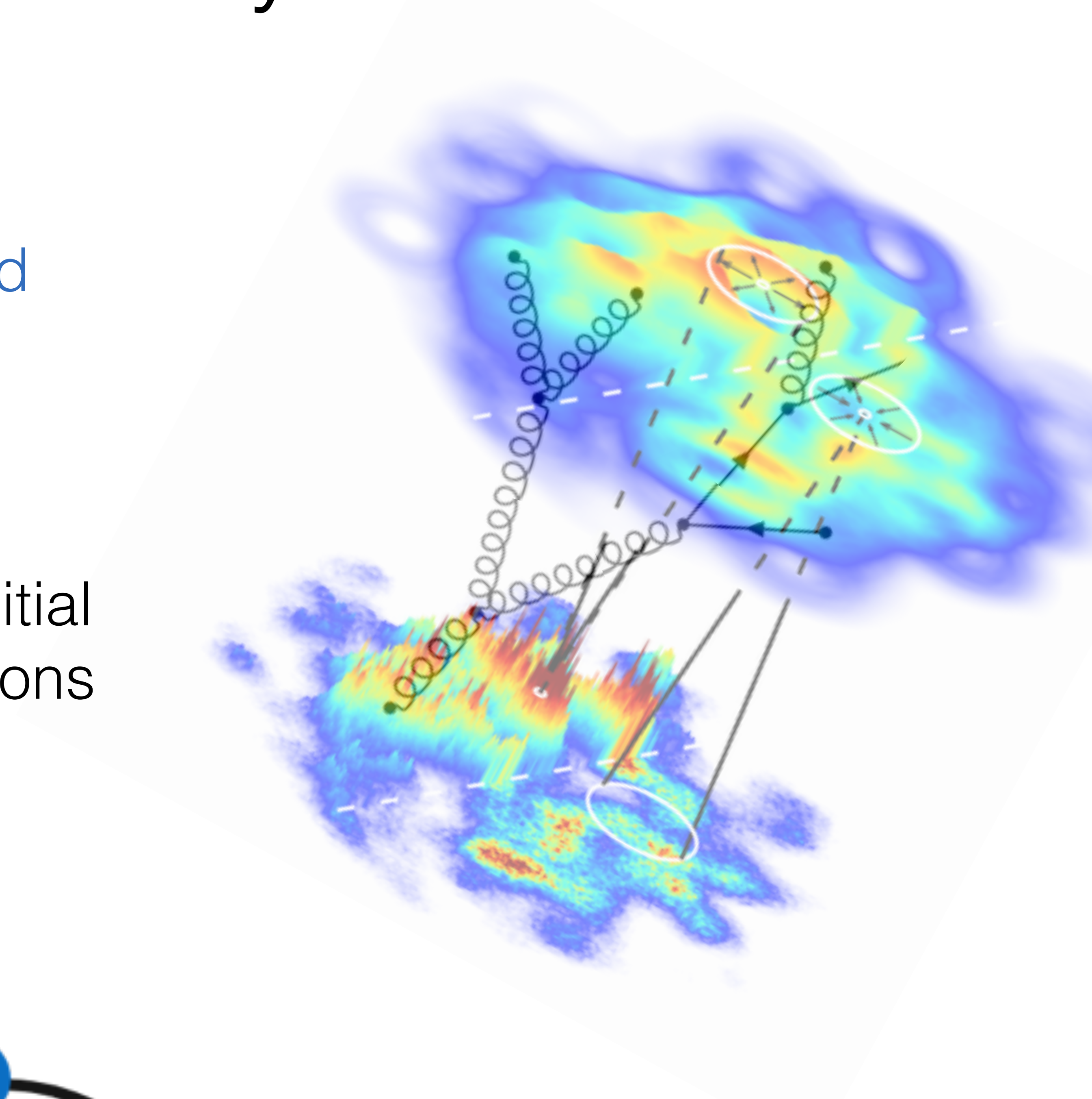
Initial Stages 2019 — Theory Overview

Sören Schlichting | Universität Bielefeld



Initial Stages 2019:
5th International Conference on the Initial Stages in High-Energy Nuclear Collisions

New York City, June 2019

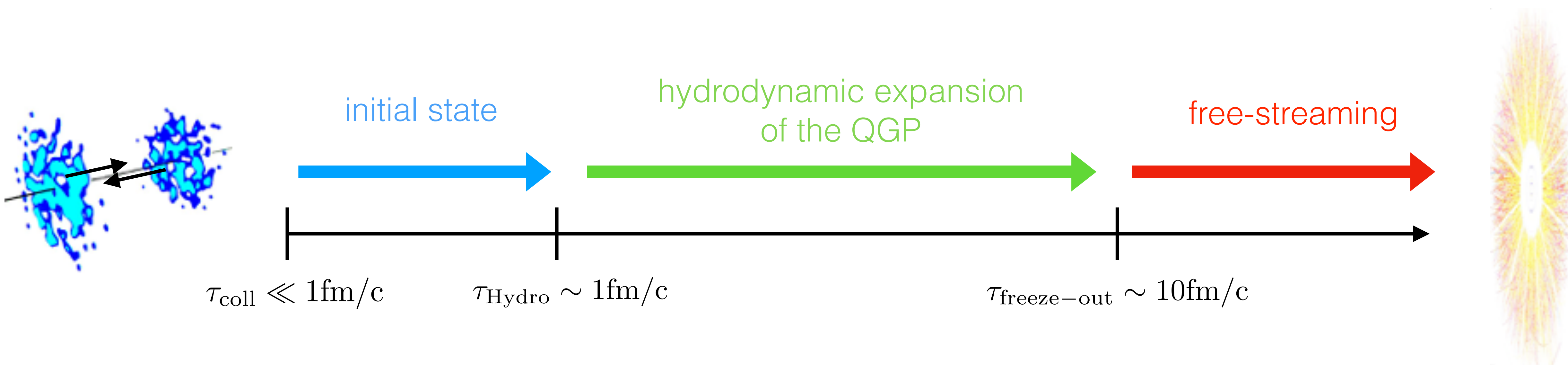
CRC-TR 211
Strong-interaction matter under extreme conditions

UNIVERSITÄT BIELEFELD

General Overview

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 macroscopic description of the space-time dynamics of the QGP

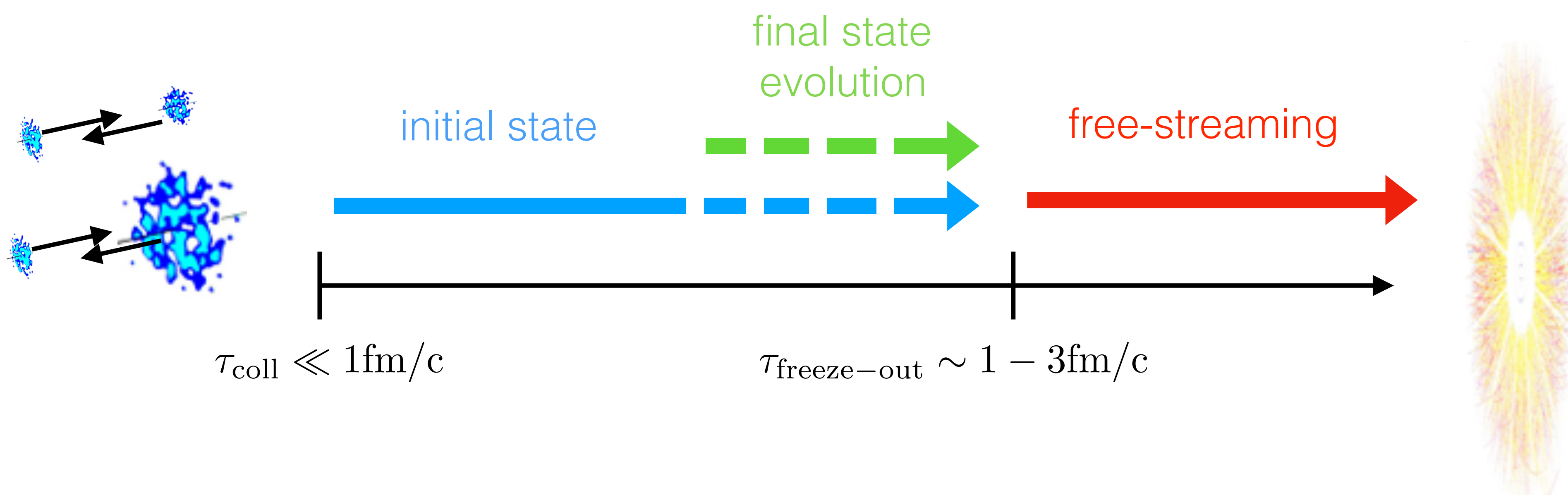


Space-time dynamics (bulk) dominated by hydrodynamics expansion

Description requires knowledge of **macroscopic properties** of initial state (energy momentum tensor $T^{\mu\nu}$, conserved currents J^{μ}) as input for hydrodynamic models

General Overview

New perspective & significant increase of interest in initial state with observation of collective behavior in small systems at RHIC (p/d/He3+A) and LHC (p+p/A)



Shorter life-time of the system (~R) increases sensitivity to initial state and early-time dynamics

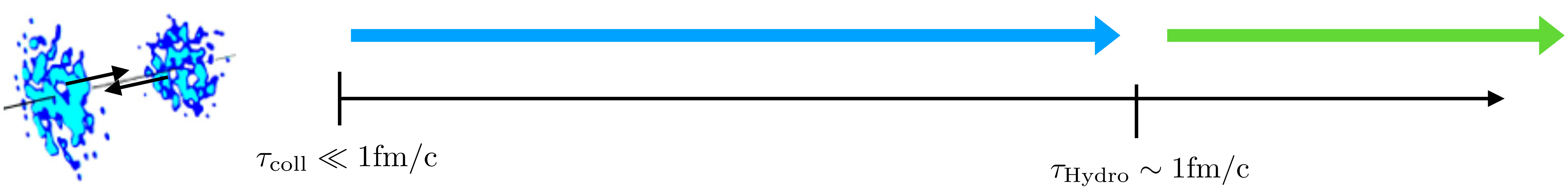
Description may require a more detailed knowledge of **microscopic properties and non-equilibrium dynamics** of initial state

Macroscopic features of initial state

Separation of time scale in high-energy collisions (top RHIC & LHC energies)

Energy deposition

Non-equilibrium evolution towards hydrodynamics



Energy deposition described in terms of different microscopic & phenomenological descriptions

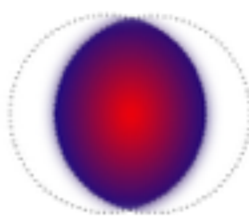
CGC: IP-Glasma, EKRT

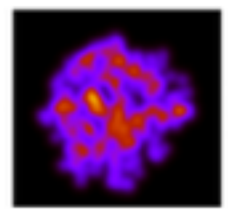
Shockwave collisions in AdS/CFT

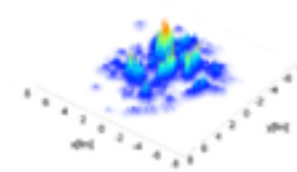
pheno: MC-Glauber, TrENtO, IP-Jazma

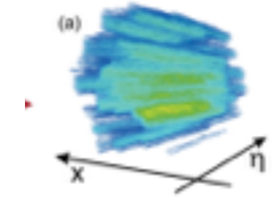
Energy deposition (x_T)

Nucleon positions and their fluctuations dictate the eccentricities ε_n of transverse profiles in A+A collisions


pre 2010

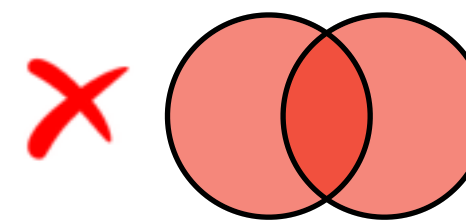

2010


2012



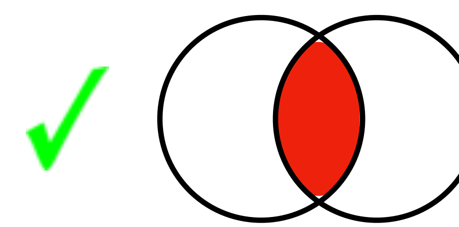
2016

Energy deposition in the transverse overlap area for each N-N collision



IP-Glasma, EKRT $\quad \epsilon(\mathbf{x}_\perp) \propto T_A(\mathbf{x}_\perp) T_B(\mathbf{x}_\perp)$

Schenke, Tribedy, Venugopalan PRC86 (2012) 034908
Niemi,Eskola,Paatalainen, PRC 93 (2016) no.2, 024907



TrENtO (p=0) $\quad s(\mathbf{x}_\perp) \propto T_A^{1/2}(\mathbf{x}_\perp) T_B^{1/2}(\mathbf{x}_\perp)$

Moreland, Bernhard, Bass PRC 92 (2015) no.1, 011901

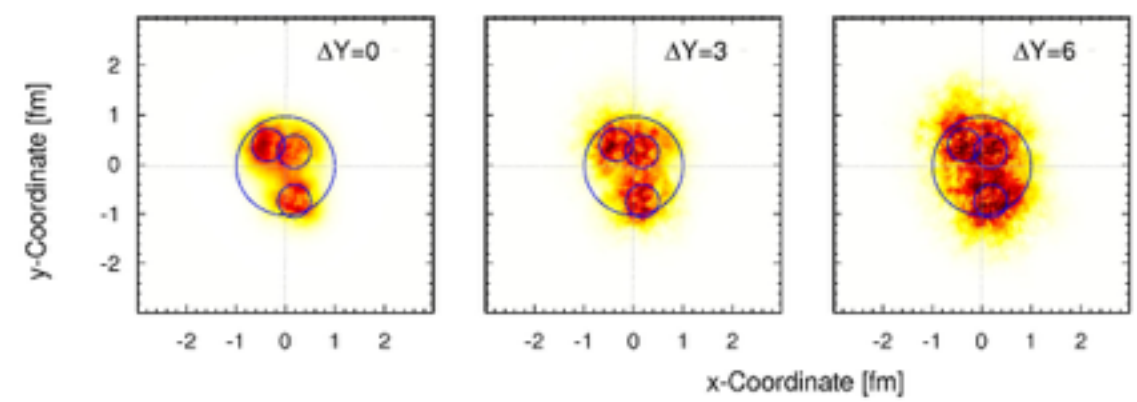
Successful description of experimental data over range of energies and systems

c.f. talks by P. Bozek Tue 16:50, G. Giacalone Tue 18:10; S. Bass Wed 17:30
posters by J. Hammelmann, F. Grassi, M. Hippert

Energy deposition (x_T)

Microscopically spatial distribution of partons in protons/nuclei responsible for x_T dependence

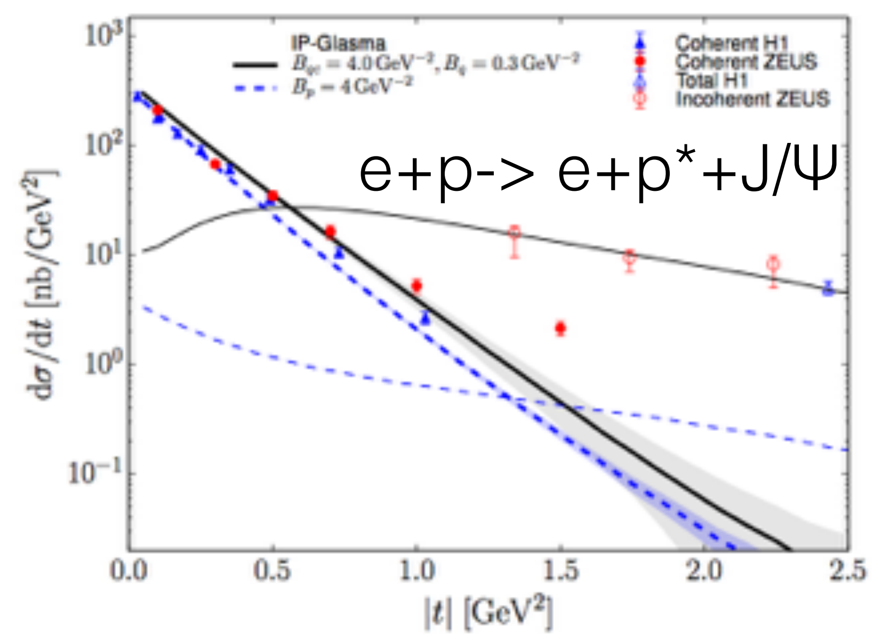
Sub-nucleonic fluctuations play a crucial role for geometry in small systems



Connection to spatial imaging of proton in e+p at EIC

coherent/incoherent diffraction probes spatial dependence/fluctuations of gluon distribution

=> constraints on models of proton structure



Schenke, Mäntysaari
PRL 117 (2016) no.5, 052301

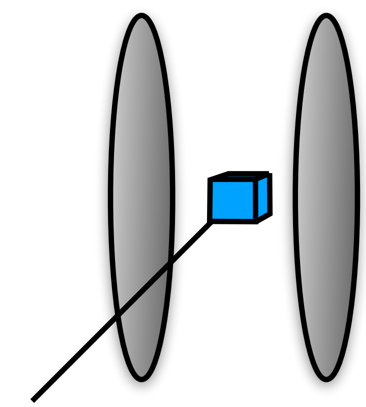
Connections to multi-parton distributions?
Future input from lattice QCD calculations of hadronic structure”

c.f. talks by A. Dumitru Tue 09:45, H. Mäntysaari Wed 11:15, J.H. Lee Thu 16:30

Non-equilibrium towards hydrodynamics

Evolution of homogenous (x_T) boost invariant (η) systems studied based on different microscopic descriptions

QCD Kinetic theory
boost invariant holography AdS/CFT
Boltzmann RTA



Similar macroscopic features

$$T^{\mu\nu} = \mathrm{diag}(e, p_T, p_T, p_L)$$

memory loss about details of initial conditions

non-equilibrium attractor

viscous hydrodynamics

local thermal equilibrium

$\tau_{\mathrm{Hydro}} \sim 1\mathrm{fm/c}$

pre-thermalization

hydrodynamization

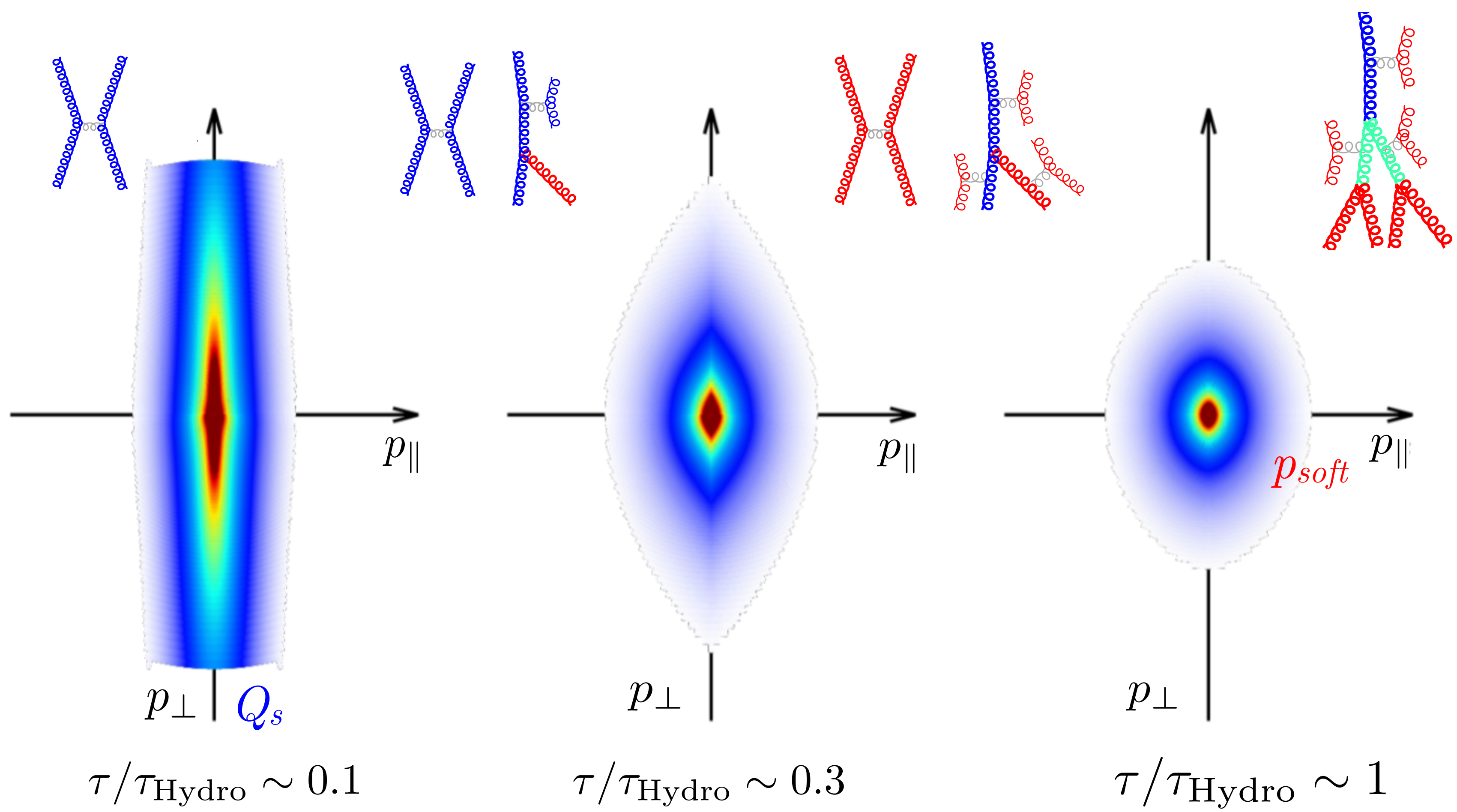
kinetic equilibration

Non-equilibrium towards hydrodynamics

Evolution of homogenous boost invariant system in QCD kinetic theory

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

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



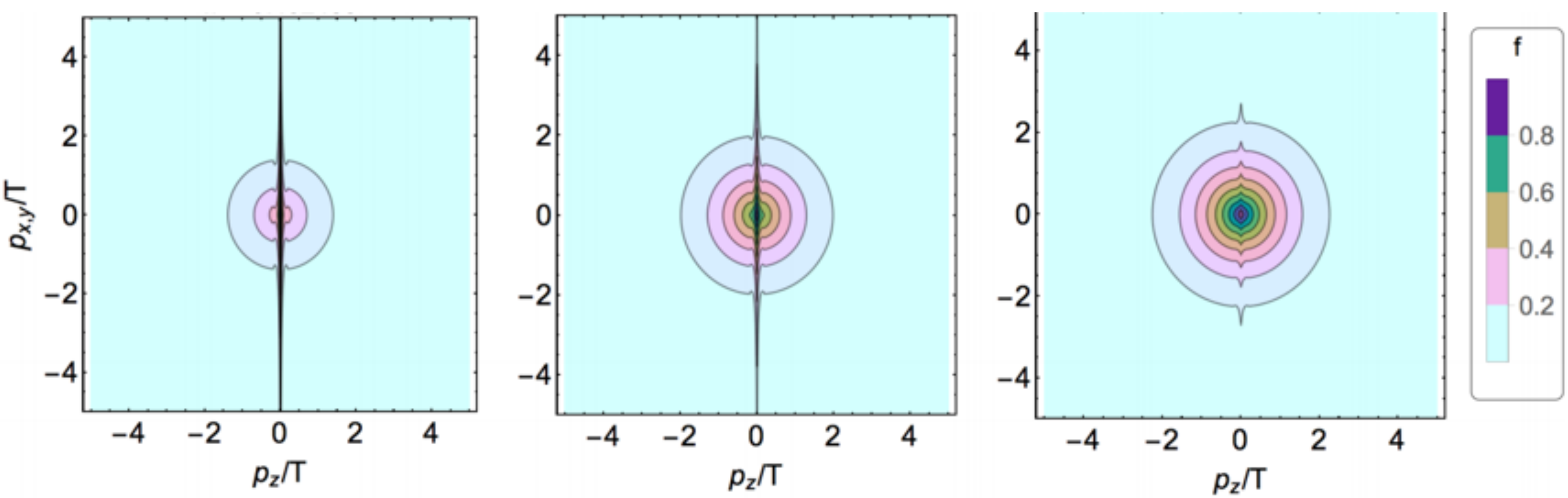
Kinetic equilibration ``bottom-up" via radiative break-up

Non-equilibrium towards hydrodynamics

Evolution of homogenous boost invariant system in Boltzmann RTA

M. Strickland JHEP 1812 (2018) 128

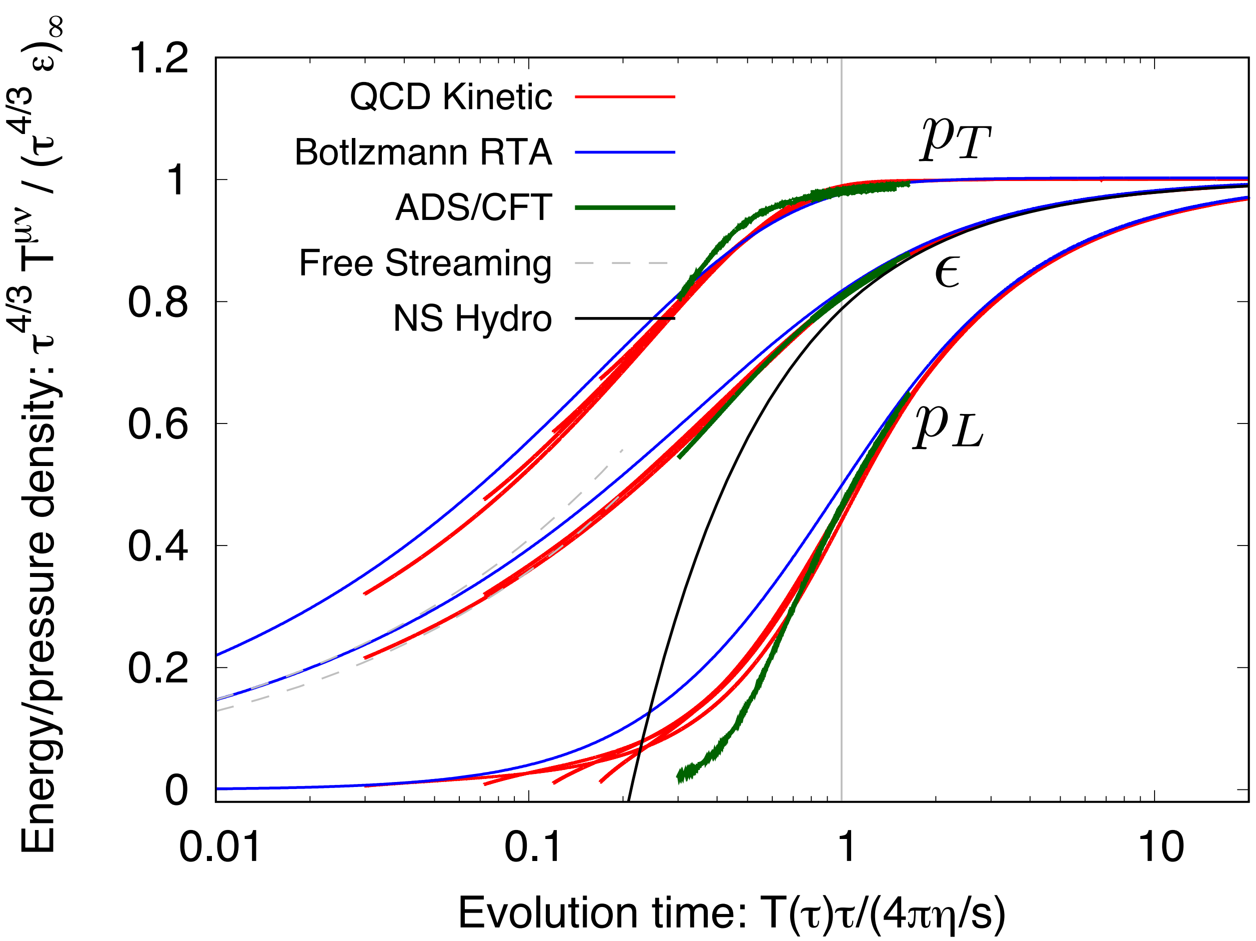
$$p^\mu \partial_\mu f(x,p) = -\frac{p^\mu u_\mu(x)}{\tau_R(x)}\Big[f(x,p) - f_{\rm eq}(x,p)\Big]$$



$\tau/\tau_{\rm Hydro} \sim 0.16$ $\tau/\tau_{\rm Hydro} \sim 0.4$ $\tau/\tau_{\rm Hydro} \sim 0.9$

Energy ($T^{\tau\tau}$) & pressure (T^{ii}) evolution

Despite microscopic differences evolution of average components of energy-momentum tensor remarkably similar



Early times:
Strongly anisotropic
& dominated by long. expansion

Intermediate times:
Effective memory loss and
onset of Isotropization

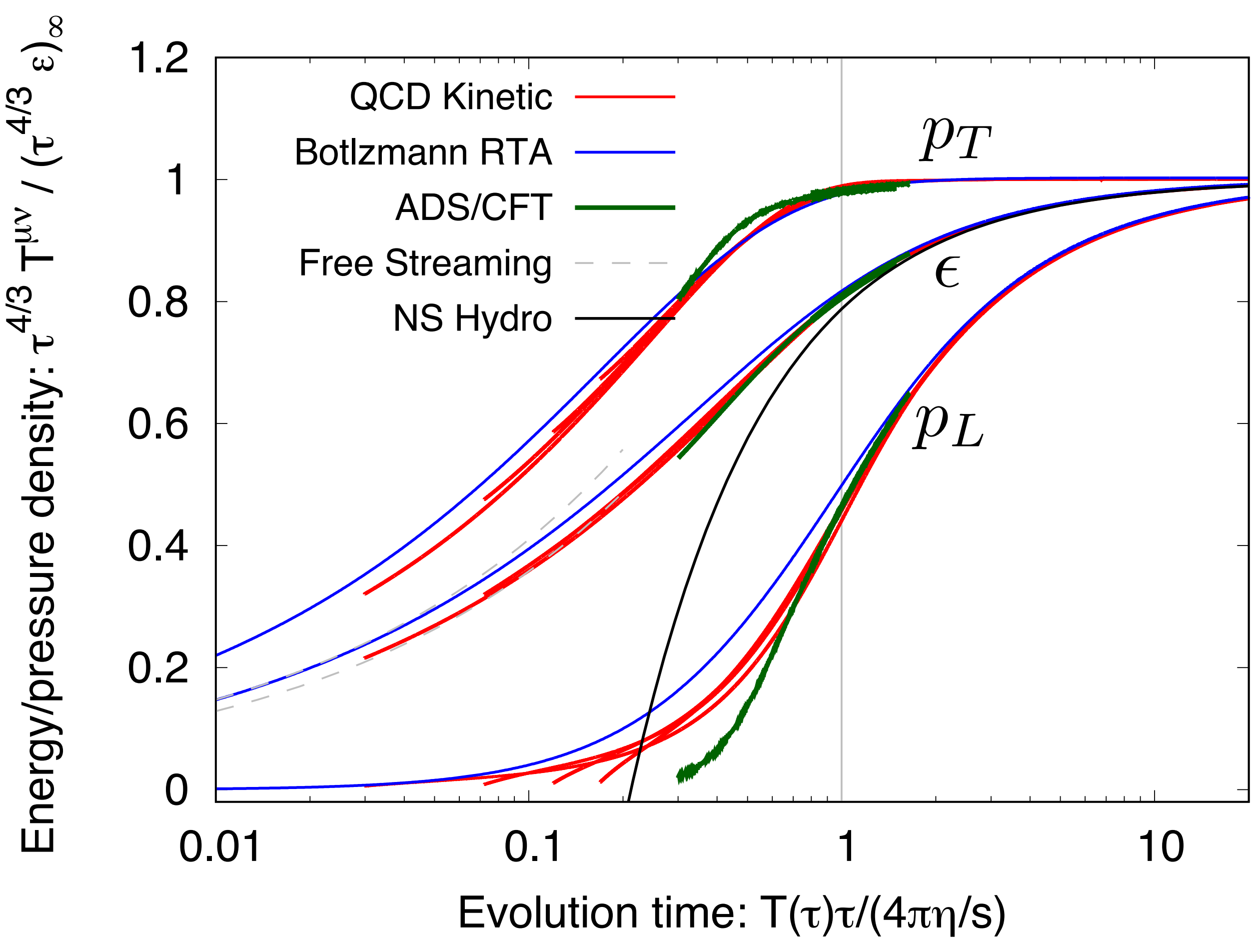
c.f. talks by J. Berges Tue 10:45, A. Mazeliauskas Tue 11:15
M. Heller Tue 11:45

Non-universality of non-equilibrium attractors:
Different transient dynamics for different microscopic descriptions

c.f. talks by J. Noronha Tue 13:30, D. Almaalol Tue 15:10, G. Denicol Tue 16:30
posters by H. Shi

Energy ($T^{\tau\tau}$) & pressure (T^{ii}) evolution

Eventually different non-equilibrium attractors match onto the universal hydrodynamics



Different microscopic descriptions suggest that viscous hydrodynamics becomes applicable on time scales

$$\tau/\tau_R^{\rm eq}(\tau) \approx 1 \qquad \tau_R^{\rm eq}(\tau) = \frac{4\pi\eta/s}{T_{\rm eff}(\tau)}$$

when Knudsen number Kn~1 and system is out-of-equilibrium

Hydrodynamization (≠ kinetic thermalization) time in A+A collisions

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

Pre-flow ($T^{\tau i}$) & Viscous corrections (T^{ij})

Gradients in x_T induce off-diagonal components of $T^{\mu\nu}$

Universal pre-flow: early expansion of matter insensitive to microscopic details

Pratt, Vredevoogd PRC79 (2009) 044915
Kurkela, Mazeliauskas, Paquet, SS, Teaney PRC 99 (2019) no.3, 034910

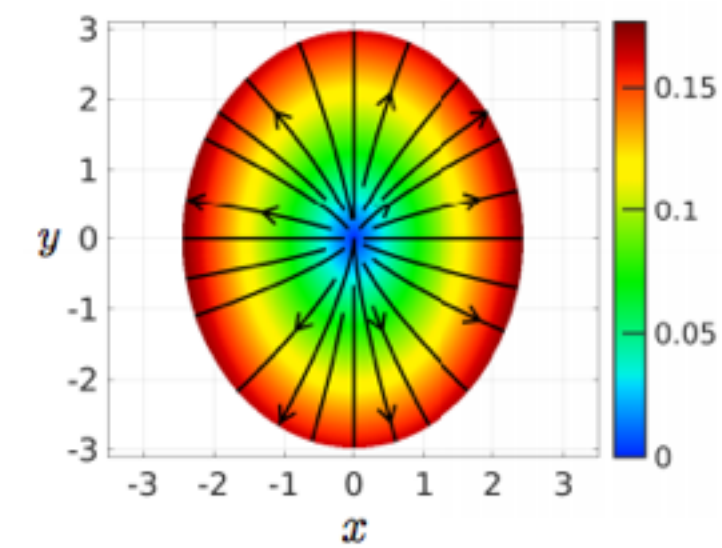
$$\frac{T^{\tau i}(\tau,\mathbf{x})}{T^{\tau\tau}(\tau,\mathbf{x})} \approx -\frac{(\tau-\tau_0)}{2}\frac{\partial^i T^{\tau\tau}(\tau_0,\mathbf{x})}{T^{\tau\tau}(\tau,\mathbf{x})}$$

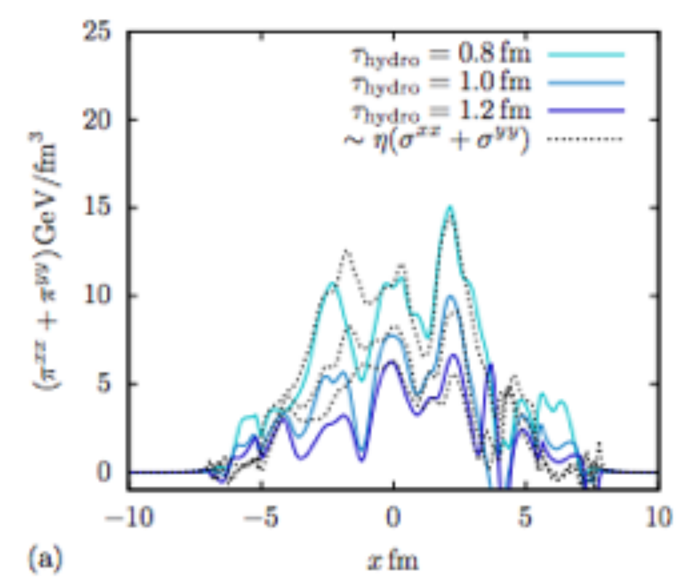
not indicative of onset of hydrodynamic flow

Viscous corrections: long wavelength components satisfy hydrodynamic constitutive equations approximately at $\tau=\tau_{\text{Hydro}}$

$$\pi^{\mu\nu}(\tau_{\text{Hydro}},\mathbf{x}) \approx \pi^{\mu\nu}_{\text{NS}}$$

P. Chesler JHEP 1603 (2016) 146





Pre-flow package KoMPoST provide unified description of pre-equilibrium evolution of $T^{\mu\nu}$ based on linear response to gradients

c.f. talk by A. Mazeliauskas Tue 11:15; poster by SS & M.Martinez

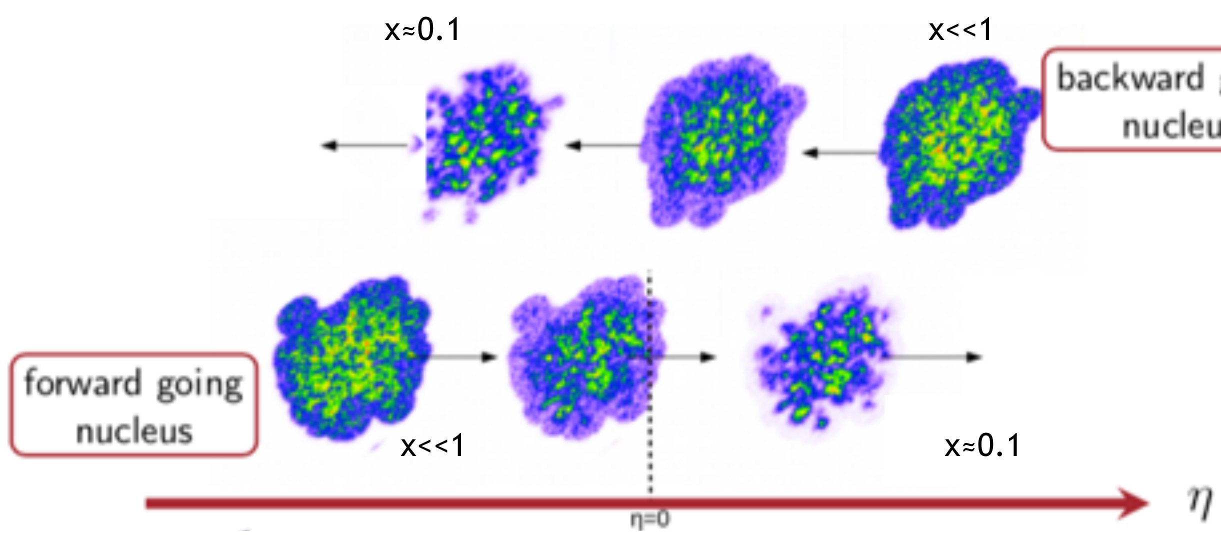
Longitudinal dynamics (η)

Boost invariance (η~0) on average is reasonable assumption for symmetric high-energy collisions

Different models for long. fluctuations based on different degrees of freedom nucleons, strings, …

c.f. talk by G-Y. Qin Tue 17:30 (AMPT+Hydro at RHIC & LHC)

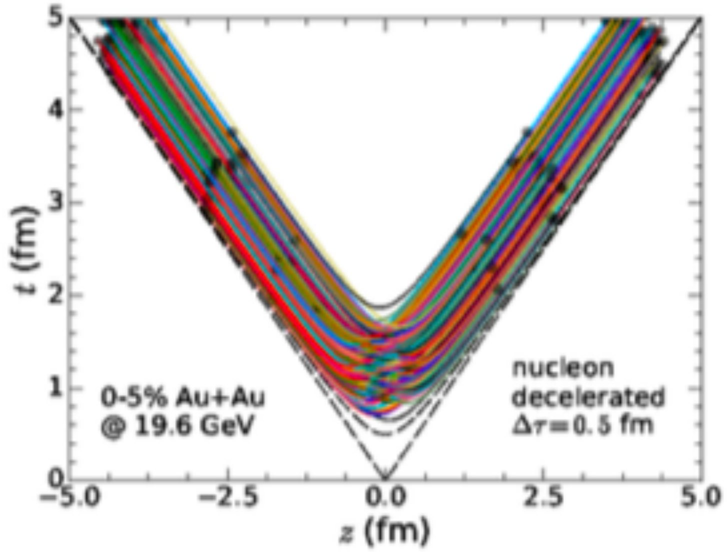
High-energy: Energy deposition at different η~y simultaneous probes gluon distribution at different x



SS Schenke PRC 94 (2016) no.4, 044907, McDonald, Jeon, NPA 982 (2019) 239-242, Ipp, Mueller PLB 771 (2017) 74-79

Significant differences in microscopic implementations; not clear how fluctuations of long. profiles are modified during the pre-equilibrium phase

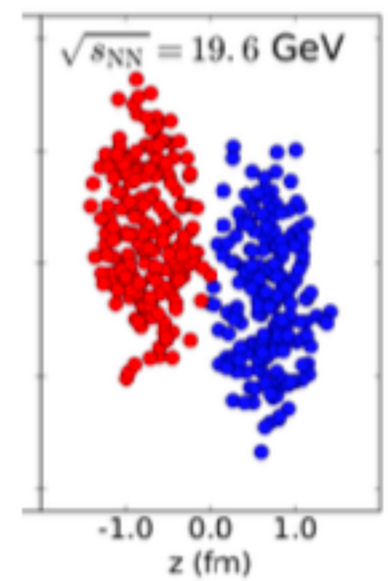
Longitudinal dynamics (η)



Lower energies: RHIC BES I/II, fixed target

No separation of central and fragmentation region

Simultaneous description of energy deposition & baryon stopping



No longer a clear separation between τ_{coll} and τ_{Hydro}

Dynamical matching between initial state/hydrodynamics

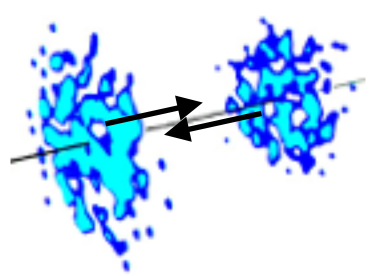
$$\partial_\mu T^{\mu\nu} = J^\mu_{\mathrm{source}}, \quad \partial_\mu J^\mu_{\mathrm{B}} = \rho_{\mathrm{source}}$$

Solid understanding of initial state (incl. fluctuations) crucial for critical point search

c.f. talk by C. Shen Wed 11:45

Sensitivity to Initial state

Space-time dynamics in nucleus-nucleus collisions dominated by hydrodynamic expansion



initial state → hydrodynamic expansion of the QGP → free-streaming

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

-> strong sensitivity to global features of initial conditions (ε_n,Ψ_n,$dS/d\eta$,…)

-> small effects of pre-equilibrium dynamics on typical observables (v_n,$\langle p_T \rangle$,…)

c.f. talks by P.Bozek Tue 16:50, M.Djordjevic Wed 15:00, S.Bass Wed 17:30 posters by M.Luzum

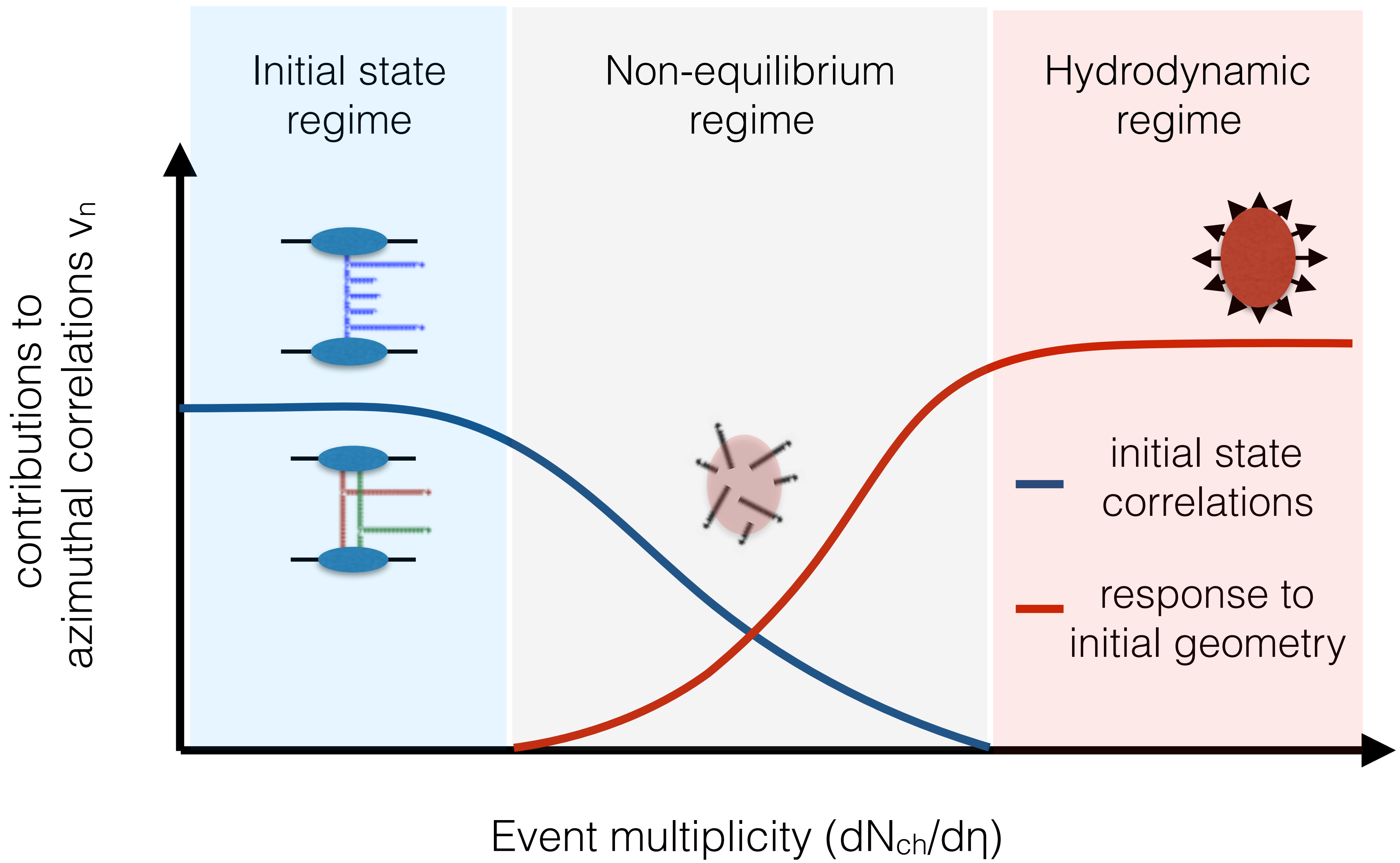
Entropy production ($dN_{ch}/d\eta$) dominated by initial state

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

but mutual uncertainties in energy deposition $\left\langle \frac{dE_\perp}{d\eta} \right\rangle_{\tau_{\rm coll}}$ and pre-equilibrium dynamics spoil sensitivity

Small systems (p/d/He3+p/A)

Shorter life-time of the system (~R) increases sensitivity to initial state and non-equilibrium dynamics



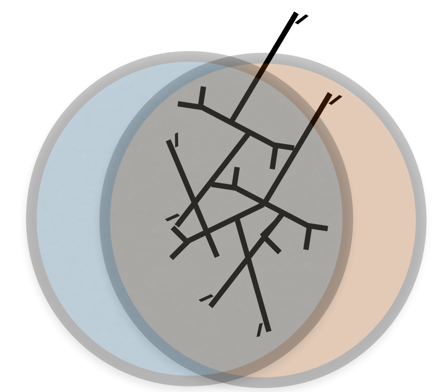
Some additional control parameters (p_T ,…) besides multiplicity $dN_{ch}/d\eta$

Hydrodynamic QGP in small systems?

Conditions for formation of near equilibrium QGP controlled by the ratio of hydrodynamization time ($\tau_{\rm Hydro}$) and system size (R)

If $\tau_{\rm Hydro}$ >> R insufficient time to achieve equilibrated QGP

If $\tau_{\rm Hydro}$ << R long lived hydrodynamic QGP phase



Based on previous estimates of the hydrodynamization time critical multiplicity can be estimated

$$\frac{\tau_{\rm Hydro}}{R} \simeq \left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}} \left(\frac{dN_{\rm ch}/d\eta}{63}\right)^{-\frac{1}{2}} \quad <=> \quad \left.\frac{dN_{\rm ch}}{d\eta}\right|_{\rm crit} = 63\left(\frac{\eta/s}{2/4\pi}\right)^{3}\left(\frac{\tau_{\rm Hydro}}{R}\right)^{-2}$$

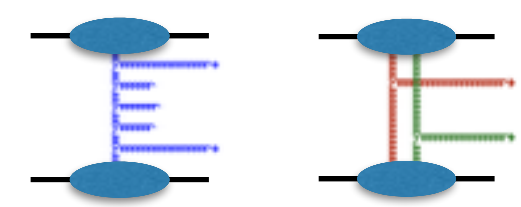
where $\left.\frac{dN_{ch}}{d\eta}\right|_{min.\ bias}^{p+p\ 7TeV} \sim 6 \quad , \quad \left.\frac{dN_{ch}}{d\eta}\right|_{min.\ bias}^{p+Pb\ 5.02TeV} \sim 16 \quad , \quad \left.\frac{dN_{ch}}{d\eta}\right|_{0-5\%}^{Pb+Pb\ 2.76TeV} \sim 1600$

Experimental results in small systems mostly fall into the regime $\tau_{\rm Hydro}$/R~1 dominated by non-equilibrium phase

Caveat: Discussion ignores effects of thermodynamic fluctuations

Small systems — Initial state correlations

QCD multi-particle production gives rise to intrinsic momentum space correlations present in the initial state

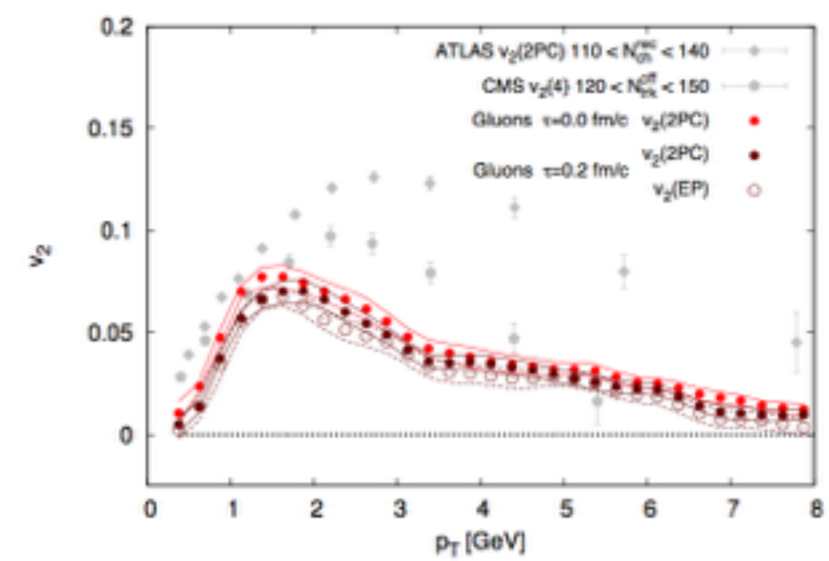


Different calculations based on Color-Glass Condensate agree on general features of correlation

Schenke, SS, Venugopalan PLB 747 (2015) 76-82
Mace, Skokov, Tribedy, Venugoplan PLB788 (2019) 161-165, …

Even & odd harmonics. $v_2, v_3, \ldots$

No significant correlation with event geometry



Effects can be sizeable ($\sim 1/N_c^2$) in small systems

Difficulties in explaining data without geometric component

c.f. talk by M. Mace Wed 9:15

Challenge: Effects of re-scattering & hadronization effects?

Small systems — Kinetic transport

Non-equilibrium description can interpolate between initial state & hydrodynamics will be needed to describe dynamics of small systems across wide range of multiplicities

New popularity of transport models
& semi-analytic transport calculations

Orjuela Koop, Adare, McGlinchey, Nagle PRC 92 (2015) no.5, 054903

Borghini, Gombeaud, EPJC 71 (2011) 1612

Kurkela,Wiedemann,Wu, PLB 783 (2018) 274-279, arXiv:1905:05139

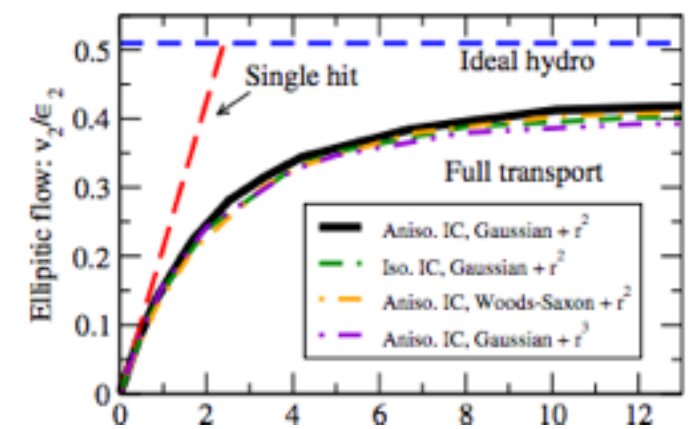
Romatschke EPJC78 (2018) no.8, 636

Small opacity can generate significant response to event geometry at low p_T

c.f. talk by U. Wiedemann Wed 14:40

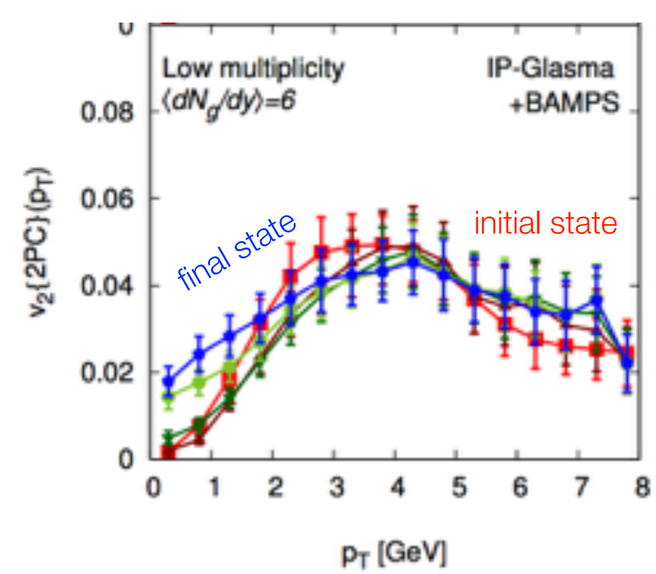
Challenge: Connections to QCD?
Validity of kinetic transport (α_S,$\lambda_{deBroglie}$/R)?

Boltzmann ITA



Kurkela,Wiedemann,Wu arXiv:1905:05139

Class. Yang-Mills (IP-Glasma)
+ pQCD transport (BAMPS)



Greif, Greiner, Schenke, SS, Xu
PRD96 (2017) no. 9, 091504

Small systems — Hydrodynamics

Best developed theoretical framework for phenomenology of bulk observables in hadronic collisions

Several calculations in general agreement with experimental data, but details start to matter

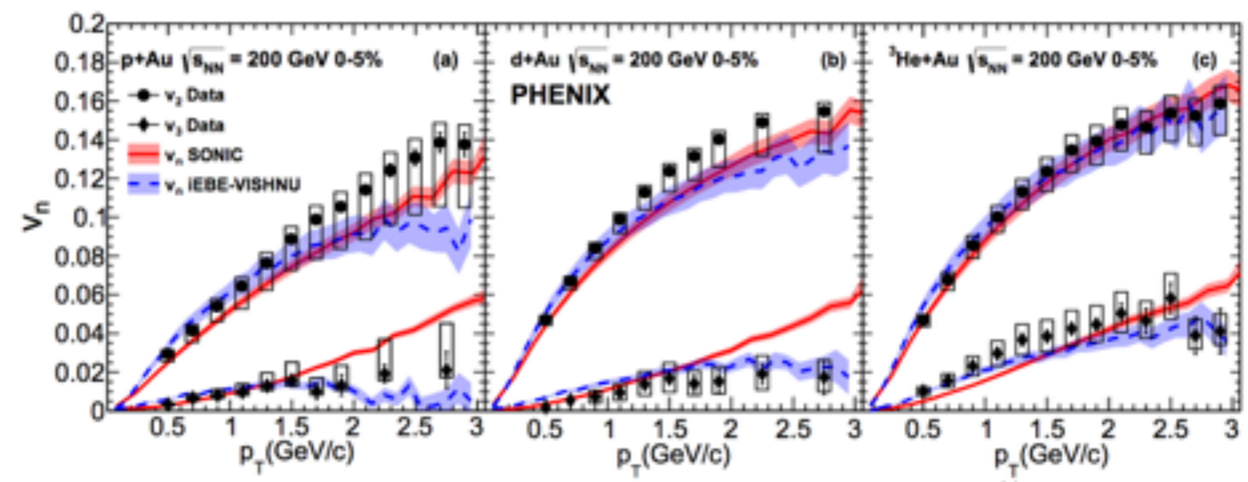
Pre-flow and initial viscous corrections become important

Non-hydrodynamic modes (included in every hydro code) can play an important role especially for $\tau < \tau_{Hydro}$

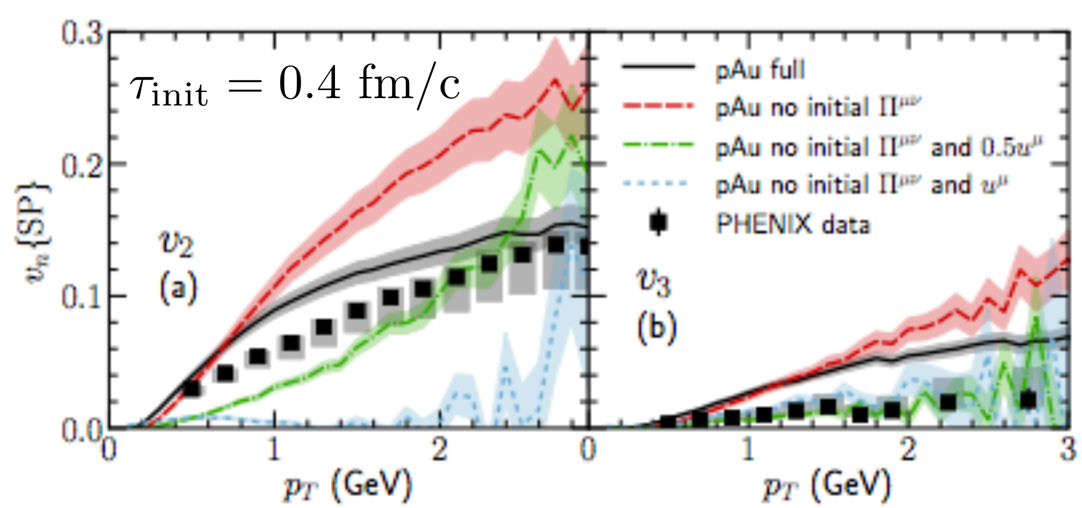
c.f. talk by W. Broniowski Wed 9:45

Challenge: Quantify uncertainties? Thermodynamic fluctuations?

PHENIX, Nature Phys. 15 (2019) no.3, 214-220



B. Schenke, C. Shen, and P. Tribedy talk presented at Rice Workshop



https://indico.cern.ch/event/771998/contributions/3339235/subcontributions/276910/attachments/1813022/2961981/talk_smallsystems_SHEN.pdf

Conclusions & Outlook

Large systems:
Solid understanding of global macroscopic properties of initial state due to microscopic insights and tight constraints from experimental data

Significant progress in theoretical description of pre-equilibrium dynamics

several things to improve: long. fluctuations, nucleon sub-structure, QGP chemistry, E&M field, …

Small systems: No clear distinction between “initial state” and later stages as separation of scales $\tau_{\mathrm{Hydro}} << \tau_{\mathrm{freeze\text{-}out}}$ ceases to exist

=> Need for unified description of non-equilibrium dynamics (initial state, evolution, hadronization, …)

Significant potential for new insights into non-equilibrium QCD beyond strict hydro regime from small system studies