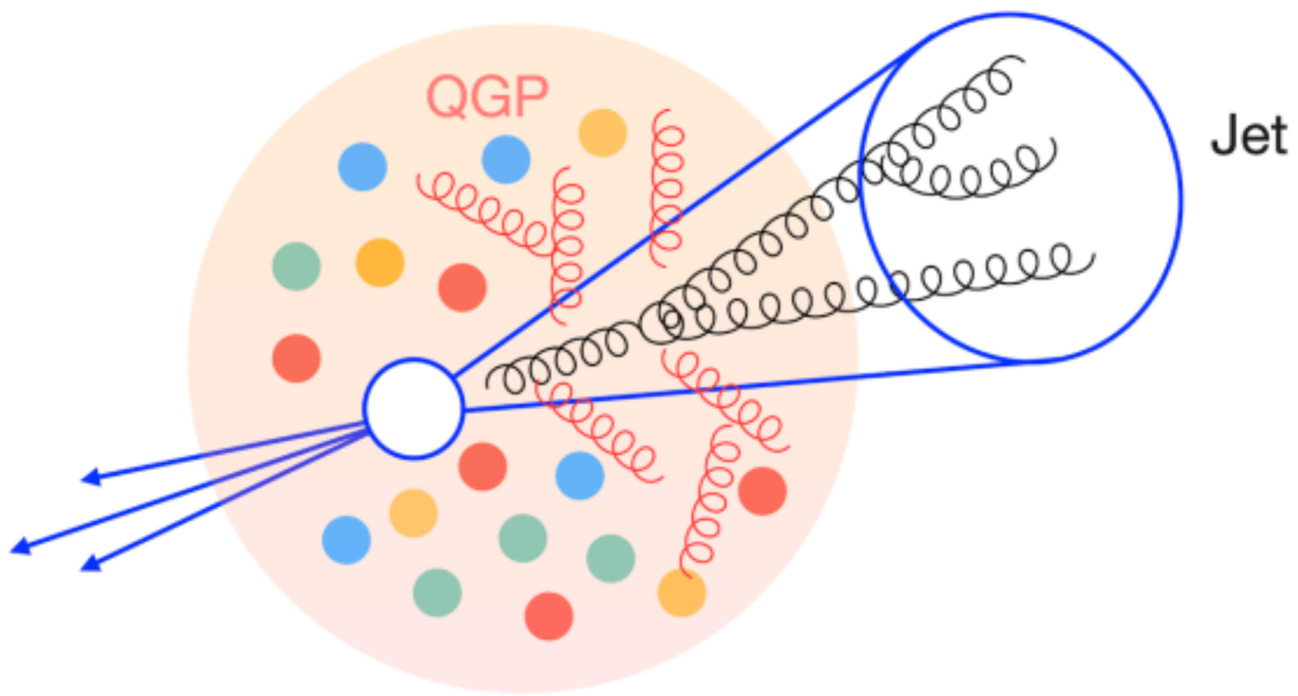

Jet quenching in anisotropic flowing matter

Xoán Mayo López, IGFAE (USC)

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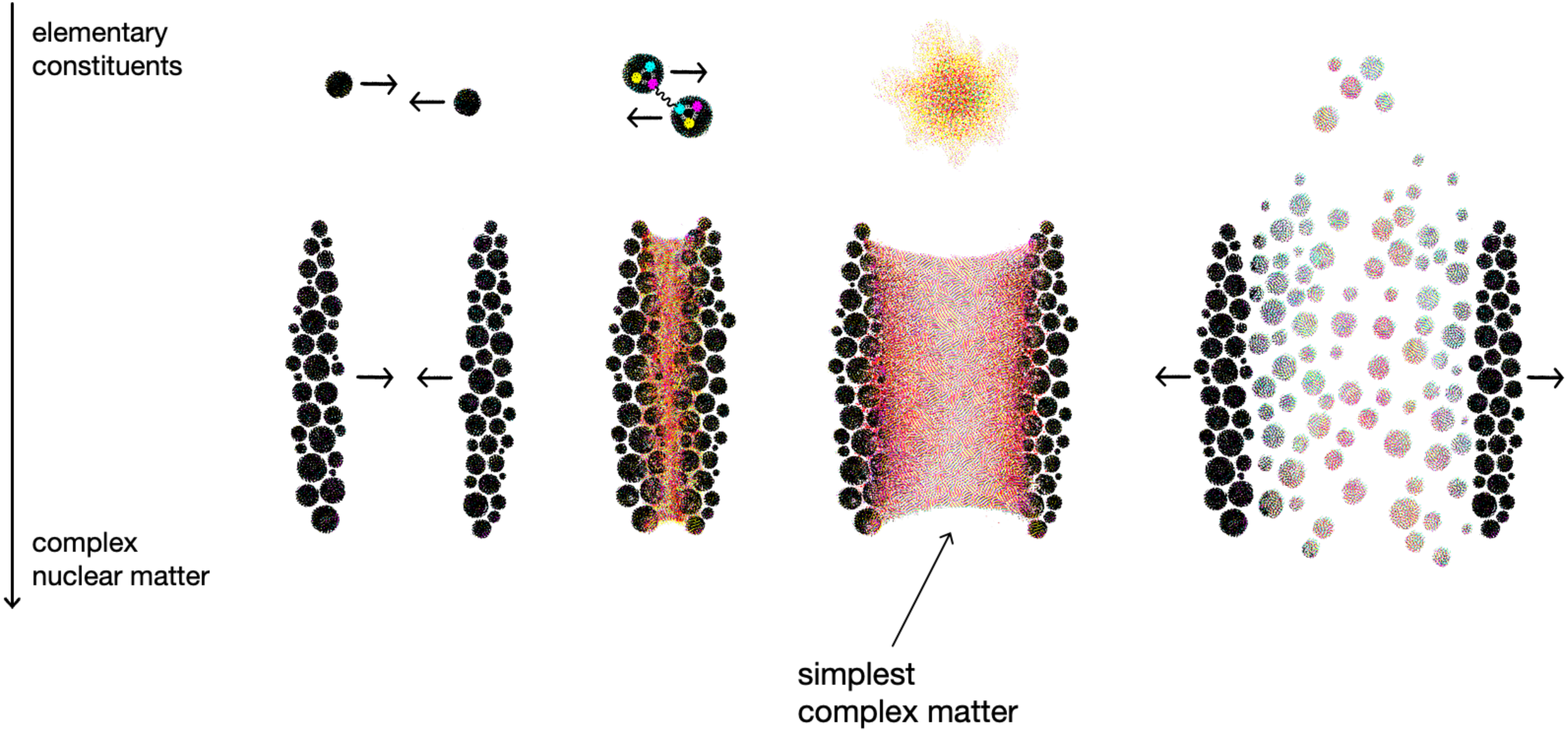
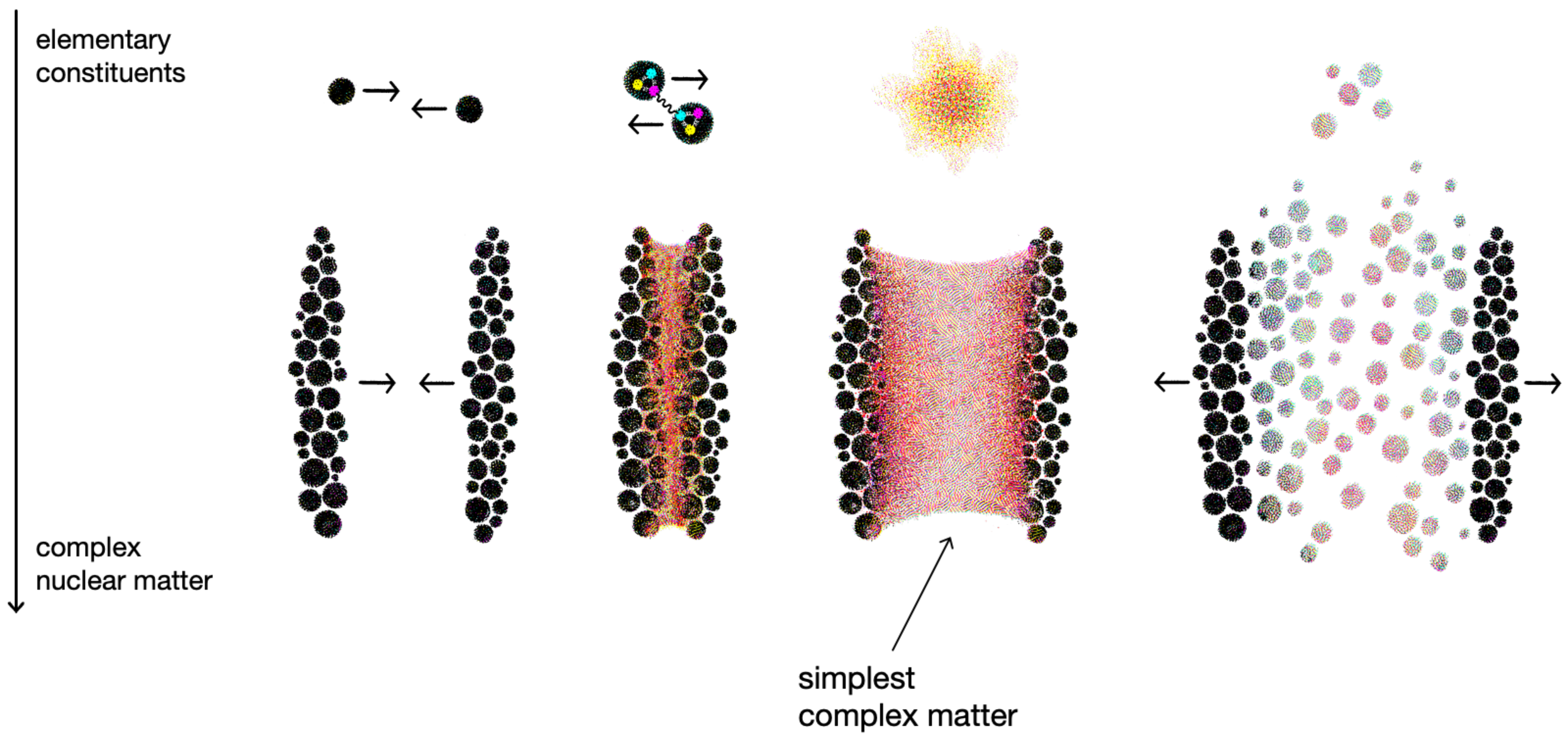
17th October 2023, Seattle

Mainly based on 2309.00683


elementary
constituents
complex
nuclear matter
simplest
complex matter



Two main sources of information:

- Soft particle coming from the thermal matter
- Hard particle: jets, quarkonia…

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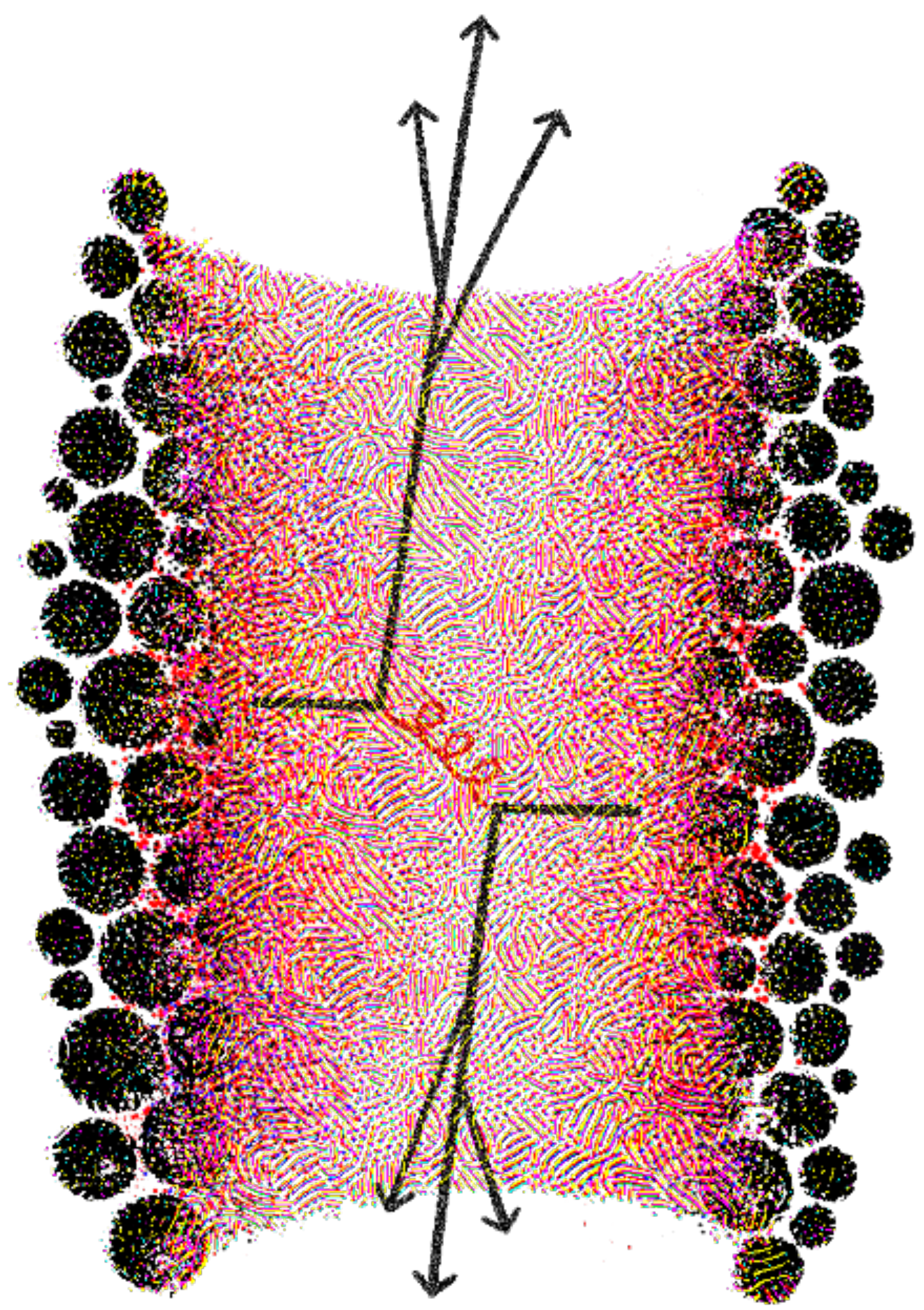
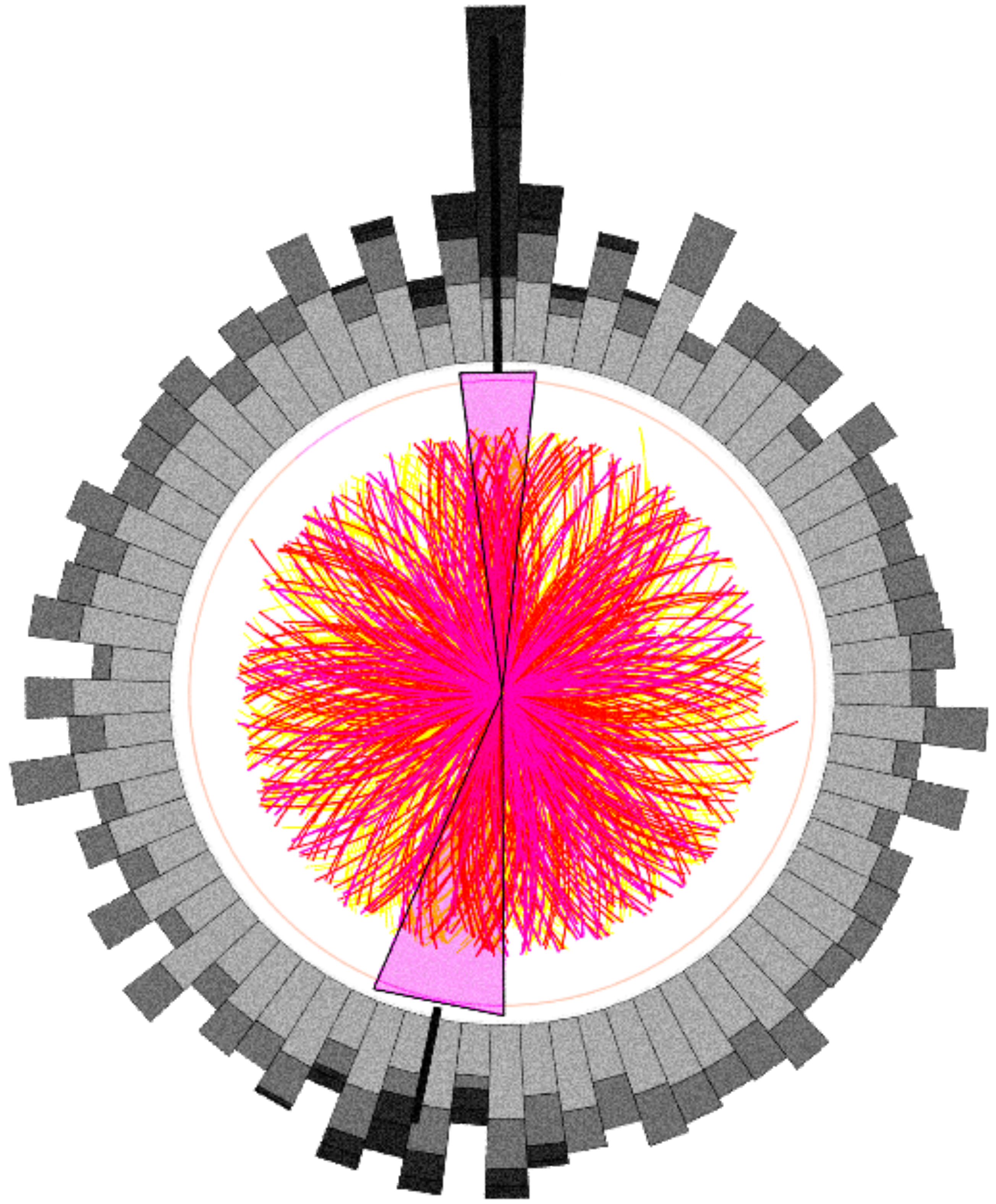


jet quenching



jets interact with the medium while propagating through it

Jet tomography

- Jet tomography: Jets as differential probes of the spatio-temporal structure of the thermal matter created in HIC

- Modification of jet properties throughout their flight encodes information about the QGP characteristics and evolution

- Most approaches to jet-medium interaction are either empirical or based on multiple simplifying assumptions

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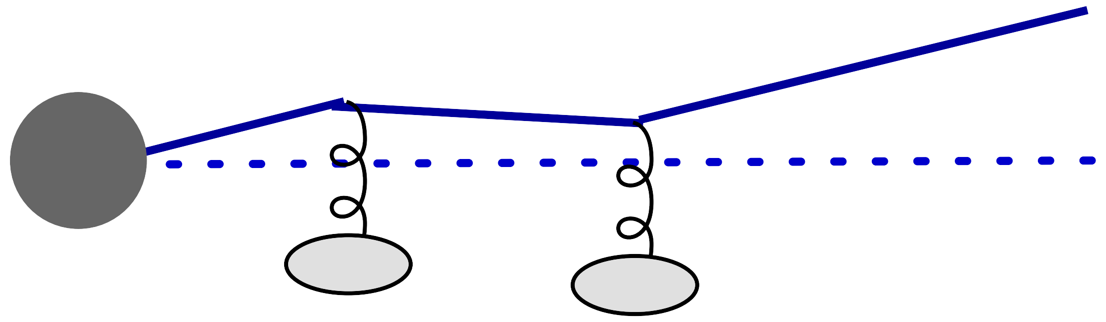
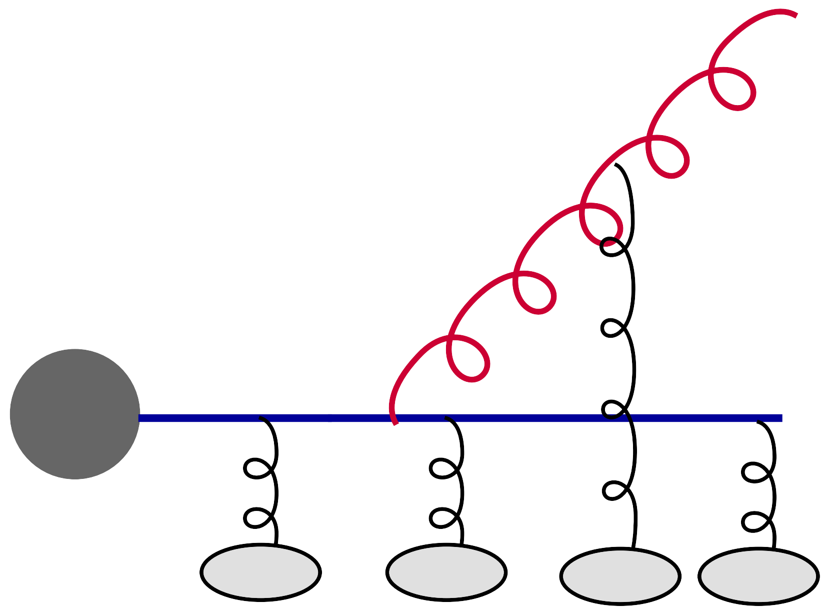
Do jets feel the transverse flow and anisotropies of the QGP?

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

Single particle broadening



Medium induced gluon radiation

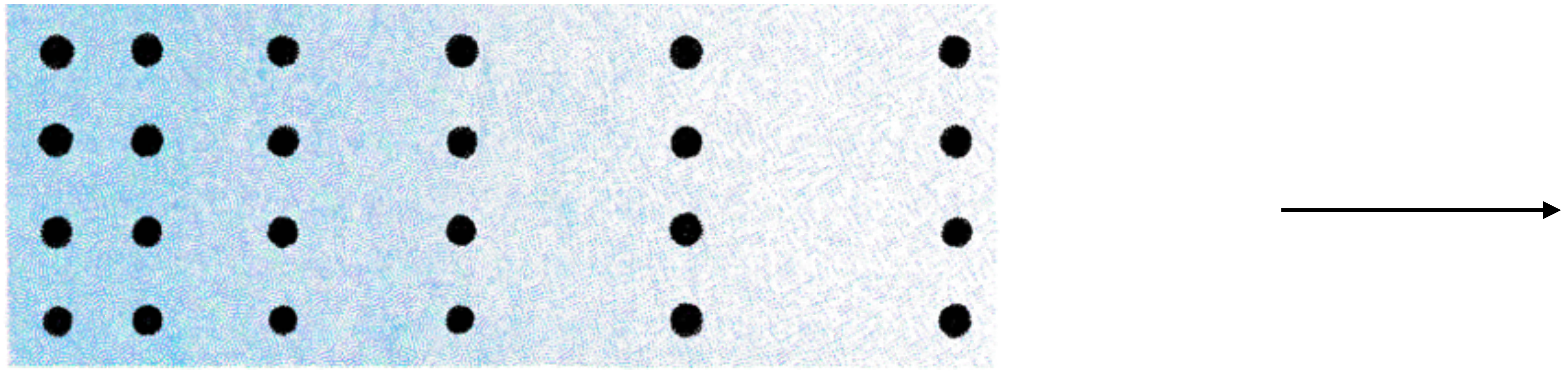


Theoretical formulation of jet quenching requires several assumptions to make it tractable. Some of the are

- 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

Background color field

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



Heavy sources

The stochastic field can be written as

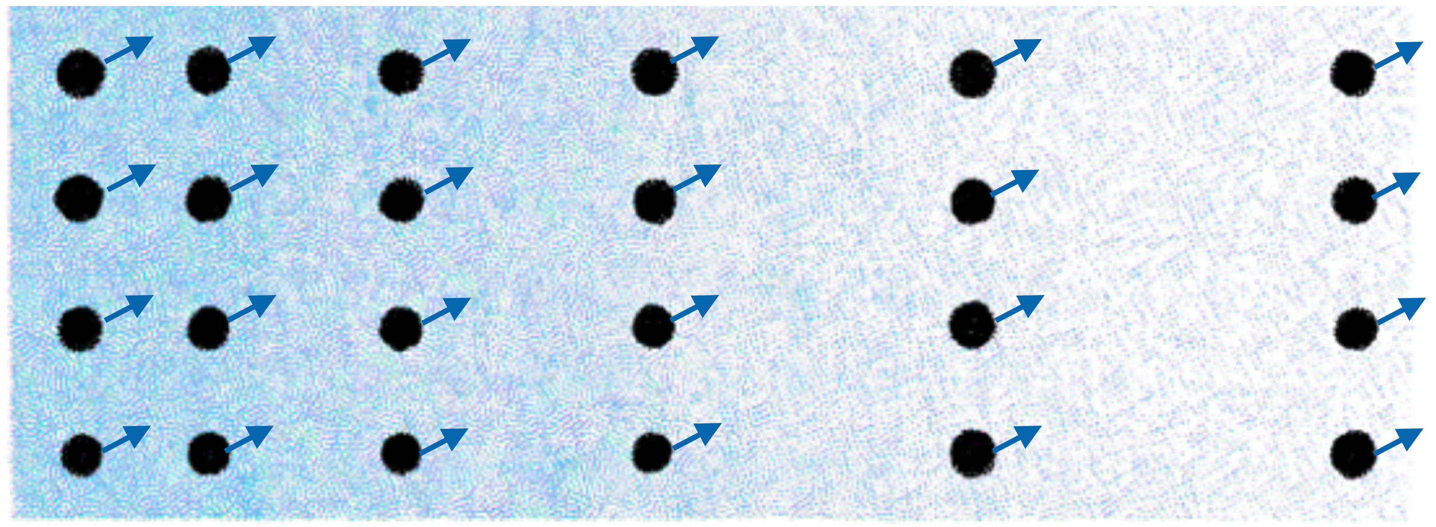
$$gA^{a\mu}(q) = \sum_{i} g^{\mu 0}\, e^{-iq\cdot x_i}\, t_i^a\, v_i(q)\, (2\pi)\delta(q_0)$$

controls the jet-medium interaction

controls de inhomogeneity

Background color field

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

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

controls the jet-medium interaction

controls de inhomogeneity

velocity of the sources

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Background color field

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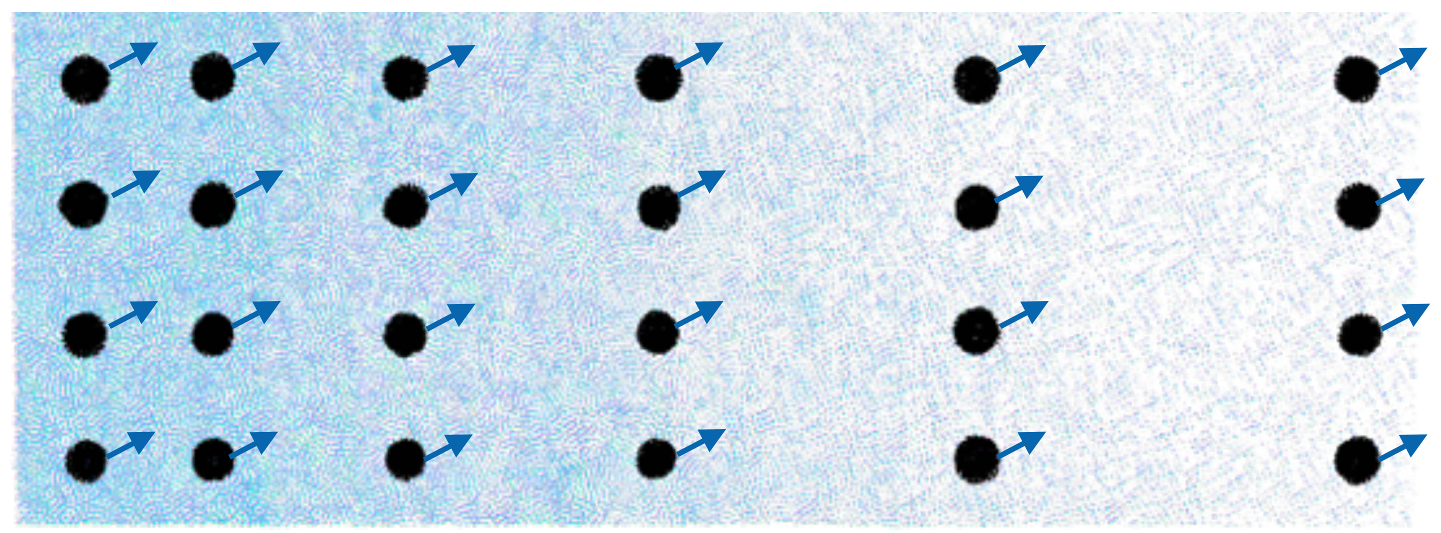

Heavy sources

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

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

The stochastic field can be written as

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

controls the jet-medium interaction

controls de inhomogeneity

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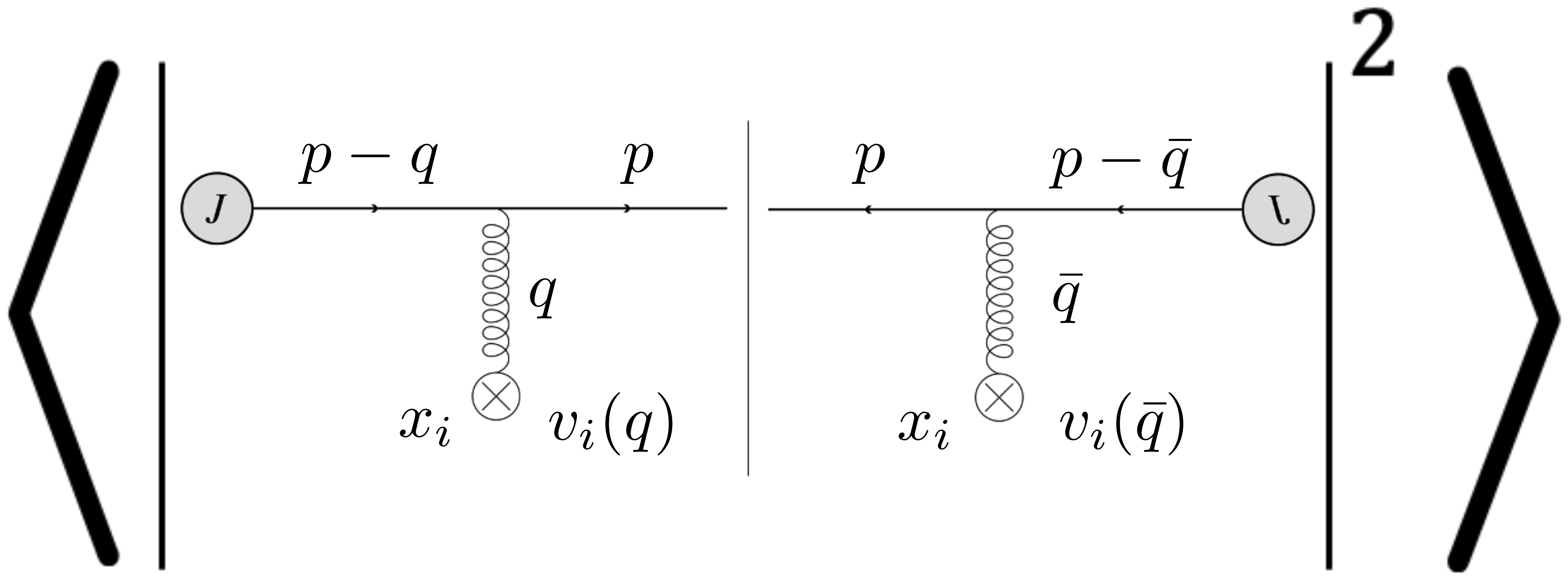
Medium average

Stochastic field $\longrightarrow$ need to specify the average over its configurations $\longrightarrow$ Gaussian statistics

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



Colour neutrality

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

Source averaging

$$\sum_i = \int d^2\boldsymbol{x}\, dz\, \rho(\boldsymbol{x}, z)$$

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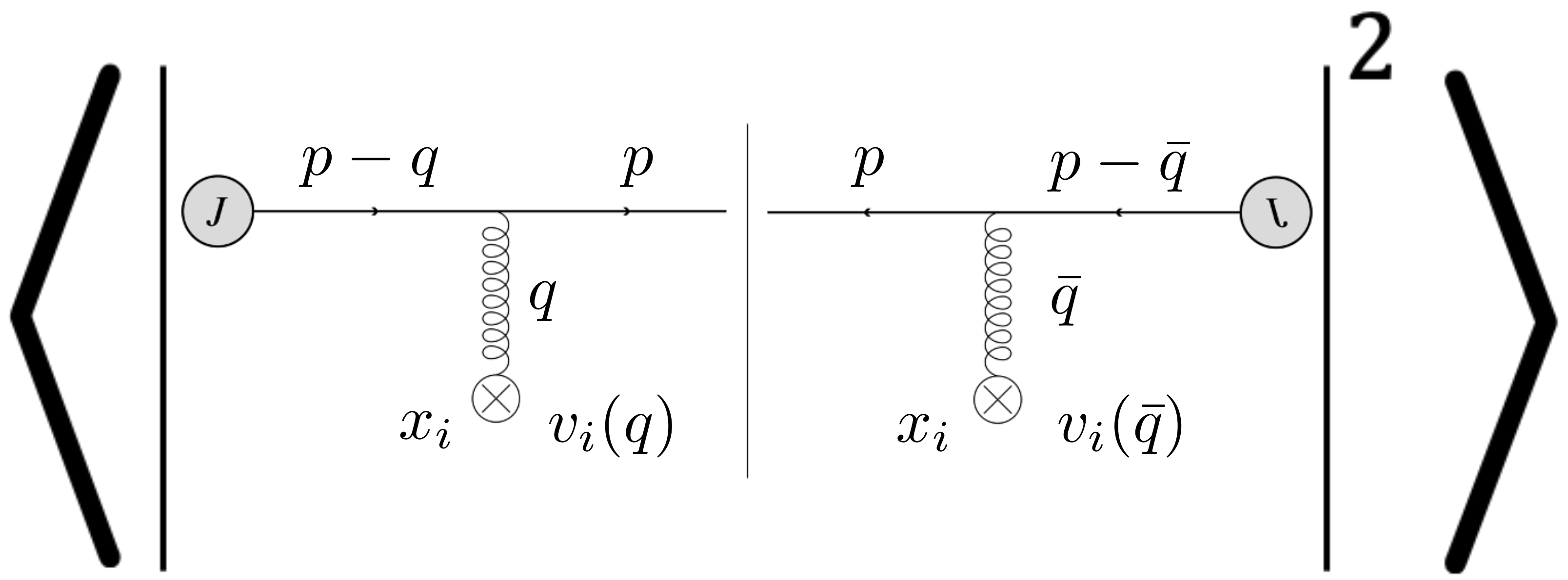
Gradients in the average

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



Transversely homogeneous matter :

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

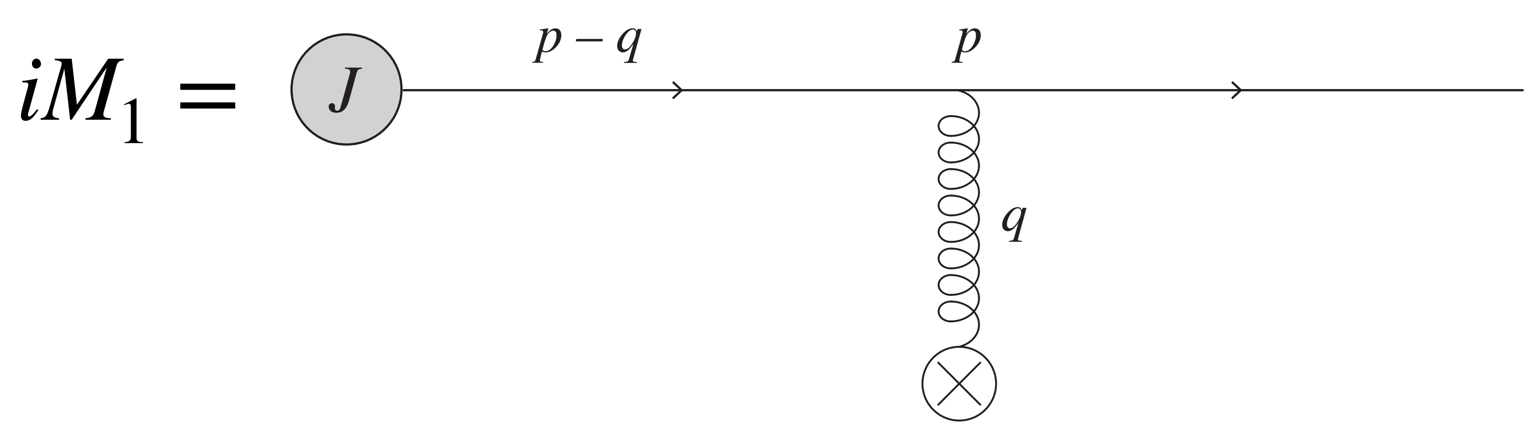
$$\int_{\boldsymbol{x}} g(z)\, e^{-i(\boldsymbol{q}\pm\bar{\boldsymbol{q}})\cdot\boldsymbol{x}} = g(z)\,(2\pi)^2\,\delta^{(2)}(\boldsymbol{q}\pm\bar{\boldsymbol{q}})$$

Transversely inhomogeneous matter :

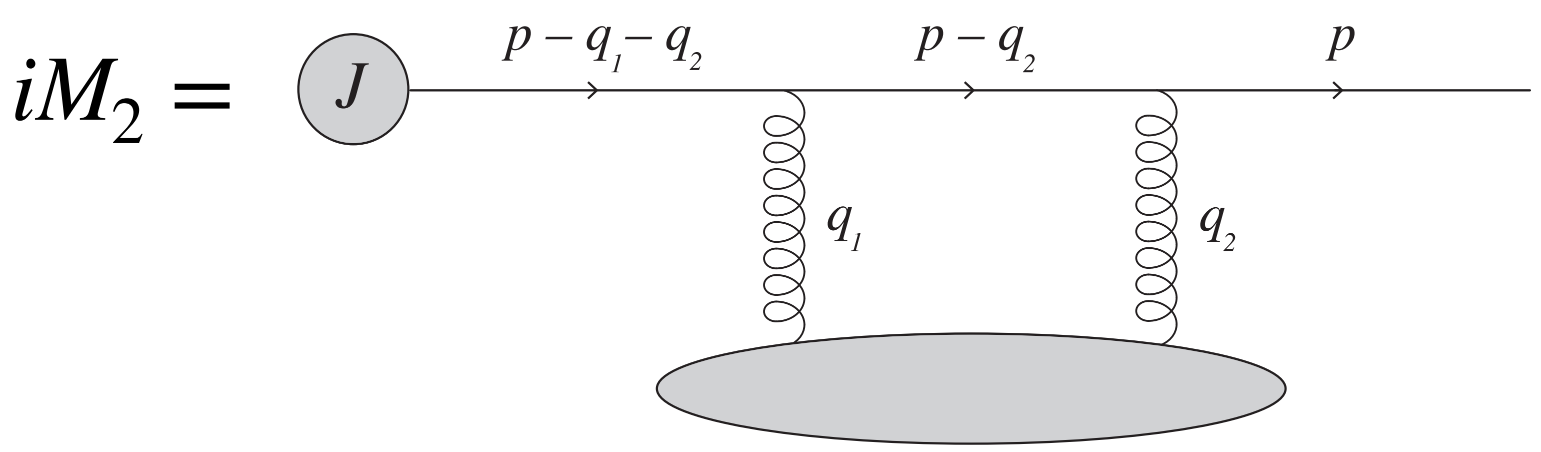
$$g(\boldsymbol{x}, z) \simeq g(z) + \boldsymbol{\nabla}_\alpha g(z)\,\boldsymbol{x}_\alpha$$

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

Two diagrams to compute



Single-Born contribution



Double-Born contribution

$$\langle |M|^2 \rangle = \langle |M_0^2| \rangle + \langle |M_1|^2 \rangle + \langle M_2 M_0^* \rangle + \langle M_2^* M_0 \rangle$$

Some assumption

- Only first subeikonal corrections are kept
- Dilute and extended medium $\mu \Delta z \gg 1$

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The final state parton distribution

$$E\frac{d\mathcal{N}}{d^2p\,dE} \equiv \frac{1}{2(2\pi)^3}\langle|M|^2\rangle$$

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Final parton distribution

The final state parton distribution

$$E\frac{d\mathcal{N}}{d^2p\,dE} = E\frac{d\mathcal{N}^{(0)}}{d^2p\,dE} + \mathcal{C}\int_0^L dz \int_{\boldsymbol{q}} \Bigg\{ \left[1 - \hat{\boldsymbol{g}}_\alpha \frac{(\boldsymbol{u}E - \boldsymbol{p} + \boldsymbol{q})_\alpha\, z}{(1-u_z)E}\right] [1 + \boldsymbol{u}\cdot\boldsymbol{\Gamma}(\boldsymbol{q})]\, E\frac{d\mathcal{N}^{(0)}}{d^2(p-q)\,dE}$$
$$- \left[1 - \hat{\boldsymbol{g}}_\alpha \frac{(\boldsymbol{u}E - \boldsymbol{p})_\alpha\, z}{(1-u_z)E}\right] [1 + \boldsymbol{u}\cdot\boldsymbol{\Gamma}_{DB}(\boldsymbol{q})]\, E\frac{d\mathcal{N}^{(0)}}{d^2p\,dE}$$
$$- \frac{1}{2}\,\hat{\boldsymbol{g}}_\alpha \frac{\partial}{\partial \boldsymbol{p}_\alpha} E\frac{d\mathcal{N}^{(0)}}{d^2p\,dE} \frac{\pi g^4 \sqrt{1-\boldsymbol{u}^2 - u_z^2}}{2\mu(1-u_z)E} \frac{\delta^{(2)}(\boldsymbol{q})}{[v(\boldsymbol{q}^2)]^2} \Bigg\} \rho(z)\,[v(\boldsymbol{q}^2)]^2$$

Initial distribution $\qquad E\frac{d\mathcal{N}^0}{d^2p dE} \equiv \frac{1}{2(2\pi)^3}|J(E,\boldsymbol{p})|^2$

Final parton distribution

The final state parton distribution

Flow corrections

Gradient corrections

$$E\frac{d\mathcal{N}}{d^2p\,dE} = E\frac{d\mathcal{N}^{(0)}}{d^2p\,dE} + \mathcal{C}\int_0^L dz \int_{\boldsymbol{q}} \Bigg\{ \left[1 - \hat{\boldsymbol{g}}_\alpha \frac{(\boldsymbol{u}E - \boldsymbol{p} + \boldsymbol{q})_\alpha\, z}{(1-u_z)E}\right] [1 + \boldsymbol{u}\cdot\boldsymbol{\Gamma}(\boldsymbol{q})]\, E\frac{d\mathcal{N}^{(0)}}{d^2(p-q)\,dE}$$
$$- \left[1 - \hat{\boldsymbol{g}}_\alpha \frac{(\boldsymbol{u}E - \boldsymbol{p})_\alpha\, z}{(1-u_z)E}\right] [1 + \boldsymbol{u}\cdot\boldsymbol{\Gamma}_{DB}(\boldsymbol{q})]\, E\frac{d\mathcal{N}^{(0)}}{d^2p\,dE}$$
$$- \frac{1}{2}\hat{\boldsymbol{g}}_\alpha \frac{\partial}{\partial \boldsymbol{p}_\alpha} E\frac{d\mathcal{N}^{(0)}}{d^2p\,dE} \frac{\pi g^4 \sqrt{1-\boldsymbol{u}^2-u_z^2}}{2\mu(1-u_z)E} \frac{\delta^{(2)}(\boldsymbol{q})}{[v(\boldsymbol{q}^2)]^2} \Bigg\} \rho(z)\, [v(\boldsymbol{q}^2)]^2$$

Initial distribution

$$E\frac{d\mathcal{N}^0}{d^2pdE} \equiv \frac{1}{2(2\pi)^3}|J(E,\boldsymbol{p})|^2$$

Final parton distribution

The final state parton distribution

Flow corrections

Gradient corrections

$$\hat{\boldsymbol{g}}_\alpha = \sum_g \left(\boldsymbol{\nabla}_\alpha g \frac{\delta}{\delta g} \right)$$

$$E\frac{d\mathcal{N}}{d^2p\,dE} = E\frac{d\mathcal{N}^{(0)}}{d^2p\,dE} + \mathcal{C}\int_0^L dz \int_{\boldsymbol{q}} \Bigg\{ \left[1 - \hat{\boldsymbol{g}}_\alpha \frac{(\boldsymbol{u}E - \boldsymbol{p} + \boldsymbol{q})_\alpha\, z}{(1-u_z)E} \right] [1 + \boldsymbol{u}\cdot\boldsymbol{\Gamma}(\boldsymbol{q})]\, E\frac{d\mathcal{N}^{(0)}}{d^2(p-q)\,dE}$$

$$- \left[1 - \hat{\boldsymbol{g}}_\alpha \frac{(\boldsymbol{u}E - \boldsymbol{p})_\alpha\, z}{(1-u_z)E} \right] [1 + \boldsymbol{u}\cdot\boldsymbol{\Gamma}_{DB}(\boldsymbol{q})]\, E\frac{d\mathcal{N}^{(0)}}{d^2p\,dE}$$

$$- \frac{1}{2}\hat{\boldsymbol{g}}_\alpha \frac{\partial}{\partial \boldsymbol{p}_\alpha} E\frac{d\mathcal{N}^{(0)}}{d^2p\,dE} \frac{\pi g^4 \sqrt{1 - \boldsymbol{u}^2 - u_z^2}}{2\mu(1-u_z)E} \frac{\delta^{(2)}(\boldsymbol{q})}{[v(\boldsymbol{q}^2)]^2} \Bigg\} \rho(z)\, [v(\boldsymbol{q}^2)]^2$$

Initial distribution

$$E\frac{d\mathcal{N}^0}{d^2p dE} \equiv \frac{1}{2(2\pi)^3} |J(E,\boldsymbol{p})|^2$$

Definition of the moments $$\langle \boldsymbol{p}_{\alpha_1} \ldots \boldsymbol{p}_{\alpha_n} \rangle \equiv \frac{\int_{\boldsymbol{p}} (\boldsymbol{p}_{\alpha_1} \ldots \boldsymbol{p}_{\alpha_n})\, E \frac{d\mathcal{N}}{d^2p\, dE}}{\int_{\boldsymbol{p}} E \frac{d\mathcal{N}^{(0)}}{d^2p\, dE}}$$ and $$E \frac{d\mathcal{N}^{(0)}}{d^2p\, dE} = \frac{f(E)}{2\pi w^2} e^{-\frac{\boldsymbol{p}^2}{2w^2}}$$

Moments of the final distribution

Definition of the moments $\langle \boldsymbol{p}_{\alpha_1} \dots \boldsymbol{p}_{\alpha_n} \rangle \equiv \dfrac{\int_{\boldsymbol{p}} (\boldsymbol{p}_{\alpha_1} \dots \boldsymbol{p}_{\alpha_n})\, E \frac{d\mathcal{N}}{d^2p\, dE}}{\int_{\boldsymbol{p}} E \frac{d\mathcal{N}^{(0)}}{d^2p\, dE}}$ and $E \dfrac{d\mathcal{N}^{(0)}}{d^2p\, dE} = \dfrac{f(E)}{2\pi w^2} e^{-\frac{\boldsymbol{p}^2}{2w^2}}$

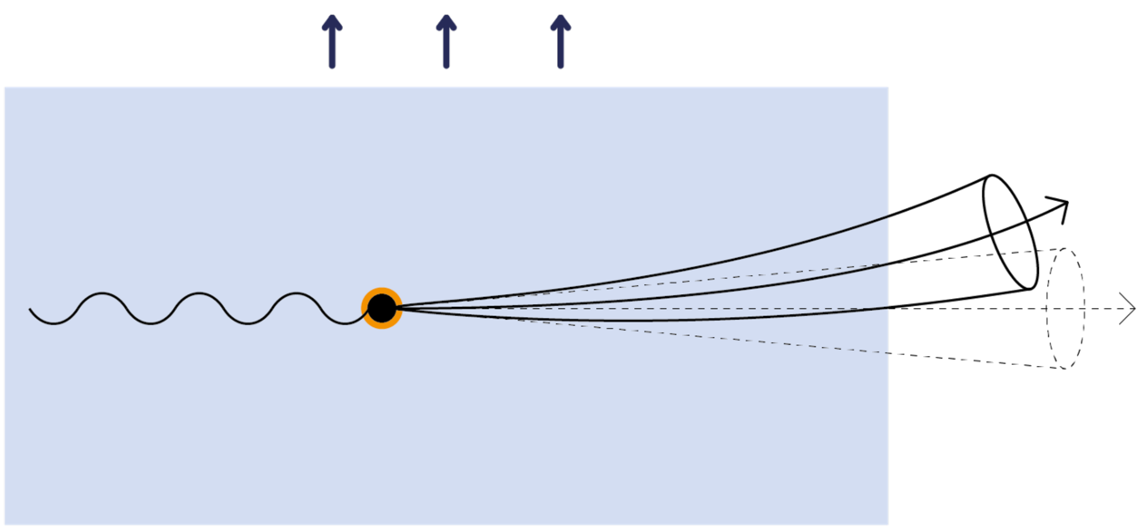
- Leading odd moments

$$\langle \boldsymbol{p}_\alpha \rangle = -\frac{1}{2}\mathcal{C}\int_0^L dz \left[1 - z\hat{\boldsymbol{g}} \cdot \frac{\boldsymbol{u}}{1-u_z}\right] \rho(z) \frac{\boldsymbol{u}_\alpha}{(1-u_z)E} \int_{\boldsymbol{q}} \boldsymbol{q}^2 \left[E\frac{f'(E)}{f(E)} + \boldsymbol{q}^2 \frac{\partial}{\partial \boldsymbol{q}^2}\right] [v(\boldsymbol{q}^2)]^2$$
$$+\,\mathcal{C}\int_0^L dz\, \hat{\boldsymbol{g}}_\alpha \frac{\pi g^4 \rho(z)\sqrt{1-\boldsymbol{u}^2-u_z^2}}{4\mu(1-u_z)E}$$

$$\langle \boldsymbol{p}_\alpha \boldsymbol{p}^2 \rangle = \mathcal{C}\int_0^L dz \int_{\boldsymbol{q}} \Bigg\{ \hat{\boldsymbol{g}}_\alpha 2w^2 \left[z\frac{\boldsymbol{q}^2}{(1-u_z)E} + \frac{\delta^{(2)}(\boldsymbol{q})}{[v(\boldsymbol{q}^2)]^2} \frac{\pi g^4 \sqrt{1-\boldsymbol{u}^2-u_z^2}}{2\mu(1-u_z)E} \right]$$
$$-\frac{1}{2}\left[1 - z\hat{\boldsymbol{g}} \cdot \frac{\boldsymbol{u}}{1-u_z}\right] \frac{\boldsymbol{u}_\alpha}{(1-u_z)E}$$
$$\times\, \boldsymbol{q}^2 \left[8w^2 + (10w^2 + \boldsymbol{q}^2)\, \boldsymbol{q}^2 \frac{\partial}{\partial \boldsymbol{q}^2} + \left(4w^2 + \boldsymbol{q}^2\right) E\frac{f'(E)}{f(E)}\right] \Bigg\} \rho(z)\, [v(\boldsymbol{q}^2)]^2$$

Along the flow

Along the gradients



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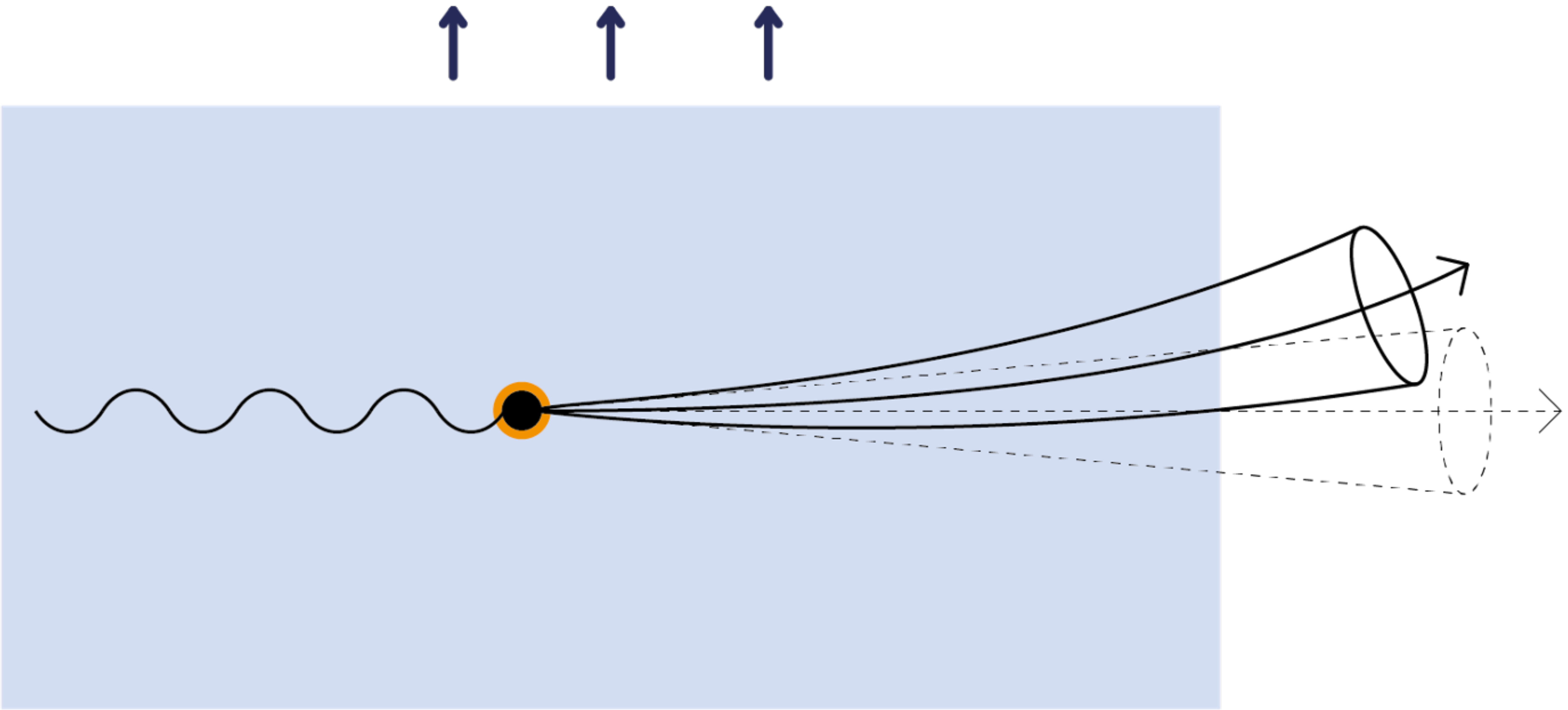
- Leading odd moments



Jets do feel flow and anisotropies

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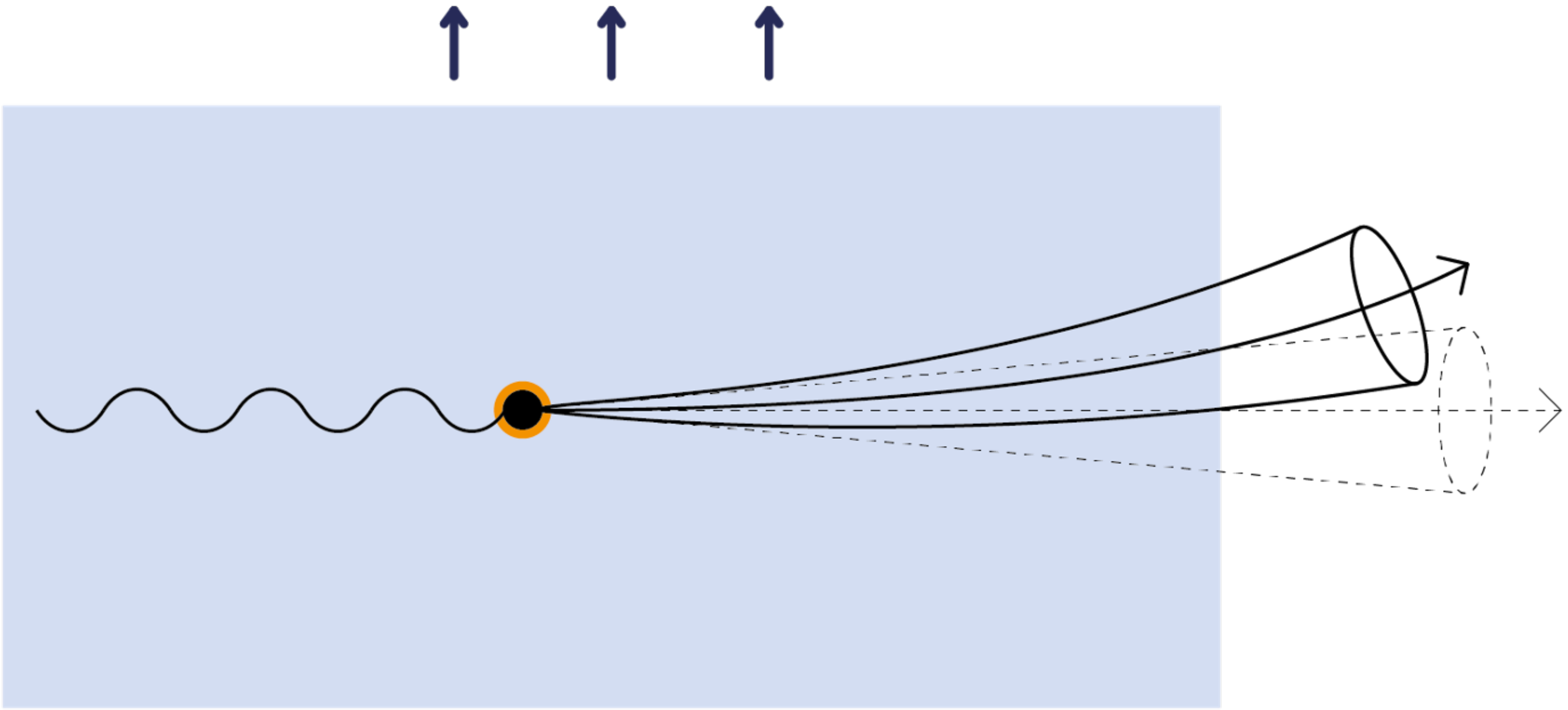

Agreement with previous results

Sadofyev et al. 2104.09513
Barata et al. 2202.08847
Andres et al. 2207.07141

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- Quadratic moment of the distribution

$$\langle \boldsymbol{p}^2 \rangle = 2w^2 + \mathcal{C} \int_0^L dz \left[1 - z\, \hat{\boldsymbol{g}} \cdot \frac{\boldsymbol{u}}{1-u_z} \right] \rho(z) \int_{\boldsymbol{q}} \boldsymbol{q}^2 \left[v(\boldsymbol{q}^2) \right]^2$$

$$\Big\downarrow \frac{\delta}{\delta L}$$

$$\hat{q}(z) = \left[1 - z\, \hat{\boldsymbol{g}} \cdot \frac{\boldsymbol{u}}{1-u_z} \right] \mathcal{C} \rho(z) \int_{\boldsymbol{q}} \boldsymbol{q}^2 \left[v(\boldsymbol{q}^2) \right]^2$$

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$$\hat{q}(z) = \left[1 - \boxed{z\, \hat{\boldsymbol{g}} \cdot \frac{\boldsymbol{u}}{1-u_z}} \right] \hat{q}_0(z)$$

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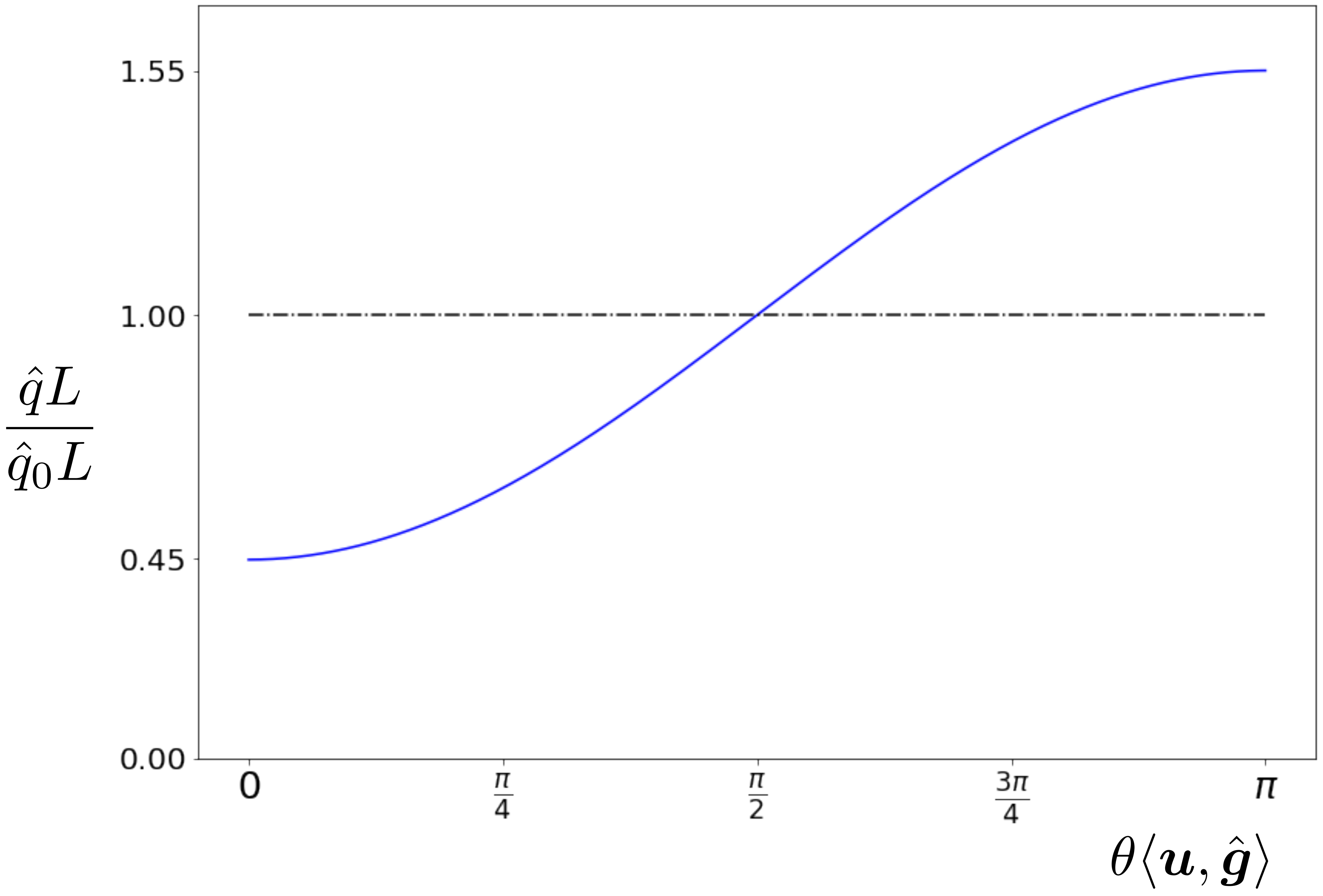
Estimation of the effect

Rough estimation of the effect

$$\hat{q}(z) = \left[1 - z\,\hat{\boldsymbol{g}} \cdot \frac{\boldsymbol{u}}{1-u_z}\right] \hat{q}_0(z)$$

- Only gradients of temperature to leading logarithm
- Everything z - independent

$$\hat{q}L = \left[1 - \frac{L}{2}\frac{\boldsymbol{\nabla}\rho}{\rho} \cdot \frac{\boldsymbol{u}}{1-u_z}\right] \hat{q}_0 L$$



Chosen parameters

$L \simeq 5\,fm$

$\left|\frac{\boldsymbol{\nabla}T}{T^2}\right| \simeq 0.05$

$T \simeq 0.3\,GeV$

$u \simeq 0.7\,c$ about $\frac{\pi}{4}$ to the z-axis

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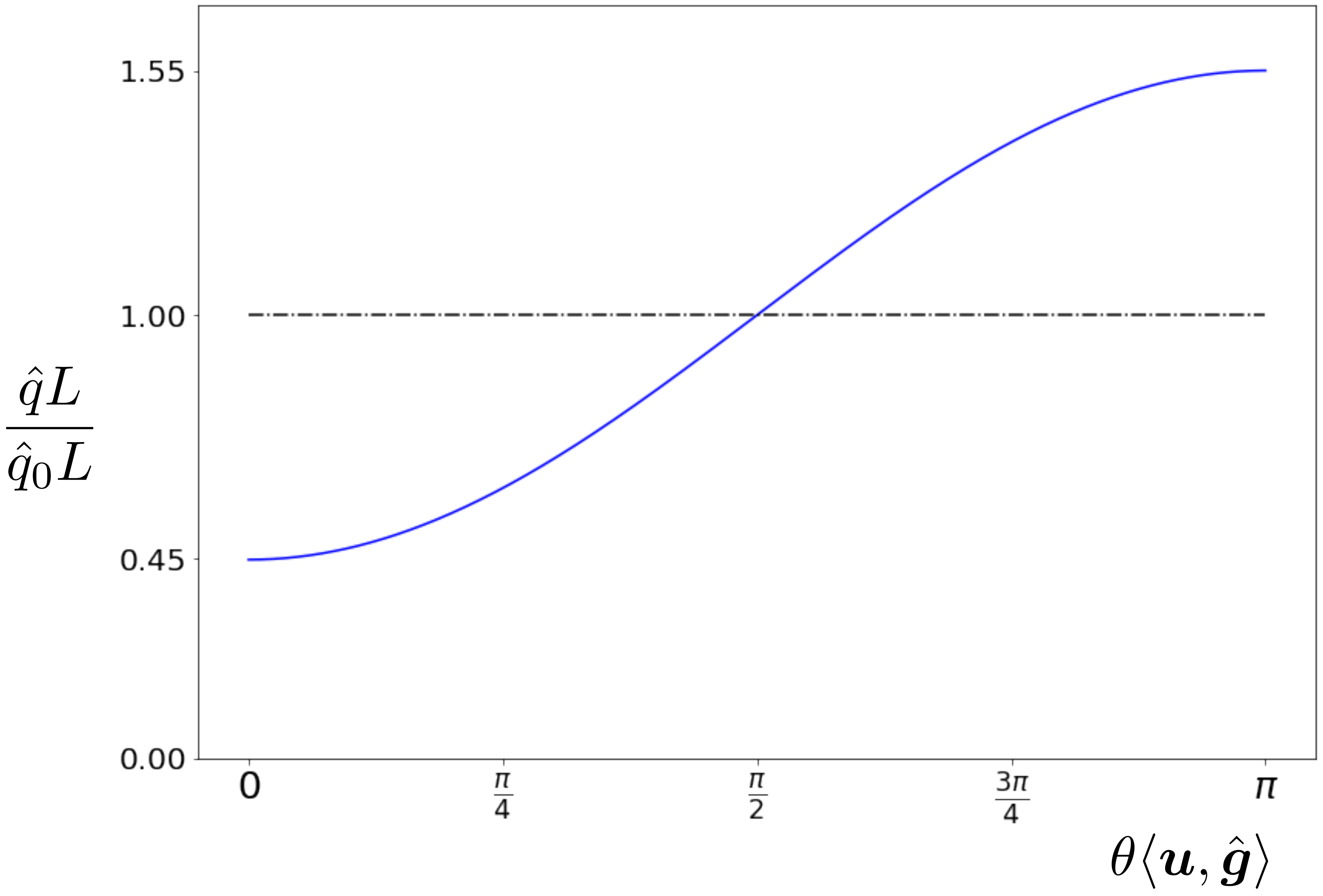
$$\hat{q}L = \left[1 - \frac{L}{2}\frac{3\left|\frac{\boldsymbol{\nabla} T}{T^2}\right| T\,|\boldsymbol{u}|\,\cos(\theta)}{1-u_z}\right] \hat{q}_0 L$$



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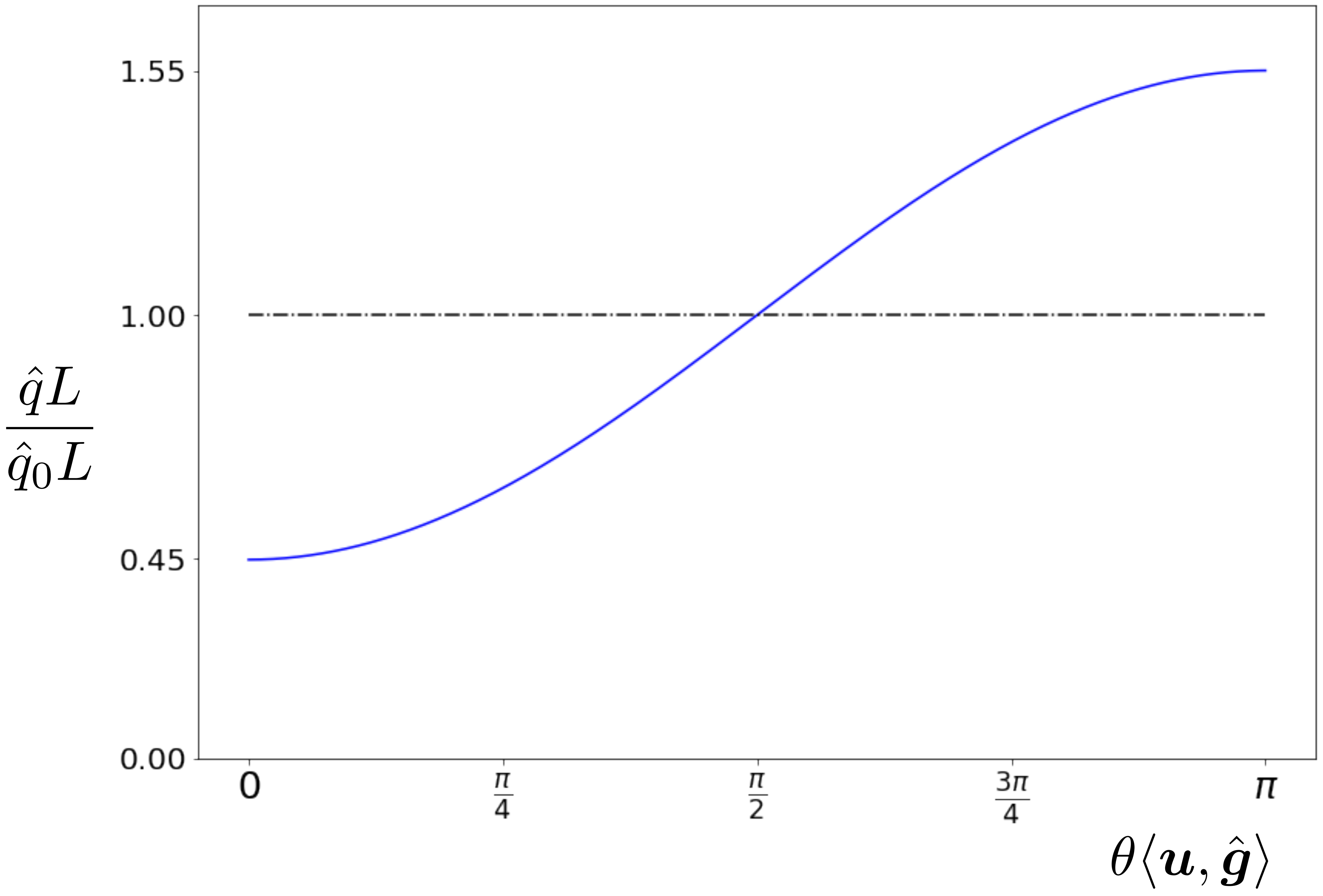

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- Full dependence $\rho \equiv \rho(T)$
- Other gradients contribute in non trivial way
- z-dependence must be taken into account

Positivity of the jet quenching parameter

The jet quenching parameter is positive

$$\left| z\hat{\boldsymbol{g}} \cdot \frac{\boldsymbol{u}}{1-u_z} \right| < 1$$ or gradient expansion brakes $$\longrightarrow \quad \hat{q}(z) = \left[1 - z\,\hat{\boldsymbol{g}} \cdot \frac{\boldsymbol{u}}{1-u_z} \right] \hat{q}_o(z)$$

Keeping full dependence $\boldsymbol{x}$ on in a crude estimate

$$\rho(\boldsymbol{x}, z) \longrightarrow \rho\left(-\frac{\boldsymbol{u}}{1-u_z} z, z \right) \simeq \left[1 - z\frac{\boldsymbol{\nabla}\rho}{\rho} \cdot \frac{\boldsymbol{u}}{1-u_z} \right] \rho(z)$$

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Broadening: to take home

Flowing anisotropic medium $\Rightarrow$ anisotropic broadening

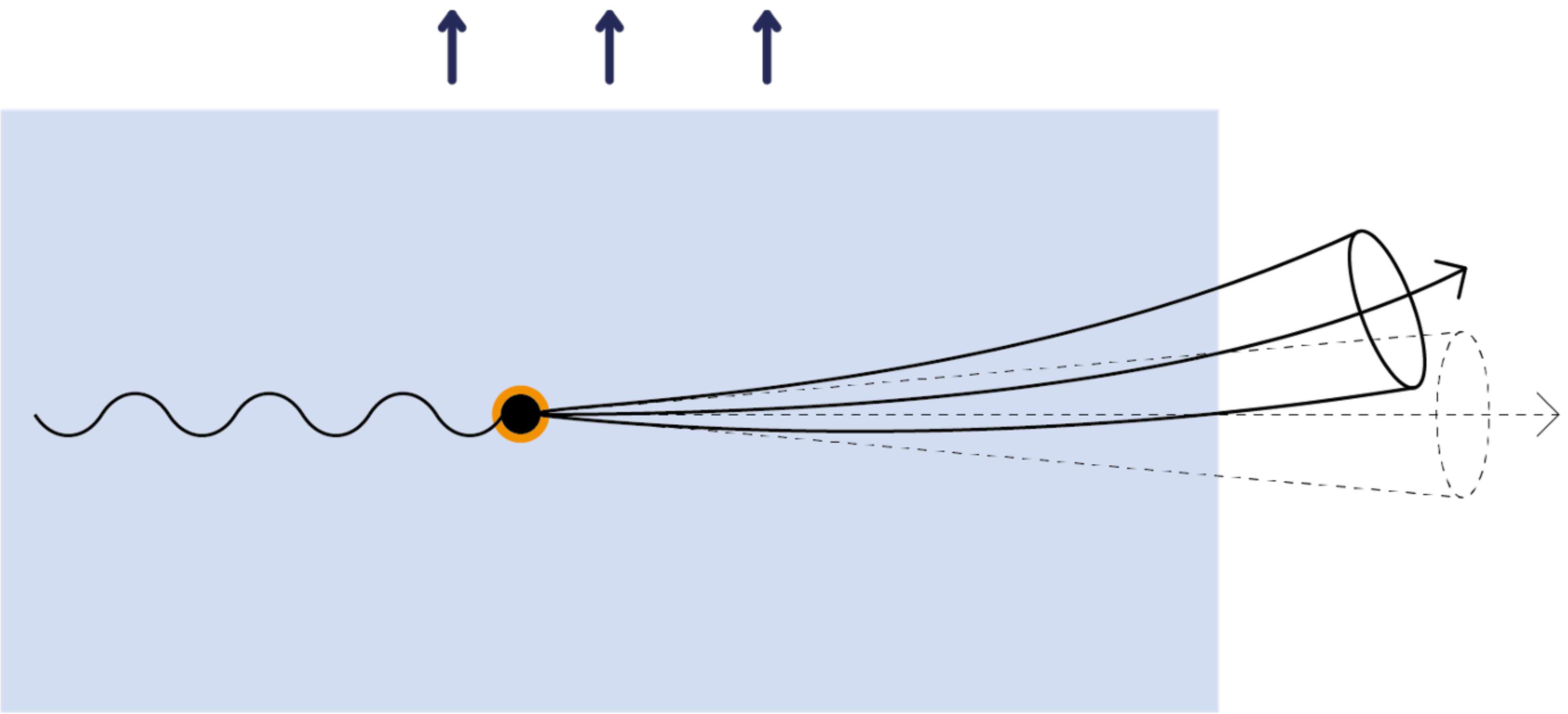
Directional effects due to transverse gradient and flow

- Odd moments of the distribution are non-zero and along gradients and flow
    - (potentially lower background but smaller effect)

Novel multiplicative effect on even moments not energy suppressed

- The jet quenching parameter gets a multiplicative correction

$$\hat{q}(z) = \left[1 - z\,\hat{\boldsymbol{g}} \cdot \frac{\boldsymbol{u}}{1-u_z}\right] \hat{q}_0(z)$$



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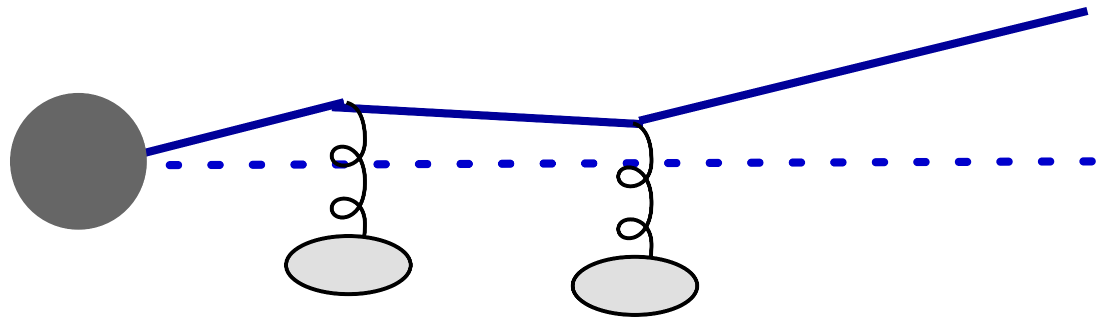
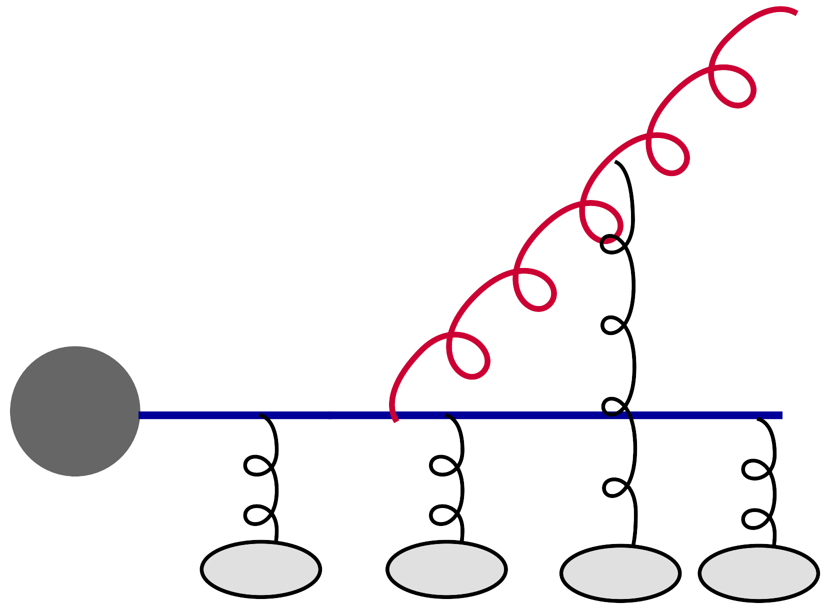
Medium-induced radiation

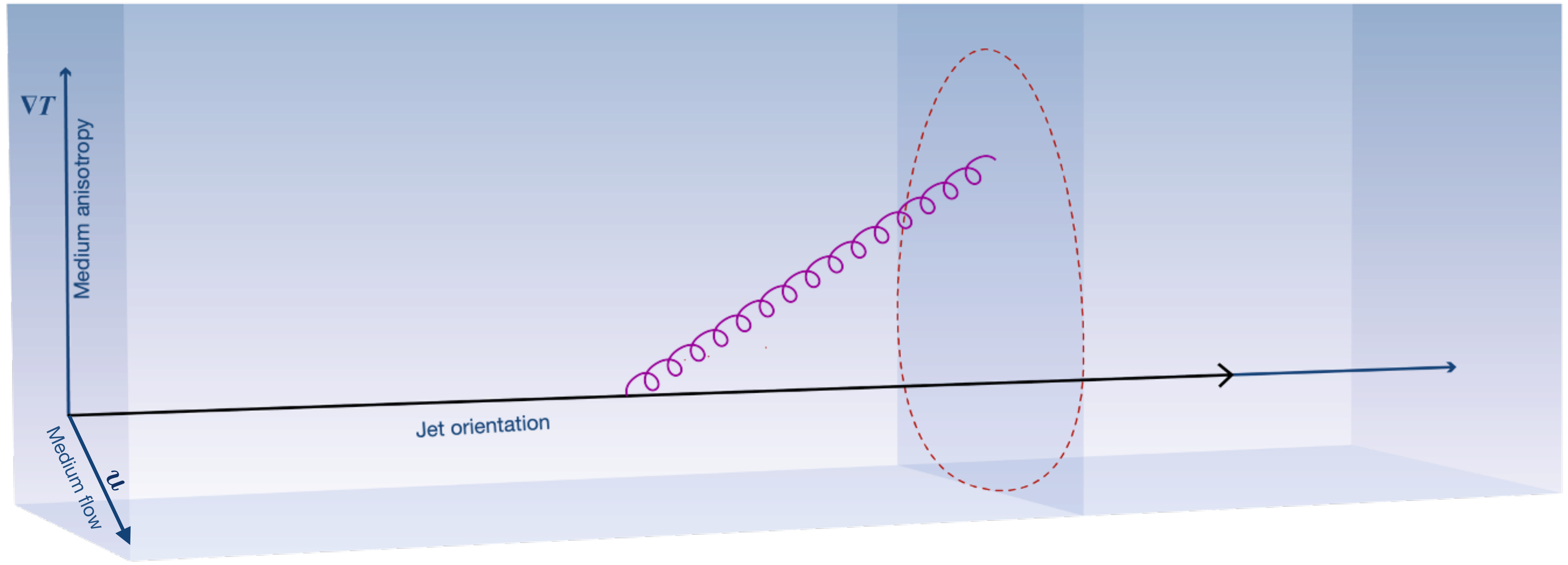
Focus on leading perturbative processes: Two processes that modify jets.

Single particle broadening ✓



Medium induced gluon radiation





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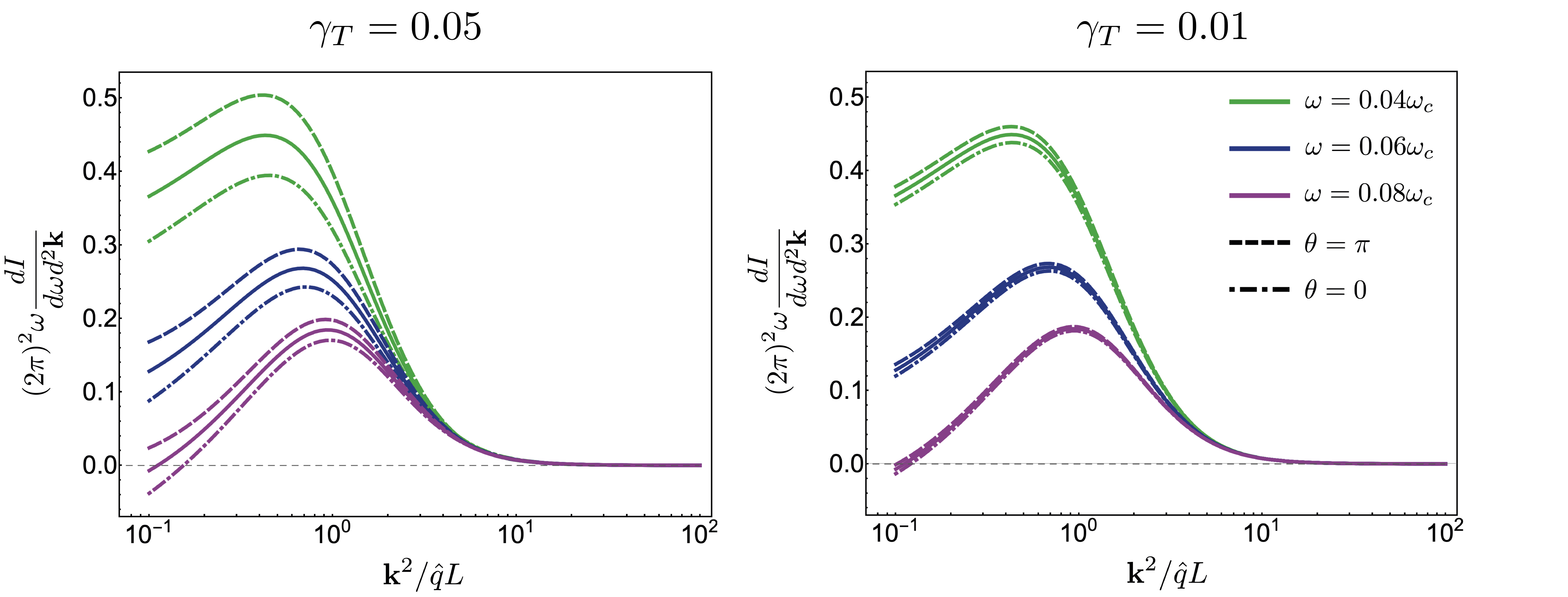
Ressummed medium-induced radiation

Ressummed spectrum with transverse gradients

Barata et al. 2304.03712

- Asymmetric medium-induced gluon spectrum



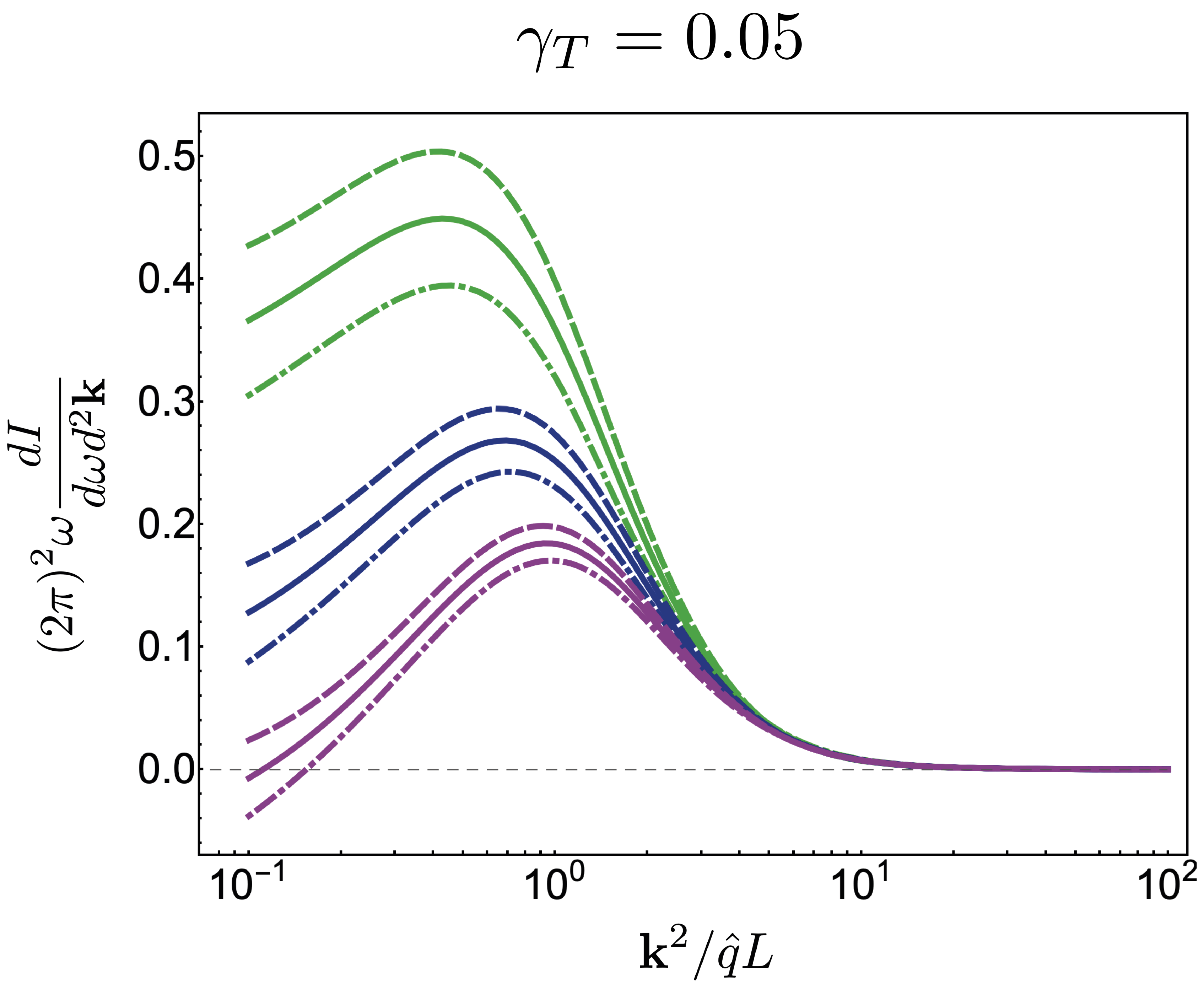
Ressummed spectrum with transverse flow

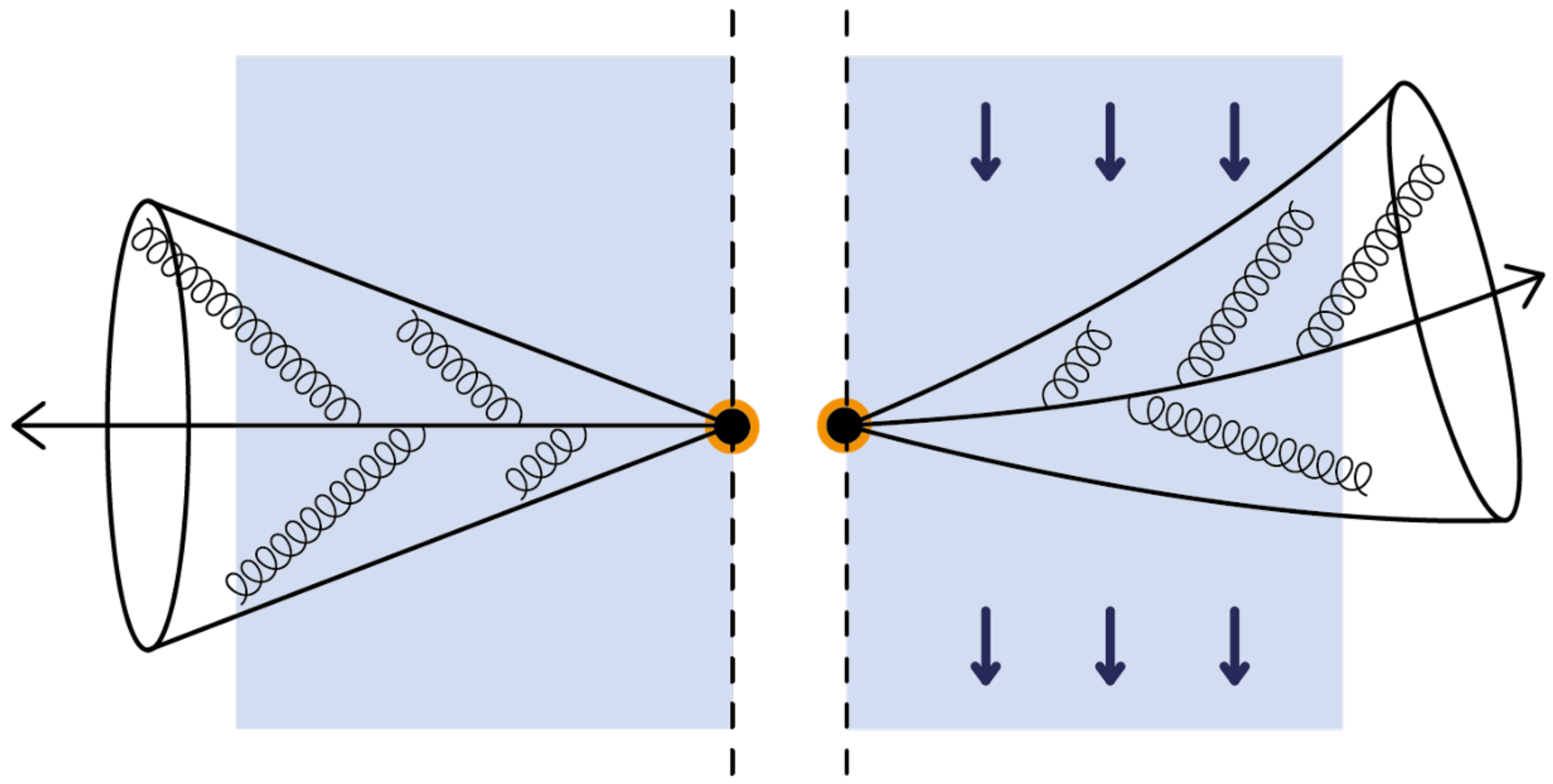
Coming soon

Ressummed medium-induced radiation

Ressummed spectrum with transverse gradients   Barata et al. 2304.03712

- Asymmetric medium-induced gluon spectrum

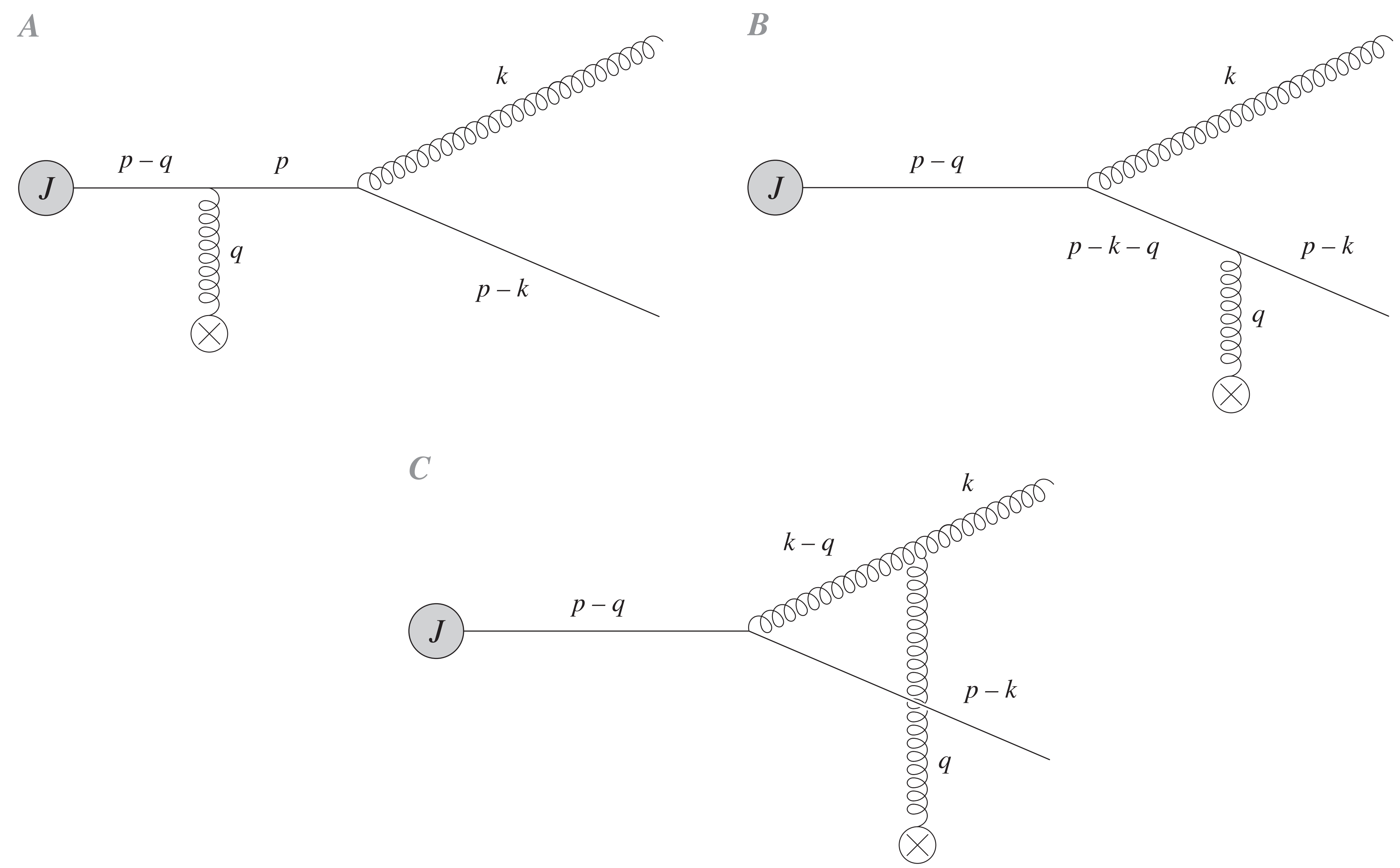


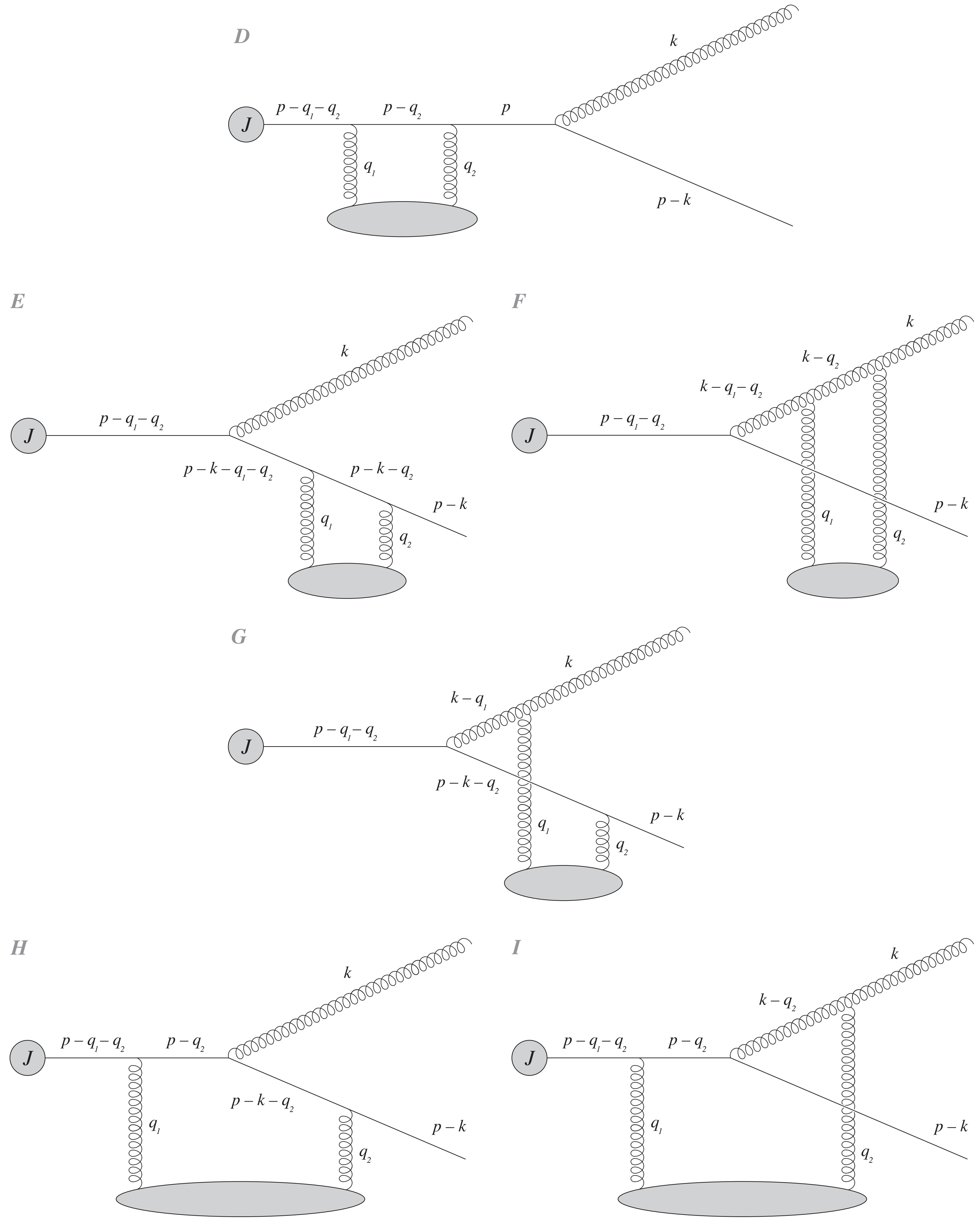


Ressummed spectrum with transverse flow   Coming soon

Medium-induced radiation

There are 9 possible diagrams





SB and DB diagrams add up to 12 different contributions

Limits of the final parton distribution

The final state parton distribution

$$E\,\frac{d\mathcal{N}^{(1)}}{d^2k\,dx\,d^2p\,dE} \equiv \frac{1}{\left[2(2\pi)^3\right]^2}\,\frac{1}{x(1-x)}\,\langle|\mathcal{R}_{N=1}|^2\rangle$$

- Static matter with full gluon kinematics

  Extending the previous result to hard gluon emissions

  Without ressummation of the interactions

  Both agree on the correspondent limit

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GLV spectrum

Gradients corrections

$$E\,\frac{d\mathcal{N}^{(1)}}{d^2k\,dx\,d^2p\,dE} = \frac{g^2\,C_F}{(2\pi)^3\,x}\left(E\,\frac{d\mathcal{N}^{(0)}}{d^2p\,dE}\right)\int_0^L dz\int_{\boldsymbol{q}}\rho(z)\,[v(\boldsymbol{q}^2)]^2$$
$$\times\left\{\frac{2\,\boldsymbol{k}\cdot\boldsymbol{q}}{\boldsymbol{k}^2(\boldsymbol{k}-\boldsymbol{q})^2}\left(1-\cos\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{2xE}z\right)\right)\left(1+\frac{\hat{\boldsymbol{g}}\cdot(\boldsymbol{k}-\boldsymbol{q})}{2xE}z\right)-\frac{\hat{\boldsymbol{g}}\cdot\boldsymbol{k}}{\boldsymbol{k}^2}\left[\frac{z}{xE}-\frac{1}{\boldsymbol{k}^2}\sin\left(\frac{\boldsymbol{k}^2}{2xE}z\right)\right]\right.$$
$$\left.+\frac{\boldsymbol{k}\cdot(\boldsymbol{k}-\boldsymbol{q})}{\boldsymbol{k}^2(\boldsymbol{k}-\boldsymbol{q})^2}\left[\frac{\hat{\boldsymbol{g}}\cdot(\boldsymbol{k}-\boldsymbol{q})}{xE}z-\hat{\boldsymbol{g}}\cdot\left(2\frac{\boldsymbol{k}-\boldsymbol{q}}{(\boldsymbol{k}-\boldsymbol{q})^2}-\frac{\boldsymbol{k}}{\boldsymbol{k}\cdot(\boldsymbol{k}-\boldsymbol{q})}\right)\sin\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{2xE}z\right)\right]\right\}$$

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- Flow-gradient mixture effect

Leading correction to the spectrum

GLV spectrum

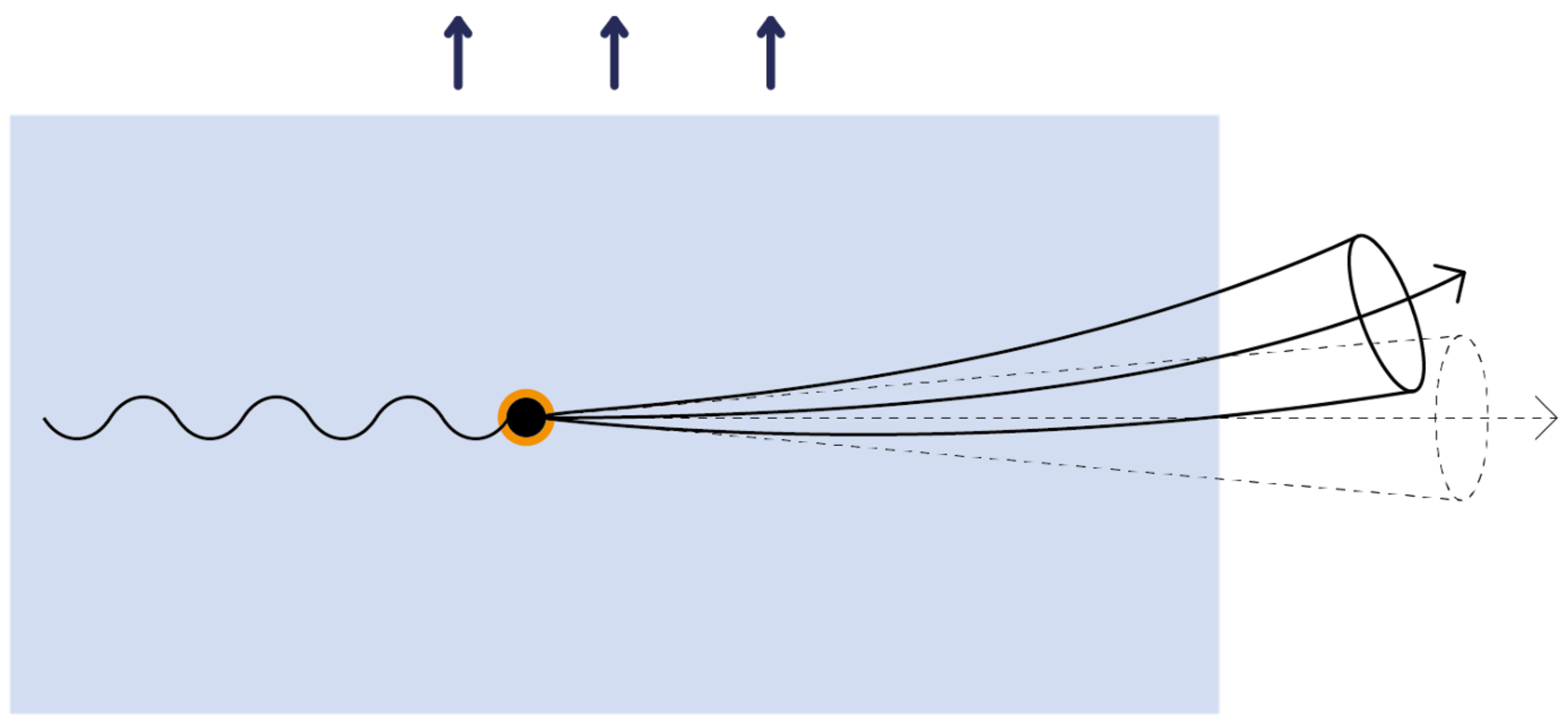
Gradient x flow corrections

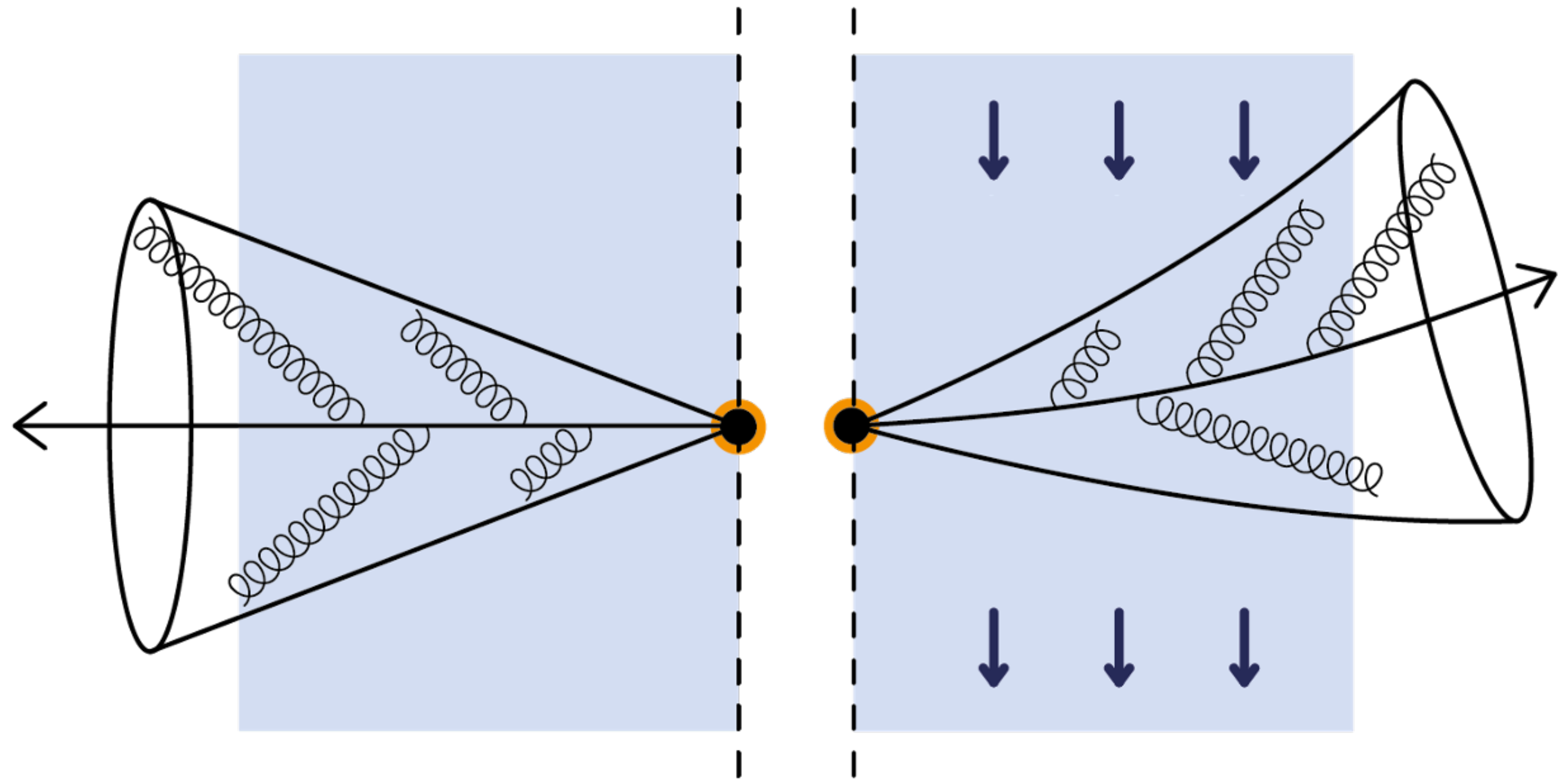
$$\omega\frac{dI}{d^2k\,d\omega} = \frac{g^2C_F}{(2\pi)^2}\int_0^L dz\int_{\boldsymbol{q}} \left[1-\hat{\boldsymbol{g}}\cdot\boldsymbol{u}\,z\right] \frac{2\,\boldsymbol{k}\cdot\boldsymbol{q}}{\boldsymbol{k}^2(\boldsymbol{k}-\boldsymbol{q})^2}\left[1-\cos\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{2xE}\,z\right)\right]\rho(z)\,[v(\boldsymbol{q}^2)]^2$$

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

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

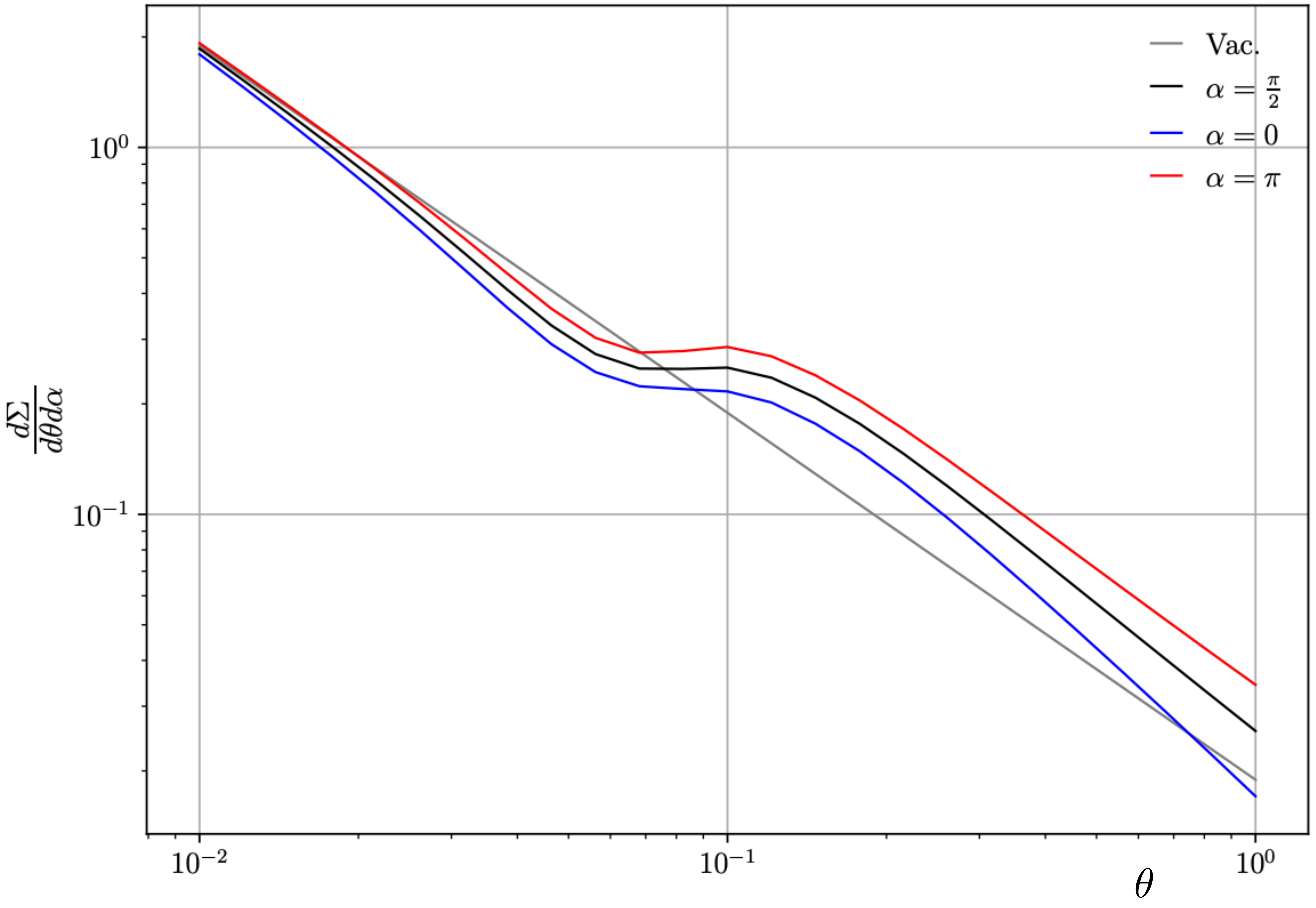




To take home

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

  They may be accessible with different substructure techniques, e.g. EECs   Barata et al. 2308.01294



Thanks