

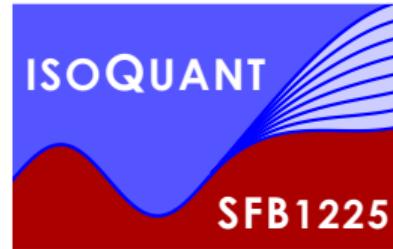
Initial conditions for nuclear collisions: theory overview

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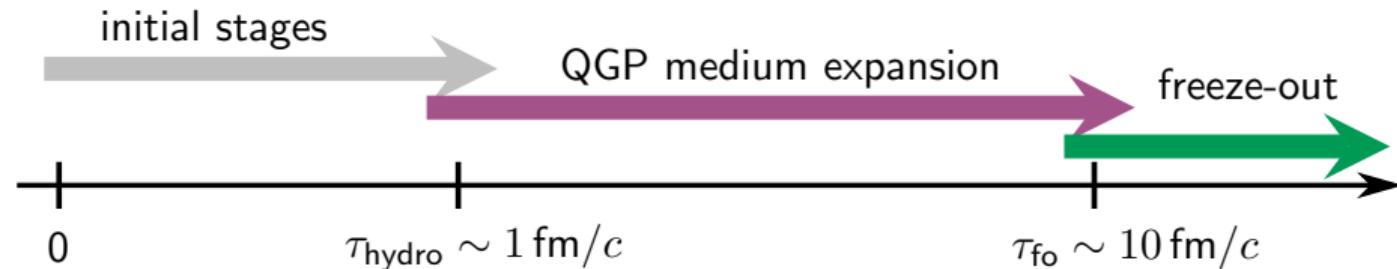
May 18, 2018

Thanks to D. Teaney, J. Noronha, M. Strickland, R. Venugopalan, S. Schlichting, J.-F. Paquet, K. Reygers, B. Schenke, K. Eskola, C. Shen, A. Ohlson, Y. Pachmayer, A. Kurkela, and E. Grossi for helpful discussions.



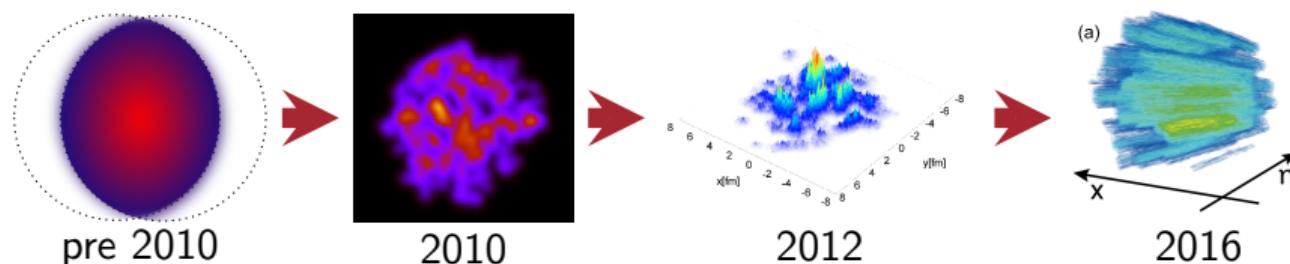
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Motivation



Why are initial stages important?

- Initial collision geometry \Rightarrow particle correlations, e.g. flow harmonics v_n .
- Damping of initial fluctuations \Rightarrow transport properties of QGP, e.g. η/s , ζ/s .
- Key in understanding thermalization \Rightarrow can be “the whole story” in small systems.



Outline

The current (space-time) picture of initial stages:

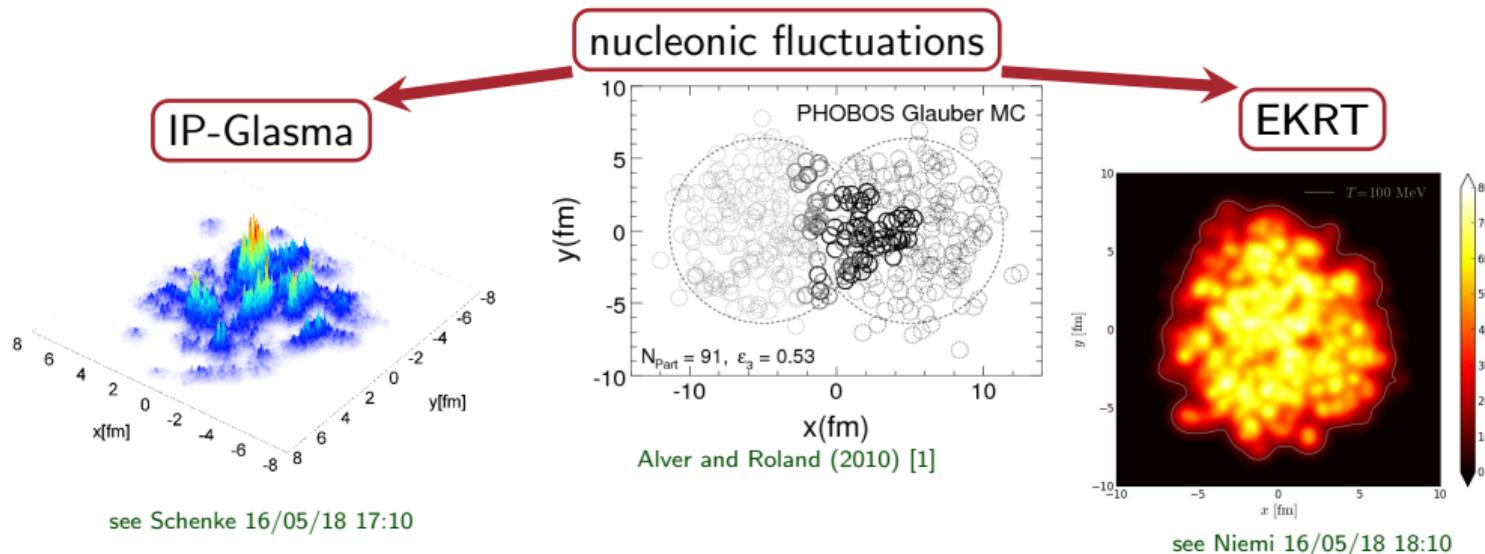
- xy Transverse geometry at mid-rapidity: subnucleonic fluctuations.
- η Breaking boost invariance: rapidity fluctuations.
- τ Pre-equilibrium dynamics: connecting initial stages to late time dynamics.

See also these plenaries:

- | | |
|--------------------------------------------|---------------------------|
| ■ Collective effects in nuclear collisions | Noronha 17/05/18 11:30 |
| ■ Small system studies | Strickland 17/05/18 12:30 |
| ■ The high baryon density region | Yin 18/05/18 9:30 |
| ■ Electroweak probes in nuclear collisions | Novitzky 18/05/18 15:00 |
| ■ Studies of Ultra Peripheral Collisions | Angerami 18/05/18 15:30 |

Current status: 2D initial conditions

State of the art 2D initial conditions for hydrodynamic evolution



Different energy liberation descriptions:

- IP-Glasma – IP-Sat dipoles and classical 2+1D Yang Mills evolution

Schenke, Tribedy, Venugopalan (2012)[2, 3]

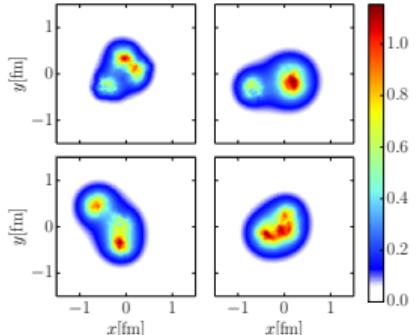
- EKRT – saturated NLO pQCD minijet production (initial energy profile)

Niemi, Eskola, Paatelainen (2016)[4]

Good agreement with data over a range of collision energies and systems.

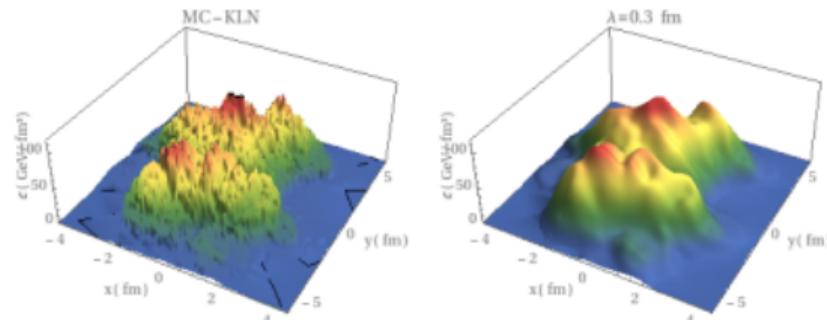
Are sub-nucleonic fluctuations important?

Yes! Proton size fluctuations



Mäntysaari, Schenke, Shen, Tribedy (2017) [6]

Maybe? Smearing out granularity



Gardim, Grassi, Ishida, Luzum, Magalhães, Noronha-Hostler (2017)[5]

■ Systematic modeling of sub-nucleonic structure

see Mäntysaari 16/05/18 17:30, Moreland 15/05/18 16:20, Schlichting's poster

⇒ *crucial for flow harmonics in proton-nucleus collisions*

■ Transverse fluctuations in nucleus-nucleus collisions

see Grassi 16/05/18 12:10

⇒ *v_n 's sensitive only to large scale fluctuations*

⇒ *need to use subleading flows and factorization ratios r_n*

Breaking boost invariance: 3D initial conditions

What is the physical origin of rapidity fluctuations?

A number of ideas:

- asymmetric energy deposition between forward and backward moving participants
Bzdak and Teaney (2012)[7], Bozek and Broniowski (2015)[8], Monnai and Schenke, (2015)[9]
- string melting in transport models (AMPT)
Pang, Petersen, Qin, Roy, Wang (2014)[10]
- quantum fluctuations of color charges in Bjorken- x evolution
Schenke and Schlichting, (2016) [11]

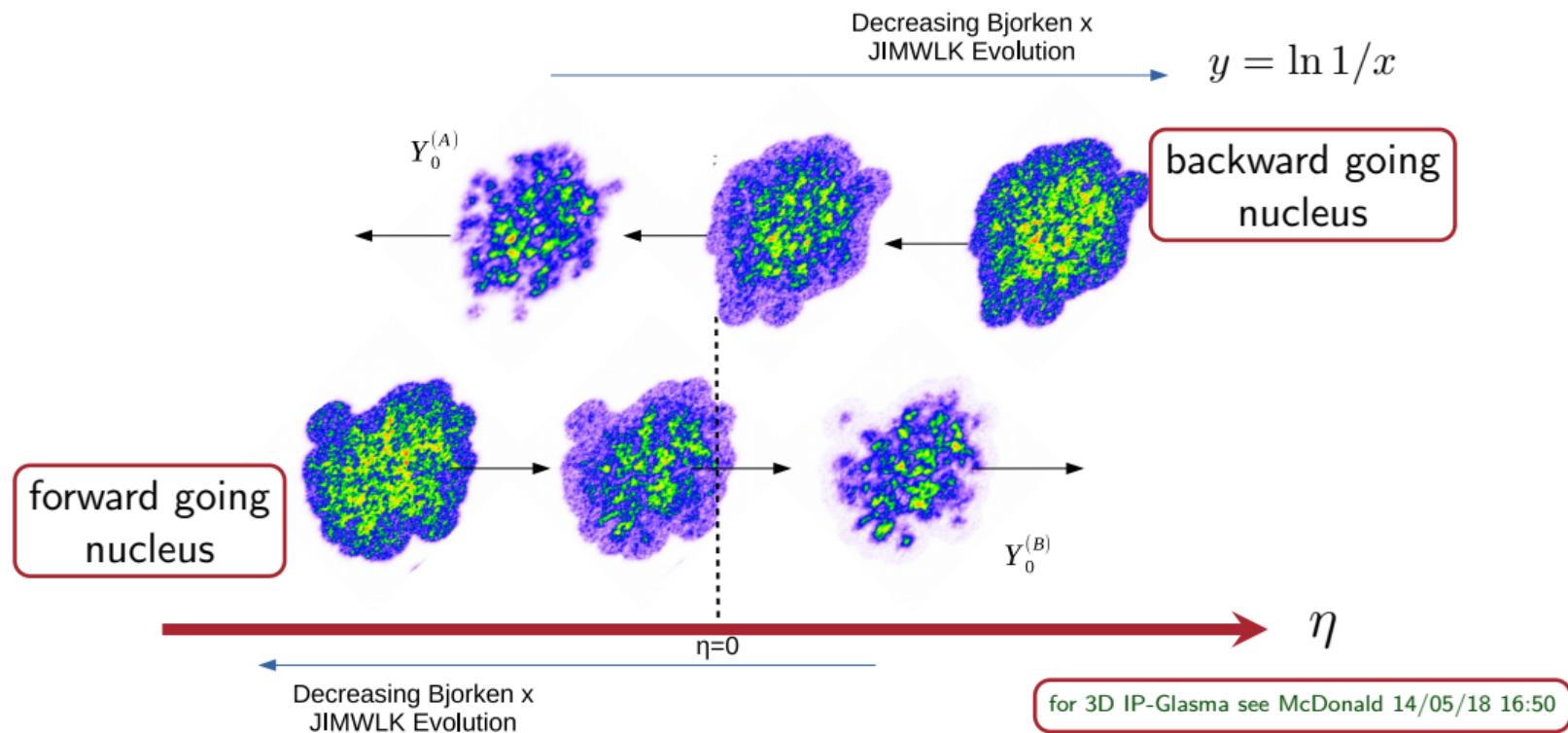
One should admit that on the physics side there is a high demand for a deeper understanding of the mechanism generating the early stage fluctuations manifest in the forward-backward flow decorrelations.

Bozek and Broniowski (2017)[12]

Motivation for understanding rapidity physics

- Probes the earliest moments in the collision
- Rich set of experimental results
- Necessary for Beam Energy Scan
- New flow observables (large directed flow of D mesons)
see Singha 16/06/18 9:40, Chatterjee 16/06/18 10:20

3D initial conditions at high energies: small- x evolution



for longitudinal fluctuations with AMPT see Wu 15/05/18 15:20

Lappi, Mantysaari, Eur. Phys. J. C (2013)
Schenke, Schlichting, PRC (2016)

3D initial conditions at lower energies: string deceleration

At low energies the nuclei crossing is slow \Rightarrow need dynamic initialization of hydrodynamics

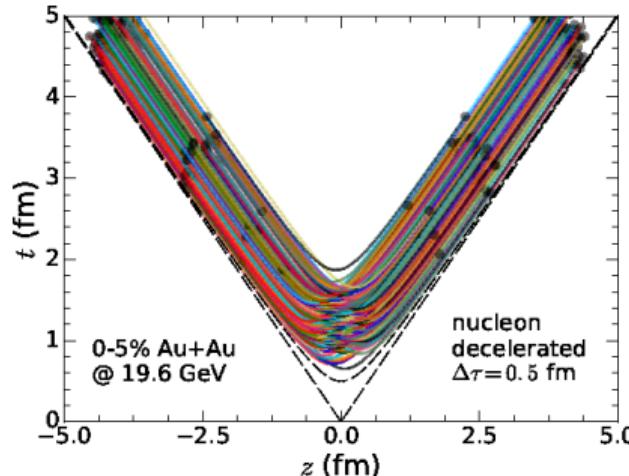
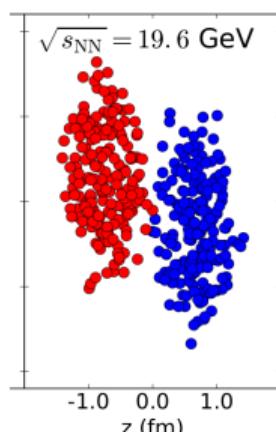
see Shen 16/05/18 11:30, Shen and Schenke (2017) [13]

- Connect participants by strings
- Evolve strings for $\Delta\tau \sim 0.5 \text{ fm}/c$
- Deposit energy and baryon density in hydrodynamics

$$\partial_\mu T^{\mu\nu} = J_{\text{source}}^\mu, \quad \partial_\mu J_B^\mu = \rho_{\text{source}}$$

\Rightarrow Collision energy dependence of rapidity distributions

\Rightarrow Important for early photon emission



- for UrQMD + hydrodynamics
- for baryon stopping

see Du 16/05/2018 11:10, Karpenko 15/05/18 09:40

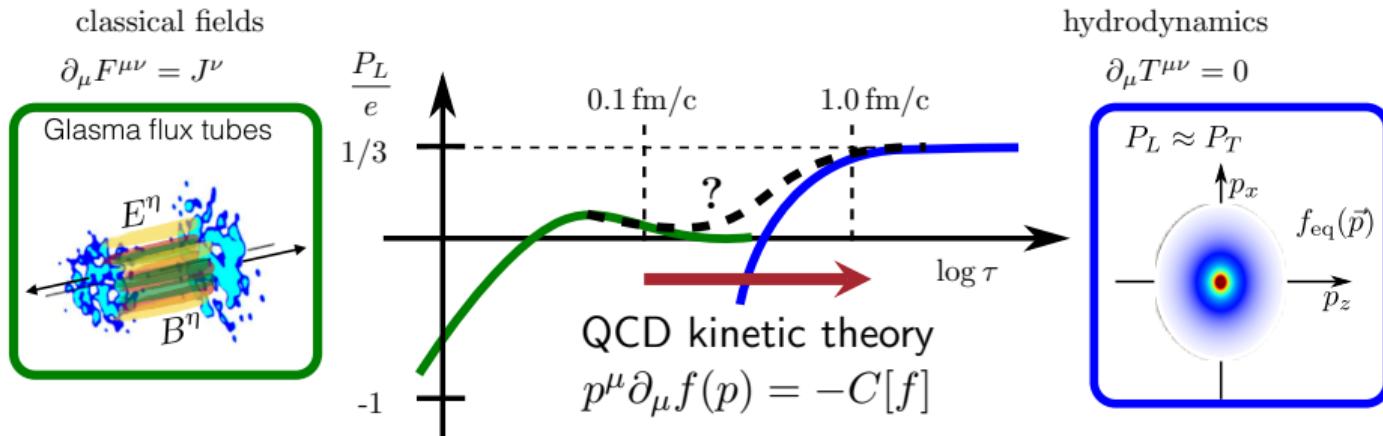
see Mohs poster and Kapusta 15/05/18 16:20

Pre-equilibrium dynamics: building a complete picture

Initial stages at very high collisions energies

- At early times $\tau \sim 1/Q_s$ particle production modeled by classical Yang-Mills evolution of strong chromo- E and B fields.
for non-equilibrium quark production in CYM see Tanji 14/05/18 17:10
- At $\tau \sim 1 \text{ fm}/c$ deviations from equilibrium described by viscous hydrodynamics
for thermalization in Bjorken and Gubser flows see Heinz 16/05/18 18:10

How to connect early particle production to subsequent hydrodynamic simulation?



for far-from-equilibrium hydrodynamics see Noronha's plenary 17/05/18 11:30

QGP description with QCD kinetic theory

Effective kinetic theory at weak coupling (AMY)

Arnold, Moore, Yaffe (2003)[14]

- describes collisions between energetic quarks and gluons in QGP
- at leading order: elastic $2 \leftrightarrow 2$ and inelastic $1 \leftrightarrow 2$ processes

\Rightarrow *the same QCD physics as in jet quenching*

$$\underbrace{\partial_\tau f + \frac{\mathbf{p}}{|p|} \cdot \nabla f - \frac{p_z}{\tau} \partial_{p_z} f}_{\text{Boltzmann equation}} = - \underbrace{\mathcal{C}_{2 \leftrightarrow 2}[f]}_{\text{Feynman diagram of two gluons interacting via a virtual gluon exchange}} - \underbrace{\mathcal{C}_{1 \leftrightarrow 2}[f]}_{\text{Feynman diagram of one gluon interacting with two gluons via a virtual gluon exchange}}$$

- interactions brings the QGP towards local thermal equilibrium
- at late times kinetic theory matches viscous hydrodynamics
- the onset of kinetic behavior seen in classical Yang-Mills simulations

Baier, Mueller, Schiff, and Son (2001)[15]

Kurkela and Zhu (2015)[16]

Berges, Boguslavski, Schlichting, Venugopalan (2014)[17], Boguslavski's poster

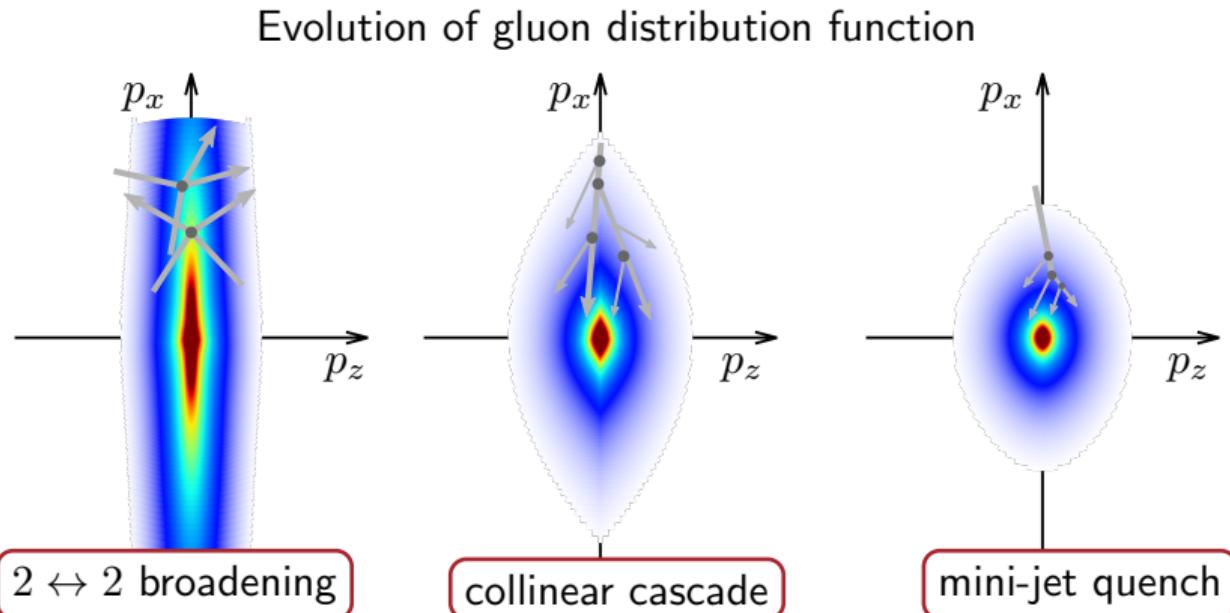
QCD kinetic theory—the bridge between classical fields and hydrodynamic descriptions.

cf. work by El, Xu and Greiner (2005) [18, 19] and see Greif 15/05/18 15:00

Three steps of thermalization in kinetic theory

Numeric simulations of gluonic plasma

Kurkela and Zhu (2015)[16] Keegan, Kurkela, AM and Teaney (2016) [20]
Kurkela, AM, Paquet, Schlichting and Teaney (2018)[21, 22]



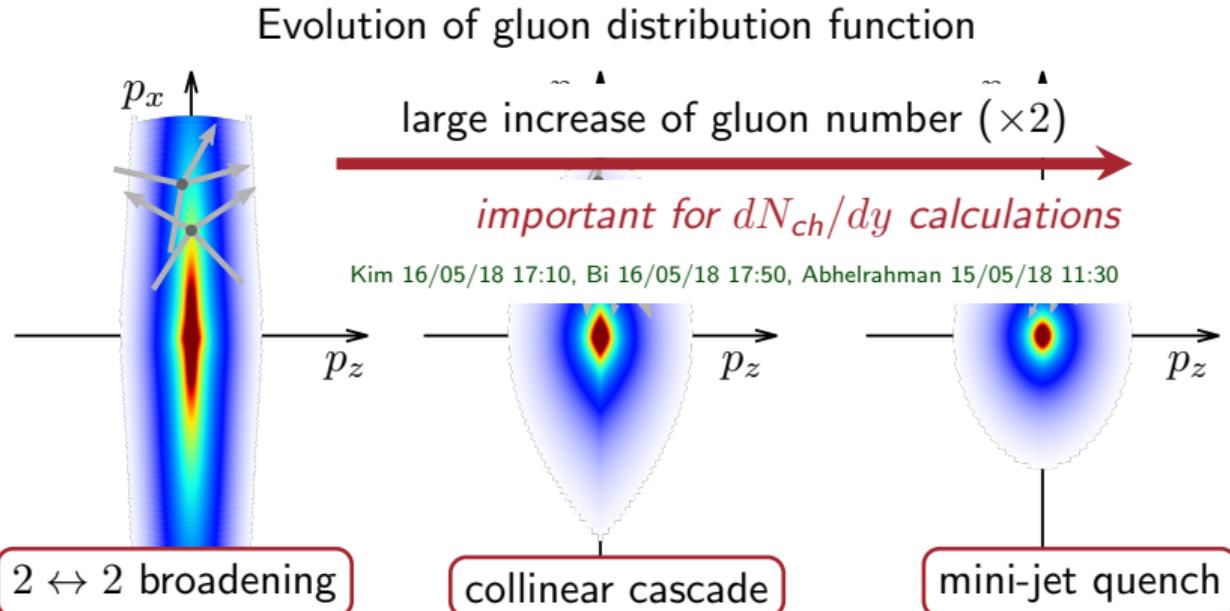
The equilibration time governed by the coupling constant

$$\alpha_s \iff \eta/s$$

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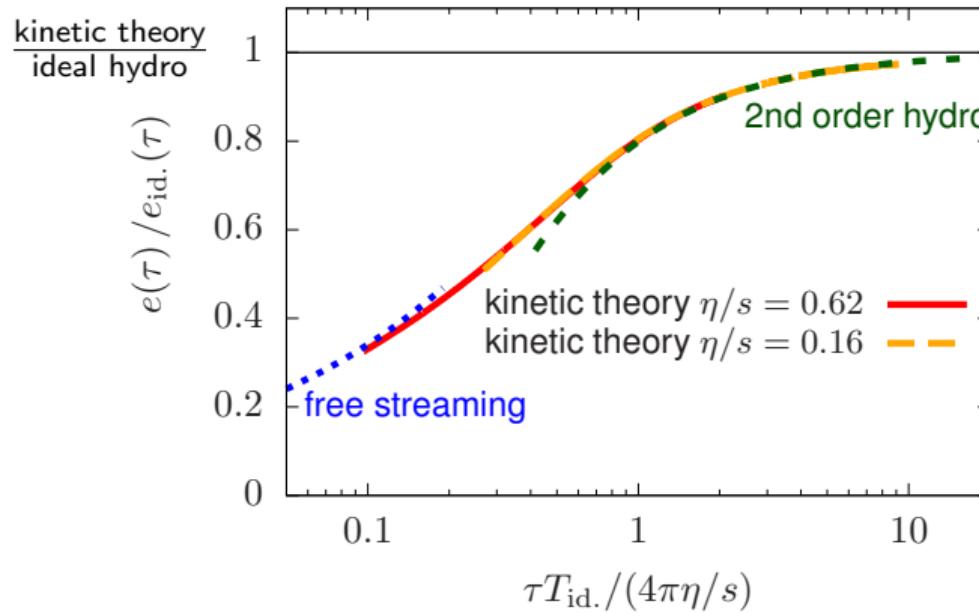


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Hydrodynamization time for boost invariant expansion

Kinetic equilibration becomes universal for scaled time $\frac{\tau}{\tau_R(\tau)} = \frac{\tau T(\tau)}{\eta/s}$

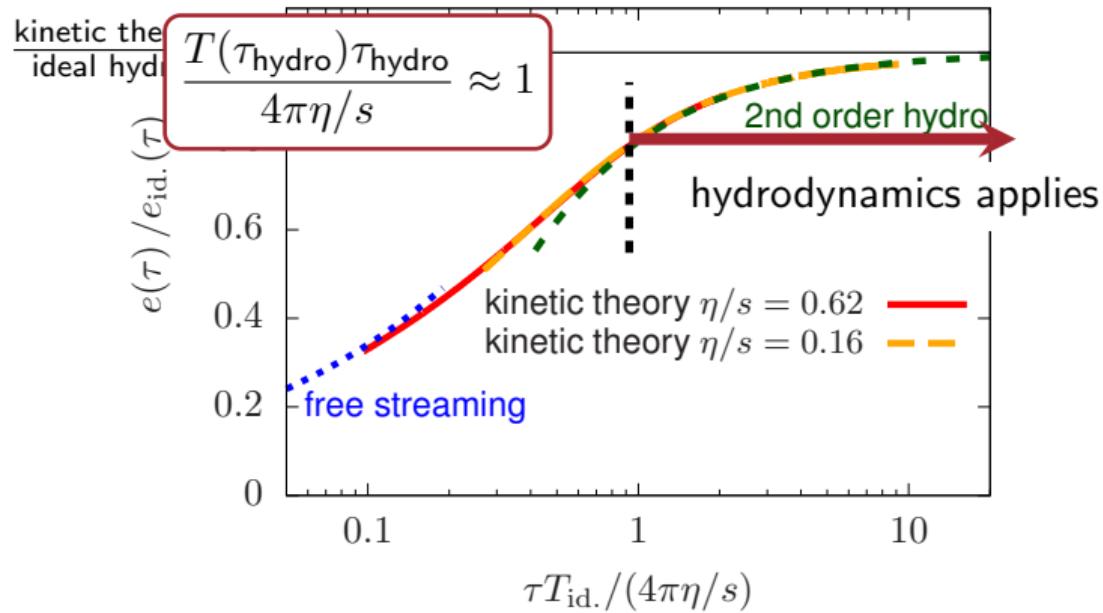


The same hydrodynamization time scale at weak and strong couplings!

Keegan, Kurkela, Romatschke, Schee and Zhu (2015) [23], Heller, Kurkela, and Spalinski (2017) [24], Strickland, Noronha, and Denicol (2017) [25]
Behtash, Cruz-Camacho, and Martinez (2017) [26], Romatschke (2017) [27]

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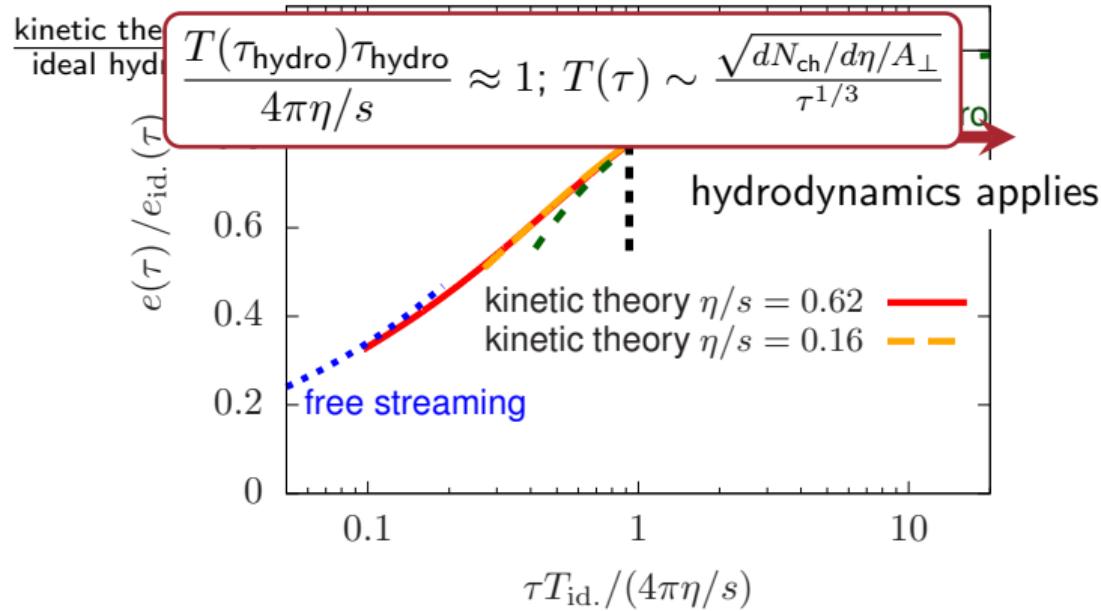


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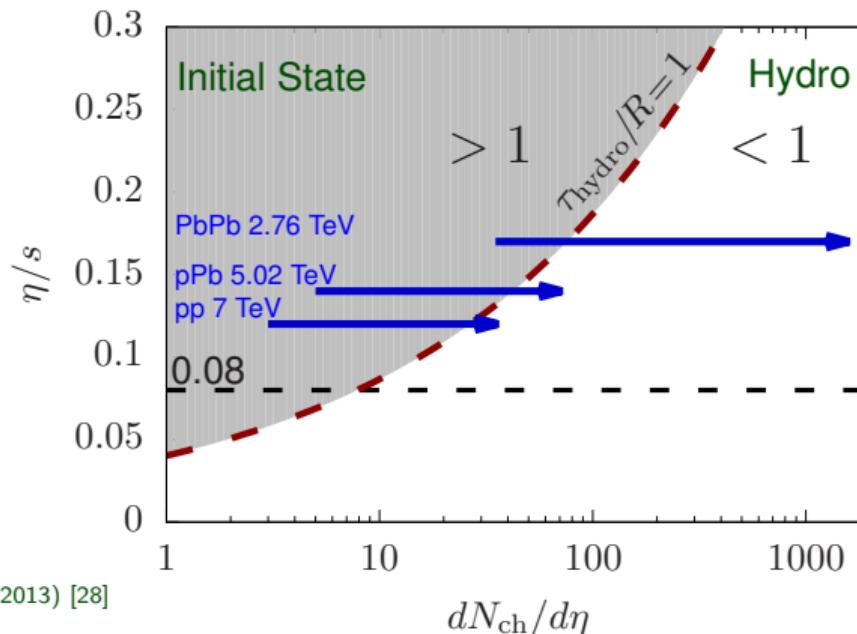
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Conformal scaling and system size

Will hydrodynamically flowing QGP be formed for a given $dN_{\text{ch}}/d\eta$?

Kurkela, AM, Paquet, Schlichting and Teaney (2018)[21]

$$\frac{\tau_{\text{hydro}}}{R} \approx \left(\frac{4\pi(\eta/s)}{2} \right)^{\frac{3}{2}} \left(\frac{dN_{\text{ch}}/d\eta}{63} \right)^{-\frac{1}{2}} \left(\frac{S/N_{\text{ch}}}{7} \right) \left(\frac{\nu_{\text{eff}}}{40} \right)^{\frac{1}{2}}$$

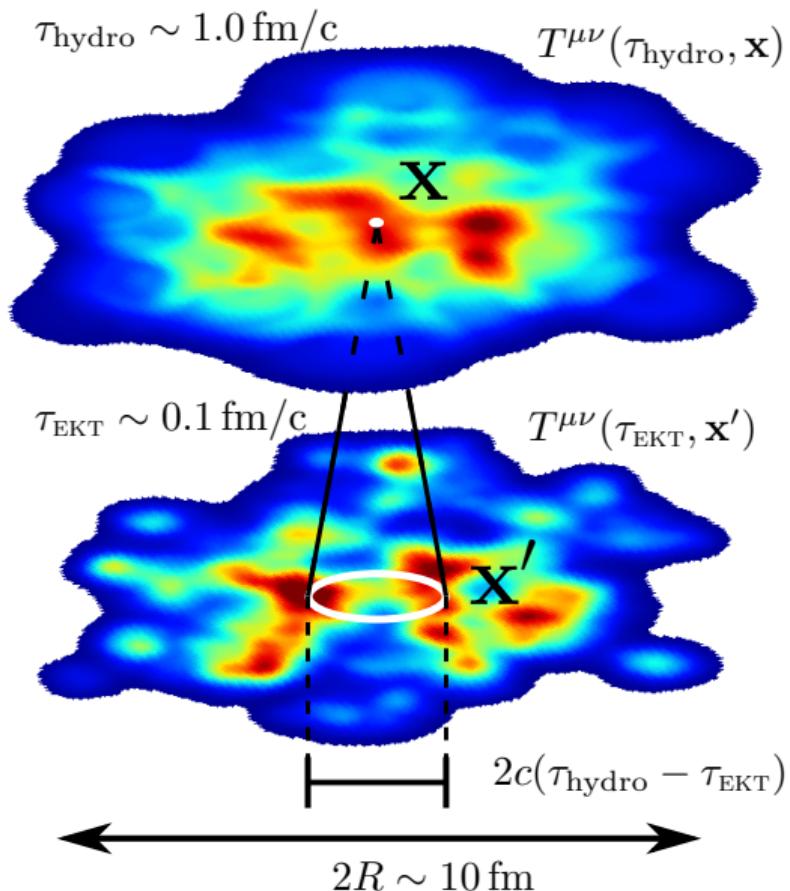


cf. earlier estimates Basar and Teaney (2013) [28]

Schlichting and Tribedy (2016)[29]

see also Kurkela 15/05/18 11:50

Practical event-by-event kinetic pre-equilibrium



Finding $T^{\mu\nu}$ at $(\tau_{\text{hydro}}, \mathbf{x})$

- By causality, only evolve *a small region around \mathbf{x} .*
- Linearize $T^{\mu\nu}(\tau_{\text{EKT}}, \mathbf{x}')$ around *local background*.
- Propagate $\delta T_x^{\mu\nu}(\tau_{\text{EKT}}, \mathbf{x}')$ with *linear response functions*.

Kinetic theory response functions

Linear response functions for initial energy and momentum perturbations

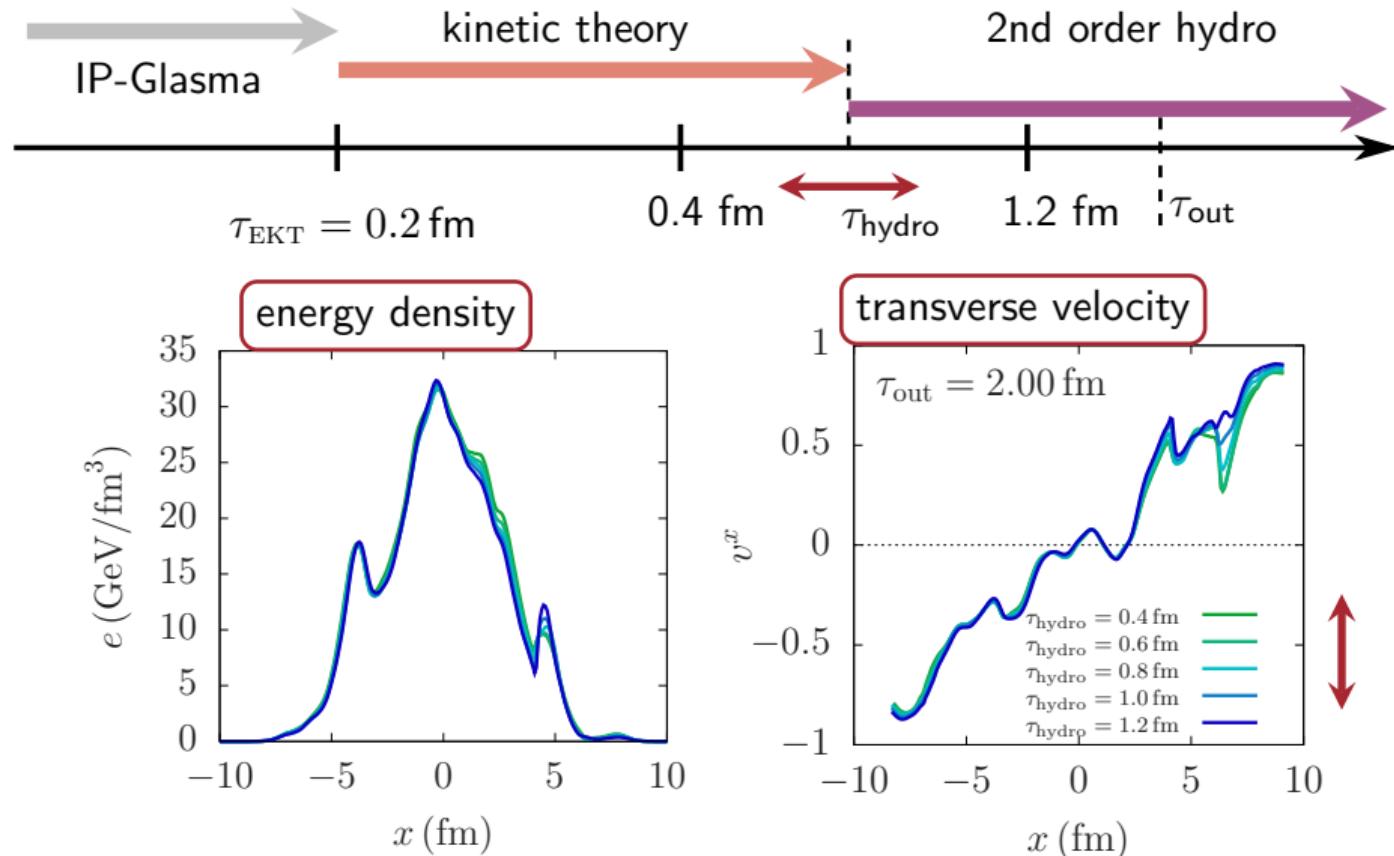
$$\underbrace{\delta T_{\mathbf{x}}^{\mu\nu}(\tau_{\text{hydro}}, \mathbf{x}')}_{\text{goes into hydro}} = \int d^2\mathbf{x}' \underbrace{G_{\alpha\beta}^{\mu\nu}(\mathbf{x} - \mathbf{x}', \tau_{\text{hydro}}, \tau_{\text{EKT}})}_{\text{linear response function}} \underbrace{\delta T_{\mathbf{x}}^{\alpha\beta}(\tau_{\text{EKT}}, \mathbf{x}')}_{\text{initial}}.$$

- do linearized kinetic theory evolution
- extract independent Green's functions for the full $T^{\mu\nu}$.
- long wavelengths & late times \Rightarrow hydrodynamic response
cf. universal velocity response Vreedevoogd and Pratt (2008) [30], Shee, Romatschke and Pratt (2013) [31]
- short wavelengths & early times \Rightarrow free streaming response
Broniowski, Florkowski and Chojnacki, and Kisiel (2008) [32] Liu, Shen and Heinz (2015) [33]

KøMPØST—linearized kinetic theory propagator of heavy ion initial conditions.
Publicly available at github.com/KMPST/KoMPoST

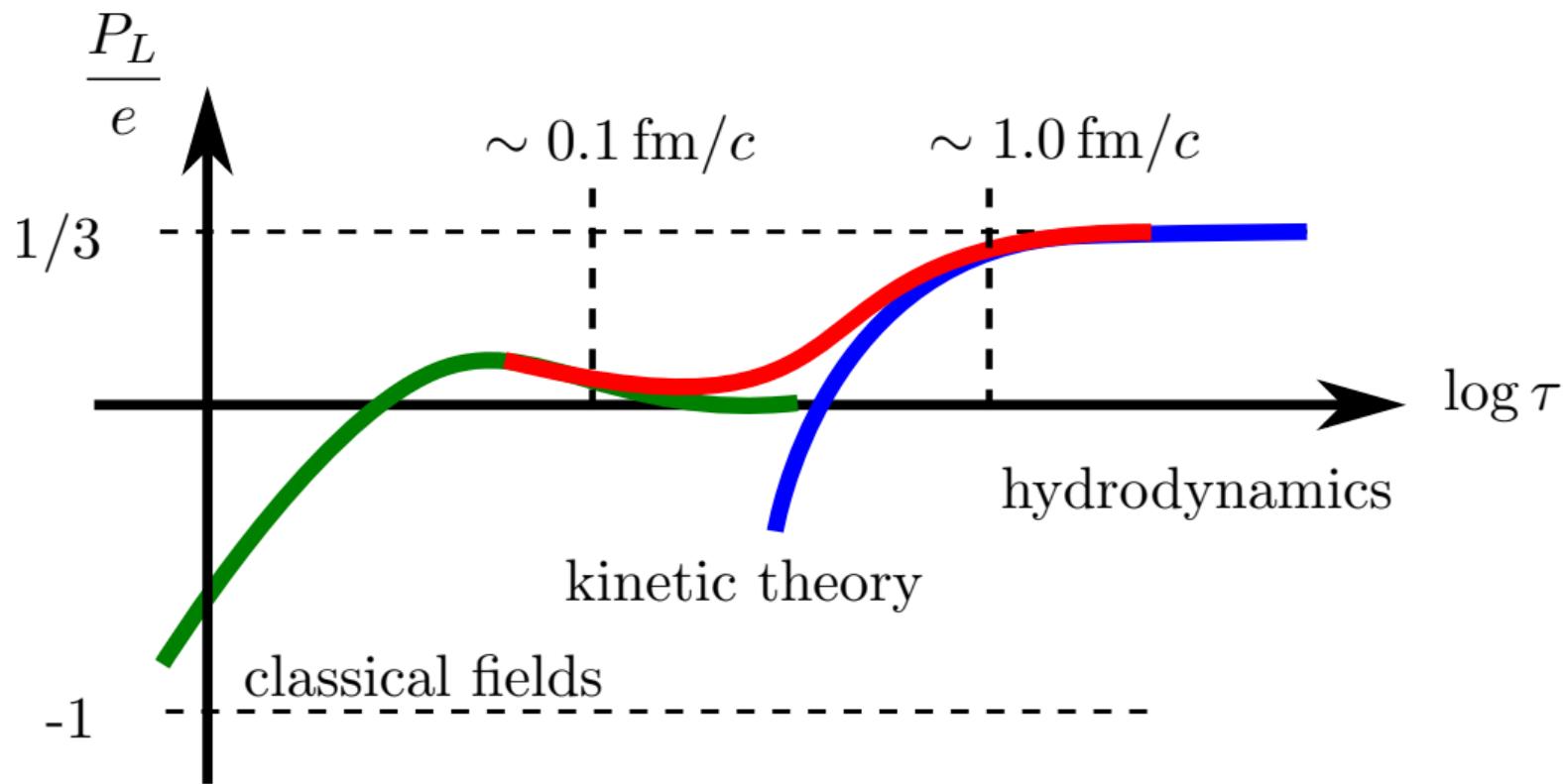
Kurkela, AM, Paquet, Schlichting and Teaney (2018)[21, 22]

Results: event-by-event initial stage matching

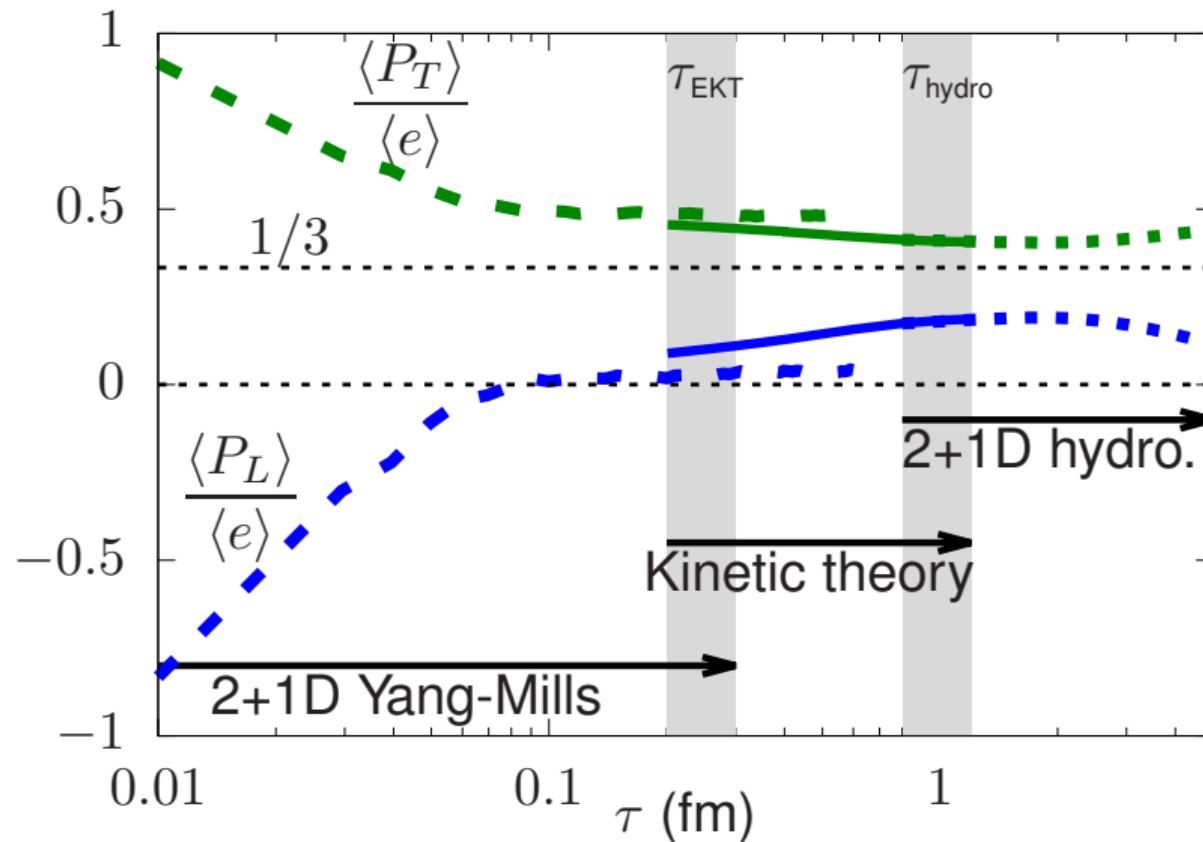


Smooth matching between kinetic phase and hydrodynamics \Rightarrow independence of τ_{hydro} .

Overlapping descriptions of initial stages at (high energy) heavy ion collisions



Overlapping descriptions of initial stages at (high energy) heavy ion collisions



Summary

- xy Good description of mid-rapidity v_n 's across many collision systems
⇒ *Can we see genuine (sub-nucleonic) QCD fluctuations?*
- η New ideas for rapidity fluctuations at low and high energies
⇒ *Can we verify the physical origin of rapidity fluctuations?*
- τ Emerging multistage picture of initial stages
⇒ *Are initial stages "the whole story" in small systems?*

Backup

IP-Glasma: data to model comparison

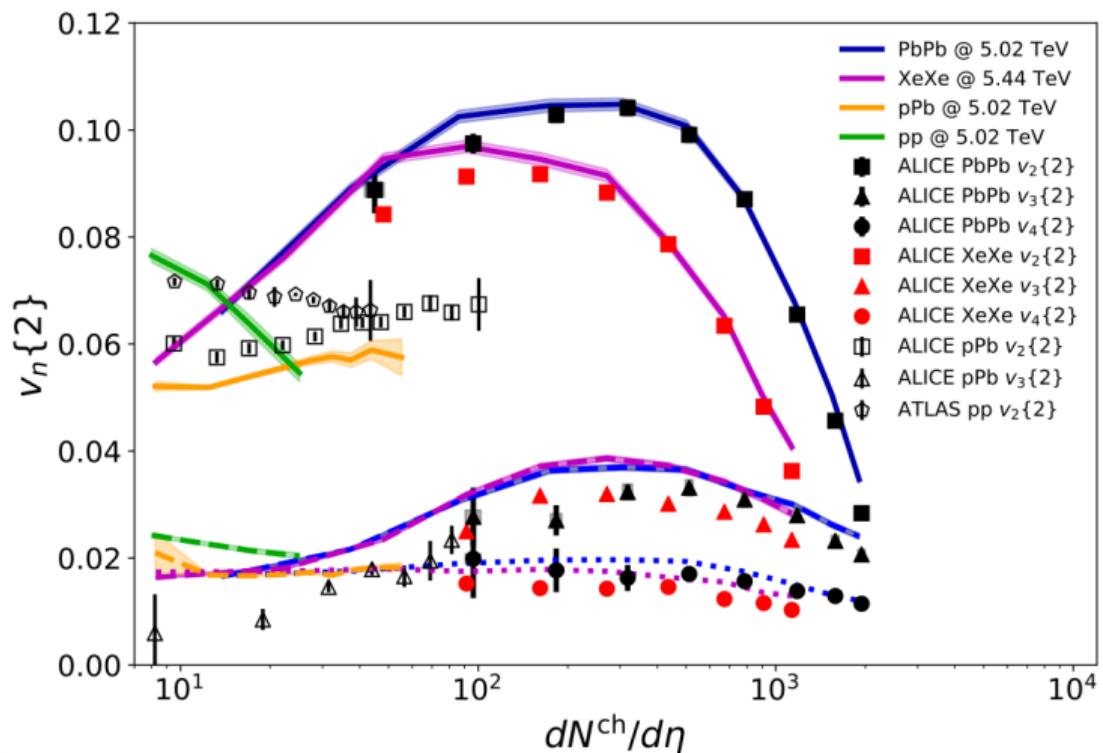


Figure: With IP-Glasma initial conditions. B. Schenke, C. Shen, P. Tribedy, in preparation

EKRT: data to model comparison

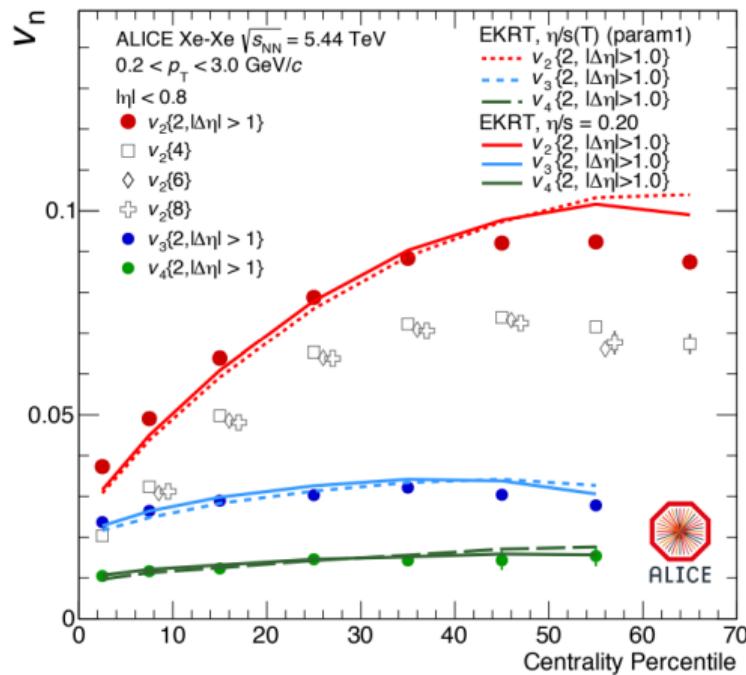
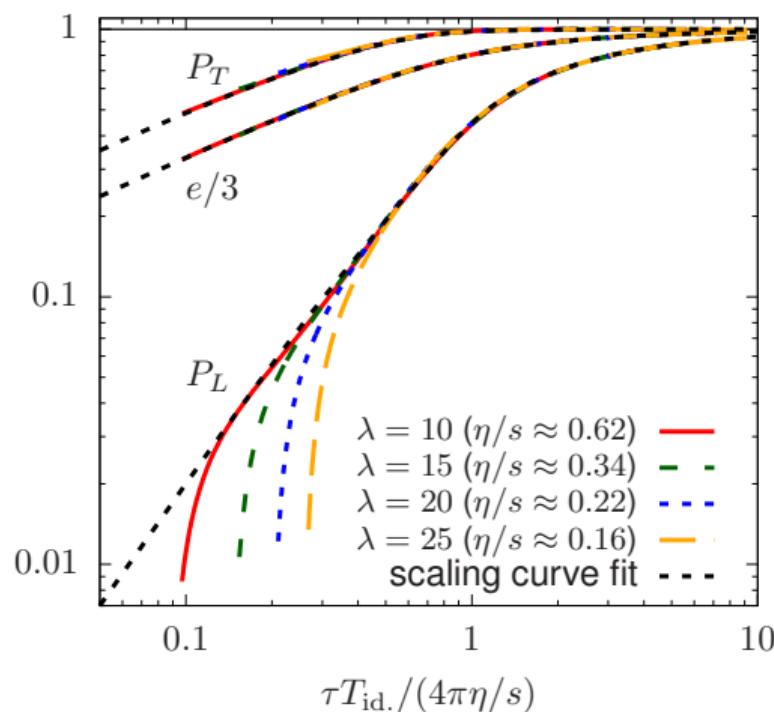
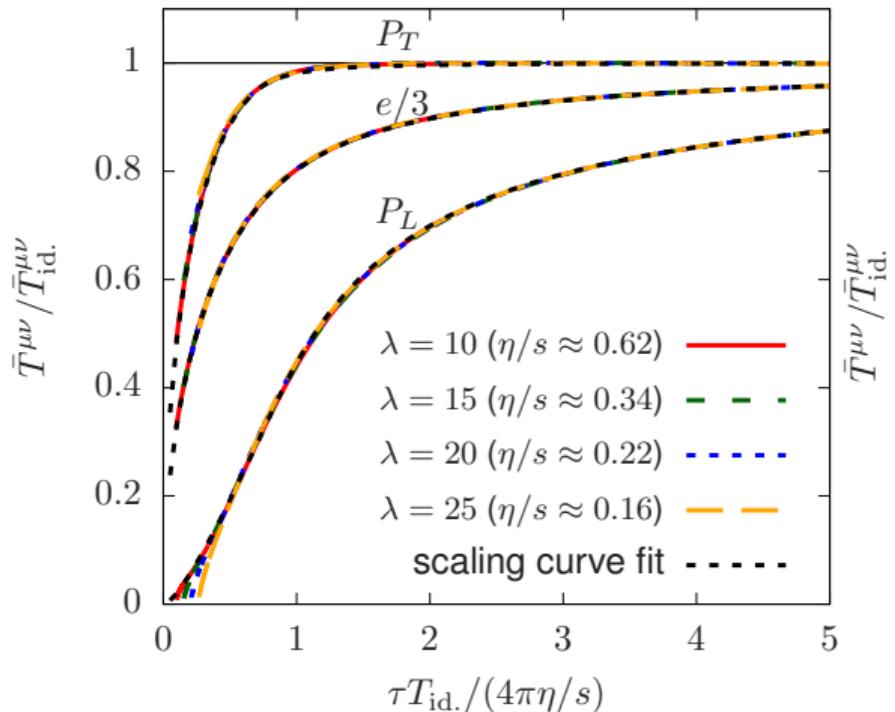


Figure: [arXiv:1805.01832]. With EKRT initial conditions Eskola, Niemi, Paatelainen and Tuominen, PRC 97, no. 3, 034911 (2018), arXiv:1711.09803

Energy momentum tensor evolution in kinetic theory

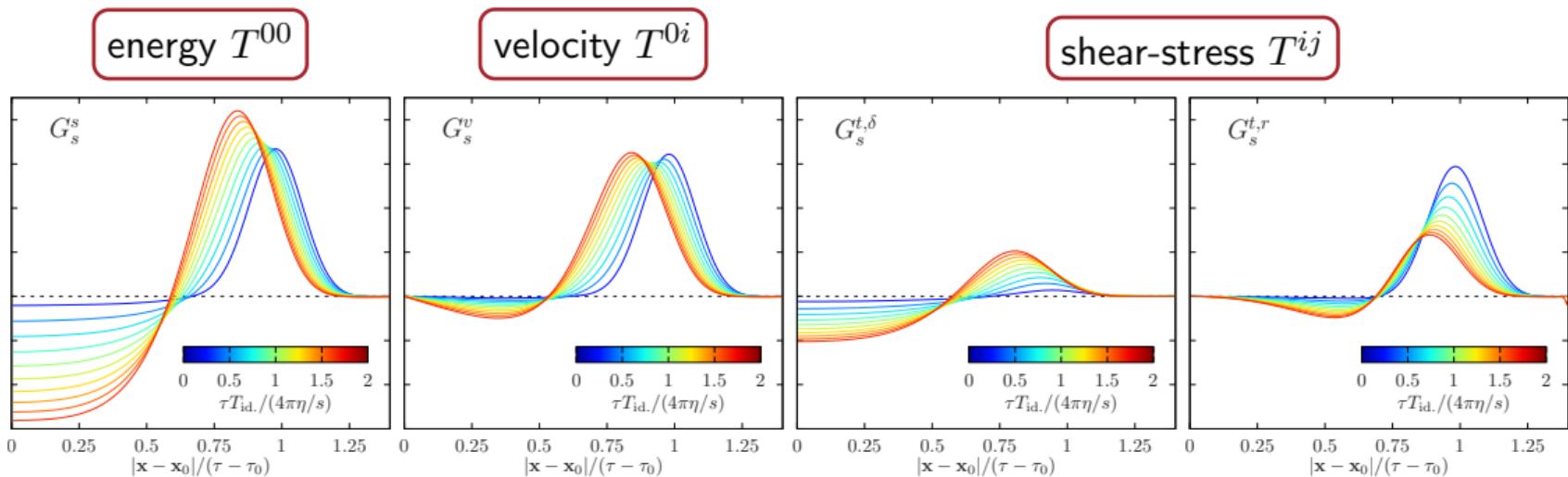


Kinetic response functions

- Response to perturbations also collapse to scaling solutions

$$\tilde{G}^{\mu\nu}\left(|\mathbf{k}|, \tau, \tau_0, e(\tau_0), \lambda\right) = \tilde{G}^{\mu\nu, \text{univ}}\left(\frac{\tau T_{\text{id.}}}{\eta/s}, |\mathbf{k}|(\tau - \tau_0)\right)$$

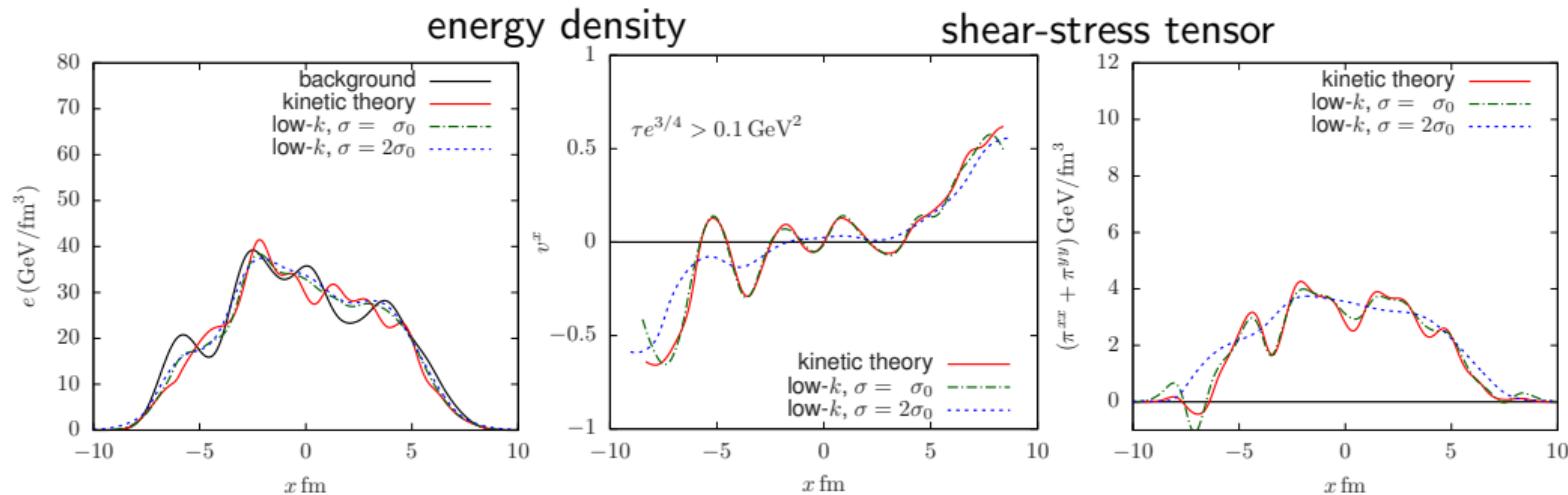
- Agrees with hydrodynamic scaling in $\tau \rightarrow \infty, |\mathbf{k}|\tau \rightarrow 0$ limit.
- Good scaling for a range of $\eta/s = 0.16\text{--}0.62$ values.



Free streaming and low- $|k|$ limits of kinetic theory

Extreme limits of kinetic response:

- small- $|k|$ expansion à la Pratt, cf. [30, 31]
- free streaming response functions, cf.[32, 33]

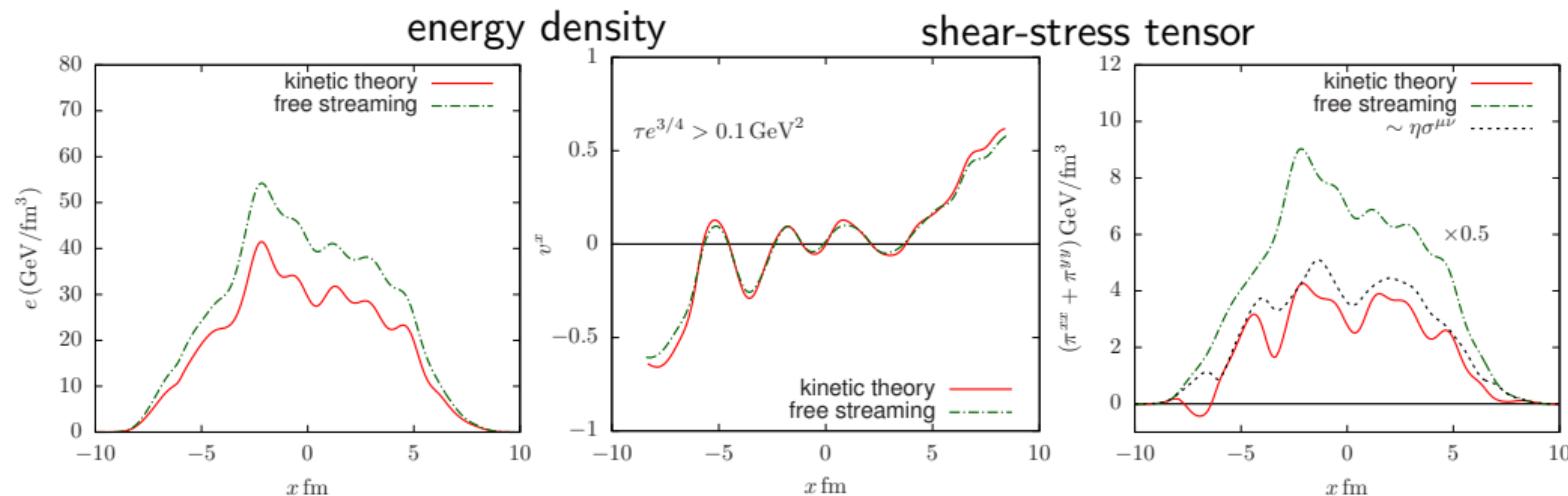


Note: MC-Glauber initial conditions

Free streaming and low- $|k|$ limits of kinetic theory

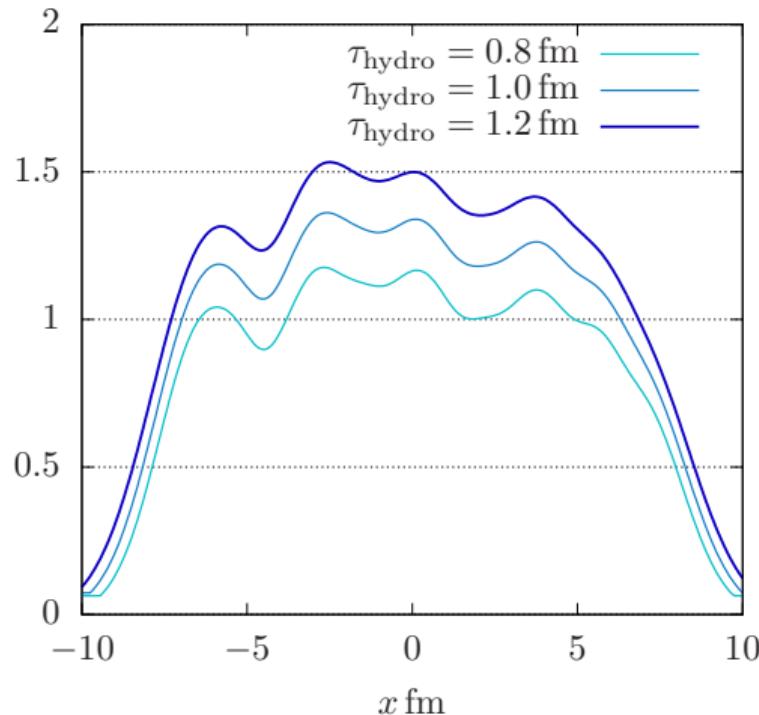
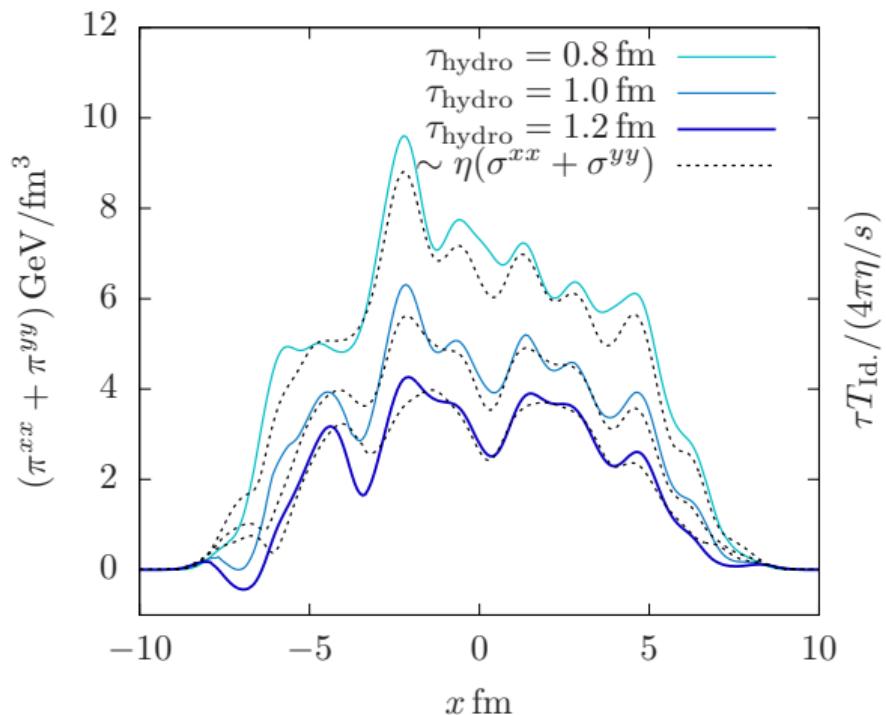
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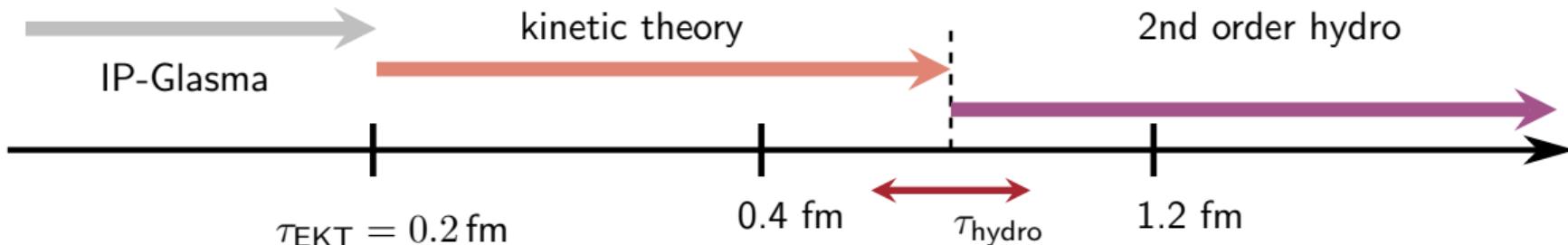
Note: MC-Glauber initial conditions

Shear-stress tensor from KøMPØST evolution

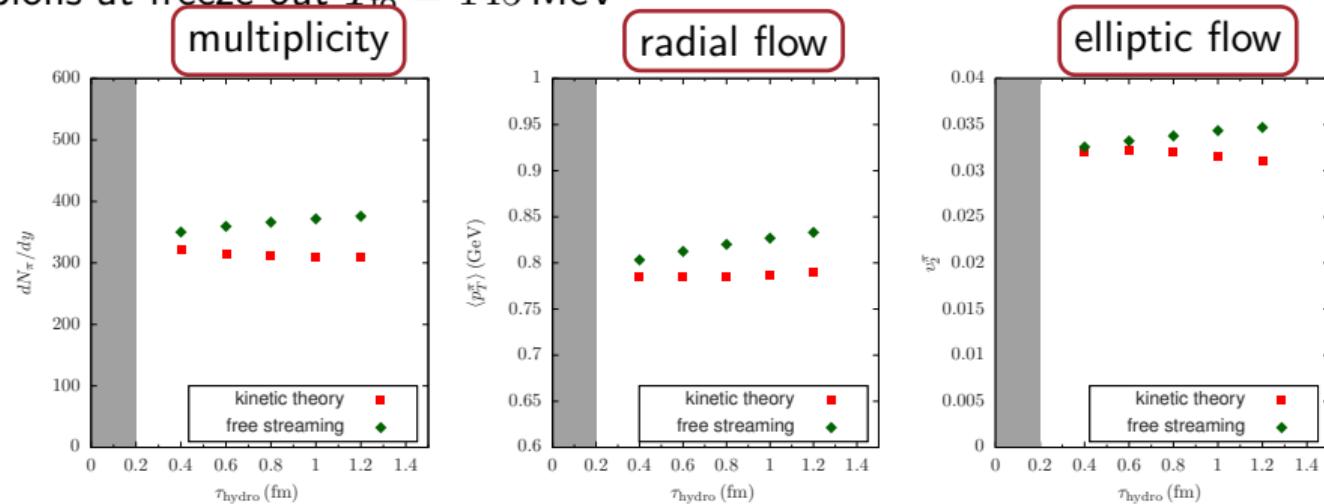


Note: MC-Glauber initial conditions

Results: Hadronic observables



Thermal pions at freeze-out $T_{\text{fo}} = 145 \text{ MeV}$



Approximate independence of τ_{hydro} for kinetic pre-equilibrium evolution!

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