Fragmentation and equilibration of jets in a QCD plasma

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June 2, 2020

Based on I.Soudi, S. Schlichting (in preparation)

The 10th edition of the **Hard and Electromagnetic Probes** International Conference

CRC-TR 211
Strong-interaction matter under extreme conditions

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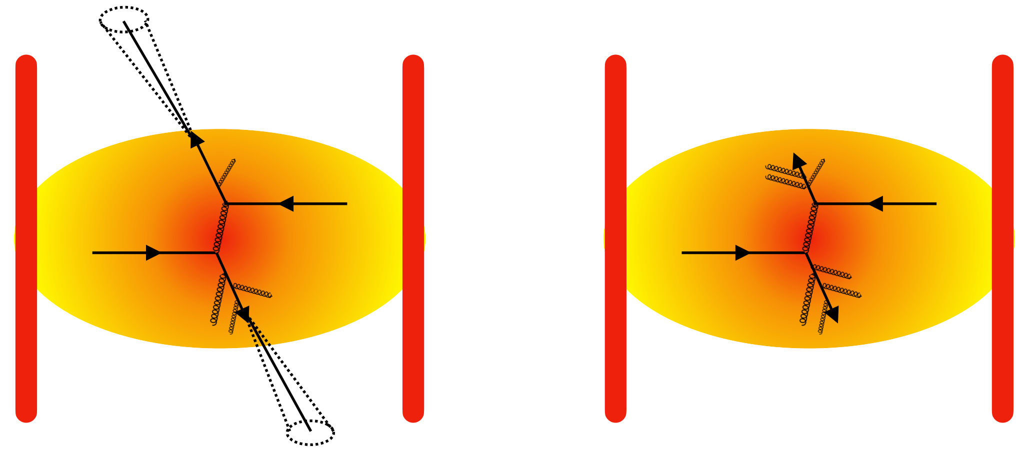
Motivation

- Understand kinetic and chemical equilibration of jets in heavy-Ion collisions

  —> with the possibility of the jet to be lost in the medium



- The processes that equilibrate the QGP are strongly reminiscent of jet-energy quenching.

  —> Maybe we can learn about QGP equilibration by looking at strongly quenched jets?

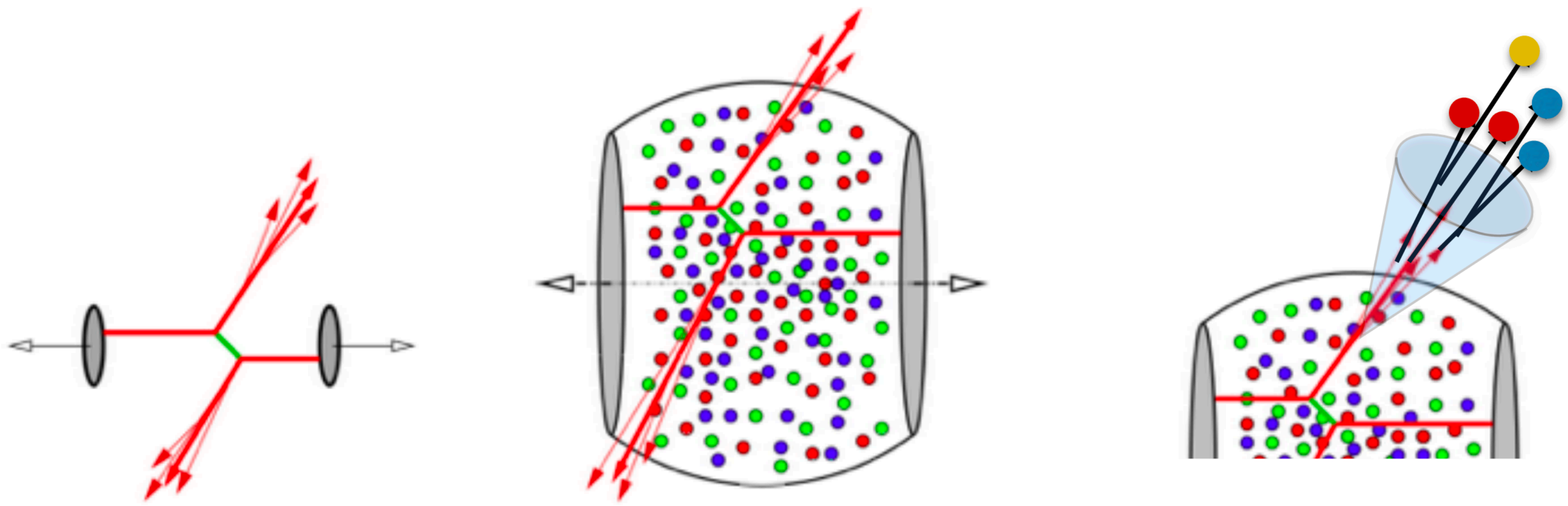
—> Provide guidance for Monte Carlo's/experiments studies.

- Large separation of scales between Hard probes $\sim p \gg T$ and the QGP

  —> Jets can be treated perturbatively.

Introduction

The jet evolution in Heavy-Ion collisions is dominated by at least three different phases:



Initial production

Interaction with medium

Vacuum shower/ Hadronization

We will discuss mainly the interaction with medium and consider the full equilibration of jets in the medium.

Effective Kinetic Theory of QCD

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We start from an effective kinetic theory at leading order:

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

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

We consider jet as linearized fluctuation over static background equilibrium

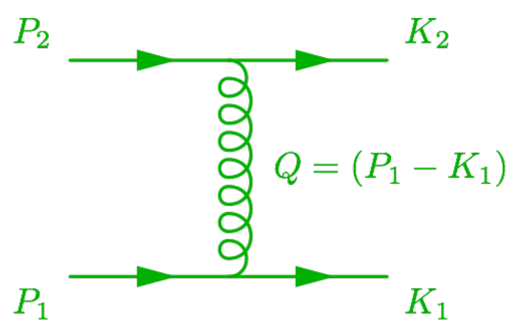
$$f(p,t) = n_{\mathrm{eq}}(p;T) + \delta f_{\mathrm{jet}}(p,t),$$

Define energy distribution (analogue to in-medium fragmentation function):

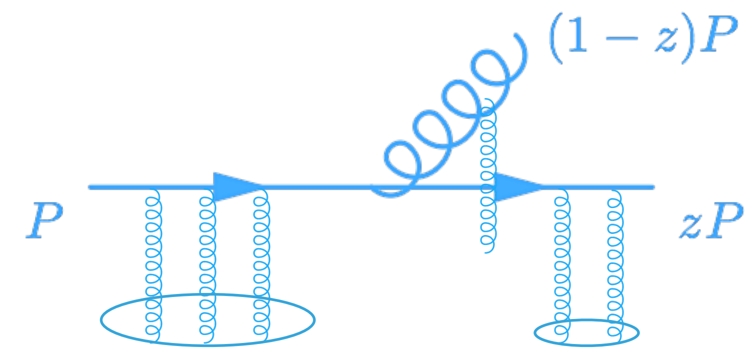
$$D_a(x,t) \equiv x \frac{dN_a}{dx} \sim \frac{\nu_a(N_f)}{E_j} p^3 \delta f(p) \bigg|_{p=xE_j},$$

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

Effective Kinetic Theory of QCD: Processes



$\Gamma \sim \gamma_{\text{eq}} \frac{T^2}{E_j^2}$



$\Gamma \sim \gamma_{\text{eq}} \sqrt{\frac{T}{E_j}}$

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

where $\gamma_{eq} \sim g^4 T$.

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

Small Angle approx.

$$C_a^{\text{small}}[\{f_i\}] = -\nabla_p \mathcal{J}_a + S_a$$

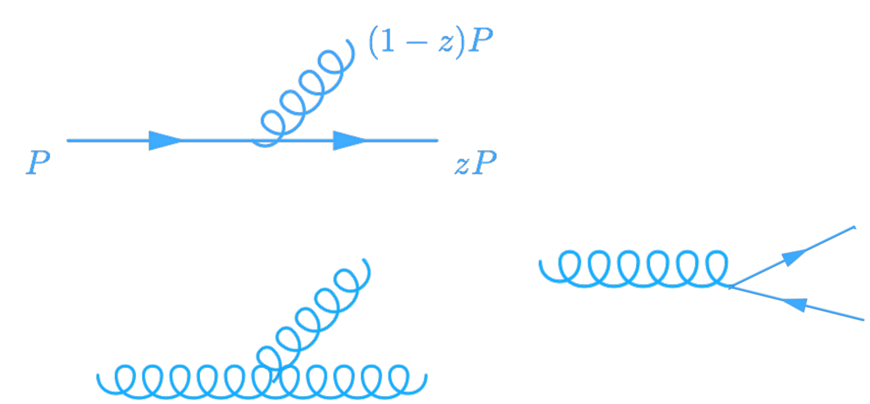
LPM resummed Rate.

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

$$C^{1\leftrightarrow 2}[\{f_i\}]$$

Diffusion $\hat{q}$ and Drag η_D

Conversion

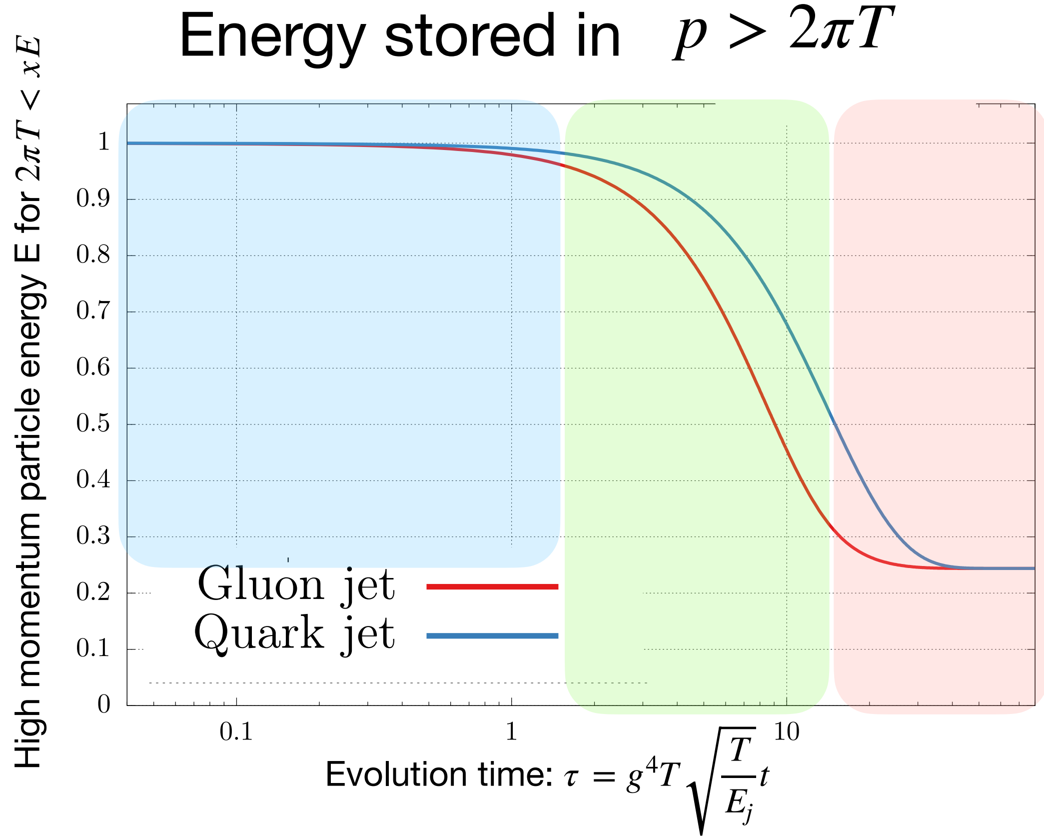


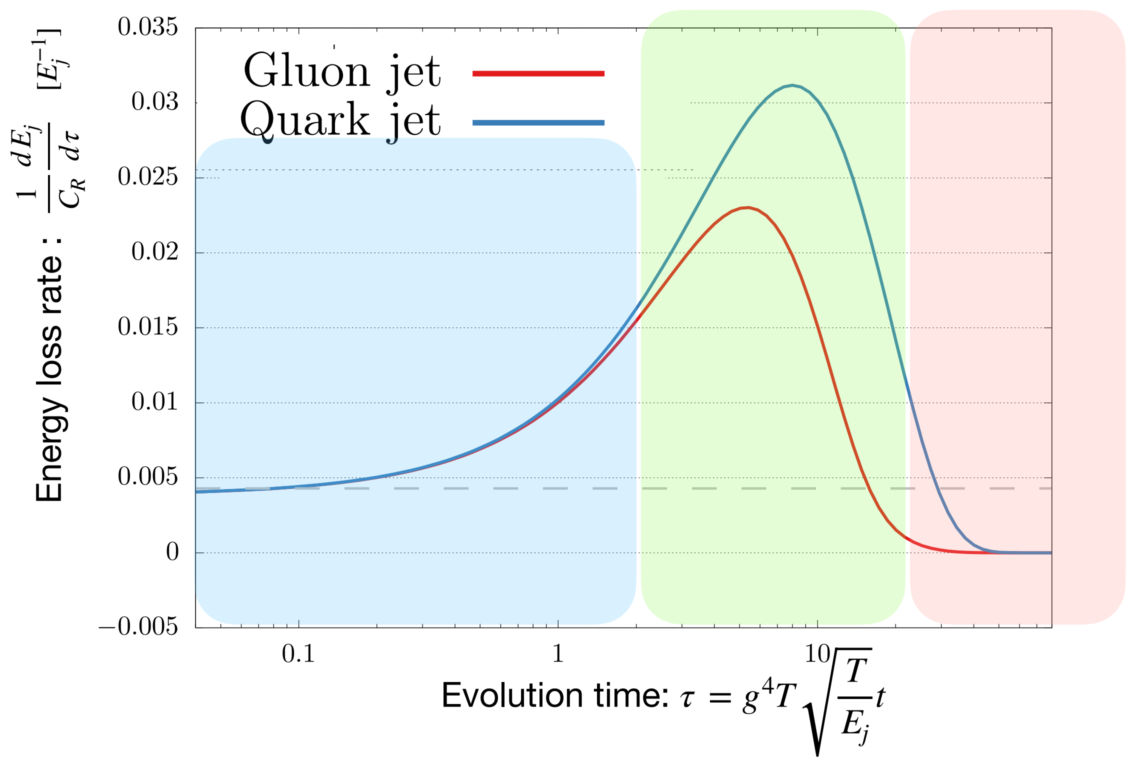
"Recoil"

Results

Evolution of the fragmentation function

For jet energy $E_j = 1000T$ and $g = 1$.





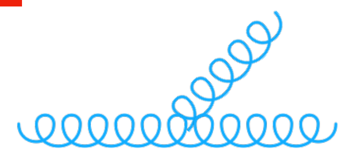
There are three regimes:

- 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.

Early time behavior : Gluon radiation

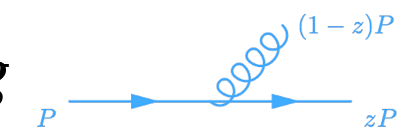
Initial Gluon Jet

Driven by the rate $g \leftrightarrow gg$

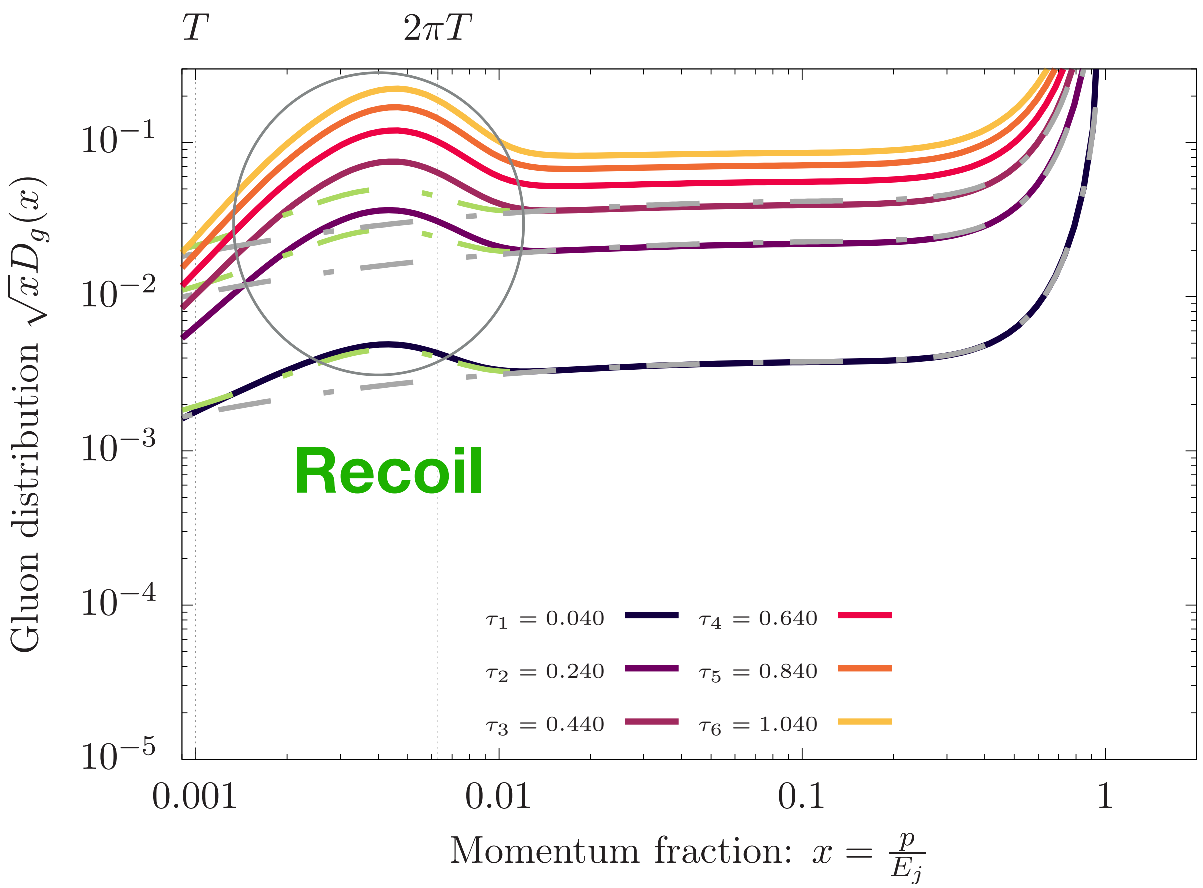


Initial Quark Jet

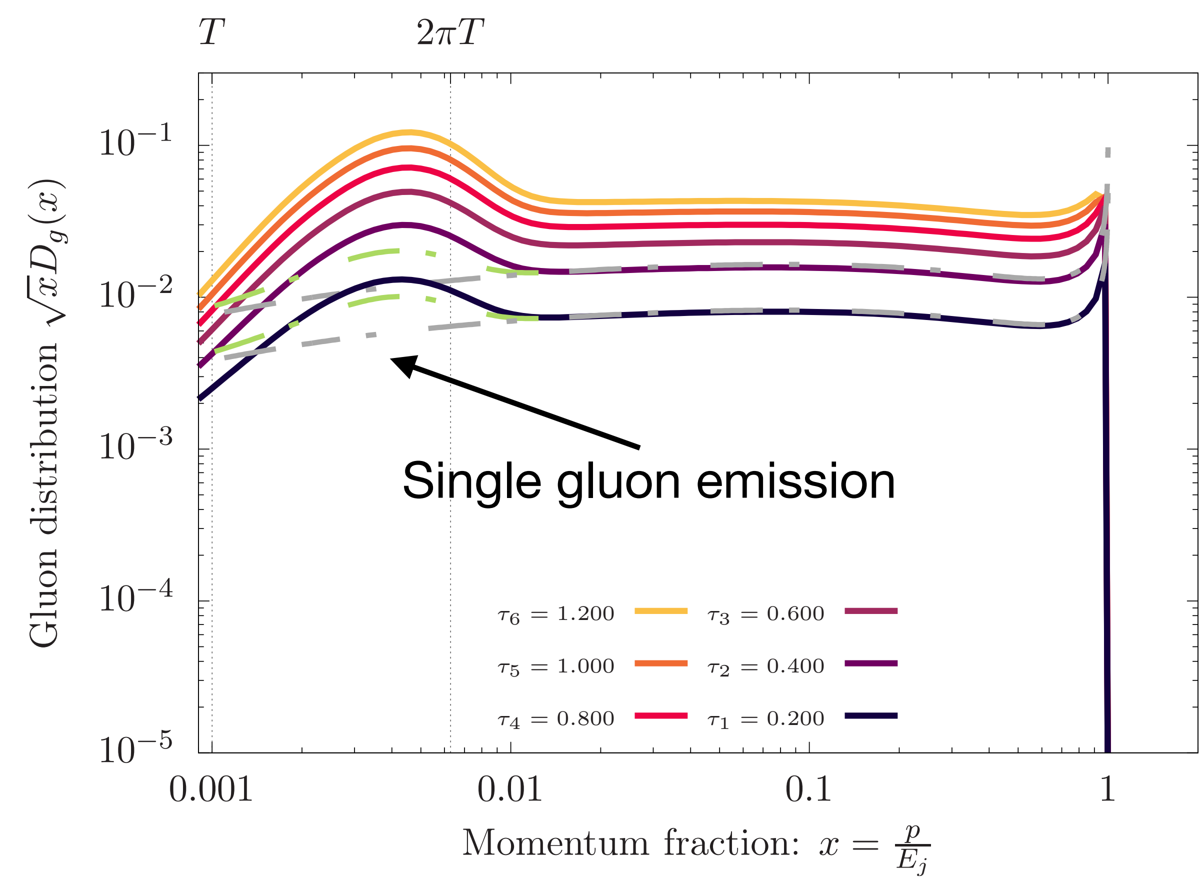
Driven by the rate $q \leftrightarrow qg$



Gluon Energy distribution



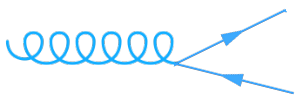
Gluon Energy distribution



Early time behavior : Quark radiation

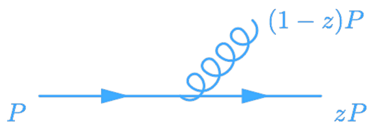
Initial Gluon Jet

Driven by the rate $g \leftrightarrow q\bar{q}$

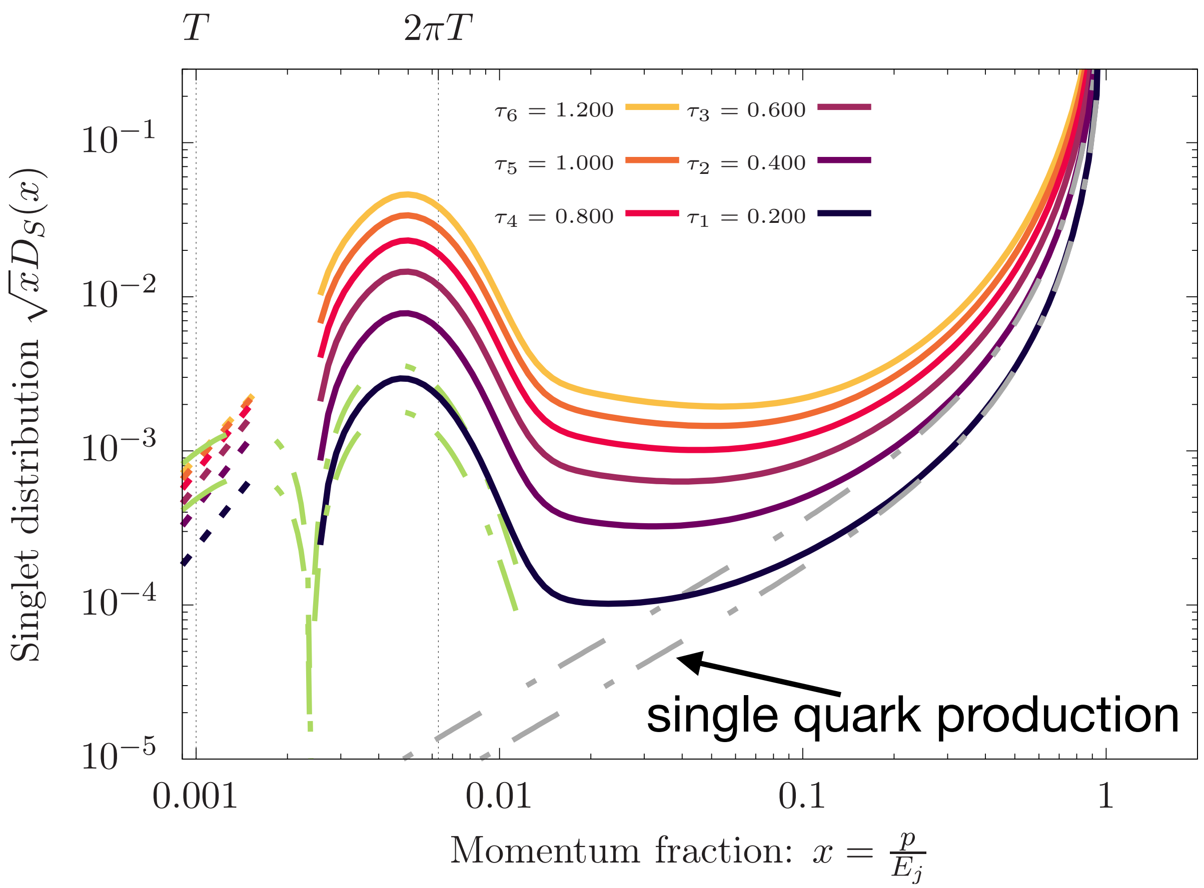


Initial Quark Jet

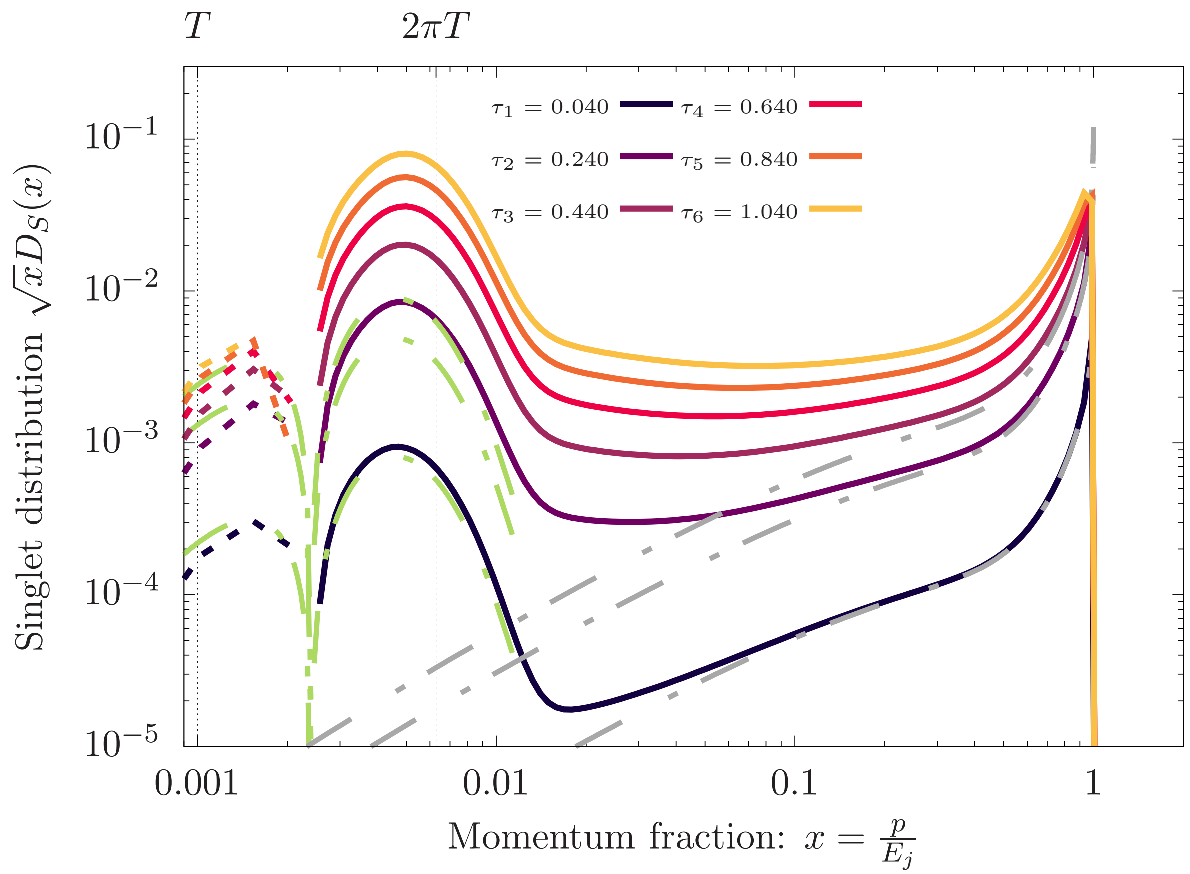
Driven by the rate $q \leftrightarrow qg$



Singlet Energy distribution



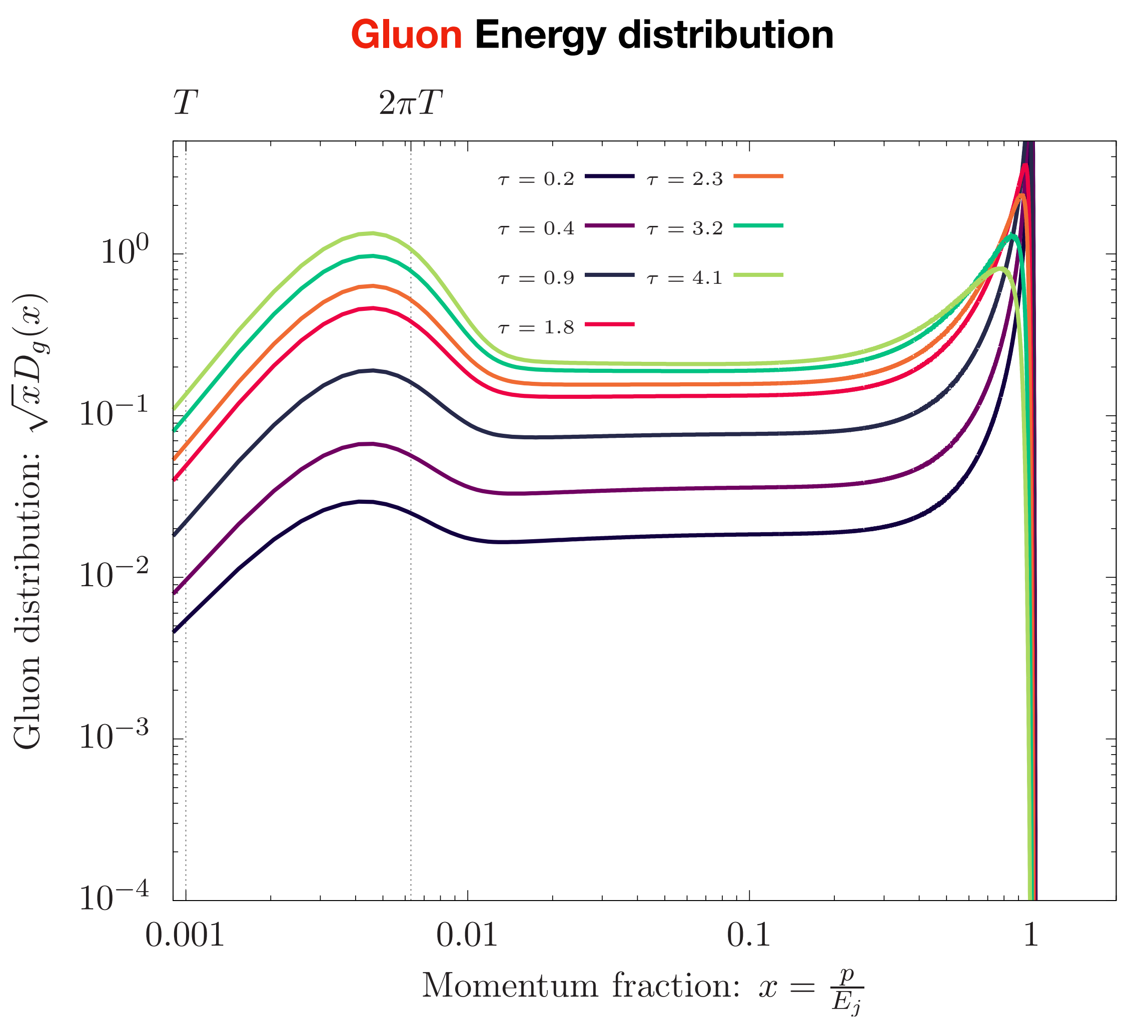
Singlet Energy distribution

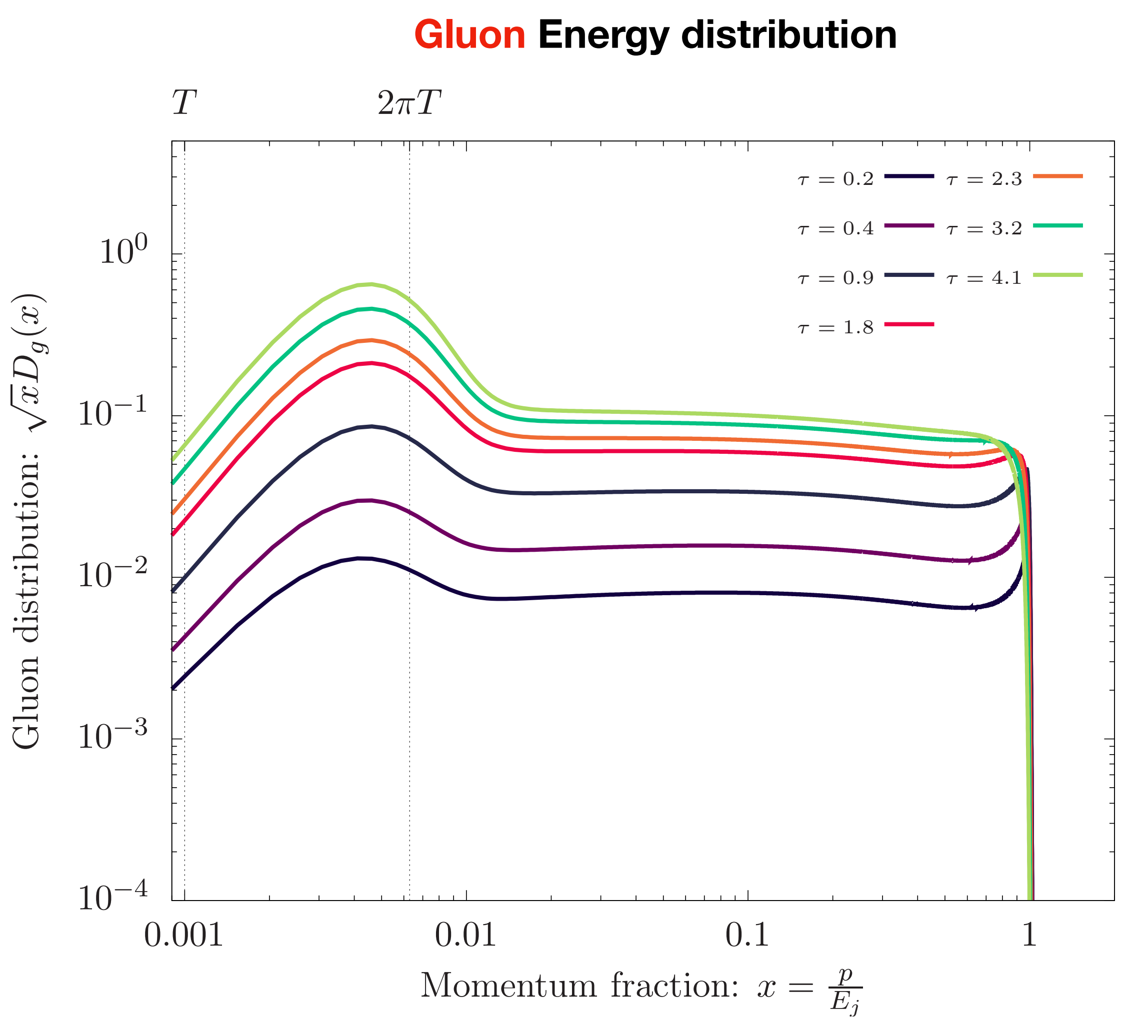


$$\text{Singlet} = \frac{D_q(x) + D_{\bar{q}}(x)}{2}$$

Initial Gluon Jet

Initial Quark Jet



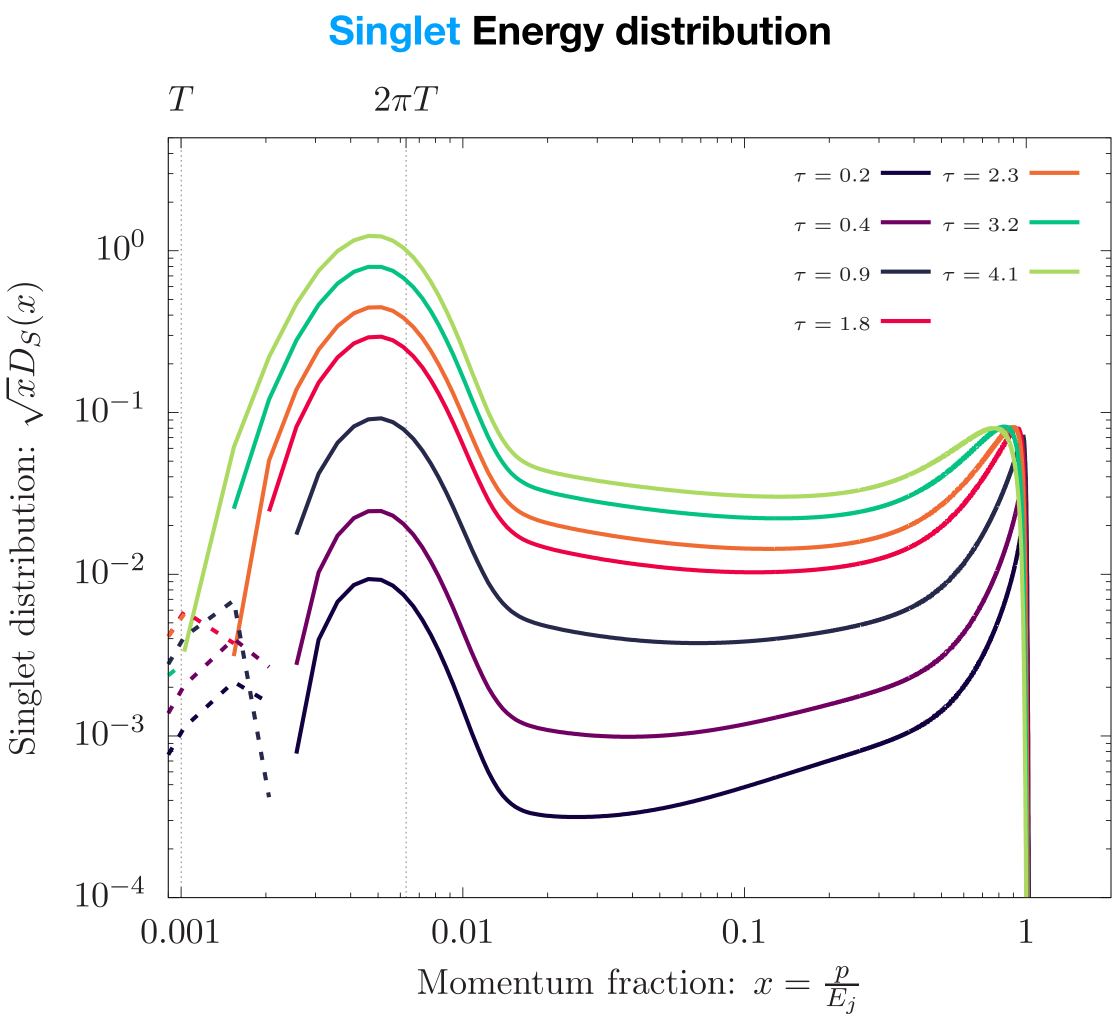


- Characteristic $D(x) \sim \frac{1}{\sqrt{x}}$ behavior, associated with invariant energy flux*.

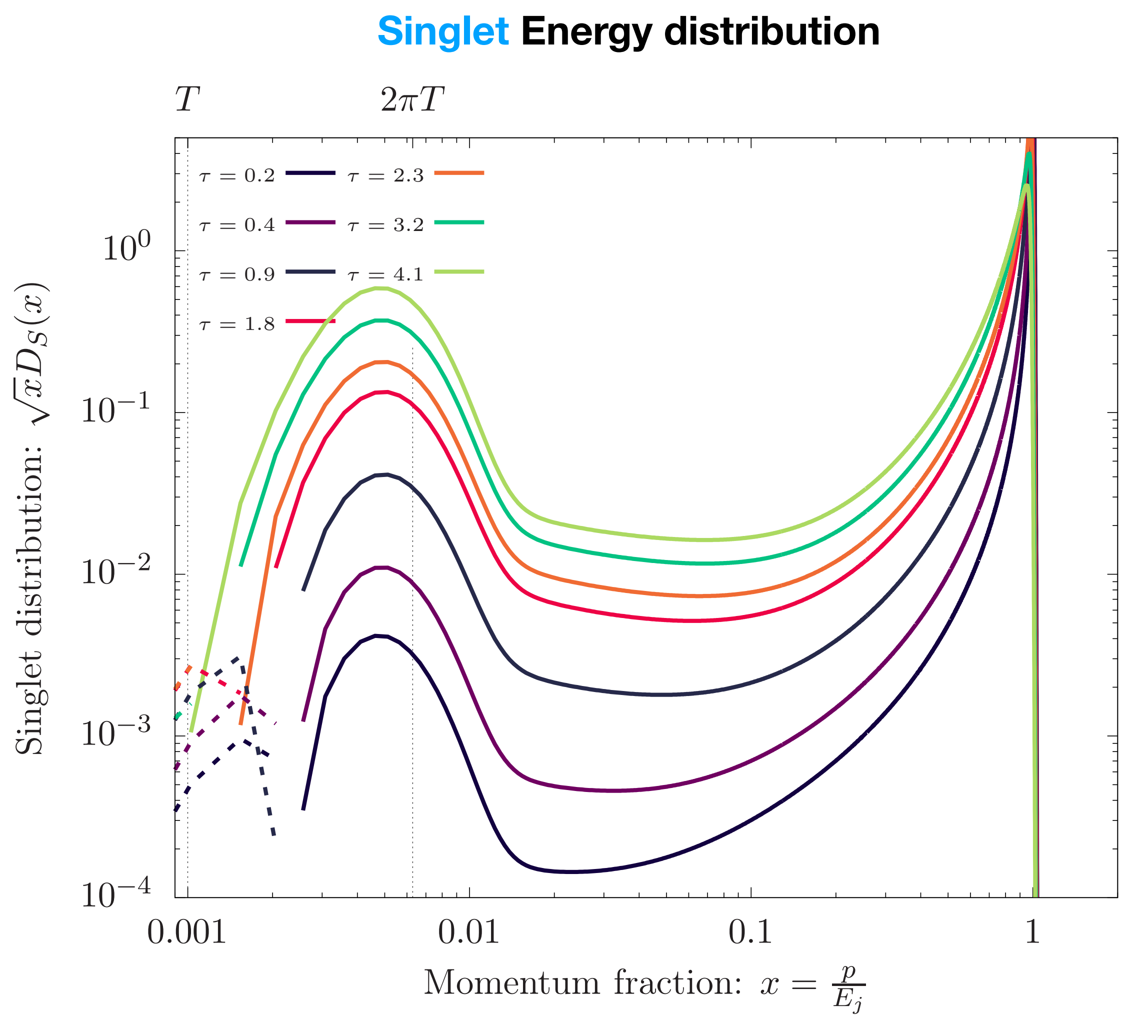
*: Mehtar-Tani, S. Schlichting arXiv: 1807.06181
*: Blaizot, Iancu, Mehtar-Tani arXiv: 1301.6102

Turbulent cascade:

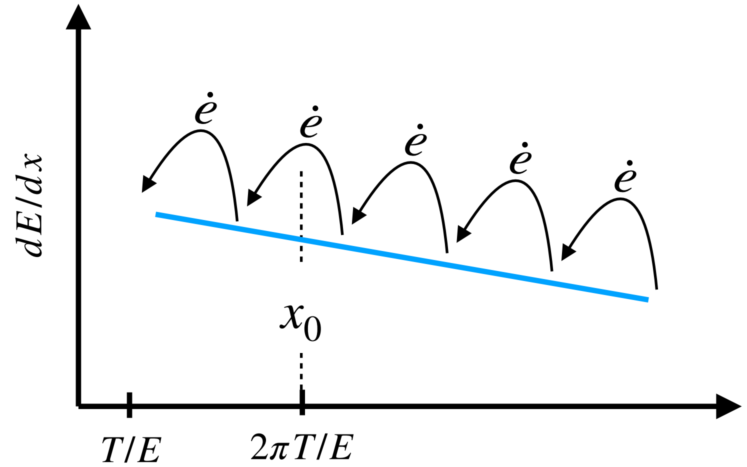
Initial Gluon Jet



Initial Quark Jet



Turbulent cascade:



Energy fraction x=p/E

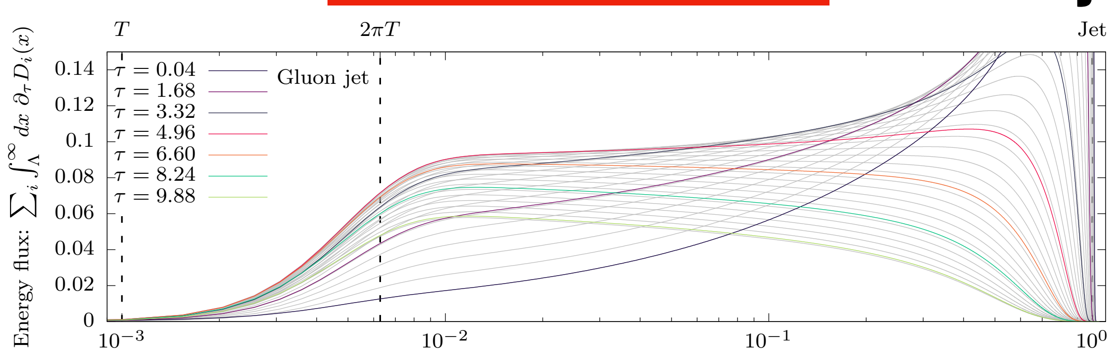
Evolution of the energy Flux up to an arbitrary scale: Λ

$$\int_{\Lambda}^{\infty} dx \sum_i \partial_\tau D_i(x)$$

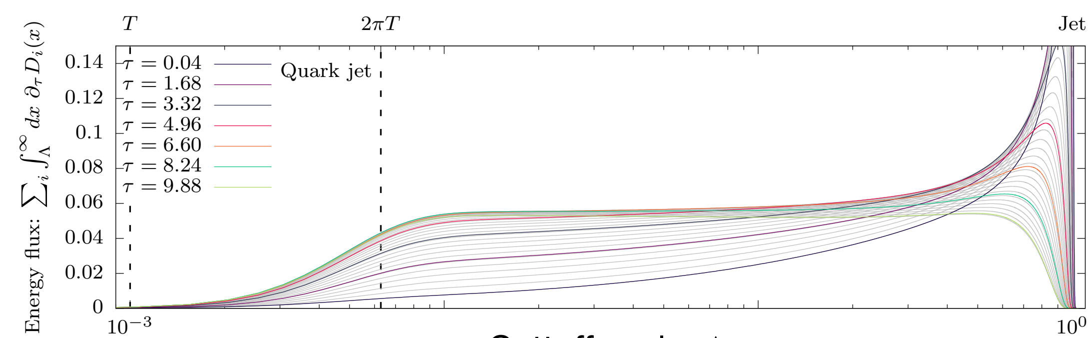
Initial Gluon Jet

Ej=1000T

Initial Quark Jet

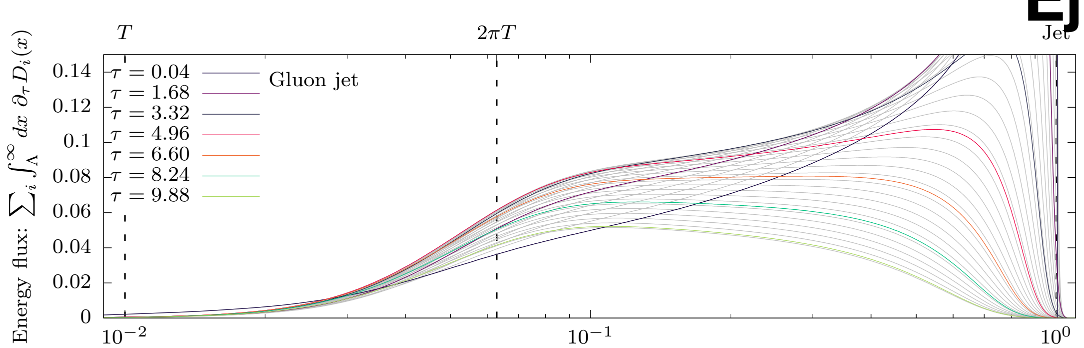


Cuttoff scale: Λ

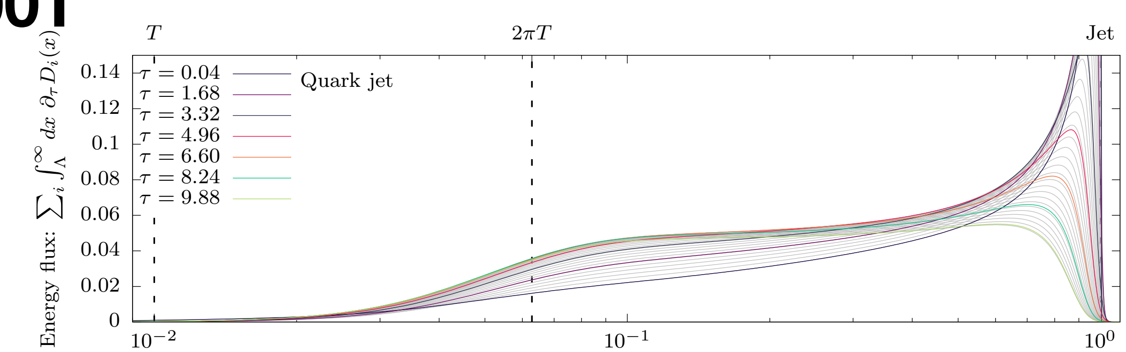


Cuttoff scale: Λ

Ej=100T



Cuttoff scale: Λ



Cuttoff scale: Λ

- Energy loss of highly energetic jet is dominated by the turbulent cascade
- Characteristic $D(x) \sim \frac{1}{\sqrt{x}}$ behavior, associated with invariant energy flux.

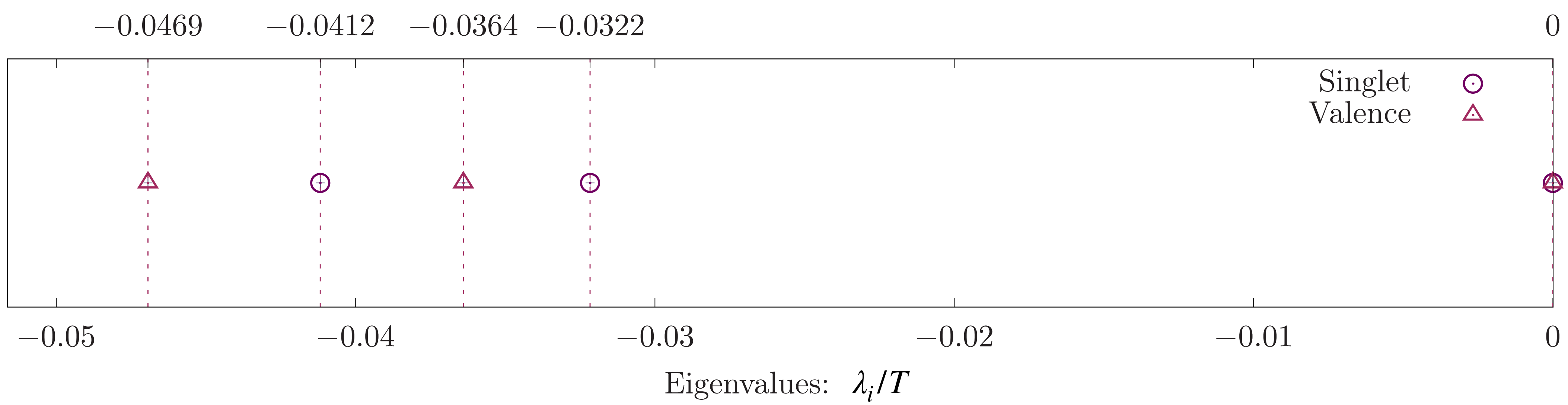
Late time behavior: Eigen value spectrum

Ultimately the jet equilibrate with the medium.

- We write the EoM as an eigenvalue problem

$$\partial_\tau \delta f_i(x,\tau) = C[\{\delta f_i\}] = \lambda_i \delta f_i \,.$$

- The low-lying eigenvalues describe the equilibration at late times.



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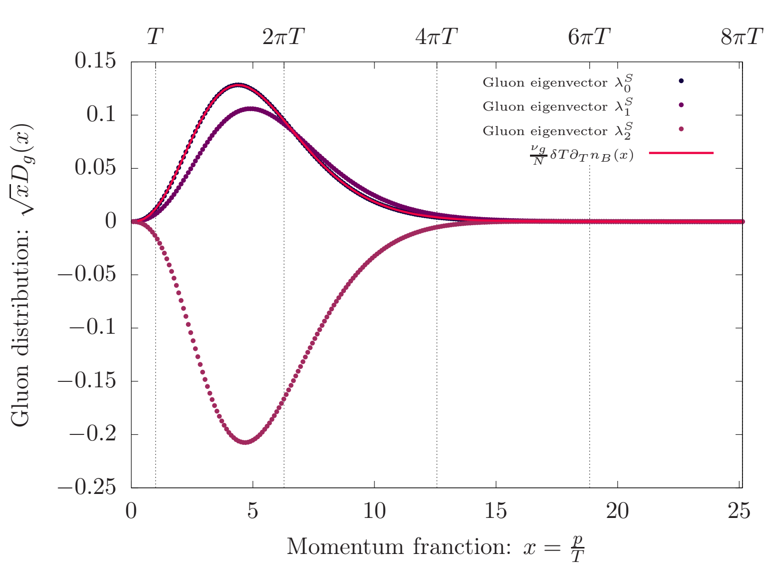
- The low-lying eigenvalues describe the equilibration at late times.

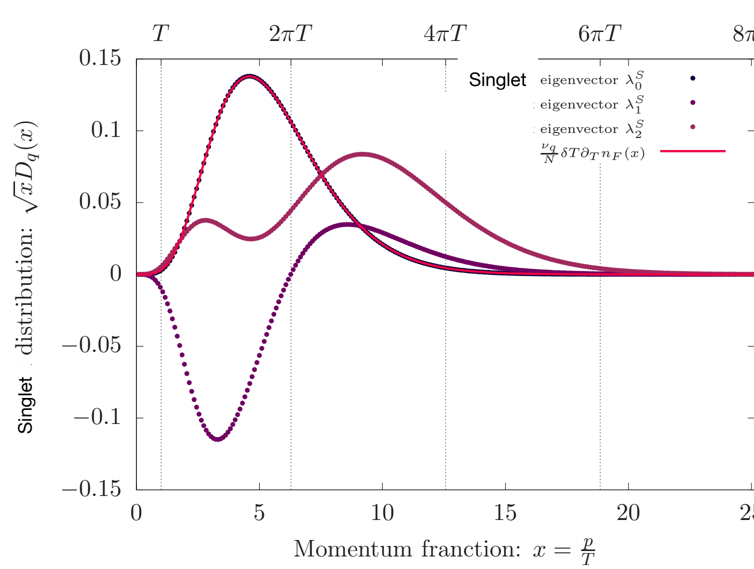
- Zero modes ($\lambda_0 = 0$) stems from conservation quantities (Energy/Valence charge) and its eigenvectors are the asymptotic behavior/stationary solution.

$$D(x, +\infty) = \delta T \partial_T n_{(Bose\ /\ Fermi)}(p;T)\,|_{p=xE_j}, \quad \text{and} \quad \delta\mu \partial_\mu n_{(Bose\ /\ Fermi)}(p;T)\,|_{p=xE_j}\,.$$

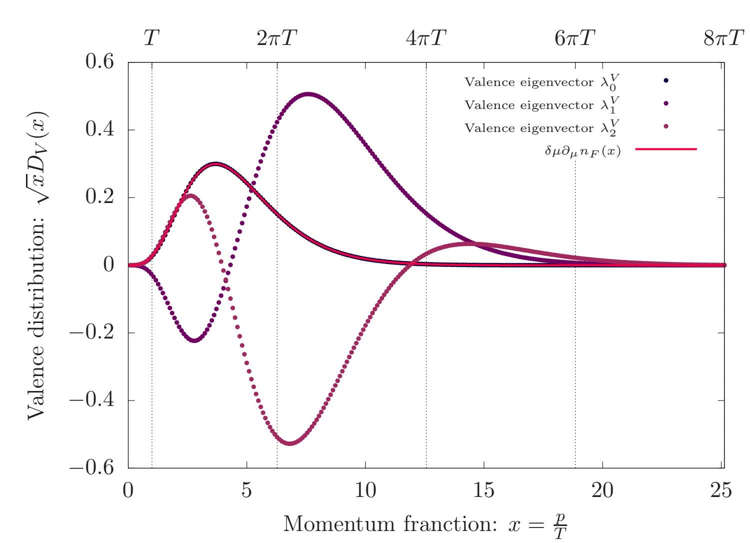
Gluon



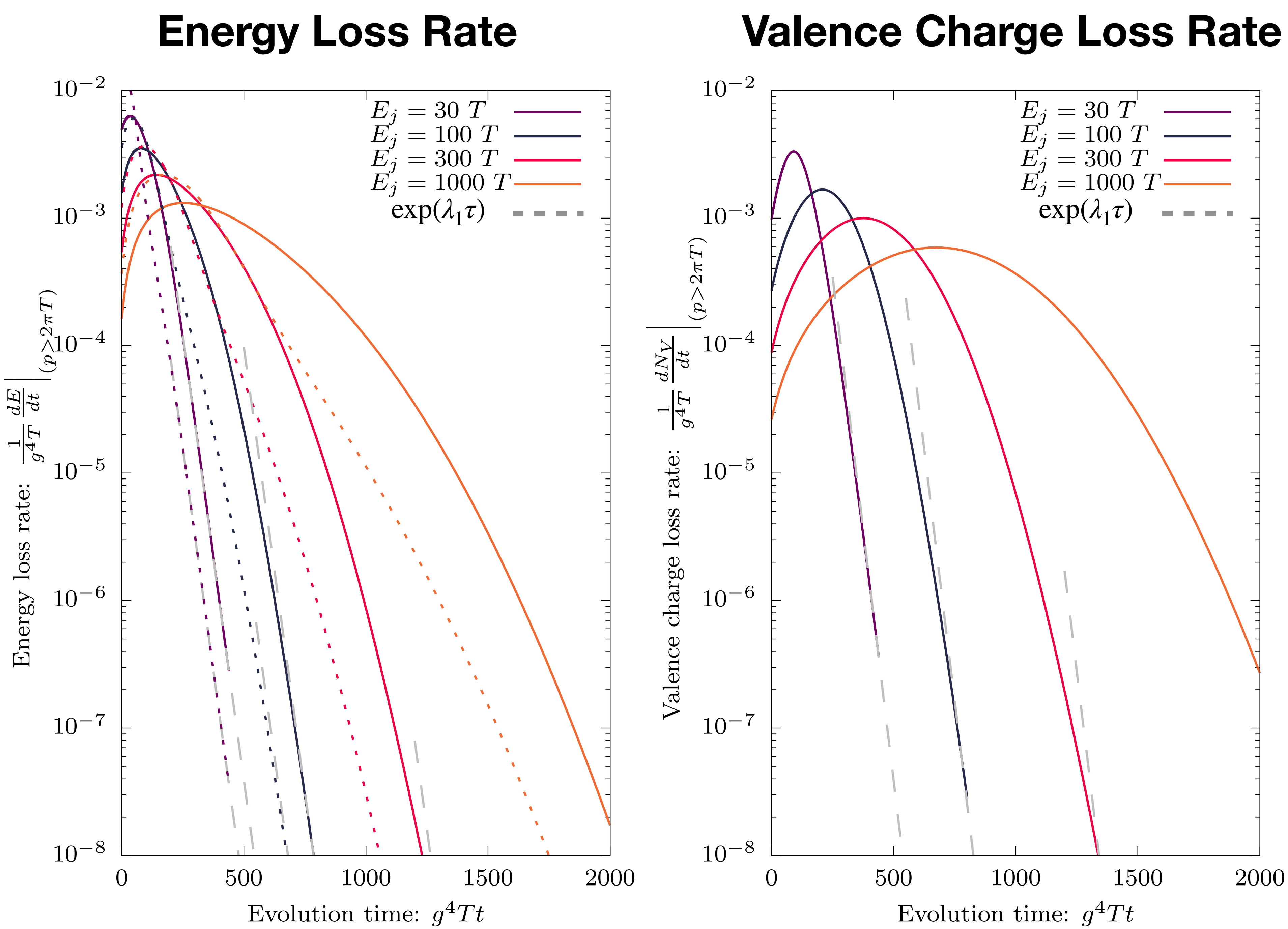
Singlet



Valence

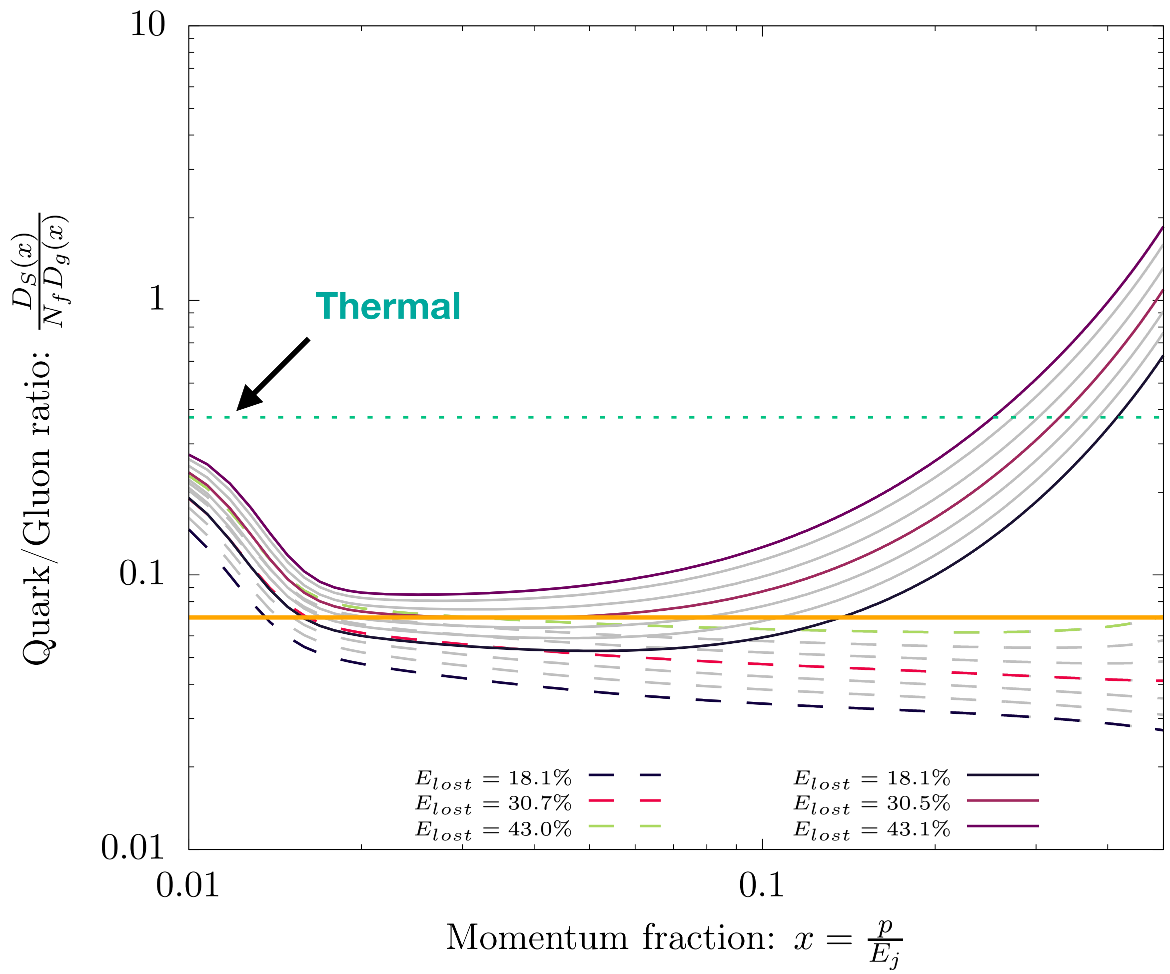


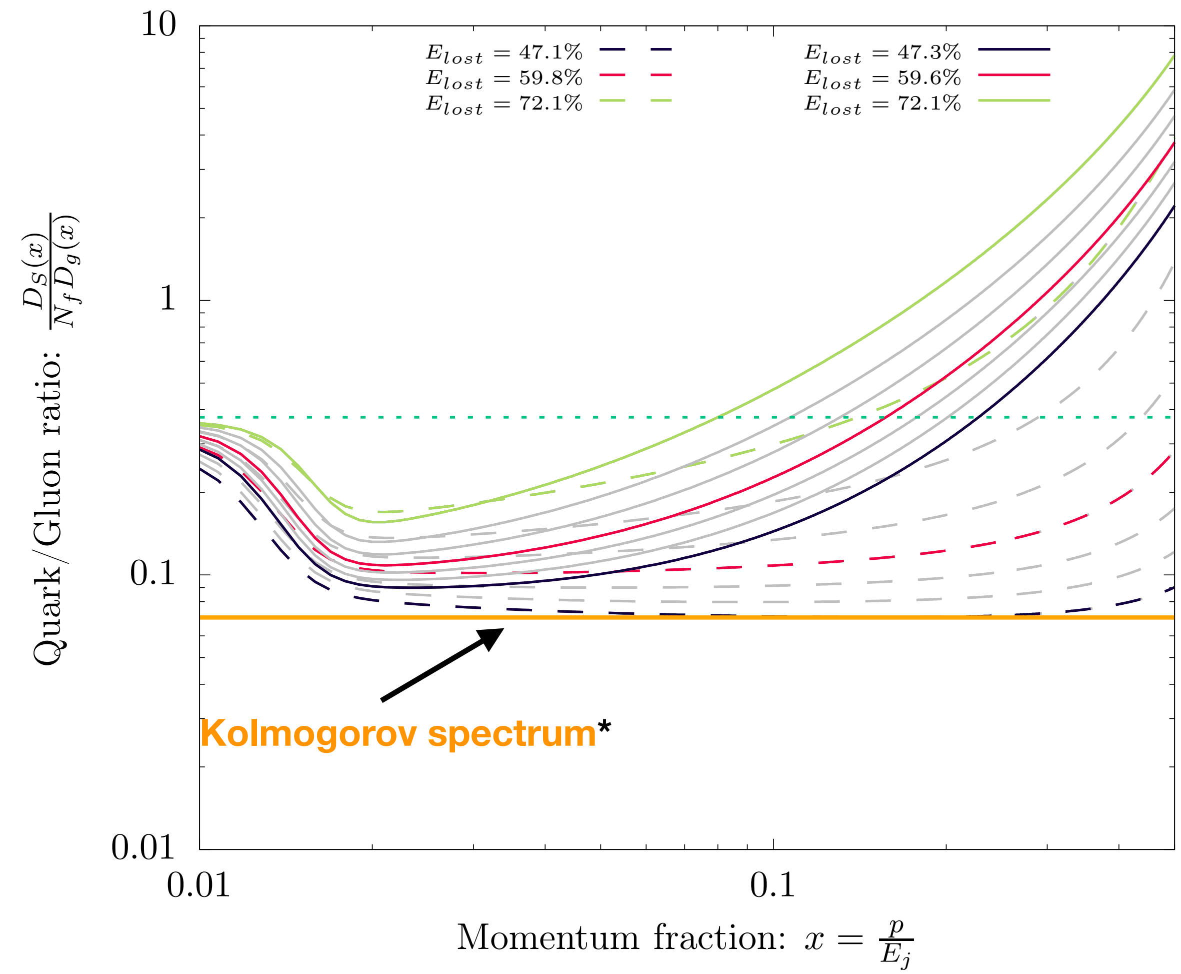
Late time behavior: late time exponential decay



- The jet has lost most energy by the time near equilibrium physics sets in —> Not relevant for jet physics.

Jet chemistry: Quark to gluon ratio





- Jet chemistry varies as function of momentum fraction and energy loss:

$x \sim T/E$	$-T/E \ll x \ll 1$	$x \sim 1$
Thermal	non-thermal (Kolmogorov)	Jet core

- Strongly quenched jets are quark rich

—> the most highly energetic particle is likely a quark

*: Mehtar-Tani, S. Schlichting arXiv:1807.06181

Conclusion & Outlook

- Jet equilibration itself is an interesting phenomena, where one can learn about QCD far from equilibrium.
- Different stages of energy loss/in-medium fragmentation of jets:
  - Initial energy loss due to soft radiation/recoil
  - Radiative break-up via turbulent cascade
  - Equilibration
- Energy loss dominated by turbulent cascade
- Strongly quenched jets are more likely to contain quarks

- Study angular dependence of the fragmentation function $D(p, t, \theta)$.

  —> Include large angle elastic processes.
- Include initial production and vacuum radiation for phenomenology.

Thank you!

Backup

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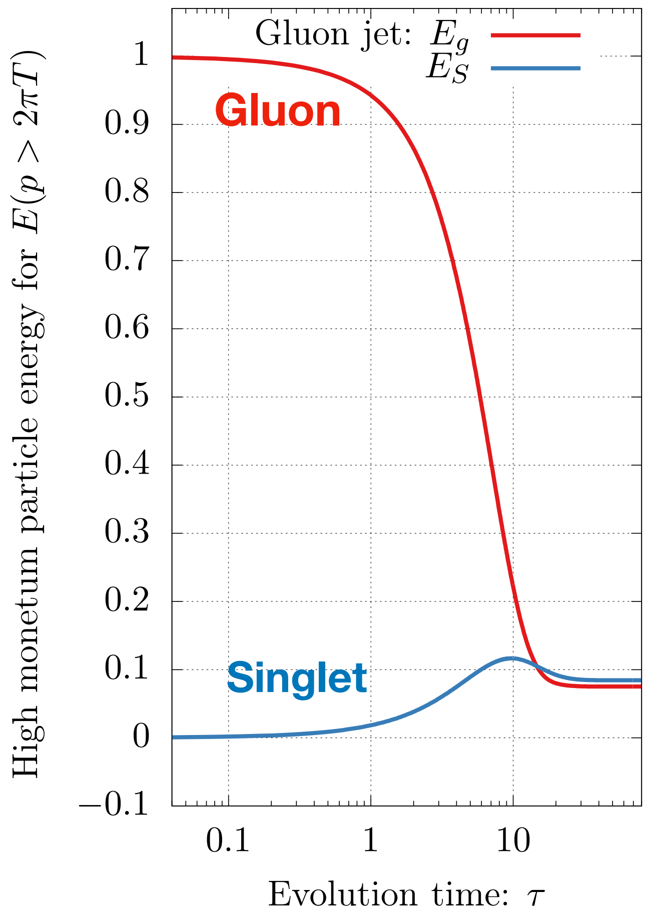
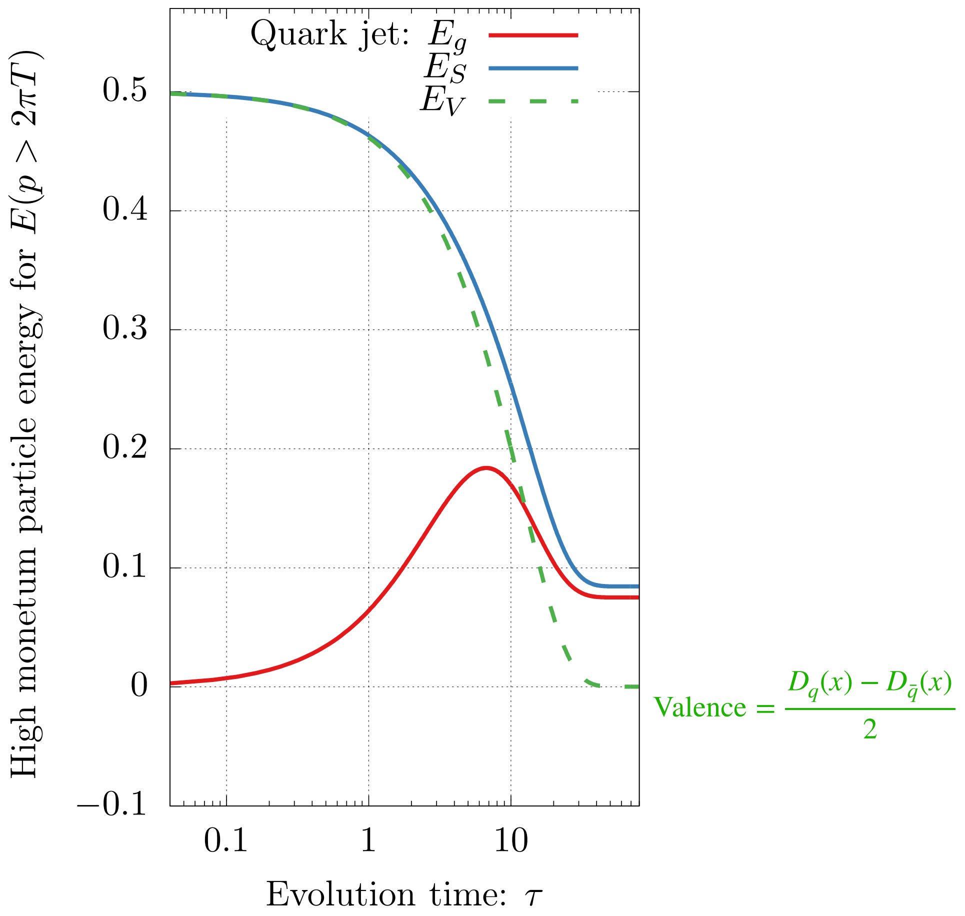
High momentum energy per species

Initial Gluon Jet



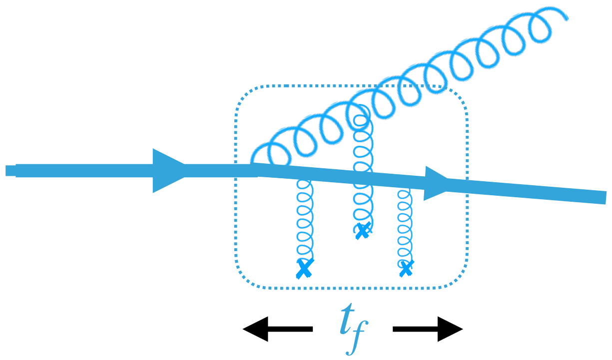
Initial Quark Jet



- Gluon loose energy faster than quarks
-

Landau-Pomeranchuk-Migdal (Lpm) effect

A particle undergoing multiple soft scattering experiences interference effects that suppresses radiation of high gluon energies.



[Landau-Pomeranchuk-Migdal (1953)]

These multiple soft scattering are taken into account in the rate

[BDMPS, Zakharov, AMY]

$$\frac{d\Gamma^a_{bc}(p,z)}{dz} = \frac{\alpha_s P_{ij}(z)}{2z(1-z)p}\int \frac{d^2p_b}{(2\pi)^2}\mathrm{Re}\quad [2\mathbf{p_b}\cdot \mathbf{g_{(z,p)}}(\mathbf{p_b})],$$

Where $g_{(z,p)}(\mathbf{p_b})$, is a solution to Schrödinger equation, with 3-Body interaction $H(t) = \delta E(\mathbf{p_b}, \mathbf{t}) - \mathbf{i}\boldsymbol{\Gamma}_\mathbf{3}(\mathbf{B}, \mathbf{t})\,.$