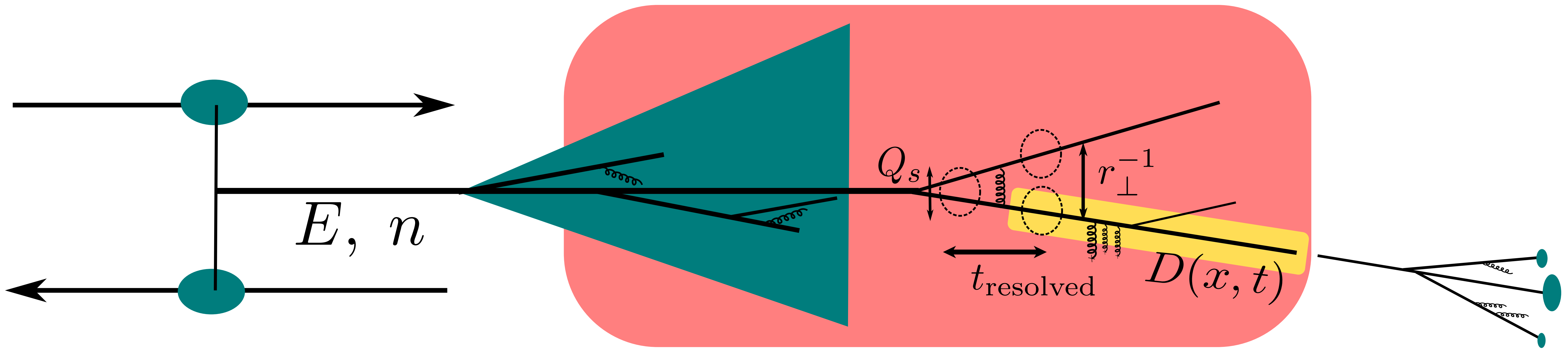



*RBRC Workshop: Predictions for sPHENIX, NY, Jul 21, 2022*

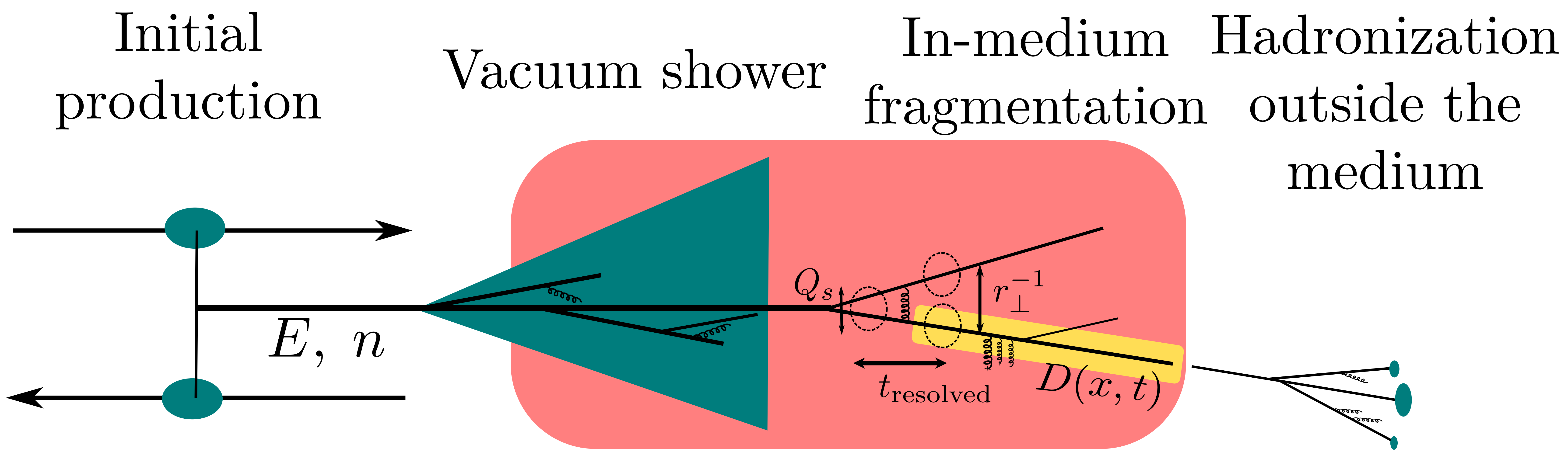
# Thermalization of highly energetic partons in a QCD plasma


Ismail Soudi


*Based on: S. Schlichting, I.S. arXiv:2008.04928*
*S. Schlichting, I.S., Y. Mehtar-Tani work in progress*

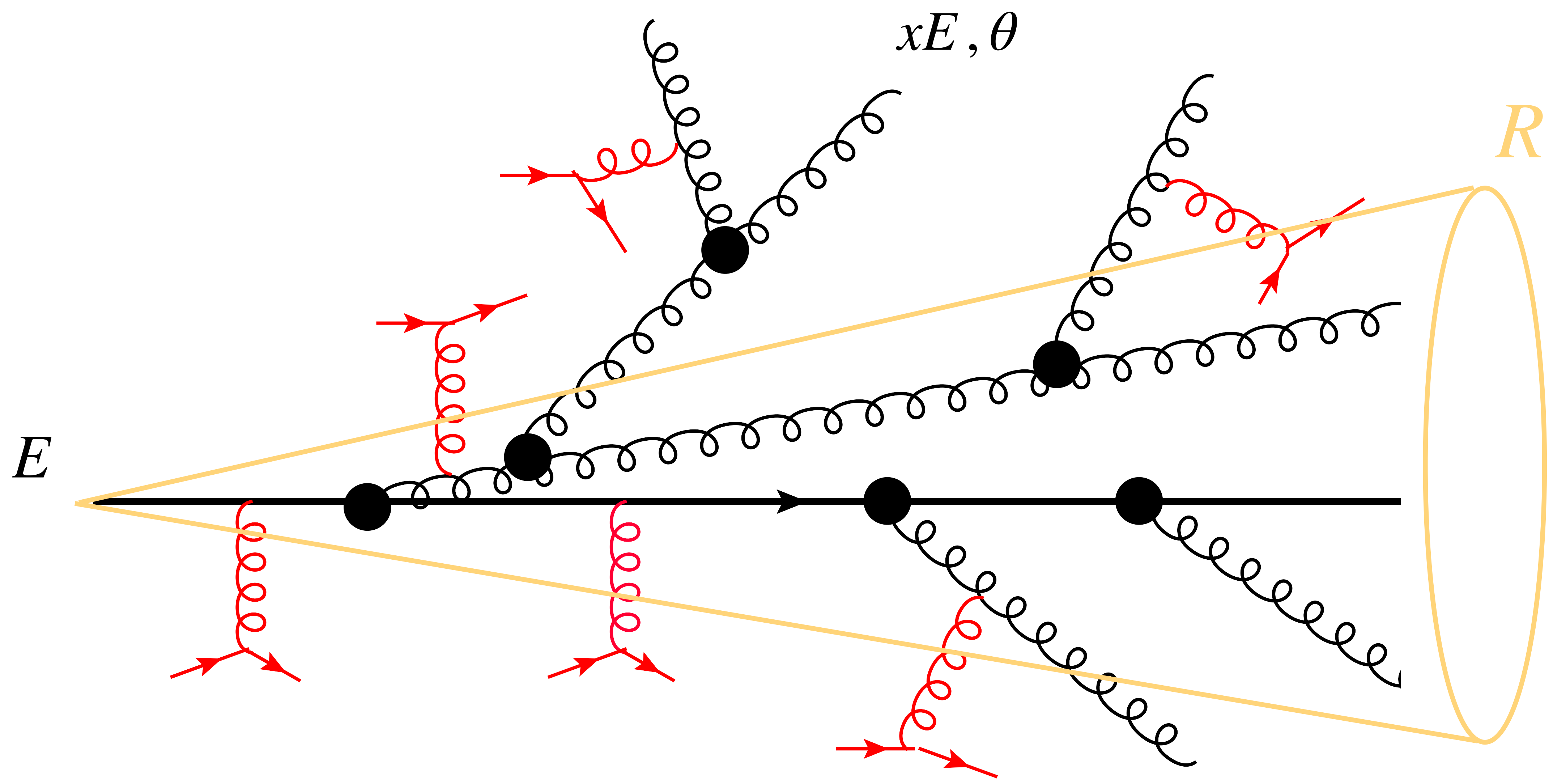

UNIVERSITÄT BIELEFELD
Fakultät für Physik
WAYNE STATE
CRC-TR 211
Strong-interaction matter under extreme conditions
JETSCAPE

# QCD Jets




- Complete picture of jet evolution in HIC is a complex task
- Different formalisms to treat this evolution: CoLBT, MARTINI, MATTER+LBT, JEWELS…
- **We focus mainly on energy loss and equilibration of hard partons in the medium**

# Our Focus




- Main focus: Hard Parton traversing the medium
- Understand: energy cascade, out-of-cone energy loss, medium response and full thermalization of the initial hard parton => Important for low energy jets at RHIC (sPHENIX)

# Effective Kinetic description

- Based on an effective kinetic theory at leading order:

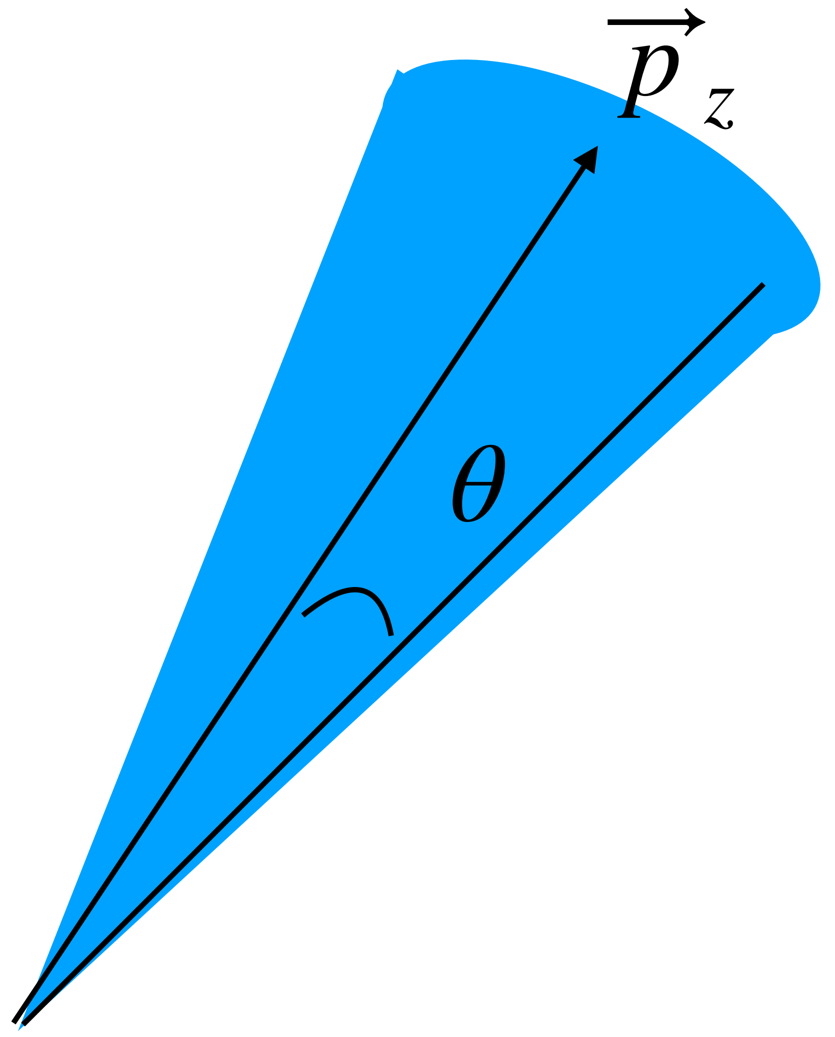
$$p^\mu \partial_\mu f_i(\vec{x}, \vec{p}, t) = C[\{f_i\}],$$

- We consider high energetic partons as linearized fluctuation over static background equilibrium

$$f(p,t) = n_{\rm eq}(p;T) + \delta f_{\rm jet}(p,t),$$

- Define energy distribution:

$$D_a(x,\theta,t) \equiv x\frac{dN_a}{dx\,d\cos\theta} \sim \frac{\nu_a(N_f)}{E_j} p^3 \delta f(p,\theta)\Big|_{p=xE_j},$$



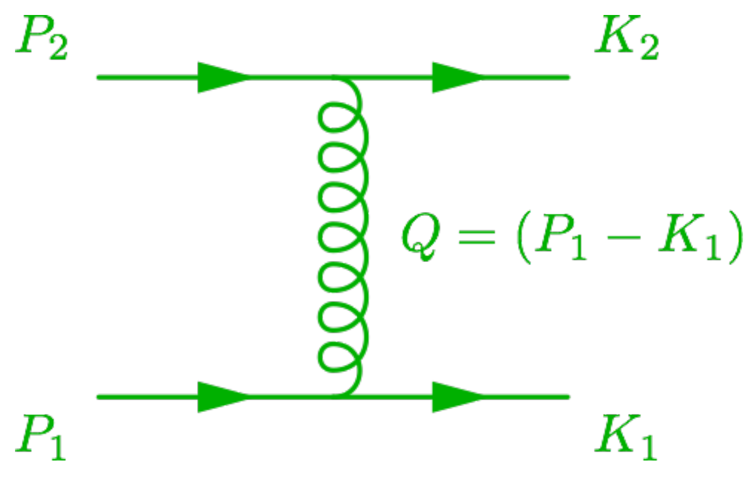

- $x = \dfrac{p}{E_j}$ is the parton momentum fraction

- $\theta$ : Polar angle of the momentum

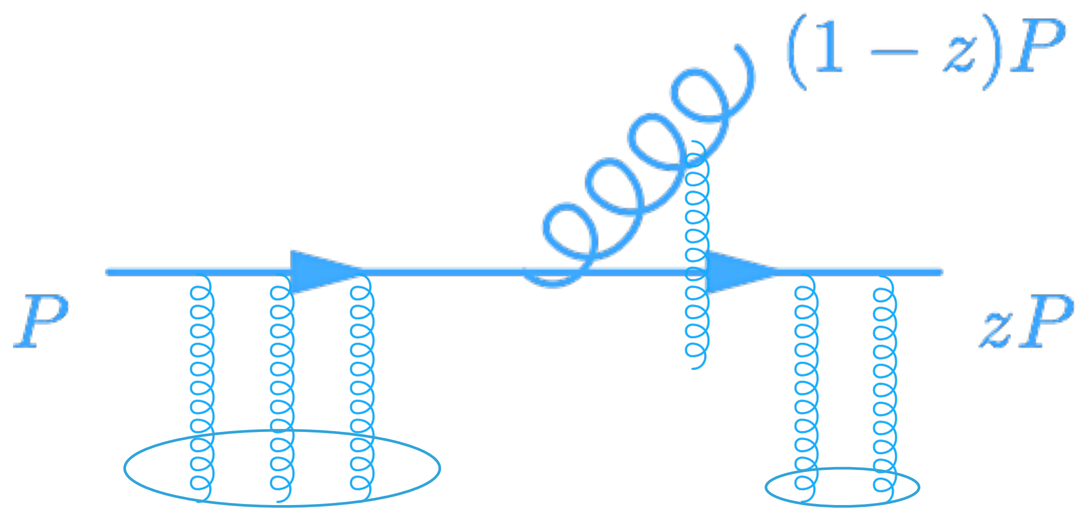
- Exact conservation of energy, momentum and valence charge → allows to study evolution from $\sim E$ to $\sim T$ including thermalization of the hard partons

# Effective Kinetic description

Elastic scatterings

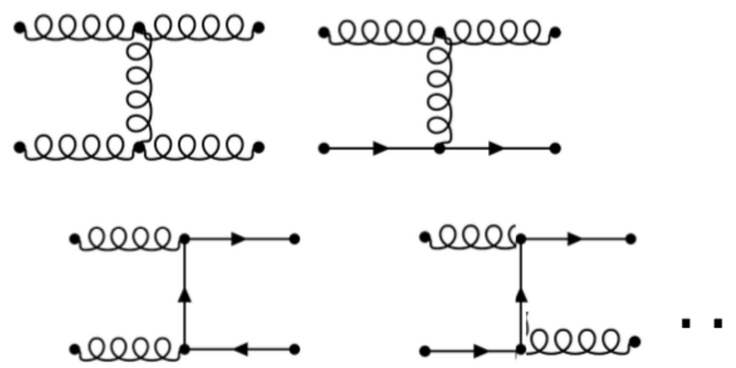



LPM resummed Rate.

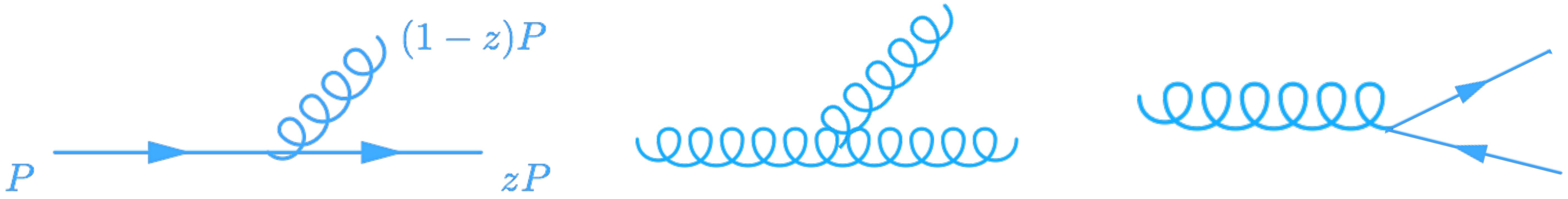



$$C[\{f_i\}] = C^{2\leftrightarrow 2}[\{f_i\}] + C^{1\leftrightarrow 2}[\{f_i\}] \quad ,$$

[J. Blaizot et al. arXiv:1402.5049]
[J. Ghiglieri et al. arXiv: 1509.07773 ]



[P. B. Arnold, G. D. Moore, and L. G. Yaffe (AMY) (2003)]

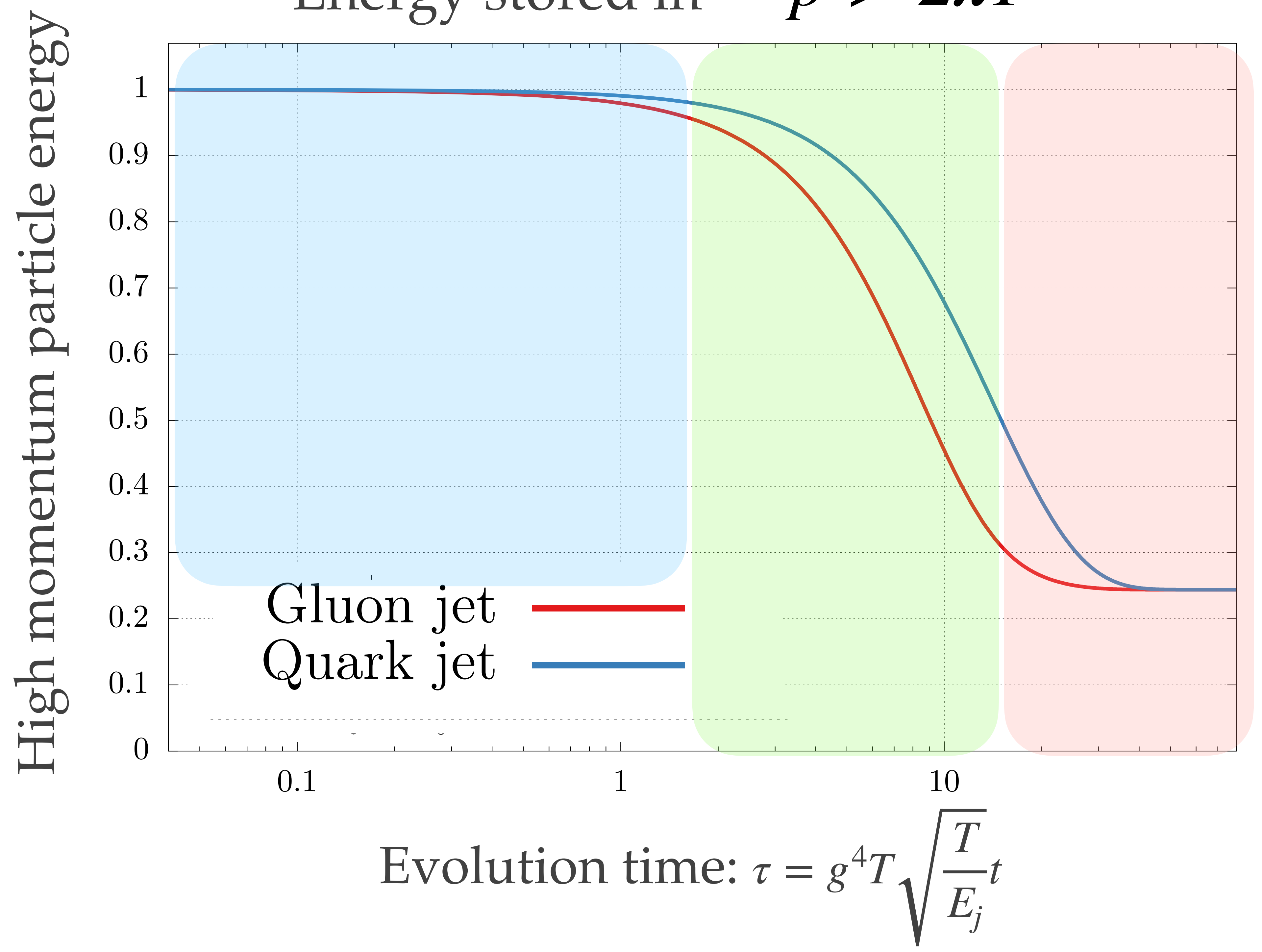


# Energy Loss: Collinear cascade

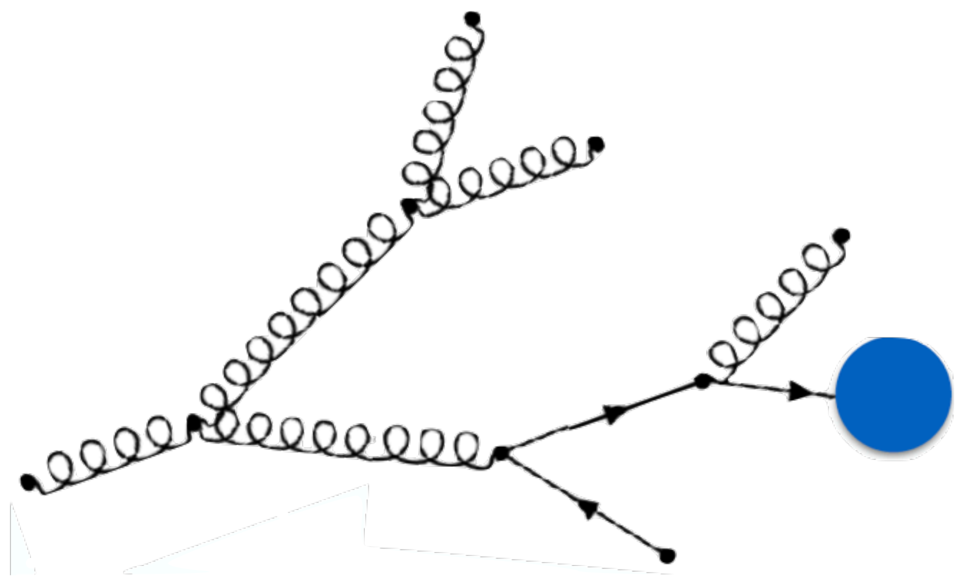
- Three regimes:
  - Initial energy loss: mediated by gluon radiation and re-coil terms.
  - Energy cascade: universality between gluon/quark Jet→ radiative break-up via successive splittings, reminiscent of turbulence
  - Equilibration: exponential decay, linear response.

Jet energy $E_j = 1000T$ and $g = 1$.

Energy stored in $p > 2\pi T$



# Collinear Cascade

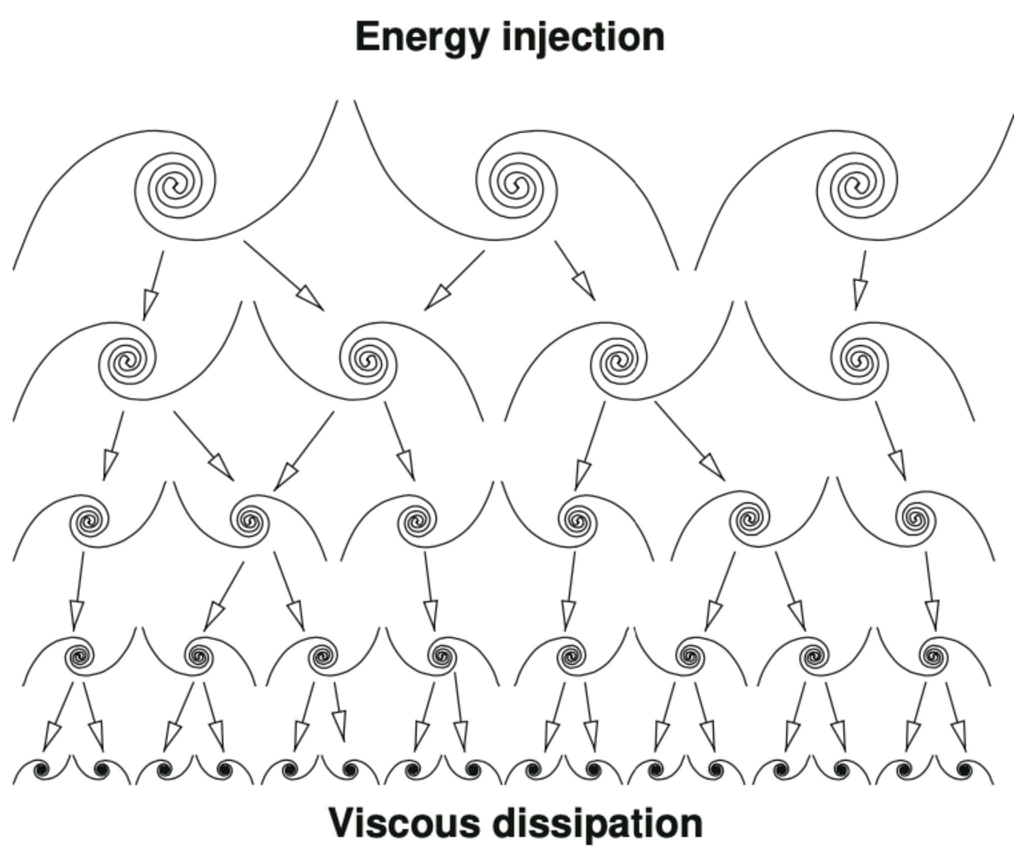


- Stationary turbulent solution in intermediate range $T/E \ll x \ll 1$

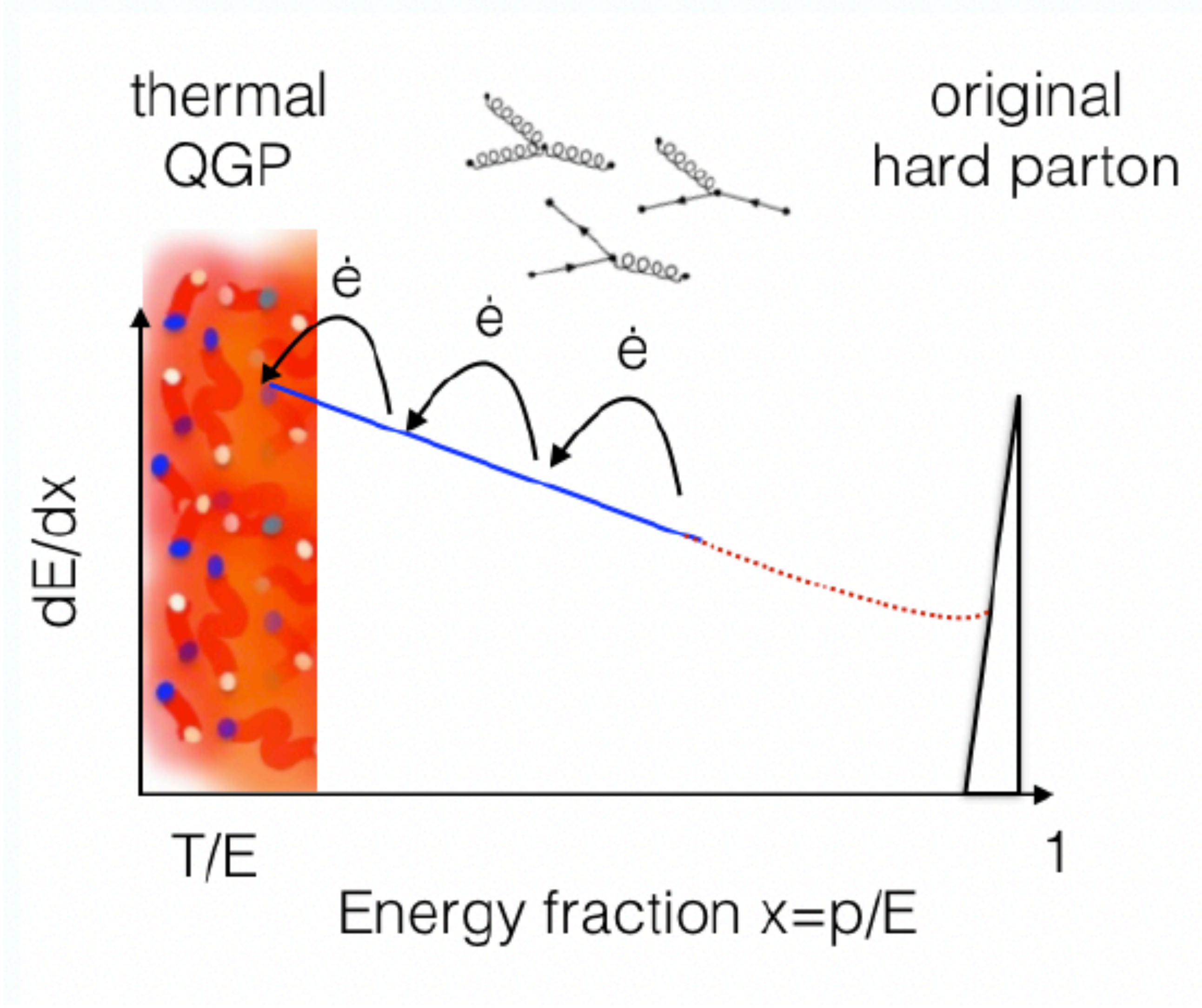

$$D_g(x) = \frac{G}{\sqrt{x}}\,, \quad D_S = \frac{S}{\sqrt{x}}\,,$$

- Scale invariant energy flux :

$$\frac{dE}{d\tau}(\Lambda) = \sum_i \int_{\Lambda/E}^{\infty} dx\ \partial_\tau D_i(x) = \left(\tilde{\gamma}_g + \frac{S}{G}\tilde{\gamma}_q\right) G(\tau)\,,$$




- Time dependent amplitude accounts for injection of energy due to radiation of hard particles $x \sim 1$:




- Chemistry fixed by the Kolmogorov spectrum:

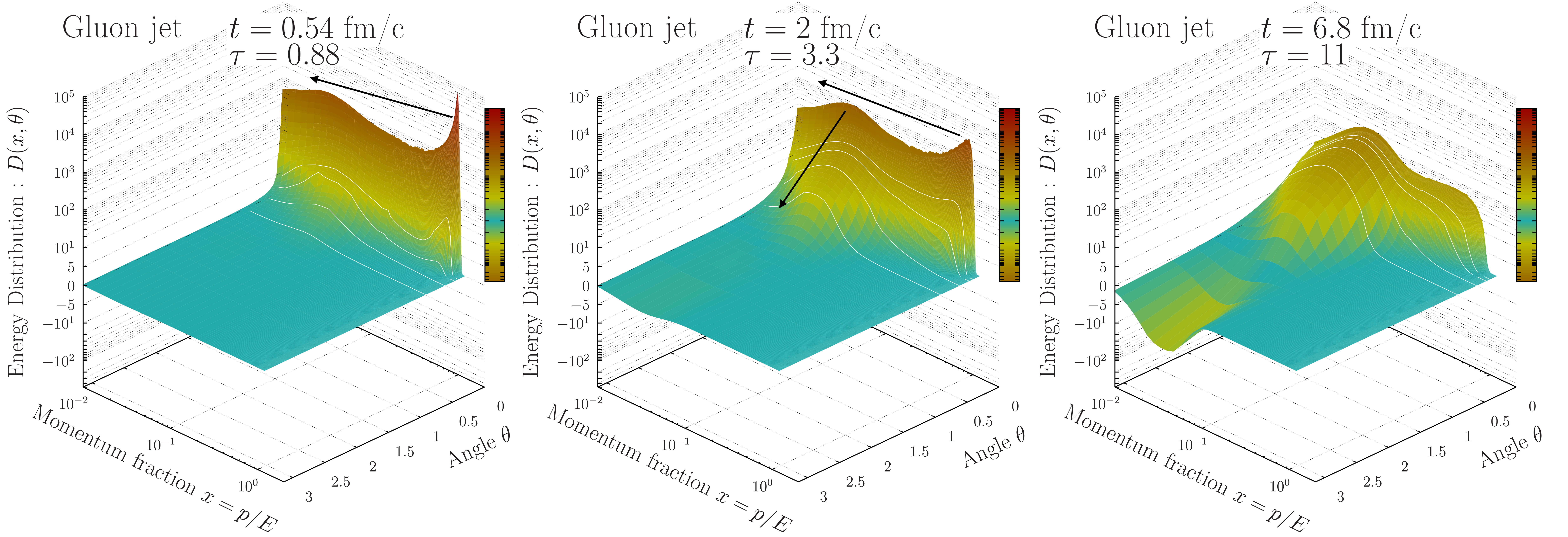
$$\frac{S}{G} = \frac{2N_f \int dz\ z\ \mathcal{K}_{qg}(z)}{\int dz\ z\ \mathcal{K}_{gq}(z)} \approx 0.07 \times 2N_f$$

# Energy Loss & Thermalization

- Collinear cascade

Jet energy $E_j = 100T$ and $g = 2$.

- Broadening of the soft fragments (p~T)




- Energy loss dominated by collinear branchings followed by thermalization of the soft sector
- Negligible broadening of hard particles; Energy loss out-of-cone mainly due to energy deposition in the soft sector

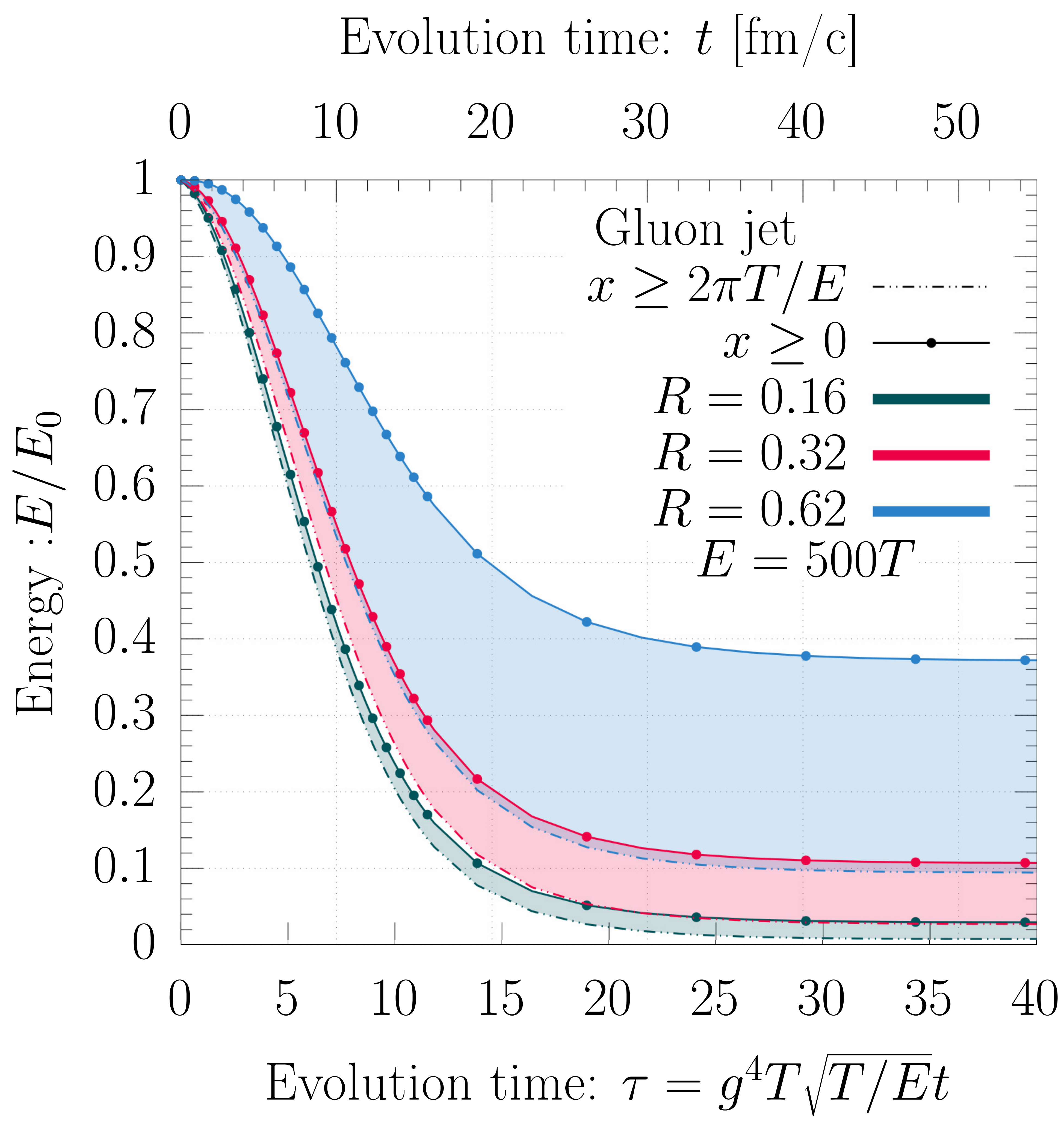
[P. B. Arnold, G. D. Moore, and L. G. Yaffe (AMY) (2003)]

# Energy Loss & Thermalization

$$E(R,\tau) = \int dx \int_{\cos R}^{1} D(x,\cos\theta,\tau)\ .$$

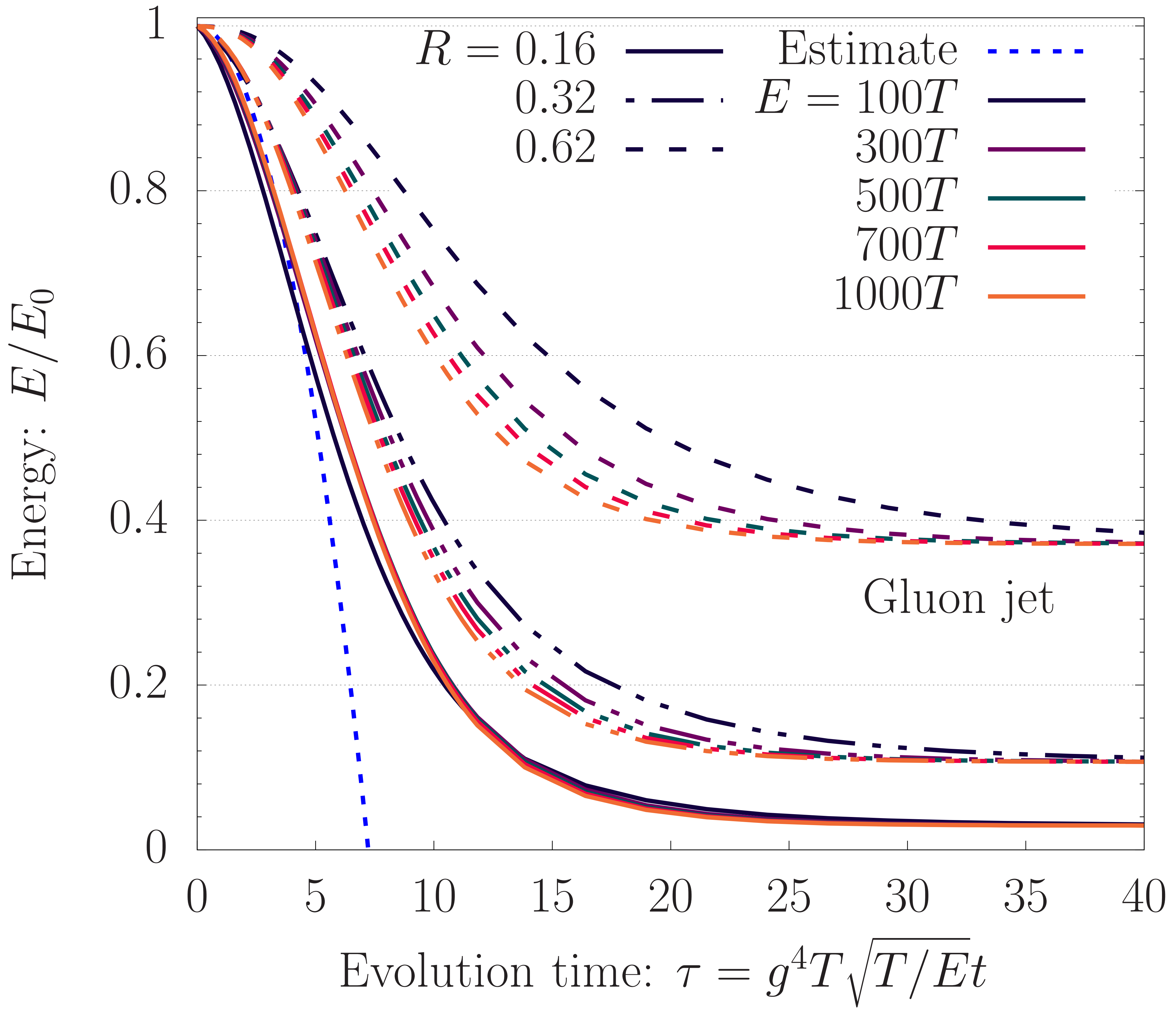
- Small cone-size: soft sector does not play a major role → similar energy loss in both momentum regions
- Larger cone-size: soft sector carries substantial fraction of the equilibrated energy at late times + early time energy loss diverges.

$$E_{2\pi}(R,\tau) = \int_{2\pi T/E}^{\infty} dx \int_{\cos R}^{1} D(x,\cos\theta,\tau)\ .$$



# Sensitivity To The Initial Parton

- Characteristic time of the turbulent cascade is $t_{th} = \frac{1}{\alpha_s}\sqrt{\frac{E}{\hat{q}}}$ (time it takes a parton to thermalize)
- Small cone-sizes show a scaling between partons of different energies.
- W/ deviations for larger cone-sizes.



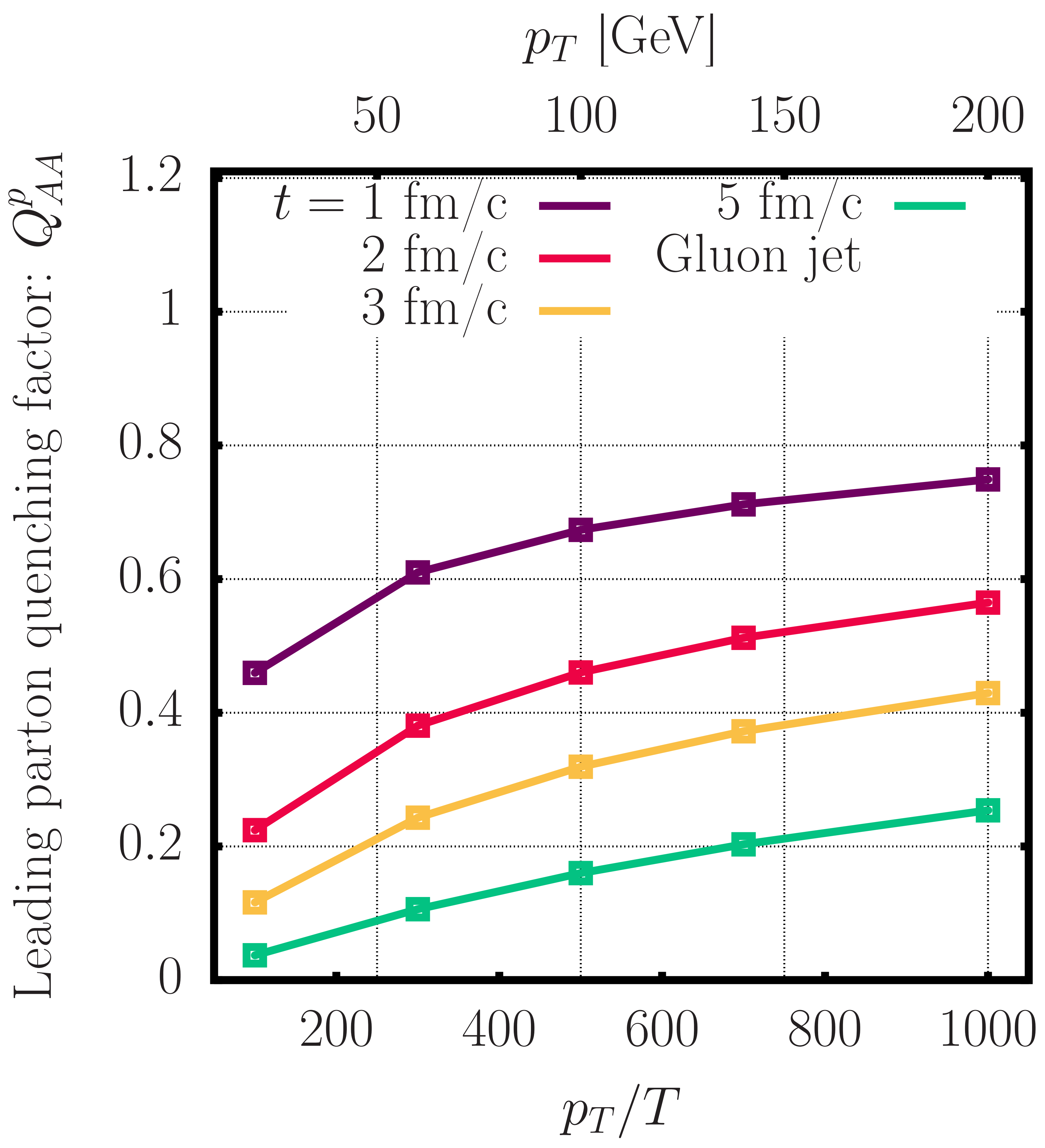
# Leading Parton Quenching Factors

$$R^X_{\mathrm{AA}}(p_T, y, \phi) \equiv \frac{1}{N_{AA}} \frac{\frac{d^2 N^X_{\mathrm{AA}}}{dp_T^2 dy}}{\frac{d^2 N^X_{\mathrm{pp}}}{dp_T^2 dy}} ,$$

- Leading parton quenching can be modeled as a moment of the distribution

$$Q^{\mathrm{p}}_{AA}(p_T) = \frac{\frac{d^2\sigma_{AA}}{dp_T^2}}{\frac{d^2\sigma_0}{dp_T^2}} = \int_0^1 \mathrm{d}x \int_{-1}^1 \mathrm{d}\cos\theta \; D\left(x, \theta, g^4 T\sqrt{xT/p_T t}\right)\left(\frac{1}{x}\right)^{2-n} .$$

- Leading parton quenching only sensitive to hard constituents, i.e. collinear cascade => in-medium splittings



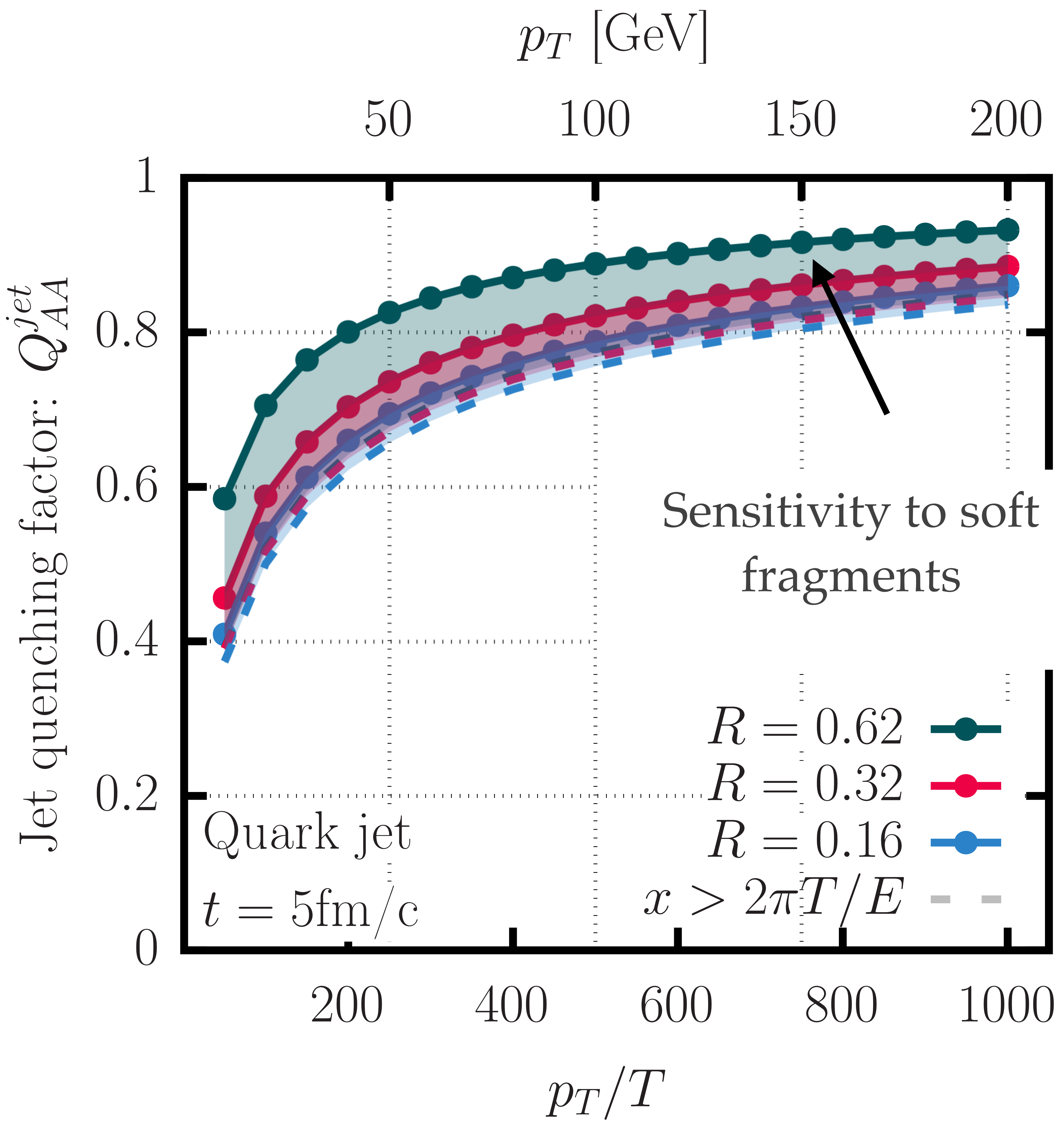

[R. Baier et al. arXiv:0106347]

# Modeling Jet Quenching

- We capture the first emission using the BDMPS finite medium rate $\frac{d\Gamma}{d\omega}(P, \omega, t)$
- Model medium energy loss by computing the energy remaining inside the cone $E(\omega, R, L - t)$ after a time ( $L - t$ )

$$Q(p_T) = \exp\left[\int_0^L \mathrm{d}t \int \mathrm{d}\omega \frac{\mathrm{d}\Gamma}{\mathrm{d}\omega}\left(1 - \mathrm{e}^{-n\frac{\omega}{p_T}\left[1-E\left(\omega,R,\tau=\frac{L-t}{t_{\mathrm{th}}}\right)\right]}\right)\right] .$$

- Jet quenching recovers energy from the soft sector for large cone size => medium response
- Energy loss currently over-estimated due to neglecting finite size effects on medium-induced emission rates (work in progress)




[R. Baier et al. arXiv: hep-ph/0106347]
[Y. Mehtar-Tani, & K. Tywoniuk arXiv: 1707.07361]

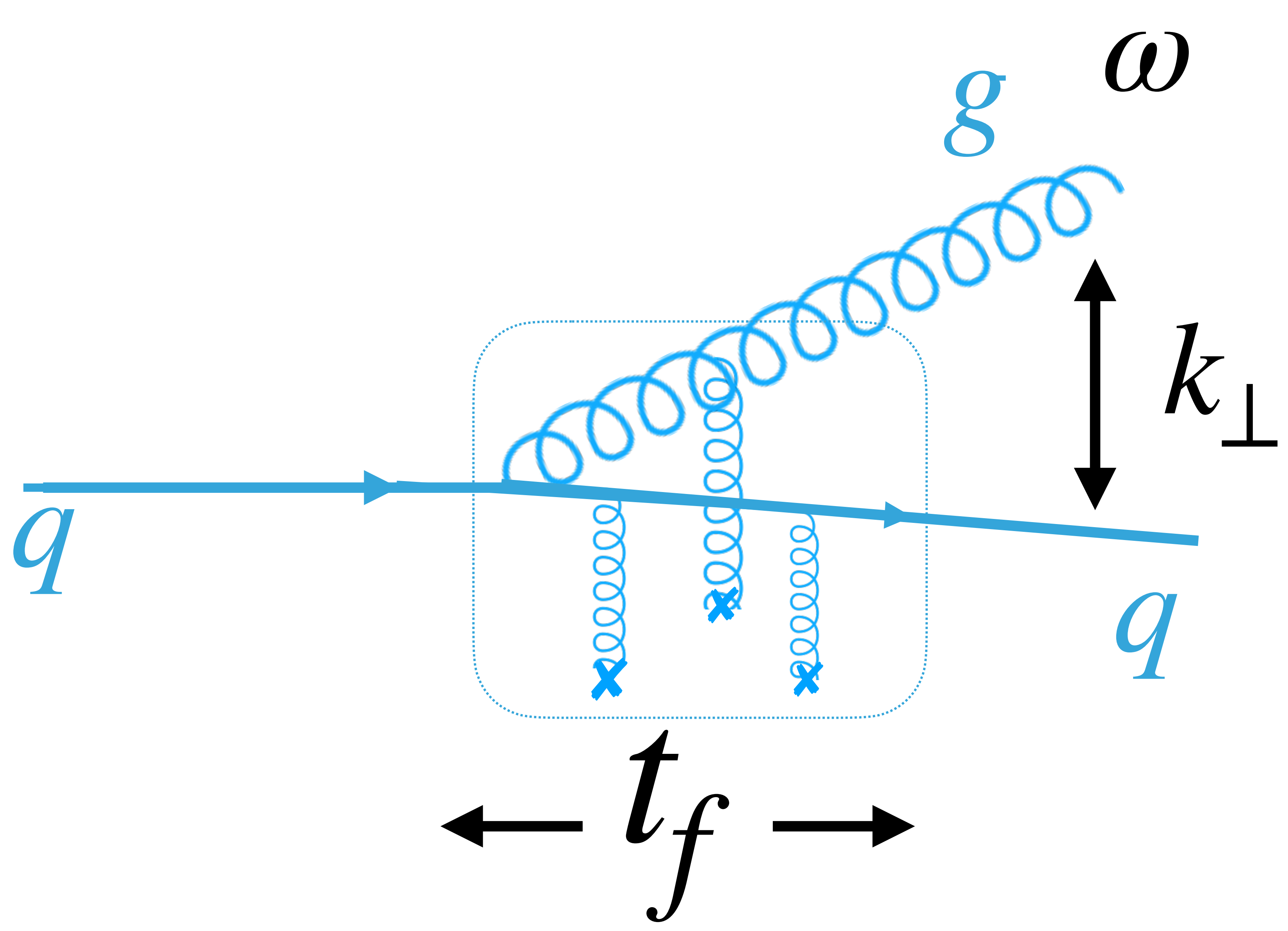
# Conclusion

- Energy loss is governed by an inverse energy cascade: driven by successive splitting
- Mechanisms underlying energy loss similar to QGP thermalization → low energetic partons ($E \lesssim 30T$) more sensitive to the medium scale
- High energy distribution stays collinear → energy at large angles ($\theta > 0.2$) is mainly sensitive to soft scales
- Leading parton quenching is sensitive to the in-medium cascade
- Jet quenching sensitive to soft physics

# Backup

# Landau-Pomeranchuck-Migdal (LPM) effect

- Multiple soft scatterings with the medium kick the parton slightly off-shell → leading to radiation of a gluon ($\omega$,**k**)
- $t_f \ll \lambda_{\text{mfp}}$: the medium cannot resolve the quanta until it's formed
- $t_f \gg \lambda_{\text{mfp}}$: multiple soft scatterings with the medium act coherently leading to interference effects that has to be resummed




$$t_f \sim \frac{2\omega}{k_\perp^2}$$

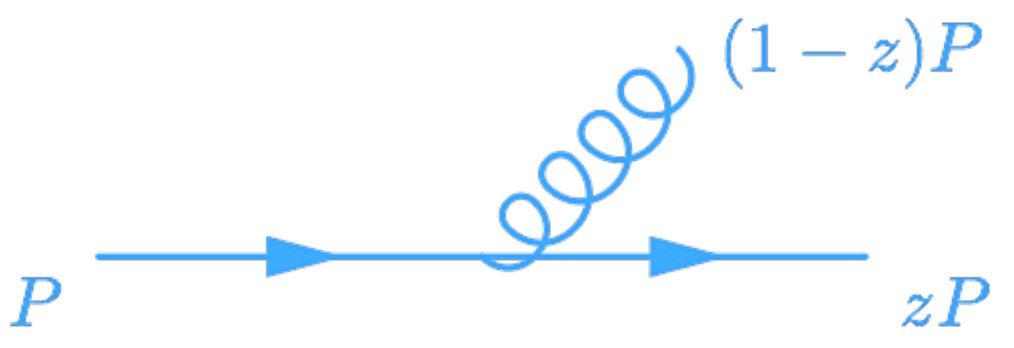
$$k_\perp \sim \hat{q} t_f$$

$$\longrightarrow \quad t_f(\omega) = \sqrt{\frac{2\omega}{\hat{q}}}$$

# Collinear Radiation

- In-medium radiation rates given by

$$\frac{d\Gamma^a_{bc}(p,z)}{dz} = \frac{\alpha_s P_{bc}(z)}{[2Pz(1-z)]^2} \int \frac{d^2\mathbf{p}_b}{(2\pi)^2}\, \mathrm{Re}\left[2\mathbf{p}_b \cdot \mathbf{g}_{(z,P)}(\mathbf{p}_b)\right] \;,$$




- where the g fct solves

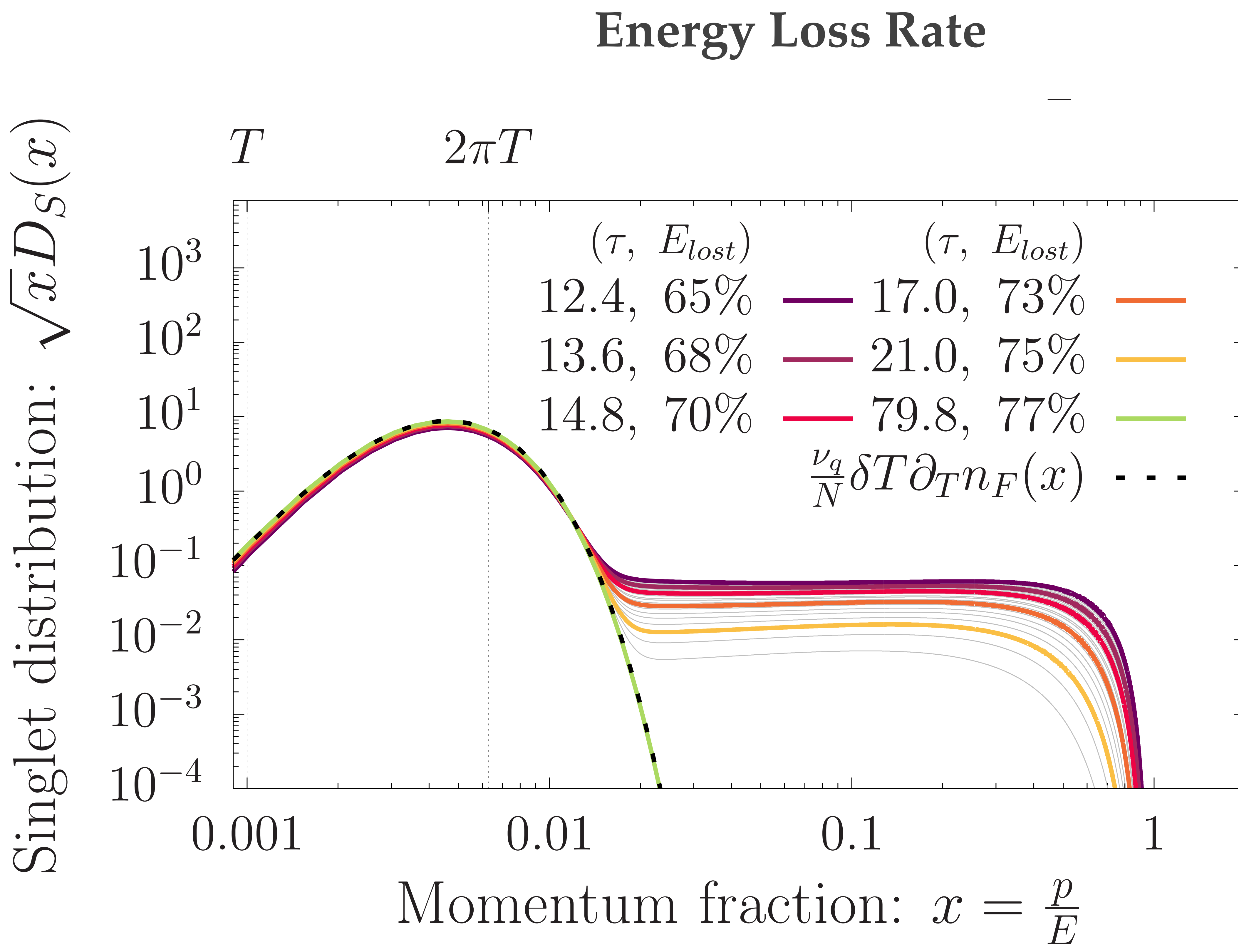
$$2\mathbf{p}_b = i\delta E(z,P,\mathbf{p}_b)\mathbf{g}_{(z,P)}(\mathbf{p}_b) + \int \frac{d^2q}{(2\pi)^2}\, \bar{C}(\boldsymbol{q}) \;\Big\{C_1\left[\mathbf{g}_{(z,P)}(\mathbf{p}_b) - \mathbf{g}_{(z,P)}(\mathbf{p}_b - \mathbf{q})\right] + C_z\left[\mathbf{g}_{(z,P)}(\mathbf{p}_b) - \mathbf{g}_{(z,P)}(\mathbf{p}_b - z\mathbf{q})\right] + C_{1-z}\left[\mathbf{g}_{(z,P)}(\mathbf{p}_b) - \mathbf{g}_{(z,P)}(\mathbf{p}_b - (1-z)\mathbf{q})\right]\Big\} \;,$$

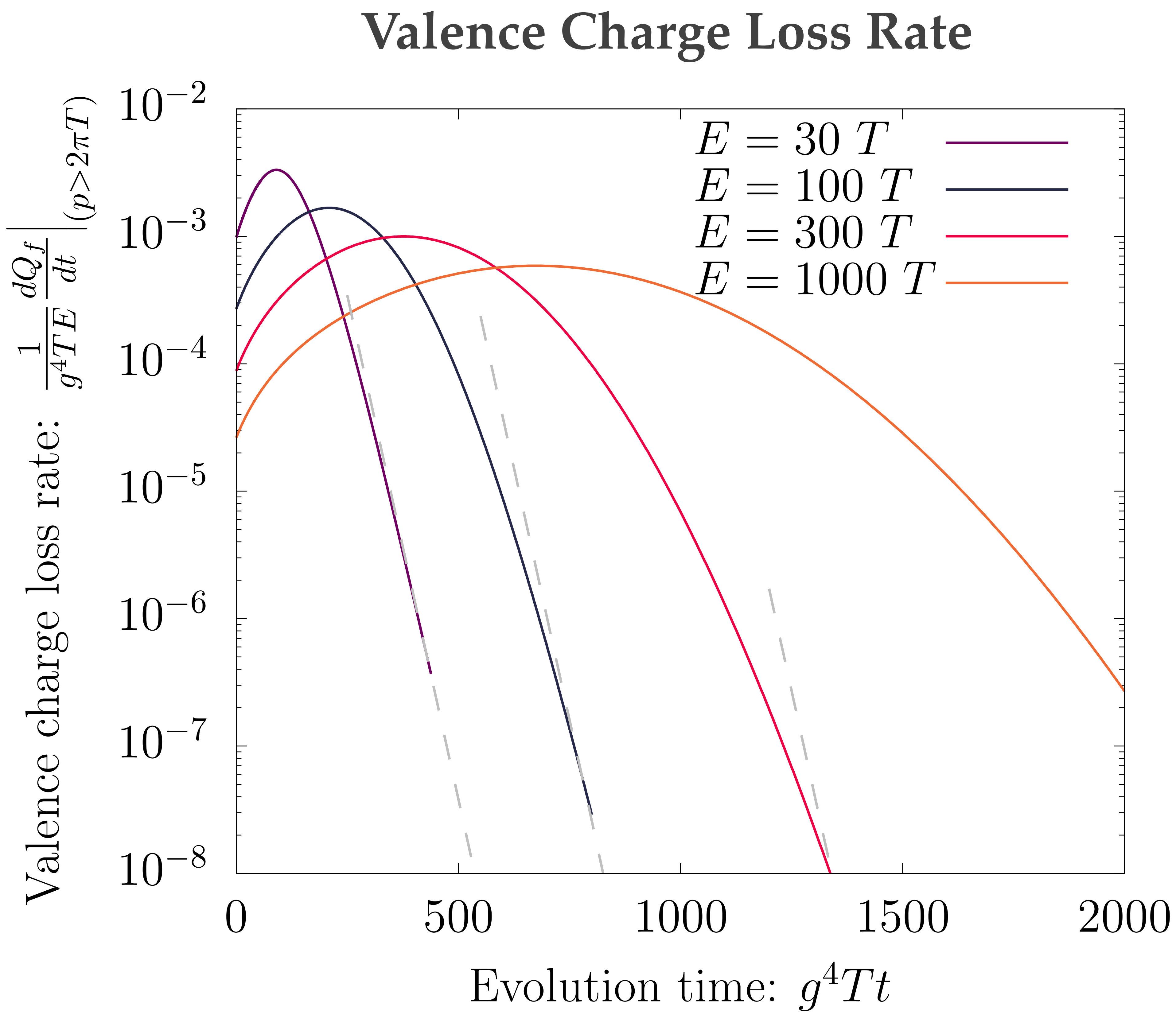
- Elastic scatterings are described using the broadening kernel

$$\bar{C}(\boldsymbol{q}) = \frac{g^2 T m_D^2}{q^2(q^2 + m_D^2)} \;.$$

$$C_a^{1\leftrightarrow 2}[\{f_i\}] = \sum_{bc}\Bigg\{ -\frac{1}{2}\int_0^1 dz \frac{d\Gamma^a_{bc}(\boldsymbol{p},z)}{dz}\Big[f_a(\boldsymbol{p})(1 \pm f_b(z\boldsymbol{p}))(1 \pm f_c(\bar{z}\boldsymbol{p})) - f_b(z\boldsymbol{p})f_c(\bar{z}p)(1 \pm f_a(\boldsymbol{p}))\Big] + \frac{\nu_b}{\nu_a}\int_0^1 \frac{dz}{z^3}\frac{d\Gamma^b_{ac}(\frac{\boldsymbol{p}}{z},z)}{dz}\Big[f_b\left(\frac{\boldsymbol{p}}{z}\right)(1 \pm f_a(\boldsymbol{p}))\left(1 \pm f_c\left(\frac{\bar{z}}{z}\boldsymbol{p}\right)\right) - f_a(\boldsymbol{p})f_c\left(\frac{\bar{z}}{z}\boldsymbol{p}\right)\left(1 \pm f_b\left(\frac{\boldsymbol{p}}{z}\right)\right)\Big]\Bigg\} \;,$$

# Late Time Thermalization



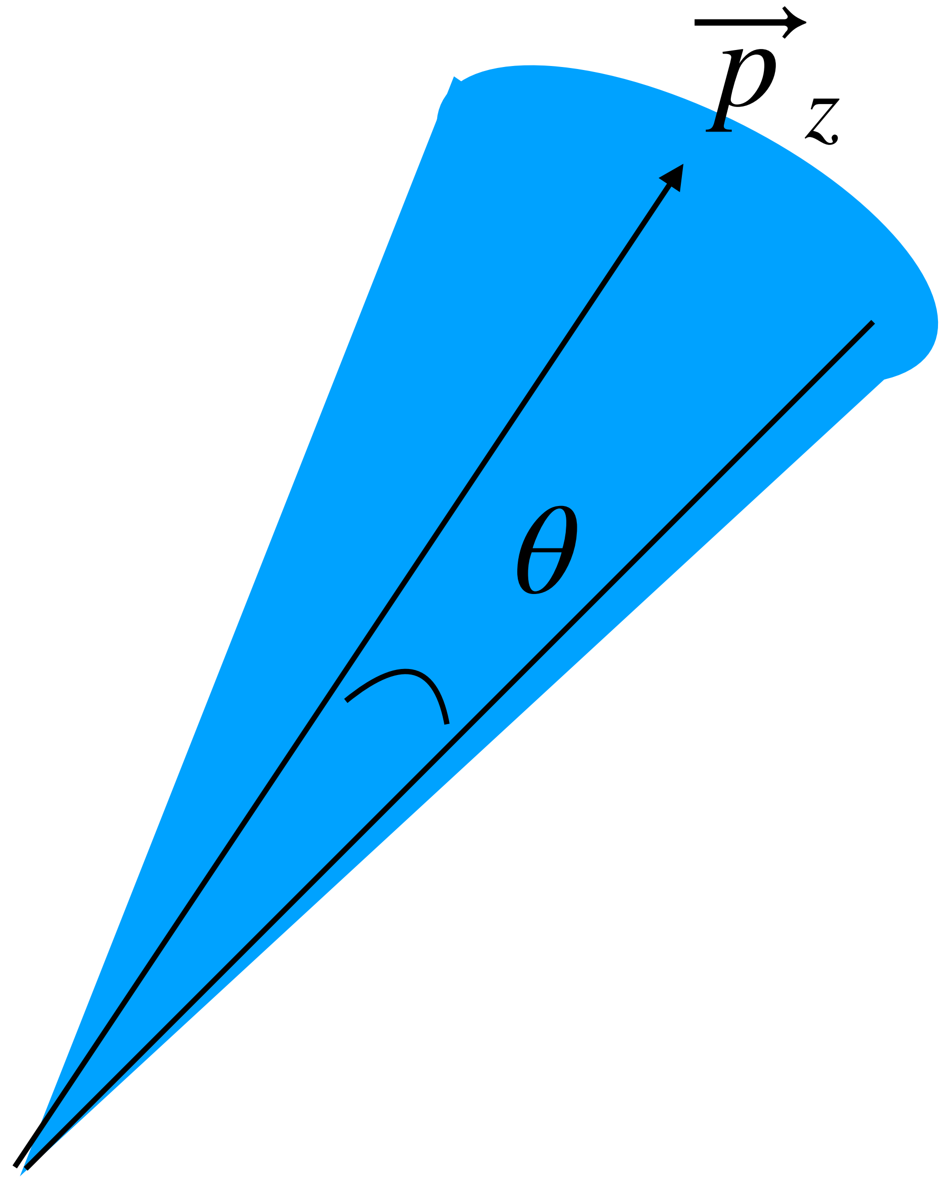



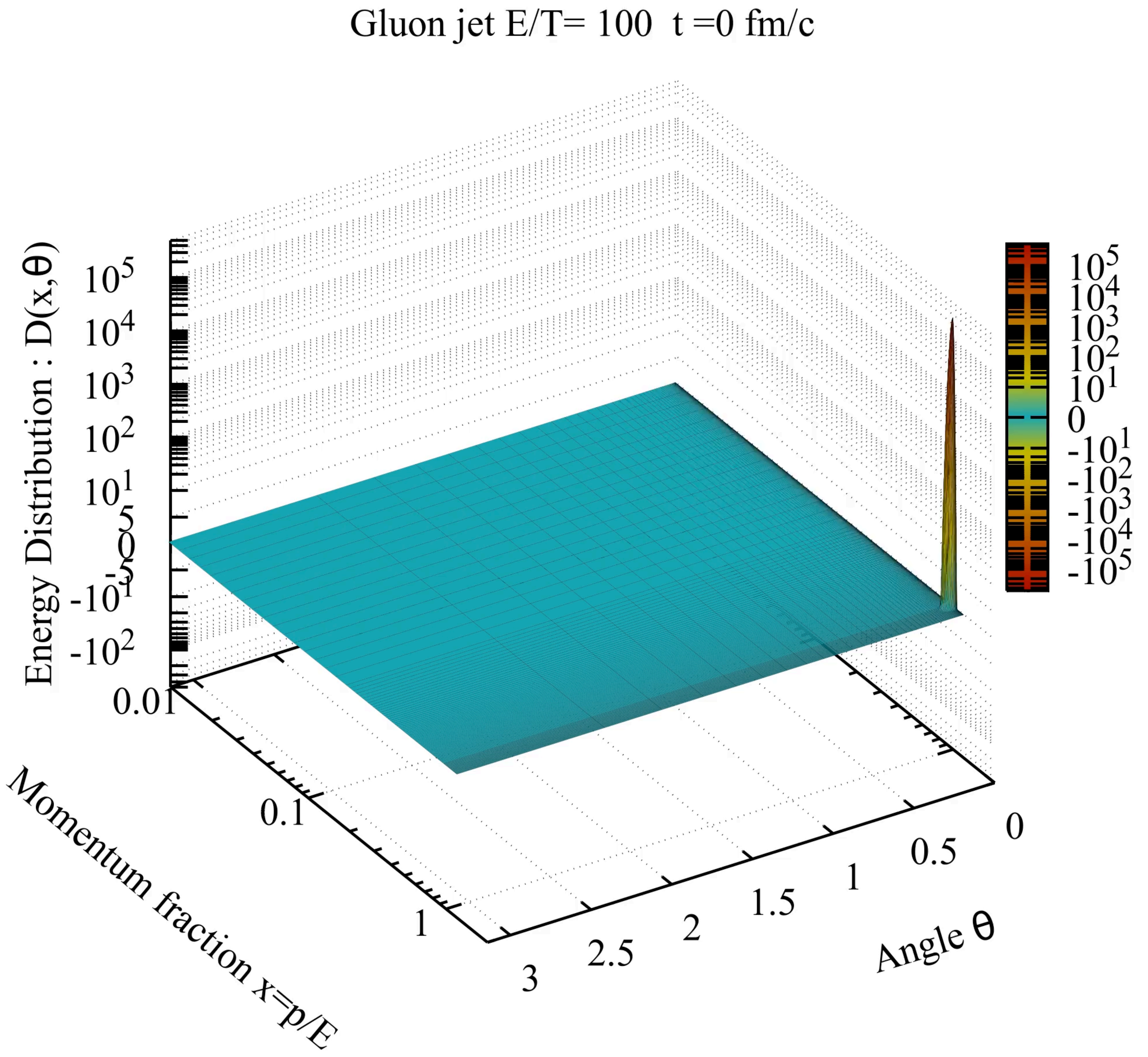

- The jet has lost most energy by the time near equilibrium physics sets in

  —> Not relevant for jet physics.

# Angular Cascade

Jet energy $E_j = 100T$ and $g = 2$.

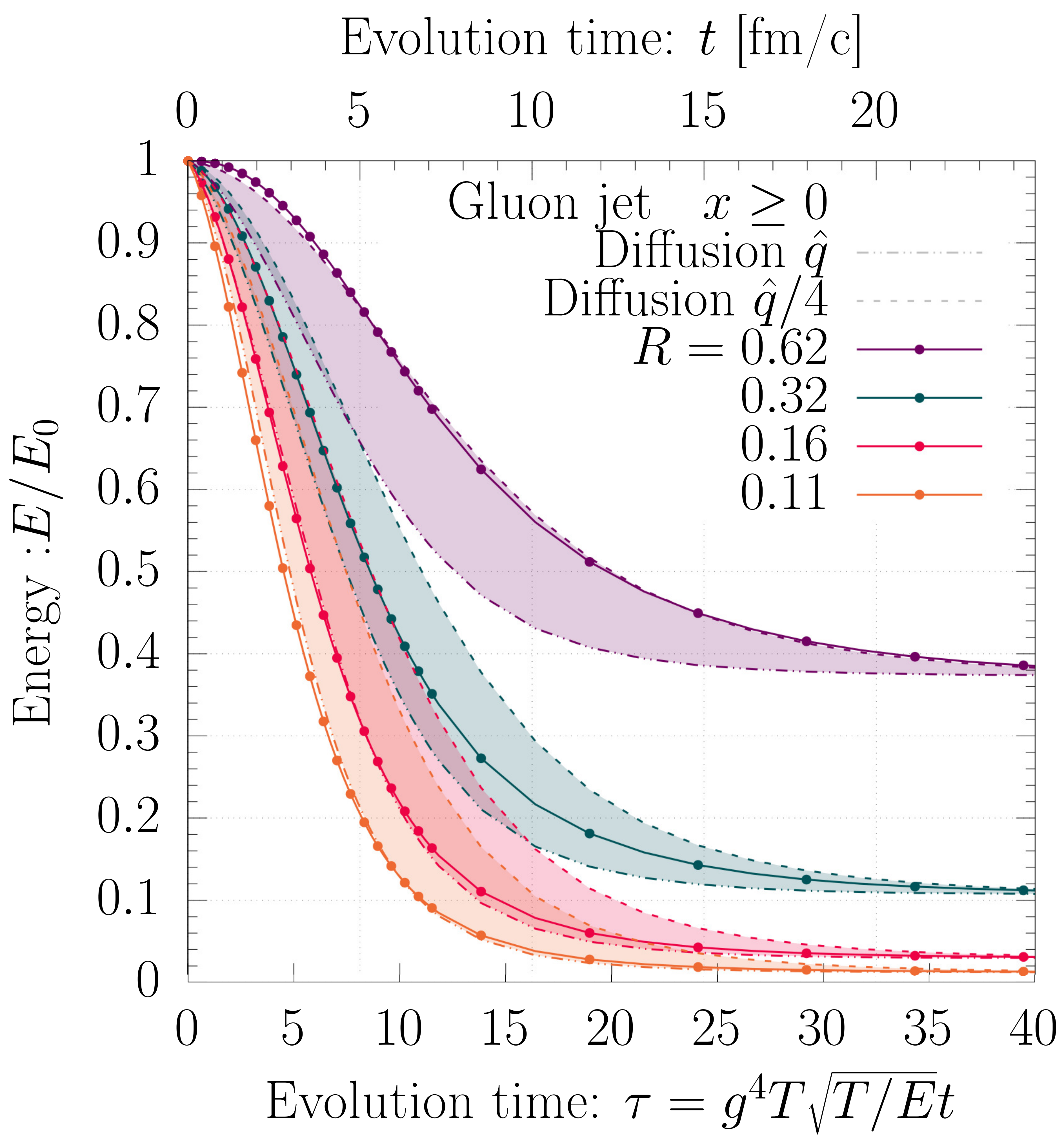


# Comparison With Small Angle Approx

$$E(R,\tau) = \int dx \int_{\cos R}^{1} D(x, \cos\theta, \tau) \ .$$

- Small angle approx can reproduce the broadening at different scales
- A scale independent broadening coefficient cannot simultaneously describe both the broadening at large momentum fraction and the equilibration in the soft scale.
- $\hat{q}$ must be scale dependent



# Quenching Factors

[R. Baier et al. In: JHEP 09 (2001), p. 033.]

**Leading Parton Quenching**

- The spectrum is computed using a convolution with particle distribution

$$\frac{d^2\sigma_{AA}}{dp_T^2}(p_T) = \int_0^\infty d^2p_T^{in} \int_0^1 \frac{dx}{x} \int_{-1}^1 d\cos\theta \; \delta^2(p_T - xp_T^{in}) \; D\left(x, \theta, \tau \equiv g^4 T \sqrt{T/p_T^{in} t}\right) \frac{d^2\sigma_0}{d^2p_T^{in}}(p_T^{in}) \, ,$$

$$Q^{\mathrm{h}}_{AA}(p_T) = \frac{\frac{d^2\sigma_{AA}}{dp_T^2}}{\frac{d^2\sigma_0}{dp_T^2}} = \int_0^1 dx \int_{-1}^1 d\cos\theta \; D\left(x, \theta, \sqrt{x\hat{q}/p_T t}\right) \left(\frac{1}{x}\right)^{2-n} \, .$$

**Jet Quenching**

- The convolution is computed using the energy remaining inside the cone