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Parton energy loss in inhomogeneous matter

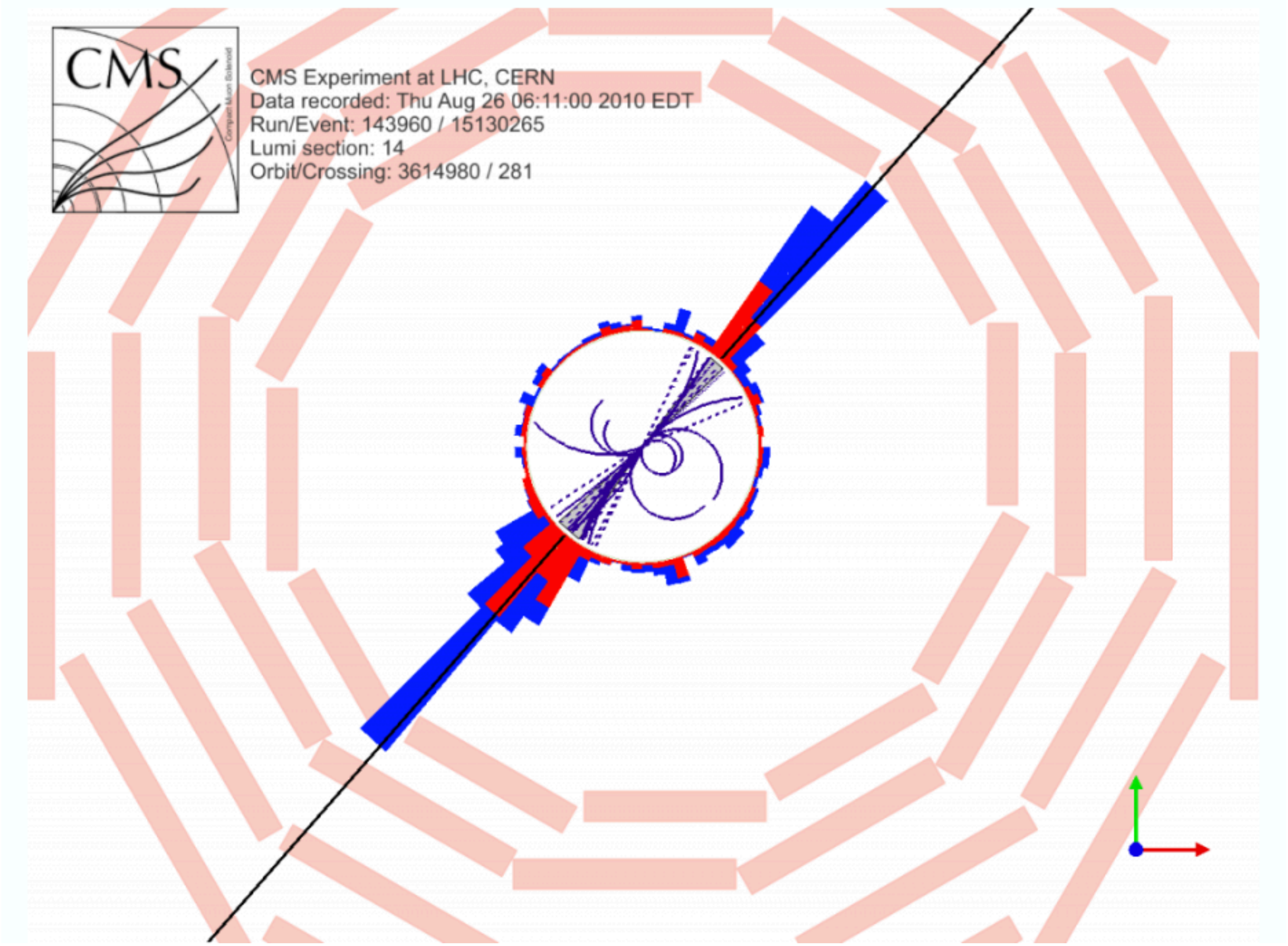
28th July 2023, JETSCAPE Summer School

João Barata, BNL

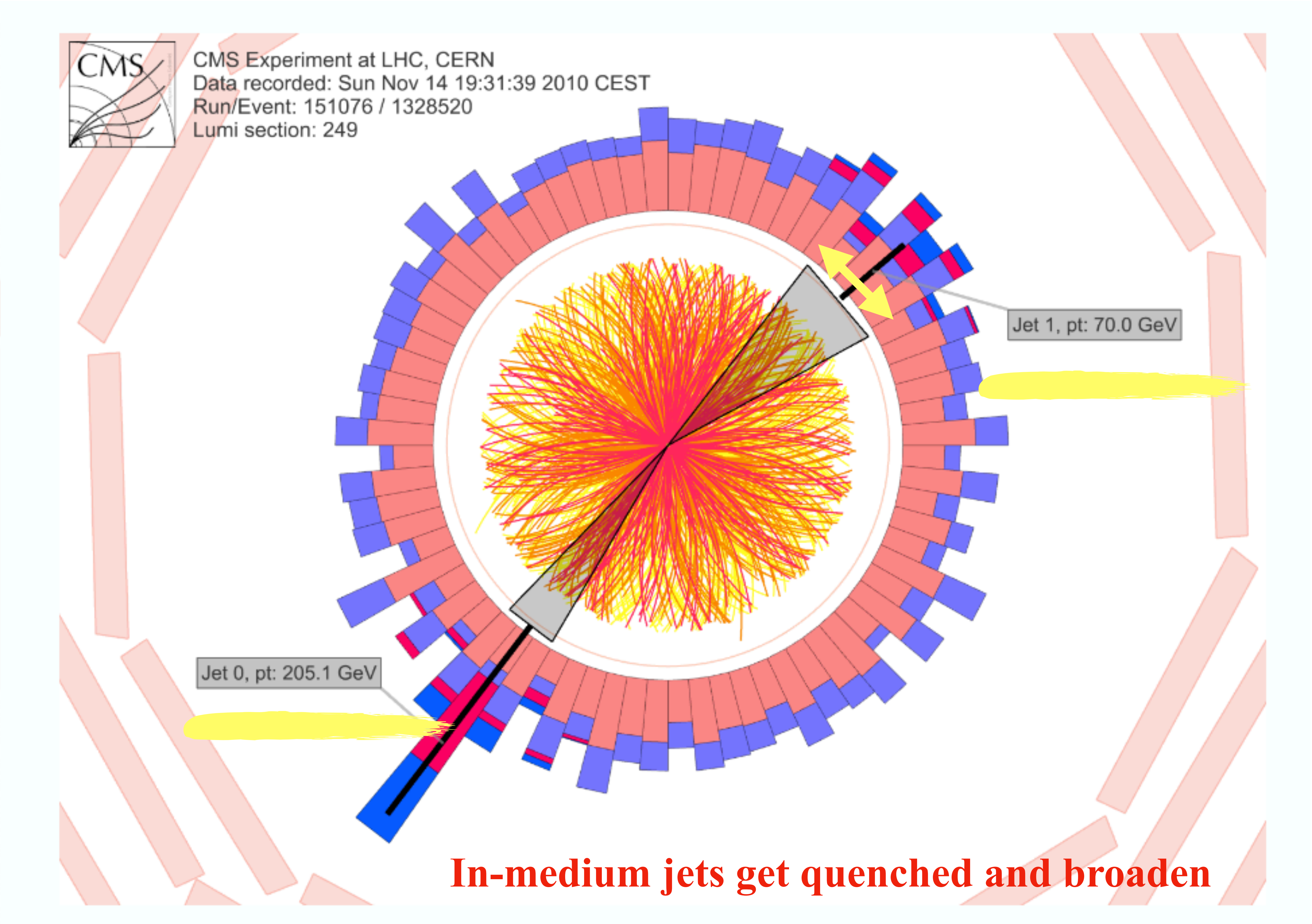
Based on work done with T. Luo, X. Mayo, G. Milhano , A. Sadofyev, C. Salgado, X.-N. Wang

2202.08847 2210.06519 2304.03712 2307(8).xxxx ongoing

Jets in hot plasmas

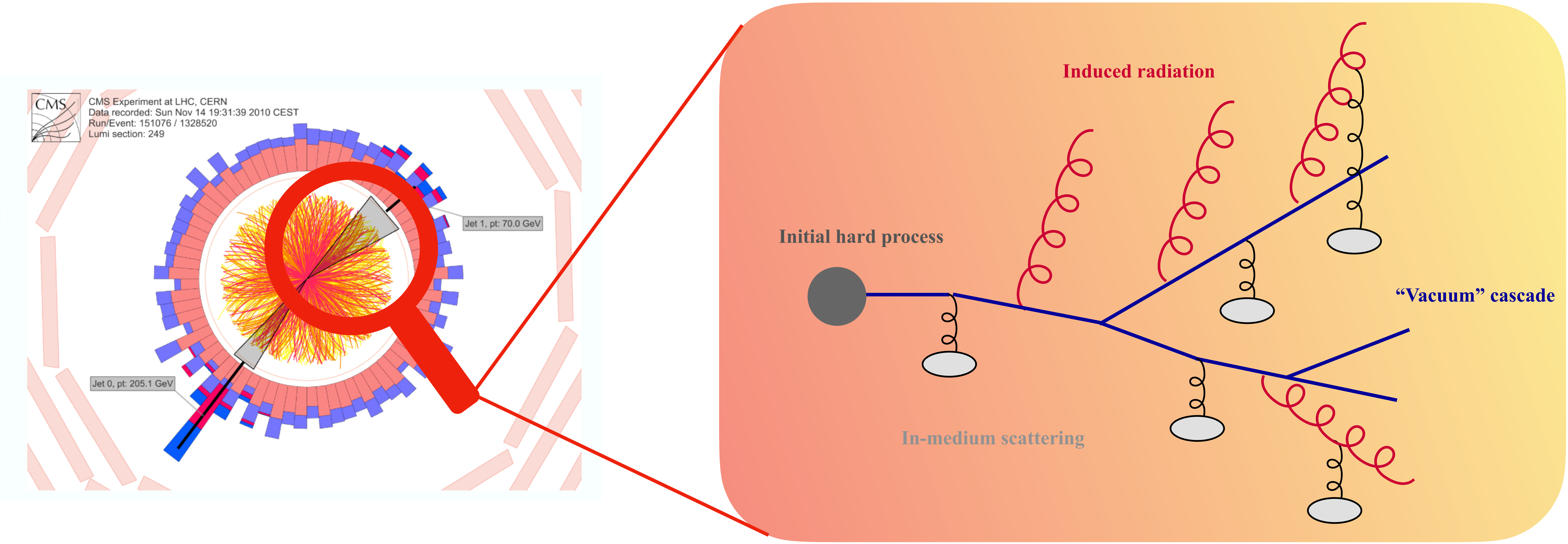


pp dijet event in CMS



PbPb dijet event in CMS

Jets in hot plasmas



Theoretical task: 1) describe medium induced modifications to jet structure

2) extract information about the medium from jet observables

Jets in hot plasmas

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How do we treat jet evolution in theory?

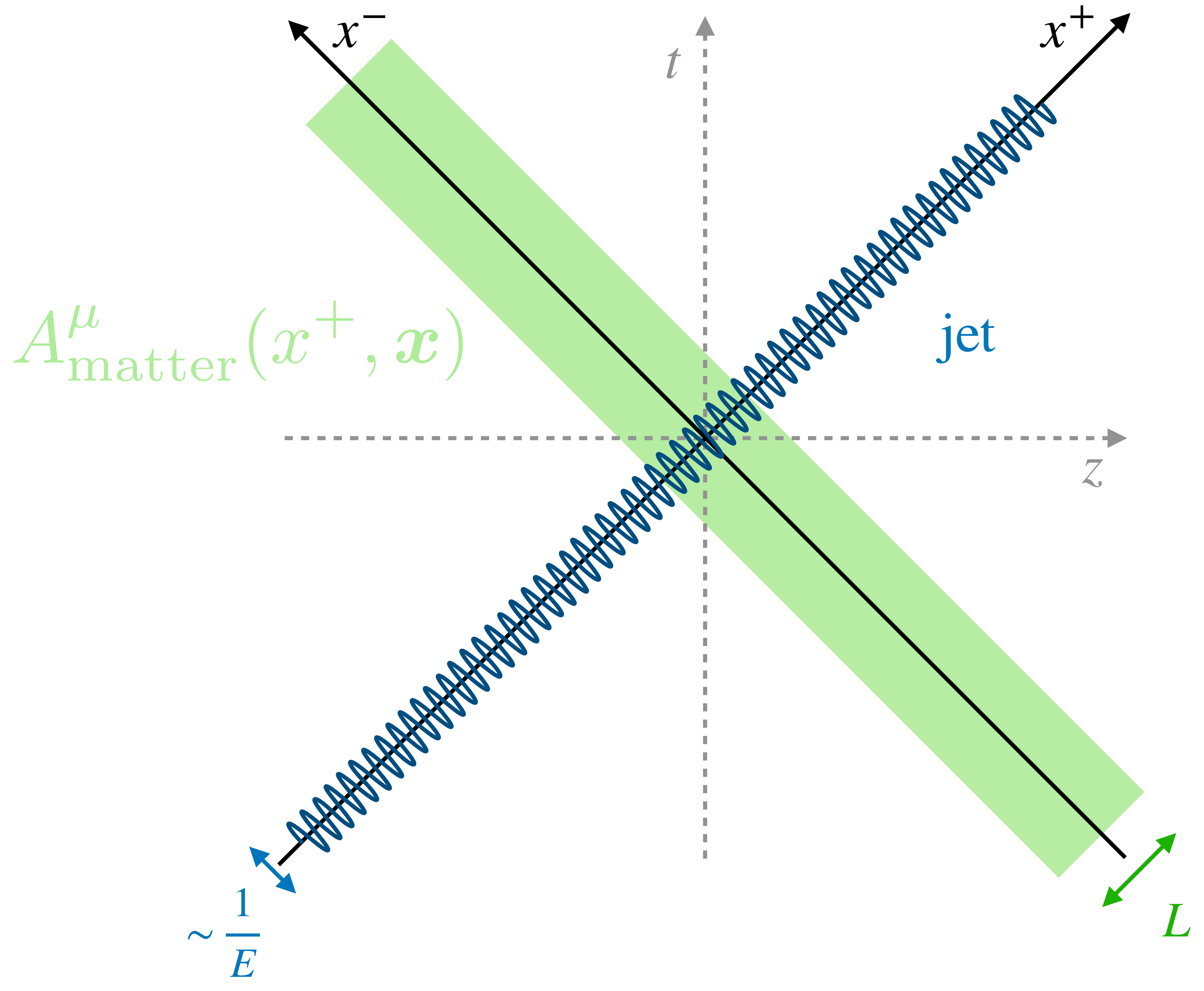
1) Use eikonal expansion, i.e. expansion in inverse powers of jet energy; keep kinetic phases

$$k^- L \sim \frac{\boldsymbol{k}^2}{2E_{\rm jet}} L$$

2) Matter enters through classical background field; usually assumed: homogeneous, infinitely long, static, …

$$A^\mu(x^+, x^-, \boldsymbol{x}) \approx A^\mu_{\rm matter}(x^+, \boldsymbol{x}) + \delta A^\mu(x^+, x^-, \boldsymbol{x})$$

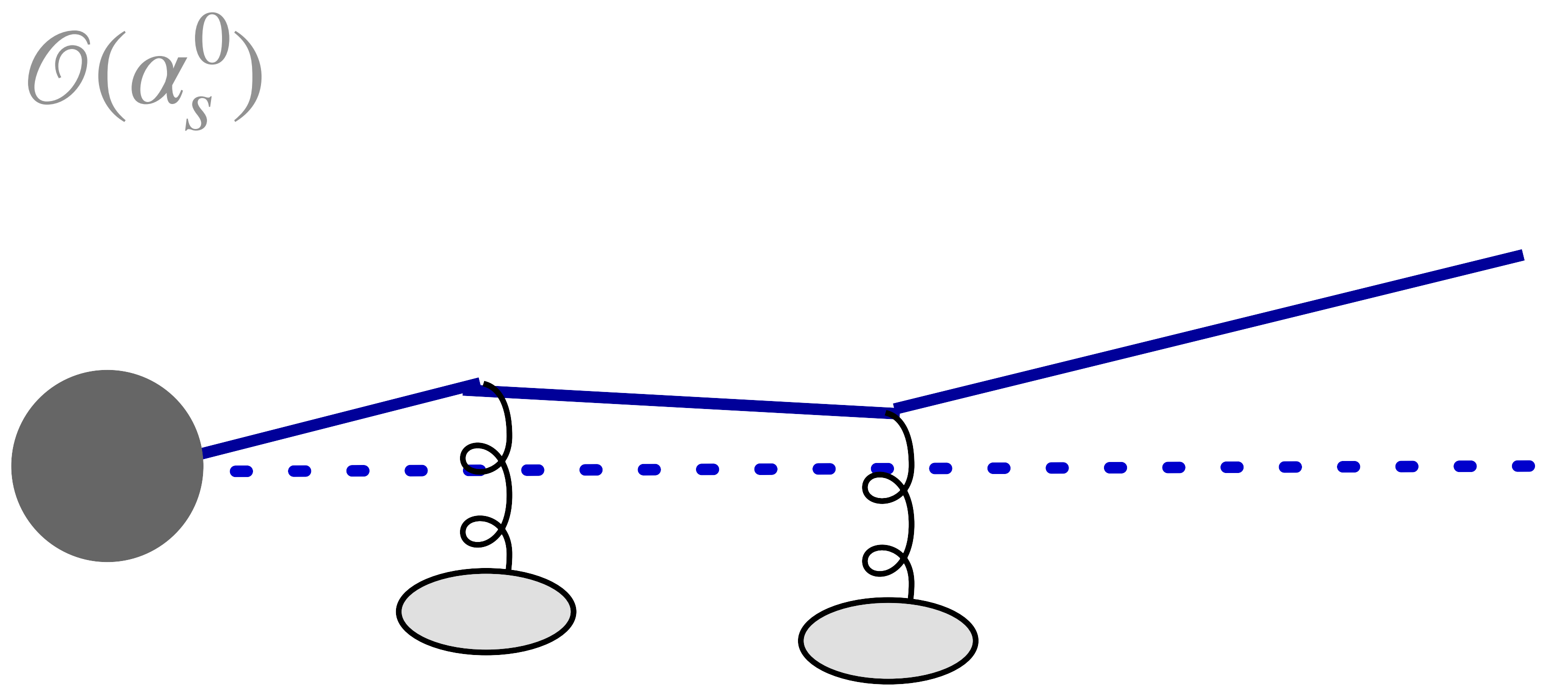
$$\langle A_{\rm matter}(x) A_{\rm matter}(y)\rangle \sim \delta(x-y)$$



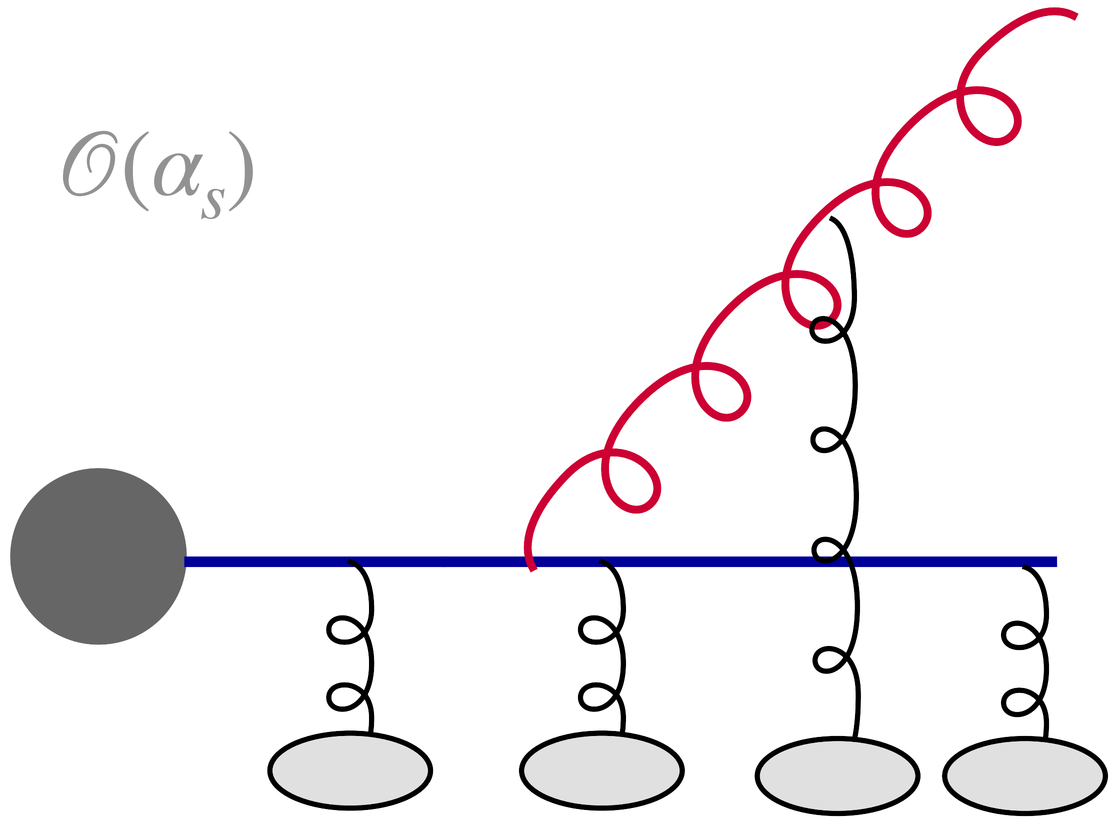
Jets in hot plasmas

How do we treat jet evolution in theory?

Even with these approximations this is a challenging problem! Focus on lowest order processes



"momentum broadening"



"medium induced gluon emission"

✓ **One can gain analytical insight into the problem: BDMPS-Z, GLV, AMY, Higher-Twist, …**

Talks by L. Apolinário, I. Soudi

✗ **Jets decouple more from plasma evolution: less sensitivity to medium properties**

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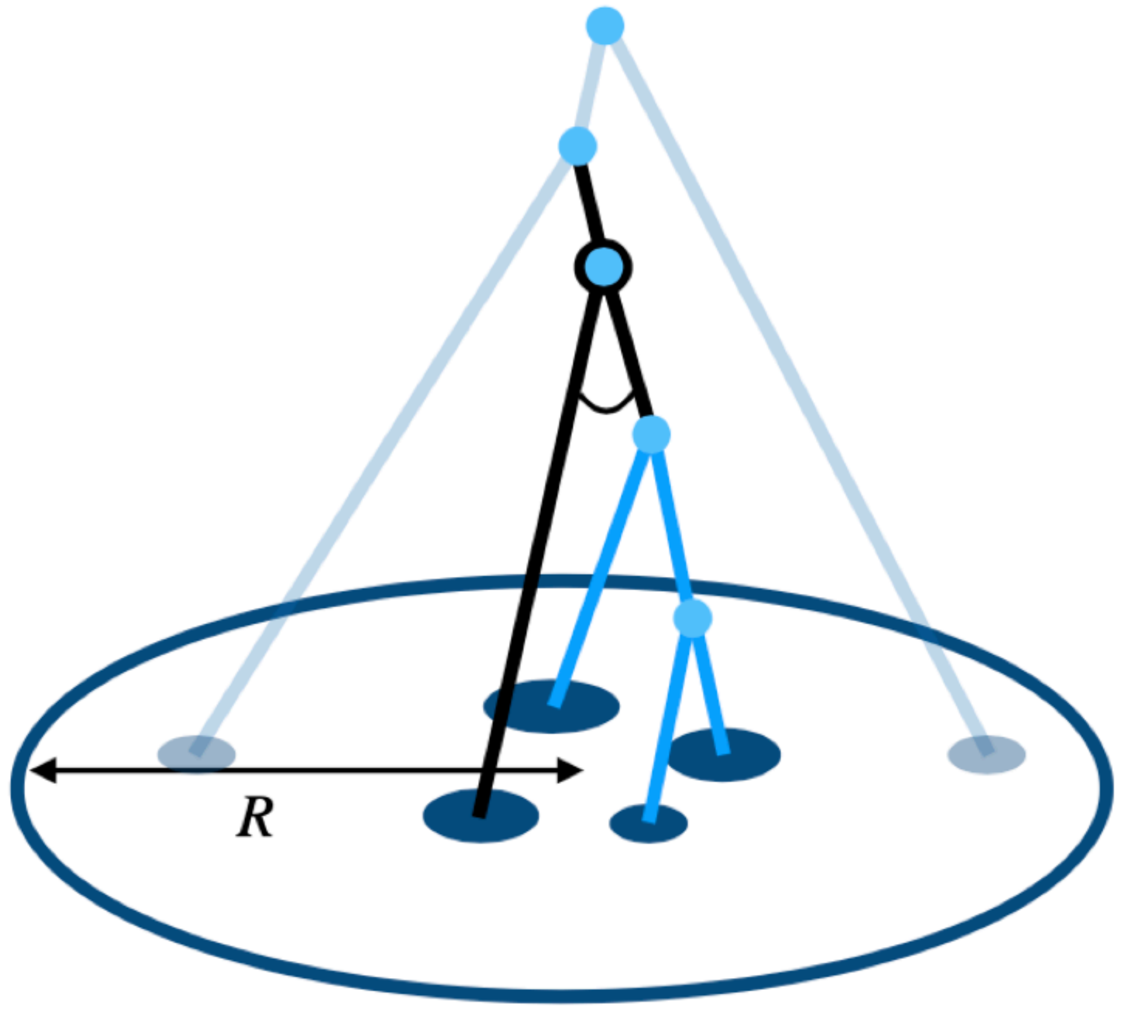
Why should we want to go beyond ?

Corrections to this picture will be NLO effect, power correction, subeikonal, …

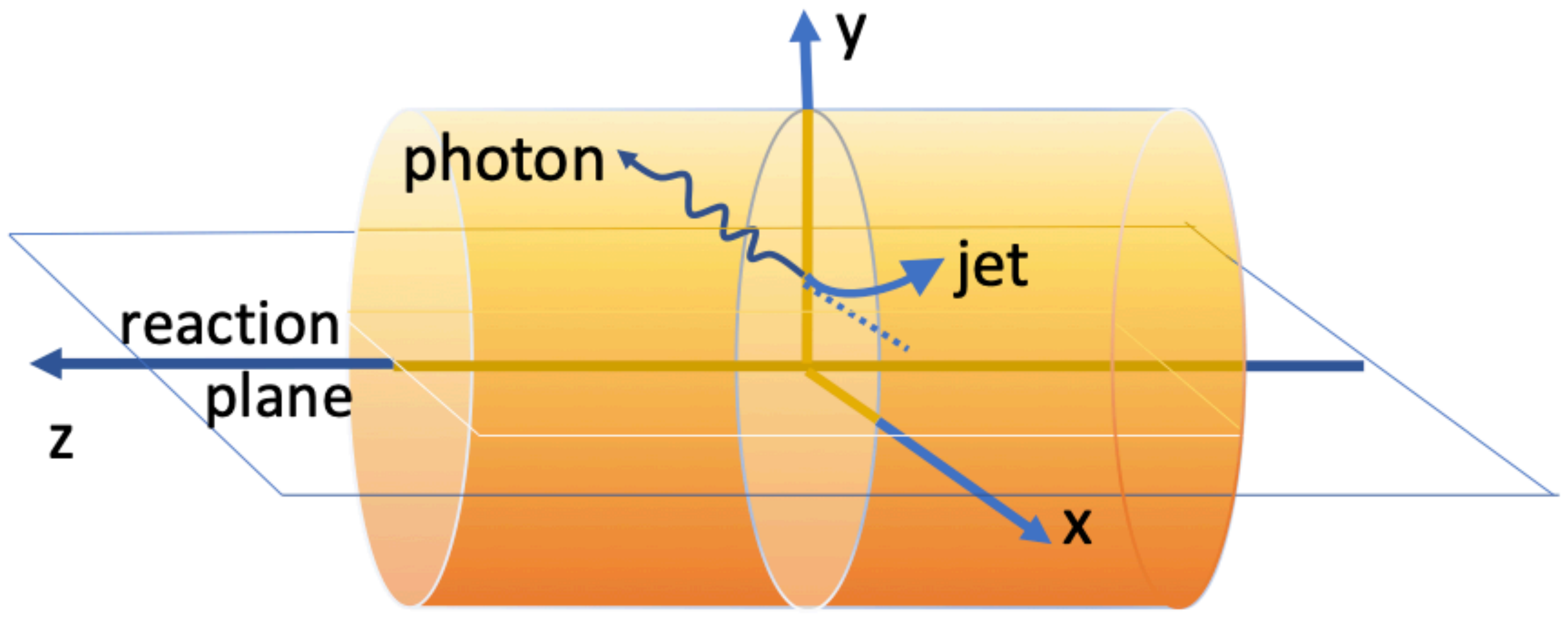
logs

Enhanced by medium parameter
Leading order effect

General move towards more differential access to medium information from jets



Jet sub-structure



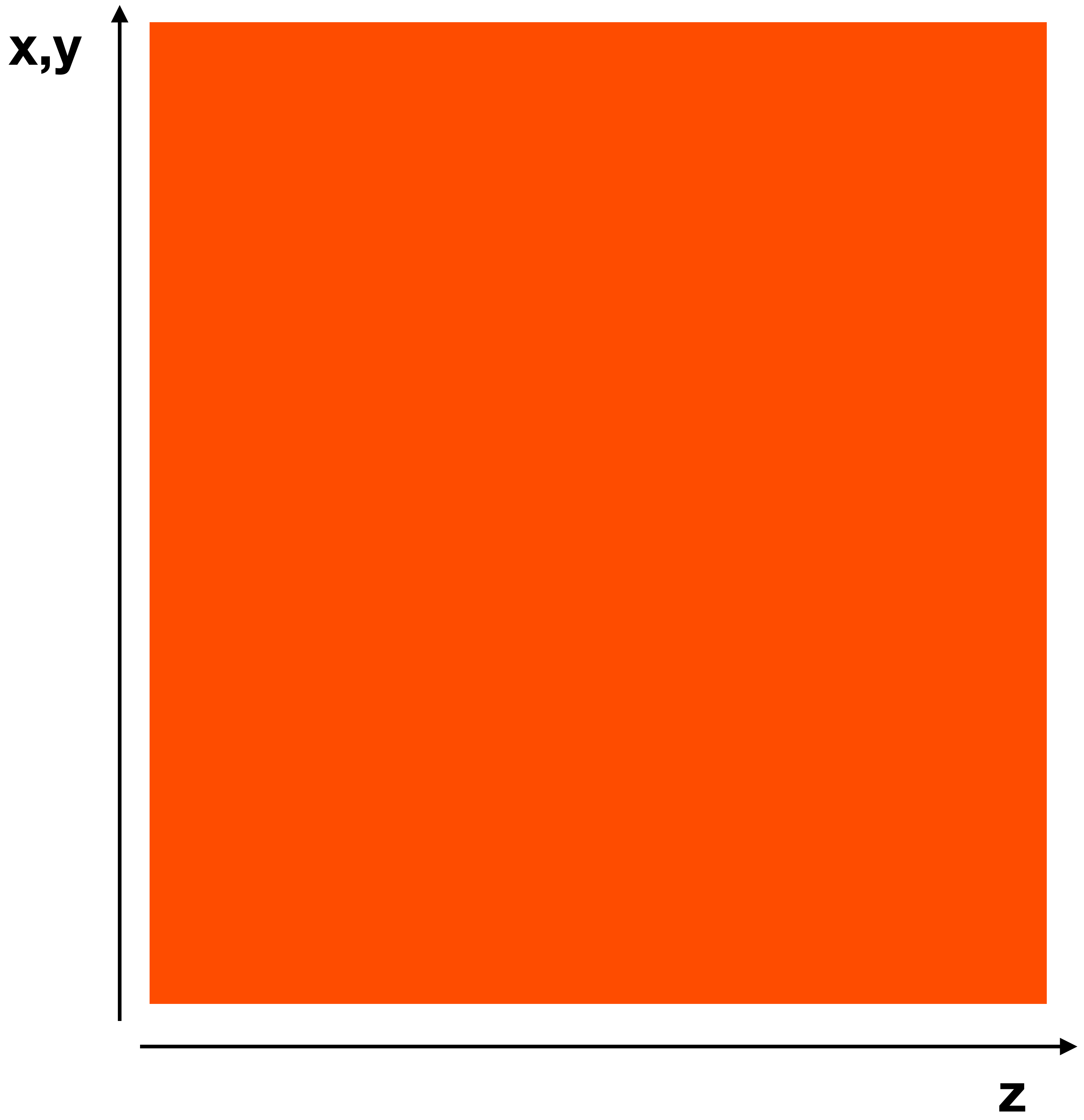
Jet tomography

Jets in hot plasmas

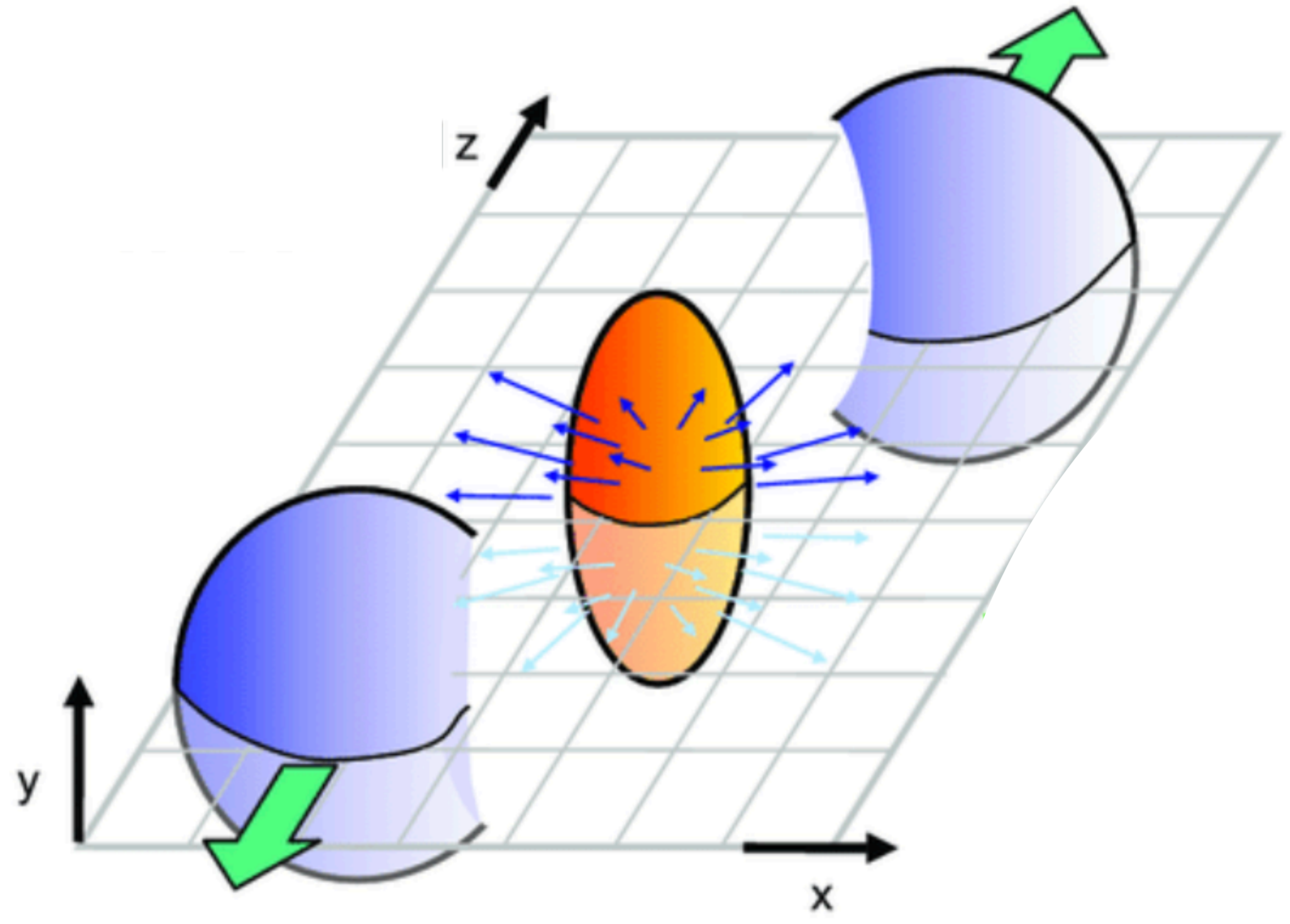
Going beyond: anisotropic matter

Why?

1 An infinitely long static medium …



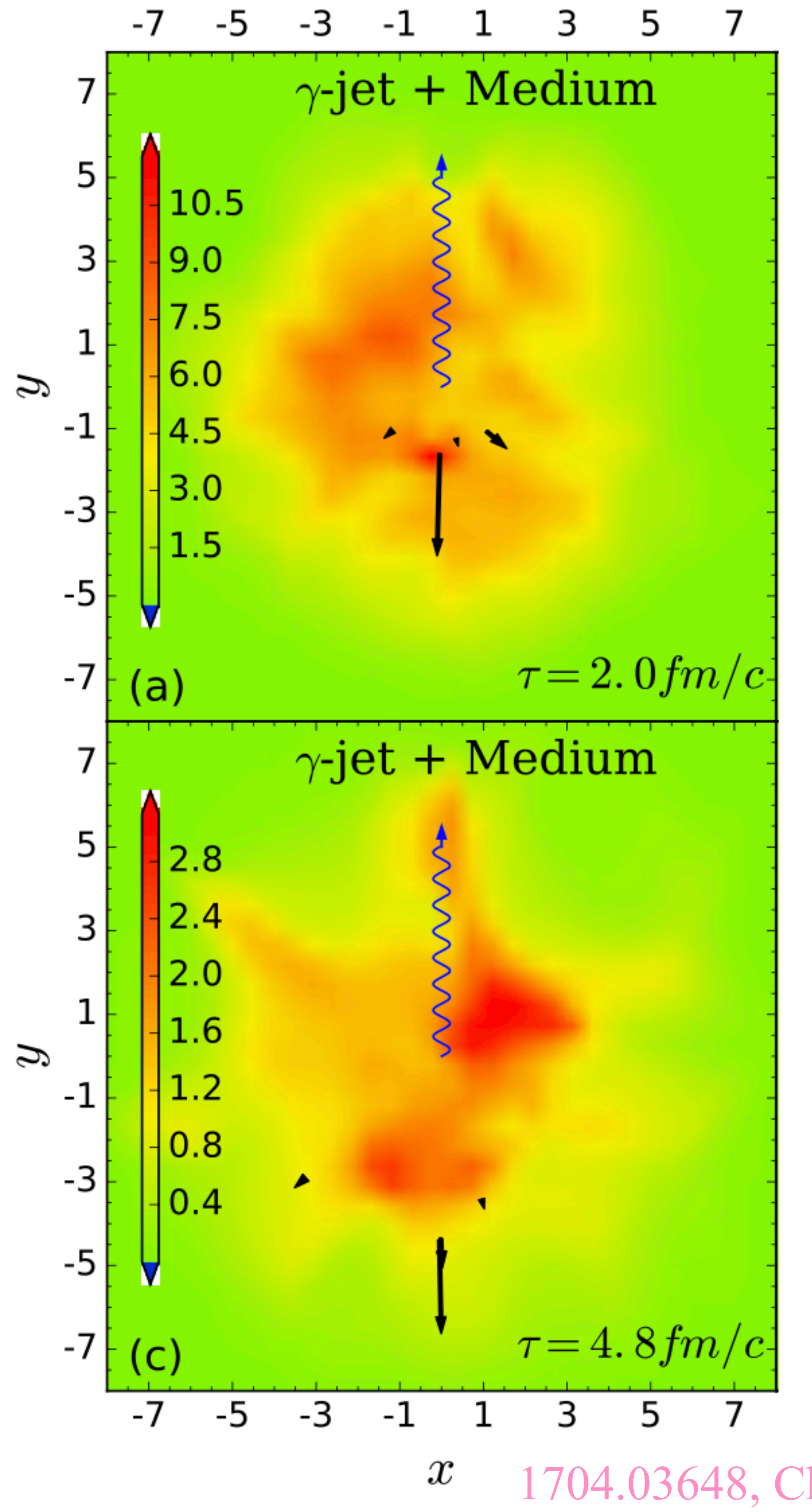
… might not be a good approximation to a real droplet



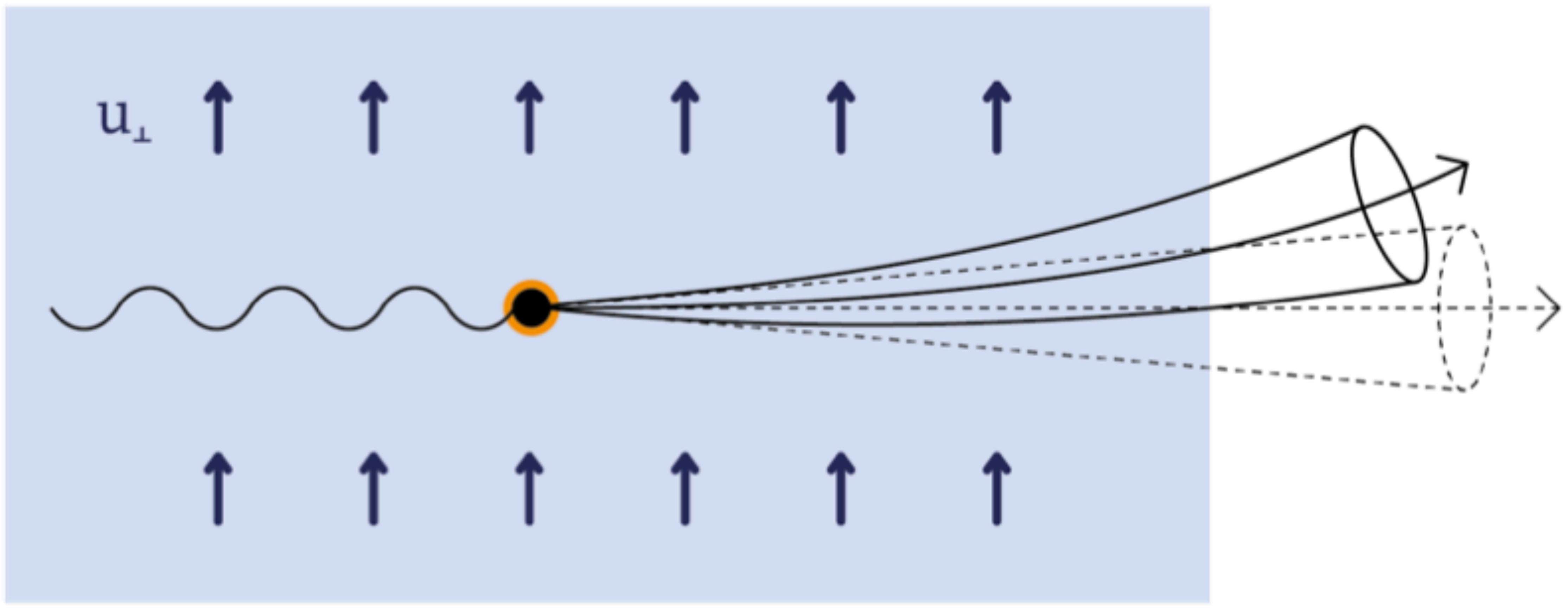
Jets in hot plasmas

Going beyond: anisotropic matter

2



1704.03648, Chen et al



2104.09513, A. Sadofyev, M. Sievert, I. Vitev

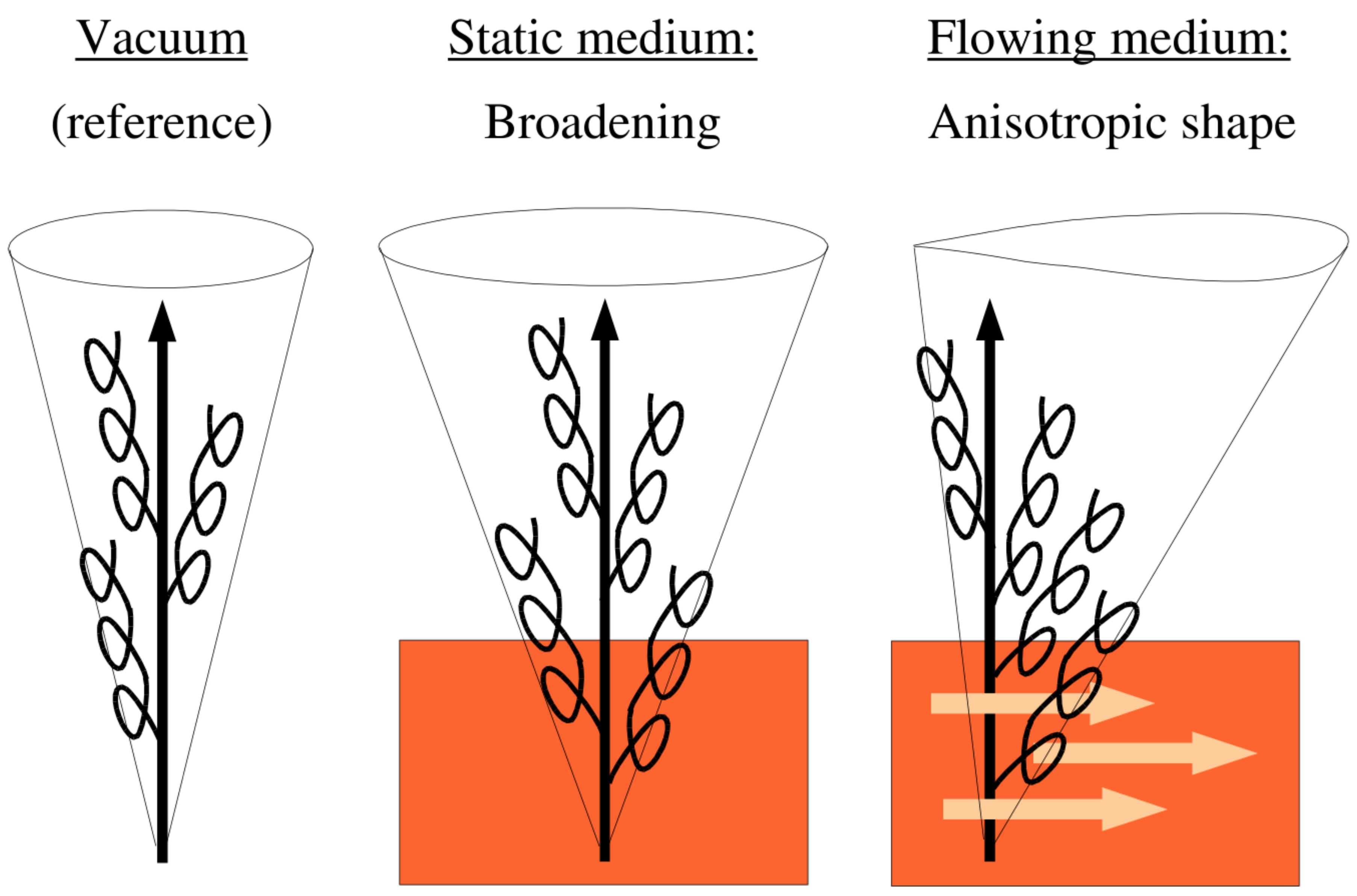
Medium response to jet

Jet response to medium

Jets in hot plasmas

Going beyond: anisotropic matter

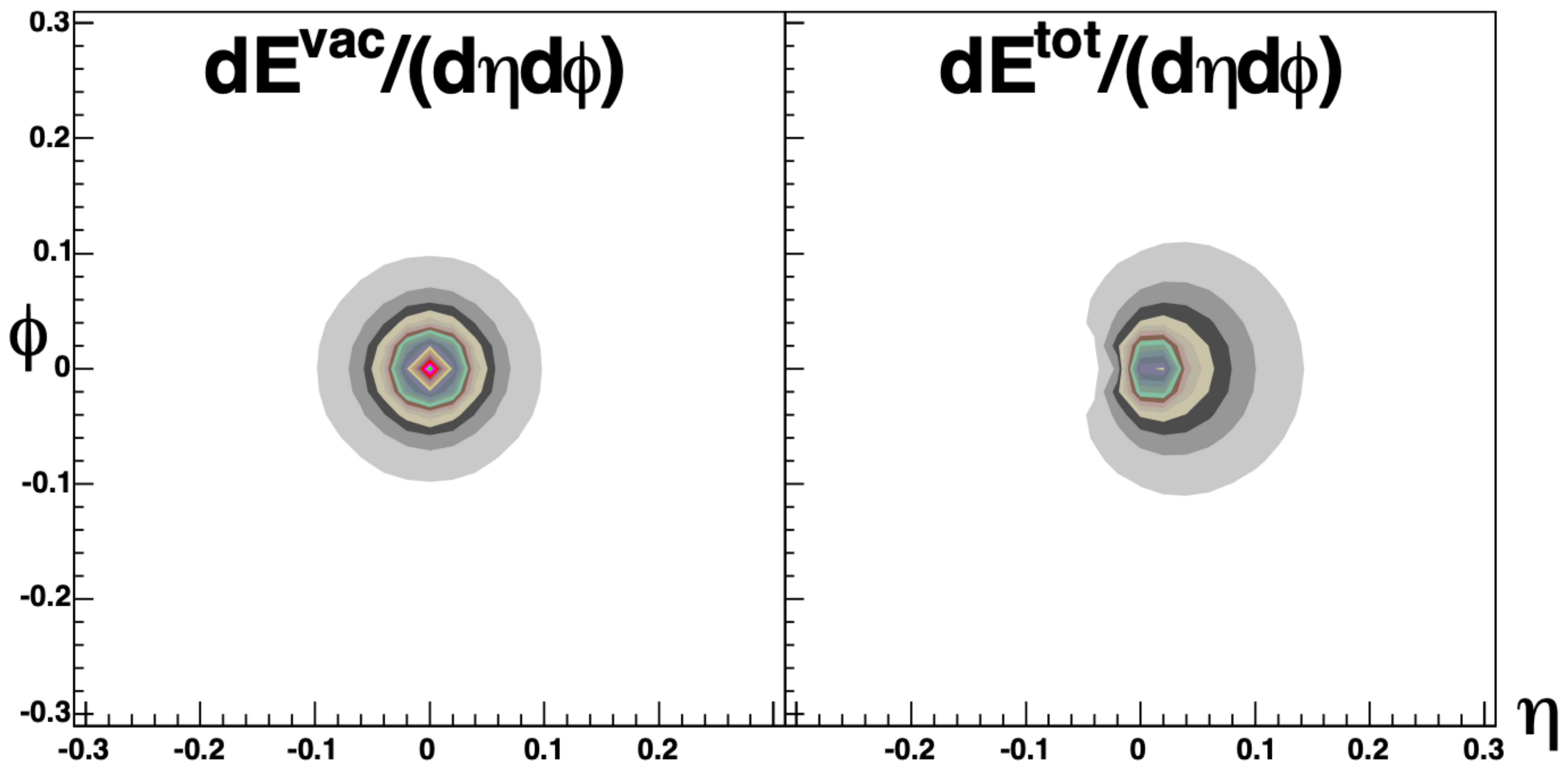
3 Previous studies considered similar effects, but at pheno level



$$|a(\mathbf{q})|^2 = \frac{\mu^2}{\pi\left[(\mathbf{q}-\mathbf{q}_0)^2+\mu^2\right]^2}$$

μ^2 ← Debye mass

2004, Armesto, Salgado, Wiedemann



Outline

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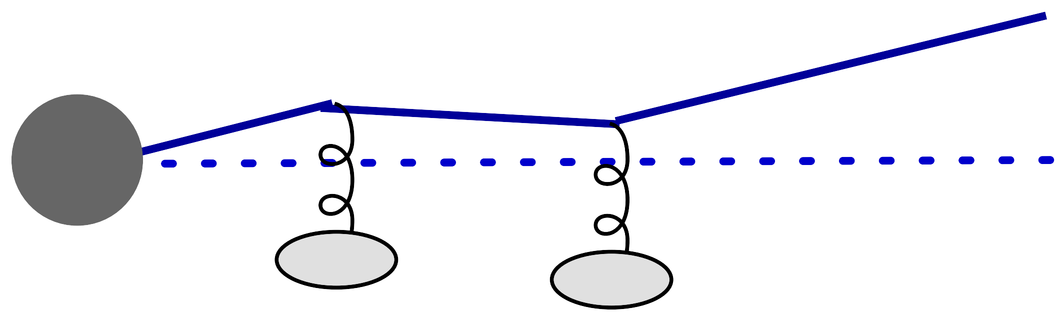
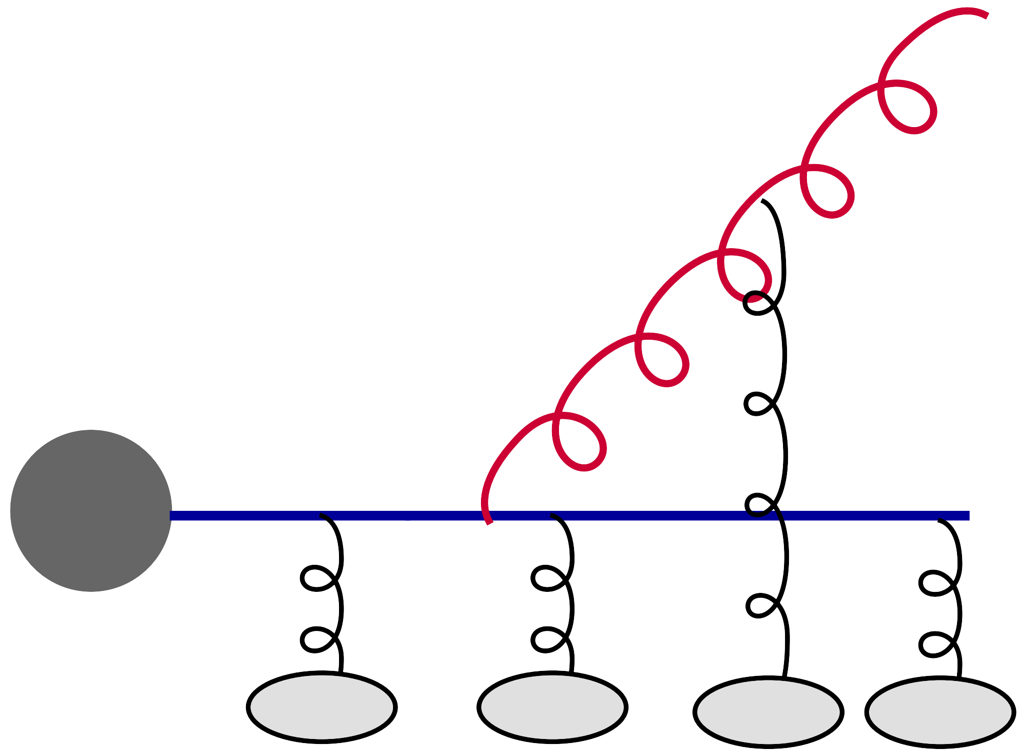
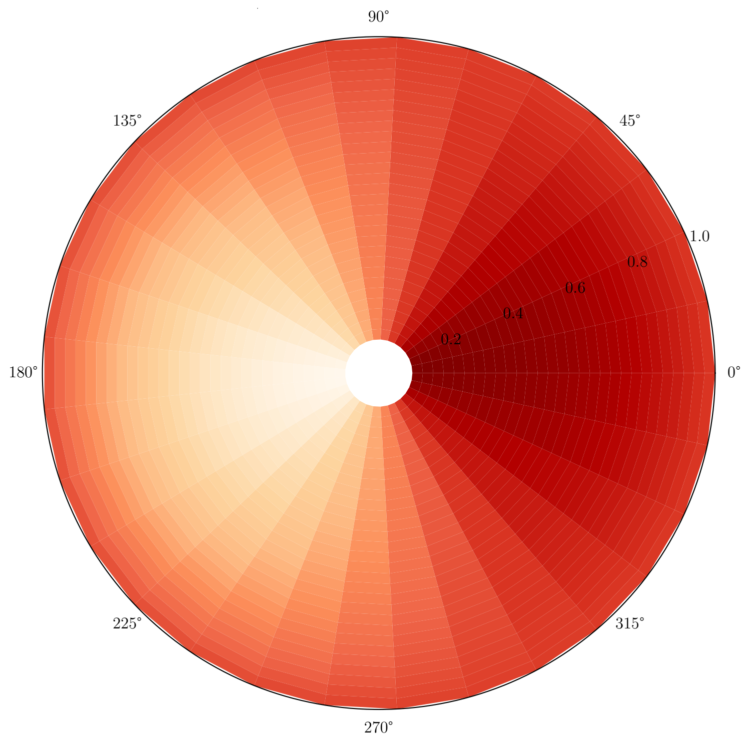
1. **Momentum broadening in dense anisotropic media**
   2202.08847 2210.06519



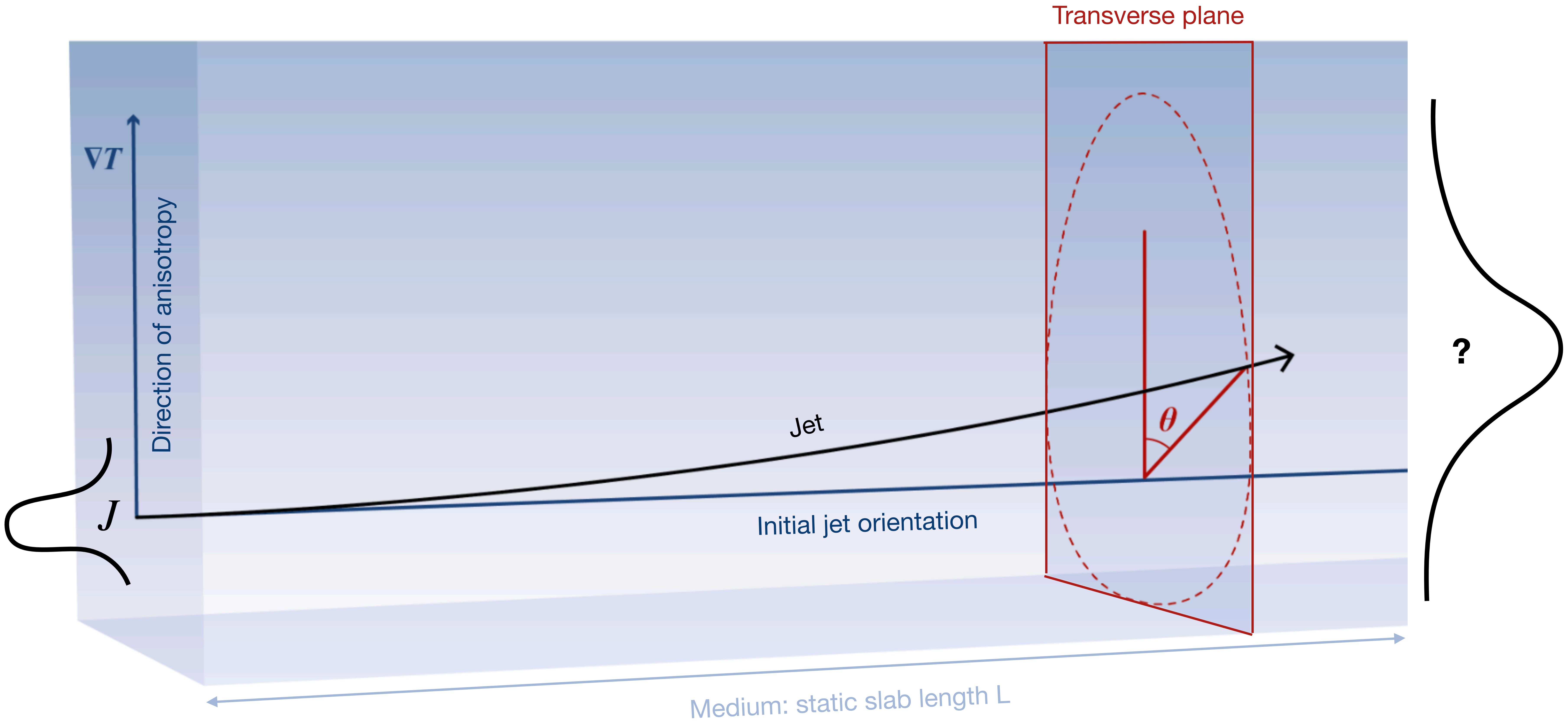
2. **Radiative energy loss in dense anisotropic media**
   2304.03712



3. **Jet observables in inhomogeneous matter**
   2308.xxxx

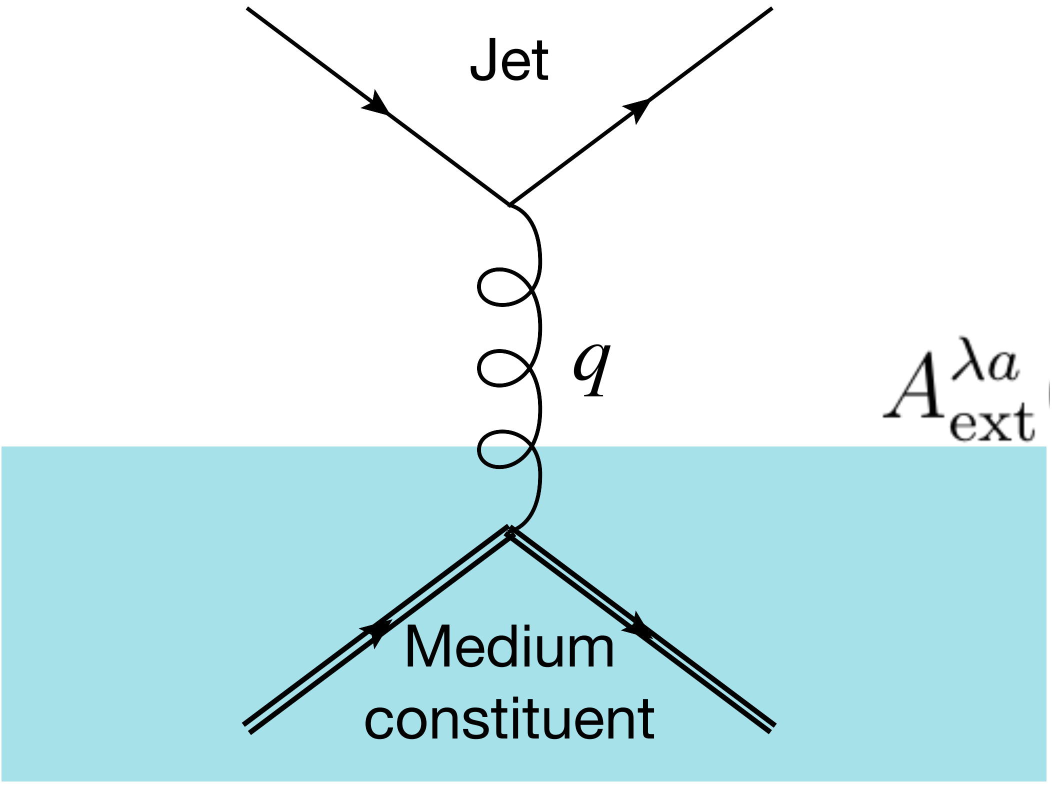


Momentum broadening in anisotropic media



Momentum broadening in anisotropic media

The medium is described by a classical field



Model dependent elastic scattering potential for source j

No energy transfer in each scattering: transverse t-channel gluon exchanges only

$$g A^{\lambda a}_{\text{ext}}(q) = -(2\pi)\, g^{\lambda 0} \sum_j e^{-i(\boldsymbol{q}\cdot\boldsymbol{x}_j + q_z z_j)}\, t^a_j\, v_j(q)\, \delta\left(q^0\right)$$

where we use the GW model

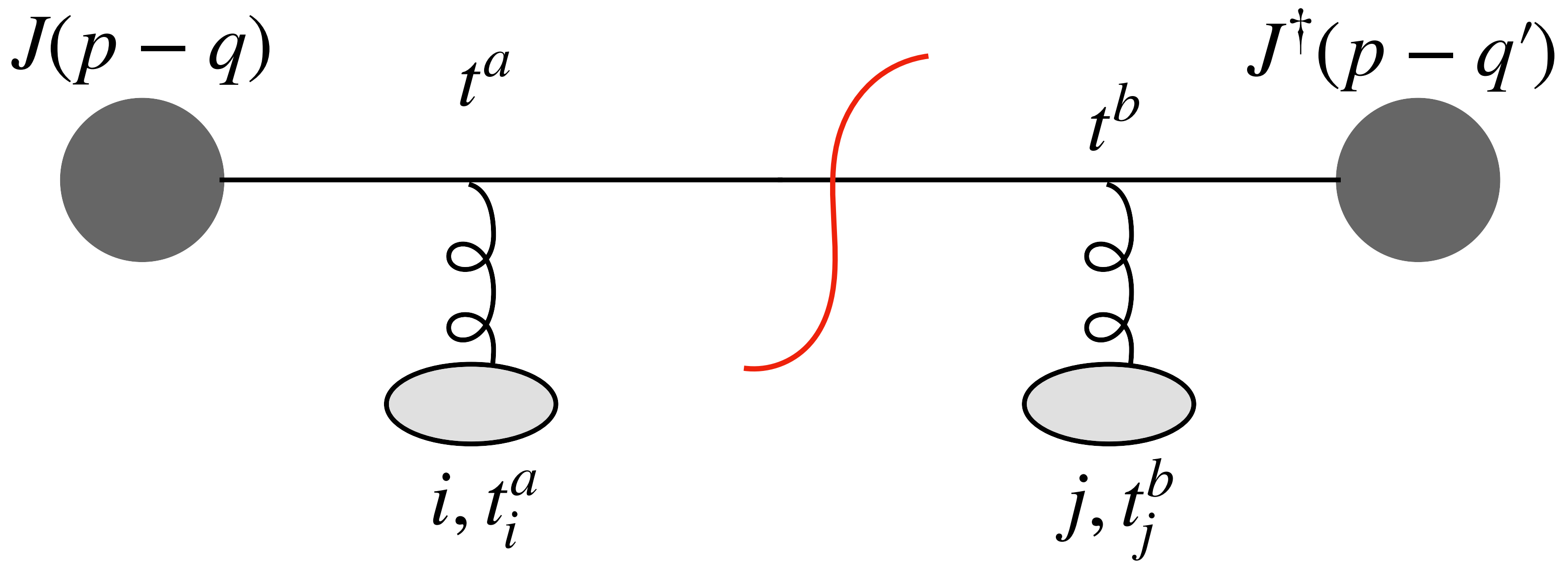
$$v_i(q) \equiv \frac{-g^2}{-q_0^2 + \boldsymbol{q}^2 + q_z^2 + \mu_i^2 - i\epsilon}$$

Medium statistics follow from 2-gluon approximation

$$\langle t^a_i t^b_j \rangle = \frac{1}{d_{\text{tgt}}} \text{tr}\left(t^a_i t^b_j\right) = \frac{1}{2C_{\bar{R}}} \delta_{ij} \delta^{ab}$$

Only non-trivial correlator

Probe interacts with the same scattering center in amplitude and conjugate amplitude



Momentum broadening in anisotropic media

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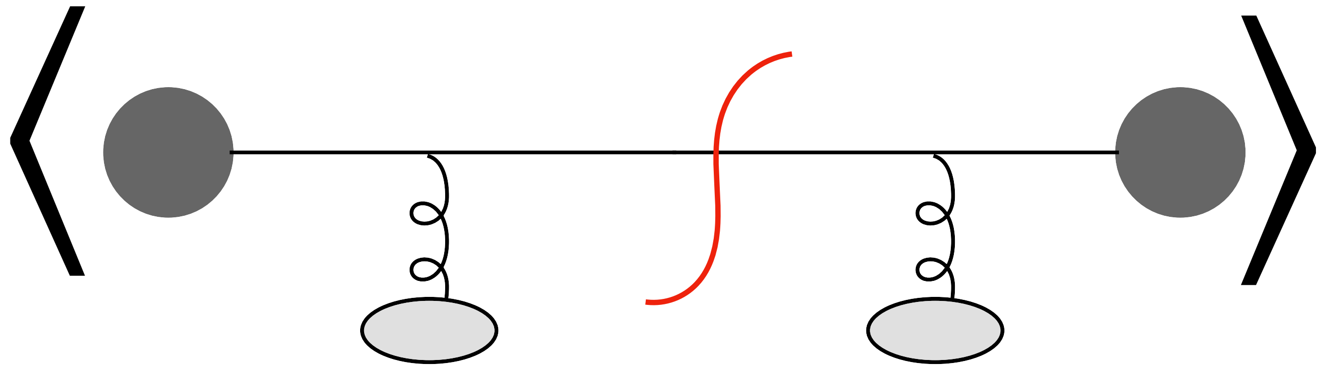
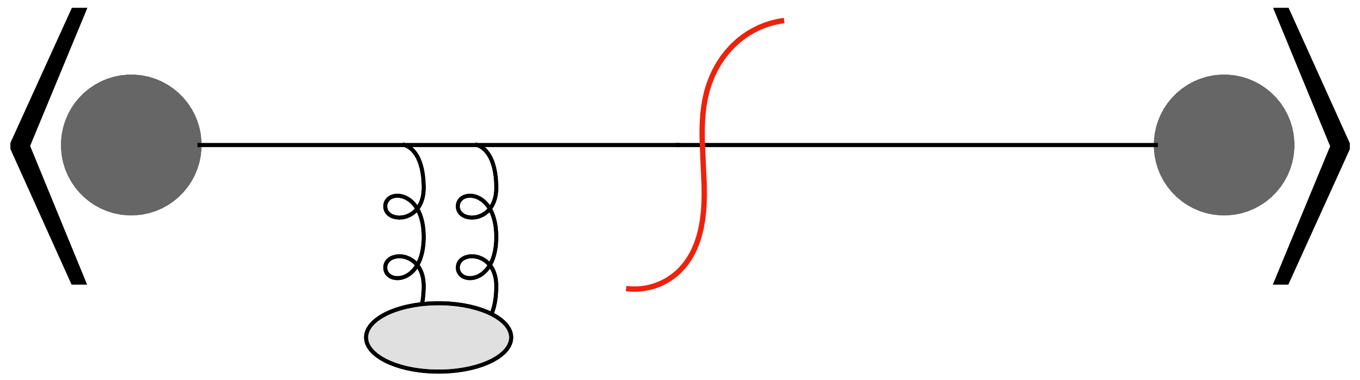
1 Compute all diagrams up to $2N$ field insertions





2 For each N, square and average the respective diagrams

$$\langle |M|^2 \rangle = \underbrace{\langle |M_0|^2 \rangle}_{N=0} + \underbrace{\langle |M_1|^2 \rangle + \langle M_2 M_0^* \rangle + \langle M_0 M_2^* \rangle}_{N=1} + \underbrace{\langle |M_2|^2 \rangle + \langle M_3 M_1^* \rangle + \langle M_1 M_3^* \rangle + \langle M_4 M_0^* \rangle + \langle M_0 M_4^* \rangle}_{N=2} + \ldots$$

The averaging is performed by taking the limit of continuous distribution in the medium

$$\sum_i f_i = \int d^2\boldsymbol{x}\, dz\, \rho(\boldsymbol{x}, z)\, f(\boldsymbol{x}, z) \xrightarrow[\nabla T = 0]{\rho(\cancel{\boldsymbol{x}}, z) \quad \mu^2(\cancel{\boldsymbol{x}}, z)} \int d^2\boldsymbol{x}_n\, e^{-i(\boldsymbol{q}_n \pm \bar{\boldsymbol{q}}_n)\cdot \boldsymbol{x}_n} = (2\pi)^2\, \delta^{(2)}(\boldsymbol{q}_n \pm \bar{\boldsymbol{q}}_n)$$

Density of scattering centers

Momentum broadening in anisotropic media

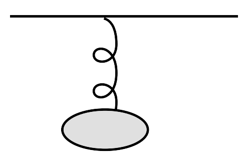
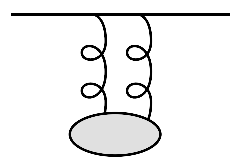
3 Resum the Opacity Series

A detailed derivation shows that the square amplitude for $2N$ insertions has the form

$$\langle |M|^2 \rangle^{(N)} = \prod_{n=1}^{N} \left[(-1) \int_0^{z_{n+1}} dz_n \int \frac{d^2\boldsymbol{q}_n}{(2\pi)^2} \mathcal{V}(\boldsymbol{q}_n, z_n) \right] |J(E, \boldsymbol{p}_{in})|^2$$

where we identify the effective scattering potential

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

The resummation in this case gives:

$$\frac{d\mathcal{N}}{d^2\boldsymbol{x}dE} = \sum_{N=0}^{\infty} \int \frac{d^2\boldsymbol{p}\, d^2\boldsymbol{r}}{(2\pi)^2} e^{i\boldsymbol{p}\cdot(\boldsymbol{x}-\boldsymbol{r})} \frac{(-1)^N \left[\mathcal{V}(\boldsymbol{r}) L\right]^N}{N!} \frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{r}dE} = e^{-\mathcal{V}(\boldsymbol{x})L} \frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{x}dE}$$

Momentum broadening in anisotropic media

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When averaging in 2 **we used**

$$\sum_i f_i = \int d^2\boldsymbol{x}\, dz\, \rho(\boldsymbol{x}, z)\, f(\boldsymbol{x}, z) \xrightarrow[\nabla T = 0]{} \int d^2\boldsymbol{x}_n\, e^{-i(\boldsymbol{q}_n \pm \bar{\boldsymbol{q}}_n)\cdot \boldsymbol{x}_n} = (2\pi)^2\, \delta^{(2)}(\boldsymbol{q}_n \pm \bar{\boldsymbol{q}}_n)$$

For anisotropic media this no longer holds; hard to tackle in general

We perform a gradient expansion for the 2 relevant parameters: ρ and μ 2104.09513, A. Sadofyev, M. Sievert, I. Vitev

$$\rho(\boldsymbol{x}, z) \approx \rho(z) + \boldsymbol{\nabla}\rho(z)\cdot \boldsymbol{x} \qquad \mu^2(\boldsymbol{x}, z) \approx \mu^2(z) + \boldsymbol{\nabla}\mu^2(z)\cdot \boldsymbol{x}$$

So that when averaging instead of a momentum space Dirac delta one obtains

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

Momentum broadening in anisotropic media

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Proceeding as in [3] **we find that**

$$\mathcal{V}'(\boldsymbol{x}) \equiv \frac{\partial}{\partial \mu^2}\mathcal{V}(\boldsymbol{x})$$

$$\frac{d\mathcal{N}^{(N)}}{d^2\boldsymbol{x}dE} = \int \frac{d^2\boldsymbol{p}\,d^2\boldsymbol{r}}{(2\pi)^2}\, e^{i\boldsymbol{p}\cdot(\boldsymbol{x}-\boldsymbol{r})}(-1)^N\left[\mathcal{V}(\boldsymbol{r})L\right]^N\left\{\frac{1}{N!} + \frac{L}{E(N+1)!} \times \sum_{m=1}^{N}\left[(N+1-m)\boldsymbol{p}\cdot\left(\frac{\mathcal{V}'(\boldsymbol{r})}{\mathcal{V}(\boldsymbol{r})}\boldsymbol{\nabla}\mu^2 + \frac{1}{\rho}\boldsymbol{\nabla}\rho\right) + i(N+1-m)^2\frac{\boldsymbol{\nabla}\mathcal{V}(\boldsymbol{r})}{\rho\,\mathcal{V}(\boldsymbol{r})}\cdot\boldsymbol{\nabla}\rho\right.\right.$$

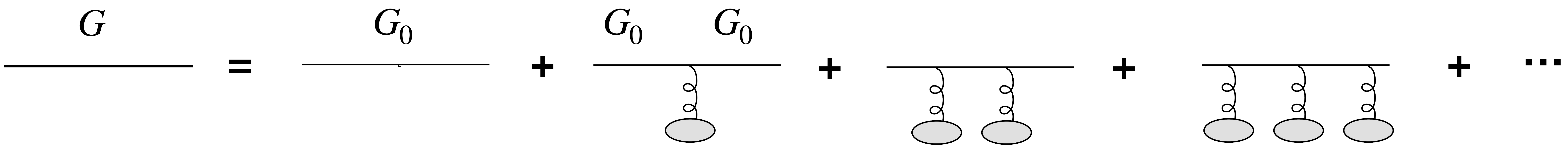
$$\left.\left. + i(N+1-m)\left(\frac{\boldsymbol{\nabla}\mathcal{V}'(\boldsymbol{r})}{\mathcal{V}(\boldsymbol{r})} + (N-m)\frac{\mathcal{V}'(\boldsymbol{r})}{\mathcal{V}(\boldsymbol{r})}\frac{\boldsymbol{\nabla}\mathcal{V}(\boldsymbol{r})}{\mathcal{V}(\boldsymbol{r})}\right)\cdot\boldsymbol{\nabla}\mu^2\right]\right\}\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{r}dE}$$

Resumming the opacity series then leads to the compact expression

$$\frac{d\mathcal{N}}{d^2\boldsymbol{x}dE} = e^{-\mathcal{V}(\boldsymbol{x})L}\left\{\left[1 - i\frac{\mathcal{V}(\boldsymbol{x})L^3}{6E}\left(\frac{\mathcal{V}'(\boldsymbol{x})}{\mathcal{V}(\boldsymbol{x})}\boldsymbol{\nabla}\mu^2 + \frac{1}{\rho}\boldsymbol{\nabla}\rho\right)\cdot\boldsymbol{\nabla}\mathcal{V}(\boldsymbol{x})\right]\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{x}dE} + i\frac{\mathcal{V}(\boldsymbol{x})L^2}{2E}\left(\frac{\mathcal{V}'(\boldsymbol{x})}{\mathcal{V}(\boldsymbol{x})}\boldsymbol{\nabla}\mu^2 + \frac{1}{\rho}\boldsymbol{\nabla}\rho\right)\cdot\boldsymbol{\nabla}\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{x}dE}\right\}$$

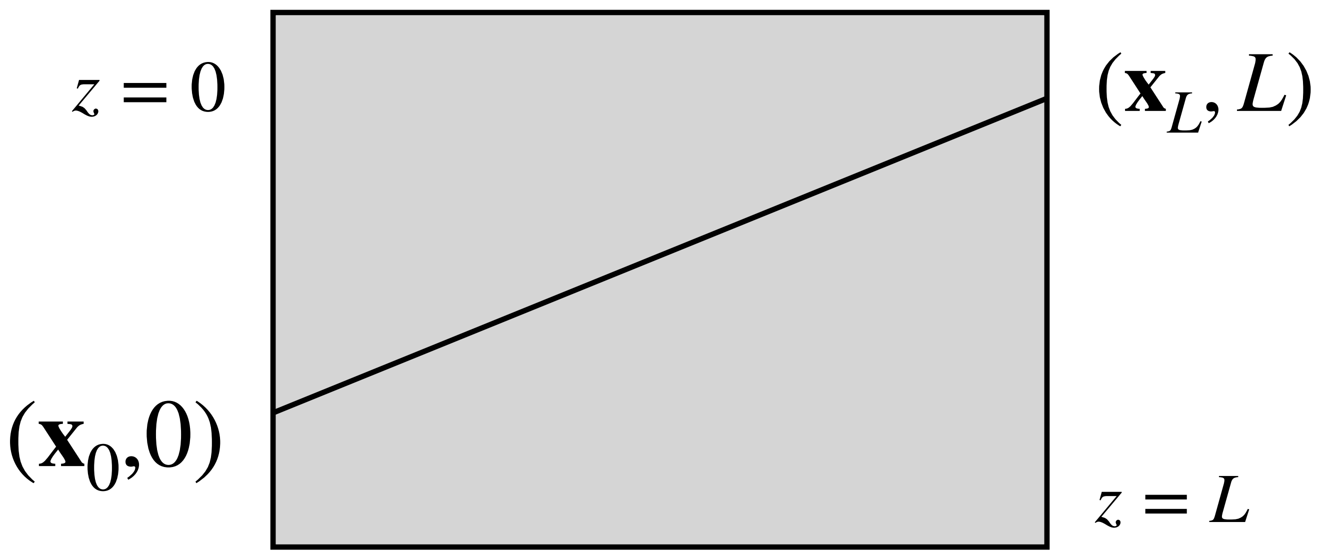
Momentum broadening in anisotropic media

1 Compute an effective in-medium propagator



This results in an effective propagator G

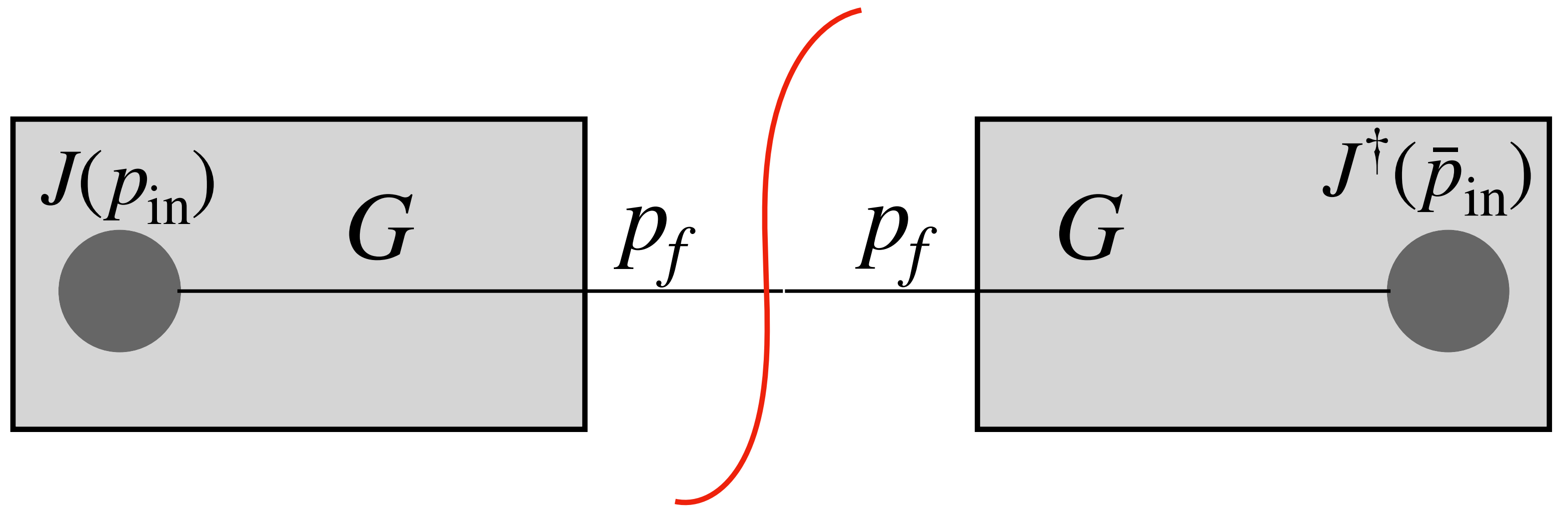
$$G(\boldsymbol{x}_L, L; \boldsymbol{x}_0, 0) = \int_{\boldsymbol{x}_0}^{\boldsymbol{x}_L} \mathcal{D}\boldsymbol{r} \exp\left(\frac{iE}{2}\int_0^L d\tau\, \dot{\boldsymbol{r}}^2\right) \mathcal{P}\exp\left(-i\int_0^L d\tau\, t^a_{\mathrm{proj}} v^a(\boldsymbol{r}(\tau),\tau)\right)$$



2 Compute the relevant Feynman diagrams

$$\langle |M|^2\rangle = \int \frac{d^2\boldsymbol{p}_{in} d^2\overline{\boldsymbol{p}}_{in}}{(2\pi)^4} \langle G(\boldsymbol{p}_f, L; \boldsymbol{p}_{in}, 0) G^\dagger(\boldsymbol{p}_f, L; \overline{\boldsymbol{p}}_{in}, 0)\rangle J(\boldsymbol{p}_{in}) J^*(\overline{\boldsymbol{p}}_{in})$$

$$g A^{\mu a}_{\mathrm{ext}}(q) = -(2\pi)\, g^{\mu 0}\, v^a(q)\, \delta\left(q^0\right) \qquad v^a(q) = \textstyle\sum_i e^{-i\vec{q}\cdot\vec{x}_i}\, t^a_i\, v_i(q)$$



Momentum broadening in anisotropic media

3 Solve the remaining average of dressed propagators

Option 1) Solve first the path integrals and then average

Equivalent to Opacity Series approach

Option 2) Perform the average before integration

In practice, by solving the remaining integrals one performs the resummation of averaged quantities directly

The **key step** is to use the fact that the color average of the potential at different positions

$$\langle t^a_{\text{proj}} v^a(\boldsymbol{r},\tau) t^b_{\text{proj}} v^{\dagger b}(\overline{\boldsymbol{r}},\overline{\tau})\rangle = \mathcal{C}\, g^4 \int dz\, d^2\boldsymbol{x}\, \rho(\boldsymbol{x},\, z) \int \frac{d^2\boldsymbol{q}\, dq_z\, d^2\overline{\boldsymbol{q}}\, d\overline{q}_z}{(2\pi)^6} \frac{e^{i\boldsymbol{q}\cdot(\boldsymbol{r}-\boldsymbol{x})} e^{-i\overline{\boldsymbol{q}}\cdot(\overline{\boldsymbol{r}}-\boldsymbol{x})} e^{iq_z(\tau-z)} e^{-i\overline{q}_z(\overline{\tau}-z)}}{(\boldsymbol{q}^2+q_z^2+\mu^2(\boldsymbol{x},z))(\overline{\boldsymbol{q}}^2+\overline{q}_z^2+\mu^2(\boldsymbol{x},z))}$$

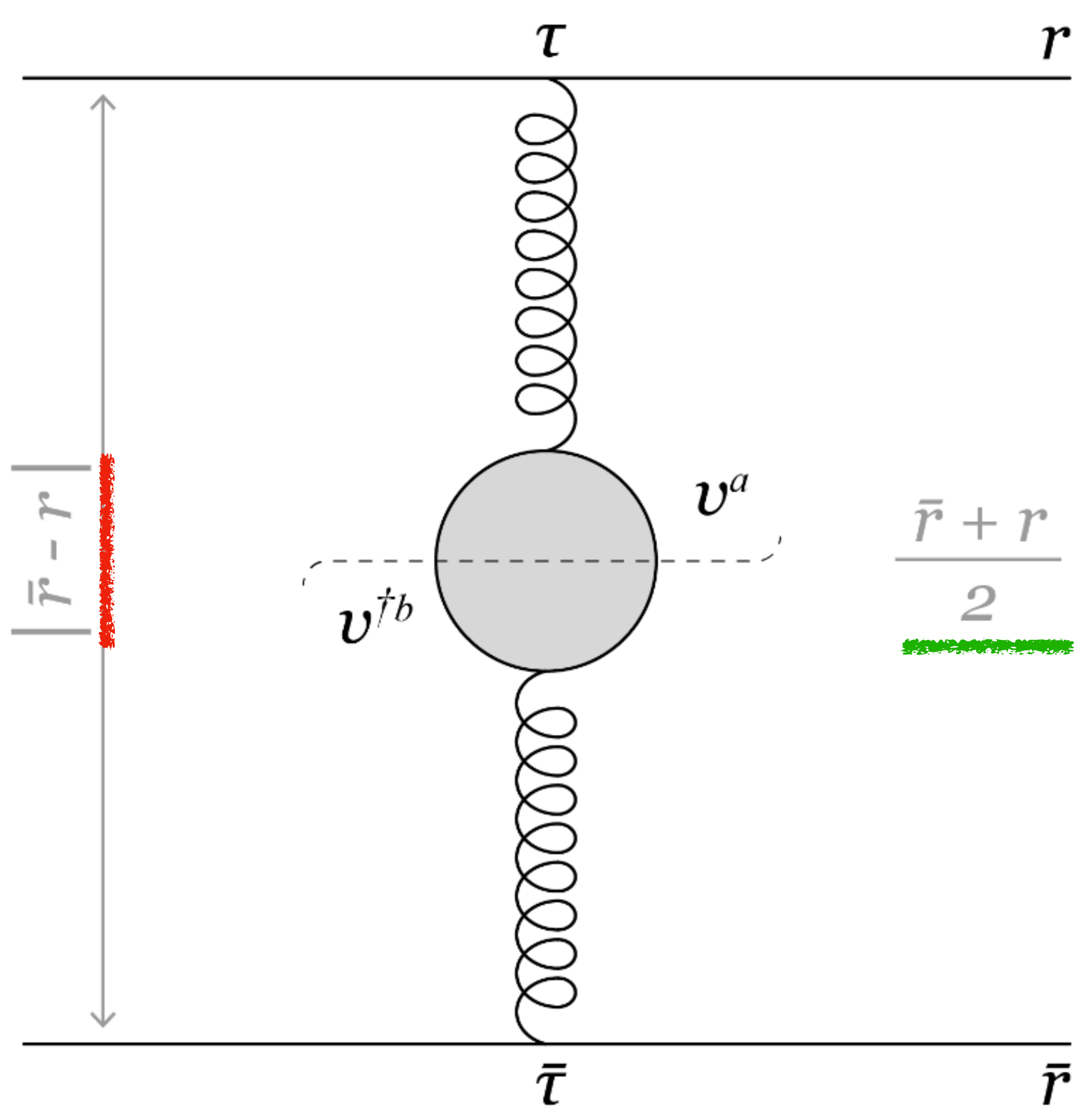
implies for $\nabla T = 0$

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

Momentum broadening in anisotropic media

To linear order in gradients from 3 **we find now**

$$\langle t^a_{\rm proj} v^a(\boldsymbol{r},\tau)\, t^b_{\rm proj} v^{\dagger b}(\bar{\boldsymbol{r}},\bar\tau)\rangle \simeq \left(1+\frac{\boldsymbol{r}(\tau)+\bar{\boldsymbol{r}}(\tau)}{2}\cdot\left(\boldsymbol{\nabla}\rho\frac{\delta}{\delta\rho}+\boldsymbol{\nabla}\mu^2\frac{\delta}{\delta\mu^2}\right)\right)\mathcal{C}\,\delta(\tau-\bar\tau)\,\rho\, g^4\int\frac{d^2\boldsymbol{q}}{(2\pi)^2}\frac{e^{i\boldsymbol{q}\cdot(\boldsymbol{r}-\bar{\boldsymbol{r}})}}{(\boldsymbol{q}^2+\mu^2)^2}$$



One can still show that the 2-point correlator exponentiates

before

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

$$\left\langle \mathcal{P}\exp\left(-i\int_0^L d\tau\, t^a_{\rm proj} v^a(\boldsymbol{r}(\tau),\tau)\right)\mathcal{P}\exp\left(i\int_0^L d\bar\tau\, t^b_{\rm proj} v^b(\bar{\boldsymbol{r}}(\bar\tau),\bar\tau)\right)\right\rangle = \exp\left\{-\int_0^L d\tau\,\left[1+\frac{\boldsymbol{r}(\tau)+\bar{\boldsymbol{r}}(\tau)}{2}\cdot\left(\boldsymbol{\nabla}\rho\frac{\delta}{\delta\rho}+\boldsymbol{\nabla}\mu^2\frac{\delta}{\delta\mu^2}\right)\right]\mathcal{V}\left(\boldsymbol{r}(\tau)-\bar{\boldsymbol{r}}(\tau)\right)\right\}$$

Center of mass of dipole — Dipole size

Momentum broadening in anisotropic media

The final distribution has the form

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

$$\frac{d\mathcal{N}}{d^2\boldsymbol{x}dE} = \mathcal{P}(\boldsymbol{x})\,\hat{\mathsf{S}}(\boldsymbol{x})\,\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{x}dE}$$

In the literature referred to as single particle broadening distribution (when Fourier transformed)

Usually a unit operator, but now it acts with ∇ on initial distribution

Effective factorization no longer holds in general due to operator nature

Still

$$\int d^2\boldsymbol{p}\,\frac{d\mathcal{N}}{d^2\boldsymbol{p}\,dE} = \left.\frac{d\mathcal{N}}{d^2\boldsymbol{x}dE}\right|_{\boldsymbol{x}=0} = \left.\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{x}dE}\right|_{\boldsymbol{x}=0} = \int d^2\boldsymbol{p}\,\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{p}\,dE}$$

Consider the case of a source with finite width

$$E\frac{d\mathcal{N}^{(0)}}{d^2\boldsymbol{p}\,dE} = \frac{f(E)}{2\pi w^2}e^{-\frac{\boldsymbol{p}^2}{2w^2}}$$

It is possible to show that even though $\langle\boldsymbol{p}\rangle = 0$

higher odd moments can be generated, for example

$$\langle p^\alpha\,\boldsymbol{p}^2\rangle = \frac{w^2L^2\mu^2}{E\,\lambda}\frac{\nabla^\alpha\rho}{\rho}\ln\frac{E}{\mu} + \frac{L^3\mu^4}{6E\,\lambda^2}\frac{\nabla^\alpha\rho}{\rho}\left(\ln\frac{E}{\mu}\right)^2$$

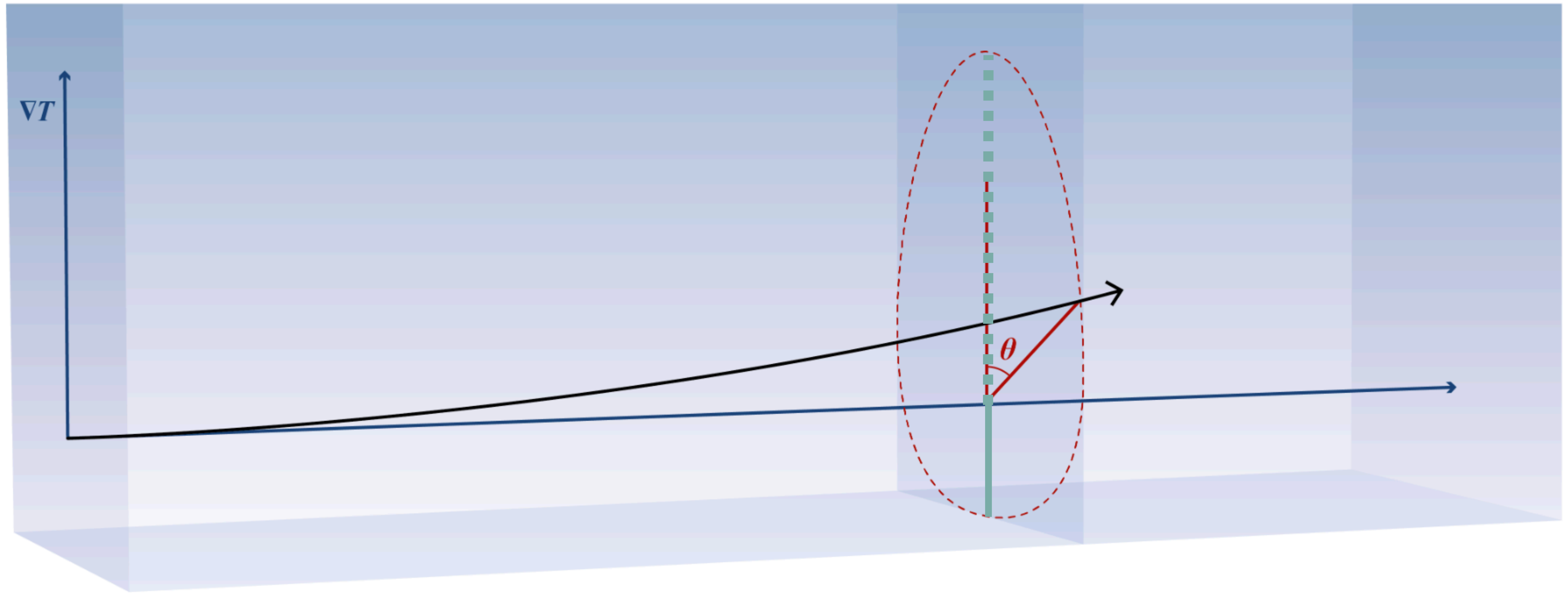
$N = 1$ $\qquad$ $N = 2$

Higher N terms dominate due to diverging potential at large momenta

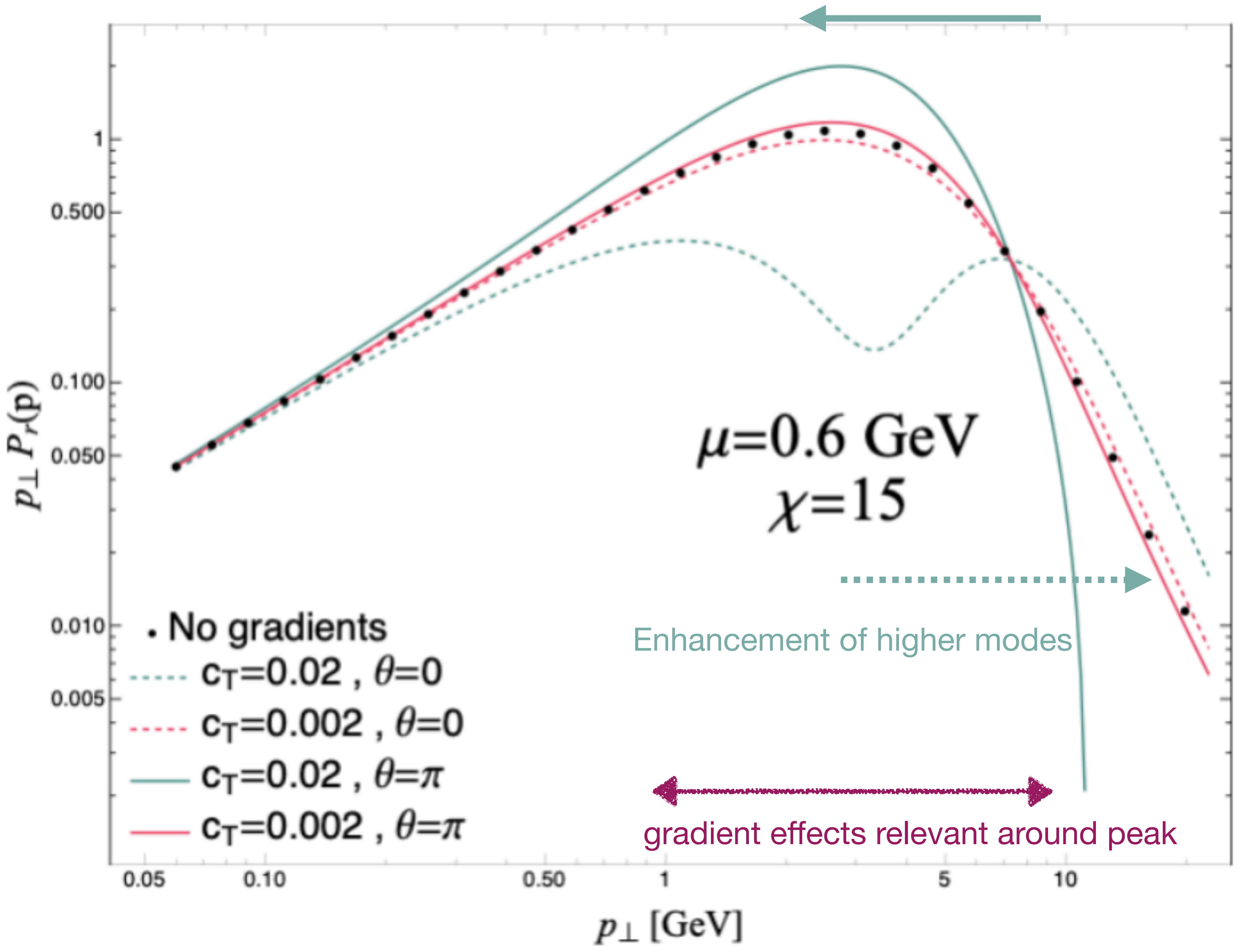
Coulomb logarithm

Momentum broadening in anisotropic media

For the full GW model we have

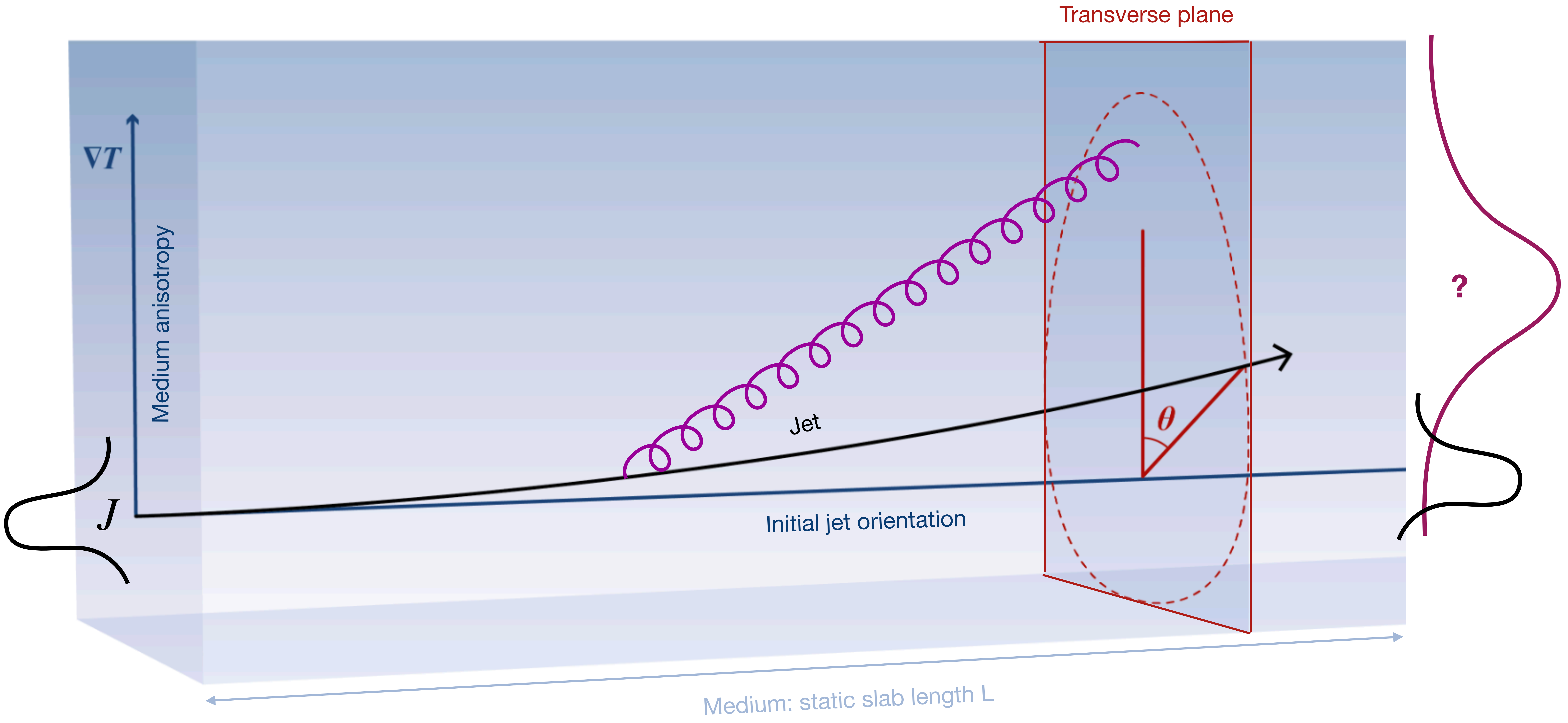


The full distribution is written in terms of the angle θ and parameter $c_T \equiv \left|\frac{\nabla T}{ET}\right|$.



$$\frac{\nabla\rho}{\rho} \sim 3\frac{\nabla T}{T}\,, \quad \frac{\nabla\mu^2}{\mu^2} \sim 2\frac{\nabla T}{T}$$

Radiative energy loss in dense anisotropic media



Radiative energy loss in dense anisotropic media

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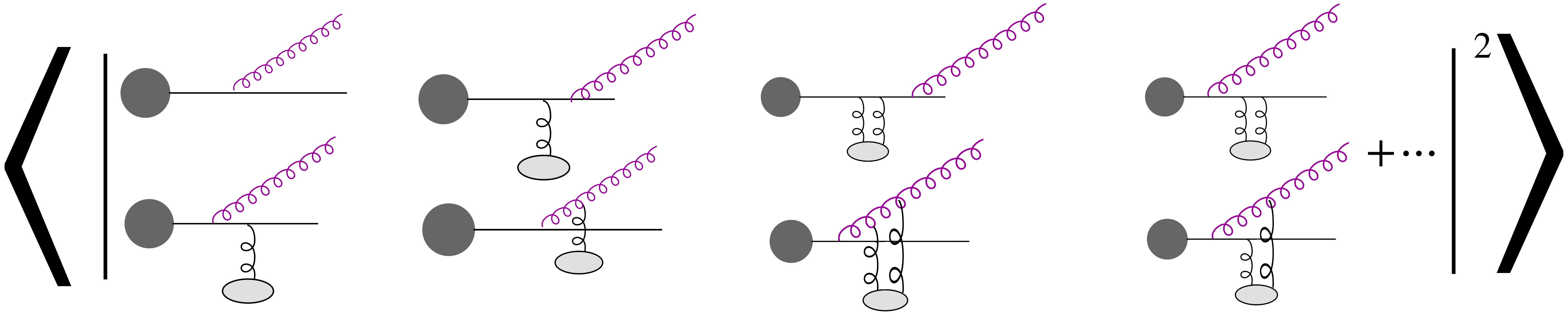
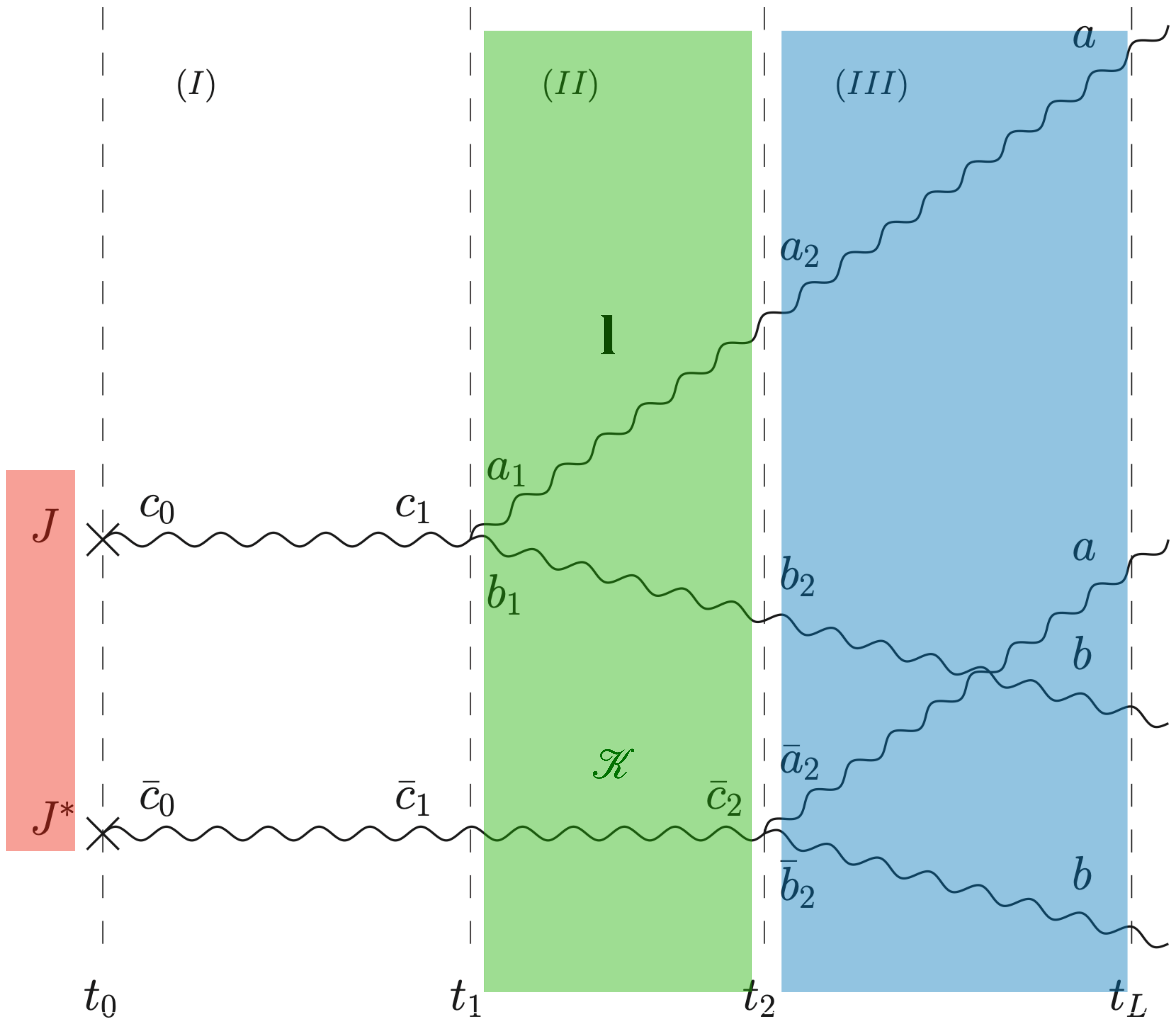
In Opacity Expansion style calculation one needs to compute

Beyond N=1, this seems to be quite hard to do



Radiative energy loss in dense anisotropic media

Using resummed propagators calculation becomes simpler



see e.g. 1209.4585, J.-P. Blaizot, F. Dominguez, E. Iancu, Y. Mehtar-Tani

Radiative energy loss in dense anisotropic media

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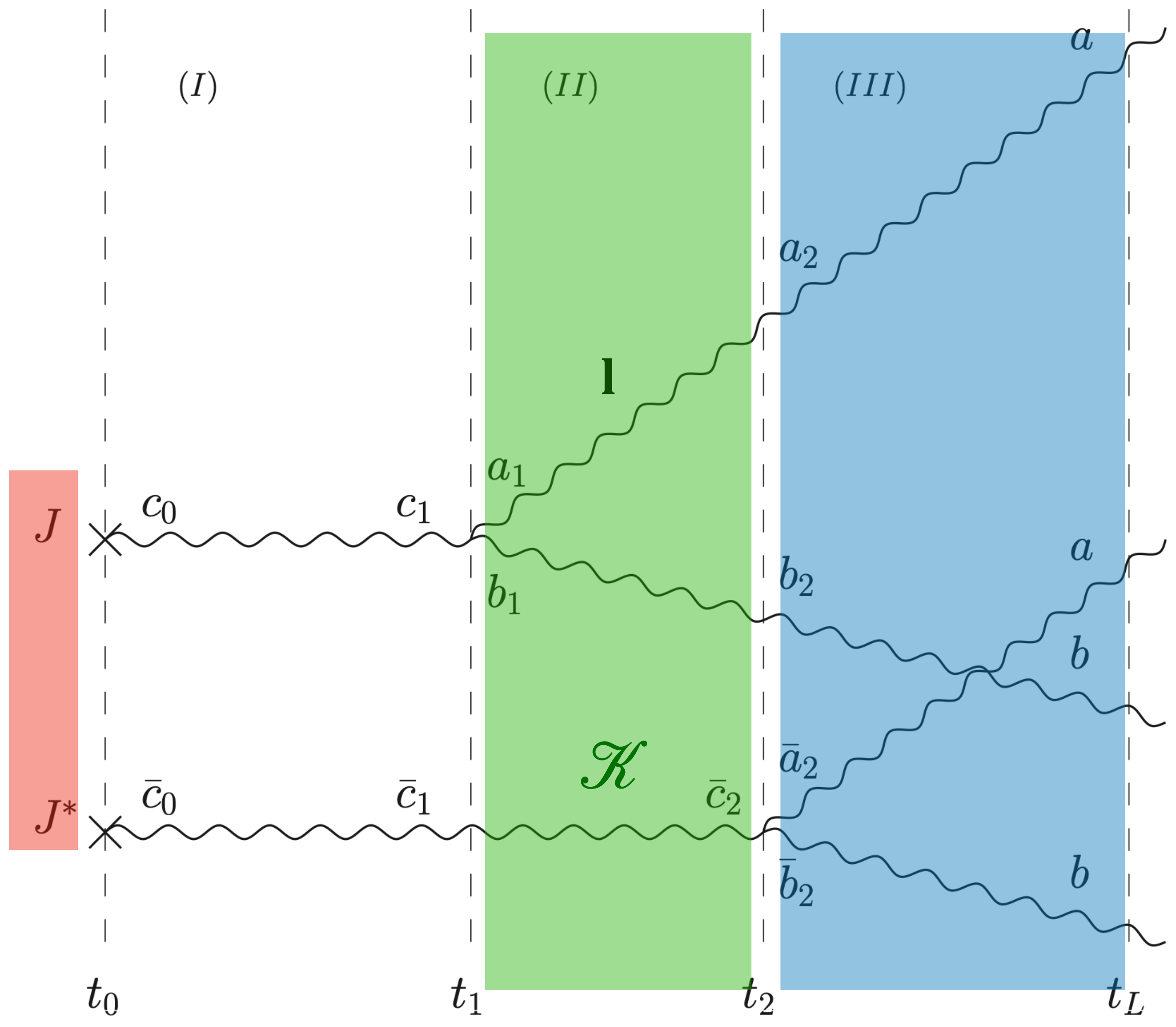


In this case, we can write the squared amplitude as

$$2(2\pi)^3\omega E\frac{d\mathcal{N}}{d\omega dE d^2\boldsymbol{k}} = \frac{2\alpha_s C_F}{\omega^2}\mathrm{Re}\int_0^\infty d\bar z\int_0^{\bar z} dz\int_{\boldsymbol{x}_{in},\boldsymbol{y}}|J(\boldsymbol{x}_{in})|^2\left[\boldsymbol{\nabla}_{\boldsymbol{x}}\cdot\boldsymbol{\nabla}_{\bar{\boldsymbol{x}}}\; S_2\left(\boldsymbol{k},\boldsymbol{k},\infty;\boldsymbol{y},\bar{\boldsymbol{x}},\bar z\right)\mathcal{K}\left(\boldsymbol{y},\boldsymbol{x}_{in},\bar z;\boldsymbol{x},\boldsymbol{x}_{in},z\right)\right]\Big|_{\boldsymbol{x}=\bar{\boldsymbol{x}}=\boldsymbol{x}_{in}}$$

Solved!

Gluon production is determined by a correlator of the form

$$\mathcal{K}\left(\boldsymbol{y},\boldsymbol{x}_{in},\bar z;\boldsymbol{x},\boldsymbol{x}_{in},z\right) = \int_{\boldsymbol{x}}^{\boldsymbol{y}}D\boldsymbol{r}\, e^{\frac{i\omega}{2}\int d\tau\,\dot{\boldsymbol{r}}^2-\int_z^{\bar z}d\tau\,\left(1+\frac{\boldsymbol{r}(\tau)+\boldsymbol{x}_{in}}{2}\cdot\hat{\boldsymbol{g}}\right)\mathcal{V}(\boldsymbol{r}(\tau)-\boldsymbol{x}_{in})}$$

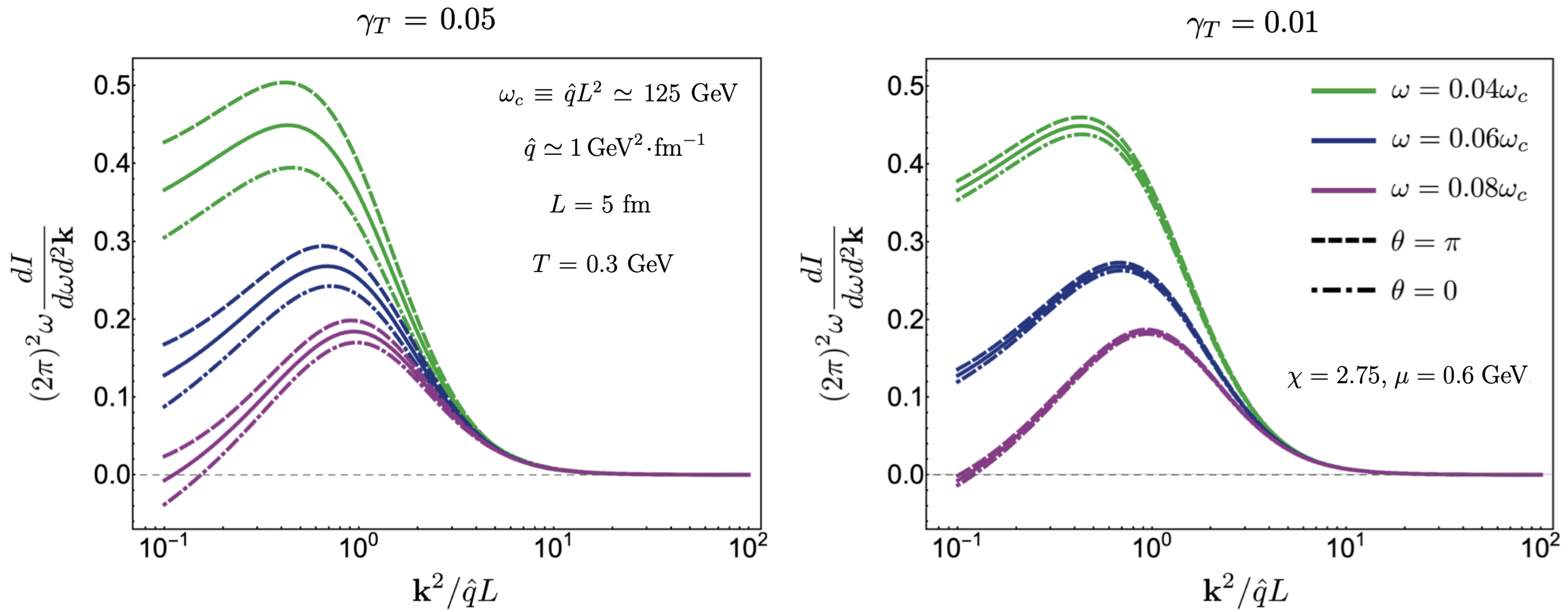
This object satisfies a simple recursive equation; expanding to first order in gradients it allows to perturbatively compute the spectrum in the form

$$\omega\frac{dI}{d\omega d^2\boldsymbol{k}} = \omega\frac{dI_0}{d\omega d^2\boldsymbol{k}} + (\hat{\boldsymbol{g}}\cdot\boldsymbol{k})\,\omega\frac{dI_1}{d\omega d^2\boldsymbol{k}} + \mathcal{O}(\hat{\boldsymbol{g}}^2)$$

$$\omega\frac{dI}{d\omega d^2\boldsymbol{k}} = \omega\frac{dI_0}{d\omega d^2\boldsymbol{k}} + \omega\frac{dI_{\mathcal{P}}}{d\omega d^2\boldsymbol{k}} + \omega\frac{dI_{\mathcal{K}}}{d\omega d^2\boldsymbol{k}} + \omega\frac{dI_{\hat{\mathsf{S}}}}{d\omega d^2\boldsymbol{k}}$$

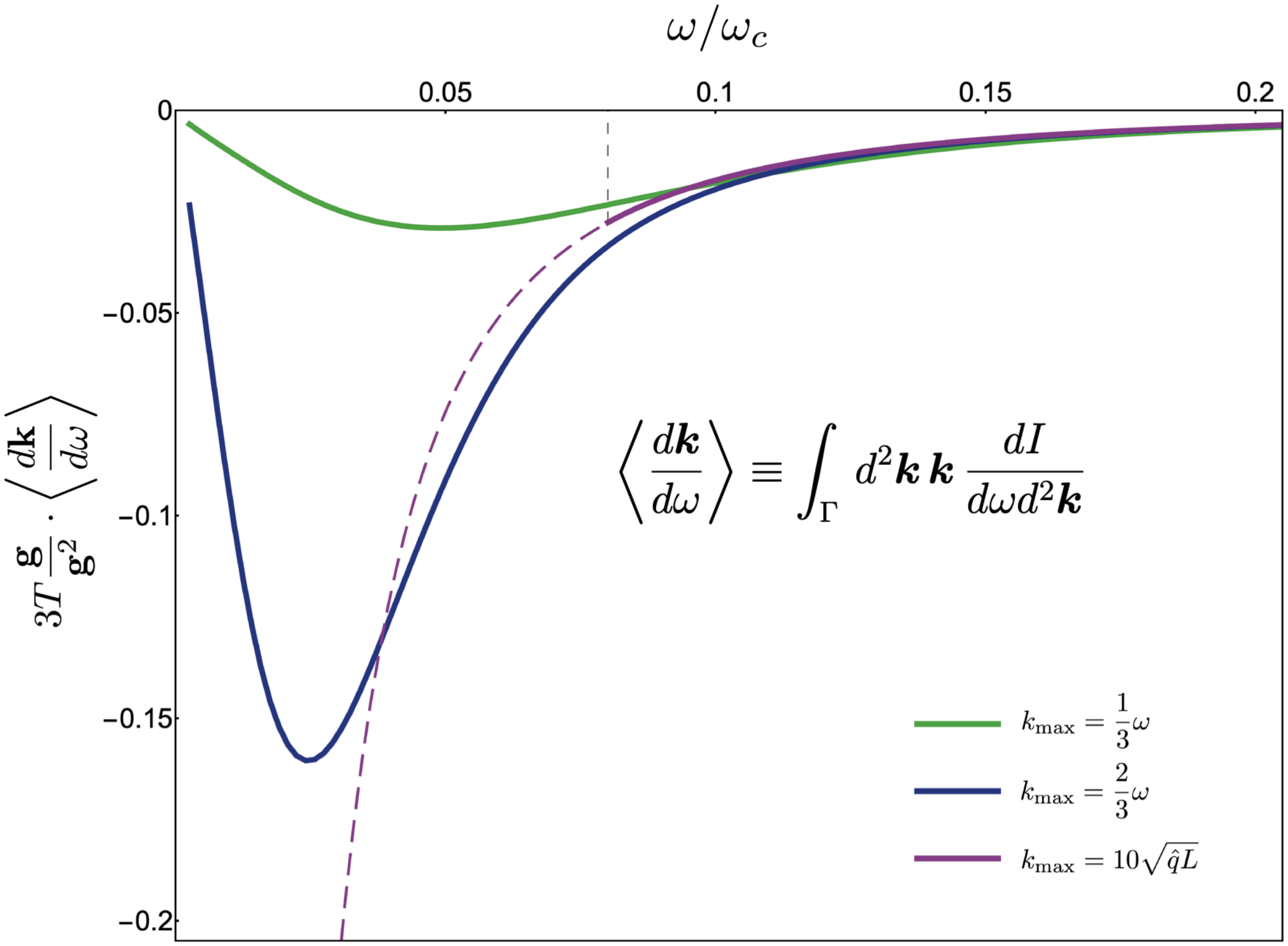
Radiative energy loss in dense anisotropic media

Numerical results, in the harmonic approximation for the in-medium scattering cross-section



$$\gamma_T = |\nabla T/T^2|$$

Radiative energy loss in dense anisotropic media



Jet observables in inhomogeneous matter

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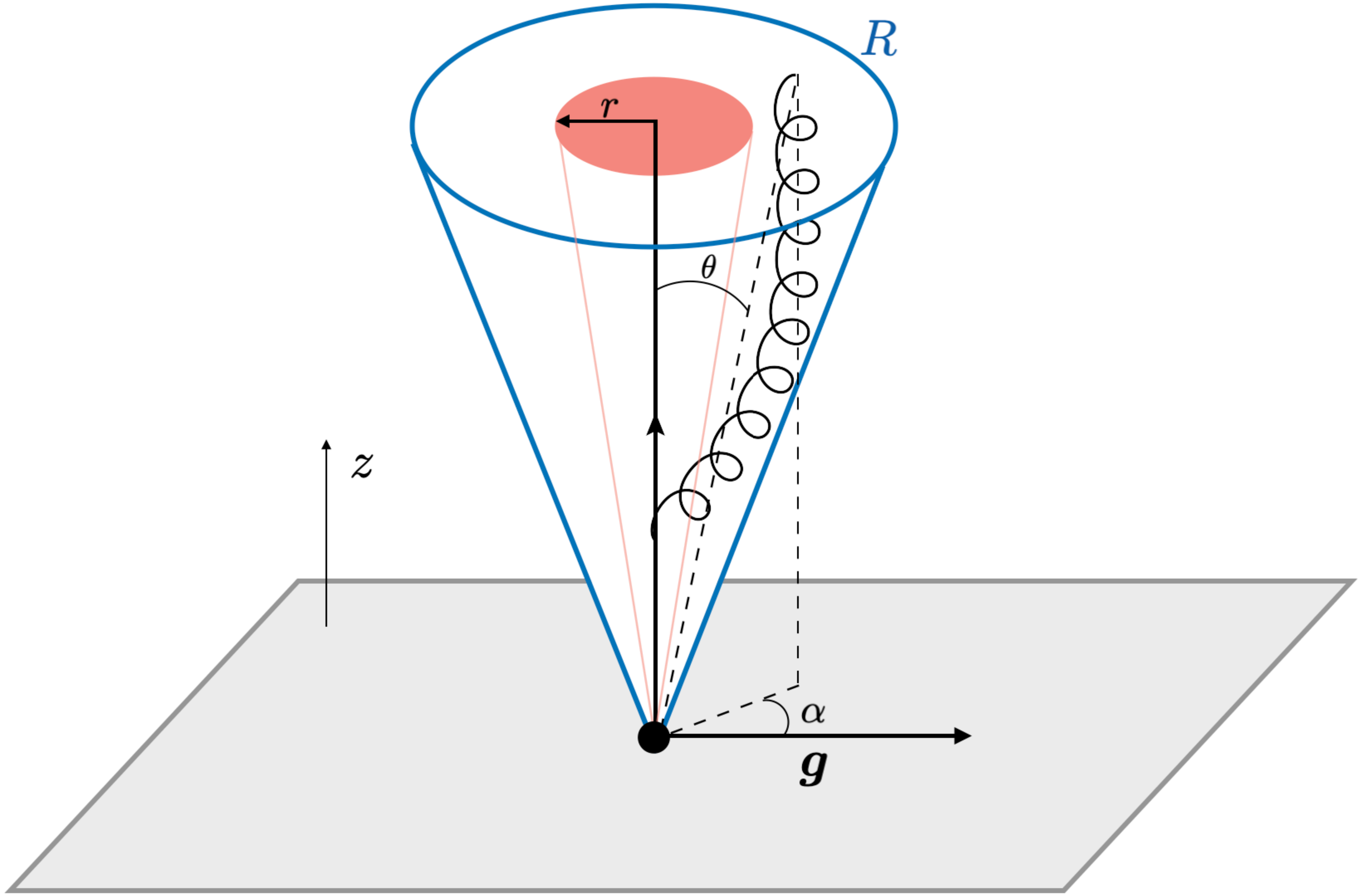


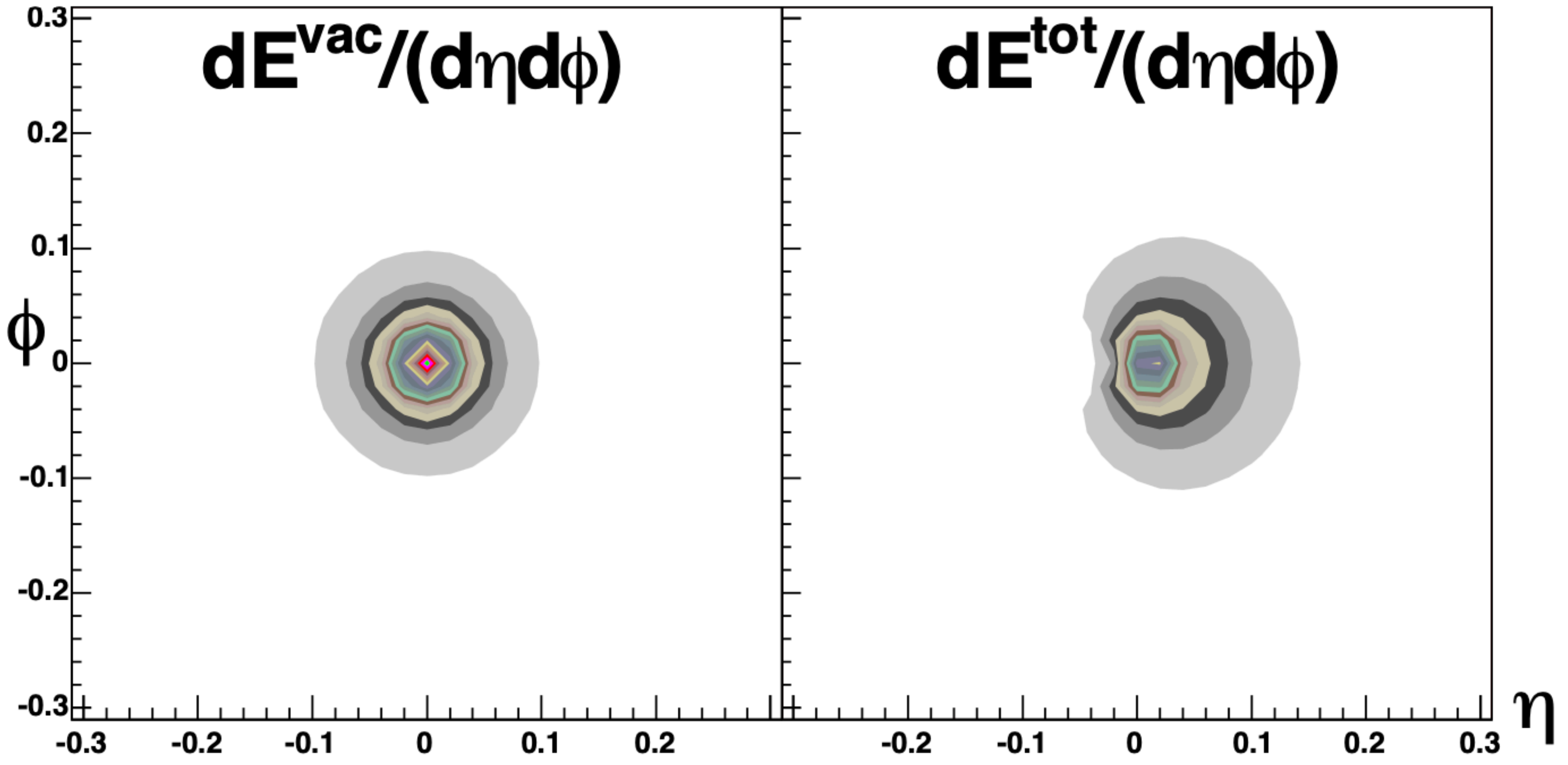
Jet observables in inhomogeneous matter

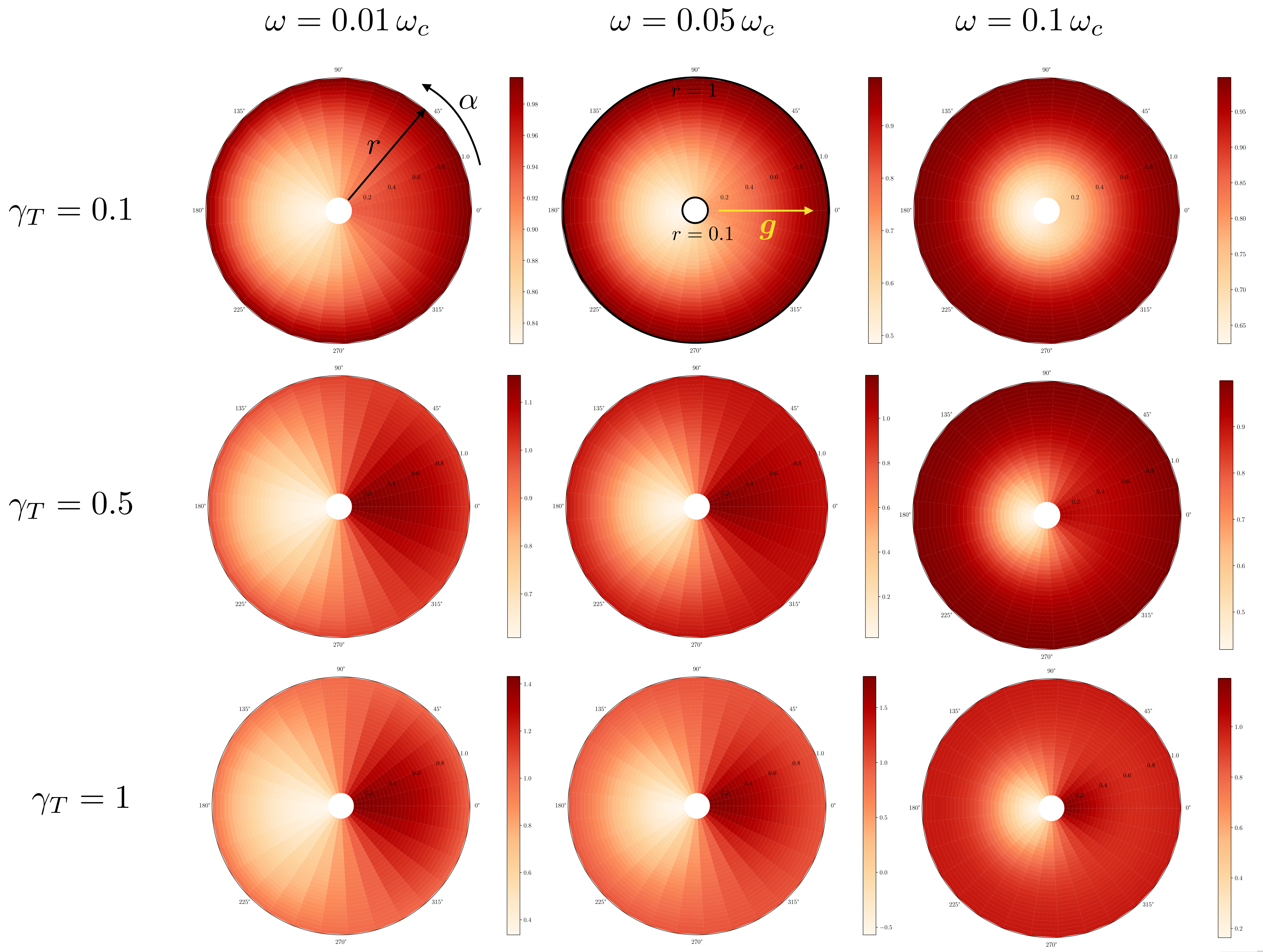
We have now the tools to compute jet observables (at least at leading order in strong coupling)

Observable 1: jet shape

$$(2\pi)p_t^{\mathrm{jet}}\frac{d\rho(r)}{d\omega d\alpha} = 1 - 2\pi\int_{\omega r}^{\omega} dk\,k\,\omega\frac{dI}{d\omega d^2\boldsymbol{k}}$$

2004, Armesto, Salgado, Wiedemann





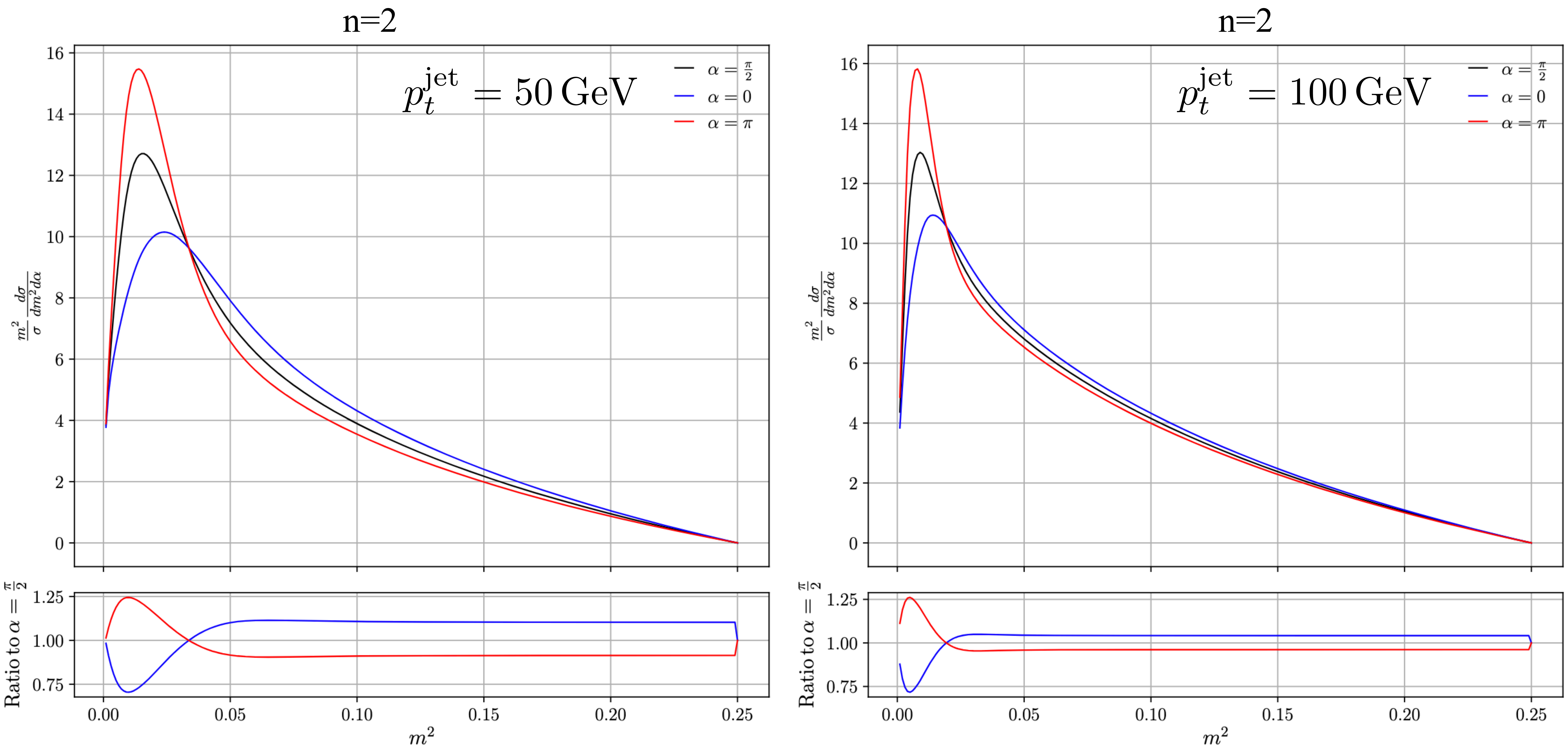
Jet observables in inhomogeneous matter

Brookhaven National Laboratory

Observable 2: jet angularities $G_n = \sum_{i \in \text{jet}} \frac{p_t^i}{p_t^{\text{jet}}} g^{(n)}(r_i)$

At leading logarithmic order we have

$$\frac{g_n}{\sigma}\frac{d\sigma}{dg_n d\alpha} = \left(\int_{\frac{g_n}{R^n}}^{1} dx \left(\frac{\omega dI}{d\omega d^2\boldsymbol{k}} \frac{(p_t^{\text{jet}})^2 x^{1-\frac{2}{n}} g_n^{\frac{2}{n}}}{n} \right)_{\theta^n = \frac{g_n}{x}} + \frac{\alpha_s C_F}{\pi^2 n} \log \frac{R^n}{g_n} \right) e^{-\frac{\alpha_s C_F}{n\pi} \log^2 \frac{R^n}{g_n}}$$



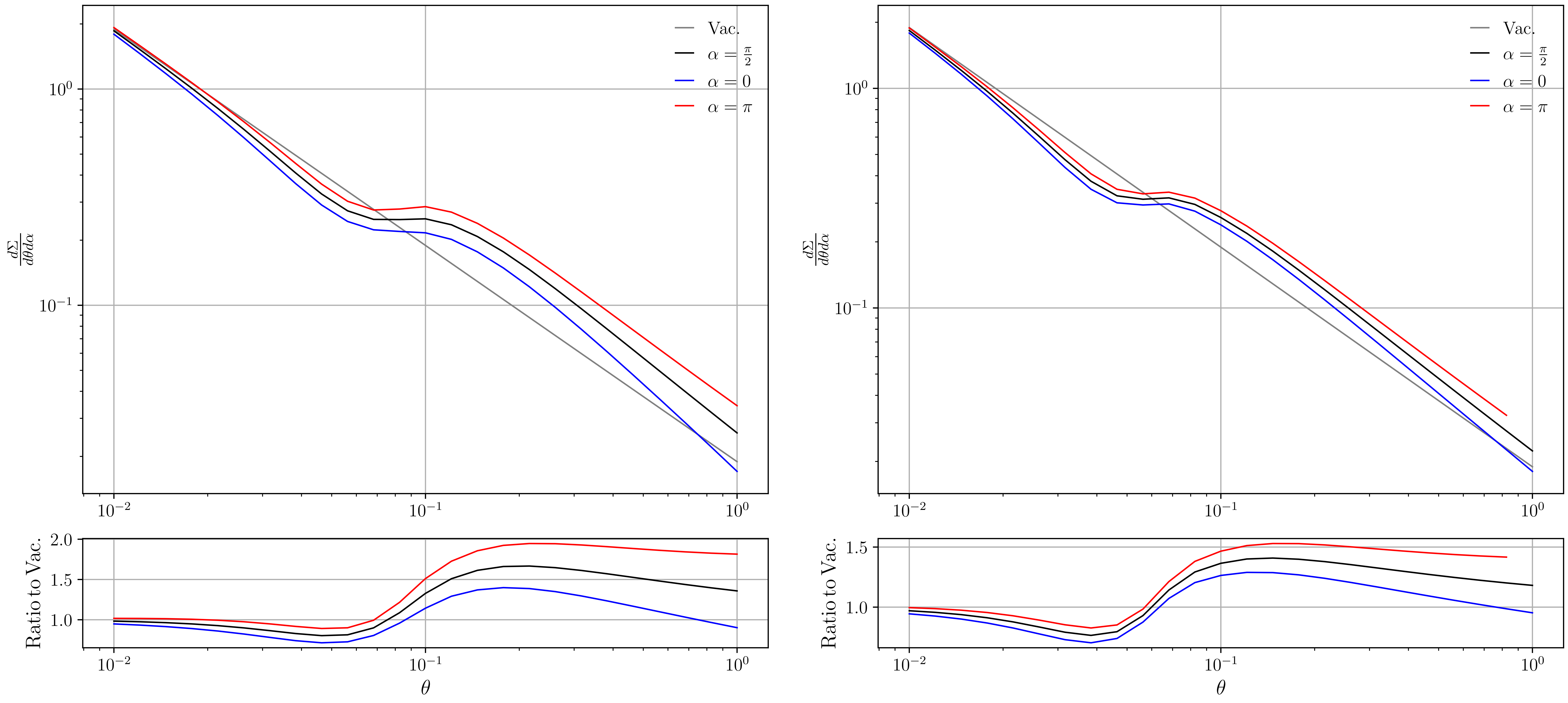
Jet observables in inhomogeneous matter

Observable 3: ENCs

Ideally we would need E3C, but already with EEC we have

$$\frac{d\Sigma}{d\theta d\alpha} = \int d\vec{n}_1 d\vec{n}_2 \, \frac{\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle}{(p_t^{\rm jet})^2} \delta(\cos(\theta_2-\theta_1)-\cos(\theta))\, \delta(\alpha-(\alpha_1-\alpha_2))$$

for HICs and refs see Andres et al (2307.06226)



Outlook

① I only discussed modifications due to anisotropies

Similar effects can be studied for medium flow

Jet Broadening in Flowing Matter – Resummation

Carlota Andres,[1,*] Fabio Dominguez,[2,†] Andrey V. Sadofyev,[2,‡] and Carlos A. Salgado[2,§]

② To go beyond we need MC with realistic geometries:

LBT model seems to agree with our approach !