Matching of initial conditions to hydro evolution

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A. Kurkela, AM, J.-F. Paquet, S. Schlichting, D. Teaney *PRC* (1805.00961), *PRL* (1805.01604)
AM, J. Berges *PRL* (1810.10554)
A. Kurkela, AM *PRD* (1811.03068), *PRL* (1811.03040)

Isolated quantum systems and universality in extreme conditions

Itermediate stages of high energy nuclear collisions

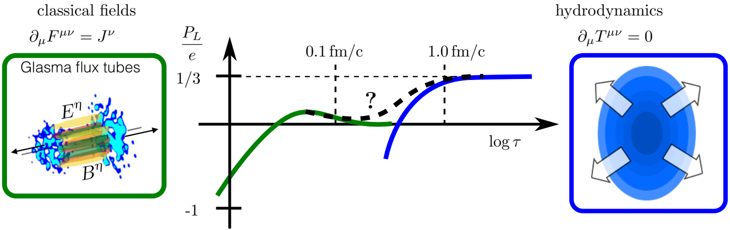
- Early times $\Longrightarrow$ classical field evolution, pre-scaling

see Berges's plenary, Tue, 10:45, AM, Berges (2018)[1]

- Late times $\Longrightarrow$ hydrodynamic attractors

see Heller's plenary, Tue, 11:45

How to map early time initial conditions to late time hydro response?



"Bottom-up" thermalization scenario

Baier, Mueller, Schiff, and Son (2001)[2]

Consequences of pre-equilibrium:

- Bulk: isotropization, entropy production, chemical equilibration.
- Transverse dynamics: radial flow generation, rise of v_n harmonics.

for strong coupling view, see Grozdanov's plenary, Thu, 11:15, van der Schee's talk, Tue, 15:20

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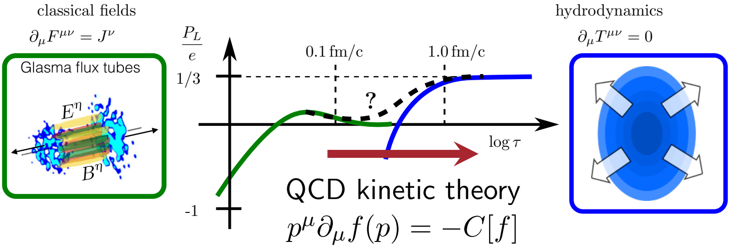

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High temperature gauge kinetic theory $\Lambda_{QCD} \ll gT \ll T$

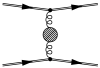
Kinetic theory of weakly coupled quark and gluon quasi-particles.

Arnold, Moore, Yaffe (2003)[3]

$$\partial_\tau f_{g,q} + \vec{v} \cdot \vec{\nabla} f_{g,q} = -\mathcal{C}_{2\leftrightarrow 2}[f] - \mathcal{C}_{1\leftrightarrow 2}[f]$$

Leading order in the coupling constant $\lambda = 4\pi\alpha_s N_c$:

- $\mathcal{C}_{2\leftrightarrow 2}[f]$ elastic scatterings: $gg \leftrightarrow gg$, $qq \leftrightarrow qq$, $qg \leftrightarrow gq$, $gg \leftrightarrow q\bar{q}$



$$= |\mathcal{M}^{gg}_{qq}|^2 = \lambda^2\, 16 \frac{d_F C_F}{C_A^2} \left[C_F \left(\frac{u}{t} + \frac{t}{u} \right) - C_A \left(\frac{t^2 + u^2}{s^2} \right) \right]$$

Hard Thermal Loop resummed propagators, screening mass $m_D \sim gT$

Braaten, Pisarski (1990) [4] for checks of HTL see Peuron's talk, Tue, 15:40

Typically consider QCD with $N_c = 3$ and $N_f = 0$ or 3 massless quarks.

Alternative kinetic descriptions:

- Relaxation time approximation — see Schlichting/Martinez's poster
- Scalar $\lambda\varphi^4$ theory — Almaalol's talk (also RTA), Tue/19, 15:40
- Isotropization time approximation — see Wu's plenary, Thu,11:45, Wiedemann's talk, Wed, 15:40

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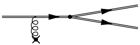
Leading order in the coupling constant $\lambda = 4\pi\alpha_s N_c$:

- $\mathcal{C}_{1\leftrightarrow 2}[f]$ medium induced colinear radiation: $g \leftrightarrow gg$, $q \leftrightarrow qg$, $g \leftrightarrow q\bar{q}$



$$= |\mathcal{M}^g_{qq}|^2 = \frac{k'^2 + p'^2}{k'^2 p'^2 p^3} \underbrace{\mathcal{F}_q(k'; -p', p)}_{\text{splitting rate}}$$

  Resummed multiple scatterings with the medium (Landau–Pomeranchuk–Migdal suppression).

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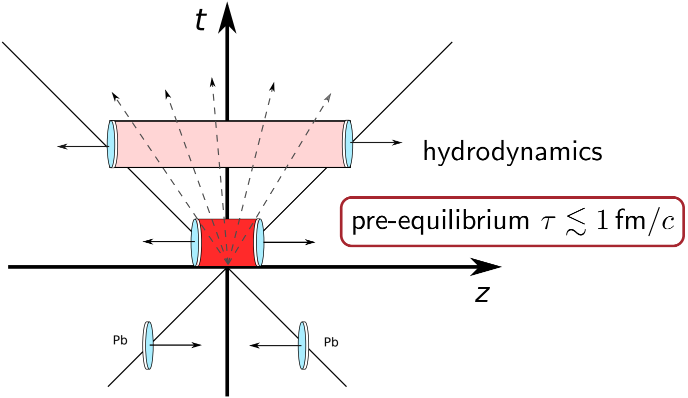
Bulk equilibration

Boost invariant expansion

In thermal equilibrium—conservation of entropy per unity rapidity Bjorken (1983)

$$\frac{dN}{d\eta} \sim \frac{dS}{d\eta} = \langle s\tau \rangle = \text{const} \quad \Longrightarrow \quad T_{\text{id.}}(\tau) \propto \frac{\langle s\tau \rangle^{1/3}}{\tau^{1/3}}$$

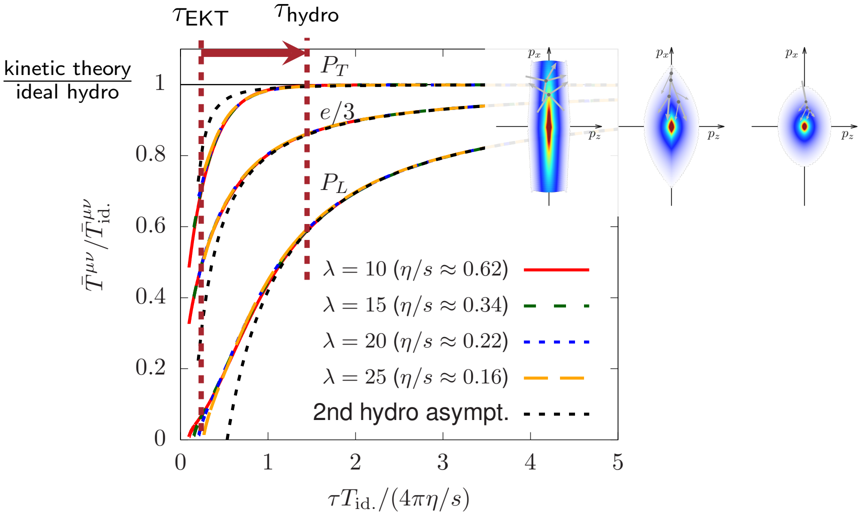


"Measure" energy with respect to ideal expansion $e_{eq} \propto T^4_{id.}$.

Time dependent mean free path $\Rightarrow \tau_R \equiv \frac{4\pi\eta/s}{T_{\text{id}}(\tau)}$

Energy-momentum tensor evolution

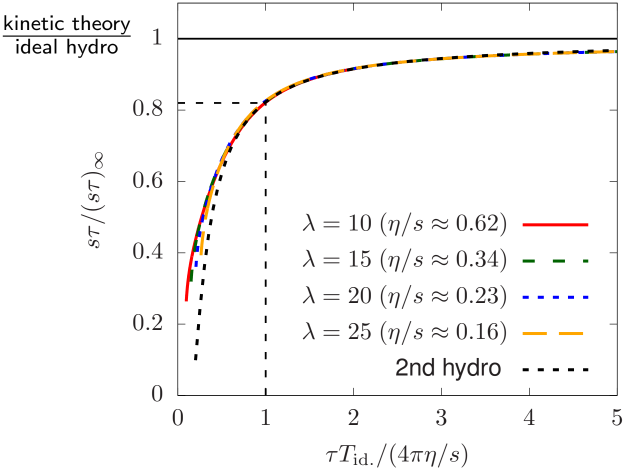
Universal isotropization in units of kinetic relaxation time $\tau_R = \frac{4\pi\eta/s}{T}$



Kurkela and Zhu (2015), Keegan, Kurkela, AM and Teaney (2016), Kurkela, AM, Paquet, Schlichting and Teaney (2018)
hydrodynamization and hydro attractors: see Shi's poster, Almaalol's talk, Tue/19, 15:40, Noronha's talk, Wed, 14:00, Denicol's talk, Tue, 17:00

Entropy production in pre-equilibrium

Nearly $\times 2$ increase in entropy in kinetic equilibration.



$$\left.\frac{dS}{dy}\right|_{\text{final}} \propto \frac{dN}{d\eta}$$

Determination of initial state properties, e.g. Q_s, sensitive to equilibration.

Keegan, Kurkela, Romatschke, Schee and Zhu (2015) Kurkela, AM, Paquet, Schlichting and Teaney (2018)

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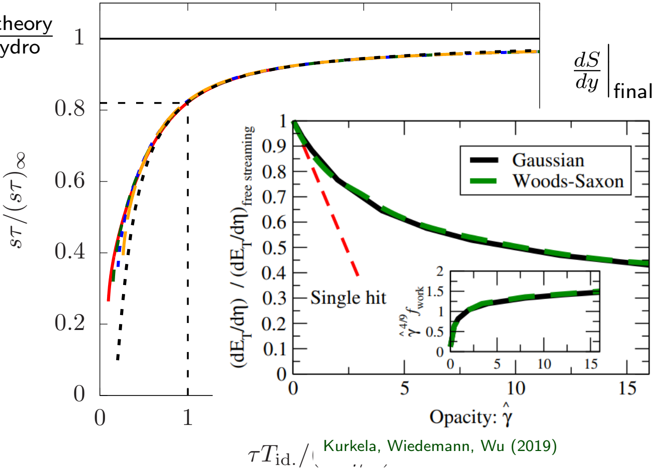

$$\left.\frac{dS}{dy}\right|_{\text{final}} \propto \frac{dN}{d\eta}$$

$$\frac{\left.\frac{dE}{d\eta}\right|_{\text{final}}}{\left.\frac{dE}{d\eta}\right|_{\text{initial}}}$$

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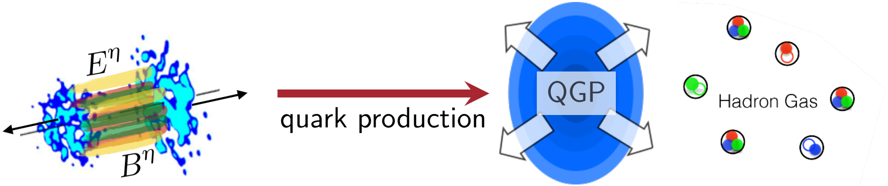
Chemical equilibration in hadronic collisions

At high energies mid-rapidity is dominated by small Bjorken-x gluons



But final state is assumed to be in chemical equilibrium:

- QGP expansion described by 3 flavour equation of state (u, d, s).
- hadron production at freeze-out consistent with thermal ensemble.

How can we produce fermions?

- Quark production from strong color fields.

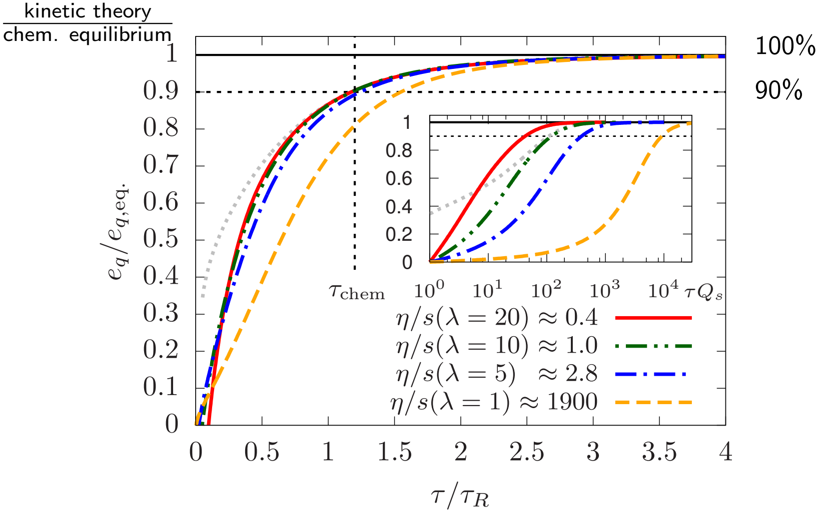
Tanji, Berges (2017) [5]
Martinez, Sievert, Wertepny (2018) [6]

- Leading order kinetics: gluon fusion $gg \leftrightarrow q\bar{q}$ and splitting $g \leftrightarrow q\bar{q}$.

Kurkela, AM (2018) [7, 8]

Quark energy equilibration

Fermion energy relative to energy in chemical equilibrium.



Chemical equilibration at $\tau_{chem} \sim 1.2\tau_R(\tau)$.

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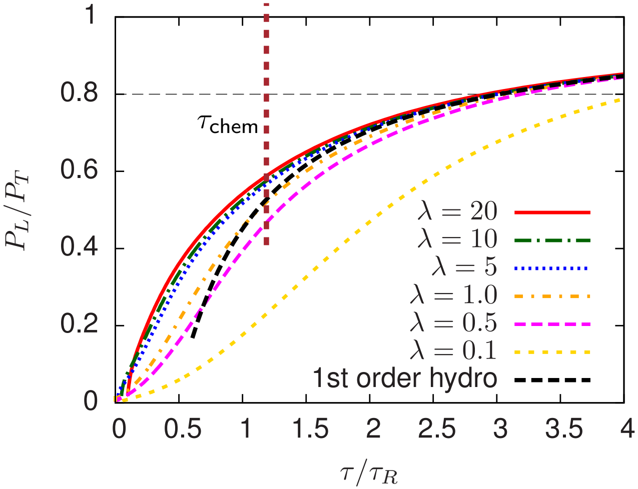
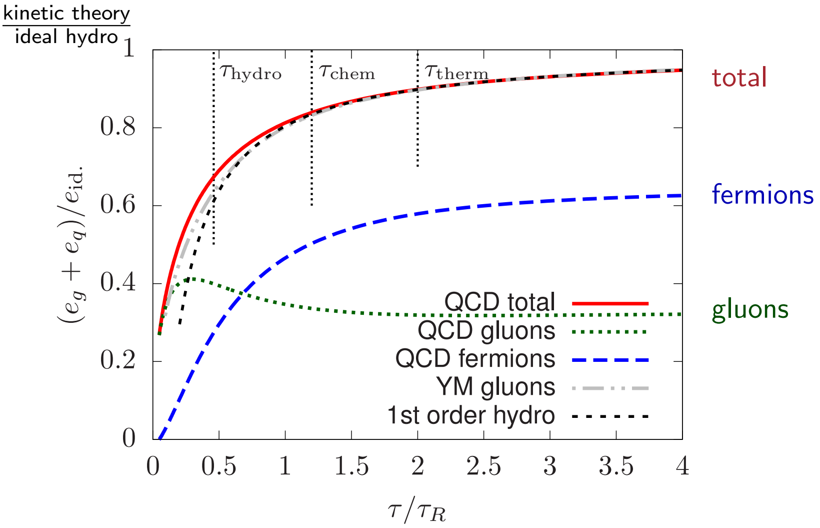


Chemical equilibration at $\tau_{chem} \sim 1.2\tau_R(\tau)$. Before isotropization!

Hydrodynamization and chemical equilibration

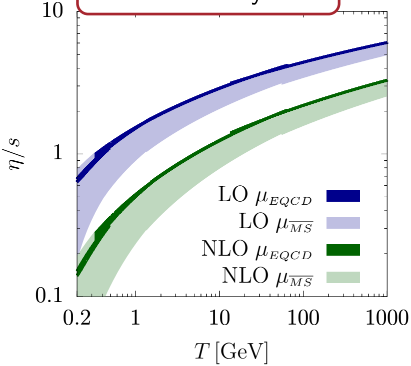


$$\underbrace{\tau_{\text{hydro}}}_{\pm 10\%\ \text{viscous}\ e(\tau)} < \underbrace{\tau_{\text{chem}}}_{\pm 10\%\ \text{fermion eq.}\ e(\tau)} < \underbrace{\tau_{\text{therm}}}_{\pm 10\%\ \text{ideal}\ e(\tau)}$$

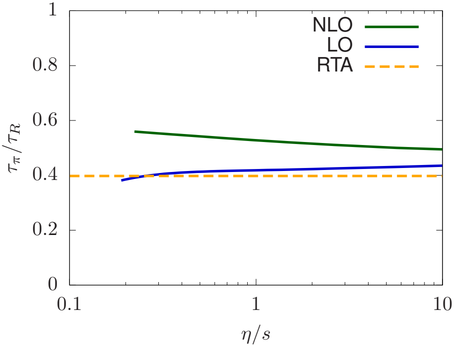
Can leading order results be informative for small η/s?

Next-to-leading order transport coefficients

Shear viscosity vs T



τ_π in units of $\tau_R = 4\pi\eta/sT$



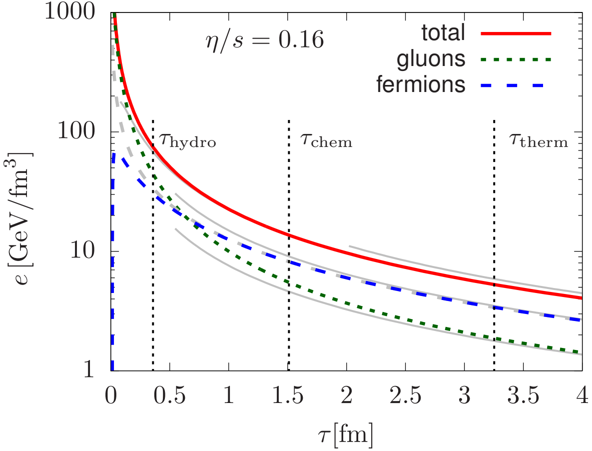
Ghiglieri, Moore, Teaney (2018) [9, 10]

- Large NLO corrections to $\eta/s(T)$.
- Small *relative* correction in 2nd/1st order transport coefficient.
- *Extrapolation scheme: adjust $\tau_R = 4\pi\eta/sT$ to match phenomenology.*

Strong to intermediate couplings: see van der Schee's talk, Tue, 15:20

Physical equilibration time-scales in hadronic collisions

$$\tau = \underbrace{(\tau/\tau_R)^{3/2}}_{\text{scaled time variable}} \times \underbrace{(4\pi\eta/s)^{3/2} \times \langle s\tau\rangle^{-1/2} \times (4\pi^2\nu_{\text{eff}}/90)^{1/2}}_{\text{phenomenological input}}$$



Input:

$\eta/s \approx 0.16$

$\langle s\tau\rangle \approx 4.1\,\text{GeV}^2$

$\nu_{\text{eff}} \approx 40$

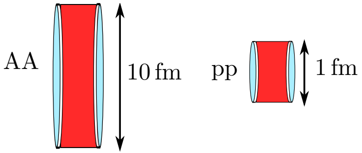
$$\underbrace{\tau_{\text{hydro}}}_{\pm 10\%\ \text{viscous}\ e(\tau)} < \underbrace{\tau_{\text{chem}}}_{\pm 10\%\ \text{fermion eq.}\ e(\tau)} < \underbrace{\tau_{\text{therm}}}_{\pm 10\%\ \text{ideal}\ e(\tau)}$$

System size and chemical equilibration time

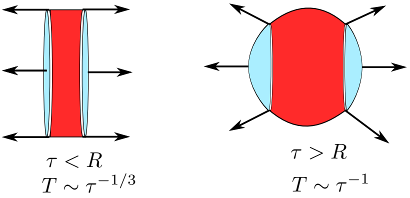
Will chemical equilibrium be reached for a given system size $dN_{\text{ch}}/d\eta$?

- Hotter system $\Rightarrow$ faster equilibration.

$$\langle \tau s \rangle \propto \frac{dN_{\text{ch}}/d\eta}{\pi R^2}$$



- Larger system $\Rightarrow$ more time to equilibrate.



$$\frac{dN_{\text{ch}}}{d\eta} \gtrsim 110 \left(\frac{\eta/s}{0.16}\right)^3 \left(\frac{\tau_{\text{chem}}}{1.2\tau_R}\right)^3 \left(\frac{\tau_{\text{chem}}}{R}\right)^{-2}$$

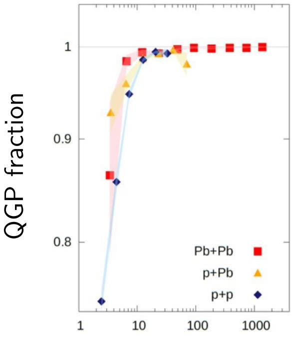
Chemical equilibrium happens at the same $dN_{ch}/d\eta$ for all systems.

Link between hadrochemistry and small systems

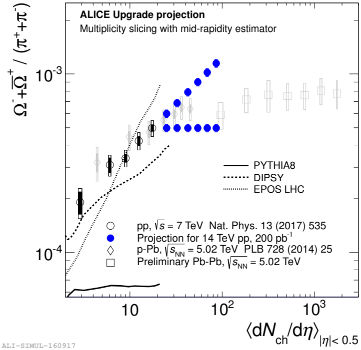
Core-corona picture of strangeness enhancement in small systems

Kanakubo, Yachibana, Hirano (2019)

Increasing fraction of equilibrated QGP in pp → p-Pb → Pb-Pb



Kanakubo, SQM 2019 $dN_{\text{ch}}/d\eta$



High Luminosity LHC Run 3 Yellow Report (2018)

Minimal conditions to equilibrate QGP in QCD kinetic theory:

$$\tau_{\text{chem}} = 1.5\,\text{fm} \times \left(\frac{\eta/s}{0.16}\right)^{\frac{3}{2}}, \quad \frac{dN_{\text{ch}}^{\text{chem}}}{d\eta} = 110 \times \left(\frac{\eta/s}{0.16}\right)^{3}.$$

Equilibration in transverse plane

Initial condition response to transverse geometry

Teaney, RICE workshop 2019

Flow in pA and AA from hydro and kinetics:

$$\underbrace{v_2}_{\text{Measured E by E flow}} = \underbrace{k_2}_{\text{Response coefficient}} \times \underbrace{\epsilon_2}_{\text{geometry}}$$

for effects of initial flow perturbation on k_n's, see Luzum's poster
for new paradigm of ϵ_n see Giacalone's talk, Tue, 18:40

Response modified by finite size and pre-equilibrium effects

$$k_2(w) = k_2^{\text{ideal}}\Big(1 - \underbrace{\frac{C_1}{w(R)}}_{\text{first order hydro}} - \underbrace{\frac{C_2}{w(R)^2}}_{\text{second order}} + \ldots\Big) \quad w \sim \frac{R}{\tau_R}, \frac{\tau_0}{\tau_R}$$

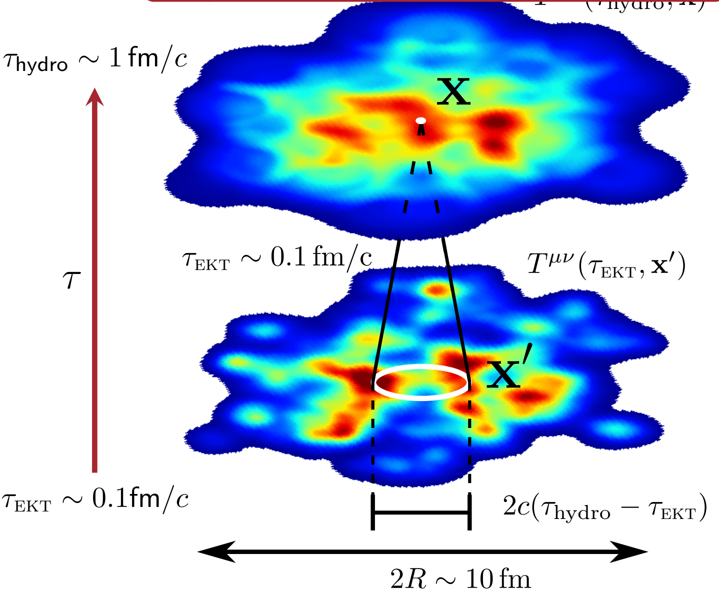
v_n/ϵ_n in kinetic theory, Kurkela, Wiedemann, Wu (2018)

Pre-equilibrium evolution of the energy-momentum tensor profile.

$$T^{\mu\nu}(\tau_{\text{EKT}}, \mathbf{x}) \underbrace{\Longrightarrow}_{\text{kinetic theory}} T^{\mu\nu}(\tau_{\text{hydro}}, \mathbf{x}) \underbrace{\Longrightarrow}_{\text{hydrodynamics}} E\,\frac{dN}{d^3p}\Big|_{\text{final}}.$$

Linear response to initial $T^{\mu\nu}$ perturbations

$$T^{\mu\nu}(\tau_{\text{hydro}}, \mathbf{x}) = \bar{T}^{\mu\nu}(\tau_{\text{hydro}}) + \delta T^{\mu\nu}(\tau_{\text{hydro}}, \mathbf{x})$$

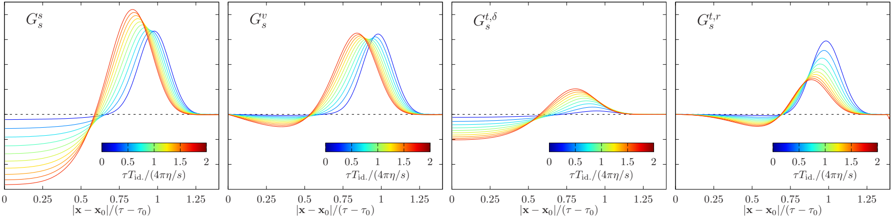


Linear-response functions from kinetic theory

$$\underbrace{\delta T^{\mu\nu}_{\mathbf{x}}(\tau_{\text{hydro}},\mathbf{x}')}_{\text{goes into hydro}} = \underbrace{\frac{\overline{T}^{\tau\tau}_{\mathbf{x}}(\tau_{\text{hydro}})}{\overline{T}^{\tau\tau}_{\mathbf{x}}(\tau_{\text{EKT}})}}_{\text{bulk eq.}} \int_{\mathbf{x}'} \underbrace{G^{\mu\nu}_{\alpha\beta}\left(\mathbf{x}-\mathbf{x}',\tau_{\text{hydro}},\tau_{\text{EKT}}\right)}_{\text{linear response function}} \underbrace{\delta T^{\alpha\beta}_{\mathbf{x}}(\tau_{\text{EKT}},\mathbf{x}')}_{\text{initial}}\,.$$

All components of energy-momentum tensor generated by kinetic response

energy→energy | energy→velocity | energy→shear-stress

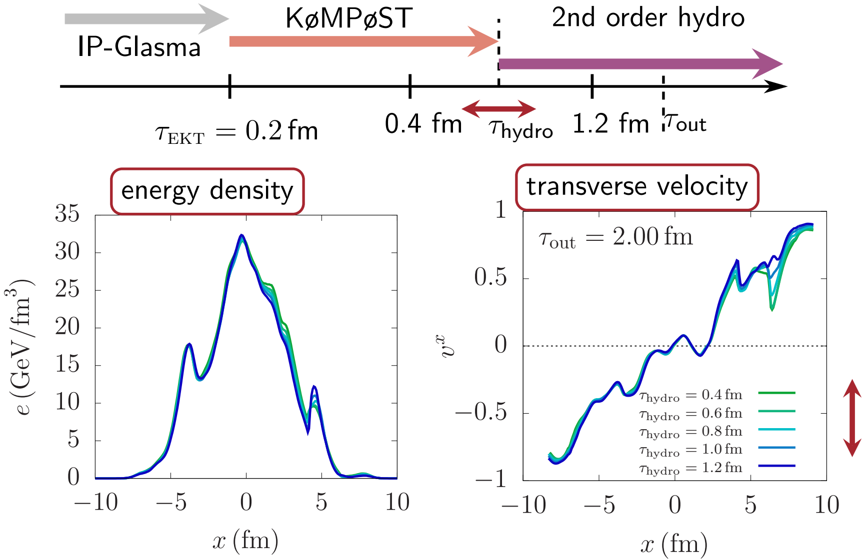


KøMPøST— event-by-event kinetic pre-equilibrium simulations.

`https://github.com/KMPST/KoMPoST` [11]

For comparison with response functions from RTA kinetics, see Schlicting/Martinez's poster

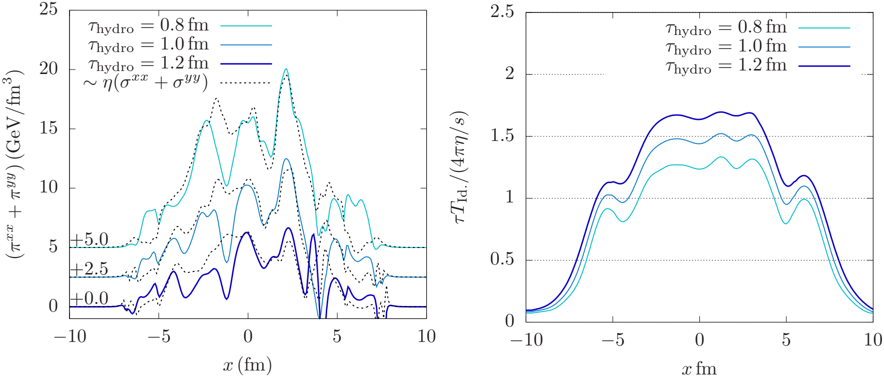
Results: event-by-event initial stage matching



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

Shear-stress tensor from KøMPøST evolution

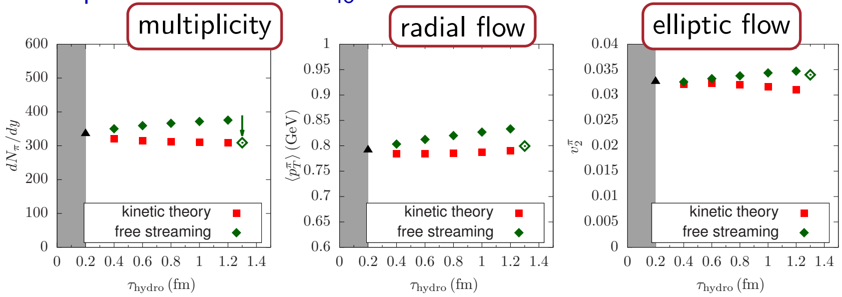
Kinetic evolution automatically satisfies constitutive equations.



Expect hydro to apply for $\tau T_{id.}/(4\pi\eta/s) > 1$

Final hadronic observables

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



- *kinetic theory — approximate independence of* τ_{hydro}
- free-streaming — need to re-adjust multiplicity

for hydrodynamics with free-streaming pre-equilibrium, see Bass's talk Wed, 17:30

- "born into QGP": $P_L = 0$ or $P_L = \frac{e}{3}$ initialization of Israel-Stewart — higher transport coefficients become relevant, e.g. τ_π.

Bulk observables only weakly sensitive to details of equilibration in PbPb.

for centrality dependence and small systems, see Wu's plenary, Thu, 11:45, Wiedemann's talk, Wed, 15:40

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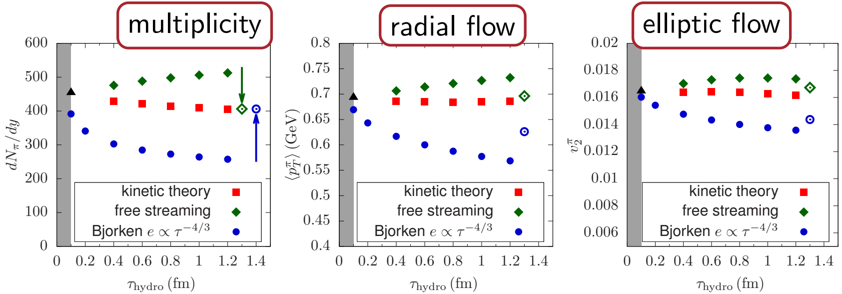

Note: MC-Glauber initial conditions

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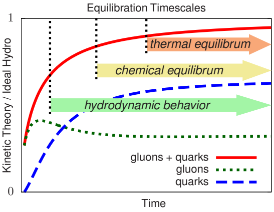
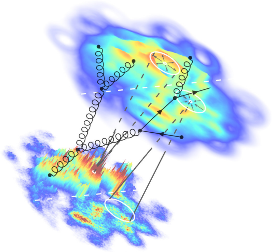
Summary and outlook

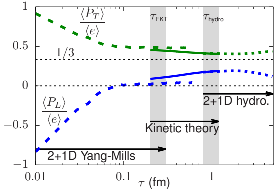
A lot of progress done using QCD kinetic theory and related methods



ordering of equilibrations



transverse response



early/late time matching

Future directions:

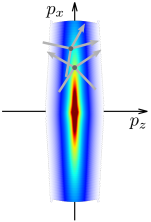
- finite size corrections to response (already done in simpler kinetics).
- non-equilibrium photon production — need control of QGP chemistry.
- timescale of heavy flavour equilibration.
- jet quenching – how opaque is non-equilibrium QGP.
- systematic comparison with strong coupling results.

"Bottom-up" thermalization scenario

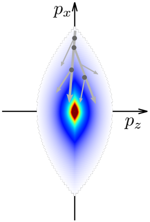
Baier, Mueller, Schiff, and Son (2001)[2]

Evolution of initially over-occupied hard gluons $p \sim Q_s \gg \Lambda_{\mathrm{QCD}}$

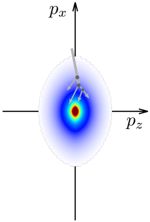
I) over-occupied	$p_z \sim \frac{Q_s}{(Q_s\tau)^{1/3}}$	$1 \ll Q_s\tau \ll \alpha_s^{-3/2}$
II) under-occupied	$p_z \sim \sqrt{\alpha_s} Q_s$	$\alpha_s^{-3/2} \ll Q_s\tau \ll \alpha_s^{-5/2}$
III) mini-jet quenching	$p_z \sim \alpha_s^3 Q_s (Q_s\tau)$	$\alpha_s^{-5/2} \ll Q_s\tau \ll \alpha_s^{-13/5}$



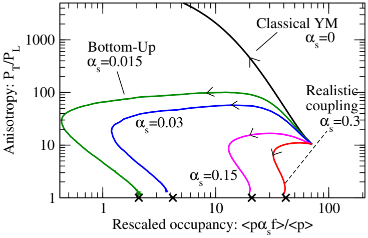
$2 \leftrightarrow 2$ broadening



collinear cascade



mini-jet quench



Berges, Boguslavski, Schlichting, Venugopalan (2014) [12]

Kurkela and Zhu (2015), Keegan, Kurkela, AM and Teaney (2016), Kurkela, AM, Paquet, Schlichting and Teaney (2018) [13, 14, 15, 16]

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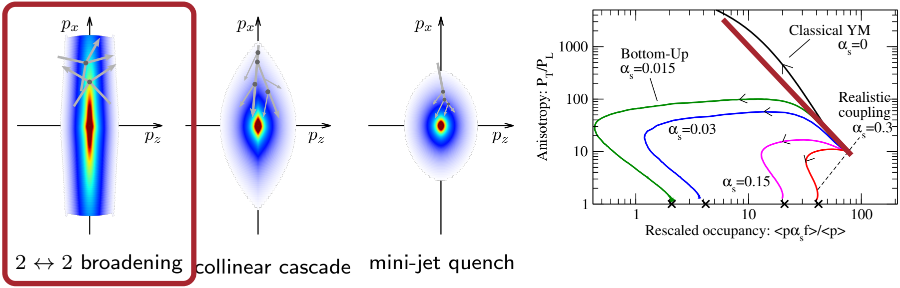
III) mini-jet quenching	$p_z \sim \alpha_s^3 Q_s (Q_s\tau)$	$\alpha_s^{-5/2} \ll Q_s\tau \ll \alpha_s^{-13/5}$



Berges, Boguslavski, Schlichting, Venugopalan (2014) [12]

Kurkela and Zhu (2015), Keegan, Kurkela, AM and Teaney (2016), Kurkela, AM, Paquet, Schlichting and Teaney (2018) [13, 14, 15, 16]

"Bottom-up" thermalization scenario

Baier, Mueller, Schiff, and Son (2001)[2]

Evolution of initially over-occupied hard gluons $p \sim Q_s \gg \Lambda_{\mathrm{QCD}}$

I) over-occupied	$p_z \sim \frac{Q_s}{(Q_s\tau)^{1/3}}$	$1 \ll Q_s\tau \ll \alpha_s^{-3/2}$
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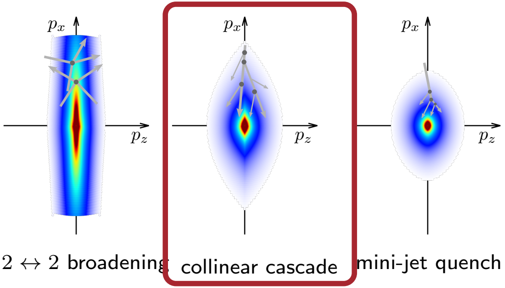

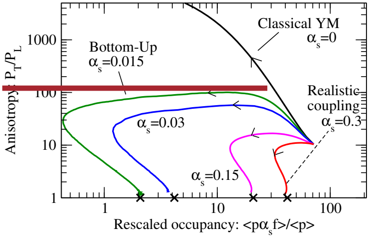

Berges, Boguslavski, Schlichting, Venugopalan (2014) [12]

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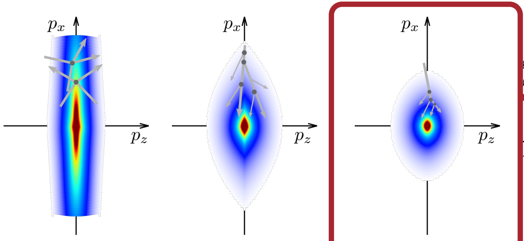
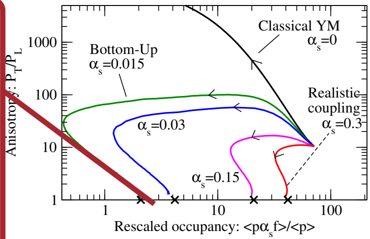


$2 \leftrightarrow 2$ broadening   collinear cascade   mini-jet quench



Berges, Boguslavski, Schlichting, Venugopalan (2014) [12]

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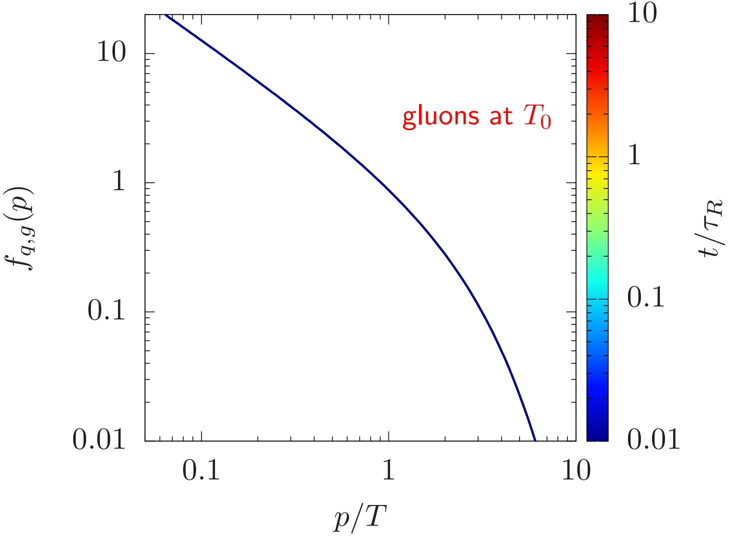
Well controlled example: gluon thermal bath with $\lambda = N_C g^2 = 0.1$

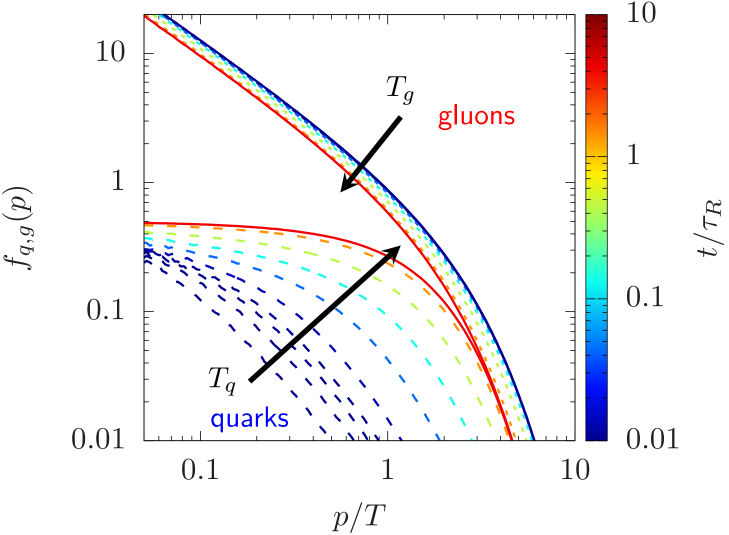
Quark production: gluon fusion $gg \to q\bar{q}$ and collinear radiation $g \to q\bar{q}$



Gluons maintain an approximate kinetic equilibrium, fermions do not.

Well controlled example: gluon thermal bath with $\lambda = N_C g^2 = 0.1$

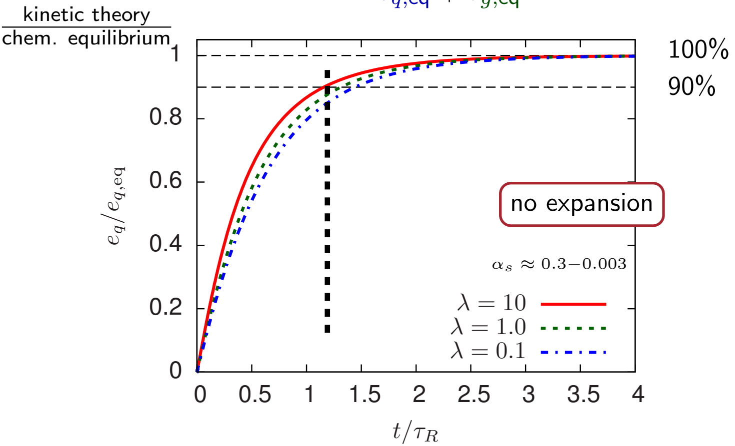
Quark production: gluon fusion $gg \to q\bar{q}$ and collinear radiation $g \to q\bar{q}$



Gluons maintain an approximate kinetic equilibrium, fermions do not.

Chemical equilibration in non-expanding systems

Equilibrium quark energy fraction $\frac{e_{q,\text{eq}}}{e_{q,\text{eq}} + e_{g,\text{eq}}} \approx 0.66$



- Scaling with kinetic relaxation time $\tau_R = \frac{4\pi\eta/s}{T_{\text{final}}} \sim \frac{1}{\lambda^2 T} \sim l_{\text{mfp}}$.
  $\eta/s \approx 1, 35, 1900$
- 90% of fermion equilibrium energy produced at $t_{\text{chem}} \sim 1.2\tau_R$.

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