Minijet 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 [2]

2. Effective kinetic theory of QCD [3]

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

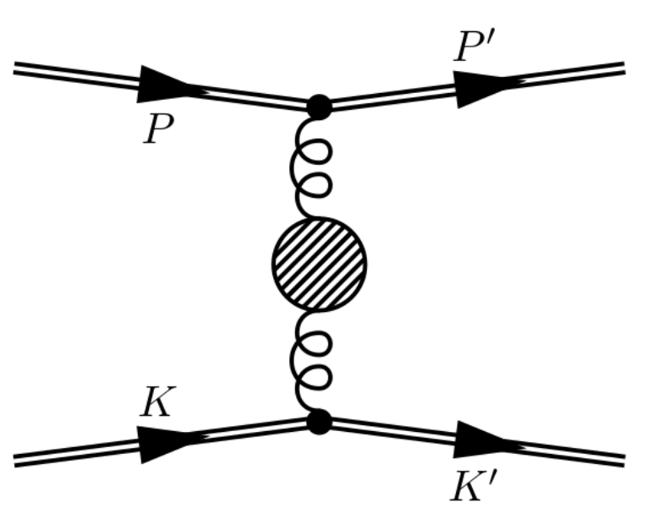
$$\left(\partial_\tau - \frac{p_z}{\tau}\partial_{p_z}\right) f(\tau, \mathbf{p}) = -C[f]$$

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

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

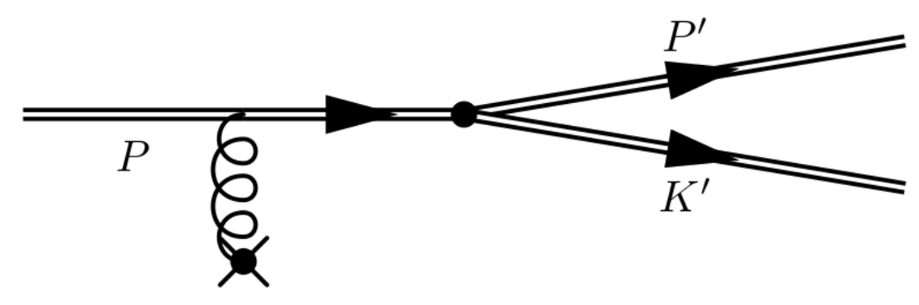
- $C_{2\leftrightarrow 2}$: soft momentum transfer regulated by

$$\frac{1}{q^2} \to \frac{1}{q^2 + \xi^2 m_D^2}$$



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

- $C_{1\leftrightarrow 2}$: 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**

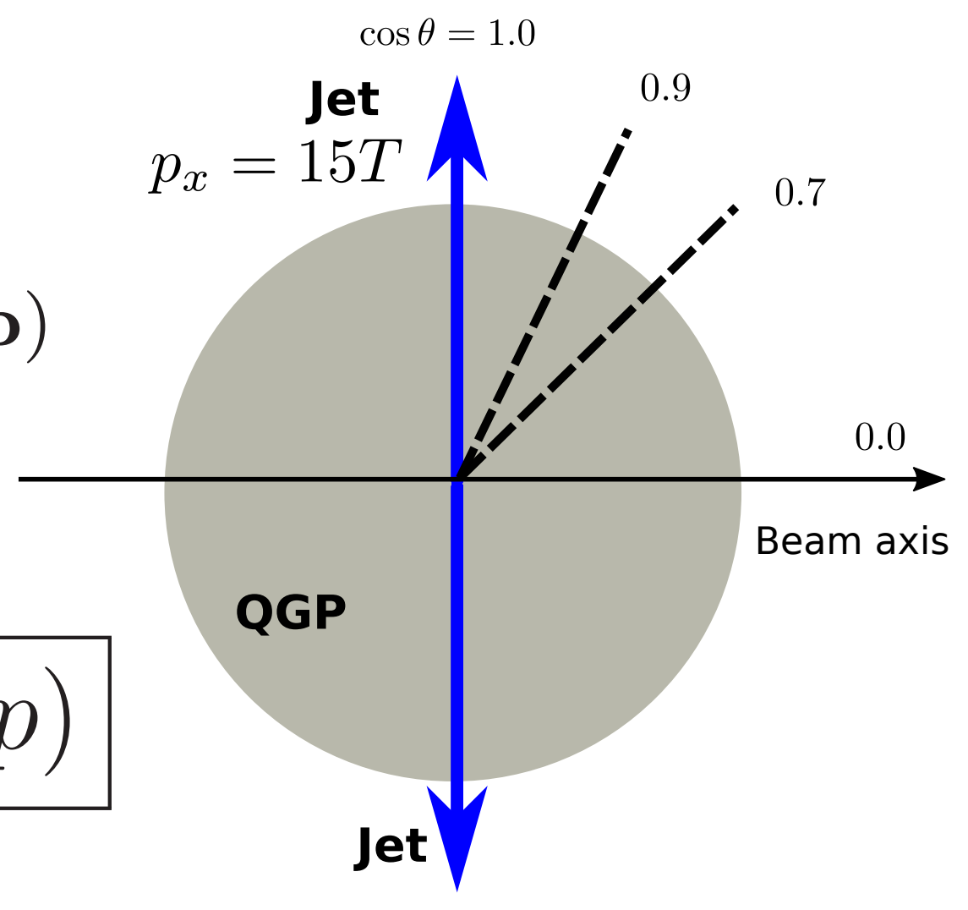
$$\left(\partial_\tau - \frac{p_z}{\tau}\partial_{p_z}\right) \delta f_{\text{Jet}}(\tau, \mathbf{p}) = -\delta C[\bar{f}, \delta f_{\text{Jet}}]$$

3. Initial conditions: i) Thermal

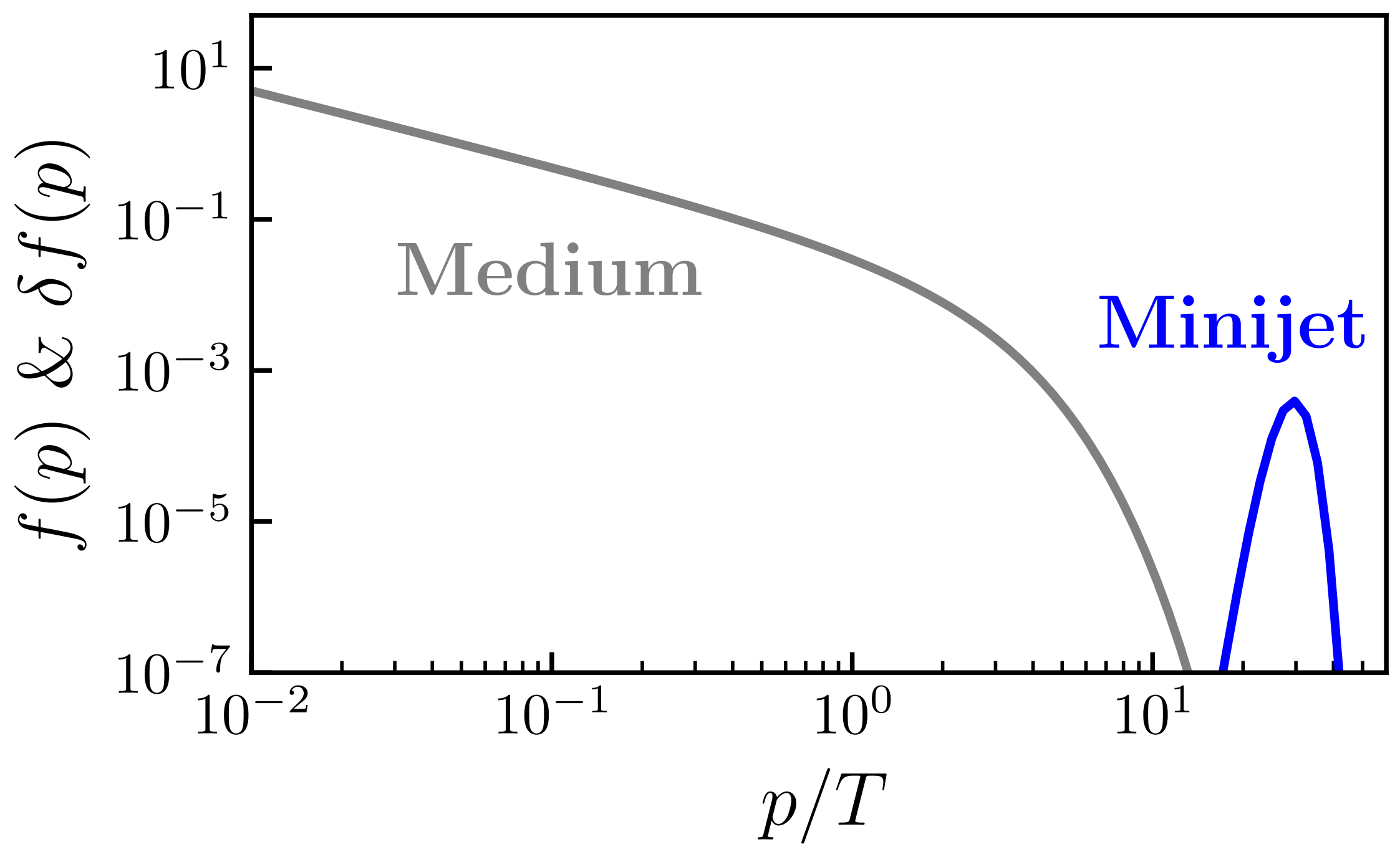
Back-to-back jets on top of a thermal background

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

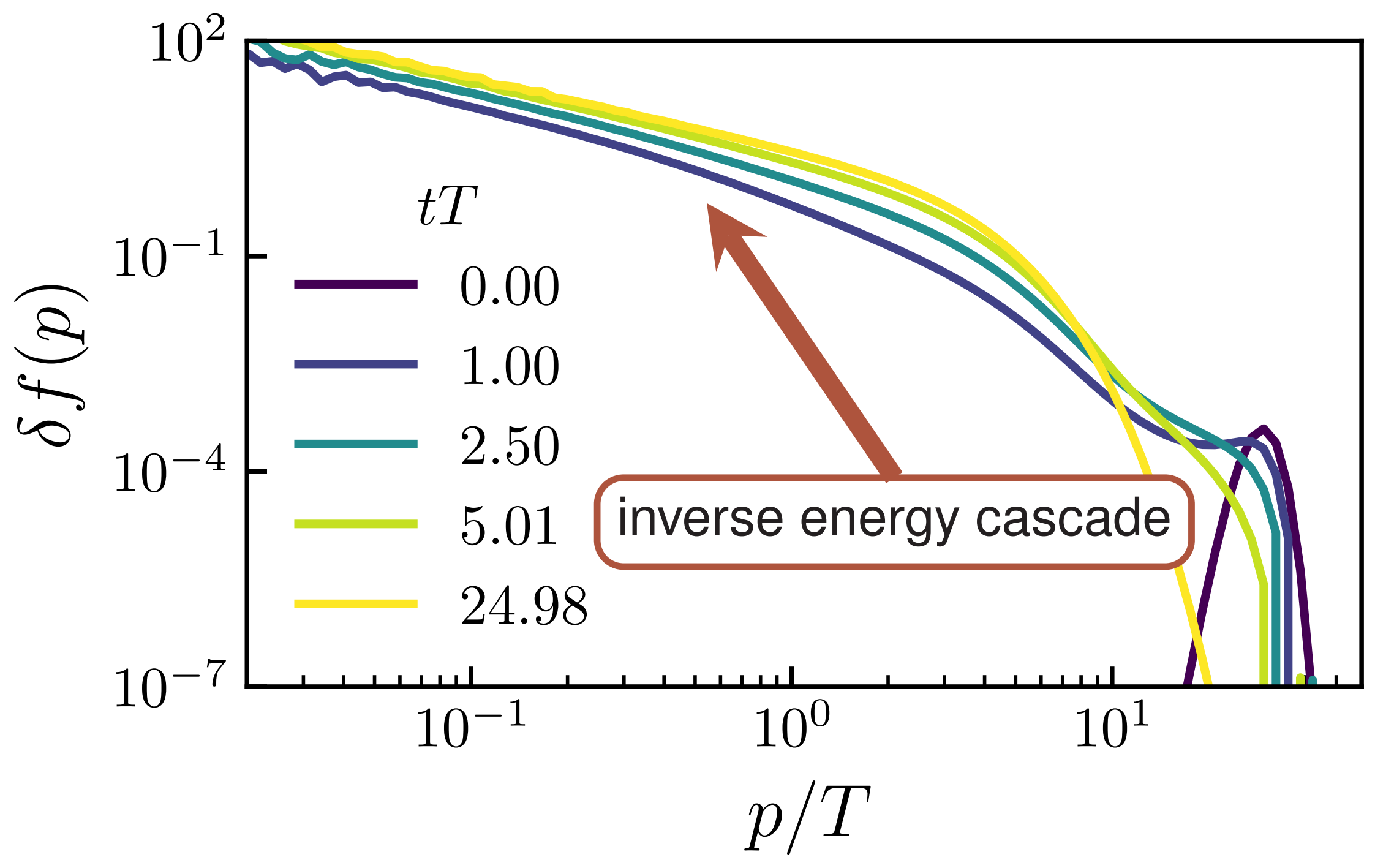
$$\boxed{\delta f_{\text{Jet}}(\tau_0, \mathbf{p}) \to \delta f_{\text{eq}}(p)}$$



Jet perturbation as Gaussian at $E = 30T$



Thermalisation of a mini-jet



During intermediate times, the evolution of the jet perturbation can be described by a scaling solution [4].

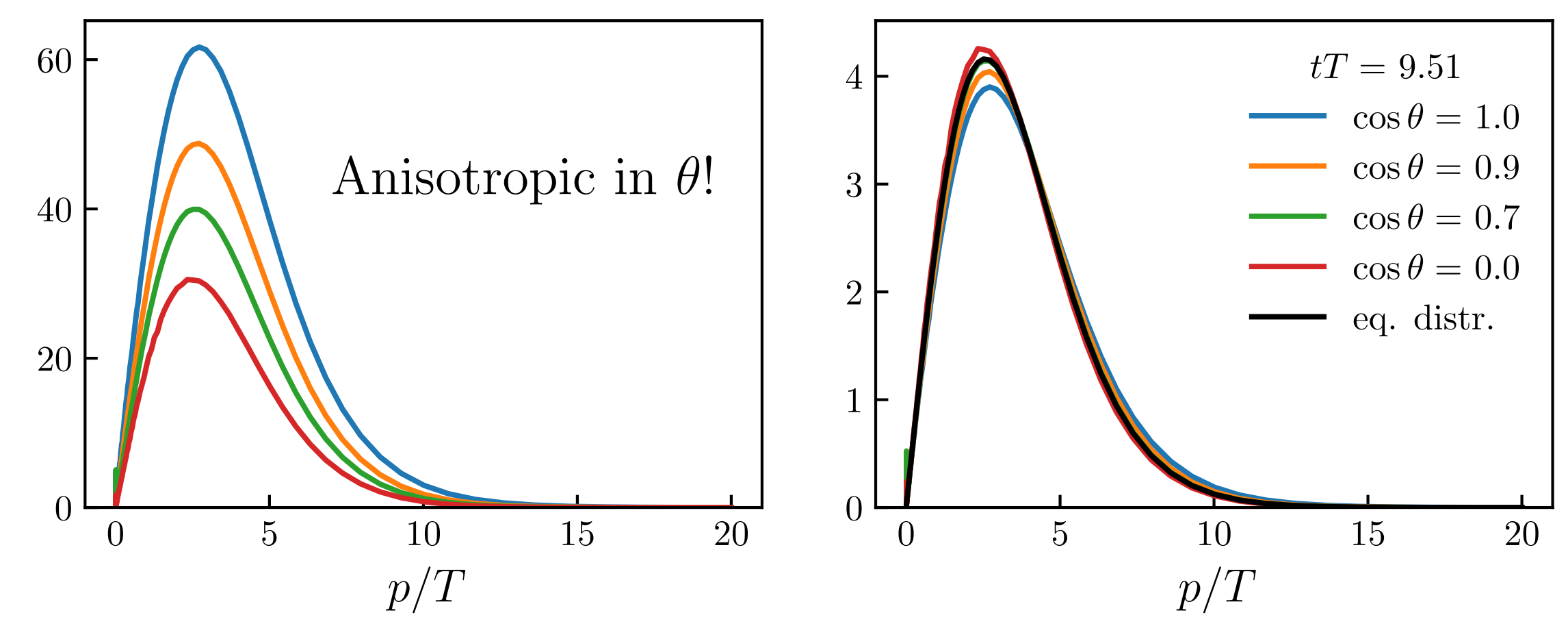
4. Equilibration and isotropisation

Equilibrated jets → increase in temperature T

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

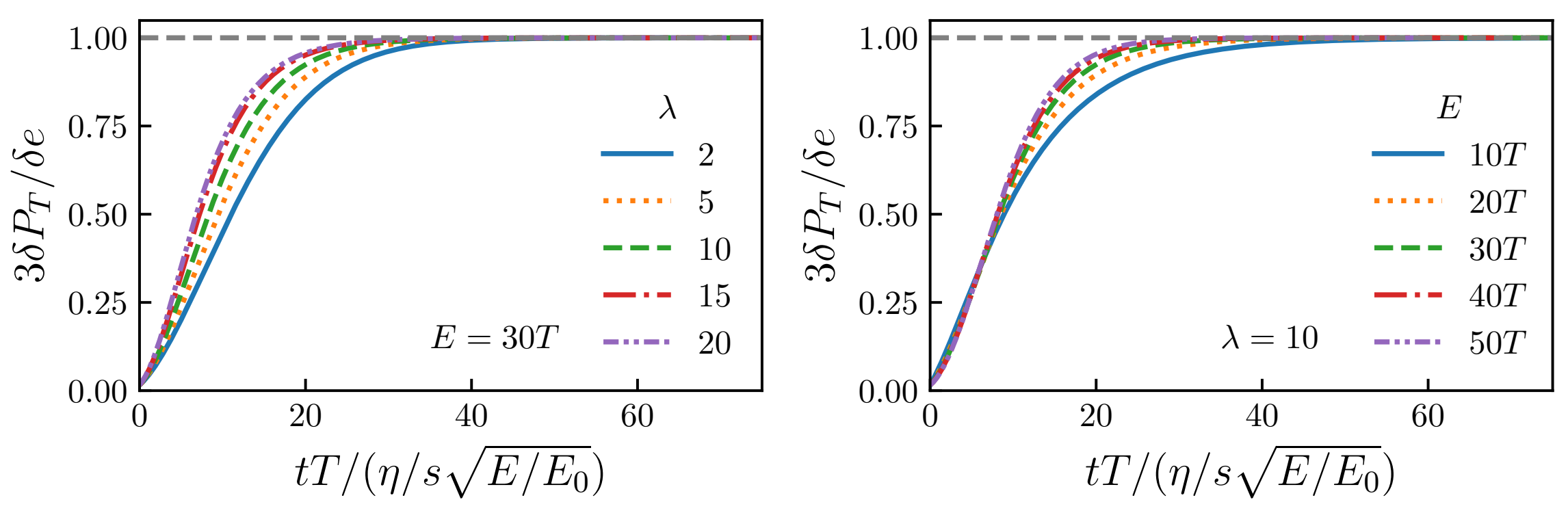
Jet distribution $p^2\delta f(\tau, p, \theta)$ for different θ

not normalized | normalized to 1



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

Subsequent pressure isotropisation for different couplings λ and energies E



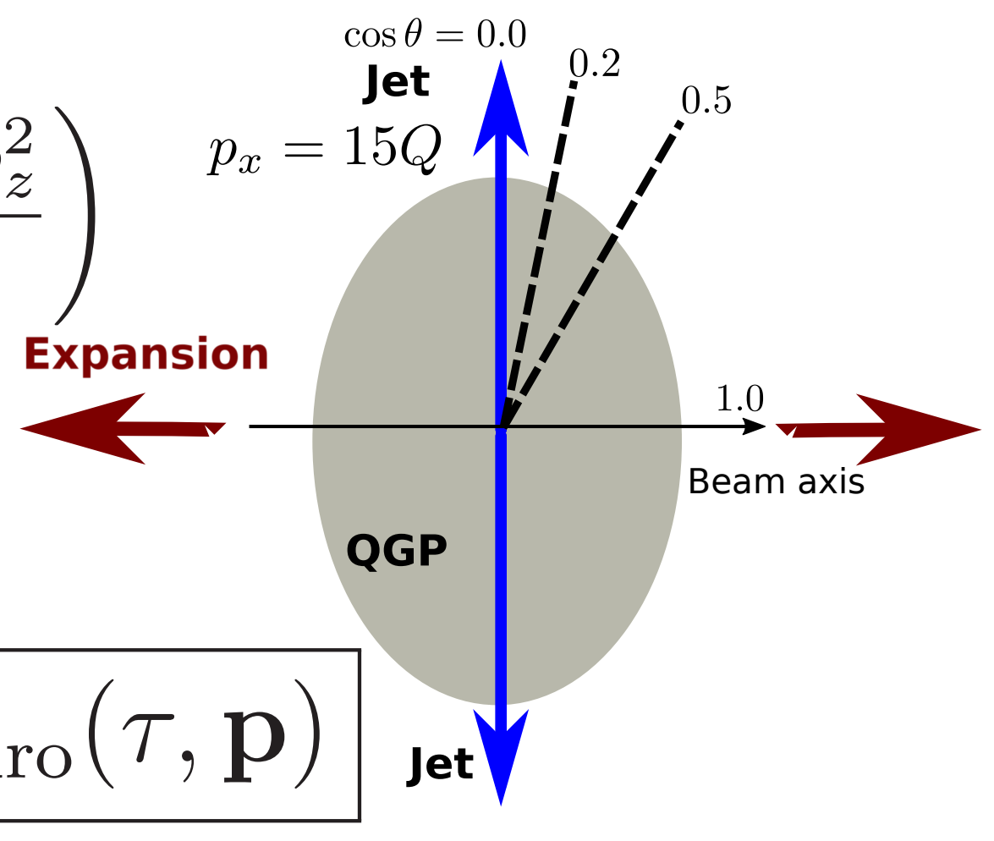
Scaling with $\eta/s \propto \lambda^{-2}$ and $\sqrt{E}$!

5. Initial conditions: ii) Anisotropic

Jet on top of non-equilibrium background, longitudinally expanding

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

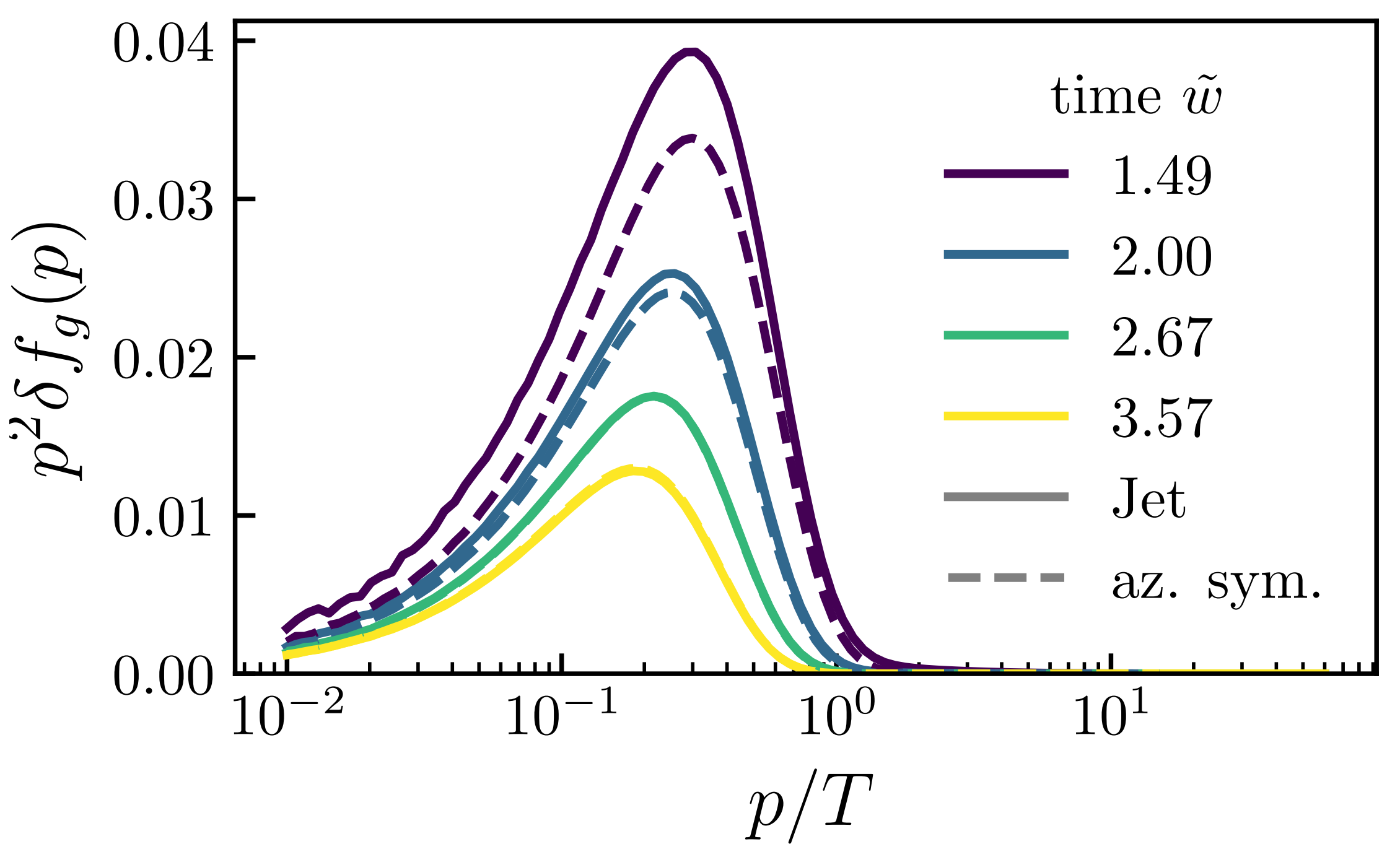
$$\boxed{\delta f_{\text{Jet}}(\tau_0, \mathbf{p}) \to \delta f_{\text{hydro}}(\tau, \mathbf{p})}$$



Hydrodynamisation of the minijet → comparison of different initial conditions

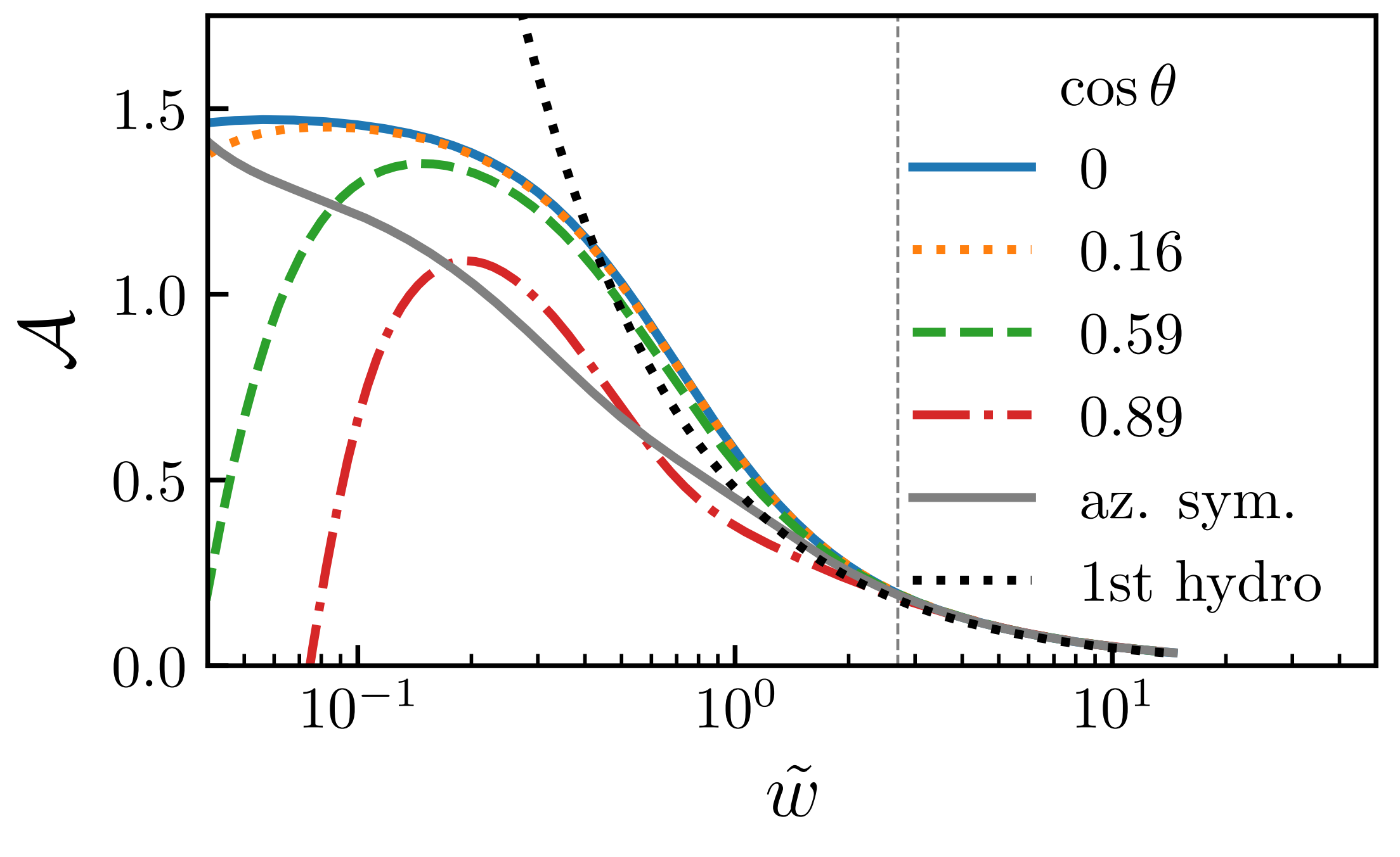
- background like azimuthally symmetric perturbation

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



- different initial orientations of the minijet

Pressure anisotropy $\mathcal{A} = \frac{P_T - P_L}{e/3}$

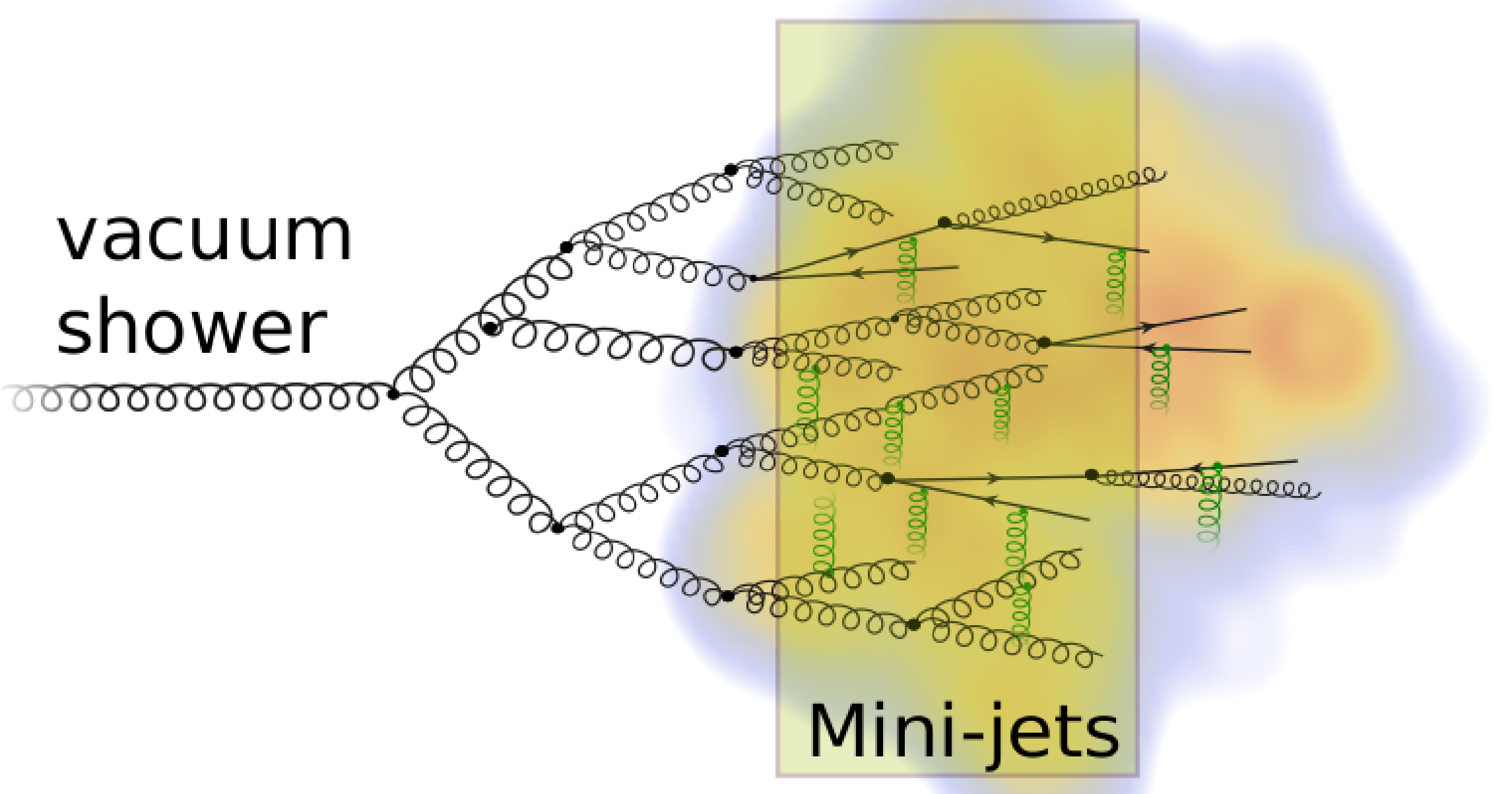


The system loses memory of the initial condition
⇒ **Hydrodynamisation!**

Timescale for quenching of minijets

$$\tau_{\text{mjh}} = 5.1\,\text{fm}\left(\frac{4\pi\eta/s}{2}\right)^{\frac{3}{2}}\left(\frac{\langle s\tau\rangle/\nu_{\text{eff}}}{4.1\,\text{GeV}^2/40}\right)^{-\frac{3}{4}}\left(\frac{E}{31\,\text{GeV}}\right)^{\frac{1}{2}}$$

Mini-jets in medium

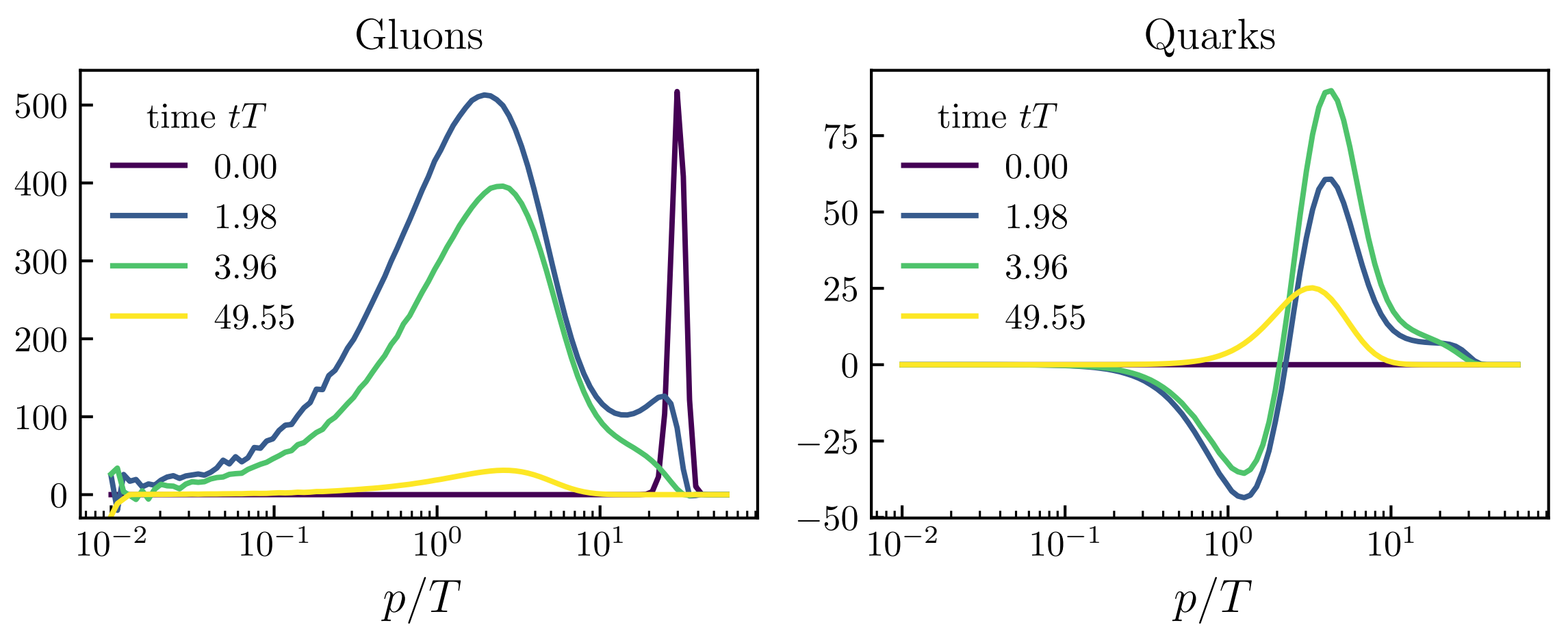


6. Chemical equilibration of jets

Initially highly occupied gluons produce quarks while thermalizing → in equilibrium more quark d.o.f. [5].

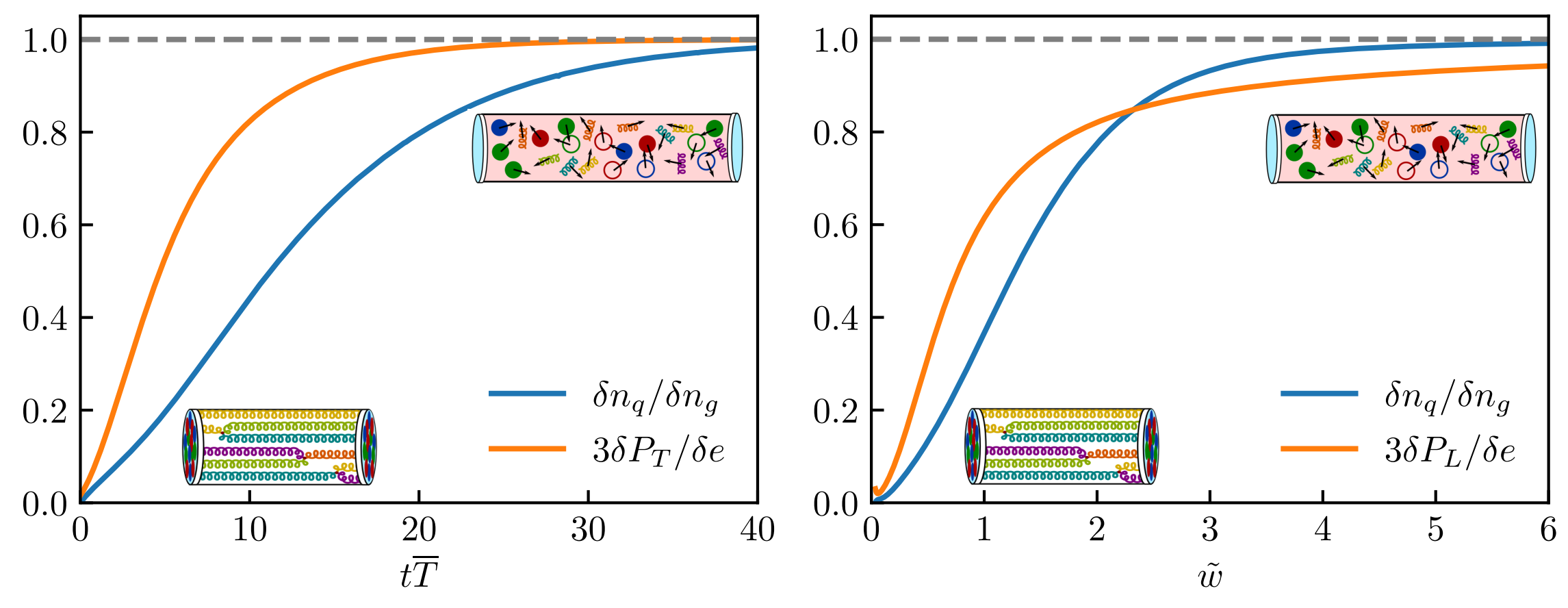
Initialize gluon jet $\delta f_g(\tau_0, \mathbf{p})$, while setting $\delta f_q(\tau_0, \mathbf{p}) = 0$.

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 $T(\theta)$.
- Equilibration scales with η/s and minijet energy $\sqrt{E}$.

expanding QGP:

- Minijets hydrodynamise around ~ 5.1 fm (later than the background).
- Chemical equilibration is reached before isotropization.

Outlook

- Jet response functions → phenomenology
- Describe thermalisation of minijet spectra from pQCD.

References

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[4] A. Kurkela, E. Lu, Phys. Rev. Lett. **113**, no. 18, 182301 (2014).

[5] A. Kurkela and A. Mazeliauskas, Phys. Rev. Lett. **122**, 142301 (2019), Phys. Rev. D **99**, no. 5, 054018 (2019).

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