INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS 25 1999 2024

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The imprints of hydrodynamics in jet quenching

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Mainly based on 2304.03712, 2309.00683, 2406.14628

In collaboration with J. Barata, M. Kuzmin, A. Sadofyev and C. Salgado

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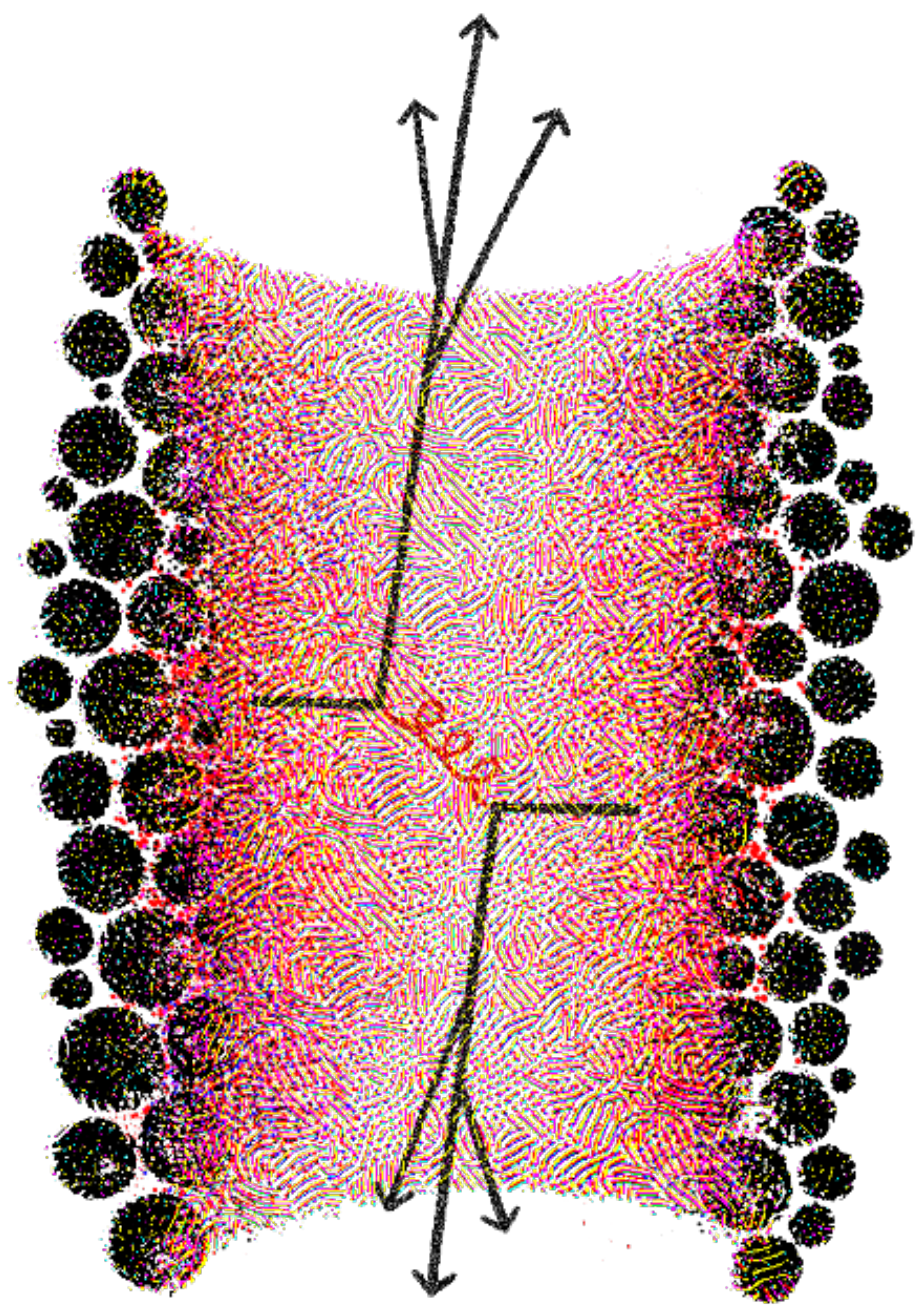
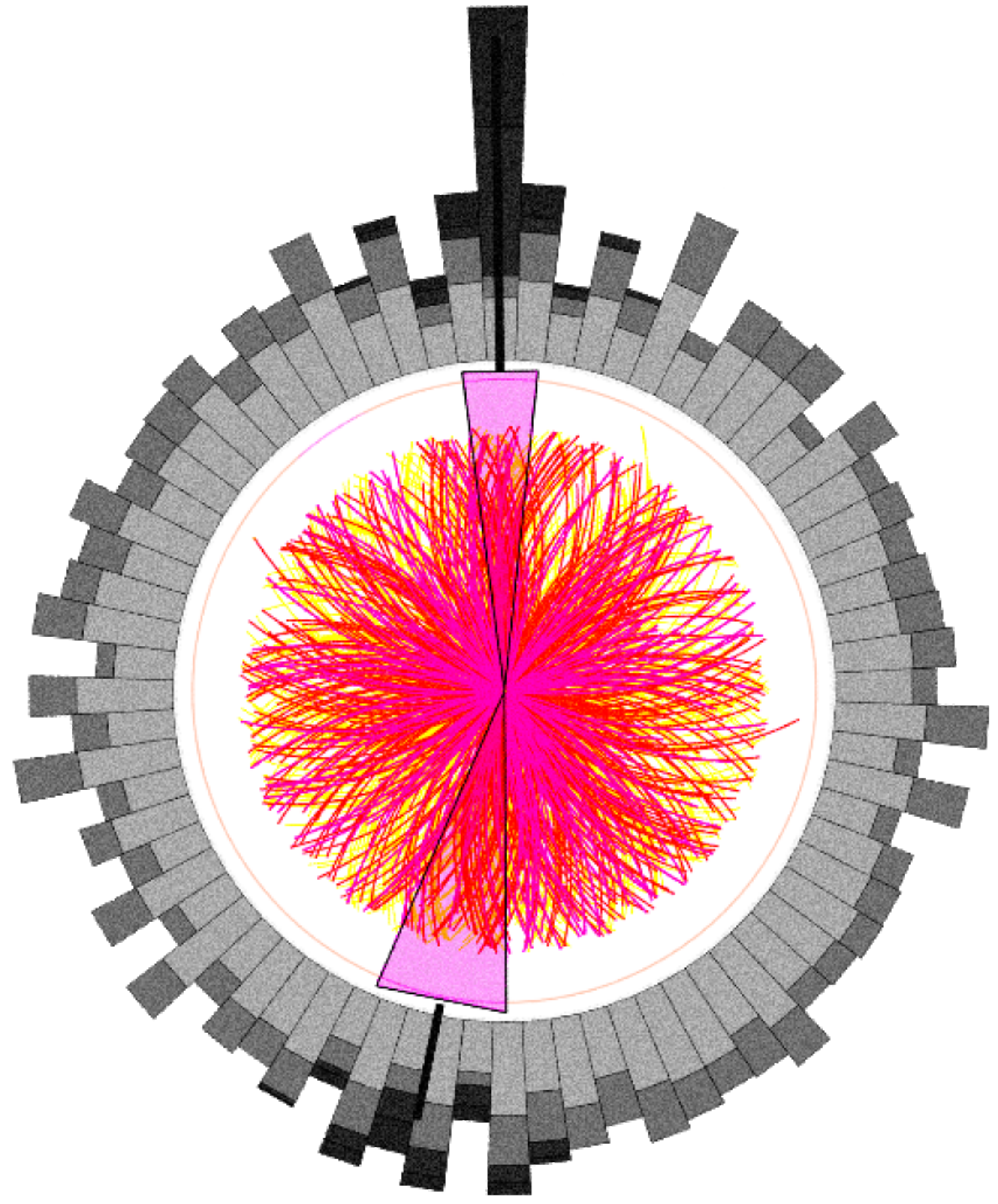
Jet tomography



jet quenching



- Jet tomography: 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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Do jets feel the transverse flow and anisotropies of the QGP?

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Florian Lindenbauer Mon
Andrey Sadofyev Mon
Sergio Barrera Mon

Joseph Bahder Tue
Dana Avramescu Tue

Tan Luo Wed
Rainer Fries Wed
Carlos Salgado Wed
João Silva Wed
Carlos Lamas Wed

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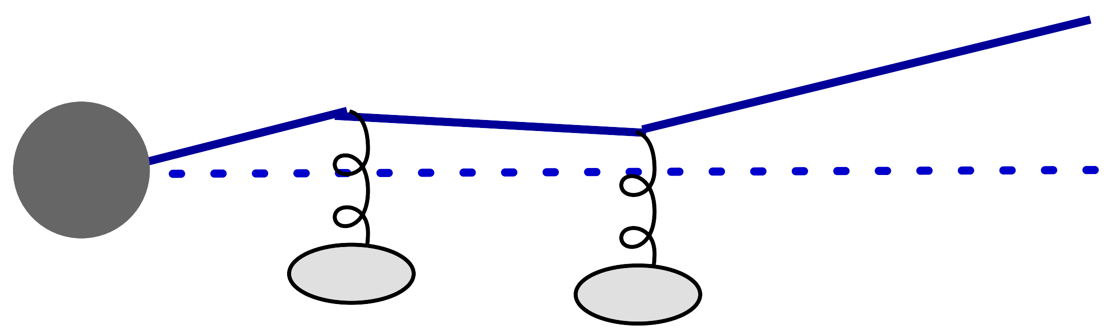
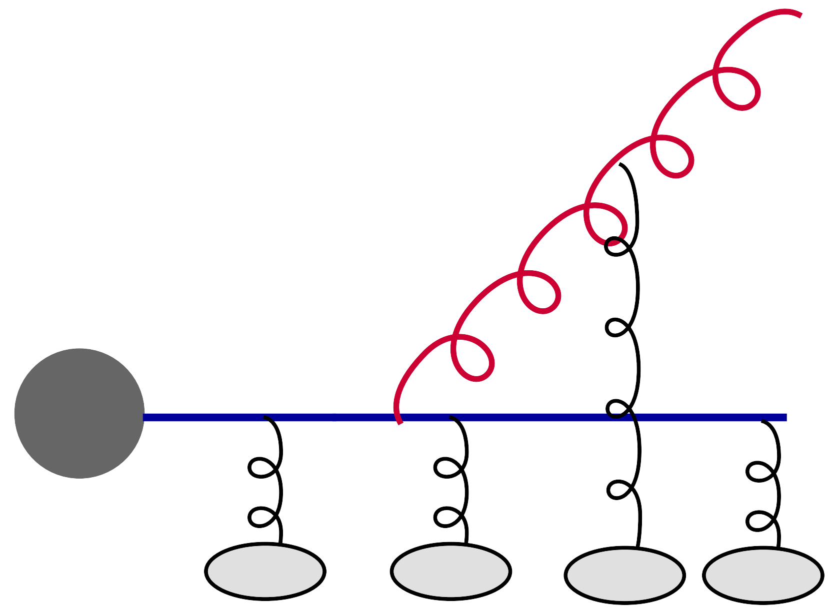
Focus on leading perturbative processes: Two processes that modify jets.

Broadening



Medium induced gluon radiation



Theoretical formulation of jet quenching requires several assumptions to make it tractable. Some of them are

- Ekional expansion; only sub-eikonal length enhanced terms are kept
- Medium is modeled by a background field
- In the simplest scenario the medium is static and homogeneous

See e.g.
Casalderrey-Solana, Salgado 2007

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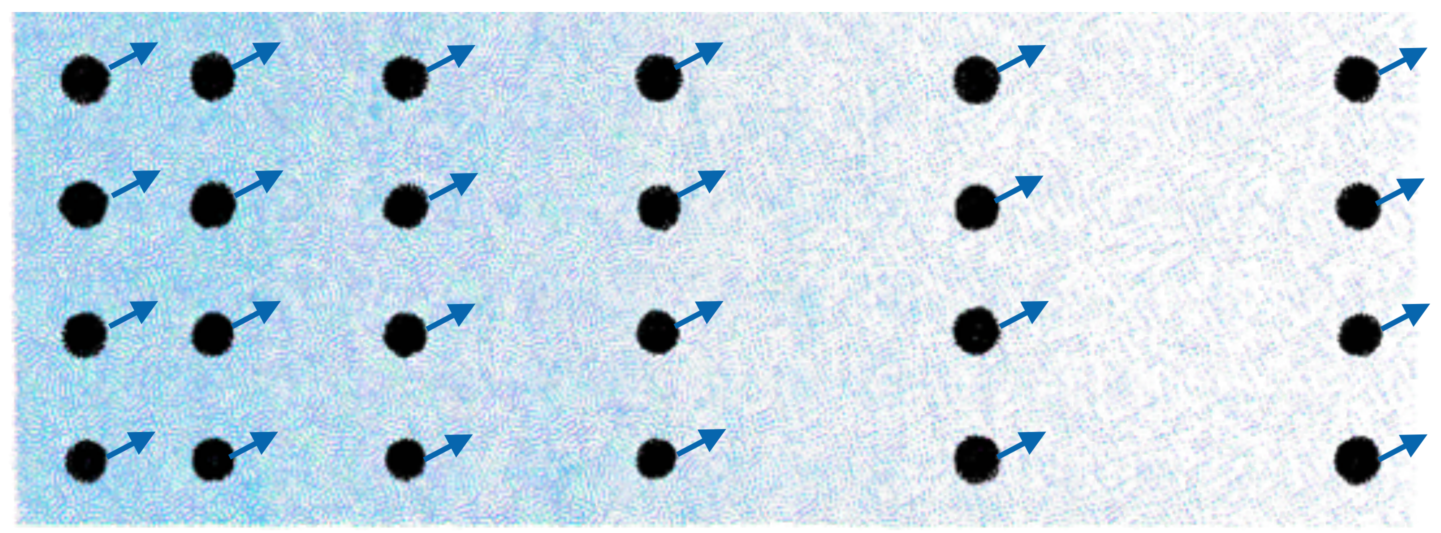
Background color field

See e.g.
Sadofyev, Sievert, Vitev PRD 2021
Andres, Dominguez, Sadofyev, Salgado PRD 2022
Kuzmin, XML, Reiten, Sadofyev PRD 2024
Kuzmin, XML 2024

The medium is modeled by a field created by a classical current of sources



→ Heavy sources

$$u_\mu = (1,\, \boldsymbol{u},\, u_z)_\mu$$

The stochastic field can be written as

$$v_i(q) = \frac{g^2}{q^2 - \mu^2 + i\epsilon}$$

$$gA^{a\mu}(q) = \sum_i u_i^\mu e^{-iq\cdot x_i}\, t_i^a\, v_i(q)\, (2\pi)\delta(q_0 - \boldsymbol{q}\cdot\boldsymbol{u} - q_z u_z)$$

- $v_i(q)$ (green): controls the jet-medium interaction
- $\sum_i$ (red): controls the inhomogeneity
- u_i^μ (blue): velocity of the sources

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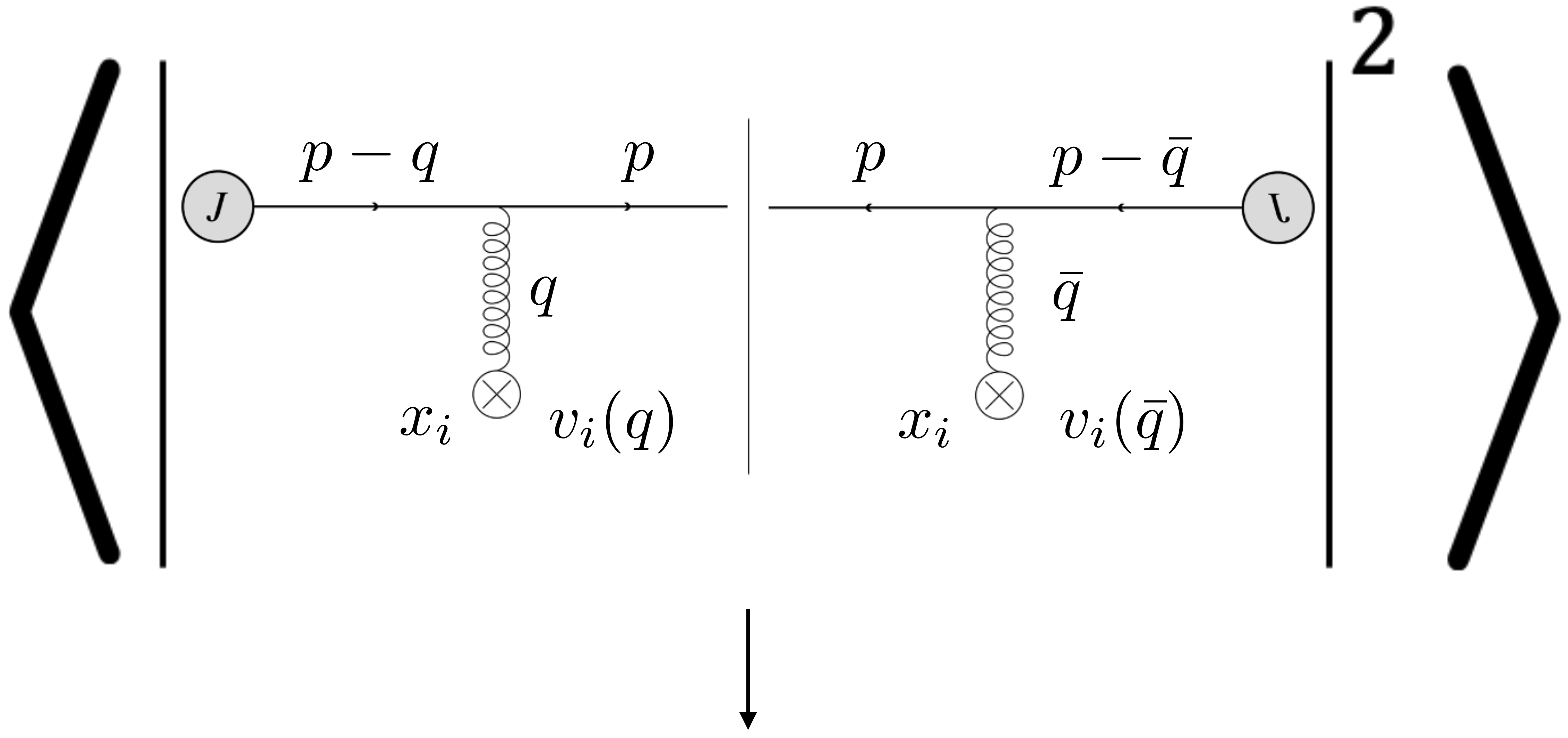
Medium average

Stochastic field ⟶ need to specify the average over its configurations ⟶ Gaussian statistics



Colour neutrality

$$\langle A^a(q)A^b(\bar{q})\rangle \sim \langle t_i^a t_j^b\rangle = \mathcal{C}\,\delta_{ij}\,\delta^{ab}$$

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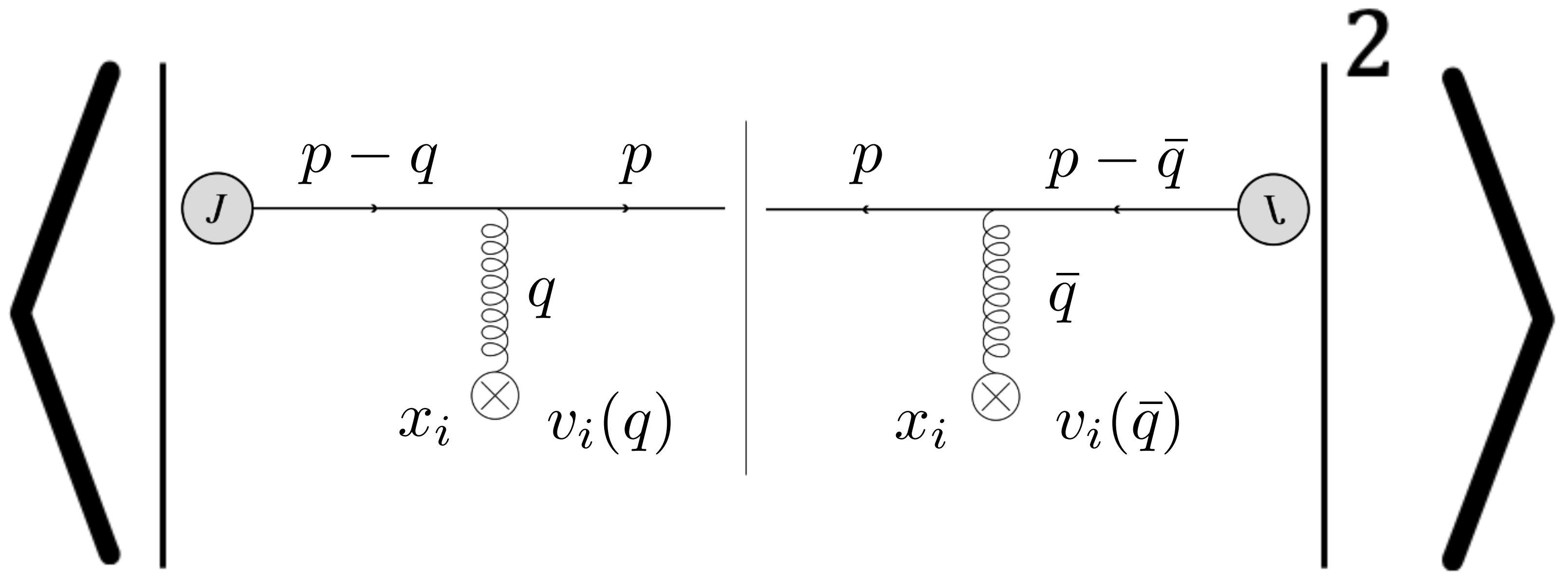
Gradients in the medium average

Hydrodynamic variables, $g(\boldsymbol{x}, z)$, encode the matter structure: $g(\boldsymbol{x}, z) \equiv \quad \rho(\boldsymbol{x}, z) \quad \mu^2(\boldsymbol{x}, z) \quad \boldsymbol{u}(\boldsymbol{x}, z) \quad u_z(\boldsymbol{x}, z)$



See e.g.

Sadofyev, Sievert, Vitev PRD 2021
Barata, Sadofyev, Salgado PRD 2022
Barata, XML, Sadofyev, Salgado PRD 2023
Kuzmin, XML, Reiten, Sadofyev PRD 2024

Transversely homogeneous matter :

$$g(\boldsymbol{x}, z) \simeq g(z)$$

$$\int_{\boldsymbol{x}} g(z)\, e^{-i(\boldsymbol{q}\pm\bar{\boldsymbol{q}})\cdot\boldsymbol{x}} = g(z)\,(2\pi)^2\,\delta^{(2)}(\boldsymbol{q}\pm\bar{\boldsymbol{q}})$$

Transversely inhomogeneous matter :

$$g(\boldsymbol{x}, z) \simeq g(z) + \boldsymbol{\nabla}_\alpha g(z)\,\boldsymbol{x}_\alpha$$

$$\int_{\boldsymbol{x}} \boldsymbol{\nabla}_\alpha g(z)\,\boldsymbol{x}_\alpha\, e^{-i(\boldsymbol{q}\pm\bar{\boldsymbol{q}})\cdot\boldsymbol{x}} = i\boldsymbol{\nabla}_\alpha g(z)\,(2\pi)^2 \frac{\partial}{\partial(\boldsymbol{q}\pm\bar{\boldsymbol{q}})_\alpha}\delta^{(2)}(\boldsymbol{q}\pm\bar{\boldsymbol{q}})$$

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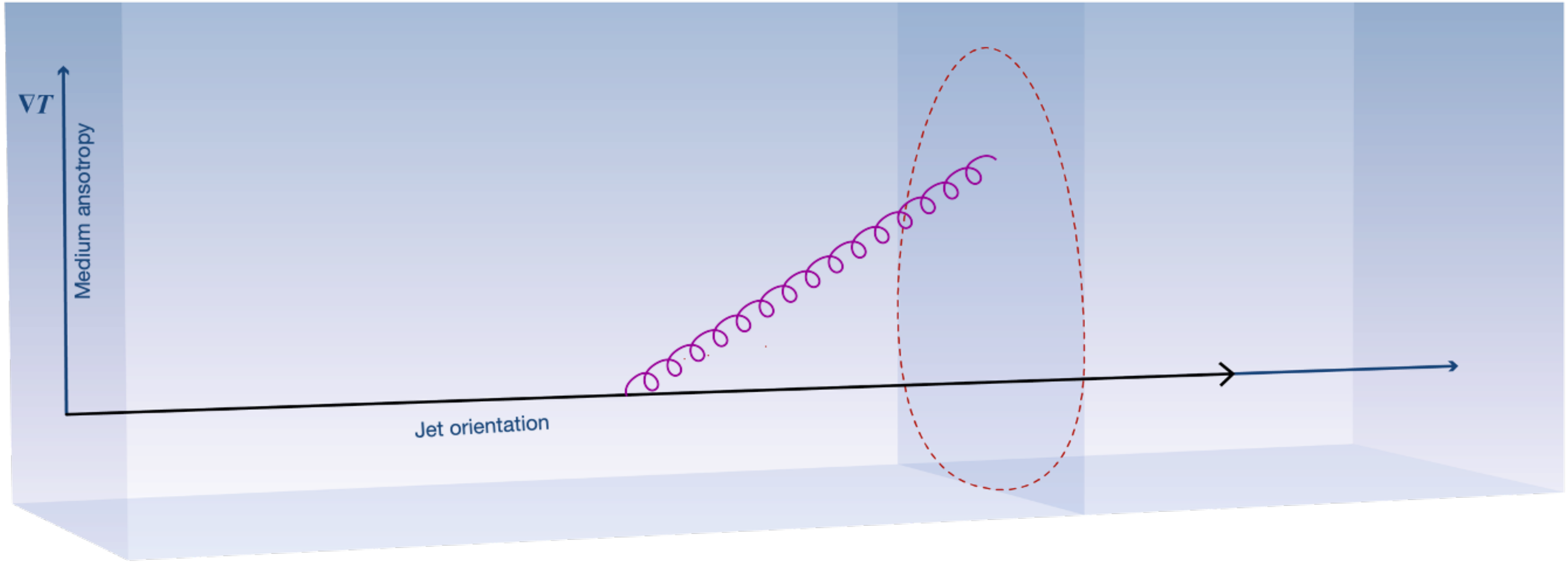
Configuration 1

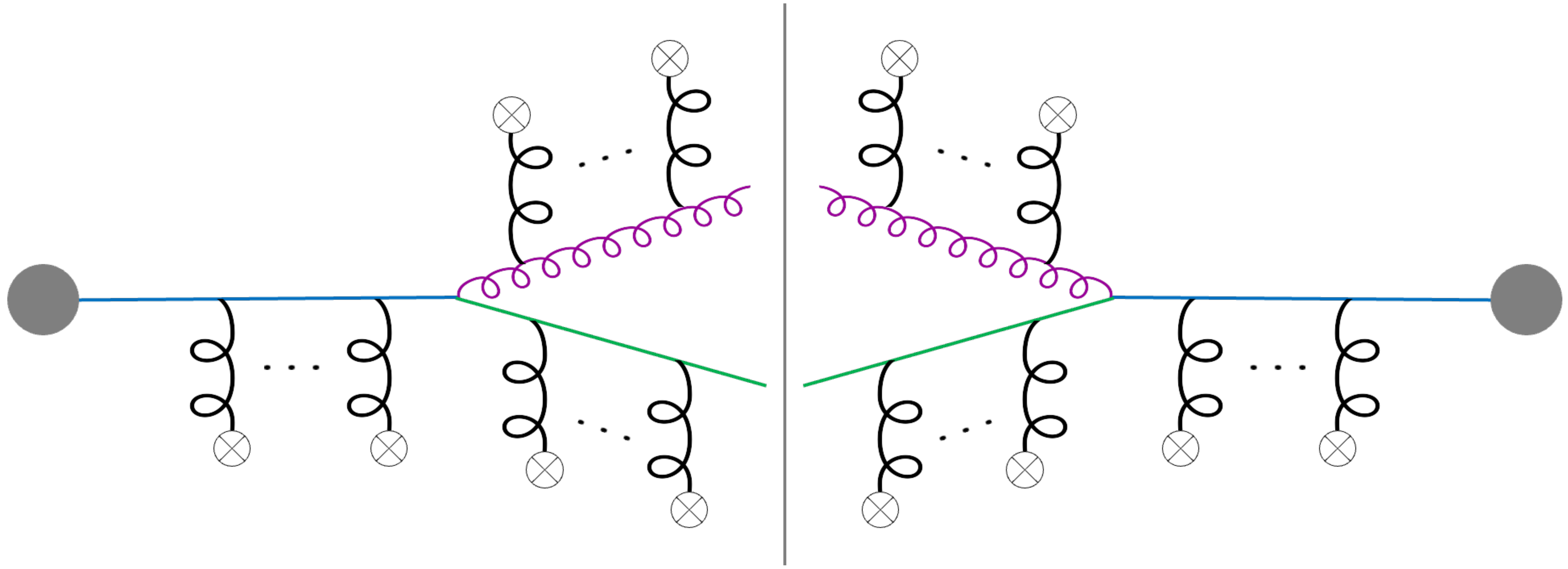
Anisotropic and static matter in the dense regime



Medium-induced radiation

The medium-induced gluon spectrum in the dense regime

$$\int \frac{dI}{d\omega\, d^2\boldsymbol{k}} \quad \frac{dN_0}{dE\, d^2\mathbf{p}} \quad \propto$$



Controls the in-medium energy loss

$$\frac{d\omega}{dL} \propto \frac{\partial}{\partial L} \int d\omega\, d^2\mathbf{k}\, \omega \frac{dI}{d\omega\, d^2\mathbf{k}}$$

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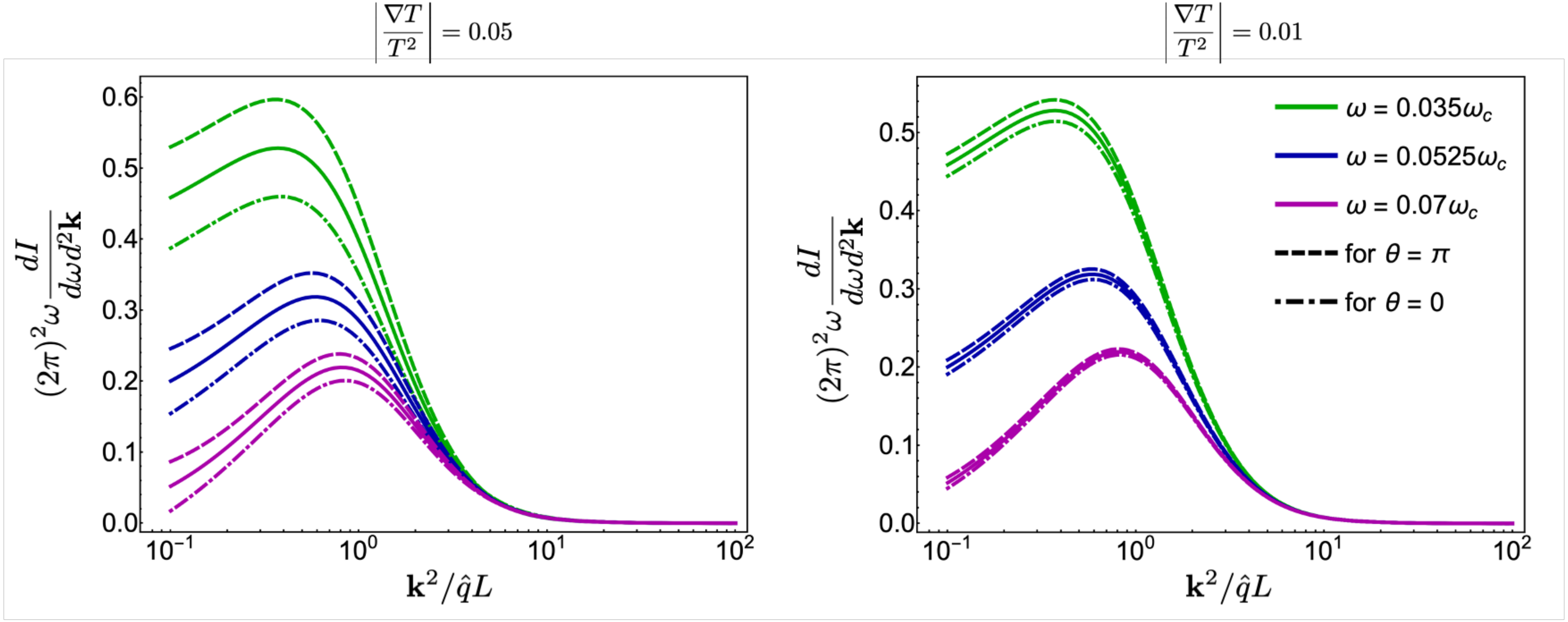
Medium-induced radiation

The spectrum is anisotropic with a modification subleading in energy

Assuming harmonic oscillator and constant density profile



See Barata, XML, Sadofyev, Salgado PRD 2023

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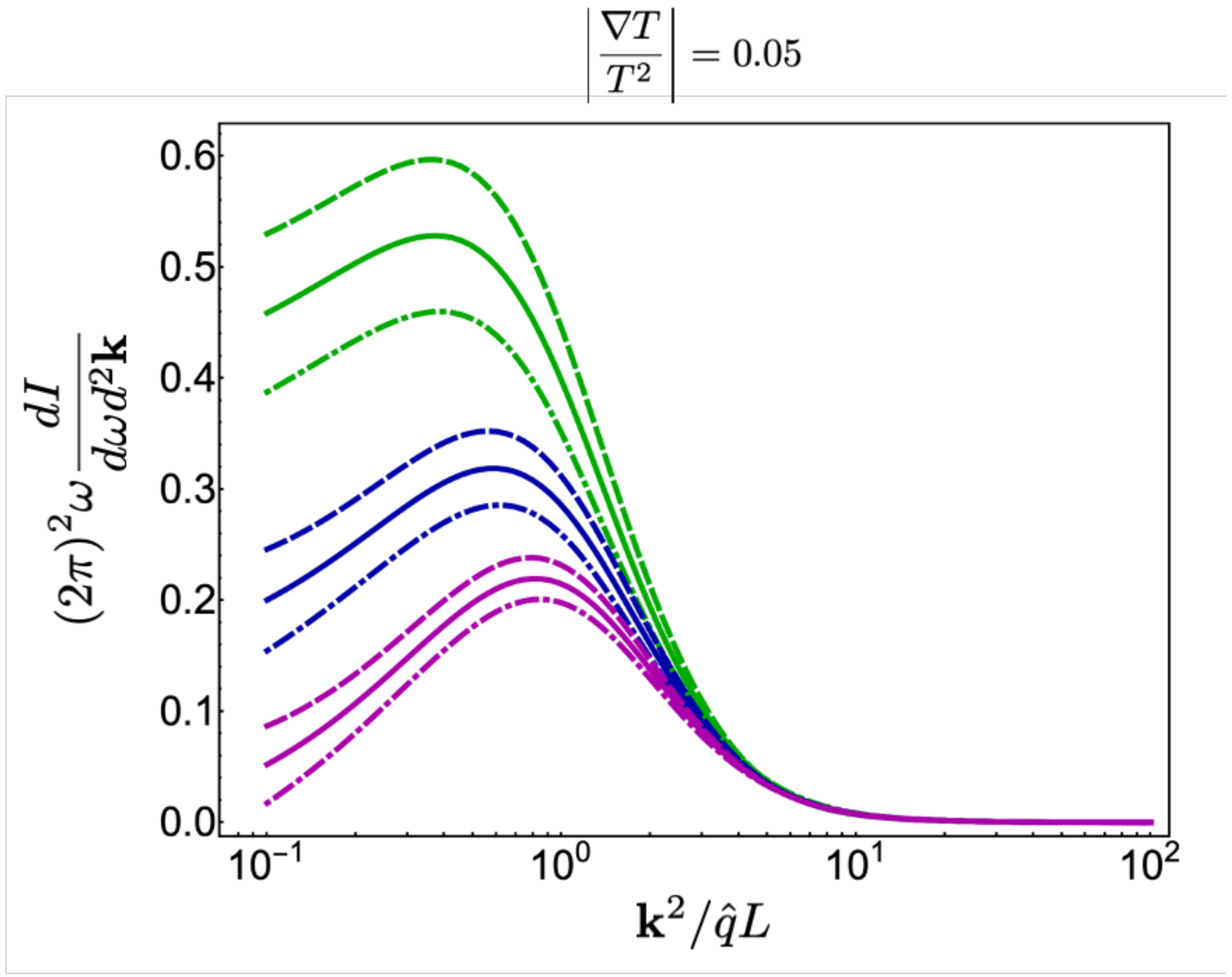

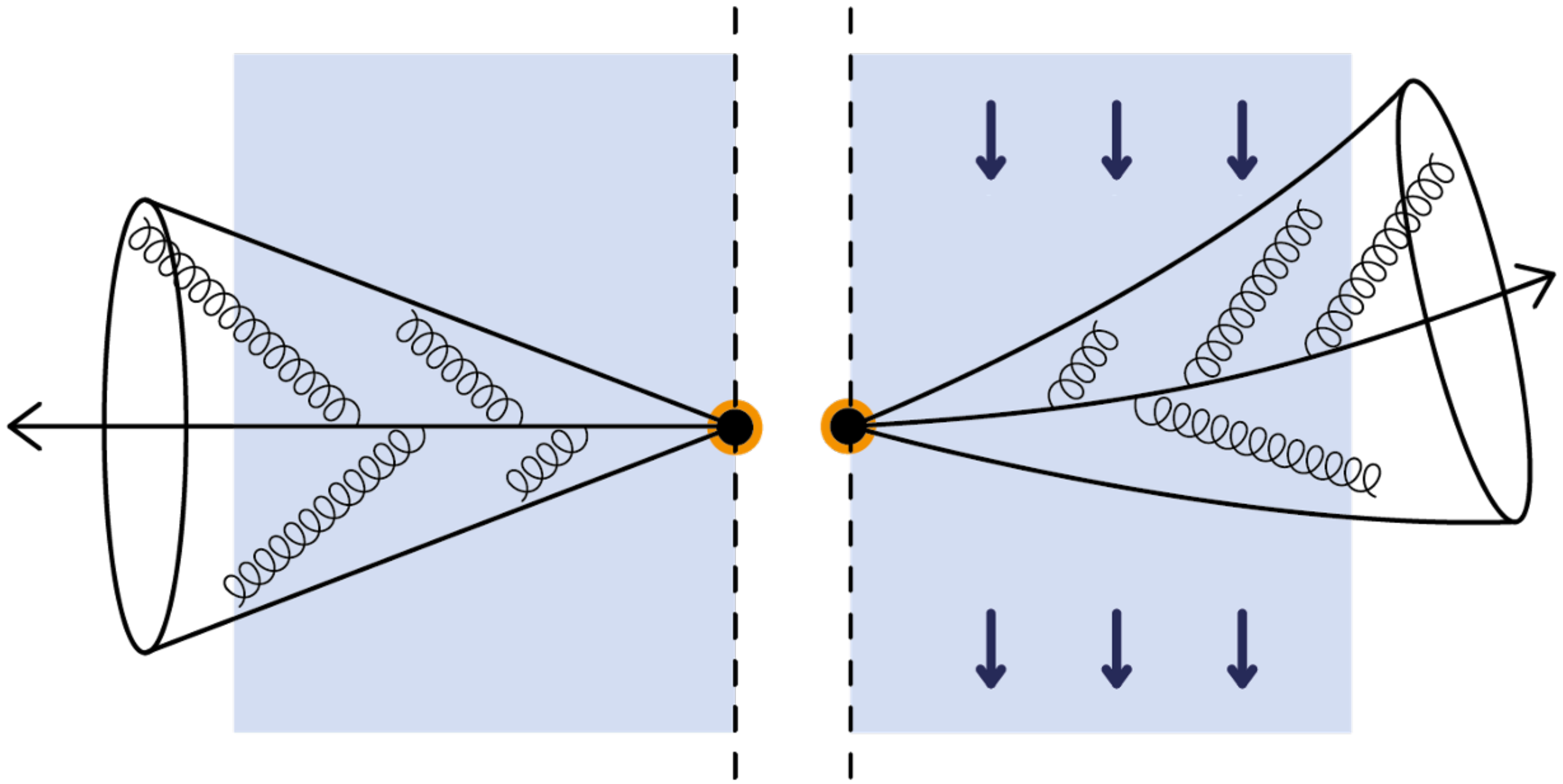

See Barata, XML, Sadofyev, Salgado PRD 2023

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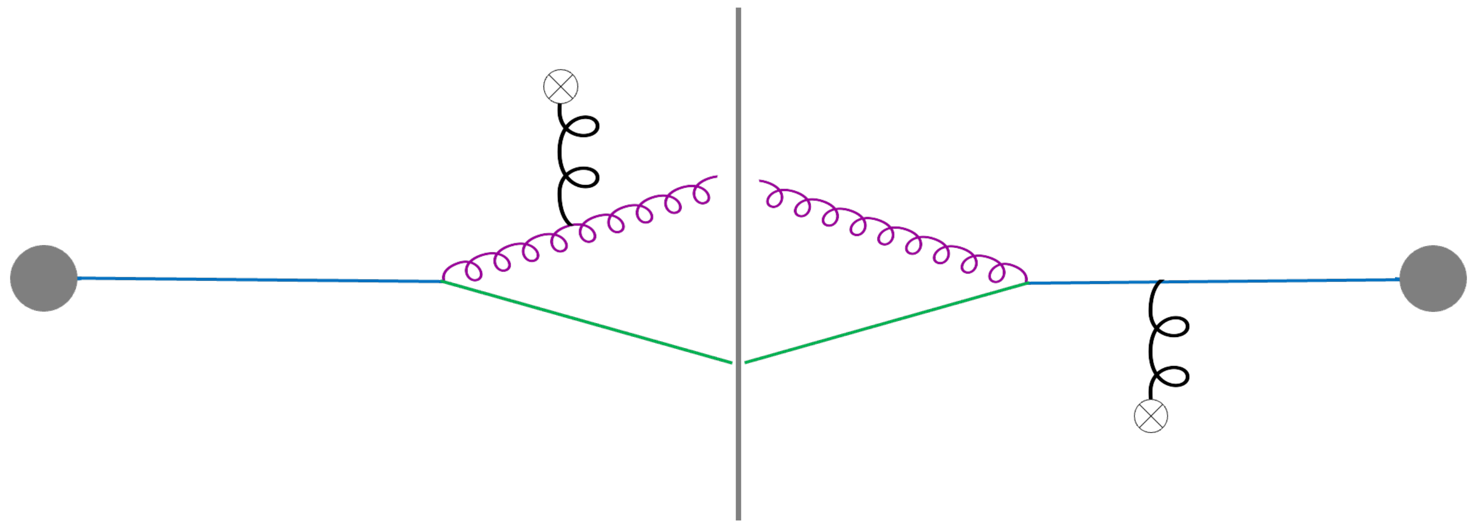
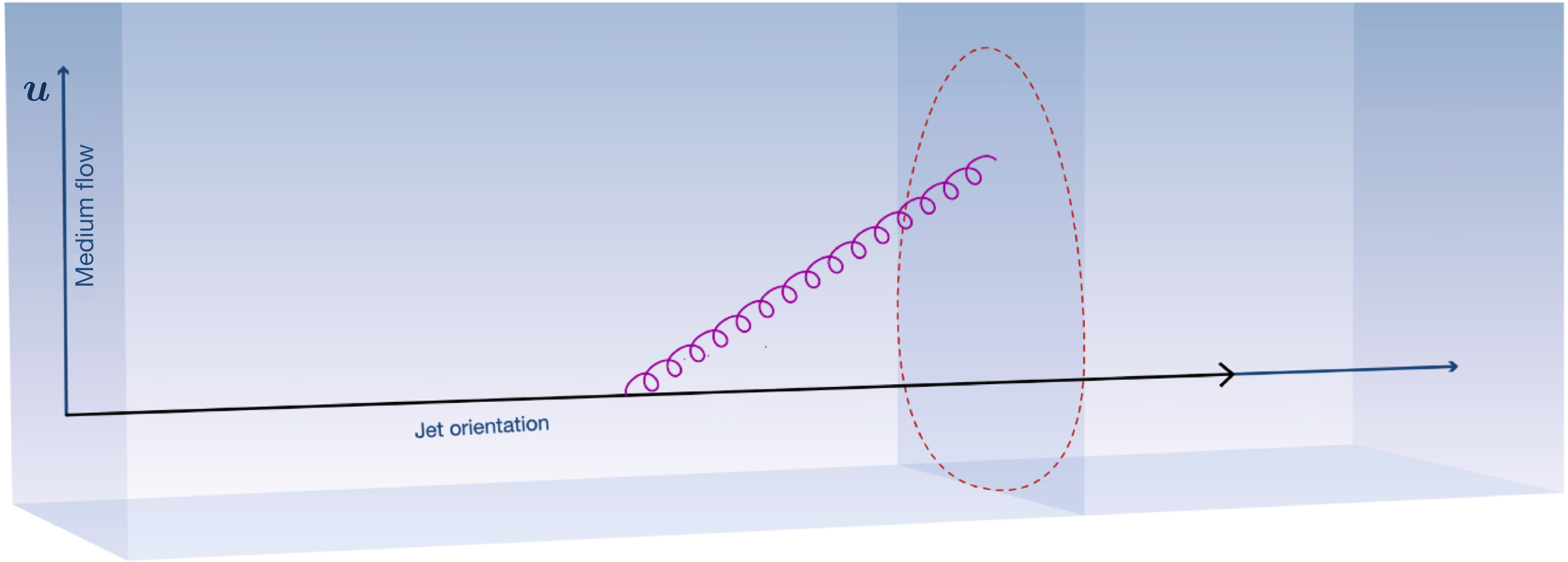


Configuration 2

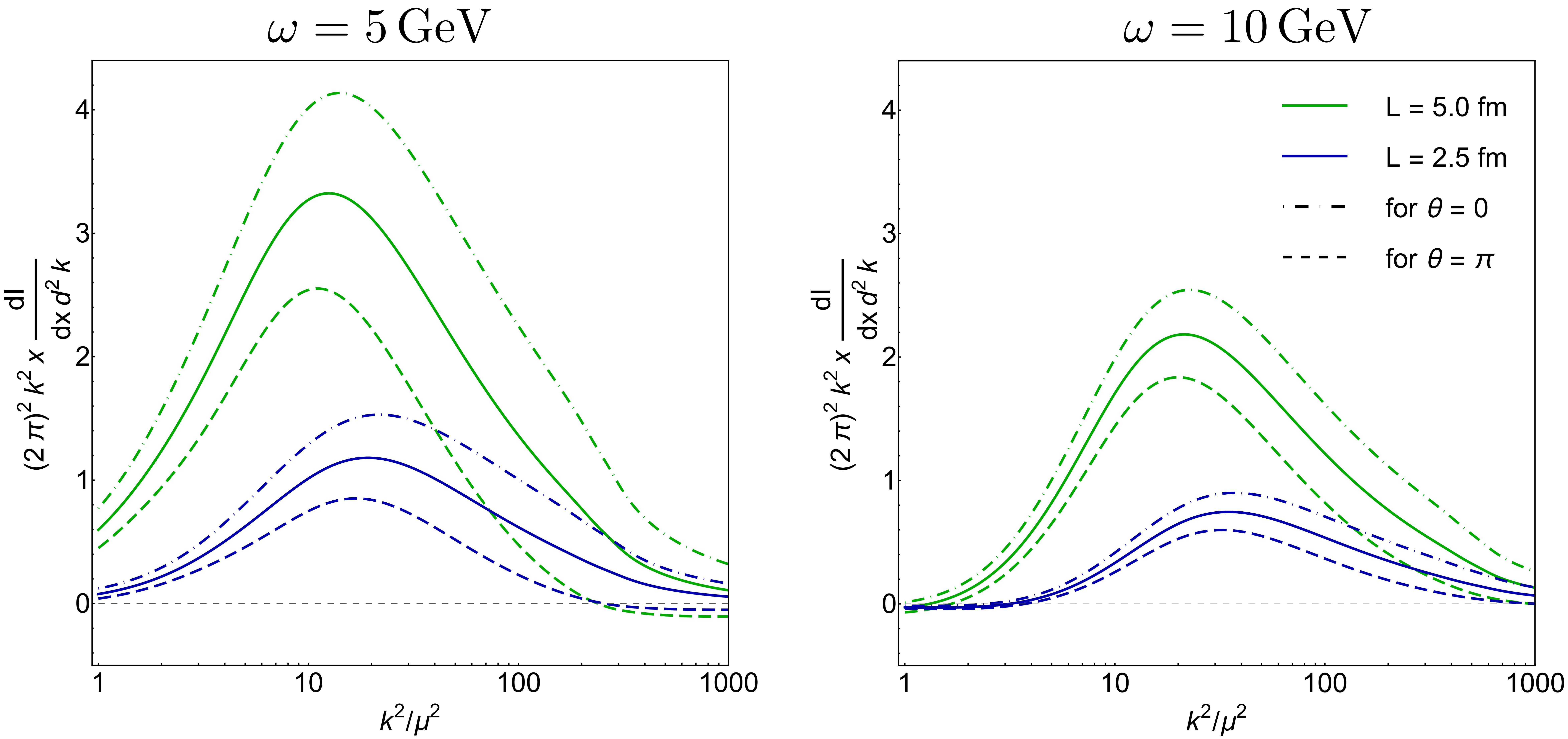
Homogeneous and flowing matter in the dilute regime



Medium-induced radiation

The spectrum is anisotropic with a modification subleading in energy

Assuming GW potential and smooth density profile in the longitudinal direction

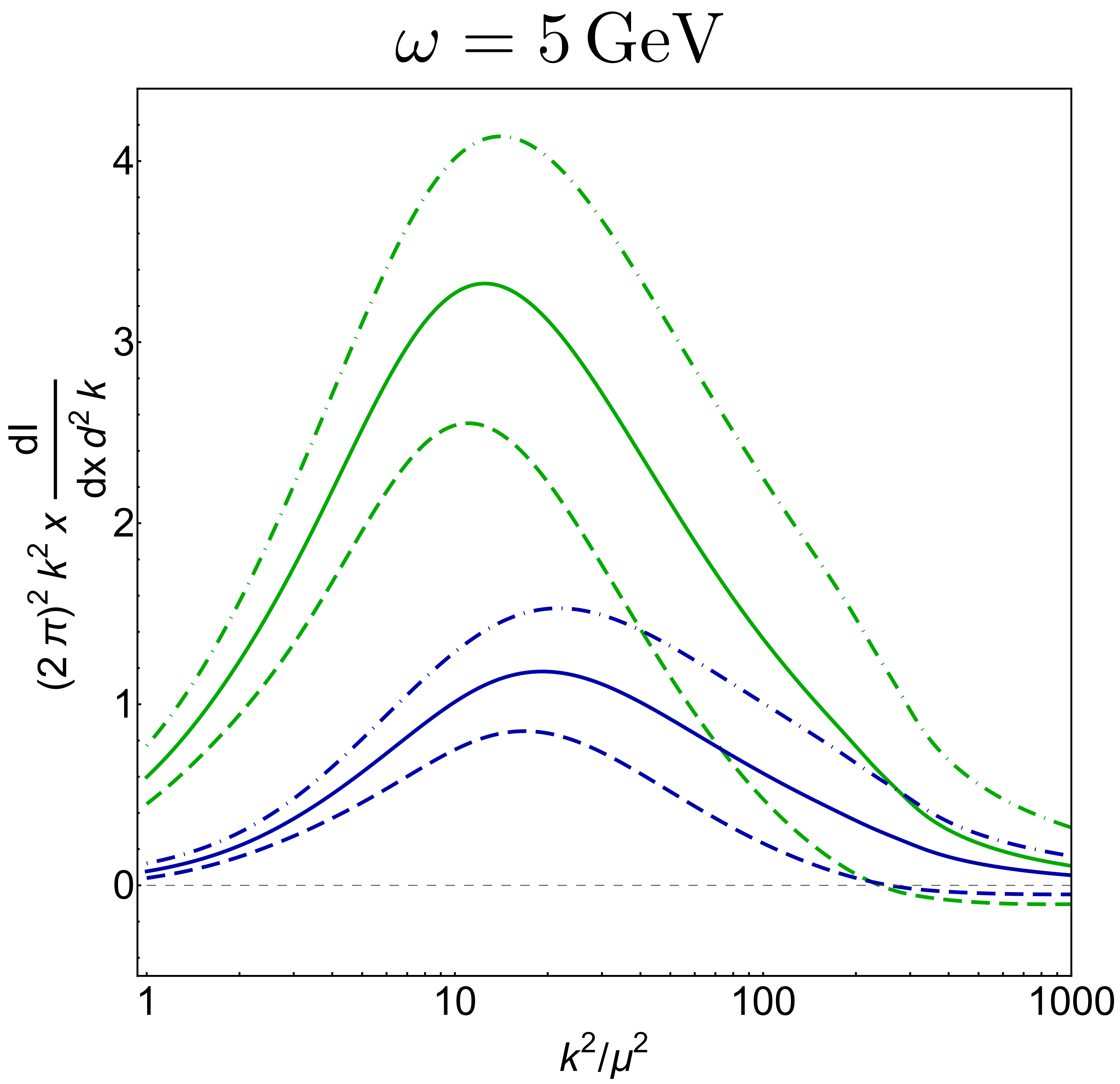


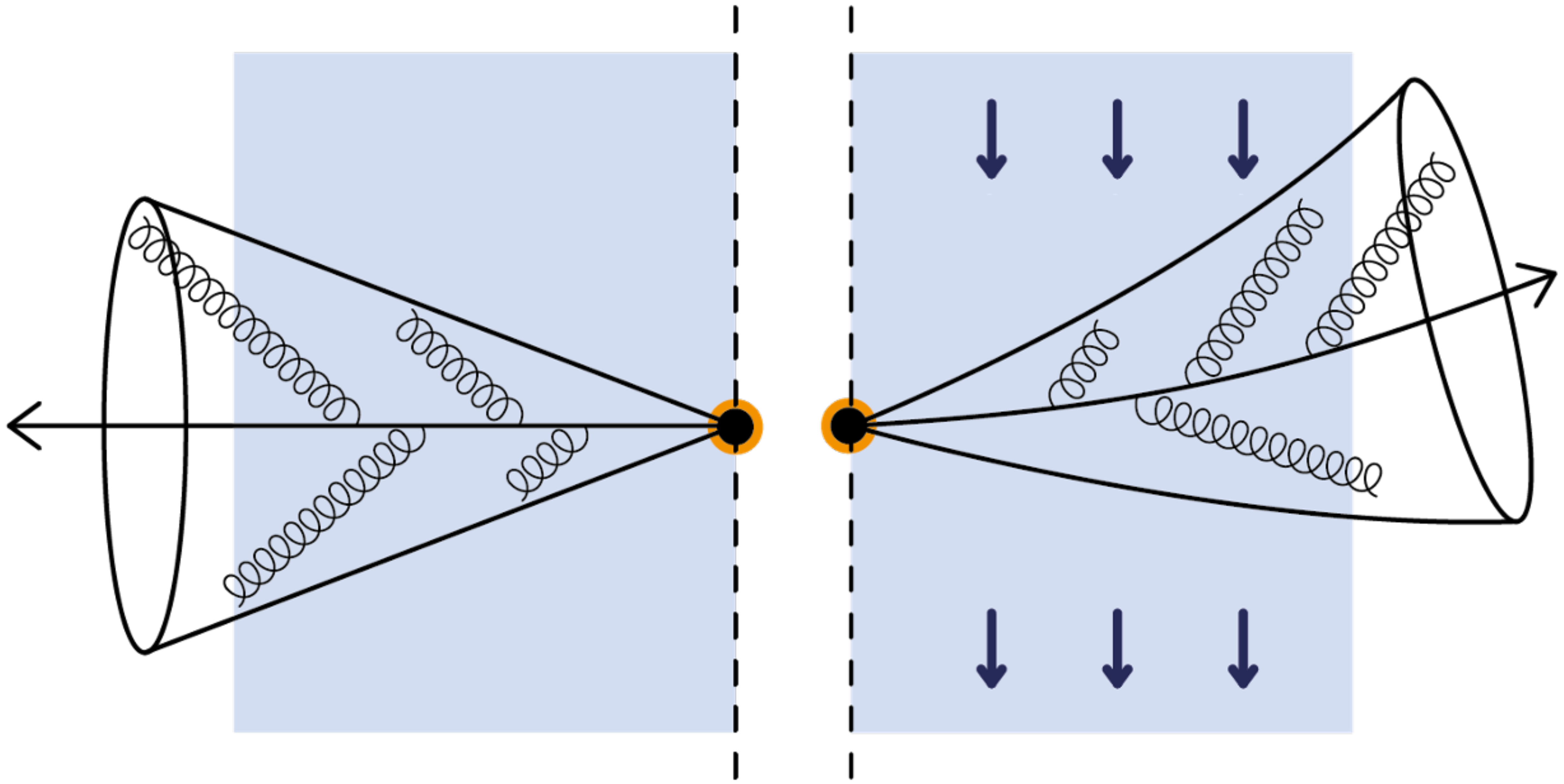
See e.g. Gyulassy, Levay, Vitev NPB 2001 Kuzmin, XML 2024

Medium-induced radiation

The spectrum is anisotropic with a modification subleading in energy

Assuming GW potential and smooth density profile in the longitudinal direction





See e.g. Gyulassy, Levay, Vitev NPB 2001 Kuzmin, XML 2024

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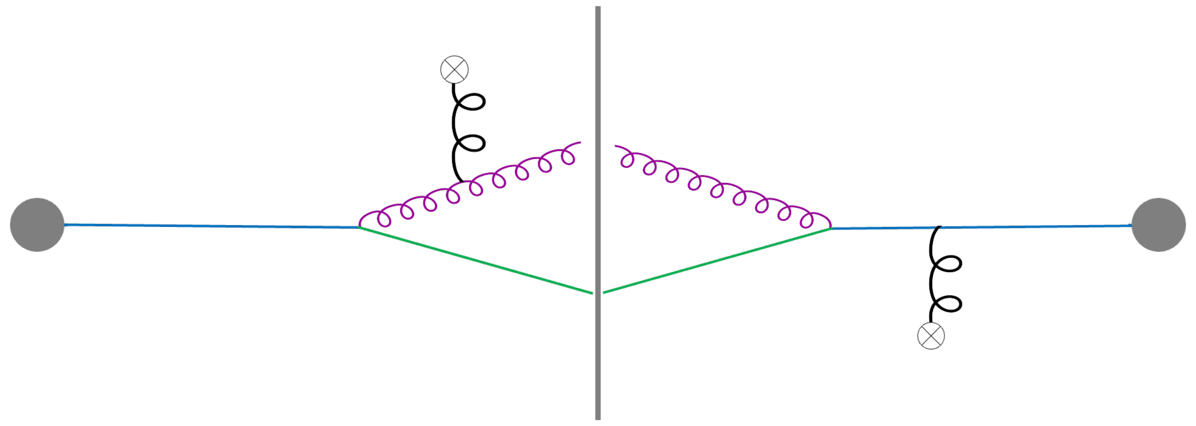
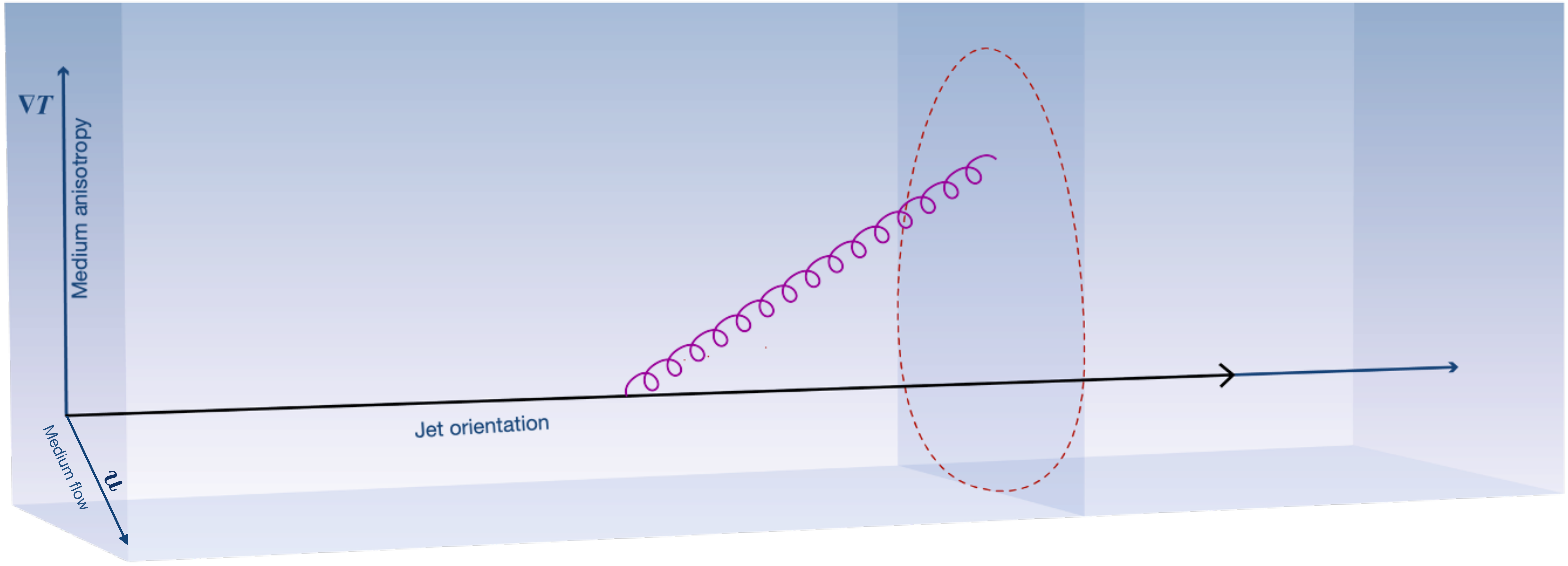
Configuration 3



Anisotropic and flowing matter in the dilute regime



Novel multiplicative correction to the leading order in energy affecting:

- the medium induced radiation $$\frac{dI}{d\omega\, d^2\boldsymbol{k}} \propto \int_0^L dz \int d^2\boldsymbol{q}\, \left[1 - 3\, z\, T\, \frac{\boldsymbol{\nabla} T \cdot \boldsymbol{u}}{1-0}\right]\left(1 - \cos\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{2\omega} z\right)\right)$$

- the broadening $$\hat{q} \propto \left[1 - \frac{3}{2}\, LT\, \frac{\frac{\boldsymbol{\nabla} T}{T^2} \cdot \boldsymbol{u}}{1 - u_z}\right] \hat{q}_{\text{iso}}$$

Rough estimate of the correction

$LT > 1$ hydro works for not too small droplets

$\left|\frac{\boldsymbol{\nabla} T}{T^2}\right| < 1$ gradient expansion

$\left|\frac{\boldsymbol{u}}{1 - u_z}\right| \sim 1$ relativistic flow

$\longrightarrow \left| LT\, \frac{\frac{\boldsymbol{\nabla} T}{T^2} \cdot \boldsymbol{u}}{1 - u_z}\right| \sim 1$

Not energy suppressed !!

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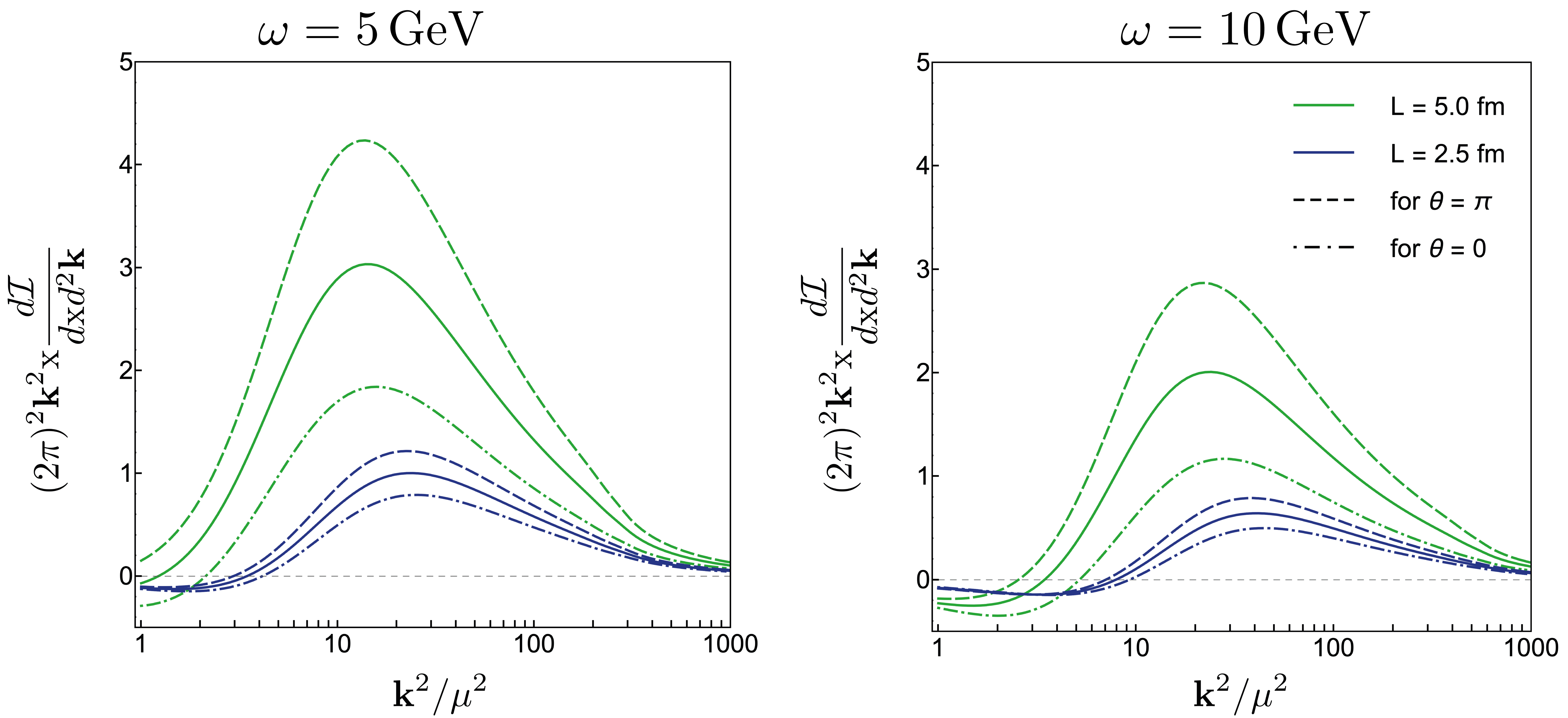
Medium-induced radiation

The spectrum si isotropic but depends on the relative direction between the transverse gradients and the flow

Assuming GW potential and smooth density profile in the longitudinal direction



Multiplicative modification of the radiation spectrum $\Rightarrow$ Modification of the induced energy loss

See Kuzmin, XML, Reiten, Sadofyev PRD 2024

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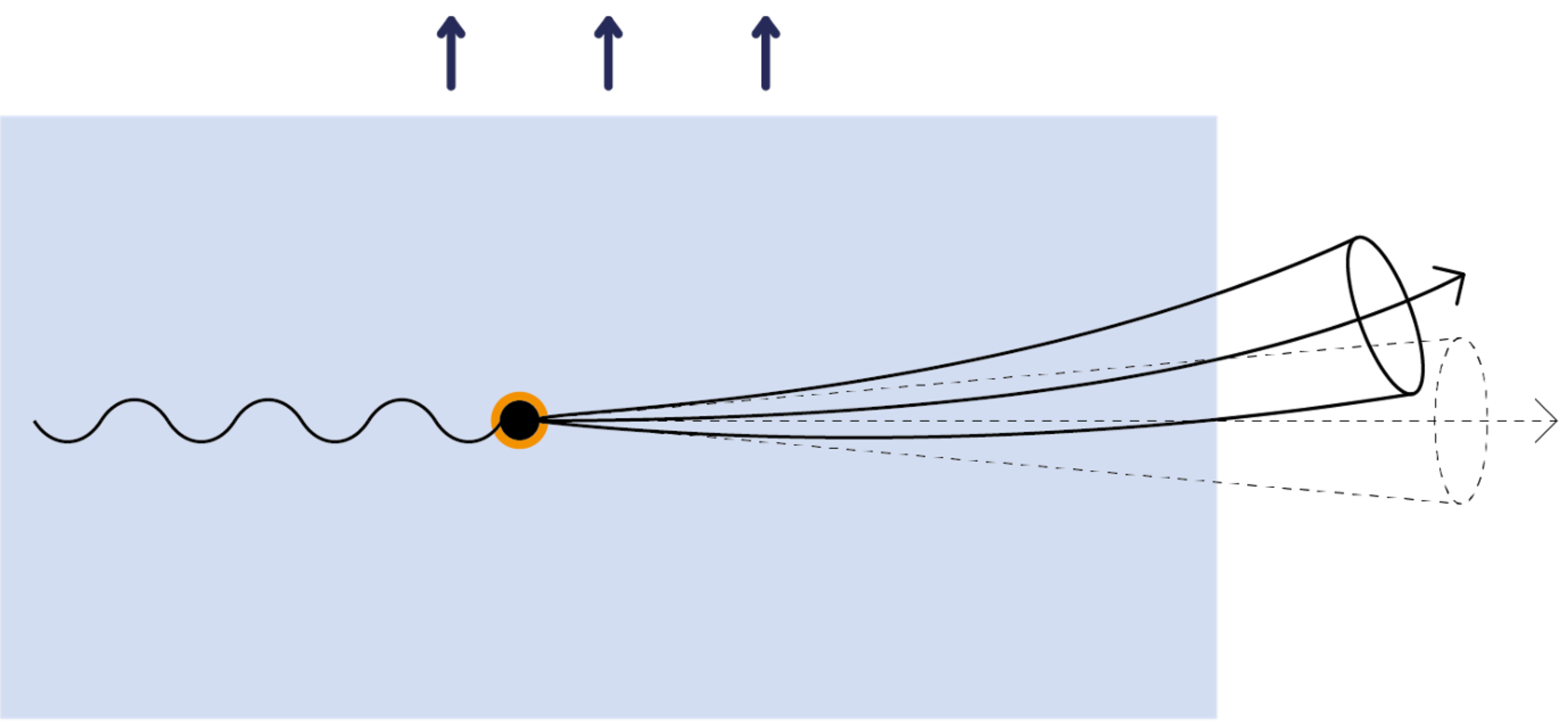
To take home

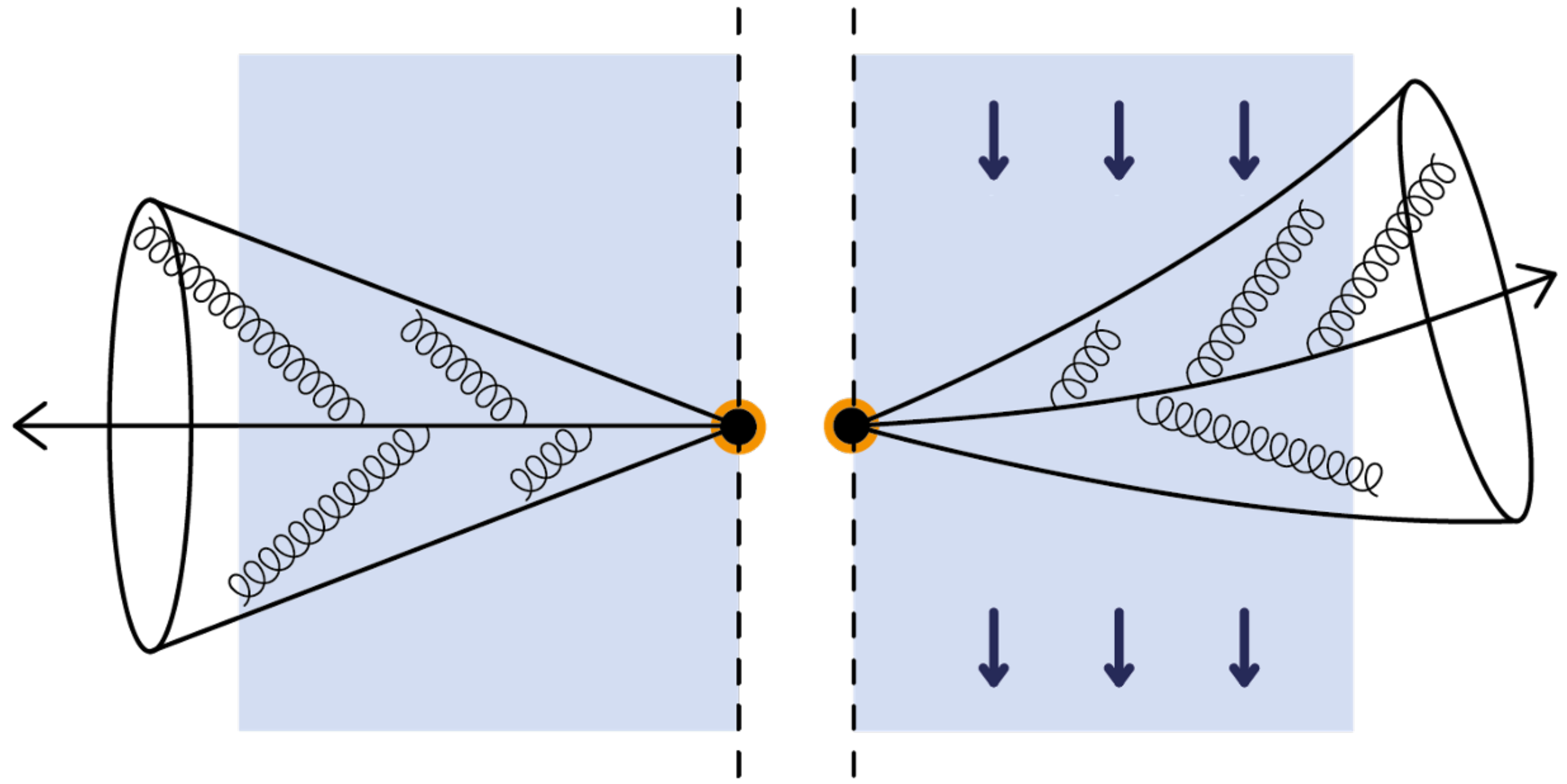
- Jets do feel the transverse flow and anisotropy, and get bended and distorted

- The transverse flow and anisotropy do affect the medium-induced radiation, modifying the jet substructure

- The interplay between flow and anisotropies modify the amount of quenching of a jet already at LO

- These effects can be probed in experiment, leading towards actual jet tomography





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Thanks

Back up

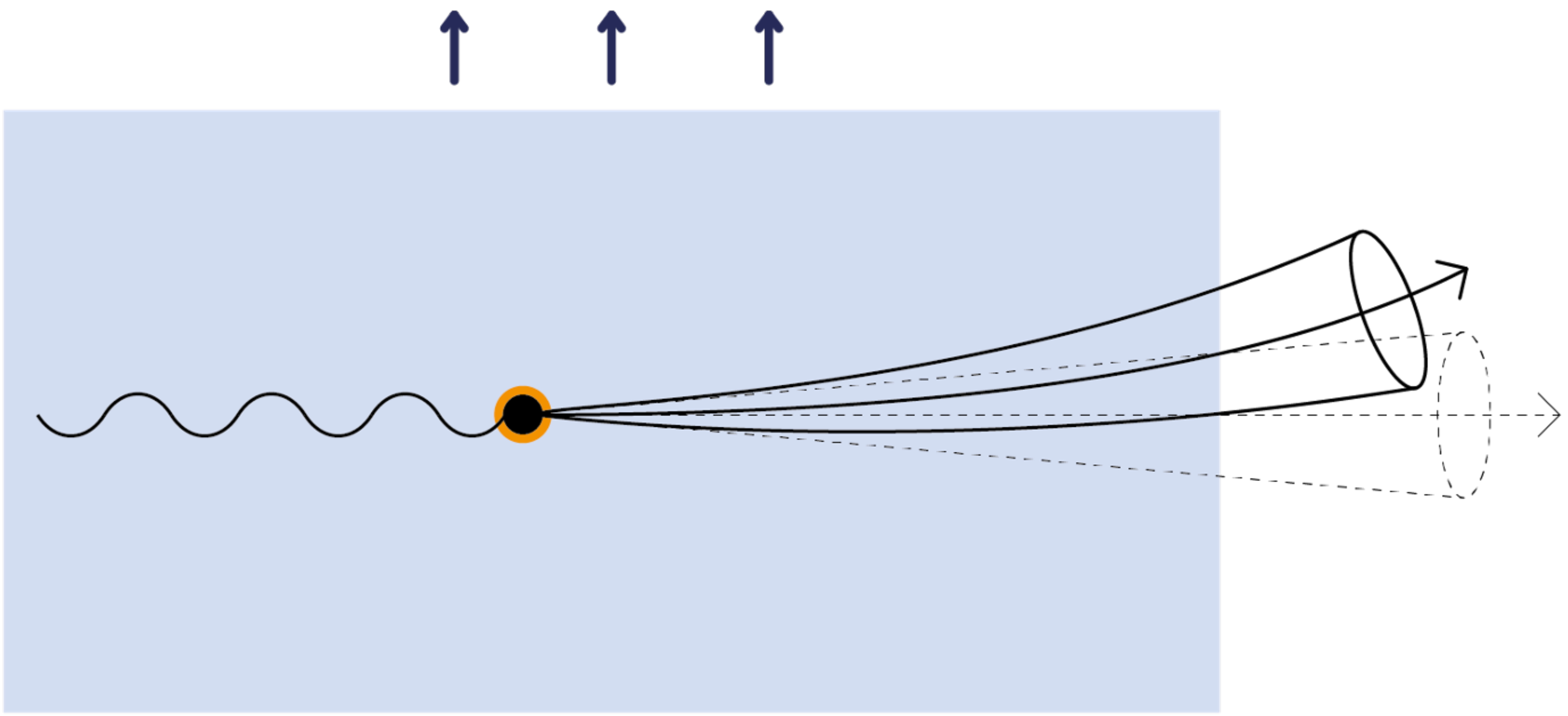
The broadening gets an anisotropic contribution subleading in energy for both configurations

↓

Averages of odd powers of $\mathbf{k}_\perp$ are non zero and along:

C1 the hydrodynamic gradients

C2 the flow of the matter



$$E \simeq 20\ \mathrm{GeV} \quad \Rightarrow \quad \theta \sim 4.5^{\mathrm{o}}$$

Averages of even powers of $\mathbf{k}_\perp$ are not modified

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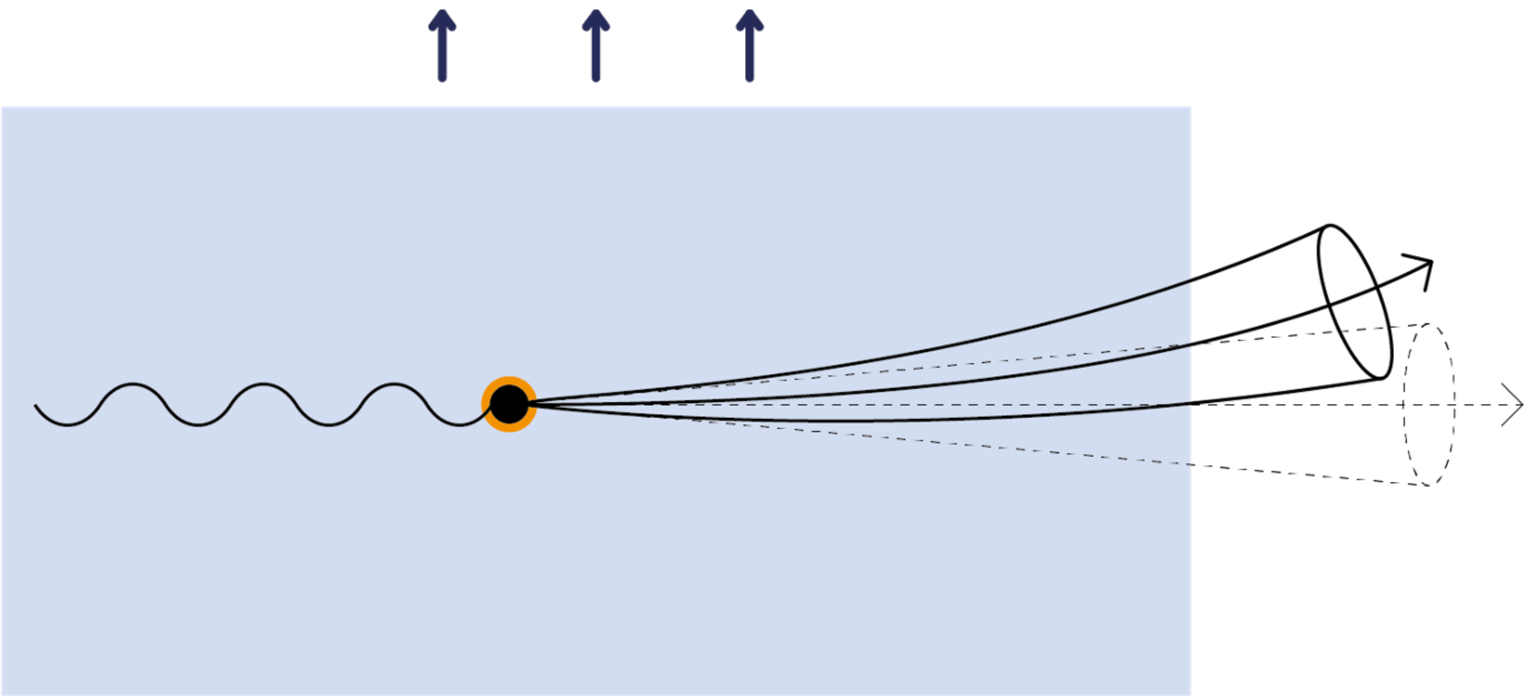
Directional broadening

Both the leading and subleading orders in energy get modified

↓

- Averages of odd powers of $\mathbf{k}_\perp$ behave exactly as in C1 and C2



- Averages of even powers of $\mathbf{k}_\perp$ get modified by at leading order in energy

$$\hat{q} \propto \left[1 - L\,\frac{\boldsymbol{\nabla} T \cdot \boldsymbol{u}}{1-u_z}\right] \hat{q}_{\rm iso}$$

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Simple physical picture