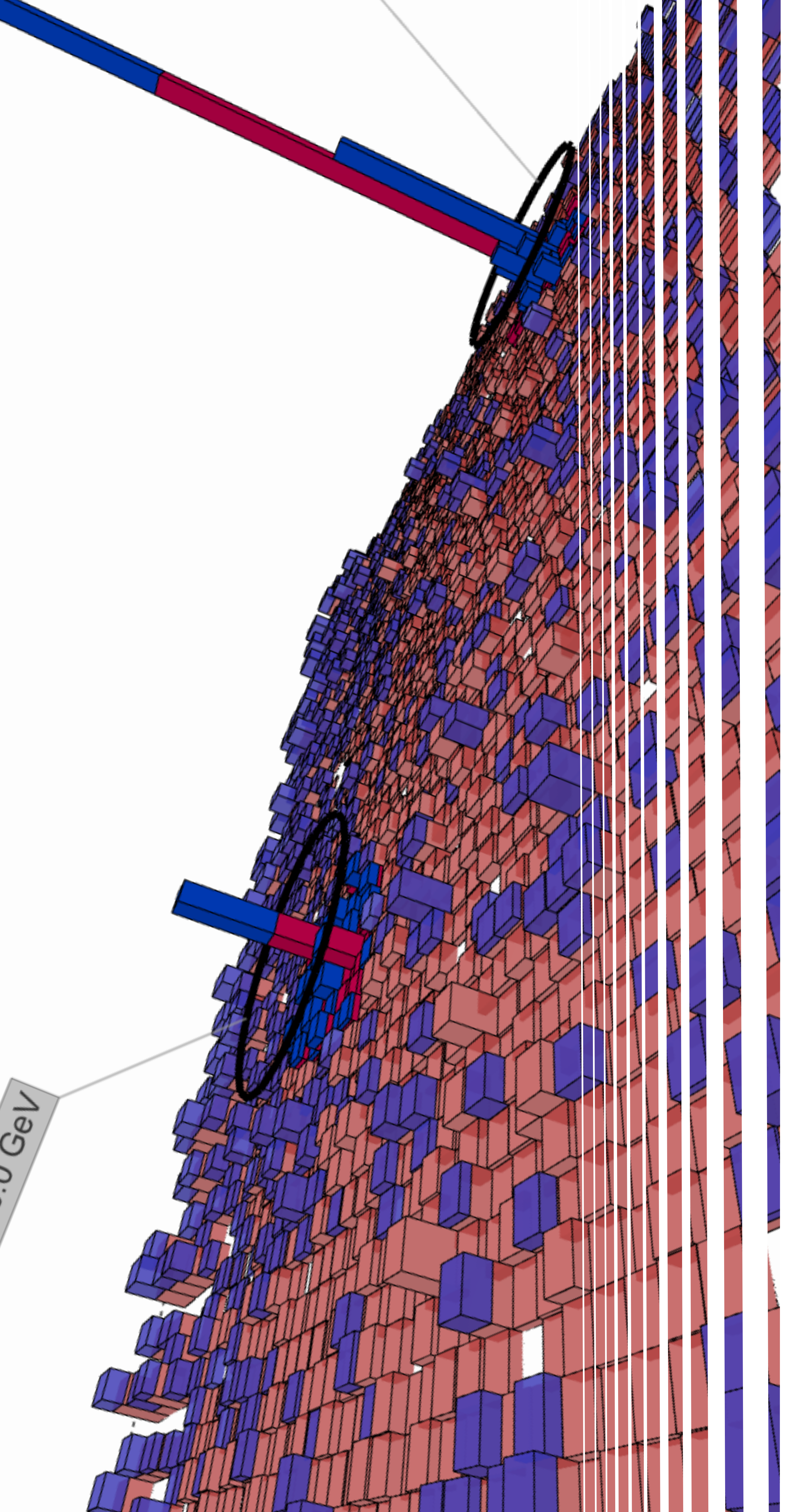

ADVANCES IN JET THERMALIZATION USING QCD KINETIC THEORY

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In collaboration with Ismail Soudi and Soeren Schlichting

CRC-TR 211
Strong-interaction matter under extreme conditions

Bundesministerium für Bildung und Forschung

Based on
Schlichting and Soudi,,
Phys.Rev.D 105 (2022) 7, 7
Mehtar-Tani, Soudi, Schlichting 2209.10569
GM, Schlichting, Soudi, *work in progress*

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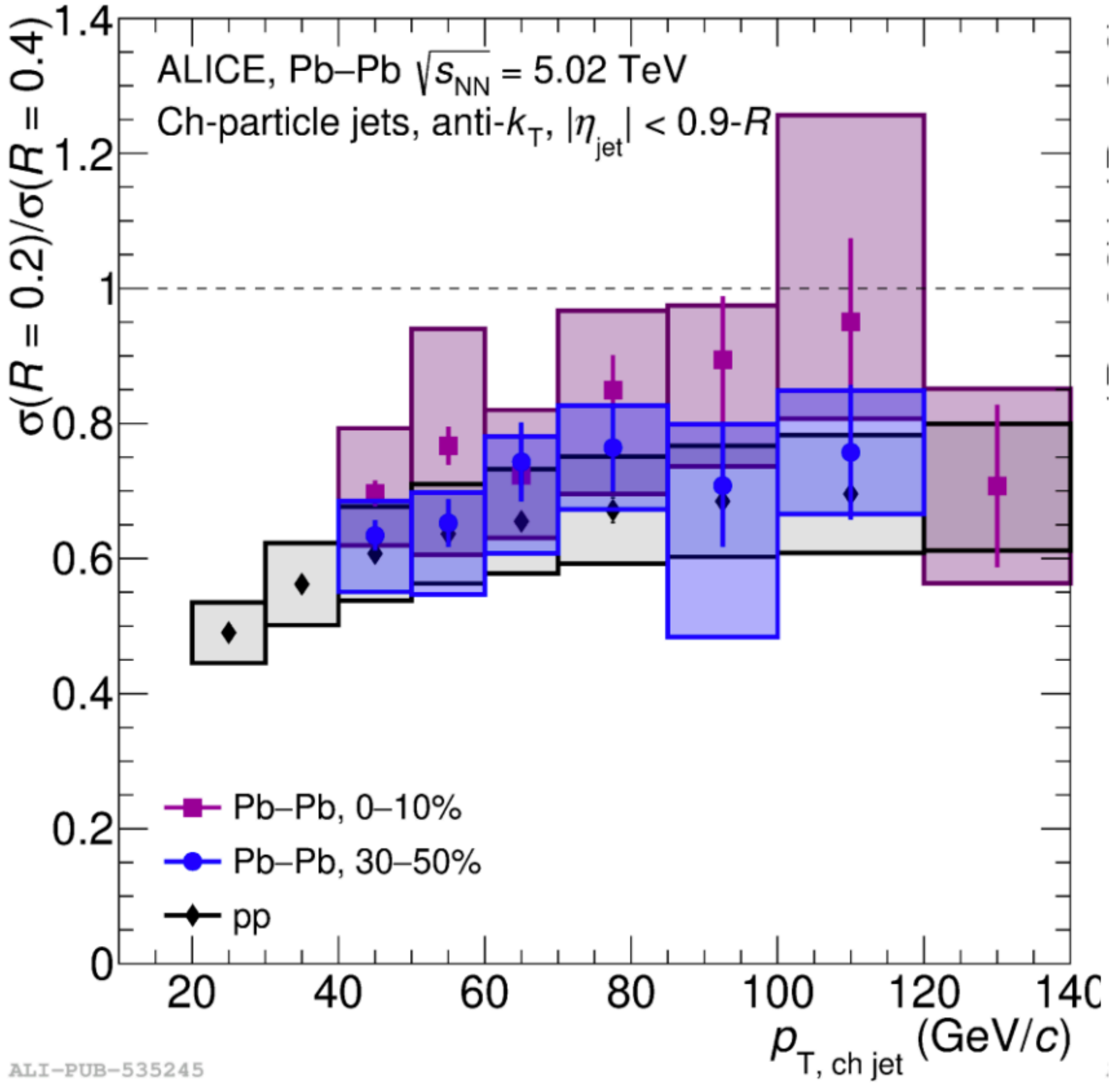
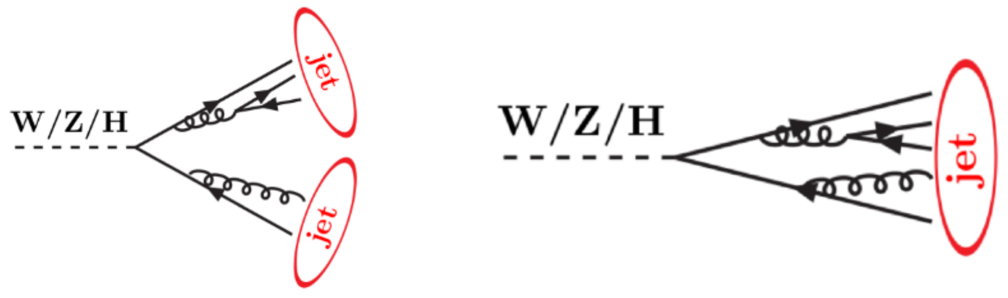
MOTIVATION

- Energy loss and thermalization of jets may be one of the only ways to explore QCD thermalization in experiment
  - Equilibration of soft large angle fragments in HE jets + complete disappearance of LE jets
- Need for a clear understanding of a diverse array of mechanisms
  - degradation of energy — medium response
  - out-of-cone energy loss — hard parton/jets thermalization
- Soft physics typically enters in available jet-energy loss models via a few parameters ($\hat{q}, p_{min}$)
  - **Final Goal:** Develop QCD kinetic theory based Jet Monte-Carlo

ALICE, arXiv: 2303.00592



Angular + soft structure will be instrumental handles in the phenomenology,



Cuts change behavior, 1-prong vs n-prong, etc.

THE METHOD: EFFECTIVE KINETIC THEORY (EKT)

- Challenge: Description of jet thermalization requires theoretical description which is valid at scales $E \sim E_{jet}$ (hard fragments) down to scales $E \sim T_{med}$ (soft fragments & thermal medium)

  Kinetic description: in-medium evolution jet fragments as collection of on-shell partons in QCD EKT. Evolution is given by

$$\left(\partial_t + \frac{\boldsymbol{p}}{|\boldsymbol{p}|} \cdot \nabla_x\right) f_a(\boldsymbol{p}, \mathbf{x}, t) = -C_a^{2\leftrightarrow 2}[\{f_i\}] - C_a^{1\leftrightarrow 2}[\{f_i\}]$$

  - Here, the *jet* is a linearized perturbation on top of (static) equilibrium background $\Rightarrow$ $\left(\partial_t + \frac{|\boldsymbol{p}|}{\boldsymbol{p}} \cdot \nabla_x\right) \delta f = C[T; \delta f]$

- Rephrase the evolution thinking about the energy distribution $D(t, x, \theta) = x \frac{dN}{dx d\cos(\theta)}$

Effective calculation of the Green's function for a perturbation (hard Parton) in a medium

(c.f. Arnold,Moore,Yaffe (LO); Ghiglieri,Moore,Teaney (NLO))

THE METHOD: EFFECTIVE KINETIC THEORY (EKT)

- Elastic interactions provide momentum broadening outside of the jet cone.

- Elastic scattering processes treated with leading order Hard Thermal Loops (HTL) screened matrix elements

$$C_a^{2\leftrightarrow 2}[\{f_i\}] = \frac{1}{2|p_1|\nu_a} \sum_{bcd} \int d\Omega^{2\leftrightarrow 2} \left|\mathcal{M}^{ab}_{cd}(\boldsymbol{p}_1, \boldsymbol{p}_2; \boldsymbol{p}_3, \boldsymbol{p}_4)\right|^2 \delta\mathcal{F}(\boldsymbol{p}_1, \boldsymbol{p}_2; \boldsymbol{p}_3, \boldsymbol{p}_4)$$

  - Including quantum statistics (Fermi suppression/Bose enhancement)effects,

$$\delta\mathcal{F}(\boldsymbol{p}_1, \boldsymbol{p}_2, \boldsymbol{p}_3, \boldsymbol{p}_4) \supset \delta f_a(\boldsymbol{p}_1)\left[\pm_a n_c(p_3) n_d(p_4) - n_b(p_2)(1 \pm n_c(p_3) \pm n_d(p_4))\right]$$

- Detailed balance allows for exact **conservation of *energy*, momentum and valence charge** of the jet allows to study evolution from $E \sim E_{jet}$ to $E \sim T_{med}$ including thermalization of the jet

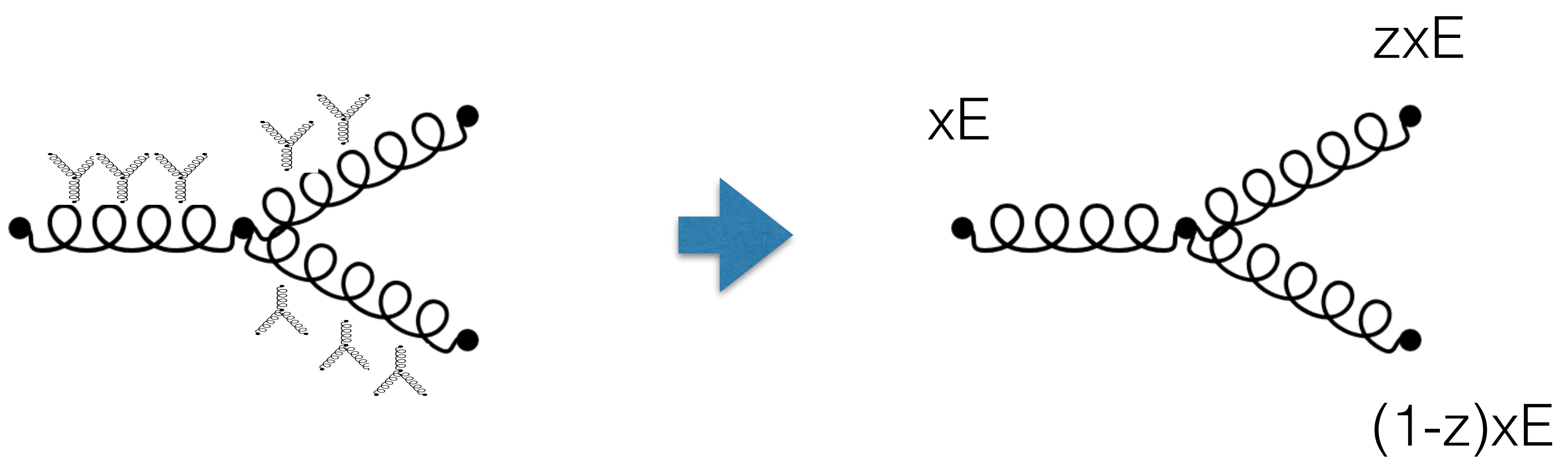
THE METHOD: EFFECTIVE KINETIC THEORY (EKT)

- Inelastic interactions are responsible for the radiative break-up of hard partons

- Numerical studies re-construction of in-medium rates in the AMY framework (incl. LPM & Bethe-Heitler regime) for an infinite medium

$$C_g^{g\leftrightarrow gg}[\{D_i\}] = \int_0^1 dz \frac{d\Gamma^g_{gg}\left(\left(\frac{xE}{z}\right), z\right)}{dz}\left[D_g\left(\frac{x}{z}\right)\left(1+n_B(xE)+n_B\left(\frac{\bar{z}xE}{z}\right)\right)+\frac{D_g(x)}{z^3}\left(n_B\left(\frac{xE}{z}\right)-n_B\left(\frac{\bar{z}xE}{z}\right)\right)+\frac{D_g\left(\frac{\bar{z}xE}{z}\right)}{\bar{z}^3}\left(n_B\left(\frac{xE}{z}\right)-n_B(xE)\right)\right]$$
$$-\frac{1}{2}\int_0^1 dz \frac{d\Gamma^g_{gg}(xE, z)}{dz}\left[D_g(x)(1+n_B(zxE)+n_B(\bar{z}xE))+\frac{D_g(zx)}{z^3}(n_B(xE)-n_B(\bar{z}xE))+\frac{D_g(\bar{z}x)}{\bar{z}^3}(n_B(xE)-n_B(zxE))\right],$$

- Quantum statistics (Fermi suppression/Bose enhancement)effects are important at the temperature scale



EKT: PROS AND CONS

- ⊕ QCD kinetic theory framework provides a robust and unified treatment of jet and medium response
  - Same setup as in studies of thermalization of QGP at early times
- ~ Infinite medium rates higher than more realistic finite medium rates
  - Too much quenching.
- ~ Time evolution of the underlying medium is costly .
- ⊖ Vacuum-like effects not included, as they effectively enter initial condition/source terms for kinetic equation
  - Phenomenological extension (e.g jet-by-jet fluctuations) as this is not a Monte-Carlo simulation

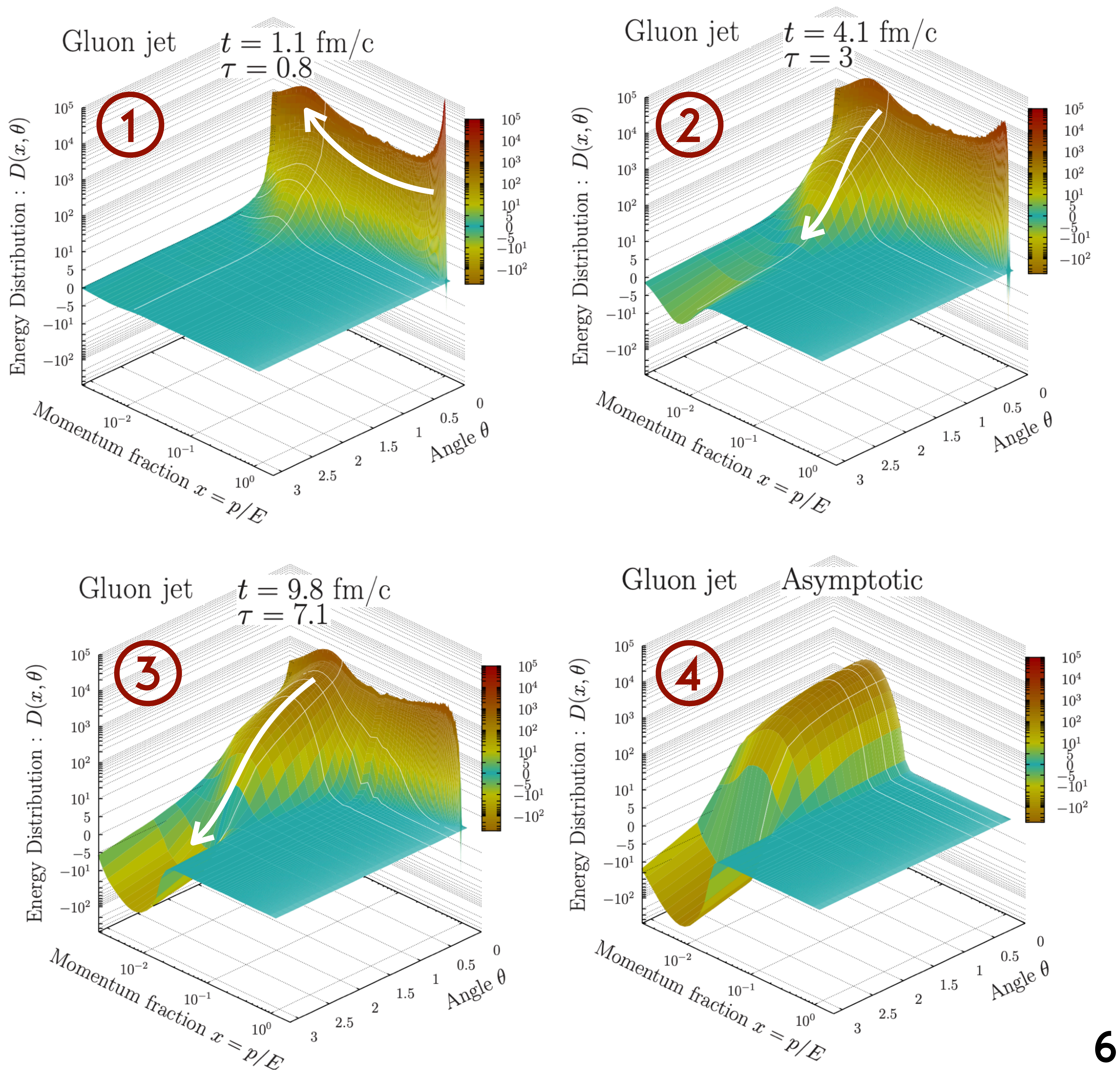
EVOLUTION OF THE JET

1 **Collinear energy cascade** towards the soft sector confined to narrow cone θ<0.3

Radiative break-up of the parton is the main contribution

2 + 3 **Angular cascade:**
Soft fragments $x \sim T/E$ spread out to large angles (θ~1) via elastic interactions

4 Jet thermalizes in a parametrically long time, when all hard partons have decayed

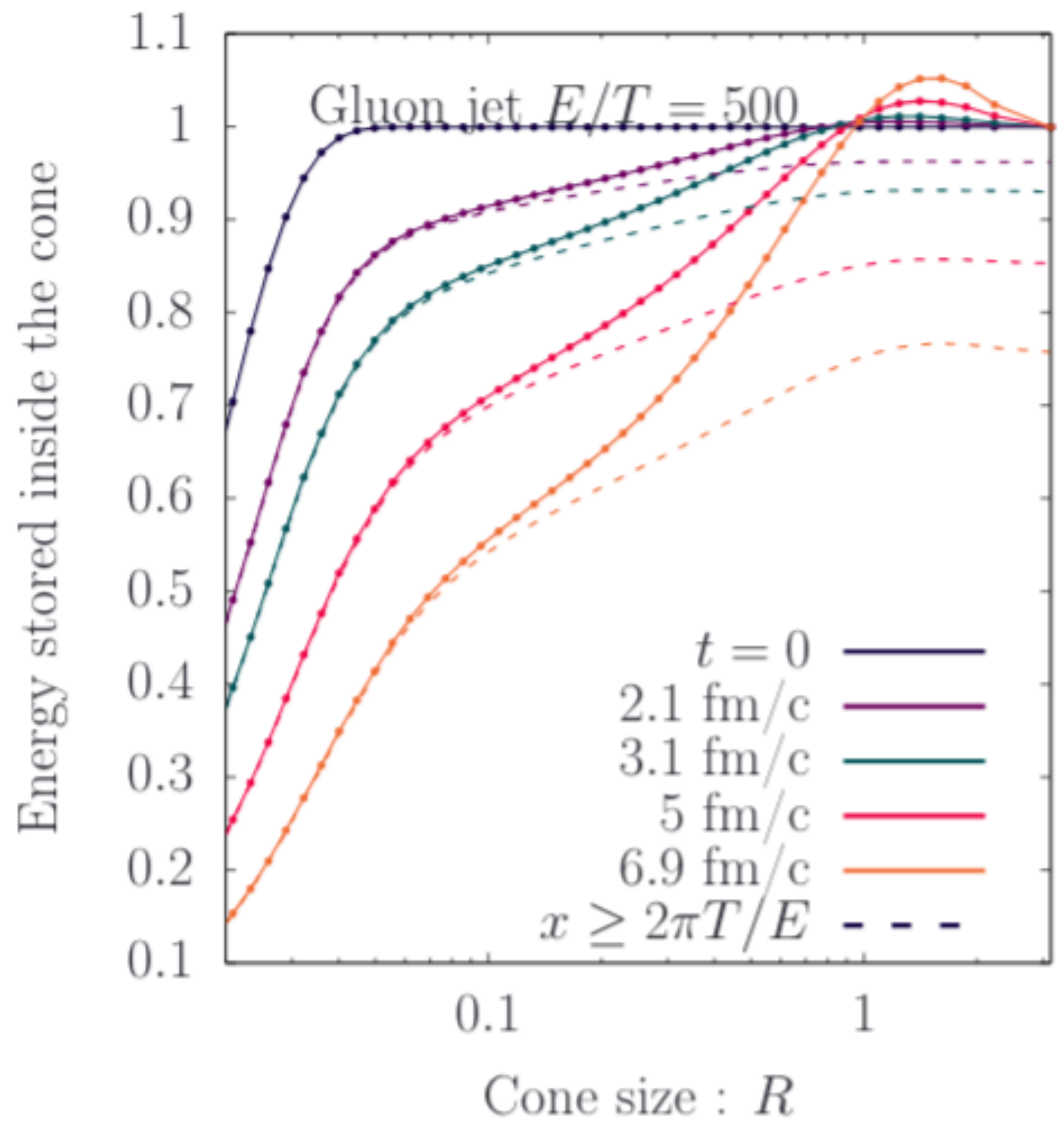


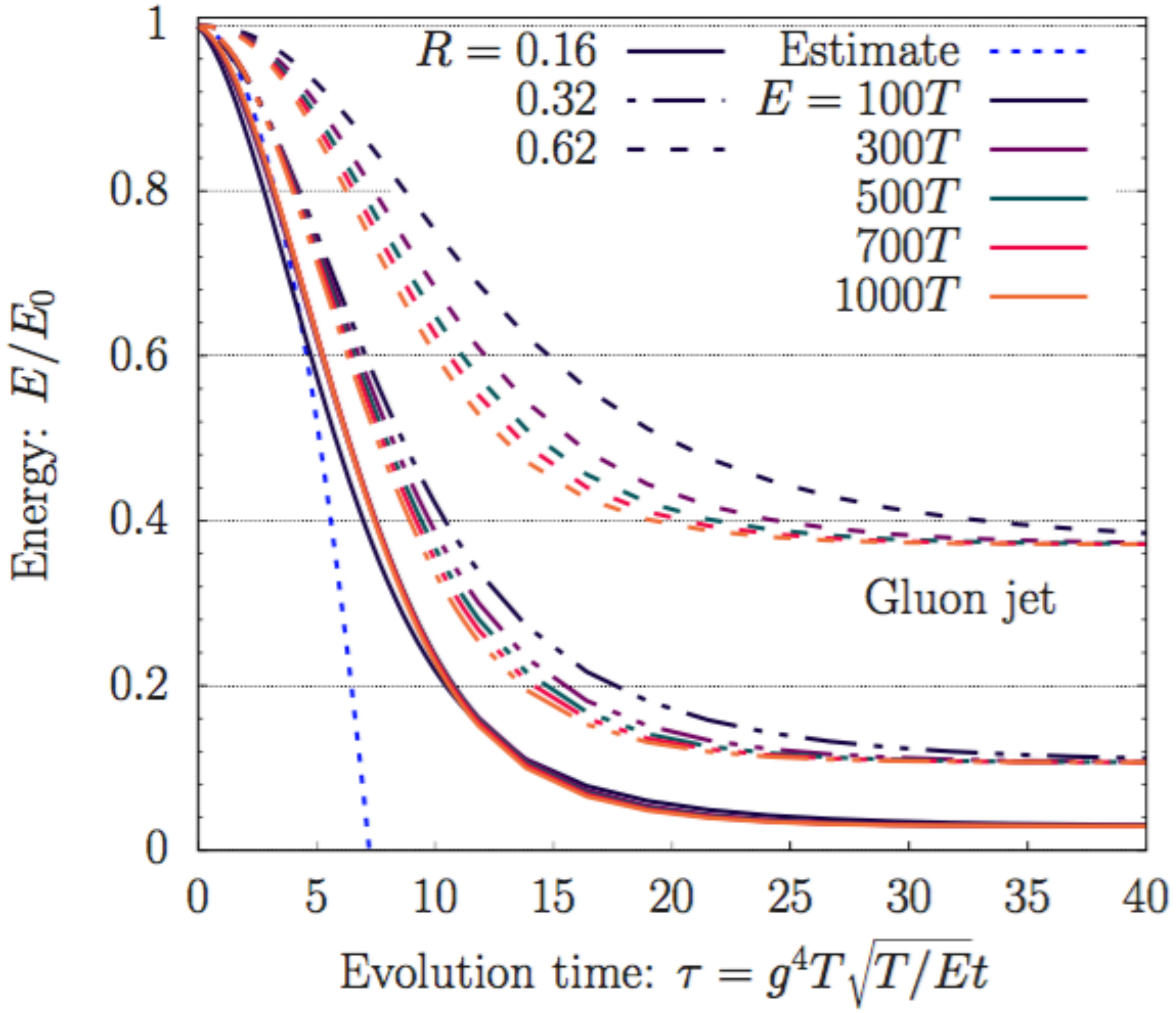
ENERGY-LOSS OUT OF CONE

- The energy inside a cone is given by

$$E(R,\tau) = E\sum_a \int \mathrm{d}x \int_{\cos R}^{1} \mathrm{dcos}\,\theta\; D_{a/\mathrm{jet}}(x,\theta,\tau)$$

- Out-of-cone energy loss for narrow cones ($R \sim 0.3$) governed by radiative break-up of hard fragments + rapid broadening of soft fragments

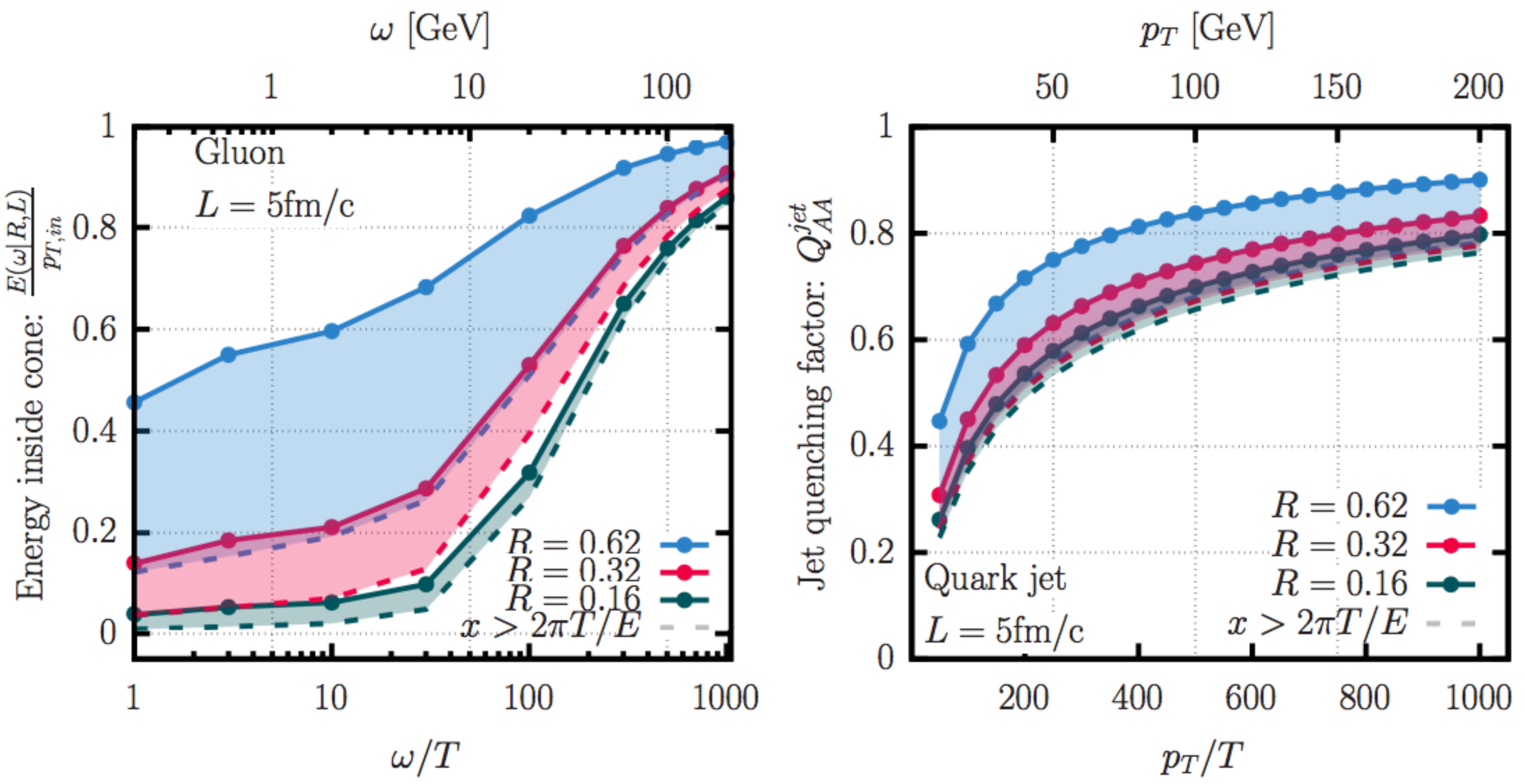




Energy (E/T) dependence governed by radiative emission rates of the primary hard parton; confirming energy loss picture

SOME EARLY PHENO: JET QUENCHING

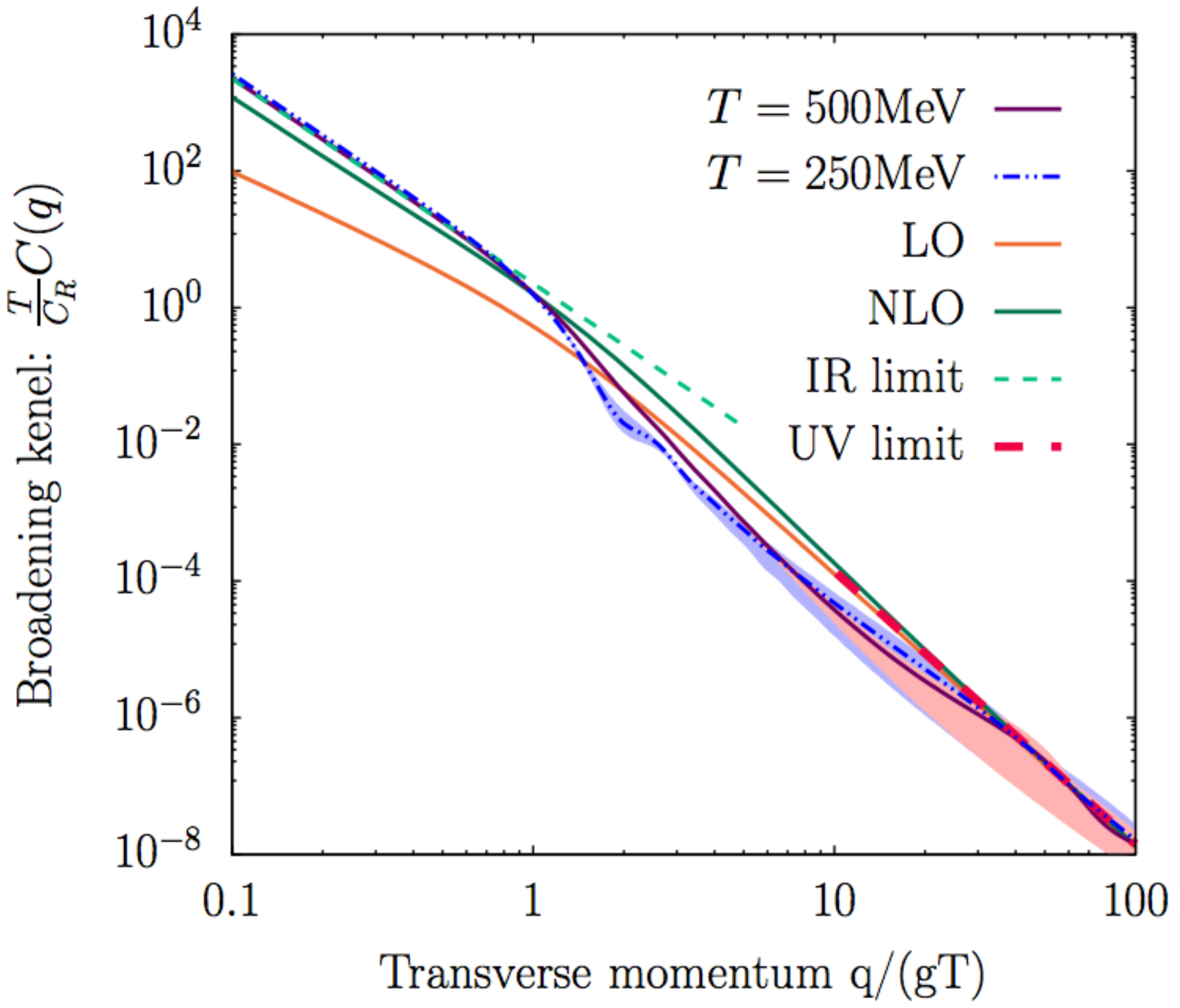
- Jet quenching of leading parton gives a remarkable sensitivity to cone size!

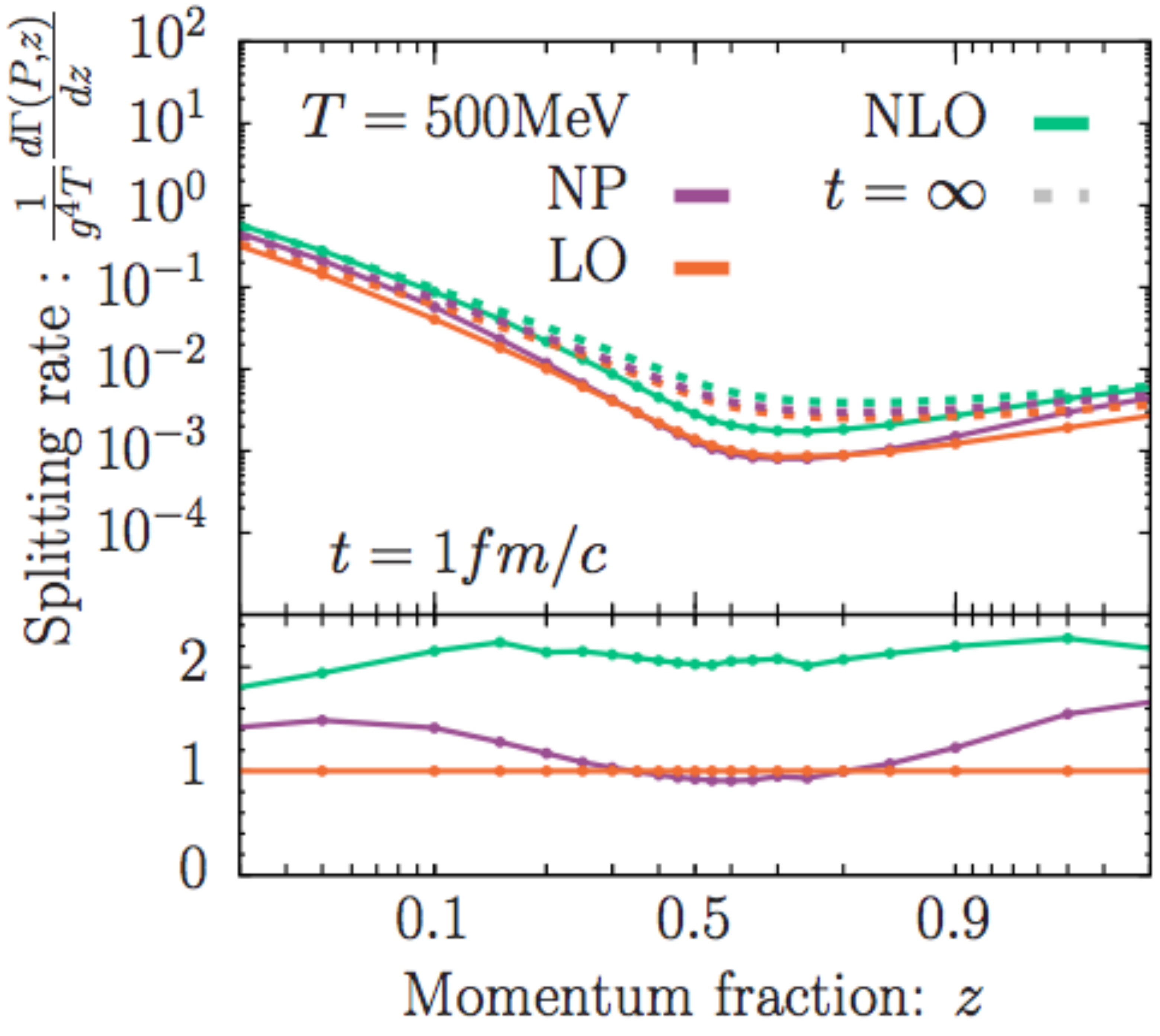


- Small sensitivity for R<0.3; can trust perturbative calculations of jet quenching
- Increased sensitivity to soft sector for R>0.3; this is where to search for medium response

IMPROVED IN-MEDIUM SPLITTING RATES

- Determination of the finite L in-medium splitting rates for non-perturbatively determined collisional broadening kernel $C(q_\perp)$
  - strong enhancement of small $q_\perp$ processes
- Significant effect of $C(q_\perp)$ on in-medium splitting rates, not clear that medium induced radiation is properly described in terms of one phenomenological quenching parameter $\hat{q}$

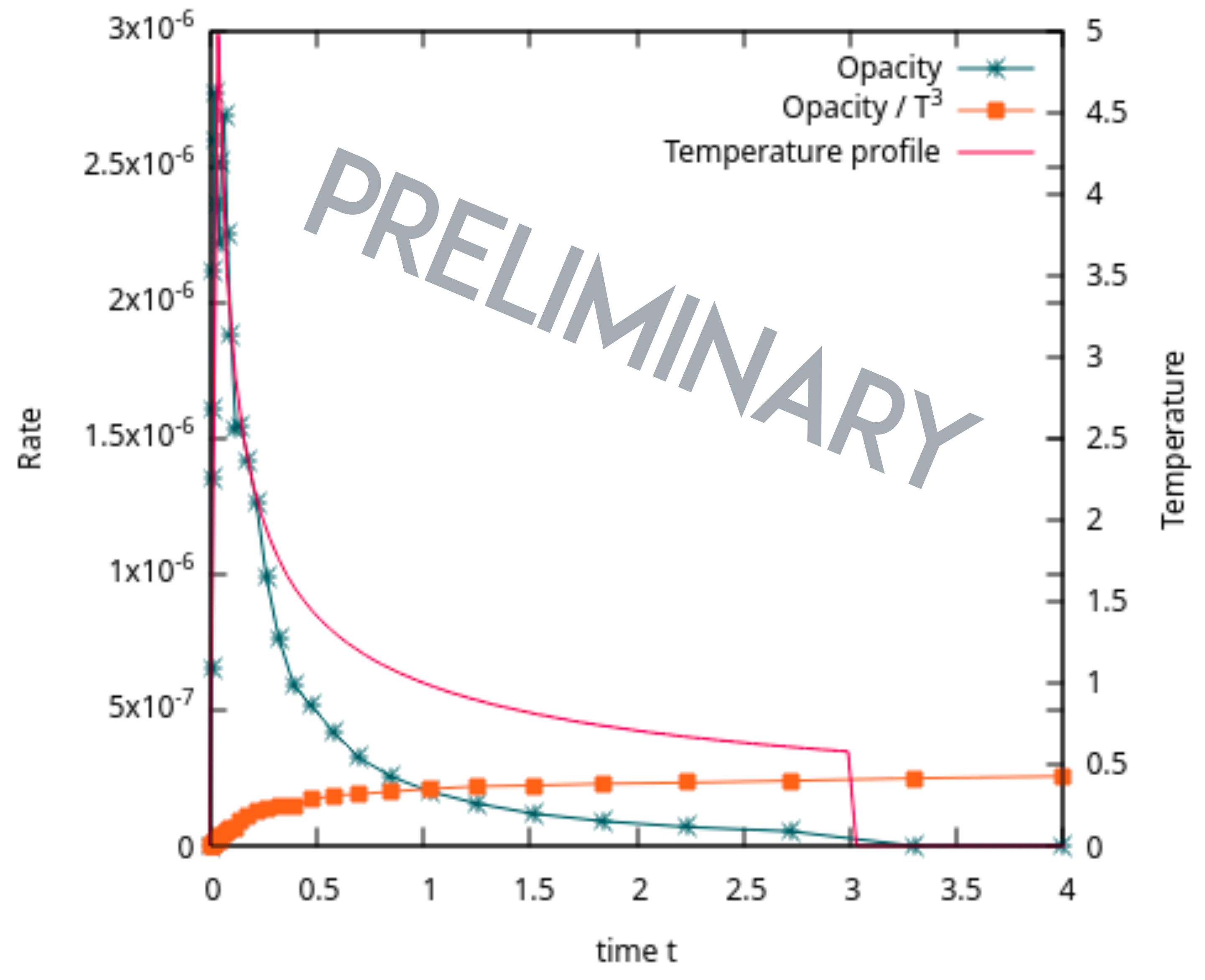




WHAT'S COMING UP?

INELASTIC

Following up on the improvement on the inelastic rates to finite size → Inclusion of medium temperature variability.



ELASTIC

By using a set of a complete set of interpolators, the problem is mapped to a linear algebra problem

$$\partial_t \delta f = C[T, \delta f] \quad \Rightarrow \quad \partial_t |\delta f\rangle = \hat{C}[T] |\delta f\rangle \quad \Rightarrow \quad |\delta f(t_{i+1})\rangle = \exp\left[\int_{t_i}^{t_{i+1}} dt\, \hat{C}[T(t)]\right] |\delta f(t_i)\rangle$$

Now, the problem is easy to solve, but $\hat{C}$ is expensive. Treat it as a change of basis.

$$|\delta f(t_{i+1})\rangle = L[T(t)] \exp\left[\int_{t_i}^{t_{i+1}} dt\, T(t)\, \hat{C}[T=1]\right] M[T(t)] |\delta f(t_i)\rangle$$

Goal: The formulation of a fast code which will allow evaluation of this evolution ***en-masse* in a jet-MC**.

WHAT'S COMING UP?

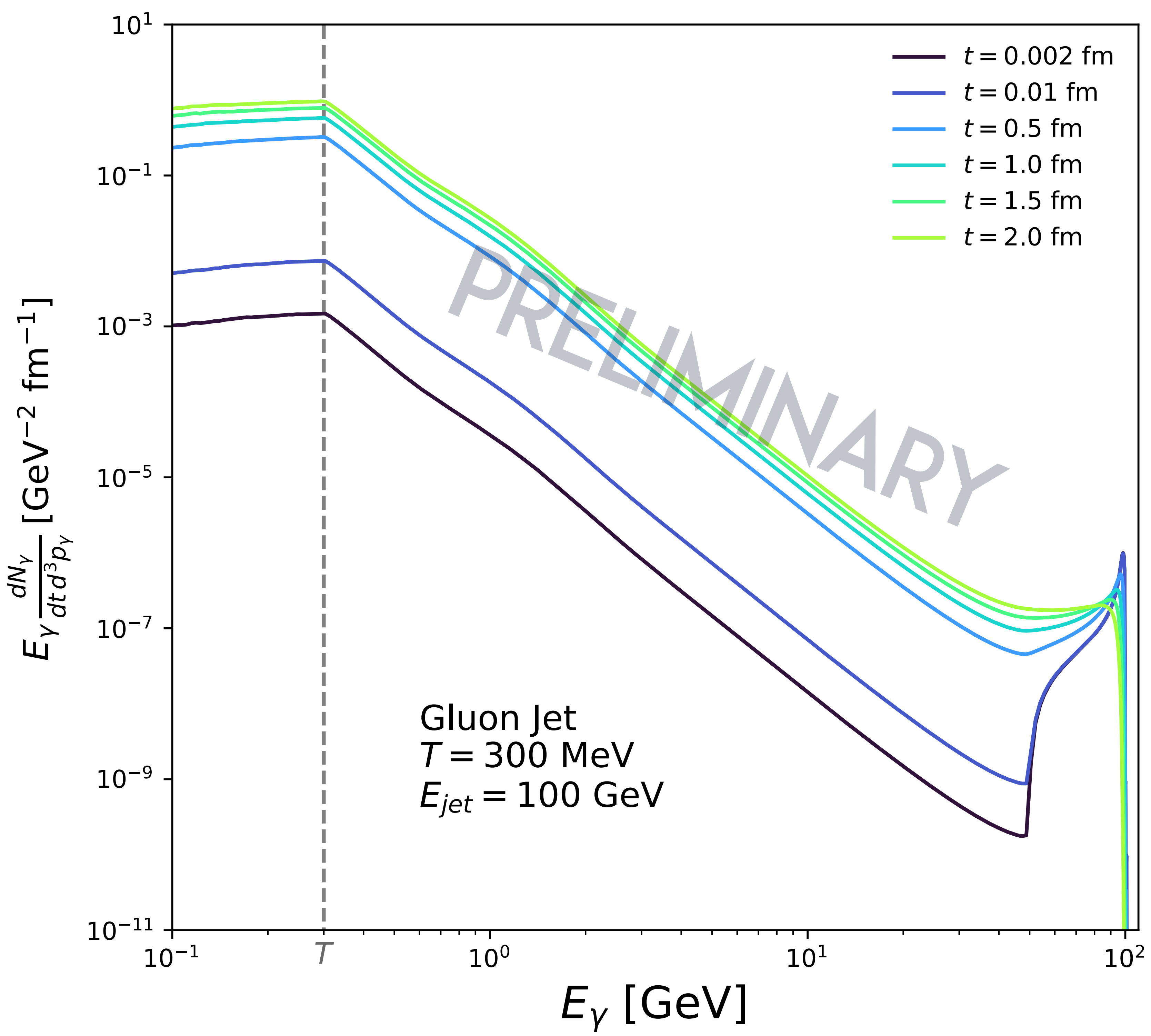
JET-PHOTONS

- Explore electro-magnetic probes induced by jets as additional possibility to study thermalization of soft fragments
- Electro-magnetic radiation sensitive to current fluctuations

$$\Gamma(Q) \sim \int_{x-y} \langle J^{\mu}(x) J^{\nu}(y) \rangle e^{iQ(x-y)}$$

- Electro-magnetic hard fragments induce rare high-$p_{\perp}$ radiation
- Soft fragments ($\sim T$) induce large current fluctuations that are correlated with the jet

GM, Gebhard, Elfner, Schlichting, *in preparation.*



Sensitive to energy deposition into soft medium but still need to estimate yields/feasibility

SUMMARY AND CONCLUSIONS

Energy loss out of the jet's cone and thermalization of highly energetic partons/jets are governed by a two stage process: 1) **nearly collinear cascade** + 2) **broadening of soft fragments**

Jets with strong suppression may be excellent probes for the thermalization dynamics, due to variation of the observables wrt. the cone-size and energy range $p_{\perp,min}$.

Next steps towards development of full MC Generator for jet quenching & medium response within QCD Kinetic Theory:

Include finite L emission rates

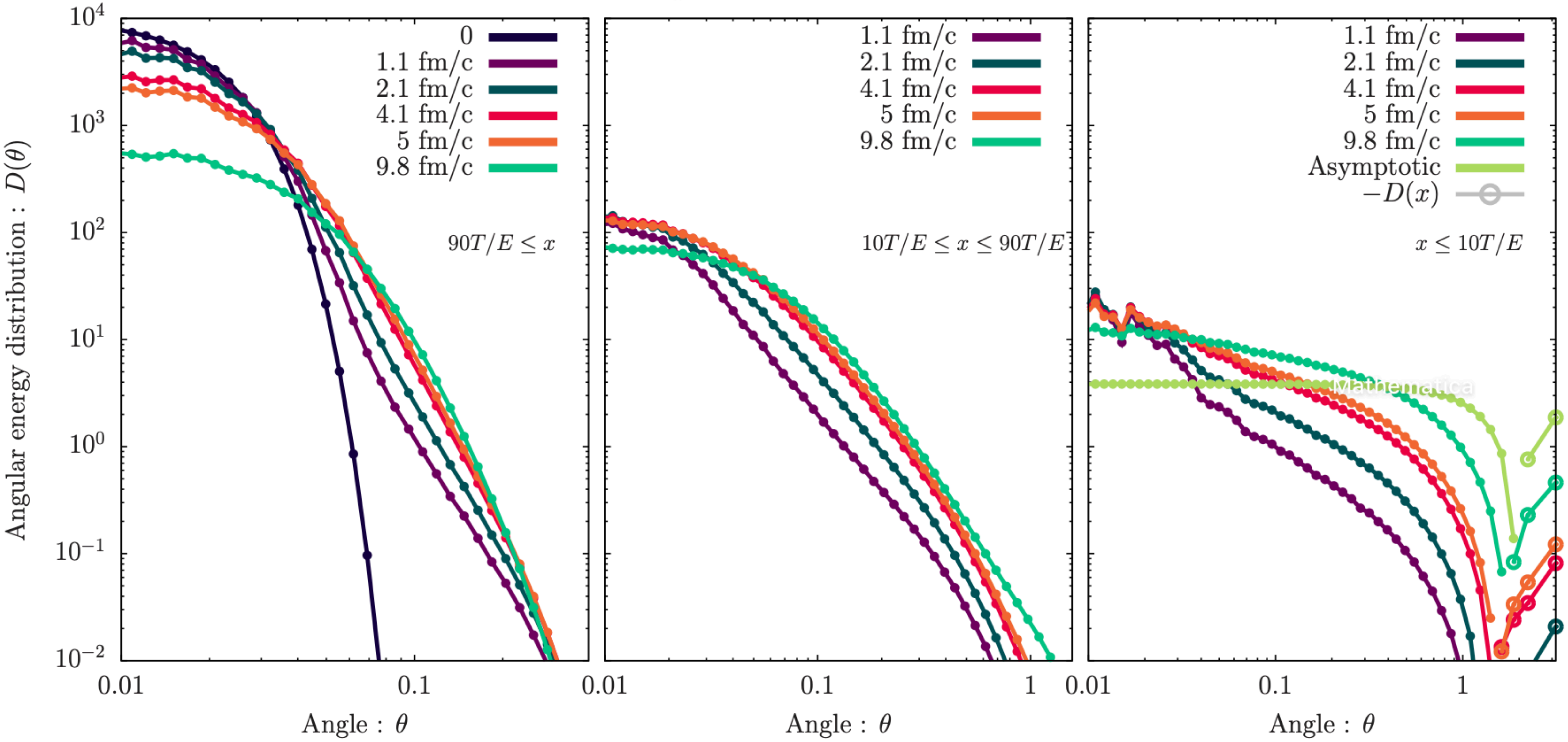
early vacuum like emissions

evolution of realistic medium Background

BACKUP

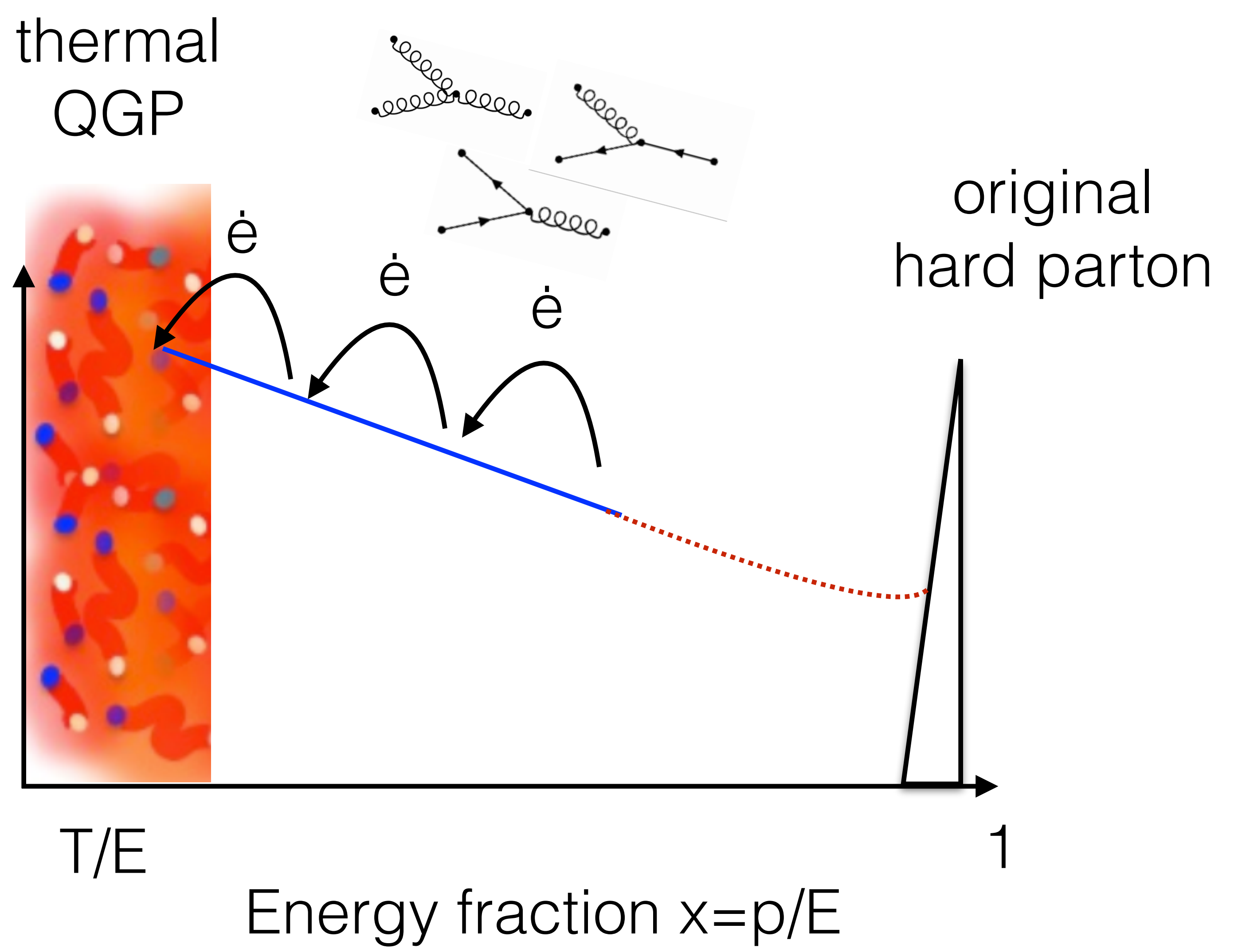
STRUCTURE OF THE ANGULAR CASCADE

$$D(\theta,t)\big|_{x_{\min}}^{x_{\max}} = \sum_a \int_{x_{\min}}^{x_{\max}} \mathrm{d}x \; D_{a/\mathrm{jet}}(x,\theta,t)$$



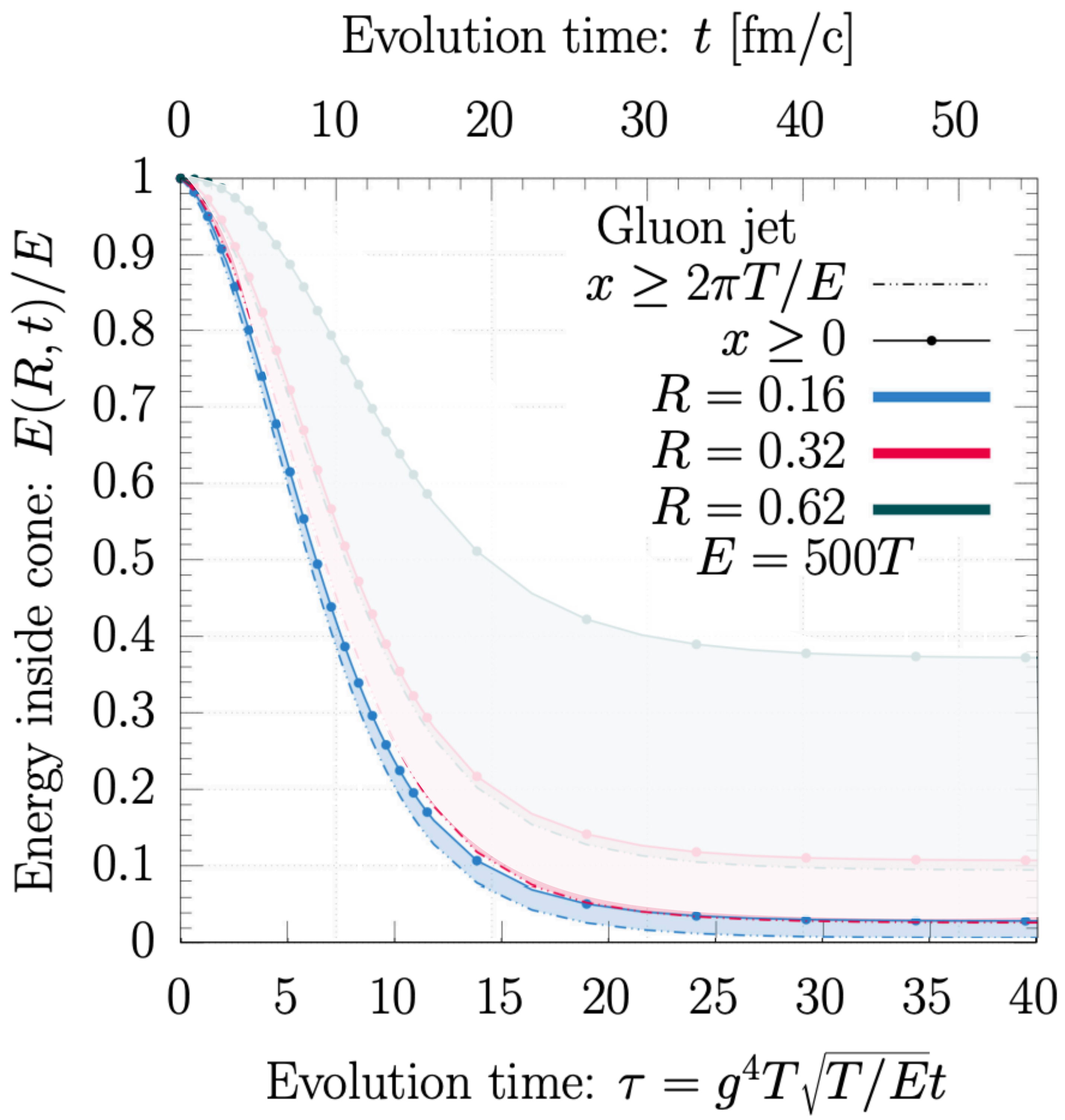
THE ENERGY CASCADE: IN-CONE ENERGY LOSS

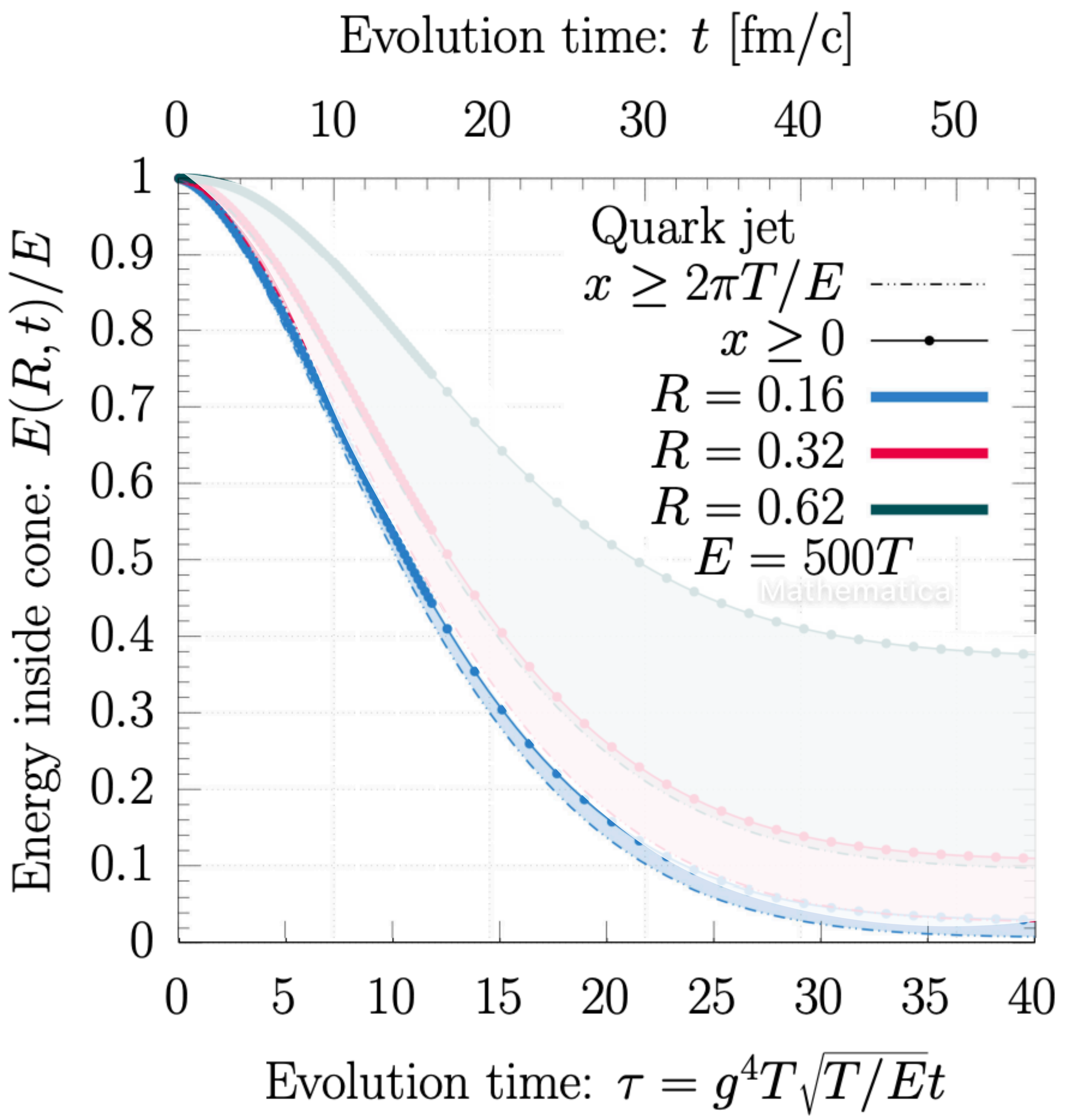
- In-elastic processes dominate at intermediate scales, $T/E \ll x \ll 1$
- In the intermediate scales, transport of energy is done via the quasi-stationary solution of the radiative kernel, namely $D(x) \sim x^{-1/2}$, which is analogous to the Kolmogorov-Zhakarov turbulent spectrum.
- The energy is transported through such a cascade all the way to T/E, where energy is absorbed by the thermal QGP and goes out to large angles



$$\frac{dE}{d\tau} = \gamma^{\text{soft-radiation}} + \gamma^{\text{recoil}} + \left(\tilde{\gamma}_g + \frac{S}{G}\tilde{\gamma}_q\right) G(\tau)$$

(c.f. Baier, Mueller, Schiff,Son; Blaizot,Mehtar-Tani,Iancu)





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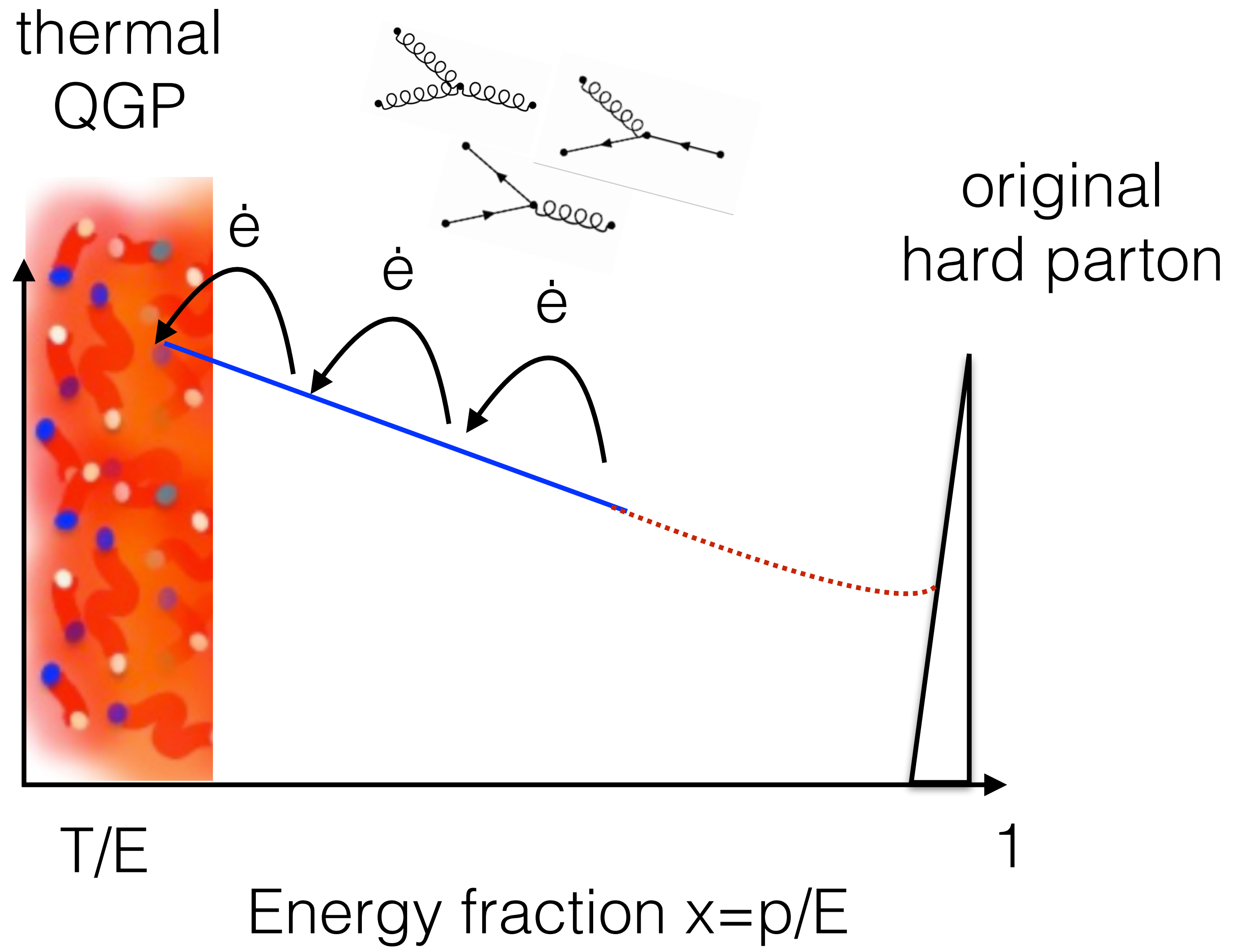

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