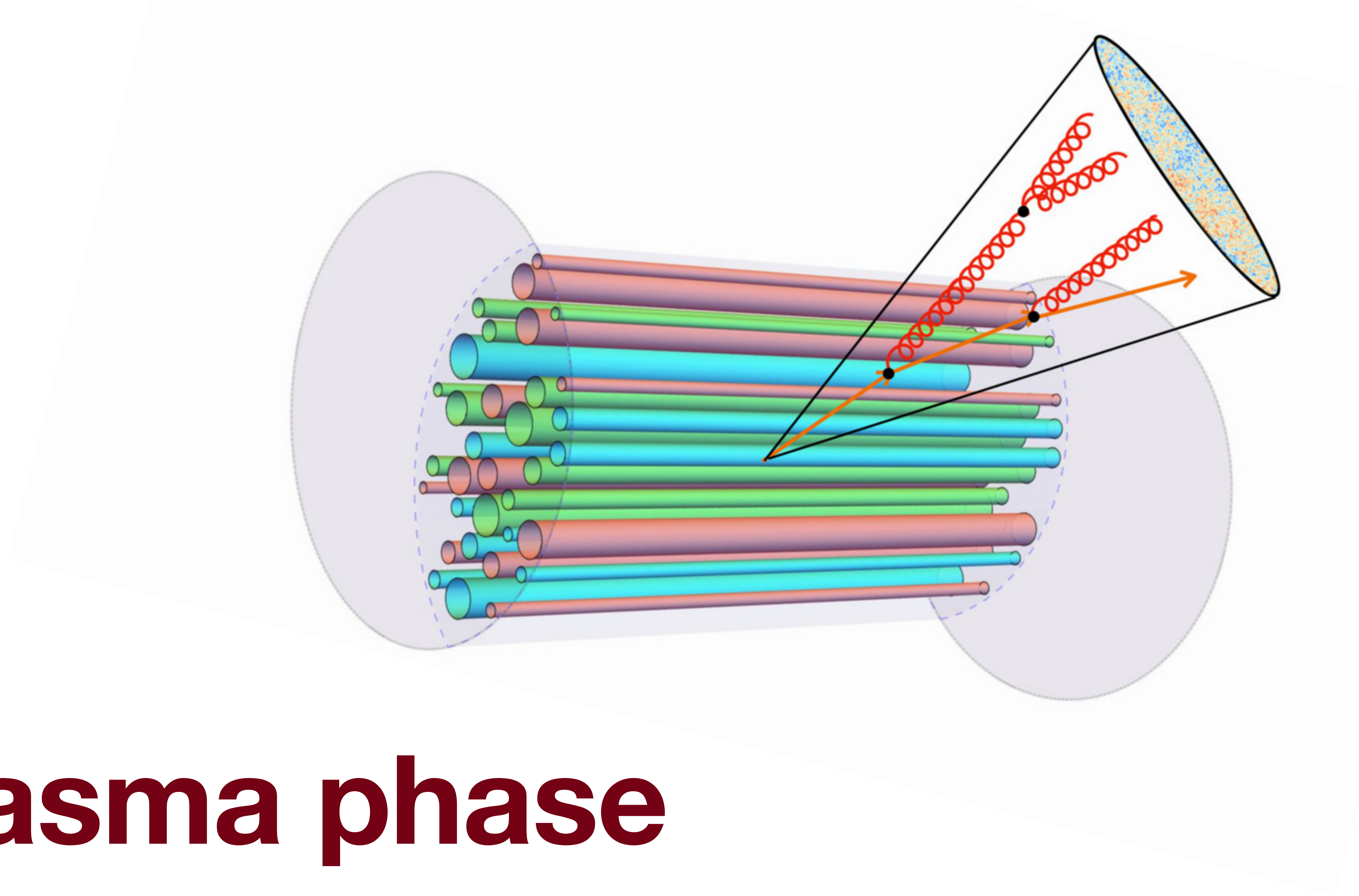

Jet quenching in the glasma phase

Xoán Mayo López, CTP-LI (MIT)

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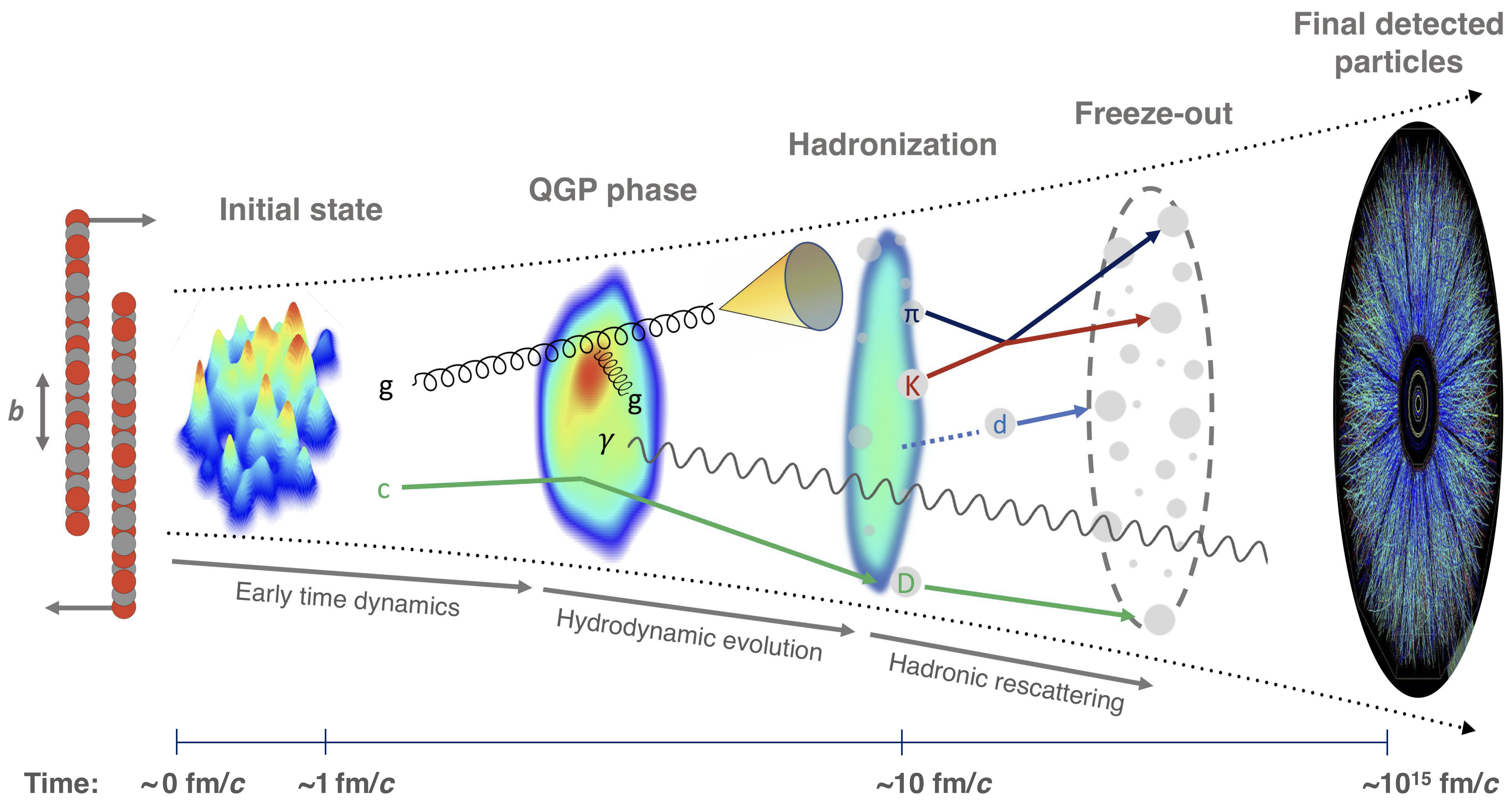
July 15th 2026, GSI

Based on 2406.07615 and 26xx.xxxxx

In collaboration with Avramescu, Barata, Hauksson, Lappi, Sadofyev

Production of qg matter



- Jet imaging: Jets as differential probes of the spatio-temporal structure of the thermal matter in HIC
- Modification of jet properties encodes information about the QGP characteristics and evolution

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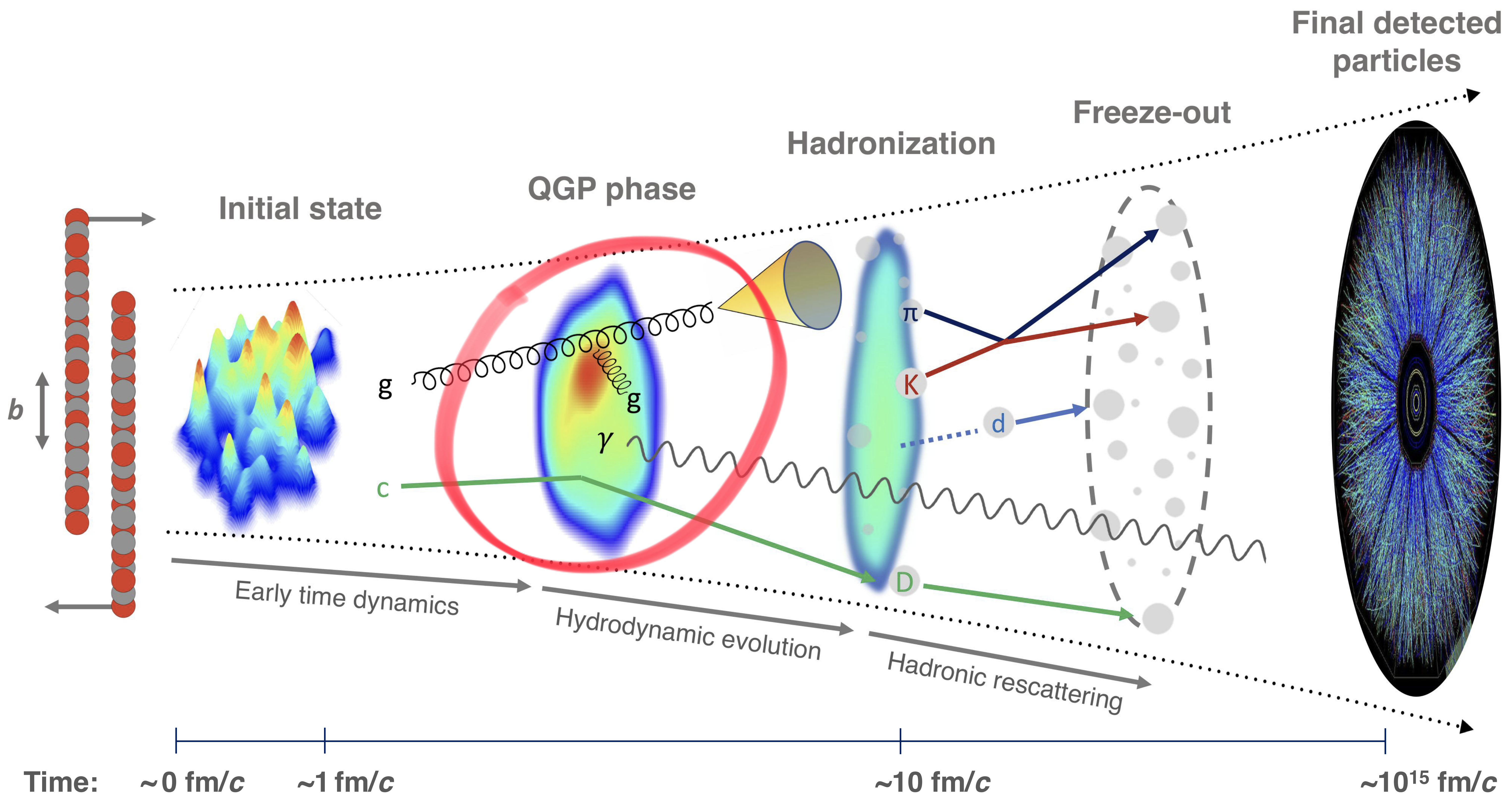
Jet quenching in the QGP phase



Formalism for weak coupling

Matter $\longrightarrow$ field produced by an stochastic ensamble of $SU(N_c)$ charged quasiparticles

Matter assumed static

$$gA^{a\mu}(q) = g^{\mu 0} \int_{\boldsymbol{x},z} e^{-i(\boldsymbol{q}\cdot\boldsymbol{x}+q_z z)} \hat{\rho}^a(\boldsymbol{x},z)\, v(q;\boldsymbol{x},z)\, (2\pi)\delta(q_0)$$

scattering potential

density of color sources

See e.g. Casalderrey-Solana, Salgado 2007

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scattering potential

density of color sources

Stochastic field $\longrightarrow$ need to specify the average over its configurations $\longrightarrow$ determined by properties of matter

Gaussian white noise statistics

$$\left\langle \hat{\rho}^a(\boldsymbol{x},z_x)\hat{\rho}^b(\boldsymbol{y},z_y)\right\rangle \propto \delta^{ab}\delta^{(2)}(\boldsymbol{x}-\boldsymbol{y})\,\delta(z_x-z_y)\,\rho(\boldsymbol{x},z_x)$$

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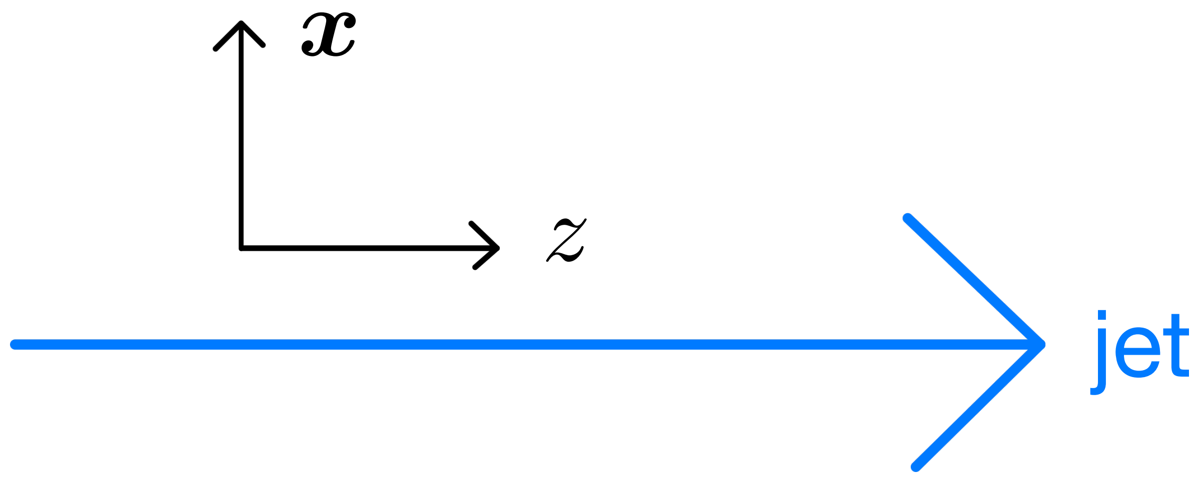

Transversely homogeneous matter

$$\rho(\boldsymbol{x},z_x) \simeq \rho(z_x)$$

See e.g. Casalderrey-Solana, Salgado 2007

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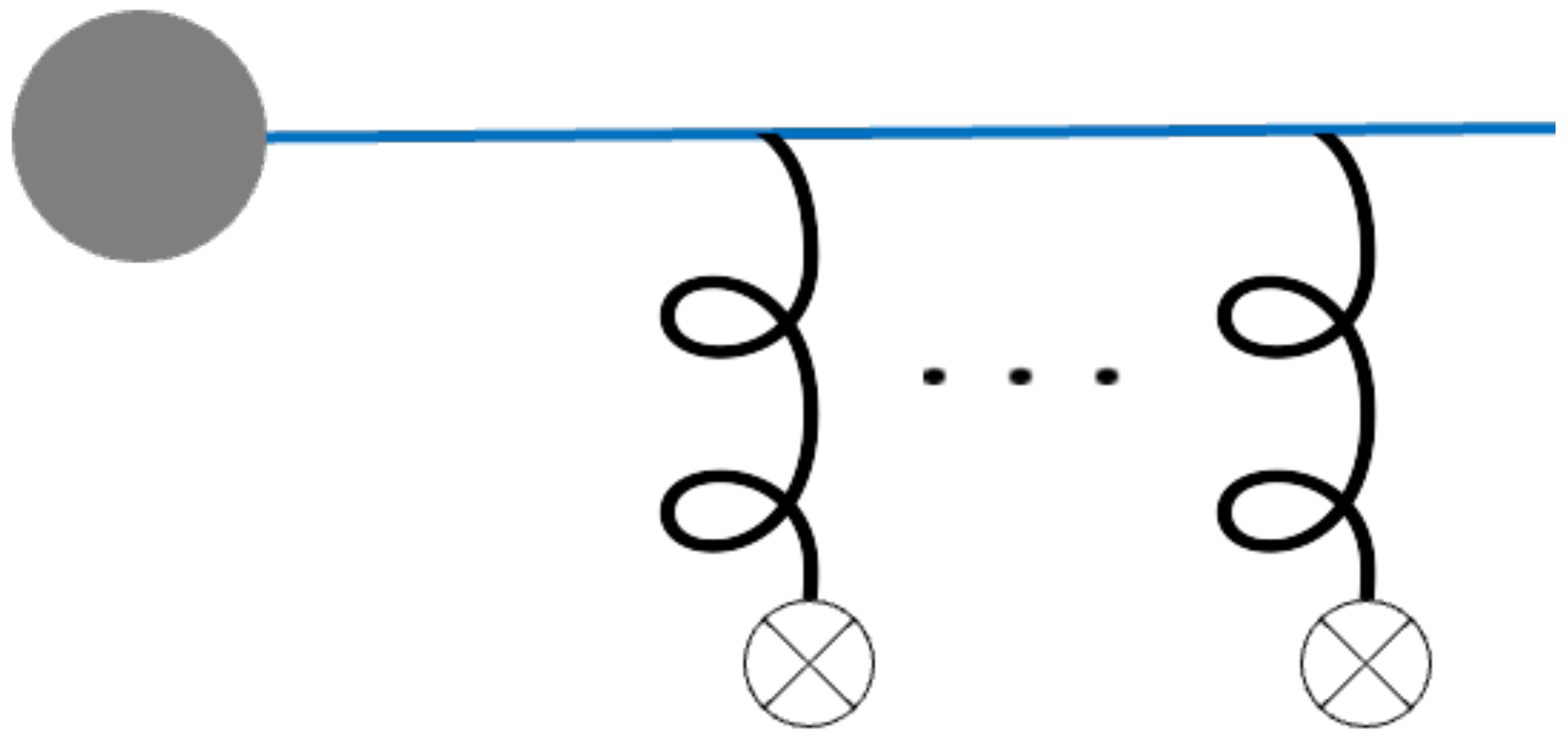
Jet quenching in the QGP phase

1. Broadening

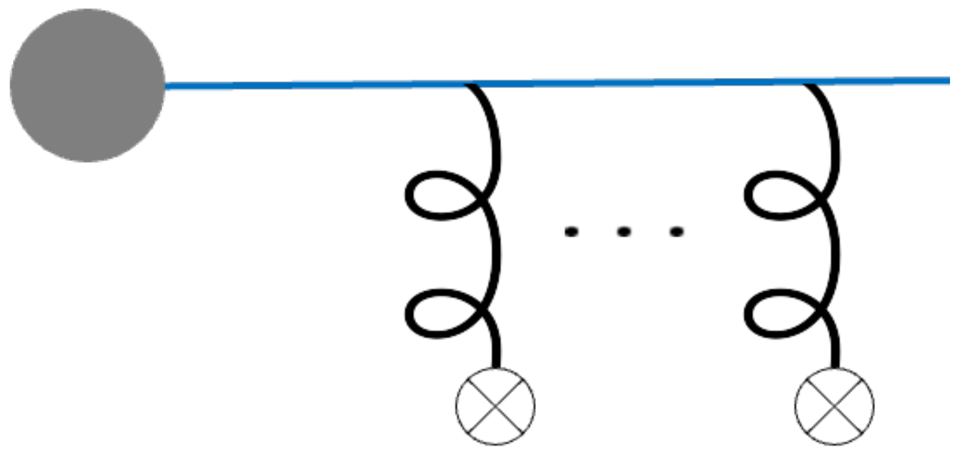
The propagator



The propagator

The interactions are resumed into effective propagators

$$M = \sum_n$$



$$\xrightarrow[\mu \Delta z \gg 1]{E \gg \perp \;\; E \gg \mu} \qquad iM(p) = \int \frac{d^2 \boldsymbol{p}_{in}}{(2\pi)^2} \, e^{i \frac{\boldsymbol{p}^2}{2E} L} \, \mathcal{G}(\boldsymbol{p}, L; \boldsymbol{p}_{in}, 0) \, J(E, \boldsymbol{p}_{in})$$

The propagator in position space

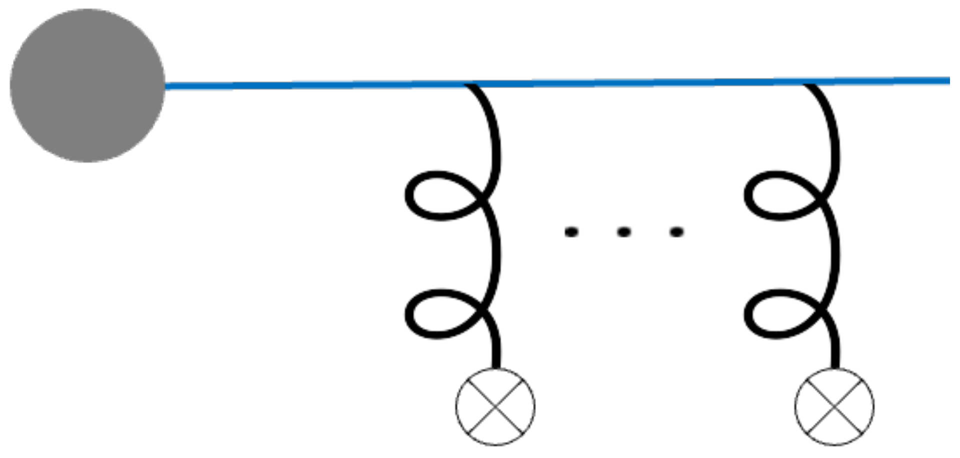
$$\mathcal{G}(\boldsymbol{x}_f, z_f; \boldsymbol{x_{in}}, z_{in}) = \int_{\boldsymbol{x}_{in}}^{\boldsymbol{x}_f} \mathcal{D}\boldsymbol{r} \; \exp\left\{ i \frac{E}{2} \int_{z_{in}}^{z_f} d\tau \, \dot{\boldsymbol{r}}^2 \right\} \mathcal{W}(\boldsymbol{r}; z_f, z_{in})$$

$$\mathcal{W}(\boldsymbol{r}; z_f, z_{in}) = \mathcal{P} \, \exp\left\{ i \int_{z_{in}}^{z_f} d\tau \, t^a \, \mathcal{A}^a(\boldsymbol{r}(\tau), \tau) \right\}$$

See e.g. Casalderrey-Solana, Salgado 2007

The propagator

The interactions are resummed into effective propagators

$$M = \sum_n$$ 

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$$\mathcal{A}^a(\boldsymbol{r}, z) = \int_{\boldsymbol{y}} \hat{\rho}^a(\boldsymbol{y}, z) v(\boldsymbol{r} - \boldsymbol{y})$$

See e.g. Casalderrey-Solana, Salgado 2007

The propagator

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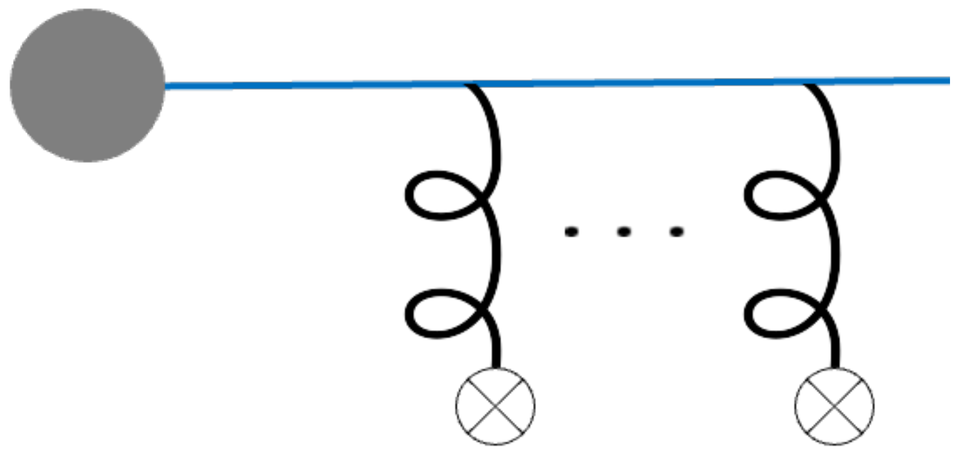

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$$\mathcal{G}(\boldsymbol{x}_f, z_f; \boldsymbol{x}_{in}, z_{in}) = \delta^{(2)}(\boldsymbol{x}_f - \boldsymbol{x}_{in})\, \mathcal{W}(\boldsymbol{x_f}; z_f, z_{in})$$

The propagator in position space

$$E \to \infty$$

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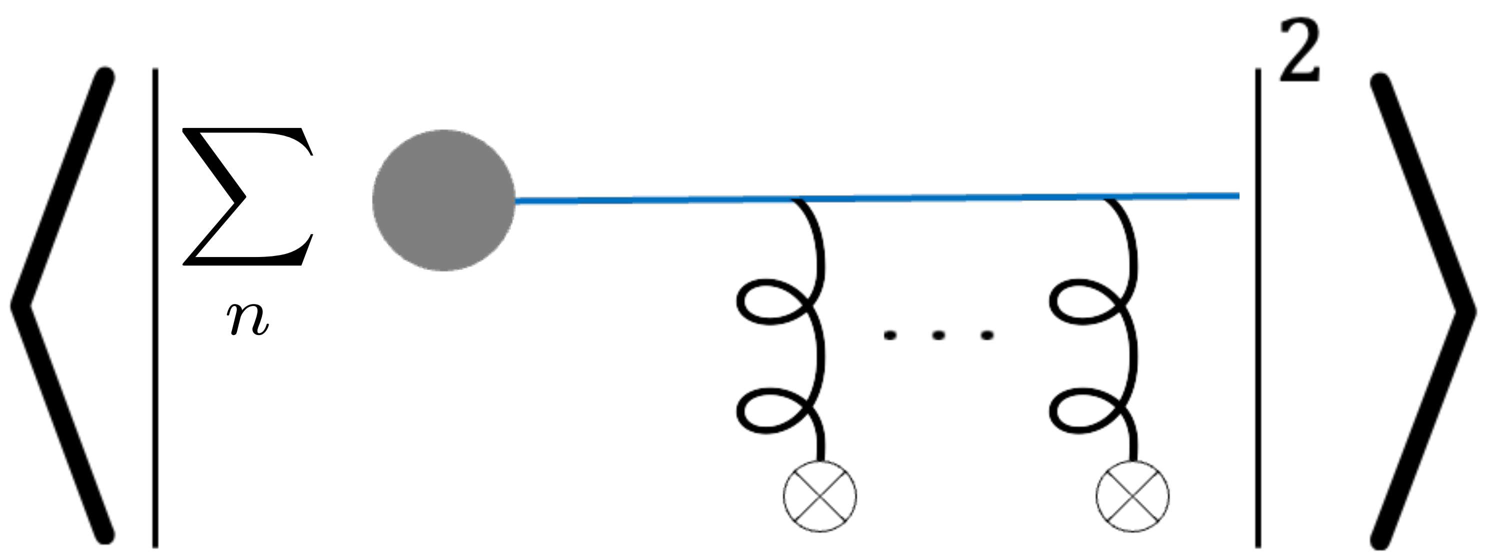
See e.g. Casalderrey-Solana, Salgado 2007

Broadening

The final state parton distribution

Squaring and averaging the resummed amplitude



$$E\,\frac{d\mathcal{N}}{d^2\boldsymbol{p}\,dE} \equiv \frac{1}{2(2\pi)^3}\left\langle |M(\boldsymbol{p})|^2 \right\rangle = \frac{1}{2(2\pi)^3}\int_{\boldsymbol{p}_{in},\bar{\boldsymbol{p}}_{in}} \langle J^\dagger(E,\bar{\boldsymbol{p}}_{in})\mathcal{G}^\dagger(\boldsymbol{p},L;\bar{\boldsymbol{p}}_{in})\mathcal{G}(\boldsymbol{p},L;\boldsymbol{p}_{in})J^\dagger(E,\boldsymbol{p}_{in})\rangle$$

Moments of the distribution $\quad \langle \boldsymbol{p}_{\alpha_1}\ldots\boldsymbol{p}_{\alpha_n}\rangle \equiv \dfrac{\int_{\boldsymbol{p}}(\boldsymbol{p}_{\alpha_1}\ldots\boldsymbol{p}_{\alpha_n})\,E\,\frac{d\mathcal{N}}{d^2p\,dE}}{\int_{\boldsymbol{p}}E\,\frac{d\mathcal{N}^{(0)}}{d^2p\,dE}}$

Jet quenching parameter $\quad \hat{q} \equiv \dfrac{\delta}{\delta L}\left\langle \boldsymbol{p}^2\right\rangle$

See e.g. Casalderrey-Solana, Salgado 2007

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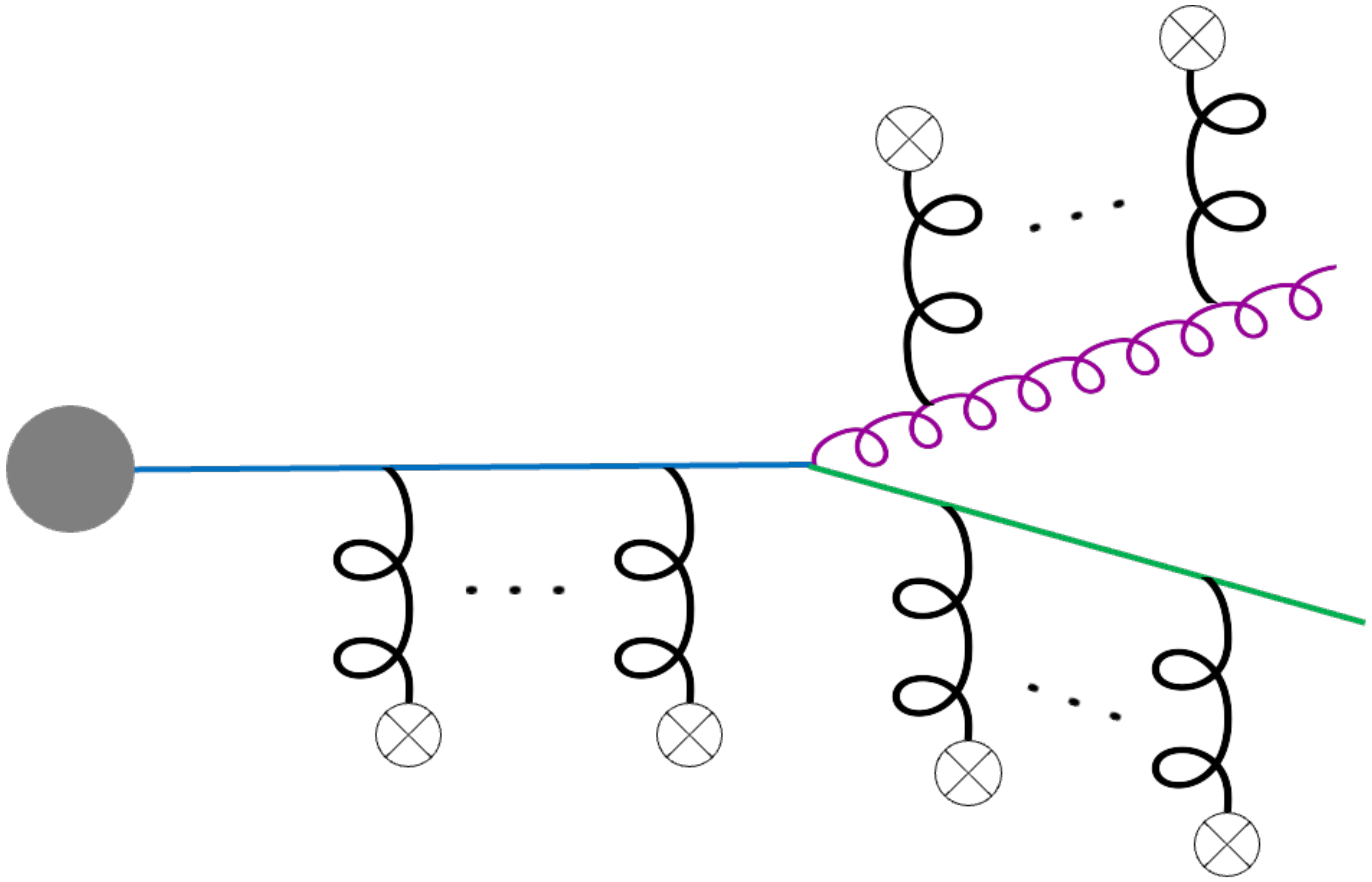
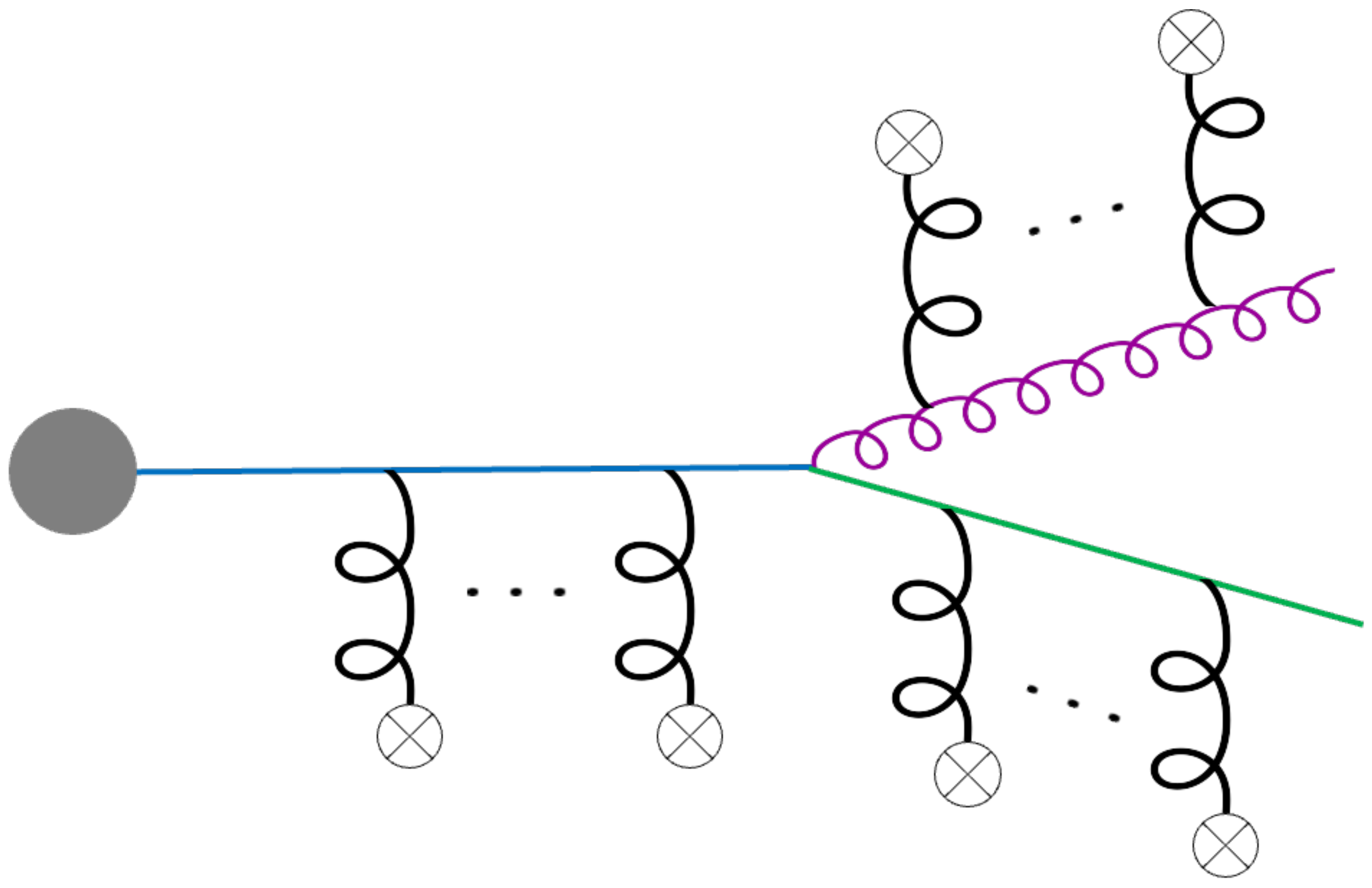
Jet quenching in the QGP phase

2. Radiation



Soft gluon radiation

The relevant diagram for the medium-induced gluon spectrum in the dense regime



Simplifying assumptions:

$E \to \infty$	Eikonal limit for quarks
$E \gg \omega$	Soft gluon approximation
$\omega \gg \perp, \mu$	But still highly energetic

The amplitude can be resummed to the simple form

$$i\mathcal{R} \simeq -\frac{g}{\omega} \lim_{z_f \to \infty} \int_0^\infty dz_s \int_{\boldsymbol{x}_{in}} e^{-i\boldsymbol{x}_{in}\cdot l} J(E, \boldsymbol{x}_{in}) \mathcal{W}(\boldsymbol{x}_{in}; \infty, z_s) t^a_{proj} \mathcal{W}(\boldsymbol{x}_{in}; z_s, 0)\, e^{i\frac{\boldsymbol{k}^2}{2\omega} z_f} \left[\boldsymbol{\epsilon} \cdot \boldsymbol{\nabla}_{\boldsymbol{x}_{in}} \mathcal{G}^{ba}(\boldsymbol{k}, z_f; \boldsymbol{x}_{in}, z_s)\right]$$

See e.g. Casalderrey-Solana, Salgado 2007

Soft gluon radiation

The final parton distribution reads

$$2(2\pi)^3\omega E\frac{d\mathcal{N}}{d\omega dE d^2\boldsymbol{k}} = \lim_{z_f\to\infty}\frac{\alpha_s}{N_c\omega^2}\Re\int_0^\infty d\bar{z}\int_0^{\bar{z}} dz\int_{\boldsymbol{x}_{in},\boldsymbol{y}}|J(E,\boldsymbol{x}_{in})|^2\Big[\boldsymbol{\nabla}_{\boldsymbol{x}}\cdot\boldsymbol{\nabla}_{\bar{\boldsymbol{x}}}$$

$$\times\left\langle\mathcal{G}^{\dagger,\bar{a}b}(\boldsymbol{k},L;\bar{\boldsymbol{x}},\bar{z})\mathcal{G}^{bc}(\boldsymbol{k},L;\boldsymbol{y},\bar{z})\,\mathcal{G}^{ca}(\boldsymbol{y},\bar{z};\boldsymbol{x},z)\mathcal{W}^{\dagger,a\bar{a}}(\boldsymbol{x}_{in};\bar{z},z)\right\rangle\Big]_{\boldsymbol{x}=\bar{\boldsymbol{x}}=\boldsymbol{x}_{in}}$$

Medium averages local in thermal matter $\left\langle\hat{\rho}^a(\boldsymbol{x},z)\hat{\rho}^b(\boldsymbol{y},\bar{z})\right\rangle\propto\delta(z-\bar{z})$

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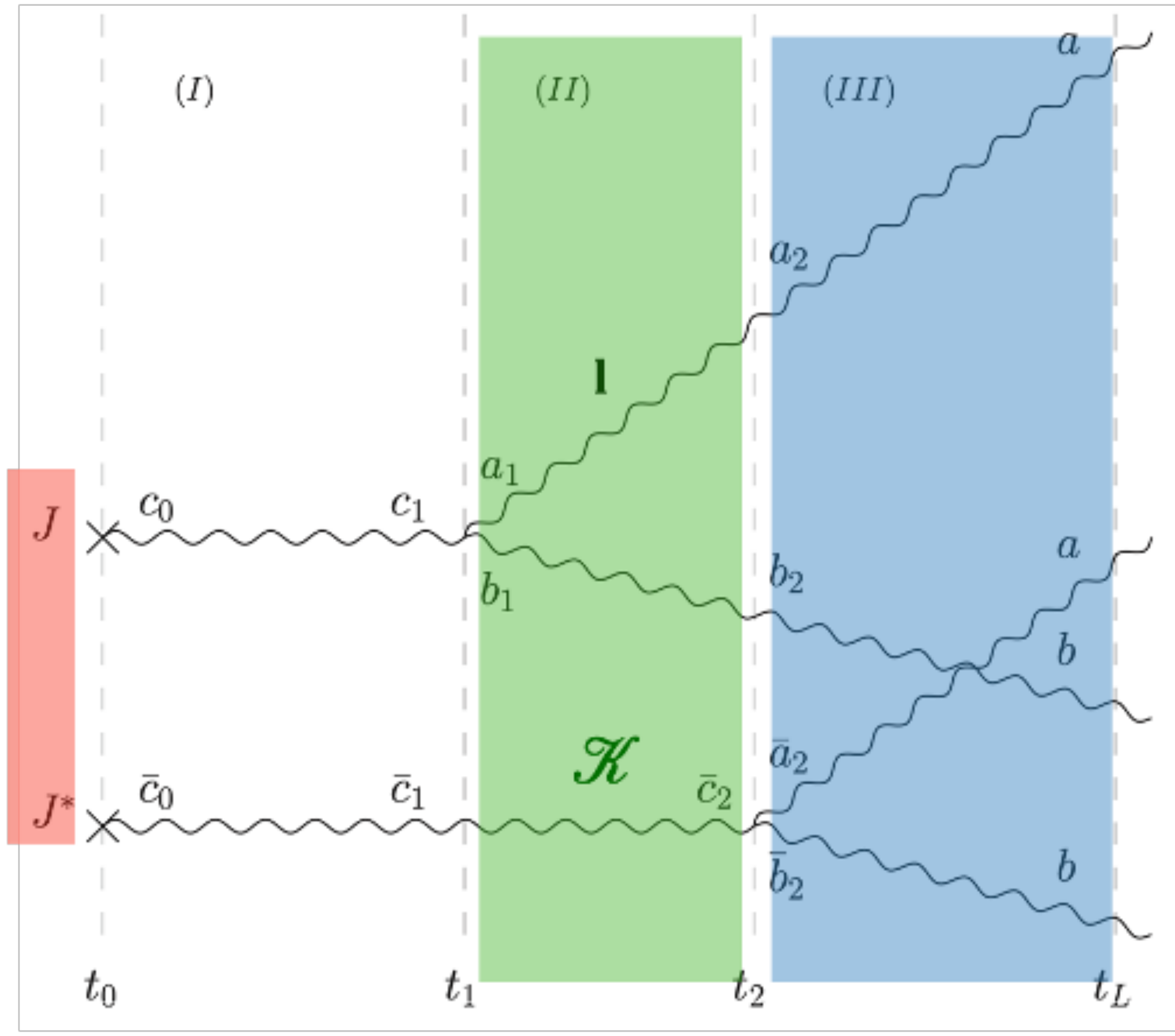

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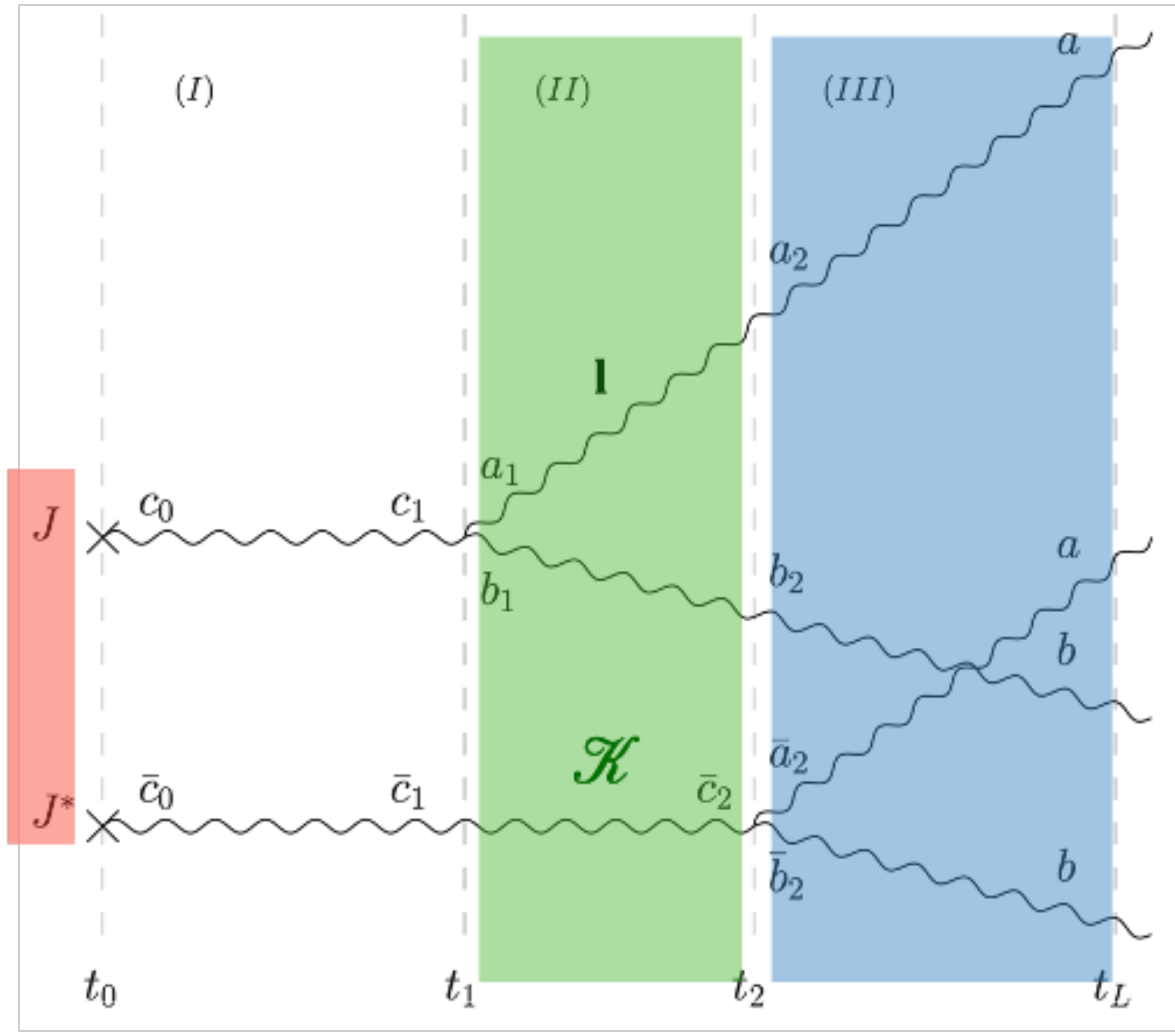
$$\times\left[\boldsymbol{\nabla}_{\boldsymbol{x}}\cdot\boldsymbol{\nabla}_{\bar{\boldsymbol{x}}} S_2\left(\boldsymbol{k},\boldsymbol{k},z_f;\boldsymbol{y},\bar{\boldsymbol{x}},\bar{z}\right)\mathcal{K}\left(\boldsymbol{y},\boldsymbol{x}_{in},\bar{z};\boldsymbol{x},\boldsymbol{x}_{in},z\right)\right]\Big|_{\boldsymbol{x}=\bar{\boldsymbol{x}}=\boldsymbol{x}_{in}}$$

Radiative kernel   Broadening kernel



See e.g. Casalderrey-Solana, Salgado 2007

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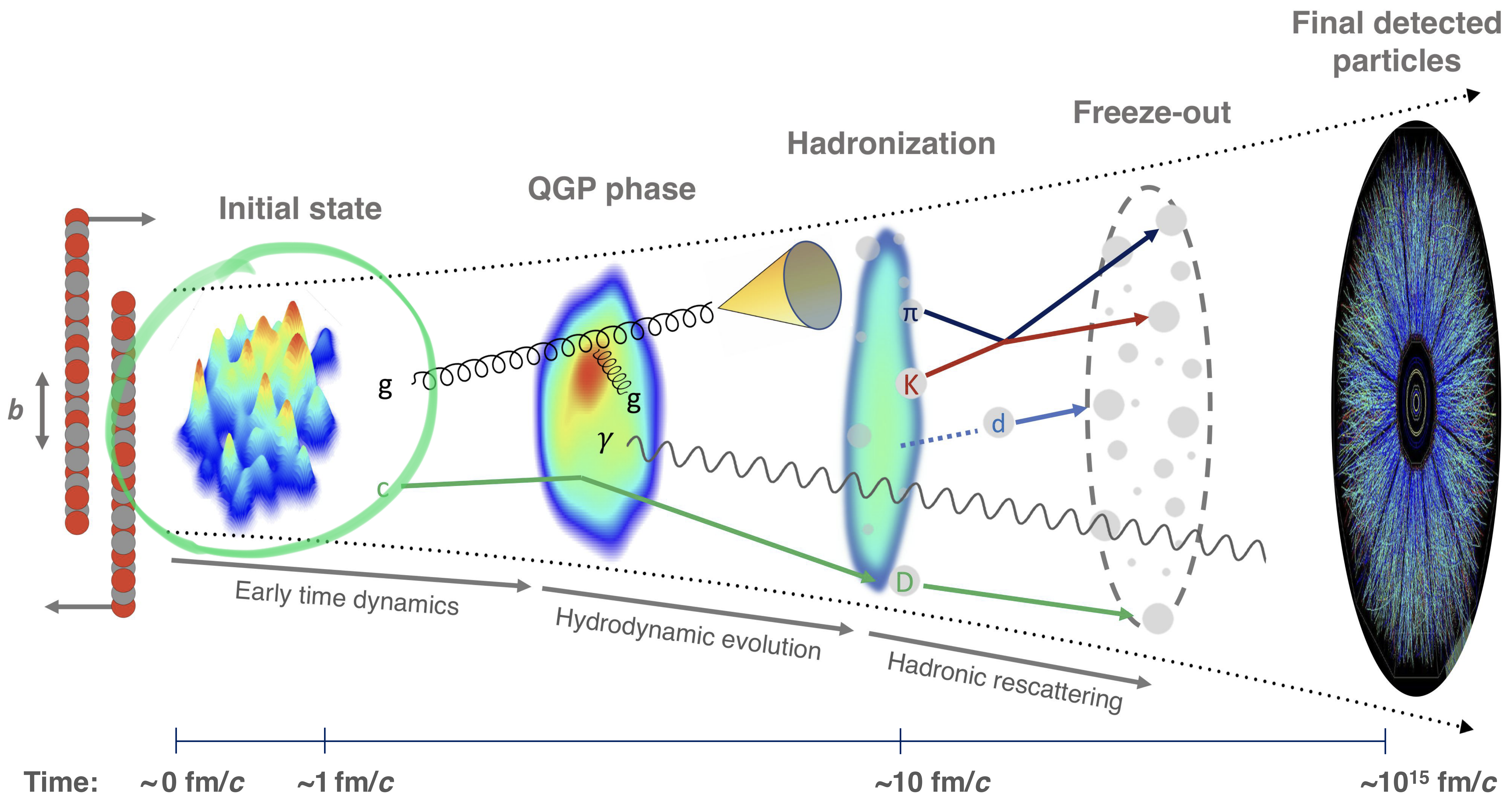
Jet quenching in the Glasma phase



The glasma

The Glasma is formed when the color fields in each nucleus start interacting just after the initial collisions

The matter has an intrinsic scale Q_s saturation scale

Finite correlation length $\sim 1/Q_s$

See e.g. Carrington, Czajka, Mrowczynski, NPA, 2020
Ipp, Müller, Schuh, PRD, 2020
Ipp, Müller, Schuh, PLB, 2020
Carrington, Czajka, Mrowczynski, PLB, 2022
Carrington, Czajka, Mrowczynski, PRC, 2022
Avramescu et al., PRD, 2023
Hauksson, Jeon, Gale, PRC, 2022
Boguslavski et al., PLB, 2024
Boguslavski et al., PLB, 2024

Confinements of gluons fields in domains of size $\sim 1/Q_s$ change the physics

No ultra local correlation from the hydrodynamic stage $\langle A(z_1)A(z_2)\rangle \nsim \delta(z_1 - z_2)$

The Glasma is short-lived but the energy density is very high

Estimates show a contribution to energy loss comparable to the QGP

Need to include the feature of the matter in the jet quenching description

Simple Glasma model for jet quenching

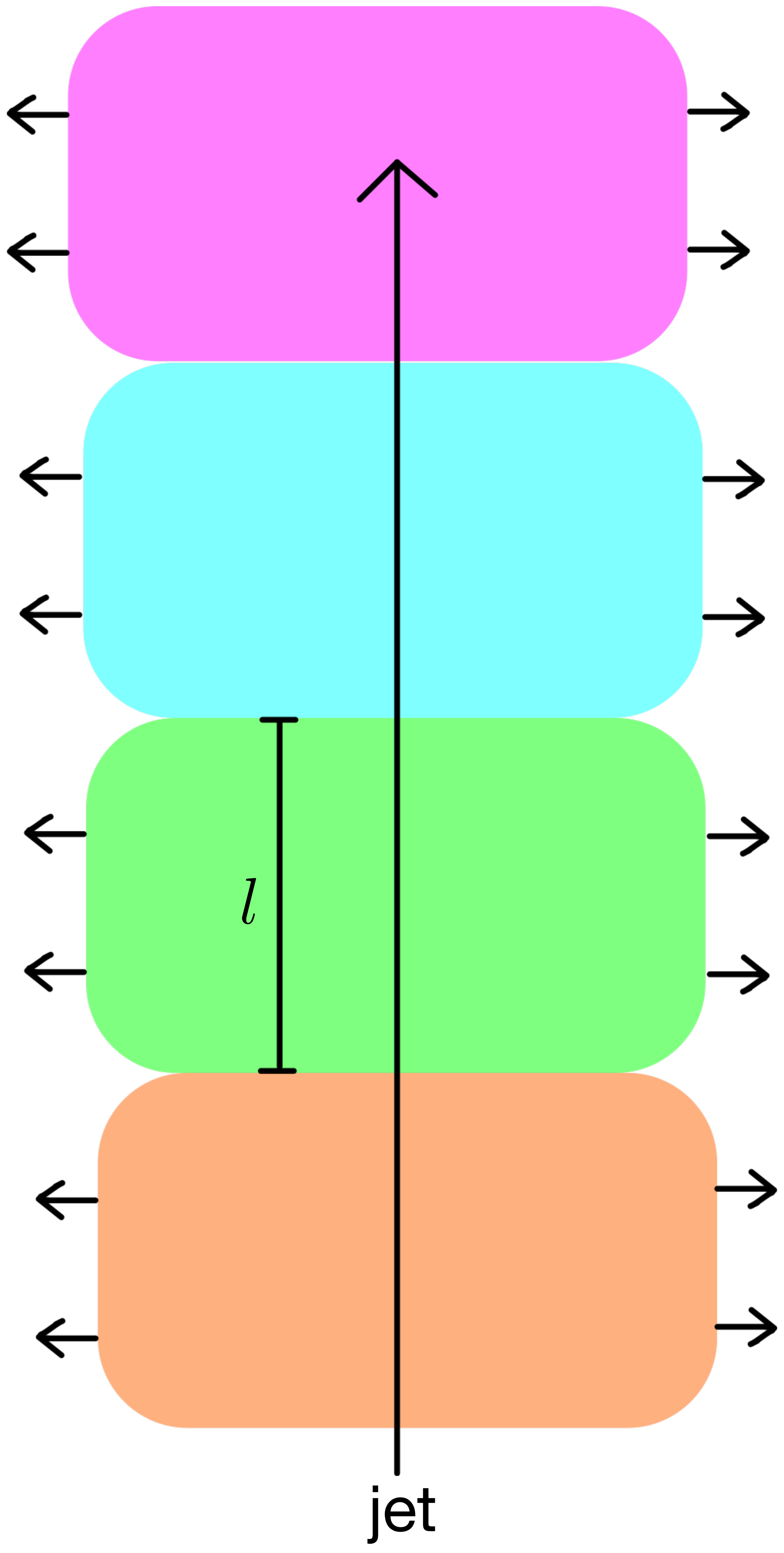
Leading parting moving at mid-rapidity along the z-axis

Packed stack of transversely infinite slabs of thickness $l \sim 1/Q_s$

$$gA^{a\mu}(\boldsymbol{x}, z) = \delta^{\mu 0}\, \boldsymbol{x} \cdot \boldsymbol{E}^a(z) = \begin{cases} \delta^{\mu 0}\boldsymbol{x} \cdot \boldsymbol{E}_1^a, & 0 \leq z < l \\ \delta^{\mu 0}\boldsymbol{x} \cdot \boldsymbol{E}_2^a, & l \leq z < 2l \\ \delta^{\mu 0}\boldsymbol{x} \cdot \boldsymbol{E}_3^a, & 2l \leq z < 3l \\ \vdots \end{cases}$$

Finite correlation of the color fields

$$\langle f(E_1^a, E_2^a, E_3^a, \cdots)\rangle = \int_{E_1} e^{-E_1^2/E_0^2} \int_{E_2} e^{-E_2^2/E_0^2} \cdots f(E_1^a, E_2^a, E_3^a, \cdots)$$



See Barata, Hauksson, XML, Sadofyev PRD 2024

Jet quenching in the Glasma phase

1. Broadening

Broadening in the Glasma

The resummation remains unmodified

$$\hat{q} \equiv \frac{\delta}{\delta L}\left\langle \boldsymbol{p}^2 \right\rangle = -\frac{1}{\mathcal{N}}\frac{1}{2(2\pi)^3}\frac{\partial}{\partial L}\int_{\boldsymbol{x}} \boldsymbol{\nabla}^2_{\boldsymbol{x}-\bar{\boldsymbol{x}}} \left(J^*(E,\bar{\boldsymbol{x}})\,\mathcal{W}^\dagger(\bar{\boldsymbol{x}})\,\mathcal{W}(\boldsymbol{x})\,J(E,\boldsymbol{x})\right)_{\bar{\boldsymbol{x}}=\boldsymbol{x}}$$

Assuming no net color for the initial distribution

$$\frac{1}{\mathcal{N}}\frac{1}{2(2\pi)^3}\,J(E,\boldsymbol{p})J^*(E,\bar{\boldsymbol{p}}) = \frac{1}{2\pi w^2}\,e^{-\frac{\boldsymbol{p}^2+\bar{\boldsymbol{p}}}{4w^2}}$$

$$\langle\hat{q}\rangle_{SU(N_c),z_{in}} = \frac{N_c^2-1}{16\pi^2}\,E_0^2\,l$$

See Barata, Hauksson, XML, Sadofyev PRD 2024

Broadening in the Glasma

The resummation remains unmodified

$$\mathcal{W}(\boldsymbol{r}; z_f, z_{in}) = \mathcal{P}\exp\left\{ i\int_{z_{in}}^{z_f} d\tau\, t^a\, \mathcal{A}^a(\boldsymbol{r}(\tau),\tau) \right\}$$

$$\downarrow$$

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Jet quenching in the Glasma phase

2. Radiation

Radiation in the QGP

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$$2(2\pi)^3\omega E\frac{d\mathcal{N}}{d\omega dE d^2\boldsymbol{k}} = \lim_{z_f\to\infty}\frac{\alpha_s}{N_c\omega^2}\Re\int_0^\infty d\bar{z}\int_0^{\bar{z}} dz\int_{\boldsymbol{x}_{in},\boldsymbol{y}}|J(E,\boldsymbol{x}_{in})|^2\Big[\boldsymbol{\nabla}_{\boldsymbol{x}}\cdot\boldsymbol{\nabla}_{\bar{\boldsymbol{x}}}$$
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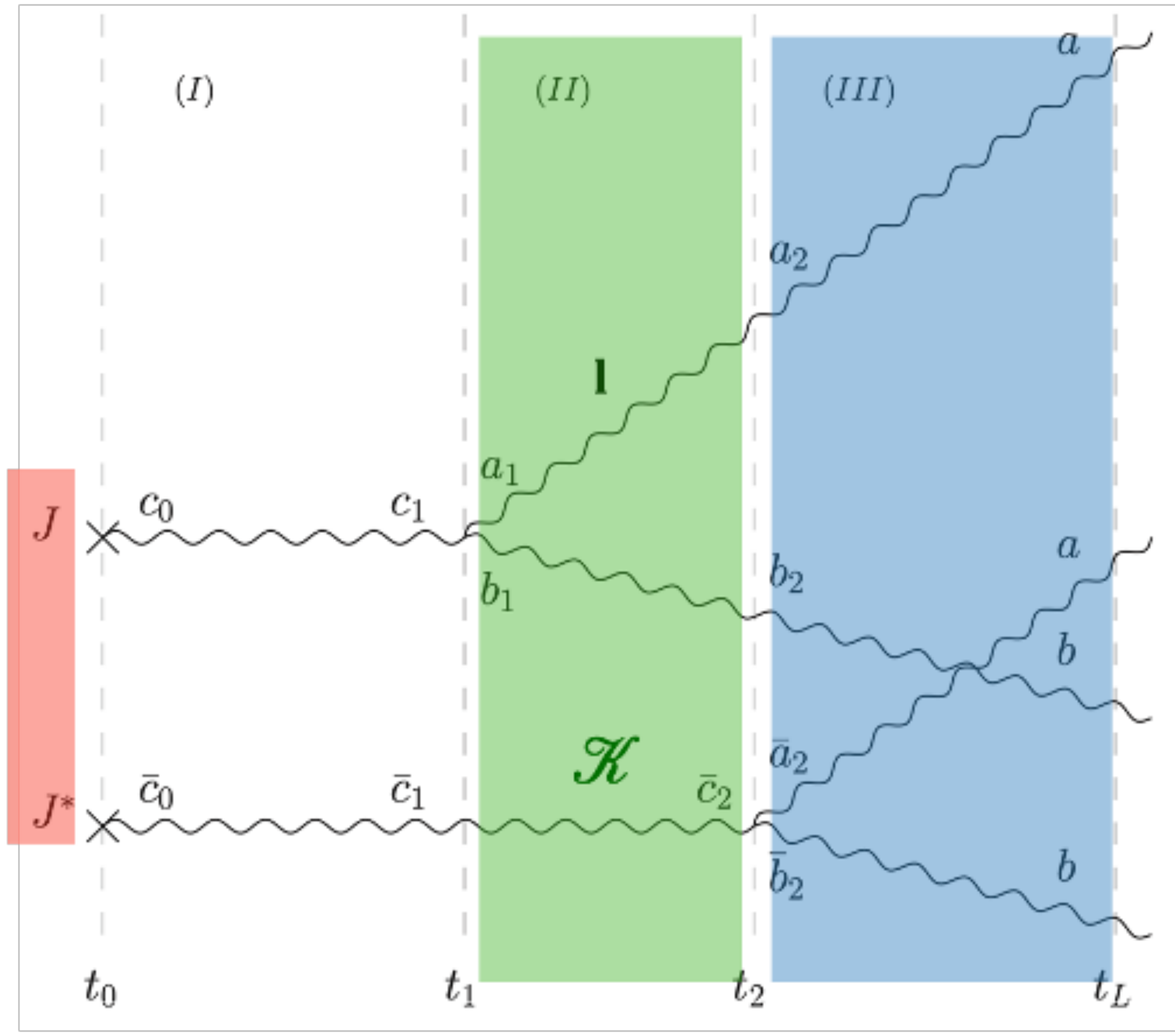
Medium averages local in thermal matter $\langle\hat{\rho}^a(\boldsymbol{x},z)\hat{\rho}^b(\boldsymbol{y},\bar{z})\rangle\propto\delta(z-\bar{z})$

$$2(2\pi)^3\omega E\frac{d\mathcal{N}}{d\omega dE d^2\boldsymbol{k}} = \lim_{z_f\to\infty}\frac{2\alpha_s C_F}{\omega^2}\Re\int_0^\infty d\bar{z}\int_0^{\bar{z}} dz\int_{\boldsymbol{x}_{in},\boldsymbol{y}}|J(E,\boldsymbol{x}_{in})|^2$$
$$\times\Big[\boldsymbol{\nabla}_{\boldsymbol{x}}\cdot\boldsymbol{\nabla}_{\bar{\boldsymbol{x}}}S_2\left(\boldsymbol{k},\boldsymbol{k},z_f;\boldsymbol{y},\bar{\boldsymbol{x}},\bar{z}\right)\mathcal{K}\left(\boldsymbol{y},\boldsymbol{x}_{in},\bar{z};\boldsymbol{x},\boldsymbol{x}_{in},z\right)\Big]\Big|_{\boldsymbol{x}=\bar{\boldsymbol{x}}=\boldsymbol{x}_{in}}$$

Radiative kernel

Broadening kernel



See Barata, Hauksson, XML, Sadofyev PRD 2024

Radiation in the QGP

The final parton distribution reads

$$2(2\pi)^3\omega E\frac{d\mathcal{N}}{d\omega dEd^2\boldsymbol{k}} = \lim_{z_f\to\infty}\frac{\alpha_s}{N_c\omega^2}\Re\int_0^\infty d\bar z\int_0^{\bar z}dz\int_{\boldsymbol{x}_{in},\boldsymbol{y}}|J(E,\boldsymbol{x}_{in})|^2\Big[\boldsymbol{\nabla}_{\boldsymbol{x}}\cdot\boldsymbol{\nabla}_{\bar{\boldsymbol{x}}}$$

$$\times\left\langle\mathcal{G}^{\dagger,\bar a b}(\boldsymbol{k},L;\bar{\boldsymbol{x}},\bar z)\mathcal{G}^{bc}(\boldsymbol{k},L;\boldsymbol{y},\bar z)\,\mathcal{G}^{ca}(\boldsymbol{y},\bar z;\boldsymbol{x},z)\mathcal{W}^{\dagger,a\bar a}(\boldsymbol{x}_{in};\bar z,z)\right\rangle\Big]_{\boldsymbol{x}=\bar{\boldsymbol{x}}=\boldsymbol{x}_{in}}$$

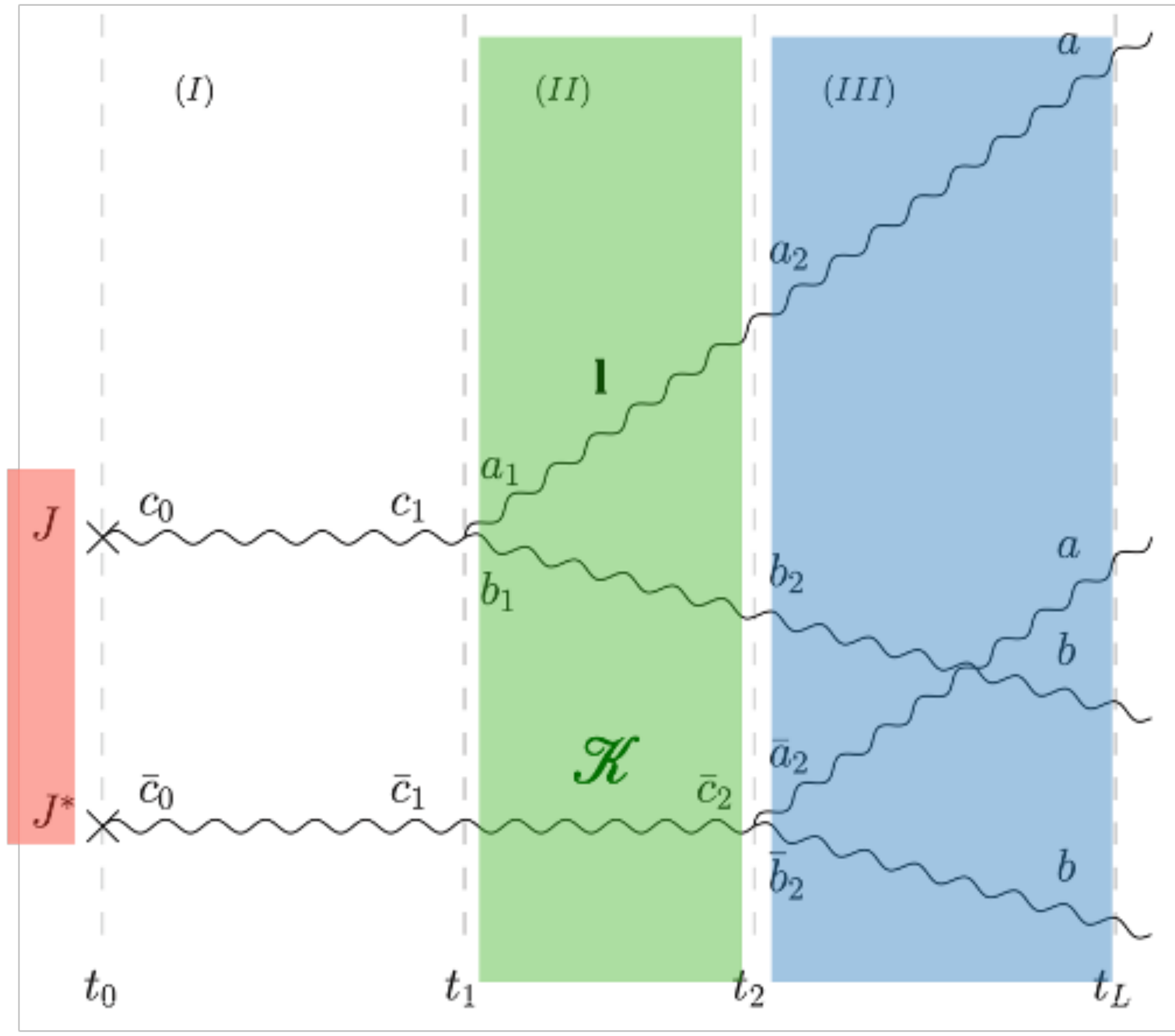
Medium averages local in thermal matter $\langle\hat\rho^a(\boldsymbol{x},z)\hat\rho^b(\boldsymbol{y},\bar z)\rangle$ … $\bar z)$

$$2(2\pi)^3\omega E\frac{d\mathcal{N}}{d\omega dEd^2\boldsymbol{k}} = \lim_{z_f\to\infty}\frac{2\alpha_s C_F}{\omega^2}\Re\int_0^\infty \; \ldots \; J(E,\boldsymbol{x}_{in})|^2$$

$$\times\Big[\boldsymbol{\nabla}_{\boldsymbol{x}}\cdot\boldsymbol{\nabla}_{\bar{\boldsymbol{x}}}S_2(\boldsymbol{k},\boldsymbol{k},z_f;\boldsymbol{y},\bar{\boldsymbol{x}},\bar z)\,\mathcal{K}(\boldsymbol{y},\ldots\Big]\Big|_{\ldots=\bar{\boldsymbol{x}}=\boldsymbol{x}_{in}}$$

Radiative kernel

Broa… g kernel



See Barata, Hauksson, XML, Sadofyev PRD 2024

Radiation in the Glasma

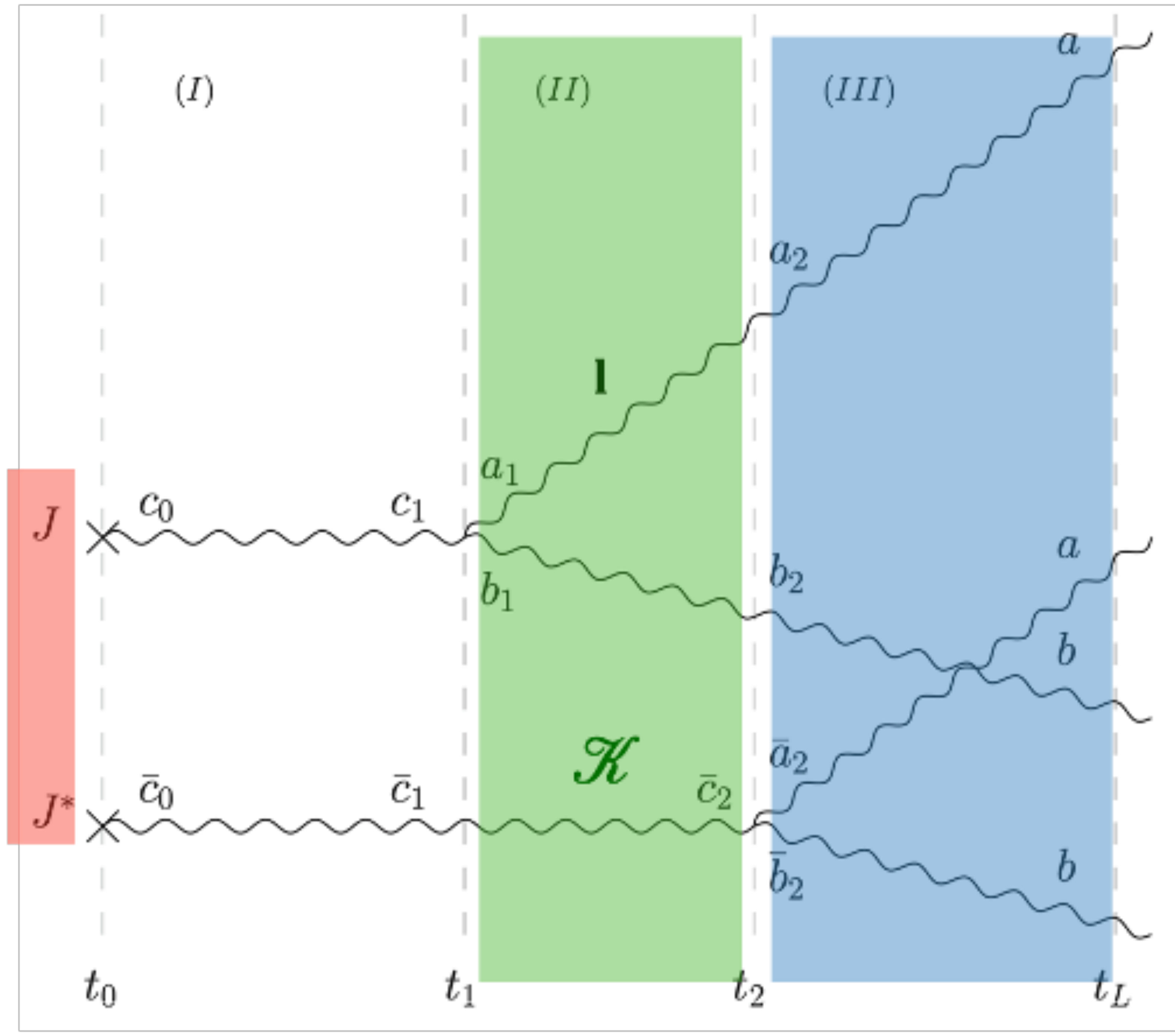
The final parton distribution reads

$$2(2\pi)^3\omega E\frac{d\mathcal{N}}{d\omega dEd^2\boldsymbol{k}} = \lim_{z_f\to\infty}\frac{\alpha_s}{N_c\omega^2}\Re\int_0^\infty d\bar{z}\int_0^{\bar{z}}dz\int_{\boldsymbol{x}_{in},\boldsymbol{y}}|J(E,\boldsymbol{x}_{in})|^2\Big[\boldsymbol{\nabla}_{\boldsymbol{x}}\cdot\boldsymbol{\nabla}_{\bar{\boldsymbol{x}}}$$
$$\times\left\langle\mathcal{G}^{\dagger,\bar{a}b}(\boldsymbol{k},L;\bar{\boldsymbol{x}},\bar{z})\mathcal{G}^{bc}(\boldsymbol{k},L;\boldsymbol{y},\bar{z})\,\mathcal{G}^{ca}(\boldsymbol{y},\bar{z};\boldsymbol{x},z)\mathcal{W}^{\dagger,a\bar{a}}(\boldsymbol{x}_{in};\bar{z},z)\right\rangle\Big]_{\boldsymbol{x}=\bar{\boldsymbol{x}}=\boldsymbol{x}_{in}}$$

not separated

Integrating over the final transverse momenta

$$\int_{\boldsymbol{k}}\mathcal{G}^{\dagger,\bar{a}b}(\boldsymbol{k},L;\bar{\boldsymbol{x}},\bar{z})\mathcal{G}^{bc}(\boldsymbol{k},L;\boldsymbol{y},\bar{z}) = \delta^{(2)}(\bar{\boldsymbol{x}}-\boldsymbol{y})\,\delta^{\bar{a}c}$$



See Barata, Hauksson, XML, Sadofyev PRD 2024

The final parton distribution reads

$$2(2\pi)^3\omega E\frac{d\mathcal{N}}{d\omega dE d^2\boldsymbol{k}} = \lim_{z_f\to\infty}\frac{\alpha_s}{N_c\omega^2}\Re\int_0^\infty d\bar{z}\int_0^{\bar{z}} dz\int_{\boldsymbol{x}_{in},\boldsymbol{y}}|J(E,\boldsymbol{x}_{in})|^2\Big[\boldsymbol{\nabla}_{\boldsymbol{x}}\cdot\boldsymbol{\nabla}_{\bar{\boldsymbol{x}}}$$

$$\times\left\langle\mathcal{G}^{\dagger,\bar{a}b}(\boldsymbol{k},L;\bar{\boldsymbol{x}},\bar{z})\mathcal{G}^{bc}(\boldsymbol{k},L;\boldsymbol{y},\bar{z})\mathcal{G}^{ca}(\boldsymbol{y},\bar{z};\boldsymbol{x},z)\mathcal{W}^{\dagger,a\bar{a}}(\boldsymbol{x}_{in};\bar{z},z)\right\rangle\Big]_{\boldsymbol{x}=\bar{\boldsymbol{x}}=\boldsymbol{x}_{in}}$$

not separated

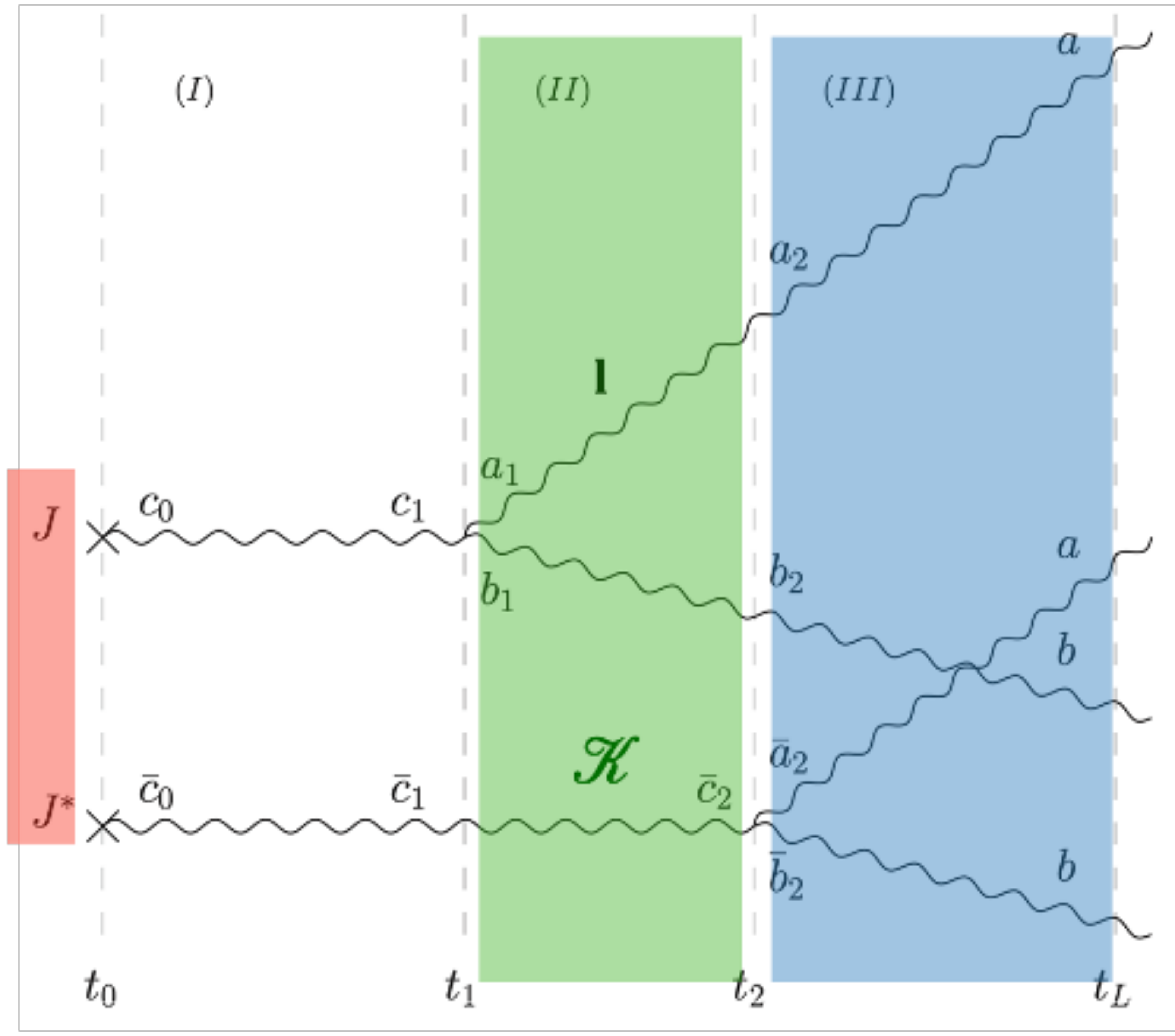
Integrating over the final transverse momenta

$$\int_{\boldsymbol{k}}\mathcal{G}^{\dagger,\bar{a}b}(\boldsymbol{k},L;\bar{\boldsymbol{x}},\bar{z})\mathcal{G}^{bc}(\boldsymbol{k},L;\boldsymbol{y},\bar{z}) = \delta^{(2)}(\bar{\boldsymbol{x}}-\boldsymbol{y})\,\delta^{\bar{a}c}$$

Extra simplifying assumptions

$$\omega E\frac{d\mathcal{N}}{d\omega dE}\equiv\omega\frac{d\mathcal{I}}{d\omega}\,E\frac{d\mathcal{N}^{(0)}}{dE}$$

$$\frac{d\Gamma}{d\omega}=\omega\frac{d\mathcal{I}}{dtd\omega}$$



See Barata, Hauksson, XML, Sadofyev PRD 2024

The radiation rate reads

$$\left\langle \frac{d\Gamma}{dx} \right\rangle = \frac{2\alpha_s C_F}{x\omega^2} \Re \int_0^t ds\, \boldsymbol{\nabla}_{\boldsymbol{x}} \cdot \boldsymbol{\nabla}_{\boldsymbol{y}} \, \langle \mathcal{K}(\boldsymbol{x}, t; \boldsymbol{y}, s) - \mathcal{K}_0(\boldsymbol{x}, t; \boldsymbol{y}, s) \rangle \Big|_{\boldsymbol{x}=\boldsymbol{y}=\boldsymbol{0}}$$

The radiation kernel is a path integral

$$\mathcal{K}(\boldsymbol{x}, t; \boldsymbol{y}, s) = \frac{1}{N_c^2 - 1} \int_{\boldsymbol{y}}^{\boldsymbol{x}} \mathcal{D}\boldsymbol{r} \, \exp\left(i \frac{\omega}{2} \int_s^t d\tau \, \dot{\boldsymbol{r}}^2 \right) \mathrm{Tr} \, \mathcal{P} \exp\left(i \int_s^t d\tau \, T^c \, \boldsymbol{r}(\tau) \cdot \boldsymbol{E}^c(\tau) \right)$$

Studied for different groups:

$U(1)$ abelian case

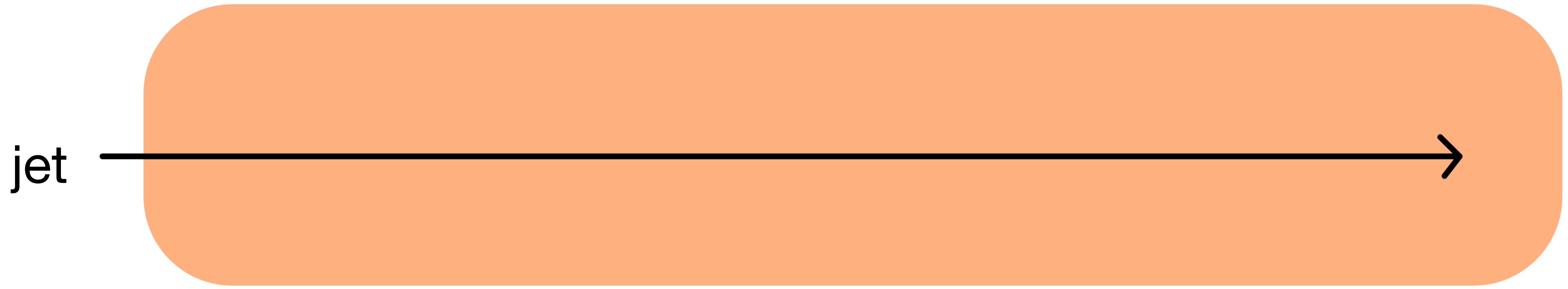
$SU(2)$ non-abelian case

See Barata, Hauksson, XML, Sadofyev PRD 2024

The abelian case

Solution for one color domain

$$\frac{d\Gamma_{\mathrm{U}(1)}}{dx} = \frac{2\alpha_s C_F}{x\pi} \Re \int_0^t ds\, \frac{1}{s^2} \left(1 - \left(1 - i\frac{E^2 s^3}{8\omega}\right) e^{-i\frac{E^2 s^3}{24\omega}}\right)$$



See Barata, Hauksson, XML, Sadofyev PRD 2024

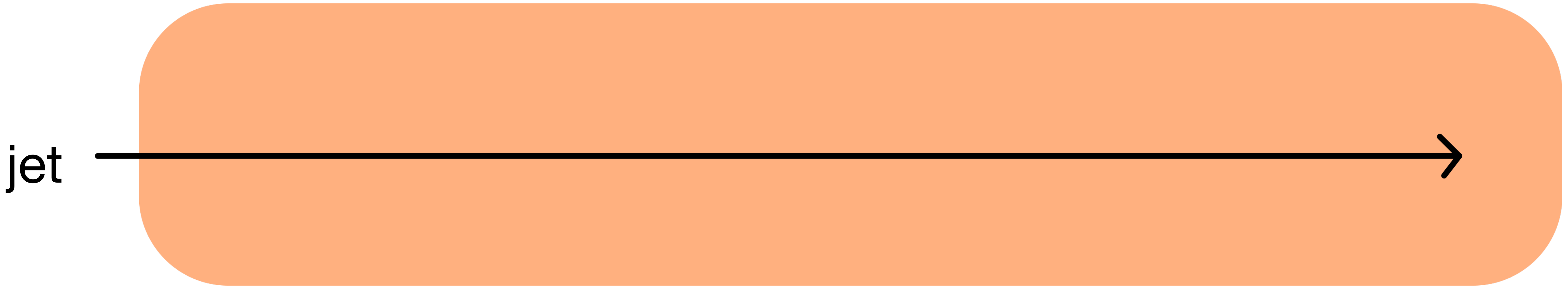
The abelian case

Solution for one color domain

$$\frac{d\Gamma_{\mathrm{U}(1)}}{dx} = \frac{2\alpha_s C_F}{x\pi}\Re\int_0^t ds\,\frac{1}{s^2}\left(1-\left(1-i\frac{E^2 s^3}{8\omega}\right)e^{-i\frac{E^2 s^3}{24\omega}}\right)$$

Performing de average

$$\left\langle \frac{d\Gamma_{\mathrm{U}(1)}}{dx}\right\rangle = \frac{2\alpha_s C_F}{\pi \mathrm{x}}\Re\int_0^t \frac{ds}{s^2}\left[\frac{1}{\sqrt{i\frac{E_0^2 s^3}{24\omega}+1}}\left(-1+\frac{3}{2\left(1-i\frac{24\omega}{E_0^2 s^3}\right)}\right)+1\right]$$



See Barata, Hauksson, XML, Sadofyev PRD 2024

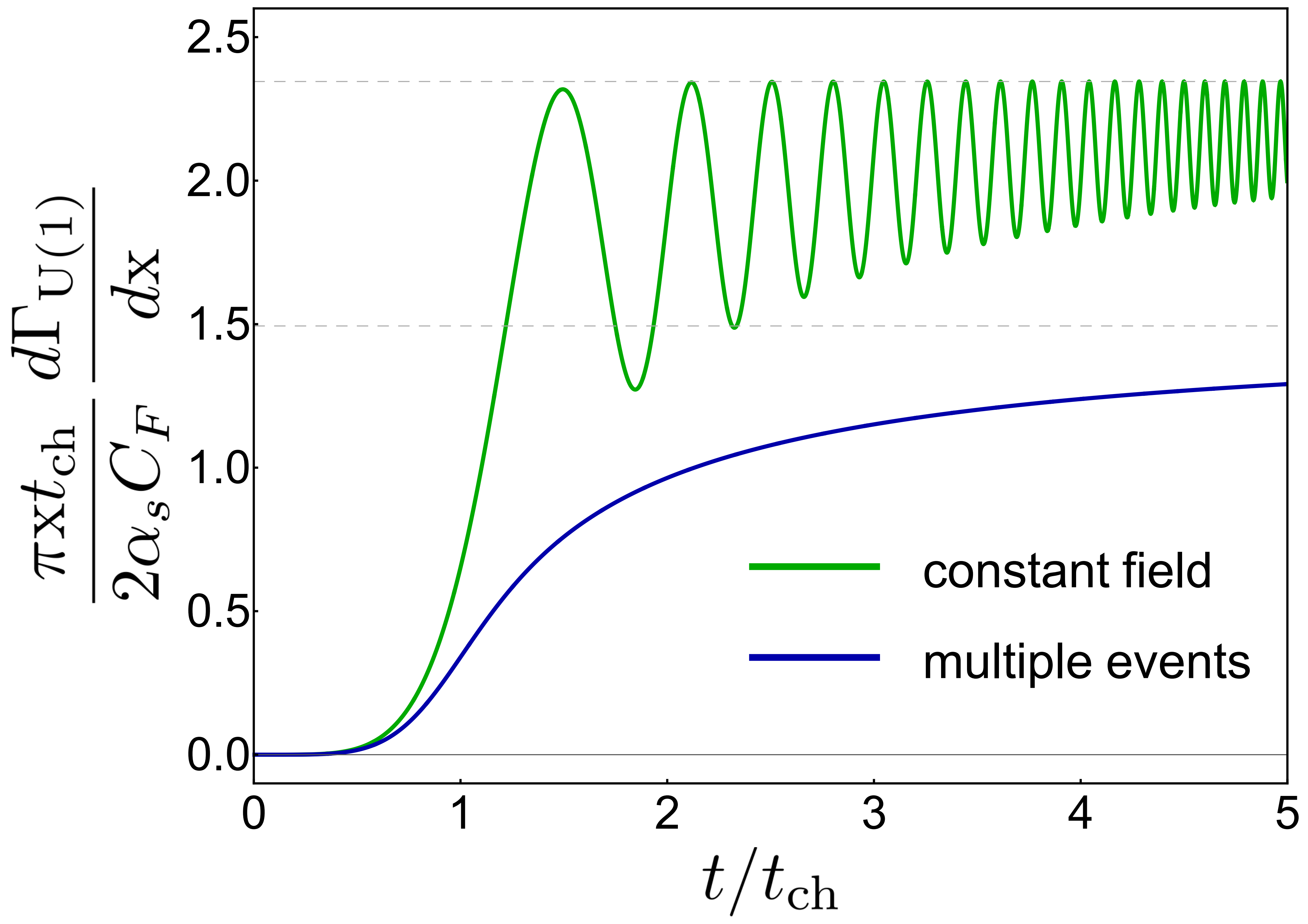
The abelian case

Solution for one color domain

$$\frac{d\Gamma_{\mathrm{U}(1)}}{dx} = \frac{2\alpha_s C_F}{x\pi}\Re\int_0^t ds\,\frac{1}{s^2}\left(1-\left(1-i\frac{E^2 s^3}{8\omega}\right)e^{-i\frac{E^2 s^3}{24\omega}}\right)$$

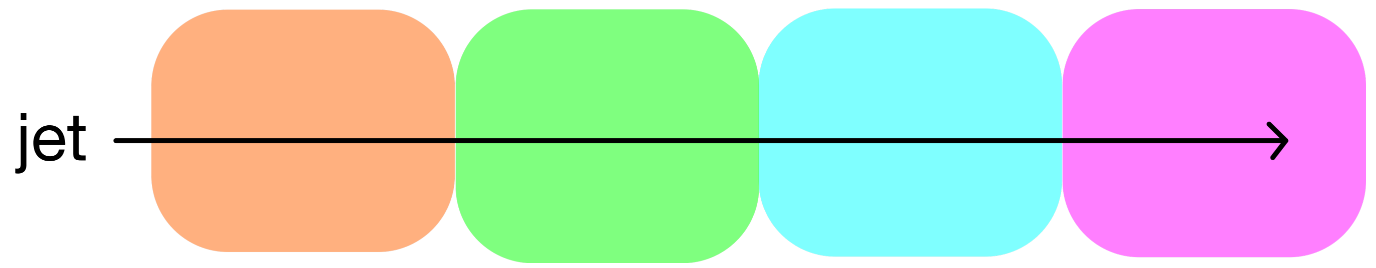
Performing de average

$$\left\langle\frac{d\Gamma_{\mathrm{U}(1)}}{dx}\right\rangle = \frac{2\alpha_s C_F}{\pi \mathrm{x}}\Re\int_0^t \frac{ds}{s^2}\left[\frac{1}{\sqrt{i\frac{E_0^2 s^3}{24\omega}+1}}\left(-1+\frac{3}{2\left(1-i\frac{24\omega}{E_0^2 s^3}\right)}\right)+1\right]$$

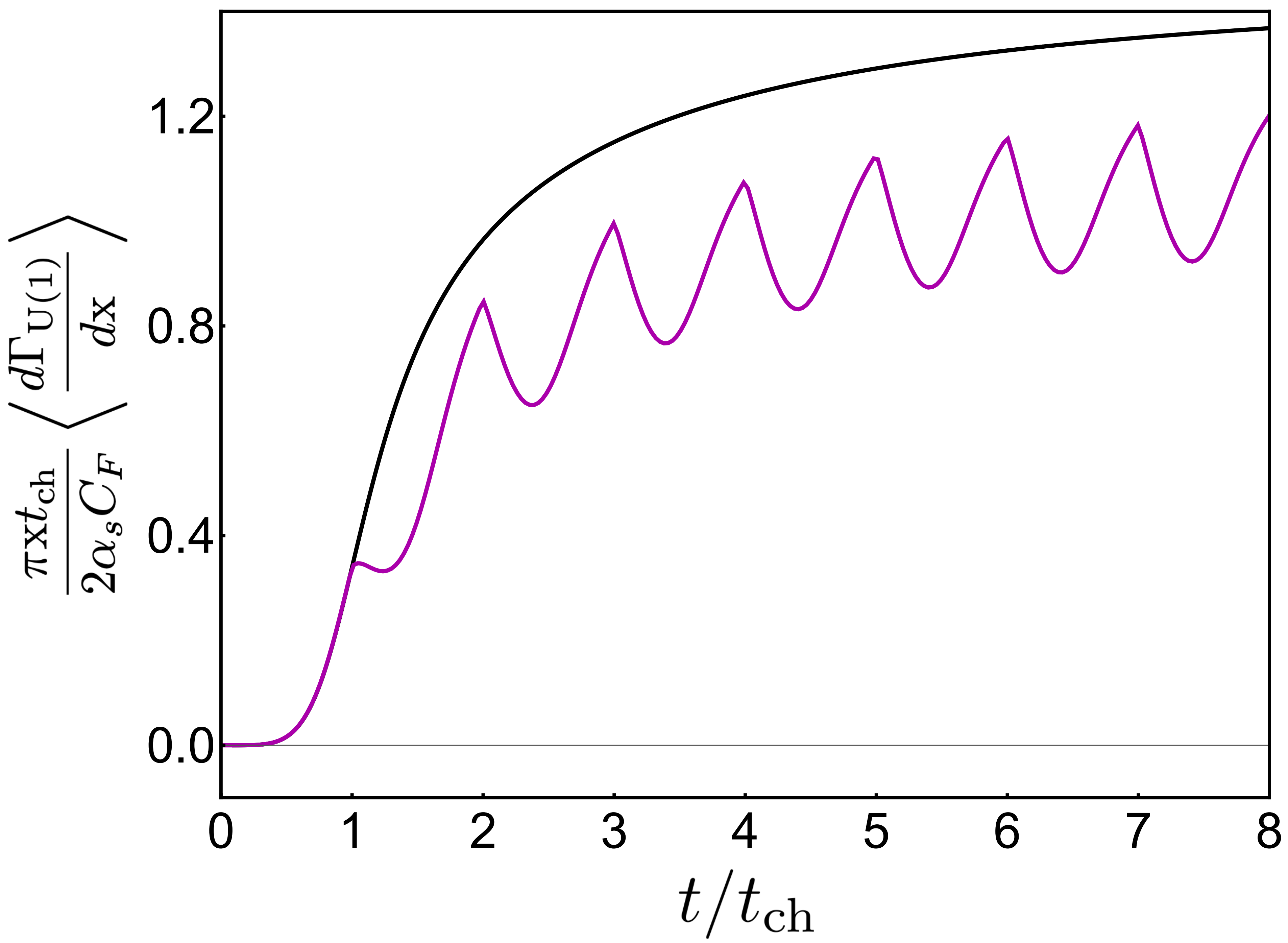


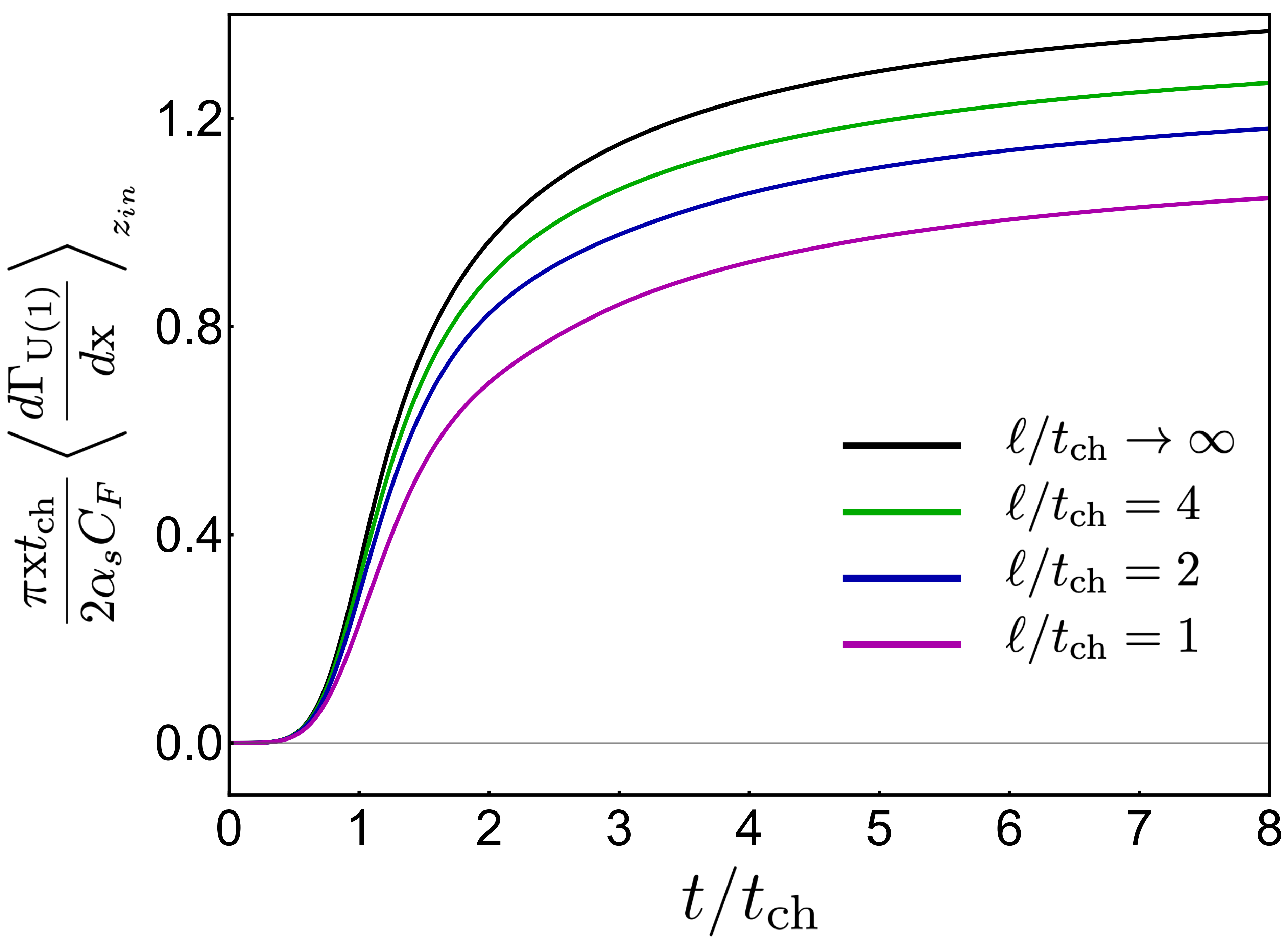
See Barata, Hauksson, XML, Sadofyev PRD 2024

The abelian case



Taking into account many different color domains



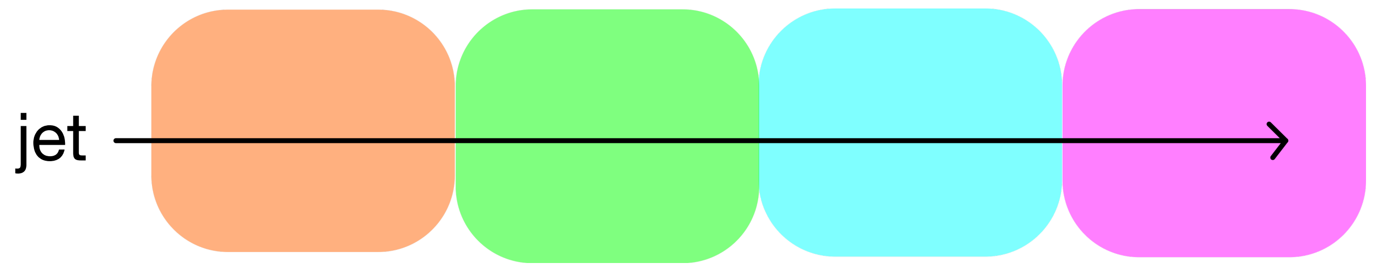


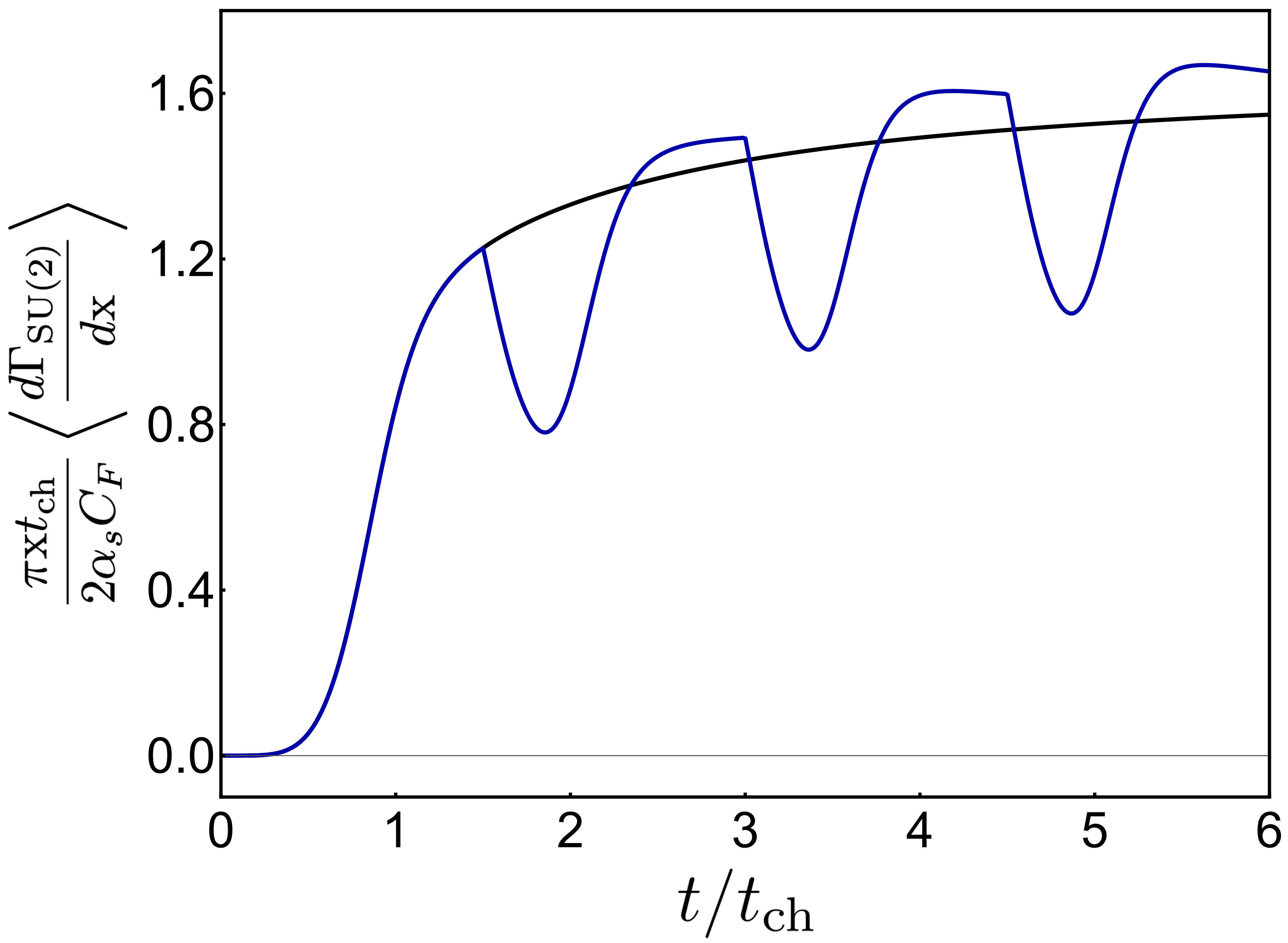
- Destructive interference when crossing between different tubes
- The more tubes traversed, the more suppression of the rate

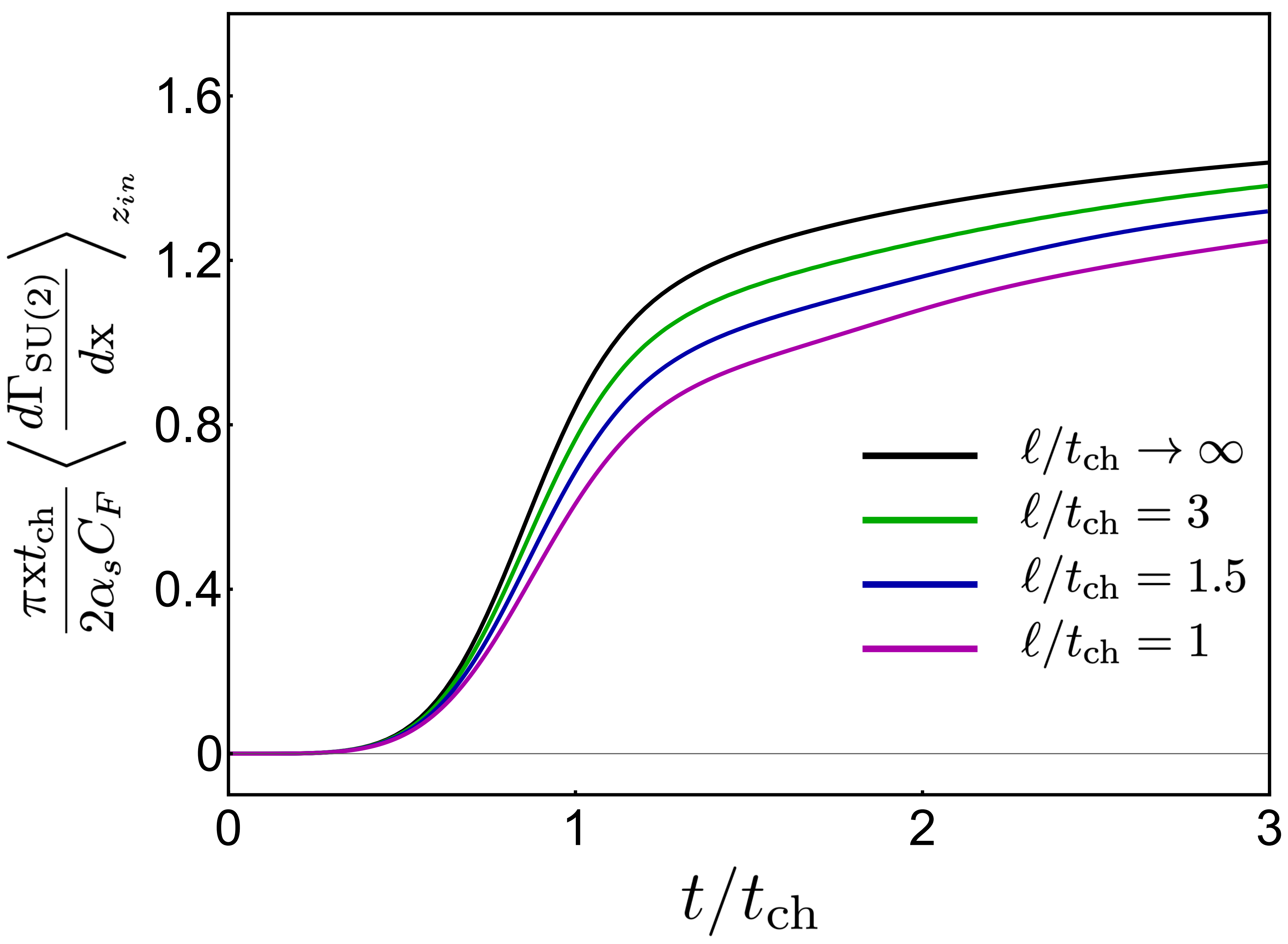
See Barata, Hauksson, XML, Sadofyev PRD 2024

The non-abelian case

Taking into account many different color domains







- Destructive interference when crossing between different tubes
- The more tubes traversed, the more suppression of the rate
- Approaches the single tube rate from above for long tubes

See Barata, Hauksson, XML, Sadofyev PRD 2024

The non-abelian case

We can do a very simple estimate of the energy loss

$$\Delta E = E \int_0^L dt \int_0^1 dx\, x \left\langle \frac{d\Gamma_{\mathrm{SU}(2)}}{dx} \right\rangle_{z_{in}}$$

Choosing $|E_0| = \sqrt{2.5}\, Q_s^2$ with $Q_s \sim 2\,\mathrm{GeV}$ to match $\langle \hat{q} \rangle_{\mathrm{SU}(3),\, z_{in}} \simeq 5\,\mathrm{GeV}^2/\mathrm{fm}$

$E = 50\,\mathrm{GeV}$ $\Delta E = 0.26\,,\ 1.97\,,\ 5.57\,\mathrm{GeV}$ $L = 0.2\,,\ 0.4\,,\ 0.6\,\mathrm{fm}$

See Barata, Hauksson, XML, Sadofyev PRD 2024

Jet quenching in the Glasma phase

3. Radiation in a not so simple model

(Not so) Simple Glasma model for jet quenching

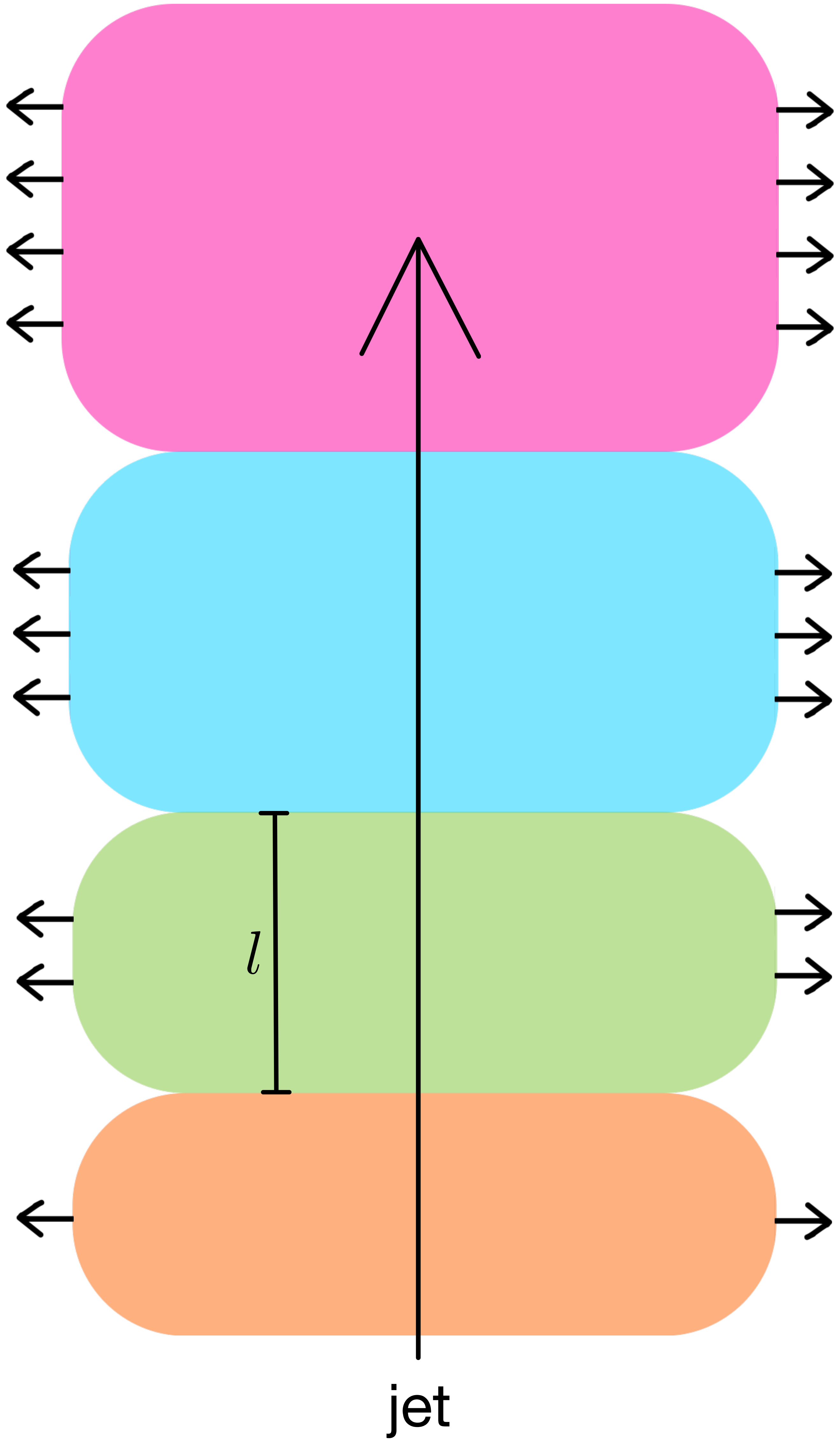
Leading parting moving at mid-rapidity along the z-axis

Packed stack of transversely infinite slabs of variable thickness

$$gA^{a\mu}(\boldsymbol{x}, z) = -\delta^{\mu 0}\,\boldsymbol{x}\cdot\boldsymbol{E}^a(z) - \frac{1}{2}\varepsilon^{0\mu jk}x_j\boldsymbol{B}^a_k(z)$$

Finite correlation of the color fields

$$\langle f(E_1^a, B_1^a, E_2^a, B_2^a, \cdots)\rangle = \int_{E_1} e^{-E_1^2/E_{01}^2}\int_{B_1} e^{-B_1^2/B_{01}^2}$$
$$\int_{E_2} e^{-E_2^2/E_{02}^2}\int_{B_2} e^{-B_2^2/B_{02}^2}\cdots f(E_1^a, B_1^a, E_2^a, B_2^a, \cdots)$$



See Avramescu, Barata, Lappi, XML, Sadofyev TBD

The radiation rate reads

$$\left\langle \frac{d\Gamma}{dx} \right\rangle = \frac{2\alpha_s C_F}{x\omega^2} \Re \int_0^t ds\, \boldsymbol{\nabla}_{\boldsymbol{x}} \cdot \boldsymbol{\nabla}_{\boldsymbol{y}} \, \langle \mathcal{K}(\boldsymbol{x}, t; \boldsymbol{y}, s) - \mathcal{K}_0(\boldsymbol{x}, t; \boldsymbol{y}, s) \rangle \Big|_{\boldsymbol{x}=\boldsymbol{y}=\boldsymbol{0}}$$

The radiation kernel is a path integral

$$\mathcal{K}(\boldsymbol{x}, t; \boldsymbol{y}, s) = \frac{1}{N_c^2 - 1} \int_{\boldsymbol{y}}^{\boldsymbol{x}} \mathcal{D}\boldsymbol{r} \; \exp\left(i \frac{\omega}{2} \int_s^t d\tau \, \dot{\boldsymbol{r}}^2 \right) \mathrm{Tr}\, \mathcal{P} \exp\left(i T^c \int_s^t d\tau \, \boldsymbol{r}(\tau) \cdot \tilde{\boldsymbol{E}}^c(\tau) \right)$$

Studied for different groups:

$U(1)$ abelian case

$SU(2)$ non-abelian case

See Avramescu, Barata, Lappi, XML, Sadofyev TBD

The radiation rate reads

$$\left\langle \frac{d\Gamma}{dx} \right\rangle = \frac{2\alpha_s C_F}{x\omega^2} \Re \int_0^t ds\, \boldsymbol{\nabla}_{\boldsymbol{x}} \cdot \boldsymbol{\nabla}_{\boldsymbol{y}} \, \langle \mathcal{K}(\boldsymbol{x}, t; \boldsymbol{y}, s) - \mathcal{K}_0(\boldsymbol{x}, t; \boldsymbol{y}, s) \rangle \Big|_{\boldsymbol{x}=\boldsymbol{y}=\boldsymbol{0}}$$

The radiation kernel is a path integral

$$\tilde{\boldsymbol{E}}^c = (E^c_x, B^c_x)$$

$$\mathcal{K}(\boldsymbol{x}, t; \boldsymbol{y}, s) = \frac{1}{N_c^2 - 1} \int_{\boldsymbol{y}}^{\boldsymbol{x}} \mathcal{D}\boldsymbol{r} \;\exp\left(i\frac{\omega}{2} \int_s^t d\tau\, \dot{\boldsymbol{r}}^2 \right) \mathrm{Tr}\, \mathcal{P} \exp\left(iT^c \int_s^t d\tau\, \boldsymbol{r}(\tau) \cdot \tilde{\boldsymbol{E}}^c(\tau) \right)$$

Studied for different groups:

$U(1)$ abelian case

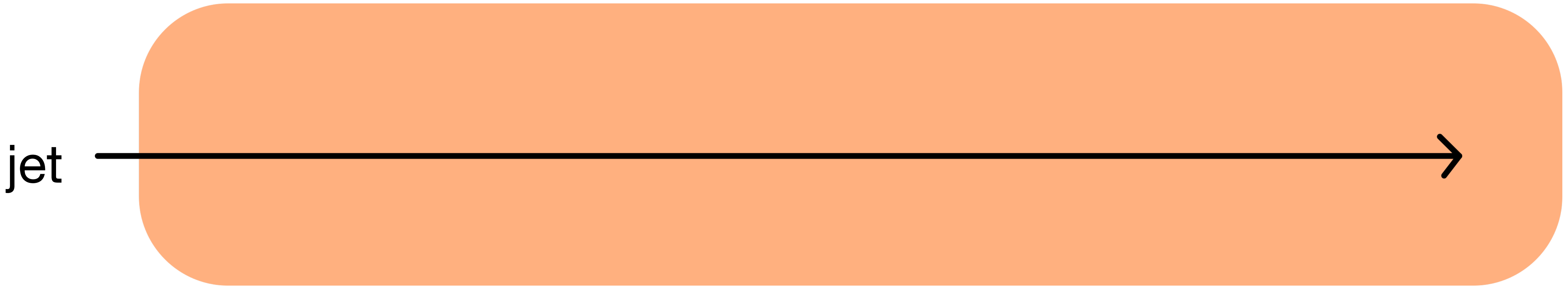
$SU(2)$ non-abelian case

See Avramescu, Barata, Lappi, XML, Sadofyev TBD

The abelian case

Solution for one color domain

$$\frac{d\Gamma_{\mathrm{U}(1)}}{d\mathrm{x}} = \frac{2\alpha_s C_F}{\mathrm{x}\,\pi}\,\mathrm{Re}\int_0^t \frac{ds}{s^2}\left(1-\left(1-\frac{i\tilde{\boldsymbol{E}}^2 s^3}{8\omega}\right)e^{-i\tilde{\boldsymbol{E}}^2 s^3/(24\omega)}\right)$$



See Avramescu, Barata, Lappi, XML, Sadofyev TBD

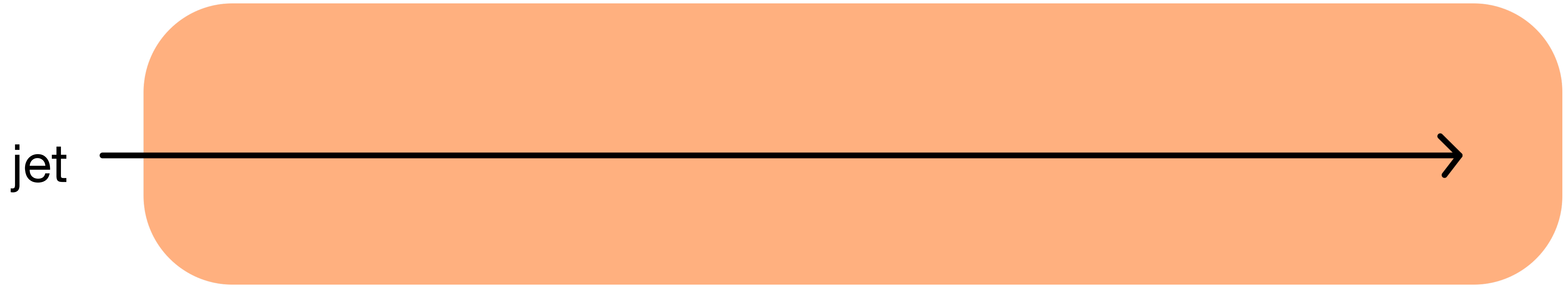
The abelian case

Solution for one color domain

$$\frac{d\Gamma_{\mathrm{U(1)}}}{d\mathrm{x}} = \frac{2\alpha_s C_F}{\mathrm{x}\,\pi}\,\mathrm{Re}\int_0^t \frac{ds}{s^2}\left(1-\left(1-\frac{i\tilde{\boldsymbol{E}}^2 s^3}{8\omega}\right)e^{-i\tilde{\boldsymbol{E}}^2 s^3/(24\omega)}\right)$$

Performing de average

$$\left\langle \frac{d\Gamma_{\mathrm{U(1)}}}{d\mathrm{x}}\right\rangle = \frac{2\alpha_s C_F}{\pi\,\mathrm{x}}\,\mathrm{Re}\int_0^t \frac{ds}{s^2}\left[\frac{1}{\sqrt{1+is^3/t_E^3}\,\sqrt{1+is^3/t_B^3}}\left(2-\frac{3}{2(1+s^3/it_E^3)}-\frac{3}{2(1+is^3/t_B^3)}\right)+1\right]$$



See Avramescu, Barata, Lappi, XML, Sadofyev TBD

The abelian case

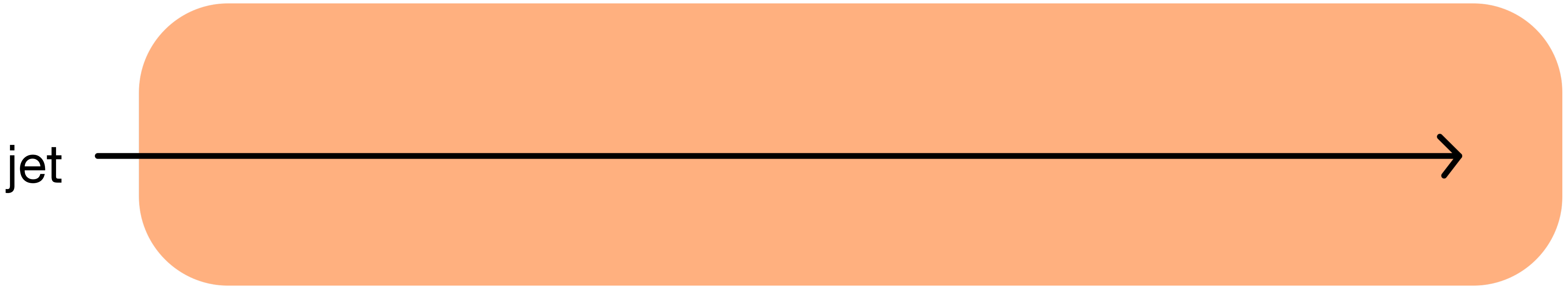
Solution for one color domain

$$\frac{d\Gamma_{\mathrm{U}(1)}}{d\mathrm{x}} = \frac{2\alpha_s C_F}{\mathrm{x}\,\pi}\,\mathrm{Re}\int_0^t \frac{ds}{s^2}\left(1-\left(1-\frac{i\tilde{\boldsymbol{E}}^2 s^3}{8\omega}\right)e^{-i\tilde{\boldsymbol{E}}^2 s^3/(24\omega)}\right)$$

Performing de average

$$t_E = (24\omega/E_0^2) \qquad t_B = (24\omega/B_0^2)$$

$$\left\langle\frac{d\Gamma_{\mathrm{U}(1)}}{d\mathrm{x}}\right\rangle = \frac{2\alpha_s C_F}{\pi\,\mathrm{x}}\,\mathrm{Re}\int_0^t \frac{ds}{s^2}\left[\frac{1}{\sqrt{1+is^3/t_E^3}\,\sqrt{1+is^3/t_B^3}}\left(2-\frac{3}{2(1+s^3/it_E^3)}-\frac{3}{2(1+is^3/t_B^3)}\right)+1\right]$$



See Avramescu, Barata, Lappi, XML, Sadofyev TBD

To take home:

- We have reviewed the theoretical formalism of jet quenching in the QGP phase

- The large value of jet quenching parameter hints at the potential of the glasma stage to modify jets

- We have studied the soft gluon radiation rate in the presence of the glasma

- We have naively estimated the amount of energy lost

- More realistic modelling of the glasma with varying correlation length and magnetic field on production stage

Dankeschön!