Fragmentation and equilibration of jets in a QCD plasma

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

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

We start from an effective kinetic theory at leading order:

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

We consider jet as linearized fluctuation over static background equilibrium

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

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

\[ D_a(x, t) \equiv x \left. \frac{dN_a}{dx} \right|_t \sim \frac{\nu_a(N_f)}{E_j} p^3 \delta f(p) \bigg|_{p = xE_j}, \]

where \( x = \frac{p}{E_j} \) is the parton momentum fraction.

Effective Kinetic Theory of QCD: Processes

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

Small Angle approx.

\[ C_{a}^{\text{small}}[\{f_i\}] = - \nabla_p \mathcal{F}_a + S_a \]

Diffusion \( \hat{Q} \) and Drag \( \eta_D \)

Conversion

“Recoil”

LPM resummed Rate.

\[ \Gamma \sim \gamma_{eq} \frac{T^2}{E_j^2} \]

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

\[ P \rightarrow \frac{(1-z)P}{zP} \Gamma \sim \gamma_{eq} \sqrt{\frac{T}{E_j}} \]

[J. Blaizot et al. arXiv:1402.5049]

[J. Ghiglieri et al. arXiv:1509.07773]

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

Driven by the rate $g \leftrightarrow gg$

**Initial Gluon Jet**

Driven by the rate $q \leftrightarrow qg$

**Initial Quark Jet**

**Gluon Energy distribution**

- Recoil

**Gluon Energy distribution**

- Single gluon emission

Momentum fraction: $x = \frac{p}{E_j}$

$I. Soudi$

Kinetic and chemical equilibration of jets

25/04/2020
Early time behavior: Quark radiation

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

Singlet Energy distribution

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

Initial Gluon Jet

Driven by the rate $q \leftrightarrow q g$

Initial Quark Jet

Singlet Energy distribution
Turbulent cascade:

**Initial Gluon Jet**

**Initial Quark Jet**

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

*: Blaizot, Iancu, Mehtar-Tani arXiv: 1301.6102
Turbulent cascade:

Initial Gluon Jet

Singlet Energy distribution

$\sqrt{x D_S(x)}$ vs $x = \frac{p}{E_j}$

Initial Quark Jet

Singlet Energy distribution

$\sqrt{x D_S(x)}$ vs $x = \frac{p}{E_j}$
Turbulent cascade:

Evolution of the energy Flux up to an arbitrary scale: $\Lambda$

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

Energy fraction $x = p/E$

- 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.
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.

![Diagram showing eigenvalues](image_url)
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Late time behavior: Eigen value spectrum

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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.

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

  \[ x \sim \frac{T}{E} \quad -\frac{T}{E} \ll x \ll 1 \quad x \sim 1 \]

  Thermal \quad \text{non-thermal (Kolmogorov)} \quad \text{Jet core}

- Strongly quenched jets are quark rich

  \( \rightarrow \) the most highly energetic particle is likely a quark

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 $D(p, t, \theta)$. $\rightarrow$ Include large angle elastic processes.

• Include initial production and vacuum radiation for phenomenology.
Backup
Jet chemistry

High momentum energy per species

Initial Gluon Jet

Initial Quark Jet

- Gluon loose energy faster than quarks

- \[
    \text{Valence} = \frac{D_q(x) - D_{\bar{q}}(x)}{2}
    \]
A particle undergoing multiple soft scattering experiences interference effects that suppresses radiation of high gluon energies.

These multiple soft scattering are taken into account in the rate

\[ \frac{d\Gamma_{bc}^a(p, z)}{dz} = \frac{\alpha_s P_{ij}(z)}{2z(1 - z)p} \int \frac{d^2p_b}{(2\pi)^2} \text{Re} \left[ 2p_b \cdot g_{(z,p)}(p_b) \right], \]

Where \( g_{(z,p)}(p_b) \), is a solution to Schrödinger equation, with 3-Body interaction

\[ H(t) = \delta E(p_b, t) - i\Gamma_3(B, t). \]