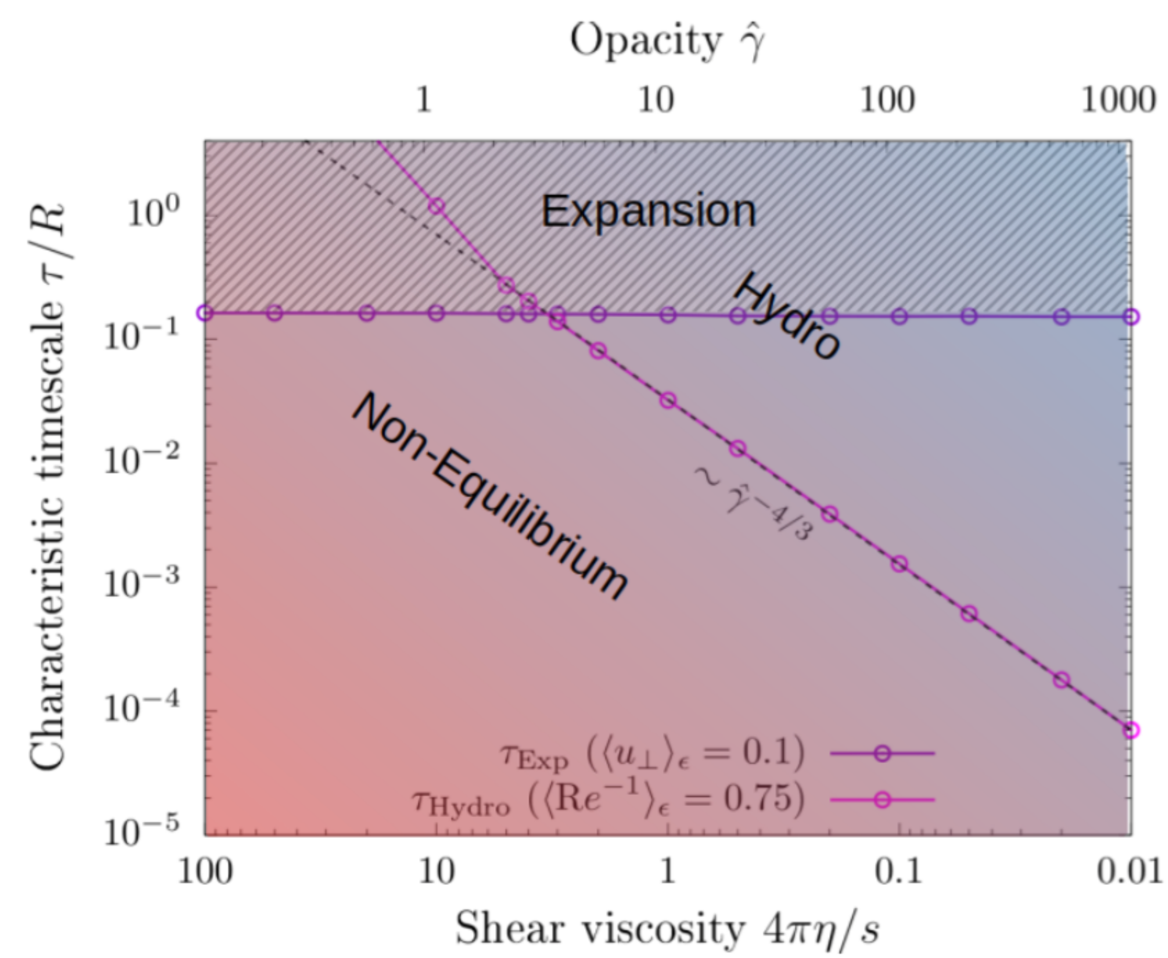
Breakdown of hydrodynamic description for large viscosities as well as for very peripheral collisions

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

Estimate that exciting transition region ~1-3 to be probed in future O+O collisions at LHC

Conclusion

Significant progress in theoretical understanding of pre-equilibrium phase allows to describe reaction dynamics of heavy-ion collisions from beginning to end

New possible links between hot QCD and cold QCD research

Phenomenological implications for entropy production as well as electromagnetic probes starting to be explored

Small systems provide unique opportunity to probe non-equilibrium QCD more directly

First steps towards understanding limits of applicability of hydrodynamic models

BUT more progress required to develop ab-initio description of QCD in small systems