Massachusetts Institute of Technology

Open heavy flavour in flowing QCD matter

Xoán Mayo López, CTP-LI (MIT)

xoanml@mit.edu

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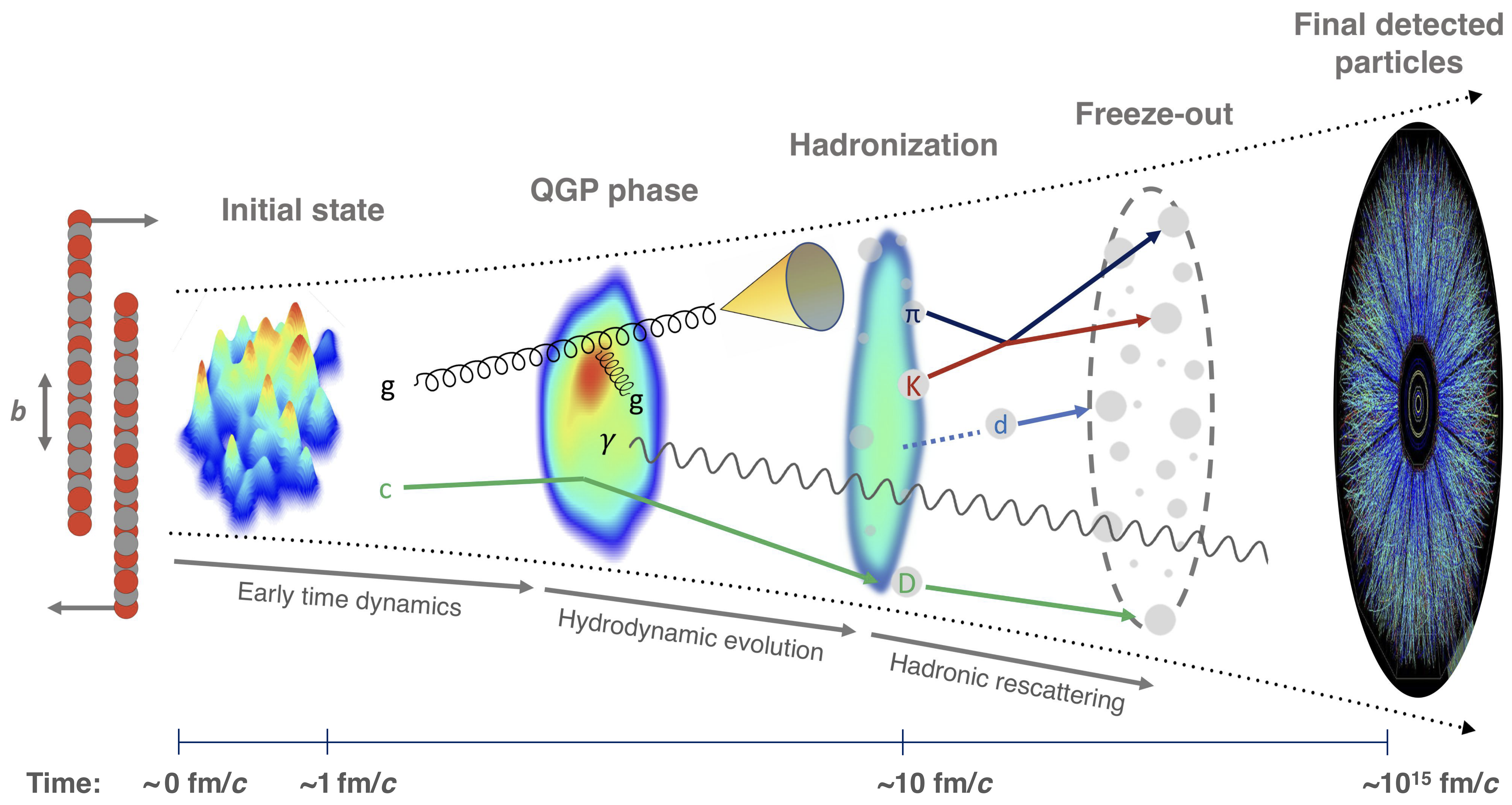
Based on 2512.11951 in collaboration with Barata, Kuzmin, Sadofyev, Salgado.

Probes of the QGP

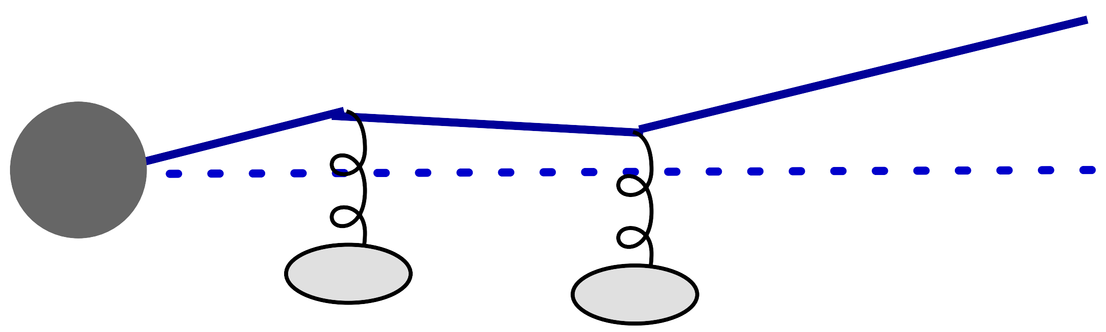


- Jet imaging: Jets as differential probes of the spatio-temporal structure of the thermal matter in HIC
- Modification of jet properties encodes information about the QGP characteristics and evolution

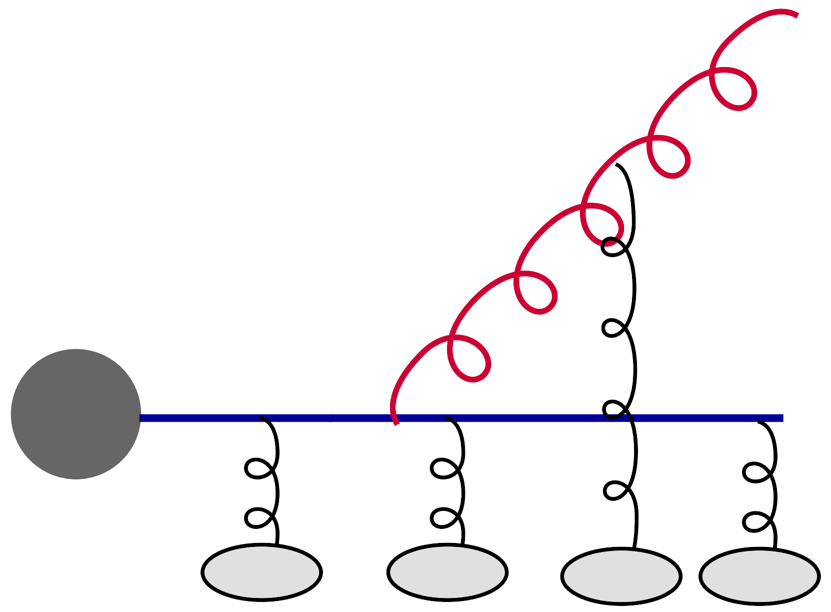
In-medium partons

Focus on leading perturbative processes: Two processes that modify the evolution of HQ.

Transverse momentum broadening



Medium induced gluon radiation



Theoretical formulation requires a tractable description of the matter

- Matter treated as a classical background field
- The field is produced by an stochastic ensemble of charged particles
- Its statistical correlations are determined by the matter properties

See e.g.
Casalderrey-Solana, Salgado 2007

Dead-cone effect present in vacuum radiation of a HQ

Radiation of a massless quark

Radiation of a massive quark

HQ as a new window

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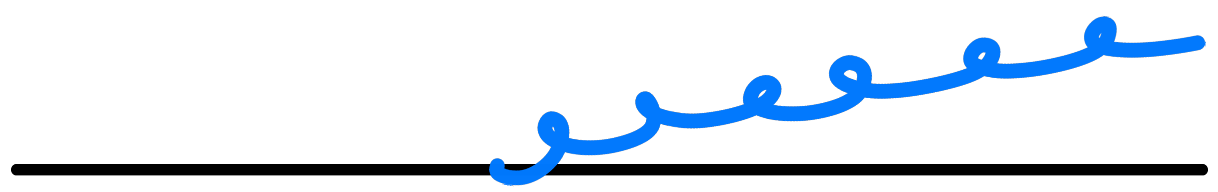
$$\frac{d\mathcal{I}}{d\omega d\theta} \simeq \frac{\alpha_s C_F}{\pi}\frac{1}{\omega}\frac{1}{\theta}$$



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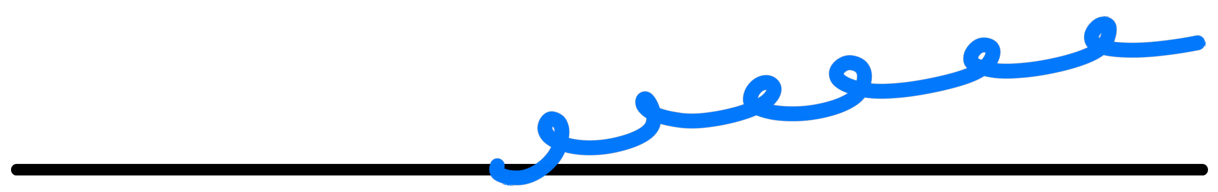

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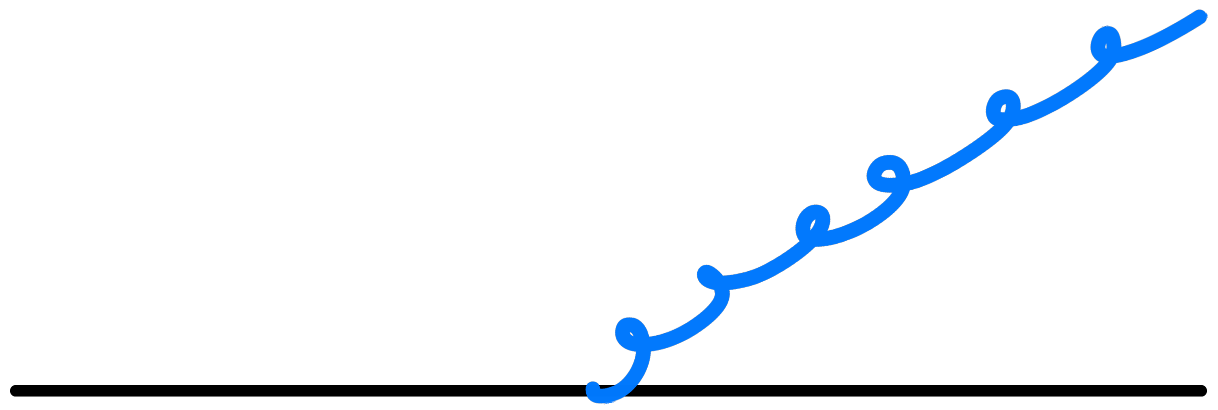

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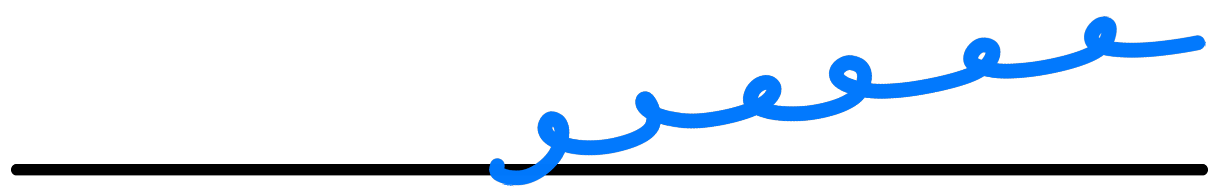

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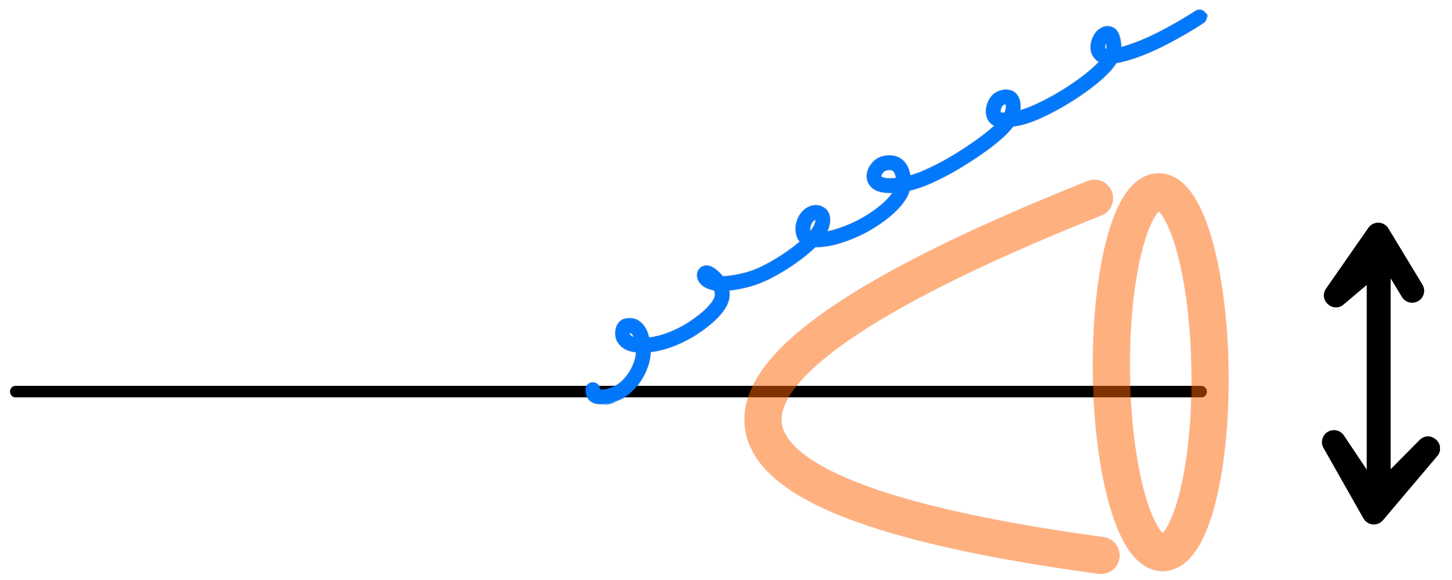

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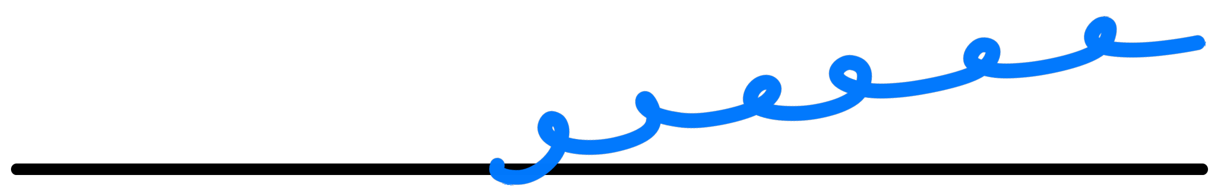

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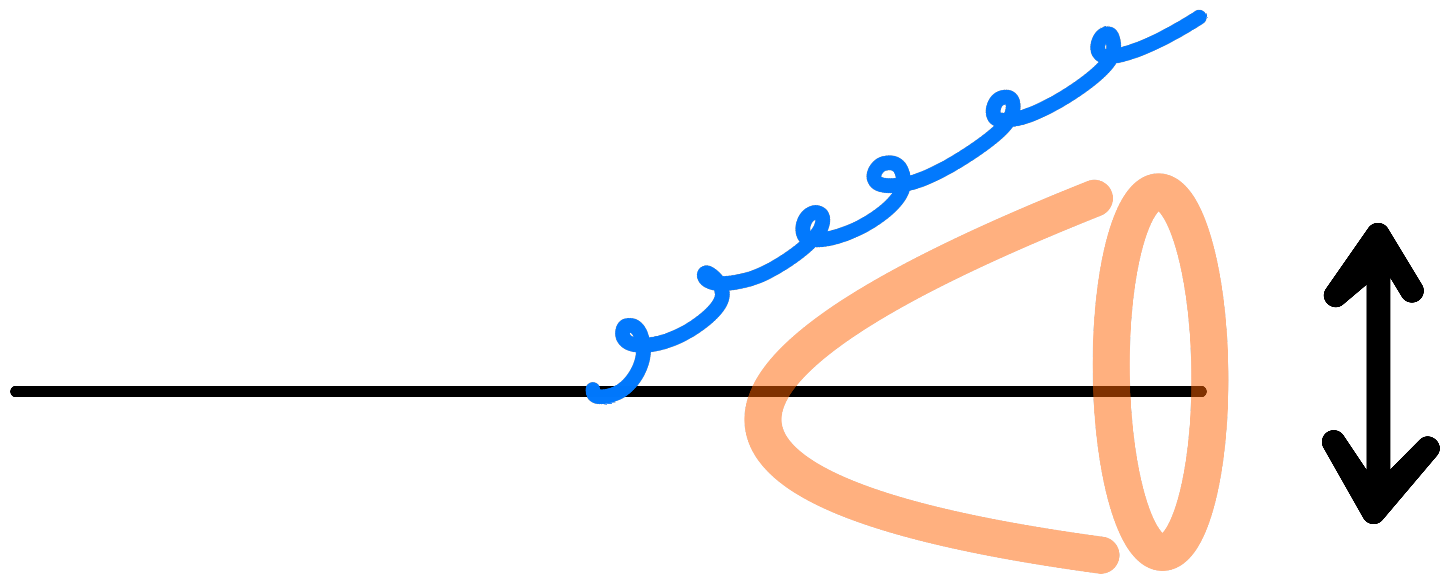

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Clean avenue to access medium induce radiation and extract information of the matter

See Armesto, Salgado, Wiedemann PRD 2004

Diagnostic tool of the bulk with the HQ mass coupling with the transverse dynamics of the bulk

Formalism for weak coupling

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

Matter flowing

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

- scattering potential (green)
- density of color sources (blue)
- velocity of the sources (red)

See e.g.
Sadofyev, Sievert, Vitev PRD 2021
Andres, Dominguez, Sadofyev, Salgado PRD 2022
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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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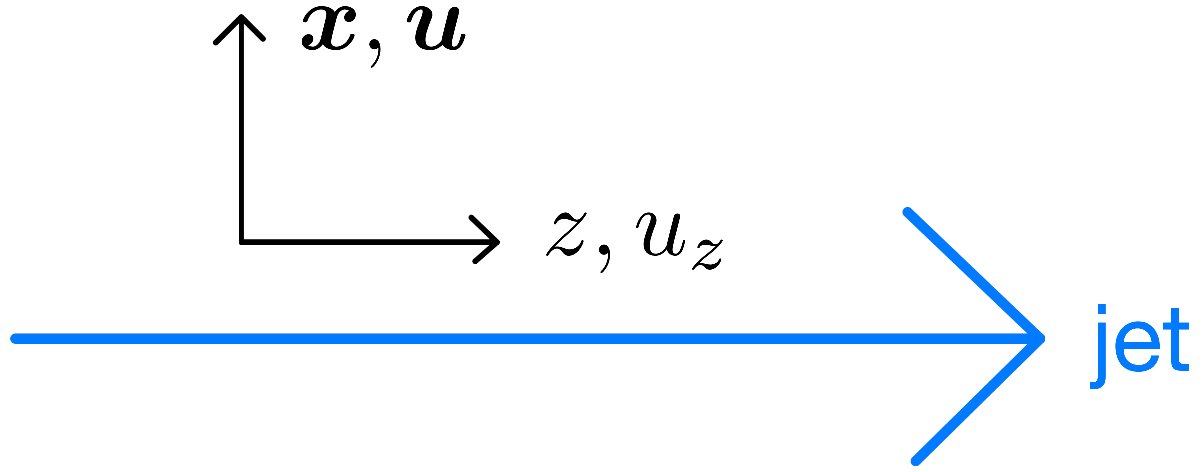

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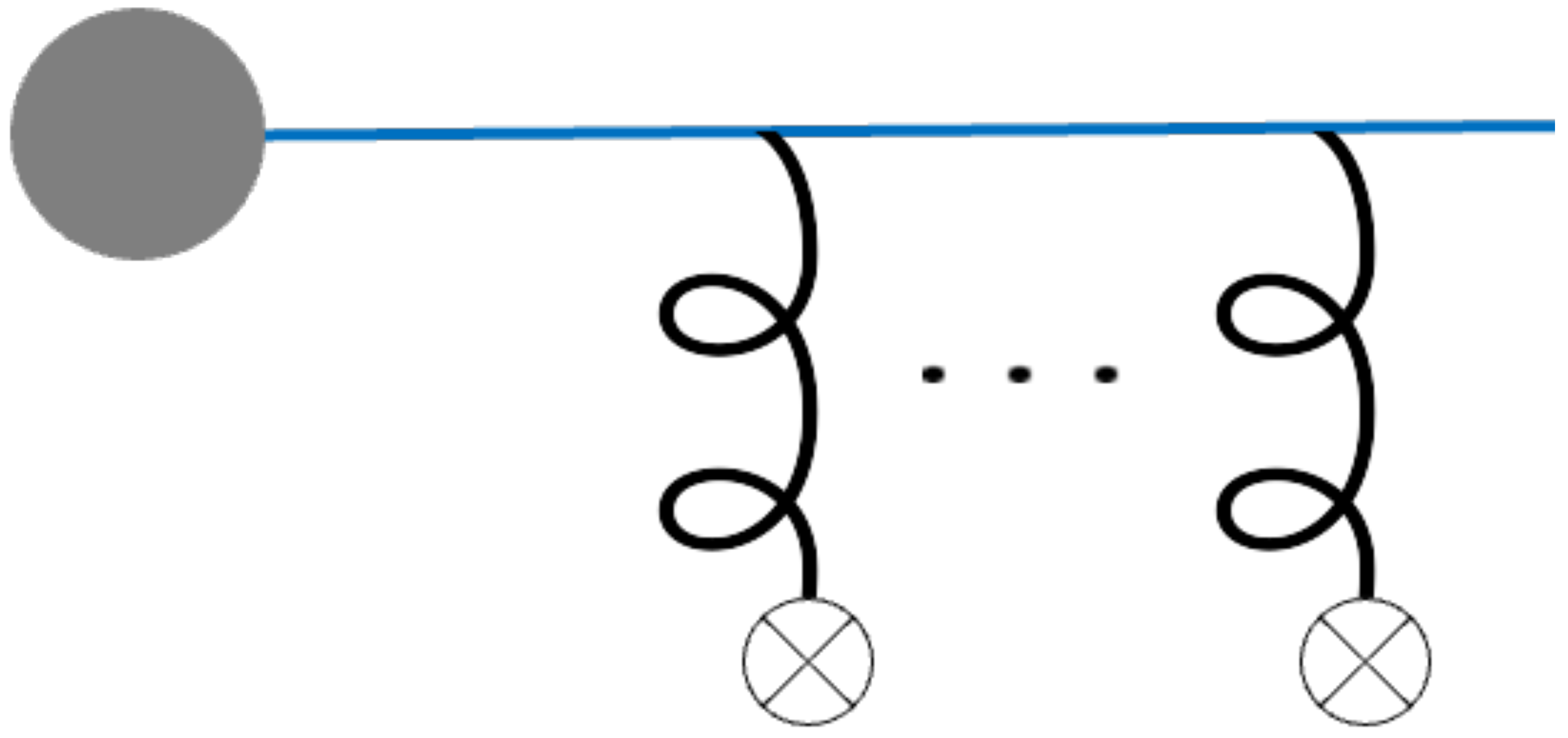
Broadening of a HQ in flowing matter

Final parton distribution

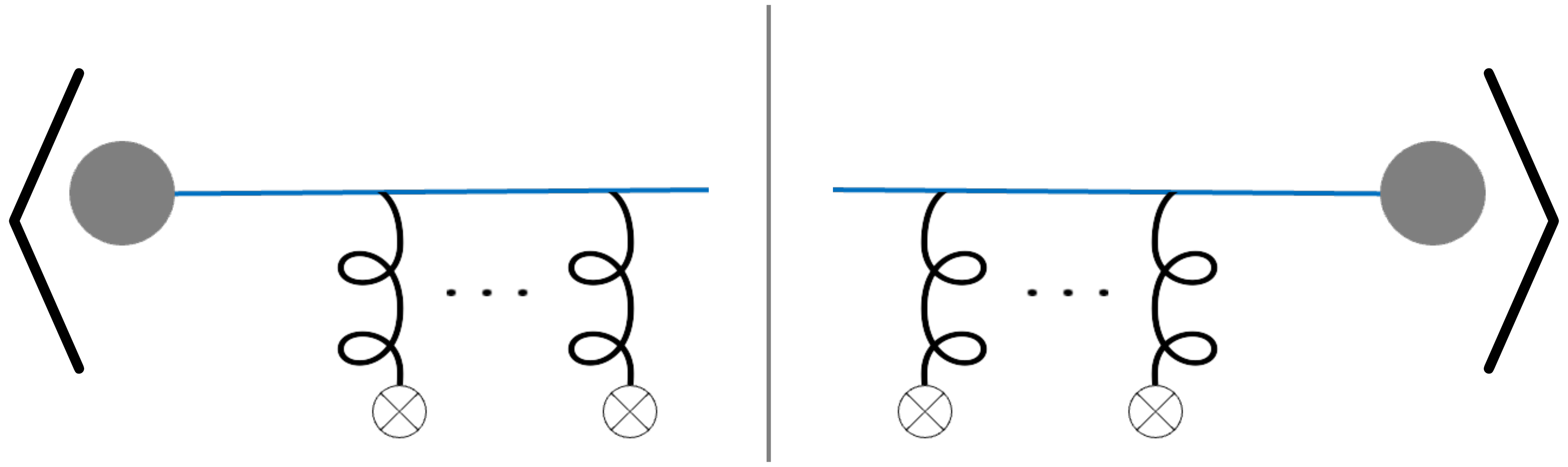
The relevant diagram



Final parton distribution

The relevant diagram

$$E\frac{d\mathcal{N}}{dE\,d^2\boldsymbol{p}} \propto$$



The jet quenching parameter can be extracted as

$$\hat{q}_{ij} \equiv \frac{\partial}{\partial L}\langle \boldsymbol{p}_i \boldsymbol{p}_j \rangle$$

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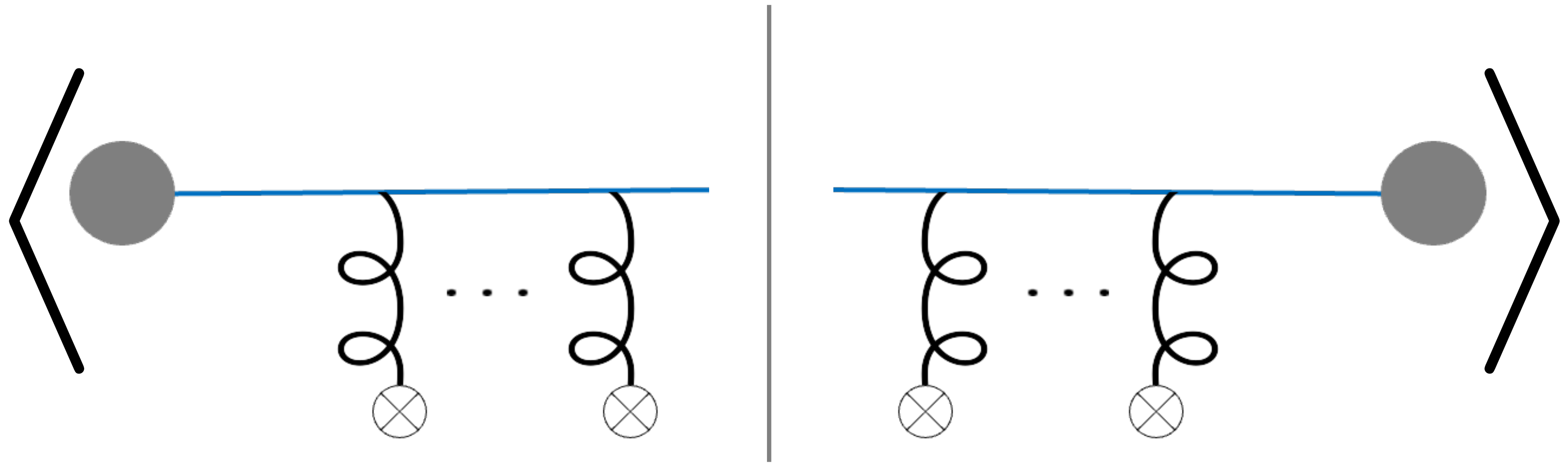

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See Barata, Kuzmin, XML, Sadofyev, Salgado 2025

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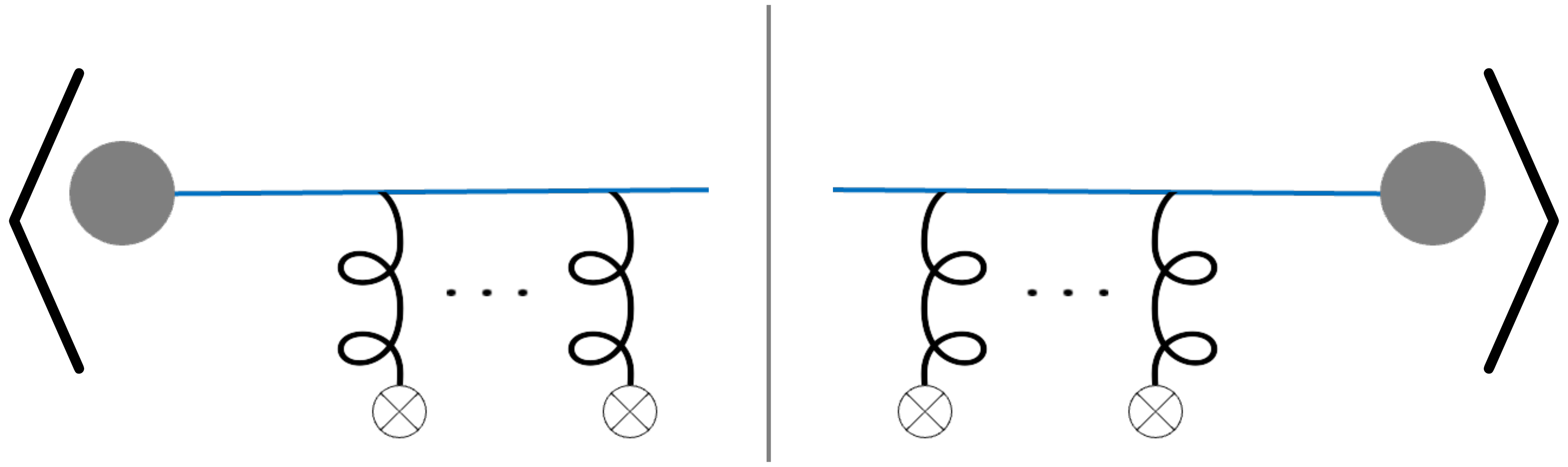

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$$W^{[u]}(\boldsymbol{y};L,0) = \mathcal{P}\exp\left\{i\int_0^L d\tau\, t^a \mathcal{A}^a\left(\boldsymbol{y} - \frac{1}{2}\frac{m_Q^2}{E^2}\frac{\boldsymbol{u}}{u^-}\tau, \tau\right)\right\}$$

See Barata, Kuzmin, XML, Sadofyev, Salgado 2025

The jet quenching parameter

The jet quenching parameter is

$$\hat{q}_{ij} = \frac{\hat{q}_0}{2}\left(1 + \frac{u^+}{u^-}\frac{m_Q^2}{E^2}\right)\left[\delta_{ij} - \frac{u_i u_j}{(u^-)^2}\frac{m_Q^2}{E^2}\right]$$

The flow induces anisotropic transverse momentum broadening

Interplay between the HQ mass and the flow generate a tensorial jet quenching parameter

See Barata, Kuzmin, XML, Sadofyev, Salgado 2025

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Isotropic result

Flow corrections

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- Isotropic result
- HQ scale
- Flow corrections

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See Barata, Kuzmin, XML, Sadofyev, Salgado 2025

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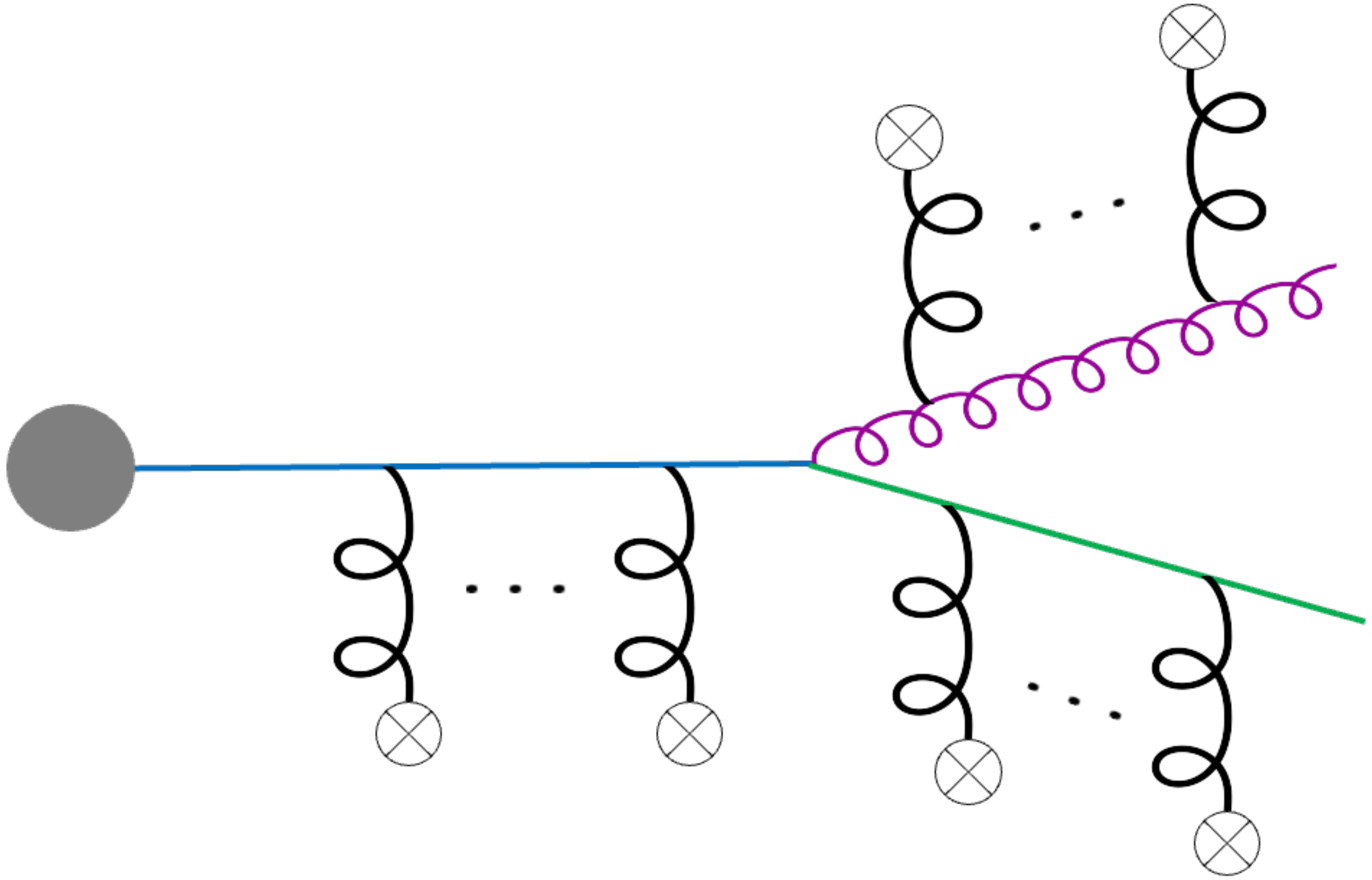
Medium induced radiation off a HQ in flowing matter

Medium induced gluon spectrum

The relevant diagram



Medium induced gluon spectrum

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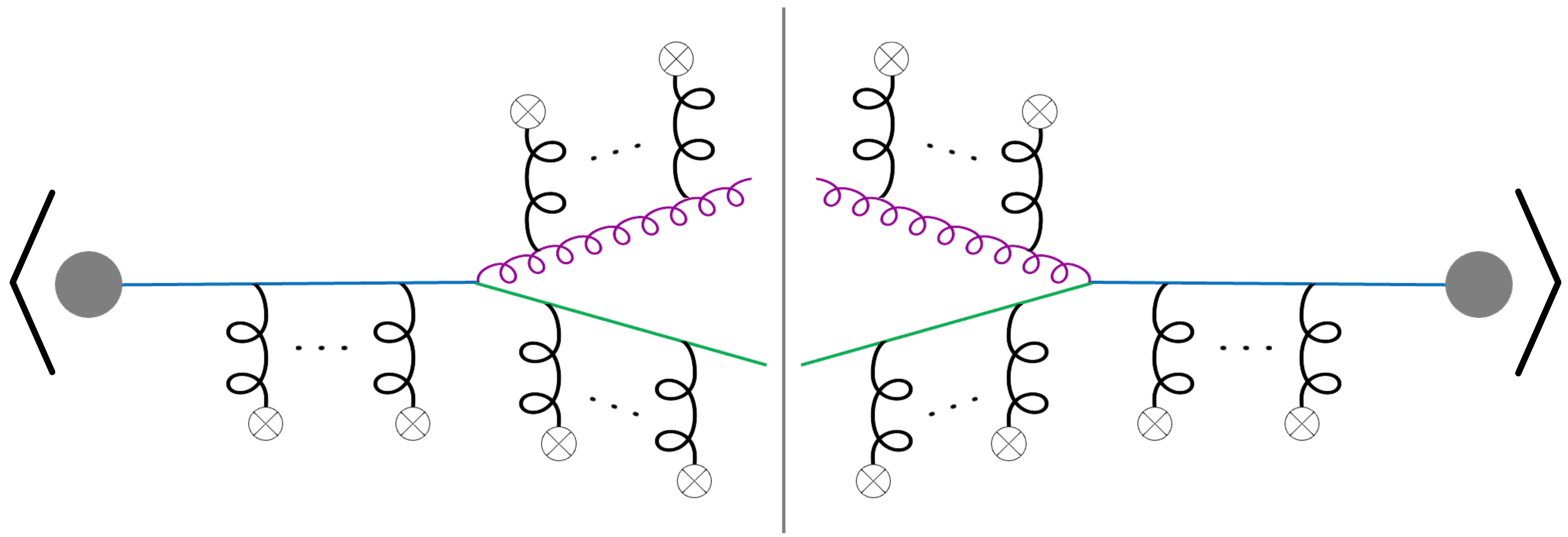
$$(2\pi)^2\omega\frac{dI}{d\omega d^2\boldsymbol{k}} \propto$$



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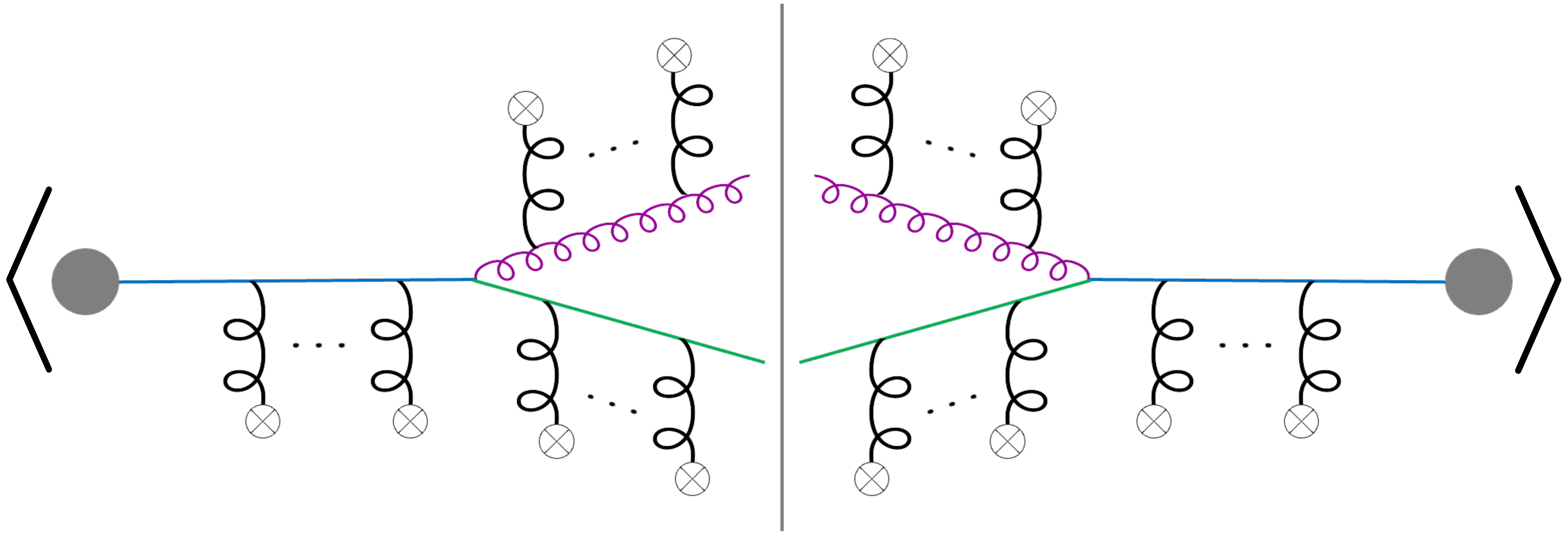

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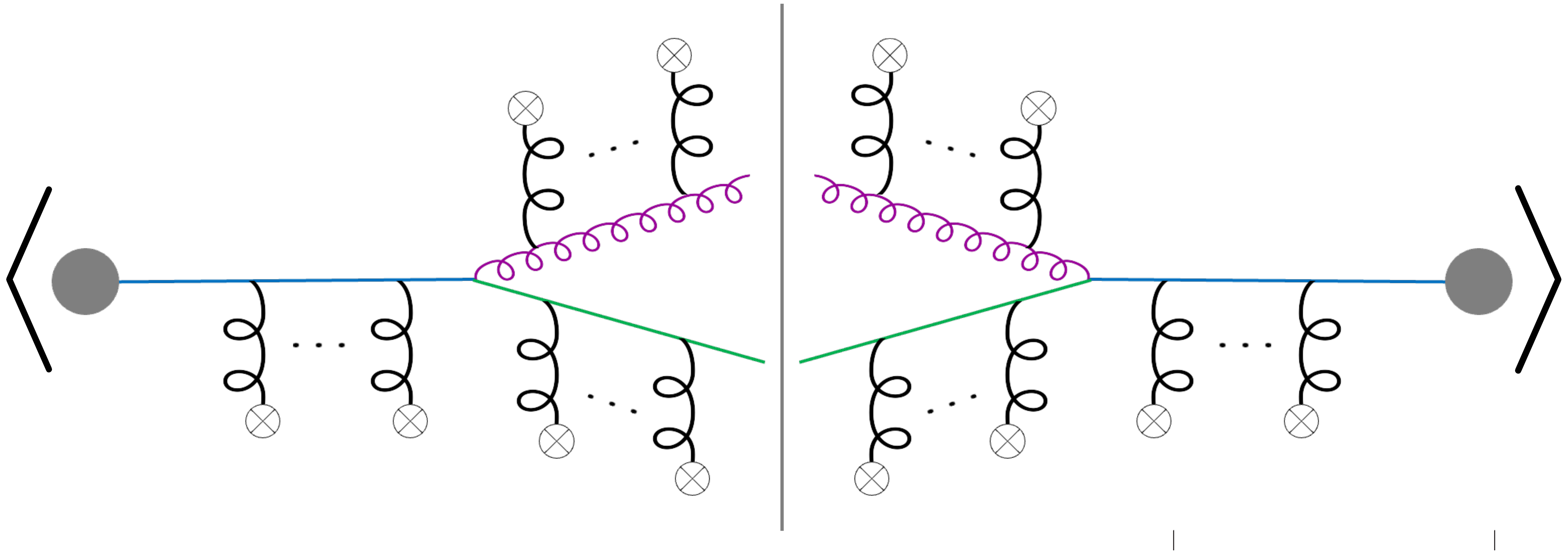

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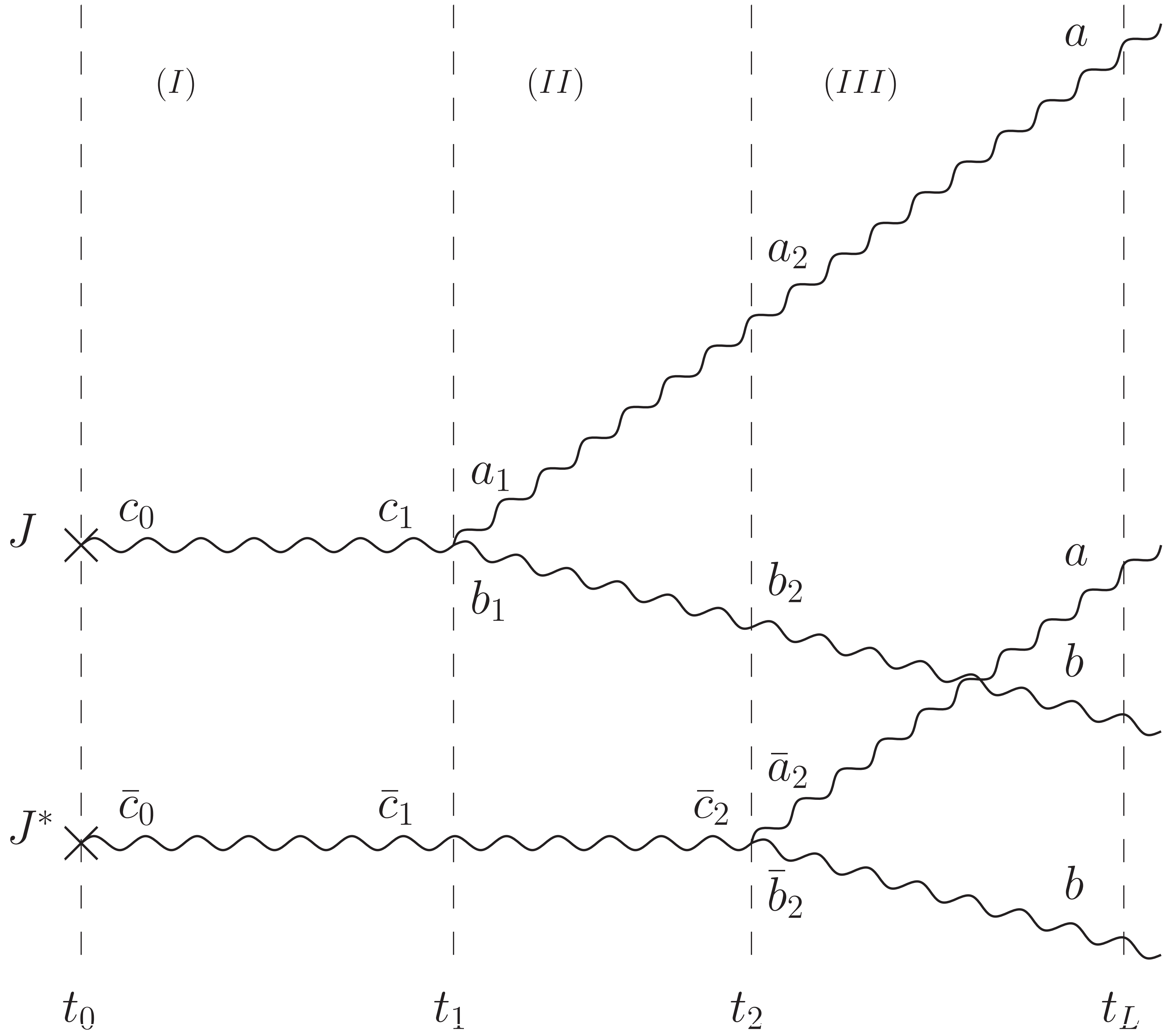

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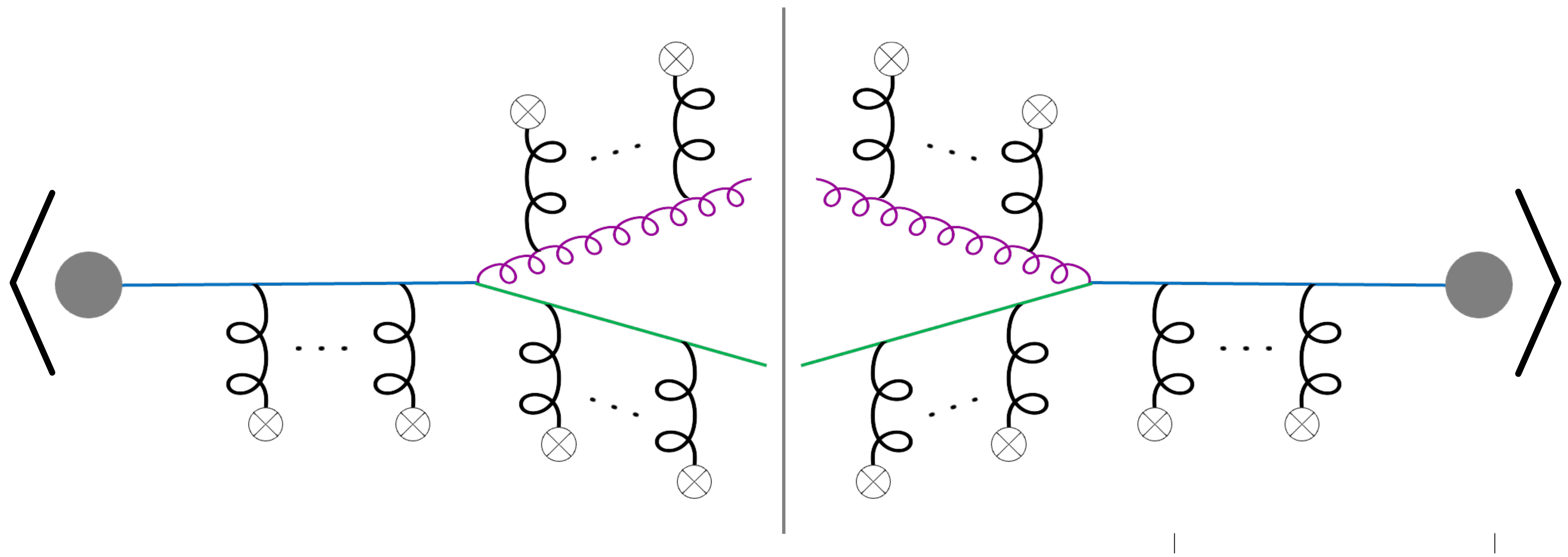

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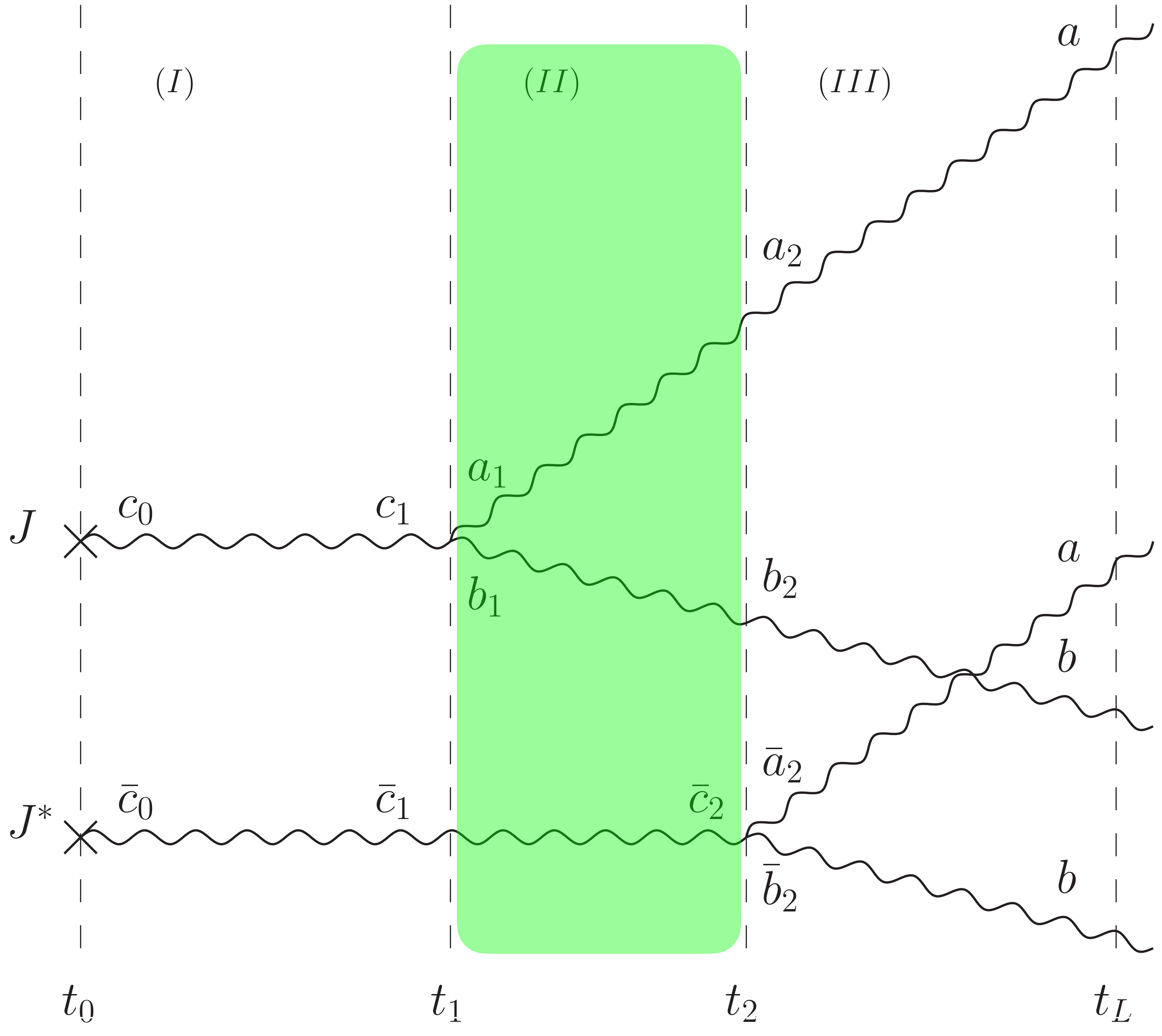

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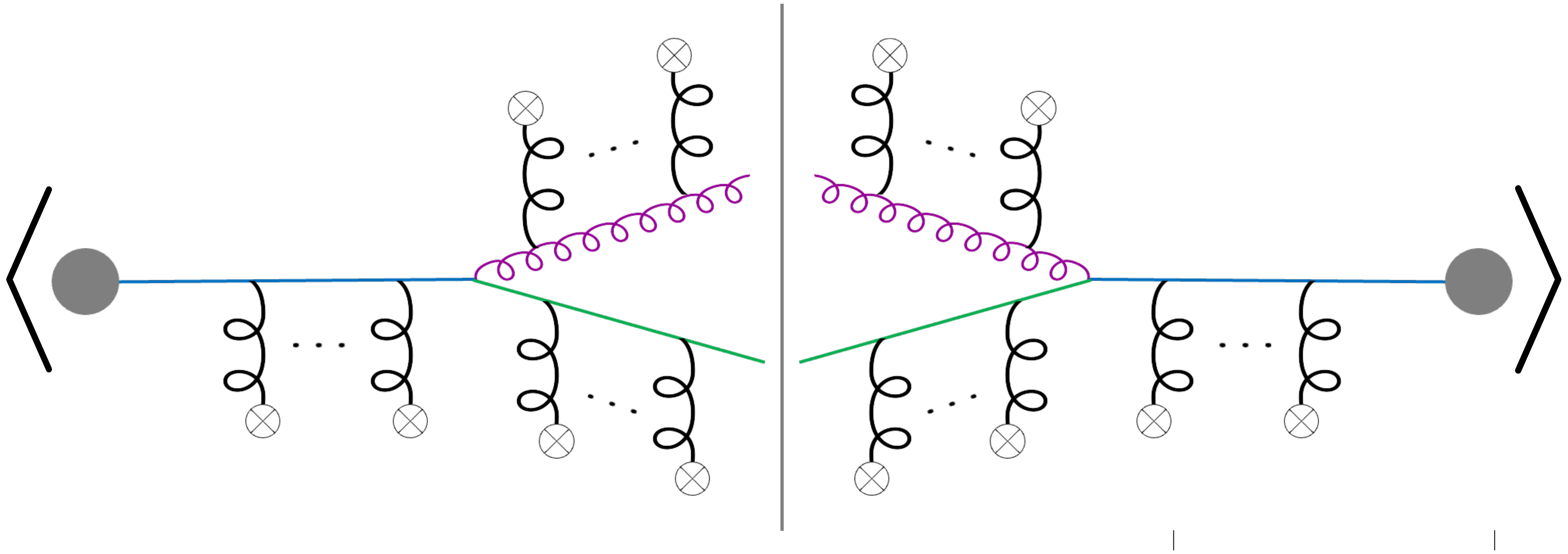

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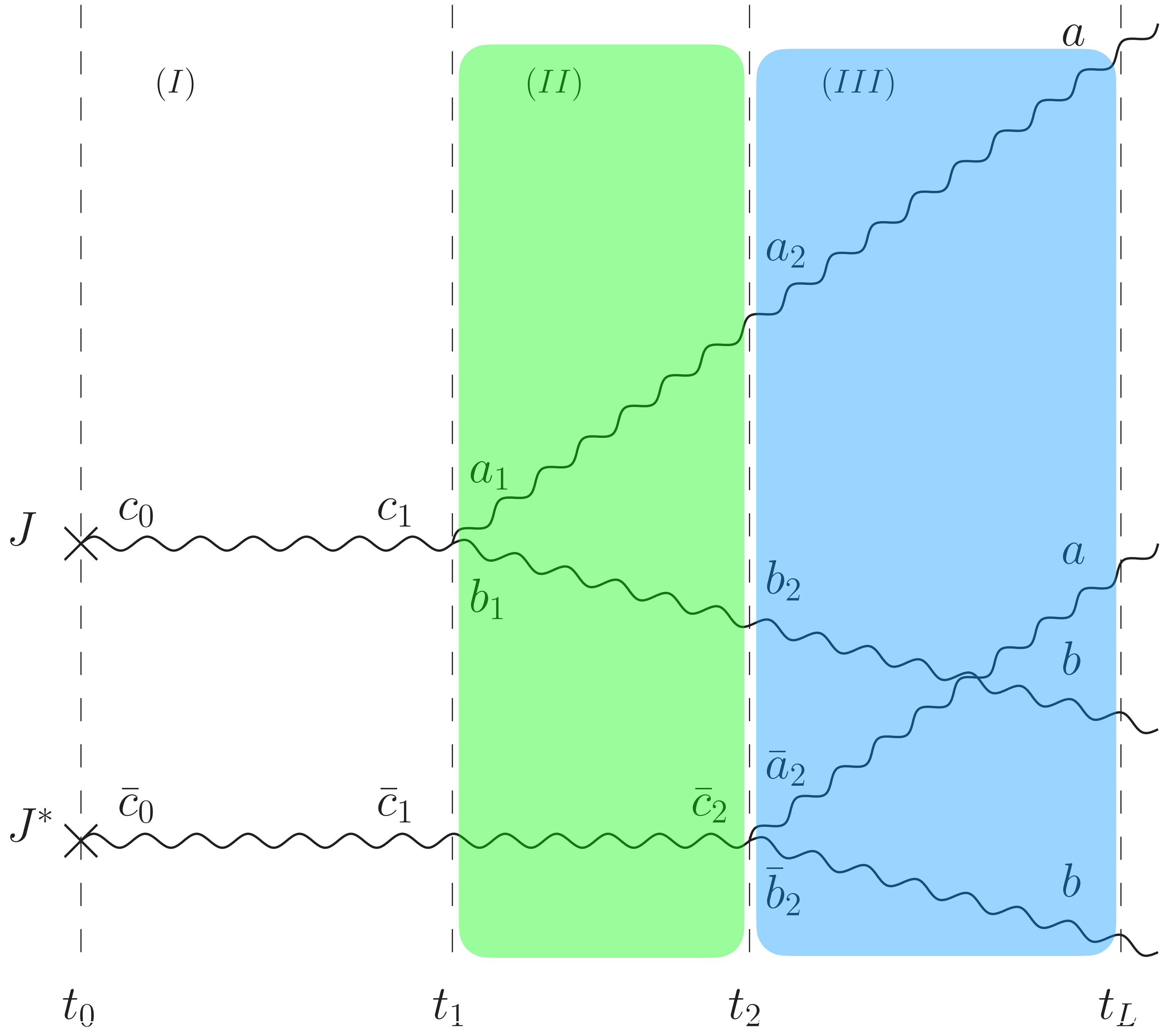

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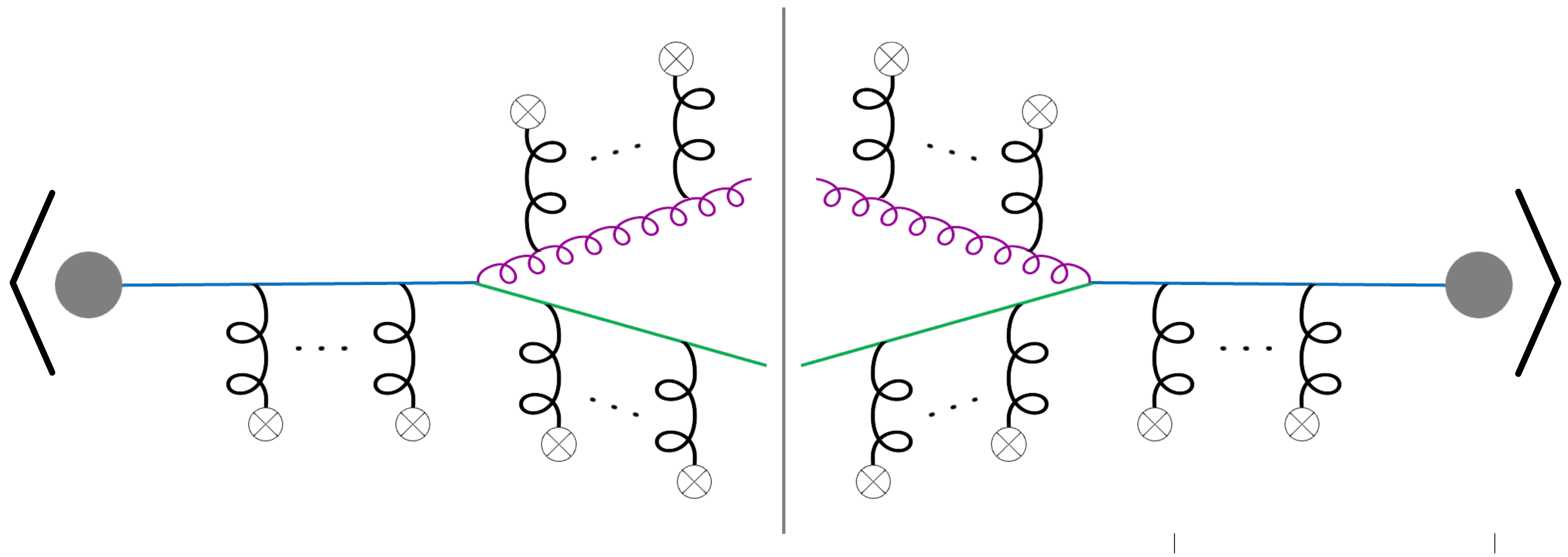

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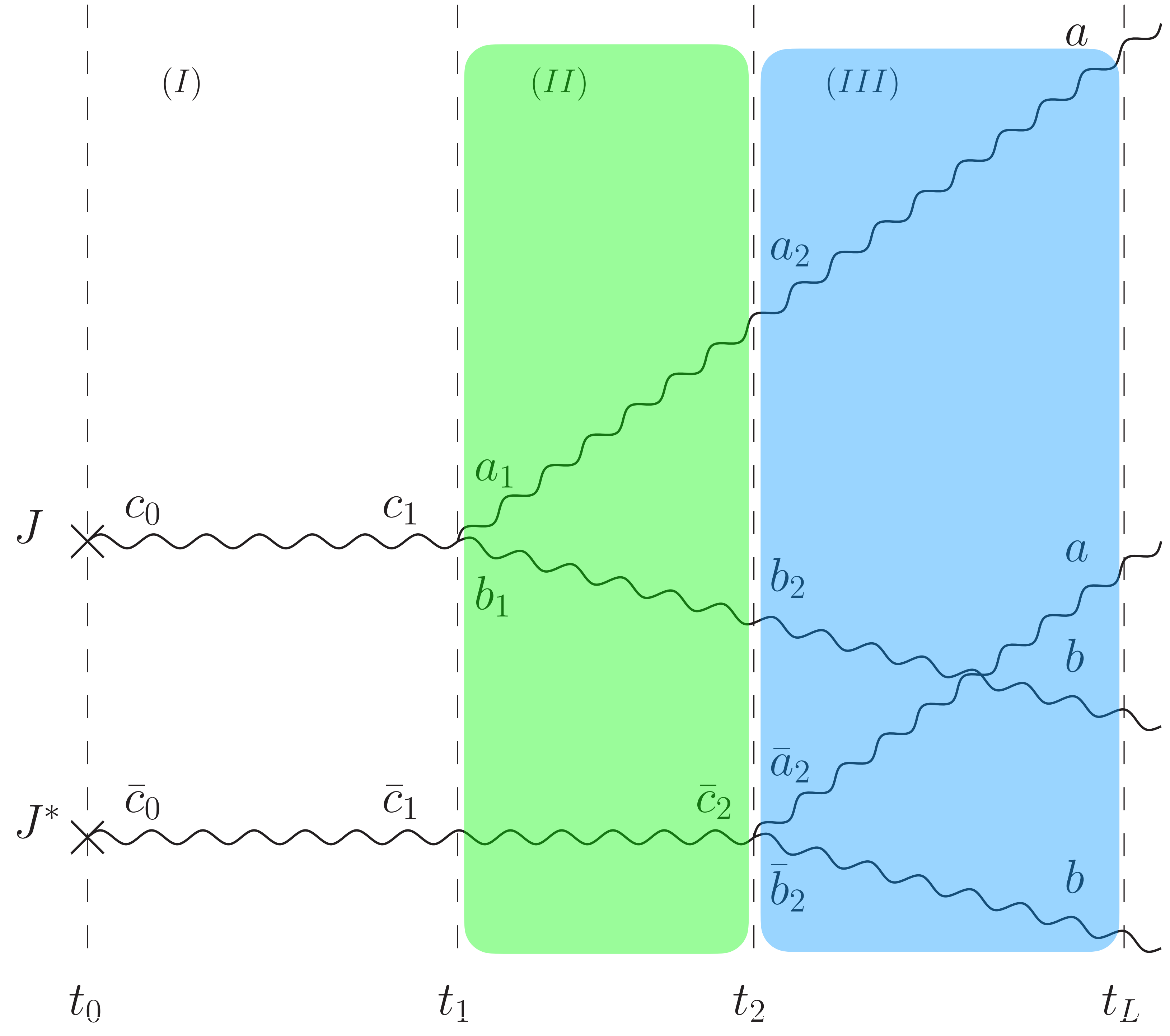
encodes the DC dynamics



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Directional dead-cone

Directional dead-cone: mass dependent coupling of HQ and flow

$$\Theta^2_{\rm dc}(\boldsymbol{k}\cdot\boldsymbol{u}) = \theta^2_{\rm dc}\left(1 - \frac{\boldsymbol{k}\cdot\boldsymbol{u}}{u^-\omega}\right)$$

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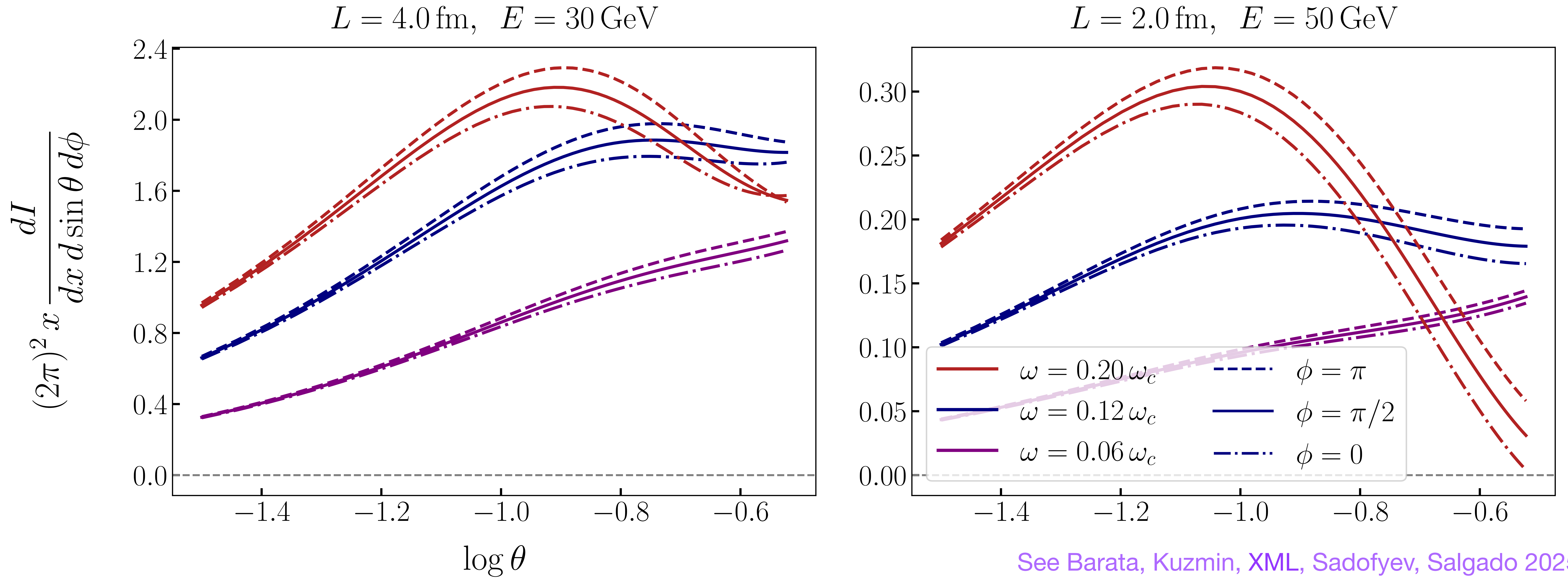
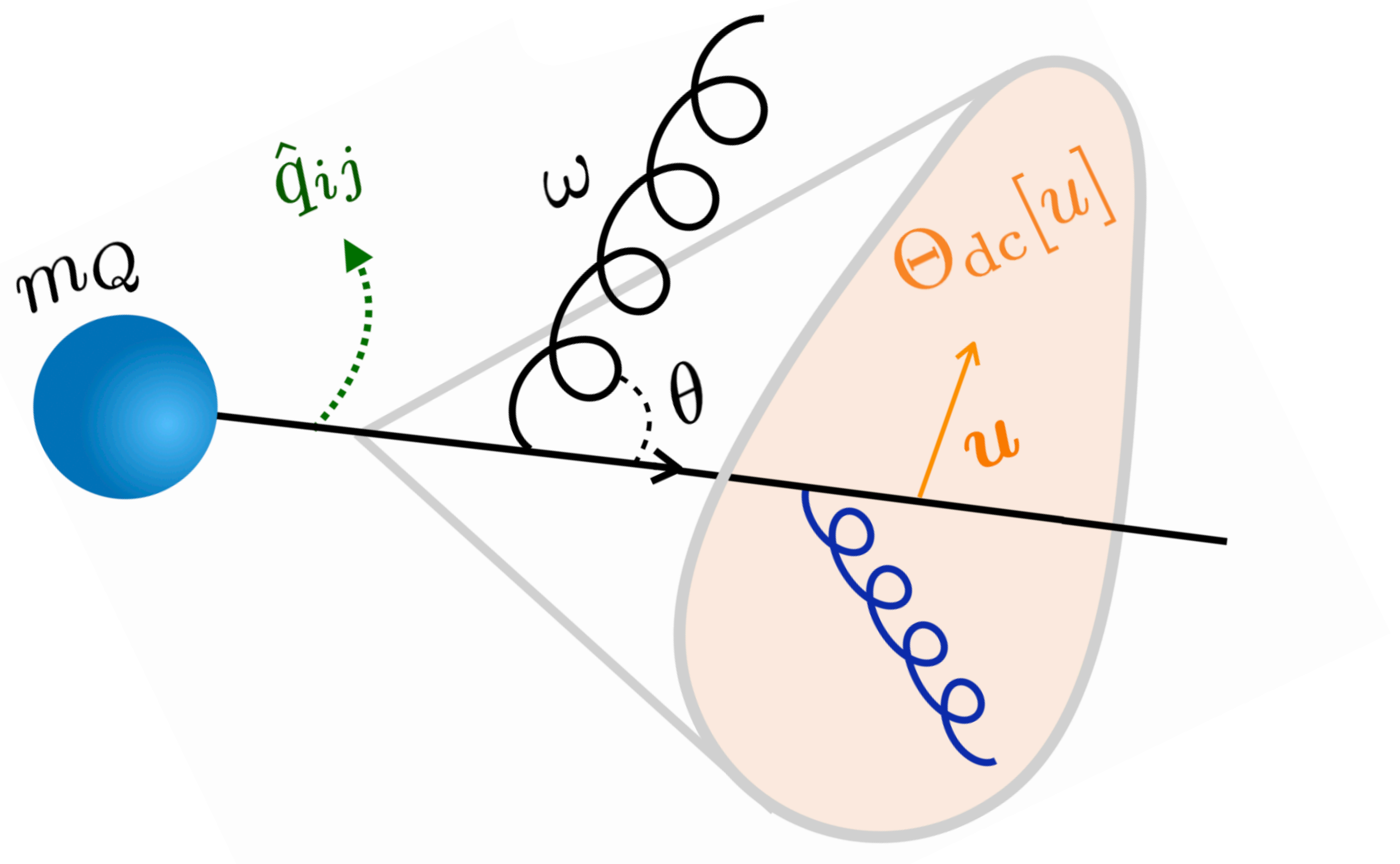
$$\Theta_{\rm dc}^2(\boldsymbol{k}\cdot\boldsymbol{u}) = \theta_{\rm dc}^2\left(1 - \frac{\boldsymbol{k}\cdot\boldsymbol{u}}{u^-\omega}\right)$$

DC becomes anisotropic and the MI radiation becomes elliptical



See Barata, Kuzmin, XML, Sadofyev, Salgado 2025

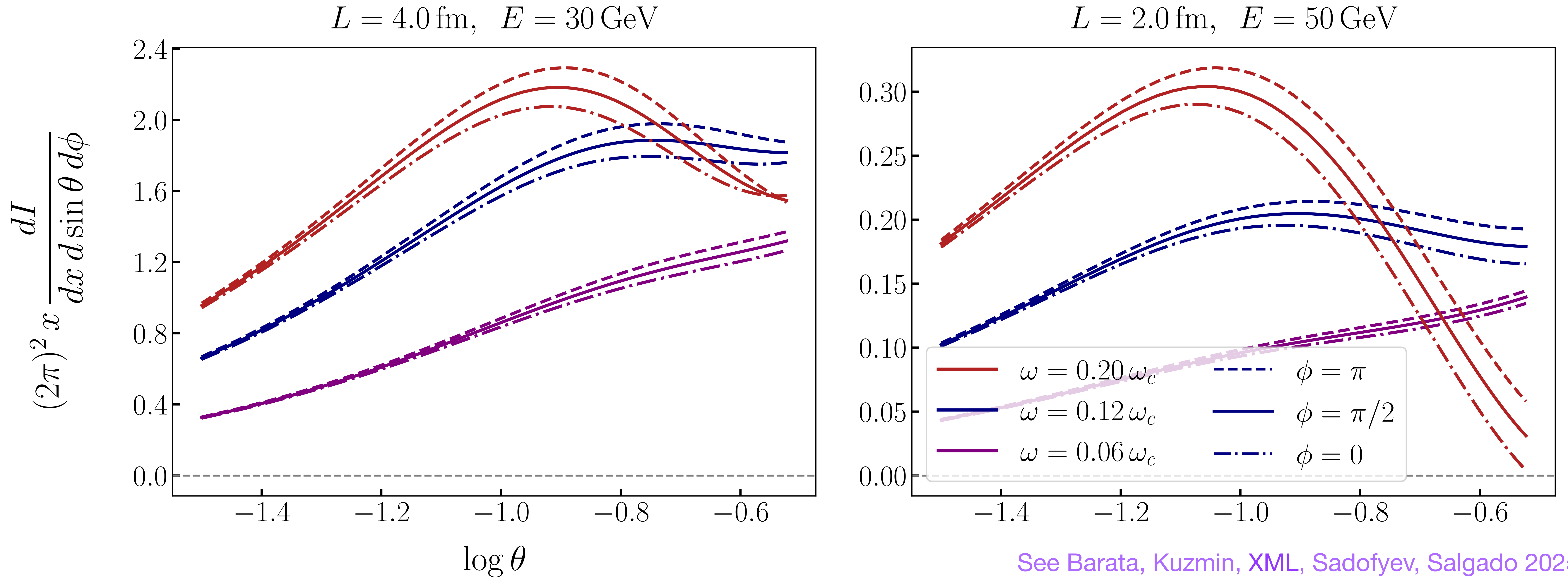
Directional dead-cone



Directional dead-cone: mass dependent coupling of HQ and flow

$$\Theta^2_{\rm dc}(\boldsymbol{k}\cdot\boldsymbol{u}) = \theta^2_{\rm dc}\left(1 - \frac{\boldsymbol{k}\cdot\boldsymbol{u}}{u^-\omega}\right)$$

DC becomes anisotropic and the MI radiation becomes elliptical



See Barata, Kuzmin, XML, Sadofyev, Salgado 2025

Conclusions

To take home:

- The HQ dead-cone effect provide a clean avenue to study medium induced radiation
- There is a mass dependent coupling of the HQ with the transverse dynamics of the matter
- The broadening in the presence of flow becomes anisotropic and the jet quenching parameter tensorial
- The medium-induced radiation inside the DC region encodes information about the transverse flow of the matter

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Thank you!