Jet tomography from large to small systems

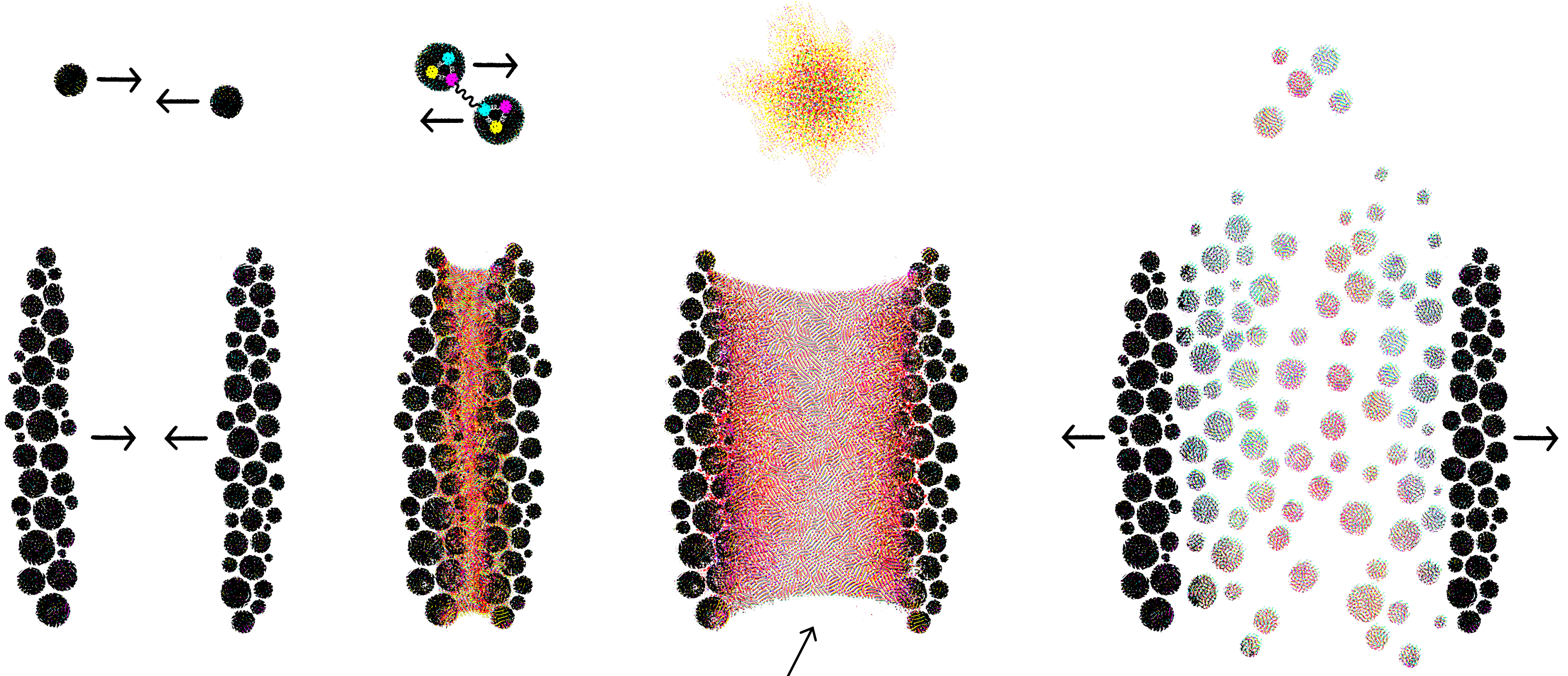
Andrey Sadofyev
University of Santiago de Compostela

jets as a tool to probe formation of QCD matter

The origin of complex matter

elementary
constituents

complex
nuclear matter



small
system

large
system

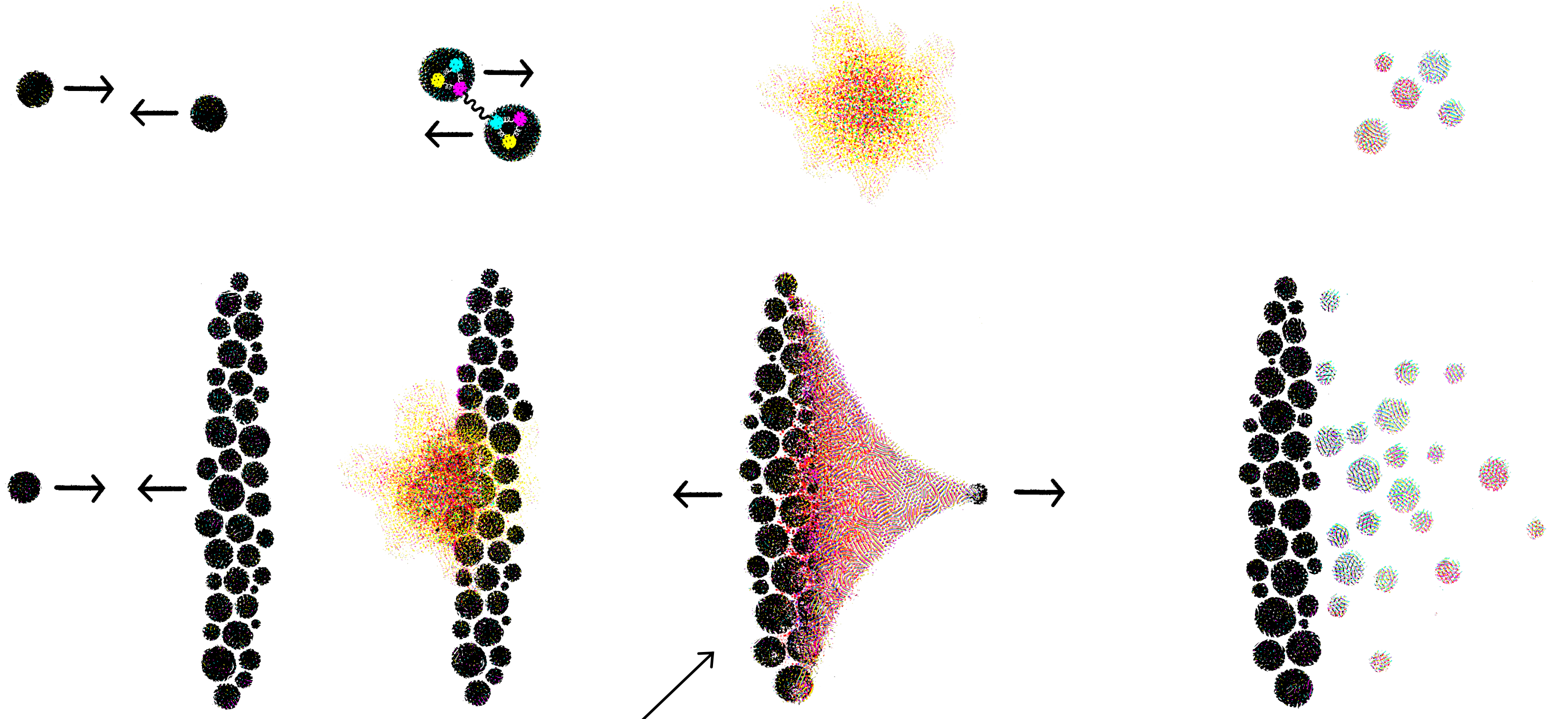
simplest
complex matter

experimental access e.g.
- Large Hadron Collider (LHC)
- Relativistic Heavy Ion Collider (RHIC)

The origin of complex matter

elementary
constituents

complex
nuclear matter



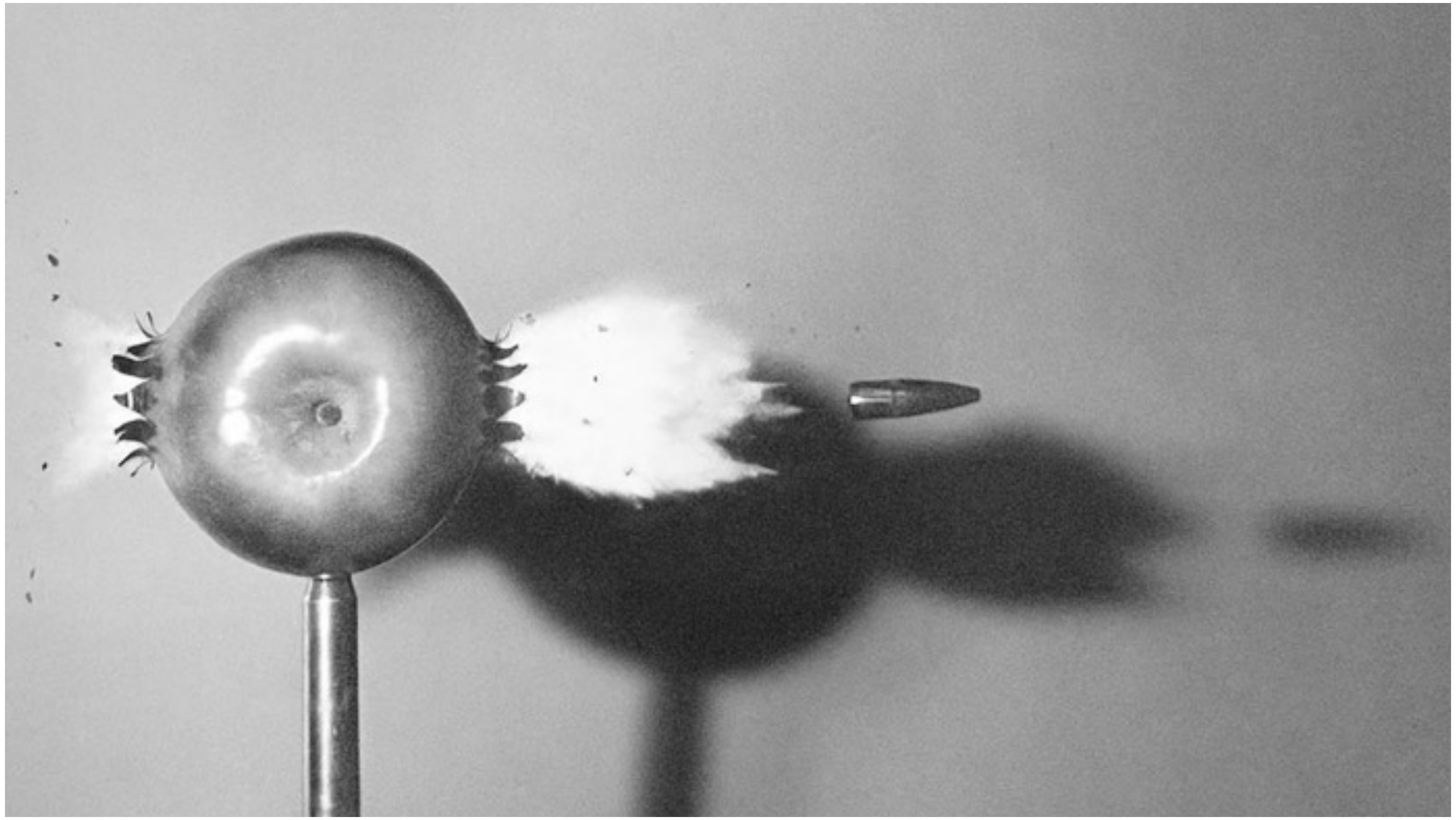
small
system

large
system

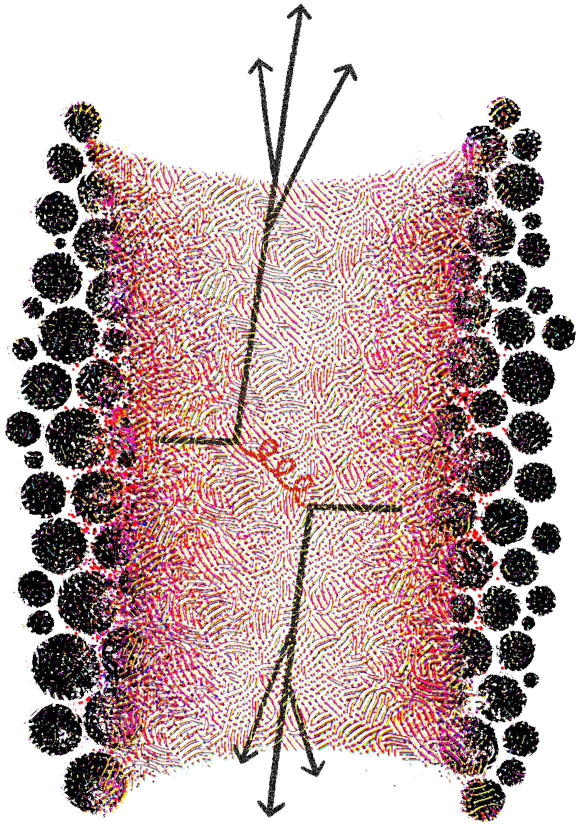
small system:
non-equilibrium matter
from elementary to complex

experimental access e.g.
- Large Hadron Collider (LHC)
- Relativistic Heavy Ion Collider (RHIC)

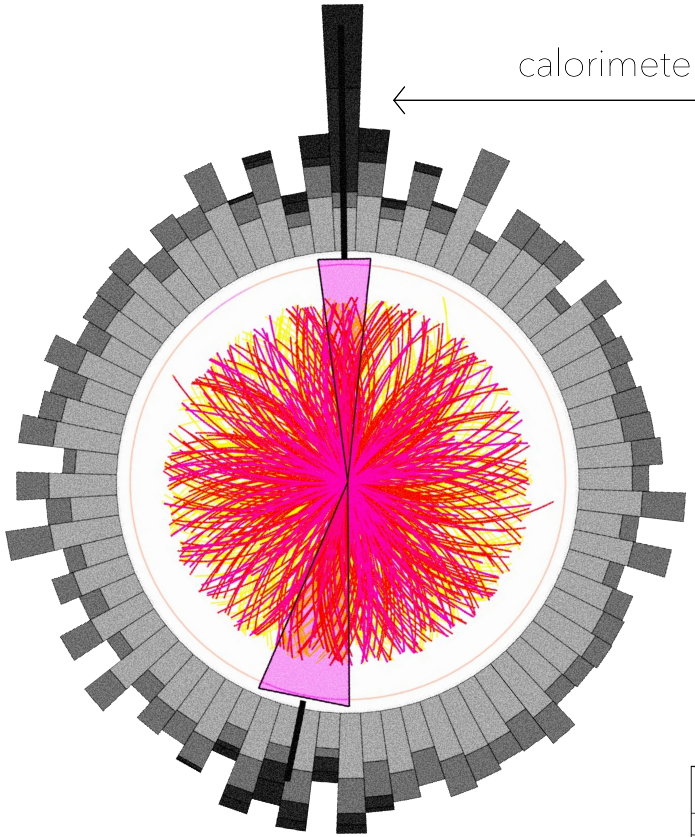
How to probe matter?



A tool to probe the QGP formation



jet quenching



jets lose energy propagating through nuclear matter

The State of the Art

Matter branch:

- the latter stages (th+ex)
- the early stages (some th)

main tool: hydrodynamics

⟵ **the gap** ⟶

compromises the success of the ongoing and future experimental programs

Jet branch:

- jets at latter stages (th+ex)
- some jet tomography

main tool: perturbative QCD

The State of the Art

Matter branch:

- the latter stages (th+ex)
- the early stages (some th)

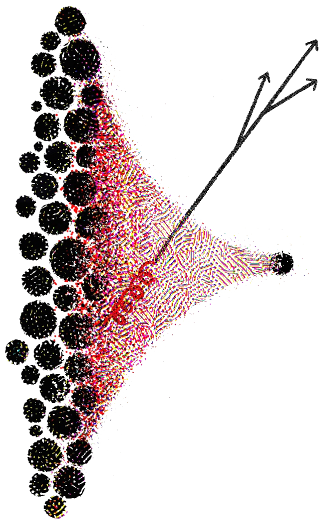
main tool: hydrodynamics

close the gap

Jet branch:

- jets at latter stages (th+ex)
- some jet tomography

main tool: perturbative QCD



- jets in non-equilibrium/evolving QCD matter (**fluctuating evolving** matter)
- formation of QCD matter in smaller systems?

formation of complex QCD matter

Why now?

Developments: jets in hydrodynamic matter
(e.g. our works during the last year)

Needs: evolving QCD matter at the LHC, RHIC, and EIC

Puzzles: collectivity in small systems vs. no jet quenching ← a clear big problem in the field to be solved

Opportunities: the upcoming large and small system experiments
(e.g. sPHENIX and O+O at the LHC)

Timing: the LHC Run 3 (2022 - 2025)
the sPHENIX program at RHIC (2023 - 2025)
the LHC Run 4 (2027+)
the EIC experiment (2030+)

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

Jets in evolving matter

What do we have?

- Jets see the matter in HIC (and DIS) at multiple scales, and essentially X-ray it;
- Current theory is based on multiple simplifying assumptions: static matter, no fluctuations, etc;

What is missing?

- The coupling of jets to the flow, to the structure (matter anisotropy), to the transverse fields during initial stages, to the fluctuations, etc.
- An updated parton evolution equation needed for most modern simulations of jets in QCD matter;
- New jet observables sensitive to the medium evolution;
- Coupled simulations of matter and jets for quantitative phenomenology;

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

Jets in evolving matter

What do we have?

- Jets see the matter in HIC (and DIS) at multiple scales, and essentially X-ray it;
- Current theory is based on multiple simplifying assumptions: static matter, no fluctuations, etc;

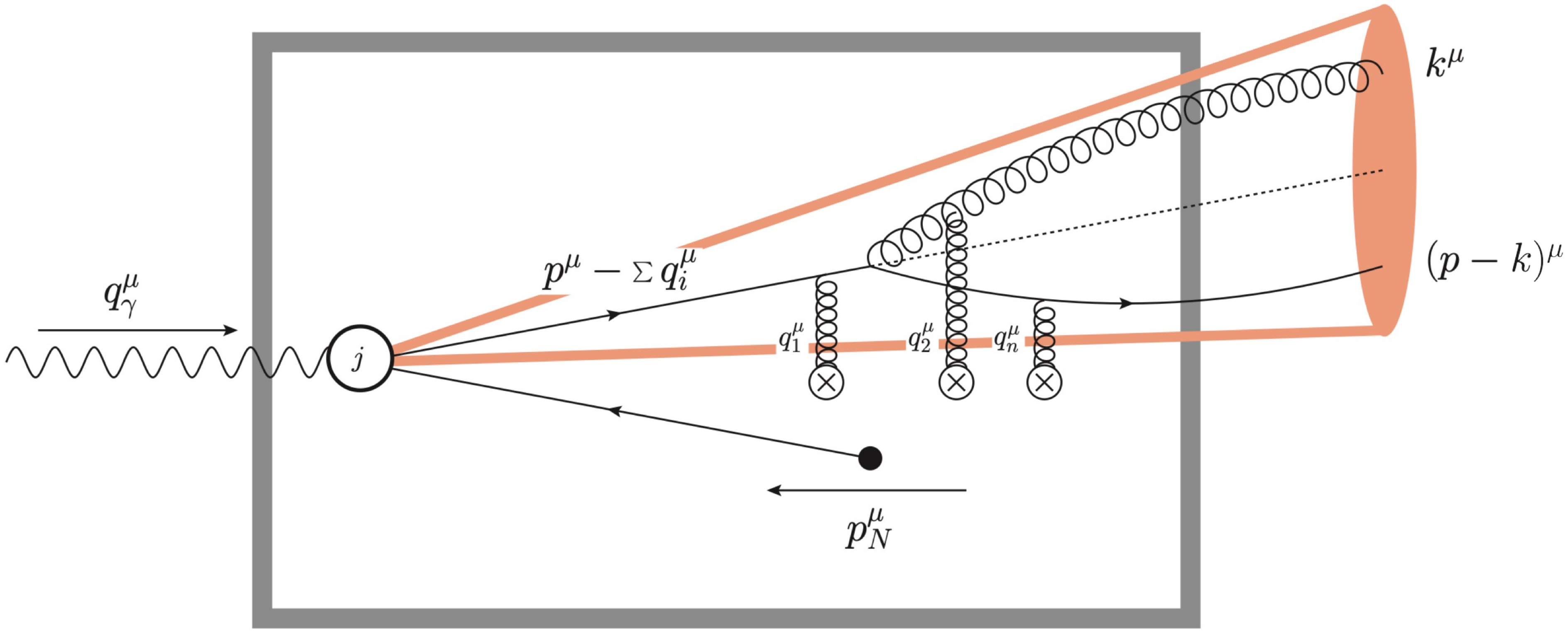
What is missing?

- The coupling of jets to the flow, to the structure (matter anisotropy), to the transverse fields during initial stages, to the fluctuations, etc.
- An updated parton evolution equation needed for most modern simulations of jets in QCD matter; ← expertise at LIP
- New jet observables sensitive to the medium evolution; ← expertise at LIP
- Coupled simulations of matter and jets for quantitative phenomenology;

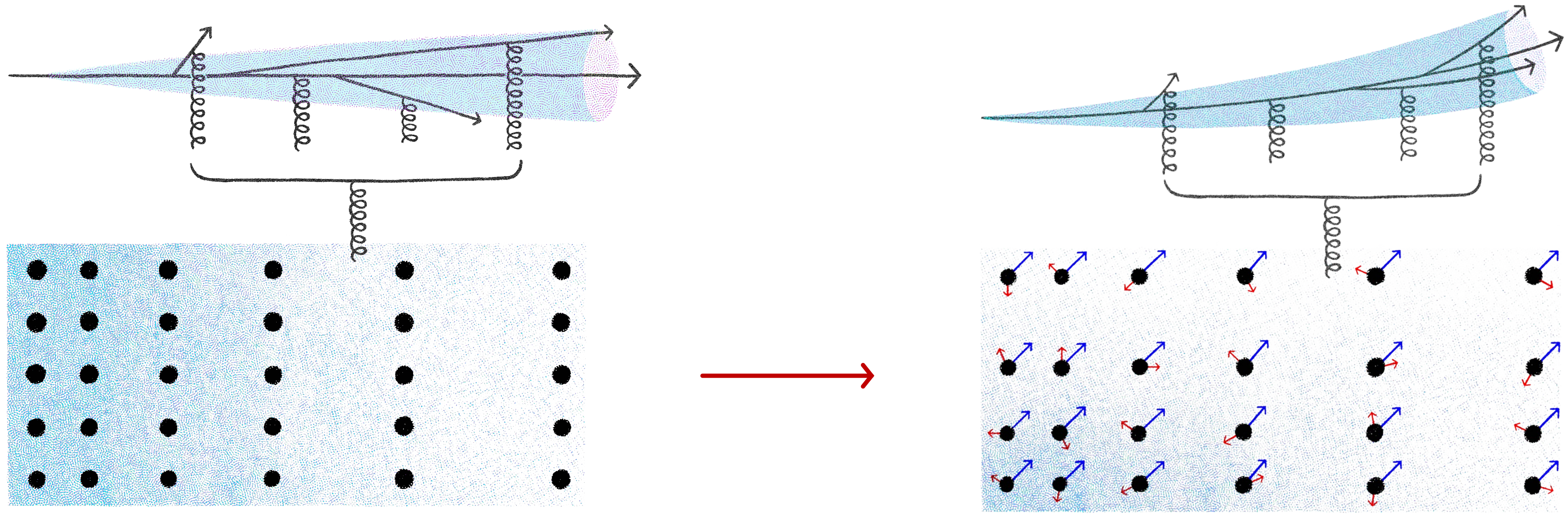
R. Baier et al, NPB, 1997
B. G. Zakharov, JETP, 1997
R. Baier et al, NPB, 1998
M. Gyulassy et al, NPB, 2000
M. Gyulassy et al, NPB, 2001

Jet quenching formalisms

QCD broadening and gluon emission (GLV/BDMPS-Z) with flow

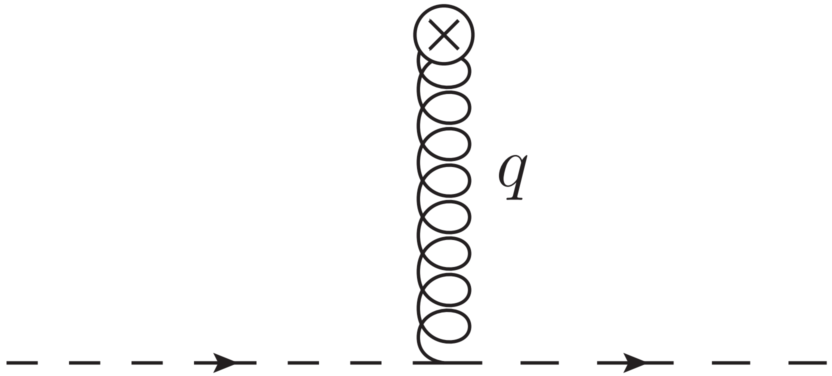


Jets in evolving matter



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

Color potential

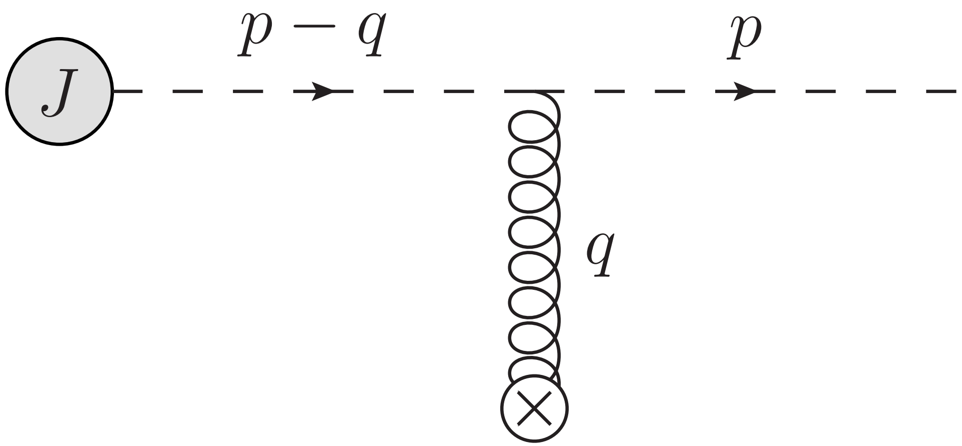


large

$$A^{\mu a}(q) = \sum_i (ig\, t_i^a)\, e^{iq\cdot x_i}\, (2p_{s\,i} - q)_\nu \frac{-ig^{\mu\nu}}{q^2 - \mu_i^2 + i\epsilon}\, (2\pi)\, \delta\Big((p_{s\,i} - q)^2 - M^2\Big)\,.$$

$v(q^2)$ -- the Gyulassy-Wang potential

Jet broadening



the initial distribution

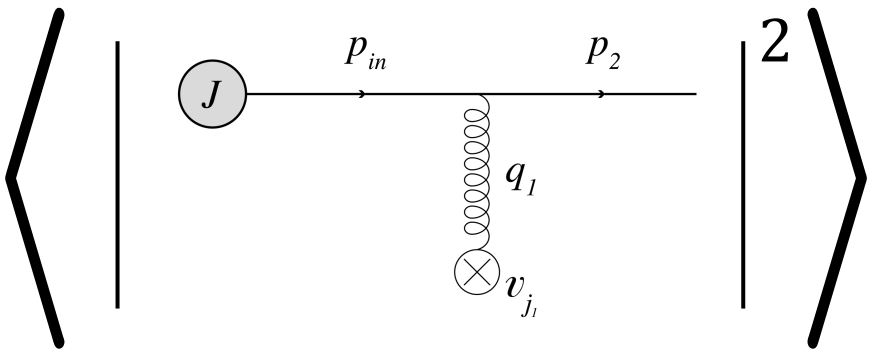
$$iM_1(p) = \int \frac{d^4q}{(2\pi)^4} \left[ig\, t^a_{\text{proj}} A^{\mu a}_{\text{ext}}(q)\, (2p-q)_\mu\right] \left[\frac{i}{(p-q)^2 + i\epsilon}\right] J(p-q)$$

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

inhomogeneity

the fluid velocity

Medium averaging



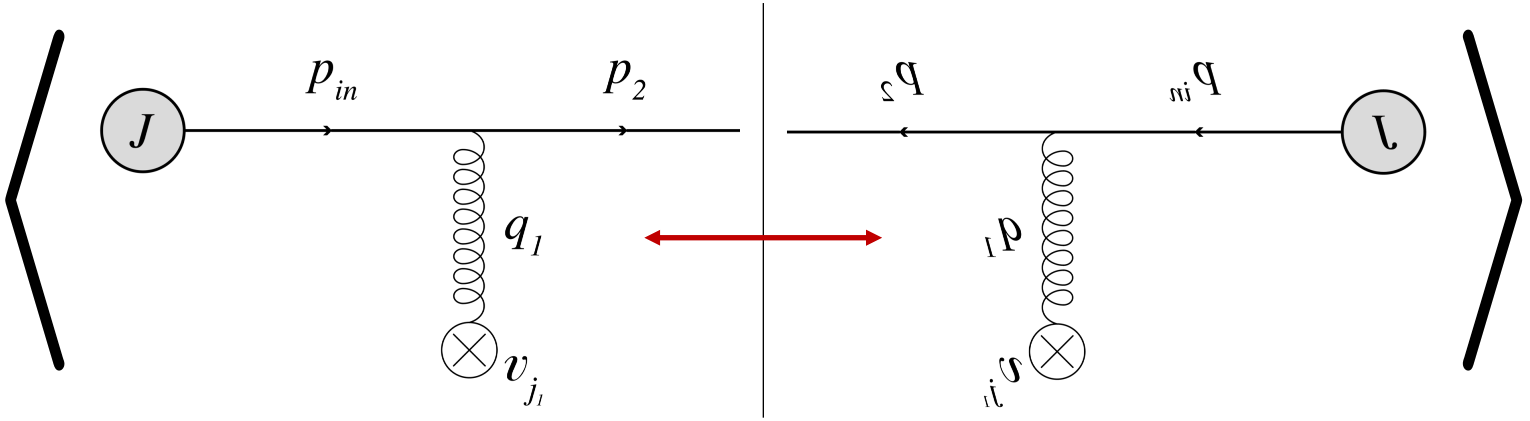
$$\langle t_i^a t_j^b \rangle = \mathcal{C} \delta_{ij} \delta^{ab}$$

color neutrality

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

source averaging

Gradient expansion



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

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

Jet broadening

uniform matter

$$\mathcal{P}^{(0)}(\boldsymbol{r}, L; \boldsymbol{r}_0, 0) = e^{-\mathcal{V}(\boldsymbol{r})L}\delta^{(2)}(\boldsymbol{r} - \boldsymbol{r}_0)$$

$$\mathcal{V}(\boldsymbol{q}, z) \equiv -\mathcal{C}\,\rho(z)\left(\left|v(q_\perp^2)\right|^2 - \delta^{(2)}(\boldsymbol{q})\int d^2\boldsymbol{l}\,\left|v(l_\perp^2)\right|^2\right)$$

Jet broadening

uniform matter

$$\mathcal{P}^{(1)}(\boldsymbol{p}, L; \boldsymbol{p}_0, 0) = \int d^2\boldsymbol{r}\, e^{-i(\boldsymbol{p}-\boldsymbol{p}_0)\cdot\boldsymbol{r}} e^{-\mathcal{V}(\boldsymbol{r})L}\, \frac{u_\alpha}{E} \Big[2L\,\boldsymbol{p}_{0\beta}\Big(\mathcal{V}(\boldsymbol{r})\delta_{\alpha\beta} + \mathcal{V}_{\alpha\beta}(\boldsymbol{r})\Big) - iL\,\nabla_\beta \mathcal{V}_{\alpha\beta}(\boldsymbol{r}) + iL^2\Big(\mathcal{V}(\boldsymbol{r})\delta_{\alpha\beta} + \mathcal{V}_{\alpha\beta}(\boldsymbol{r})\Big)\nabla_\beta\mathcal{V}(\boldsymbol{r})\Big]$$

$$\mathcal{V}_{\alpha\beta} = \mathcal{C}\,\rho\,\left[-\boldsymbol{q}_\alpha\boldsymbol{q}_\beta\,\frac{\partial v^2}{\partial q_\perp^2} - (2\pi)^2\delta^{(2)}(\boldsymbol{q})\,\frac{\delta_{\alpha\beta}}{2}\int\frac{d^2\boldsymbol{l}}{(2\pi)^2}\,v(l_\perp^2)^2\right]$$

Jet broadening

uniform matter

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

- The odd moments of this re-summed final distribution are proportional to the transverse flow velocity, while 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 -- $E \to \infty$

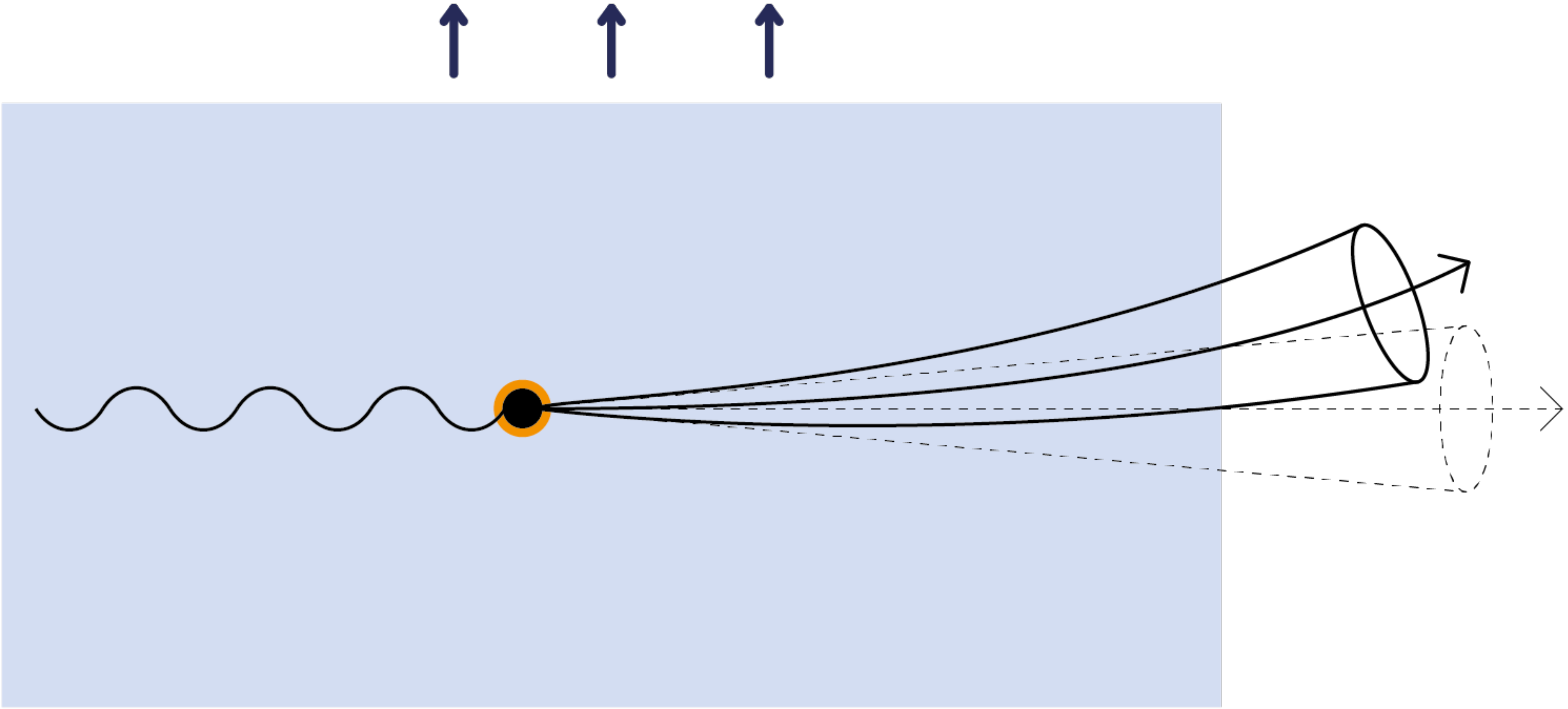
$$\langle p_\perp^{2k}\boldsymbol{p}\rangle = \int \frac{d^2\boldsymbol{p}\, d^2\boldsymbol{r}}{(2\pi)^2}\, p_\perp^{2k}\boldsymbol{p}\, e^{-i\boldsymbol{p}\cdot\boldsymbol{r}} e^{-\mathcal{V}(\boldsymbol{r})L} = 0 + \mathcal{O}\left(\frac{\perp}{E}\right)$$

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

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

Jet broadening

uniform matter



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

Jet broadening

inhomogeneous matter

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

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

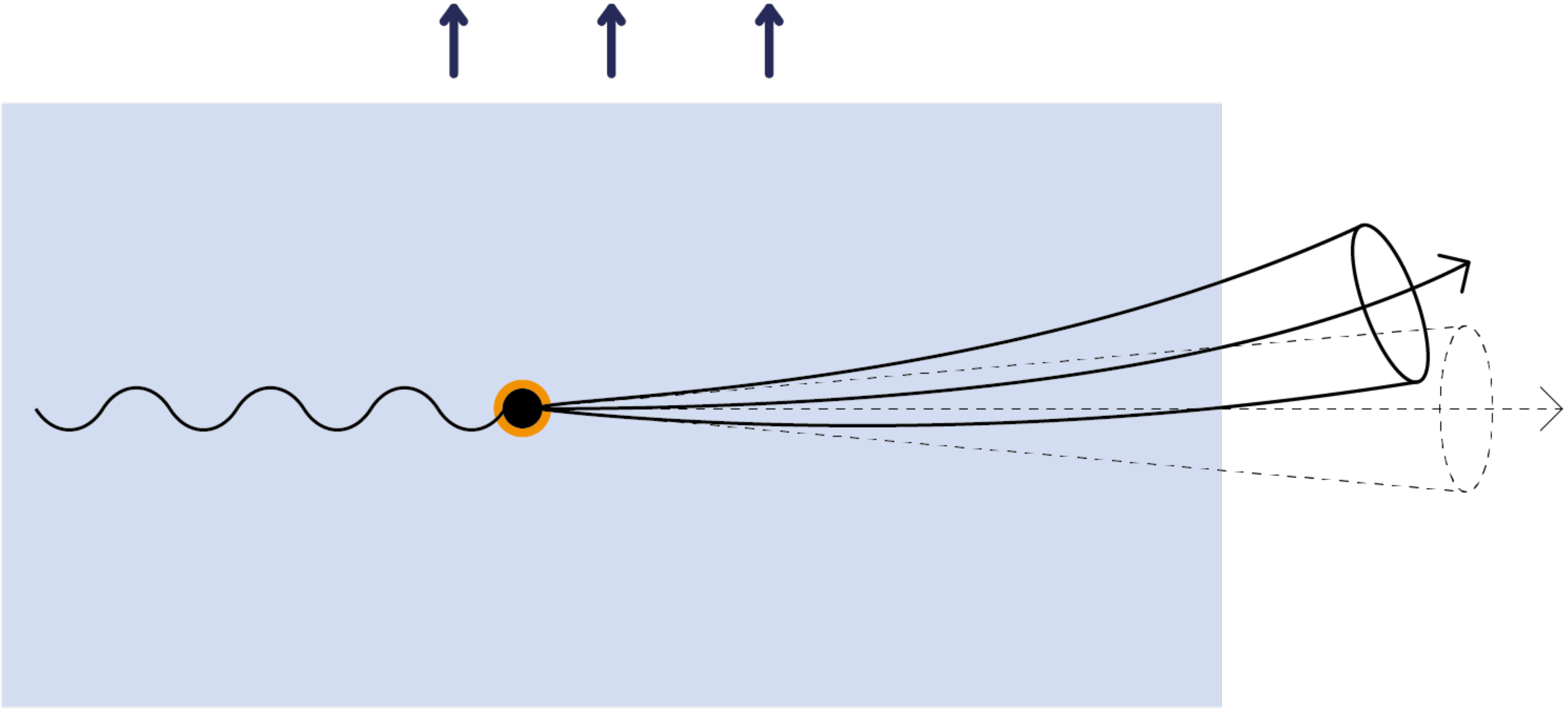
$$\hat{\boldsymbol{g}} \equiv \left(\boldsymbol{\nabla}\rho\frac{\delta}{\delta\rho}+\boldsymbol{\nabla}\mu^2\frac{\delta}{\delta\mu^2}\right)$$

$\rho \sim T^3$

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

Jet broadening

inhomogeneous matter



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

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

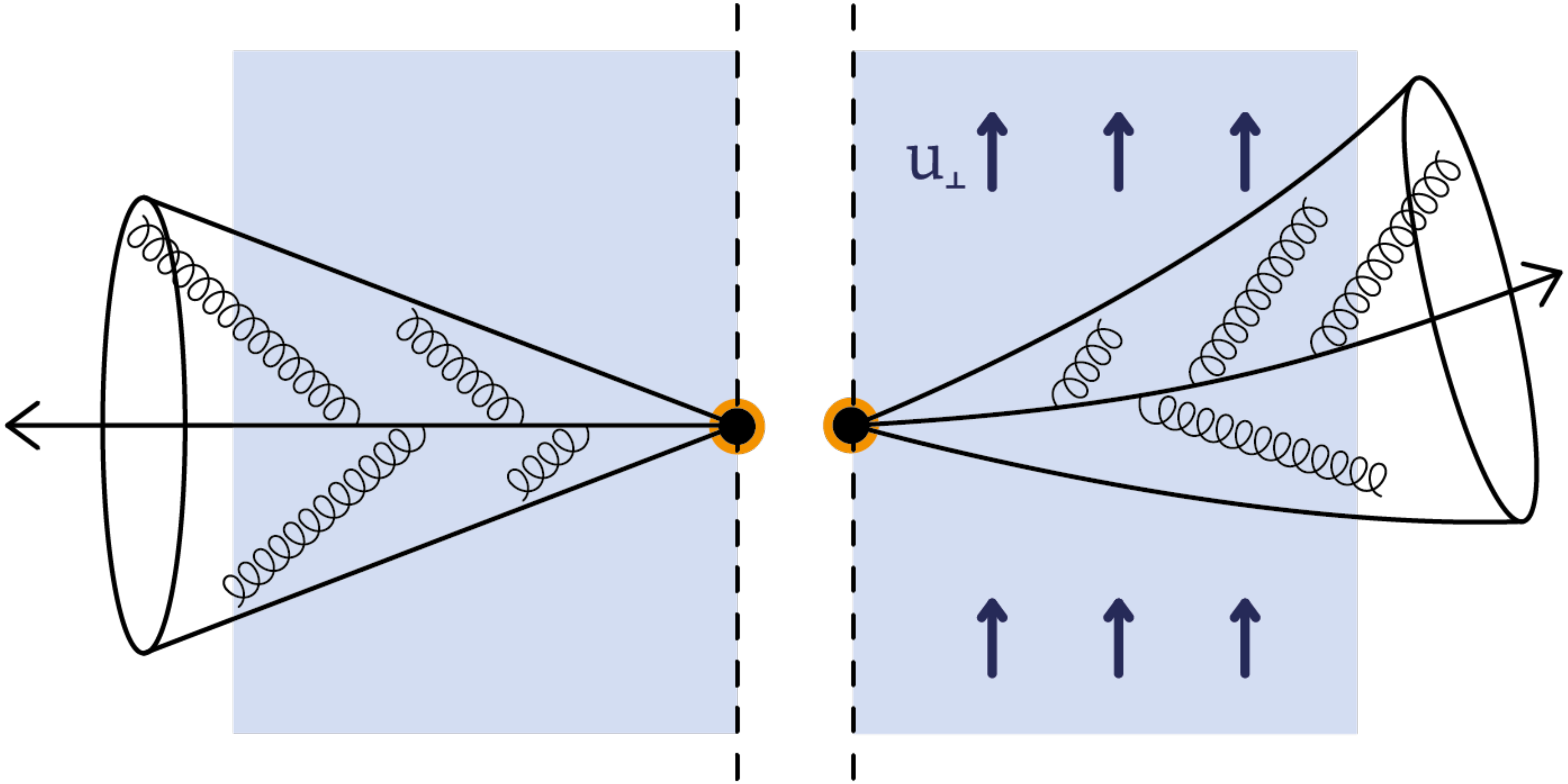
$$\left\langle \frac{\mathbf{p}}{E} \frac{p_\perp^2}{\mu^2} \right\rangle \simeq \chi^2 \frac{L\nabla T}{2T} \frac{\mu^2}{E^2} \left(\log \frac{E}{\mu} \right)^2$$

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

↓

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

Gluon emission



Summary

- We have already constructed a generalization of the jet quenching theory which includes the effects of the medium evolution and structure;
- It still should be further improved to take into account the non-equilibrium dynamics and the medium response (and more differential properties: heavy flavor, spin effects, etc.)
- Now we can make the next step turning to the actual phenomenology, and seek for the relevant observables, sensitive to the medium evolution;
- Having all these elements will allow us to turn to coupled simulations of the matter and jet observables, which are needed for quantitative predictions/analysis;