

Thermalisation of mini-jets in QCD kinetic theory

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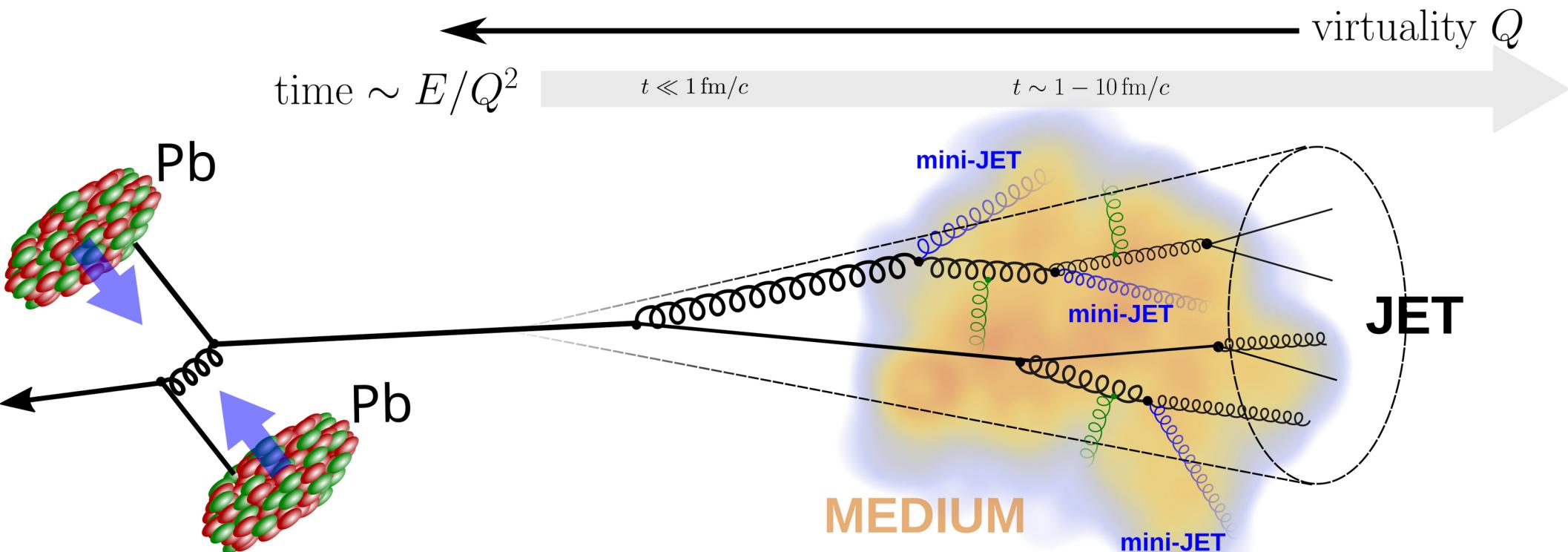


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Jasmine Brewer, AM, Fabian Zhou, *in preparation*

Jet-quenching in QGP



See also Singh, Tue 9:50, Kuha, Tue 17:30

Goal: study how jets deposit energy in QGP

QCD kinetic theory

Arnold, Moore, Yaffe (2003)

Boltzmann equation for gluon and quark distribution functions

$$\partial_t f(t, \mathbf{x}, \mathbf{p}) + \frac{\mathbf{p}}{|\mathbf{p}|} \cdot \nabla_{\mathbf{x}} f(t, \mathbf{x}, \mathbf{p}) = -\mathcal{C}_{2 \leftrightarrow 2}[f] - \mathcal{C}_{1 \leftrightarrow 2}[f]$$

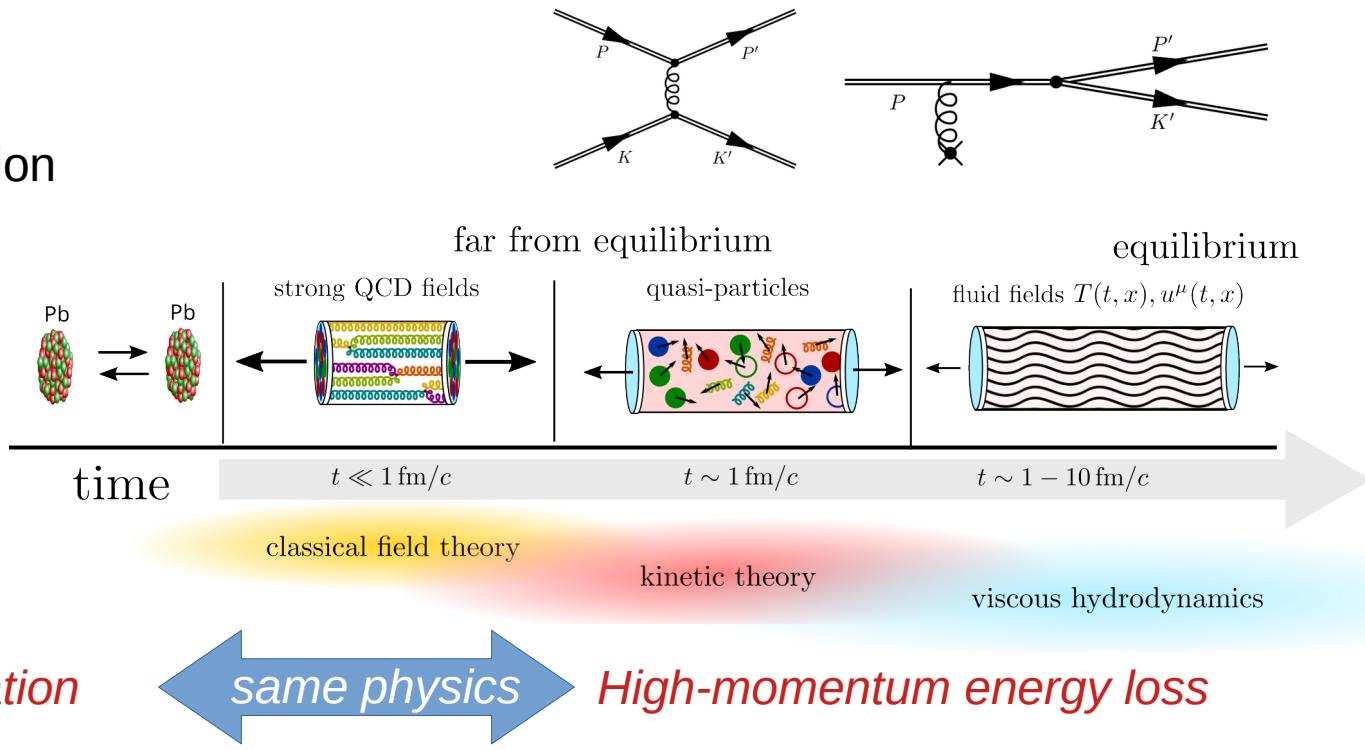
Leading order processes:

- Elastic scatterings
- Medium induced radiation

Successful description of QCD thermalisation

Reviews: Schlichting and Teaney, 1908.02113
Berges, Heller, AM, Venugopalan, 2005.12299

Bottom-up thermalisation picture
Baier, Mueller, Schiff, Son (2001)



Mini-jet evolution

Solve coupled differential equations:

Background Boltzmann equation:

$$\left(\partial_\tau + \frac{p_z}{\tau} \partial_{p_z} \right) \bar{f}(\tau, \mathbf{p}) = -C[\bar{f}]$$

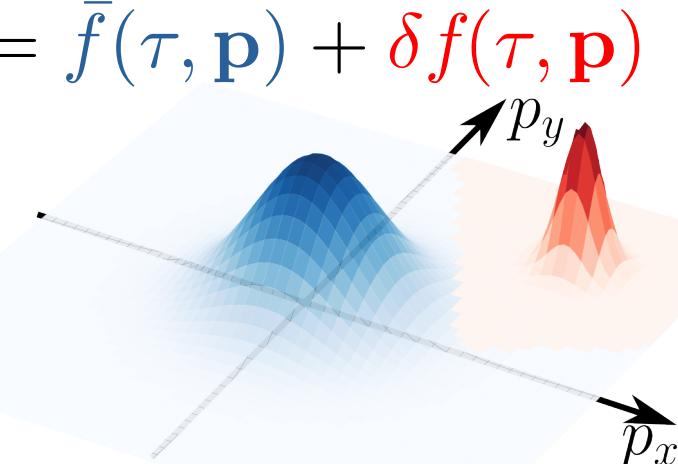
Linearized Boltzmann coupled to background:

$$\left(\partial_\tau + \frac{p_z}{\tau} \partial_{p_z} \right) \delta f(\tau, \mathbf{p}) = -\delta C[\bar{f}, \delta f]$$

No back reaction and no self-interaction!

- Background thermalisation: Kurkela, Zhu [1506.06647], Kurkela, Mazeliauskas [1811.03068], Du, Schlichting [2012.09079] for particle implementation see Zapp Wed 12:40
- Mini-jet thermalisation in kinetic theory:
 - Isotropic, non-expanding: Kurkela and Lu [1405.6318]
 - Thermal background, non-expanding: Methar-Tani, Schlichting, Soudi [2209.10569]

New: Perturbations on top of an expanding background!



Case I: Static thermal background (gluons only)

Gaussian perturbation at $p_z = 15T$

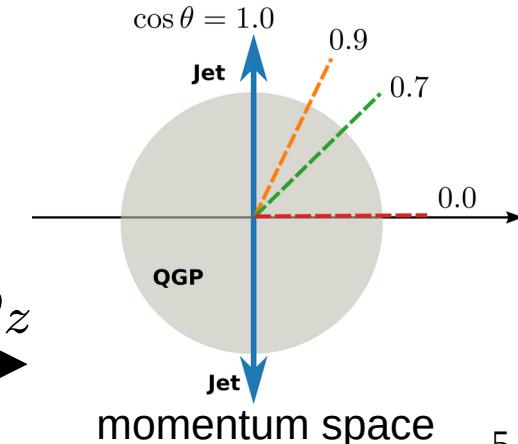
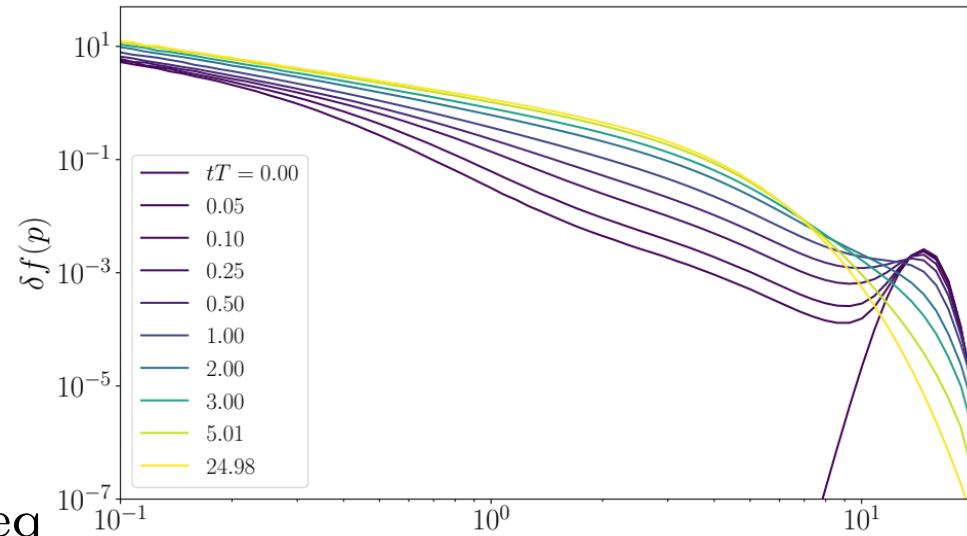
Two conserved quantities:

- Energy → temperature increase
- Momentum → velocity field

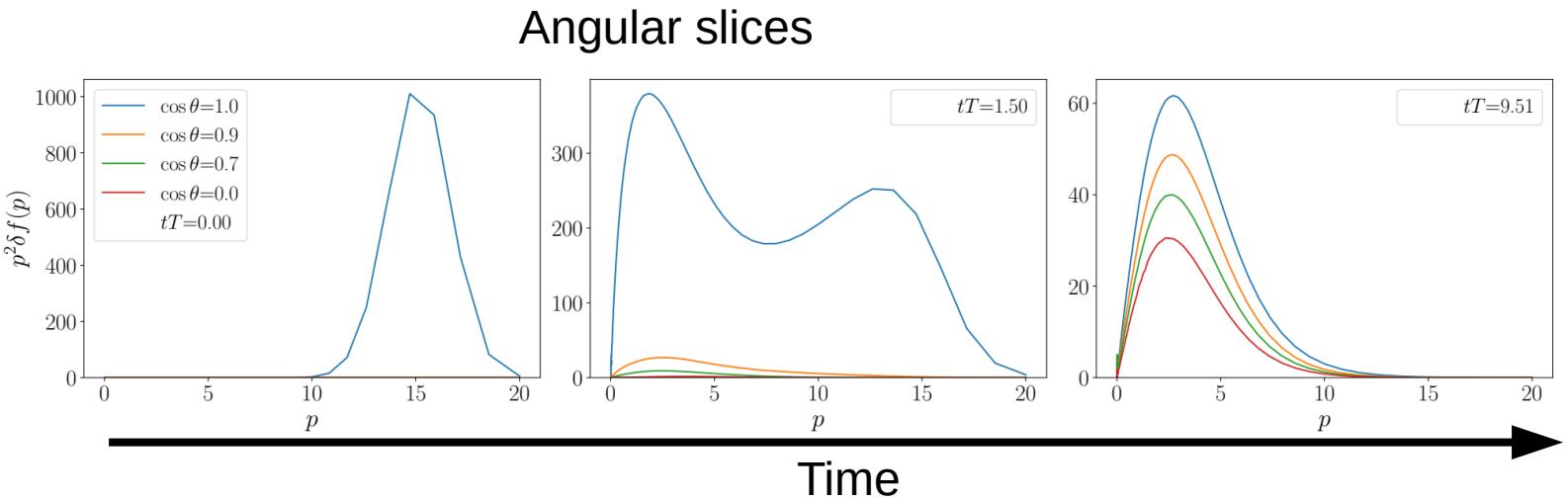
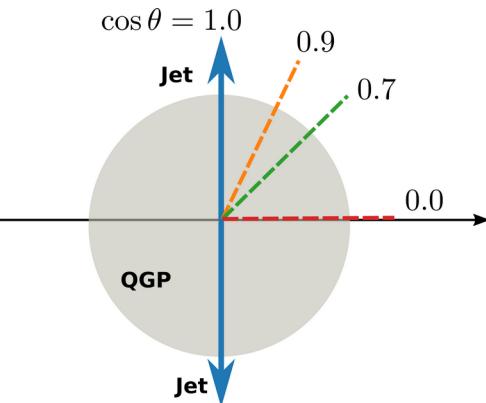
Equilibrium state for a perturbation:

$$\delta f_{\text{eq}}(\mathbf{p}) = (\delta T \partial_T + \delta u^z \partial_{u^z}) \bar{f}_{\text{eq}}$$

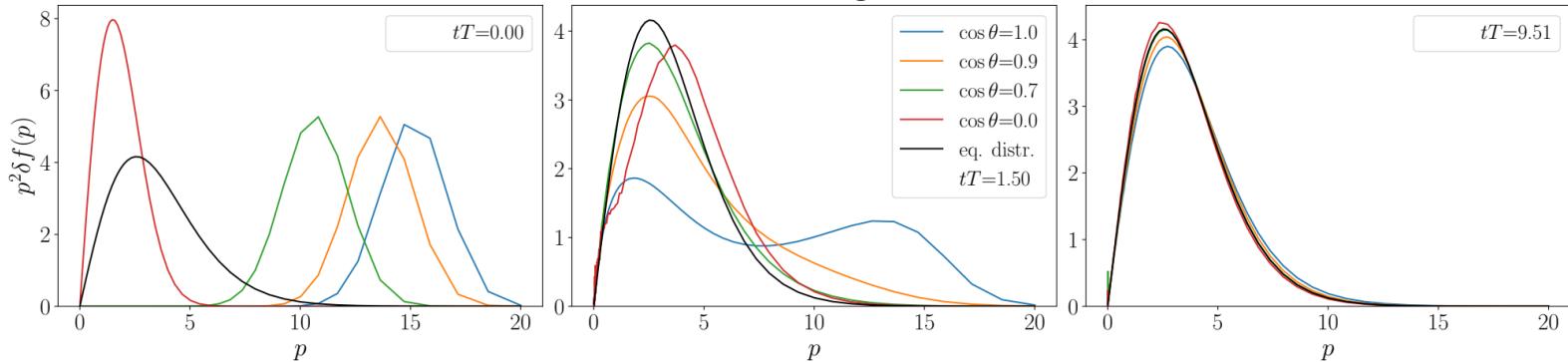
$$\delta f(\mathbf{p}) = \underbrace{\frac{1}{2}(\delta f(\mathbf{p}) + \delta f(-\mathbf{p}))}_{\text{Parity: even}} + \underbrace{\frac{1}{2}(\delta f(\mathbf{p}) - \delta f(-\mathbf{p}))}_{\text{odd}}.$$



Angle resolved di-jet thermalisation



Normalized distributions



Each angular slice thermalise first, before isotropising!

Angle dependent temperature

Consider n^{th} moment of distribution function

$$I_n(\theta) \equiv 4\pi \int \frac{p^2 dp}{(2\pi)^3} p^n f(p, \theta)$$

$$= \mathcal{N}_n \times T_n(\theta)^{n+3}$$

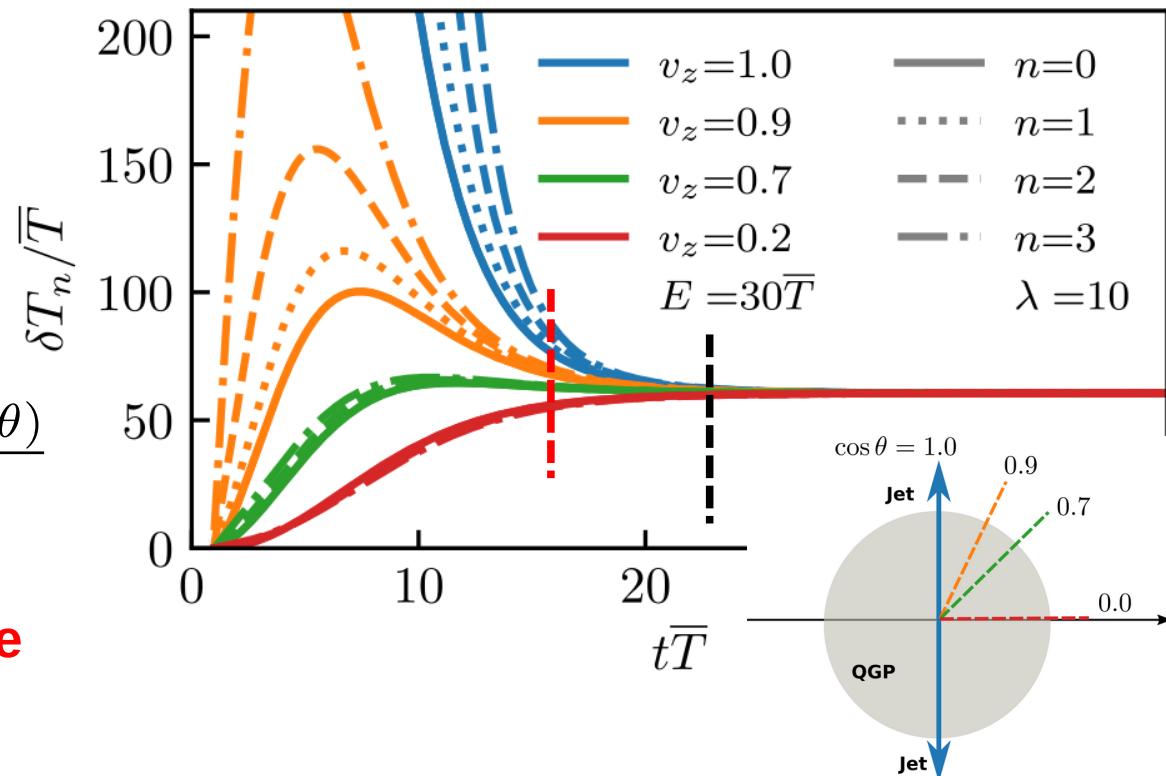
In equilibrium $T_n(\theta) \rightarrow \bar{T}$

For di-jet perturbation:

$$\delta I_n(\theta) = \mathcal{N}_n (n+3) T^{n+3} \frac{\delta T_n(\theta)}{\bar{T}}$$

**Collapse of different moments
→ angle dependent temperature**

$$\delta f_{\text{eq}} = \frac{\delta T(\theta)}{T} \frac{p}{T} \bar{f}_{\text{eq}} (1 + \bar{f}_{\text{eq}})$$

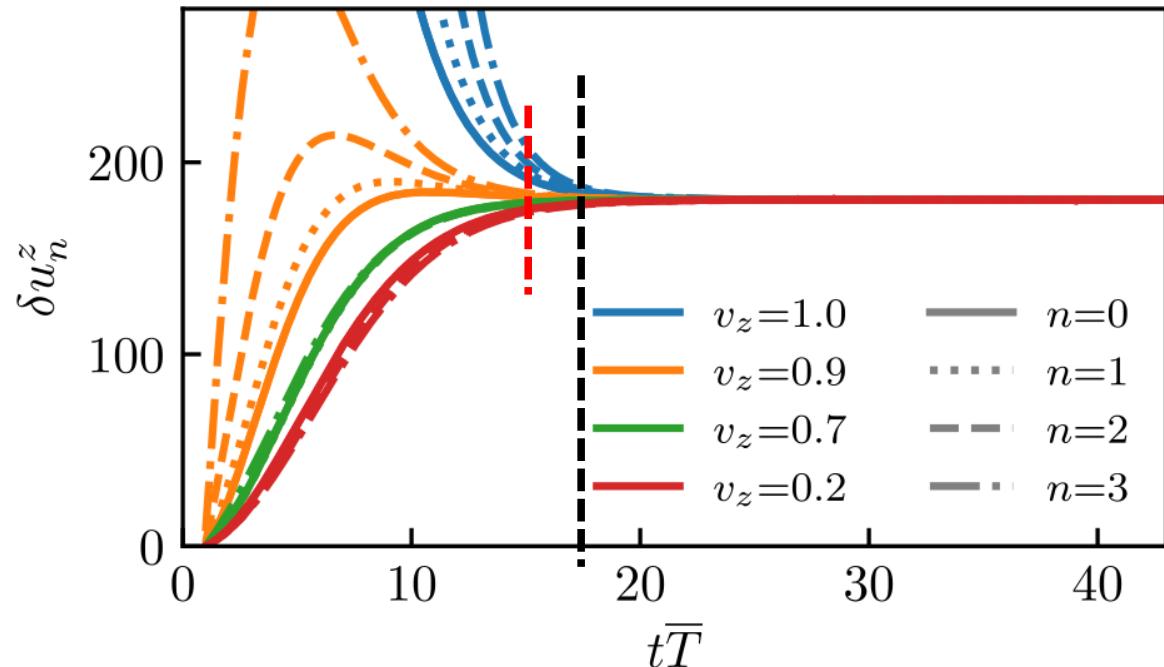


Jet-anti-jet thermalisation

Equilibrium distribution for jet-anti-jet: $\delta f_{\text{eq}} = \delta u^z \cos \theta \frac{p}{T} \bar{f}_{\text{eq}} (1 + \bar{f}_{\text{eq}})$

Define velocity field from moments: $\delta I_n(\theta) = \mathcal{N}_n(n+3) T^{n+3} \delta u_n^z(\theta) \cos \theta$

**Velocity perturbation is intrinsically anisotropic
→ faster equilibration than temperature perturbation**

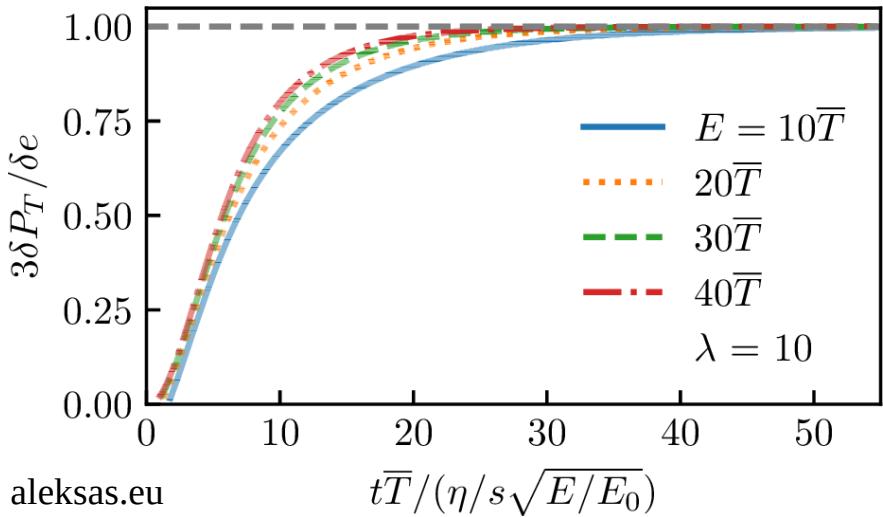
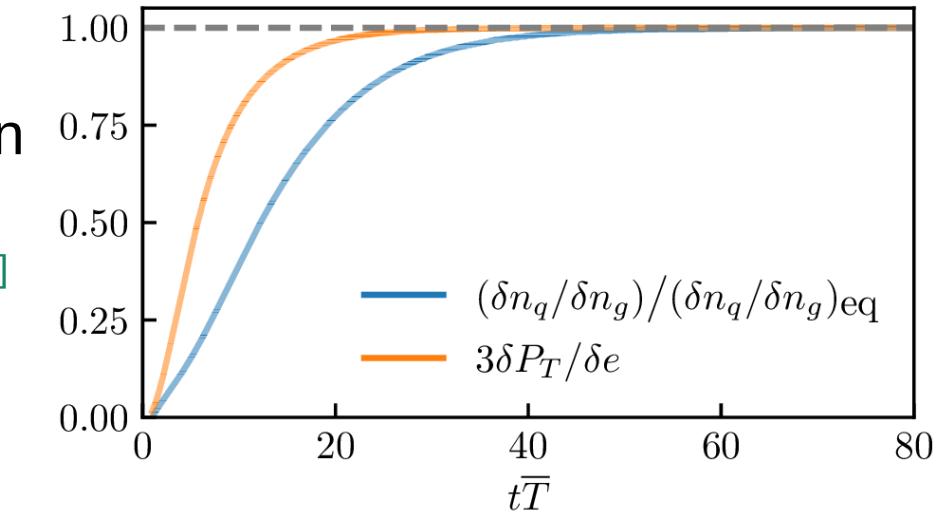
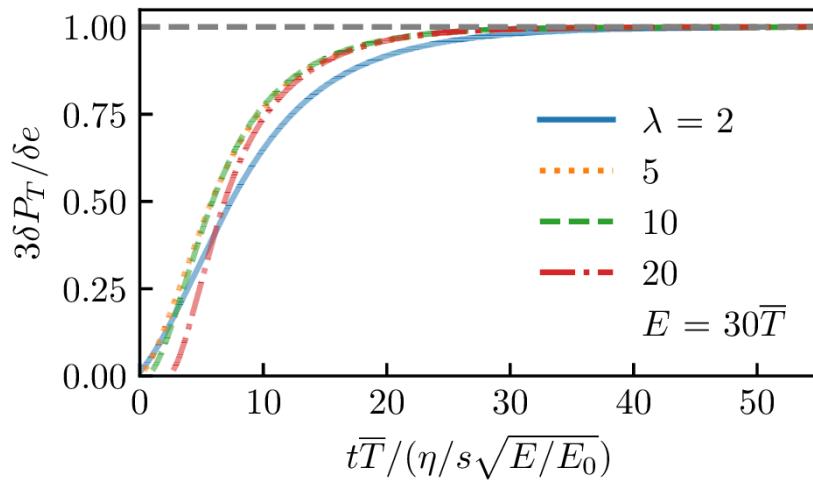


Case II: Gluon jet in thermal QCD background

For thermal QCD background:

- Chemical equilibration *after* isotropisation
- Isotropisation time scales with viscosity and mini-jet energy c.f. Kurkela and Lu [1405.6318]

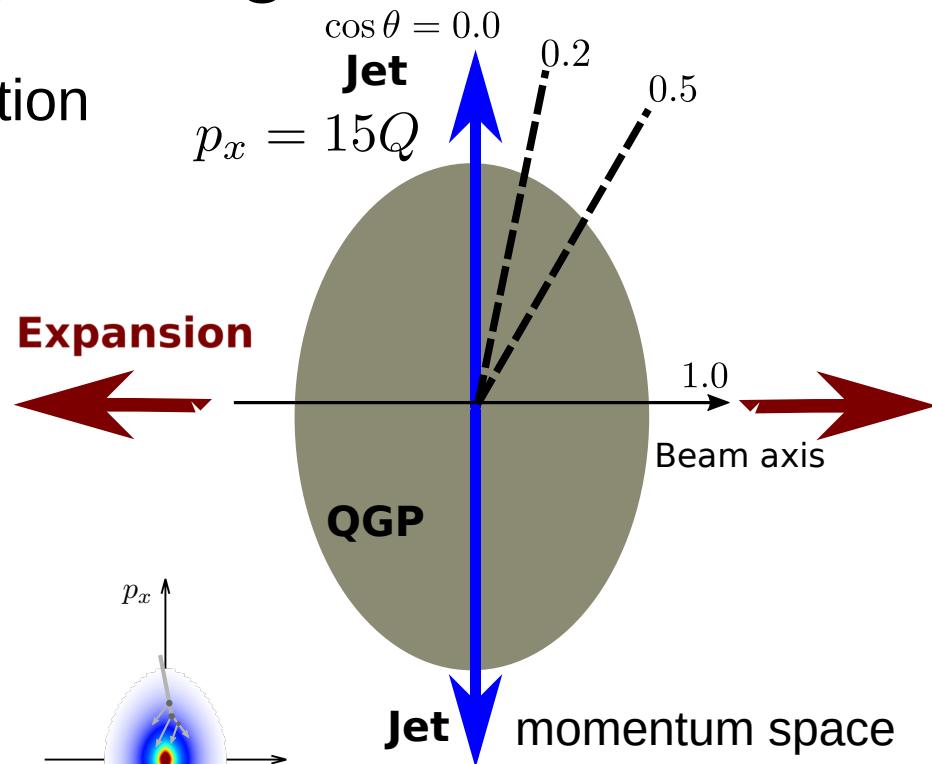
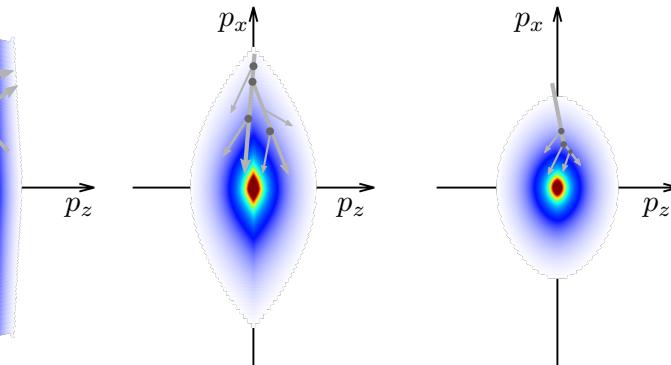
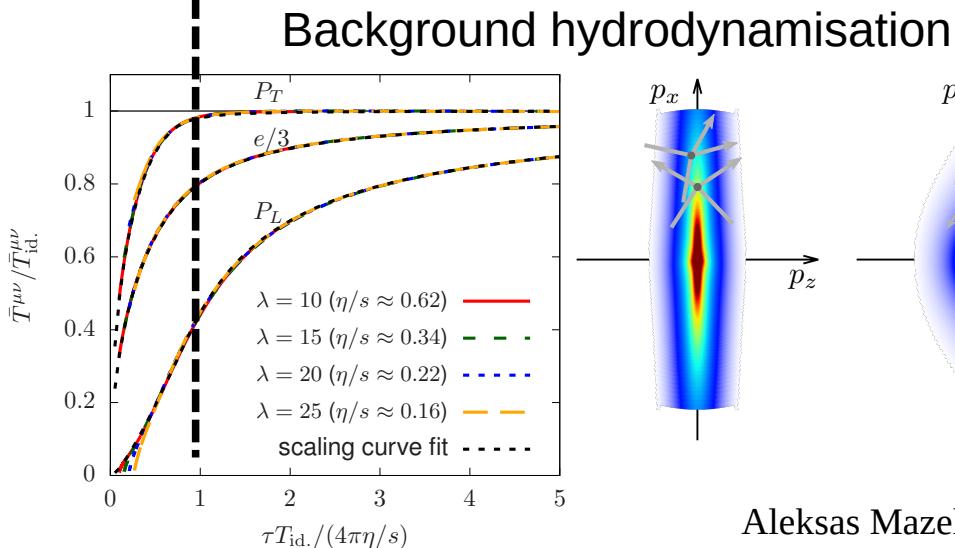
$$t_{\text{eq}} \propto \frac{\eta/s}{T} \sqrt{E/T}$$



Case III: Expanding background

- Consider mini-jet in the transverse direction
- Longitudinally expanding background

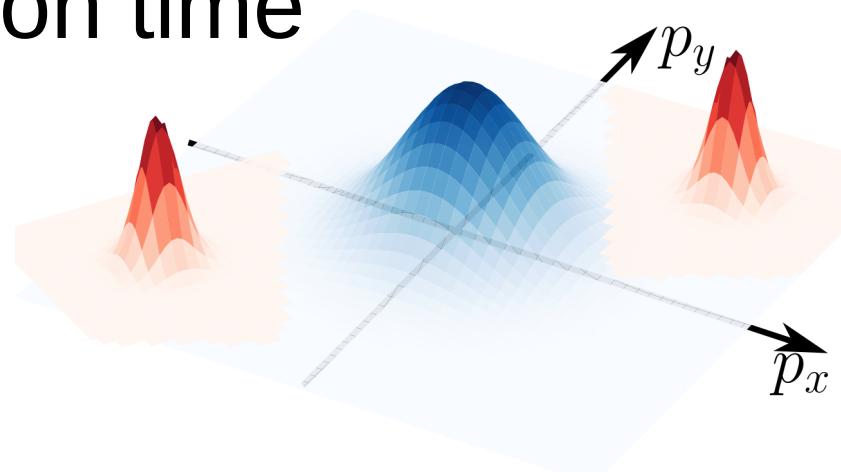
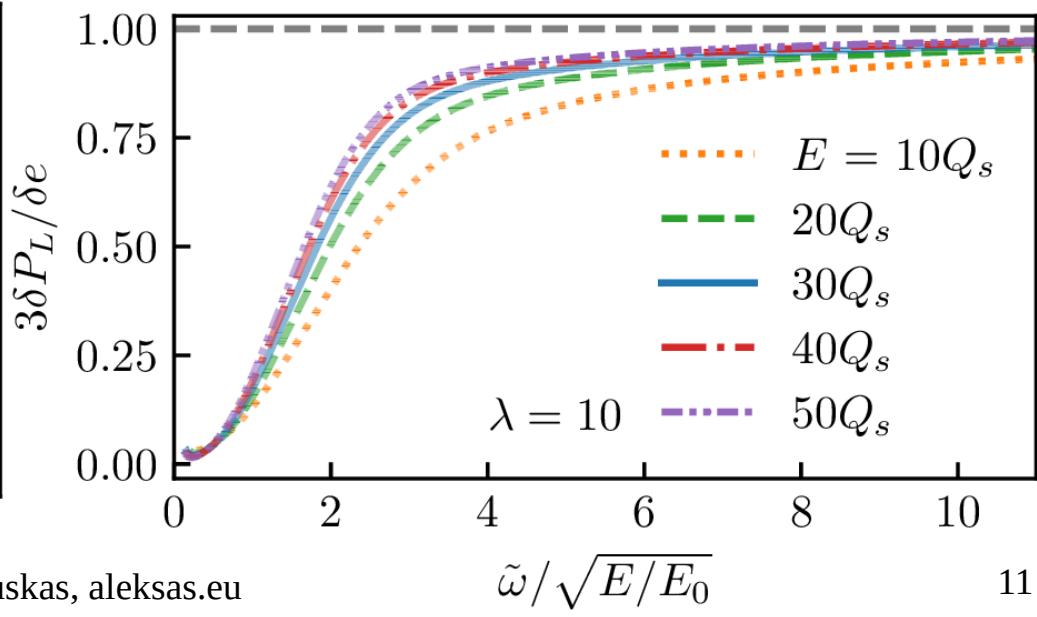
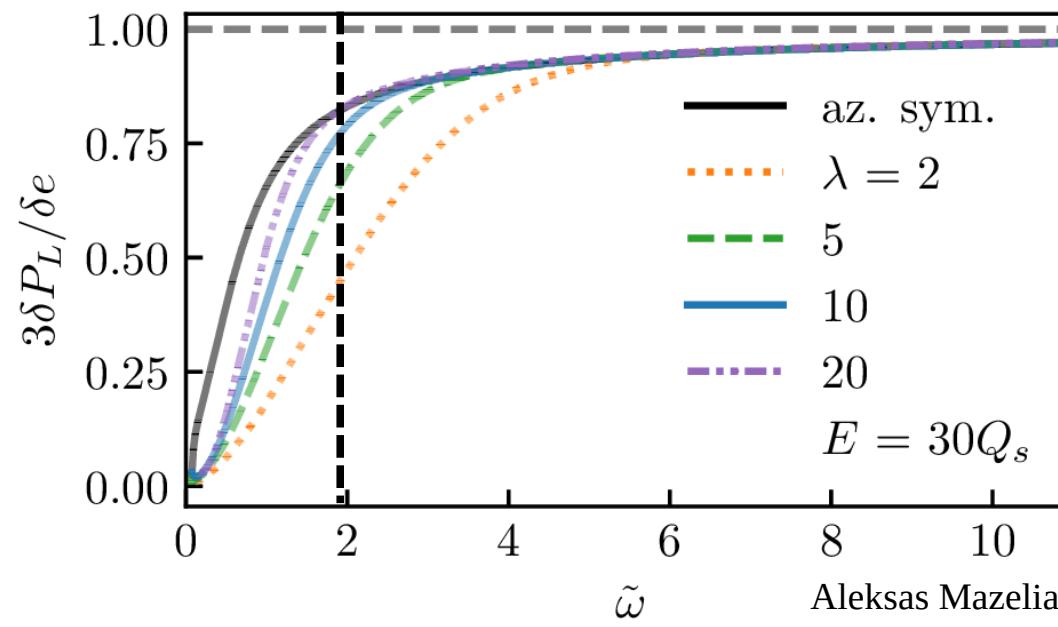
$$\tilde{w}_{\text{hydro}} = \frac{\tau T}{4\pi\eta/s} \approx 1$$



Hydrodynamisation time

Compare equilibration of two perturbations: di-jet and azimuthally symmetric perturbation

- Jet hydrodynamisation is achieved later than for background $\tilde{w}_{\text{eq}} > 1$
 - Equilibration times scales with \sqrt{E}



Summary & Outlook

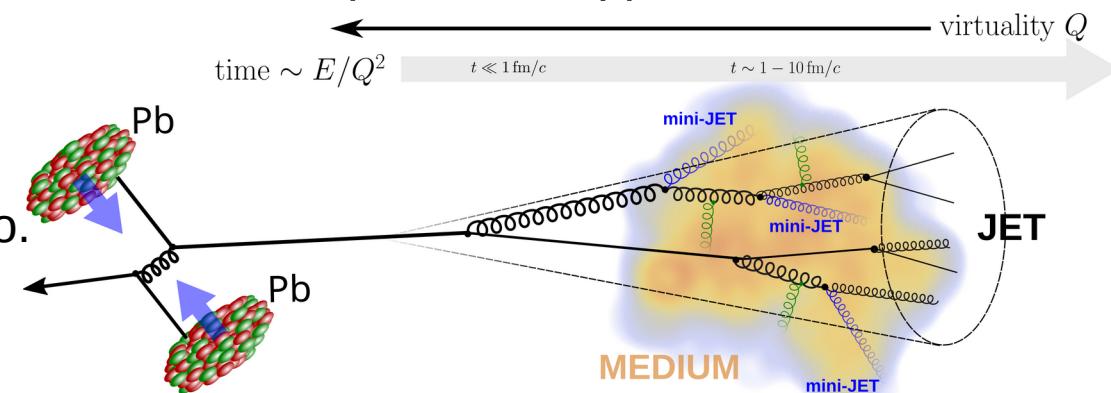
Studied mini-jet thermalisation in QCD kinetic theory:

Thermal background:

- Angular dependent equilibration due to fast colinear radiation.
- Chemical equilibration *after* isotropization in QCD.

Expanding background:

- Hydrodynamisation slower than background, scales with sq. root of energy.
- Chemical equilibration *before* isotropisation in QCD (see backup).

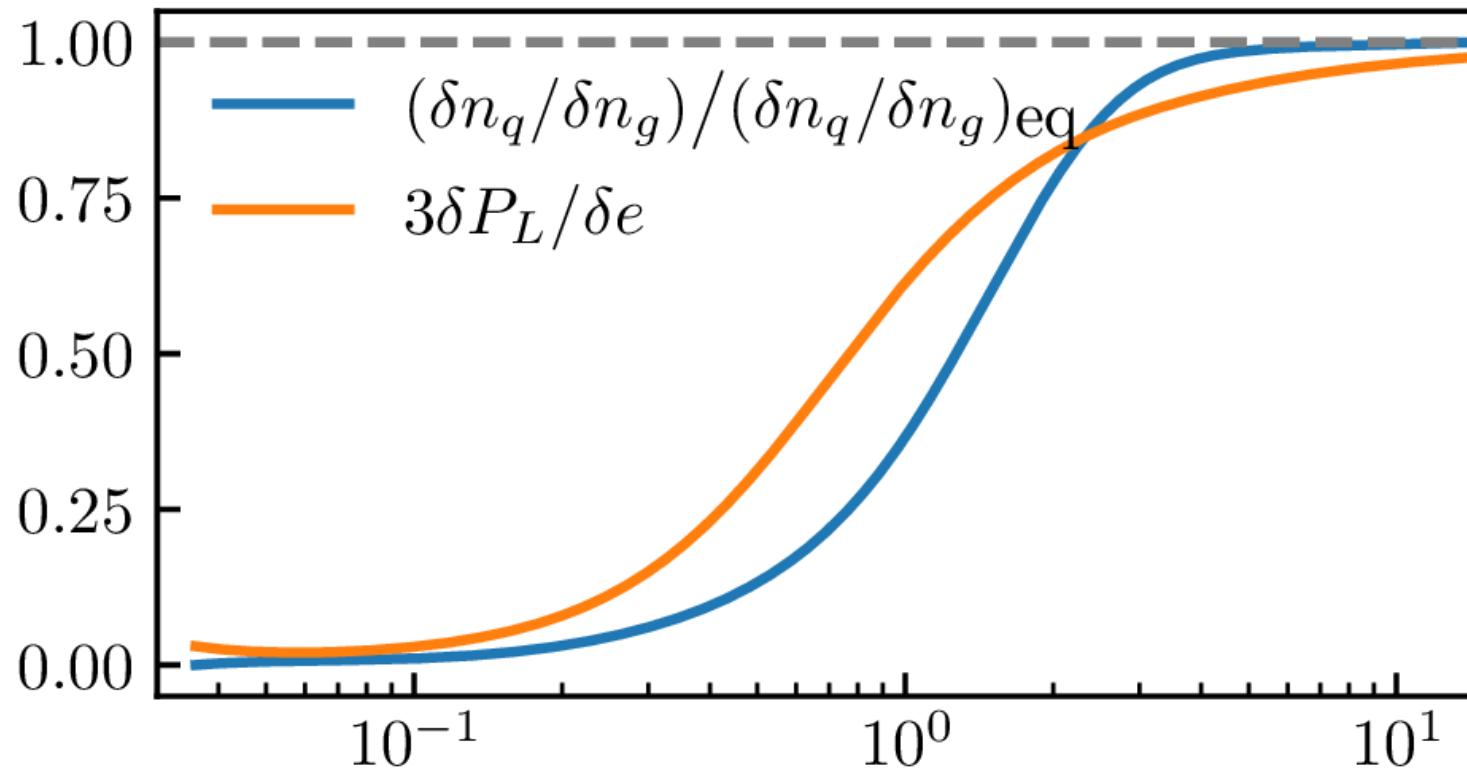


Outlook:

- Model spatial localisation of a jet.
- Interface with vacuum shower and hydro.

Thank you!

Chemical equilibration in expanding case



Chemical equilibration happens *before* isotropisation