

Chemical equilibration of QGP in hadronic collisions

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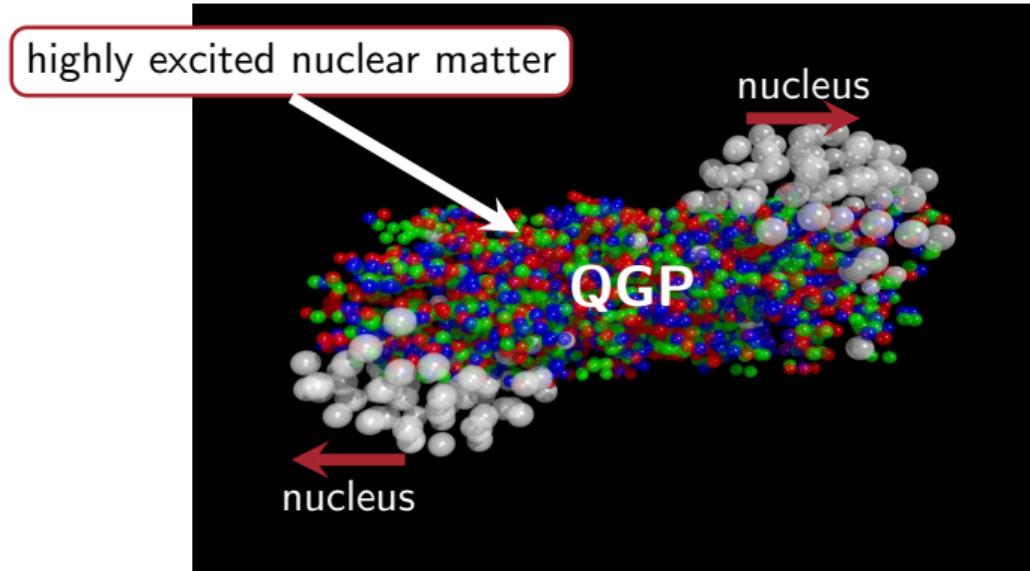
A. Kurkela, AM

PRD [1811.03068], *PRL* [1811.03040]



Revealing new phenomena of fundamental interactions

Heavy-ion collisions push nuclear matter in far-from-equilibrium state.

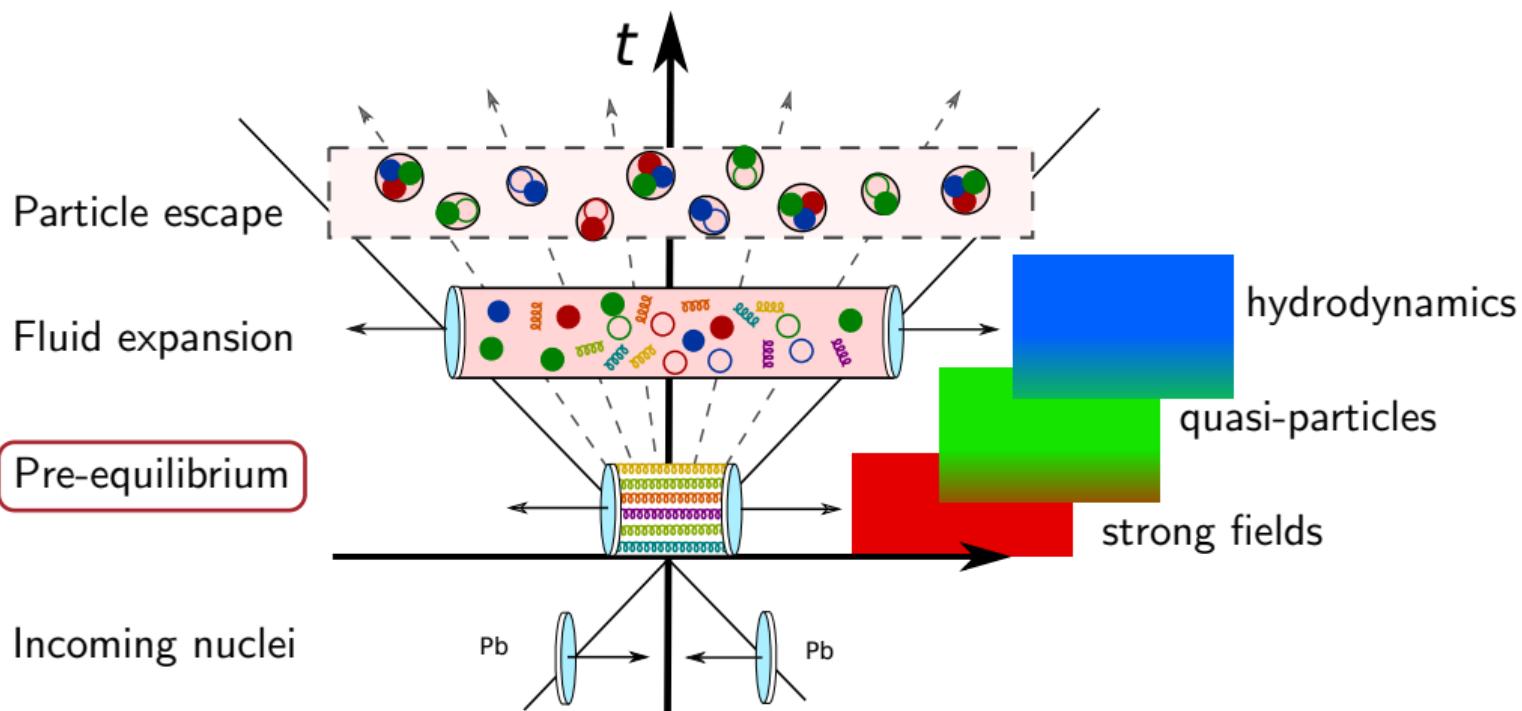


UrQMD, Marcus Bleicher

A new phase of matter is created — the Quark-Gluon Plasma (QGP).

Space-time picture of heavy ion collisions

Thermalization in QCD, J. Berges, M.P. Heller, AM, R. Venugopalan (2020) [1]



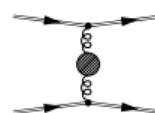
QCD kinetic theory — bridge between early and late time dynamics.

Effective description of $p \sim T$ quasi-particles governed by Boltzmann equation

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

The same collision processes as in jet quenching or medium photon emission.

- 1 2 \leftrightarrow 2 elastic scatterings: $gg \leftrightarrow gg$, $qq \leftrightarrow qq$, $qg \leftrightarrow gq$, $gg \leftrightarrow q\bar{q}$


$$= |\mathcal{M}_{gg}^{gg}|^2 = g^4 \frac{9}{2} \left[3 - \frac{st}{u^2} - \frac{su}{t^2} - \frac{tu}{s^2} \right]$$

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

Contains the right physics for the “bottom-up” thermalization in QCD.

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

see reviews by Teaney and Schlichting (2019) [3], Berges, Heller, AM and Venugopalan (2020) [1]

see also the talk by Xiaojian Du right after this talk.

High temperature QCD kinetic theory

Arnold, Moore, Yaffe (2003)[4]

Effective description of $p \sim T$ quasi-particles governed by Boltzmann equation

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

The same collision processes as in jet quenching or medium photon emission.

- 2 1 \leftrightarrow 2 medium induced collinear radiation: $g \leftrightarrow gg$, $q \leftrightarrow qg$, $g \leftrightarrow q\bar{q}$

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

Resummed multiple scatterings with the medium (LPM suppression).

Contains the right physics for the “bottom-up” thermalization in QCD.

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

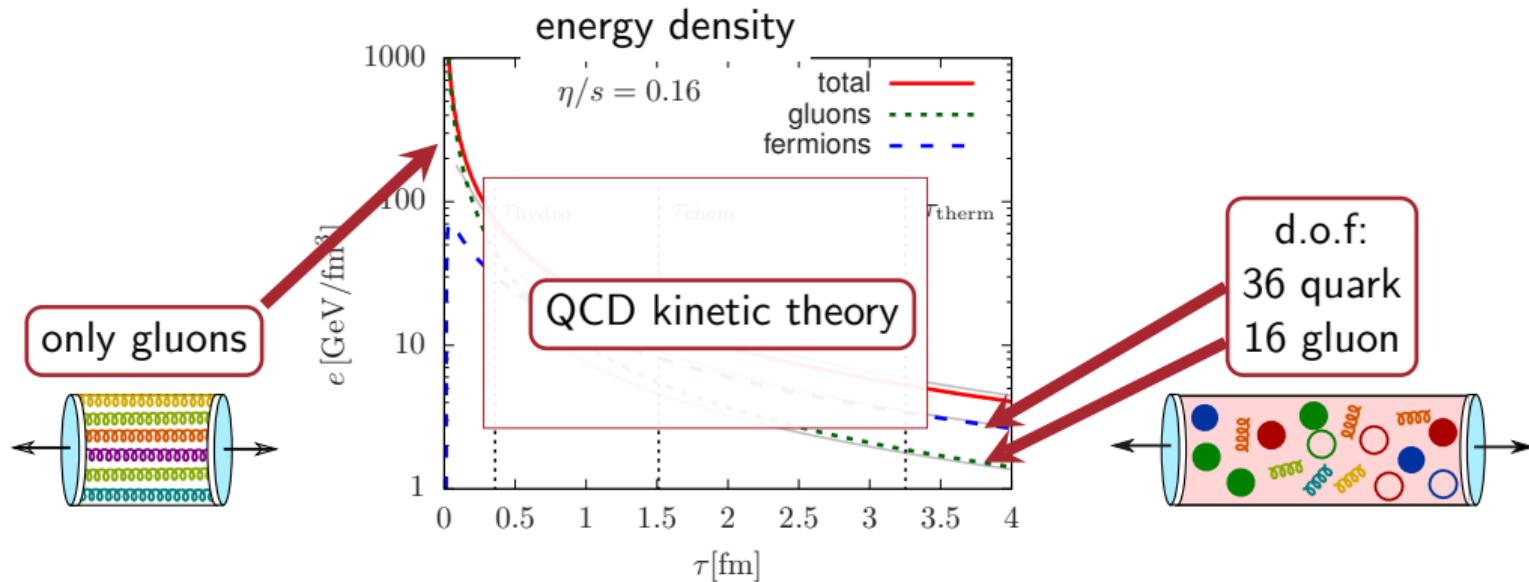
see reviews by Teaney and Schlichting (2019) [3], Berges, Heller, AM and Venugopalan (2020) [1]

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Fermion production in QCD kinetic theory

- Initial state is dominated by gluonic fields.
- In chemical equilibrium u, d, s quarks carry most of the total energy.

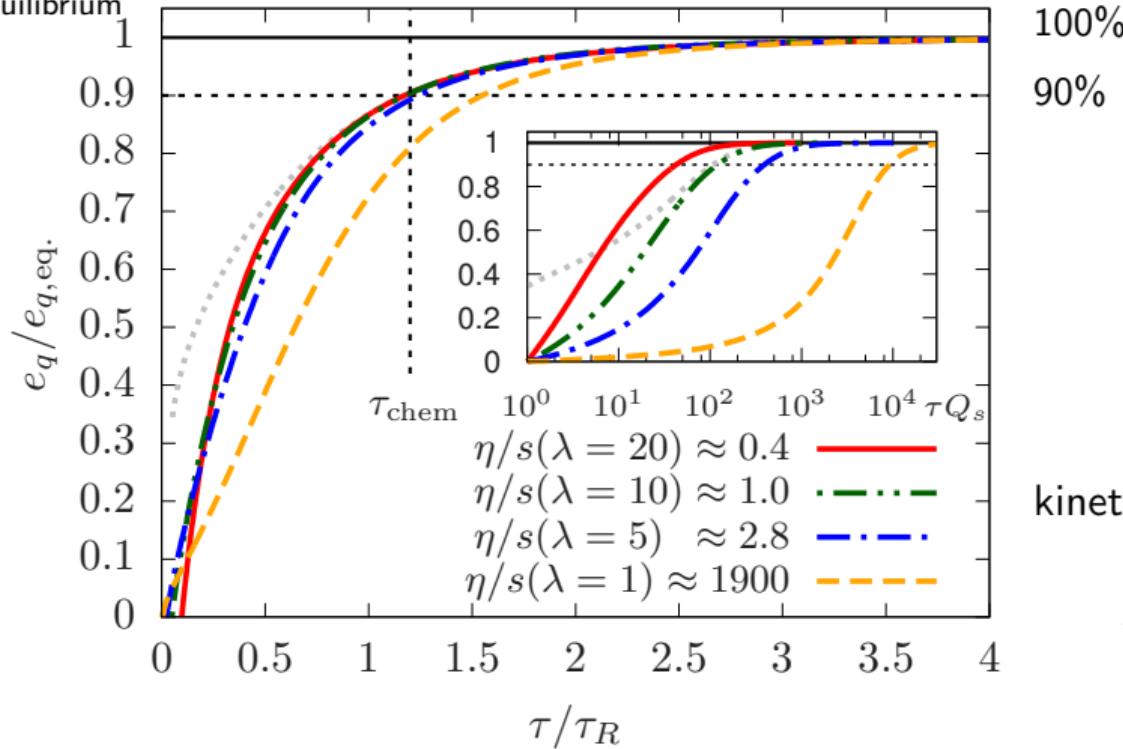
Fermions are produced through fusion $gg \rightarrow q\bar{q}$ and splitting $g \rightarrow q\bar{q}$.



Kurkela, AM, PRL, PRD, (2018) [5, 6]

Fermion energy relative to energy in chemical equilibrium.

kinetic theory
chem. equilibrium

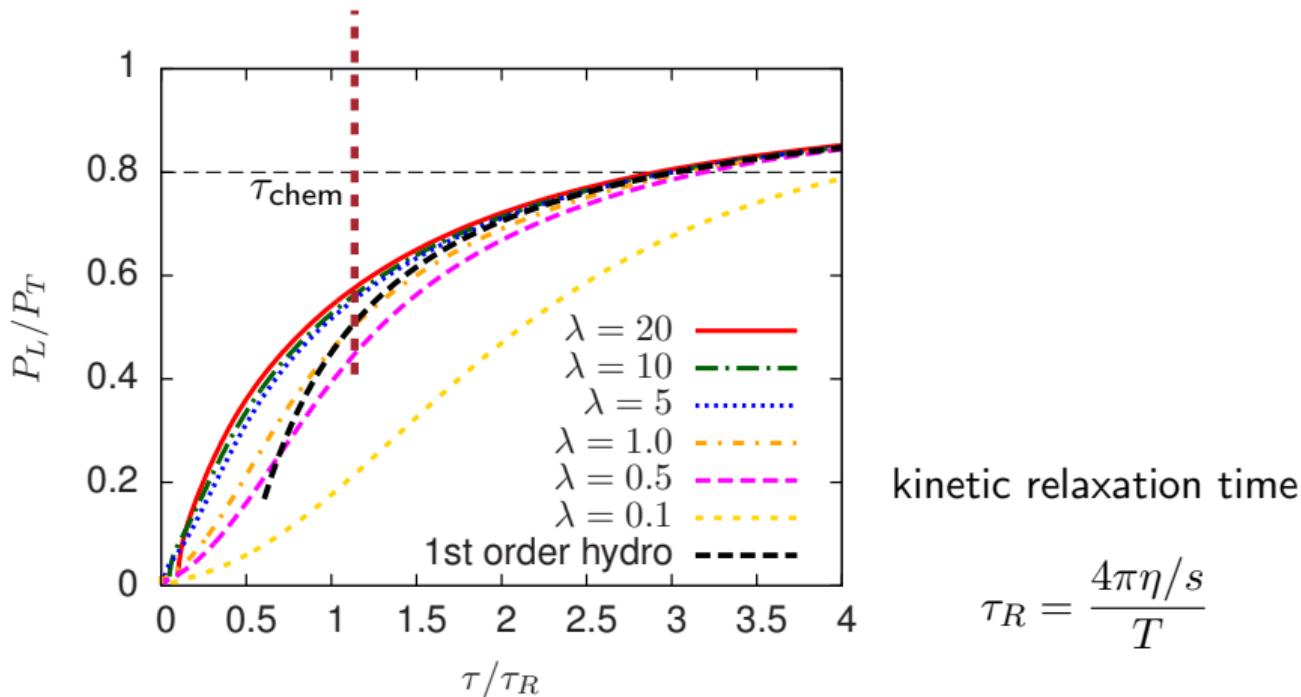


kinetic relaxation time

$$\tau_R = \frac{4\pi\eta/s}{T}$$

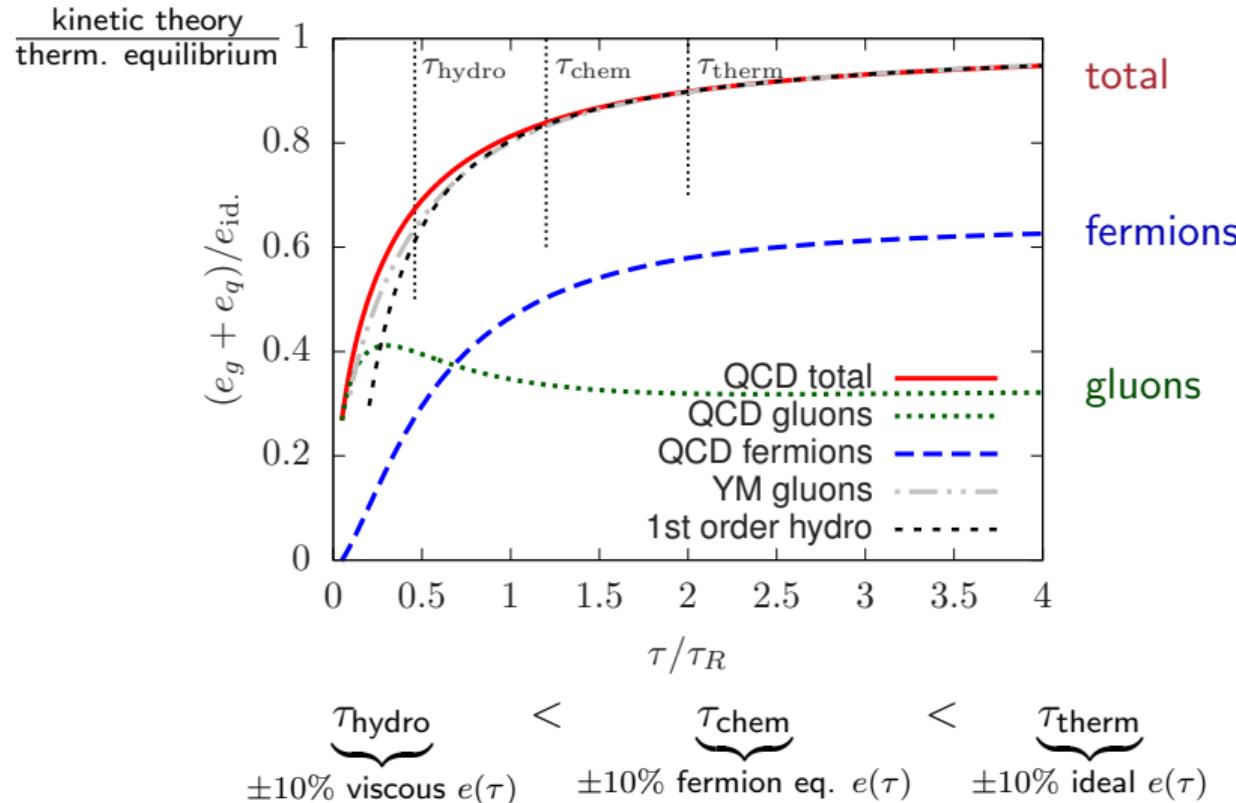
Chemical equilibration at $\tau_{\text{chem}}/\tau_R(\tau) \sim 1.2$.

Fermion energy relative to energy in chemical equilibrium.



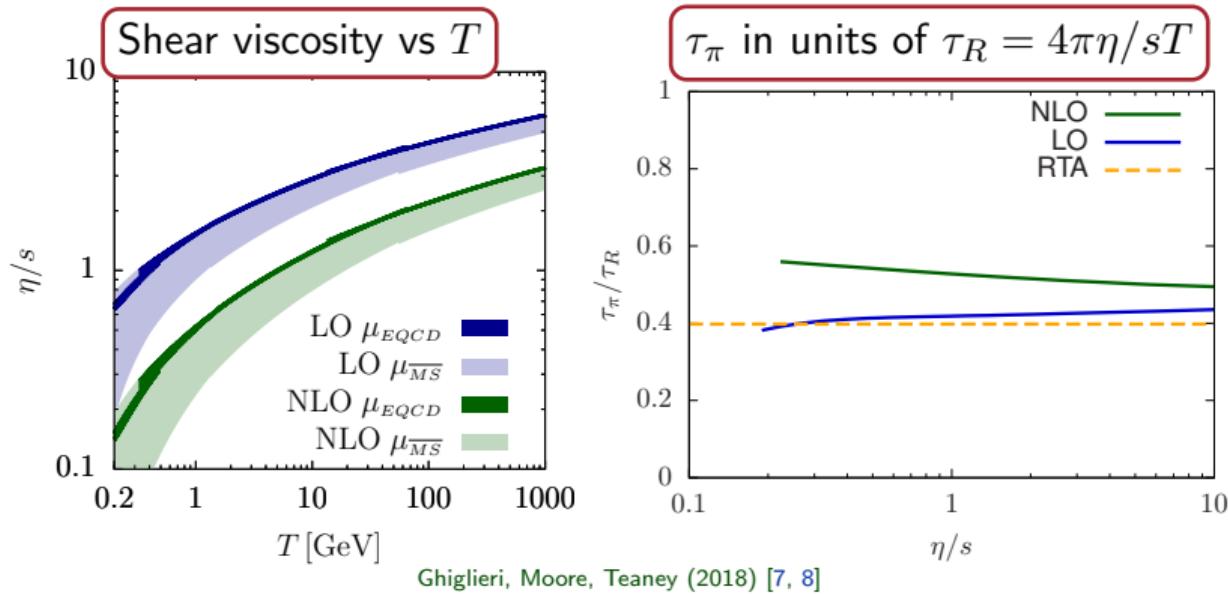
Chemical equilibration at $\tau_{chem}/\tau_R(\tau) \sim 1.2$. Before isotropization!

Hydrodynamization and chemical equilibration



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

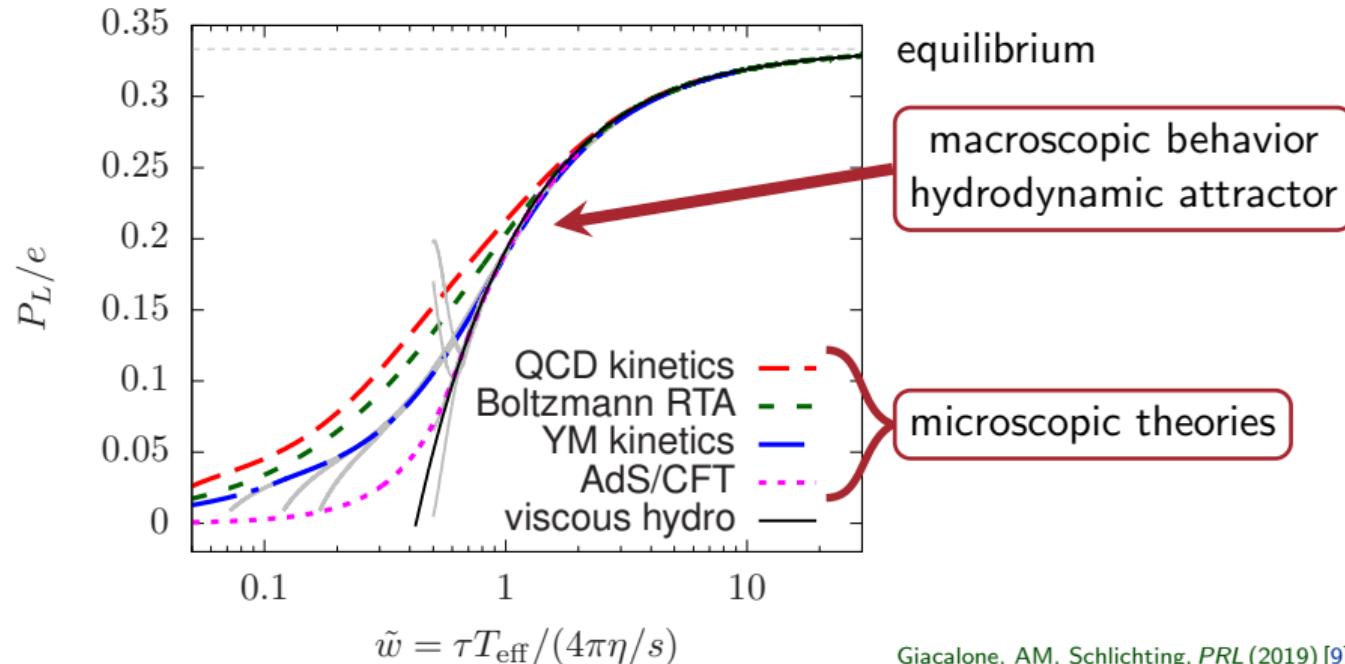
Next-to-leading order transport coefficients



- Large NLO corrections make $\eta/s(T)$ much smaller.
- But small *relative* correction in 2nd order transport coefficients.
- *Extrapolation scheme: adjust $\tau_R = 4\pi\eta/sT$ to match phenomenology.*

Emergence of effective macroscopic descriptions far-from-equilibrium

$$\frac{P_L}{e} = f \left[\tilde{w} = \frac{\tau}{\tau_R} \right], \text{relaxation time } \tau_R = \frac{4\pi\eta/s}{T}$$



see talk by Wilke van der Schee later

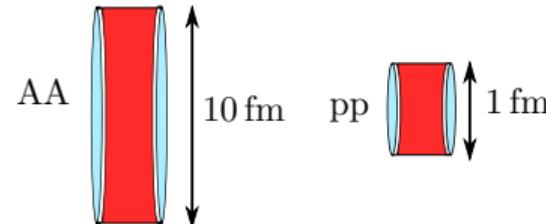
Giacalone, AM, Schlichting, *PRL* (2019) [9]

Universal scaling with particle multiplicity

Estimate system life-time in units of kinetic relaxation time $\tau_R = (4\pi\eta/s)/T$

- Hotter system \Rightarrow faster equilibration.

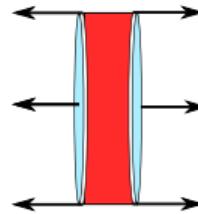
$$\tau T^3 \propto \frac{dN_{ch}/d\eta}{\pi R^2}$$



- Larger system \Rightarrow more time to equilibrate.

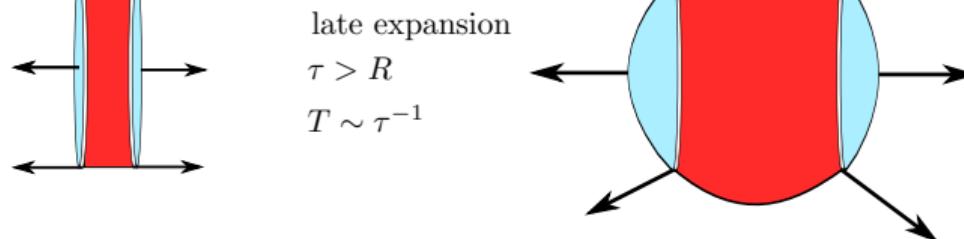
early expansion

$$\begin{aligned} \tau &< R \\ T &\sim \tau^{-1/3} \end{aligned}$$



late expansion

$$\begin{aligned} \tau &> R \\ T &\sim \tau^{-1} \end{aligned}$$

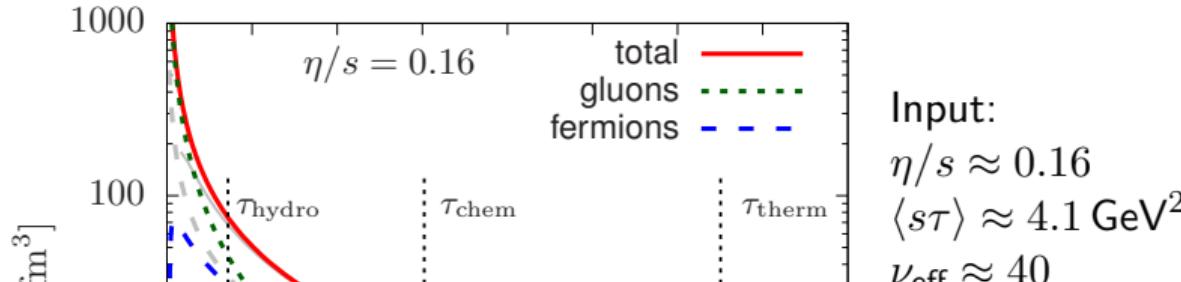


$$\frac{\text{life-time}}{\tau_R} \sim \frac{RT}{4\pi\eta/s} \sim \left(\frac{dN_{ch}}{d\eta} \right)^{1/3} \quad \text{independent of } R!$$

cf. earlier estimates Basar and Teaney (2013) [10], Schlichting and Tribedy (2016)[11]

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:

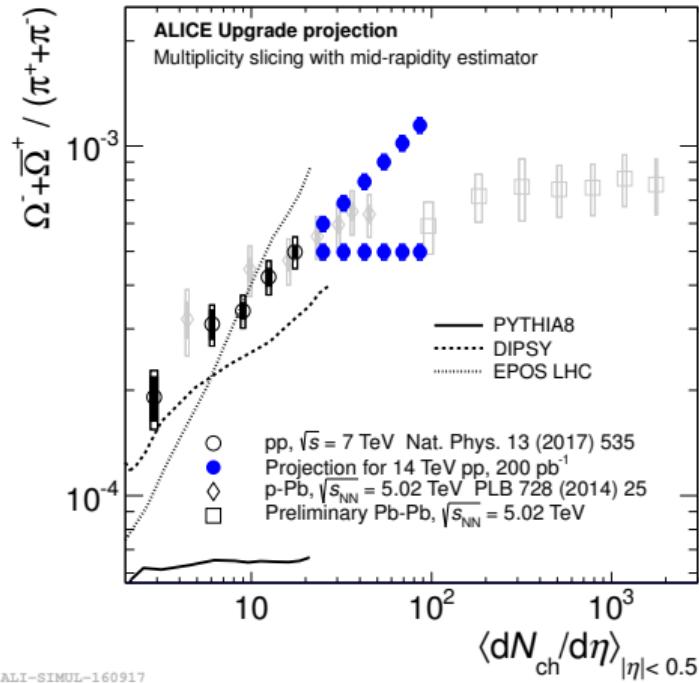
$$\eta/s \approx 0.16$$

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

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

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

Will strangeness saturate in high multiplicity pp collisions?



QGP chemical equilibration

$$\frac{dN_{\text{ch}}}{d\eta} \gtrsim 10^2 \left(\frac{\eta/s}{0.16} \right)^3$$

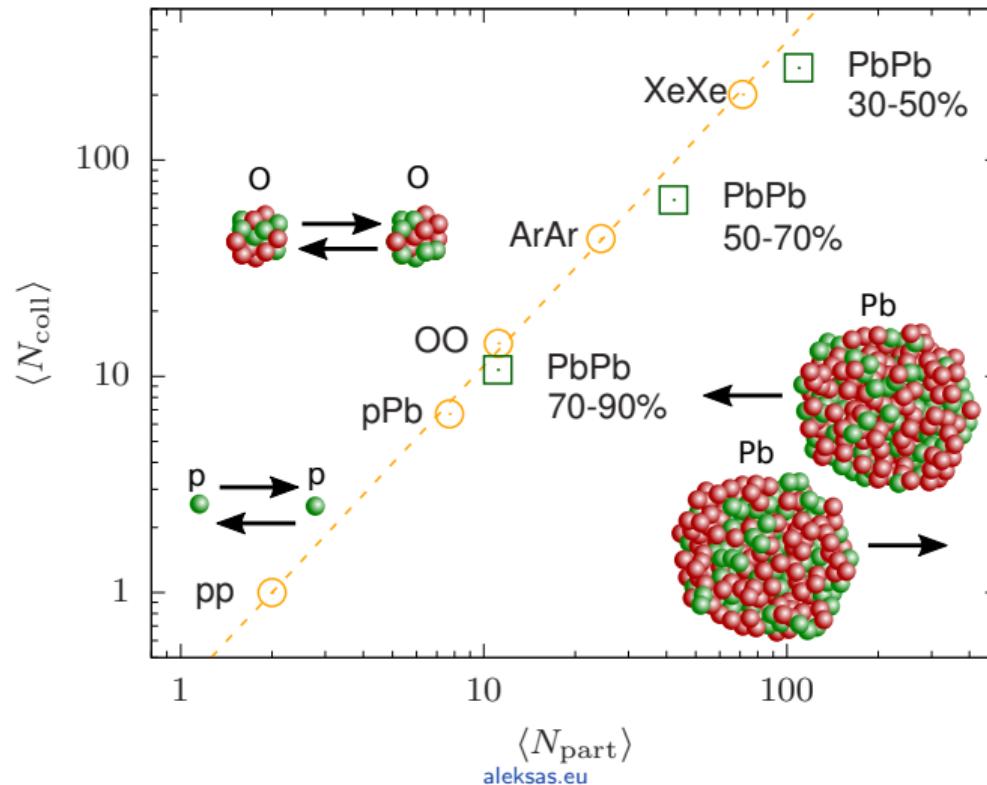
Citron et al., CERN Yellow Report (2018) [12]

High-luminosity LHC run will answer this question conclusively.

System size scan with light-ions at LHC

Proposed short runs of OO, pO in 2022, possible ArAr run in LHC run 5

Citron et al., CERN Yellow Report (2018) [12]



Summary

- Detailed understanding of different stages of QCD thermalization.
- Establishing rapid chemical equilibration in QCD kinetic theory
- Phenomenological predictions for equilibration time and system size.

Outlook:

- Hard probes in non-equilibrium plasma, e.g., photons see J.F. Paquet talk on Monday
- Equilibration in small systems.

Giacalone, AM, Schlichting, in progress; Kurkela, AM, Törnkvist, in progress

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