Mini-jet quenching in non-equilibrium quark-gluon plasma

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1. Motivation

- Interactions between the Quark Gluon Plasma (QGP) and hard partons lead to the phenomenon of *jet quenching*.
- *Kinetic theory* describes the equilibration of the far-from-equilibrium state.
  → approach to hydrodynamics

Study of mini-jets thermalizing in the non-eq. plasma [1]

2. Effective kinetic theory of QCD [2]

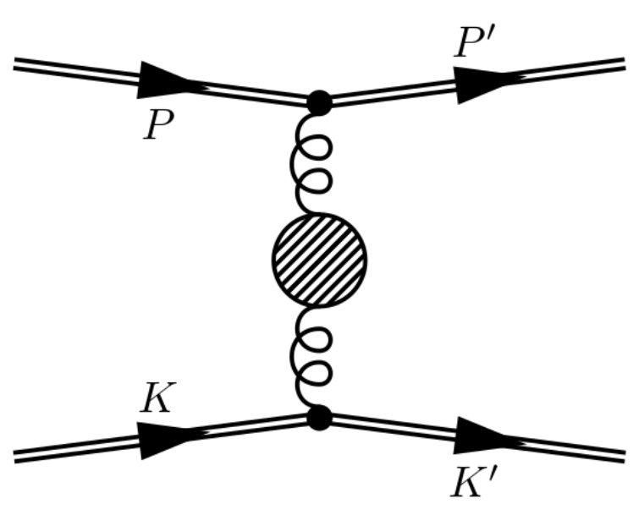
Boost invariant transport equation for phase space distribution $f(\tau,\mathbf{p})$ of different particle species:

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

Leading order (in $\lambda = N_c g^2$) elastic and inelastic processes

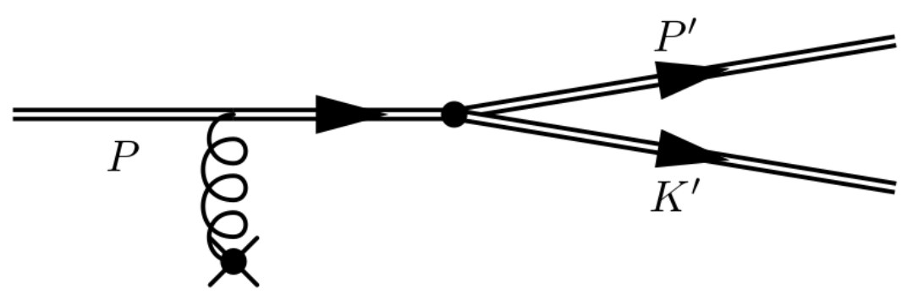
$$C[f](\mathbf{p}) = C_{2\leftrightarrow 2}[f](\mathbf{p}) + C_{1\leftrightarrow 2}[f](\mathbf{p})$$

- $C_{2\leftrightarrow 2}$: soft momentum transfer regulated by
  $$\frac{1}{q^2} \to \frac{1}{q^2+\xi^2 m_D^2}$$



$$|\mathcal{M}^{gg}_{gg}|^2 = 2\lambda^2\nu\left(9 + \frac{(s-t)^2}{u^2} + \frac{(u-s)^2}{t^2} + \frac{(t-u)^2}{s^2}\right)$$

- $C_{1\leftrightarrow 2}$: strictly collinear, includes LPM-suppression



$$\gamma^g_{gg} = \frac{p^4+p'^4+k'^4}{p^3 p'^3 k^3}\underbrace{\mathcal{F}_g\left(p;p',k'\right)}_{\text{splitting rate}}$$

Treat jet as a linear perturbation around background

$$f(\tau,\mathbf{p}) = \bar{f}(\tau,\mathbf{p}) + \delta f_{\text{Jet}}(\tau,\mathbf{p})$$

⇒ **linearized Boltzmann equation for mini-jet**

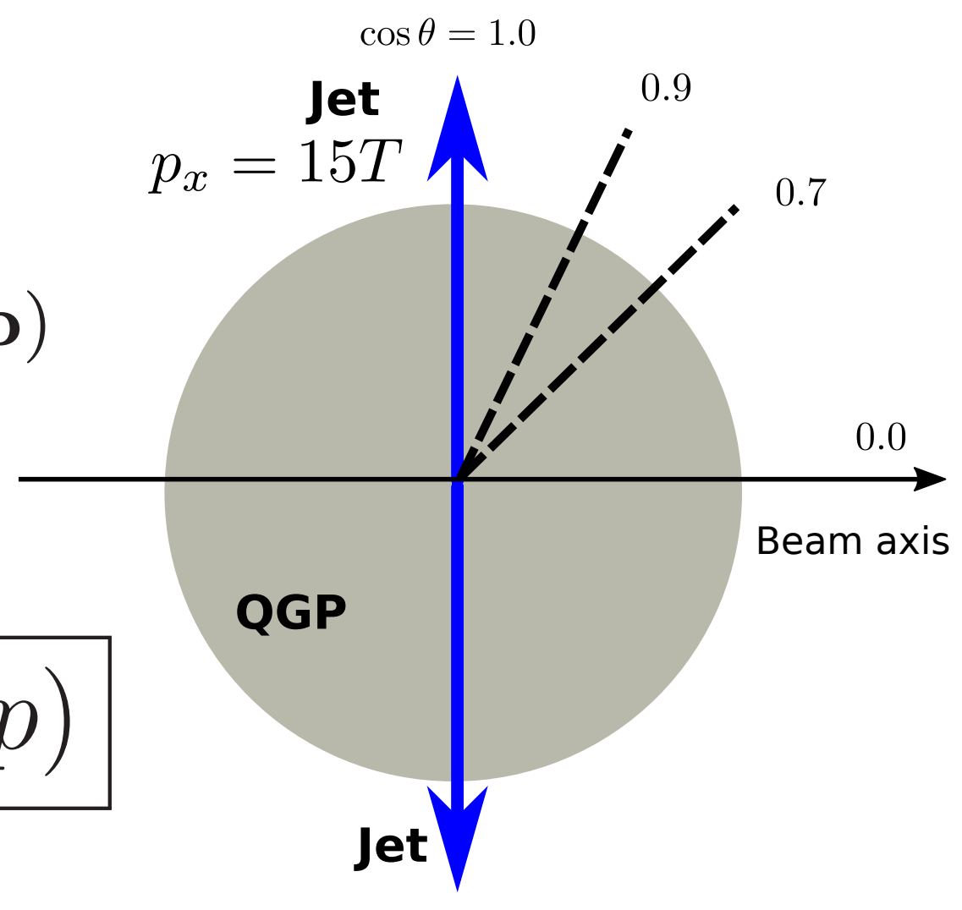
$$\left(\partial_\tau - \frac{p_z}{\tau}\partial_{p_z}\right)\delta f_{\text{Jet}}(\tau,\mathbf{p}) = -\delta C[\bar{f},\delta f_{\text{Jet}}]$$

3. Initial conditions: i) Thermal

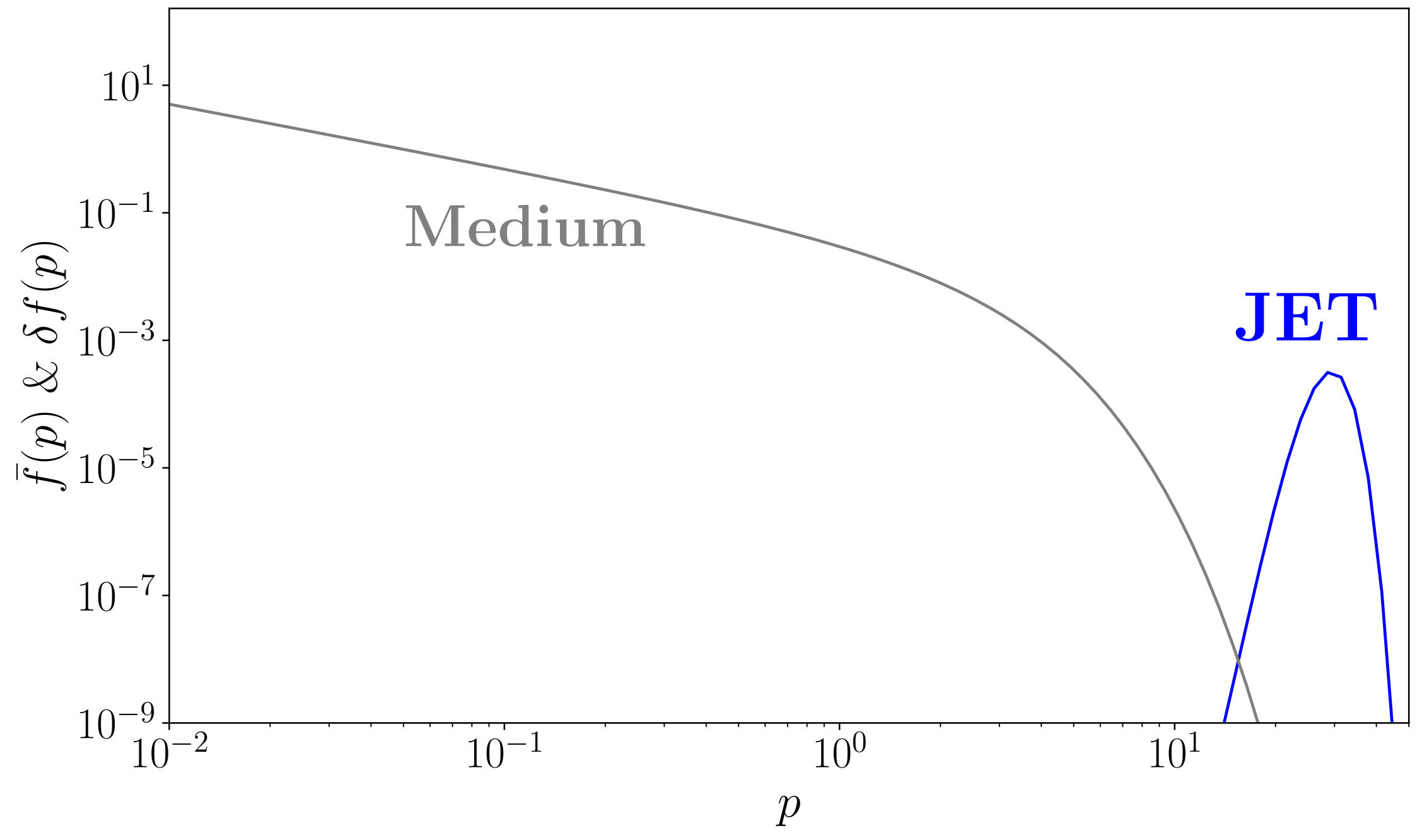
Back-to-back jets on top of a thermal background

$$f(\tau_0,\mathbf{p}) = f_{\text{eq}}(p) + \delta f_{\text{Jet}}(\tau_0,\mathbf{p})$$

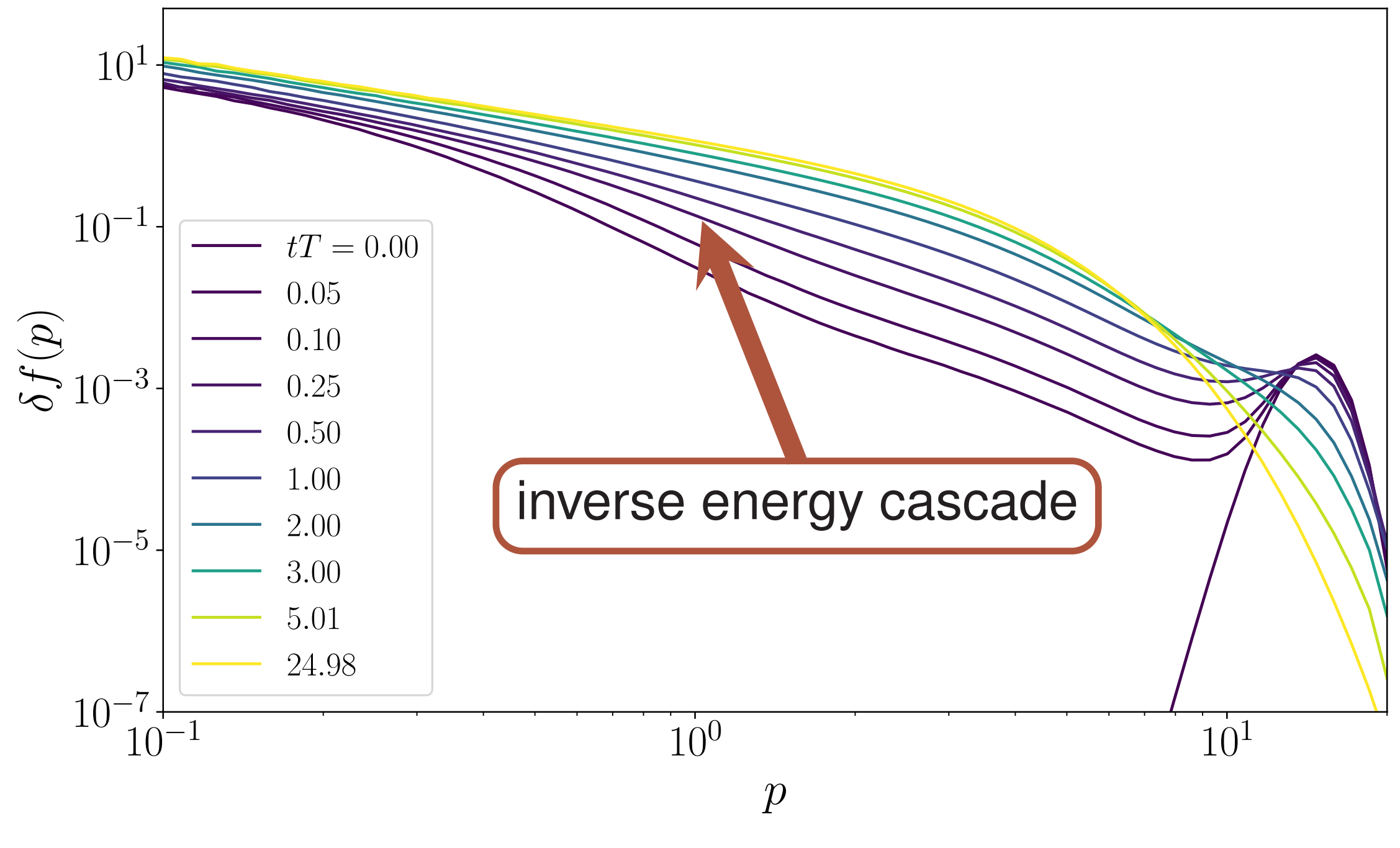
$$\boxed{\delta f_{\text{Jet}}(\tau_0,\mathbf{p}) \to \delta f_{\text{eq}}(p)}$$



Jet perturbation as Gaussian at $E = 15T$



Thermalization of a mini-jet



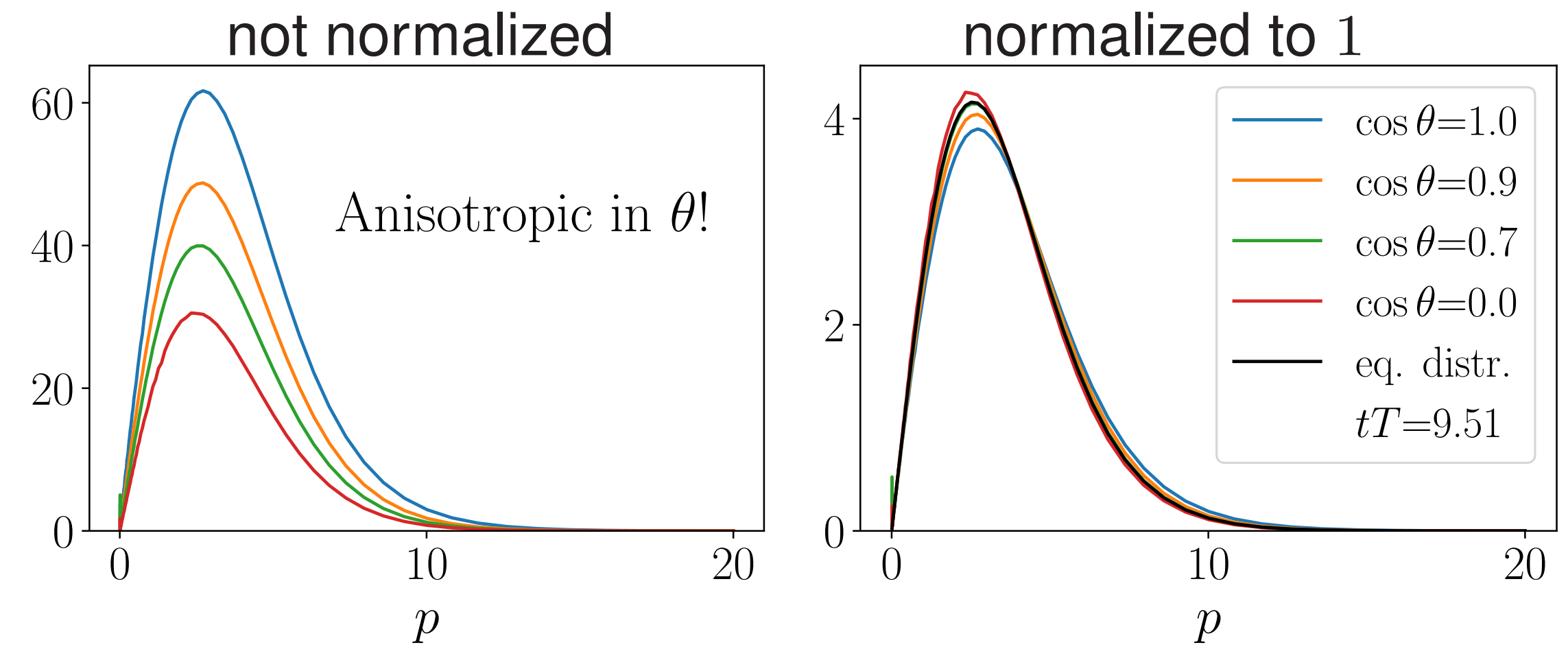
During intermediate times, the evolution of the jet perturbation can be described by a scaling solution [3].

4. Angular dependent equilibration

Equilibrated jets → increase in temperature T

$$\Leftrightarrow \delta f_{\text{eq}}(p) = \partial_T f_{\text{eq}}\left(\frac{p}{T}\right)\delta T$$

Jet distribution $p^2\delta f(\tau,p,\theta)$ for different θ


not normalized
normalized to 1

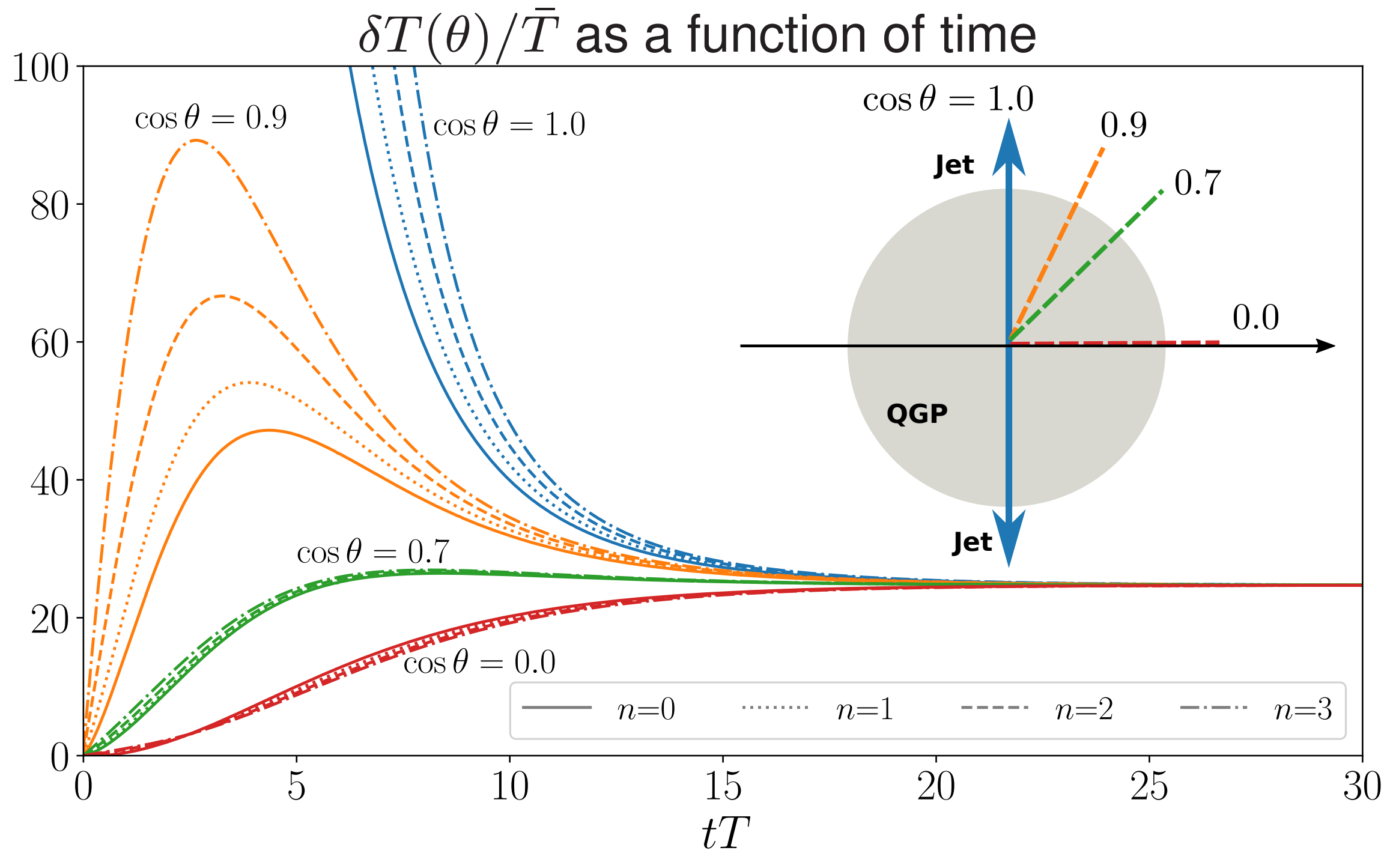
Inelastic processes produce thermal distributions along each slice in θ ⇒ temperature $T(\theta)$.

θ-dependent moments of δf_{Jet}

$$I_n(\theta) \equiv 4\pi\int\frac{p^2\,dp}{(2\pi)^3}p^n f(p,\theta) = \mathcal{N}_n \times T(\theta)^{n+3}$$

Defines angular dependent temperature $\bar{T} + \delta T(\theta)$
→ agrees for all n and θ in equilibrium

$\delta T(\theta)/\bar{T}$ as a function of time



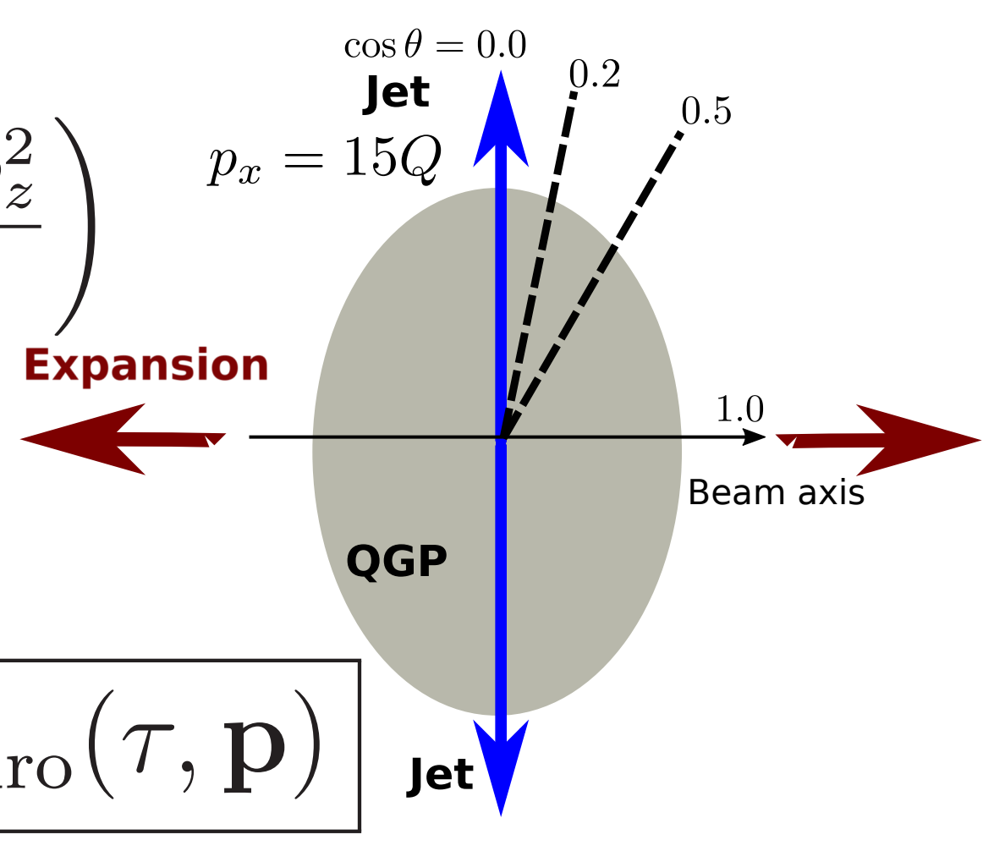
Different moments n agree before different angles θ do!

5. Initial conditions: ii) Anisotropic

Jet on top of non-equilibrium background, longitudinally expanding

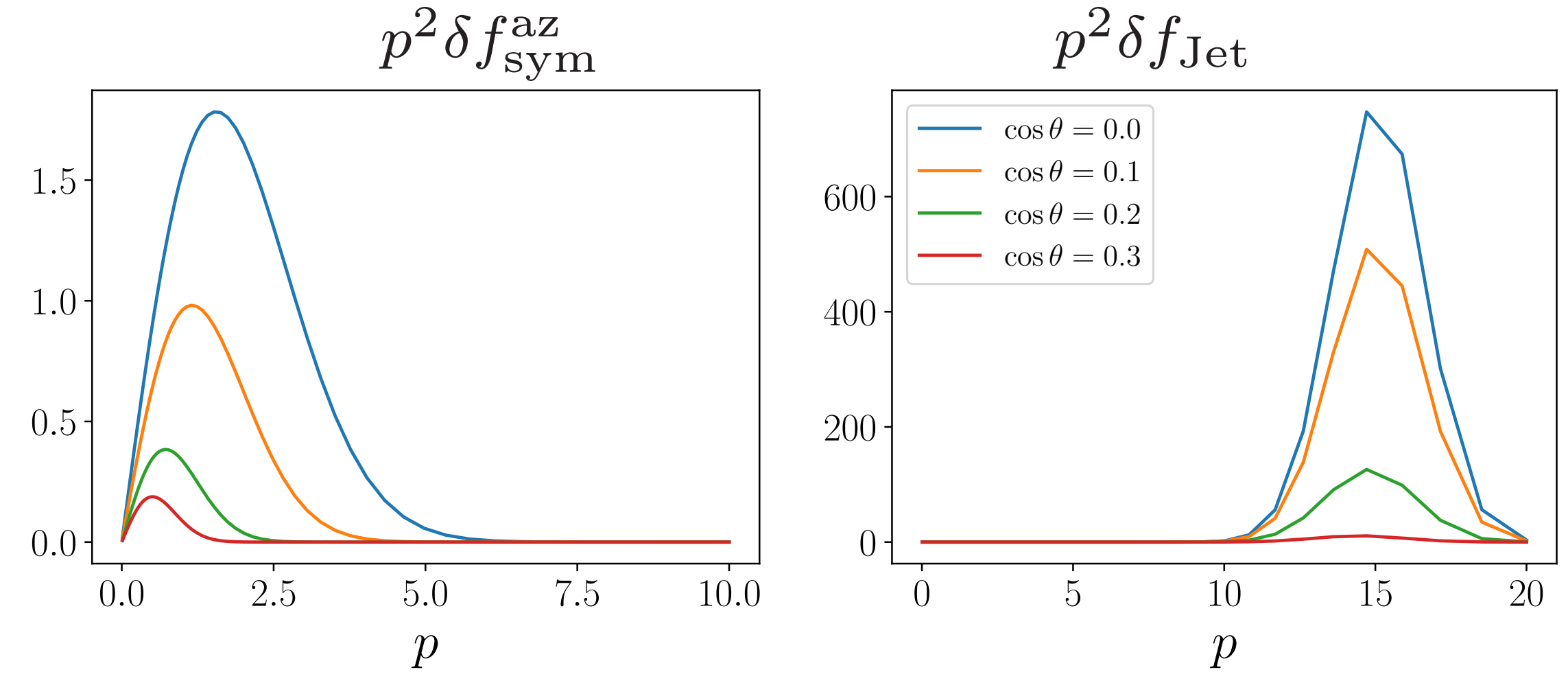
$$\bar{f}(\tau,\mathbf{p}) \propto \exp\left(-\frac{2}{3}\frac{p_\perp^2+\xi^2 p_z^2}{Q^2}\right)$$

$$\boxed{\delta f_{\text{Jet}}(\tau_0,\mathbf{p}) \to \delta f_{\text{hydro}}(\tau,\mathbf{p})}$$

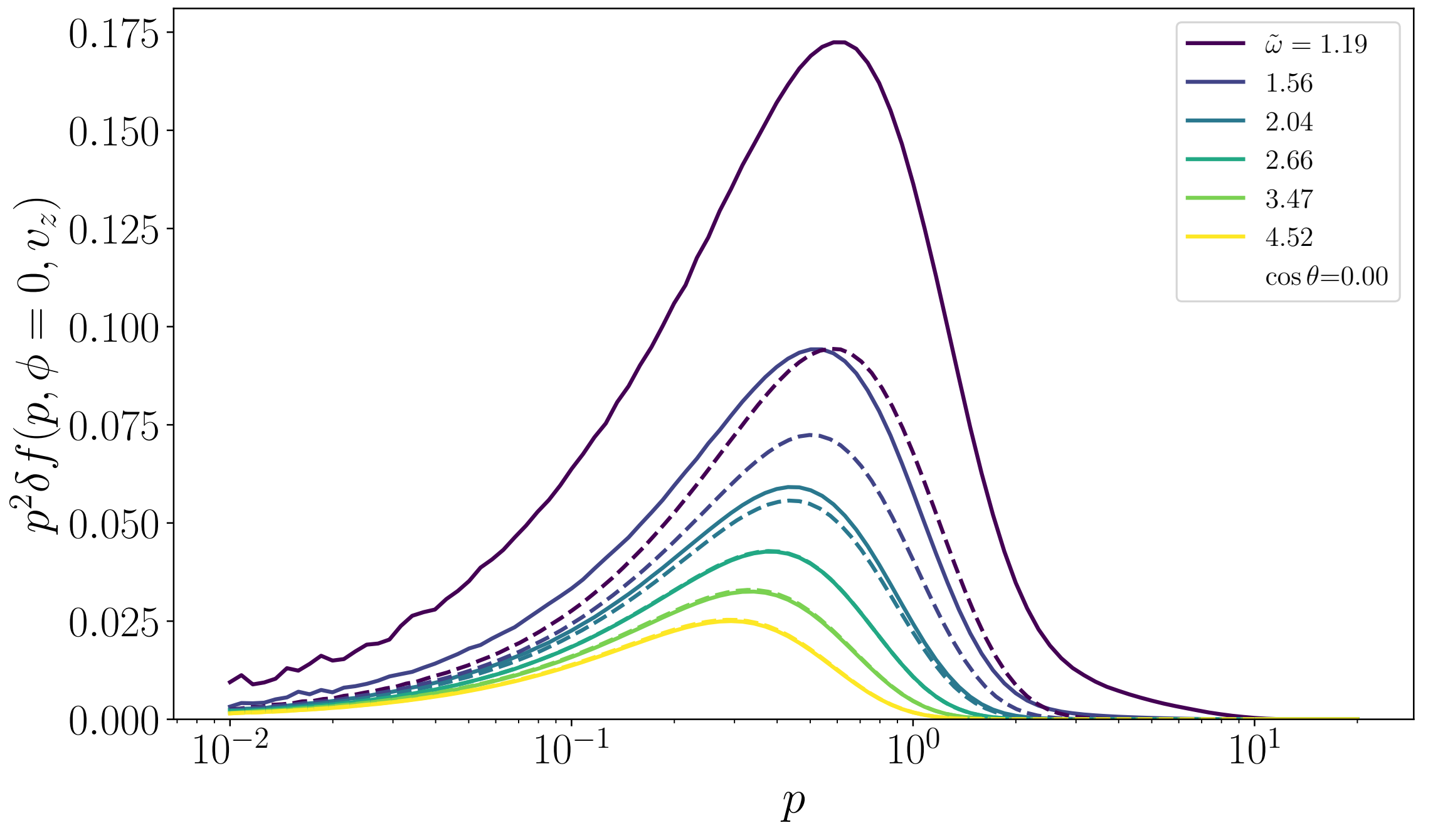


Study the hydrodynamization of the jet: comparison of its time evolution to an azimuthally symmetric perturbation.

Initial condition of the az. sym. perturbation and the jet

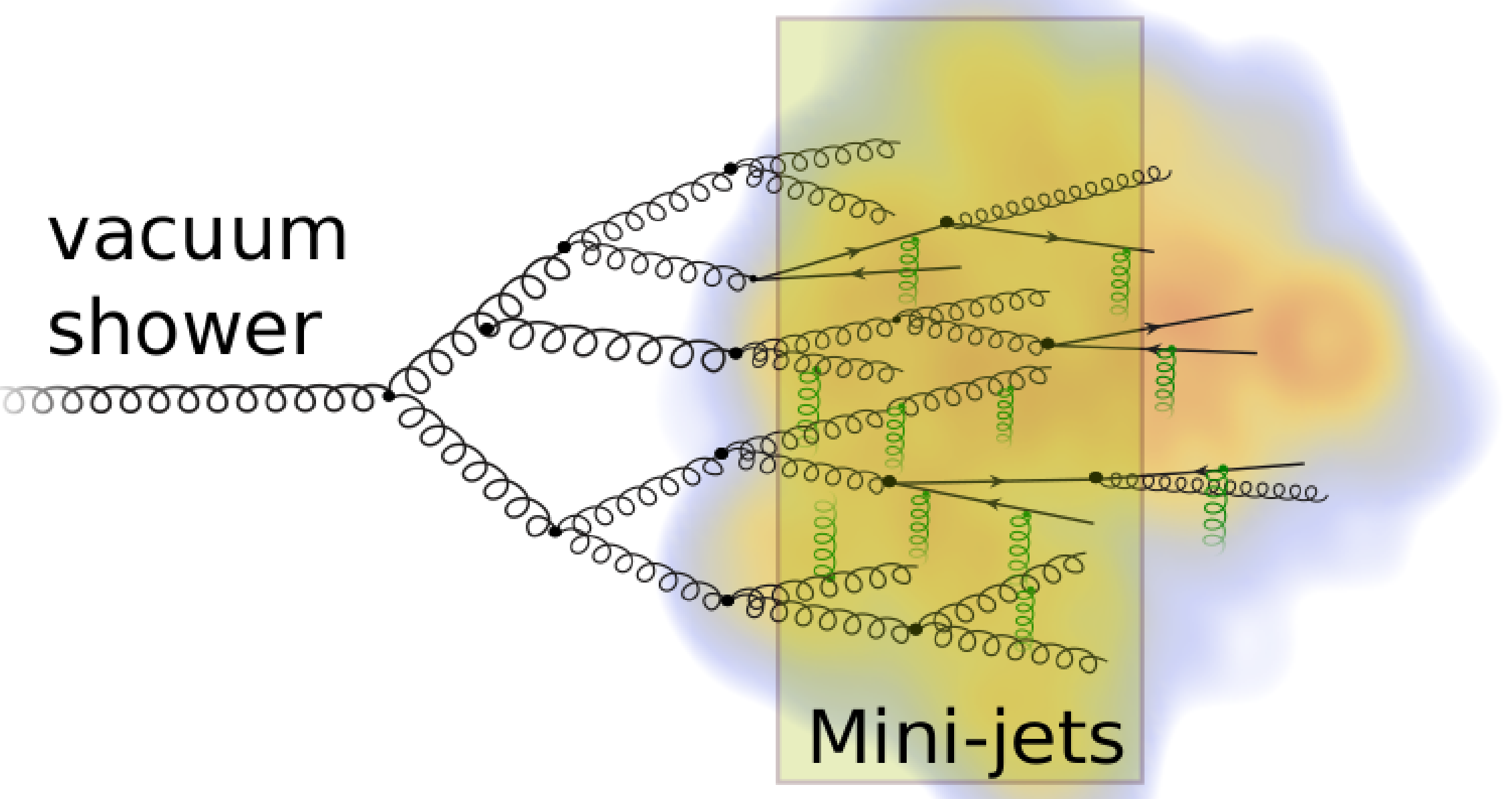

$p^2\delta f^{\text{az}}_{\text{sym}}$
$p^2\delta f_{\text{Jet}}$

Collapse of the jet distribution with the az. sym. perturbation after $\tilde{\omega} \approx 2$



The system loses memory of the initial condition
⇒ **Hydrodynamization!**

Mini-jets in medium

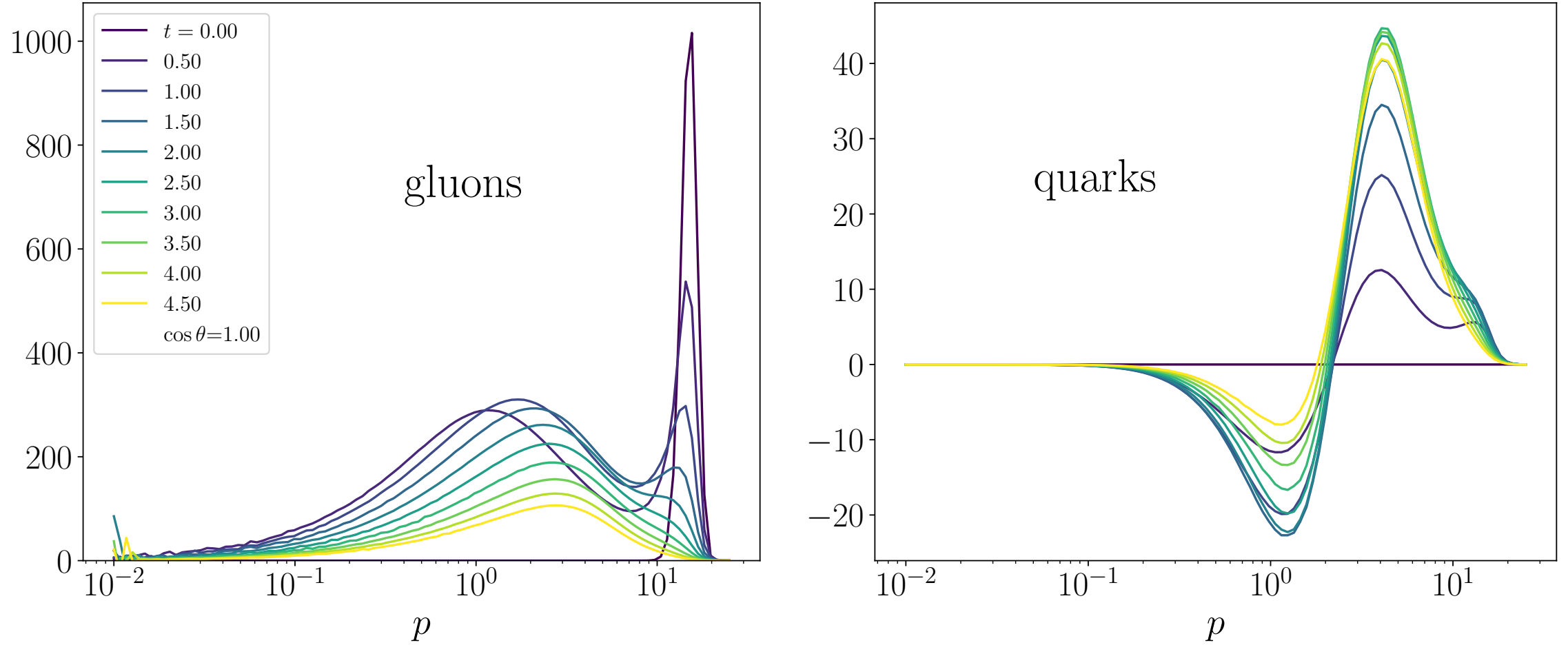


6. Chemical equilibration of jets

Initially highly occupied gluons produce quarks while thermalizing → in equilibrium more quark d.o.f. [4].

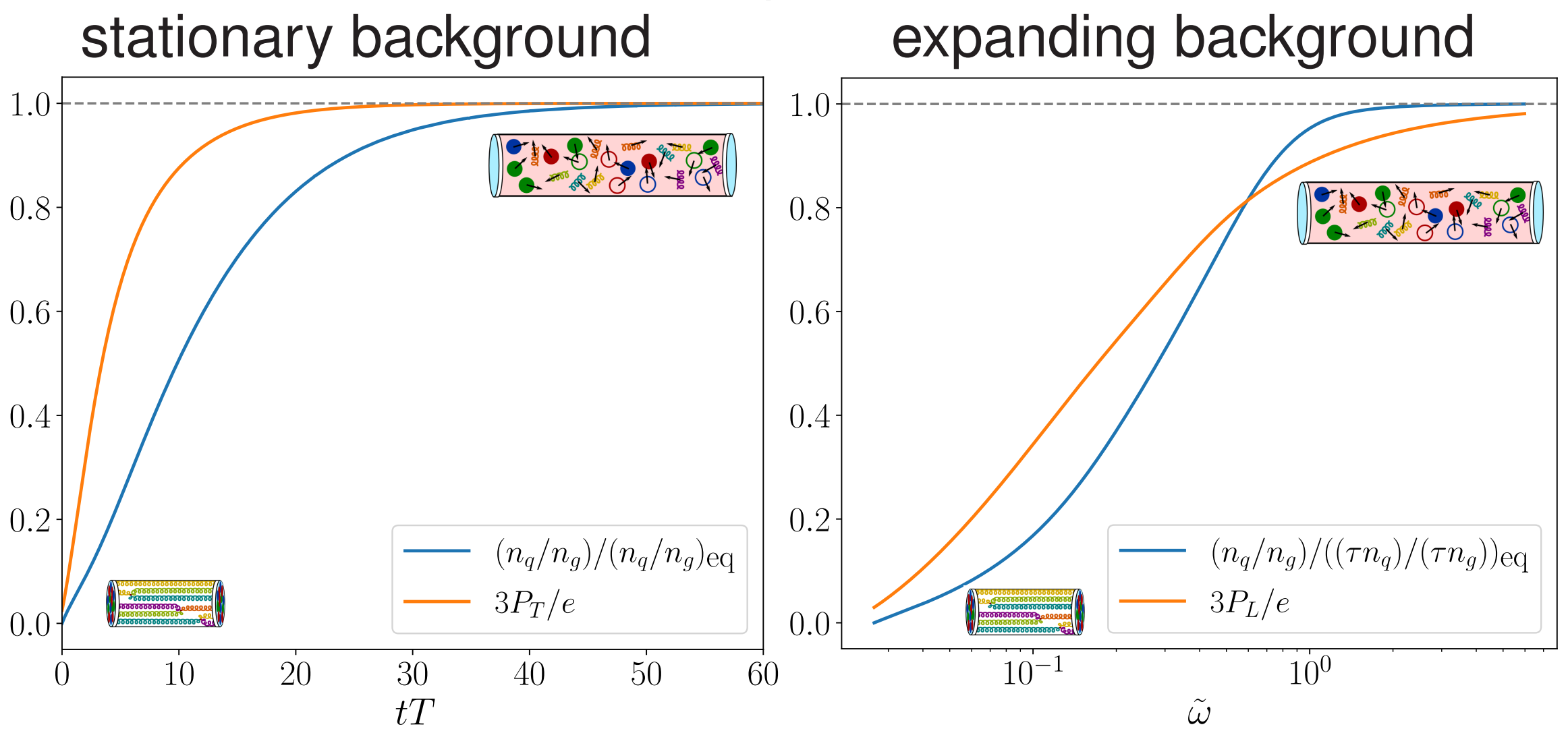
Initialize gluon jet $\delta f_g(\tau_0,\mathbf{p})$, while setting $\delta f_q(\tau_0,\mathbf{p}) = 0$.

Time evolution of gluon and quark distribution



Relevant processes deplete soft quarks for early times. Hard gluon scatters off the soft quark background.

Chemical equilibration for


stationary background
expanding background

While expanding, the system reaches chemical equilibrium faster than isotropization.

Conclusions & Outlook

static QGP:

- Radiation leads to thermal distributions with $T(\theta)$.
- Elastic processes build up early velocity field (not shown).

expanding QGP:

- Mini-jet hydrodynamize later than the background.
- With expansion, chemical equilibration is reached before isotropization.

Outlook

- get parametric estimates of equilibration time scales
- jet response functions → phenomenology
- transverse dynamics → small systems

References

[1] Y. Mehtar-Tani, S. Schlichting, I. Soudi, JHEP05(2023)091.
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