Photon Production from a Medium-Induced Parton Cascade

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CRC–TR 211
Strong-interaction matter under extreme conditions

Contents

General Motivation

- Learning about the Quark-Gluon-Plasma (QGP) + QCD phase diagram

→ Production of back-to-back partons with high-p_T (jet)

→ Altered jet structure and energy due to propagation through QGP (jet quenching)

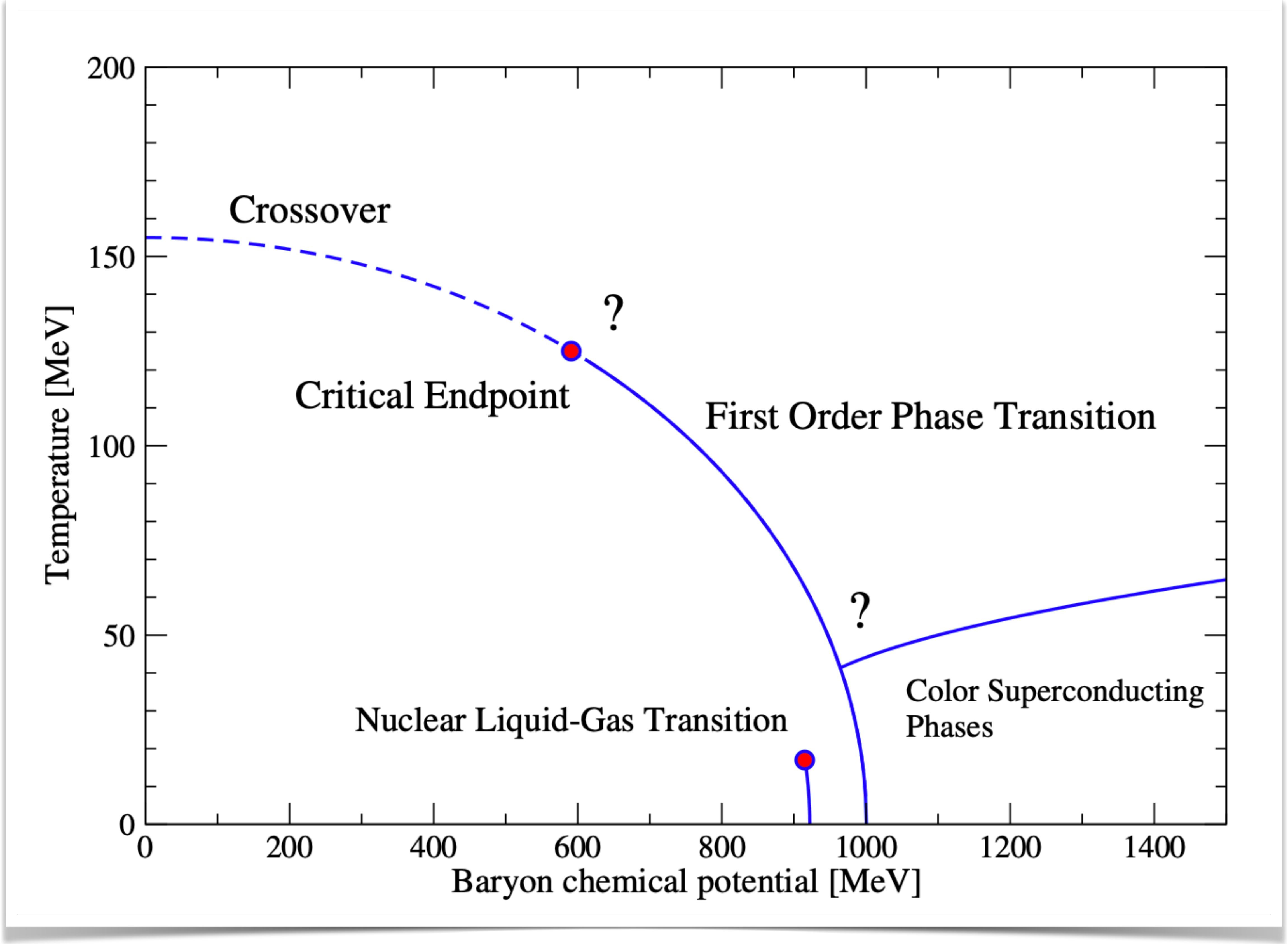
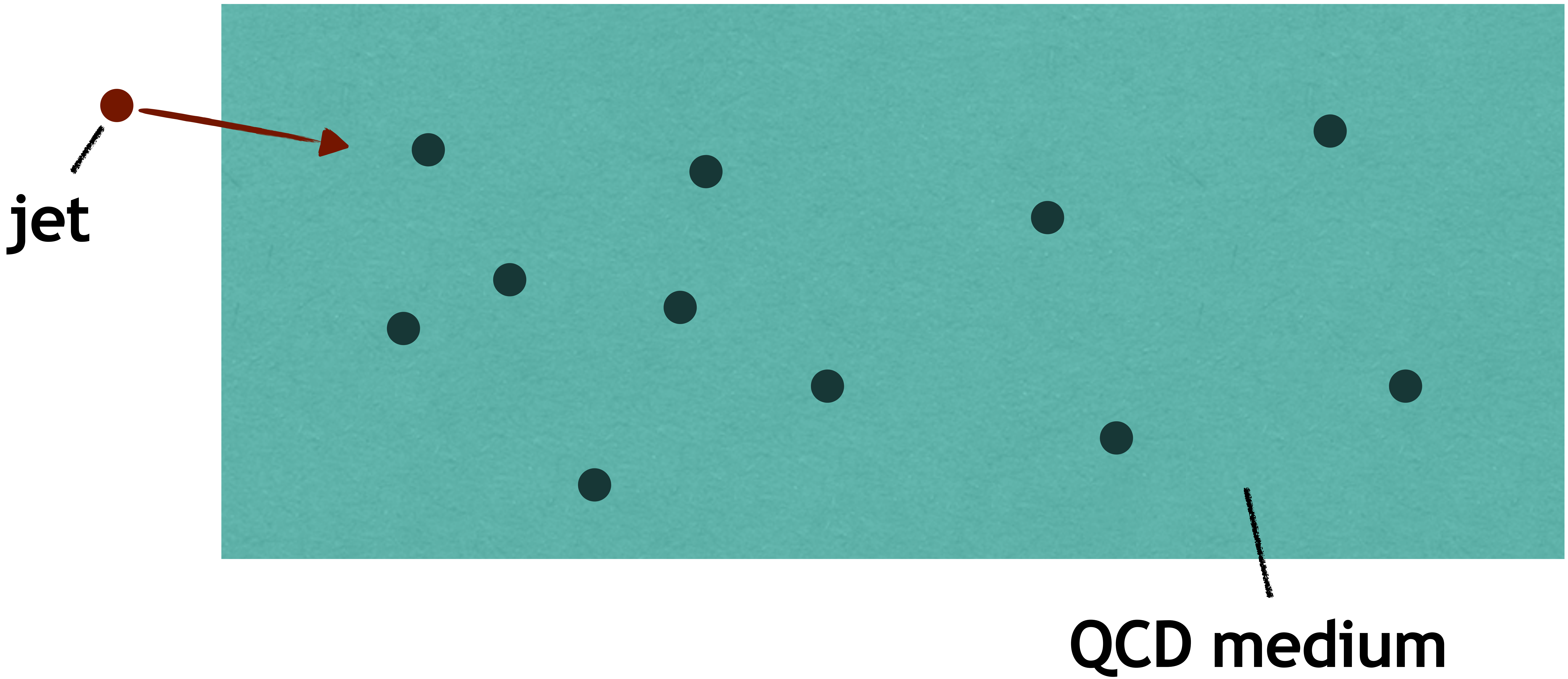
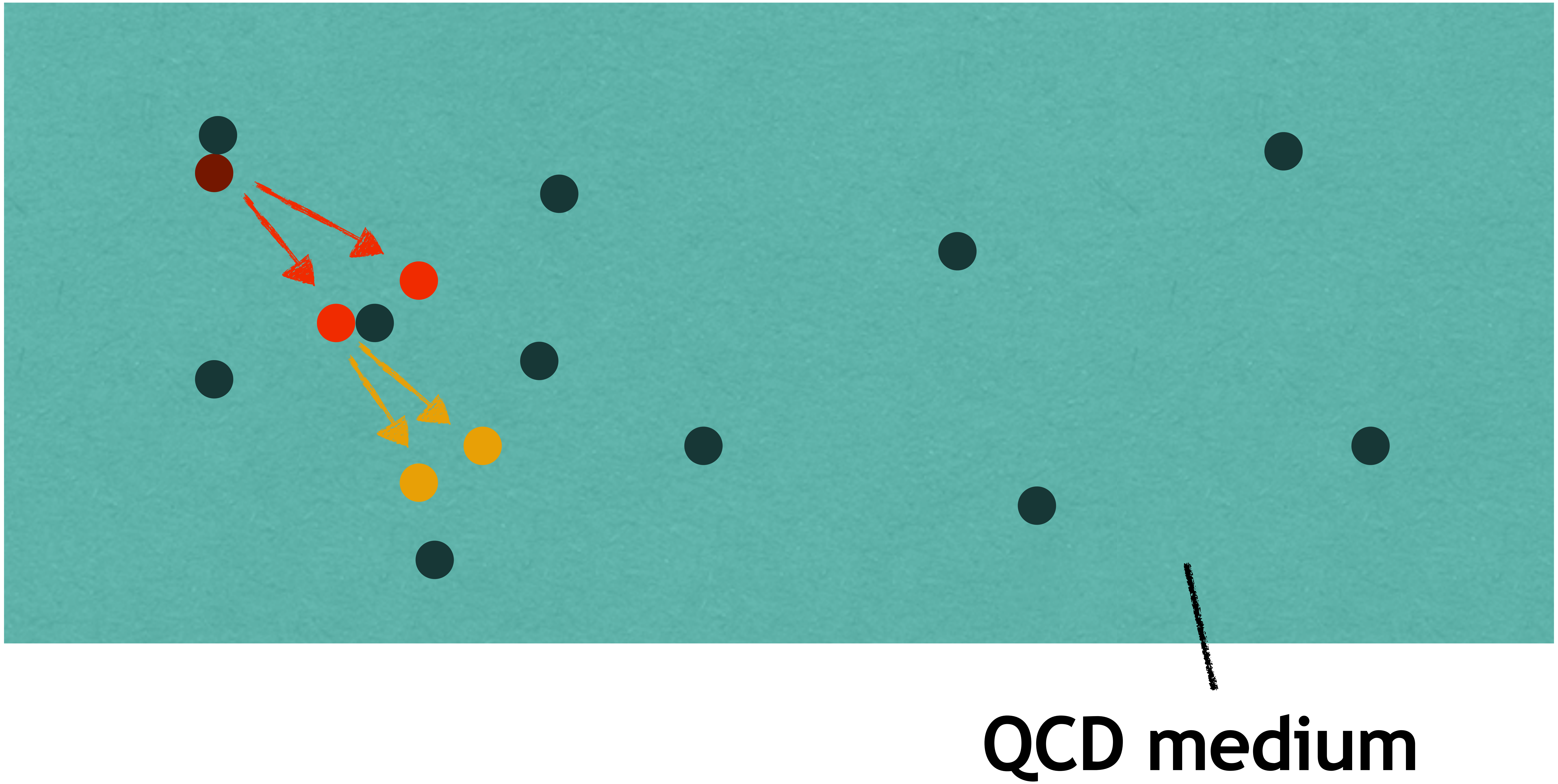


Figure from C.S. Fischer,
Progress in Particle and Nuclear Physics 105 (2019)

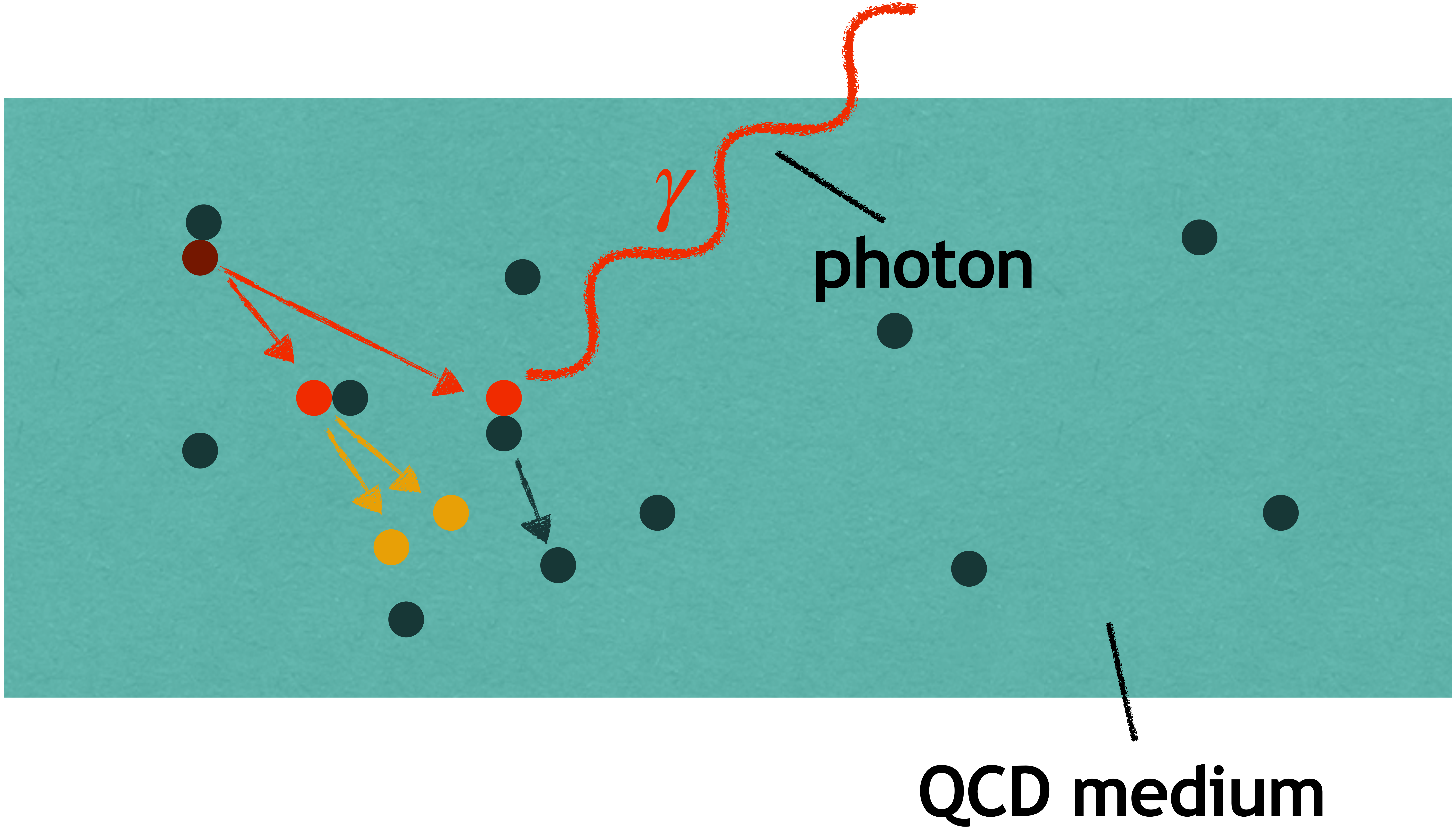
In-Medium Jet Fragmentation



In-Medium Jet Fragmentation



Photons from Jet-Medium Interactions

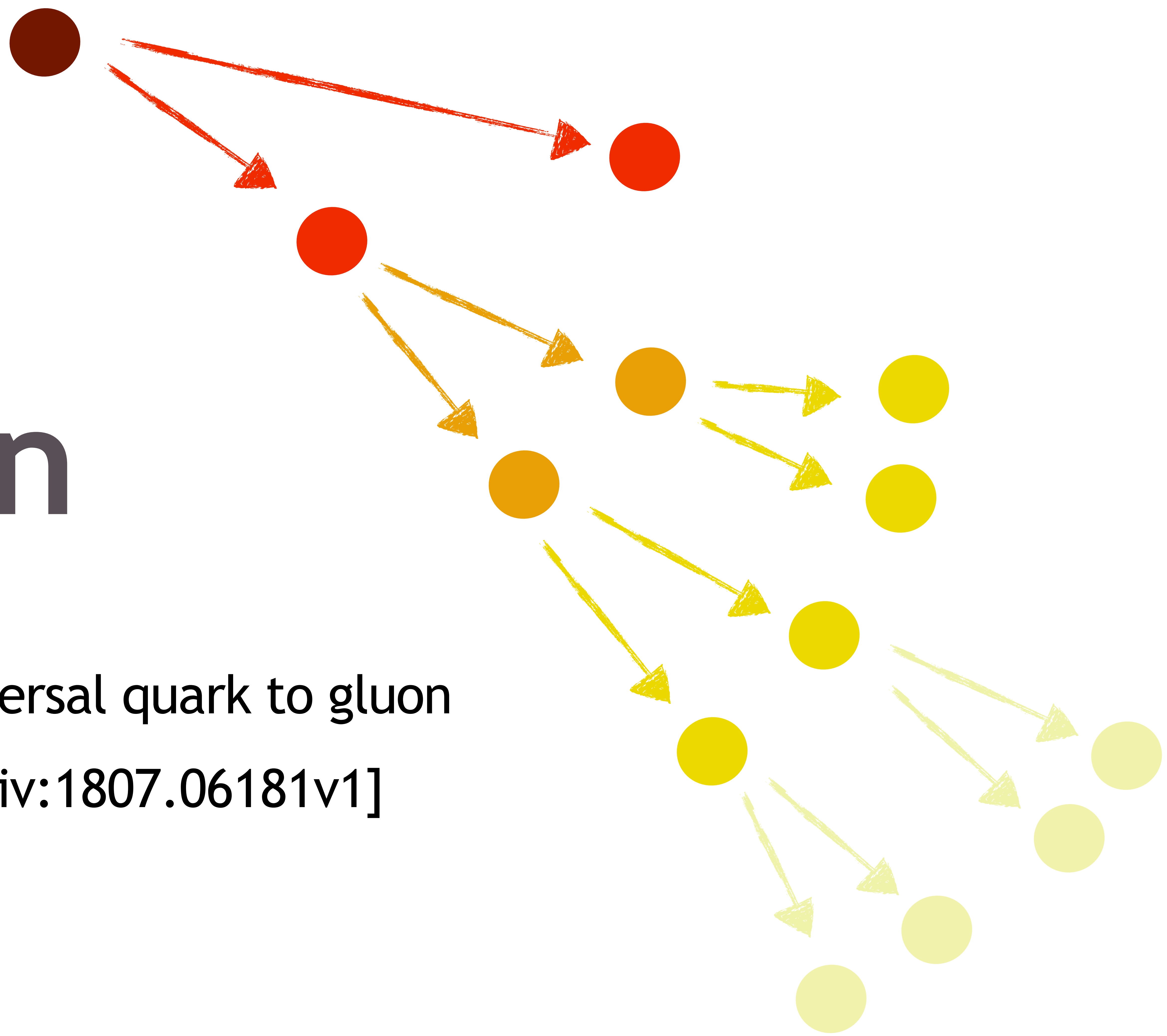


- photons are produced by interactions of jet partons with medium partons
- interact only electromagnetically
- mean free path > typical size of the medium

photons from jet-medium interactions as direct probes of the QCD medium

Parton Evolution

Y. Mehtar-Tani and S. Schlichting (2018). “Universal quark to gluon ratio in medium-induced parton cascade“ [arXiv:1807.06181v1]



Kinetic Approach

- Boltzmann equation

$$\left(\partial_t + \frac{\vec{p}}{|\vec{p}|}\boldsymbol{\nabla}_{\vec{r}}\right) f_a(t,\vec{r},\vec{p}) \;=\; \left(\frac{\partial f_a}{\partial t}\right)_{coll} \;\equiv\; C_a[\{f_i\}]$$

- Include jet partons as a linearized perturbation

$$f_a(t,\vec{r},\vec{p}) \;=\; \underbrace{n_a(|\vec{p}|)}_{\text{thermal}} + \underbrace{\boxed{\delta f_a(t,\vec{r},\vec{p})}}_{\text{jet}}$$

Evolution Equations

- Valid in LPM regime ($T \ll E \ll E_{jet}$) and infinitely large medium

$$\partial_t D_g(x,t) = \frac{1}{\bar{t}_{br}(E_{jet})}\left(\int_0^1 \mathrm{d}z\, \mathcal{K}_{gg}(z)\left[\sqrt{\frac{z}{x}}D_g\left(\frac{x}{z}\right) - \frac{z}{\sqrt{x}}D_g(x)\right] + \int_0^1 \mathrm{d}z\, \mathcal{K}_{gq}(z)\sqrt{\frac{z}{x}}D_S\left(\frac{x}{z}\right) - \int_0^1 \mathrm{d}z\, \mathcal{K}_{qg}(z)\frac{z}{\sqrt{x}}D_g(x)\right)$$

$$\partial_t D_S(x,t) = \frac{1}{\bar{t}_{br}(E_{jet})}\left(\int_0^1 \mathrm{d}z\, \mathcal{K}_{qq}(z)\left[\sqrt{\frac{z}{x}}D_S\left(\frac{x}{z}\right) - \frac{1}{\sqrt{x}}D_S(x)\right] + \int_0^1 \mathrm{d}z\, \mathcal{K}_{qg}(z)\sqrt{\frac{z}{x}}D_g\left(\frac{x}{z}\right)\right)$$

$$\partial_t D_{NS}^{(a)}(x,t) = \frac{1}{\bar{t}_{br}(E_{jet})}\int_0^1 \mathrm{d}z\, \mathcal{K}_{qq}(z)\left[\sqrt{\frac{z}{x}}D_{NS}^{(a)}\left(\frac{x}{z}\right) - \frac{1}{\sqrt{x}}D_{NS}^{(a)}(x)\right]$$

with

$$D_a(t,x) = x\frac{\mathrm{d}N_a}{\mathrm{d}x}$$

&

$$\bar{t}_{br}(E) \equiv \frac{\pi}{\alpha_s}\sqrt{\frac{C_{R,jet}\,E}{\hat{q}}}$$

Y. Mehtar-Tani and S. Schlichting, JHEP 09 (2018)

Evolution Equations

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$$\partial_t D_g(x,t) = \frac{1}{\bar{t}_{br}(E_{jet})}\left(\int_0^1 \mathrm{d}z\, \boxed{\mathcal{K}_{gg}(z)}\left[\sqrt{\frac{z}{x}}D_g\left(\frac{x}{z}\right) - \frac{z}{\sqrt{x}}D_g(x)\right] + \int_0^1 \mathrm{d}z\, \boxed{\mathcal{K}_{gq}(z)}\sqrt{\frac{z}{x}}D_S\left(\frac{x}{z}\right) - \int_0^1 \mathrm{d}z\, \boxed{\mathcal{K}_{qg}(z)}\frac{z}{\sqrt{x}}D_g(x)\right)$$

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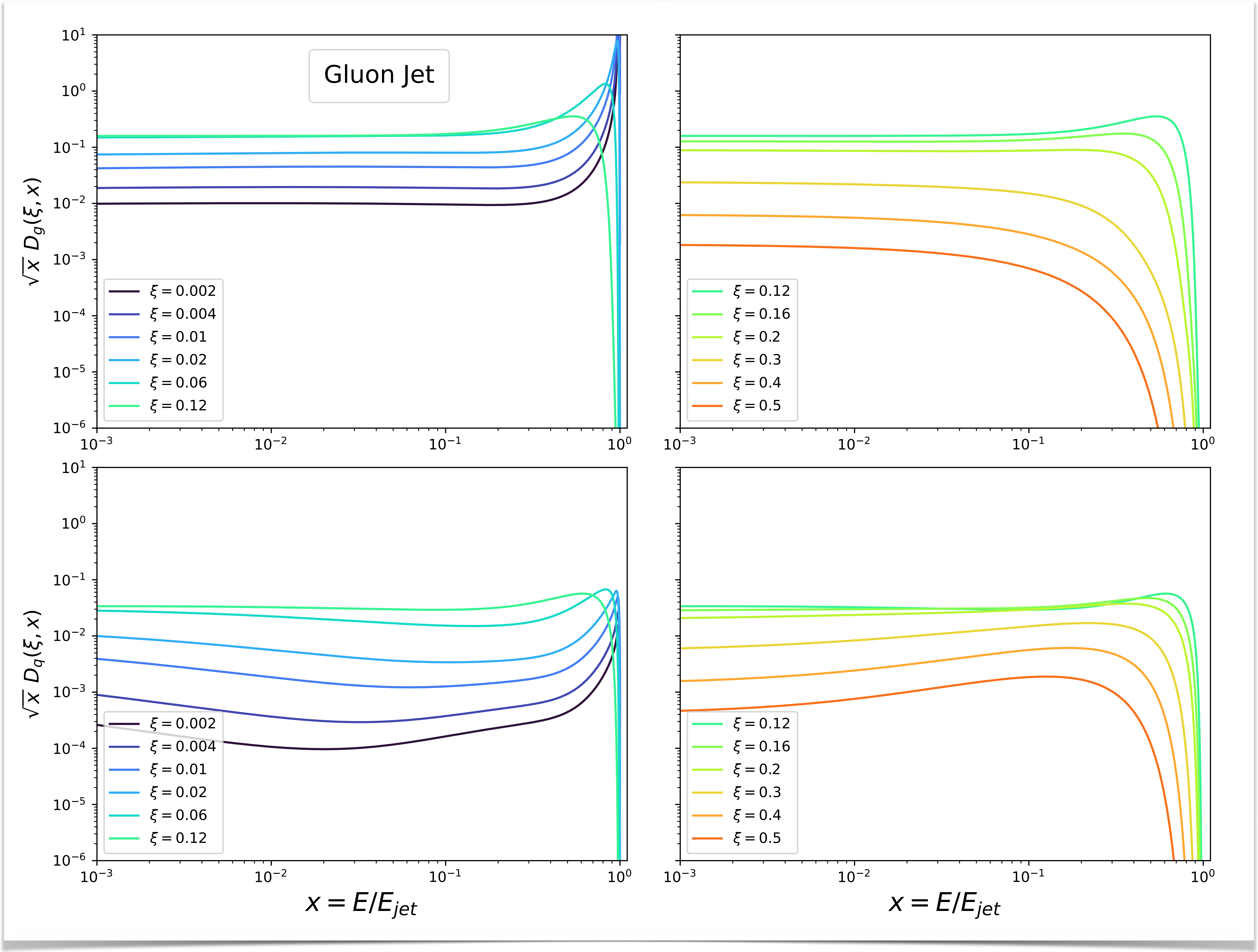
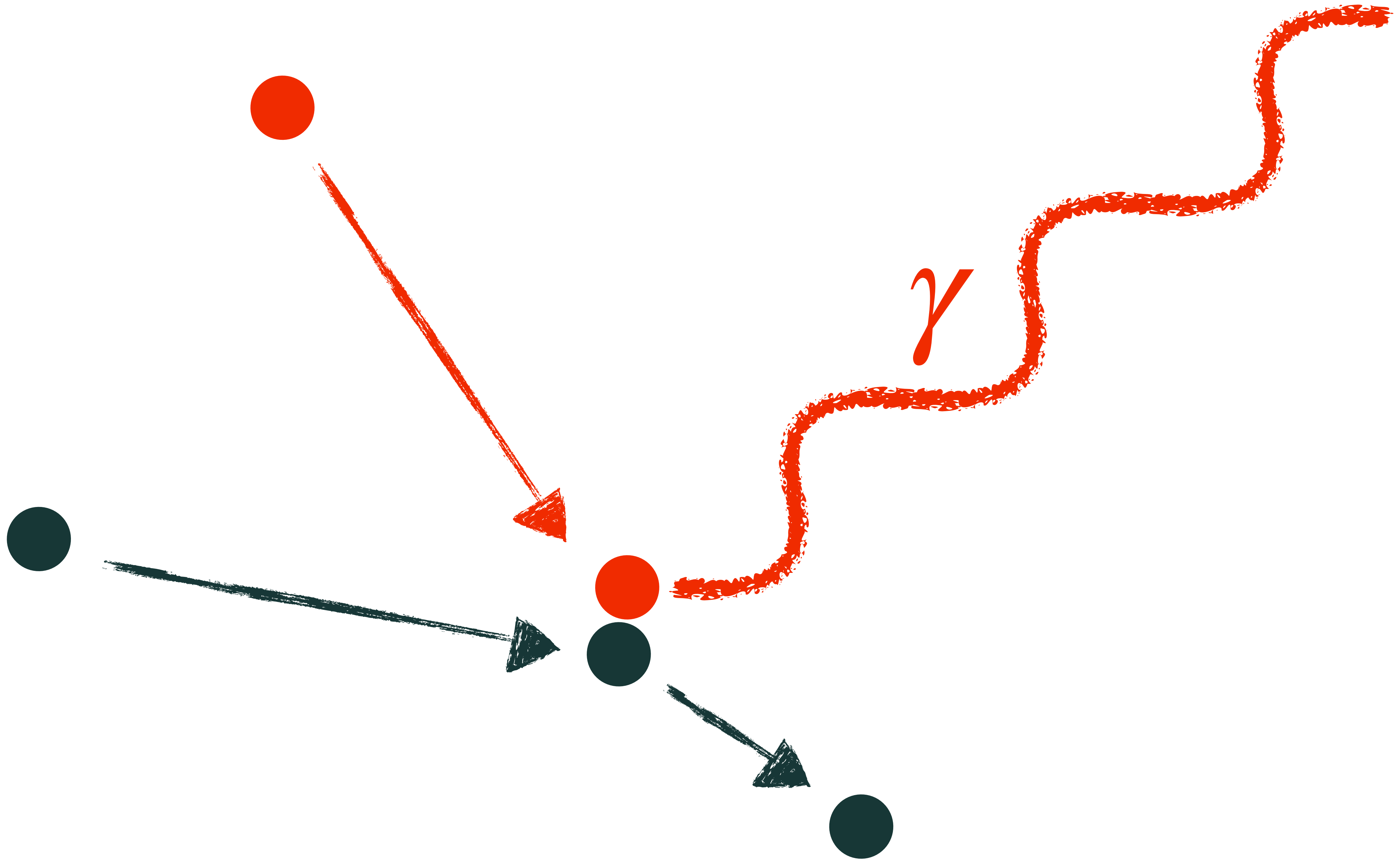
$\longrightarrow$ **Inelastic collisions and radiative emissions (LPM suppressed)**

$1 \leftrightarrow 2$ **processes:** $g \leftrightarrow gg$, $g \leftrightarrow q\bar{q}$, $q \leftrightarrow gq$ **and** $\bar{q} \leftrightarrow g\bar{q}$



- Early peak at high parton energies ($x \sim 1$)
- Power-law dependent energy flow towards smaller energies
- Rising distributions ($x < 1$) until $\xi \sim 0.2$



Photon Production

Kinetic Approach

- General kinetic production rate:

$$E_\gamma \frac{\mathrm{d}N_\gamma}{\mathrm{d}t\ \mathrm{d}^3r\ \mathrm{d}^3p_\gamma} = \frac{1}{2(2\pi)^8} \int \frac{\mathrm{d}^3p_1}{2E_1} \frac{\mathrm{d}^3p_2}{2E_2} \frac{\mathrm{d}^3p_3}{2E_3} \delta^4(P_1 + P_2 - P_3 - P_\gamma) \, |\mathcal{M}(P_1, P_2, P_3, P_\gamma)|^2 \, f_1(P_1) \, f_2(P_2) \big(1 \pm f_3(P_3)\big)$$

squared amplitudes

one-particle distribution functions

Kinetic Approach

- General kinetic production rate:

$$E_\gamma \frac{\mathrm{d}N_\gamma}{\mathrm{d}t\ \mathrm{d}^3r\ \mathrm{d}^3p_\gamma} = \frac{1}{2(2\pi)^8} \int \frac{\mathrm{d}^3p_1}{2E_1} \frac{\mathrm{d}^3p_2}{2E_2} \frac{\mathrm{d}^3p_3}{2E_3} \delta^4(P_1 + P_2 - P_3 - P_\gamma) \left|\mathcal{M}(P_1, P_2, P_3, P_\gamma)\right|^2 \boxed{f_1(P_1)\, f_2(P_2) \left(1 \pm f_3(P_3)\right)}$$

$$f_a(t, \vec{r}, \vec{p}) = \underbrace{n_a(|\vec{p}|)}_{\text{thermal}} + \underbrace{\delta f_a(t, \vec{r}, \vec{p})}_{\text{jet}}$$

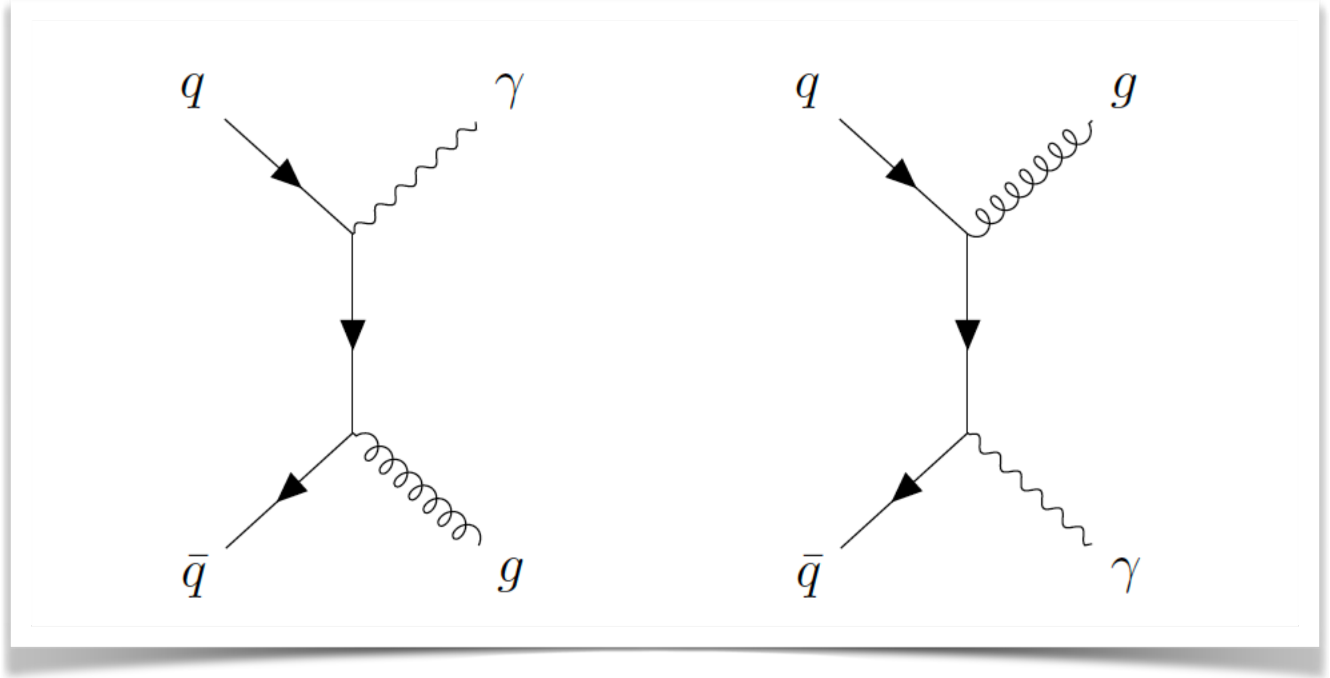
Keeping only terms of order $\mathcal{O}(\delta f)$

Kinetic Approach

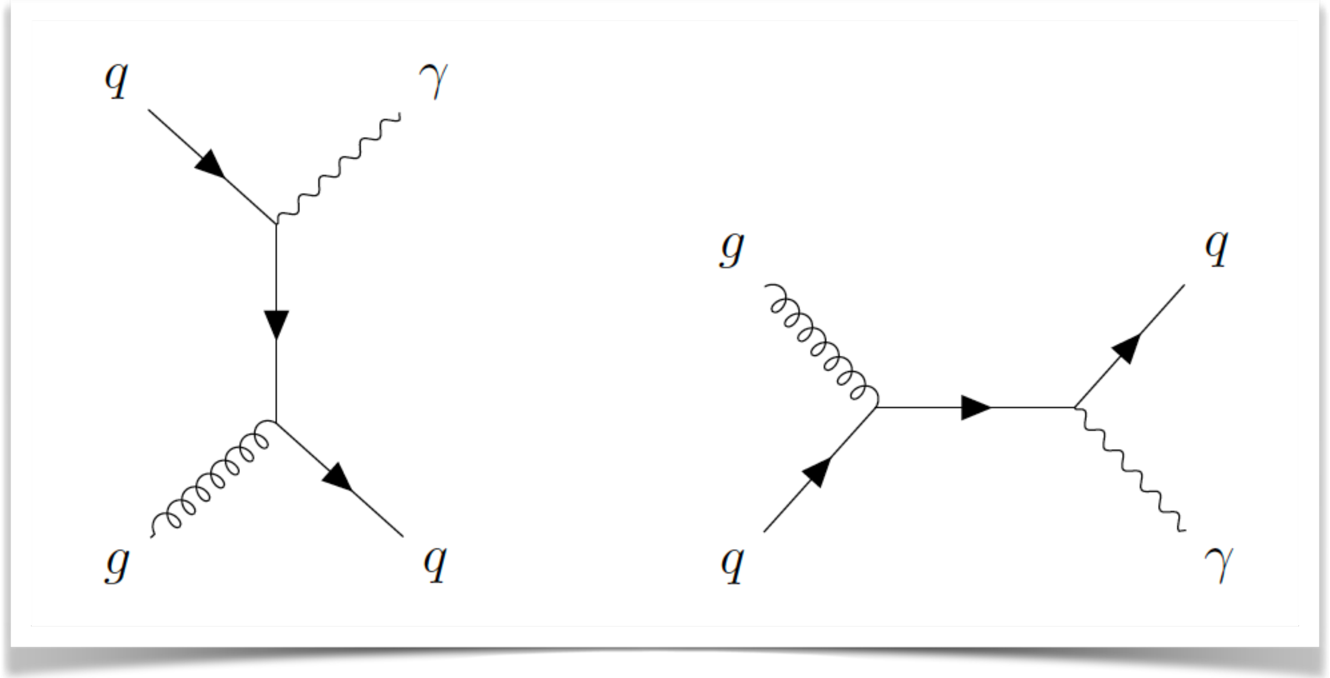
- General kinetic production rate:

$$E_\gamma \frac{\mathrm{d}N_\gamma}{\mathrm{d}t\ \mathrm{d}^3r\ \mathrm{d}^3p_\gamma} = \frac{1}{2(2\pi)^8} \int \frac{\mathrm{d}^3p_1}{2E_1} \frac{\mathrm{d}^3p_2}{2E_2} \frac{\mathrm{d}^3p_3}{2E_3} \delta^4(P_1 + P_2 - P_3 - P_\gamma) \boxed{|\mathcal{M}(P_1, P_2, P_3, P_\gamma)|^2} f_1(P_1)\, f_2(P_2) \left(1 \pm f_3(P_3)\right)$$

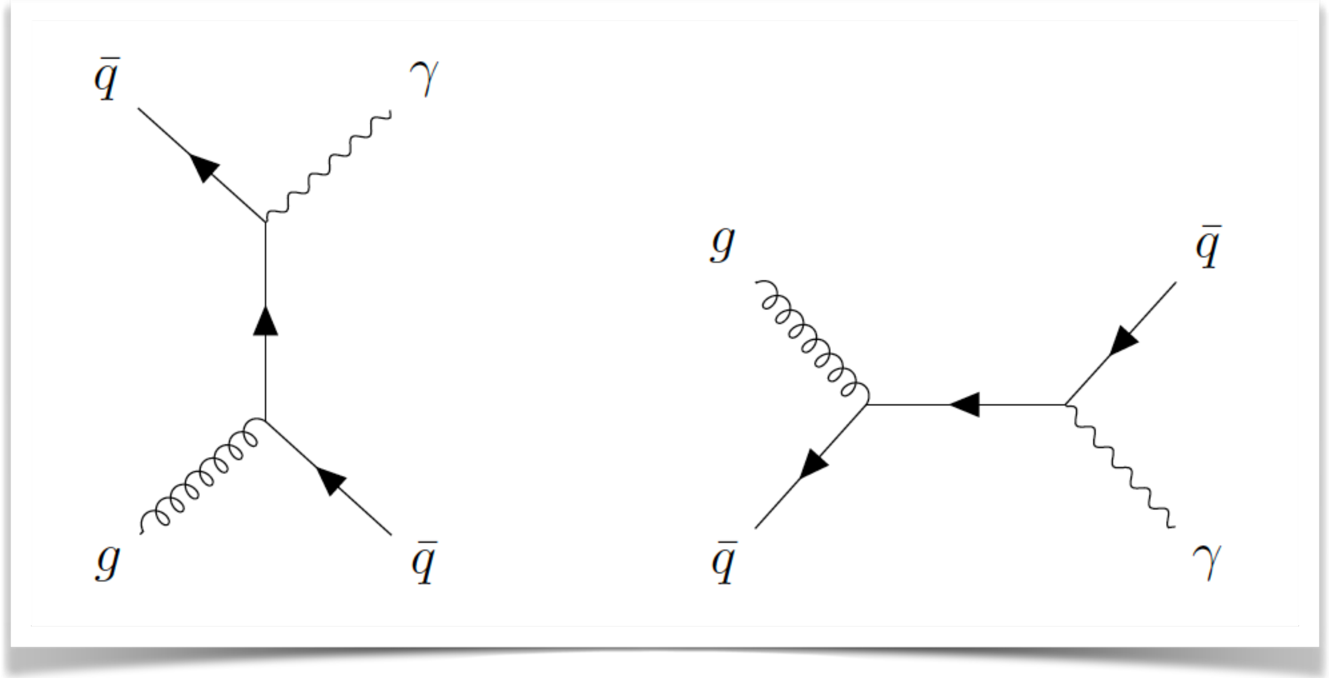
- Included processes: 2 <-> 2 scatterings



pair annihilation

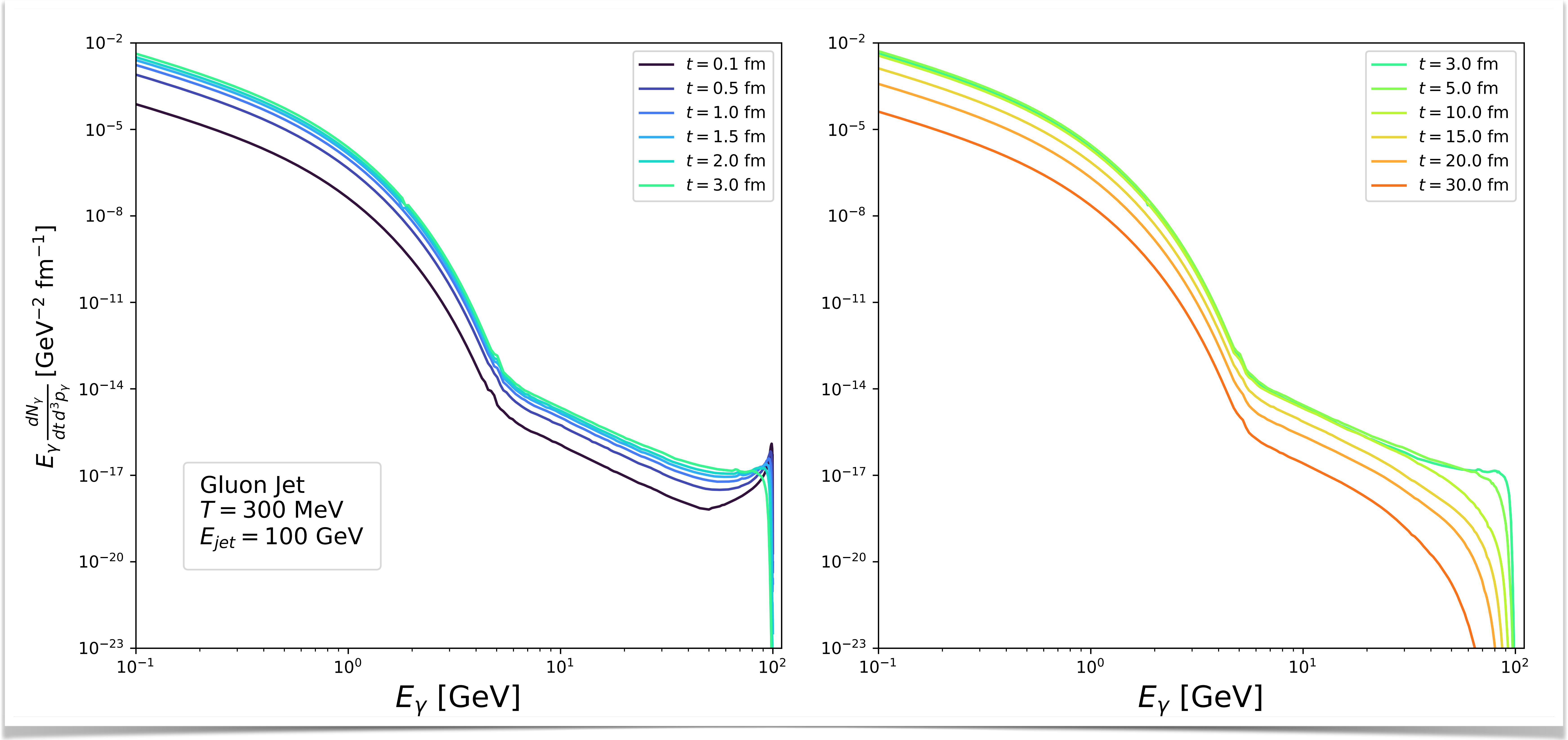


Compton scattering (quarks)



Compton scattering (antiquarks)

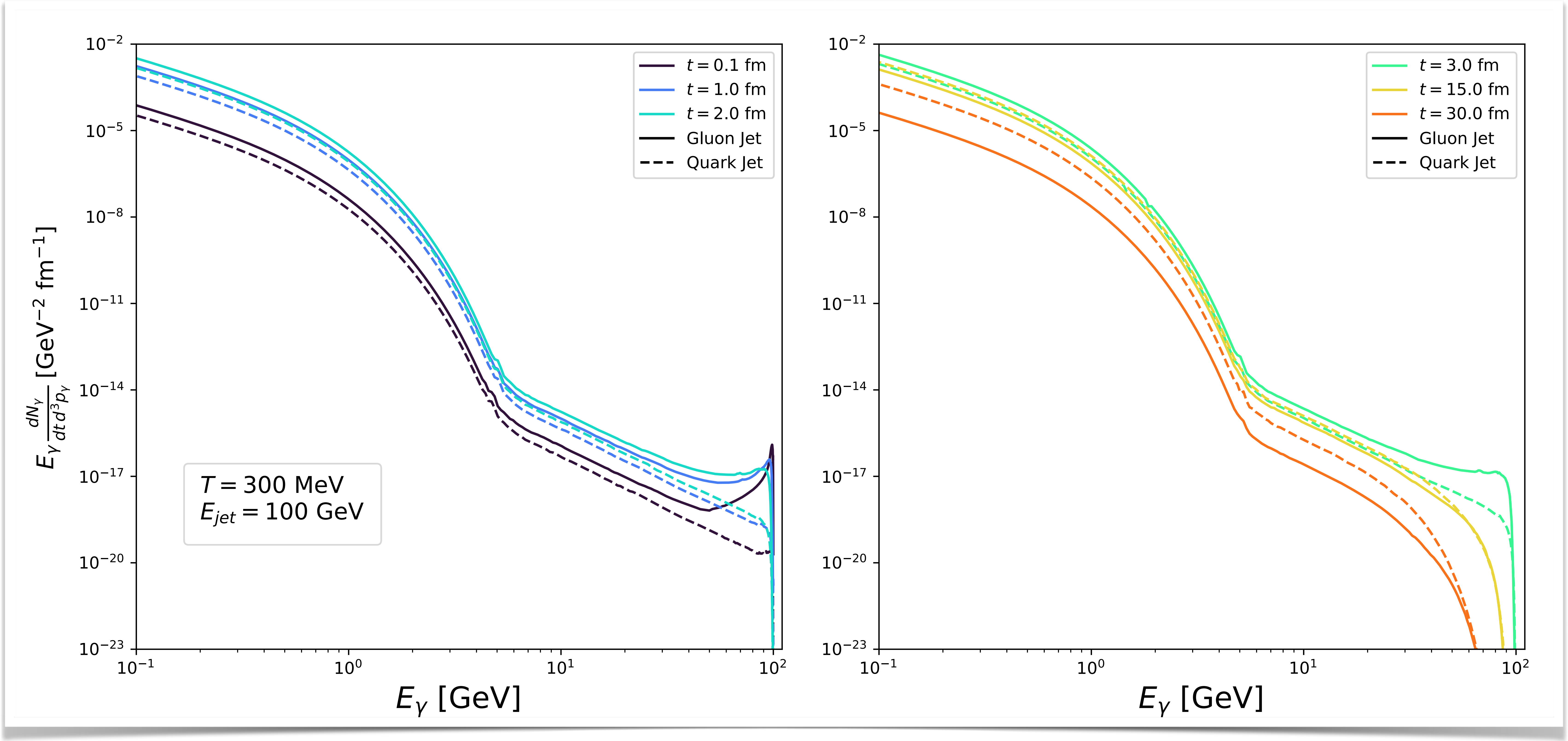
Static Medium



- low E_γ (< 5 GeV) thermally dominated
- Power law dependence for 5 GeV < E_γ < E_{jet}
- High-E_γ peak at $\sim E_{jet}$ for early times
- At first rising rates ($E_\gamma < E_{jet}$) followed by decreasing rates

Static Medium

Quark jet vs Gluon jet



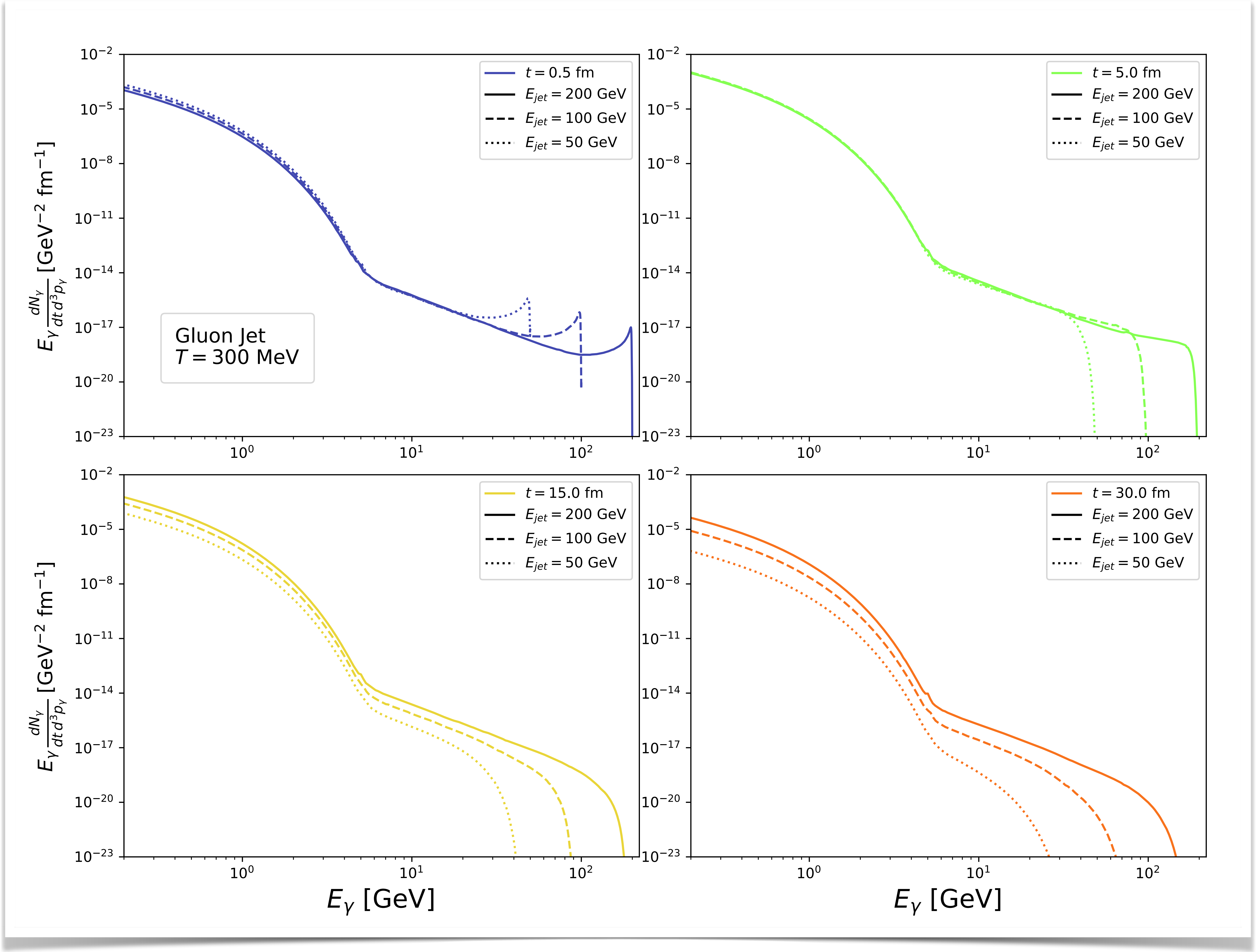
- Absence of initial high-E_γ peak

→ Due to Compton scattering

- Slower decrease

Static Medium

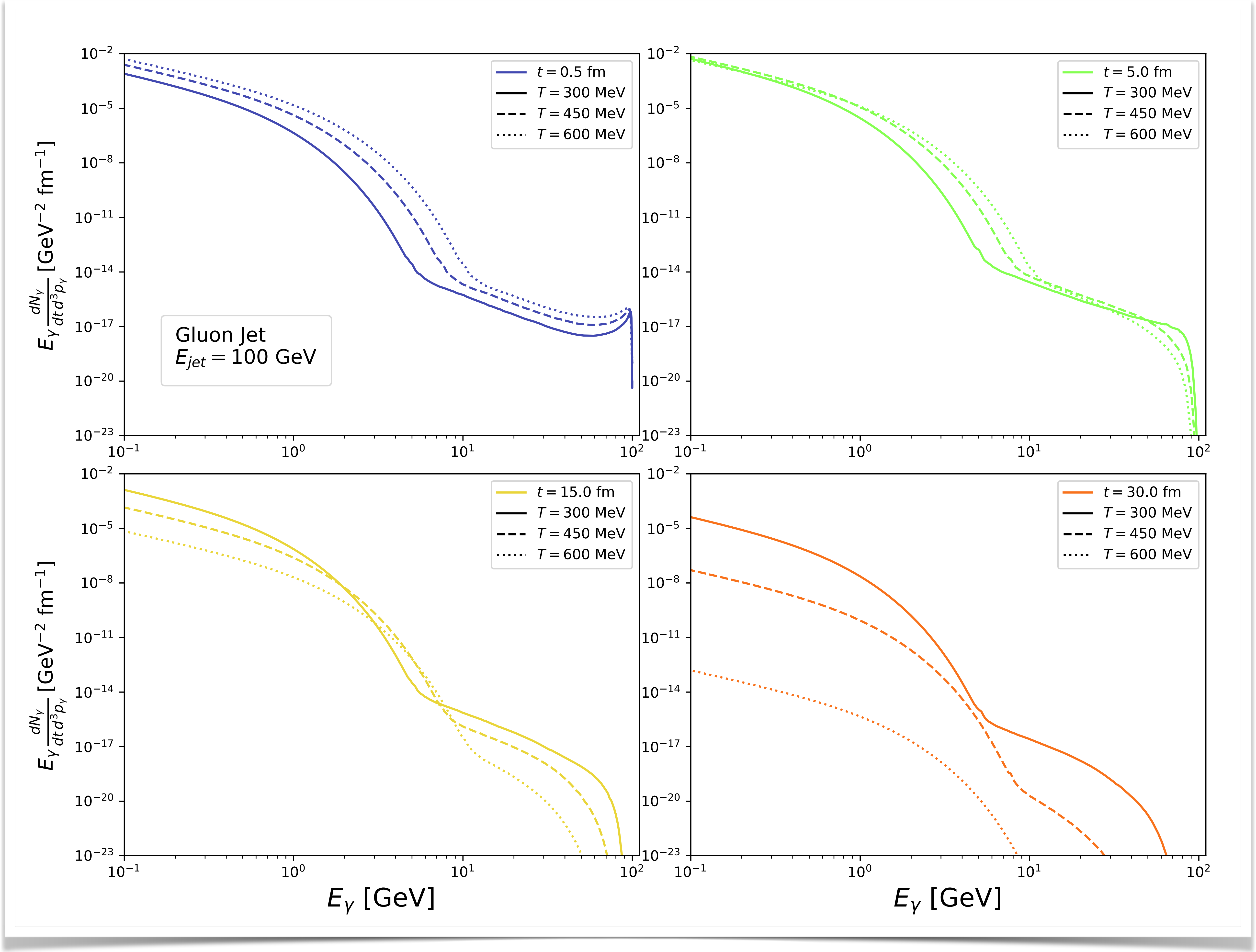
Jet energy comparison



- Photon rates for jets with less energy decrease faster

Static Medium

Medium temperature comparison



- Width of thermally dominated region bigger for higher T
- Initially higher photon production for higher T over all energy scales
- Photon rates for media with higher T decrease faster

Dynamical Evolution

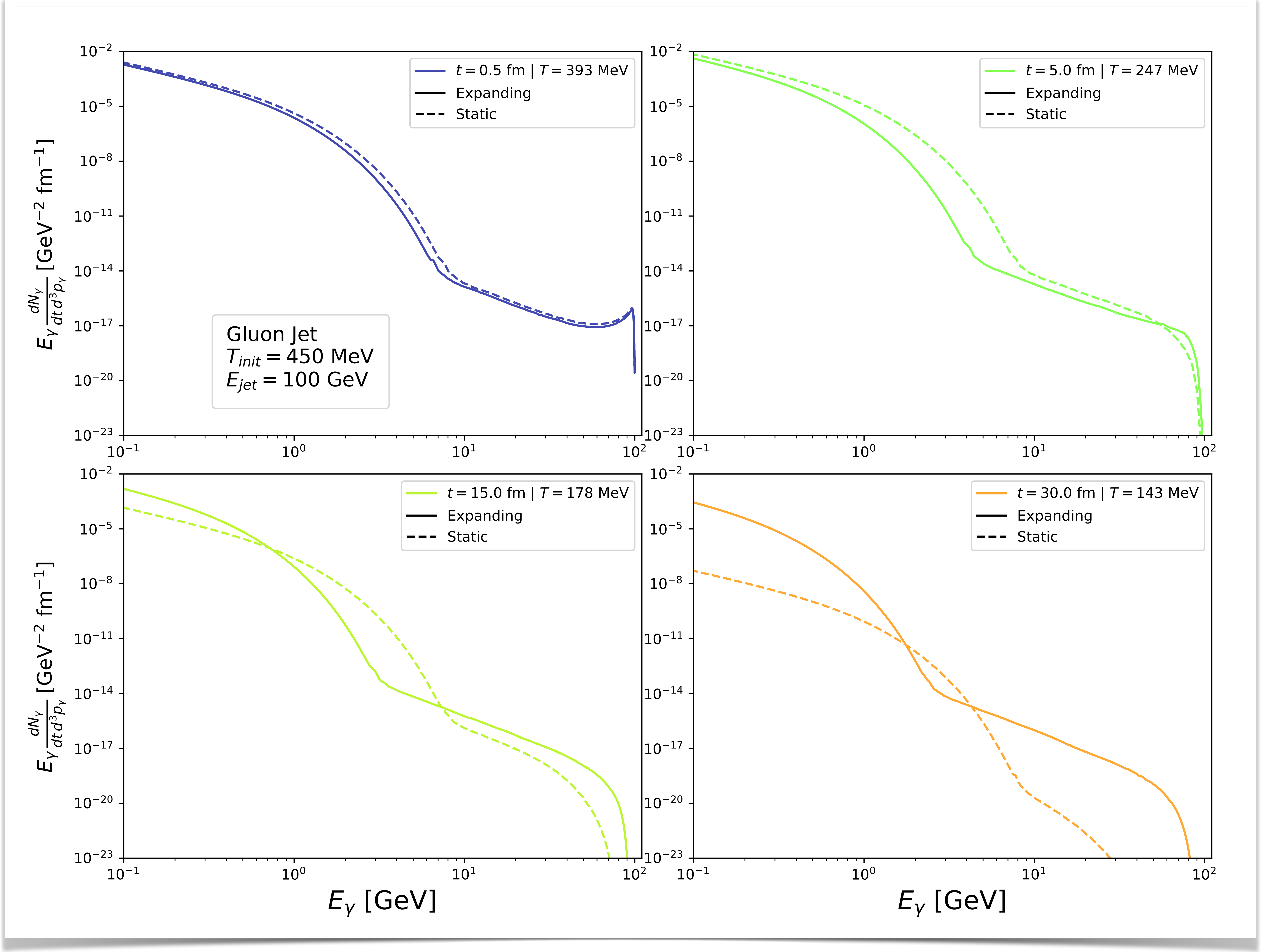
Bjorken expansion

- 1D Bjorken expanding medium
- Time-dependent medium temperature:

$$T(\tau) \; = \; T_{init} \left(\frac{\tau_{init}}{\tau} \right)^{1/3}$$

- Series of adiabatic temperature changes

Expanding Medium



- At earlier times, photon rates of the static medium are higher

  ➜ Higher thermal contributions

  ➜ Faster rise for smaller t

- Higher T imply faster decrease

  ➜ Rates for static medium smaller for bigger t

Summary

- Correlation of signatures of parton evolution and photon spectra:
  - power law dependence (energy flux)
  - peak at high energies
- Prediction of absence of high-E_γ peak for quark jet
- Analysis of how the photon spectrum depends on E_{jet} and T
- First improvement by introducing a Bjorken expanding medium

Outlook

- Further expanding the model
  - integrating rates over time
  - folding with distribution of jet production in HIC

→ Estimate of photon production from jet-medium interactions

- Including near-collinear bremsstrahlung

Backup Slides

Collision Terms

Parton evolution equation $\partial_t D_a(t,x) = C_a[\{D_i\}]$ where:

$$C_g[\{D_i\}] = \int_0^1 \mathrm{d}z \left(\frac{\mathrm{d}\Gamma^g_{gg}\left(\frac{xE_{jet}}{z}, z\right)}{\mathrm{d}z} D_g\left(\frac{x}{z}\right) - \frac{1}{2}\frac{\mathrm{d}\Gamma^g_{gg}\left(xE_{jet}, z\right)}{\mathrm{d}z} D_g(x) \right) - \int_0^1 \mathrm{d}z\, \frac{1}{2}\frac{\mathrm{d}\Gamma^g_{q\bar{q}}\left(xE_{jet}, z\right)}{\mathrm{d}z} D_g(x) + \int_0^1 \mathrm{d}z\, \frac{\mathrm{d}\Gamma^q_{gq}\left(\frac{xE_{jet}}{z}, z\right)}{\mathrm{d}z} D_S\left(\frac{x}{z}\right)$$

$$C_S[\{D_i\}] = \int_0^1 \mathrm{d}z \left(\frac{\mathrm{d}\Gamma^q_{gq}\left(\frac{xE_{jet}}{z}, 1-z\right)}{\mathrm{d}z} D_S\left(\frac{x}{z}\right) - \frac{\mathrm{d}\Gamma^q_{gq}\left(xE_{jet}, z\right)}{\mathrm{d}z} D_S(x) \right) + \int_0^1 \mathrm{d}z\, \frac{\mathrm{d}\Gamma^g_{q\bar{q}}\left(\frac{xE_{jet}}{z}, z\right)}{\mathrm{d}z} D_g\left(\frac{x}{z}\right)$$

$$C_{NS}[\{D_i\}] = \int_0^1 \mathrm{d}z \left(\frac{\mathrm{d}\Gamma^q_{gq}\left(\frac{xE_{jet}}{z}, 1-z\right)}{\mathrm{d}z} D_{NS}\left(\frac{x}{z}\right) - \frac{\mathrm{d}\Gamma^q_{gq}\left(xE_{jet}, z\right)}{\mathrm{d}z} D_{NS}(x) \right)$$

S. Schlichting and I. Soudi, arXiv:2008.04928 [hep-ph] (2020)

Collision Terms

Splitting rates:

$$\frac{\mathrm{d}\Gamma^{g}_{gg}\left(xE_{jet}, z\right)}{\mathrm{d}z} \simeq \frac{1}{\bar{t}_{br}(E_{jet})\sqrt{x}}\mathcal{K}_{gg}(z) = \frac{1}{\bar{t}_{br}(E_{jet})\sqrt{x}}C_A\frac{\left(1-z(1-z)\right)^2}{z(1-z)}\sqrt{\frac{(1-z)C_A+z^2C_A}{z(1-z)}}$$

$$\frac{\mathrm{d}\Gamma^{g}_{q\bar{q}}\left(xE_{jet}, z\right)}{\mathrm{d}z} \simeq \frac{1}{\bar{t}_{br}(E_{jet})\sqrt{x}}\mathcal{K}_{qg}(z) = \frac{1}{\bar{t}_{br}(E_{jet})\sqrt{x}}N_fT_F\left(z^2+(1-z)^2\right)\sqrt{\frac{C_F-z(1-z)C_A}{z(1-z)}}$$

$$\frac{\mathrm{d}\Gamma^{q}_{gq}\left(xE_{jet}, z\right)}{\mathrm{d}z} \simeq \frac{1}{\bar{t}_{br}(E_{jet})\sqrt{x}}\mathcal{K}_{gq}(z) = \frac{1}{\bar{t}_{br}(E_{jet})\sqrt{x}}\frac{C_F}{2}\frac{1+(1-z)^2}{z}\sqrt{\frac{(1-z)C_A+z^2C_F}{z(1-z)}}$$

$$\frac{\mathrm{d}\Gamma^{q}_{gq}\left(xE_{jet}, 1-z\right)}{\mathrm{d}z} \simeq \frac{1}{\bar{t}_{br}(E_{jet})\sqrt{x}}\mathcal{K}_{qq}(z) = \frac{1}{\bar{t}_{br}(E_{jet})\sqrt{x}}\mathcal{K}_{gq}(1-z)$$

Y. Mehtar-Tani and S. Schlichting, JHEP 09 (2018)
S. Schlichting and I. Soudi, arXiv:2008.04928 [hep-ph] (2020)

Photon Production Integral

Squared Amplitudes:

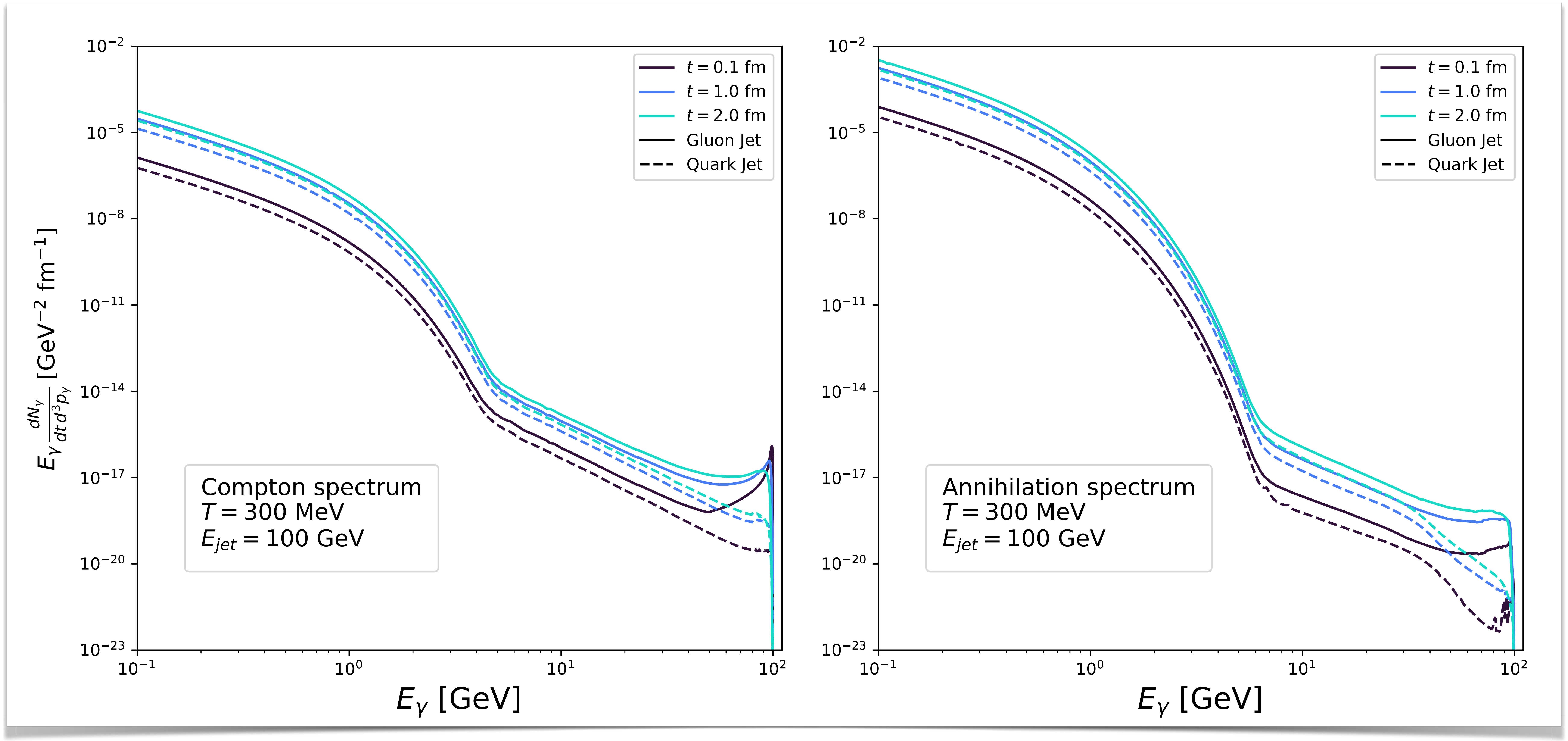
$$|\mathcal{M}_{anni}|^2 = \frac{64}{3} 16\pi^2 \alpha_{em}\,\alpha_s\,\frac{u^2+t^2}{ut}$$

$$|\mathcal{M}_{Comp}|^2 = \frac{128}{3} 16\pi^2 \alpha_{em}\,\alpha_s\,\frac{u^2+s^2}{-us}$$

Expression summed over all processes m and terms of order $\mathcal{O}(\delta f_i)$

$$E_\gamma \frac{\mathrm{d}N_\gamma}{\mathrm{d}t\ \mathrm{d}^3p_\gamma} = \frac{1}{2(2\pi)^8} \int \frac{\mathrm{d}^3p_1}{2E_1}\frac{\mathrm{d}^3p_2}{2E_2}\frac{\mathrm{d}^3p_3}{2E_3}\,\delta^4(P_1+P_2-P_3-P_\gamma)\sum_m \Big[|\mathcal{M}_m(P_1,P_2,P_3,P_\gamma)|^2 \times$$
$$\times\Big(n_1(|\vec{p}_1|)n_2(|\vec{p}_2|)\delta\bar{f}_3(t,\vec{r},\vec{p}) + n_1(|\vec{p}_1|)\delta\bar{f}_2(t,\vec{r},\vec{p})\,(1\pm n_3(|\vec{p}_3|)) + \delta\bar{f}_1(t,\vec{r},\vec{p})n_2(|\vec{p}_2|)\,(1\pm n_3(|\vec{p}_3|))\Big)\Big]$$

Comparison Annihilation and Compton



Static Medium

Parton Distributions different T