Thermalisation of minijets in QCD kinetic theory

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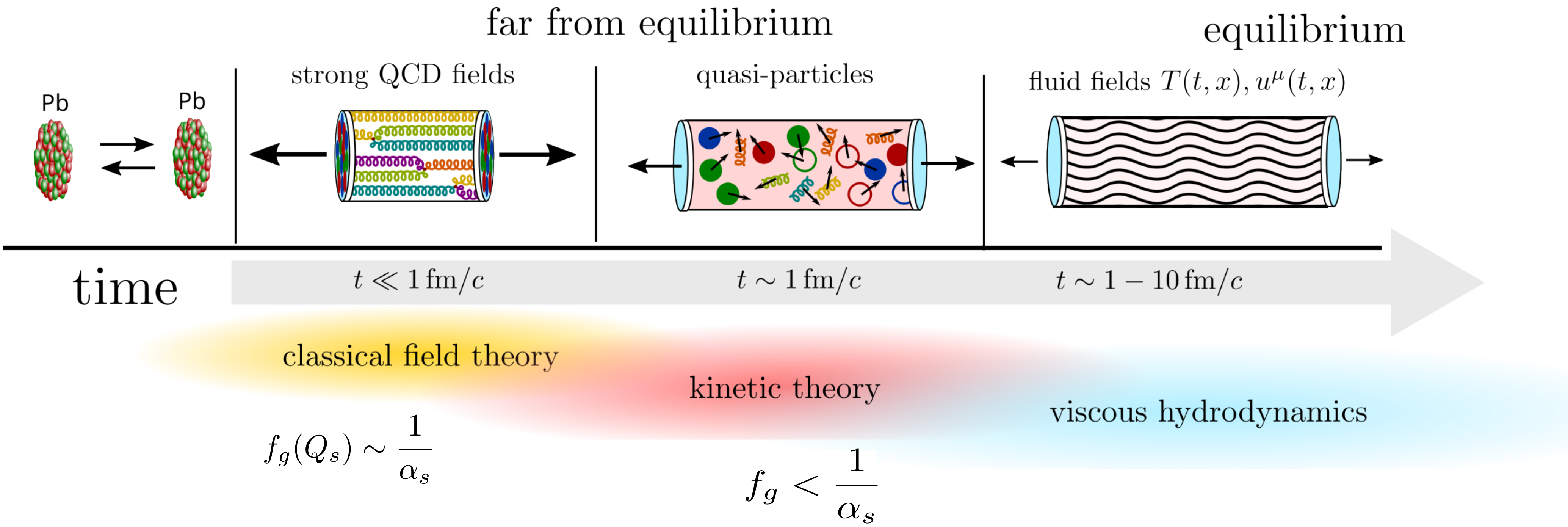
Fabian Zhou, Jasmine Brewer, AM, arXiv:2402.09298 (as of today!)


QCD thermalisation

Berges, Heller, AM, Venugopalan RMP (2021)

High-energy limit $\alpha_s \ll 1$ of QCD



- Initial conditions: highly occupied gluons fields
- Intermediate times: quark and gluon quasi-particles

QCD effective kinetic theory

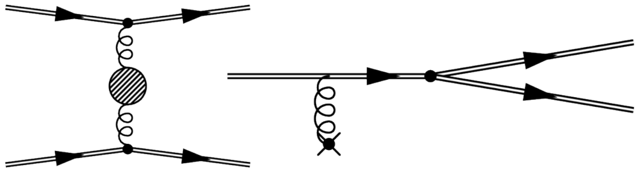
Arnold, Moore, Yaffe JHEP (2003)

Underlying quantum field theory

2-point correlations $$\mathcal{L}_{\mathrm{QCD}} = \bar{q}\left(i\gamma^\mu D_\mu - m\right)q - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a$$

Boltzmann equation for quark and gluon distributions

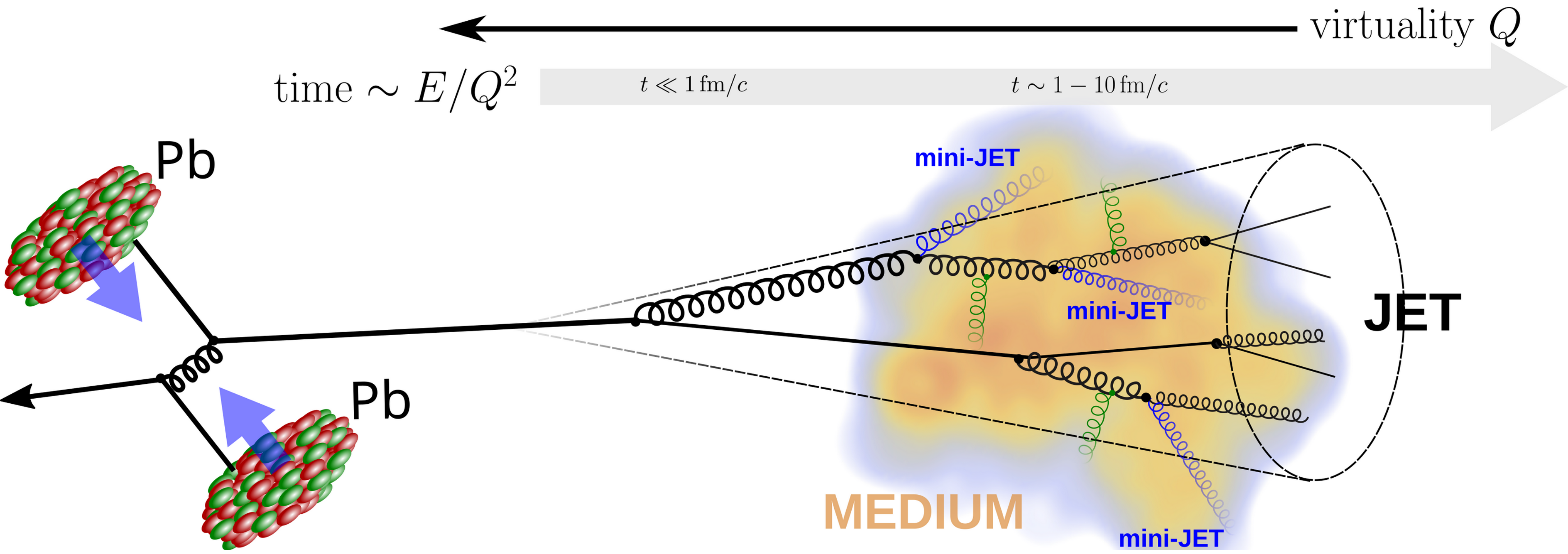
phase-space distribution $$\partial_t f(t,\mathbf{x},\mathbf{p}) + \frac{\mathbf{p}}{|p|}\cdot\nabla_{\mathbf{x}} f(t,\mathbf{x},\mathbf{p}) = -\mathcal{C}_{2\leftrightarrow 2}[f] - \mathcal{C}_{1\leftrightarrow 2}[f]$$



- Leading order scattering processes for massless quarks and gluons:
  - Elastic scattering with isotropic screening
  - Medium-induced collinear radiation with LPM resummation

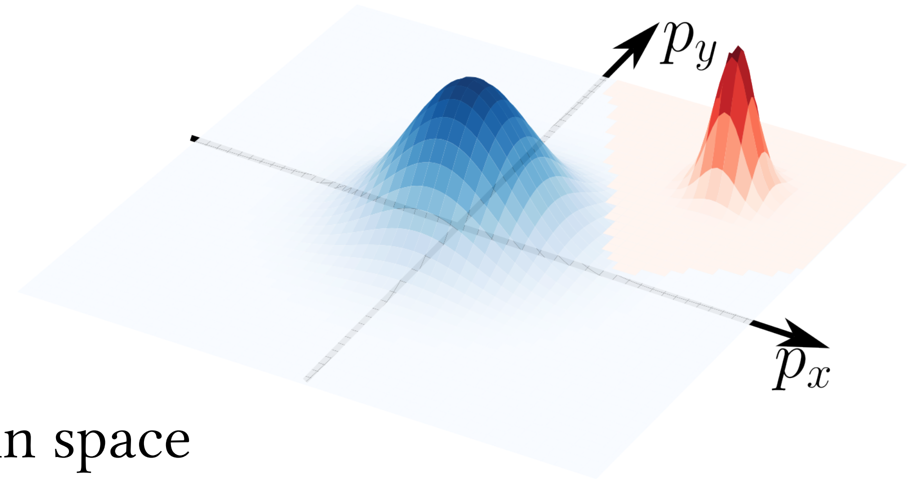
- **Low-momentum thermalisation $\Longleftrightarrow$ high-momentum energy loss**

Jet quenching in QGP



Goal: study how on-shell partons (minijets) thermalise in QGP

Minijet perturbation



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

background perturbation

- Background distribution homogeneous in space
- Minijet: gaussian perturbation localised in momentum: $E \gg T$ or Q_s
- Perturbation homogeneous in space ⟶ “spatially averaged” minijets

- Background thermalisation: Kurkela, Zhu [1506.06647], Kurkela, AM [1811.03068], Du, Schlichting [2012.09079]
- Minijet 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!

Linearised kinetic theory

Background Boltzmann equation (non-linear):

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

Linearised 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!

Scenarios:

1) Thermal static background
2) Anisotropic background with no expansion
3) Anisotropic background with expansion

Equilibrium distribution of a minijet

Minijet carries two conserved quantities:

- Energy ⟶ temperature increase
- Momentum ⟶ velocity field

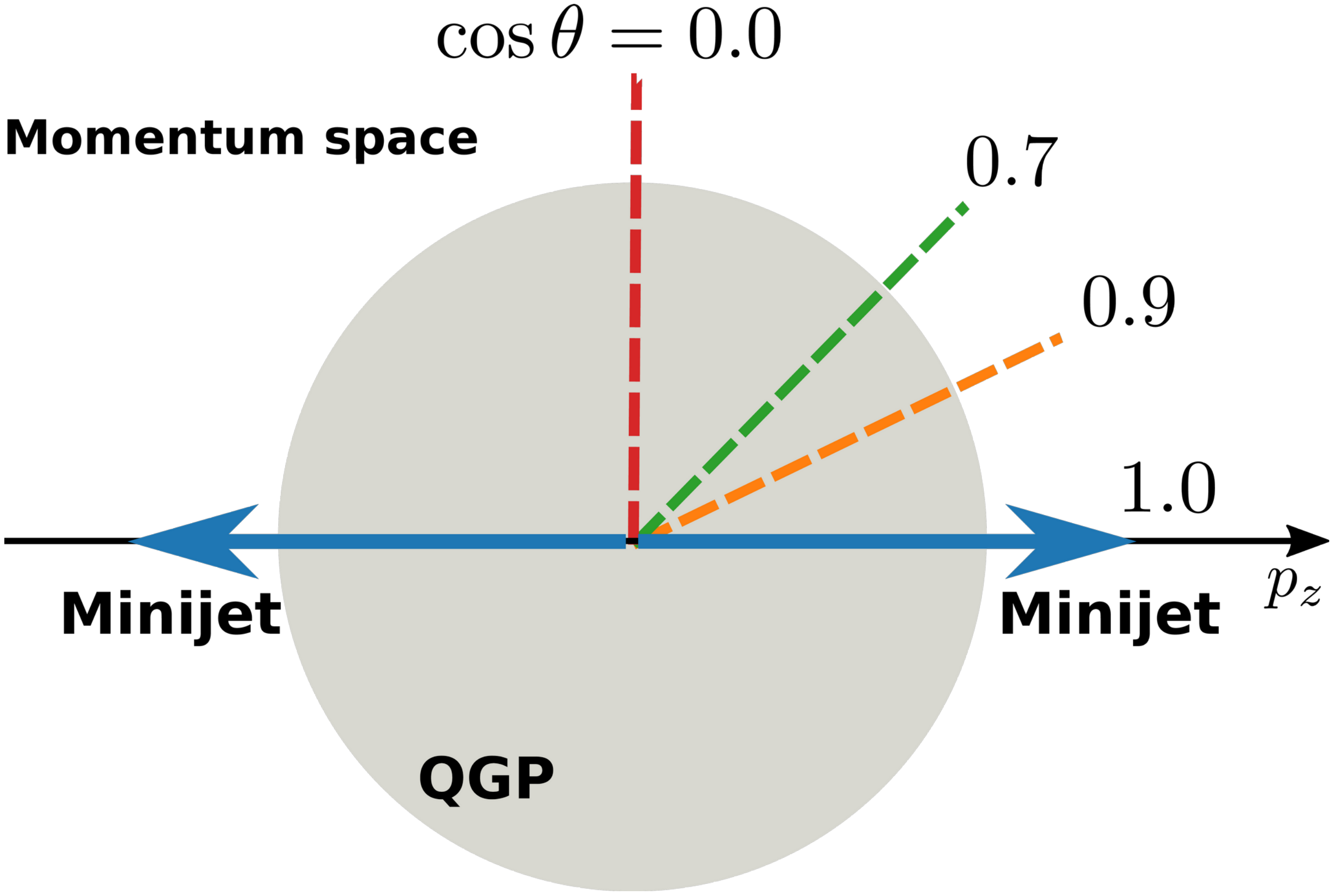
Equilibrium state for a perturbation:

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

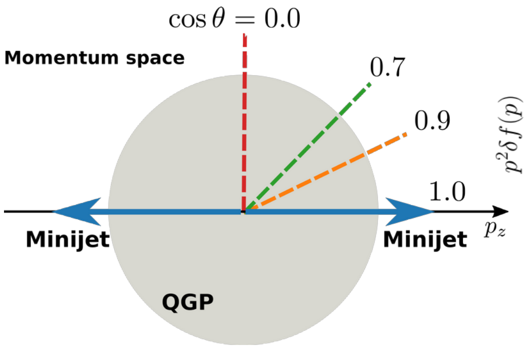
Parity: even odd

$$\delta f(\mathbf{p}) = \underbrace{\frac{1}{2}\left(\delta f(\mathbf{p}) + \delta f(-\mathbf{p})\right)}_{\text{net-energy}} + \underbrace{\frac{1}{2}\left(\delta f(\mathbf{p}) - \delta f(-\mathbf{p})\right)}_{\text{net-momentum}}.$$

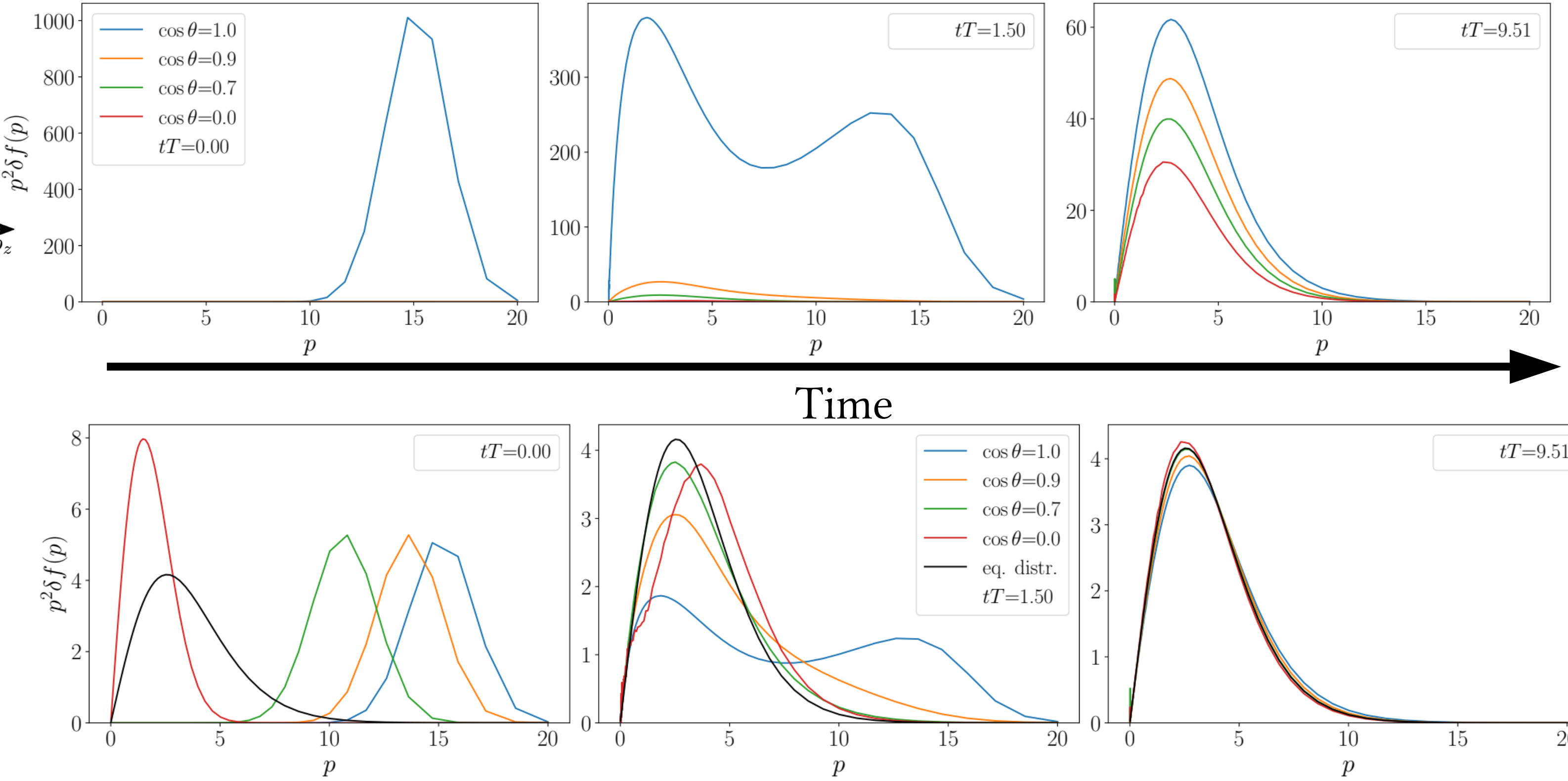
Minijets in static isotropic background



Angle resolved net-energy thermalisation



Angular slices



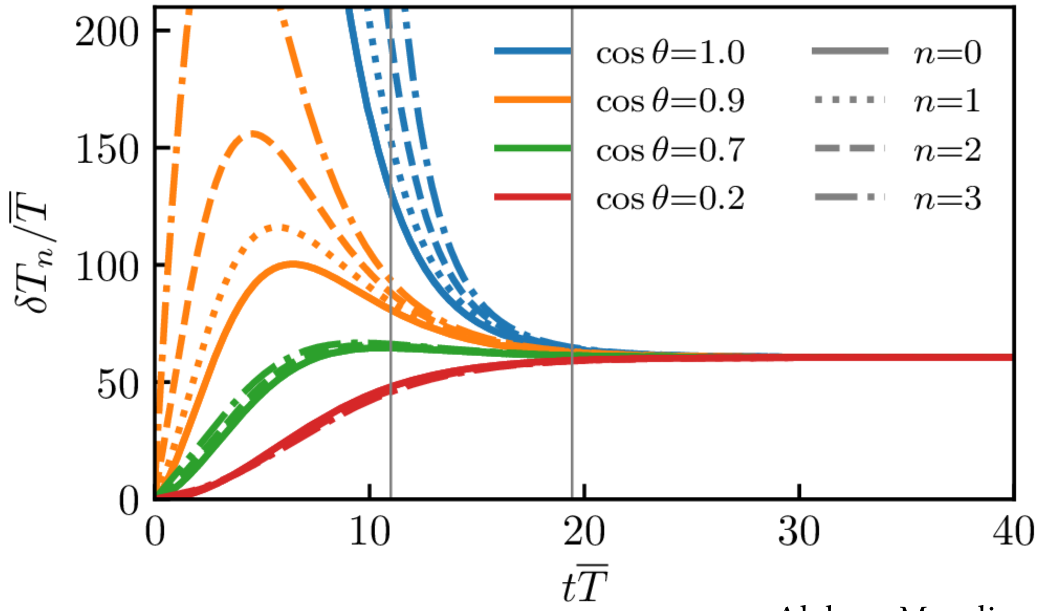
Normalised gluon distributions

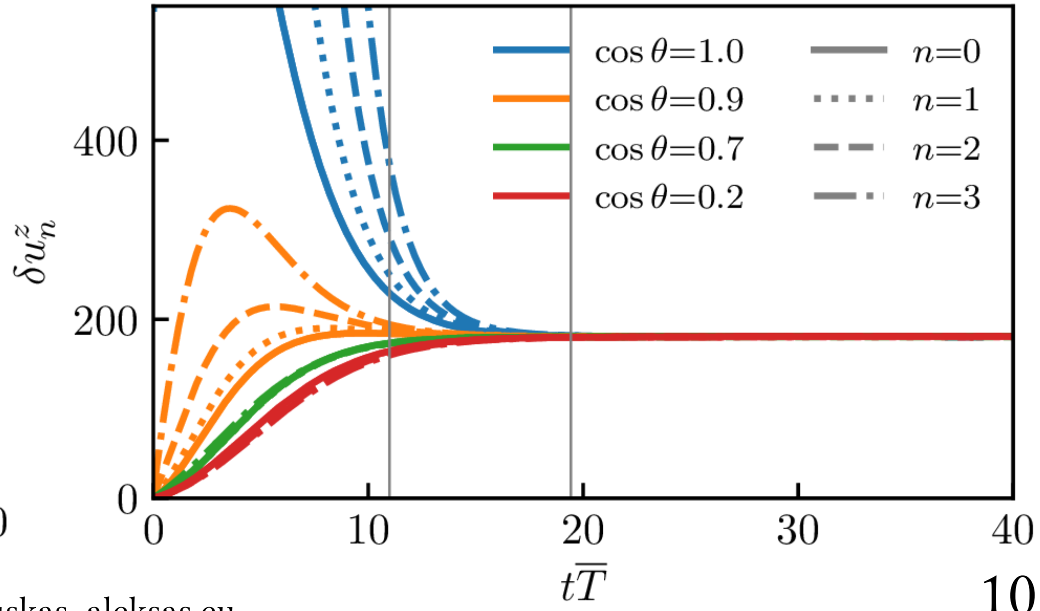
Each angular slice thermalise first, before isotropising!

Effective temperature and velocity

Equilibrium distribution: $\delta f_{\rm eq} = \left(\frac{\delta T}{T} + \delta u^z \cos\theta\right) \frac{p}{T} \bar{f}_{\rm eq}(1+\bar{f}_{\rm eq})$

Extract effective temperature or velocity for each angular slice from moments: $I_n(\theta) \equiv 4\pi \int \frac{p^2 dp}{(2\pi)^3} p^n f(p,\theta)$

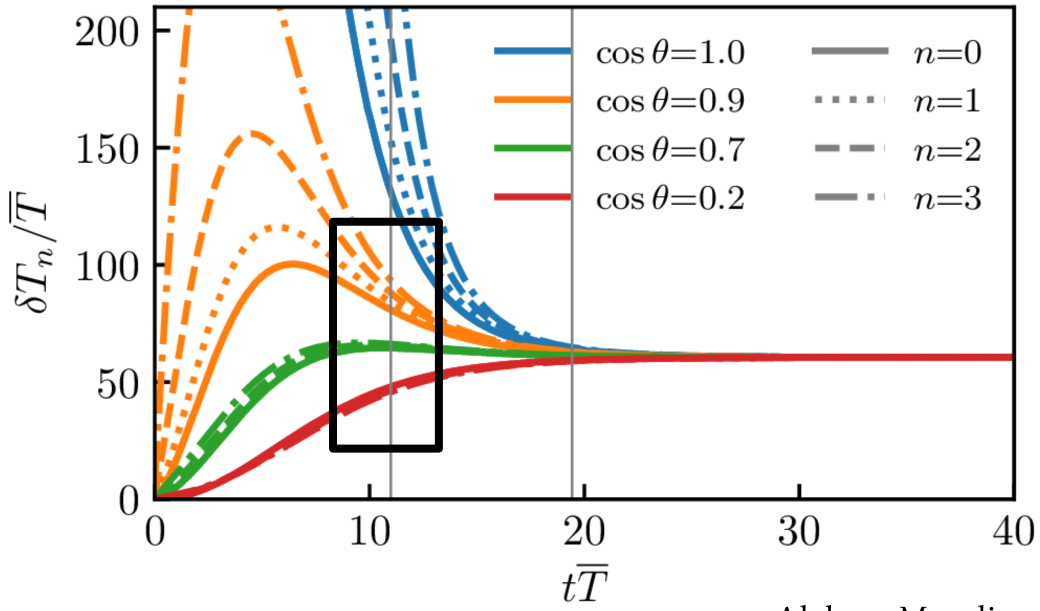


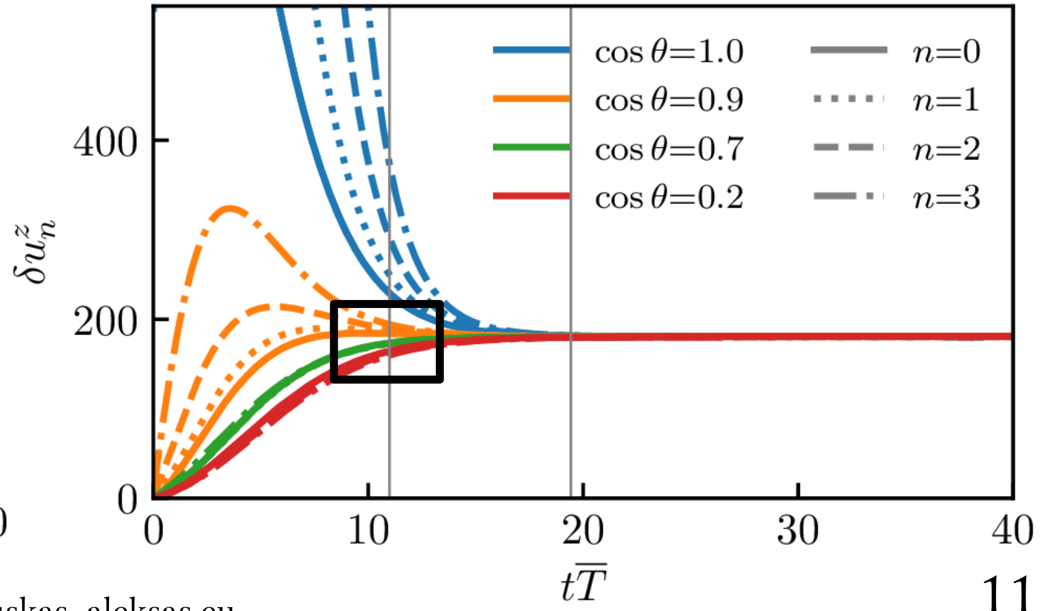


Effective temperature and velocity

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

Two stage thermalisation of net-energy perturbations



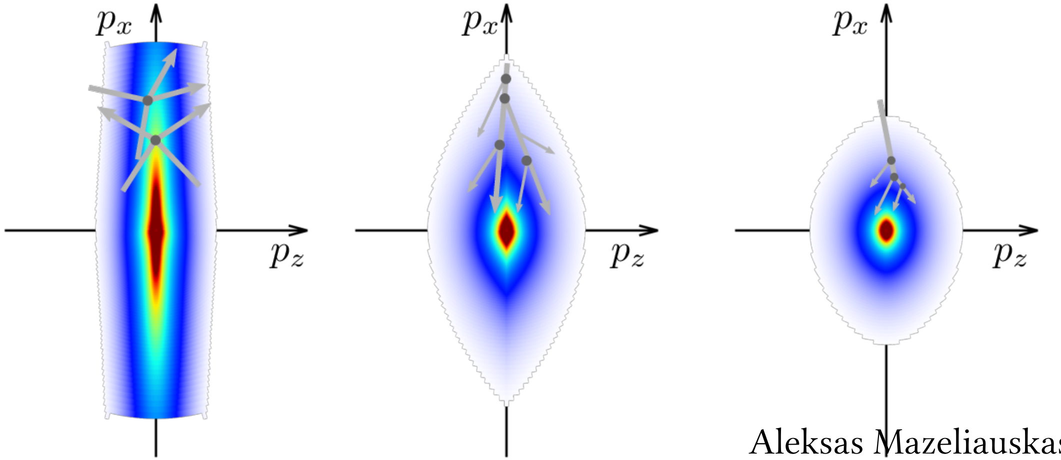


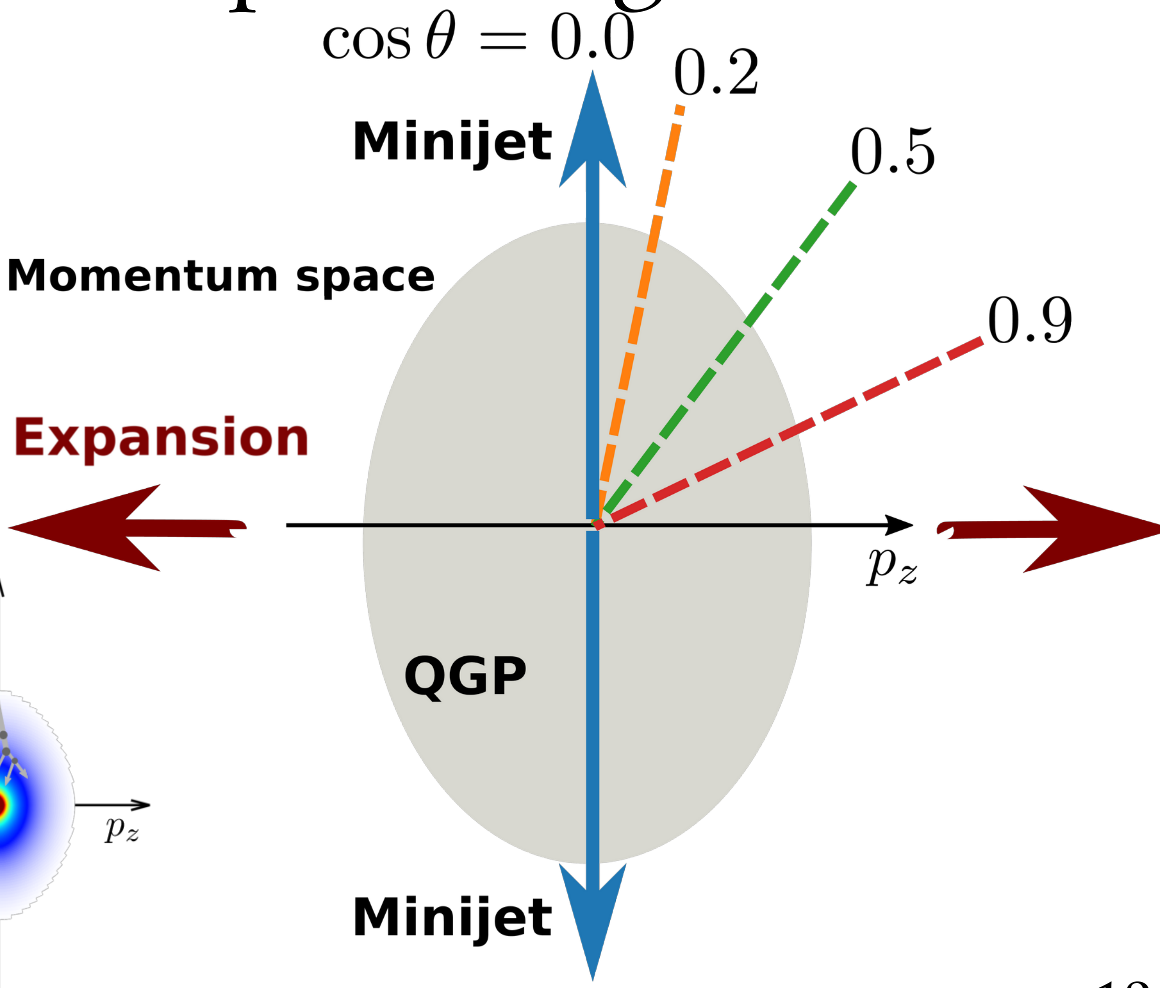
Minijets in anisotropic background

CGC motivated background

$$\bar{f} = \frac{2A}{\lambda} \frac{Q_0 \exp[-\frac{2}{3}(p_T^2 + \xi^2 p_z^2)/Q_0^2]}{\sqrt{p_T^2 + \xi^2 p_z^2}}$$

Bottom-up thermalisation



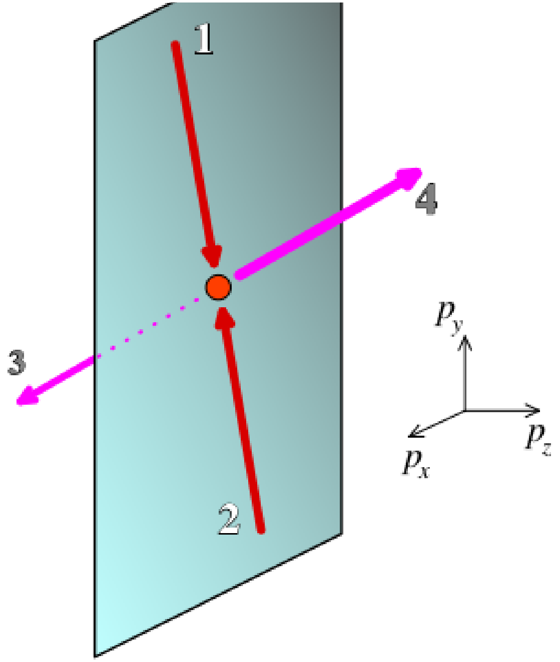


Out-of-plane scatterings

Isotropisation driven by elastic scatterings

$$C_{2\leftrightarrow 2} \propto \int |\mathcal{M}_{2\leftrightarrow 2}|^2 [f_1 f_2 (1+f_3)(1+f_4) - f_3 f_4 (1+f_1)(1+f_2)]$$

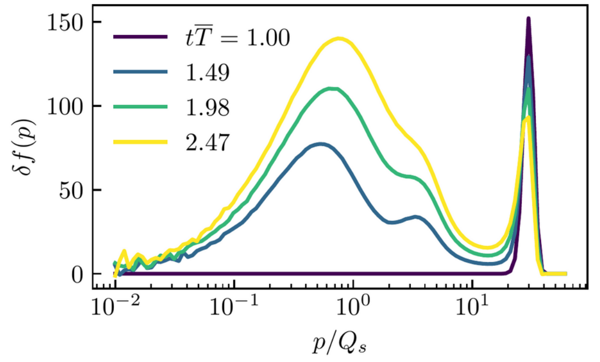
- For highly-occupied f$\gg$ 1 cubic terms dominate
  $\longrightarrow$ classical (field) approximation
- Out of plane f$\ll$ 1 due to high-anisotropy
  $\longrightarrow$ quadratic (quantum) term dominates

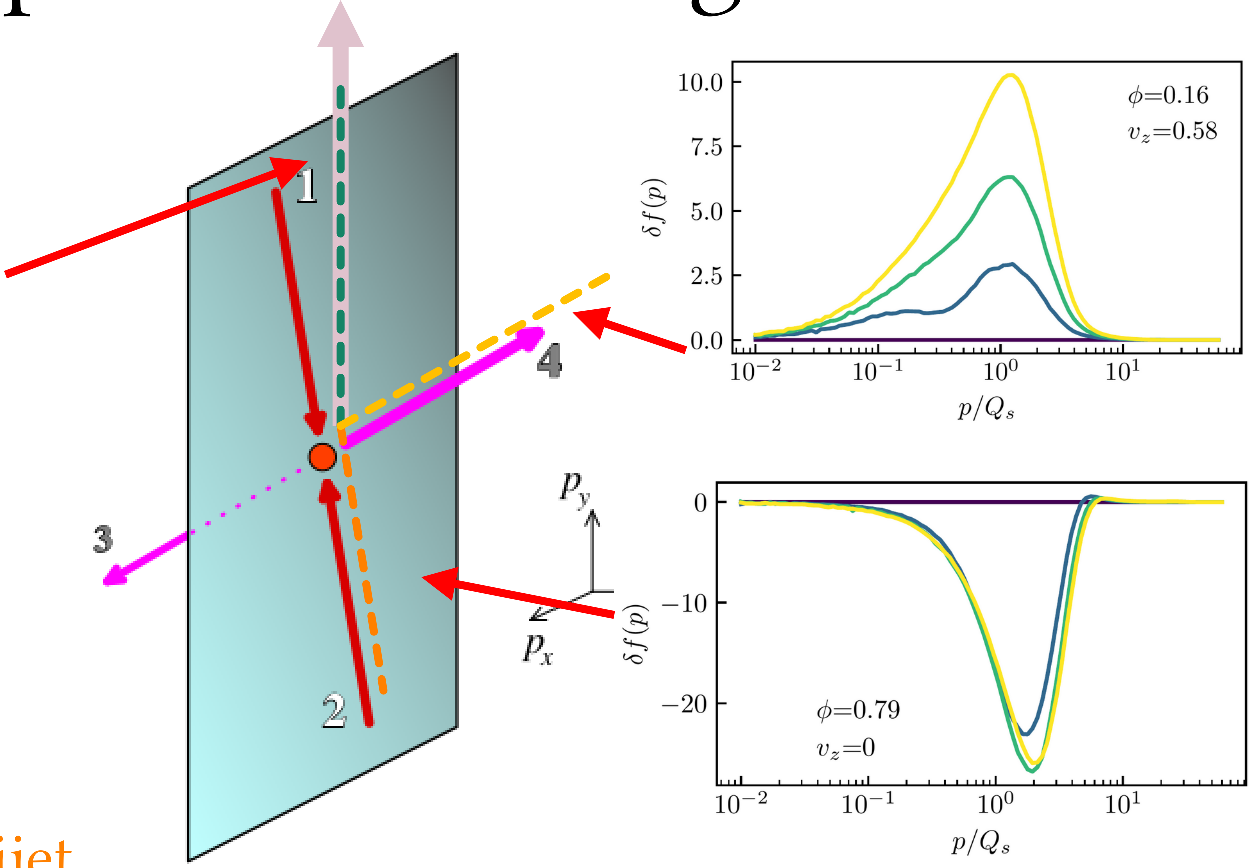


Epelbaum, Gelis, Jeon, Moore, Wu JHEP 2015

Initial isotropisation driven by quadratic terms

Out-of-plane scatterings

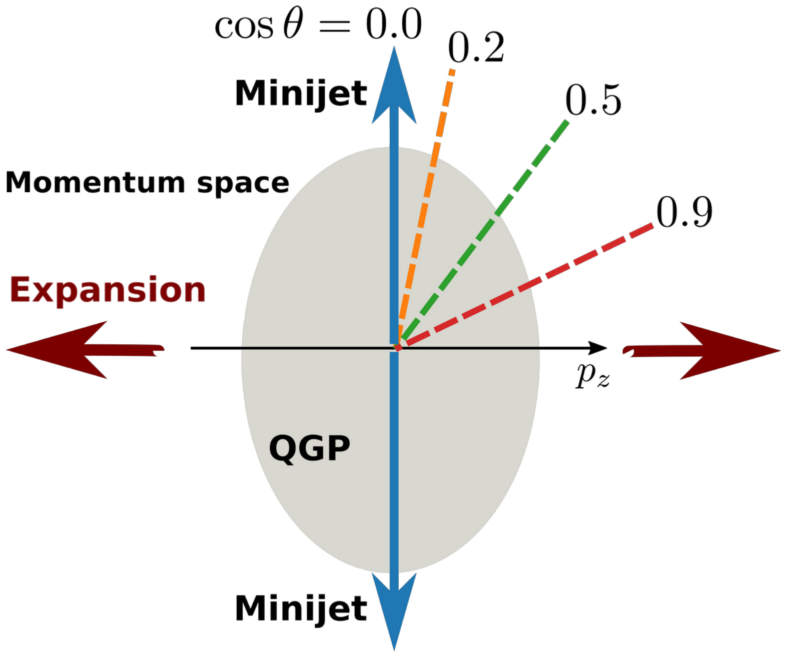




Perturbation evolution:

1) Along the minijet
2) Out of plane
3) In-plane away from minijet

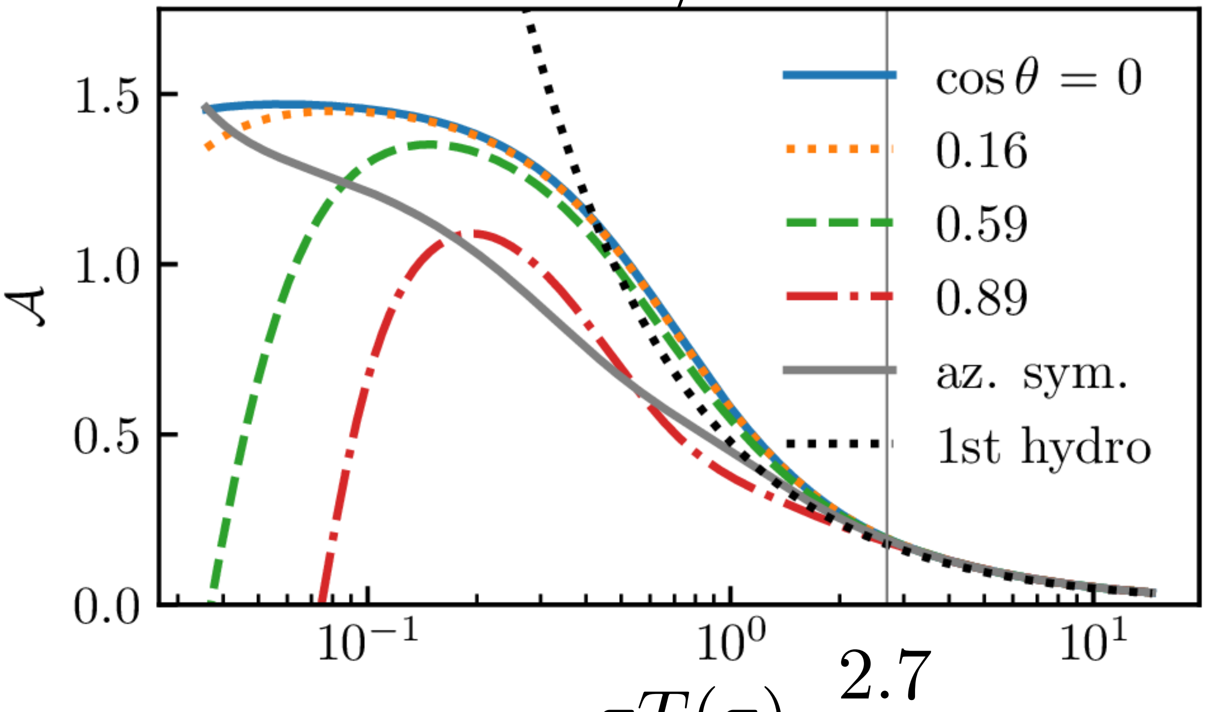
Minijet hydrodynamisation time



Initial memory lost by

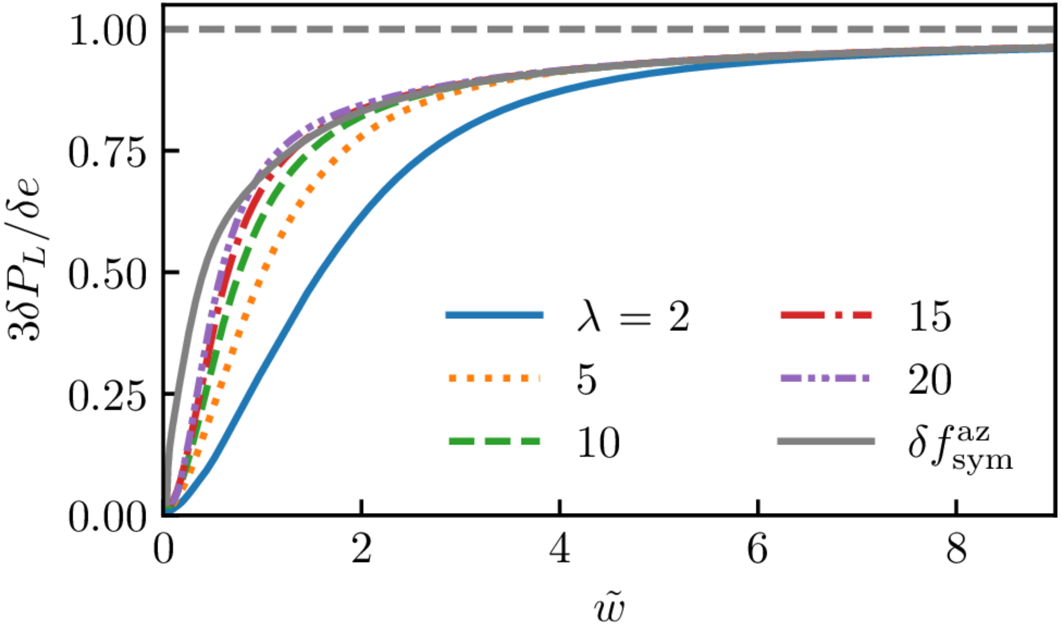
$$\tilde{w}_{\mathrm{mjh}} = 2.7$$

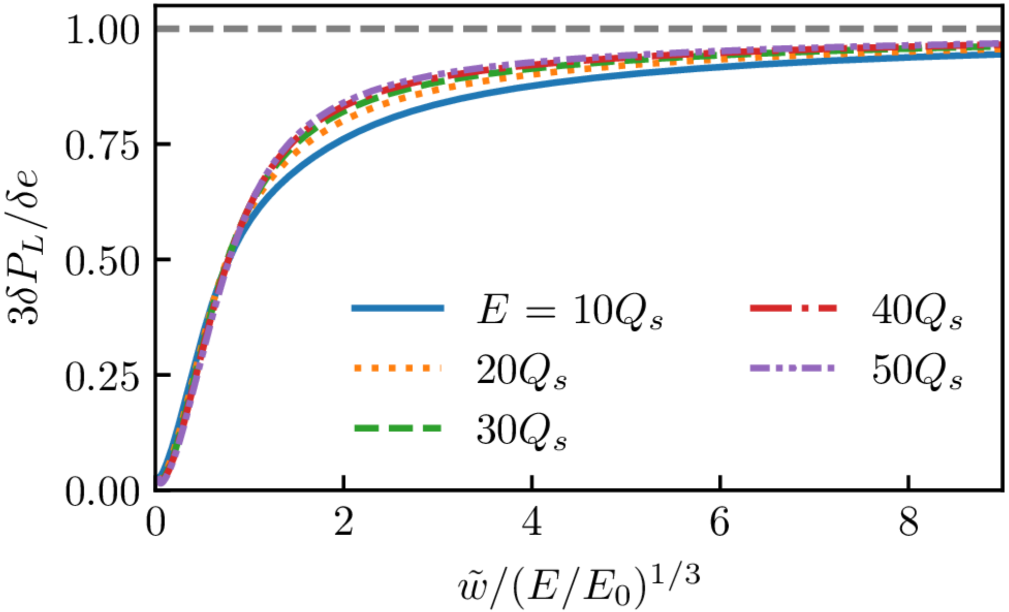
$$\mathcal{A} = \frac{P_T - P_L}{e/3}$$



$$\tilde{w} = \frac{\tau T(\tau)}{4\pi\eta/s}$$

Scaling with coupling and energy

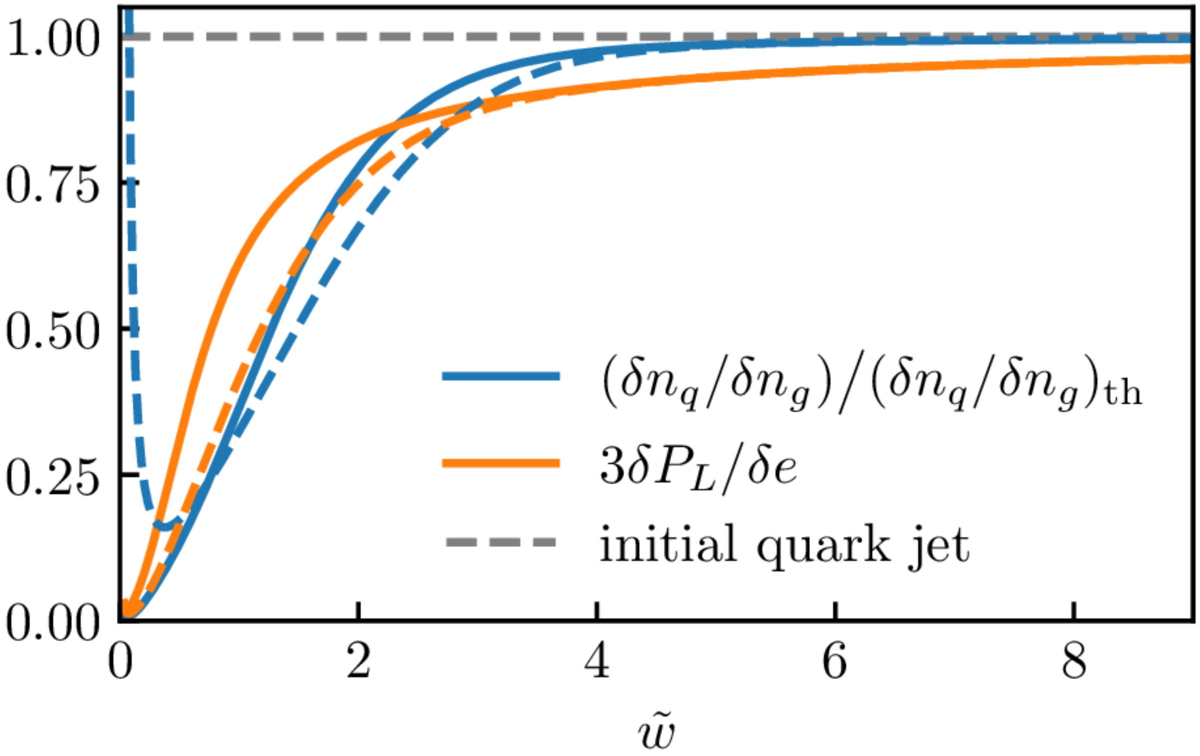




$$\tilde{w}_{\rm mjh} = 2.7\sqrt[3]{E/E_0} \Longrightarrow \tau_{\rm mjh} = 5.1\,{\rm fm}\left(\frac{4\pi\eta/s}{2}\right)^{3/2}\left(\frac{E}{31\,{\rm GeV}}\right)^{1/2}$$

Caveats:
- No vacuum shower
- No running coupling
- No 3D expansion

Quark and gluon minijets



Gluon over-population in quark minijets

Summary & Outlook

Studied minijet thermalisation in QCD kinetic theory:

Zhou, Brewer, AM, arXiv:2402.09298

Thermal background:

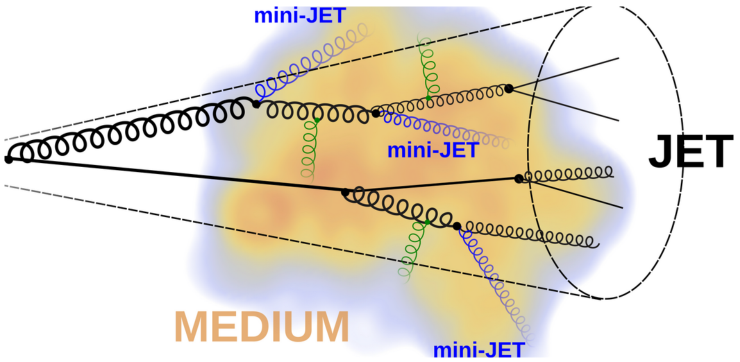
- Two step thermalisation of net-energy perturbations.

Expanding background:

- Hydrodynamisation time of minijets: $\tilde{w}_{\mathrm{mjh}} = 2.7\sqrt[3]{E/E_0}$

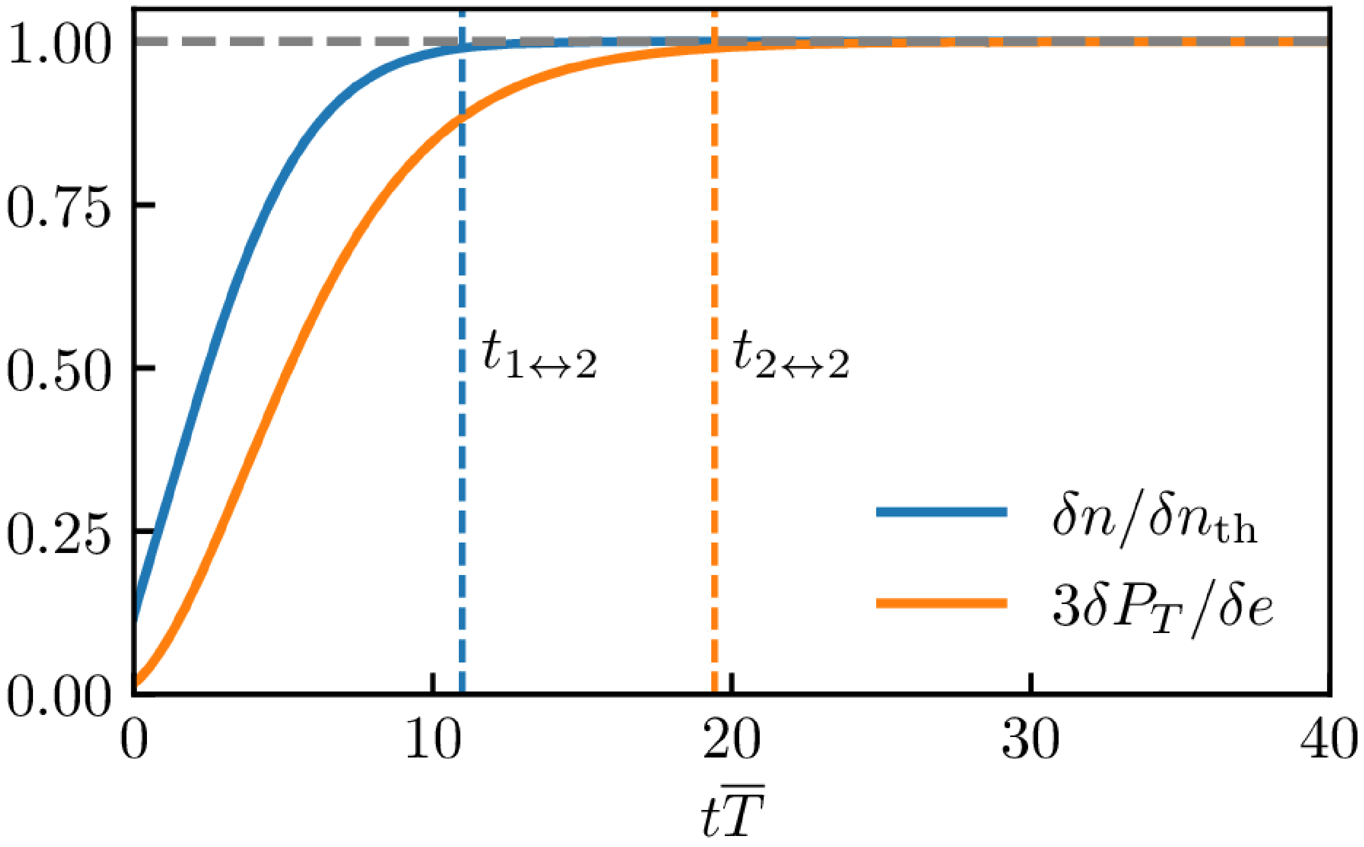
Outlook:

- Spatial response to minijets à la KøMPøST
- Interface between vacuum shower and hydro.



Thank you!

Elastic vs inelastic processes



Colinear radiation balanced by merging