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Jet quenching in evolving anisotropic matter

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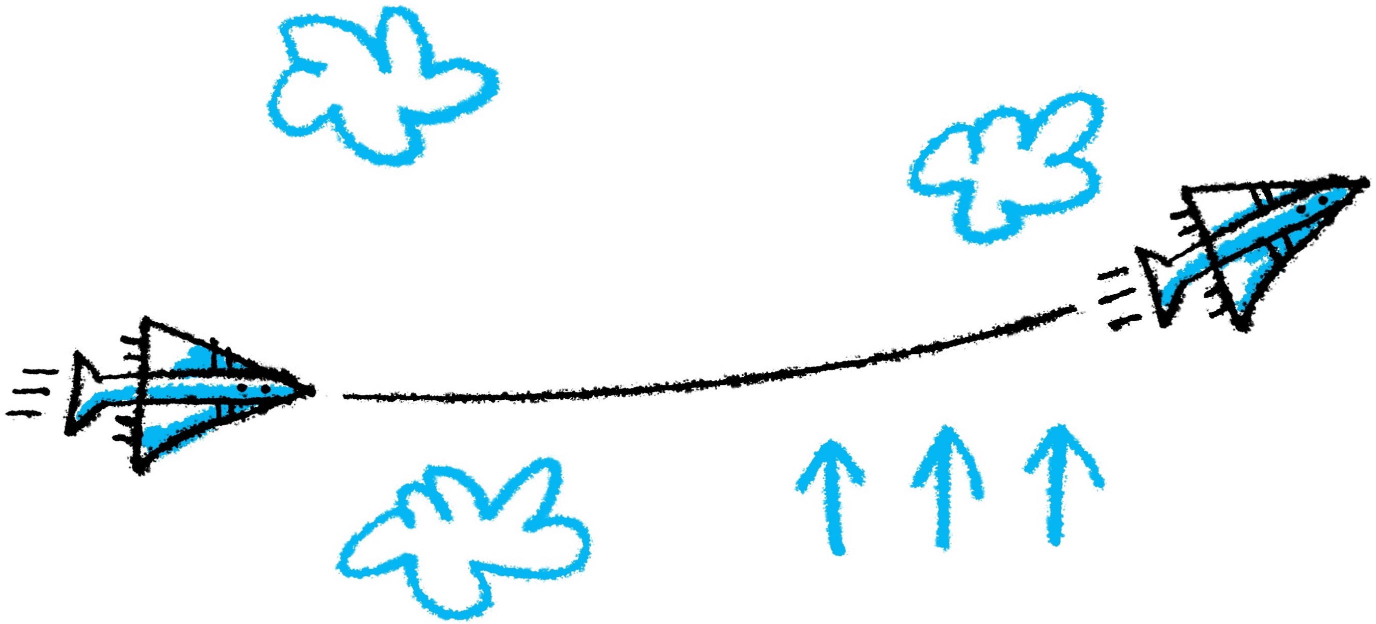
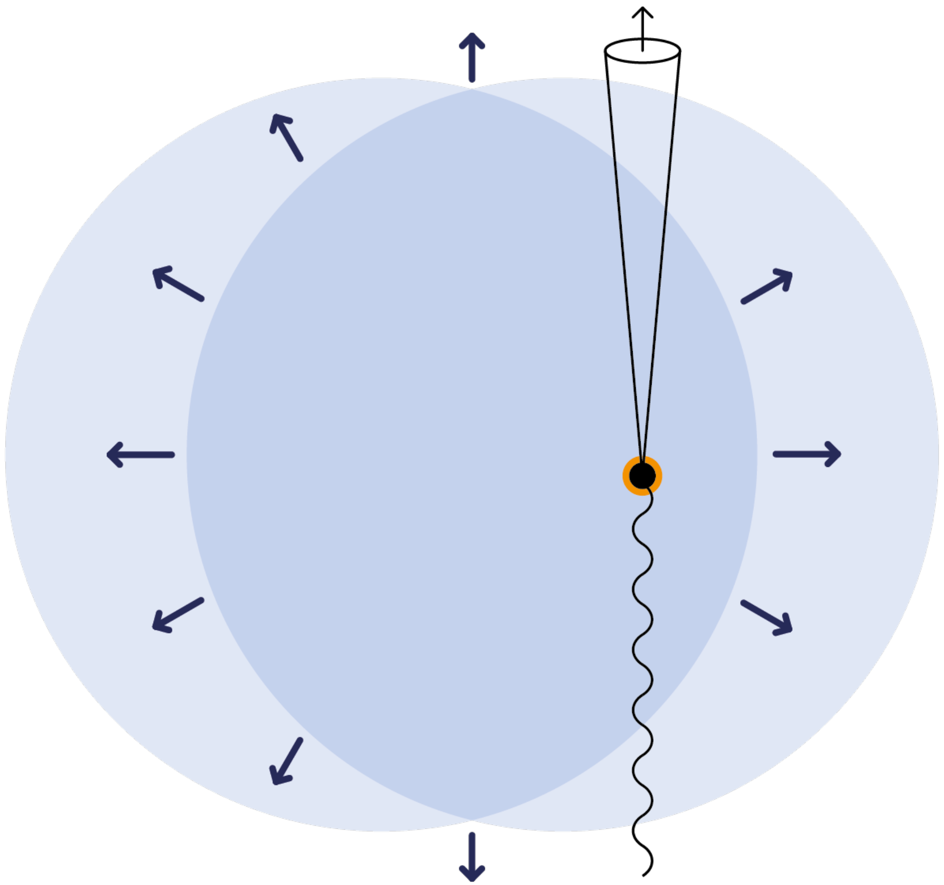
Jet tomography

- Jets see the matter in HIC at multiple scales, and essentially X-ray it;
- The existing jet quenching theory is based on multiple simplifying assumptions: large parton energy, static matter, no fluctuations, etc;
- There is a very recent progress on the medium motion and structure effects in jet quenching and this is the focus of this talk;
- The developed formalism can be also applied to include orbital motion of nucleons and some of the in-medium fluctuations to the energy loss in cold nuclear matter;





R. Baier et al, NPB, 1997
B. G. Zakharov, JETP, 1997
R. Baier et al, NPB, 1998
M. Gyulassy et al, NPB, 2000
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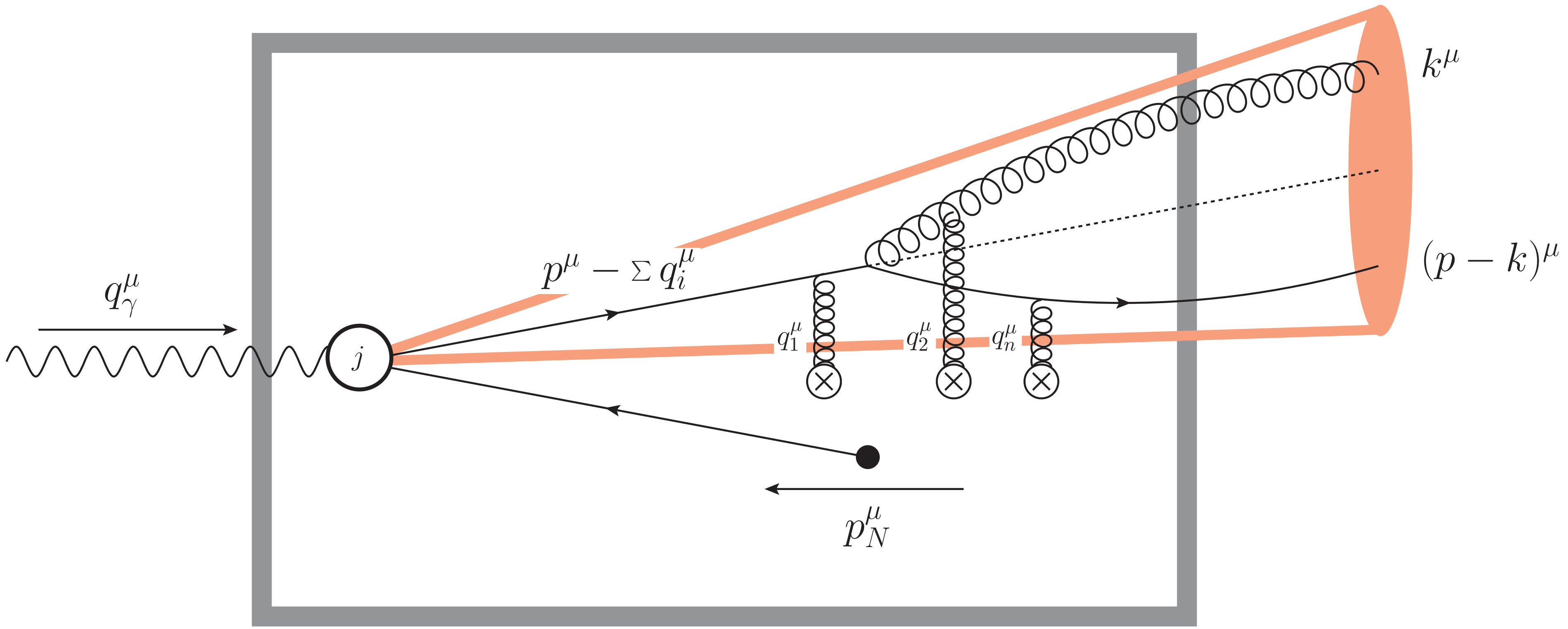
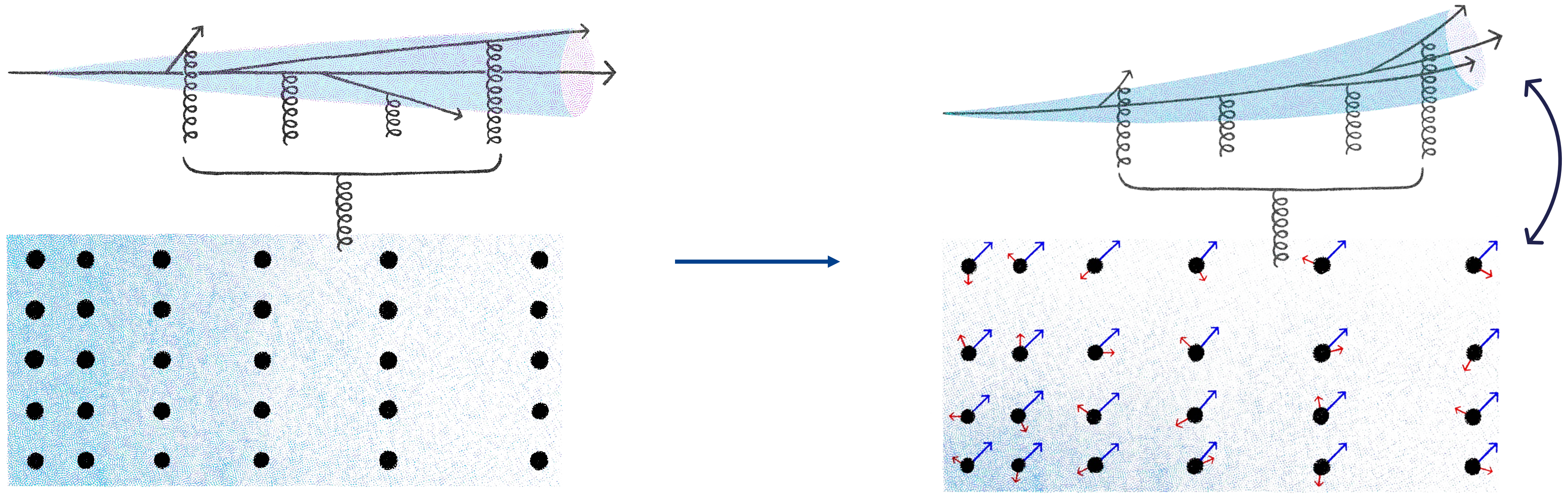
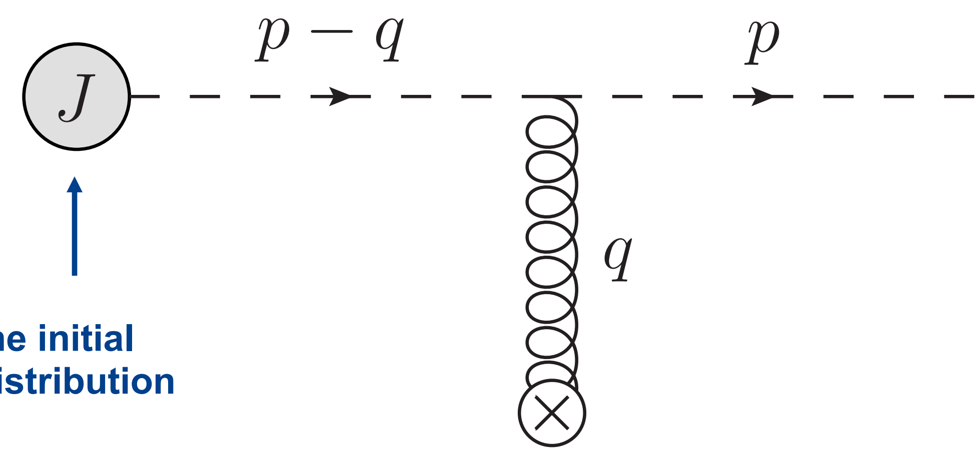




Color potential



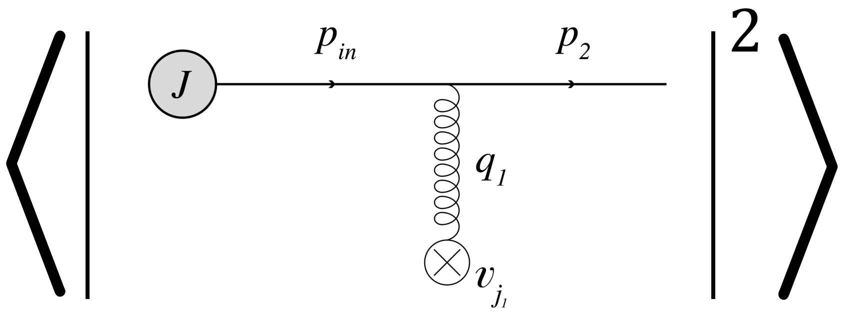
the initial distribution

$$gA^{\mu a}_{ext}(q) = \sum_i e^{iq\cdot x_i}\, t^a_i\, u^\mu_i\, v_i(q)\, (2\pi)\, \delta\left(q^0 - \vec{u}_i \cdot \vec{q}\right)$$

inhomogeneity

the fluid velocity

Medium averaging



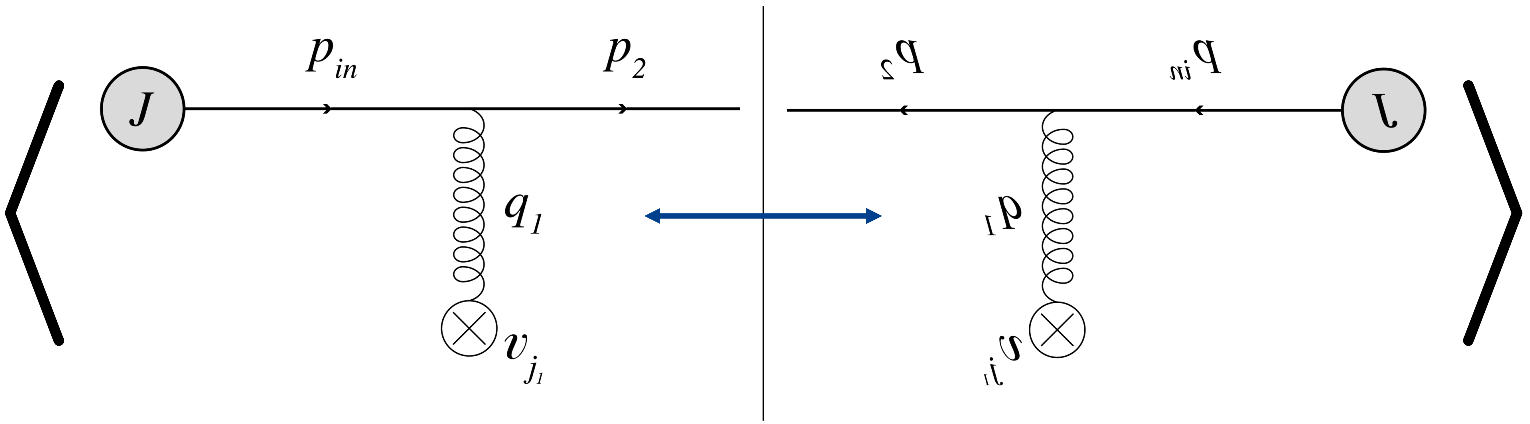
$$\langle t_i^a t_j^b \rangle = \mathcal{C}\delta_{ij}\delta^{ab}$$

color neutrality

$$\sum_i = \int d^3x \, \rho(\vec{x})$$

source averaging

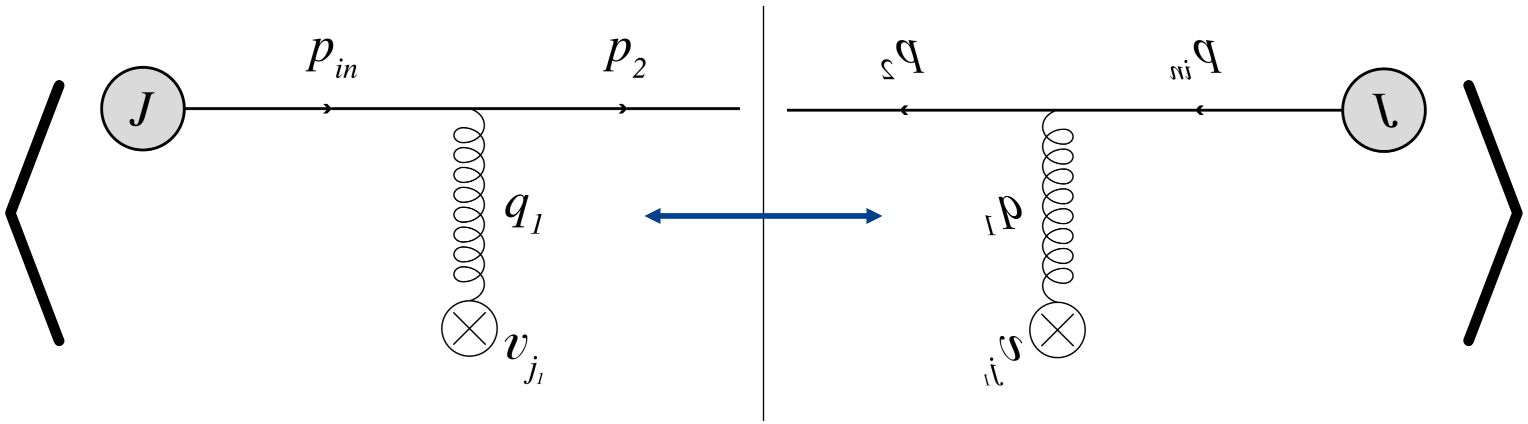
Medium averaging



$$\int d^2\mathbf{x}_n \, e^{-i(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)\cdot \mathbf{x}_n} = (2\pi)^2 \, \delta^{(2)}(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)$$

$$\rho \sim T^3$$

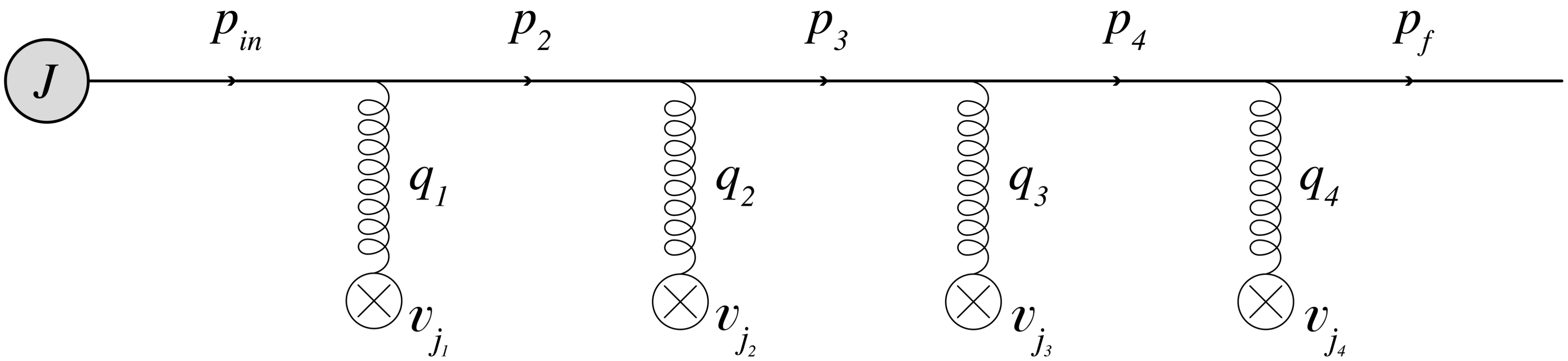
Medium averaging



$$\int d^2\mathbf{x}_n\, e^{-i(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)\cdot\mathbf{x}_n} = (2\pi)^2\, \delta^{(2)}(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)$$

$$\int d^2\mathbf{x}_n\, x_n^\alpha\, e^{-i(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)\cdot\mathbf{x}_n} = i\,(2\pi)^2\, \frac{\partial}{\partial(q_n \pm \overline{q}_n)_\alpha}\, \delta^{(2)}(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)$$

The broadening



$E \to \infty$

$v(q)$

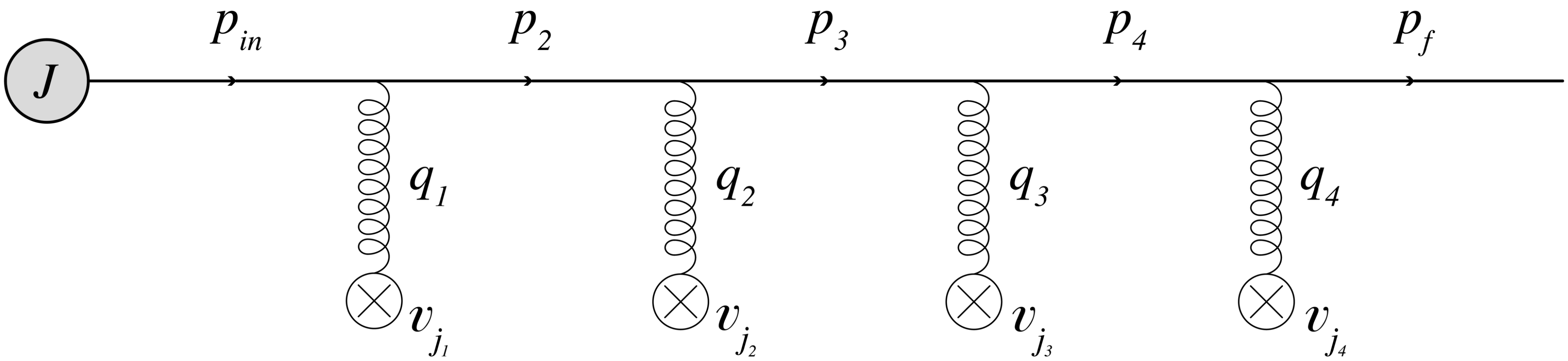
$\mu \ll E \qquad \mu z \gg 1$

$$iM(p) = \int \frac{d^2\mathbf{p}_{in}}{(2\pi)^2} e^{i\frac{\mathbf{p}_f^2}{2E}L}\, G(\mathbf{p}_f, L; \mathbf{p}_{in}, 0)\, J\,(E, \mathbf{p}_{in})$$

single particle propagator

MARIE CURIE ACTIONS

The broadening



$$G(\mathbf{x}_L, L; \mathbf{x}_0, 0) = \int_{\mathbf{x}_0}^{\mathbf{x}_L} \mathcal{D}\mathbf{r} \exp\left(\frac{iE}{2}\int_0^L d\tau\, \dot{\mathbf{r}}^2\right) \mathcal{P}\exp\left(-i\int_0^L d\tau\, t^a_{\text{proj}} v^a(\mathbf{r}(\tau), \tau)\right)$$

Jet broadening

inhomogeneous matter

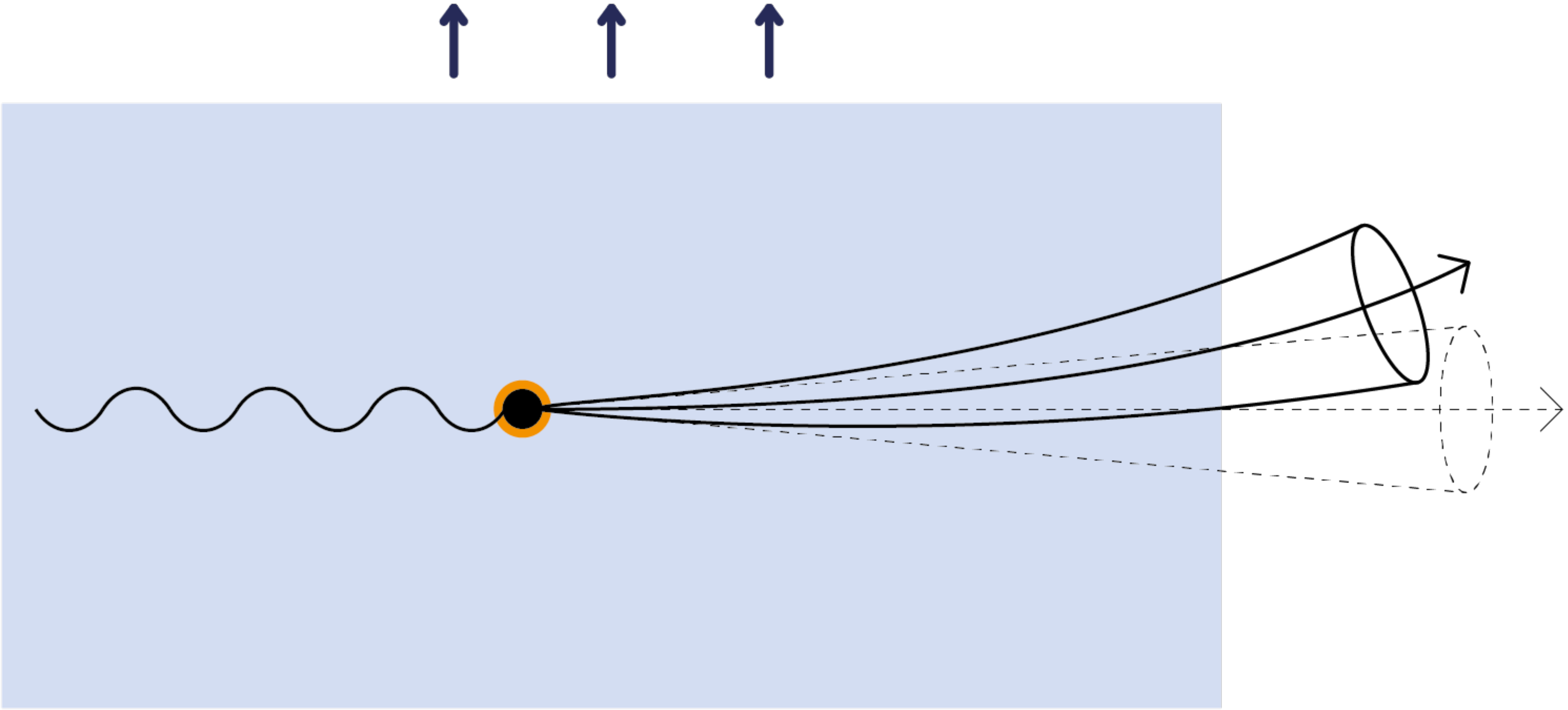
$$E\frac{d\mathcal{N}^{(0)}}{d^2\mathbf{p}_0 dE} = \frac{1}{2(2\pi)^3}|J(p_0)|^2 = f(E)\delta^{(2)}(\mathbf{p}_0)$$

$$\frac{d\mathcal{N}}{d^2\boldsymbol{x}dE} \simeq \exp\{-\mathcal{V}(\boldsymbol{x})L\}\left\{\left[1-\frac{iL^3}{6E}\boldsymbol{\nabla}\mathcal{V}(\boldsymbol{x})\cdot\hat{\boldsymbol{g}}\,\mathcal{V}(\boldsymbol{x})\right]\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{x}dE} + \frac{iL^2}{2E}\hat{\boldsymbol{g}}\,\mathcal{V}(\boldsymbol{x})\cdot\boldsymbol{\nabla}\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{x}dE}\right\}$$

$$\hat{\boldsymbol{g}} \equiv \left(\boldsymbol{\nabla}\rho\frac{\delta}{\delta\rho} + \boldsymbol{\nabla}\mu^2\frac{\delta}{\delta\mu^2}\right)$$

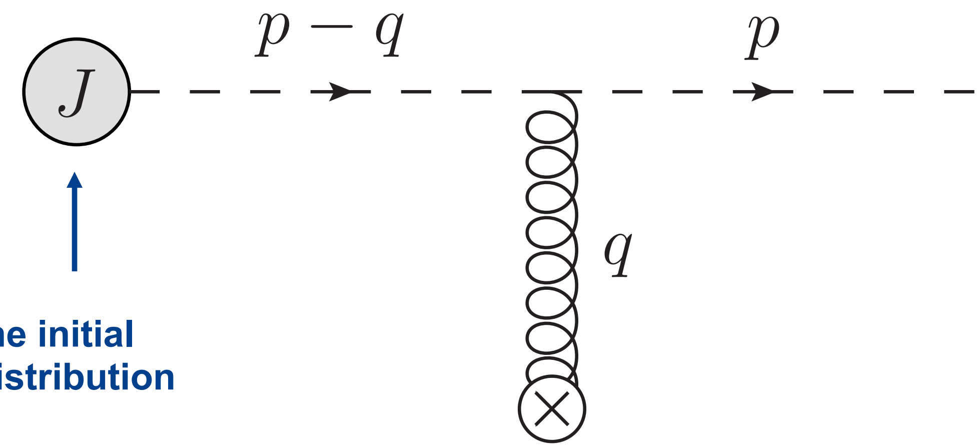
$\rho \sim T^3$

$$\langle \mathbf{p}\, p_\perp^2 \rangle \simeq \chi^2\,\frac{L\nabla T}{2T}\,\frac{\mu^4}{E}\left(\log\frac{E}{\mu}\right)^2$$



$$\langle \mathbf{p}\, p_\perp^2 \rangle \simeq \chi^2 \, \frac{L \nabla T}{2T} \, \frac{\mu^4}{E} \left(\log \frac{E}{\mu} \right)^2$$

Color potential



the initial distribution

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inhomogeneity

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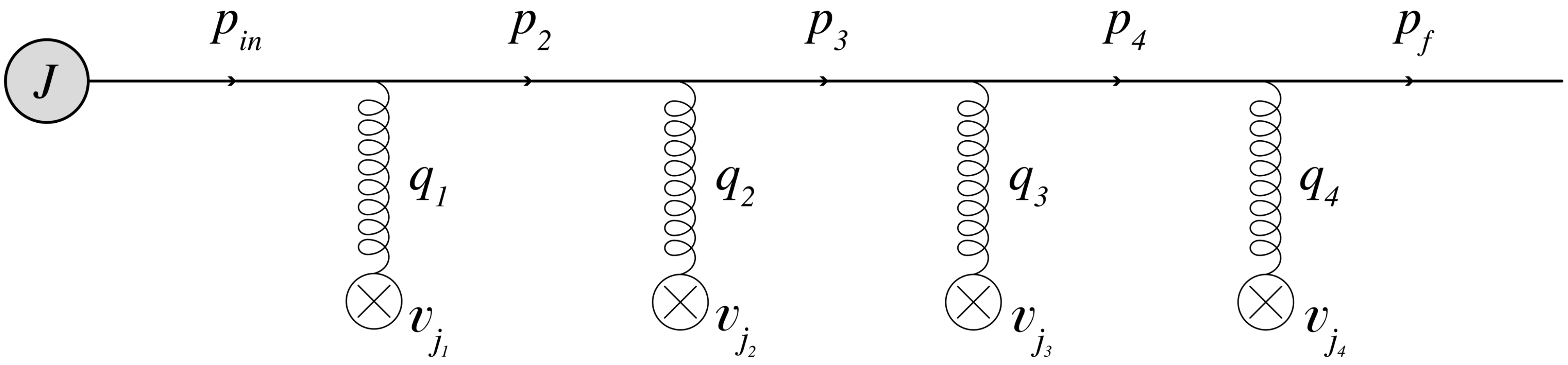
Jet broadening



$$i\mathcal{M}_n(p) = e^{-i\left(\mathbf{u}\cdot\mathbf{p}-\frac{p_\perp^2}{2E}\right)L} \int \frac{d^2\mathbf{p}_0}{(2\pi)^2}\, \mathcal{G}_n(\mathbf{p}, L; \mathbf{p}_0, 0)\, J\big(E - \mathbf{u}\cdot(\mathbf{p}-\mathbf{p}_0), \mathbf{p}_0\big)\,,$$

Jet broadening

uniform matter

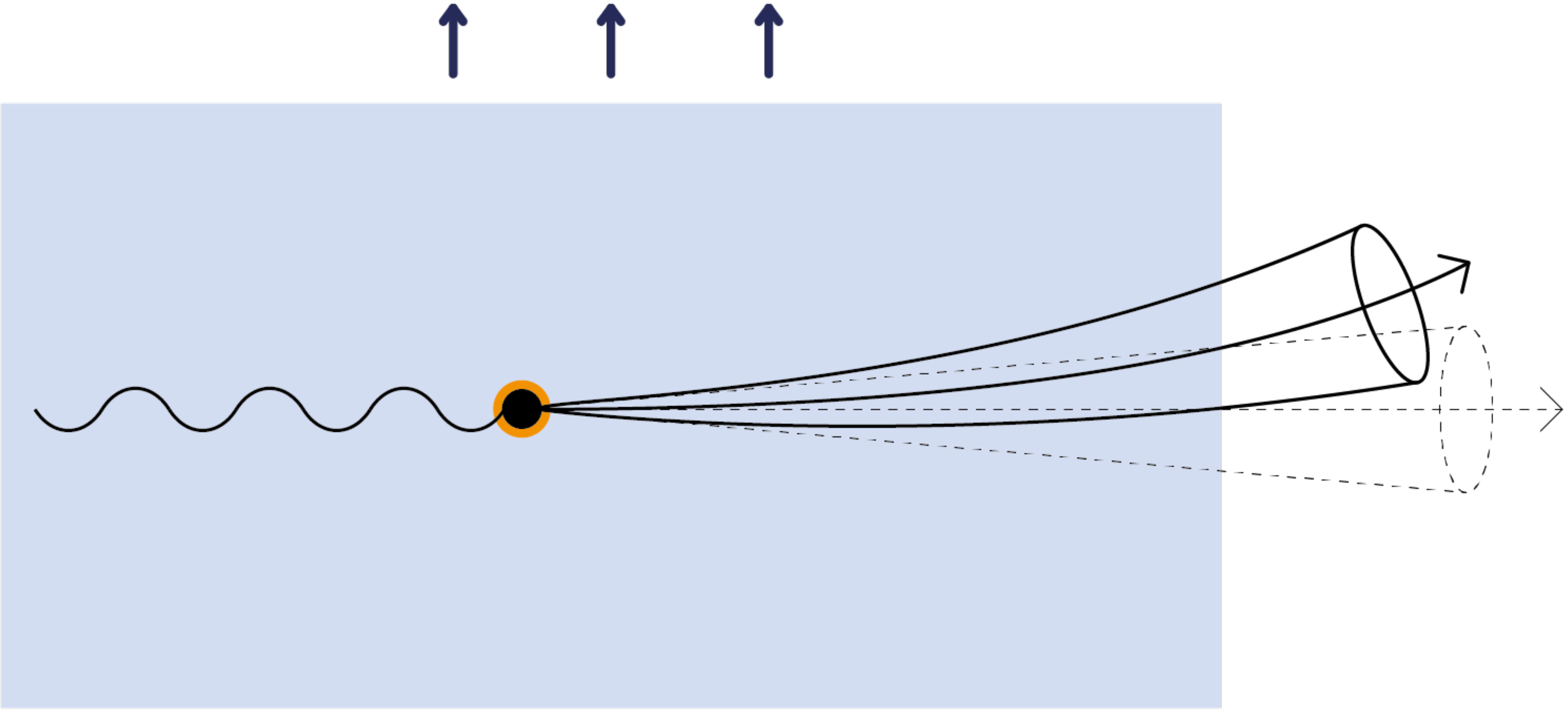
$$E\frac{d\mathcal{N}^{(0)}}{d^2\mathbf{p}_0 dE} = f(E)\delta^{(2)}(\mathbf{p}_0)$$

Eikonal approximation -- $E \to \infty$

$$\langle p_\perp^{2k}\boldsymbol{p}\rangle = \int \frac{d^2\boldsymbol{p}\, d^2\boldsymbol{r}}{(2\pi)^2}\, p_\perp^{2k}\boldsymbol{p}\, e^{-i\boldsymbol{p}\cdot\boldsymbol{r}} e^{-\mathcal{V}(\boldsymbol{r})L} = 0 + \mathcal{O}\left(\frac{\perp}{E}\right)$$

Opacity expansion -- $\chi \equiv \mathcal{C}\frac{g^4\rho}{4\pi\mu^2}L \ll 1$

$$\langle p_\perp^{2k}\boldsymbol{p}\rangle \simeq -\frac{\boldsymbol{u}}{2E}\mathcal{C}\rho L \int \frac{d^2\boldsymbol{p}}{(2\pi)^2}\, p_\perp^{2k+2}\left[E\frac{f'(E)}{f(E)}\, v(p_\perp)^2 + p_\perp^2\,\frac{\partial v^2}{\partial p_\perp^2}\right]$$



$$\langle \mathbf{p} \rangle \simeq 3\,\chi\,\mathbf{u}\,\frac{\mu^2}{E}\log\frac{E}{\mu}$$

Jet broadening

uniform matter

- Opacity $\chi \approx 4$
- $u \approx 0.7$ (about $\pi/4$ to z-axis)
- $\mu = gT$ with $g \approx 2$ and $T \approx 500\ MeV$

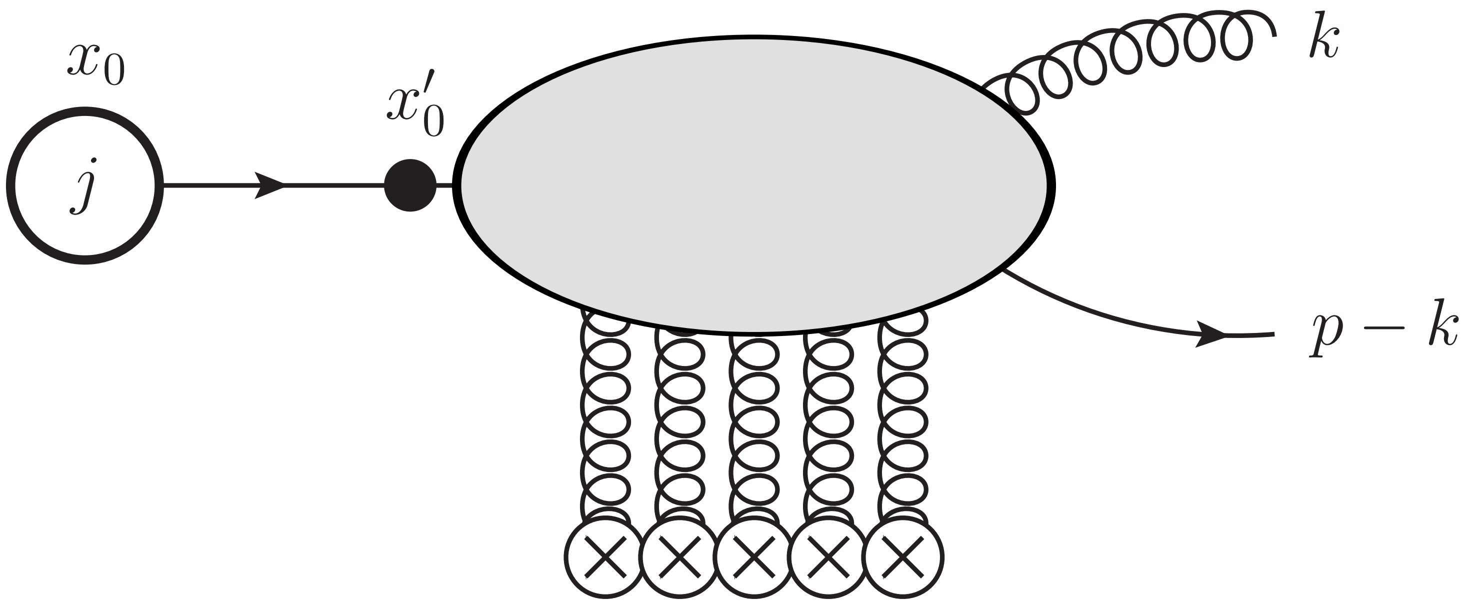
$$\left\langle \frac{p_\perp}{E} \right\rangle \simeq 3\,\chi\,\frac{u_\perp}{1-u_z}\,\frac{\mu^2}{E^2}\log\frac{E}{\mu}$$

What jet energy corresponds to $\langle\theta\rangle \approx 1^o$?

↓

$E \sim 50\ \text{GeV}$

Gluon emission



Gluon emission

$$iR \simeq -\frac{g}{xE} \lim_{z_f\to\infty} \int_0^\infty dz_s \int d^2x_0 \, e^{-i\mathbf{x}_0\cdot\mathbf{l}_f} J(\mathbf{x}_0)$$

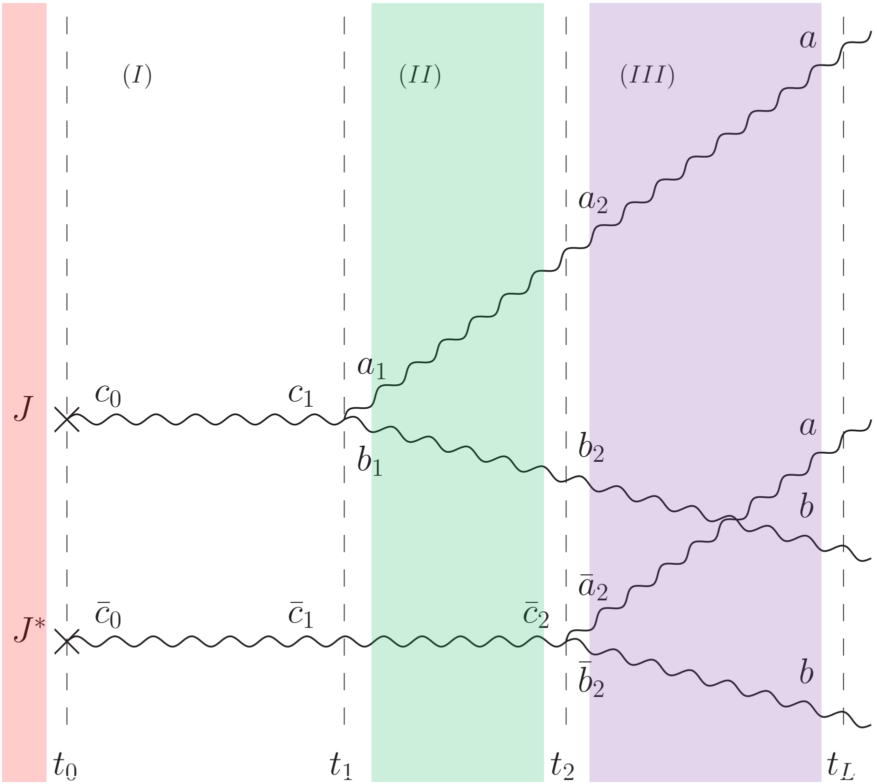
$$\times\, \mathcal{W}(\mathbf{x}_0;\infty,z_s)\, t^a_{proj}\, \mathcal{W}(\mathbf{x}_0;z_s,0)\; e^{i\frac{\mathbf{k}_f^2}{2\omega}z_f} \left[\epsilon\cdot\vec{\nabla}_{\mathbf{x}_0}\mathcal{G}^{ba}\left(\mathbf{k}_f,z_f;\mathbf{x}_0,z_s\right)\right]$$

energy fraction

Wilson line ($x \ll 1$)

the gluon (single-particle) propagator

Gluon emission



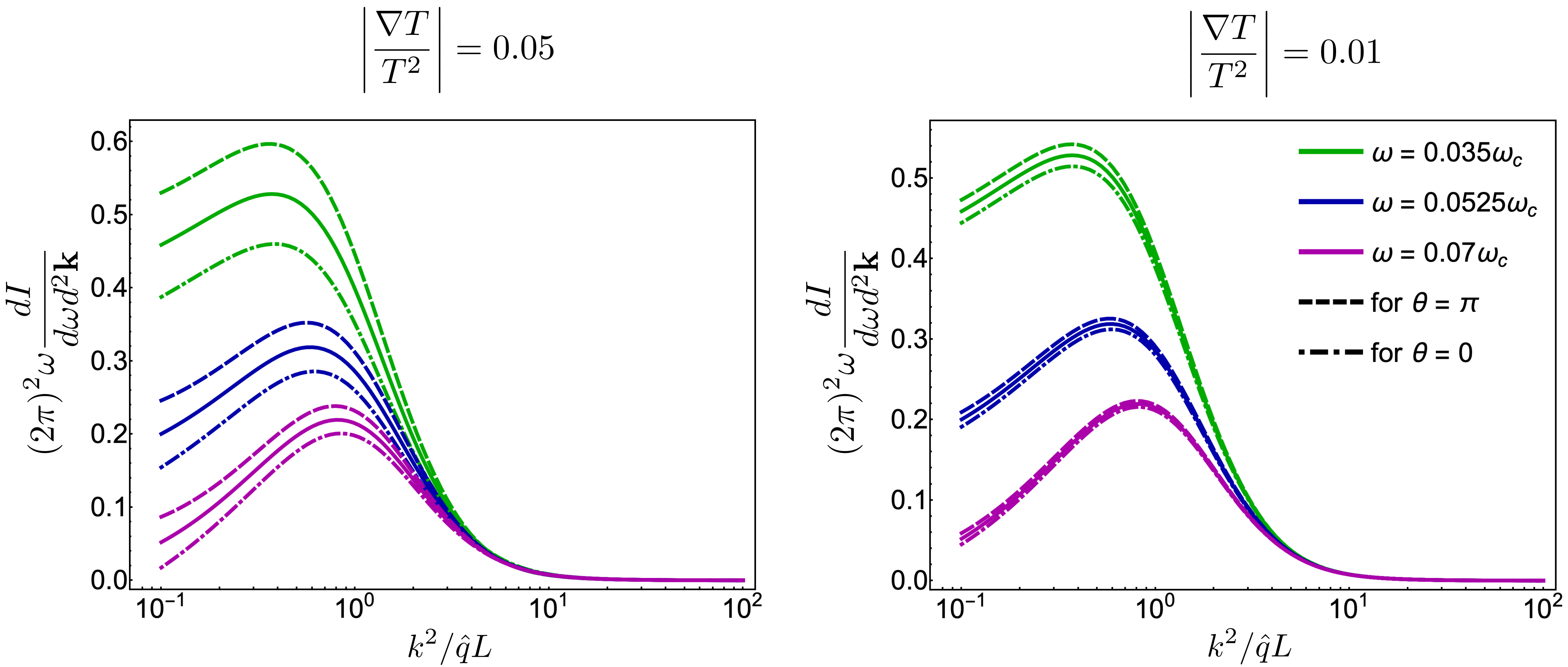
$$(2\pi)^2\omega\frac{d\mathcal{N}}{d\omega d^2\mathbf{k}} = \frac{\alpha_s}{N_c\,\omega^2}\mathrm{Re}\int_0^L d\bar{z}\int_0^{\bar{z}} dz\int_{\mathbf{x}_0,\mathbf{y}} |J(\mathbf{x}_0)|^2\Big[(\nabla_{\mathbf{x}}\cdot\nabla_{\bar{\mathbf{x}}})$$

$$\times\left\langle \mathcal{G}^{bc}(\mathbf{k},L;\mathbf{y},\bar{z})\,\mathcal{G}^{\dagger\,\bar{a}b}(\mathbf{k},L;\bar{\mathbf{x}},\bar{z})\right\rangle\left\langle \mathcal{G}^{ca}(\mathbf{y},\bar{z};\mathbf{x},z)\,\mathcal{W}_A^{\dagger\,a\bar{a}}(\mathbf{x}_0;\bar{z},z)\right\rangle\Big]\Big|_{\mathbf{x}=\bar{\mathbf{x}}=\mathbf{x}_0}$$

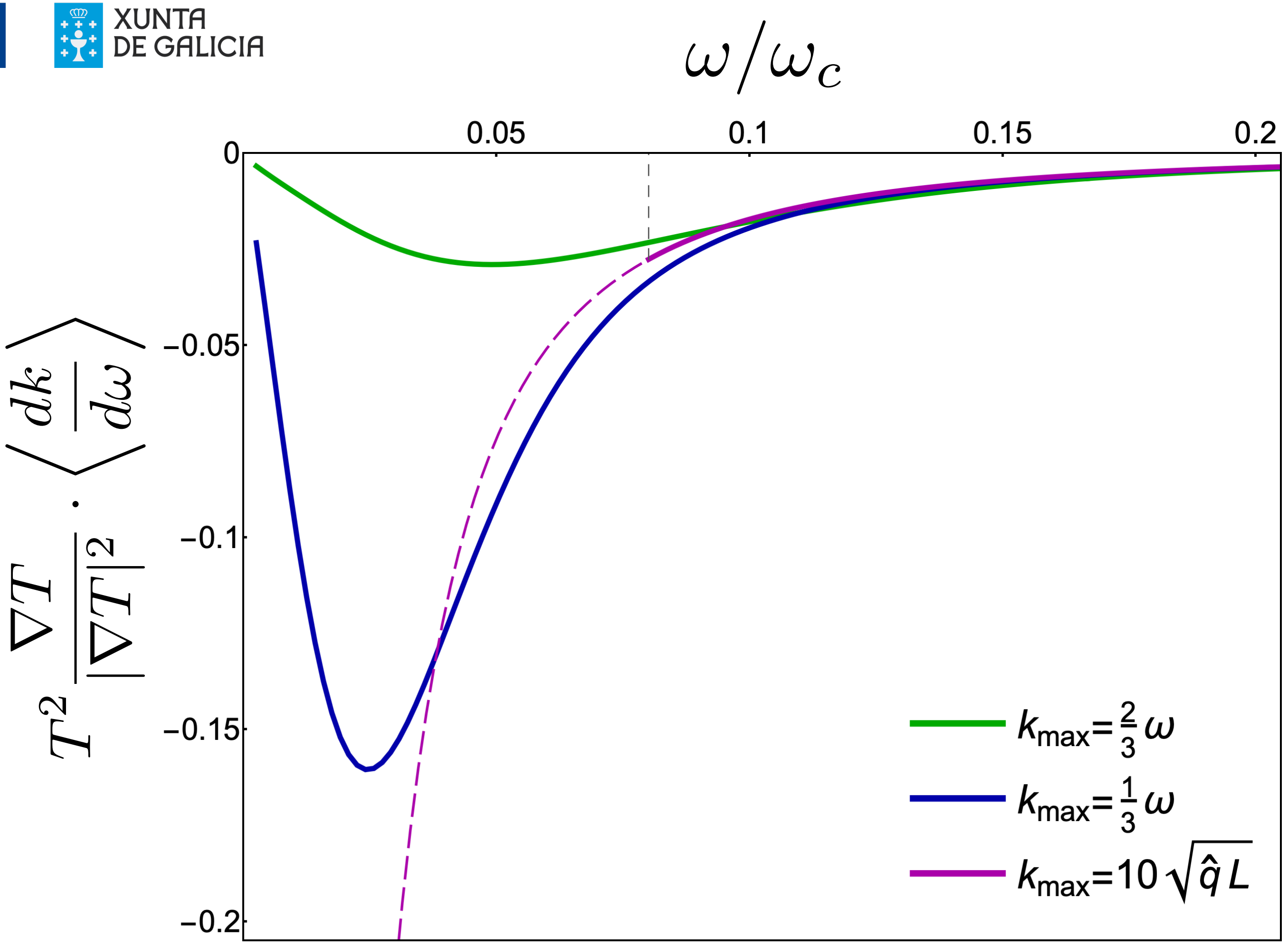
broadening of the gluon (already have it with ∇)

emission kernel

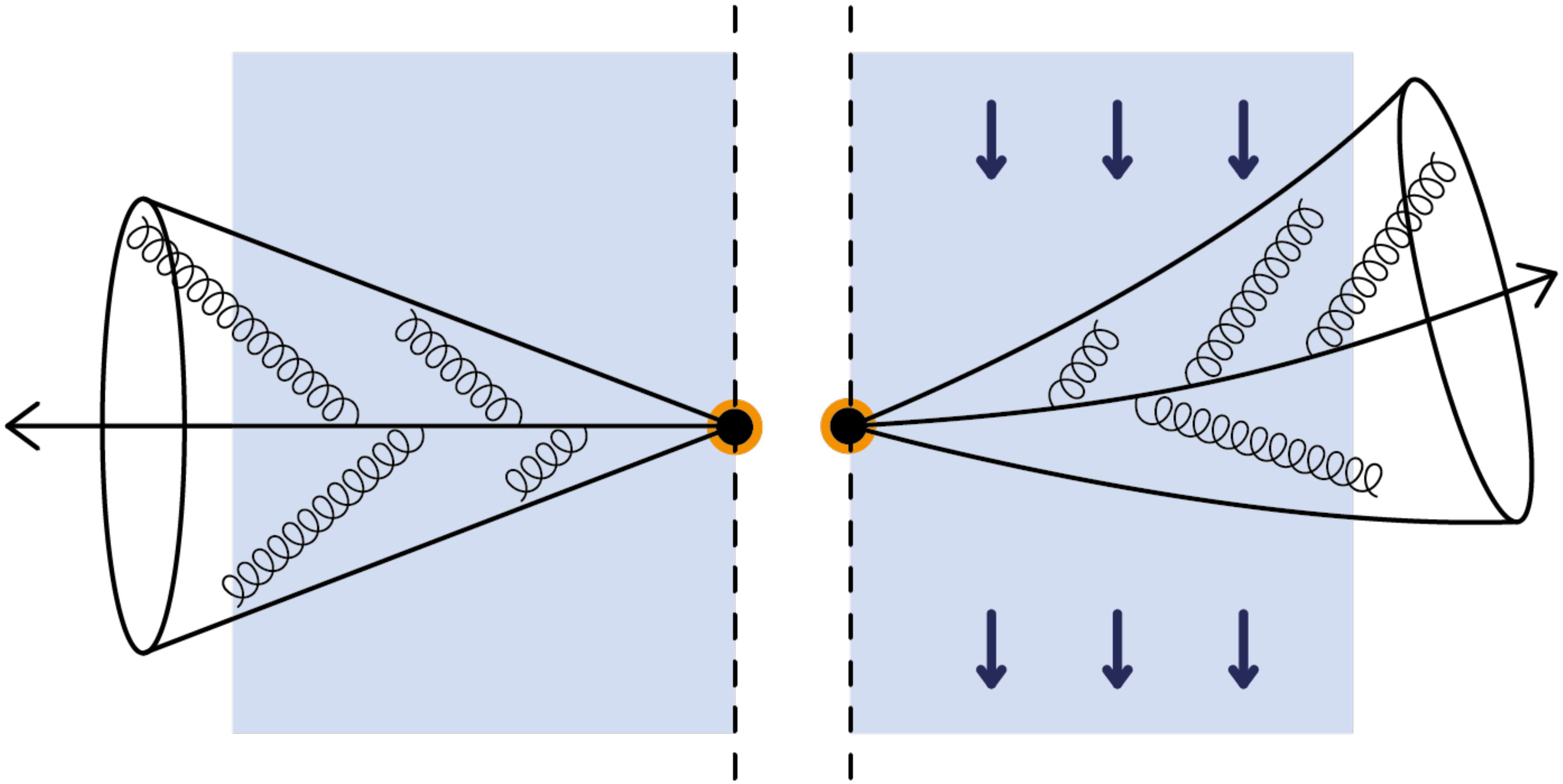
$$\delta\mathcal{K}(\mathbf{y},\bar{z};\mathbf{x},z) = -\int_z^{\bar{z}} ds\int_{\mathbf{w}} \mathcal{K}_0(\mathbf{y},\bar{z};\mathbf{w},s)\,\delta\mathcal{V}(\mathbf{w},s)\,\mathcal{K}_0(\mathbf{w},s;\mathbf{x},z)$$



$$L = 5\text{fm}, \quad T = 0.3\text{GeV}, \quad \hat{q} = 1\text{GeV}^2 \cdot \text{fm}^{-1}$$



$$\left\langle \frac{d\mathbf{k}}{d\omega} \right\rangle \equiv \int_\Gamma d^2\mathbf{k}\,\mathbf{k}\,\frac{dI}{d\omega d^2\mathbf{k}}$$



Summary

- Jets do feel the transverse flow and anisotropy, and get bended;
- The transverse flow and anisotropy do affect the medium-induced radiation, bending the substructure of jets;
- These effects can be in principle probed in experiment, leading us towards actual jet tomography;
- One should also expect similar evolution-induced effects for the other probes of nuclear matter;