Phenomenology of the early time dynamics

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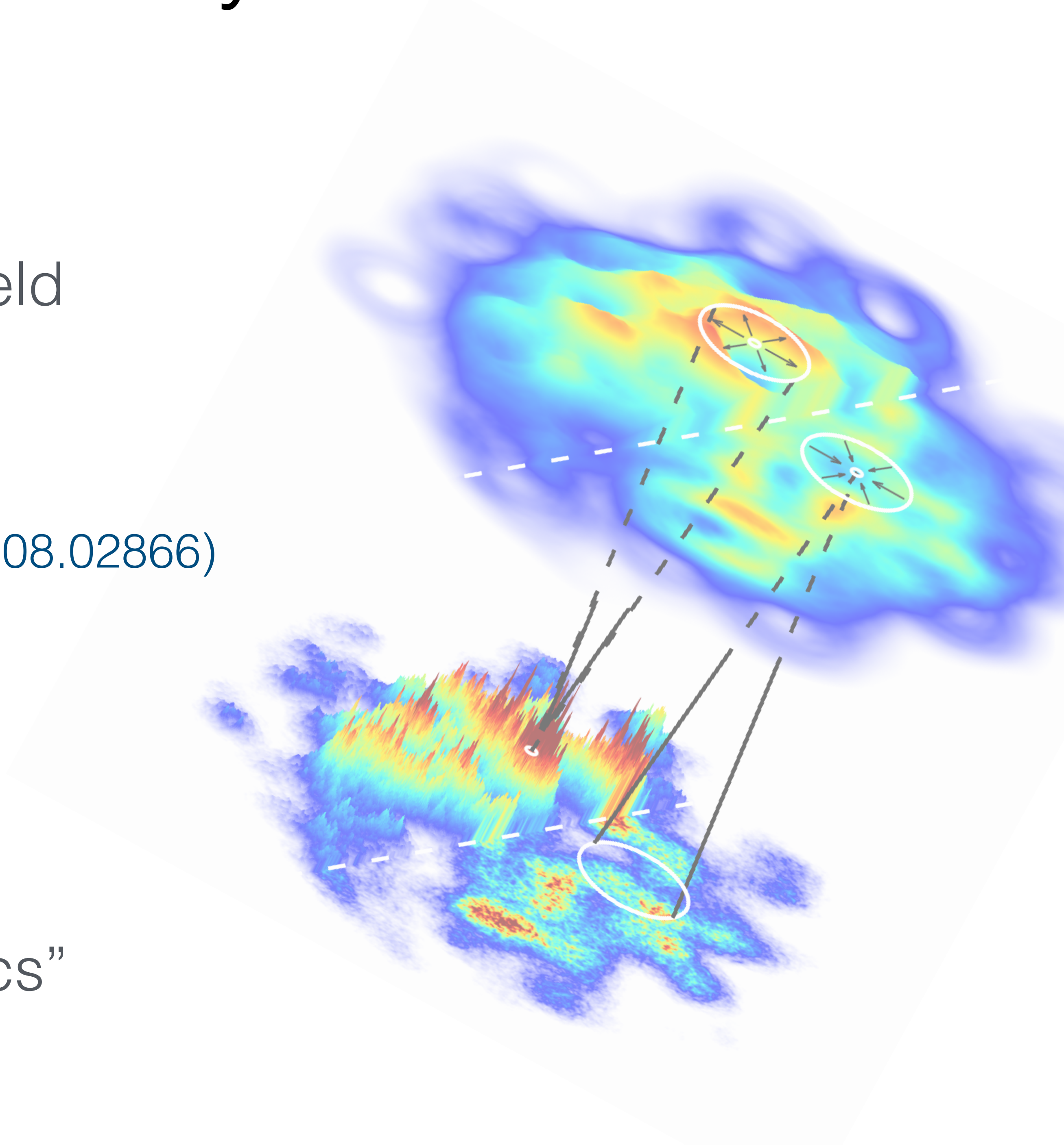

Based on
Giacalone, Mazeliauskas, SS
Phys.Rev.Lett. 123 (2019) 26, 262301 (arXiv:1908.02866)

Ambrus, SS, Werthmann
PRD105 (2022) 1, 014031 &in preparation

Gluodynamics Workshop
"From initial gluons to Hydrodynamics"
Oct 2022

CRC-TR 211
Strong-interaction matter under extreme conditions

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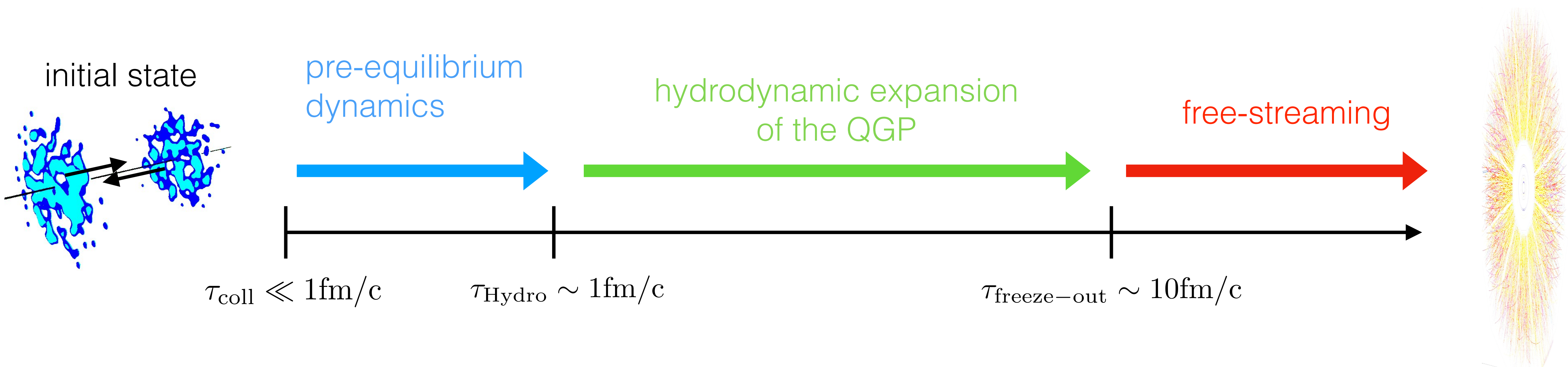
Heavy-Ion Collisions

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 clear separation of time scales in the reaction dynamics



Space-time dynamics (bulk) dominated by hydrodynamics expansion; typical flow observables in HICs mostly sensitive to near-equilibrium QGP properties

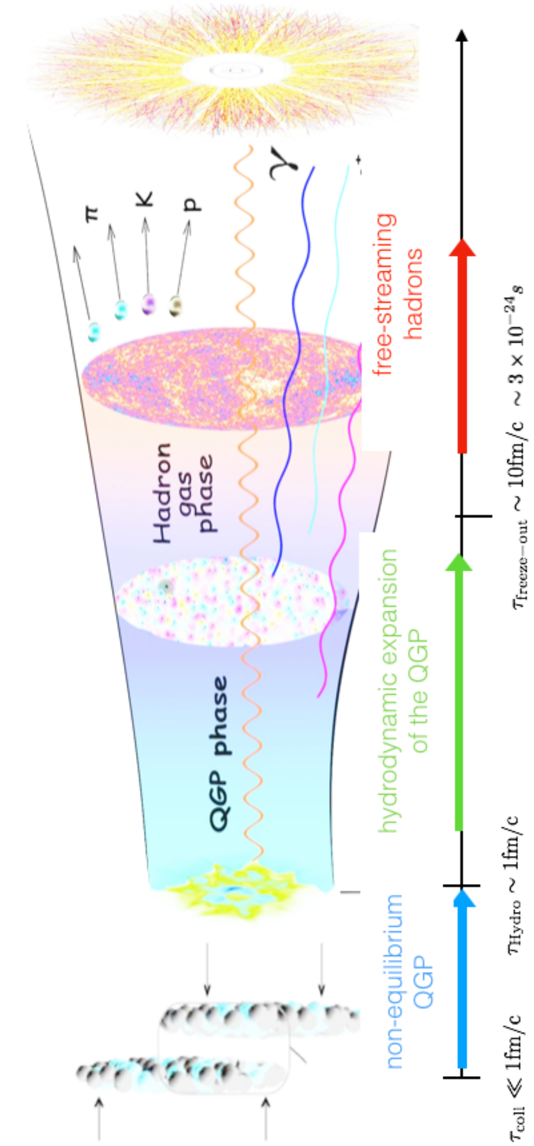
Exploring the early stages of HICs

1. Investigate bulk properties of heavy-ion collisions that are only sensitive to early-time dynamics

2. Explore smaller lifetime of smaller systems (high-mult. p+p,p/d/He+Au,p+Pb,future O+O) to enhance impact of pre-equilibrium stage

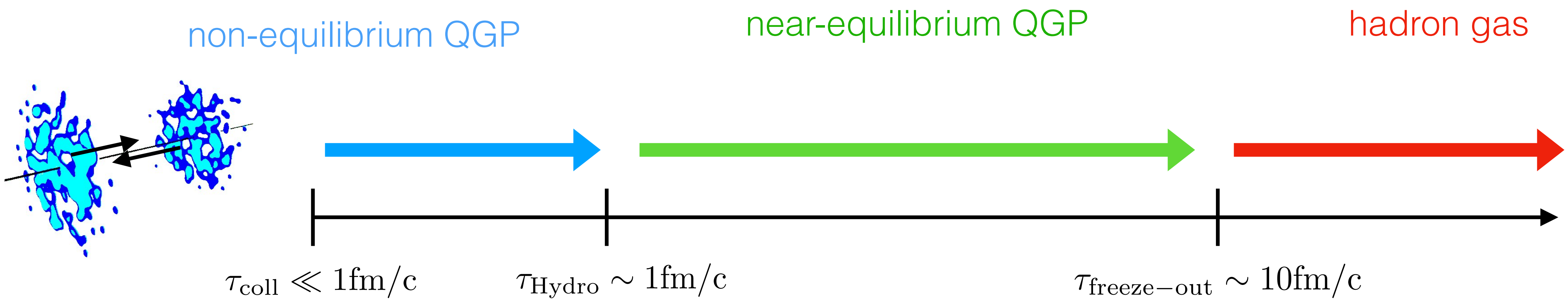
3. Exploit multi-messenger nature of Heavy-Ion collisions to study rare probes such high-energy Jets or electro-magnetic radiation

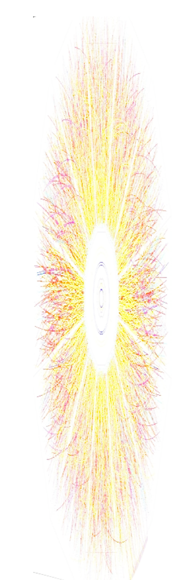
(c.f. talks by C. Andres, M. Strickland)



Early time dynamics & entropy production

High-energy heavy-ion collisions described by multi-stage evolution





Entropy production in HICs is dominated by early time dynamics and directly accessible by measurement of $dN_{ch}/d\eta$

Schematically:

(nearly) isentropic hydrodynamic expansion

$$\left\langle \frac{dE_\perp^0}{d\eta} \right\rangle_{\tau_{\rm coll}} \rightarrow \left\langle \frac{dS}{d\eta} \right\rangle_{\tau_{\rm Hydro}} \rightarrow \left\langle \frac{dS}{d\eta} \right\rangle_{\tau_{\rm freeze-out}} \approx \left\langle \frac{dS}{d\eta} \right\rangle_{\tau_{\rm Hydro}} \rightarrow \left\langle \frac{dN_{\rm ch}}{d\eta} \right\rangle \approx \left\langle \frac{S}{N_{\rm ch}} \right\rangle \left\langle \frac{dS}{d\eta} \right\rangle_{\tau_{\rm freeze-out}}$$

initial entropy production

freeze-out

Based on insights from non-equilibrium studies, can now make relation between $dE_T^0/d\eta$ and $dN_{ch}/d\eta$ explicit

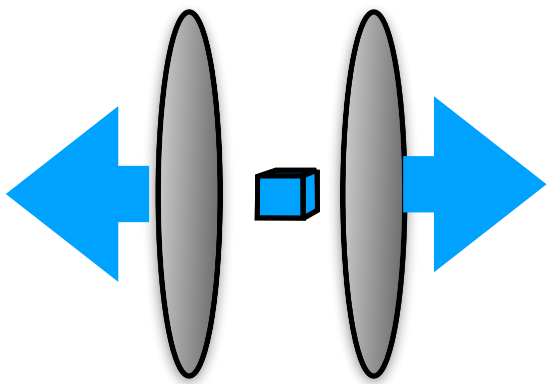
Early time dynamics & entropy production

Early time dynamics (τ<1fm/c) of large systems well described by one dimensional Bjorken expansion

Evolution of energy density is governed by conservation equation

$$\partial_\tau \epsilon = -\frac{\epsilon}{\tau} - \frac{P_L}{\tau}$$

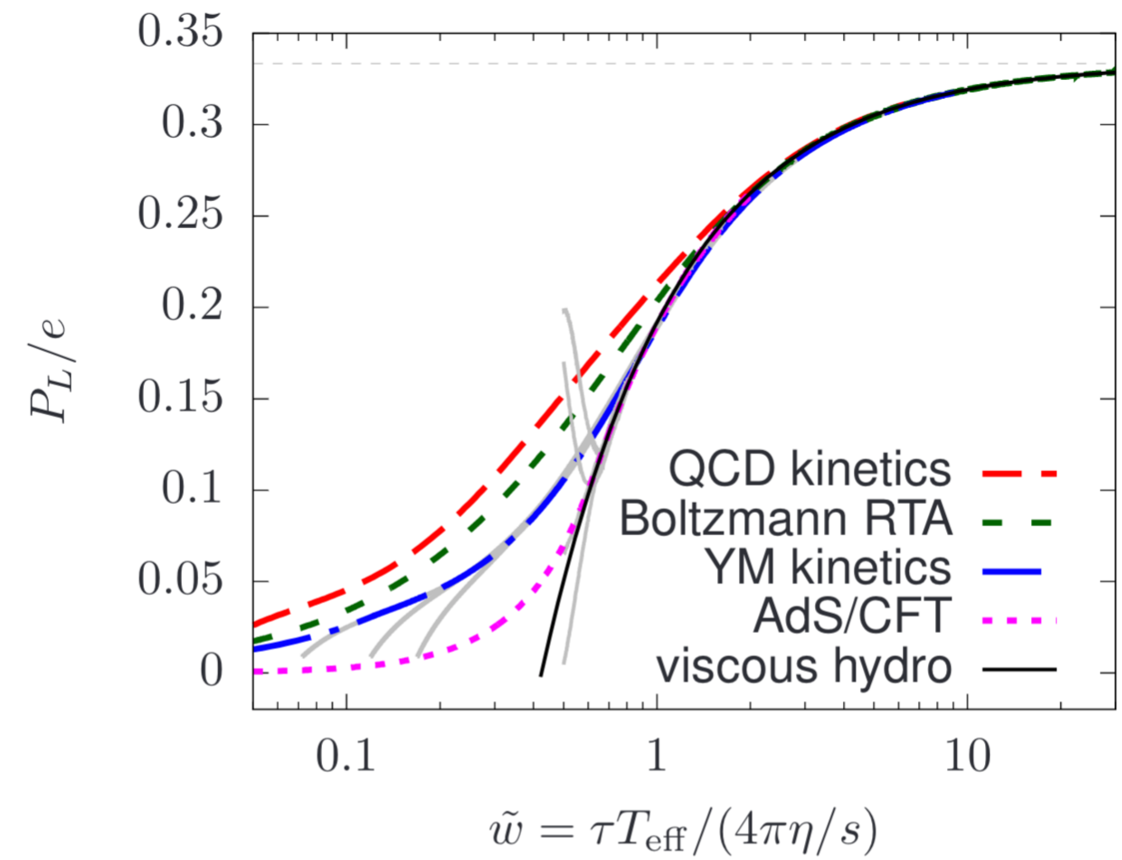
expansion work



Need non-equilibrium generalization of EoS $P_L(e)$ to integrate conservation law and compute $e(\tau)$

Early time dynamics & entropy production

Different microscopic calculations in QCD/YM/RTA Kinetic theory & AdS/CFT indicate convergence of P_L/e to hydrodynamic attractor



Early time dynamics (long. expansion dominated):

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

Late time dynamics (close to equilibrium):

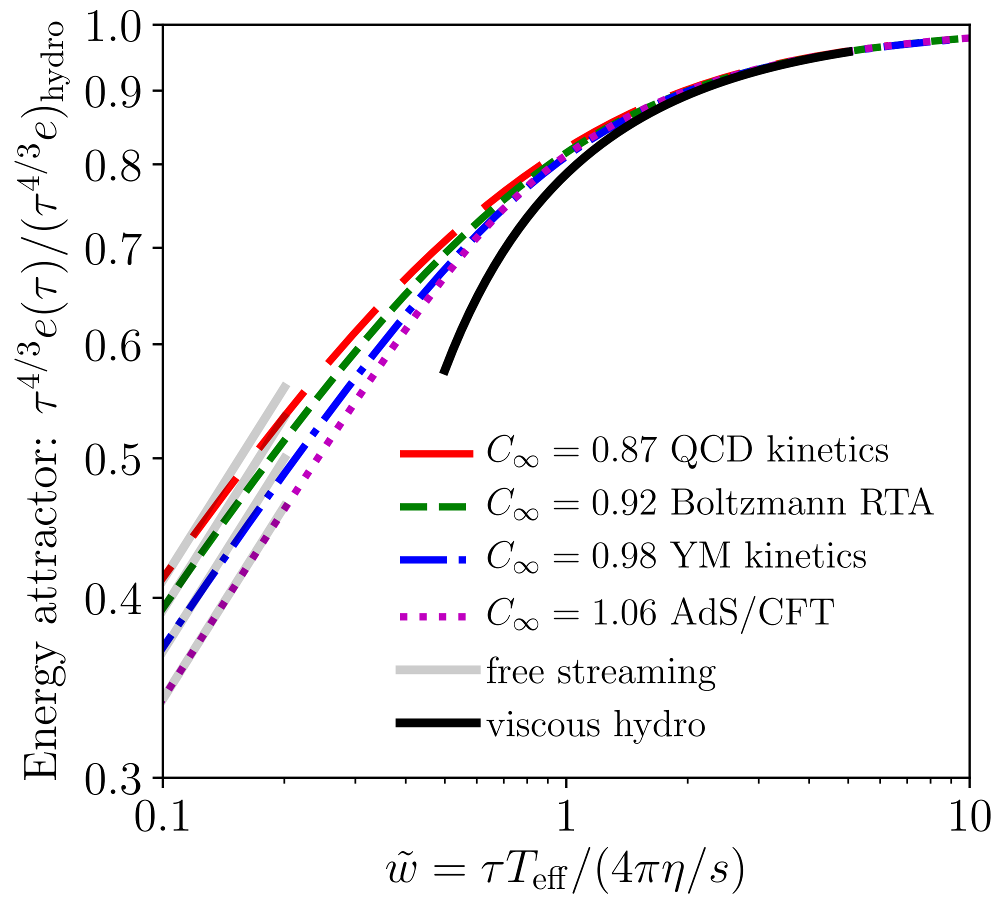
$\tilde{w} \gg 1$ viscous hydrodynamics ($P_L/e \approx 1/3 - 4/9\pi\tilde{w}$)

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

Hydrodynamic attractors

Evolution of energy-density during pre-equilibrium phase obtained by integrating the conservation law

$$\frac{e(\tau)\tau^{4/3}}{e_{\rm hydro}\tau_{\rm hydro}^{4/3}} = \mathcal{E}\left(\tilde{w} = \frac{T_{\rm eff}(\tau)\tau}{4\pi\eta/s}\right)$$



Universal early and late time behavior

$\tilde{w} \ll 1$ macroscopically free-streaming

$$\mathcal{E}(\tilde{w} \ll 1) = C_\infty^{-1}\tilde{w}^{4/9}$$

$\tilde{w} \gg 1$ viscous hydrodynamics

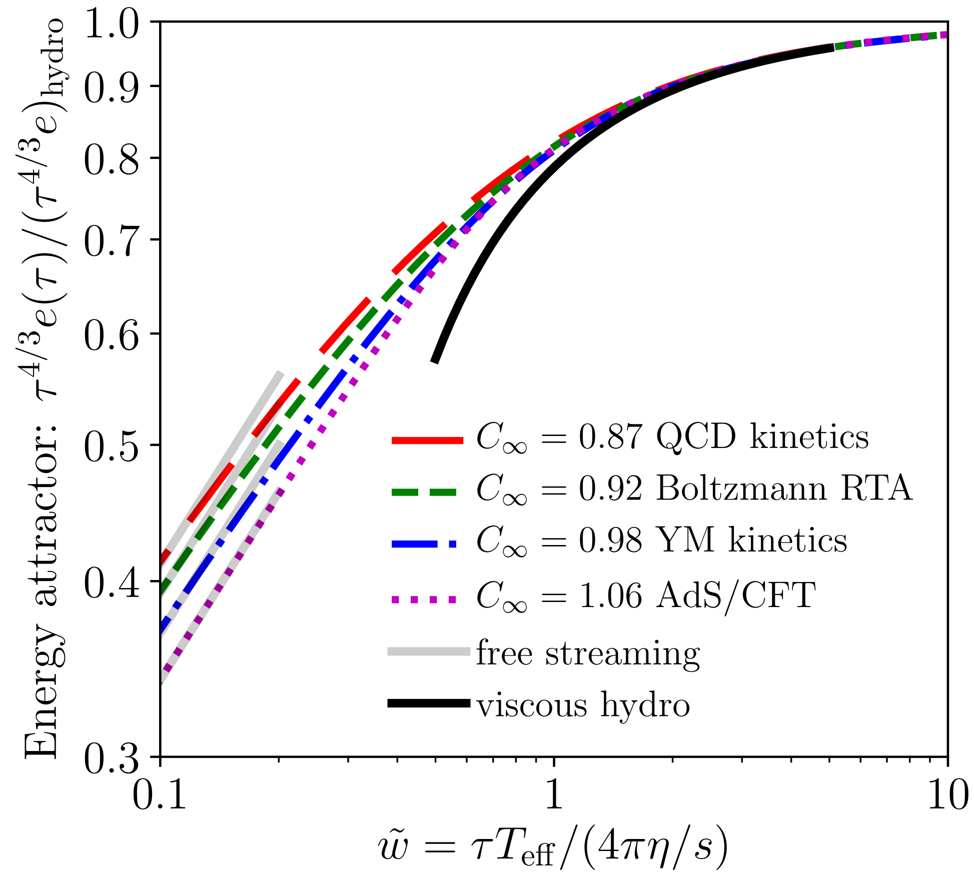
$$\mathcal{E}(\tilde{w} \gg 1) = 1 - \frac{2}{3\pi\tilde{w}}$$

Surprisingly small differences between different microscopic theories, characterized by a single constant C_∞~0.95±0.15

Giacalone, Mazeliauskas, SS PRL 123 (2019) 26, 262301

Entropy production in HICs

Based on hydrodynamic attractor curve for energy density one can use thermodynamic relations s=(e+p)/T and EOS once QGP is close to equilibrium to calculate entropy



$$(s\tau)_{\rm hydro} = \frac{4}{3} C_\infty^{3/4} \left(4\pi\frac{\eta}{s}\right)^{1/3} \left(\frac{\pi^2}{30}\nu_{\rm eff}\right)^{1/3} (e\tau)_0^{2/3}$$

Since overall entropy is approx. conserved during hydro expansion charged particle multiplicity at freeze-out directly determined

$$\frac{dN_{\rm ch}}{d\eta} \approx A_\perp\,(s\tau)_{\rm hydro}\frac{N_{\rm ch}}{S}$$

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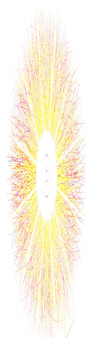
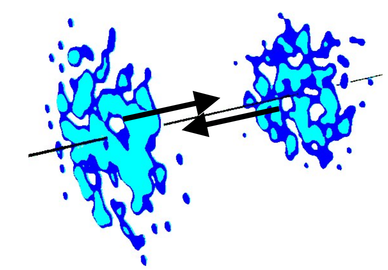
Entropy production in HICs

Explicit one-to-one correspondence between initial state energy density and charged particle multiplicity including all relevant pre-factors



$$\frac{dN_{\rm ch}}{d\eta} \approx \frac{4}{3}\left(\frac{N_{\rm ch}}{S}\right) A_{\perp} C_{\infty}^{3/4} \left(4\pi\frac{\eta}{s}\right)^{1/3} \left(\frac{\pi^2}{30}\nu_{\rm eff}\right)^{1/3} (\epsilon\tau)_0^{2/3}$$



<u>Sensitivities/Uncertainties:</u>

Equilibrium properties: $N_{ch}/S \sim 7.5$, $\nu_{eff} \sim 40$ approximately known

Non-equilibrium/transport properties:
$C_{\infty} \sim 0.95 \pm 0.15$ surprisingly well constraint
$4\pi\ \eta/s \sim (1\text{-}3)$ not well constraint in relevant temperature range ($T \sim 4T_c$)

Initial state energy density:
$(e\tau)_0$ significant uncertainties from small-x TMDs
and perturbative corrections

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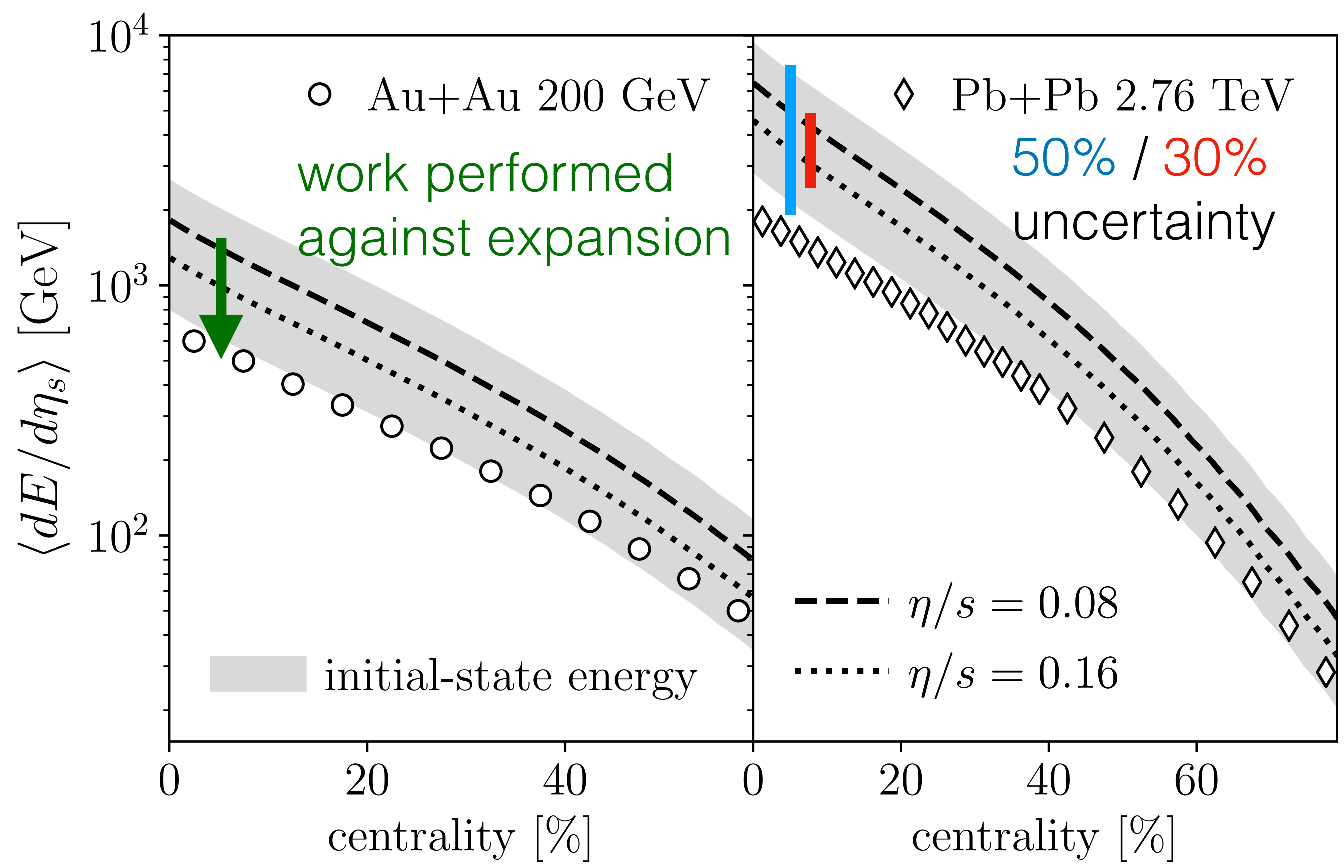
Connecting Initial State & Final State

Sensitivity to η/s and $(e\tau)_0$ can be exploited to obtain new constraints on initial state & transport properties

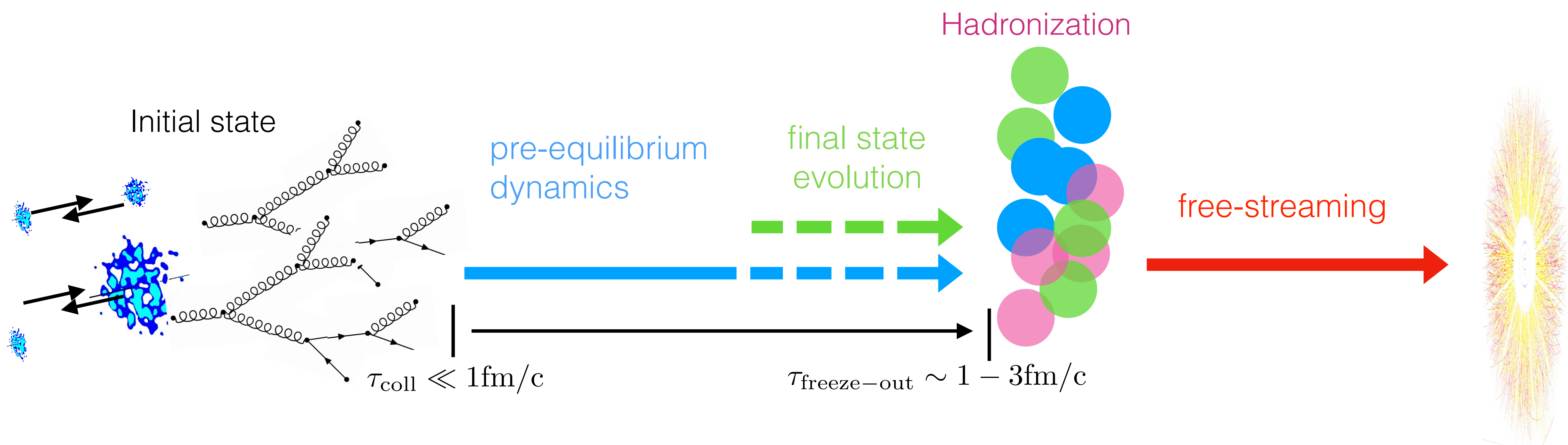


Explicit connection between Heavy-Ion Physics to small-x Physics at EIC & Hadron Colliders

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

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

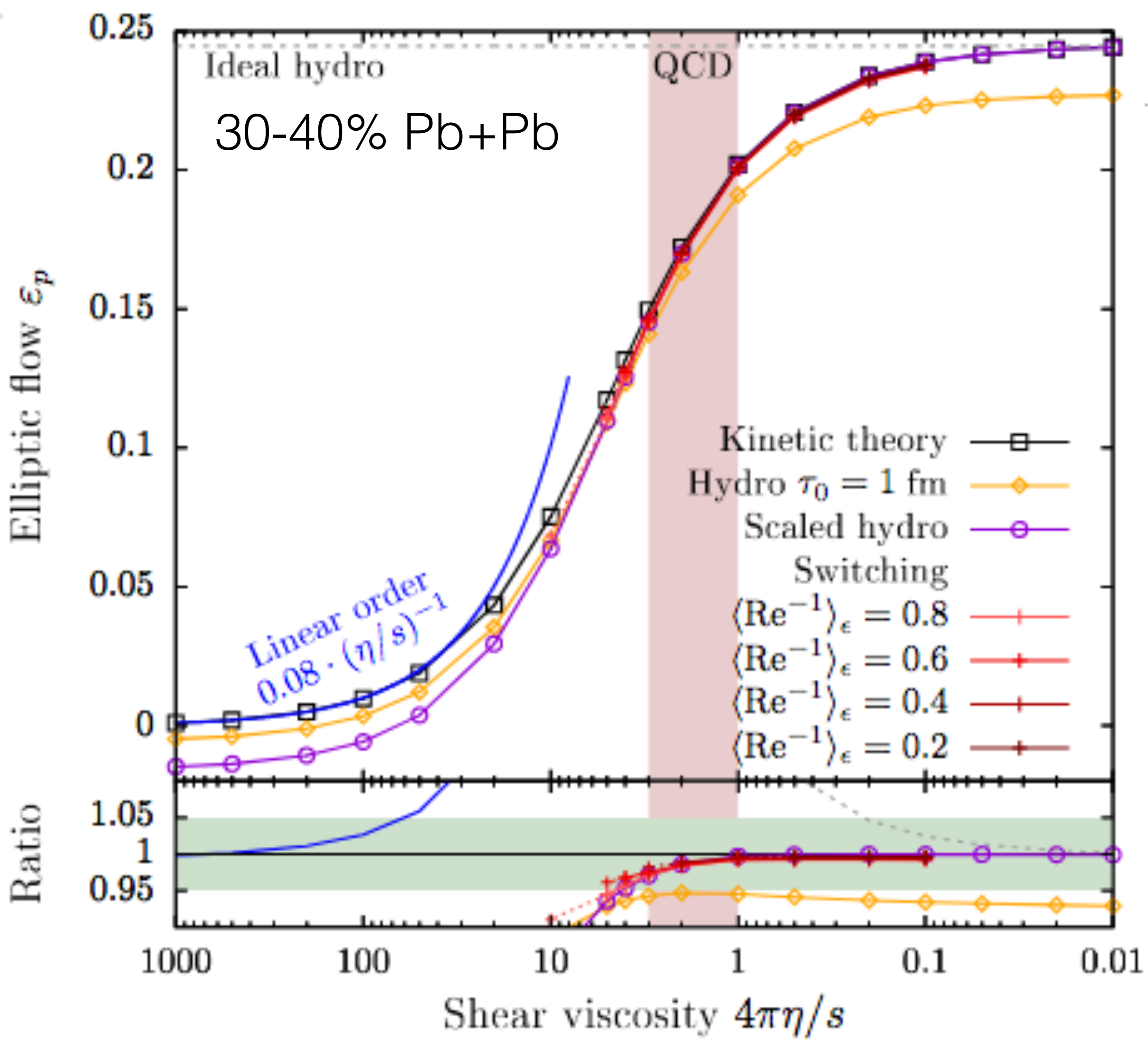
Due to particular simplicity, all results only depends on initial geometry and one single opacity parameter

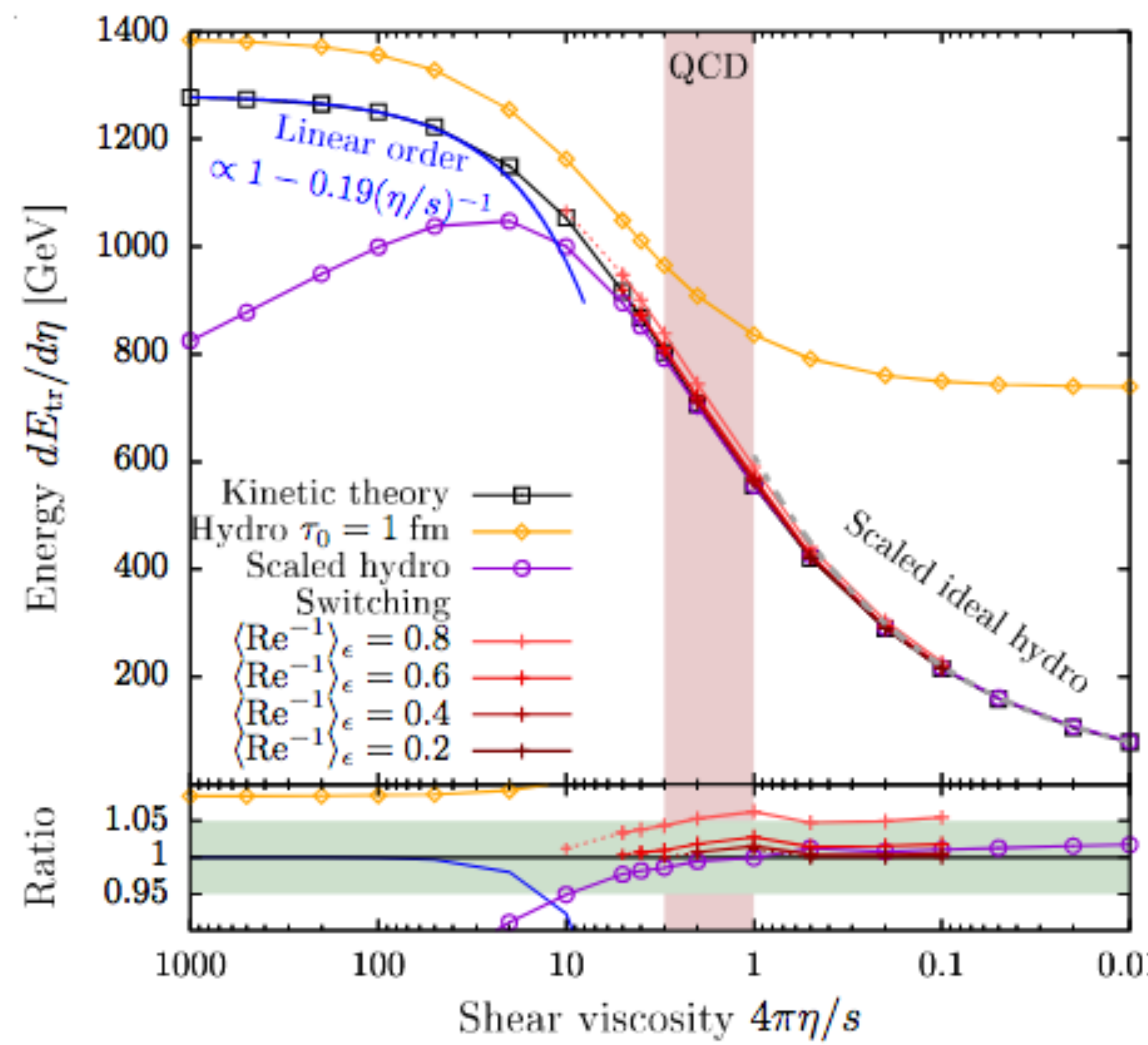
$$\hat{\gamma} = \frac{1}{5\eta/s}\left(\frac{R}{\pi a}\frac{\mathrm{d}E_\perp^0}{\mathrm{d}\eta}\right)^{1/4},$$

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

Opacity dependence of Flow

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

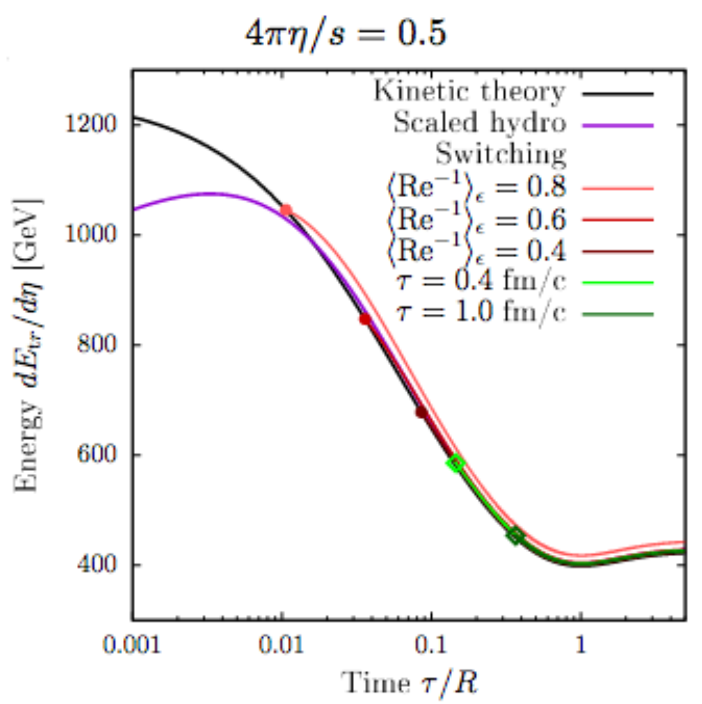


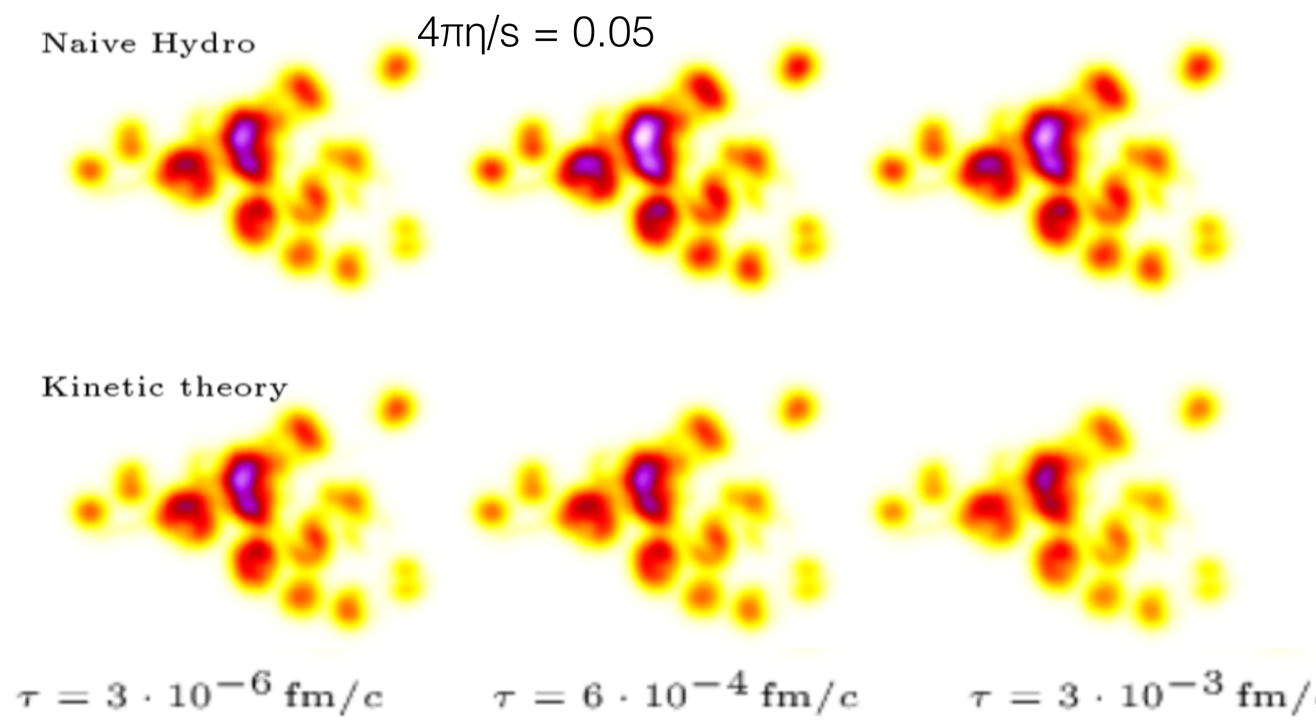


Hydrodynamics applicable for semi-central Pb+Pb collisions at LHC iff sufficient care is taken

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





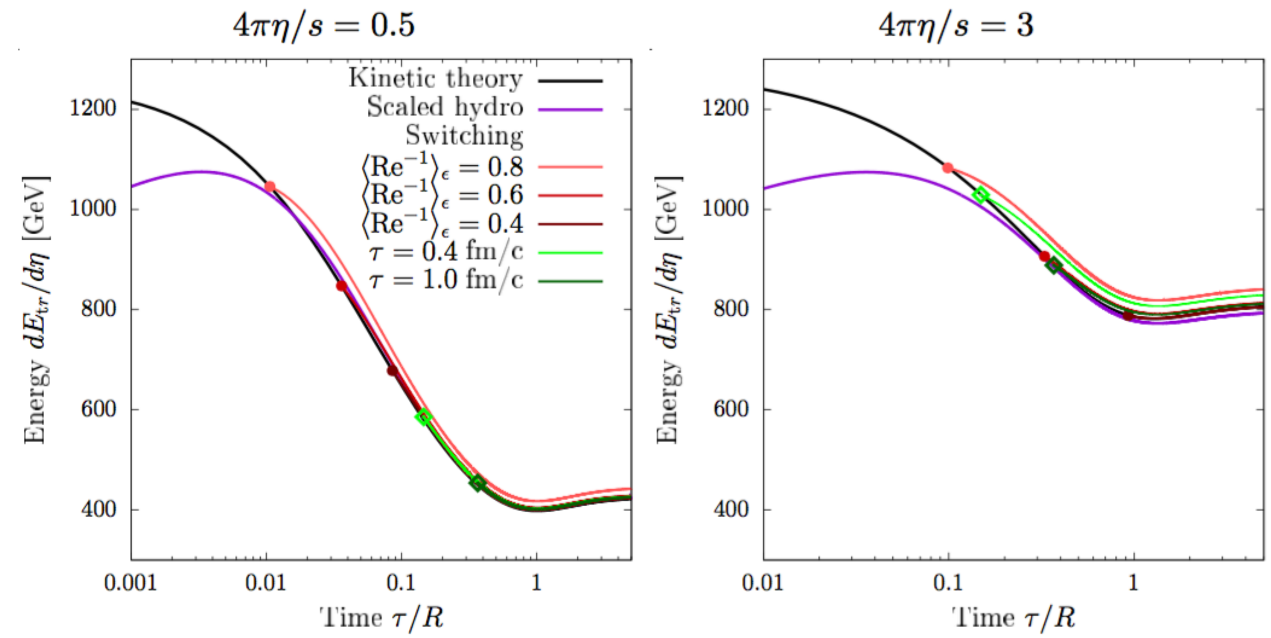
Non-trivial effect of pre-equilibrium dynamics on transverse flow due to inhomogeneous long. cooling

Ambrus, SS, Werthmann PRD105 (2022) 1, 014031

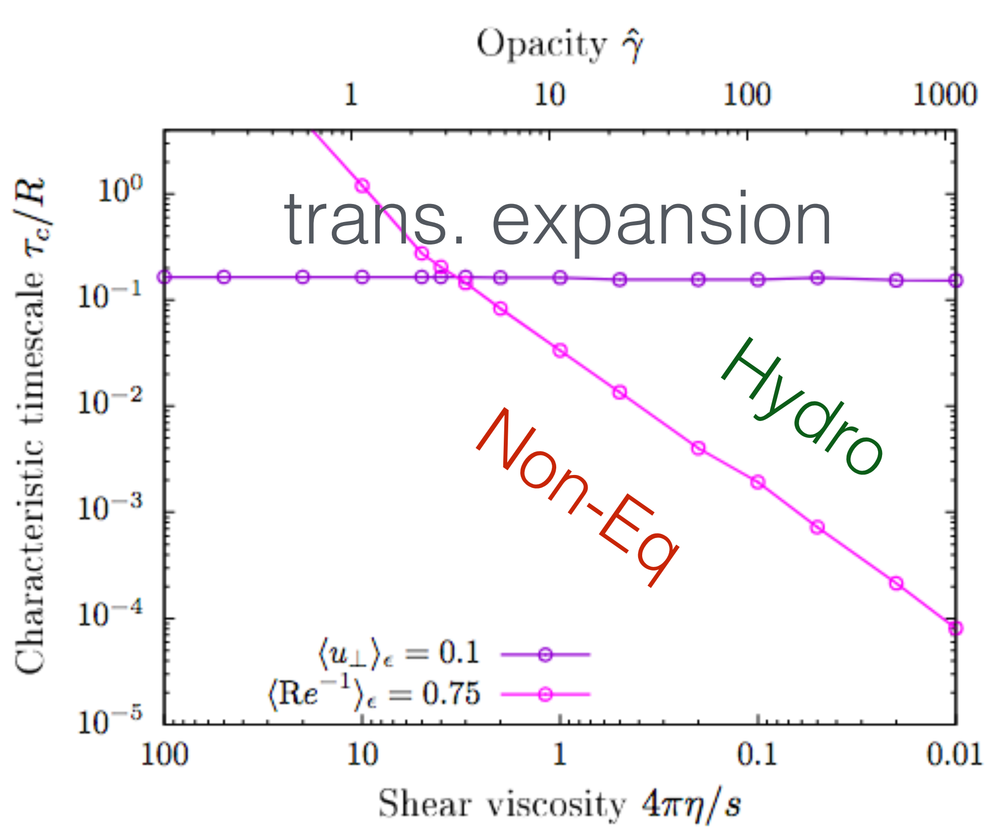
Early pre-equilibrium phase is essential to properly map initial state to transverse flow

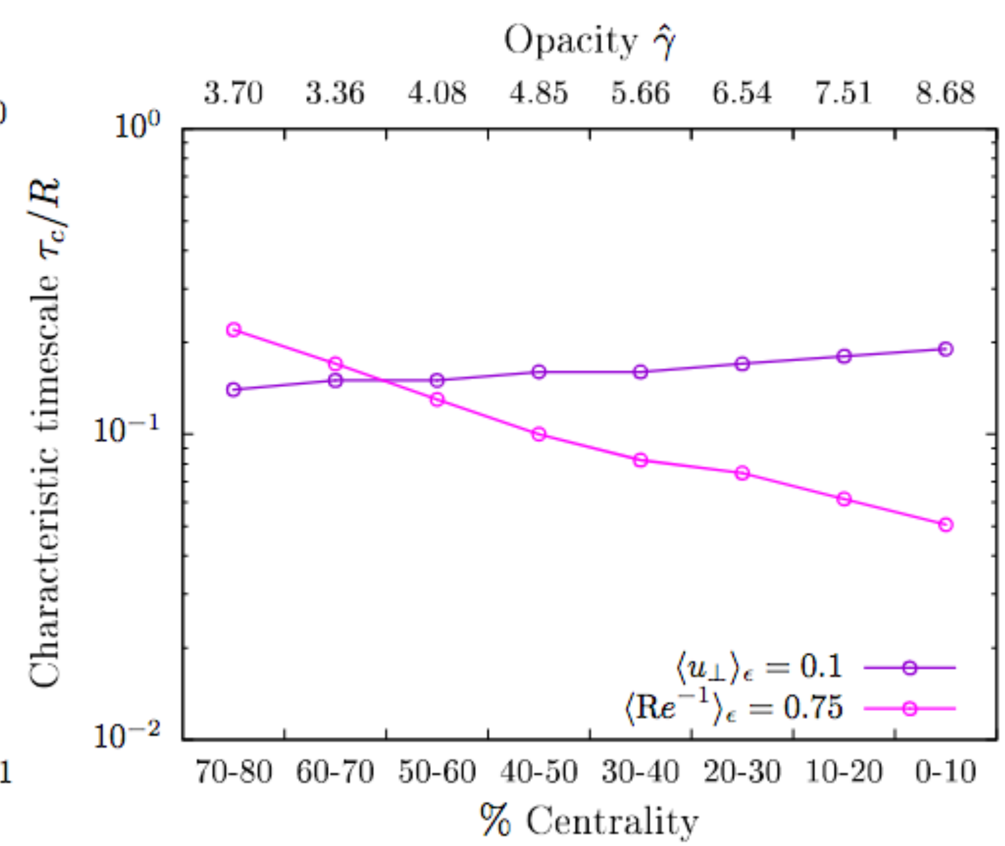
Hydrodynamics in small systems?

Hydrodynamics applicable below Re_c^{-1}~0.7 across different centralities & viscosities



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



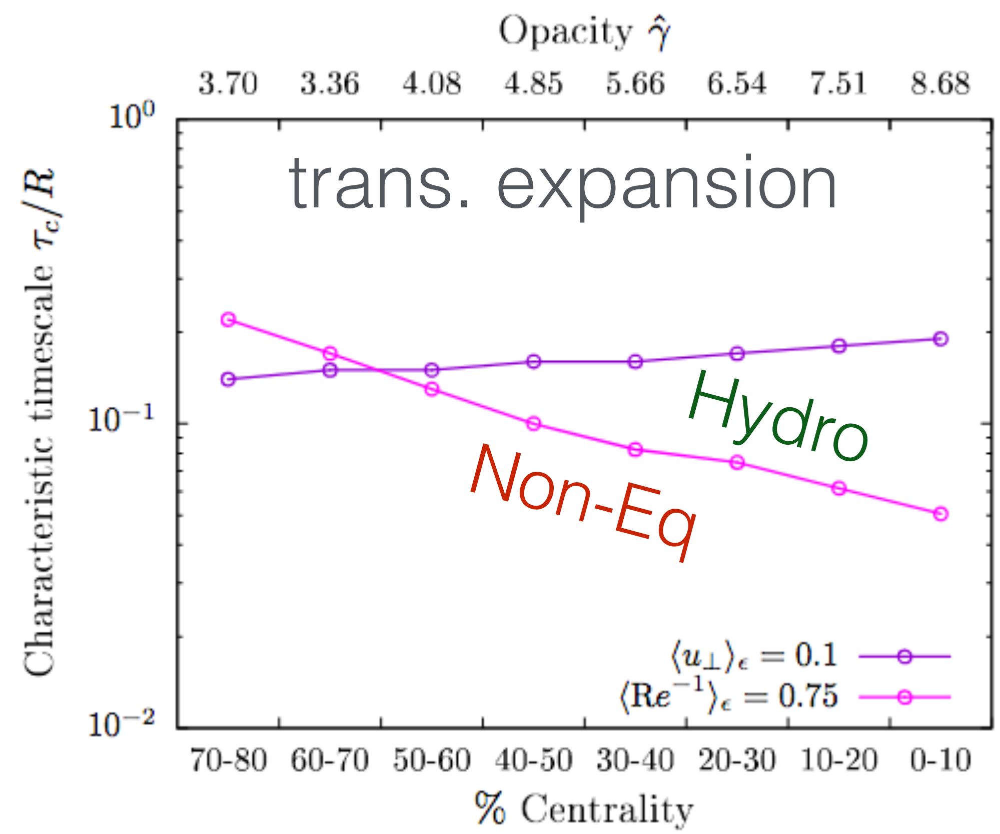


Hydrodynamics in small systems?

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

Conclusion

Significant progress in theoretical understanding of pre-equilibrium phase allows to study various manifestations in experiments

- Entropy production provides a very direct probe of early non-equilibrium phase
- BUT progress in calculation of initial state energy density highly desirable

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