Horizon 2020
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Jet quenching in evolving anisotropic matter

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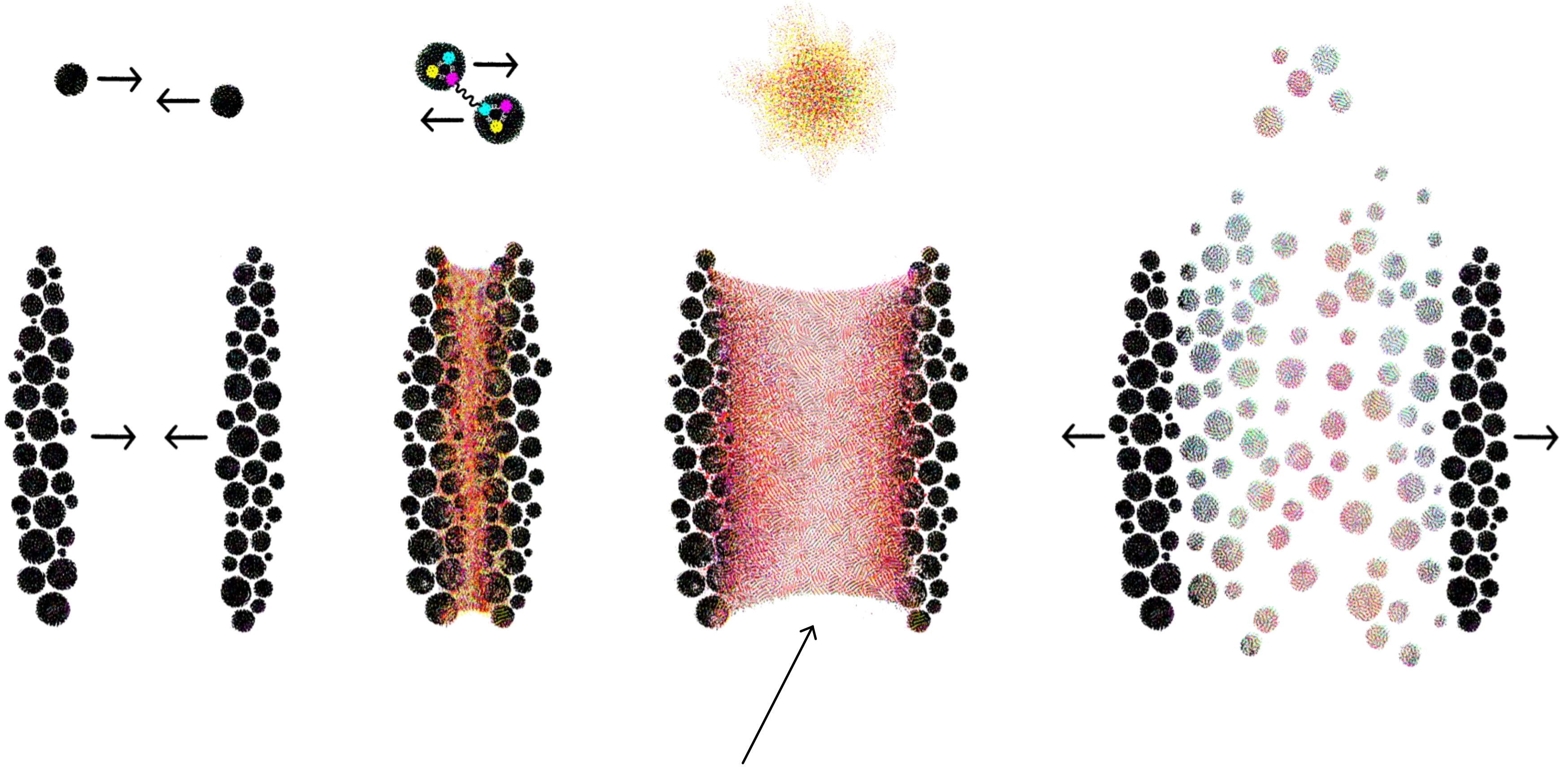


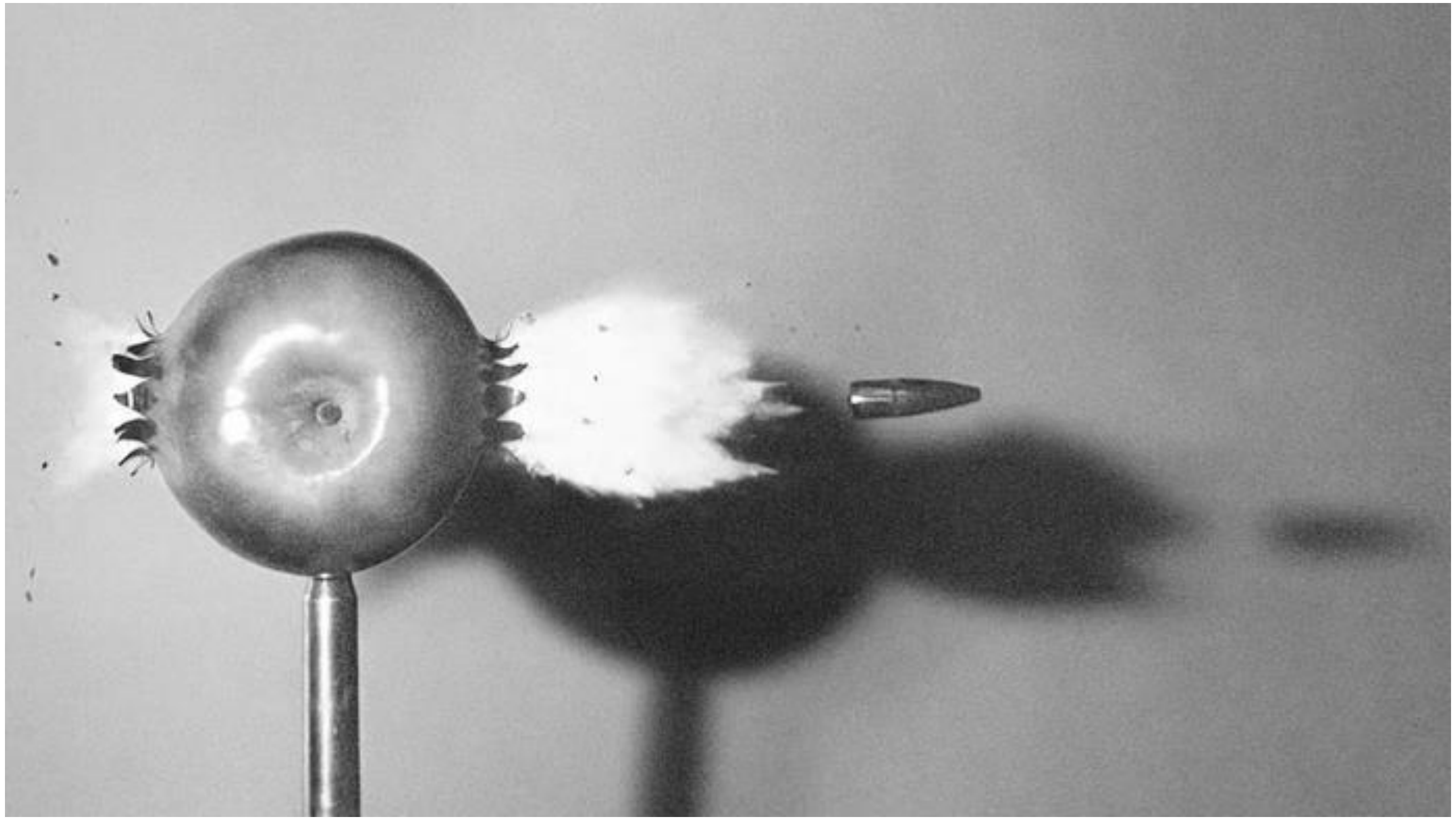
elementary
constituents

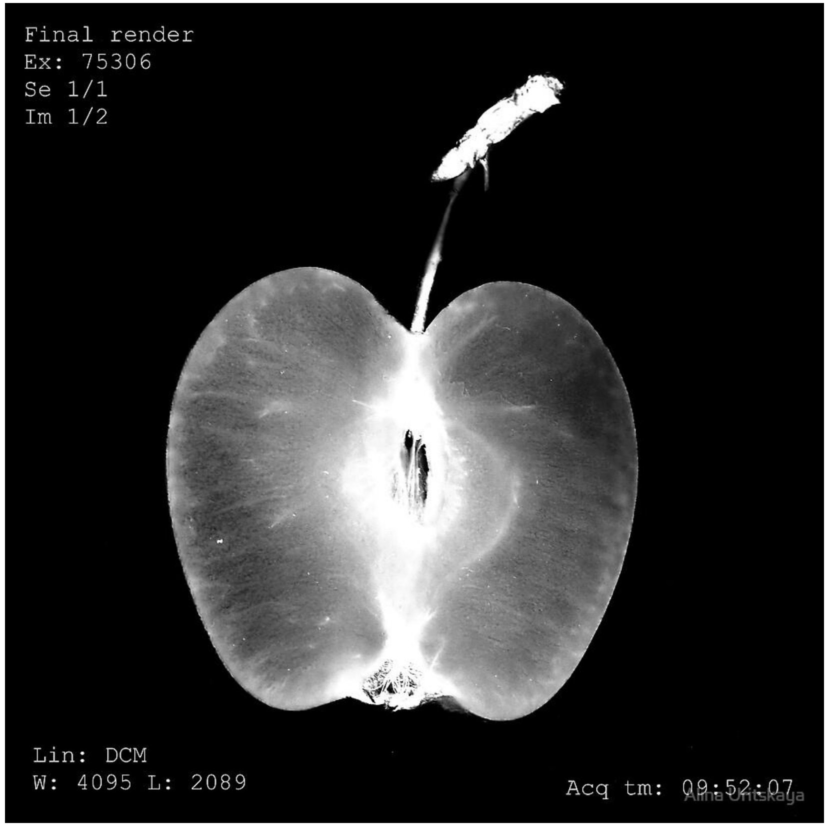
complex
nuclear matter

small
system

large
system

simplest
complex matter

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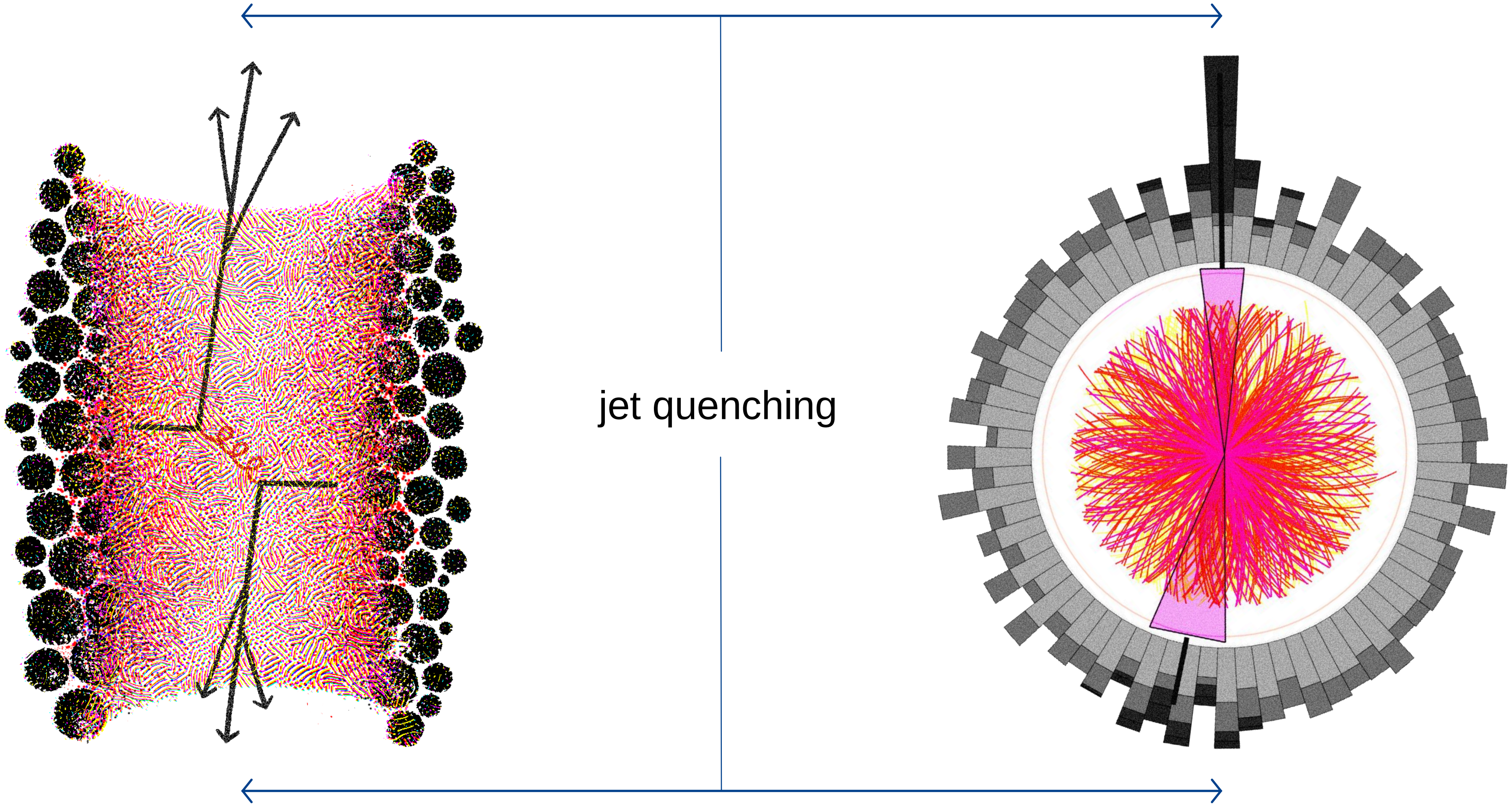
Alina Uritskaya



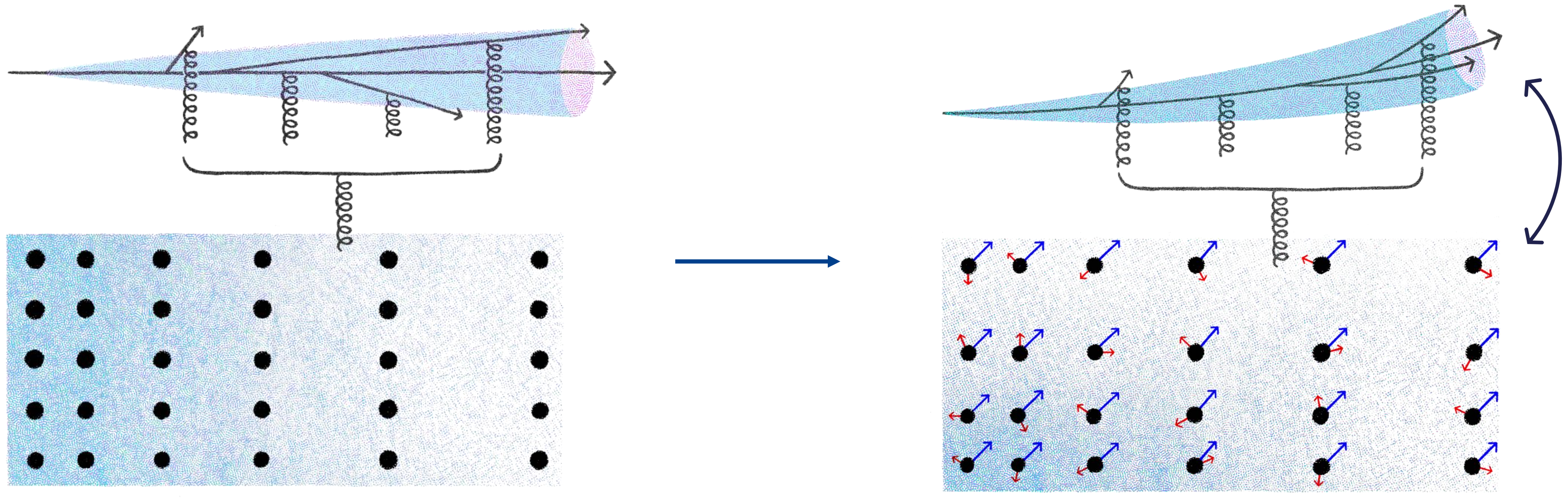
jet quenching

jets lose energy propagating through nuclear matter

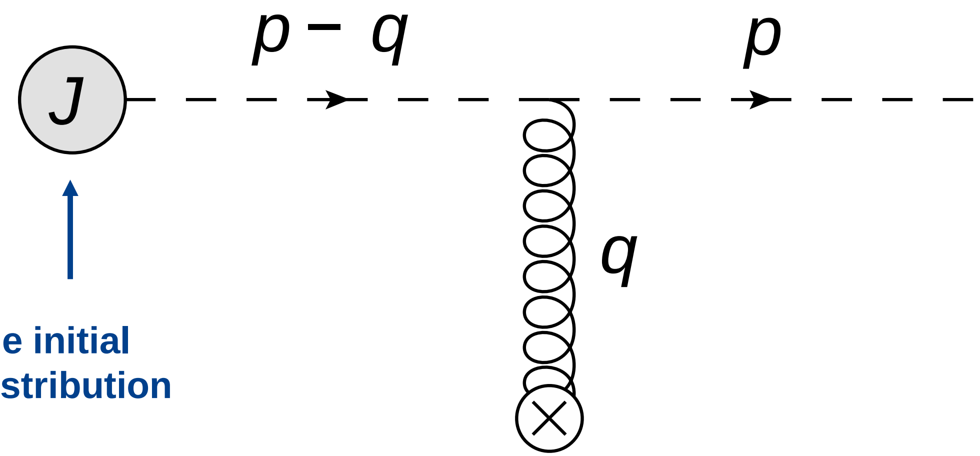
AS, M. Sievert, I. Vitev, PRD, 2021
J. Barata, AS, C. Salgado, PRD, 2022
C. Andres, F. Dominguez, AS, CS, PRD, 2022
J. Barata, AS, X.-N. Wang, arxiv 2022
J. Barata, X. Mayo, AS, CS, 2022 (?)

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;



Color potential



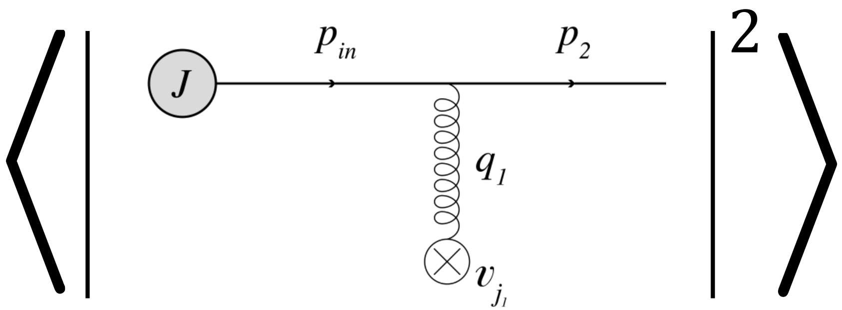
the initial distribution

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

inhomogeneity

the fluid velocity

Medium averaging



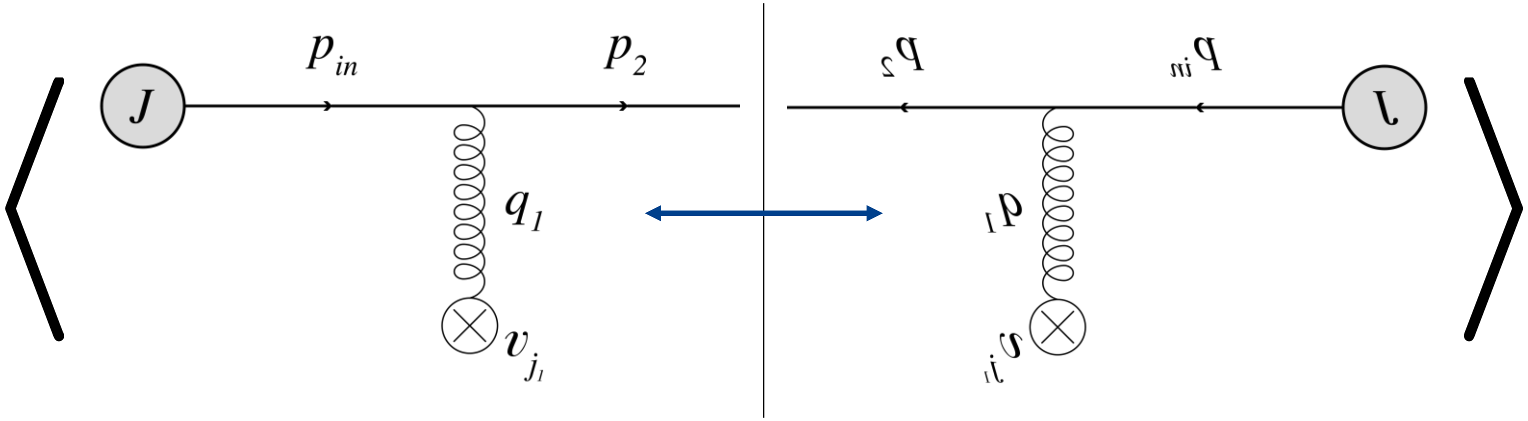
$$\langle t_i^a t_j^b \rangle = \mathcal{C}\delta_{ij}\delta^{ab}$$

color neutrality

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

source averaging

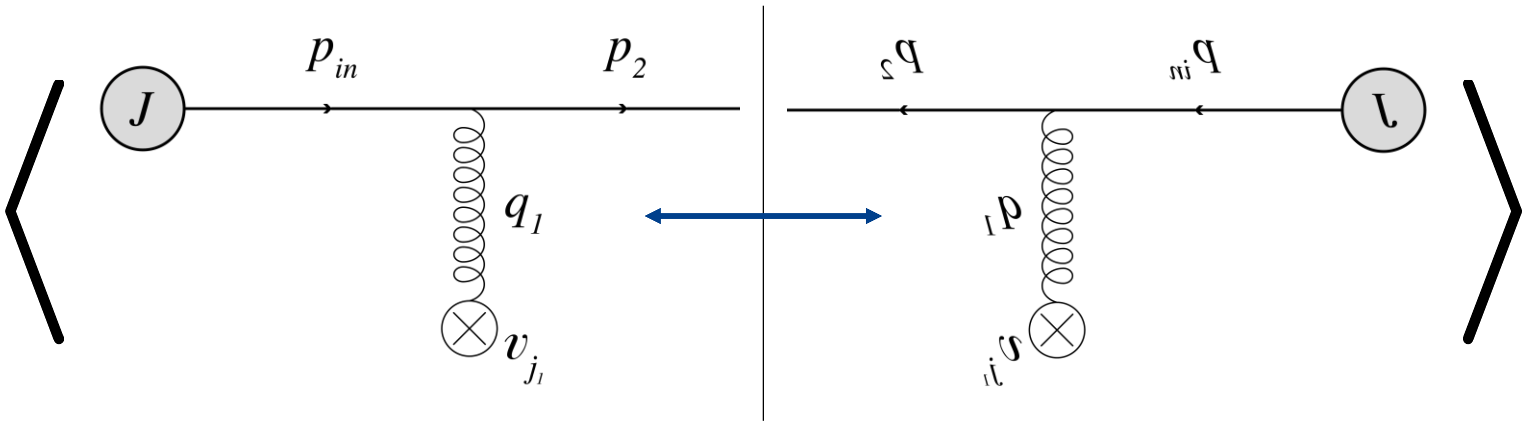
Medium averaging



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

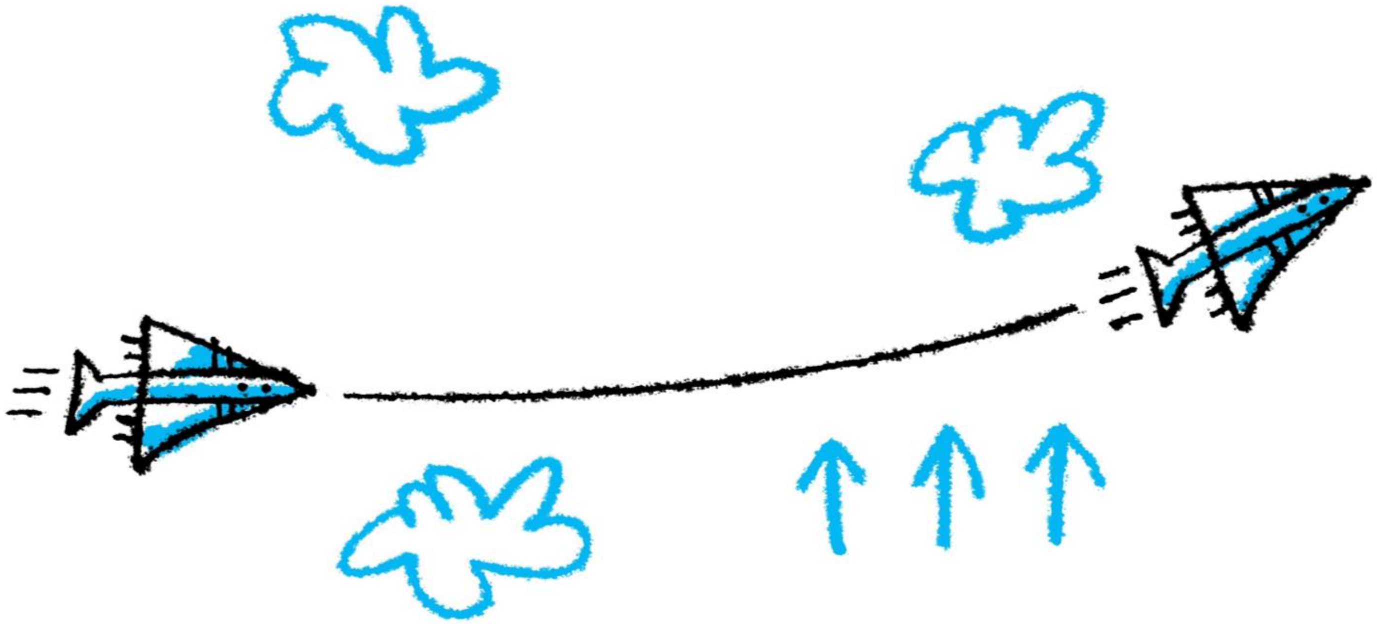
$$\rho \sim T^3$$

Medium averaging

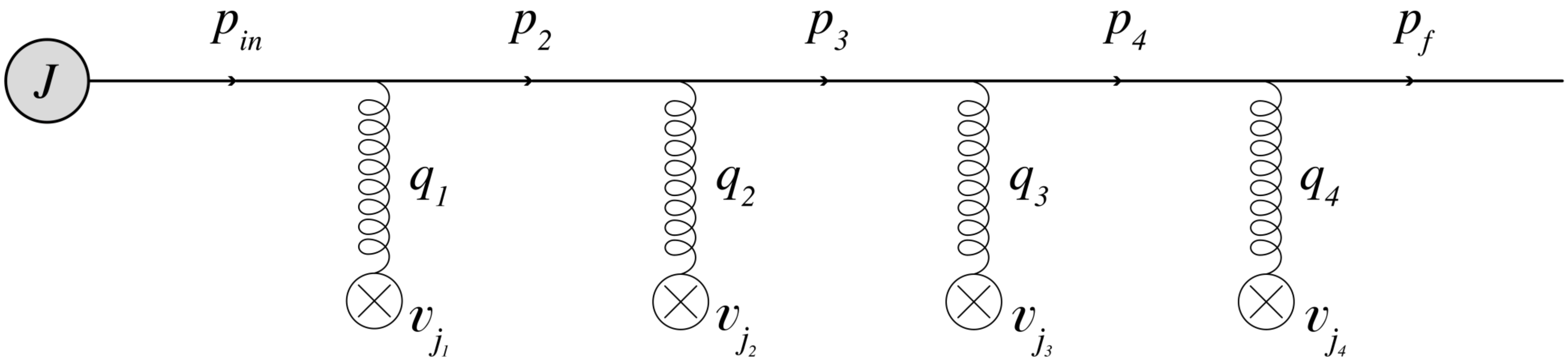


$$\int d^2\mathbf{x}_n\, e^{-i(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)\cdot\mathbf{x}_n} = (2\pi)^2\, \delta^{(2)}(\mathbf{q}_n \pm \overline{\mathbf{q}}_n)$$

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



Jet broadening



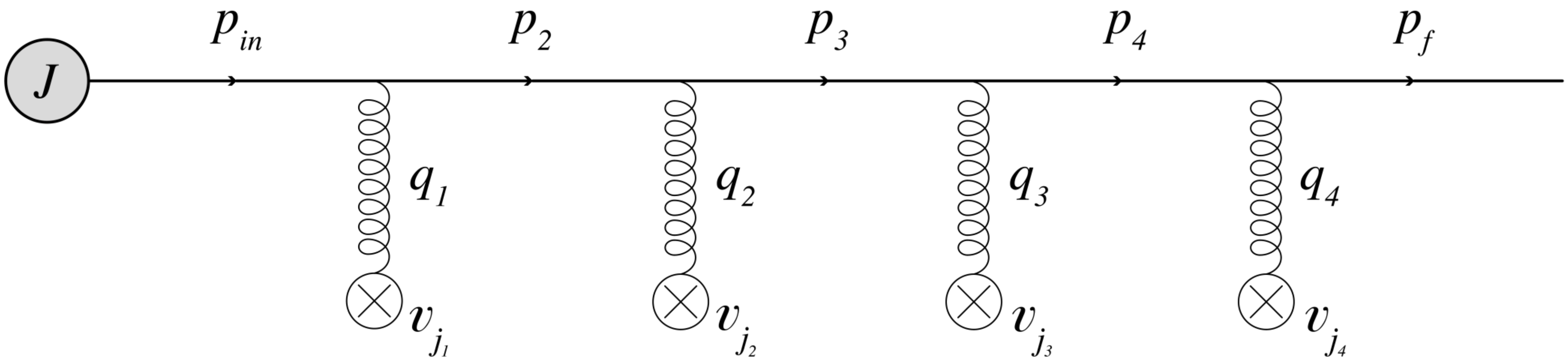
$E \to \infty$

$$\begin{tikzcd} & v(q) & \\ \mu \ll E \arrow[ur] & & \mu z \gg 1 \arrow[ul] \end{tikzcd}$$

$\longrightarrow$

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

Jet broadening



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

$$\mathbf{\Omega} = -\frac{\mathbf{p}-\mathbf{q}}{E} + \frac{\mathbf{q}}{E}\,\frac{(\mathbf{p}-\mathbf{q})^2-\mathbf{p}^2}{v(\mathbf{q}^2)}\,\frac{\partial v}{\partial \mathbf{q}^2}$$

Jet broadening

$$\frac{\partial}{\partial L}\mathcal{G}(\mathbf{p},L;\mathbf{p}_0,z_0) = i\left(\mathbf{u}\cdot\mathbf{p} - \frac{p_\perp^2}{2E}\right)\mathcal{G}(\mathbf{p},L;\mathbf{p}_0,z_0)$$
$$+\, i\int\frac{d^2\mathbf{q}}{(2\pi)^2}\;[1+\mathbf{u}\cdot\mathbf{\Omega}(\mathbf{p},\mathbf{q})]\;v(q_\perp^2)\,\hat{\rho}^a(\mathbf{q},L)\,t^a\,\mathcal{G}(\mathbf{p}-\mathbf{q},L;\mathbf{p}_0,z_0)\,,$$

not a convolution anymore

$$\mathcal{G}(\mathbf{p},L;\mathbf{p}_0,z_0) = \mathcal{G}^{(0)}(\mathbf{p},L;\mathbf{p}_0,z_0) + \mathcal{G}^{(1)}(\mathbf{p},L;\mathbf{p}_0,z_0) + \mathcal{O}\left(\frac{\perp^2}{E^2}\right)$$

still can be solved analytically

Broadening probability

$$\frac{1}{d_{proj}}\left\langle \mathrm{Tr}\left[\mathcal{G}^{\dagger}(\boldsymbol{p}_0', 0; \boldsymbol{p}_{,} L)\, \mathcal{G}(\boldsymbol{p}, L; \boldsymbol{p}_0, 0)\right]\right\rangle \equiv (2\pi)^2 \delta^{(2)}(\boldsymbol{p}_0 - \boldsymbol{p}_0')\, \mathcal{P}(\boldsymbol{p}, L; \boldsymbol{p}_0, 0)$$

$$\frac{\partial}{\partial L}\mathcal{P}(\boldsymbol{p}, L; \boldsymbol{p}_0, 0) = -\int \frac{d^2\boldsymbol{q}}{(2\pi)^2}\,\sigma(\boldsymbol{p}, \boldsymbol{q}; L)\,\mathcal{P}(\boldsymbol{p} - \boldsymbol{q}, L; \boldsymbol{p}_0, 0)$$

$$\mathcal{P}(\boldsymbol{p}, 0; \boldsymbol{p}_0, 0) = (2\pi)^2 \delta^{(2)}(\boldsymbol{p} - \boldsymbol{p}_0)$$

Jet broadening

$$E\,\frac{d\mathcal{N}}{d^2\boldsymbol{p}\,dE} = \int \frac{d^2\boldsymbol{p}_0}{(2\pi)^2}\,\mathcal{P}(\boldsymbol{p}, L; \boldsymbol{p}_0, 0)\left[1 - \boldsymbol{u}\cdot(\boldsymbol{p} - \boldsymbol{p}_0)\frac{\partial}{\partial E}\right] E\,\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{p}_0\,dE}$$

- The odd moments are proportional to the transverse flow velocity, the even moments are unmodified;

- The initial and final distributions are not factorized anymore in coordinate space (due to the energy derivative);

Jet broadening

uniform matter

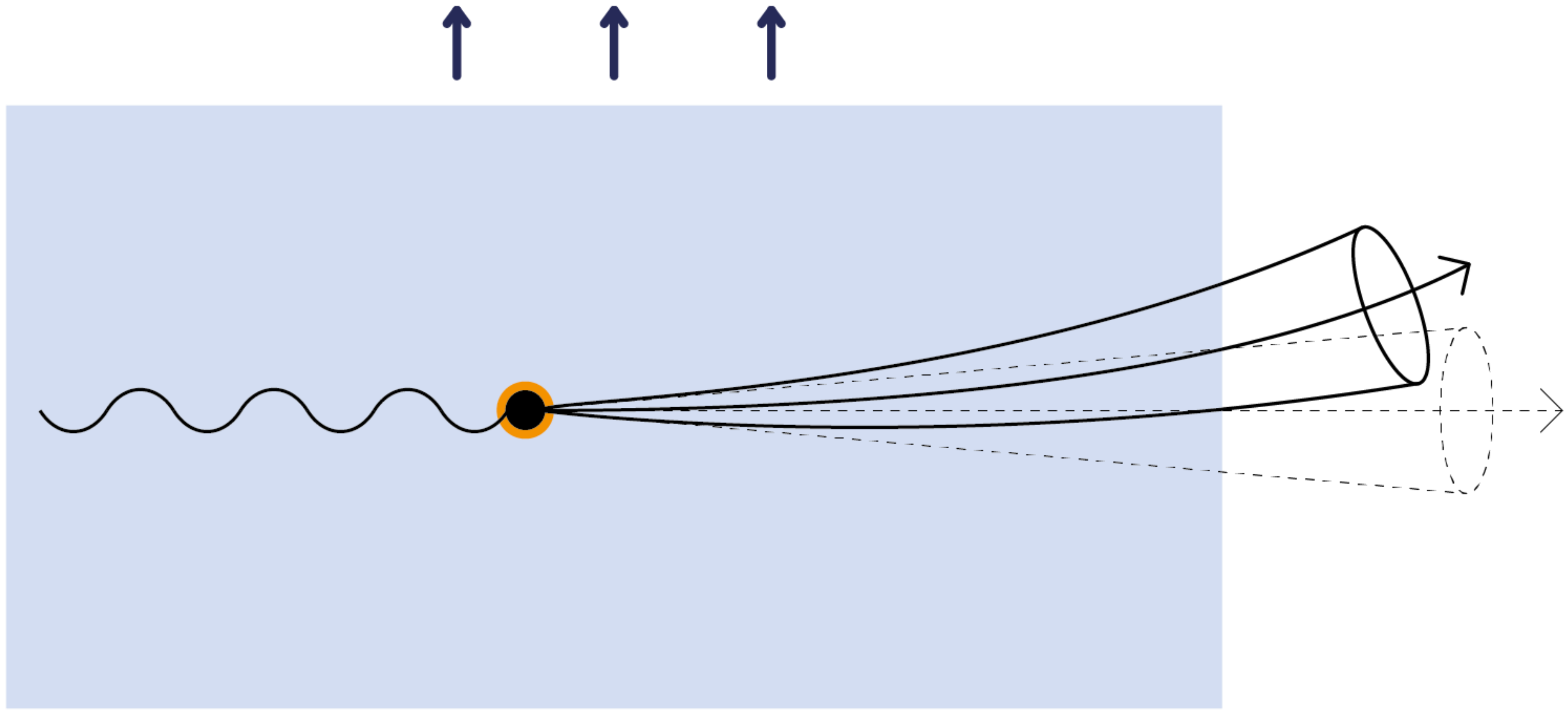
$$E\frac{d\mathcal{N}^{(0)}}{d^2\mathbf{p}_0 dE} = f(E)\delta^{(2)}(\mathbf{p}_0)$$

Eikonal approximation -- $E \to \infty$

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

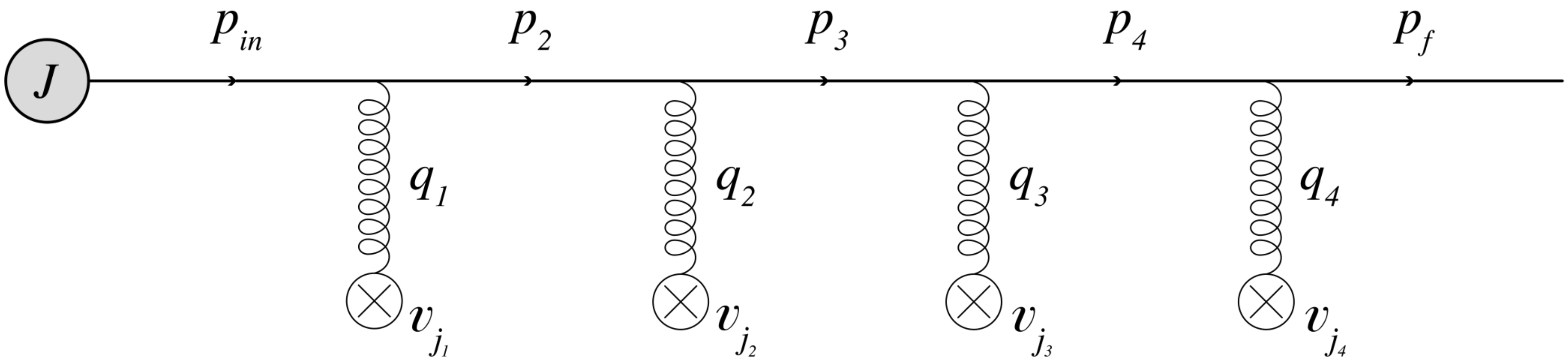
Opacity expansion -- $\chi \equiv \mathcal{C}\frac{g^4\rho}{4\pi\mu^2}L \ll 1$

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



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

The propagator



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

J. Barata, AS, C. Salgado, PRD, 2022

Jet broadening

$$\left\langle \mathcal{P}\exp\left(-i\int_0^L d\tau\, t^a_{\mathrm{proj}} v^a(\boldsymbol{r}(\tau),\tau)\right)\mathcal{P}\exp\left(i\int_0^L d\overline{\tau}\, t^b_{\mathrm{proj}} v^b(\overline{\boldsymbol{r}}(\overline{\tau}),\overline{\tau})\right)\right\rangle$$

$$= \exp\left\{-\int\limits_0^L d\tau\,\left[1+\frac{\boldsymbol{r}(\tau)+\overline{\boldsymbol{r}}(\tau)}{2}\cdot\hat{\boldsymbol{g}}\right]\mathcal{V}\left(\boldsymbol{r}(\tau)-\overline{\boldsymbol{r}}(\tau)\right)\right\}$$

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

$$\left\langle G(\boldsymbol{x}_L,L;\boldsymbol{x}_0,0)G^\dagger(\overline{\boldsymbol{x}}_L,L;\overline{\boldsymbol{x}}_0,0)\right\rangle$$

$$=\int^{\boldsymbol{u}_L}\mathcal{D}\boldsymbol{u}\int^{\boldsymbol{w}_L}\mathcal{D}\boldsymbol{w}\,\exp\left\{\int_0^L d\tau\,\left[iE\,\dot{\boldsymbol{u}}\cdot\dot{\boldsymbol{w}}-(1+\boldsymbol{w}\cdot\hat{\boldsymbol{g}})\,\mathcal{V}\left(\boldsymbol{u}(\tau)\right)\right]\right\}$$

Jet broadening

inhomogeneous matter

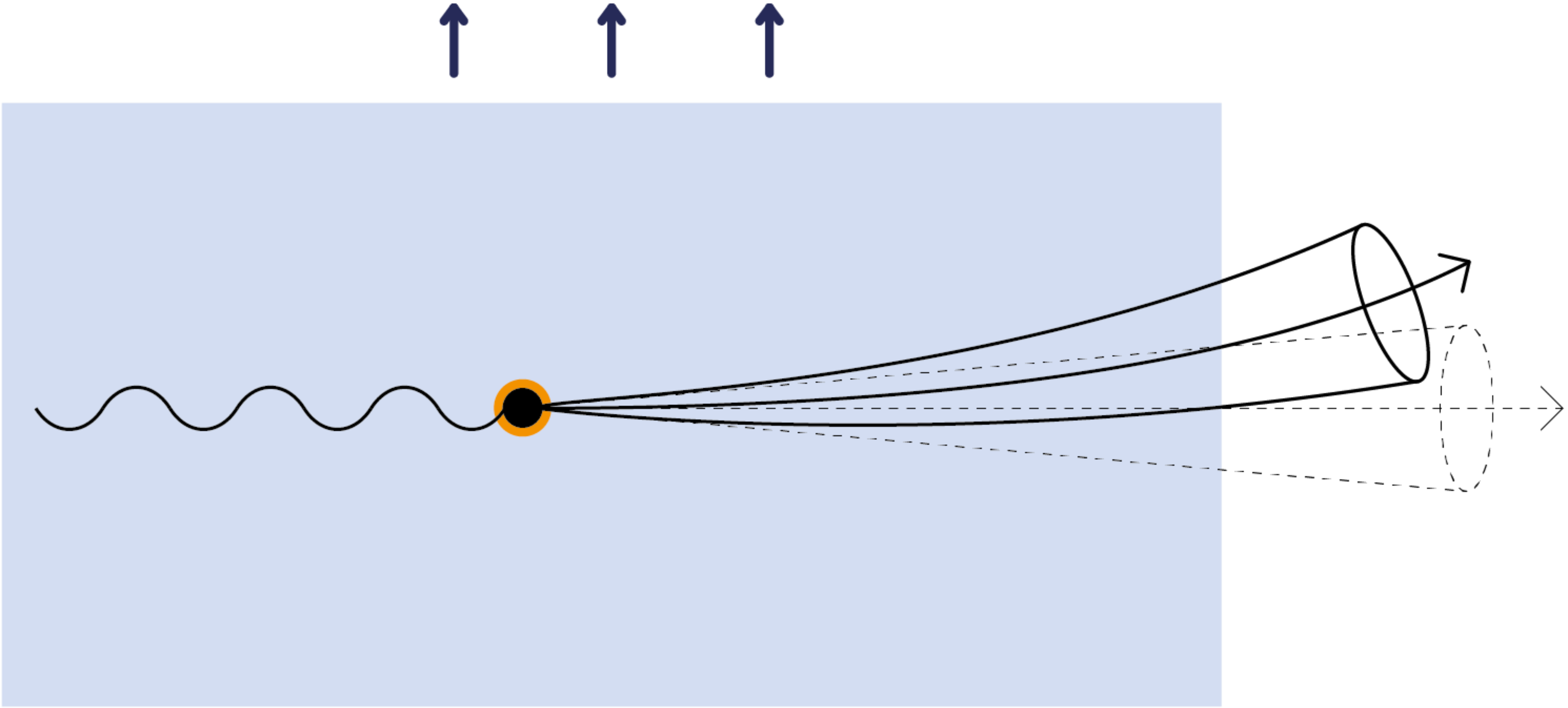
$$E\frac{d\mathcal{N}^{(0)}}{d^2\mathbf{p}_0 dE} = \frac{1}{2(2\pi)^3}|J(p_0)|^2 = f(E)\delta^{(2)}(\mathbf{p}_0)$$

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

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

$$\Big\downarrow \quad \rho \sim T^3$$

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



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

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 $\langle\theta\rangle \approx 1^o$?

↓

Jet energies: $E < 50\ \mathrm{GeV}$

Jet broadening

inhomogeneous matter

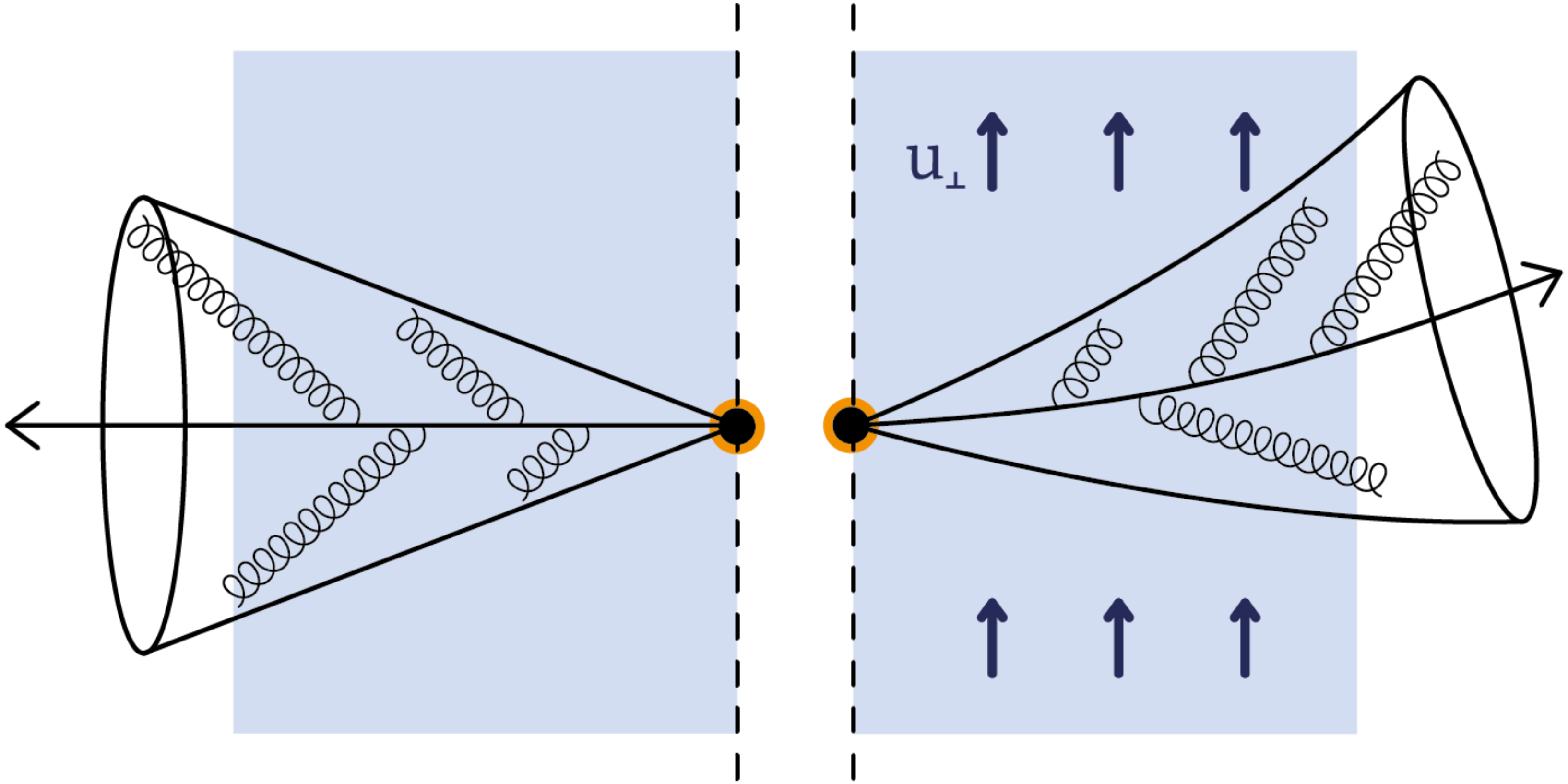
- Opacity $\chi \approx 4$
- $\mu = gT$ with $g \approx 2$ and $T \approx 500\ MeV$
- $L\nabla T > T$

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

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

↓

Jet energies: $E < 100\ \mathrm{GeV}$



$$\left\langle \frac{\mathbf{k}}{k_\perp^2} \right\rangle \simeq \frac{N_c \chi}{C_F\, xE}\mathbf{u}$$

Summary

- Jets do feel the transverse flow and anisotropy, and get bended;
- The transverse flow and anisotropy are expected to 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;
- The initial and final state effects are not factorized anymore;
- One may also expect similar evolution-induced effects for other probes of nuclear matter, e.g. quarkonium;