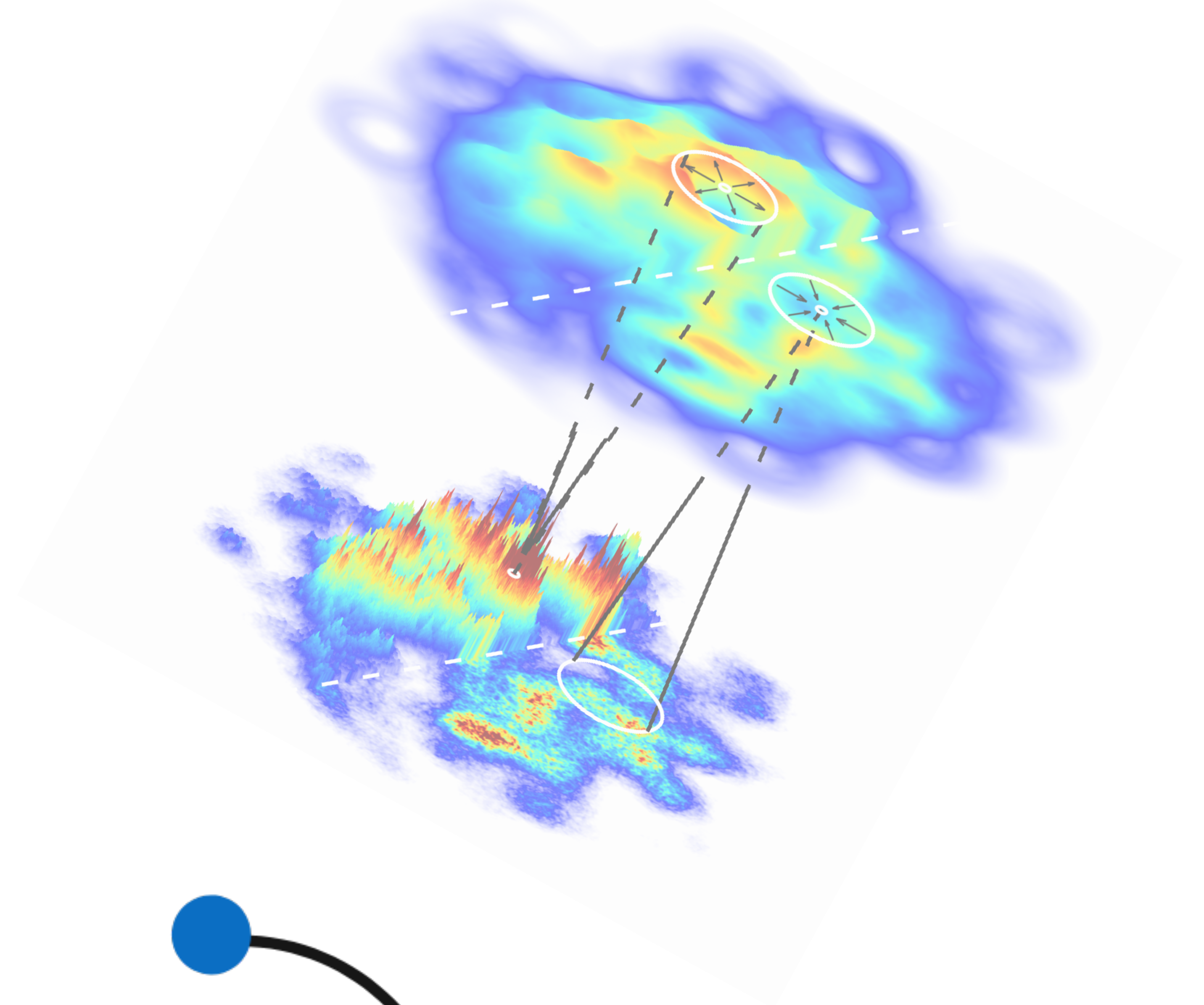


Thermalisation across system size

Sören Schlichting | Universität Bielefeld



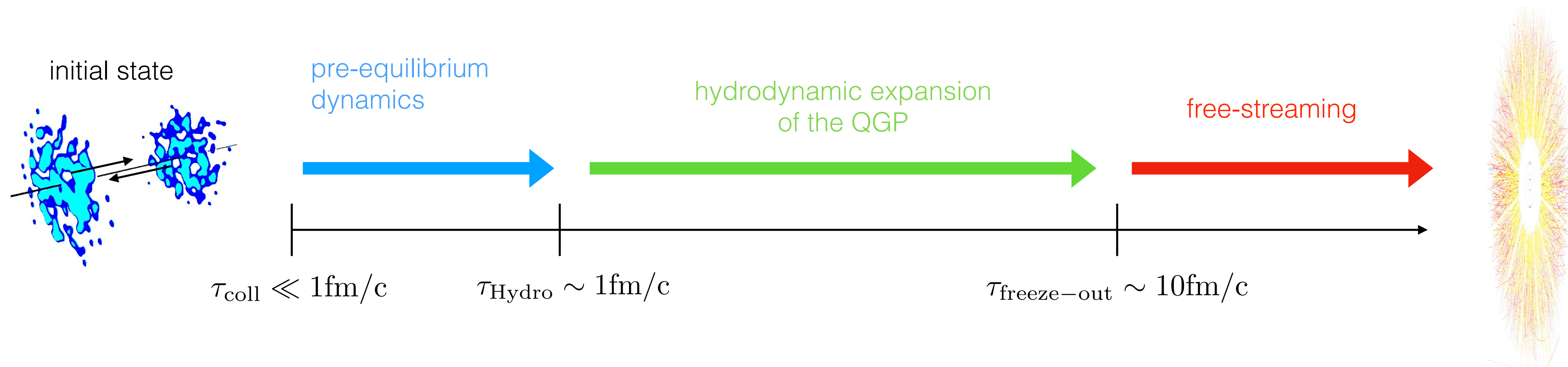
EMMI Workshop on Light Ion Collisions
Heidelberg, Sept 2026



Dynamics of Heavy-Ion Collisions

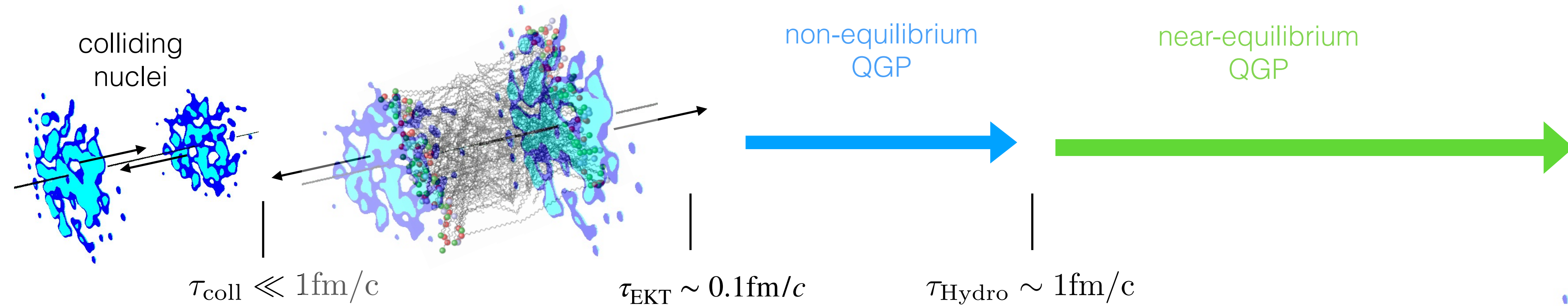
Dynamical description of Heavy-Ion collisions from underlying theory of QCD remains an outstanding challenge

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

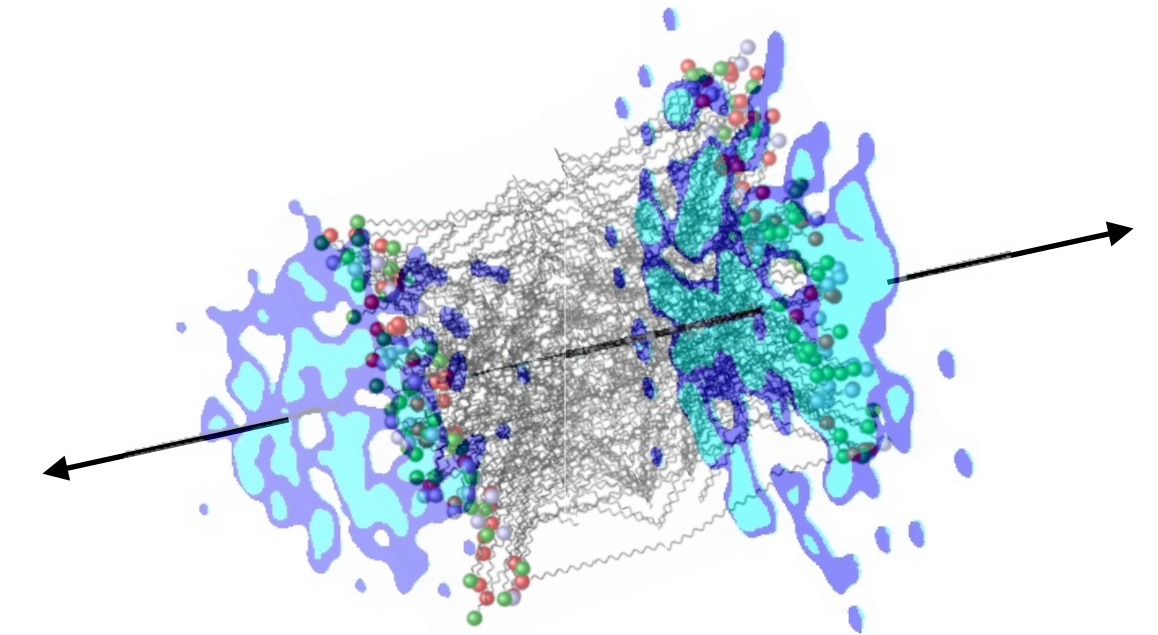


Dynamical description of equilibration process during the pre-equilibrium phase is essential for continuous description of space-time dynamics

Thermalisation in 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 (Bjorken flow)

Kinetic Equilibration — Hydrodynamic attractors

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

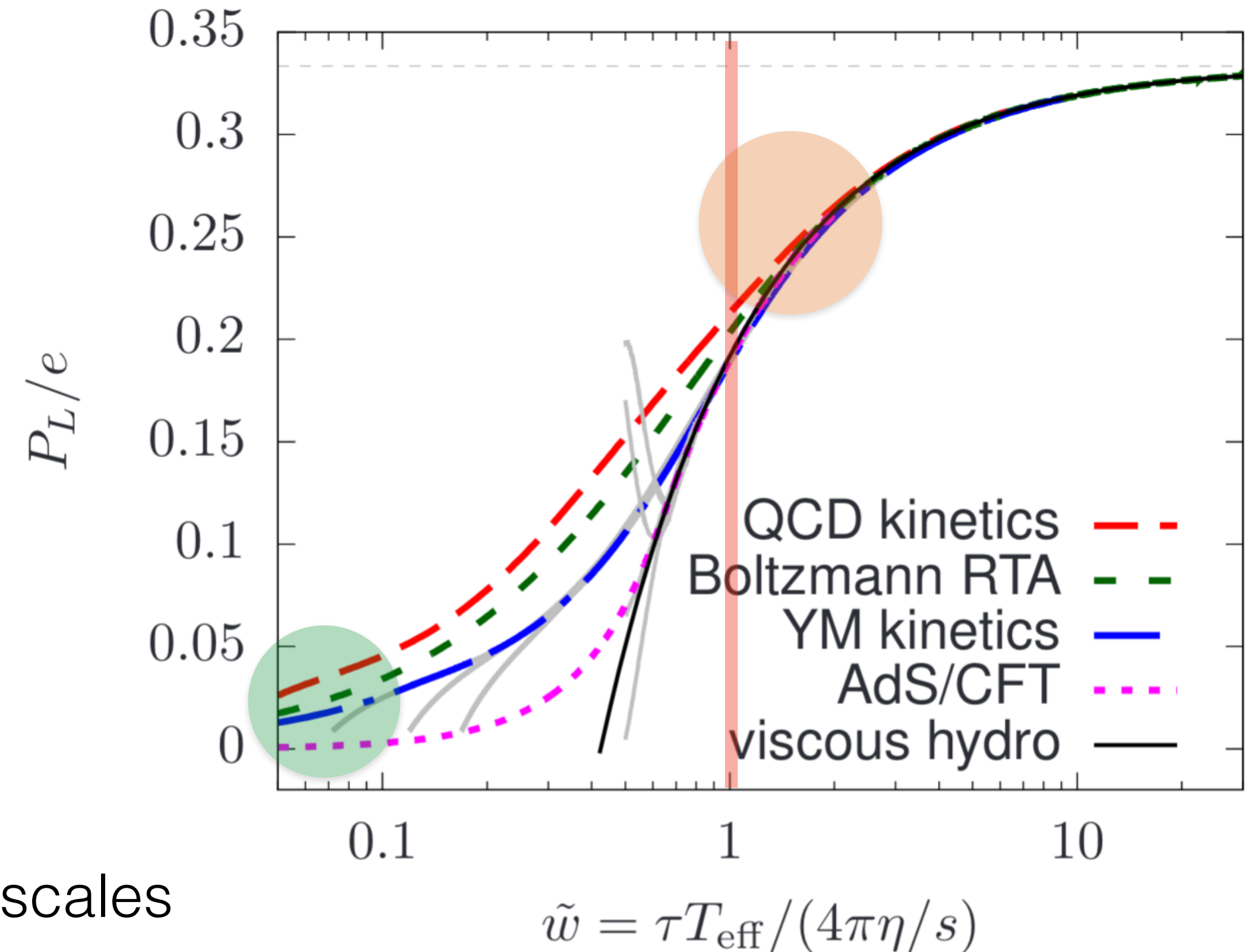
Early times (expansion dominated):

$\tilde{w} \ll 1$ 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



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

Chemical Equilibration

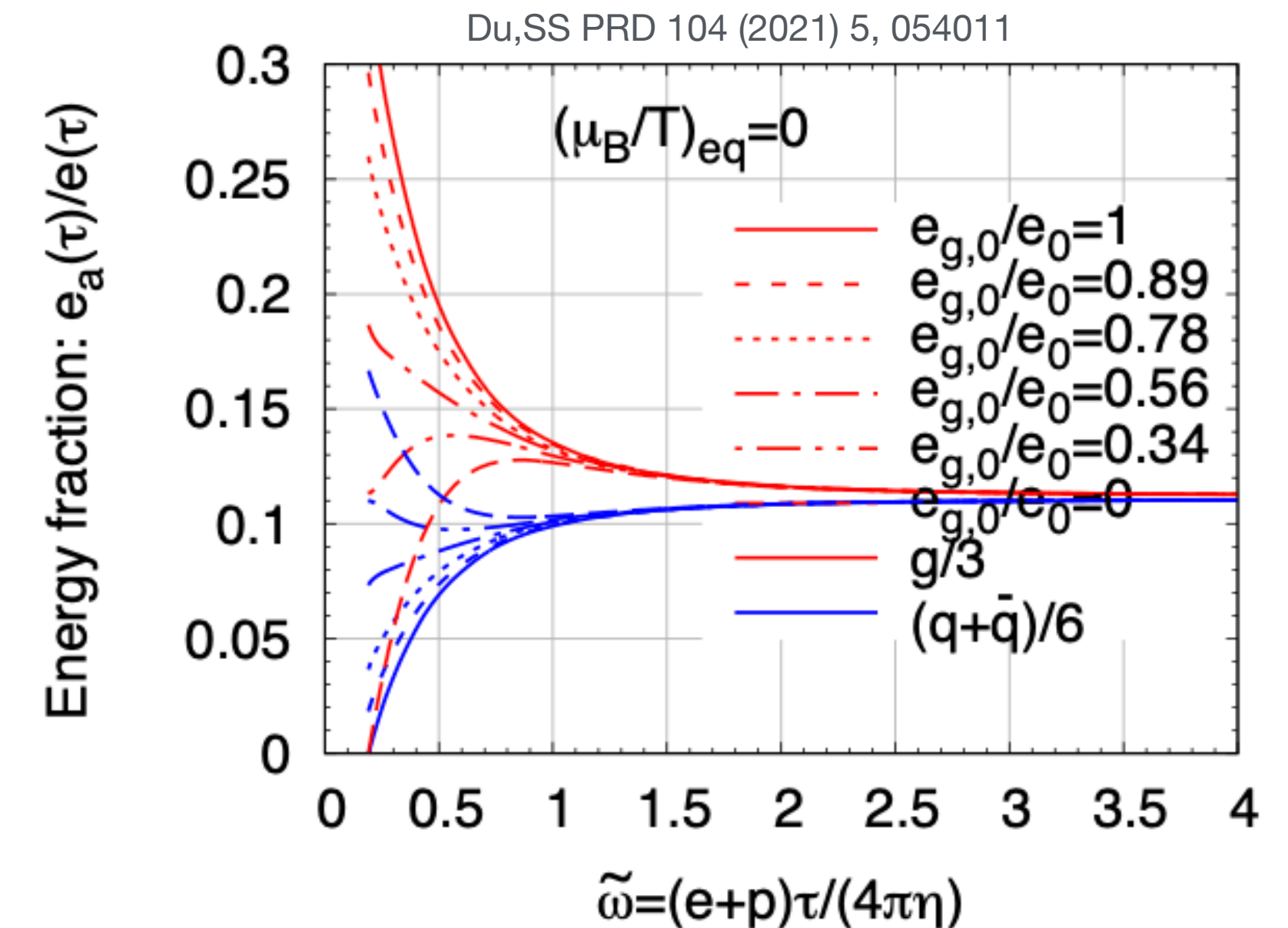
Chemical equilibration in QCD Kinetic Theory proceeds roughly on the same time scale as kinetic equilibration

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

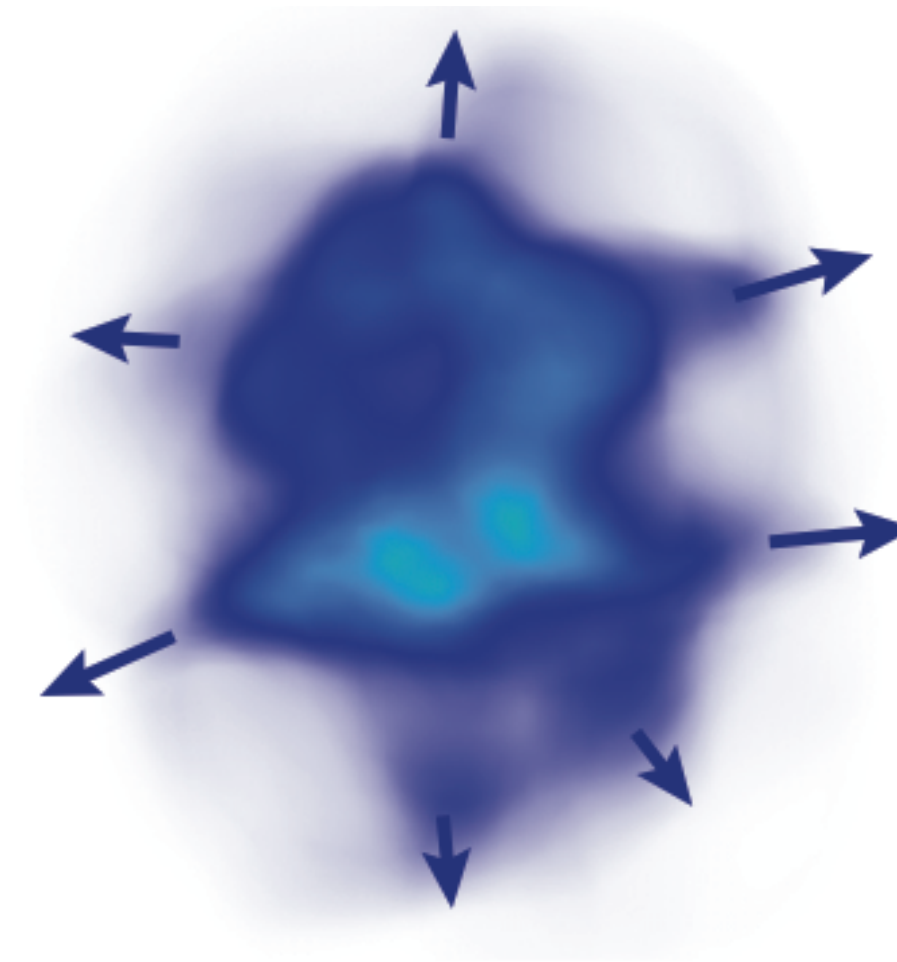
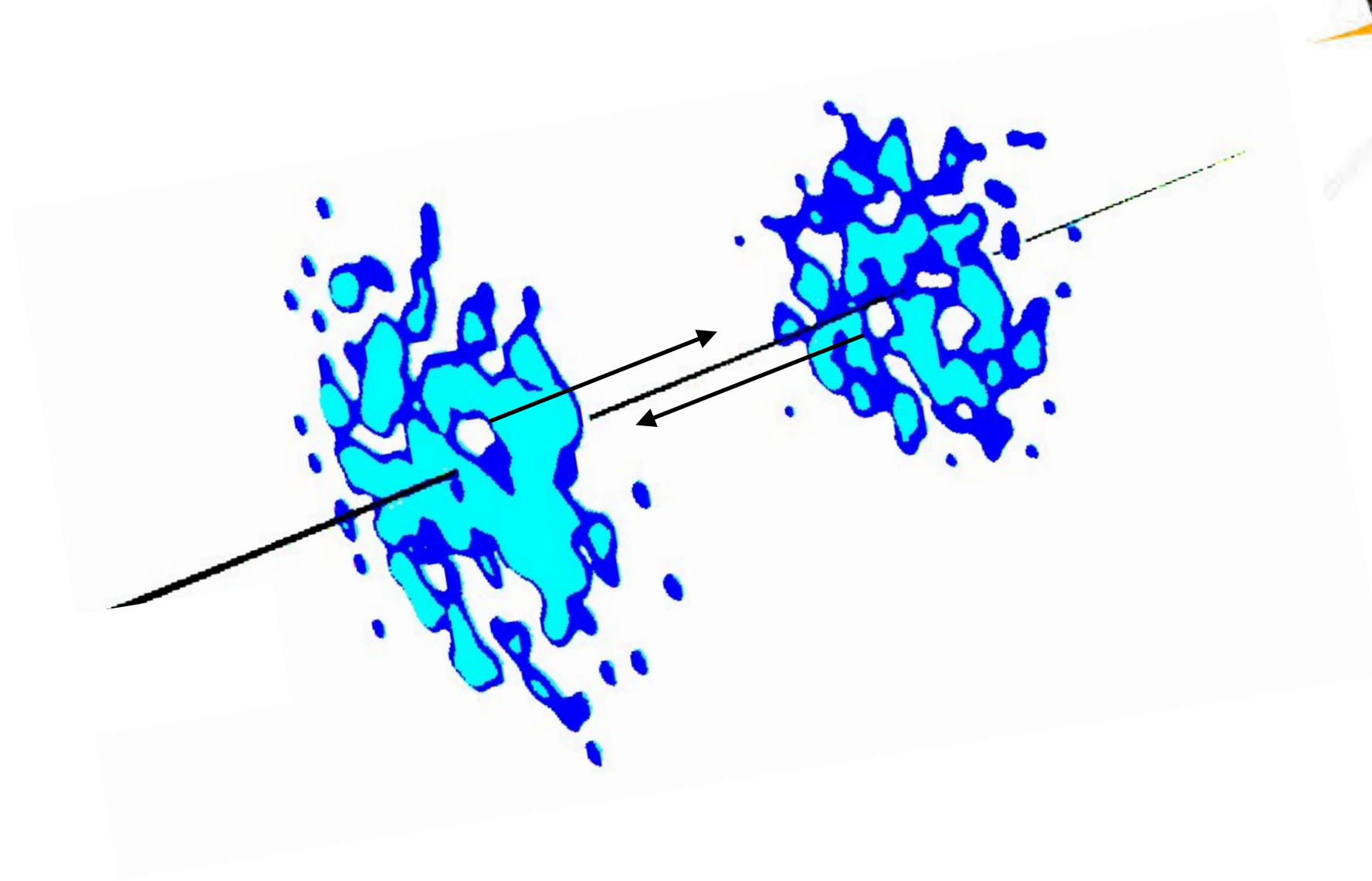
Since interaction are required to change QGP chemistry the initial **gluon dominance persist** up to τ_{Hydro}

->No genuine early time attractors

Beyond bulk flow, which is only sensitive to energy-momentum tensor different observables e.g. electro-magnetic probes or heavy-flavours have different sensitivity to early QGP chemistry



2



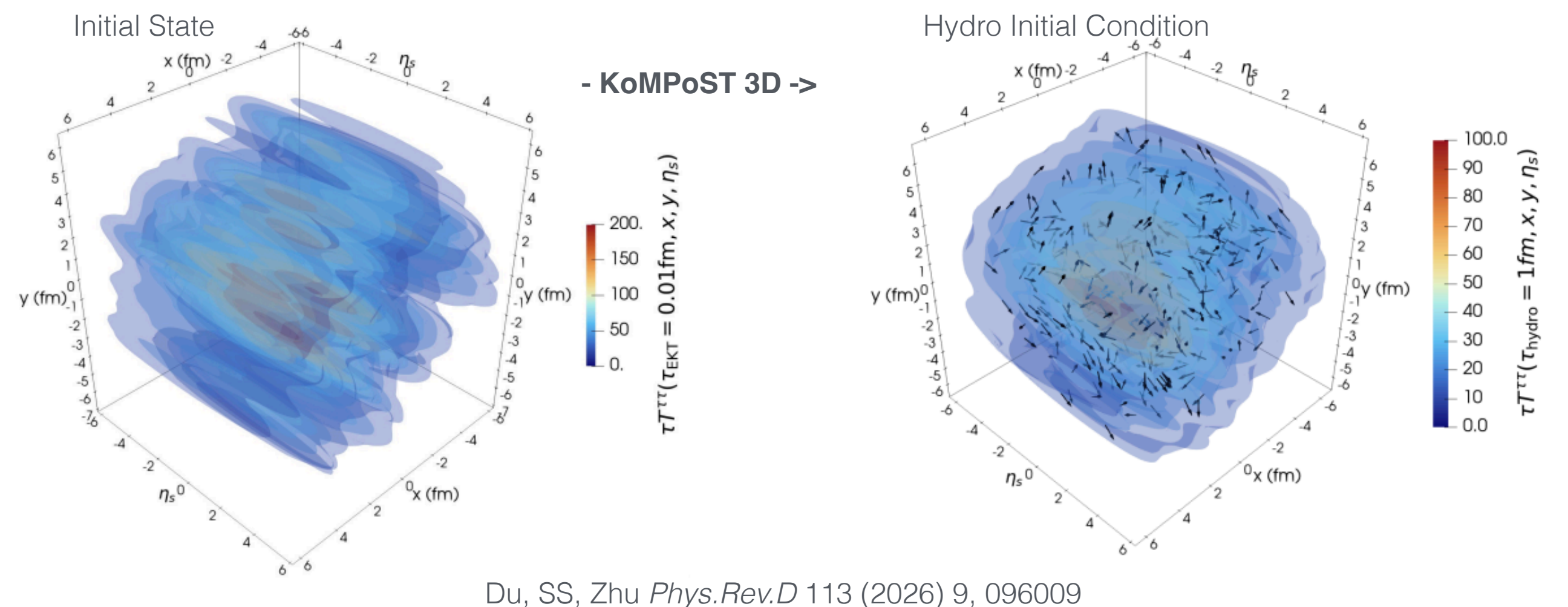
Phenomenology of
pre-equilibrium phase in HICs

Event-by-event pre-eq with KØMPØST

Effective macroscopic description of pre-equilibrium dynamics in HICs possible on event-by-event basis available in KØMPØST

2+1D: KØMPØST: Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910
3D: Du, SS, Zhu *Phys.Rev.D* 113 (2026) 9, 096009

Non-equilibrium linear response



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

Bjorken flow attractor

Non-Eq Green's functions from QCD kinetic theory

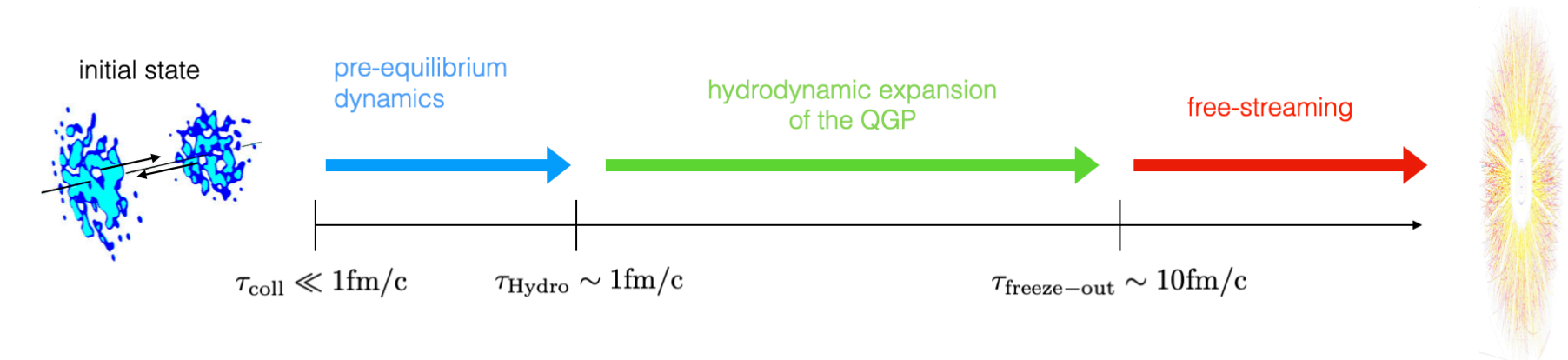
Initial state fluctuations

Conceptually important but typically small effects on transverse flow observables (e.g. v_n), due to relatively short duration of pre-eq stage

c.f. talk by J. Zhu

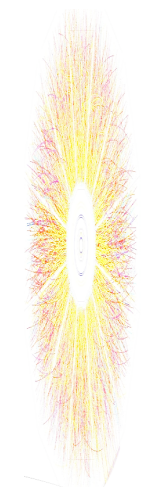
Entropy production

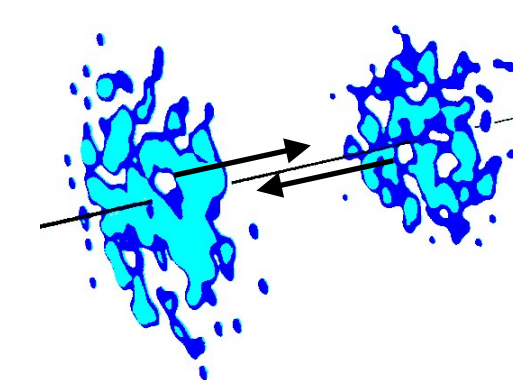
Entropy production occurs pre-dominantly during the pre-equilibrium stage, where QGP is out-of-equilibrium



Experimentally probed in terms of charged particle multiplicity

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



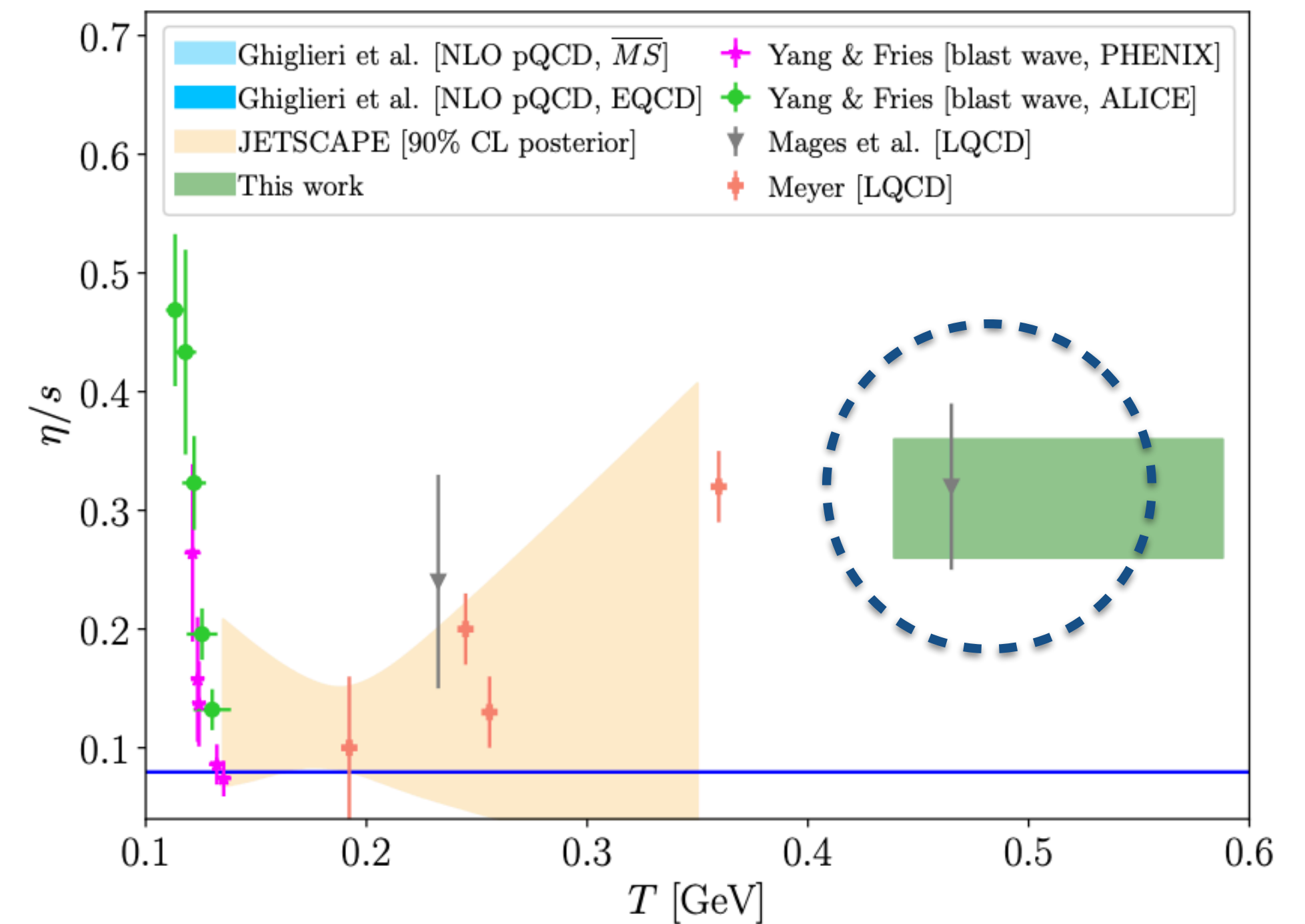
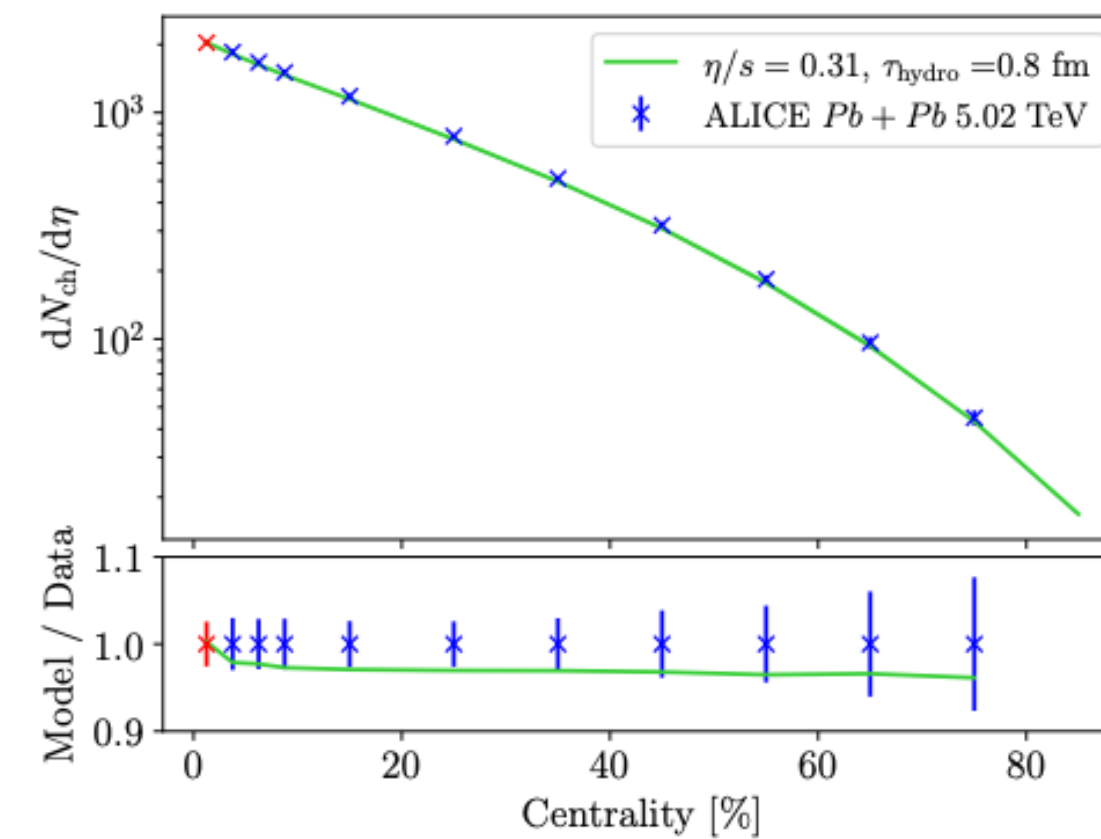
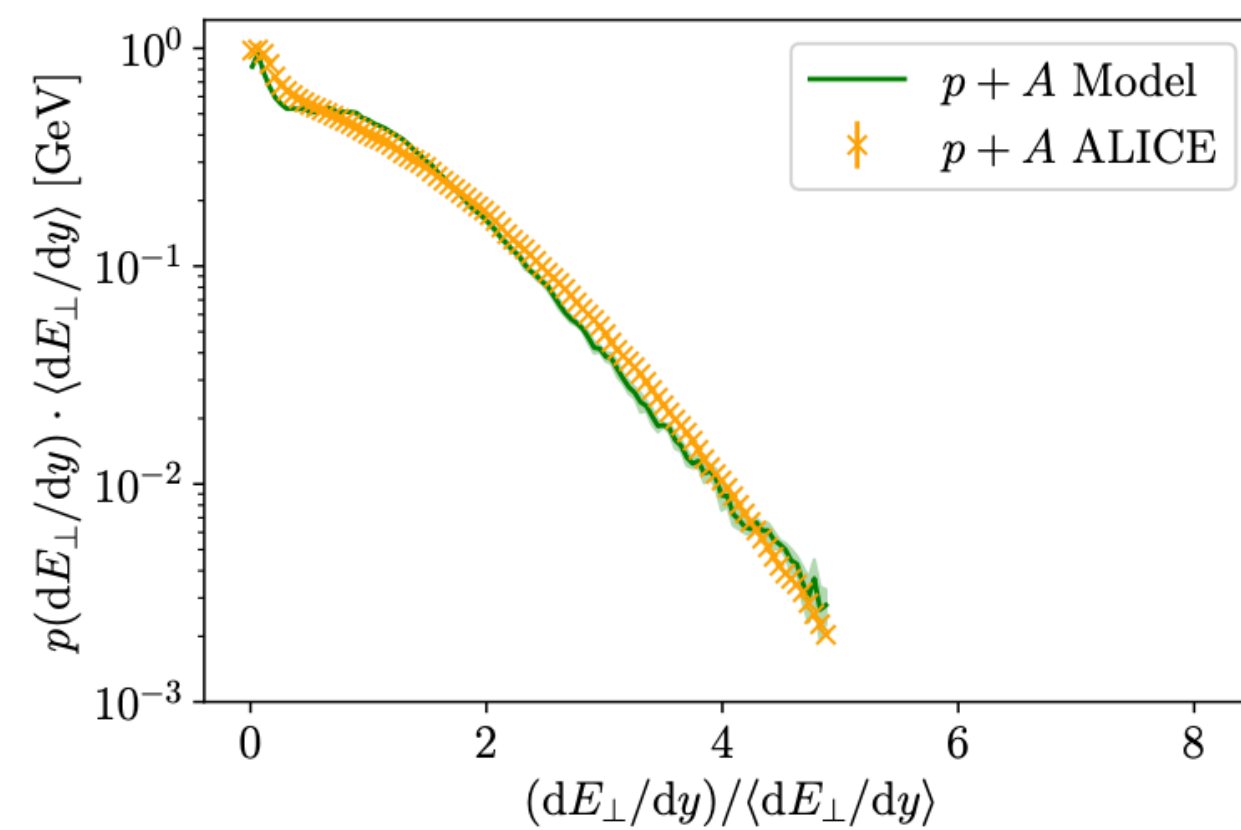
$$\frac{dN_{\text{ch}}}{d\eta} \simeq \frac{4}{3} \left(\frac{N_{\text{ch}}}{S} \right) C_{\infty}^{3/4} \left(4\pi\eta/s \right)^{1/3} \left(\frac{\pi^2}{30} \nu_{\text{eff}} \right)^{1/3} \int d^2\mathbf{x}_{\perp} \left(\frac{dE_{\perp}^0}{d^2\mathbf{x}_{\perp} d\eta} \right)^{2/3}$$


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 $dE_0/d^2\mathbf{x}_{\perp}d\eta$ (typically treated as free parameter)

Proof of principle

Combined statistical analysis of
p+p/A ($dE/d\eta$) and A+A data ($dN/d\eta$)



=> Constraint on high temperature shear viscosity
solely from multiplicity measurement

Need relatively large viscosity to produce enough entropy to match
 $dN/d\eta$ measurement in A+A

Andronic, Borghini, Du, Klein-Böding, Kurpczak, Roch, SS, *JHEP* 04 (2026) 185

Electromagnetic probes (γ)

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

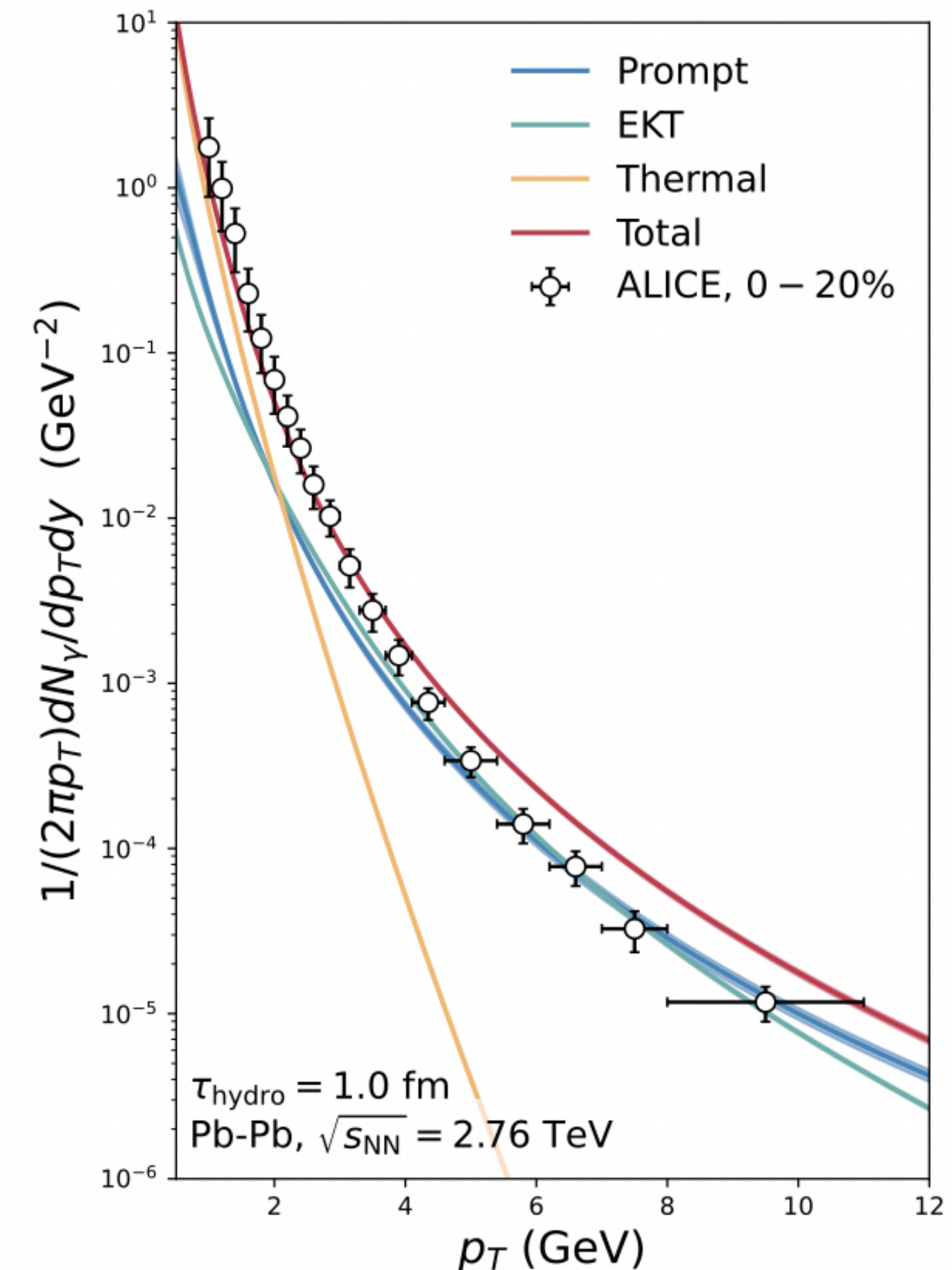
Universal scaling of photon p_T spectrum in terms of shear viscosity η/s and entropy density $dS/d\eta \sim (T\tau^{1/3})^3$

Garcia-Montero, Mazeliauskas, Plaschke, SS arXiv:2308.09747

Garcia-Montero, Plaschke, SS *Phys.Rev.D* 111 (2025) 3, 034036

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

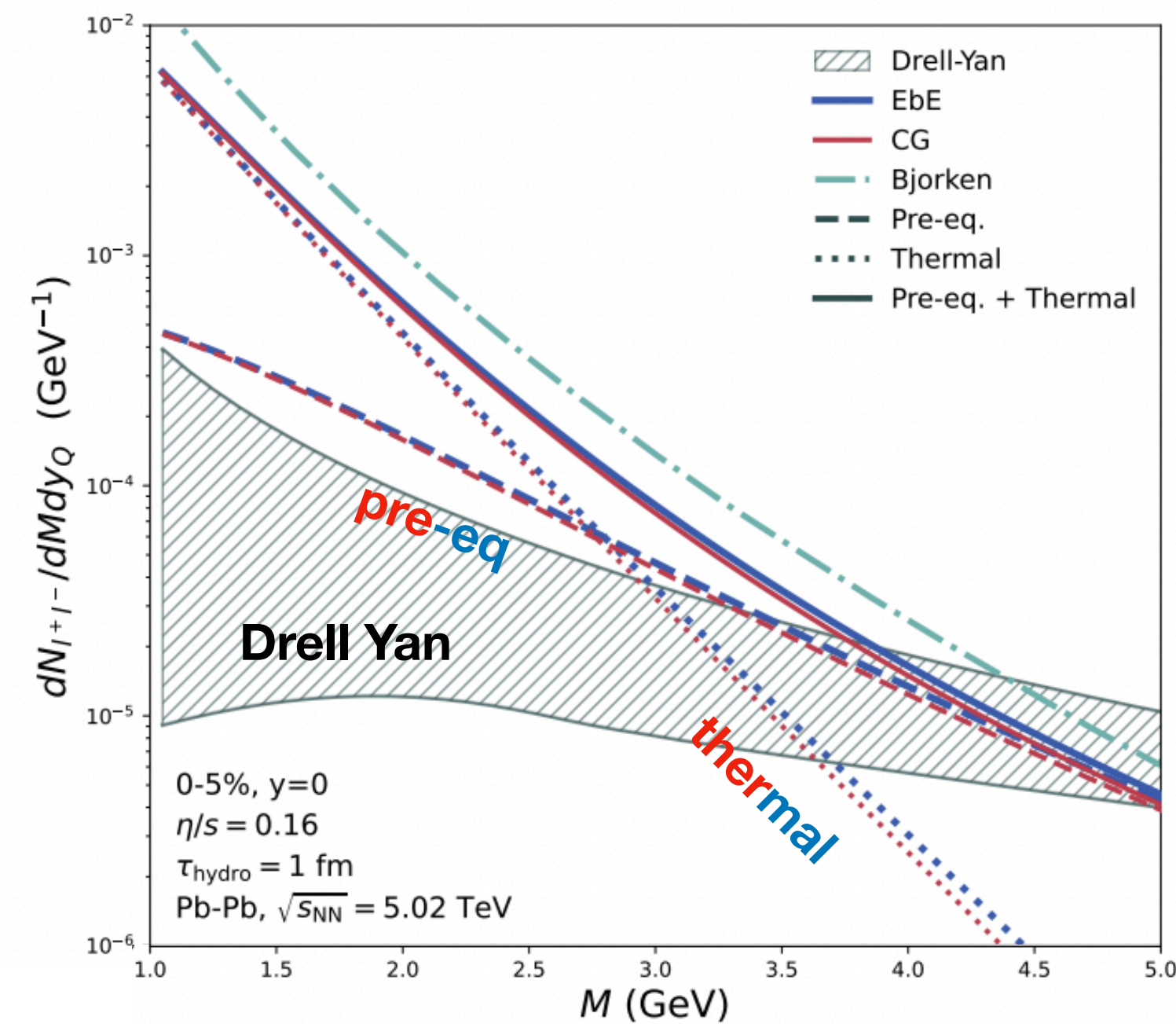
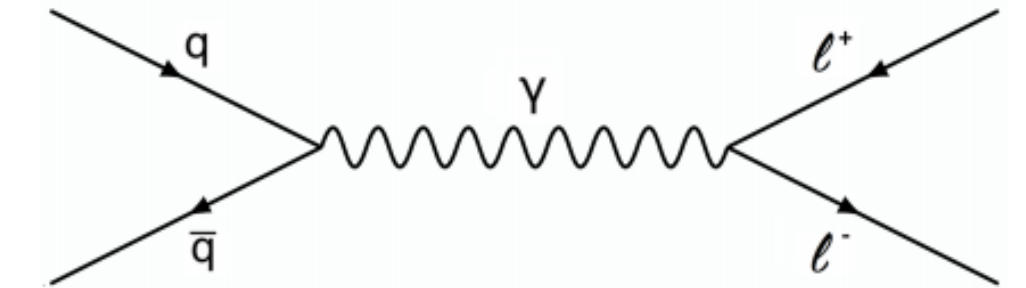
Sizeable pre-eq contribution at $p_T > 2 \text{ GeV}$ but not exceeding thermal+prompt contributions



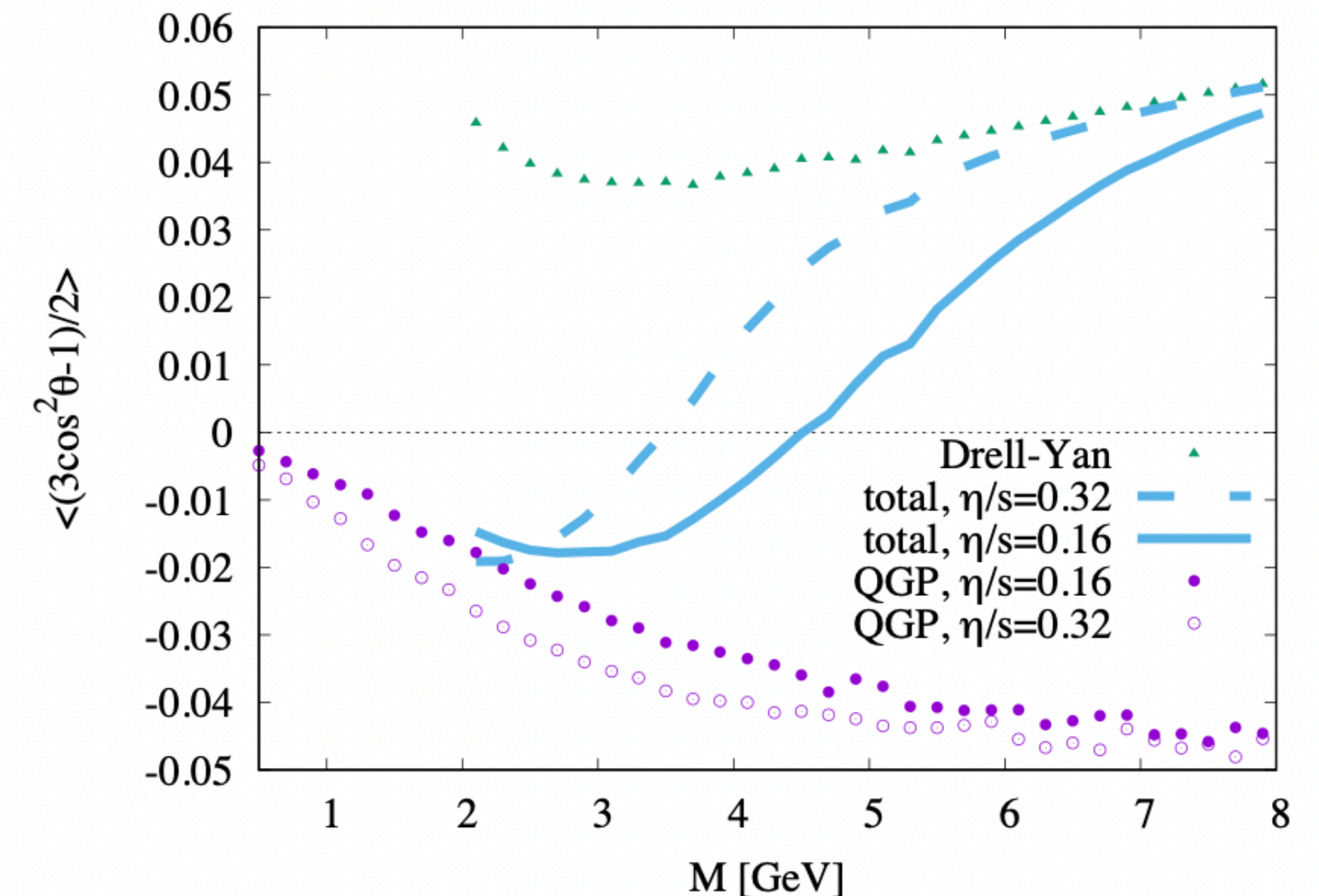
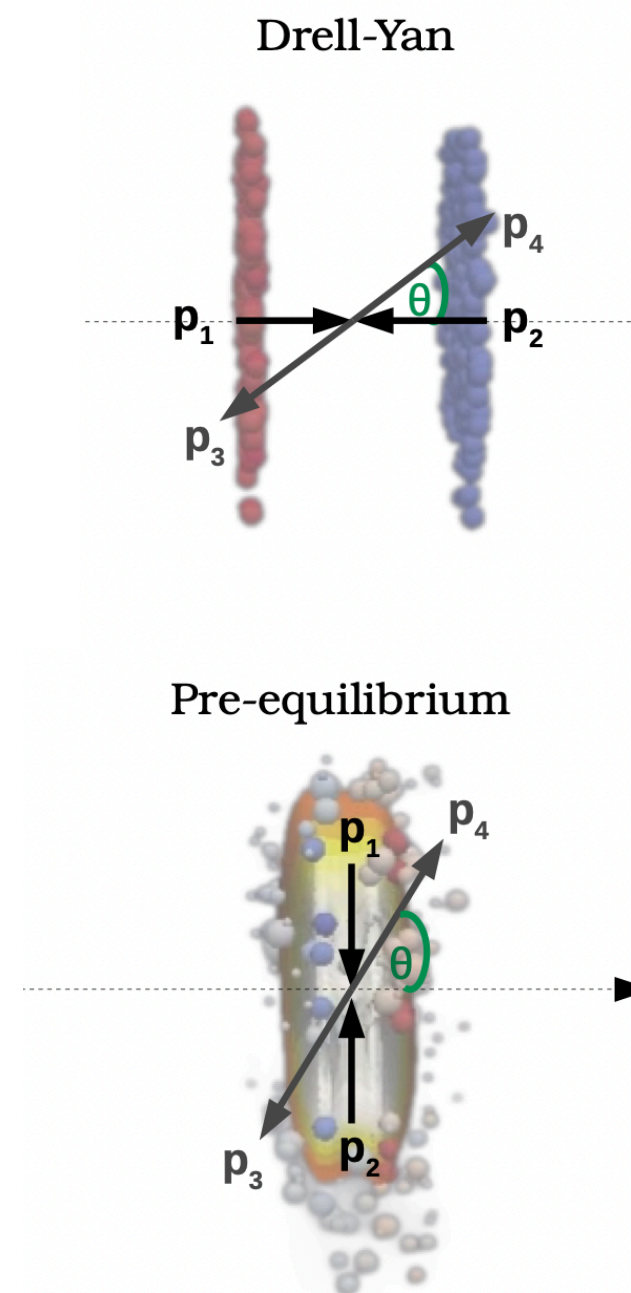
Electromagnetic probes (l^+l^-)

Di-lepton ($e^+e^-/\mu^+\mu^-$) pairs with **invariant mass $\sim$ GeV** pre-dominantly produced from Drell-Yan and during the initial state as late stage production is suppressed

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



Garcia-Montero, Plaschke, *SS Phys.Rev.D* 111 (2025) 3, 034036



Coquet,Du,Ollitrault,SS,Winn; *Phys.Rev.Lett.* 132 (2024) 23, 232301

New window into pre-equilibrium dynamics for $2 \text{ GeV} < M < 4 \text{ GeV}$

Direct probe of QGP anisotropy via polarisation in CS frame

Hard probes and heavy-flavour

Effect on hard probes and heavy flavour being actively explored, naive expectation

Barata, Boguslavski, Lindenbauer, Sadofyev *Phys.Rev.D* 113 (2026) 11, 114009

$$\frac{d\Gamma}{dz}(E, z) = \frac{\alpha_s}{\pi} P_{g \rightarrow gg}(z) \sqrt{\frac{(1 - z(1 - z))\hat{q}}{2z(1 - z)E}}$$

$$\frac{d\Gamma}{dz}(Q_s, z \approx 1/2) \tau_{\text{th}} \sim O(1)$$

$$\frac{d\Gamma}{dz}(E, z) \sim \tau_{\text{th}}^{-1} \frac{P_{gg}(z)}{P_{gg}(1/2)} \sqrt{3Q_s/E}$$

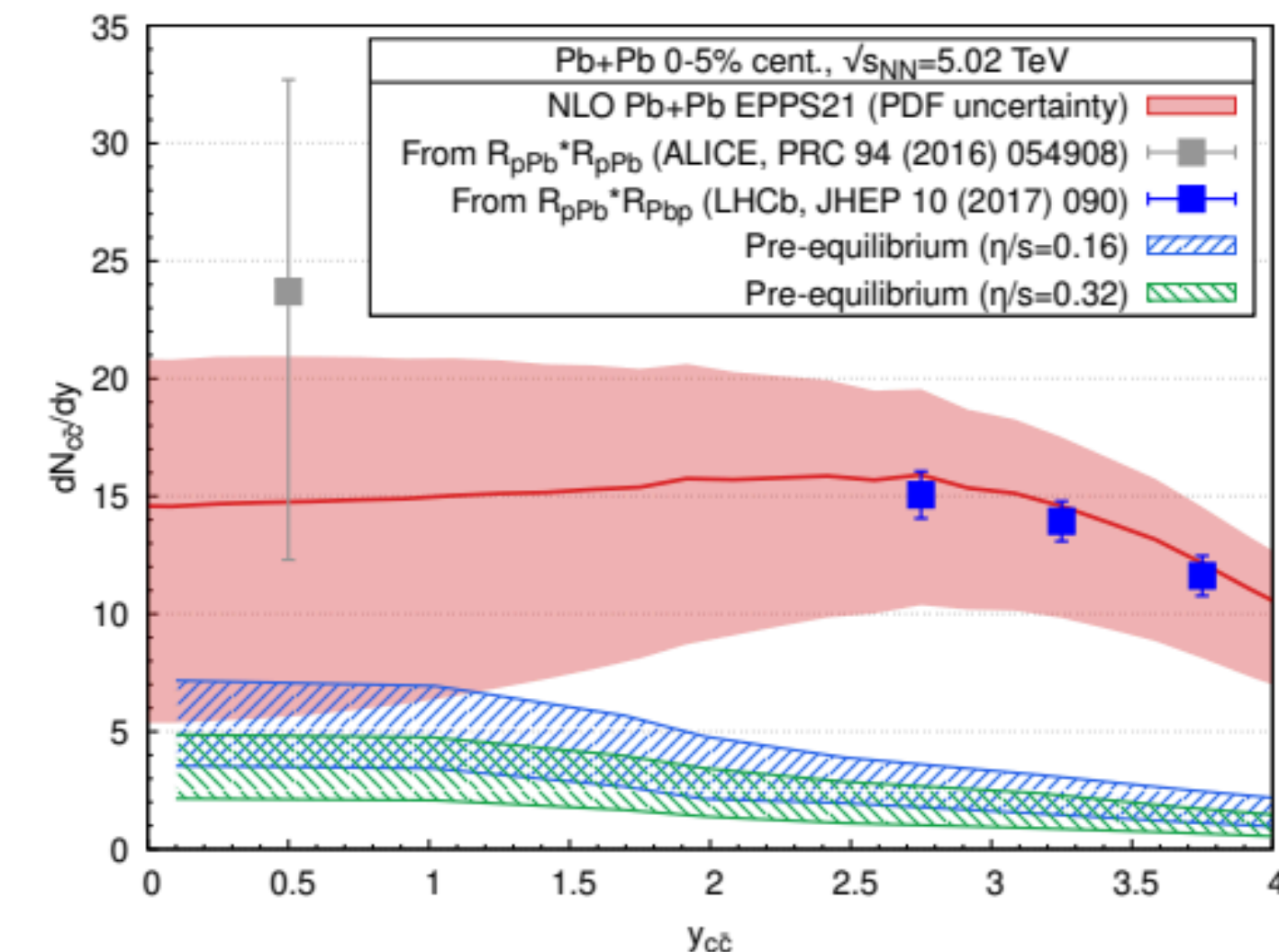
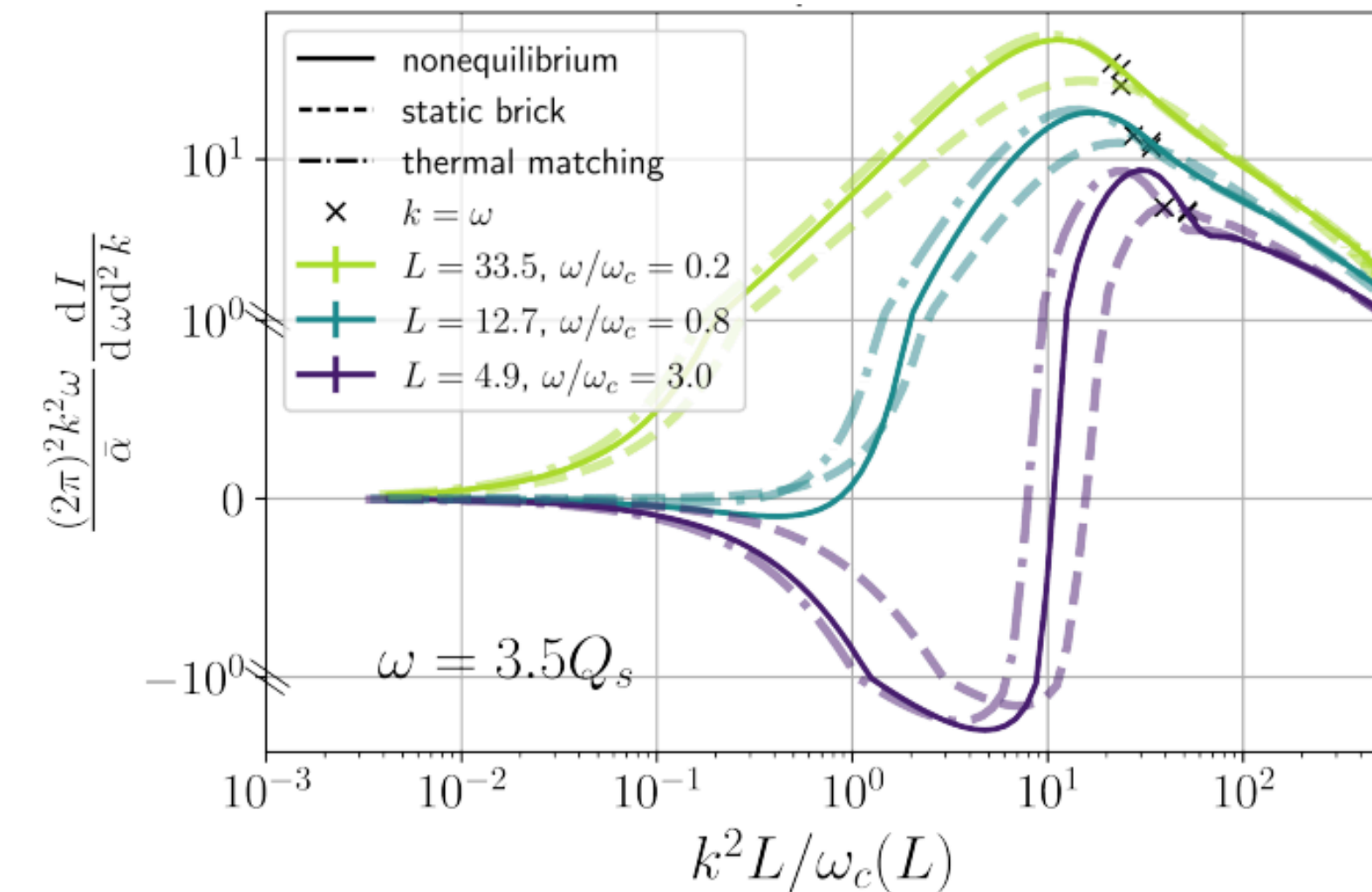
Charm production during the pre-equilibrium stage also possible

Uphoff, Fochler, Xu, Greiner *Phys.Rev.C* 82 (2010) 044906

Coquet, Faure, Spier, SS, Winn *Phys.Lett.B* 881 (2026) 140931

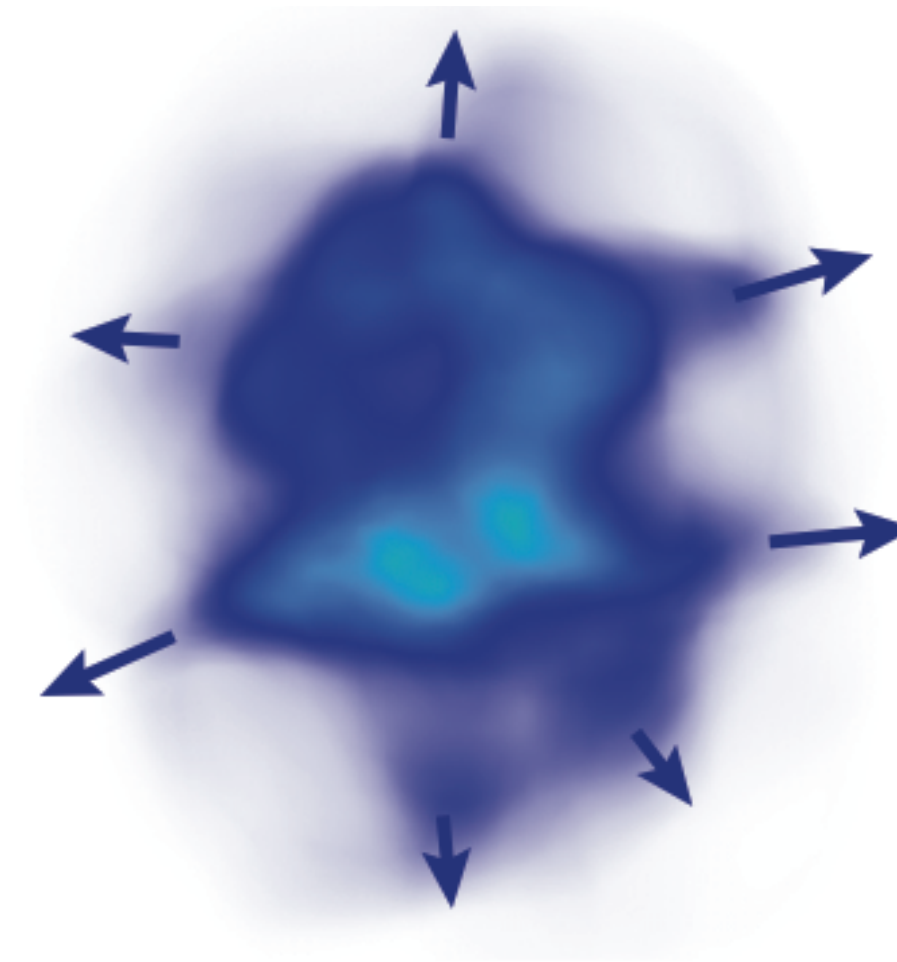
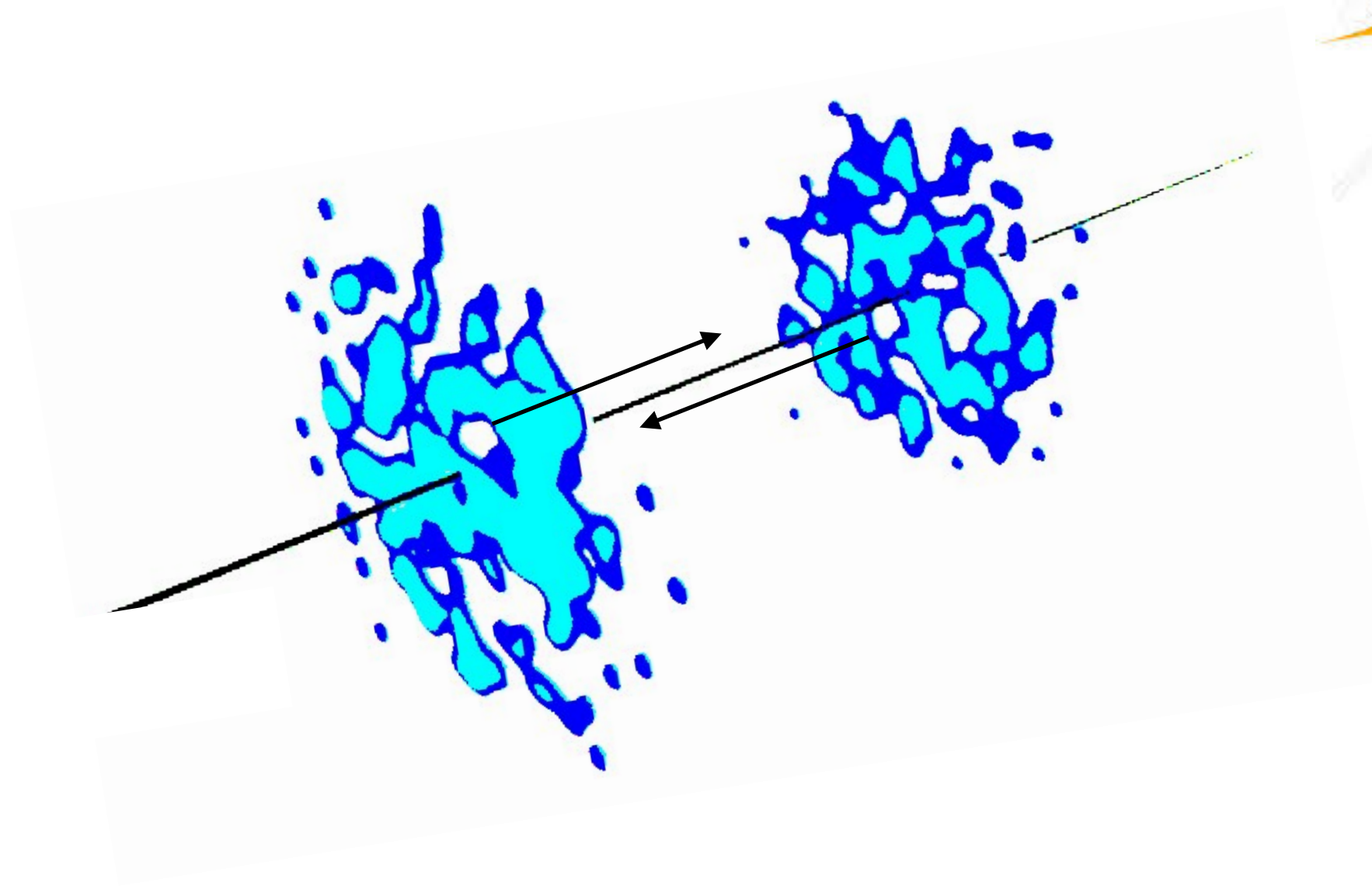
-> Potentially ~10% contribution to total charm cross section

Barata, Boguslavski, Lindenbauer, Sadofyev *Phys.Rev.D* 113 (2026) 11, 114009



Coquet, Faure, Spier, SS, Winn *Phys.Lett.B* 881 (2026) 140931

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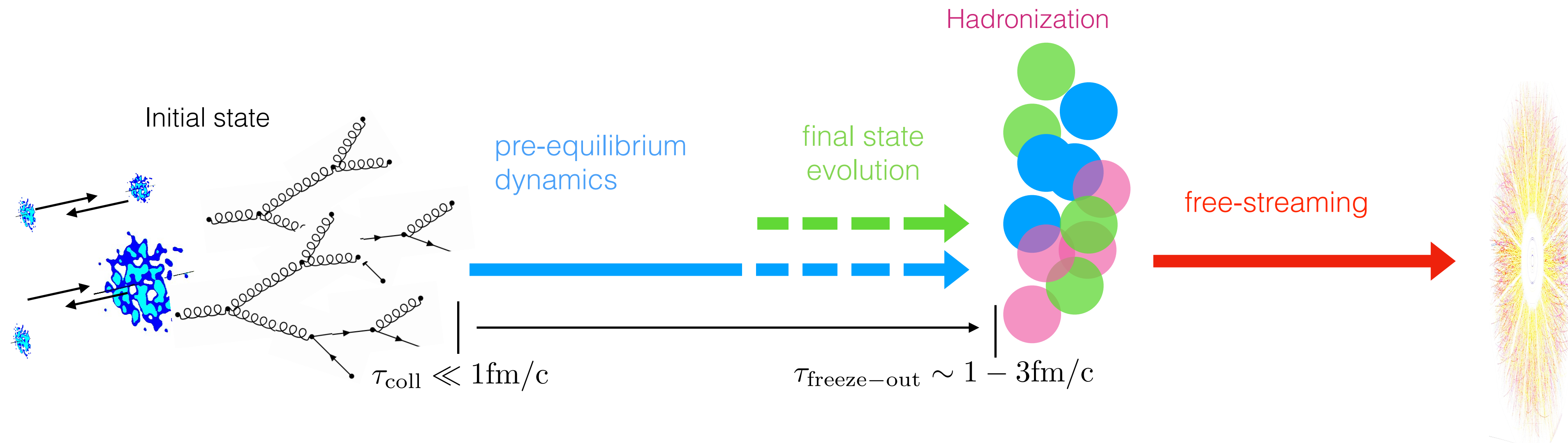


Small system &
development of collective flow

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



What is range of applicability of standard model of HICs applicable?

Can we see its failure in p+p, p/d/He3+A or O+O collisions at RHIC/LHC?

Non-eq description of flow

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

c.f. talks by F. Taghavi; V. Nugara; F. Frasca

meanwhile explored systematically within simplified description in conformal RTA

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

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

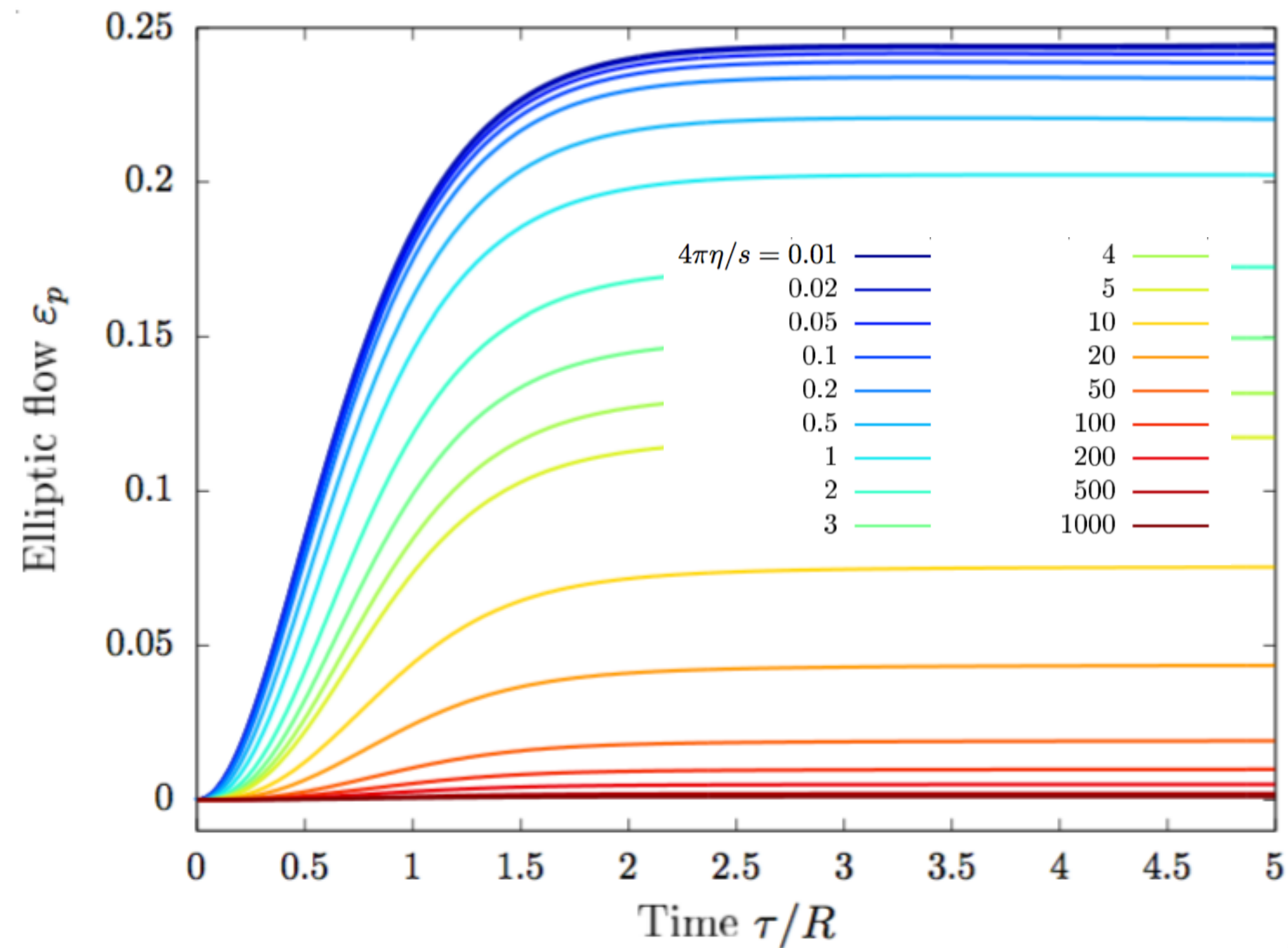
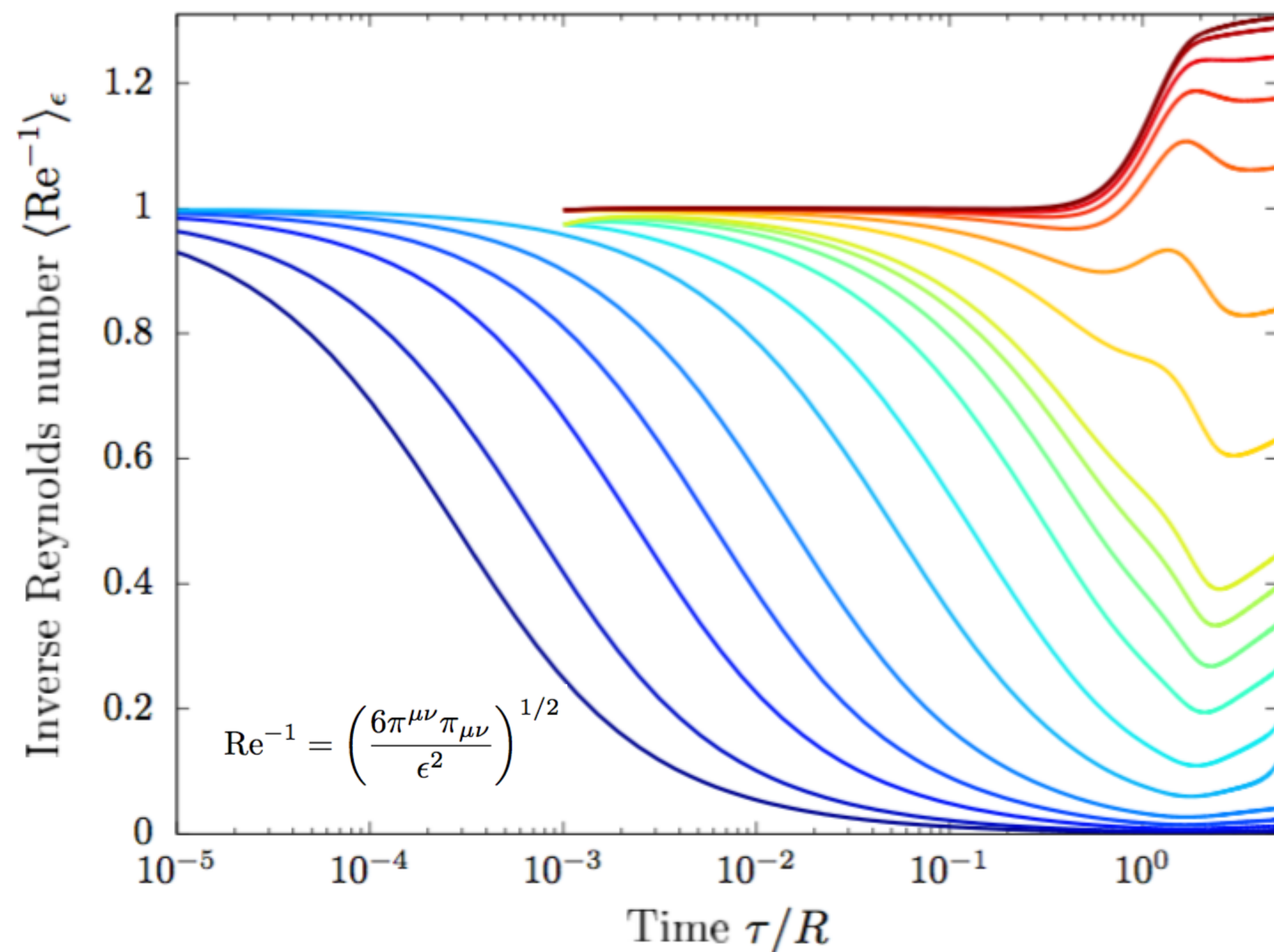
$$\hat{\gamma} = \frac{1}{5\eta/s} \left(\frac{R}{\pi a} \frac{dE_\perp^0}{d\eta} \right)^{1/4},$$

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

Opacity dependence of Flow

Observable: Energy flow e_p can be directly defined in ANY microscopic theory (incl. hydro) to avoid all ambiguities related to hadronization effects

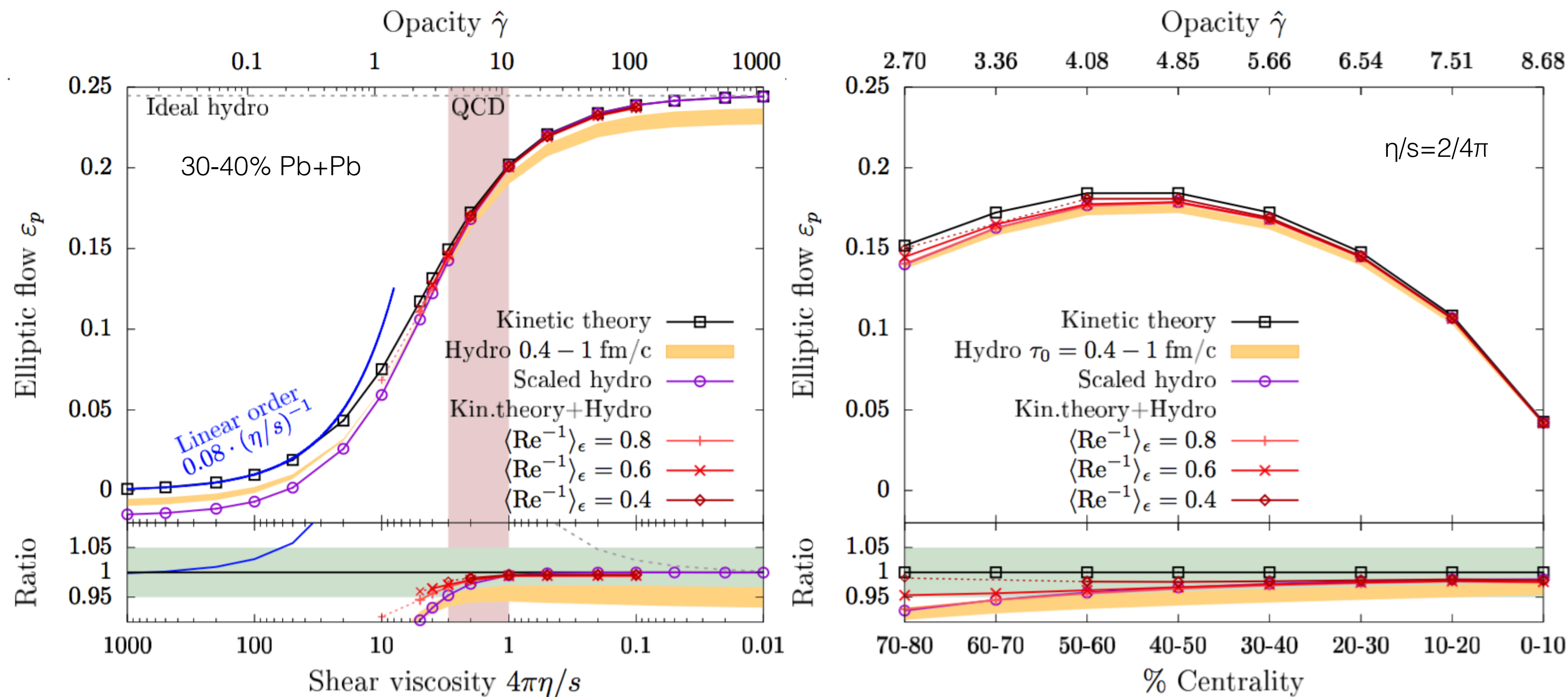


Amrus,SS, Werthmann PRL 130 (2023) 15, 152301; PRD 107 (2023) 9

Despite microscopic differences, smooth transition from non-interacting ($\eta/s \rightarrow \infty$) to strongly interacting limit ($\eta/s \rightarrow 0$)

Opacity dependence of Flow

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



Ambrus,SS, Werthmann PRL 130 (2023) 15, 152301; PRD 107 (2023) 9
Peng, Ambrus, Werthmann, SS, Heinz Phys.Rev.C 113 (2026) 2, 024918

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

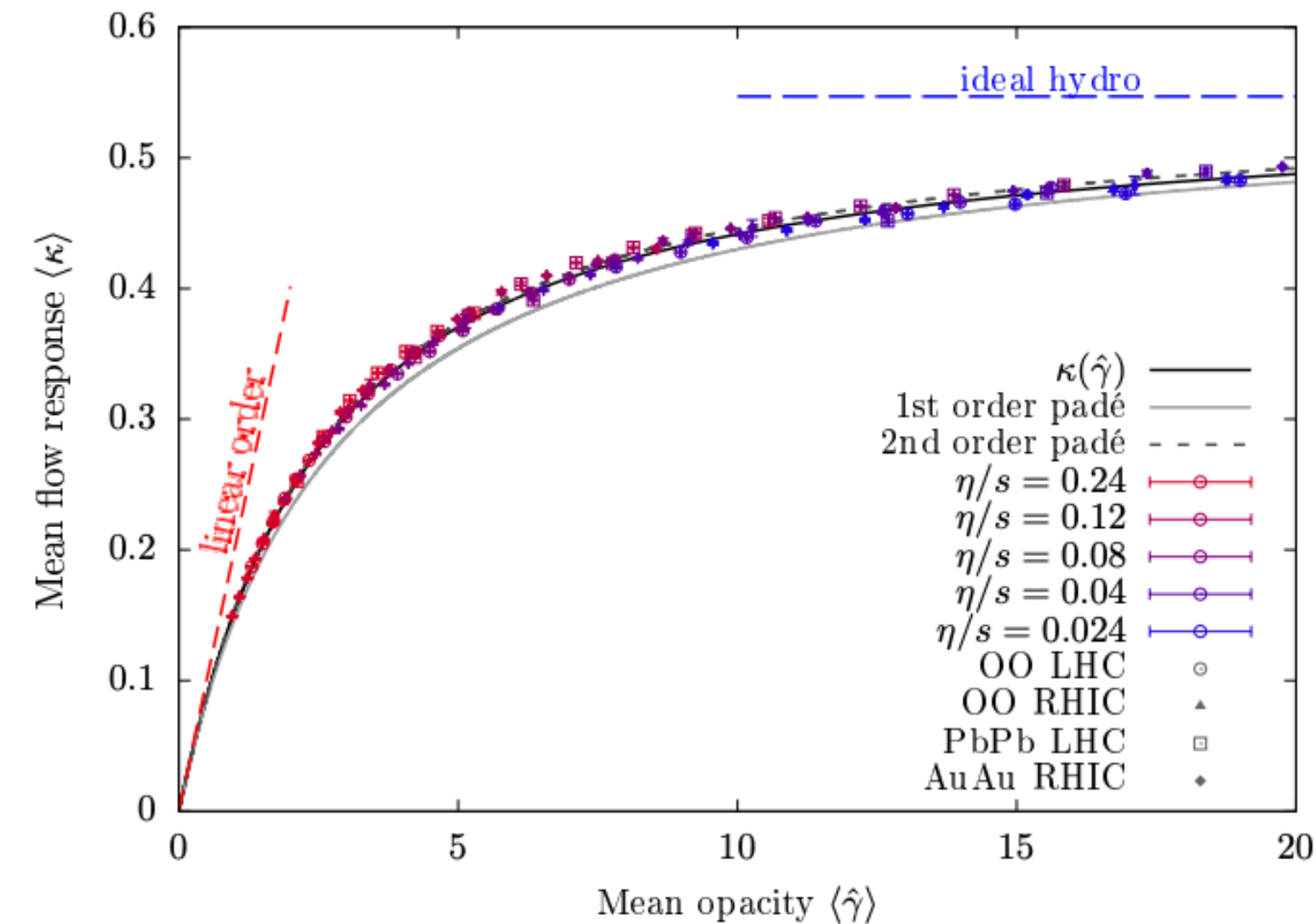
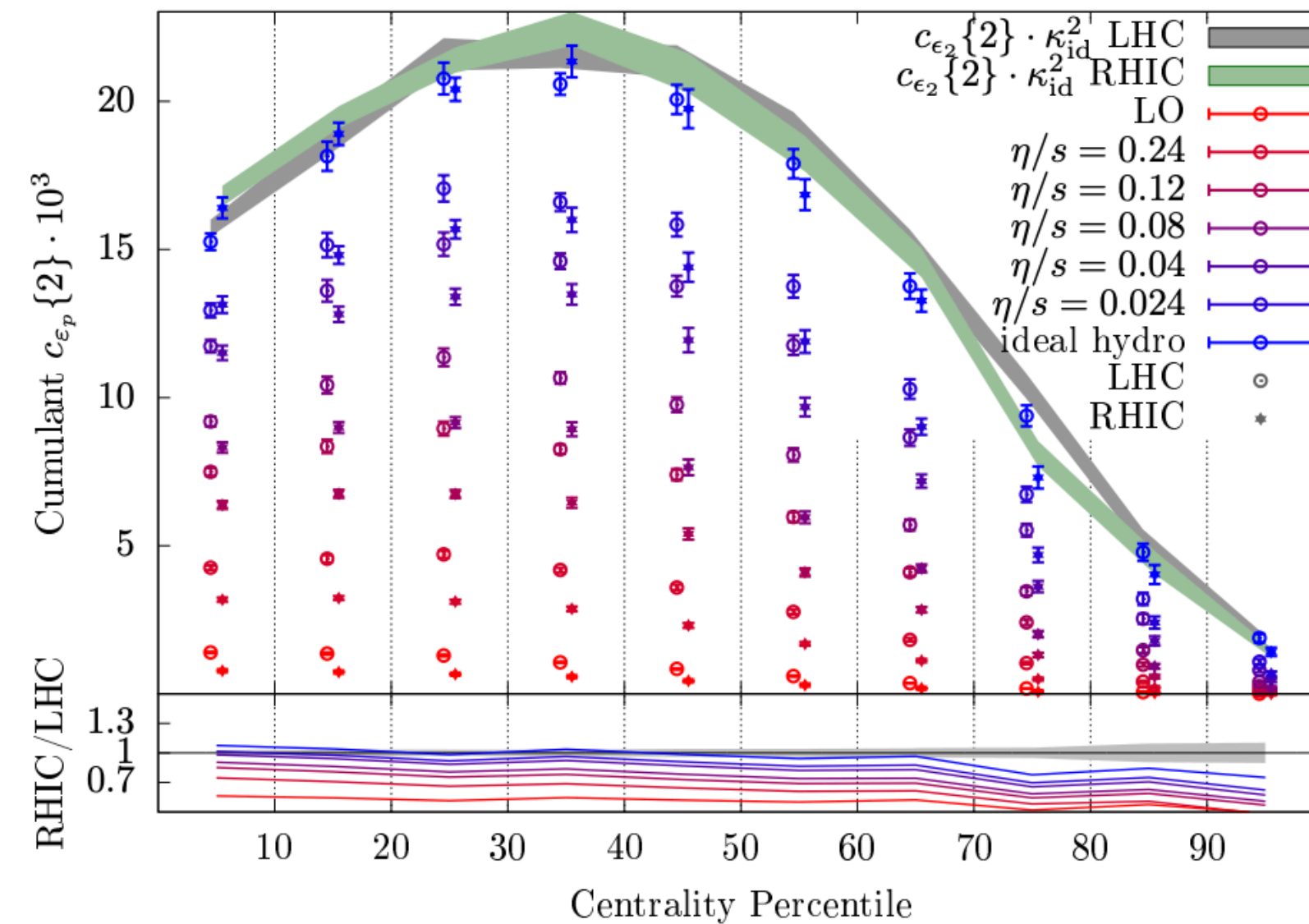
Hydrodynamics breaks slowly for opacities < 3

$$\blacksquare \text{ pp: } \hat{\gamma} \approx 0.88 \left(\frac{\eta/s}{0.16} \right)^{-1} \left(\frac{R}{0.4 \text{ fm}} \right)^{1/4} \left(\frac{dE_{\perp}^{(0)}/d\eta}{5 \text{ GeV}} \right)^{1/4}$$

$$\blacksquare \text{ PbPb: } \hat{\gamma} \approx 9.2 \left(\frac{\eta/s}{0.16} \right)^{-1} \left(\frac{R}{6 \text{ fm}} \right)^{1/4} \left(\frac{dE_{\perp}^{(0)}/d\eta}{4000 \text{ GeV}} \right)^{1/4}$$

expect $\sim 10\%$ errors
(overestimating dissipative effects) for opacities $\sim 1-3$
relevant for O+O

Event-by-event O-O collisions



Elliptic flow determined by **opacity** and **initial eccentricity** $v_2 \simeq K\epsilon_2$

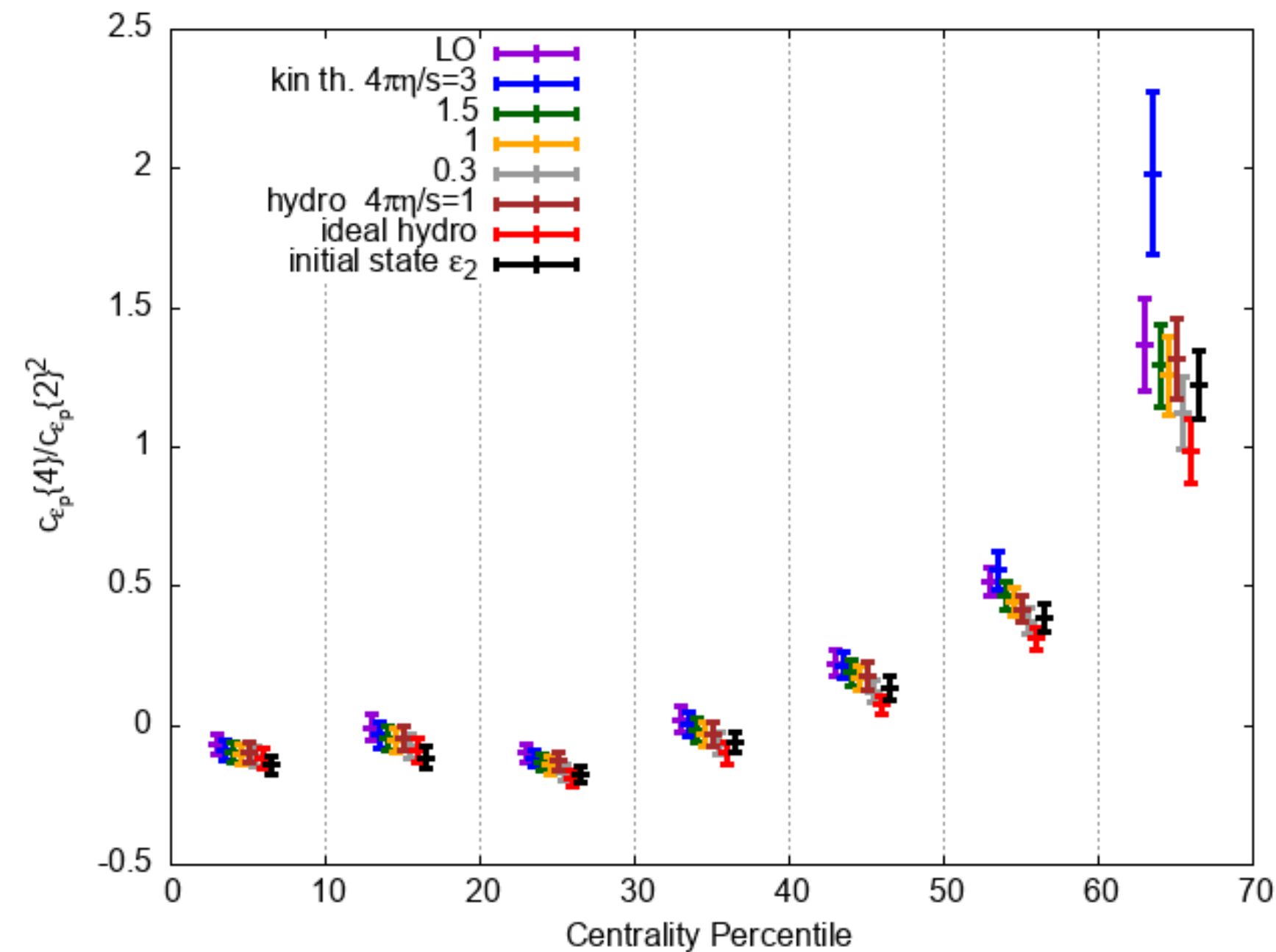
=> Study **initial state geometry** (e.g. nuclear structure) by varying geometry at fixed opacity (e.g. isobars Zr+Zr vs. Ru+Ru)

Study **dynamical response** by varying opacity e.g. simultaneously investigating same system at RHIC and LHC (or LHC and LHC injection energy)

$$\kappa(\hat{\gamma} \ll 1) = \kappa'_0 \hat{\gamma}$$

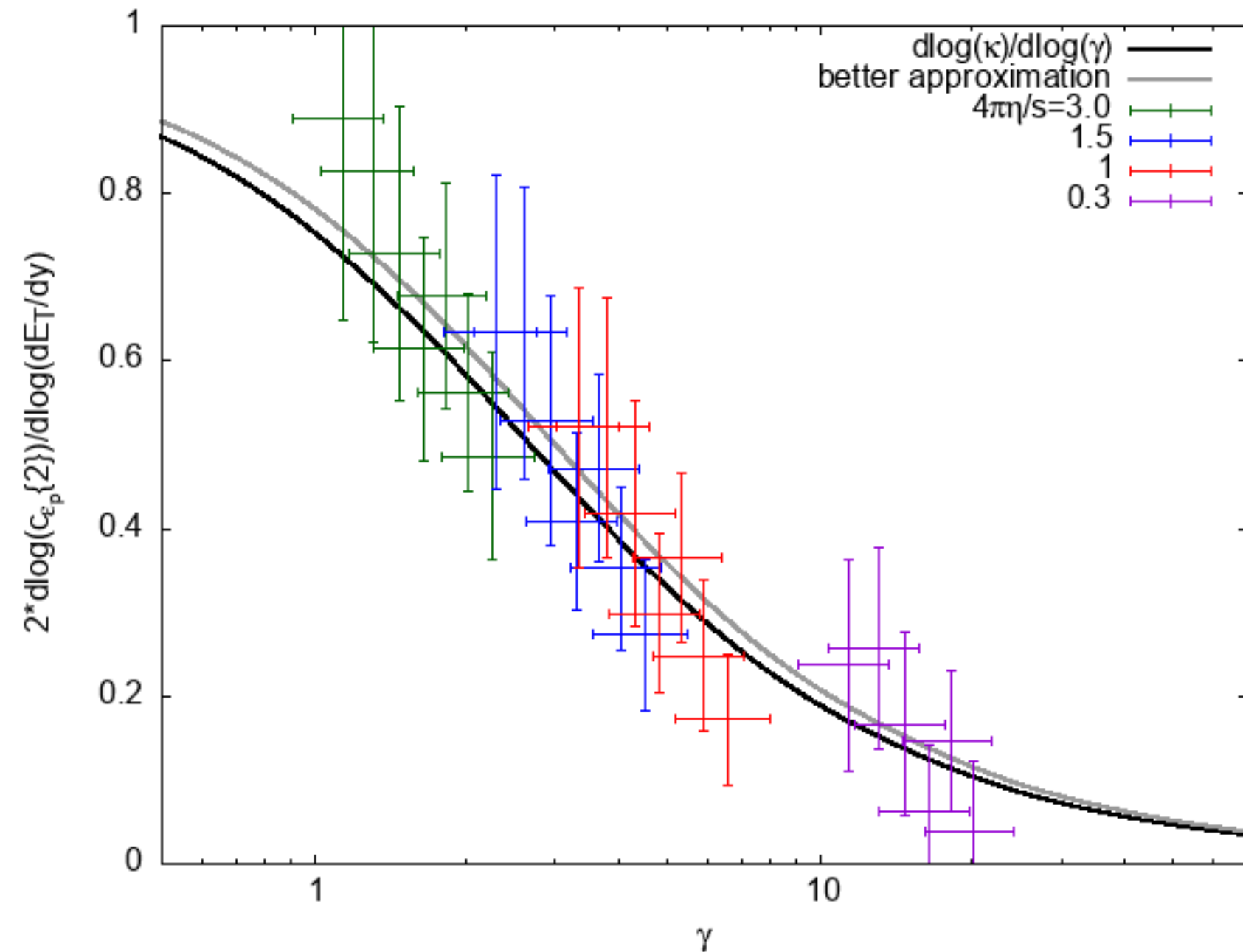
$$\kappa(\hat{\gamma} \gg 1) = \kappa_{Id}$$

Event-by-event O-O collisions



Cumulant ratio of energy flow mostly sensitive to initial state geometry

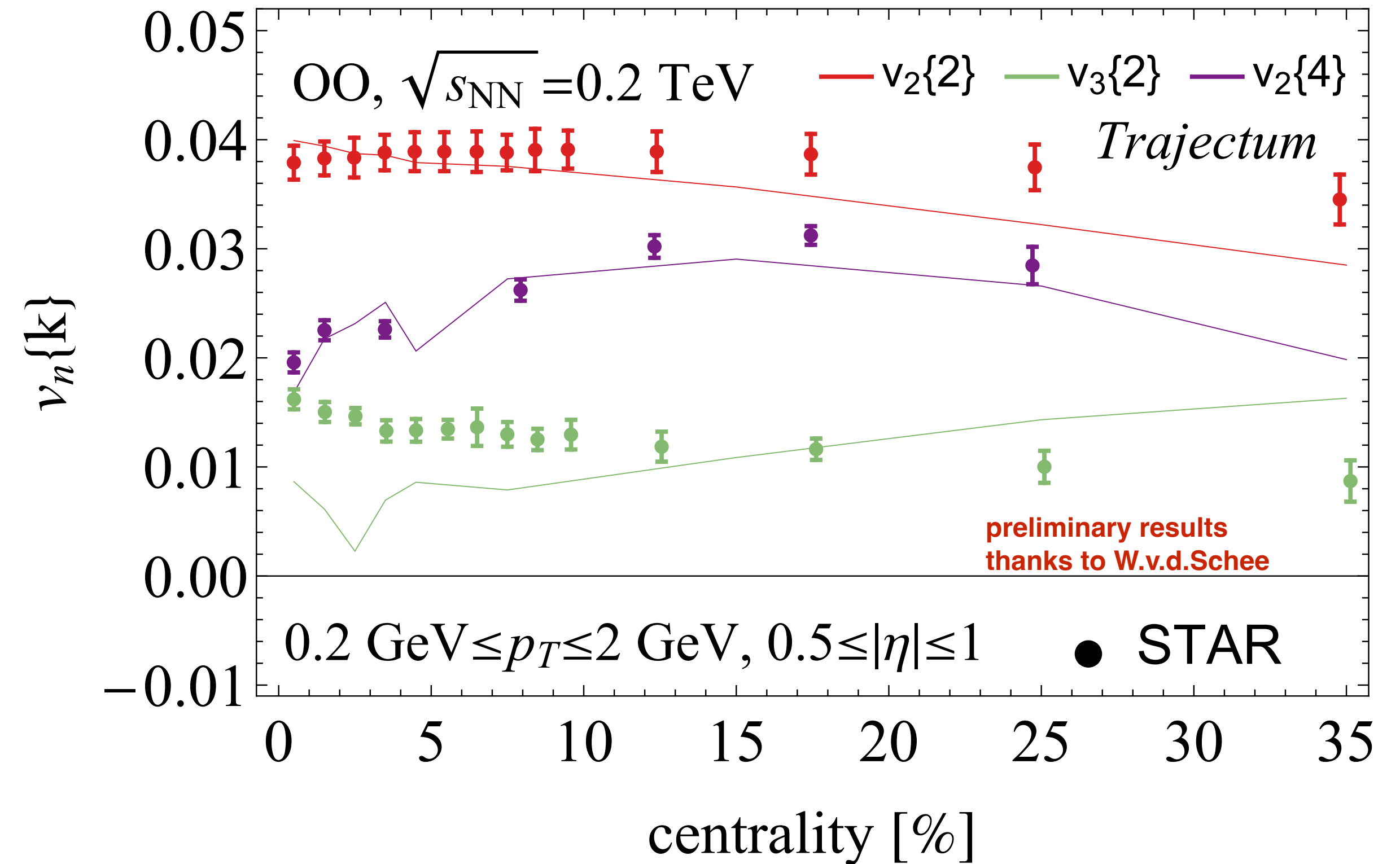
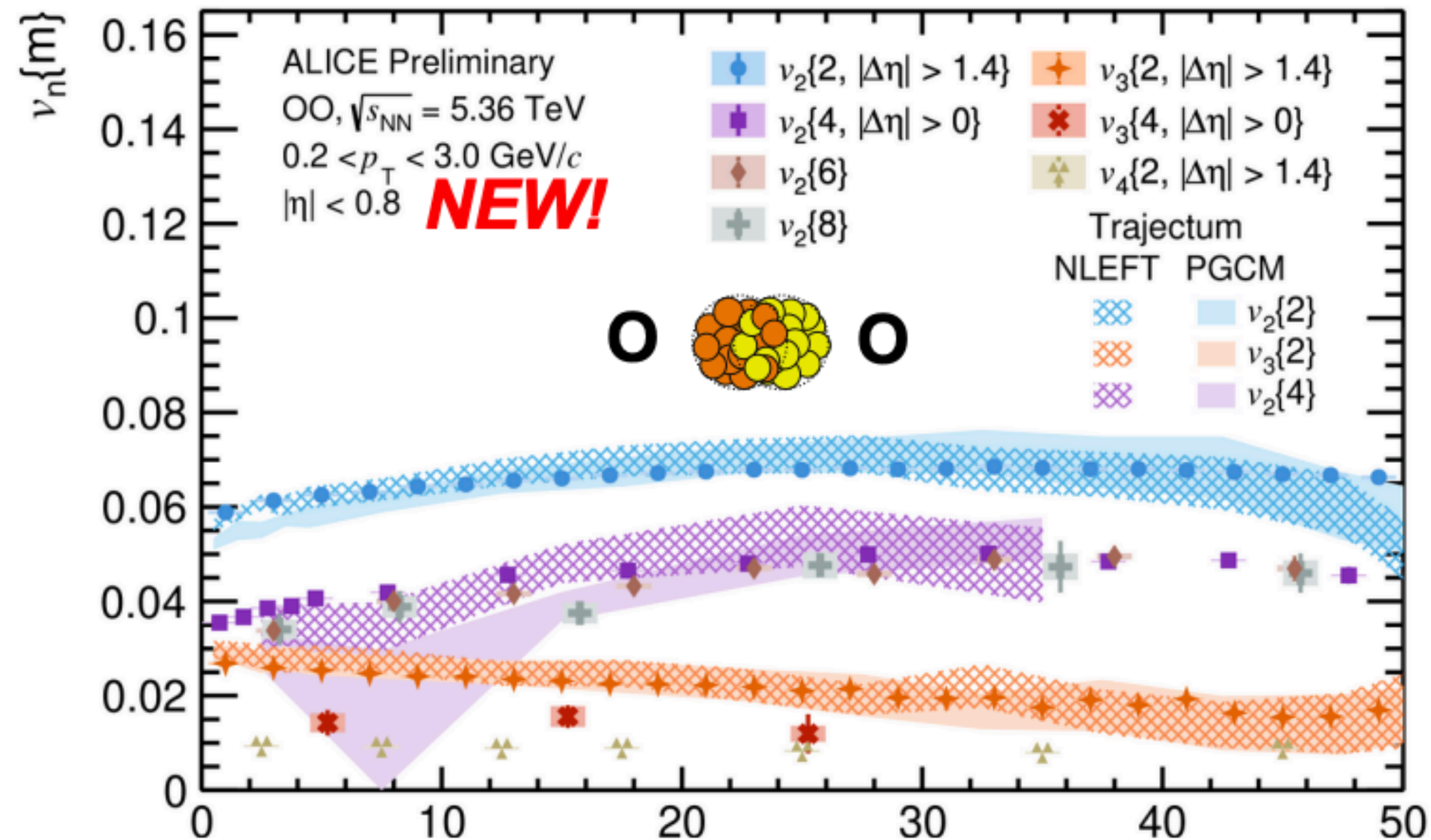
c.f. talk by J. Jia



Change in energy flow between RHIC and LHC density sensitive to change in opacity

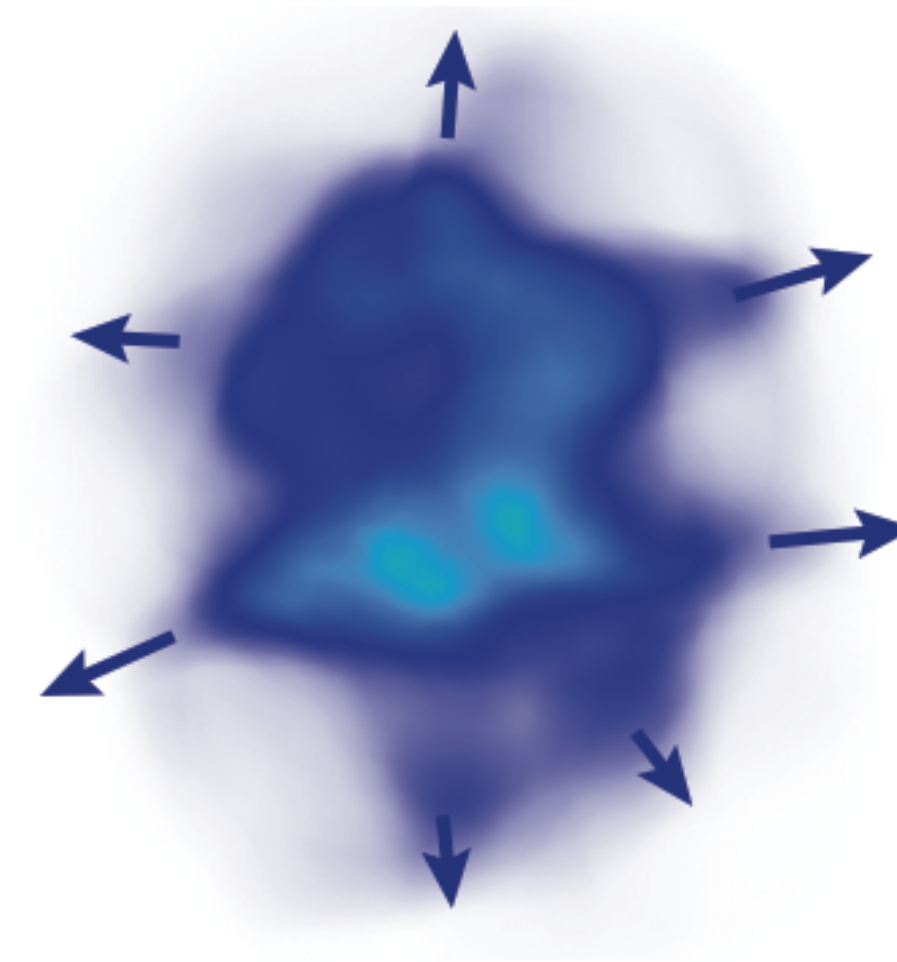
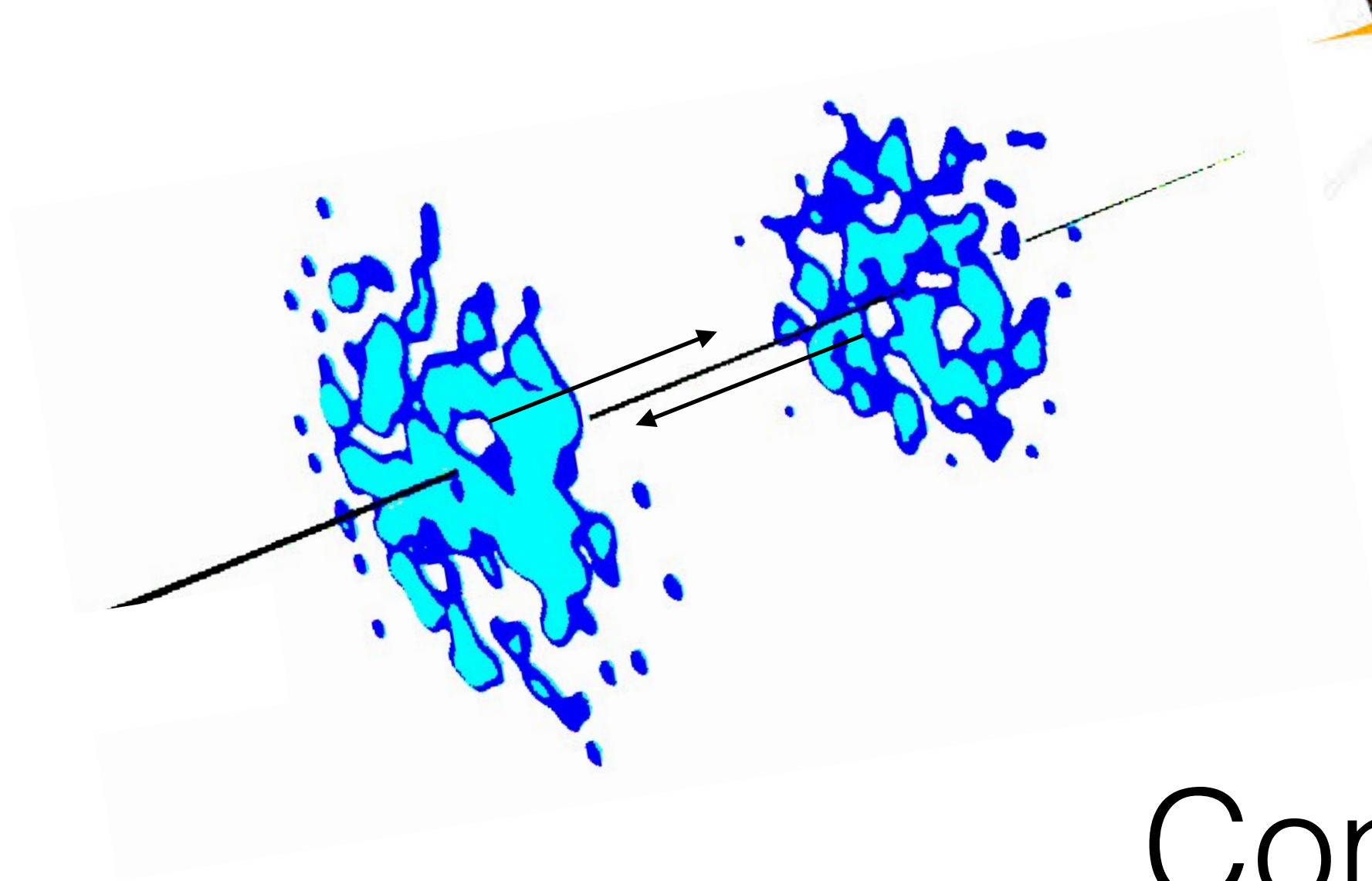
Same system at different energies provides sensitive probe to constrain viscosities and search for tensions with standard hydrodynamic models

Event-by-event O-O collisions



Hydrodynamic predictions in good agreement with central O+O data, but should pay close attention to details as systematic deviations may hint at gradual breakdown of the standard model

4



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

Emerging phenomenology of pre-equilibrium phase

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

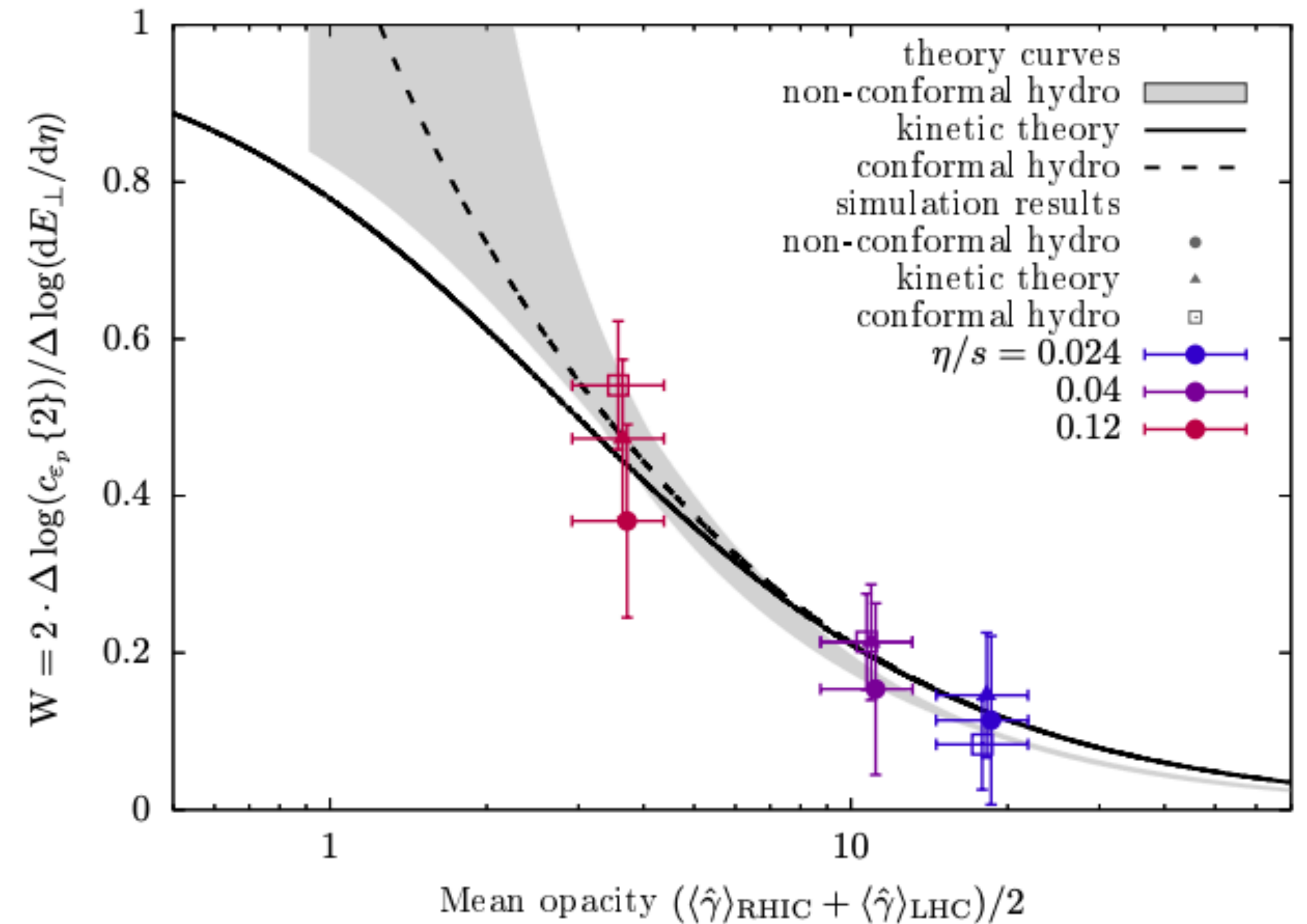
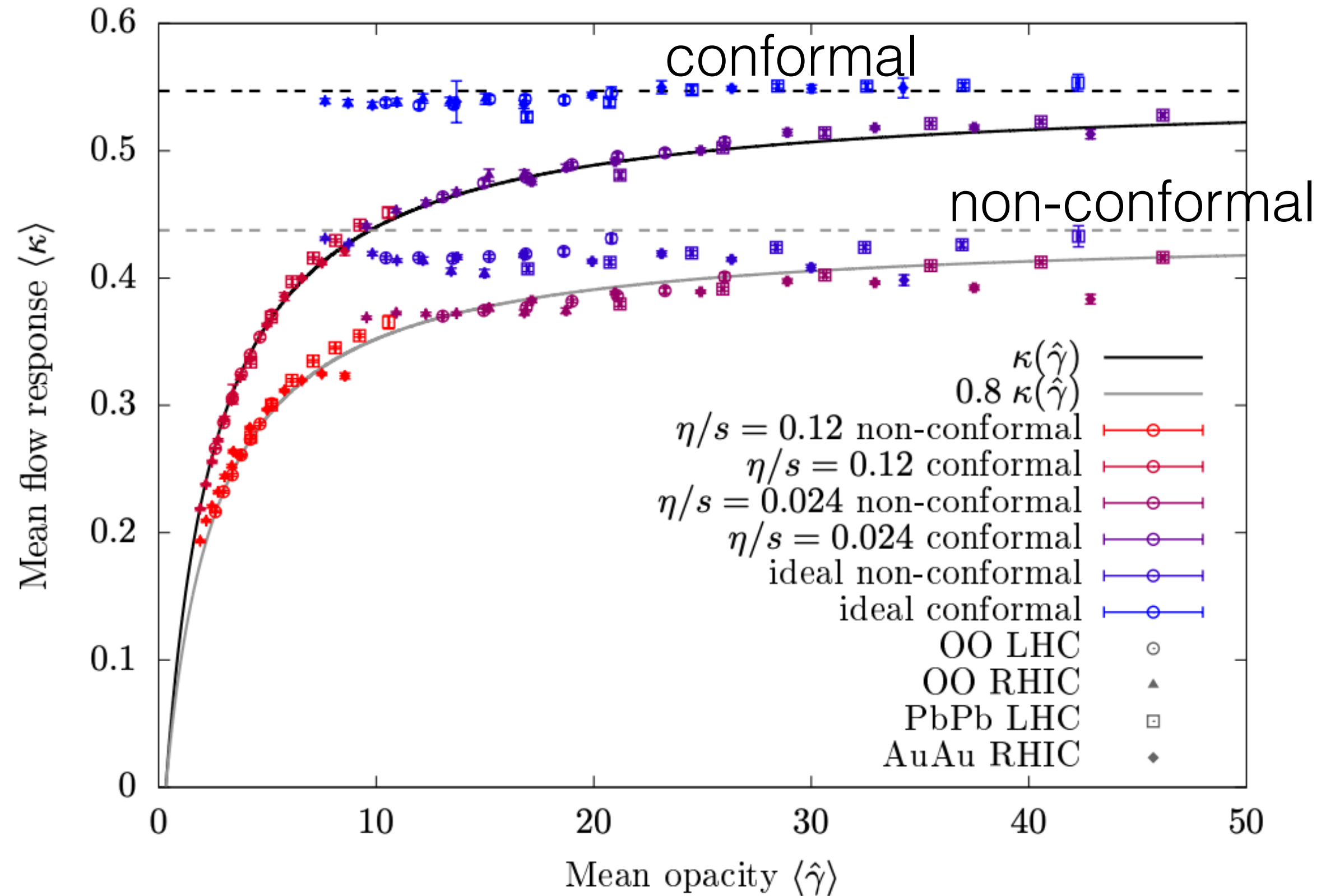
Small systems provide opportunity to explore more features of non-equilibrium QCD

- Same probes as in HICs should be explored theoretically and experimentally

Deviations from hydrodynamic predictions should be taken serious in the search for indications of breakdown of standard model of HICs

- if necessary need to go even smaller (e.g. He+He)

Non-conformal effects



Qualitatively, the change in energy-flow response is still a very sensitive probe of degree of hydrodynamic behaviour