Hydrodynamic attractors, initial state energy and particle production in relativistic nuclear collisions

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

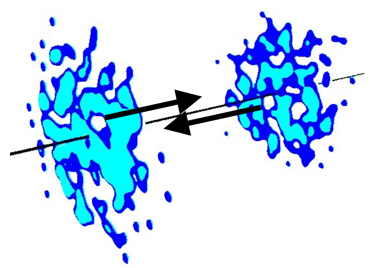
Bullet Talk @ Initial Stages 2021 (online)

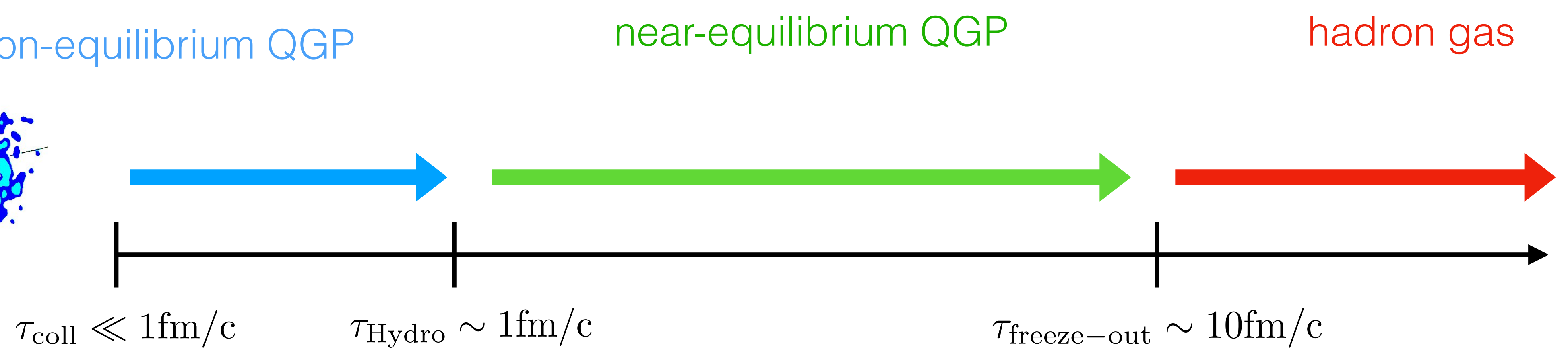
CRC-TR 211
Strong-interaction matter under extreme conditions

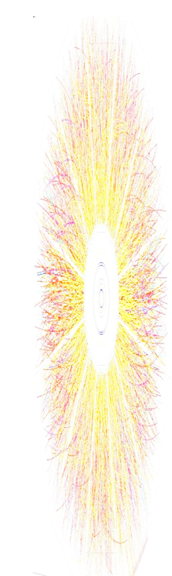
UNIVERSITÄT BIELEFELD

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

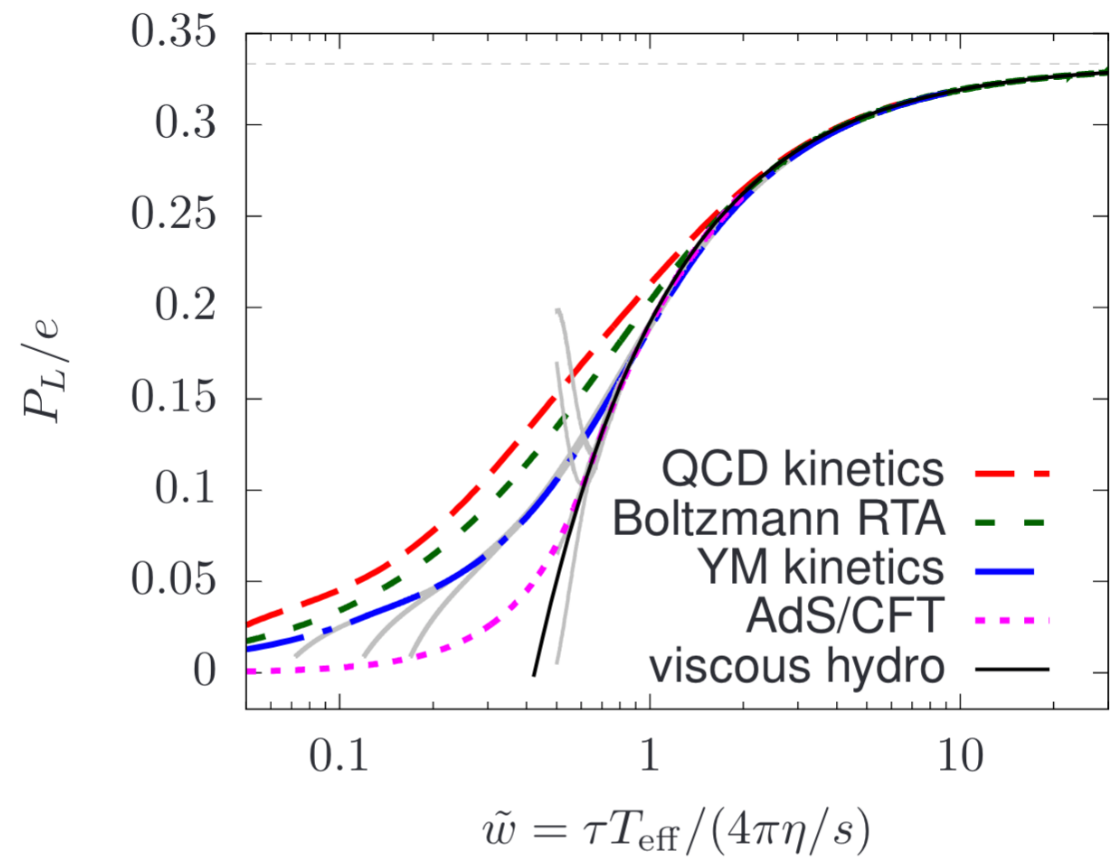
Early time dynamics & entropy production

Early time dynamics (τ<1fm/c) 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



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

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

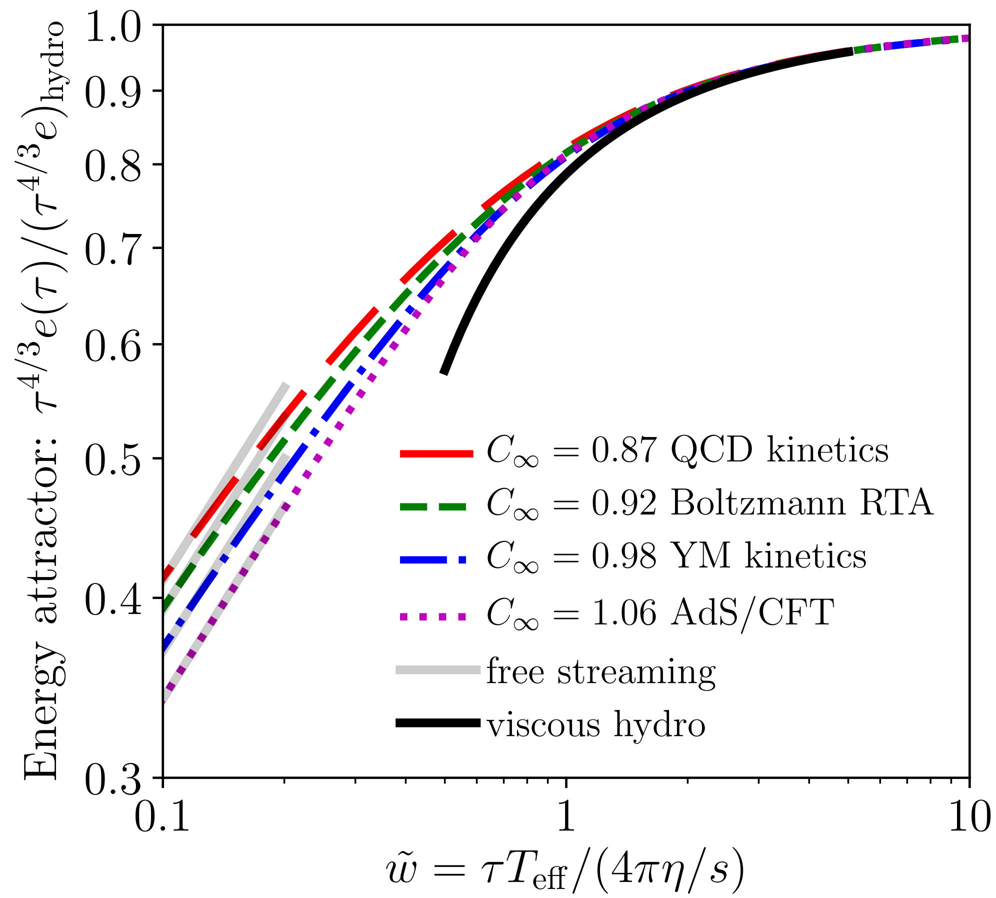
$\tilde{w} \gg 1$ viscous hydrodynamics ($P_L/e \approx 1/3 - 4/9\pi\tilde{w}$)

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: Kamata, Martinez, Plaschke, Ochsenfeld, SS PRD 102 (2020) 5, 056003 AdS/CFT: Romatschke PRL 120 (2018) no.1, 012301

Hydrodynamic attractors

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

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



Universal 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 $C_\infty \sim 0.95 \pm 0.15$

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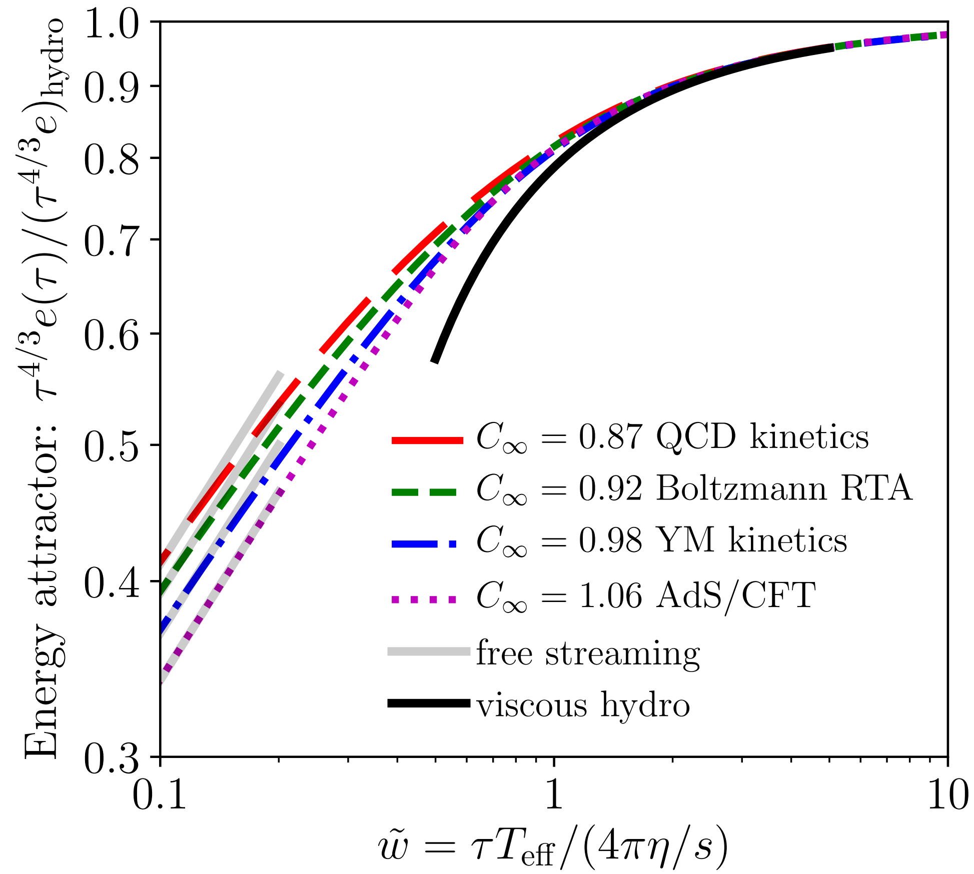
Entropy production in HICs

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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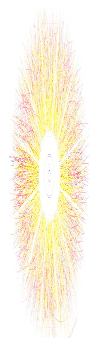
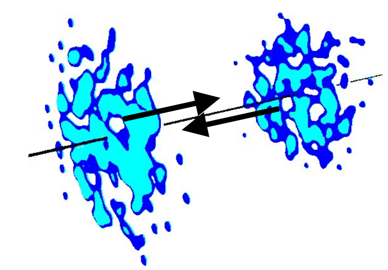
Entropy production in HICs

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

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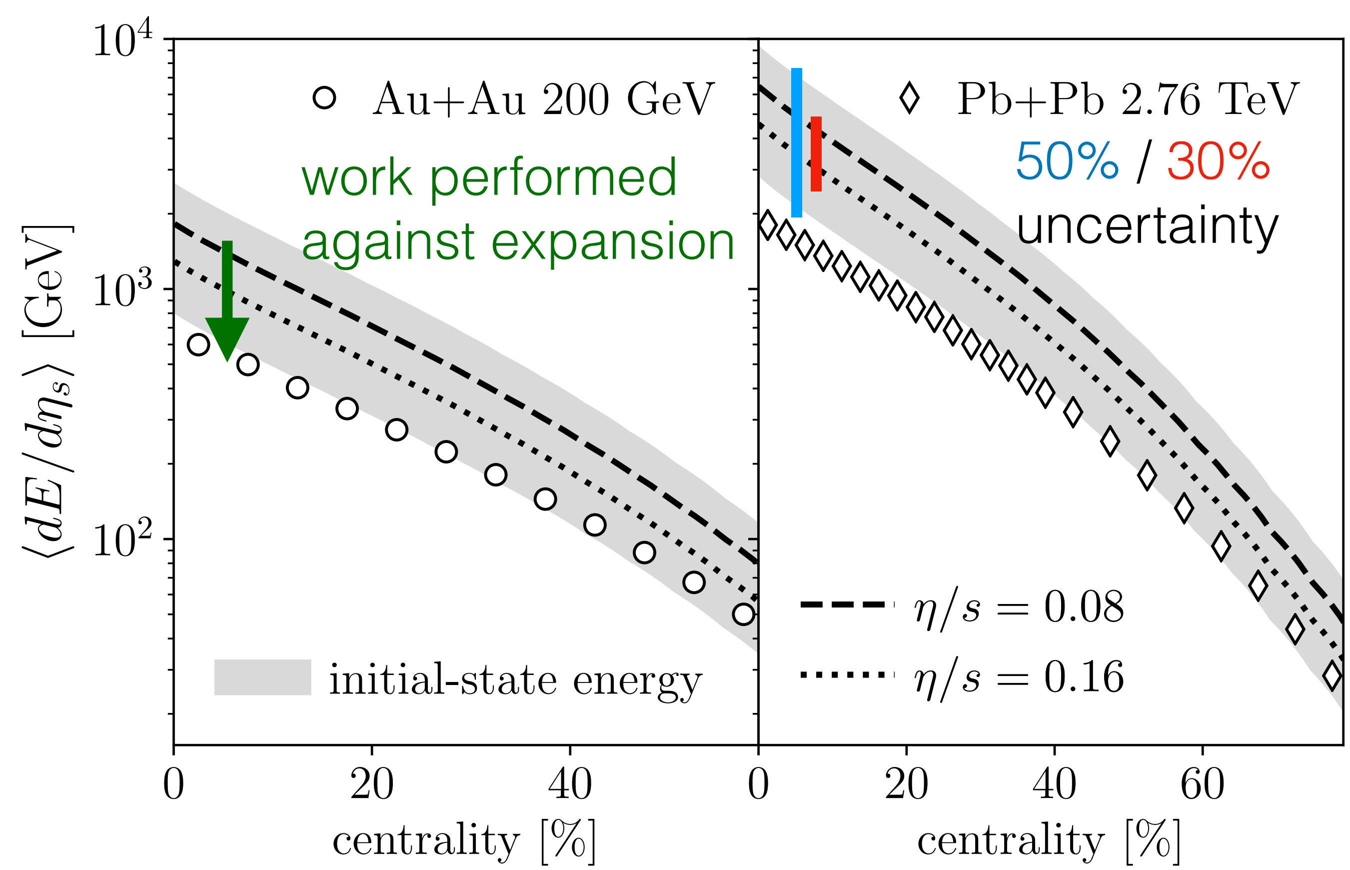
Conclusions

Established explicit relation between initial state energy density and charged particle multiplicity based on hydrodynamic attractors describing entropy production during the pre-equilibrium stage

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

Connect Heavy-Ion Physics to small-x Physics at EIC & Hadron Colliders



Different phenomenological applications in HIC (initial state geometry, pre-equilibrium di-lepton production, …)

(c.f. talks by J.-F. Paquet, M. Coquet)