Minijet quenching in non-equilibrium quark-gluon plasma

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SoftJet2024

with J. Brewer, A. Mazeliauskas, JHEP 2402.09298

Motivation

- Jet quenching

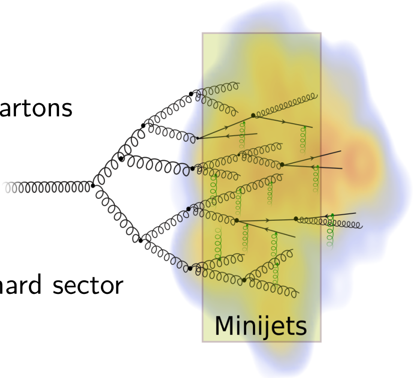
  interactions between QGP & hard partons

- Kinetic Theory

  describes the physics in the soft & hard sector

- Minijets

  no vacuum radiation



Goal: describe parton energy loss in an expanding plasma

Outline

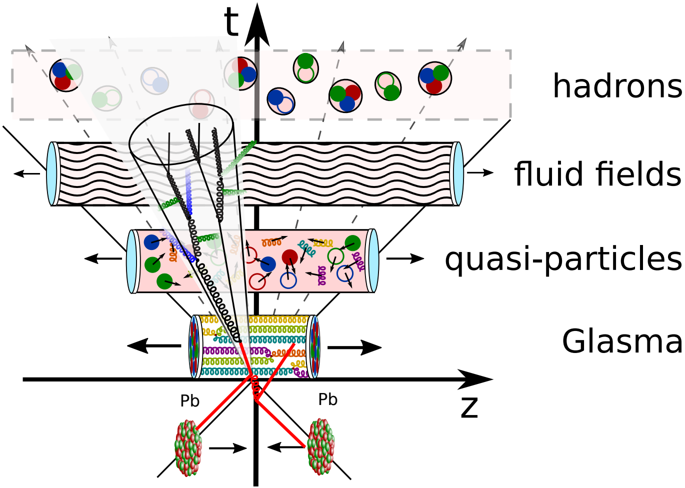
Leading order kinetic theory

Minijets as linear perturbations

Non-boost invariant EKT

Summary

Main stages of a heavy ion collision



- study minijets in the pre-equilibrium phase

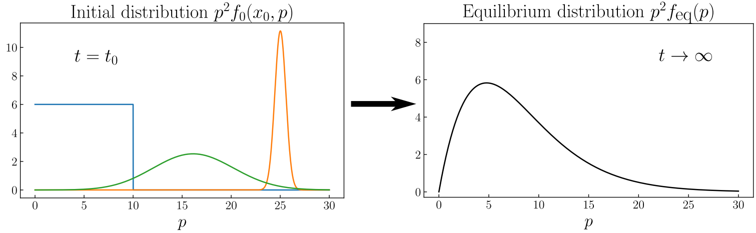
Framework

- Effective Kinetic Theory for high temperature gauge theories
  Arnold, Moore, Yaffe (2003), JHEP 0209353

- weakly coupled quasi-particle picture, $\lambda = 4\pi\alpha_s N_c$

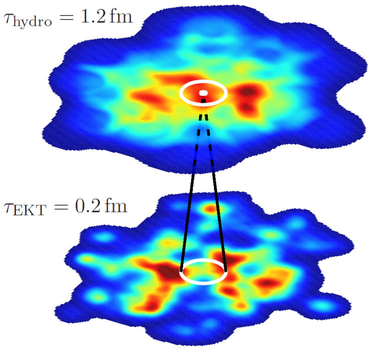
  $\rightarrow$phase space distribution $f(\tau, \mathbf{x}, \mathbf{p})$

$$(\partial_\tau + \mathbf{v}\cdot\nabla_{\mathbf{x}})f(\tau,\mathbf{x},\mathbf{p}) = -C[f]$$



Out-of-equilibrium initial state is transported to equilibrium

Expanding QGP



KøMPøST, PRC 1805.00961

- longitudinal expansion
- approximate boost invariance
- homogeneity in the transverse plane

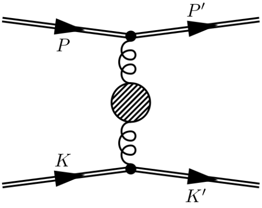
$$\left(\partial_\tau - \frac{p_z}{\tau}\partial_{p_z}\right) f(\tau, \mathbf{p}) = -C[f]$$

- leading order elastic and inelastic scattering processes

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

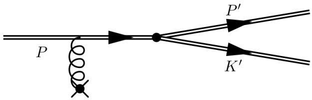
Collision kernel

$C_{2\leftrightarrow 2}$



- small momentum transfer $q = |\mathbf{p}' - \mathbf{p}| \ll 1$ regulated by
$$\frac{1}{q^2} \to \frac{1}{q^2 + m_{\text{eff}}^2}$$

$C_{1\leftrightarrow 2}$

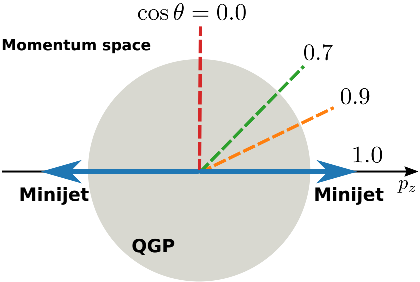


- medium induced radiation of gluons
- $g \to q\bar{q}$ splittings
- LO: strictly collinear

1. Initial conditions: thermal, non-expanding

- background + linear perturbation

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



- linearized Boltzmann eq.

$$\partial_\tau \delta f = -\delta C[\delta f, f_{\text{eq}}]$$

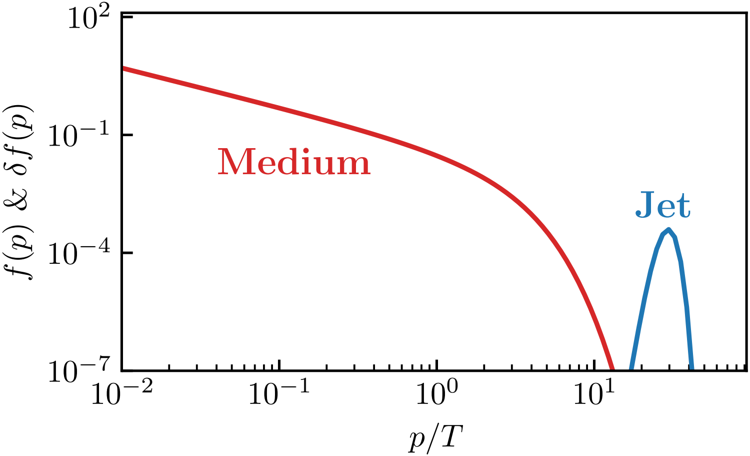
Mehtar-Tani, Schlichting, Soudi, JHEP 2209.10569

Barrera, HP2024

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

1. Initial conditions: thermal, non-expanding

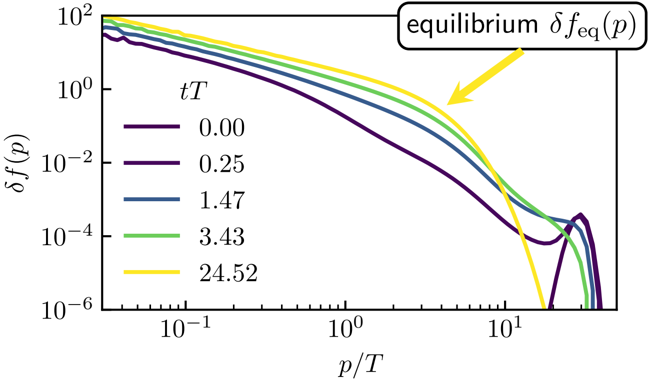
- initial jet distribution $\delta f_{\text{Jet}}(\tau_0, \mathbf{p}) \propto \delta(\mathbf{p} - \mathbf{p}_0)$



Initial condition for the jet on top of a thermal background

Inverse energy cascade

$$\partial_\tau \delta f = -\delta C[\delta f, f_{\rm eq}]$$

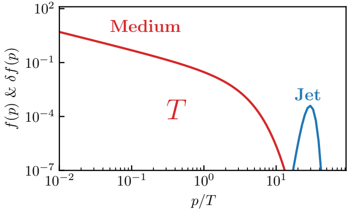


1) build up of soft bath 2) transport of energy
for isotropic case see Kurkela and Lu, PRL 1405.6318

- How is $\delta f_{\rm eq}(p)$ approached?

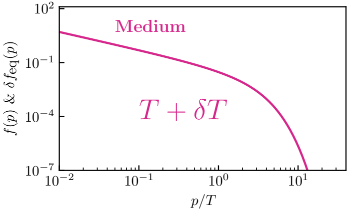
Equilibrium distribution $\delta f_{\mathrm{eq}}(p)$

Initial temperature T



$\xrightarrow{\text{equilibration}}$

Final temperature $T + \delta T$



$$\delta f_{\mathrm{Jet}}(\tau_0, \mathbf{p}) \xrightarrow{\text{equilibration}} \delta f_{\mathrm{eq}}\left(\frac{p}{T}\right) \approx \underbrace{\partial_T f_{\mathrm{eq}}\left(\frac{p}{T}\right)}_{\text{eq. distr.}} \times \underbrace{\delta T}_{\text{magnitude}}$$

- Study time evolution of $\delta f_{\mathrm{Jet}}(\tau, \mathbf{p})$ and its angular (θ) structure

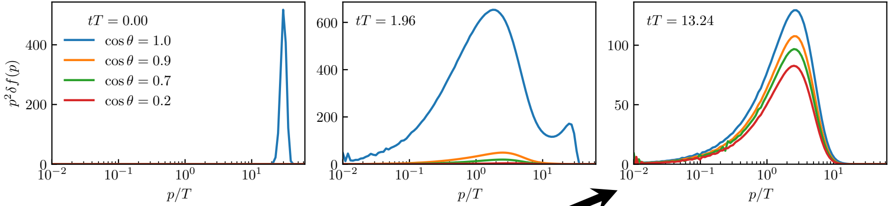
Jet distributions

- equilibrated perturbation

$$\delta f_{\text{eq}}\left(\frac{p}{T}\right) = \underbrace{\partial_T f_{\text{eq}}\left(\frac{p}{T}\right)}_{\text{eq. distr.}} \times \underbrace{\delta T}_{\text{magnitude}}$$

- evolve $\delta f_{\text{Jet}}(\tau, \mathbf{p})$ for θ-slices

time $\longrightarrow$



same shape, different magnitude?

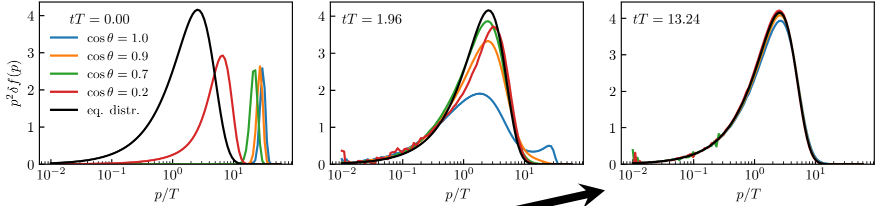
Jet distributions

- equilibrated perturbation

$$\delta f_{\text{eq}}\left(\frac{p}{T}\right) = \underbrace{\partial_T f_{\text{eq}}\left(\frac{p}{T}\right)}_{\text{eq. distr.}} \times \underbrace{\delta T}_{\text{magnitude}}$$

- Normalise $\int dp p^2 \delta f(p,\theta) = 1$ for each θ

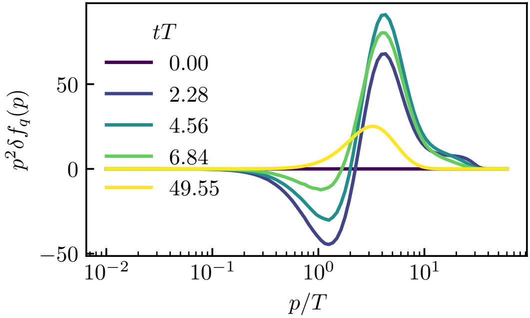
time $\longrightarrow$



Equilibrium distributions with temperatures $\delta T(\theta)$

Fermions

- initialise: $\delta f_g(\tau_0, \mathbf{p}) \propto \delta(\mathbf{p} - \mathbf{p}_0)$, $\delta f_q(\tau_0, \mathbf{p}) = 0$



Quark distribution in jet direction

- early times: depletion of quarks around $p \sim T$

  $\rightarrow$ hard gluon scatters off of the soft background

2. Initial conditions: anisotropic, expanding

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

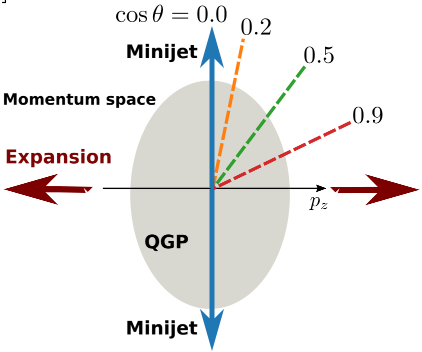
- non-thermal medium

$$\bar{f}(\tau_0,\mathbf{p}) \propto \exp\left(-\frac{2}{3}\frac{p_\perp^2+\xi^2 p_z^2}{Q^2}\right)$$

- evolving according to

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

Kurkela and Zhu, PRL 1506.06647
Kurkela and Mazeliauskas,
PRD 1811.03068, PRL 1811.03040

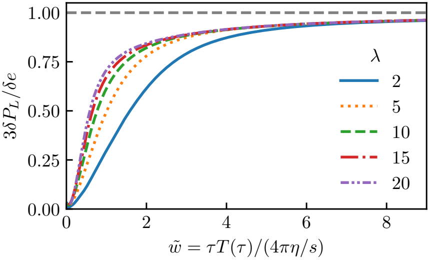


$\bar{f}(\tau,\mathbf{p})$: approach to hydrodynamics!

Pressure equilibration minijet

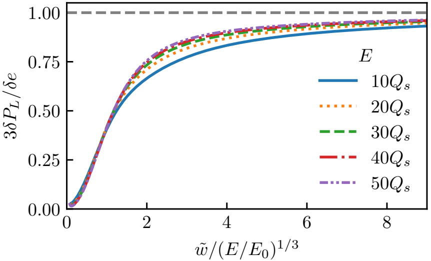
- $\delta P_L = \delta T^{zz} = \int_{\mathbf{p}} \frac{p^z p^z}{p} f(\tau, \mathbf{p})$

Different couplings λ



Scaling with $\eta/s \sim \lambda^{-2}$

Different jet energies E



Scaling with $E^{1/3}$

Curves collapse by rescaling time with $\eta/s\sqrt{E}$

Hydrodynamisation of jets

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

- thermal, non-expanding background:

  $\delta f_{\text{eq}}(p) \to$ known analytic expression

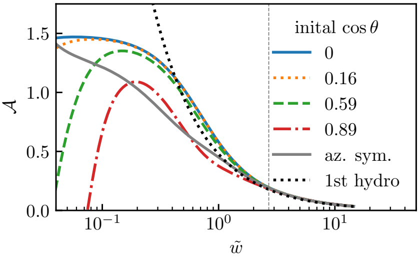
- non-equilibrium, expanding background:

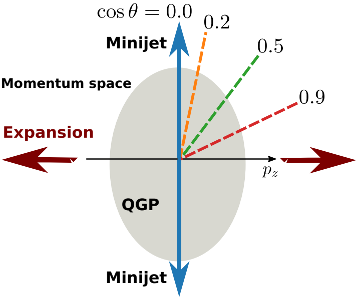
  no analytic expression for δf_{hydro}

- hydrodynamisation: loss of memory about initial conditions

Hydrodynamisation

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

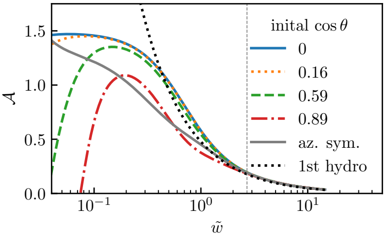




- initial conditions:
  - jets with different initial $\cos\theta$
  - background like perturbation (azimuthally symmetric)

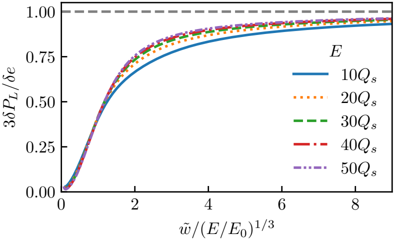
Indistinguishability around $\tilde{w}_{\text{mjh}} \approx 2.7$ $\rightarrow$ **Hydrodynamisation**

Hydrodynamisation time



$\tilde{w}_{\mathrm{mjh}} \approx 2.7$

+



scaling with $\eta/s\sqrt{E}$

- timescale of minijet quenching

$$\tau_{\mathrm{mjh}} = 5.1\,\mathrm{fm}\left(\frac{4\pi\eta/s}{2}\right)^{3/2}\left(\frac{E}{31\,\mathrm{GeV}}\right)^{1/2}$$

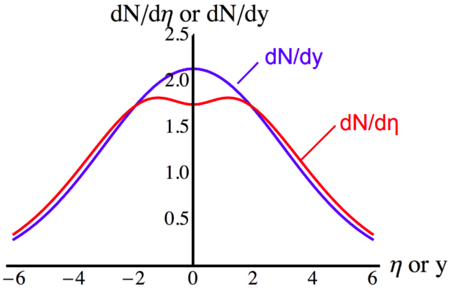
Caveats:

- only Bjorken expansion
- no running coupling

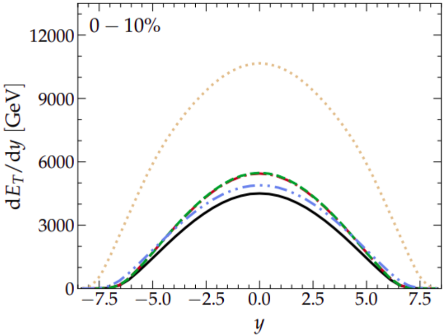
Non-boost invariant EKT

- relax boost invariance → spatial z-coordinate

$$(\partial_t + v_z \partial_z)\, f(t, z, \mathbf{p}) = -C[f]$$



Reygers, Stachel, Lectures



Eskola et al., 2406.17592

- Goal: pre-equilibrium simulations without boost invariance

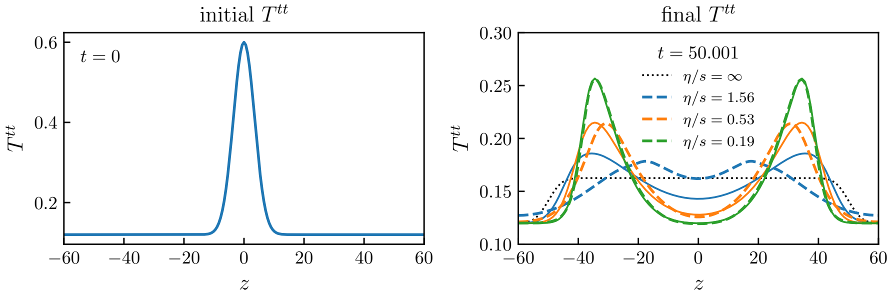
First step: Gaussian perturbations in z

Bhambure, Mazeliauskas, Paquet, Singh, Teaney, FZ, *in preparation*

- Kinetic Theory comparison to density frame hydrodynamics

  Teaney et al., 2403.04185

$$(\partial_t + v_z \partial_z)\, f(t, z, \mathbf{p}) = -C[f] \quad \rightarrow \quad T^{\mu\nu}(t, z)$$



- small η/s reproduces hydro $\leftrightarrow$ large η/s approaches free streaming

Summary & Outlook

Minijets as perturbations on top of a background

static QGP:

- thermal distribution with $T(\theta)$

expanding QGP:

- minijets hydrodynamise (later than the background)

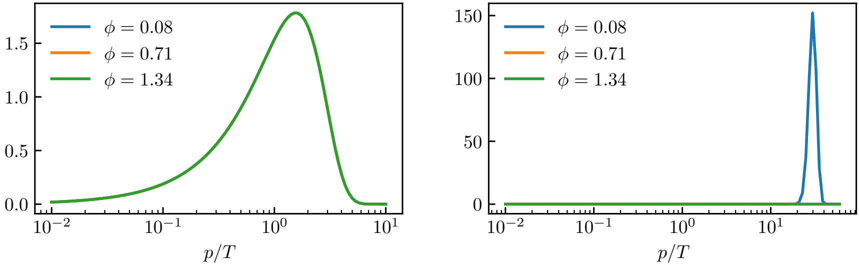
Outlook:

- longitudinal dynamics $z \to \eta$
- extract jet response functions $\to$ phenomenology

Comparison with background-like perturbation

- azimuthal symmetric (ϕ): $\delta f^{\mathrm{az}}_{\mathrm{sym}}(\tau_0,\mathbf{p}) = \epsilon \bar{f}(\tau_0,\mathbf{p})$

$$\bar{f} + \delta f^{\mathrm{az}}_{\mathrm{sym}} = (1+\epsilon)\bar{f}$$

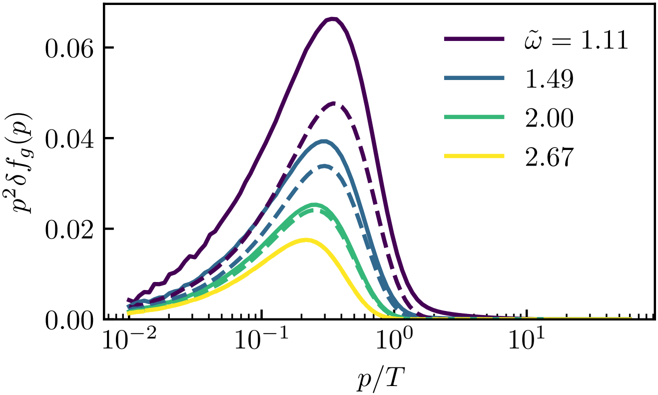


(a) $p^2 \delta f^{\mathrm{az}}_{\mathrm{sym}}(\tau_0, p, \phi)$ (b) $p^2 \delta f_{\mathrm{Jet}}(\tau_0, p, \phi)$

- Hydrodynamization occurs, if both perturbations are indistinguishable

Hydrodynamisation

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



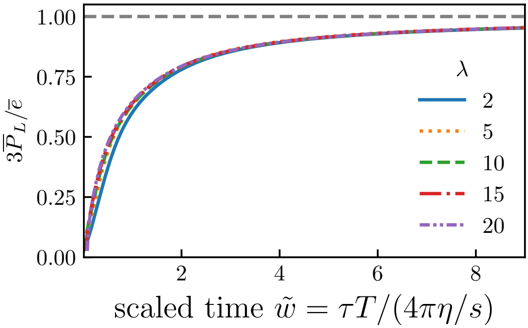
$\delta f_g(p)$ vs. $\delta f^{\mathrm{az}}_{\mathrm{sym}}$

- loss of memory about the initial conditions

$\rightarrow$ **Hydrodynamisation**

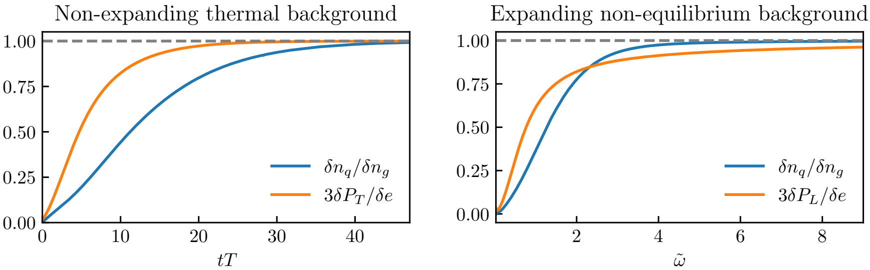
Pressure equilibration background

- energy momentum tensor $T^{\mu\nu} = \int_{\mathbf{p}} \frac{p^\mu p^\nu}{p} f(\tau, \mathbf{p})$
- $T^{\mu\nu}_{\text{eq}} = \text{diag}(e, P, P, P)$ with $P = e/3$
- Background longitudinal pressure $\overline{P}_L = \overline{T}^{zz}$



Chemical equilibration

- compare with kinetic equilibrium (isotropy of pressure)



- in chemical equilibrium more fermionic degrees of freedom
- chem. equilibration not affected by expansion

Backup

Equations of motion from 2PI effective action

$$\left[iG_{0,ac}^{-1,\mu\gamma}(x;\mathcal{A})+\Pi_{ac}^{(0),\mu\gamma}(x)\right]\rho_{\gamma\nu}^{cb}(x,y)$$
$$=-\int_{y^0}^{x^0}dz\Pi_{ac}^{(\rho),\mu\gamma}(x,z)\rho_{\gamma\nu}^{cb}(z,y) \tag{1}$$
$$\left[iG_{0,ac}^{-1,\mu\gamma}(x;\mathcal{A})+\Pi_{ac}^{(0),\mu\gamma}(x)\right]F_{\gamma\nu}^{cb}(x,y)$$
$$=-\int_{t_0}^{x^0}dz\Pi_{ac}^{(\rho),\mu\gamma}(x,z)F_{\gamma\nu}^{cb}(z,y)+\int_{t_0}^{y^0}dz\Pi_{ac}^{(F),\mu\gamma}(x,z)\rho_{\gamma\nu}^{cb}(z,y) \tag{2}$$

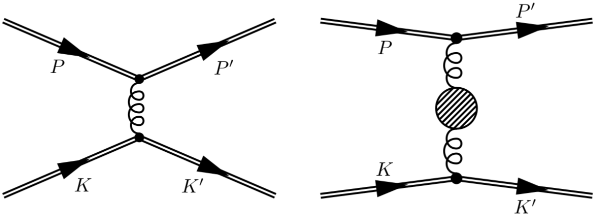
Backup

- local homogeneity $\rightarrow$ relative coordinate $s^\mu = x^\mu - y^\mu$ and center coordinate $X^\mu = \frac{1}{2}(x^\mu + y^\mu)$
- gradient expansion in X^μ
- to lowest order, spectral function ρ is on shell
  $\rightarrow$ quasi-particle picture
- non-equilibrium distribution function $f(X, p)$:

$$F(X, p) = -i\left[\frac{1}{2} \pm f(X, p)\right]\rho(X, p)$$

$$\Rightarrow p^\mu \partial_\mu f(X, p) = -C[f]$$

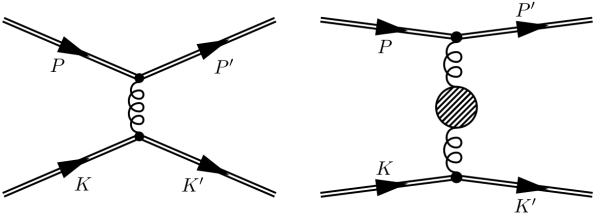
$2 \leftrightarrow 2$



Hard (left) and soft (right) medium regulated scattering

$$C_{2\leftrightarrow 2}[f](\mathbf{p}) = \frac{1}{4p\nu} \int_{\mathbf{k},\mathbf{p}',\mathbf{k}'} (2\pi)^4 \delta^{(4)} \left(p^\mu + k^\mu - p'^\mu - k'^\mu\right)$$
$$\times |\mathcal{M}|^2 \{ \underbrace{f_{\mathbf{p}} f_{\mathbf{k}} \left(1 \pm f_{\mathbf{p}'}\right) (1 \pm f_{\mathbf{k}'})}_{\text{loss}} - \underbrace{f_{\mathbf{p}'} f_{\mathbf{k}'} (1 \pm f_{\mathbf{p}}) (1 \pm f_{\mathbf{k}})}_{\text{gain}} \} \tag{3}$$

$2 \leftrightarrow 2$



Hard (left) and soft (right) medium regulated scattering

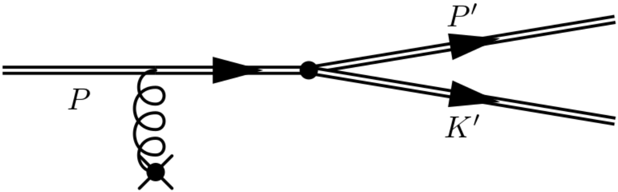
$$|\mathcal{M}|^2 = 2\lambda^2\nu\left(9 + \frac{(s-t)^2}{u^2} + \frac{(u-s)^2}{t^2} + \frac{(t-u)^2}{s^2}\right)$$

- small momentum transfer $q = |\mathbf{p}' - \mathbf{p}| \ll 1$ regulated by

$$\frac{1}{q^2} \to \frac{1}{q^2 + m_{\text{eff}}^2}$$

$$m_{\text{eff}}^2 = 2g^2 \int \frac{d^3\mathbf{p}}{(2\pi)^3 p}\left[N_c f_{\mathbf{p}}^g + N_f f_{\mathbf{p}}^q\right]$$

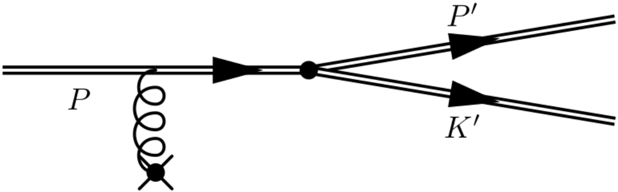
$1 \leftrightarrow 2$



effective $1 \leftrightarrow 2$ process

$$C_{1\leftrightarrow 2}[f](\mathbf{p}) = \frac{1}{2}\frac{1}{\nu}(2\pi)^3 \int_{\tilde{\mathbf{p}},\mathbf{p}',\mathbf{k}'} (2\pi)^4 \delta^{(4)}\left(\tilde{p}^{\mu} - p'^{\mu} - k'^{\mu}\right)$$
$$\times \left[\delta^{(3)}(\mathbf{p} - \tilde{\mathbf{p}}) - \delta^{(3)}\left(\mathbf{p} - \mathbf{p}'\right) - \delta^{(3)}\left(\mathbf{p} - \mathbf{k}'\right)\right]$$
$$\times \gamma\{\underbrace{f_{\mathbf{p}}\left(1 \pm f_{\tilde{\mathbf{p}}'}\right)(1 \pm f_{\mathbf{k}'})}_{\text{loss}} - \underbrace{f_{\mathbf{p}'} f_{\mathbf{k}'}\left(1 \pm f_{\tilde{\mathbf{p}}}\right)}_{\text{gain}}\} \tag{4}$$

$1 \leftrightarrow 2$



effective $1 \leftrightarrow 2$ process

- LO $\rightarrow$ strictly collinear
- medium induced radiation of gluons
- $N+1 \leftrightarrow N+2$ effectively $1 \leftrightarrow 2$

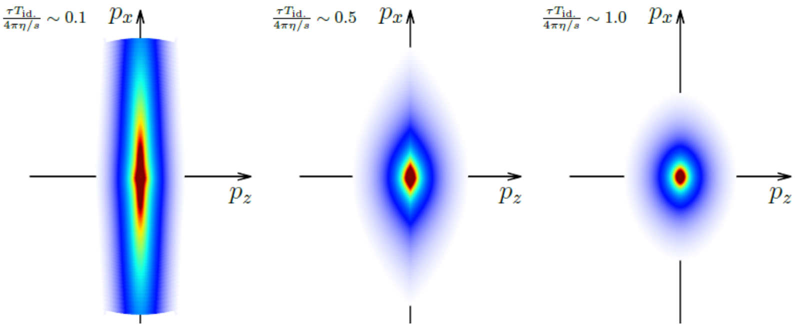
$1 \leftrightarrow 2$

Parton going through the medium, Figure from [1]

- hard parton receiving multiple kicks
- formation time $\tau_f \sim E$
- BH: $l_f \ll l_{\mathrm{mfp}}$, independent emissions
- LPM: $l_f \sim l_{\mathrm{mfp}}$, destructive interference $\rightarrow$ suppression

Bottom-up thermalization

Baier, Müller, Schiff, Son (2001)

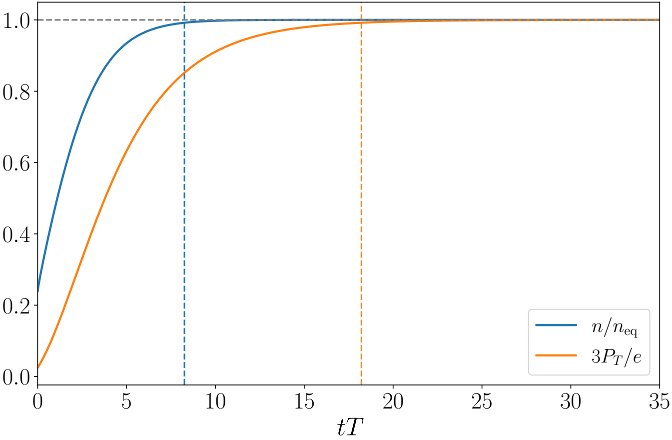


Isotropization of the distribution, Figure from [2]

- 1: overoccupied system getting more anisotropic
- 2: population of soft gluons
- 3: inverse energy cascade

Radiation vs. elastic scattering

- particle number $n = \int_{\mathbf{p}} f(\tau, \mathbf{p}) \to C_{1\leftrightarrow 2}[f]$
- transverse pressure $P_T = \frac{1}{2}\int_{\mathbf{p}} p_\perp^2/p f(\tau, \mathbf{p}) \to C_{2\leftrightarrow 2}[f]$



Equilibration along each θ-slice

Equilibrium distribution

- equilibrated jet $\rightarrow$ change in temperature δT and velocity δu^z

$$\delta f_{\mathrm{eq}}(\mathbf{p}) = (\delta T \partial_T + \delta u^z \partial_{u^z})\, n_{\mathrm{BE}}\left(p_\mu u^\mu / T\right)\Big|_{u^z=0}$$

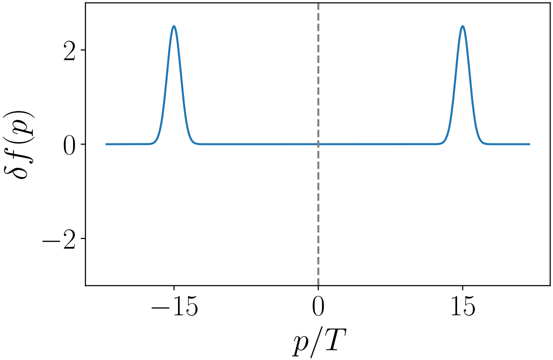
$$\delta f_{\mathrm{eq}}(p,\theta) = \left(\delta u^z \cos\theta + \frac{\delta T}{T}\right) F(p/T)$$

- both contributions can be disentangled

Equilibrium distribution

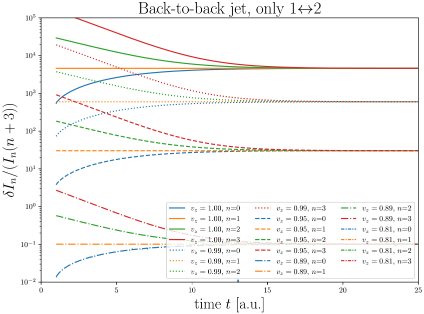
- back-to-back jet conserves net momentum:

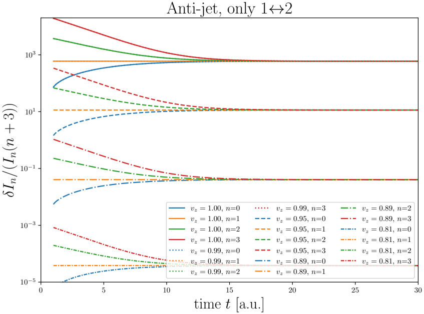
$$\delta f_{\mathrm{eq}}(p,\theta) = \left(\cancel{\delta u^z \cos\theta} + \frac{\delta T}{T} \right) F(p/T)$$



Initial condition: back-to-back jet

Only $1 \leftrightarrow 2$





- similar timescales of equilibration
  $\Rightarrow$ 2↔2 contribute more to equilibration of the anti-jet

Moments of δf

- angular effective temperature

$$I_n(\theta) \equiv 4\pi \int \frac{p^2 dp}{(2\pi)^3} p^n f(p,\theta) = \mathcal{N}_n \times T(\theta)^{n+3} \tag{5}$$

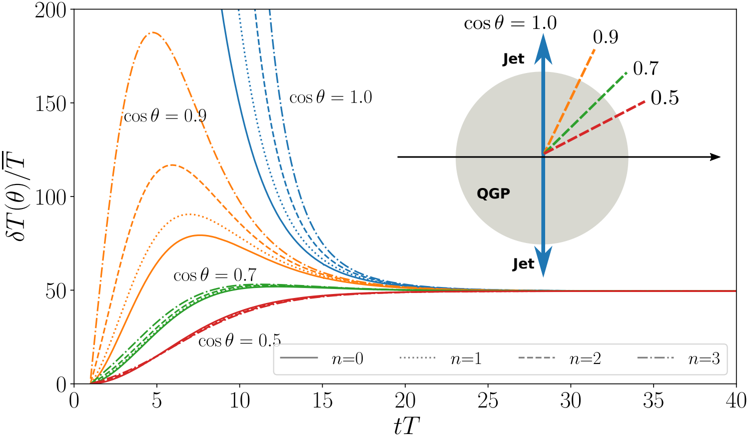
$$T(\theta) = \overline{T} + \delta T(\theta)$$

- temperature perturbation

$$\frac{\delta T(\theta)}{\overline{T}} = \frac{\delta I_n(\theta)}{(n+3)\bar{I}_n(\theta)}$$

- look at time evolution!

Moments of δf



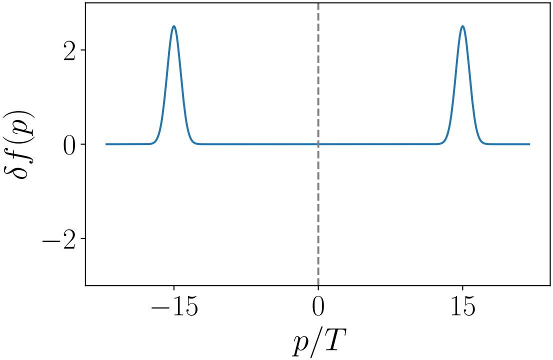
Moments of the back-to-back jet

- different moments agree before different angles do!

Equilibrium distribution

- back-to-back jet conserves net momentum:

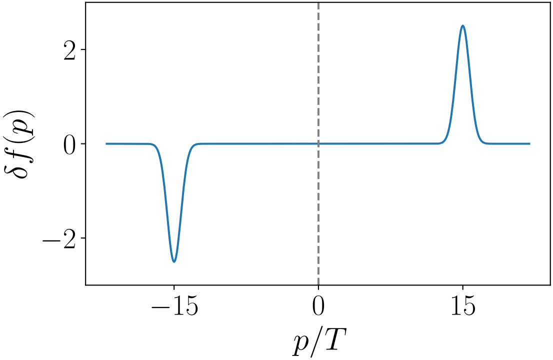
$$\delta f_{\mathrm{eq}}(p,\theta) = \left(\cancel{\delta u^z \cos\theta} + \frac{\delta T}{T}\right) F(p/T)$$



Initial condition: back-to-back jet

Anti-jet

- introduce anti-jet → no energy deposited, **only** net momentum

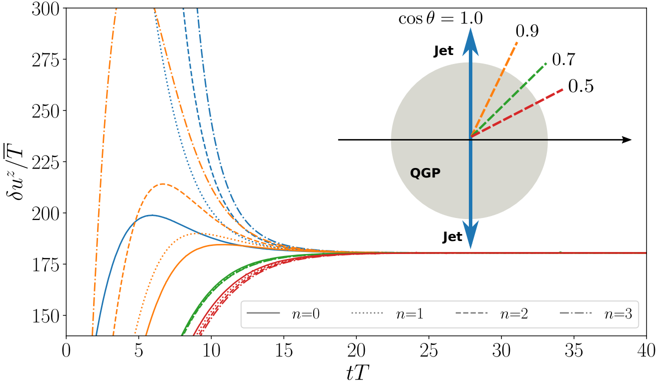


Particle and "hole"

$$\delta f_{\mathrm{eq}}(p,\theta) = \left(\delta u^z \cos\theta + \cancel{\frac{\delta T}{T}}\right) F(p/T)$$

- allows us to study the build up of δu^z

Moments of δf_{anti}



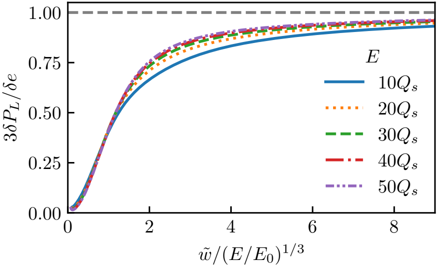
Collapse of different θ much earlier!

$$\delta f_{\mathrm{eq}}(p,\theta) = (\delta u^z \cos\theta)\, F(p/T)$$

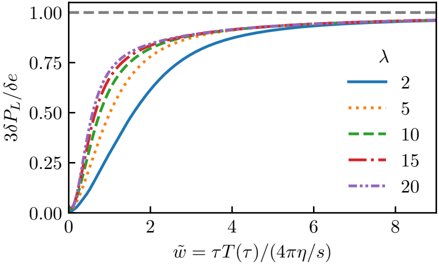
- θ-dependence $\rightarrow$ faster reached by elastic processes
- single jet: velocity builds up faster than temperature

Pressure equilibration

- scaled time $\tilde{\omega} = \tau/\tau_R$ with $\tau_R = \frac{4\pi\eta/s}{T(\tau)}$
- effective temperature from $e(\tau) = \nu_{\text{eff}} \frac{\pi^2}{30} T(\tau)^4$



(c) Scaling with jet energy E



(d) coupling λ