Chemical equilibration of QGP in hadronic collisions

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A. Kurkela, AM (2018) [1, 2]

Phys. Rev. D99 (1811.03068)
Phys. Rev. Lett. 122 (1811.03040)

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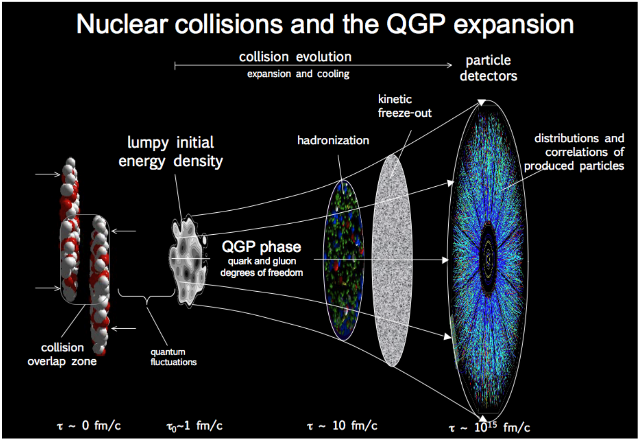
CERN

Isolated quantum systems and universality in extreme conditions

Heavy ion collisions

Nuclear collision programs at RHIC (since 2000) and LHC (since 2010).

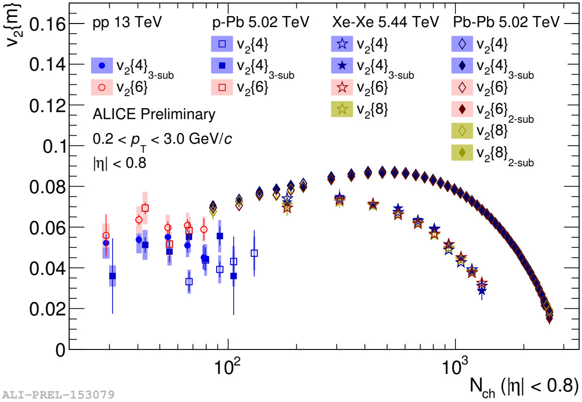


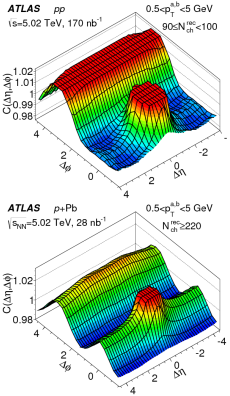
Sorensen, Quark-gluon plasma 4, 2010

- Range of collision energies: 7.7-200 GeV, 2.76 TeV, 5.02 TeV.
- Different systems: PbPb, pPb, pp, AuAu, pAu, dAu, ^{3}HeAu...

Evidence for equilibration of QGP

Collective particle flow seen even in the smallest collision systems.



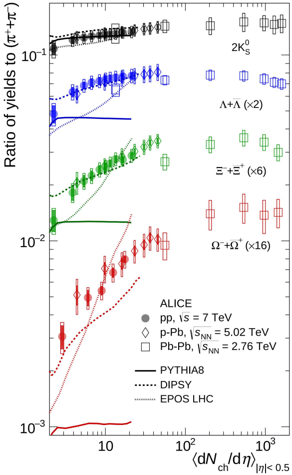


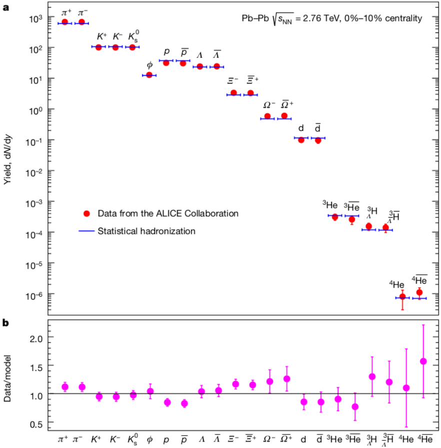
ATLAS Phys.Rev. C96 (2017) no.2, 024908

Is hydrodynamically flowing QGP formed in pp and pA collisions?

Strangeness enhancement in high multiplicity pp and pPb collisions

Qualitative change in hadron production.





ALICE Nature Physics (2017) Andronic, Braun-Munziger, Redlich, Stachel, Nature (2018)

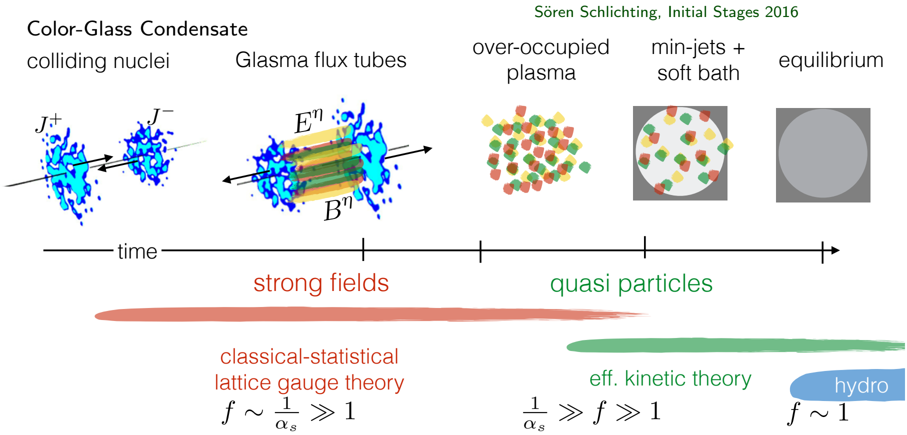
Is strangeness enhancement due to chemically equilibrating QGP?

Weak coupling picture of QCD equilibration

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

- strong gluon fields $A_\mu \sim \frac{1}{g} \implies$ classical field description
- particle scatterings isotropize and equilibrate plasma $\implies$ "Bottom-up" thermalization scenario

Baier, Mueller, Schiff, and Son (2001)[3]
Berges, Boguslavski, Schlichting, Venugopalan (2014) [4] Kurkela and Zhu (2015) [5]


Sören Schlichting, Initial Stages 2016

Color-Glass Condensate
colliding nuclei

Glasma flux tubes

over-occupied plasma

min-jets + soft bath

equilibrium

strong fields

quasi particles

classical-statistical lattice gauge theory
$f \sim \frac{1}{\alpha_s} \gg 1$

eff. kinetic theory
$\frac{1}{\alpha_s} \gg f \gg 1$

hydro
$f \sim 1$

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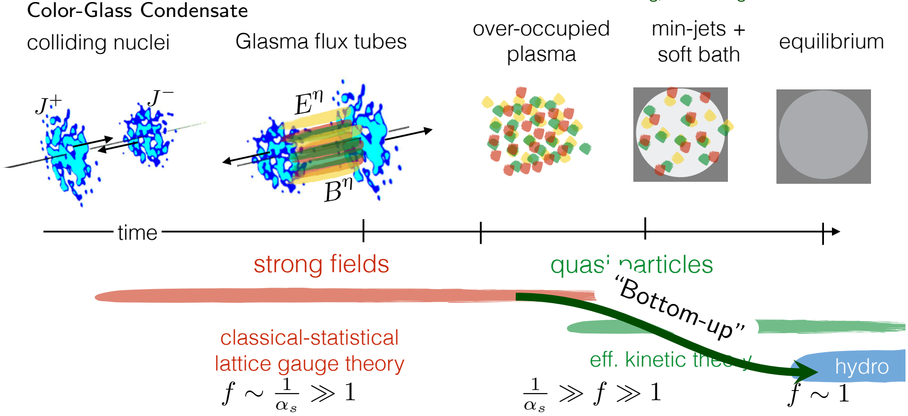

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Color-Glass Condensate

colliding nuclei

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"Bottom-up"

classical-statistical lattice gauge theory

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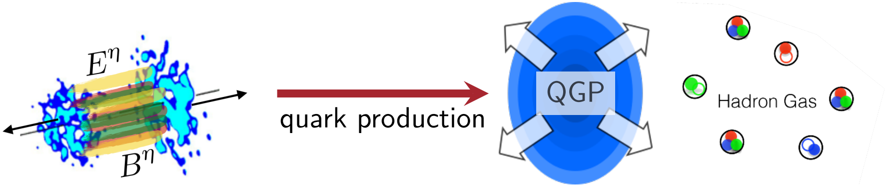
Fermion production in weakly coupled QCD

Initial state is dominated by gluon fields



quark production

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) [6]
Martinez, Sievert, Wertepny (2018) [7]

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

Kurkela, AM (2018) [1, 2]

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

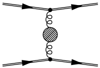
Kinetic theory of weakly coupled quark and gluon quasi-particles.

Arnold, Moore, Yaffe (2003)[8]

$$\partial_\tau f_{g,q} - \frac{p_z}{\tau}\partial_{p_z} f_{g,q} = -\mathcal{C}_{2\leftrightarrow 2}[f] - \mathcal{C}_{1\leftrightarrow 2}[f]$$

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

- 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) [9]

High-pT QCD kinetic theory ⇒ parton energy loss
Low-pT QCD kinetic theory ⇒ thermalization

We will consider QCD with $N_c = 3$ and $N_f = 3$ massless quarks ($\mu_B = 0$).

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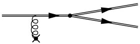
Leading order in the coupling constant $\lambda = 4\pi\alpha_s N_c$:

- Medium induced colinear radiation: $g \leftrightarrow gg$, $q \leftrightarrow qg$, $g \leftrightarrow q\bar{q}$



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

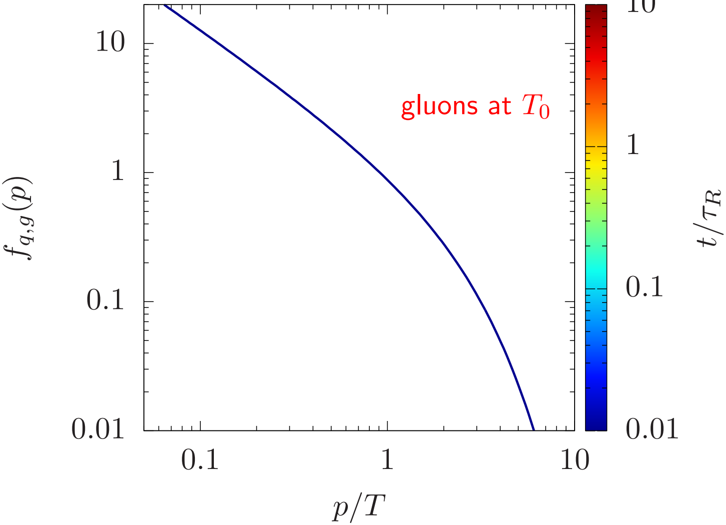
Resummed multiple scatterings with the medium (Landau–Pomeranchuk–Migdal suppression).

High-pT QCD kinetic theory $\Rightarrow$ parton energy loss
Low-pT QCD kinetic theory $\Rightarrow$ thermalization

We will consider QCD with $N_c = 3$ and $N_f = 3$ massless quarks ($\mu_B = 0$).

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.

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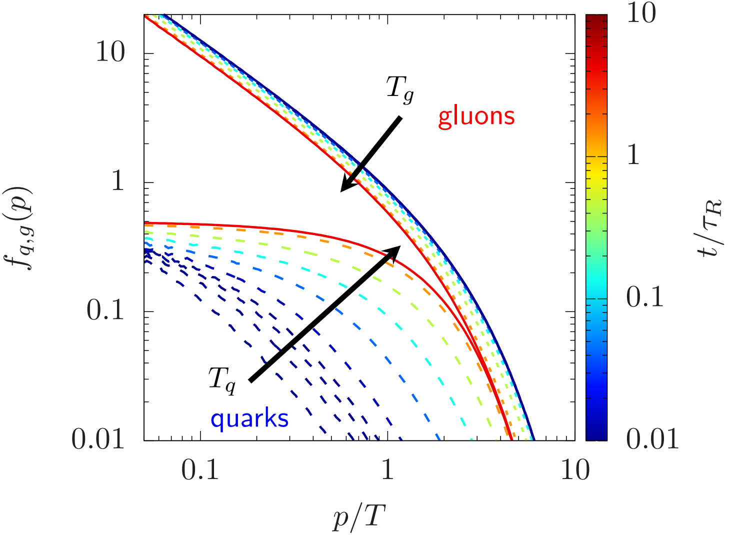
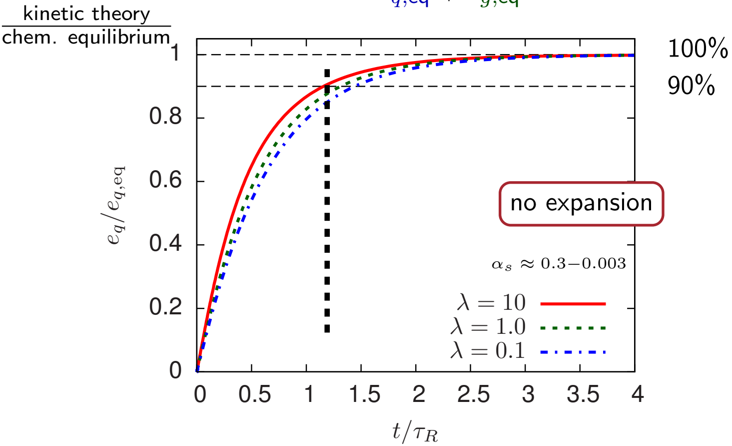


Gluons maintain an approximate kinetic equilibrium, fermions do not.

Chemical equilibration in non-expanding systems

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

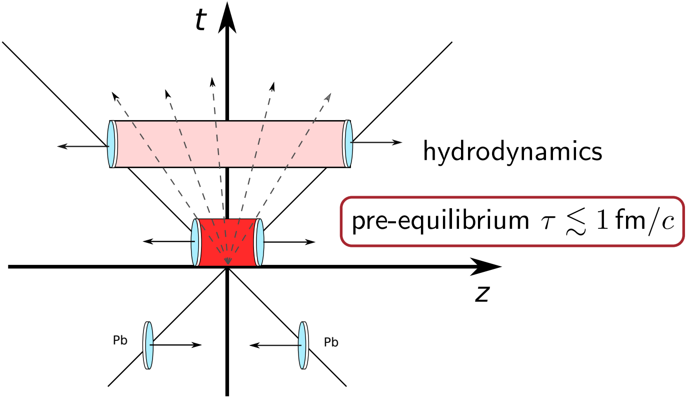


- Scaling with kinetic relaxation time $\tau_R = \frac{4\pi\eta/s}{T_{\text{final}}} \sim \frac{1}{\lambda^2 T} \sim l_{\text{mfp}}$.
  $\eta/s \approx 1, 35, 1900$
- 90% of fermion equilibrium energy produced at $t_{\text{chem}} \sim 1.2\tau_R$.

Boost invariant expansion

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

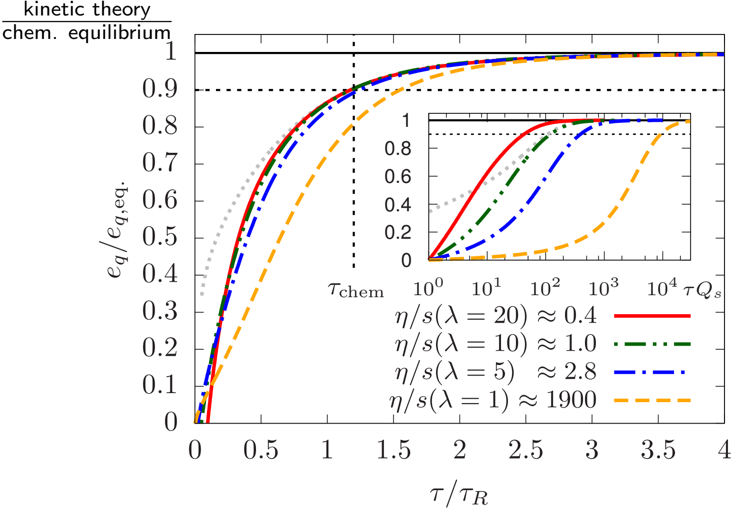
$$\frac{dN}{d\eta} \sim \frac{dS}{d\eta} = \langle s\tau \rangle = \text{const} \quad \Longrightarrow \quad T_{\text{id.}}(\tau) \propto \frac{\langle s\tau \rangle^{1/3}}{\tau^{1/3}}$$



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

Chemical equilibration with expansion

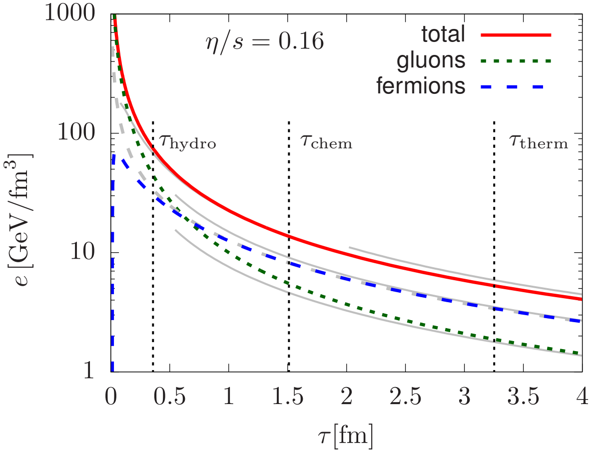
Time dependent mean free path $\Rightarrow \tau_R \equiv \frac{4\pi\eta/s}{T_{\text{id}}(\tau)}$



Chemical equilibration at $\tau_{\mathit{chem}} \sim 1.2\tau_R(\tau)$ for $\alpha_s \sim 0.3$

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:

$\eta/s \approx 0.16$

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

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

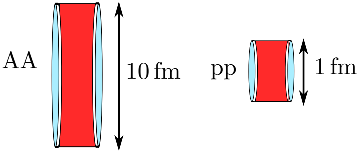
$$\underbrace{\tau_{\text{hydro}}}_{\pm 10\%\text{ viscous } e(\tau)} < \underbrace{\tau_{\text{chem}}}_{\pm 10\%\text{ fermion eq. } e(\tau)} < \underbrace{\tau_{\text{therm}}}_{\pm 10\%\text{ ideal } e(\tau)}$$

System size and chemical equilibration time

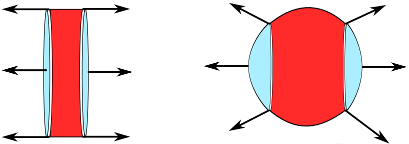
Will chemical equilibrium be reached for a given system size $dN_{\mathsf{ch}}/d\eta$?

- Hotter system ⇒ faster equilibration.

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



- Larger system ⇒ more time to equilibrate.



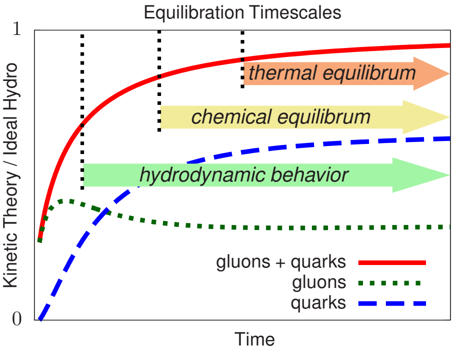
$\tau < R$
$T \sim \tau^{-1/3}$

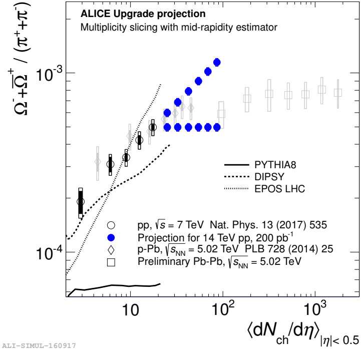
$\tau > R$
$T \sim \tau^{-1}$

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

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

Summary





High Luminosity LHC Run 3 Yellow Report (2018)

Ordering of equilibration timescales in QCD kinetic theory

$$\tau_{\text{hydro}} < \tau_{\text{chem}} < \tau_{\text{therm}}$$

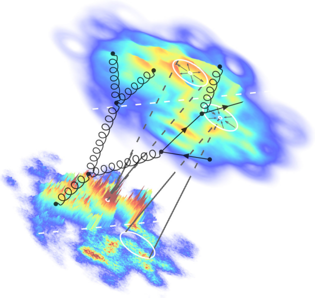
Direct link between transport properties, system size and chemistry.

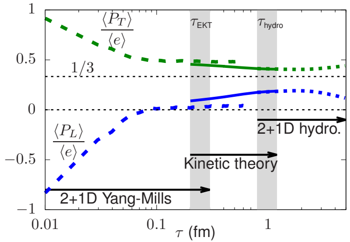
$$\tau_{\text{chem}} = 1.5\,\text{fm} \times \left(\frac{\eta/s}{0.16}\right)^{\frac{3}{2}}, \qquad \frac{dN_{\text{ch}}^{\text{chem}}}{d\eta} = 110 \times \left(\frac{\eta/s}{0.16}\right)^{3}.$$

Outlook: transverse pre-equilibrium evolution

KøMPøST— event-by-event kinetic pre-equilibrium for heavy ion collisions.

$$\underbrace{\delta T^{\mu\nu}_{\mathbf{x}}(\tau_{\text{hydro}},\mathbf{x}')}_{\text{goes into hydro}} = \int d^2\mathbf{x}' \; \underbrace{G^{\mu\nu}_{\alpha\beta}\left(\mathbf{x}-\mathbf{x}', \tau_{\text{hydro}}, \tau_{\text{EKT}}\right)}_{\text{linear response function}} \underbrace{\delta T^{\alpha\beta}_{\mathbf{x}}(\tau_{\text{EKT}},\mathbf{x}')}_{\text{initial}} .$$





https://github.com/KMPST/KoMPoST [12]   Kurkela, AM, Paquet, Schlichting and Teaney (2018)[10, 11]

To do:

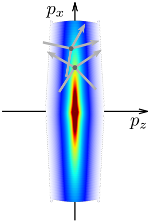
- radial expansion $\Longrightarrow$ important for small systems.
- quark response functions $\Longrightarrow$ photon production.
- finite fermion mass $\Longrightarrow$ breaking of conformal and flavour symmetries.

“Bottom-up” thermalization scenario

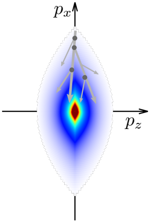
Baier, Mueller, Schiff, and Son (2001)[3]

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

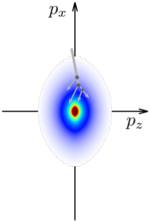
I) over-occupied	$p_z \sim \frac{Q_s}{(Q_s\tau)^{1/3}}$	$1 \ll Q_s\tau \ll \alpha_s^{-3/2}$
II) under-occupied	$p_z \sim \sqrt{\alpha_s} Q_s$	$\alpha_s^{-3/2} \ll Q_s\tau \ll \alpha_s^{-5/2}$
III) mini-jet quenching	$p_z \sim \alpha_s^3 Q_s (Q_s\tau)$	$\alpha_s^{-5/2} \ll Q_s\tau \ll \alpha_s^{-13/5}$



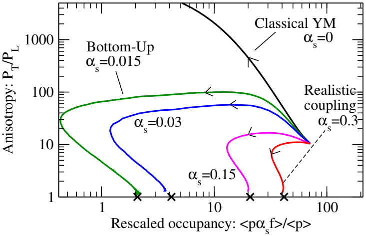
$2 \leftrightarrow 2$ broadening



collinear cascade



mini-jet quench



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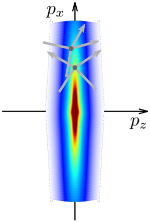

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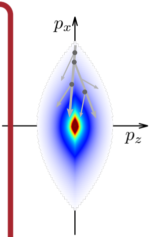
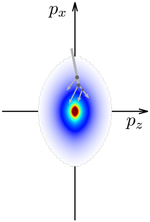


collinear cascade



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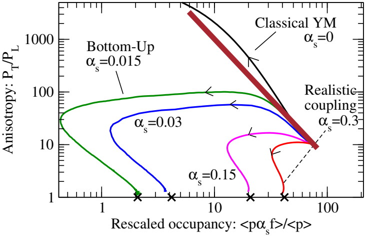

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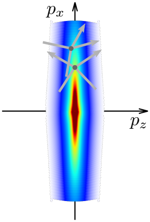

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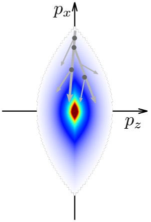

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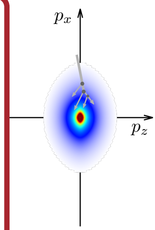

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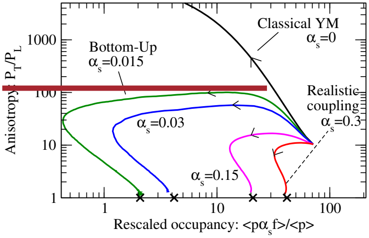

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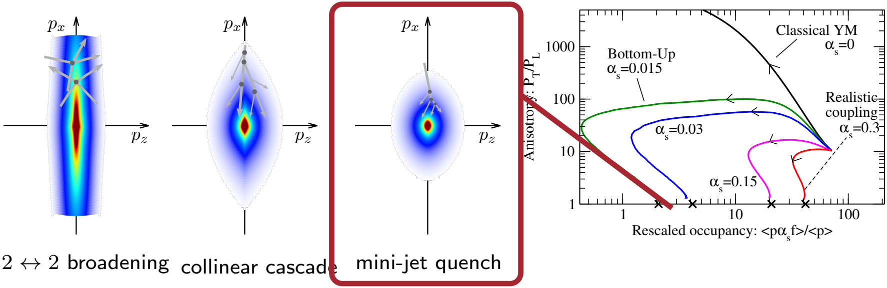

$2 \leftrightarrow 2$ broadening collinear cascade mini-jet quench

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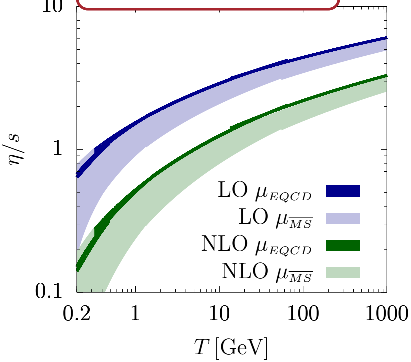
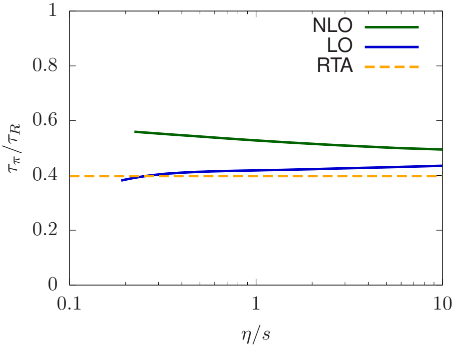
Next-to-leading order transport coefficients

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

Shear viscosity vs T



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



Ghiglieri, Moore, Teaney (2018) [14, 15]

- 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.*

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