Early time dynamics of the QGP

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CRC-TR 211
Strong-interaction matter under extreme conditions

Based on

X.Du, SS arXiv:2012.09068; 2012.09079
M.Coquet, X.Du, J.-Y. Ollitrault, SS, M.Winn arXiv:2104.07622
G. Giacalone, A.Mazeliauskas, SS arXiv:1908.02866
V. Ambrus, SS, C. Werthmann arXiv:2109.03290

Zimanyi School
Dec 21

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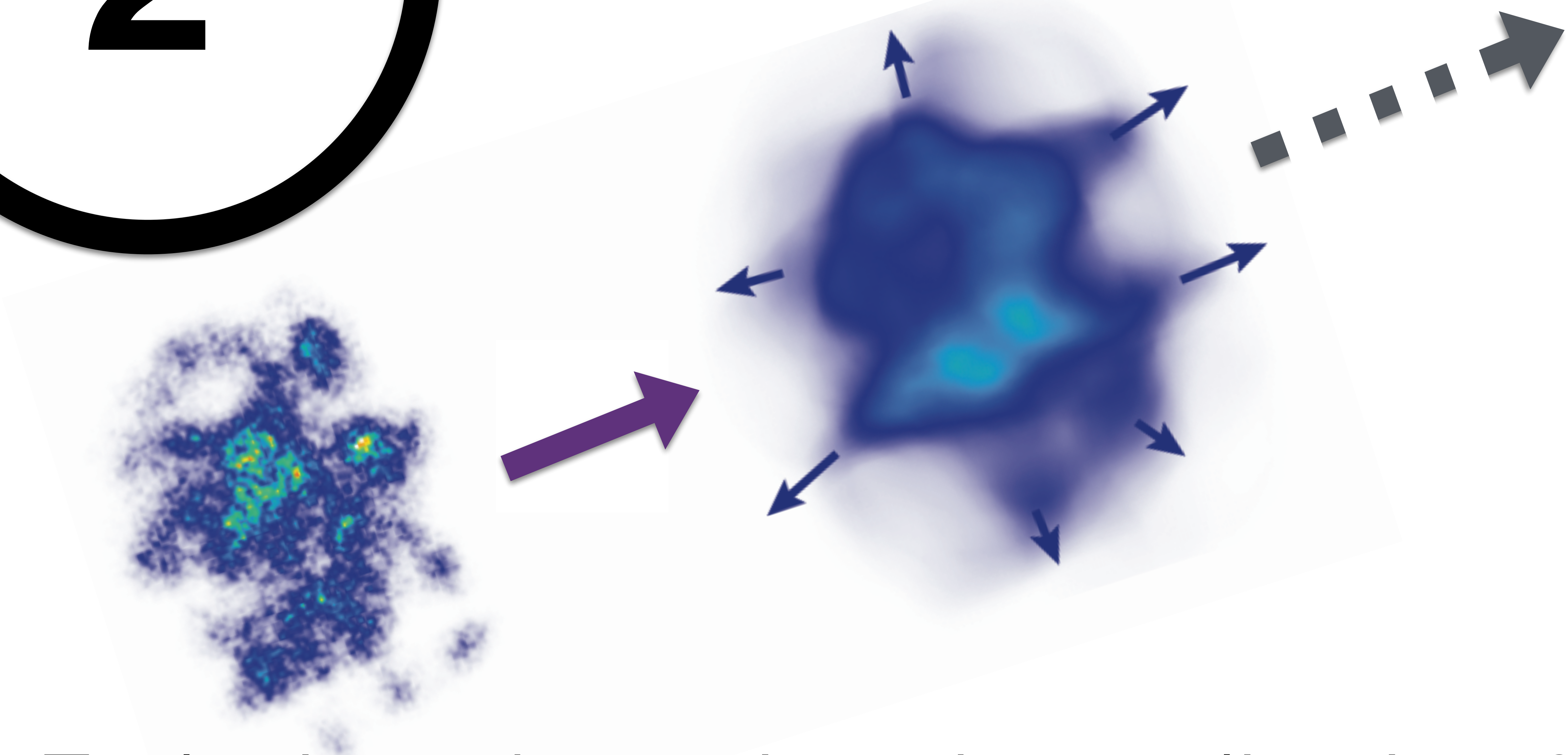
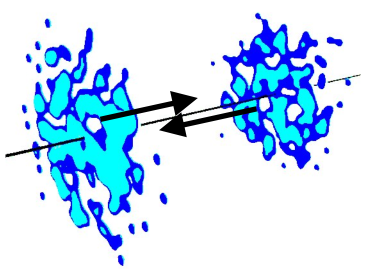
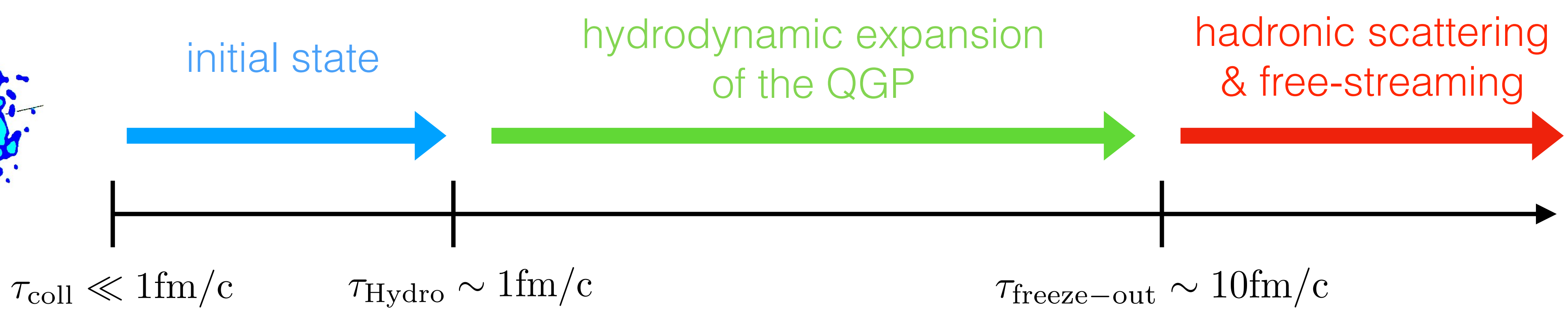


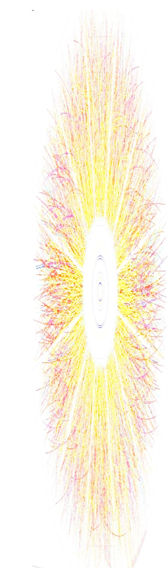
Early time dynamics, thermalization & hydrodynamics

Early time dynamics

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



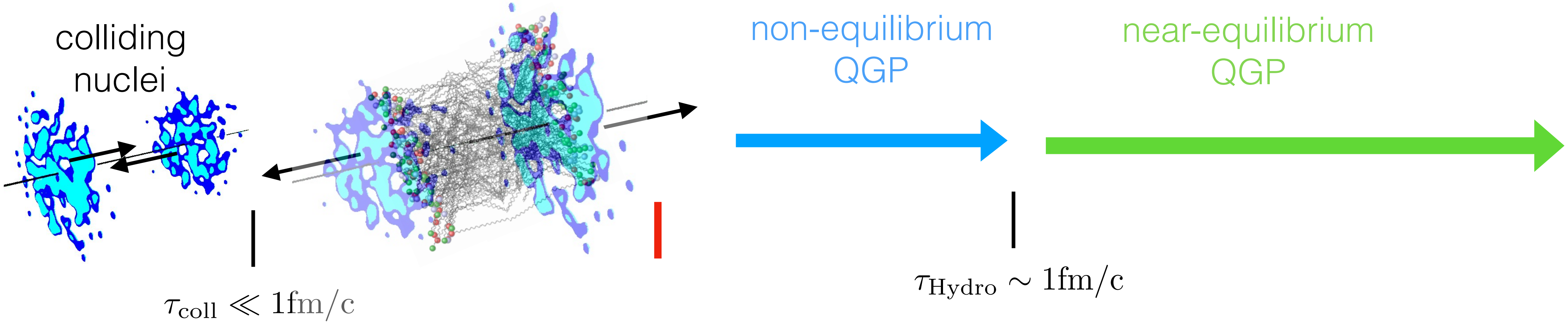




Space-time dynamics dominated by hydrodynamics expansion
-> excellent description of typical flow observables based on hydro models

Dynamical description of initial state/onset of hydrodynamics theoretically desirable; new ways to connect cold QCD and hot QCD

Initial state & Equilibration of HICs



Energy deposition can be calculated within Color-Glass Condensate effective theory of high-energy QCD

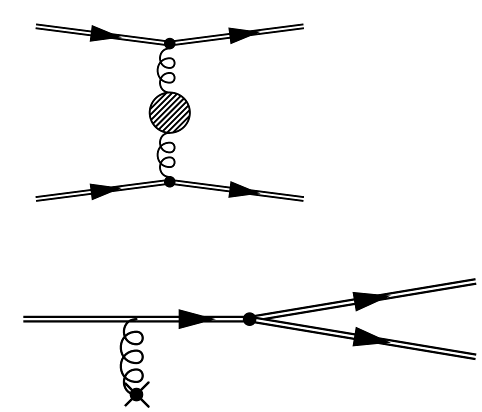
McLerran, Venugopalan PRD49 (1994) 2233-2241, Kovner, McLerran, Weigert D52 (1995) 6231-6237

-> Gluon dominated initial state far-from equilibrium

Significant progress to understand subsequent equilibrium process based on studies in QCD kinetic theory

Arnold,Moore,Yaffe JHEP 0301 (2003) 030

$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{2\leftrightarrow 2}[f] + C_{1\leftrightarrow 2}[f]$$

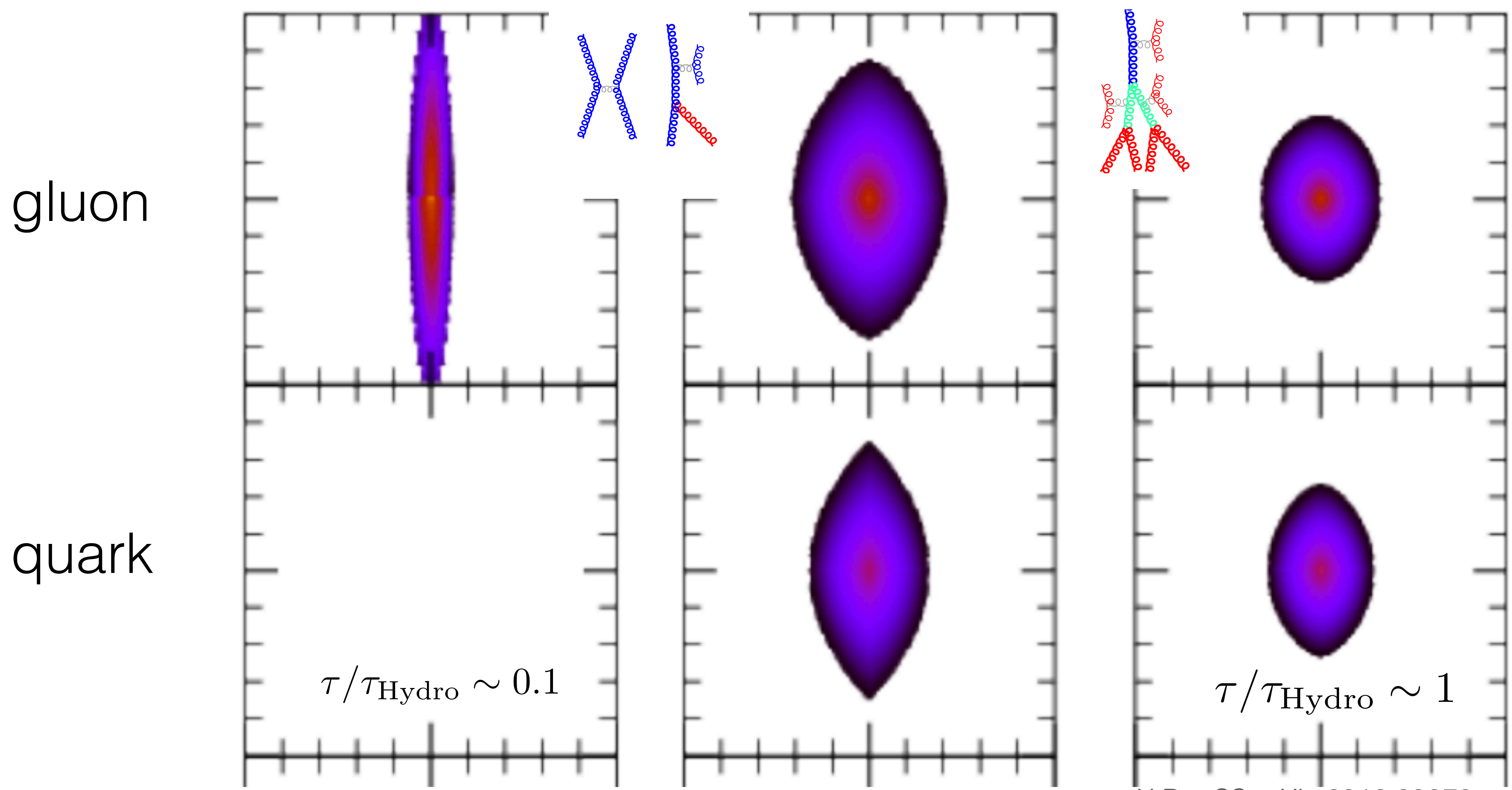


Equilibration of HICs

Equilibration proceeds ``bottom-up'' via radiative break-up of hard gluons

Kurkela, Zhu PRL 115 (2015) 182301; Keegan,Kurkela,Mazeliauskas,Teaney JHEP 1608 (2016) 171;
Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910

Baier et al. Phys.Lett.B 502 (2001) 51-58

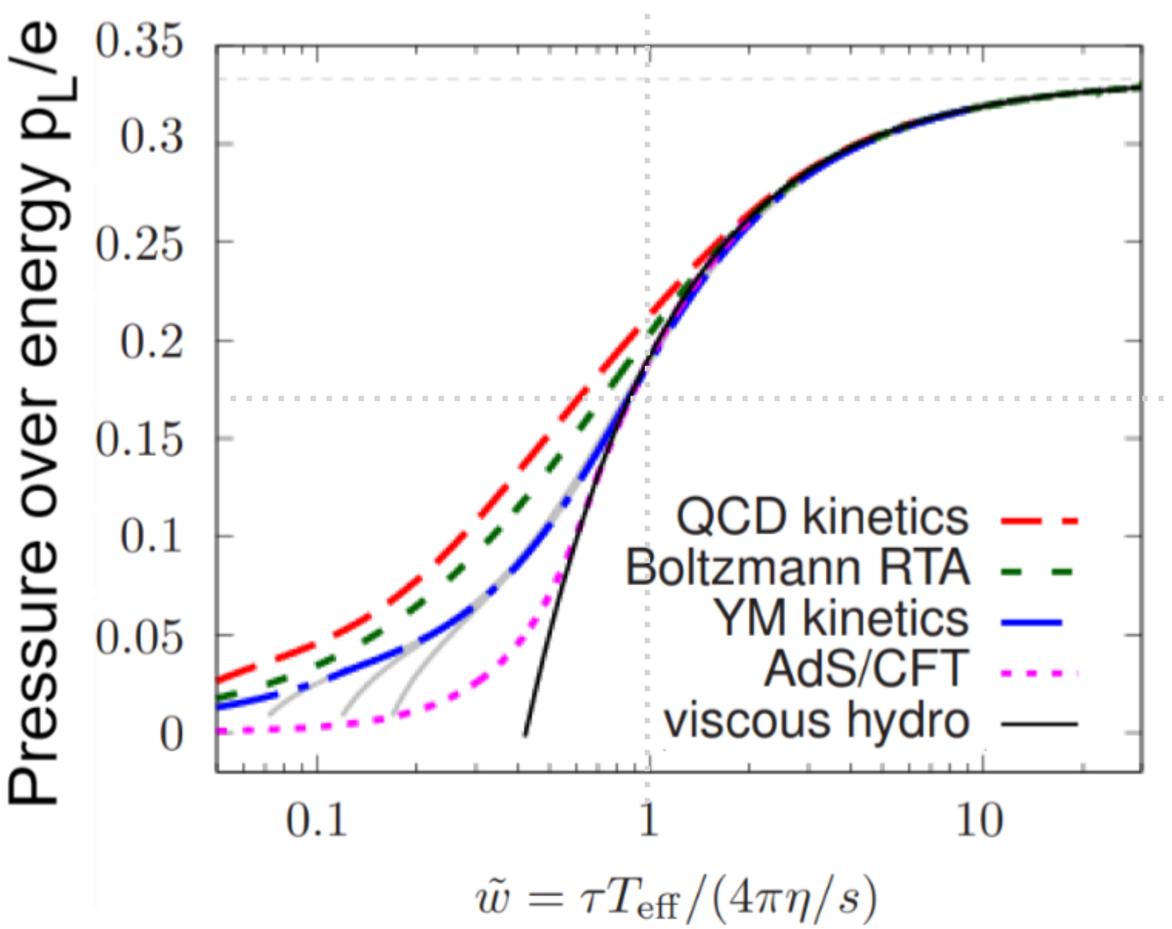


X.Du, SS arXiv:2012.09079

Pre-equilibrium QGP gluon dominated & highly anisotropic

Hydrodynamic behavior

Non-equilibrium evolution of energy-momentum tensor in QCD kinetic theory allows to study applicability of hydrodynamics (Bjorken flow/1D boost-inv. expansion)



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

Viscous hydrodynamics becomes applicable on time scales

Kurkela, Mazeliauskas, Paquet, SS, Teaney 1805.01604; 1805.00961

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

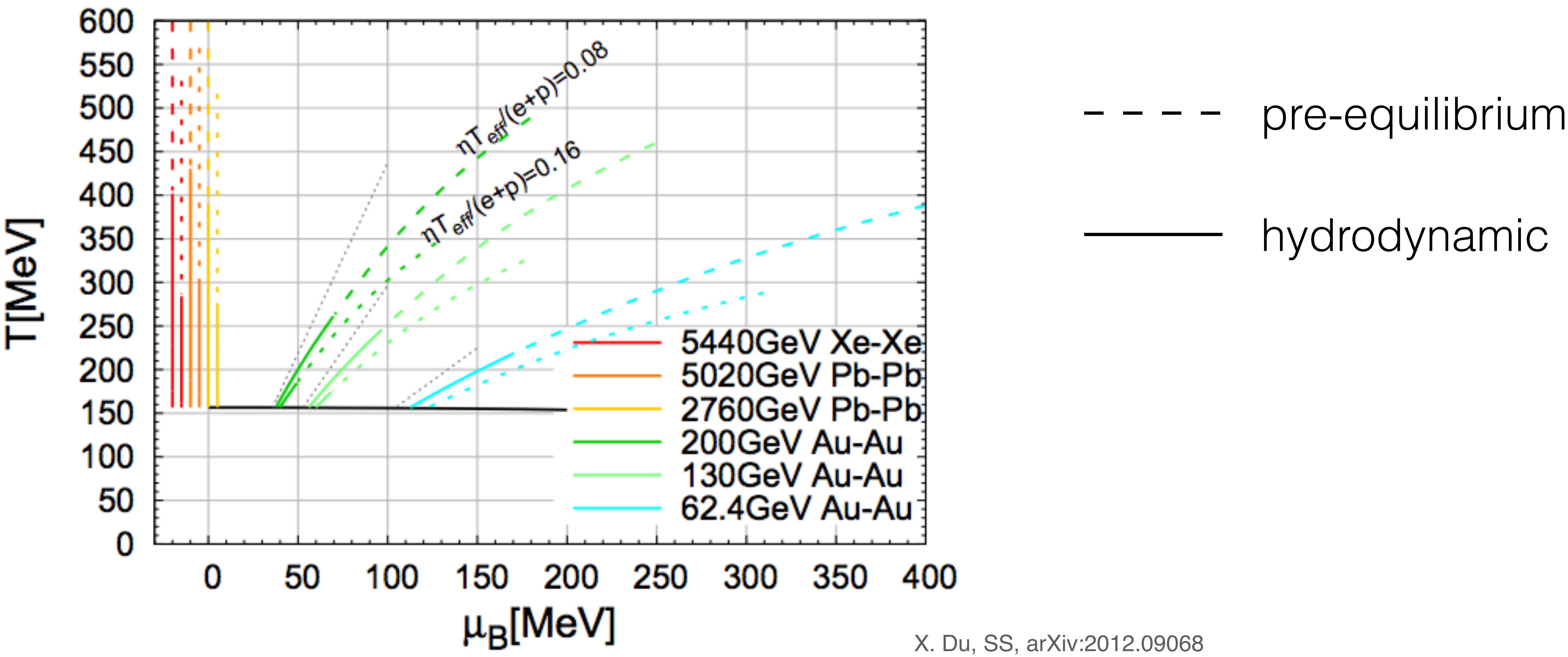
$$\tau_{\rm hydro} \approx 1.1\,{\rm fm}\left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}}\left(\frac{\langle\tau s\rangle}{4.1\,{\rm GeV}^2}\right)^{-1/2}$$

when the QGP is significantly out-of-equilibrium

Despite significant differences in underlying microscopics, similiar macroscopic behavior emerges in different microscopic theories

Equilibration at finite density

Extension of equilibration studies to finite net-baryon density

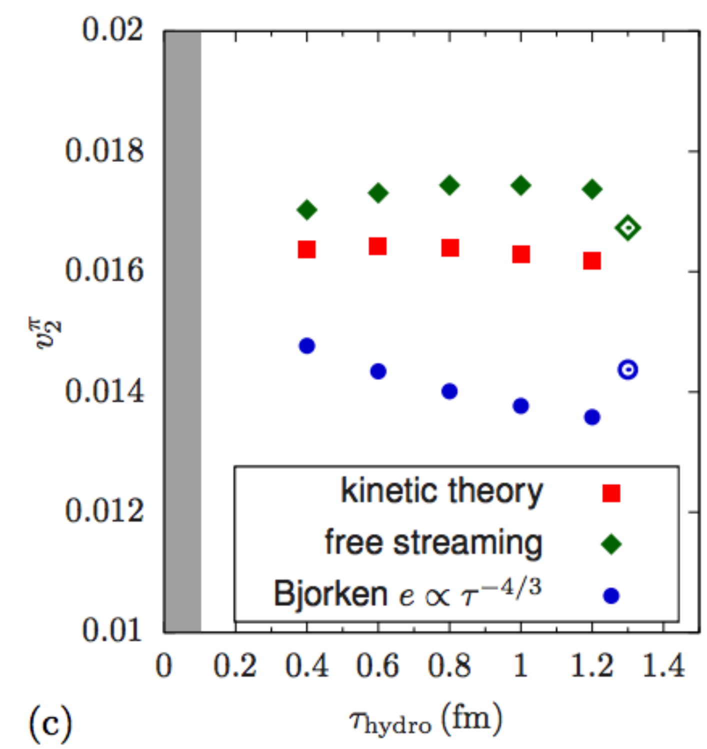


X. Du, SS, arXiv:2012.09068

Due to smaller energy densities hydrodynamization is delayed at lower collision energies, QGP can spend significant amount of time away from equilibrium

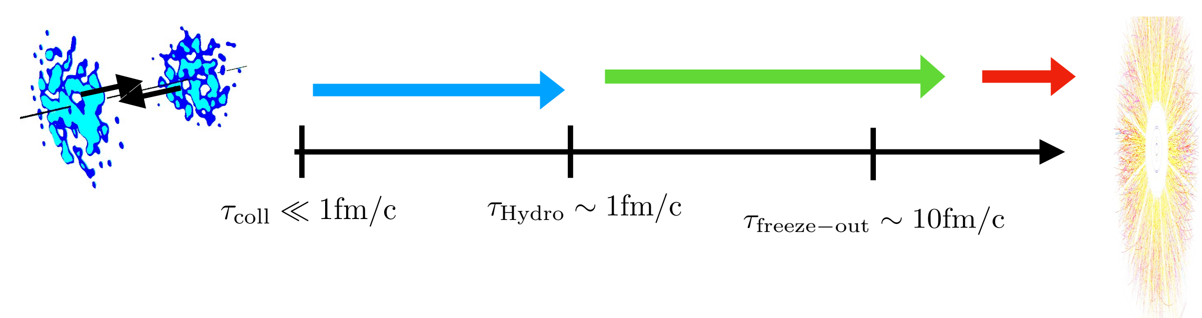
Dynamics of HICs

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



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

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



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

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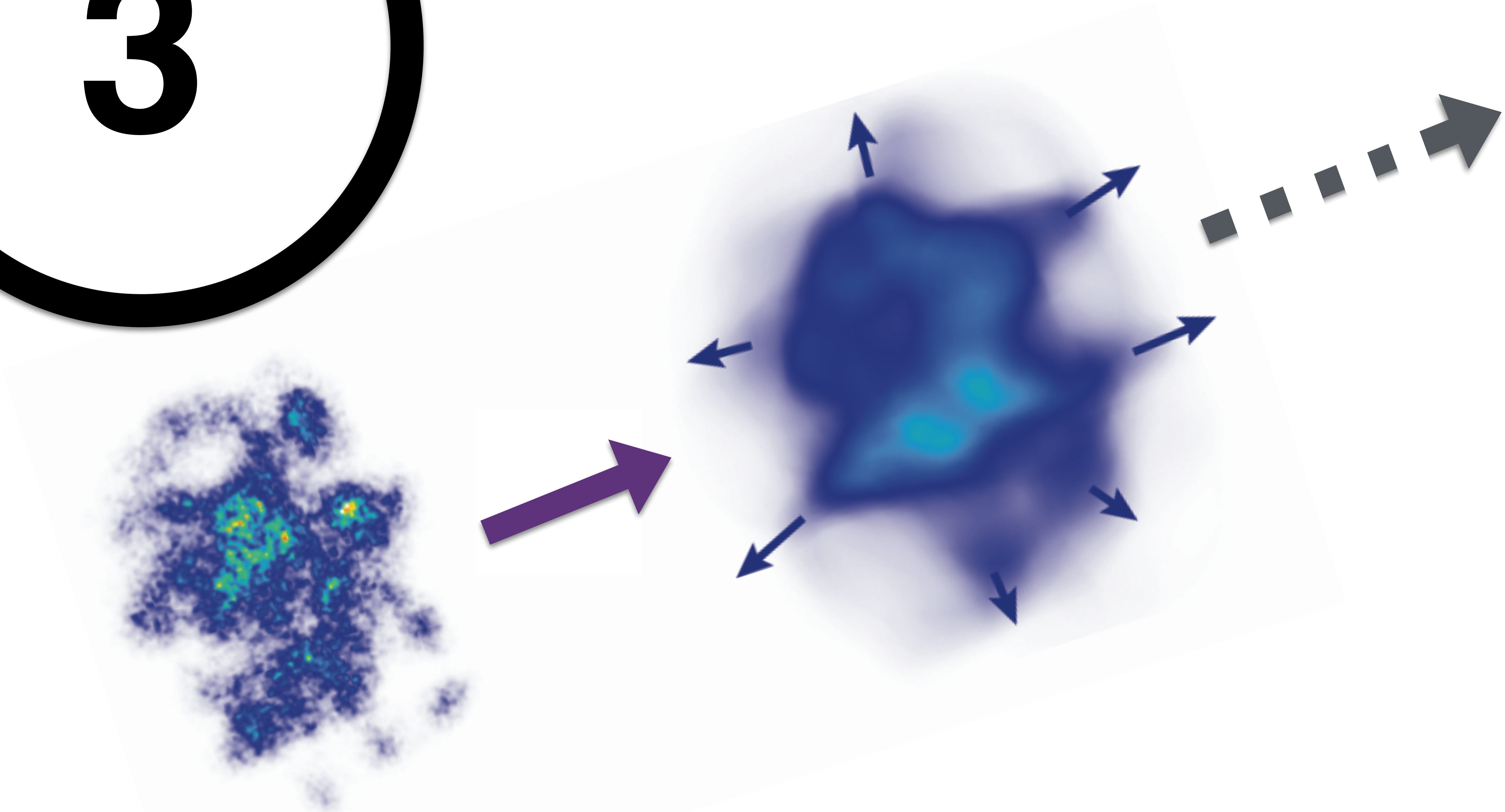


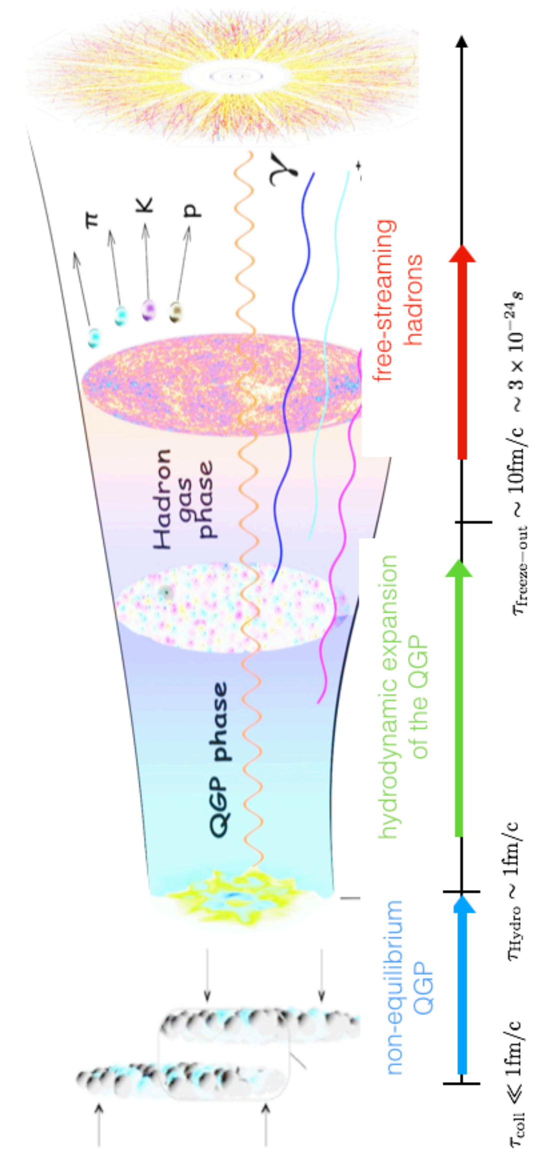
Phenomenological applications

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



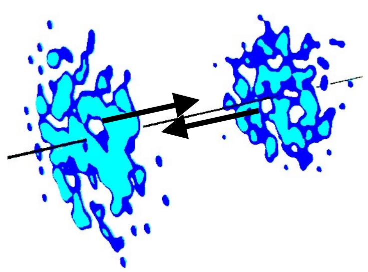
Sensitivity to Initial state

Entropy production occurs only when system is significantly out-of-equilibrium

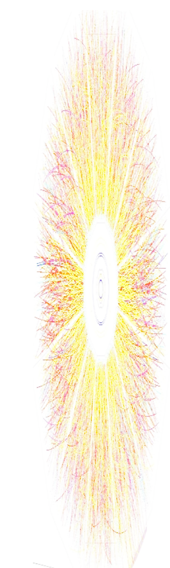
non-equilibrium QGP

near-equilibrium QGP

hadron gas



$\tau_{\mathrm{coll}} \ll 1\mathrm{fm/c}$ $\quad$ $\tau_{\mathrm{Hydro}} \sim 1\mathrm{fm/c}$ $\quad$ $\tau_{\mathrm{freeze-out}} \sim 10\mathrm{fm/c}$



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

Schematically:

(nearly) isentropic expansion

energy deposition

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

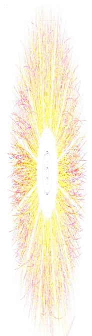
initial entropy production

freeze-out

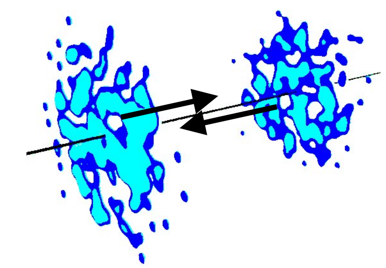
Giacalone, Mazeliauskas, SS PRL 123 (2019) 26, 262301

Entropy production in HICs

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



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



<u>Sensitivities/Uncertainties:</u>

Equilibrium properties: N_{ch}/S~7.5, ν_{eff} ~40 approximately known

Non-equilibrium/transport properties:
C_∞~0.95±0.15 surprisingly well constraint
4π η/s~(1-3) not well constraint in relevant temperature range (T~4T_c)

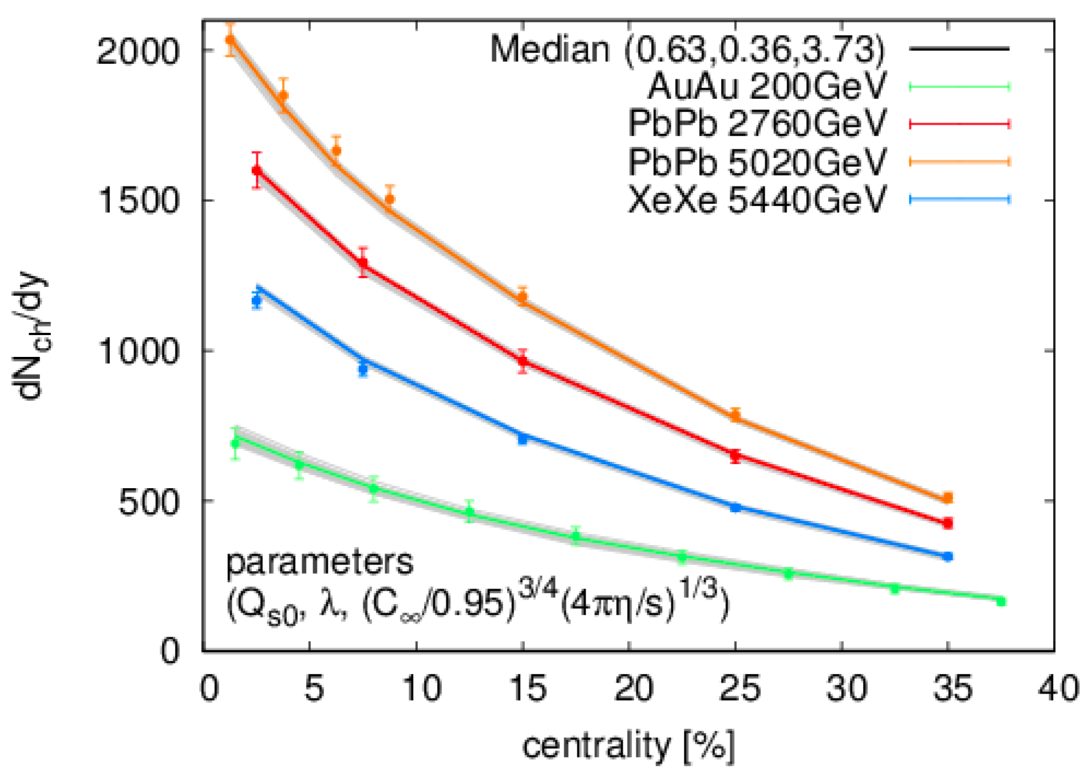
Initial state energy density:
$(e\tau)_0$ calculable in high-energy QCD with significant uncertainties from small-x TMDs

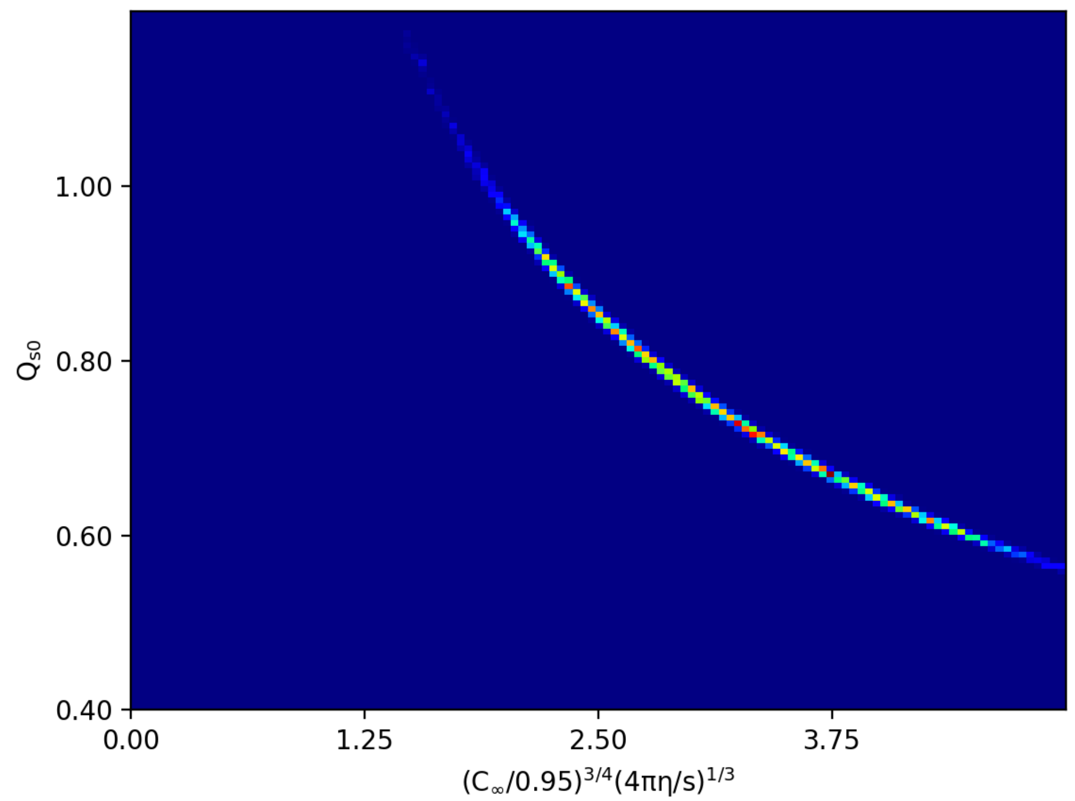
Giacalone, Mazeliauskas, SS PRL 123 (2019) 26, 262301

Initial state in HICs

Since $dN_{ch}/d\eta$ is measured with high precision in HICs, can be exploited to simultaneously constrain initial state TMDs & transport properties (η/s)

Proof-of-principle: Statistical analysis of GBW model to simultaneously determine Q_s and (η/s)





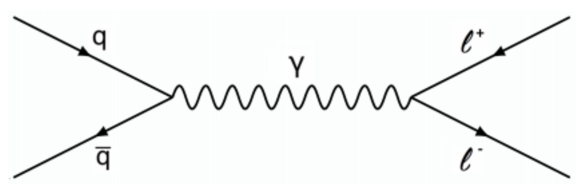
Description of space-time dynamics from beginning to end enables important link between EIC physics and Heavy-Ion physics

Y.Hoffmann, BSc Thesis; Du,Hoffmann,SS, work in progress

Di-lepton production in HICs

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 produced during the initial state; late stage production is suppressed by exp(-M/T)



Non-equilibrium production requires production of quark/anti-quarks from gluon dominated initial state; pre-equilibrium yields suppressed by

short duration of pre-equilibrium phase

quark/anti suppression at early times

Calculate pre-equilibrium di-lepton production for LO process, with parametrized phase-space distribution

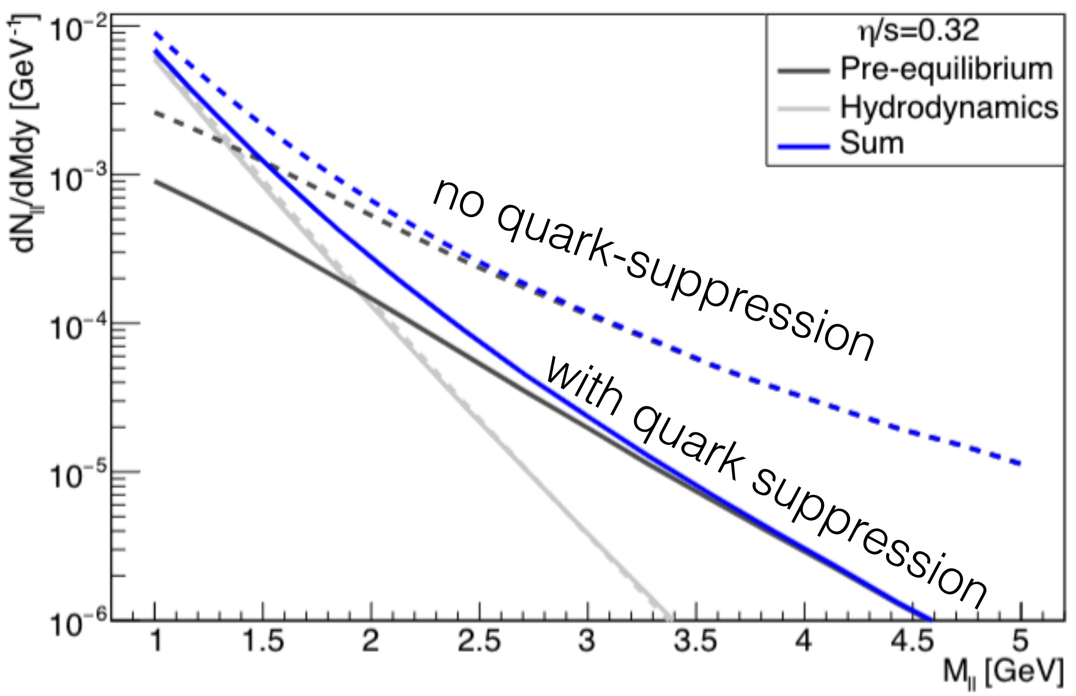
$$f_{q/\bar{q}}(\tau, p_t, p_z) = q(\tau) f_{FD}\left(\frac{\sqrt{p_t^2 + \xi^2(\tau) p_z^2}}{\Lambda(\tau)}\right)$$

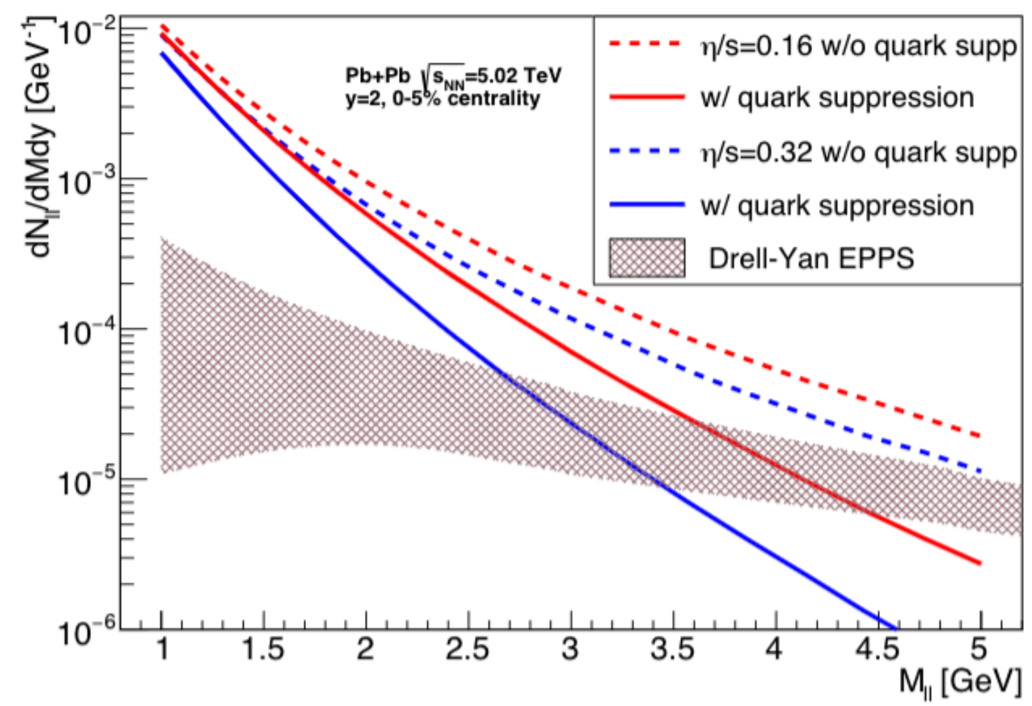
with anisotropy ξ, energy scale Λ, and quark-suppression factor q matched to macroscopic evolution of pL/e, e, e_q/e_g and energy scale fixed by $dN_{ch}/d\eta$

Coquet,Du,Ollitrault,SS,Winn; arXiv:2104.07622

Di-lepton production in HICs

Distinguish between production in the pre-equilibrium (w<1) and hydrodynamic (w>1) stages





Coquet,Du,Ollitrault,SS,Winn; arXiv:2104.07622

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

Small systems

c.f. talk by C. Werthmann

Effective kinetic description of 2+1D boost-invariant systems, including non-trivial geometry in transverse plane, within conformal RTA Boltzmann equation

$$p^\mu \partial_\mu f = C_{RTA}[f] = \frac{p_\mu u^\mu}{\tau_R}(f_{eq} - f)\ , \quad \tau_R = 5\frac{\eta}{s}T^{-1}$$

Single conformal scaling variable/opacity parameter in 2+1D governs system size/coupling dependence

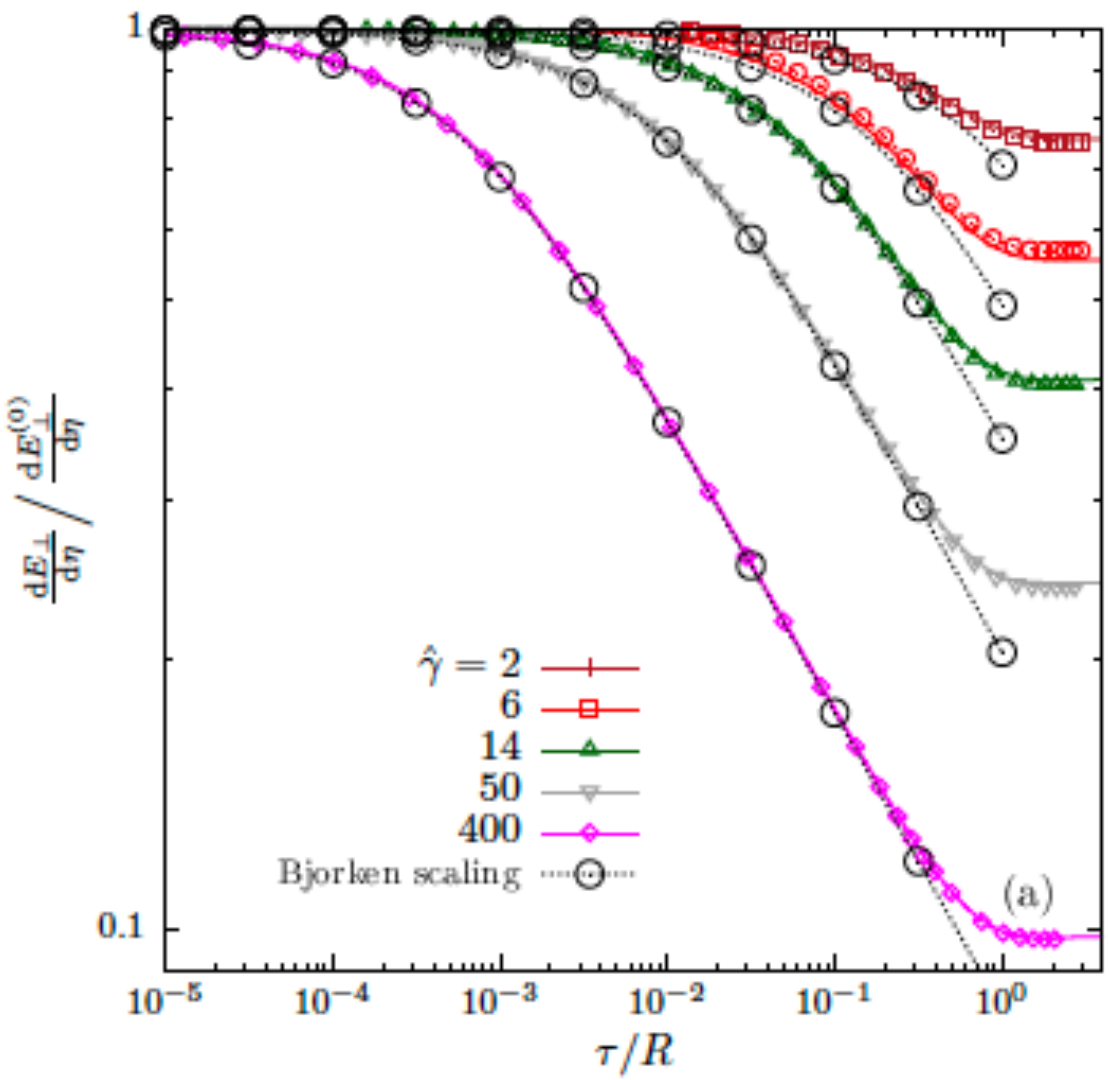
Kurkela, Wiedemann, Wu EPJC 79 (2019) 965; Ambrus, SS, Werthmann arXiv:2109.03290

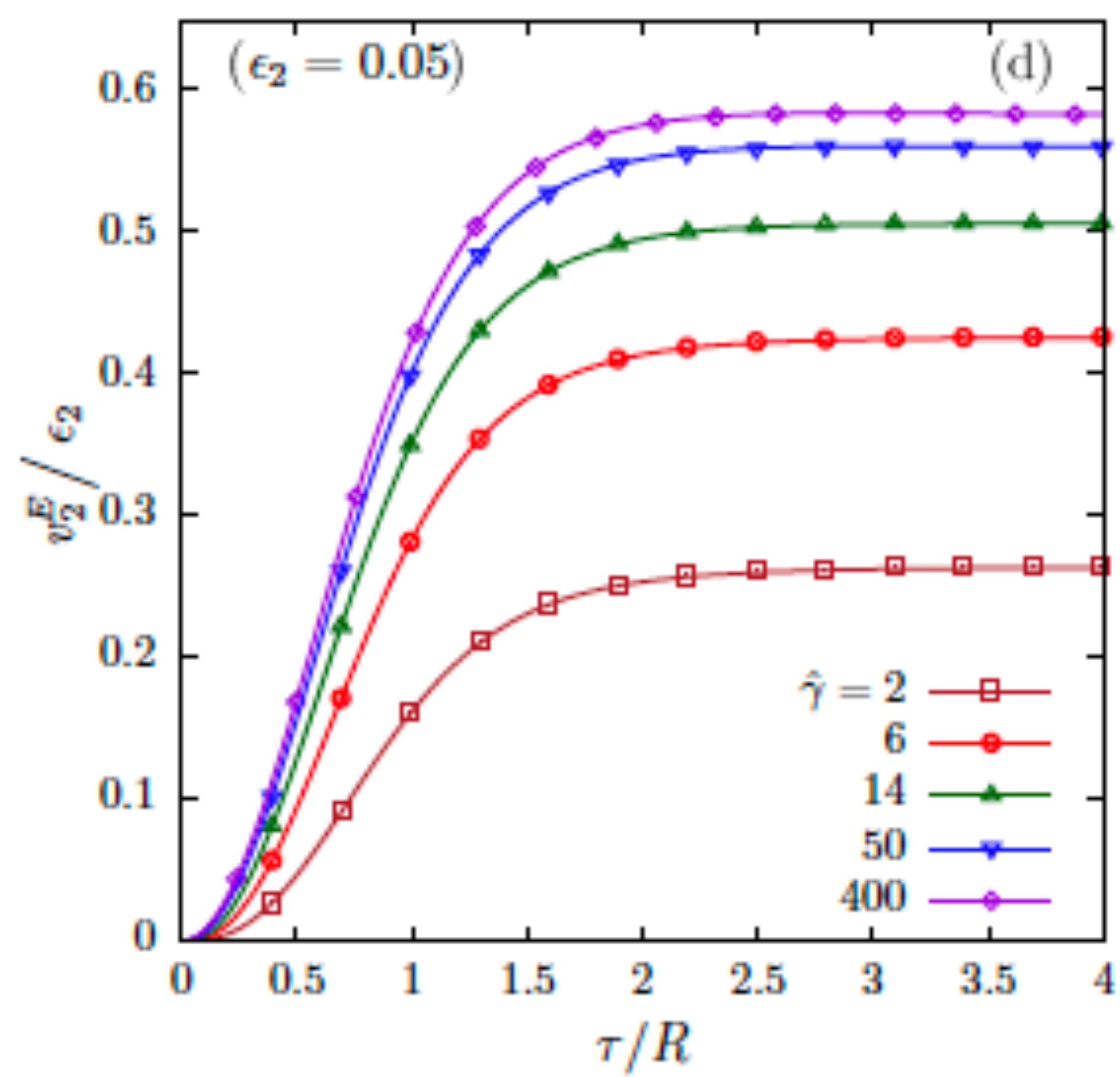
$$\hat{\gamma} = \left(5\frac{\eta}{s}\right)^{-1}\left(\frac{30}{\nu_{\text{eff}}\pi^2}\frac{1}{\pi}\frac{\mathrm{d}E_\perp^{(0)}}{\mathrm{d}\eta}R\right)^{1/4}$$

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

Small systems

Early long. cooling well described by Bjorken dynamics for sufficiently large opacities

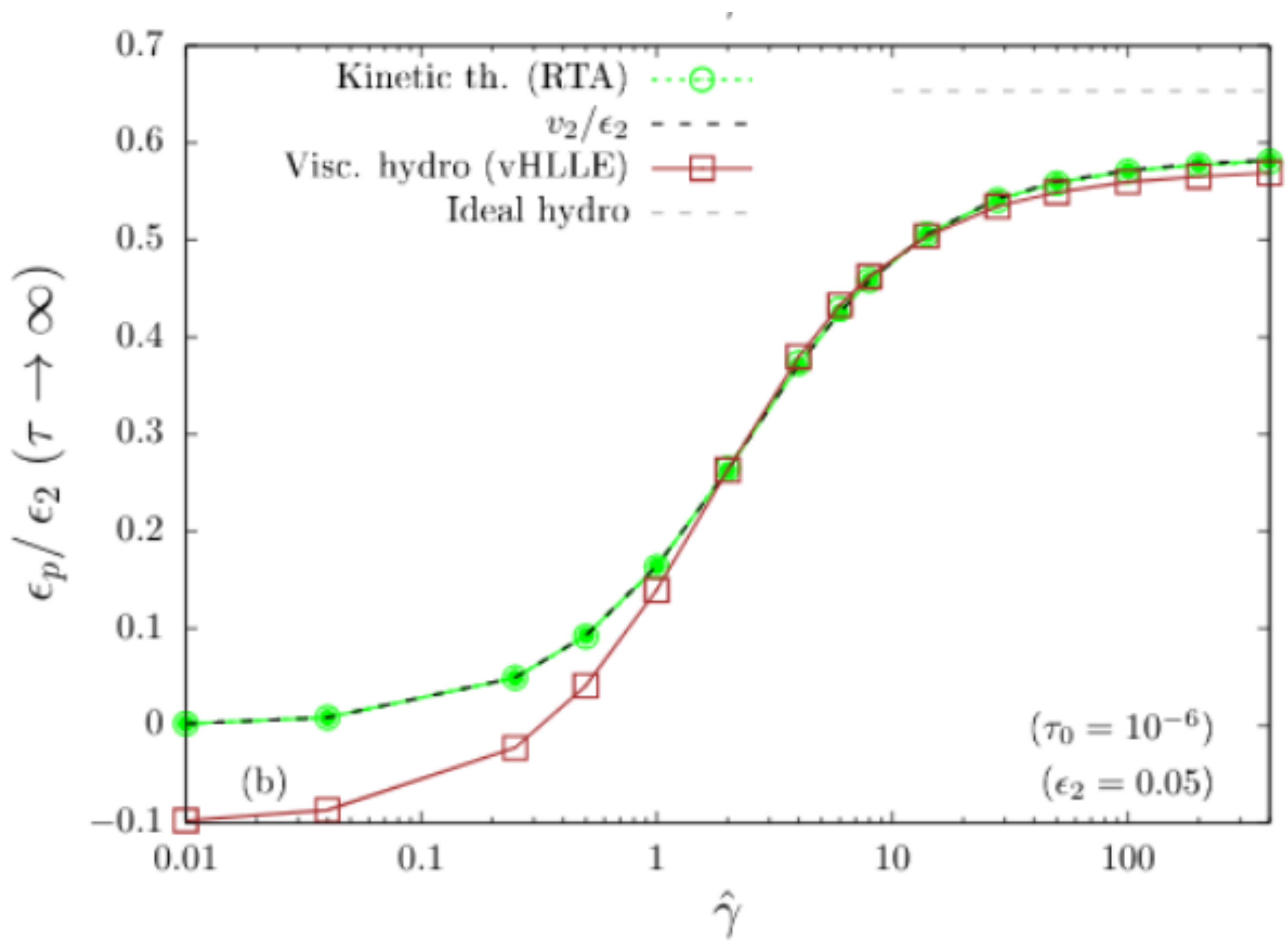




Development of transverse flow show significant opacity dependence in relevant range of opacities

Ambrus, SS, Werthmann arXiv:2109.03290

Hydrodynamics in small systems?



Despite reasonable quantiative description at moderate opacities discrepancies between Kinetic Theory (RTA) and hydrodynamics persist even at very large opacities due to inhomogenous cooling

Hydrodynamics does not properly describe early pre-equilibrium stage; need to include pre-equilibrium stage in theoretical description of HICs

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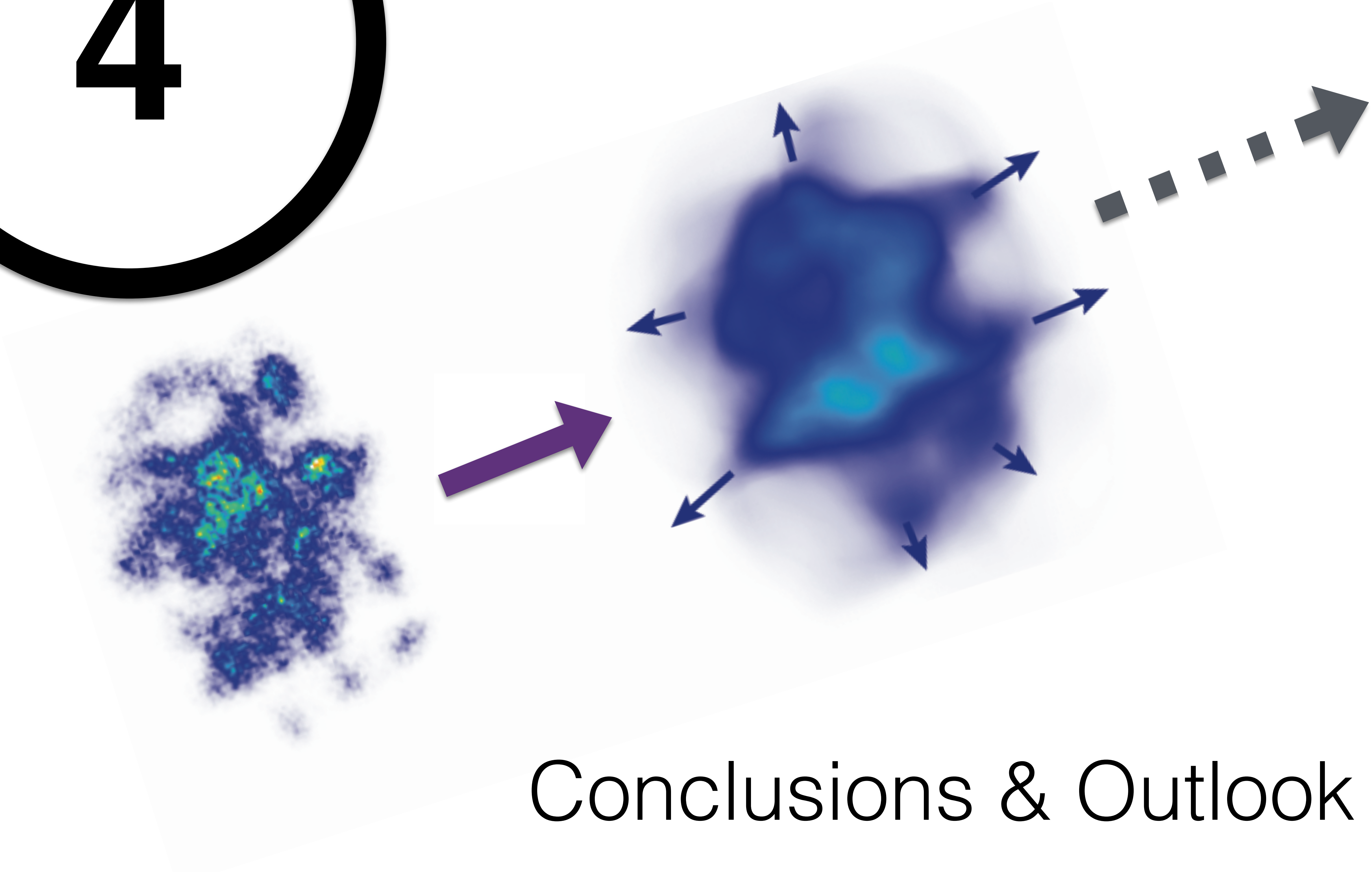


Conclusions & Outlook

Conclusions & Outlook

Developments in equilibration dynamics enable to include pre-equilibrium stage into event-by-event studies of heavy-ion collisions

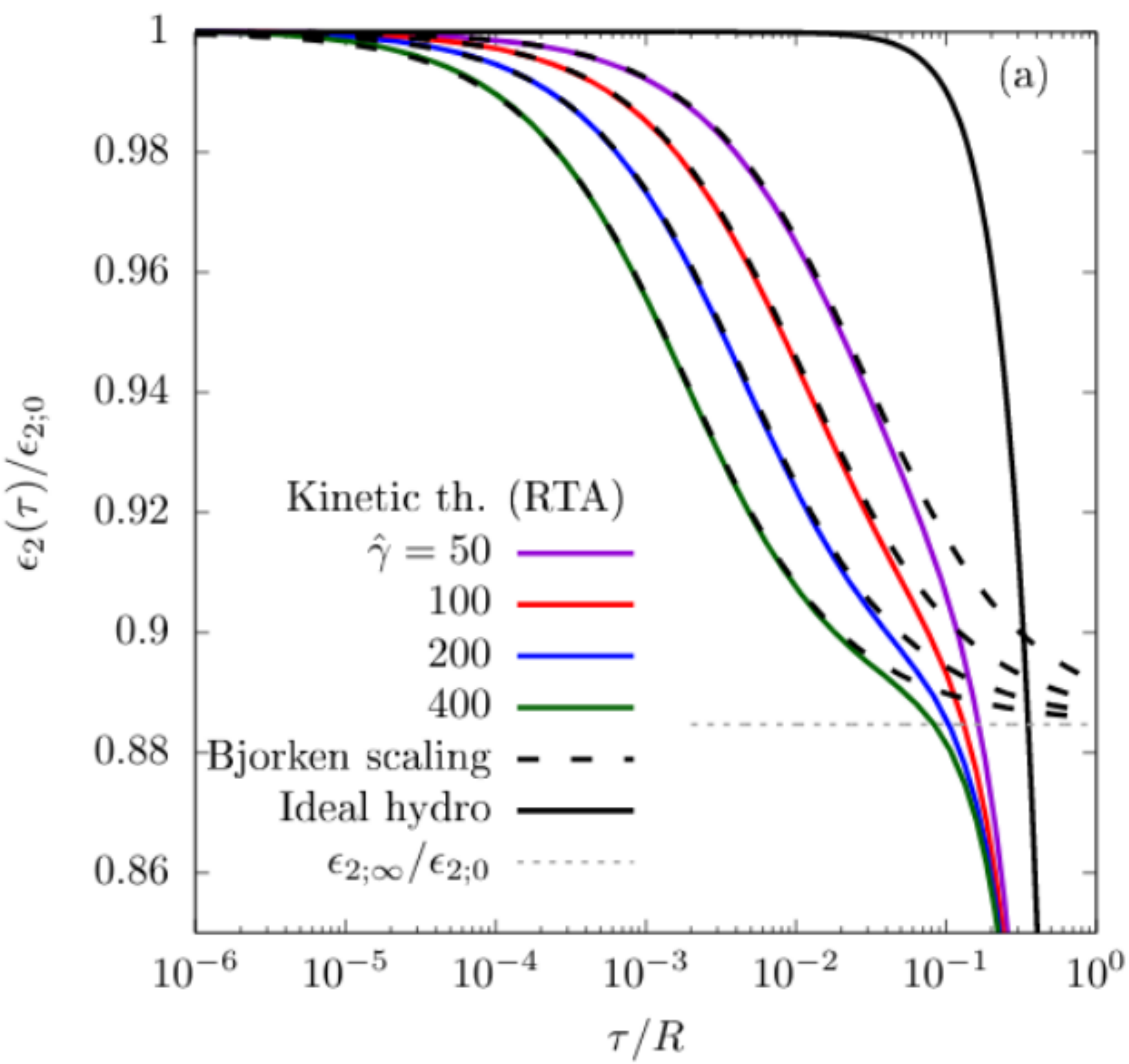
Connecting initial state and final state in heavy-ion collisions enables new links between hot QCD (heavy-ions) and cold QCD physics (EIC)

Exciting directions to explore non-equilibrium QCD dynamics with electro-magnetic probes & in small systems

Still many things to be explored in small systems, longitudinal dynamic, jets, …

Backup

Inhomogenous cooling



Due to in homogenous cooling, eccentricity depletes before transverse expansion sets in

Initial state in HICs

Since $dN_{ch}/d\eta$ is measured with high precision in HICs, can be exploited to simultaneously constrain initial state TMDs & transport properties (η/s)

Proof-of-principle calculation based on k_T factorization calculation in GBW model

$$Q^2_{s,A}(x,\mathbf{b}) = Q^2_{s,0}(x/x_0)^{-\lambda}\ \sigma_0 T_A(\mathbf{b})$$

$$\phi^{(1)}_{(U)}(x,\mathbf{b},\mathbf{k}) = 4\pi^2 \frac{(N_c^2-1)}{g^2 N_c} \frac{\mathbf{k}^2}{Q^2_{s,adj}(x,\mathbf{b})} \exp\left\{-\frac{\mathbf{k}^2}{Q^2_{s,adj}(x,\mathbf{b})}\right\}$$

$$\frac{dN_g}{d^2\mathbf{b}d^2\mathbf{P}dy} = \frac{\alpha_s N_c}{\pi^4 \mathbf{P}^2 (N_c^2-1)} \int \frac{d^2\mathbf{k}}{(2\pi)^2}\ \Phi_A(x_A, \mathbf{b}+\mathbf{b}_0/2, \mathbf{k}) \Phi_B(x_B, \mathbf{b}-\mathbf{b}_0/2, \mathbf{P}-\mathbf{k})$$

$$(e\tau)_0 = \int d^2\mathbf{P}\ |\mathbf{P}|\ \frac{dN_g}{d^2\mathbf{b}d^2\mathbf{P}dy} = \frac{(N_c^2-1)}{4g^2 N_c \sqrt{\pi}} \frac{Q_A^2 Q_B^2}{(Q_A^2+Q_B^2)^{5/2}} \left[2Q_A^4 + 7Q_A^2 Q_B^2 + 2Q_B^4\right]$$

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

Y.Hoffmann, BSc Thesis; Du,Hoffmann,SS, work in progress