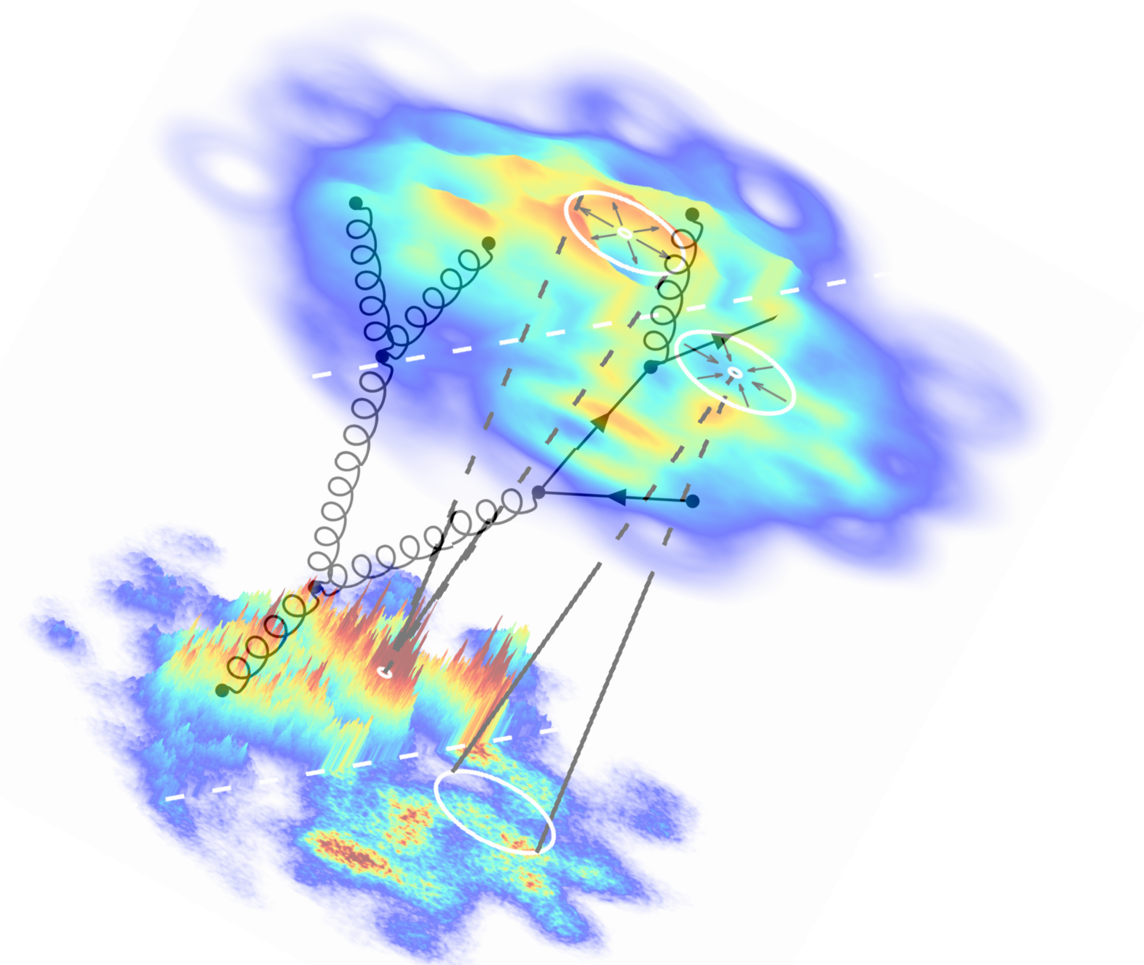
Equilibration of the QGP and it's phenomenological consequences



Sören Schlichting | Universität Bielefeld

ICTS Program "Extreme Nonequilibrium QCD (ONLINE)" | Oct 2020

CRC-TR 211
Strong-interaction matter under extreme conditions

UNIVERSITÄT BIELEFELD

Overview

1 Microscopic and macroscopic aspects of QGP equilibration

2a Early time dynamics & entropy production

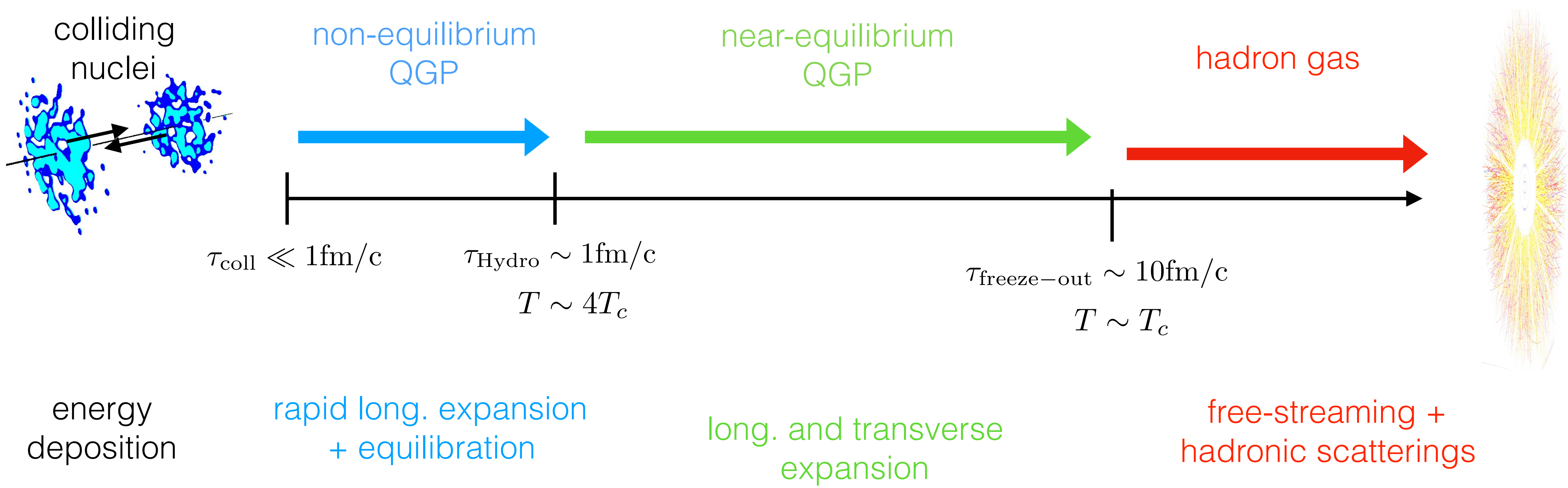
2b Di-lepton production during the pre-equilibrium stage

3 Conclusions & Outlook

Dynamics of HICs

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 eff. descriptions of QCD exploiting separation of time scales in the reaction dynamics



Theoretical description based on multi-stage evolution models

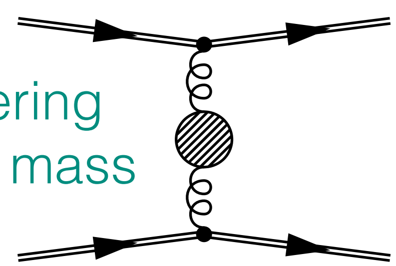
Equilibration of QGP at weak-coupling

Significant progress in understanding microscopic & macroscopic features of equilibration based on numerical solutions of effective kinetic theory of QCD at LO*

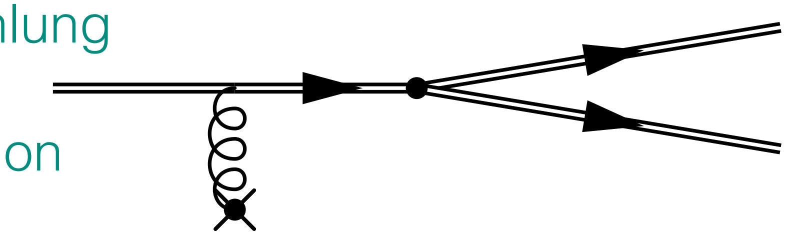
Arnold,Moore,Yaffe JHEP 0301 (2003) 030

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

elast. 2<->2 scattering
screened by Debye mass



collinear 1<->2 Bremsstrahlung
incl. LPM efffect
via eff. vertex re-summation



Solve numerically as integro-differential equation for Bjorken flow, with in-medium matrix elements for 2<->2 and 1<->2 processes self-consistently determined

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
Kurlela, Mazeliauskas *PRD* 99 (2019) 5, 054018; PRL 122 (2019) 142301;
SS, Du in preparation

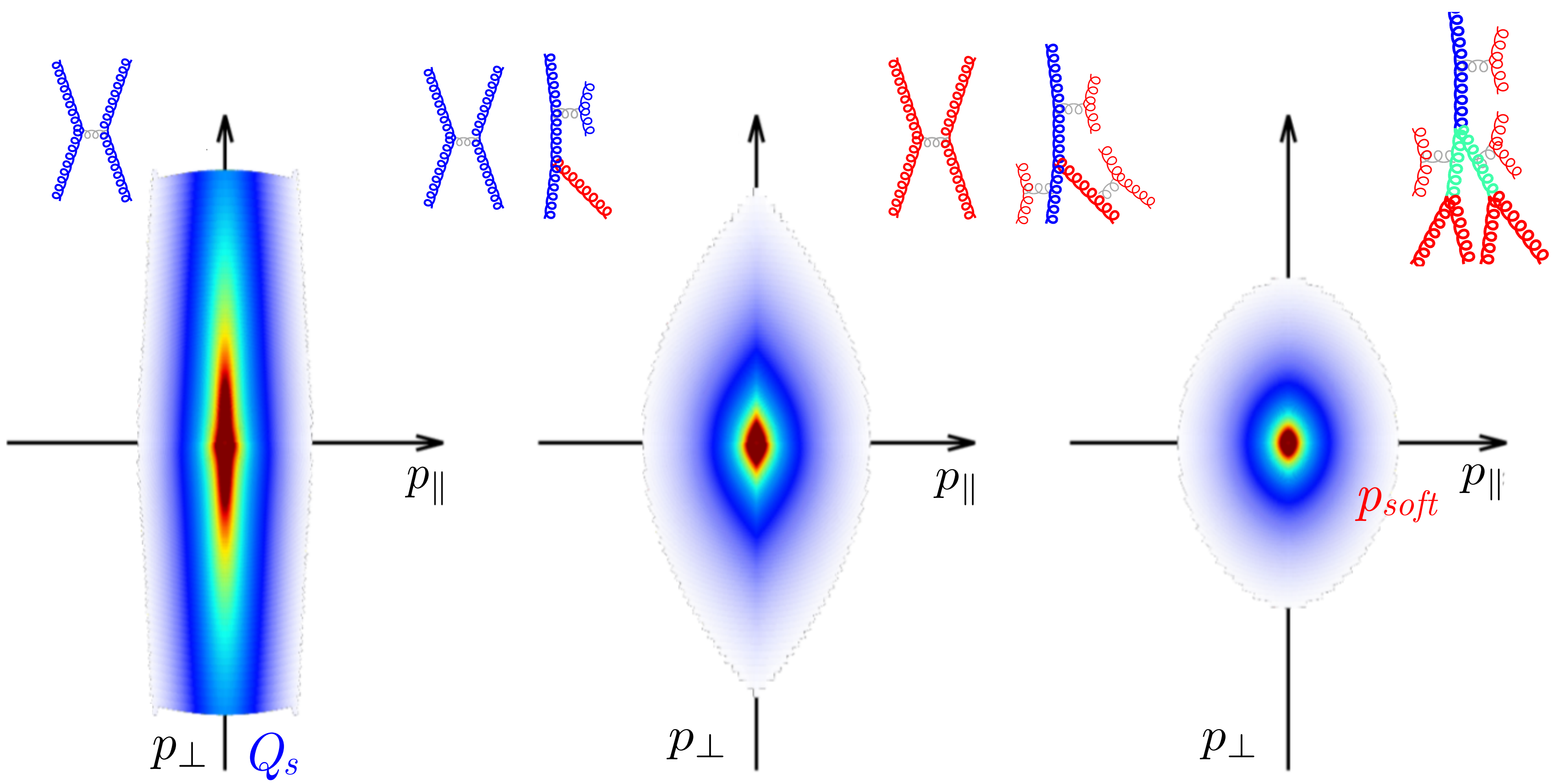
*Note that expansion is in g rather than $\alpha_s = g^2/4\pi$

Microscopic evolution

Evolution of homogenous boost invariant system in pure-glue QCD

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

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



$\tau/\tau_{\rm Hydro} \sim 0.1$ $\tau/\tau_{\rm Hydro} \sim 0.3$ $\tau/\tau_{\rm Hydro} \sim 1$

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

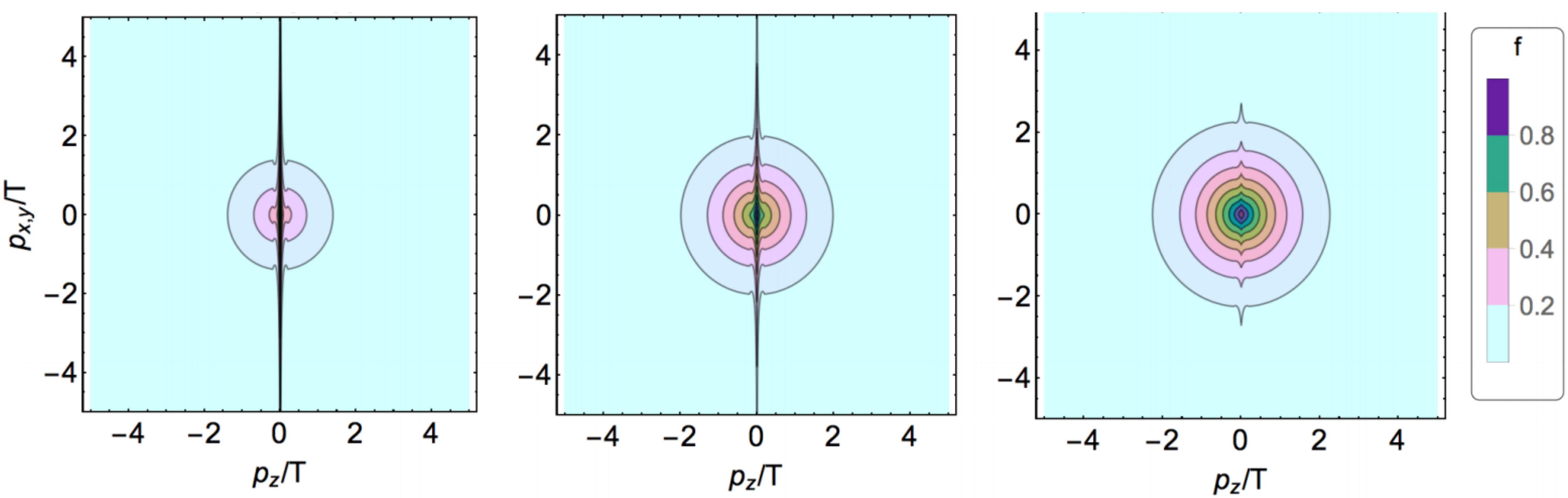
see talk by X.Du for latest results on Nf=3 QCD at zero/non-zero density

Microscopic evolution

Evolution of homogenous boost invariant system in Boltzmann RTA

M. Strickland JHEP 1812 (2018) 128

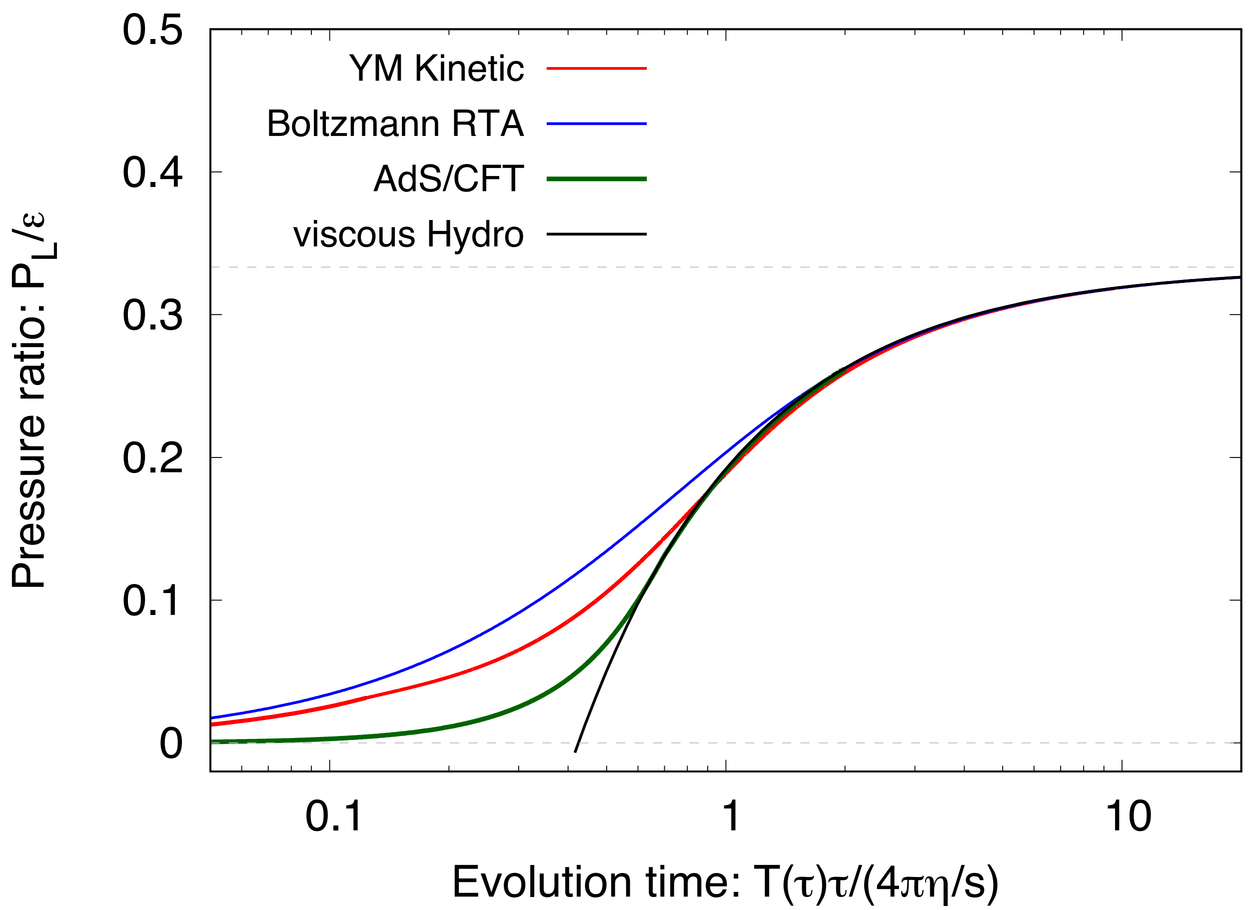
$$p^\mu \partial_\mu f(x,p) = -\frac{p^\mu u_\mu(x)}{\tau_R(x)}\Big[f(x,p) - f_{\rm eq}(x,p)\Big]$$



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

Energy & pressure evolution

Despite clear microscopic differences the macroscopic features of the evolution are remarkably similar when compared in meaningful fashion



Viscous hydrodynamics becomes applicable on time scales

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

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

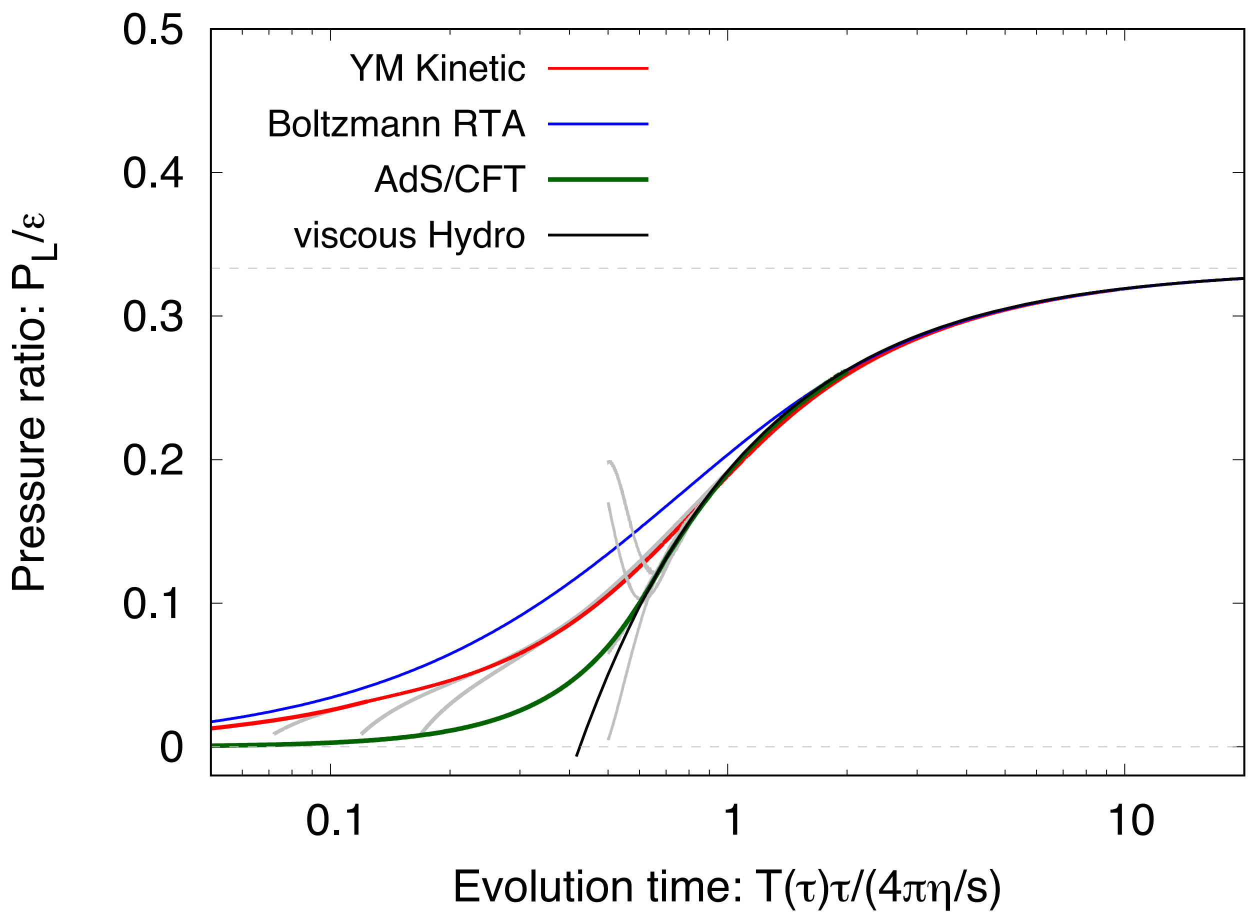
Hydrodynamization (≠ kinetic thermalization) time in A+A collisions

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

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:Kamata, Martinez, SS in prep. AdS/CFT: Romatschke PRL 120 (2018) no.1, 012301

Hydrodynamic attractors

Effective memory loss occurs at very early times $\tau \ll \tau_{Hydro}$
where long. expansion dominates the dynamics



Non-equilibrium evolution towards hydrodynamics described by "hydrodynamic attractor"

Heller, Spalinski PRL 115 (2015) no.7, 072501

Effective constitutive relations
for far-from-equilibrium systems

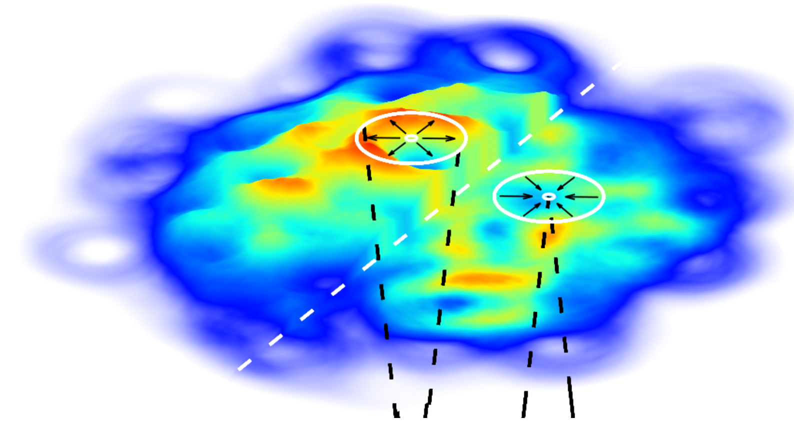
$$\frac{P_L}{\epsilon} = f(\epsilon, \tau) = f\left(\tilde{w} = \frac{T(\tau)\tau}{4\pi\eta/s}\right)$$

Different microscopic theories have different attractors

Universality at early times (free-streaming)
& late times (visc. hydrodynamics)

Non-equilibrium linear response

Exploit memory loss to use macroscopic degrees of freedom $T^{\mu\nu}$ for description of pre-equilibrium dynamics



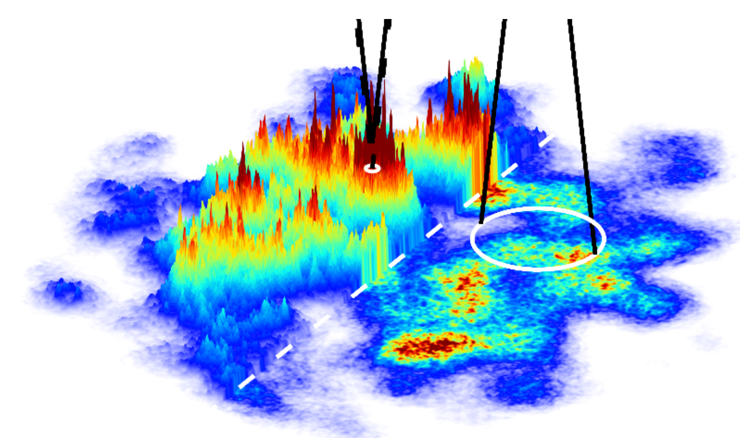
Decomposing $T^{\mu\nu}(x)$ into a local average $T^{\mu\nu}_{BG}(x)$ and fluctuations $\delta T^{\mu\nu}(x)$,are small on scales $c(\tau_{Hydro}-\tau_0)$, they can be treated in linear response theory

non-equilibrium Greens function of energy-momentum tensor

$$T^{\mu\nu}(\tau,x) = T^{\mu\nu}_{BG}(\tau) + \int_{\odot} G^{\mu\nu}_{\alpha\beta}(\tau,\tau_0,x,x_0)\delta T^{\alpha\beta}(\tau_0,x_0)$$

non-equilibrium evolution of (local) average background

KoMPoST package* provides implementation for event-by-event description of pre-equilibrium dynamics



*Code publicly available at github.com/KMPST/KoMPoST

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

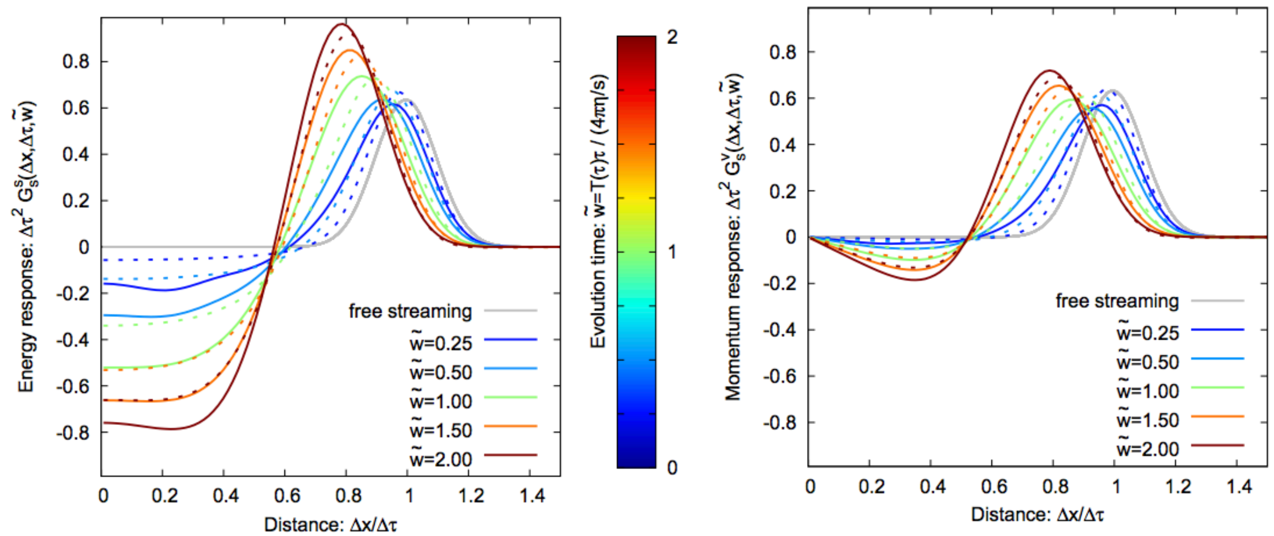
Dynamics of HICs

Non-equilibrium Green's functions calculated from microscopic theory

Keegan,Kurkela, Mazeliauskas, Teaney JHEP 1608 (2016) 171
Kurkela, Mazeliauskas, Paquet, SS, Teaney PRC 99 (2019) no.3, 034910

-> largely insensitive to underlying microscopics

Pratt, Vredevoogd PRC79 (2009) 044915
Kamata, Martinez, Plaschke, Ochsenfeld, SS *PRD* 102 (2020) 5, 056003

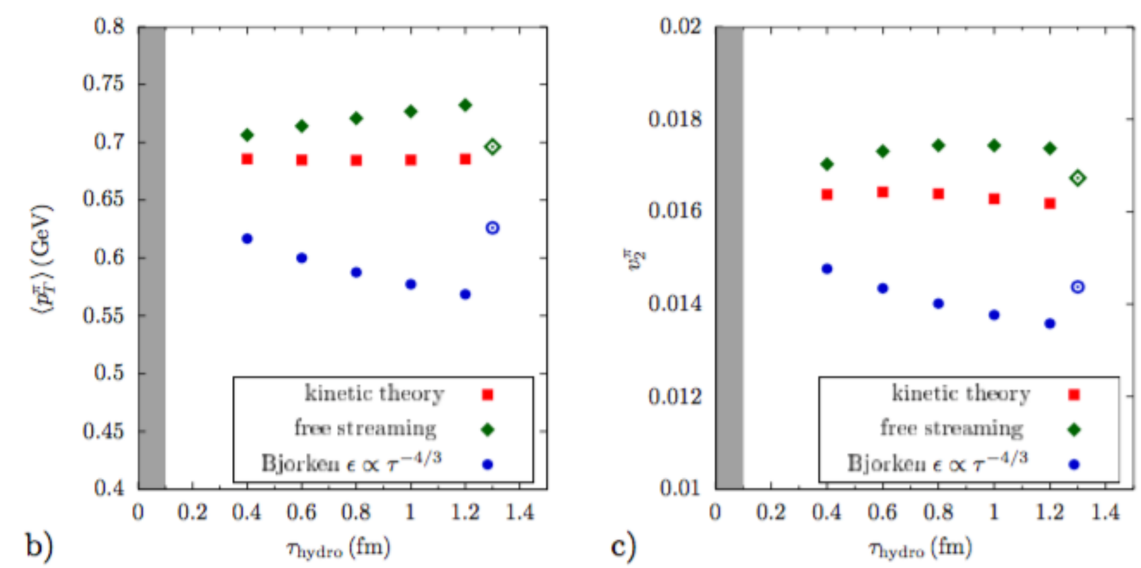


Kamata, Martinez, Plaschke, Ochsenfeld, SS *PRD* 102 (2020) 5, 056003

Small effects of pre-equilibrium dynamics on typical observables (v_n,$\langle p_T \rangle$,...) dominated by transverse expansion of QGP (~1-10fm/c)

Controlled extraction of near-equilibrium and transport properties of QGP (EoS,η/s,..) based on hydrodynamic simulations

Difficult to gain access to non-equilibrium in nucleus-nucleus collisions



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

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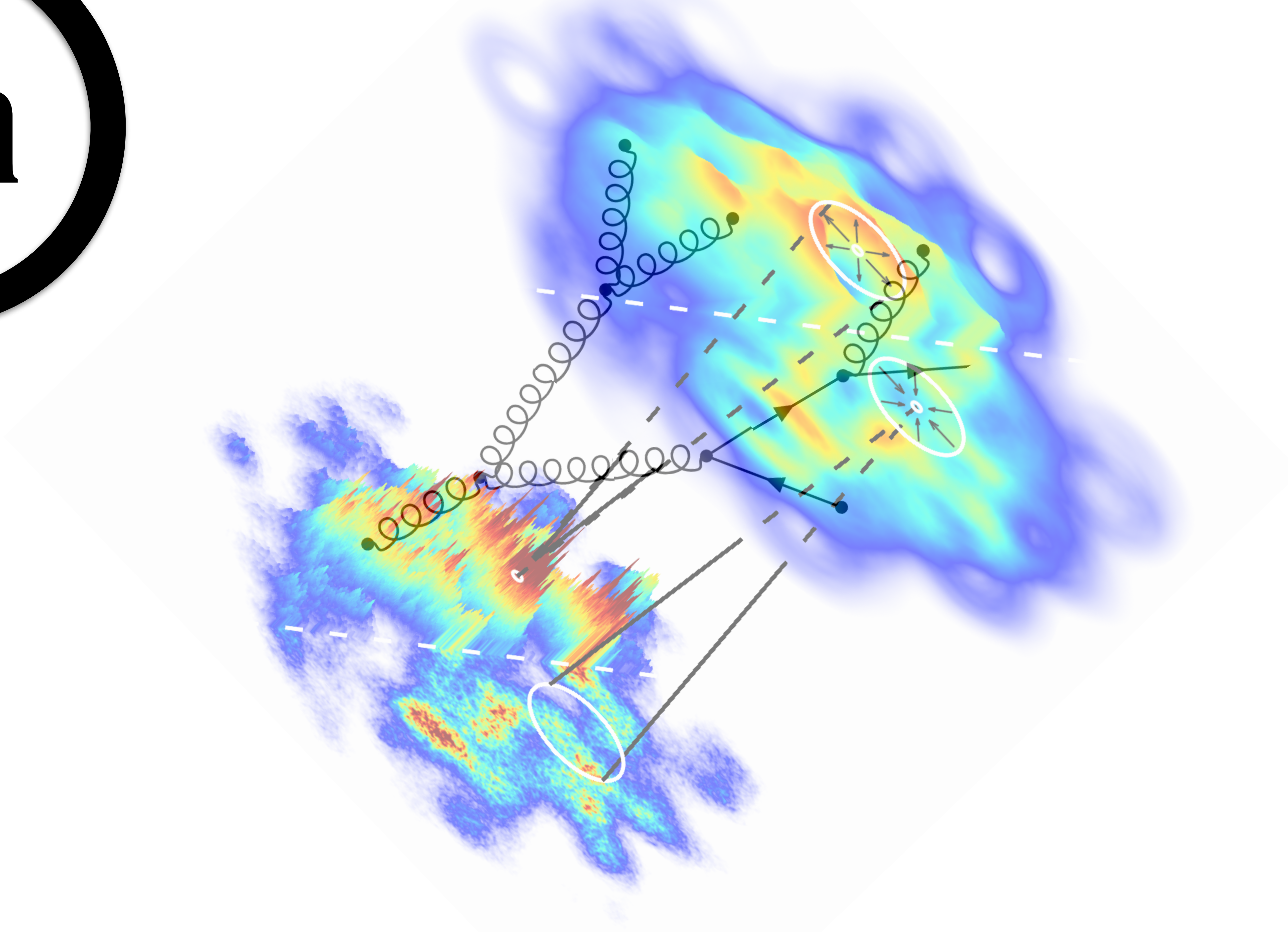


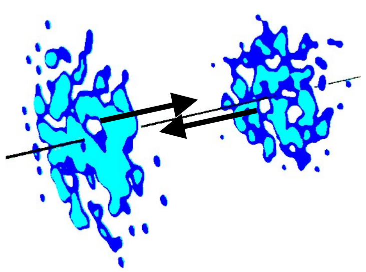
Early time dynamics & entropy production

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

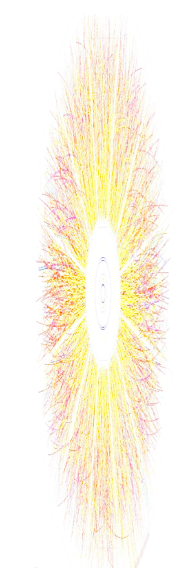
Sensitivity to Initial state

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

non-equilibrium QGP near-equilibrium QGP hadron gas



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



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

Schematically:

(nearly) isentropic expansion

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

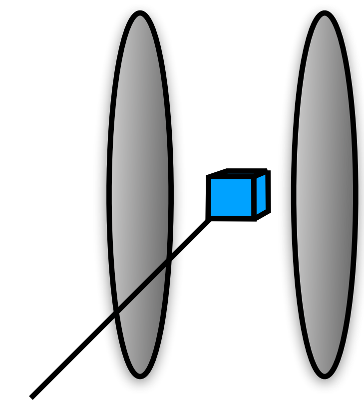
initial entropy production freeze-out

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

Early time dynamics & entropy production

Non-equilibrium initial state better characterized in terms of energy density (e), better to use entropy density (s) only once system is close to equilibrium

Generally interested in evolution over short time scales $\tau \sim 1\text{fm/c} << R_A$ where long. expansion is rapid ($\sim 1/\tau$) but transverse dynamics ($\sim 1/R$) can be neglected



Energy momentum tensor assumes average form $T^{\mu\nu} = \mathrm{diag}(e, p_T, p_T, p_L)$

Evolution of energy density is governed by conservation equation

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

Need one additional relation $P_L(e,\tau)$ to obtain evolution

Early time dynamics & entropy production

Equilibrium: Equation of state

$$\frac{P_L}{\epsilon} = \frac{1}{3}$$

Near-equilibrium:

Hydrodynamic constitutive relations based on grad. expansion

$$\frac{P_L}{\epsilon} = \frac{1}{3} - \frac{16}{9}\frac{\eta/s}{T(\tau)\tau}$$

Far-from equilibrium:

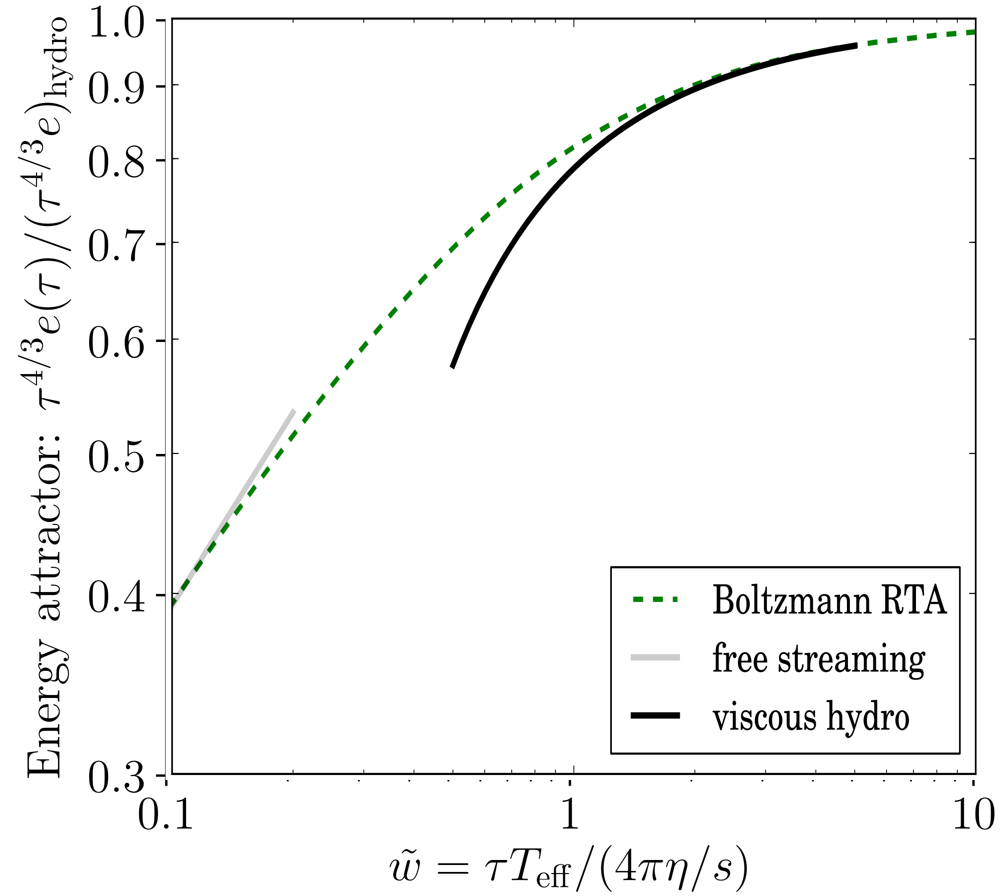
Generally no EoS/const. relation for P_L/e

$$\frac{P_L}{\epsilon} = f\left(\tilde{w} = \frac{T(\tau)\tau}{4\pi\eta/s}\right)$$

Non-equilibrium attractors provide effective constitutive equations

Hydrodynamic attractors

Effective constitutive equation allows to obtain evolution of energy density from



conservation law

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

+

eff. constitutive relation

$$\frac{P_L}{\epsilon} = f\left(\tilde{w} = \frac{T(\tau)\tau}{4\pi\eta/s}\right)$$

yielding

$$e(\tilde{w}_\tau) = e(\tilde{w}_0)\exp\left(-\int_{\tilde{w}_0}^{\tilde{w}_\tau} \frac{d\tilde{w}}{\tilde{w}} \frac{1 + P_L(\tilde{w})/e(\tilde{w})}{\frac{3}{4} - \frac{1}{4}P_L(\tilde{w})/e(\tilde{w})}\right)$$

conveniently characterized by energy attractor function

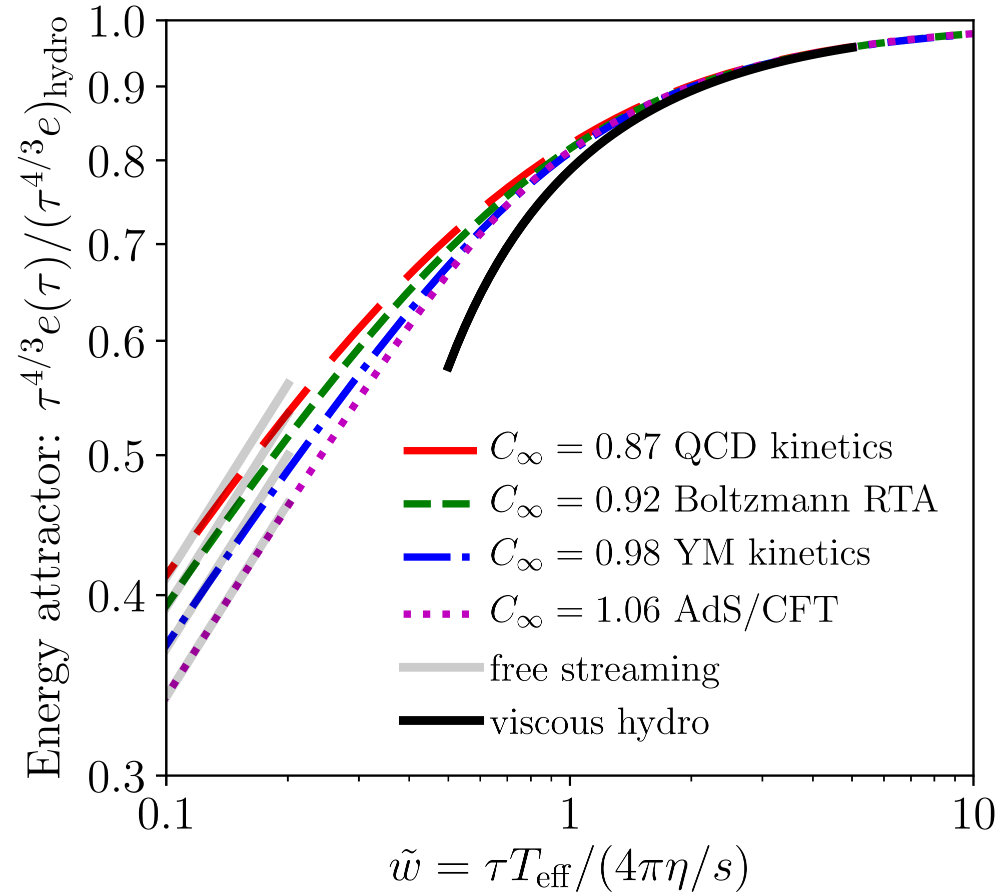
$$\frac{e(\tau)\tau^{4/3}}{e_{\rm hydro}\tau_{\rm hydro}^{4/3}} = \mathcal{E}\left(\tilde{w} = \frac{T_{\rm eff}(\tau)\tau}{4\pi\eta/s}\right)$$

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

Hydrodynamic attractors

Evolution of energy-density during pre-equilibrium phase described by

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



Universal characteristics at early and late times

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

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

$\tilde{w} \gg 1$ viscous hydrodynamics ($P_L/e \approx 1/3$- visc. correction)

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

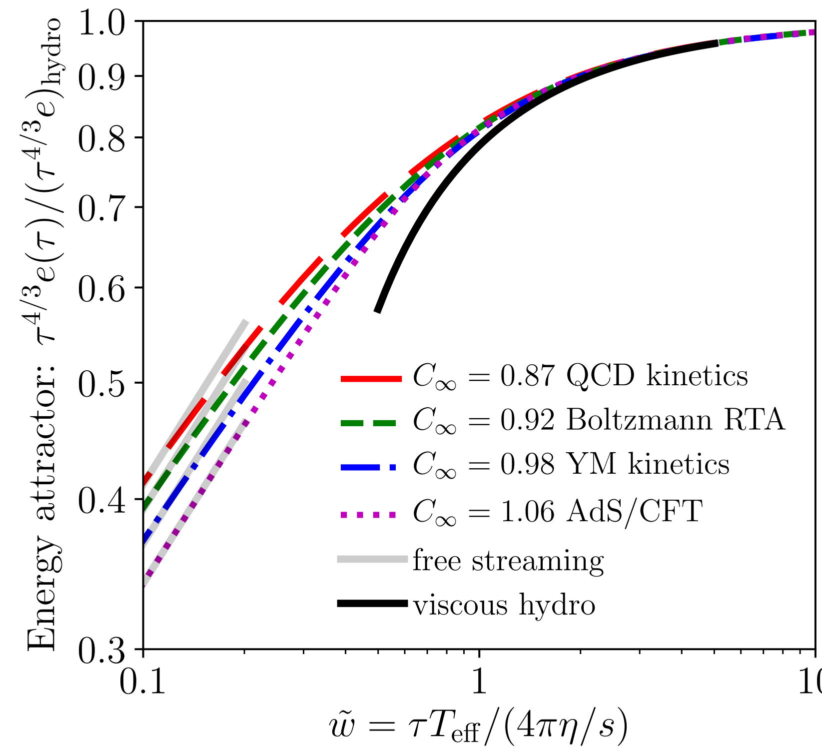
Surprisingly small differences between microscopic theories

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

Entropy production in HICs

Based on hydrodynamic attractor curve for energy density

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



can use thermodynamic relations s=(e+p)/T and EOS once QGP is close to equilibrium to calculate entropy

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

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

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

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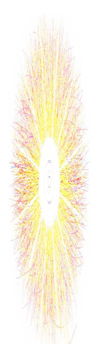
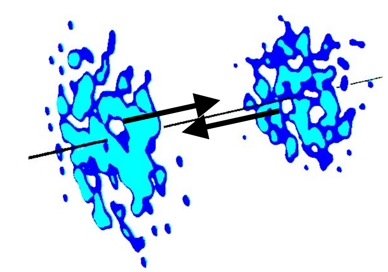
Entropy production in HICs

Based on macroscopic considerations one can establish one-to-one correspondence between initial state energy density and charged particle multiplicity including all relevant pre-factors



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



Sensitivities/Uncertainties:

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:
$(\epsilon\tau)_0$ significant uncertainties from small-x TMDs and perturbative corrections

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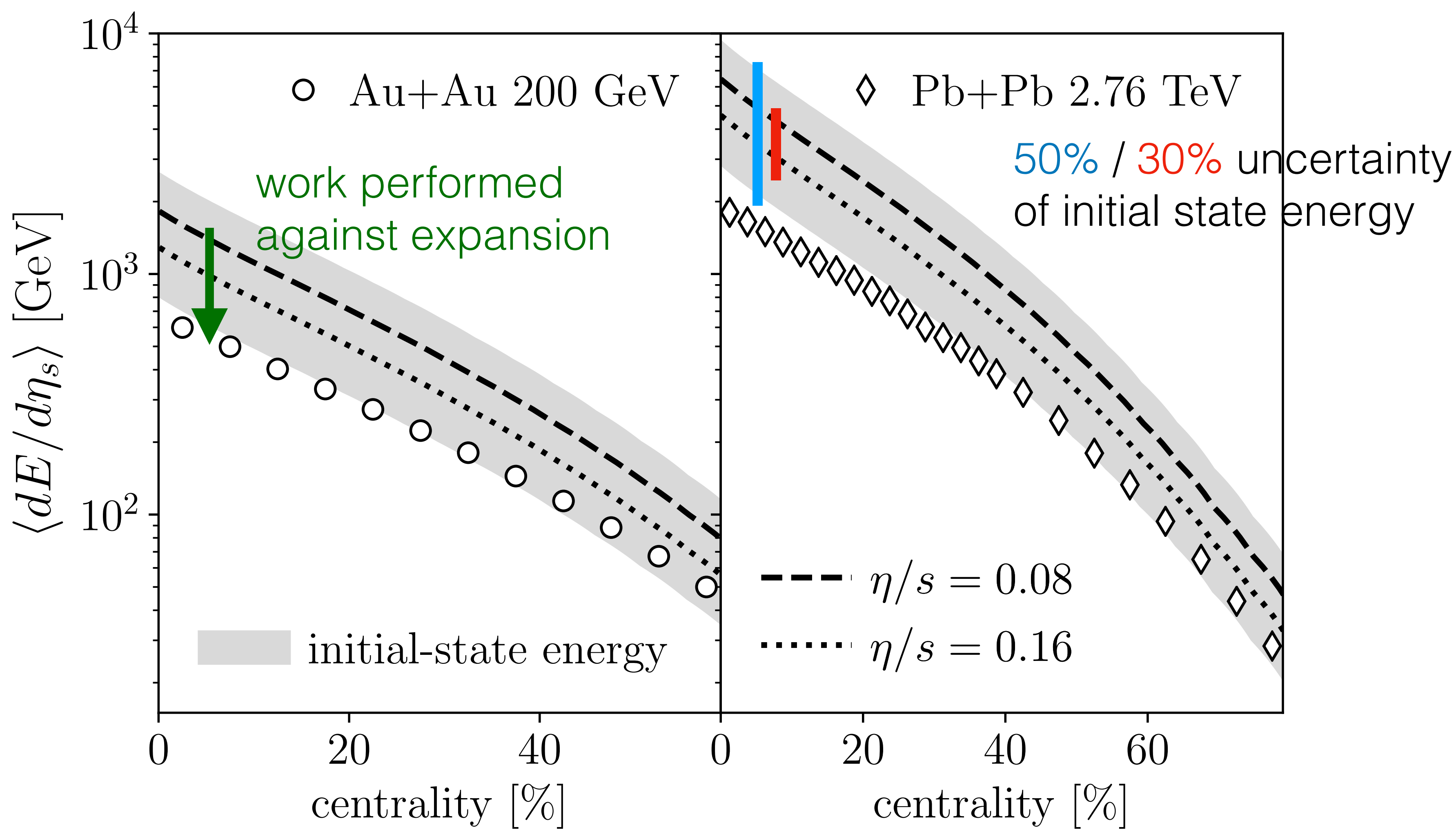
Initial state in HICs



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

Establish link between initial state and finale state to connect Heavy-Ion Physics to small-x Physics at EIC & Hadron Colliders

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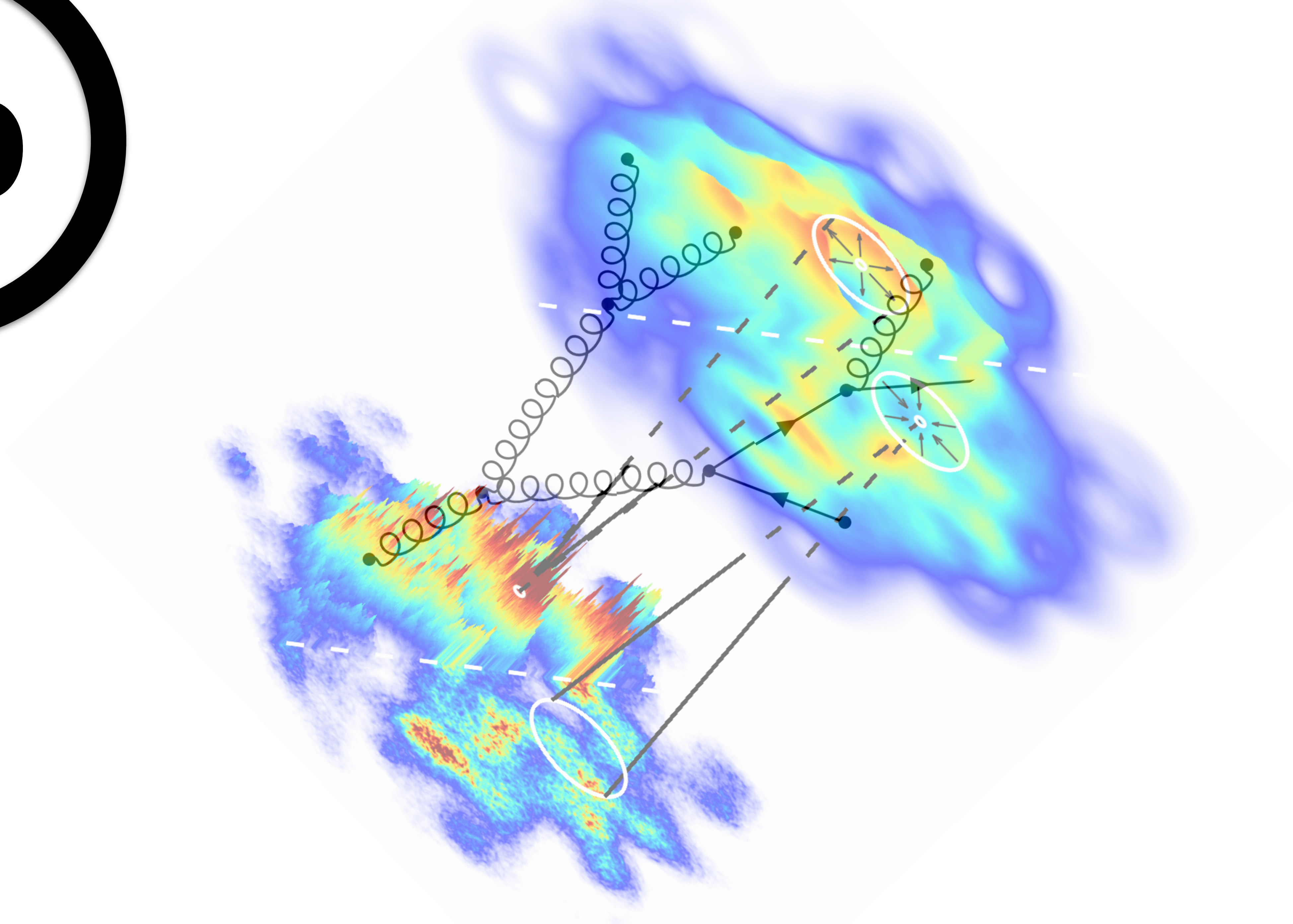
2b



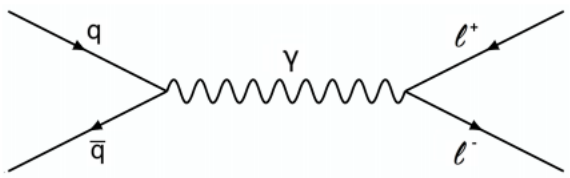
Di-lepton production during the pre-equilibrium stage

Work in progress

M.Coquet, J.-Y. Ollitrault, SS, M. Winn

Di-lepton production

Electro-magnetic probes are produced throughout the entire lifetime of the QGP and escape the plasma without re-interaction



Equilibrium di-lepton production rate at LO:

$$\frac{dN^{l^+l^-}}{d^4x d^4Q} = -\frac{\alpha_{em}^2}{6\pi^3 Q^2}\theta(Q^2-4m^2)\left(1+\frac{2m^2}{Q^2}\right)\left(1-\frac{4m^2}{Q^2}\right)^{1/2}\sum_f q_f^2 \Pi^{\mu,<}_{\mu}(Q)\ .$$

$Q^2 \gg T^2$

$$\Pi^{\mu<}_{\mu}(Q)\Big|_{\mathrm{eq}} \simeq -\frac{N_c Q^2}{2\pi} n_{BE}(q_0)$$

Early stages are different from thermal QGP emission

non-equilibrium QGP is hotter, highly anisotropic, not in chemical equilibrium

$$\Pi^{\mu,<}_{\mu}(Q) = -\frac{N_c Q^2}{4\pi^2 q}\int d^3p\ \frac{1}{p^2}\delta\left(\cos\theta_{pq} - \frac{q^2+2pq_0-q_0^2}{2pq}\right) f_q(p) f_{\bar{q}}(q-p)\ \theta(q^- < p < q^+)$$

=> Explore high invariant mass di-leptons as probe of early QGP

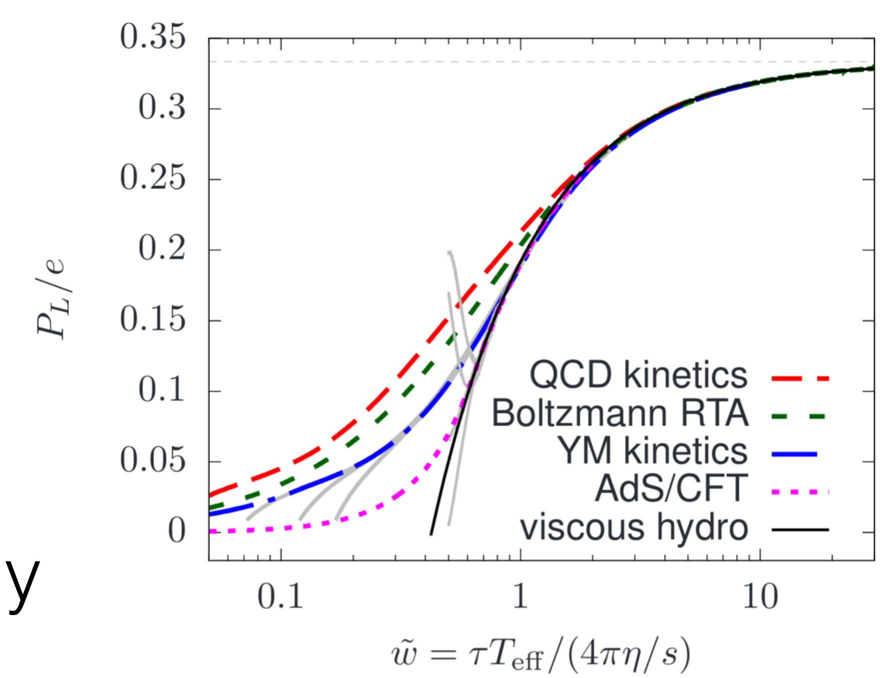
Martinez, Strickland PRC 78 (2008) 034917; Ryblewski, Strickland PRD 92, 025026 (2015); Churchill, Yan, Jeon, Gale arXiv:2008.02902

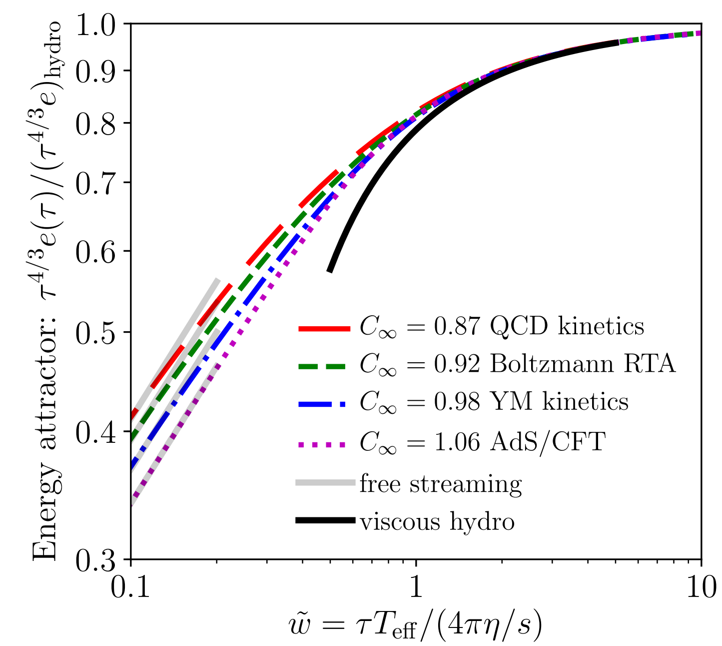
Di-lepton production

We employ LO di-lepton rate with parametrized phase-space distribution of the aHydro form

$$f_q(\tau, p_T, y-\eta) = q(\tau) f_{FD}\Big(-\sqrt{p_T^2 + \xi^2(\tau) p_T^2 \sinh^2(y-\eta)}/T_{\rm eff}(\tau)\Big)$$
$$f_g(\tau, p_T, y-\eta) = f_{BE}\Big(-\sqrt{p_T^2 + \xi^2(\tau) p_T^2 \sinh^2(y-\eta)}/T_{\rm eff}(\tau)\Big)$$

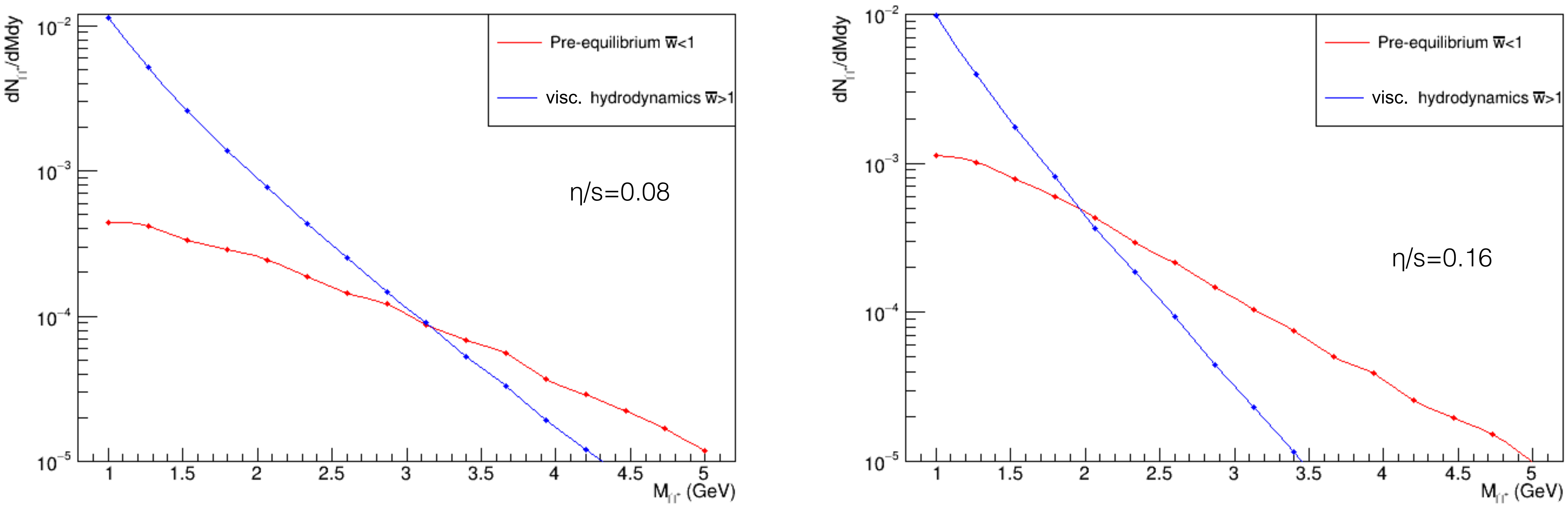
with anisotropy parameter and eff. temperature matched to P_L/e and e for non-equilibrium attractors and initial energy density e matched to dN_{ch}/dy





so far did not account for quark suppression, but can be easily included by considering e_q/e_g

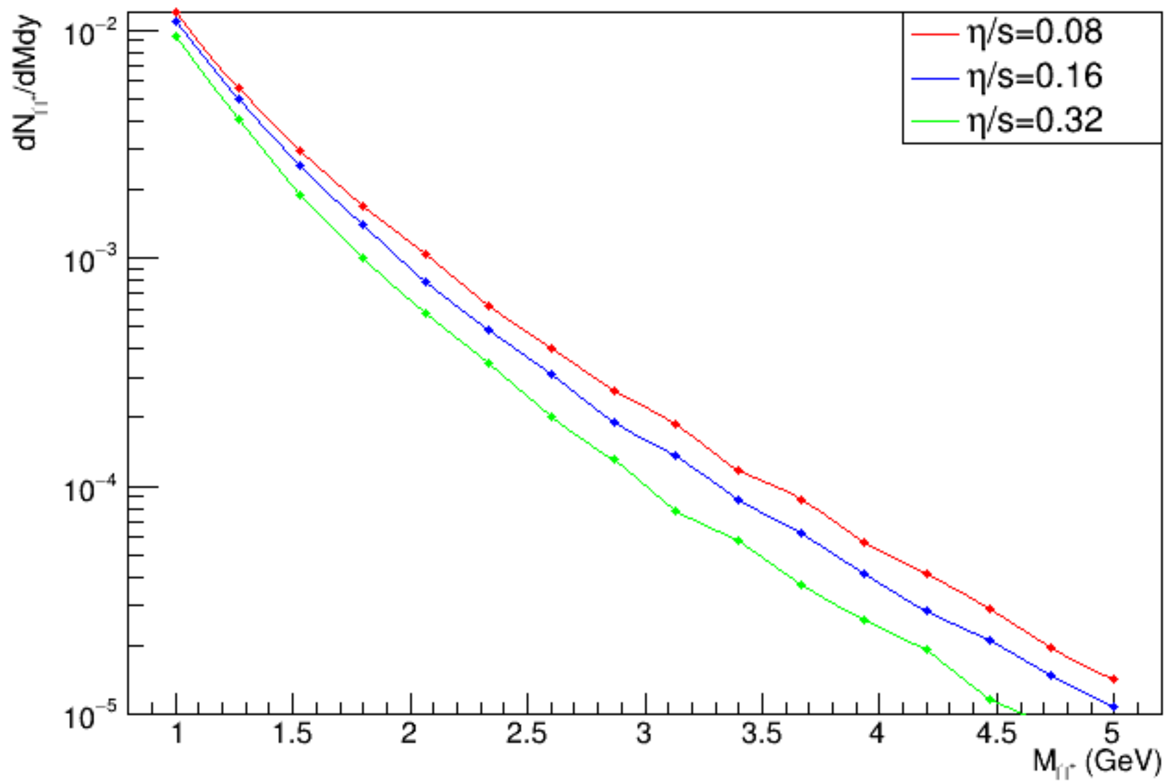
Di-lepton production



M.Coquet, J.-Y. Ollitrault, SS, M. Winn work in progress

Depending on value of η/s considerable contributions from pre-equilibrium regime (w<1)

Di-lepton production



Open issues: Background from Drell-Yan and Jet's

Extend calculations to include full non-equilibrium phase-space distribution, beyond LO emission rates for photons/di-leptons

photon production: $\sim f_q$ di-lepton production: $\sim f_q f_q$

possible window into QGP chemistry at early times?

Churchill, Yan, Jeon, Gale arXiv:2008.02902

M.Coquet, J.-Y. Ollitrault, SS, M. Winn work in progress

Conclusions & Outlook

Significant progress in understanding and describing early-time dynamics/ equilibration of QGP

KoMPoST: Event-by-event pre-equilibrium dynamics & initial conditions for Hydro Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910

Entropy production in HICs dominated by early time pre-equilibrium dynamics

Based on hydro attractors can connect properties of initial state with experimental measurements

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

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

Electro-magnetic probes & Jet's provide other promising avenues to explore non-equilibrium QCD in heavy-ion collisions

Backup

Estimating magnitude of effects

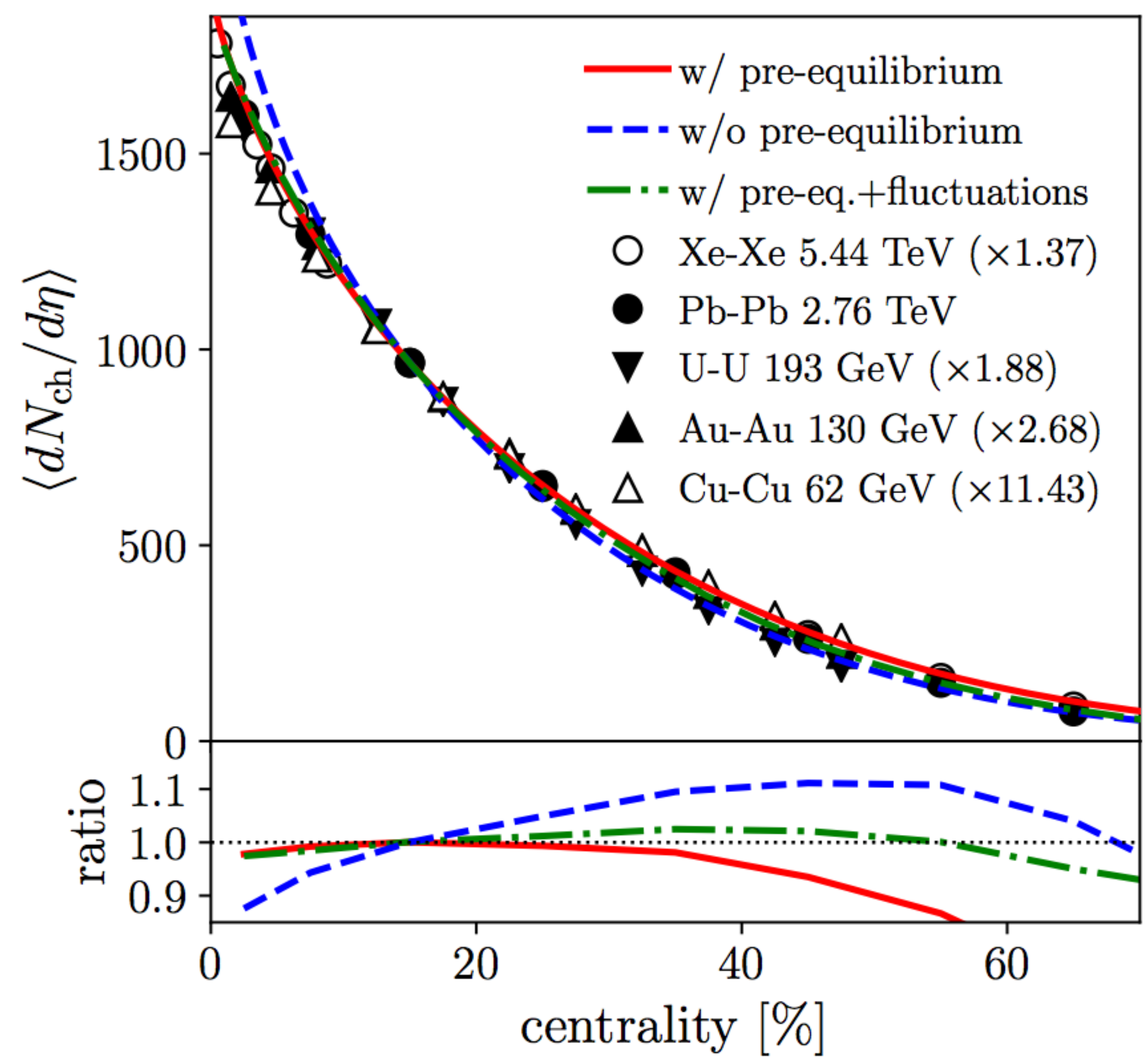
Estimate pre-equilibrium effects within simplistic saturation model

Initial state scenario:
No entropy production
$N_{ch} \sim N_{gluon}$

$$(n\tau)_0(\mathbf{x}_\perp) \propto (Q_s^<)^2(\mathbf{x}_\perp),$$

Thermalized scenario:
Pre-eq entropy production
$N_{ch} \sim S_{Hydro}$

$$(e\tau)_0(\mathbf{x}_\perp) \propto (Q_s^<)^2(\mathbf{x}_\perp) Q_s^>(\mathbf{x}_\perp)$$



Sensitivity for centrality dependence only on the few percent level, mainly due to the fact that normalization is adjusted to reproduce data

Entropy production in Hydrodynamics

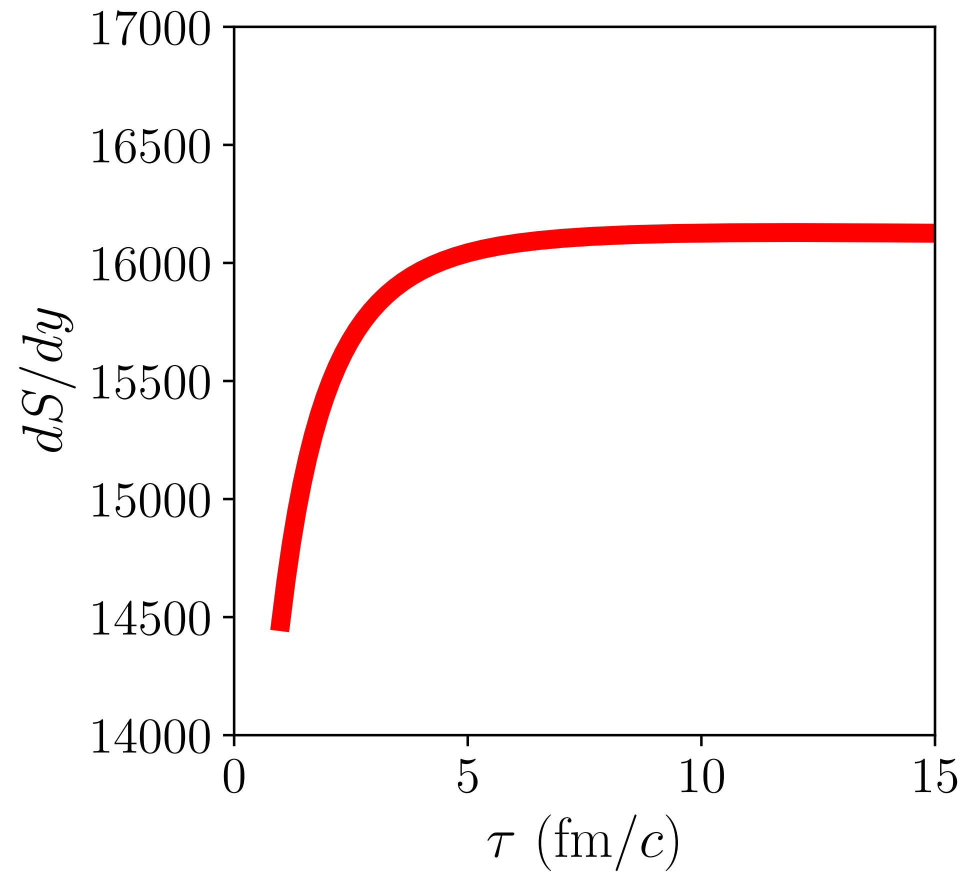
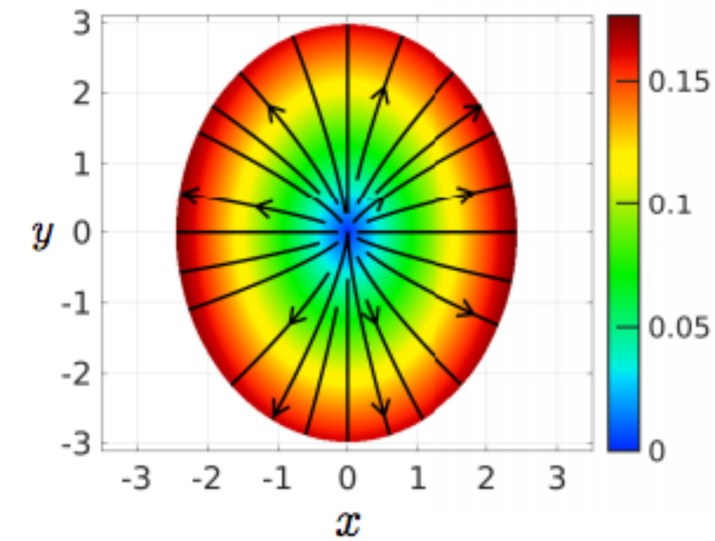


Fig. by G. Giacalone

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

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

P. Chesler JHEP 1603 (2016) 146

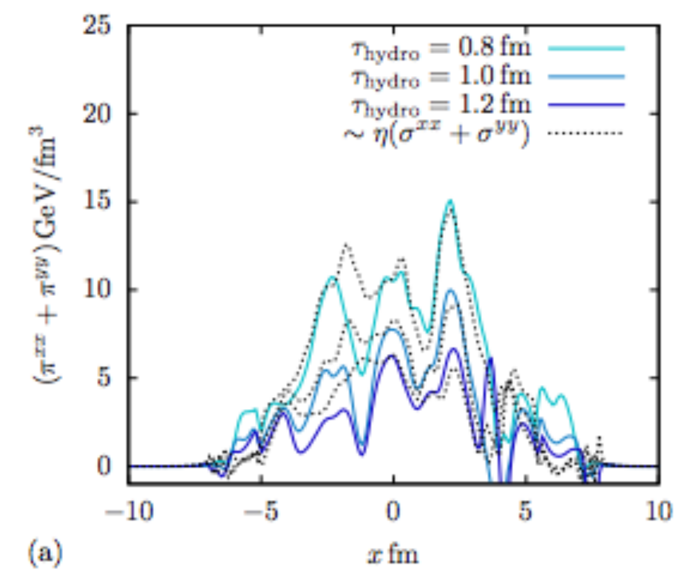


Universal pre-flow: early expansion of matter insensitive to microscopic details

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 $\tau=\tau_{Hydro}$

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

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

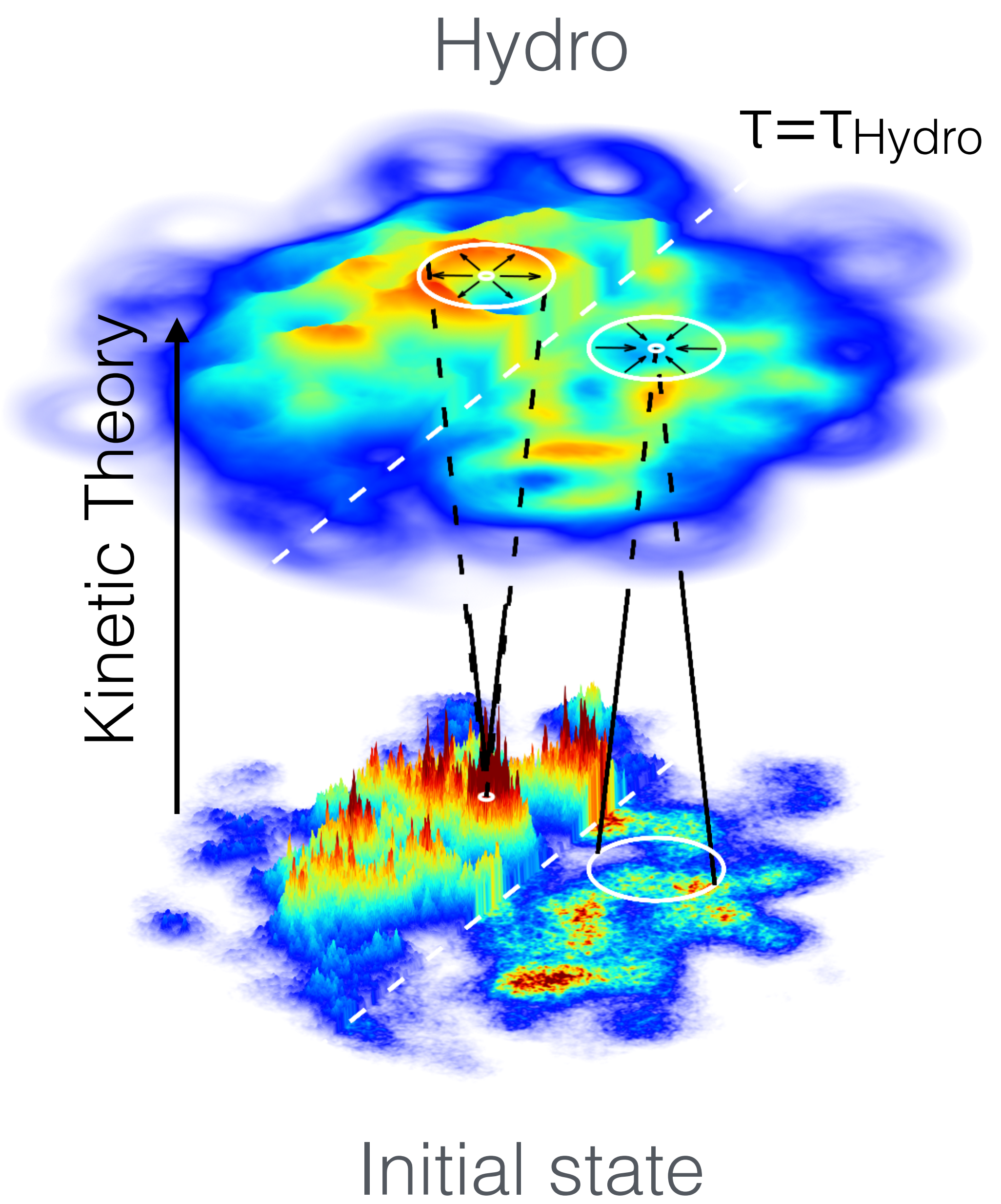
KoMPoST

Macroscopic description of pre-equilibrium dynamics

Exploit memory loss to use macroscopic degrees of freedom $T^{\mu\nu}$ for description of pre-equilibrium dynamics

Separation of scales between evolution time τ_{Hydro} and typical size scale of gradients R_A

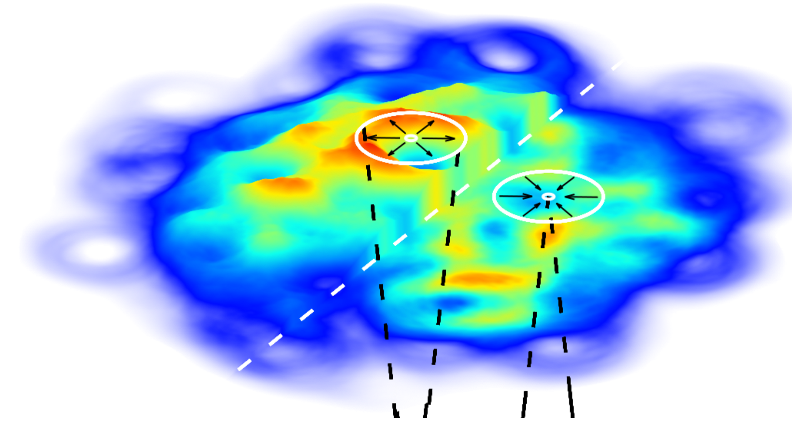
Decomposing $T^{\mu\nu}(x)$ into a local average $T^{\mu\nu}_{BG}(x)$ and fluctuations $\delta T^{\mu\nu}(x)$,are small on scales $c(\tau_{Hydro}-\tau_0)$, they can be treated in linear response theory



Keegan,Kurkela, Mazeliauskas, Teaney JHEP 1608 (2016) 171
Kurkela, Mazeliauskas, Paquet, SS, Teaney arXiv:1805.01604; arXiv:1805.00961

Non-equilibrium linear response

Energy-momentum tensor at τ_{Hydro} can be reconstructed directly from initial conditions

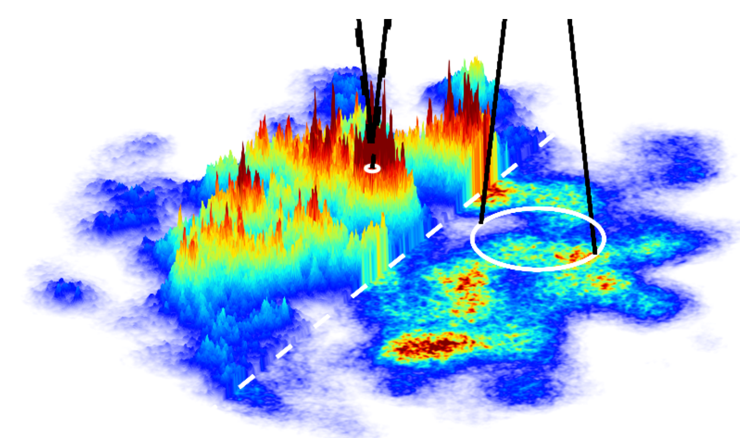


$$T^{\mu\nu}(\tau,x) = T^{\mu\nu}_{BG}(\tau) + \int_{\odot} G^{\mu\nu}_{\alpha\beta}(\tau,\tau_0,x,x_0)\delta T^{\alpha\beta}(\tau_0,x_0)$$

non-equilibrium evolution of (local) average background

non-equilibrium Greens function of energy-momentum tensor

Instead of event-by-event Monte-Carlo, effective kinetic theory simulations performed only once to compute evolution of background $T^{\mu\nu}{}_{BG}$ and Greens functions $G^{\mu\nu}{}_{\alpha\beta}$



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