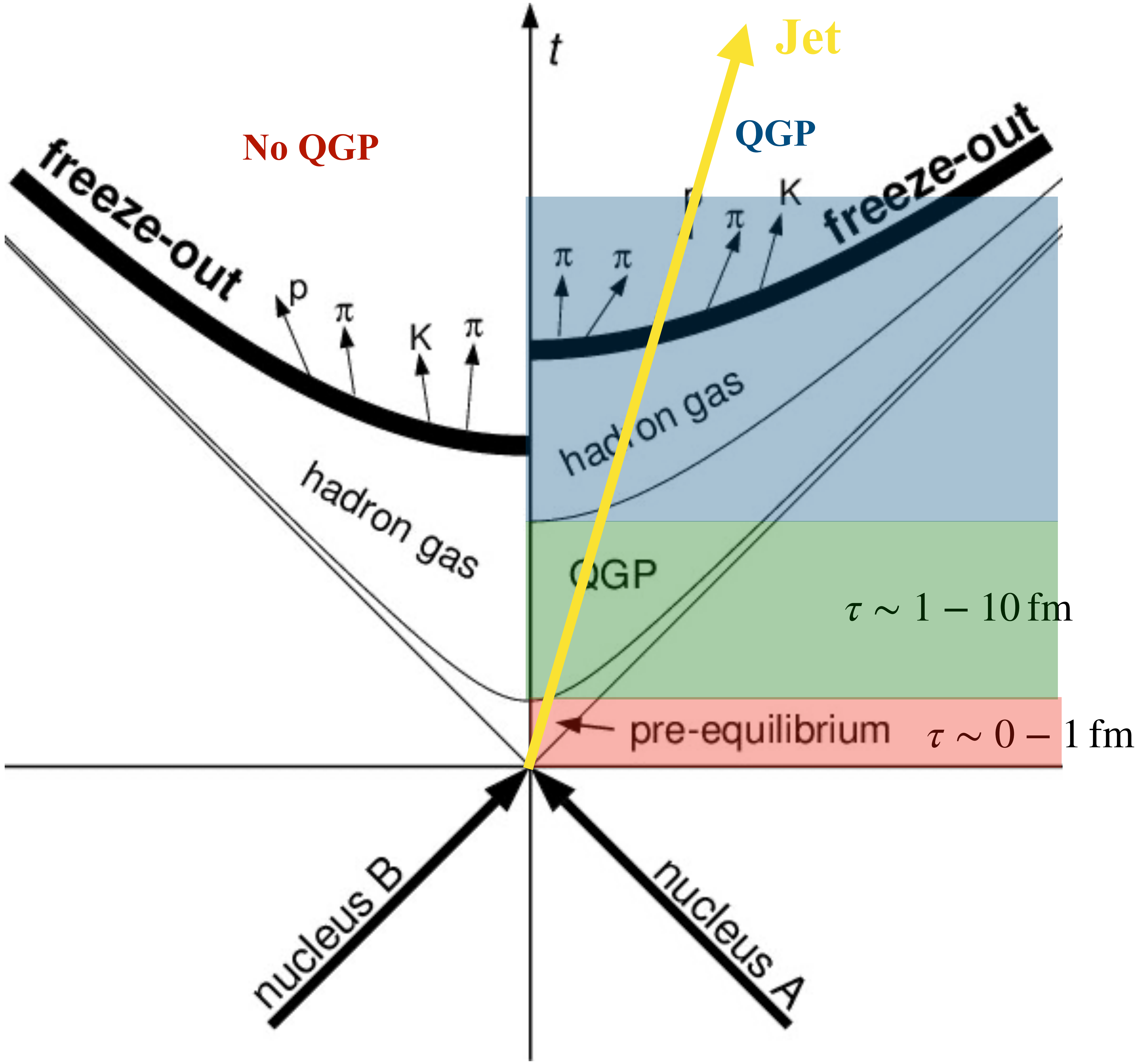
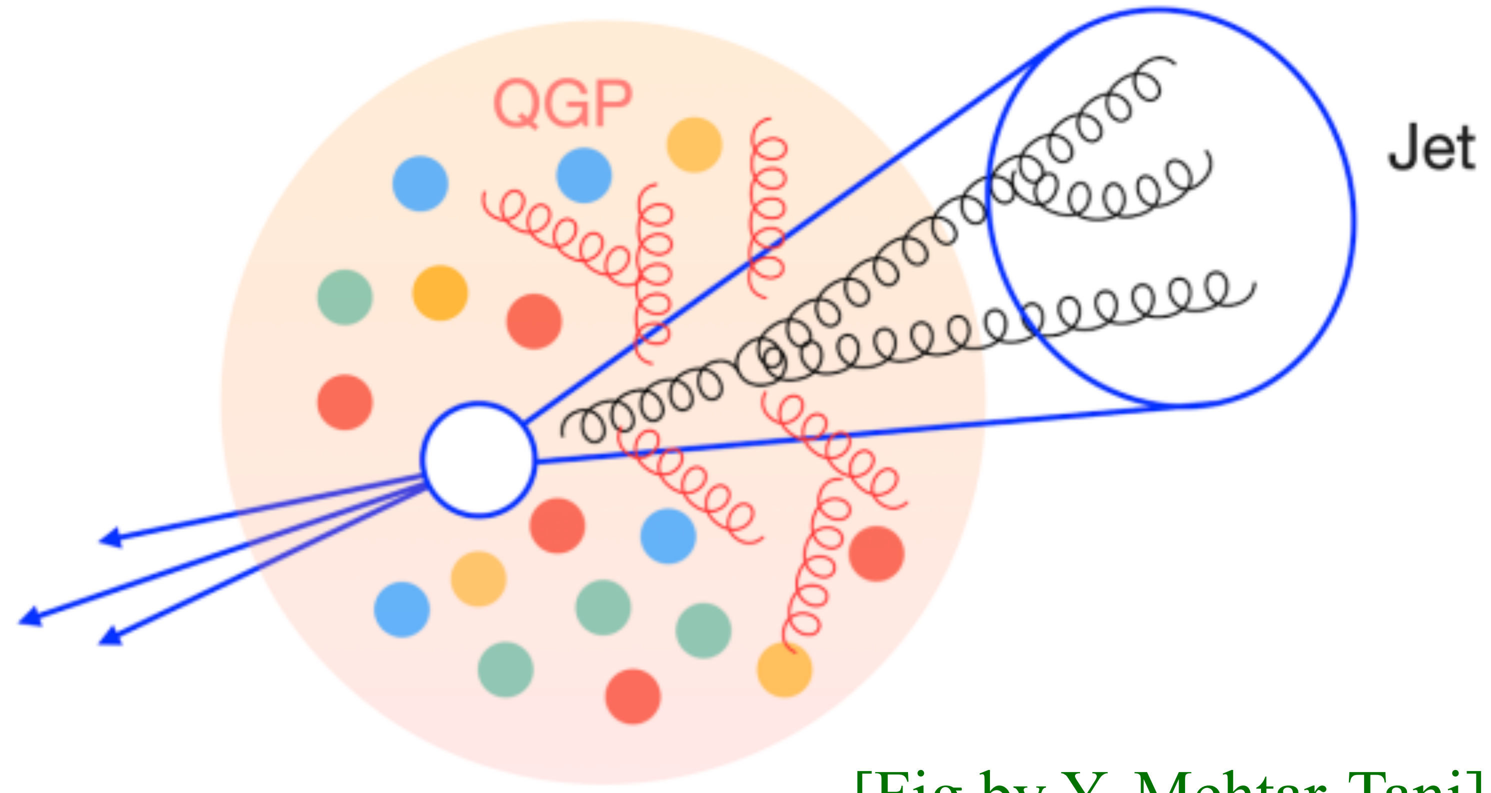
Jet anisotropies in jet quenching

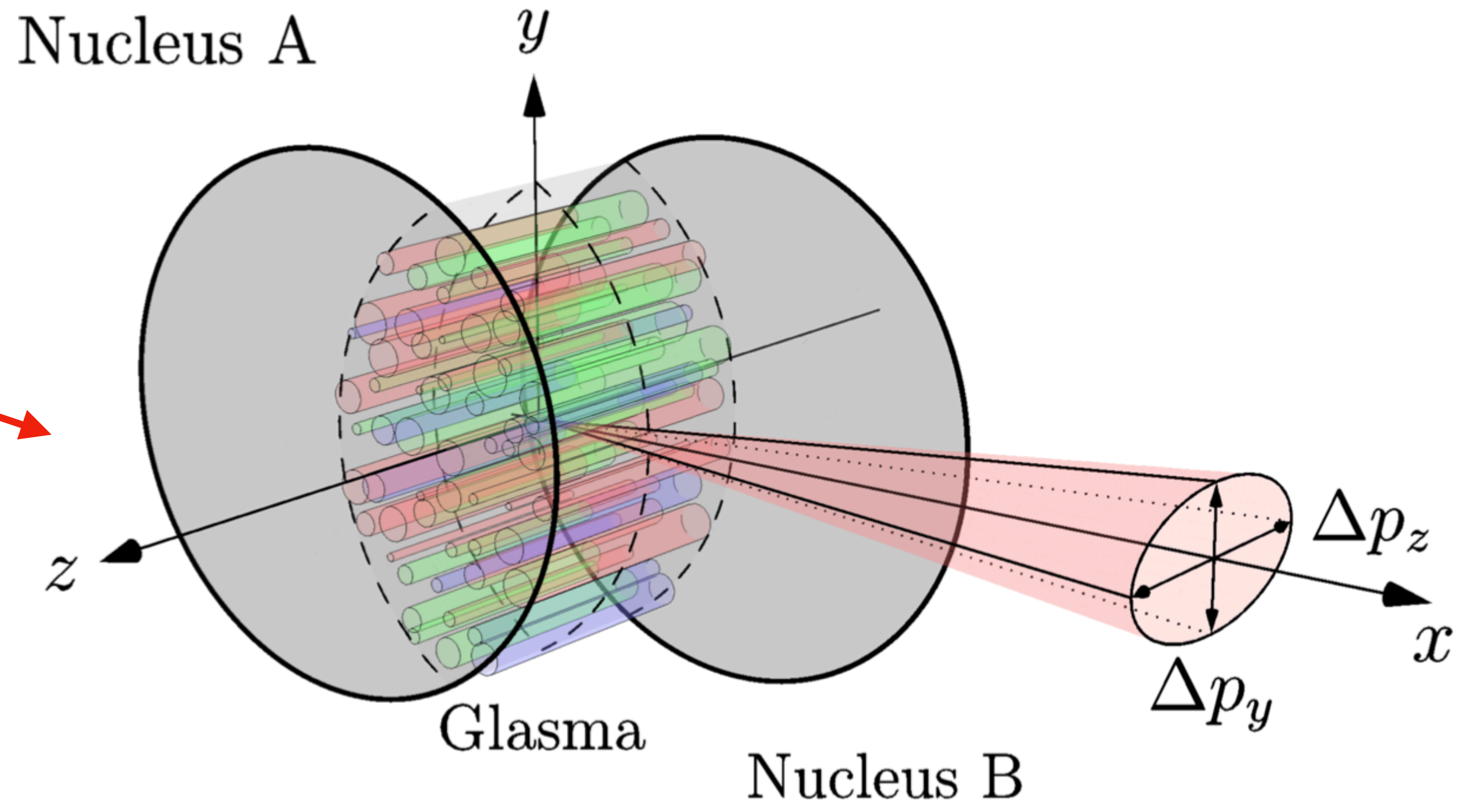
4th September 2024, Muenster

João Barata, BNL





[Fig by Y. Mehtar-Tani]



[A. App, D. I. Muller, D. Schuh, 2009.14206]

The Landscape

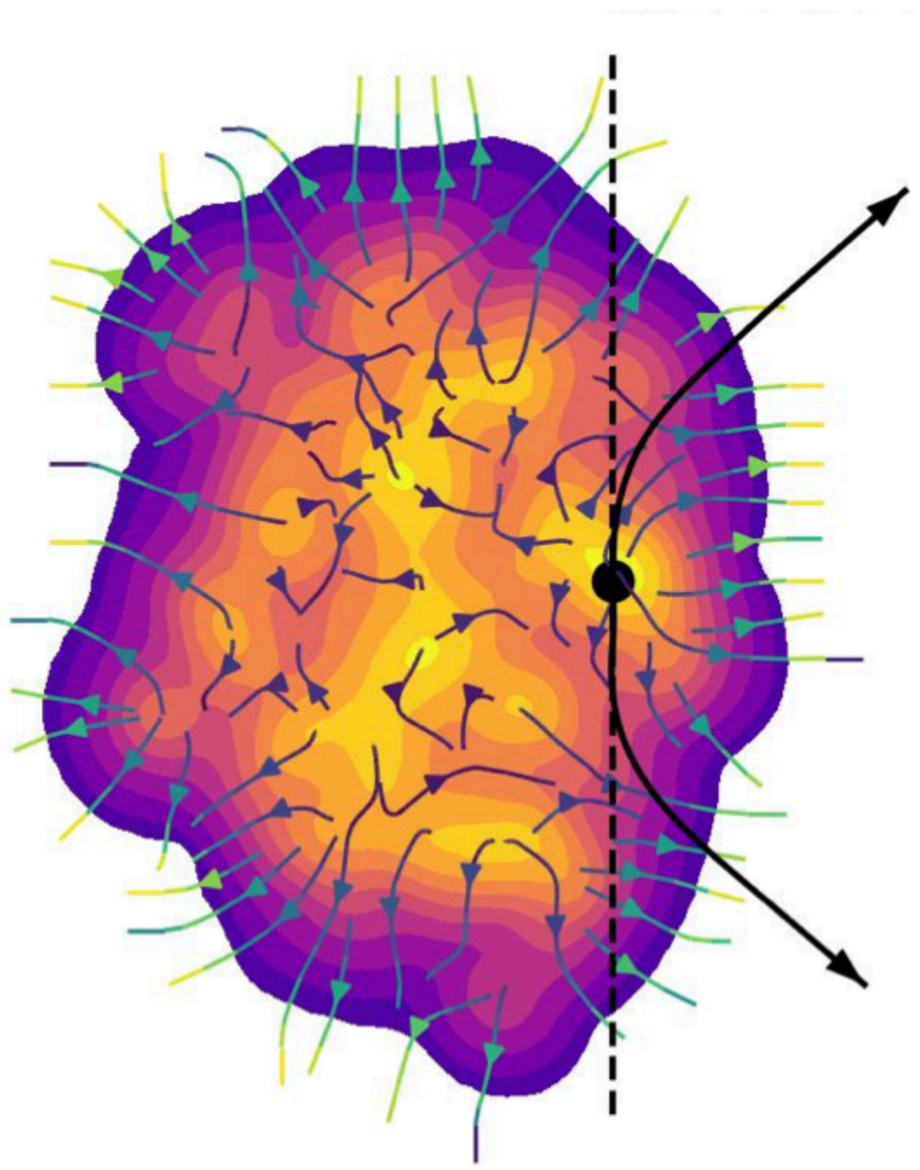
The Landscape

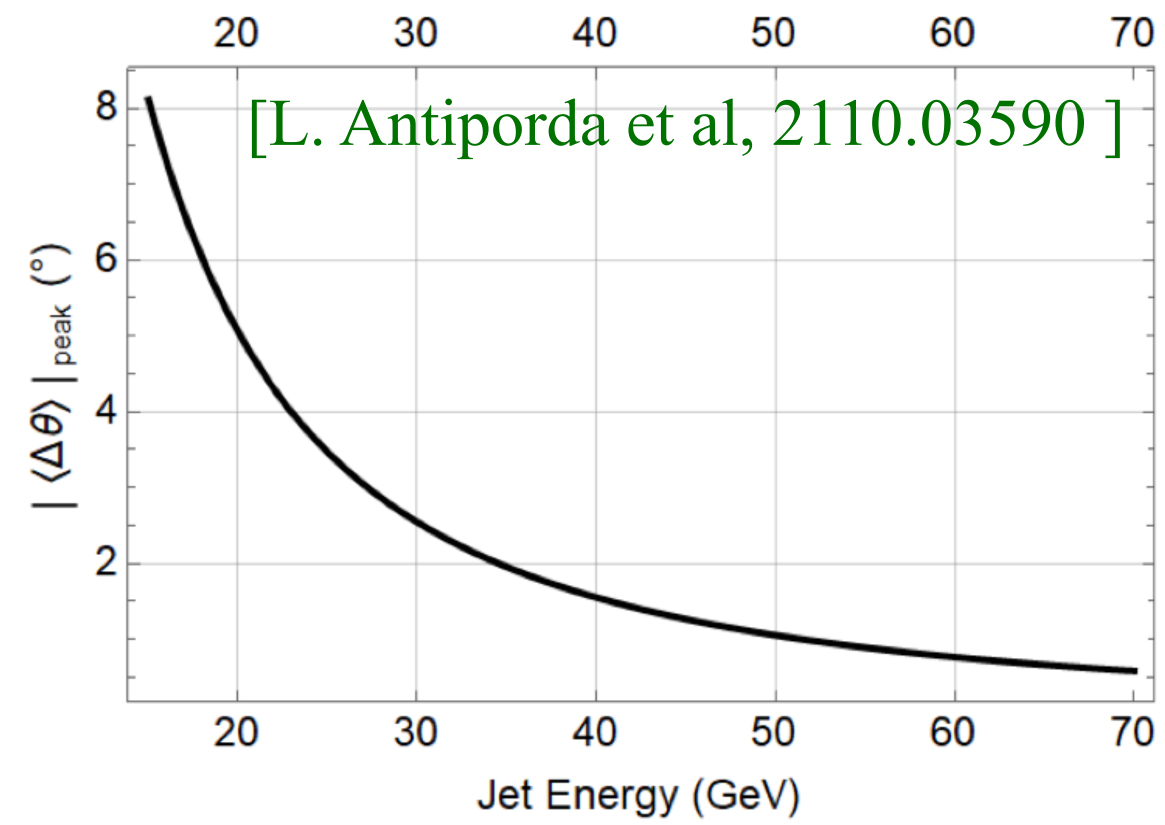
Jet evolution in hydrodynamical phase

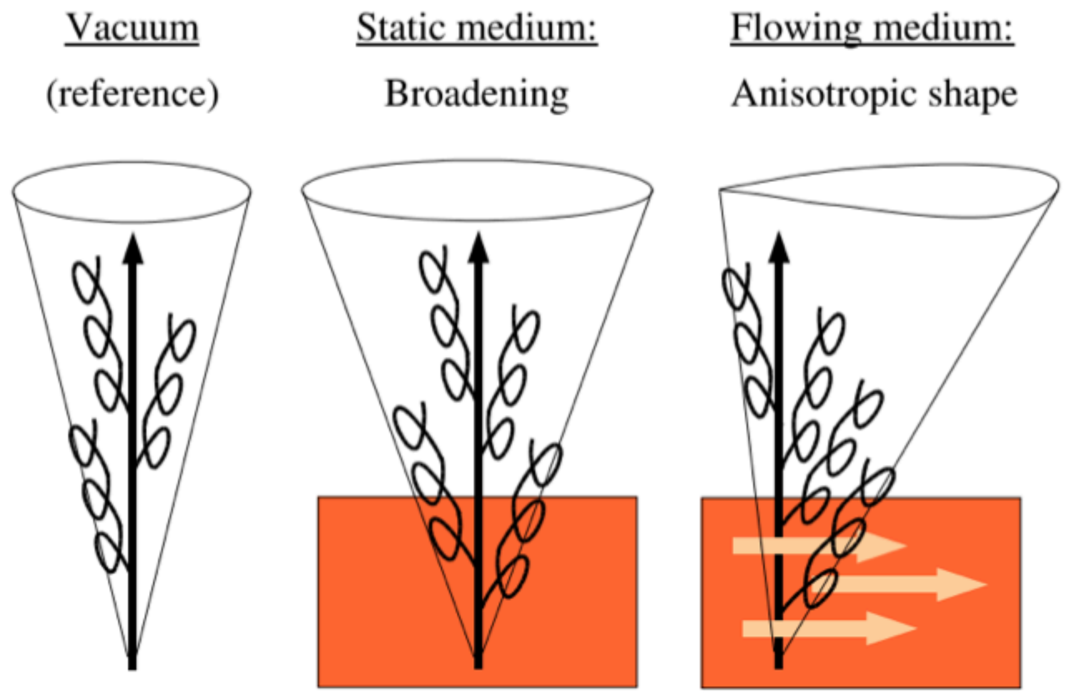
Flowing matter: 2104.09513 [N=1], 2207.07141 [Resummation], 2406.14628 [Gluon radiation], 2309.00683 [Flowing anisotropic matter], …

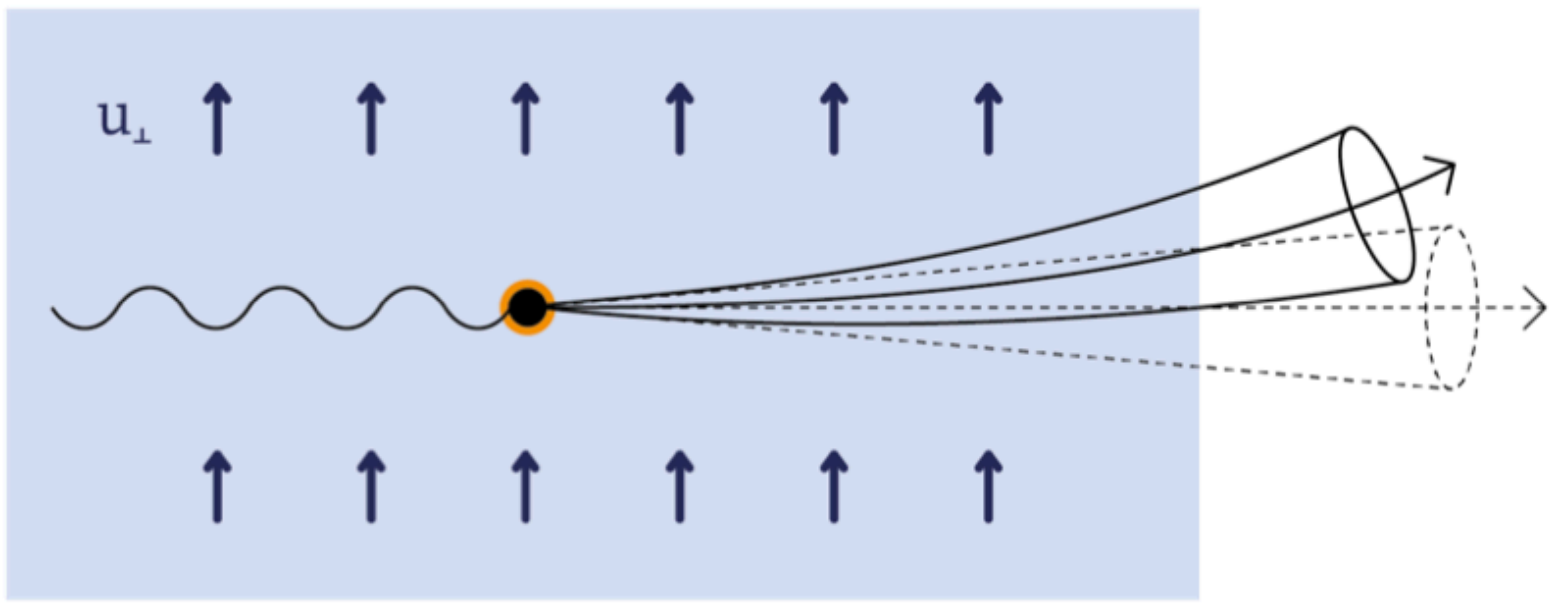
Matter gradients: 2104.09513 [N=1], 2202.08847 [Resummation], 2210.06519 [Kinetic Th.], 2304.03712 [Gluon Radiation], 2204.05323 [Broadening]

Jet observables/Pheno: 2110.03590 [Jet drift], 2308.01294 [Jet substructure], DREENA, …



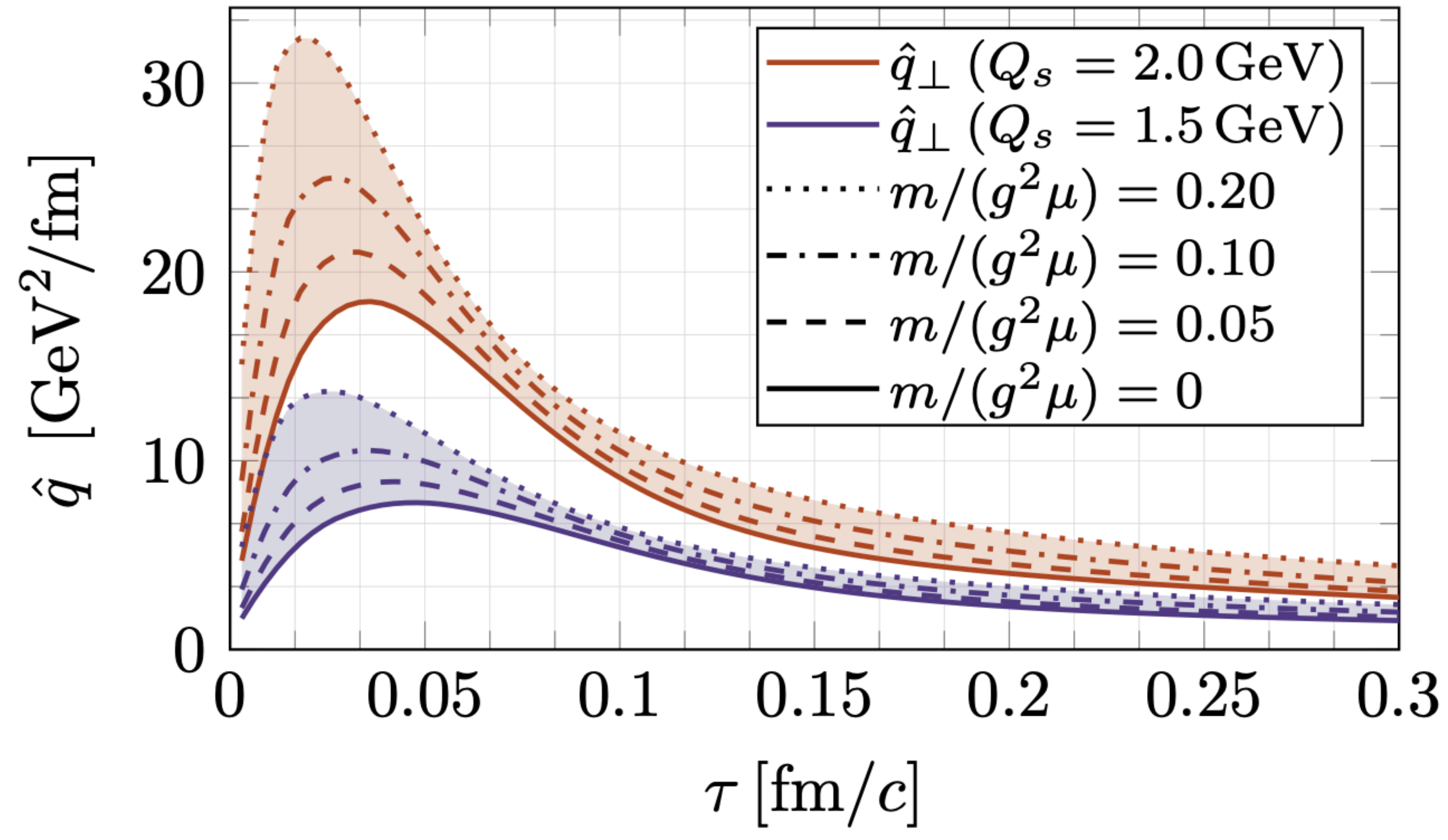


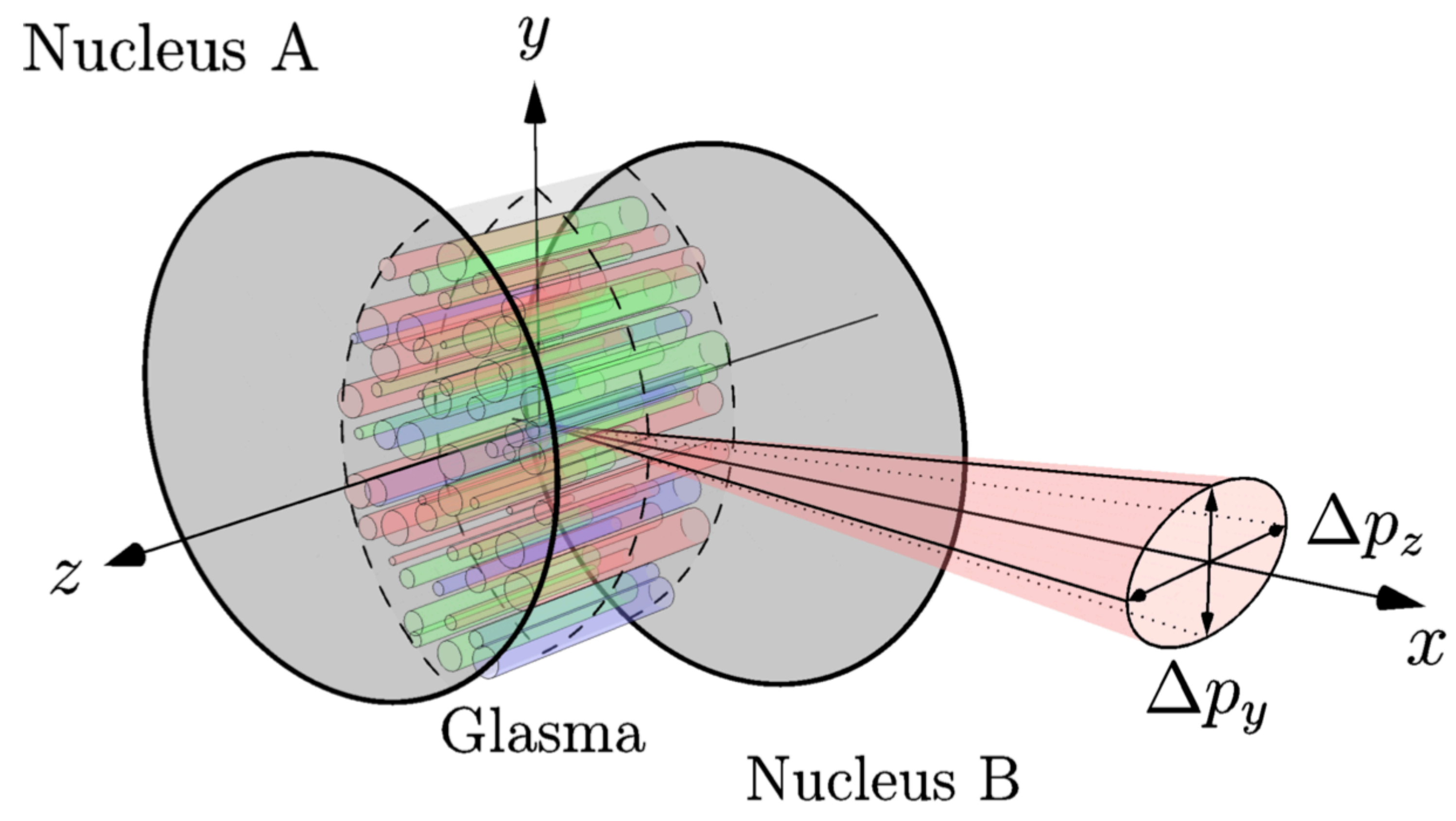




The Landscape

[A. Ipp, D. I. Muller, D. Schuh, 2009.14206]





Jet evolution in the early stages

Momentum broadening in early stages: Works by Avramescu et al; Lindebauer et al; Muller et al, …

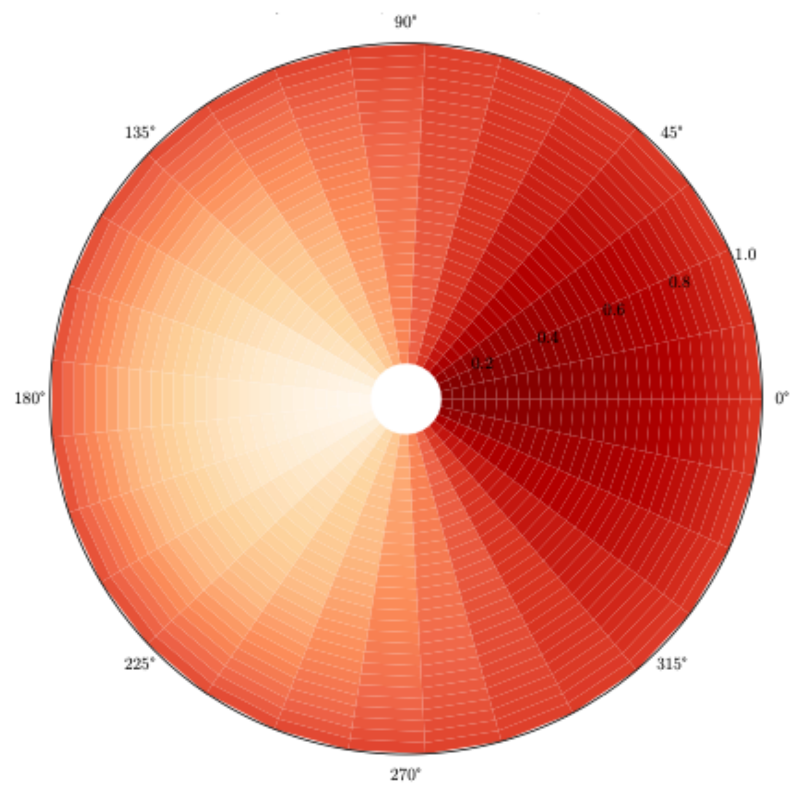
Radiative spectrum in "glasma": 2306.20307 [Photons], 2303.03914 [Gluon branching], 2407.04774 [Quark antenna], 2406.07615 [Spatial correlations]

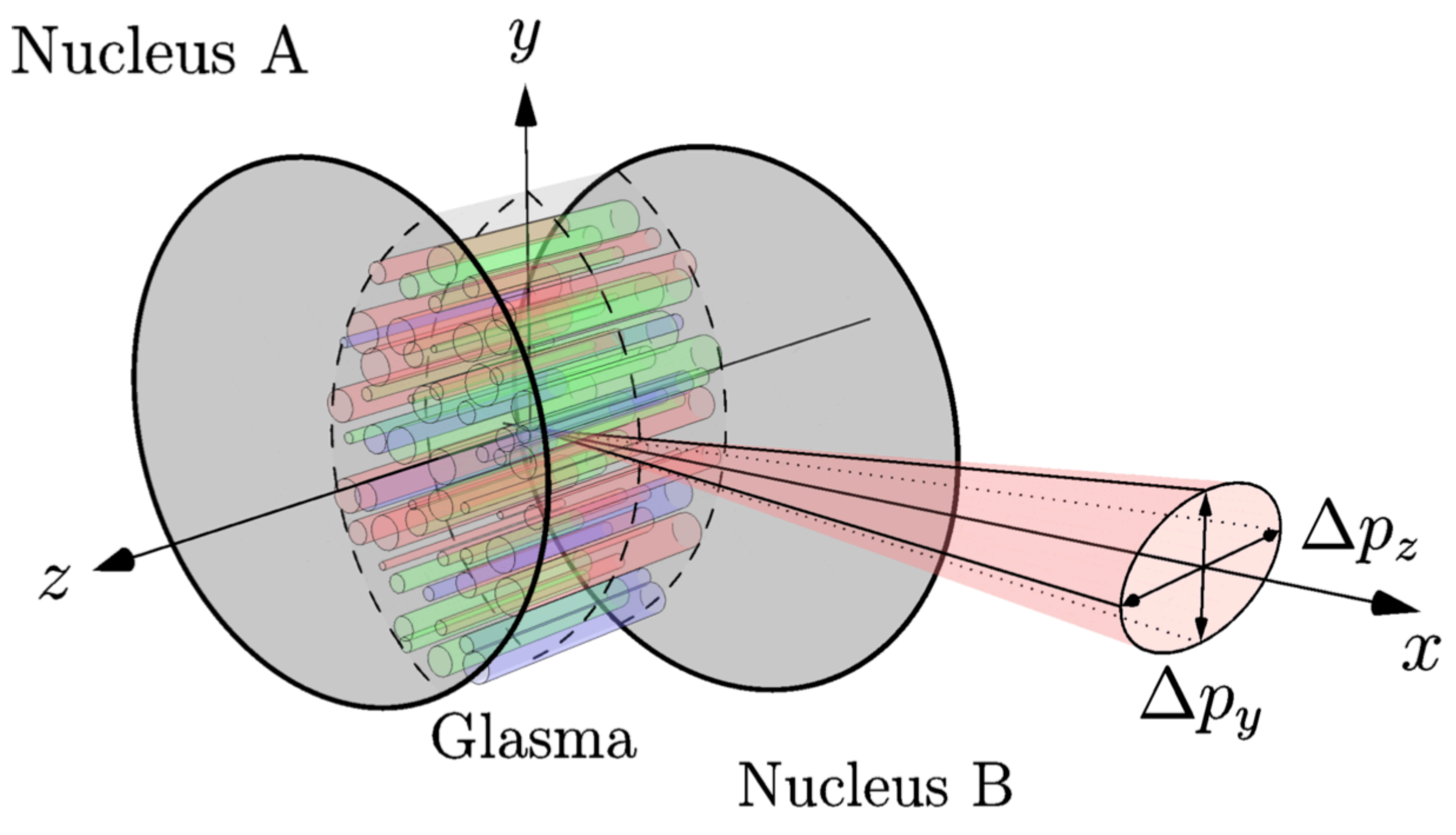
A lot of recent pheno and theory activity, but why is this important ? Can we measure ?

The Questions

The Questions

1) How about existing measurements (e.g. Jet FF, jet radial profile)? What insights do they provide ? Do we need new tools ? Yes





2) Are there any new (orthogonal) observables that we need to consider ?

A few, but not studied in great detail in theory or pheno; small exp. interest

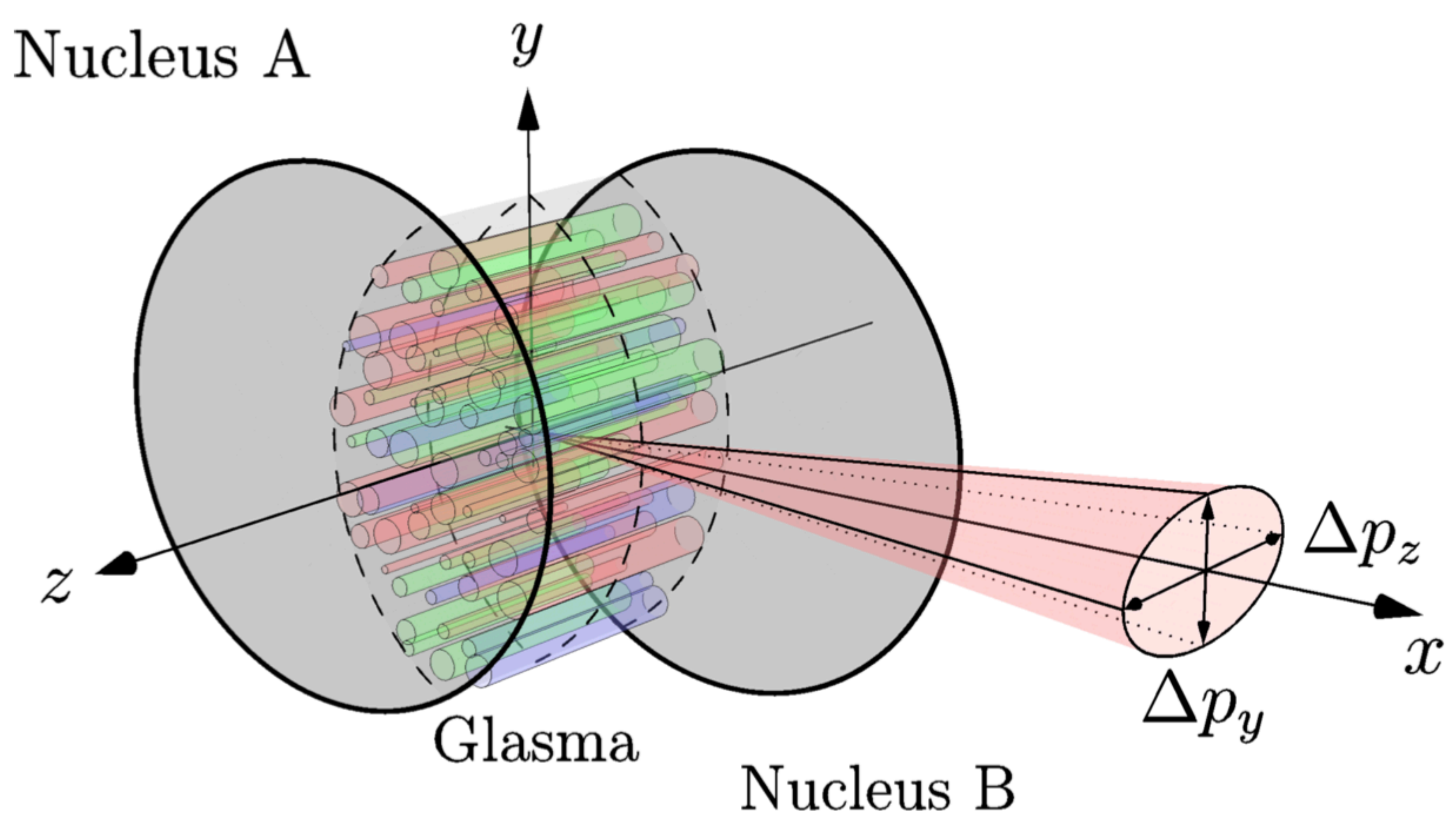
3) Based on our physics goals, can we already identify a particular set of observables ?

Yes: azimuthally unintegrated jet substructure obs. , spin dependent obs., …

Why is this hard(er) ? Soft-hard correlation, more differential obs., less theoretical control, …

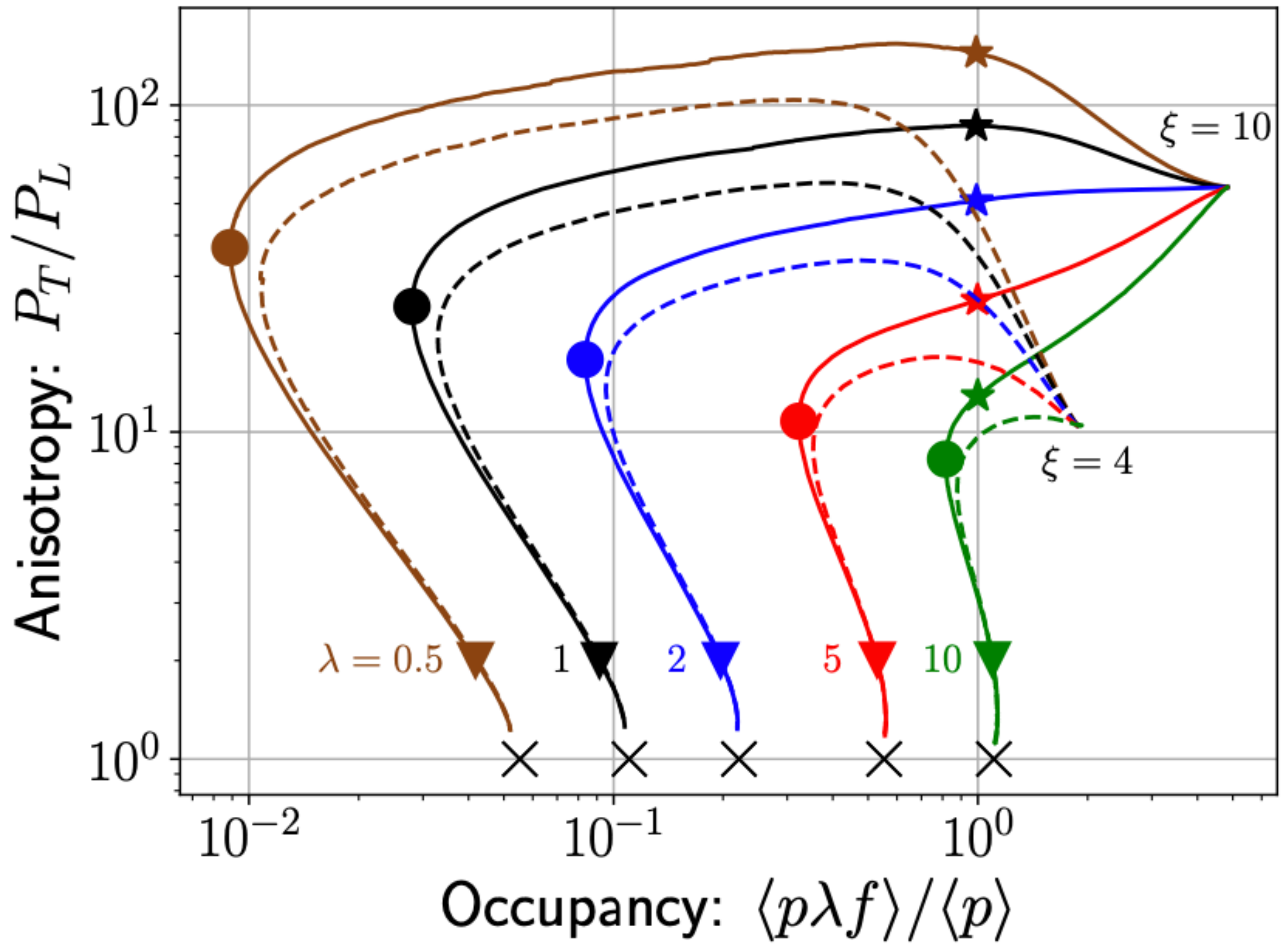
Another Landscape

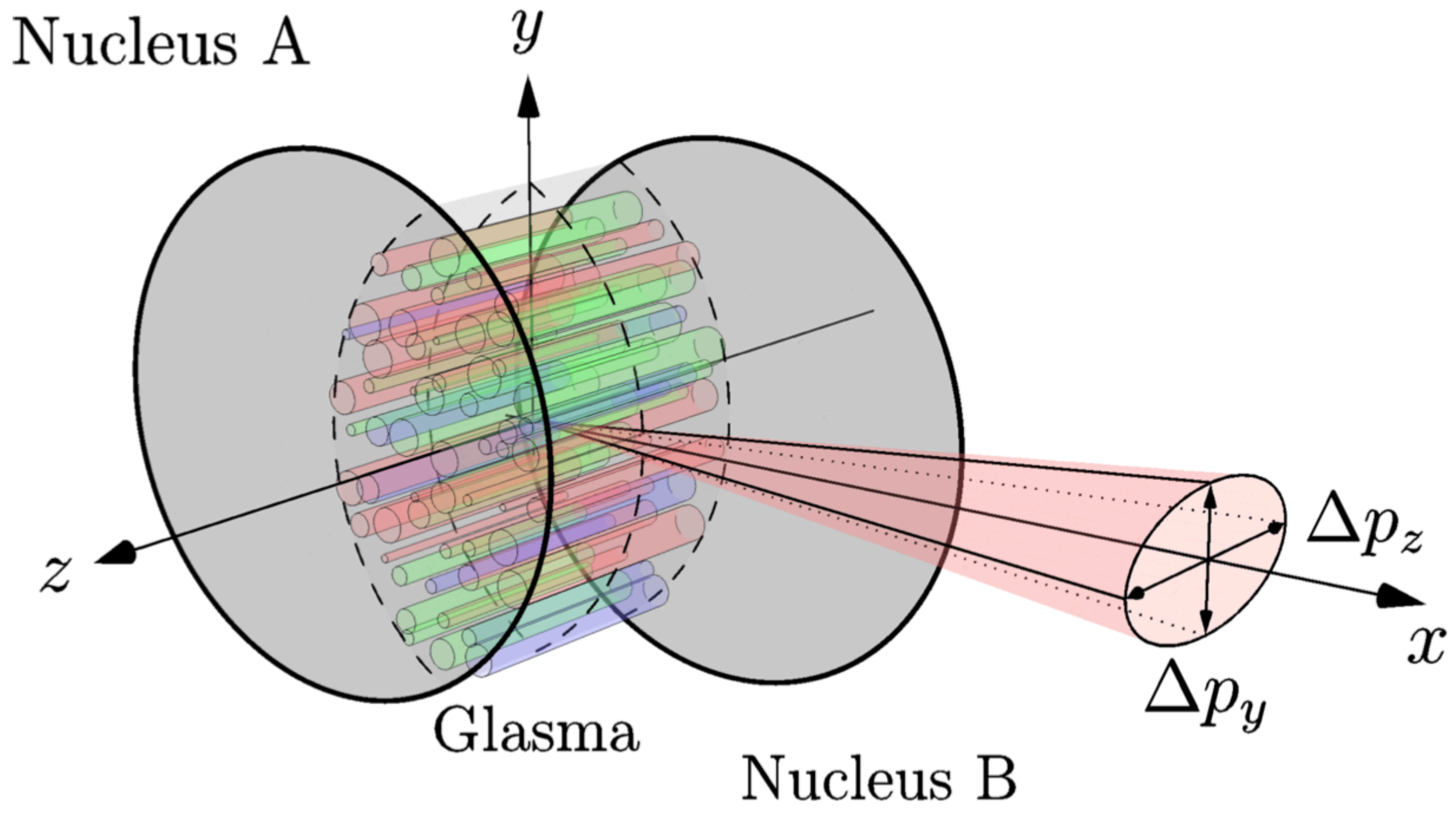
Jet evolution in the Glasma



Why are the early stages "different"

[F. Lindebauer, et al, 2023]





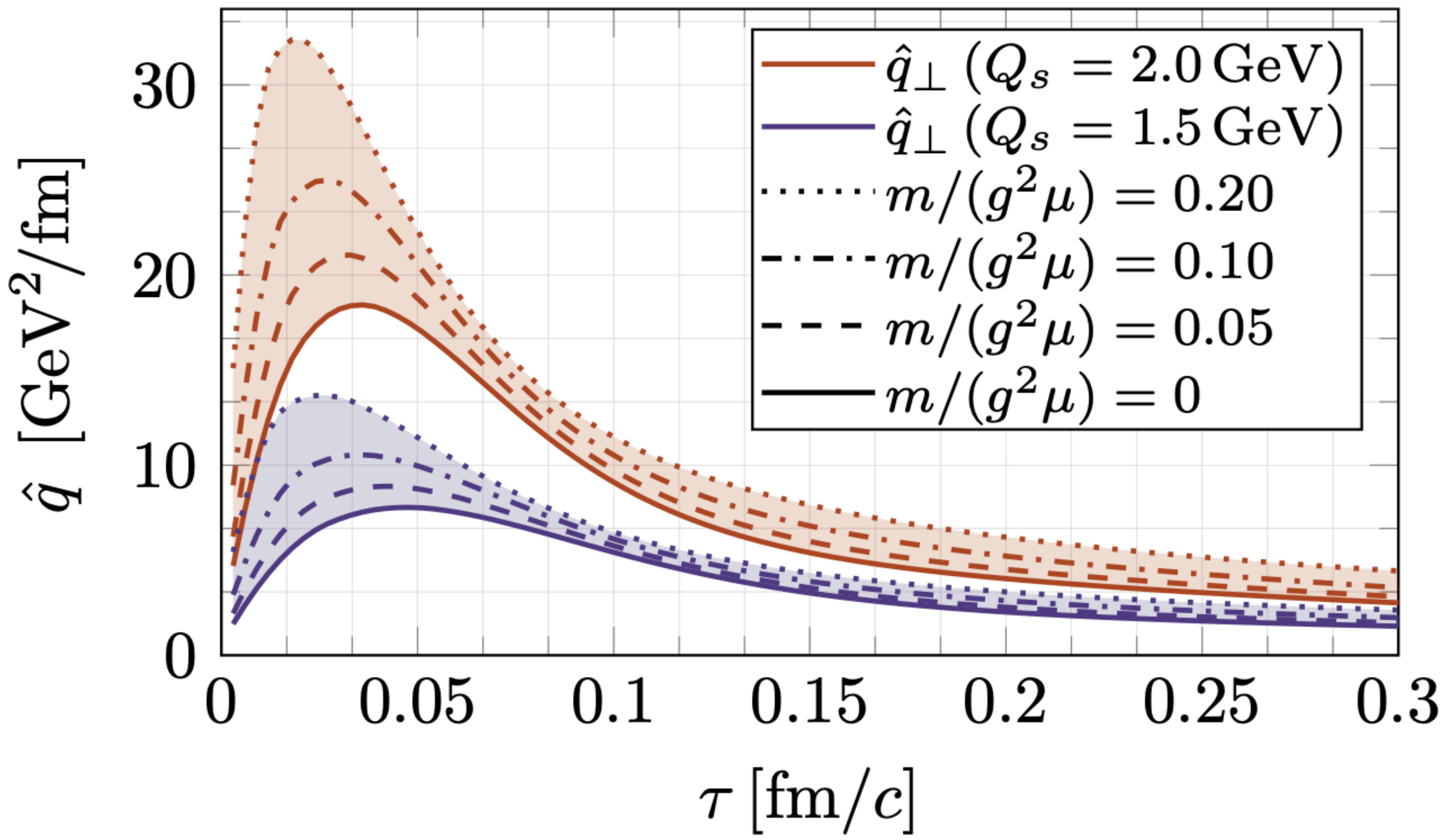
- At early times there is a big pressure anisotropy
- This reflects in an anisotropic transport coefficient
  [Can be washed out by hydro expansion]

$$\hat{q}_x \gg \hat{q}_y$$

- Furthermore, the observed jet quenching coefficient seems to be much larger than the hydro one
  [Observables integrate over jet path]

$$\hat{q}_{\text{early}} \gg \hat{q}_{\text{hydro}}\,,\ \tau_{\text{hydro}} \gg \tau_{\text{early}}$$

[A. Ipp, D. I. Muller, D. Schuh, 2009.14206]



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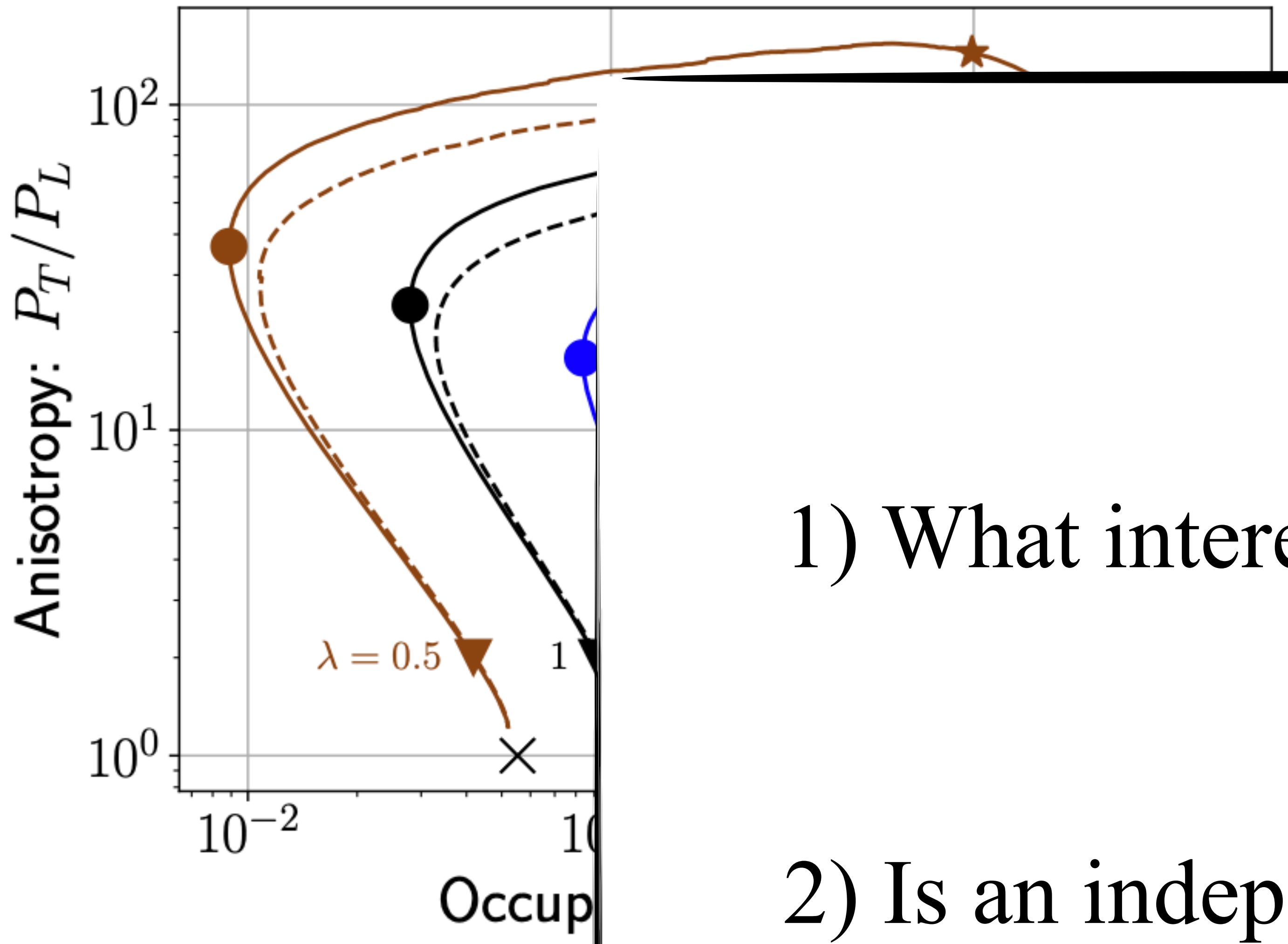


oefficient
d out by hydro expansion]

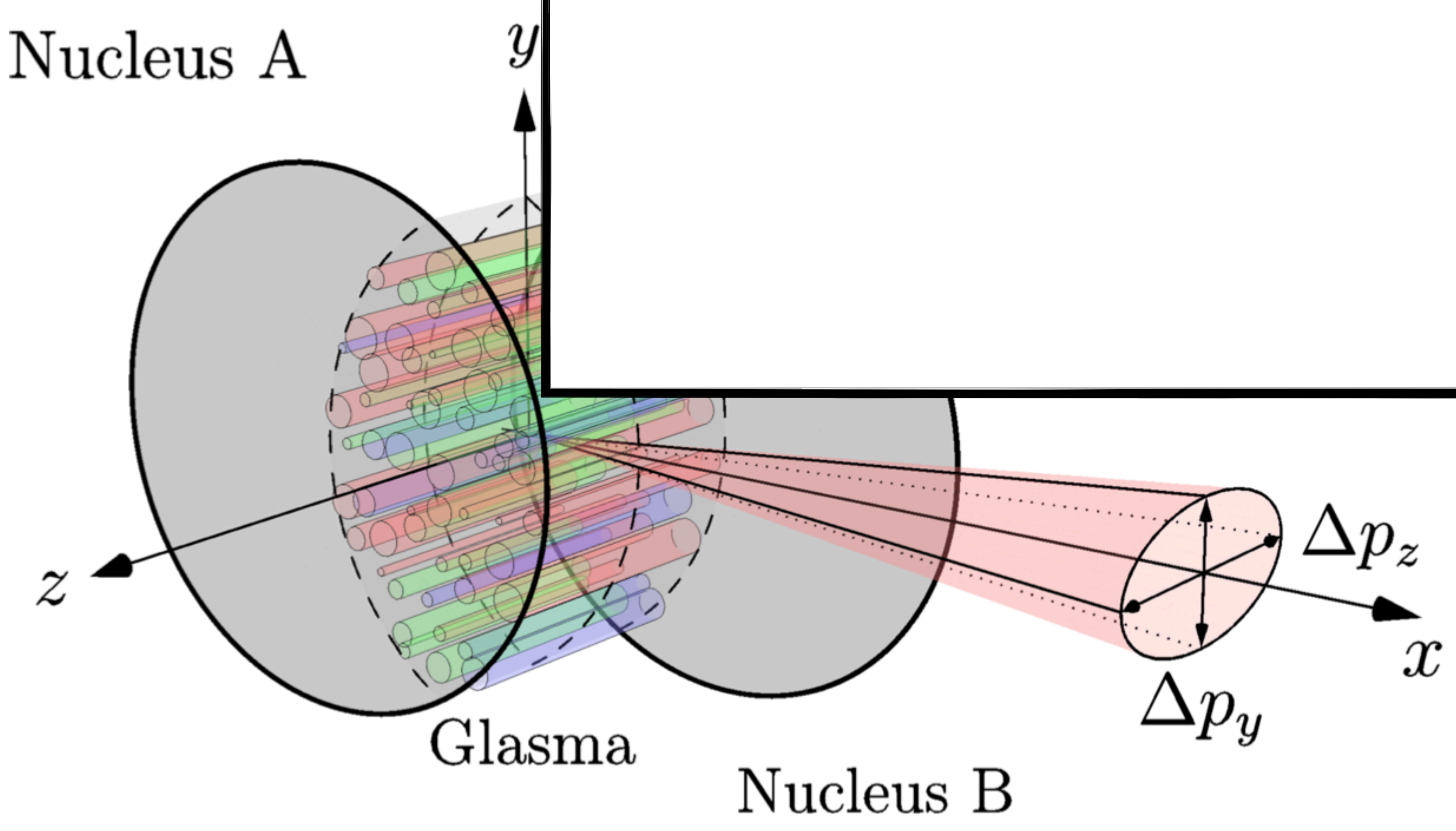
coefficient

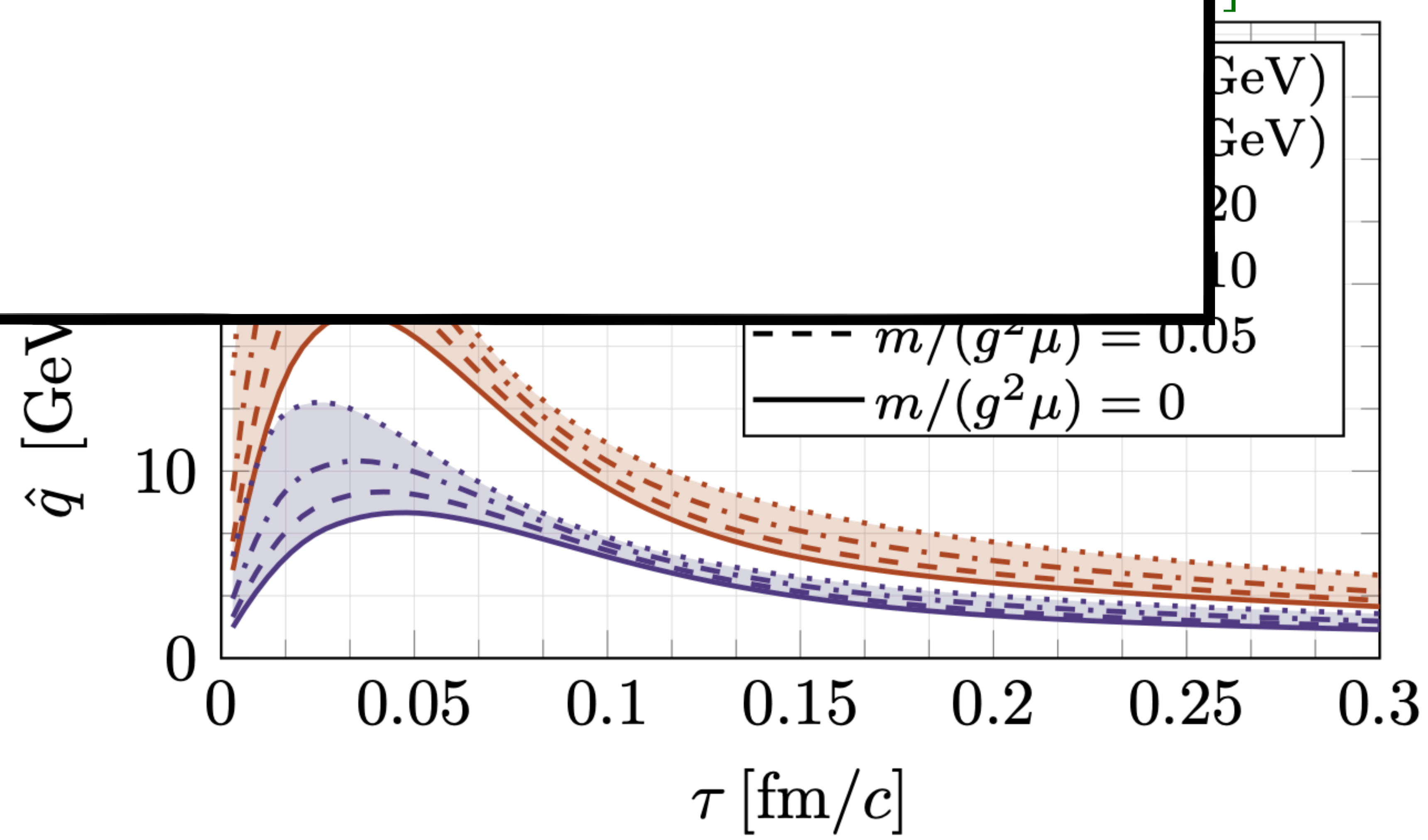
oservables integrate over jet path]

early

1) What interesting features can we see from early time anisotropies?

2) Is an independent multiple scattering picture still meaningful ?





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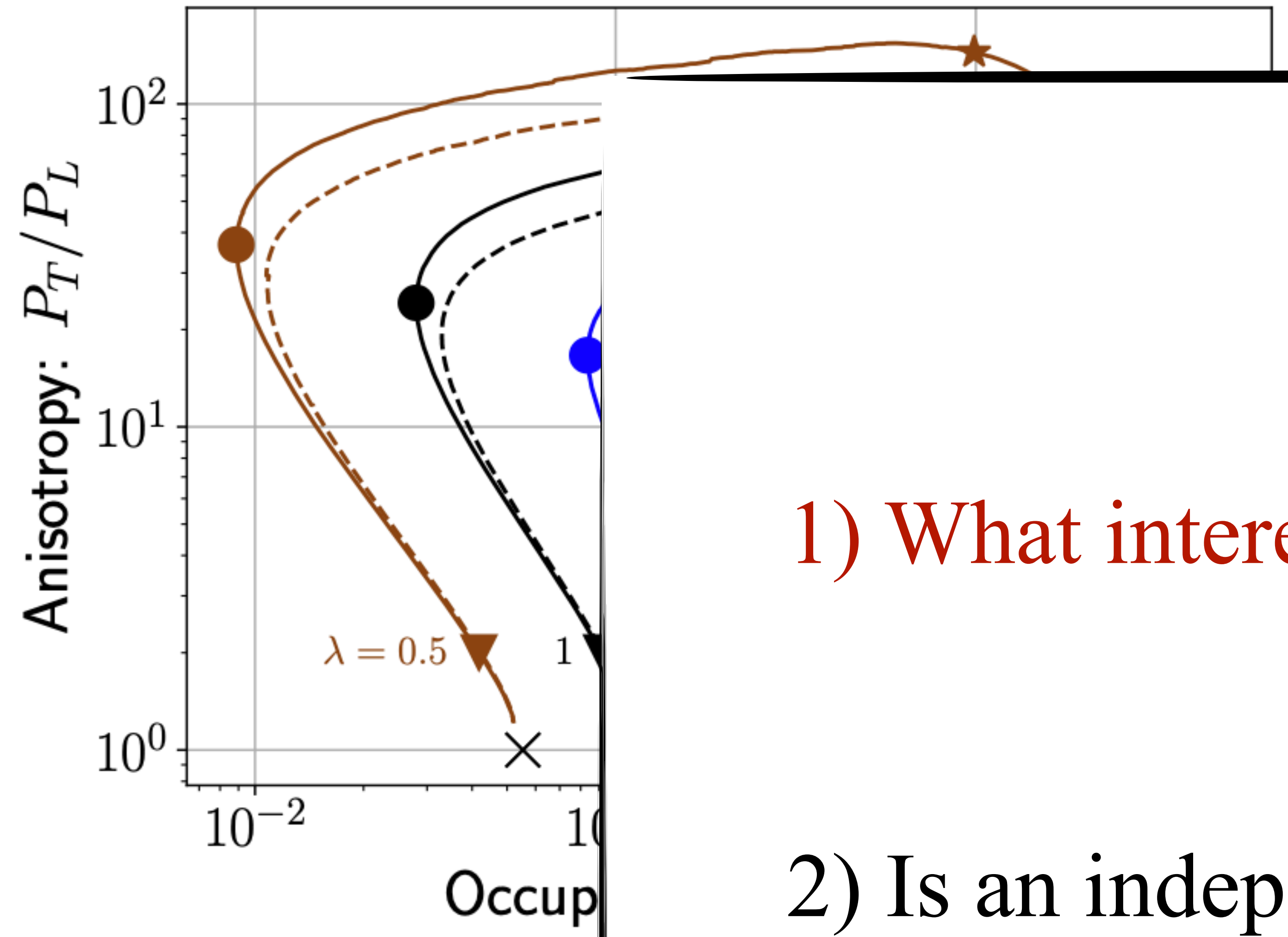

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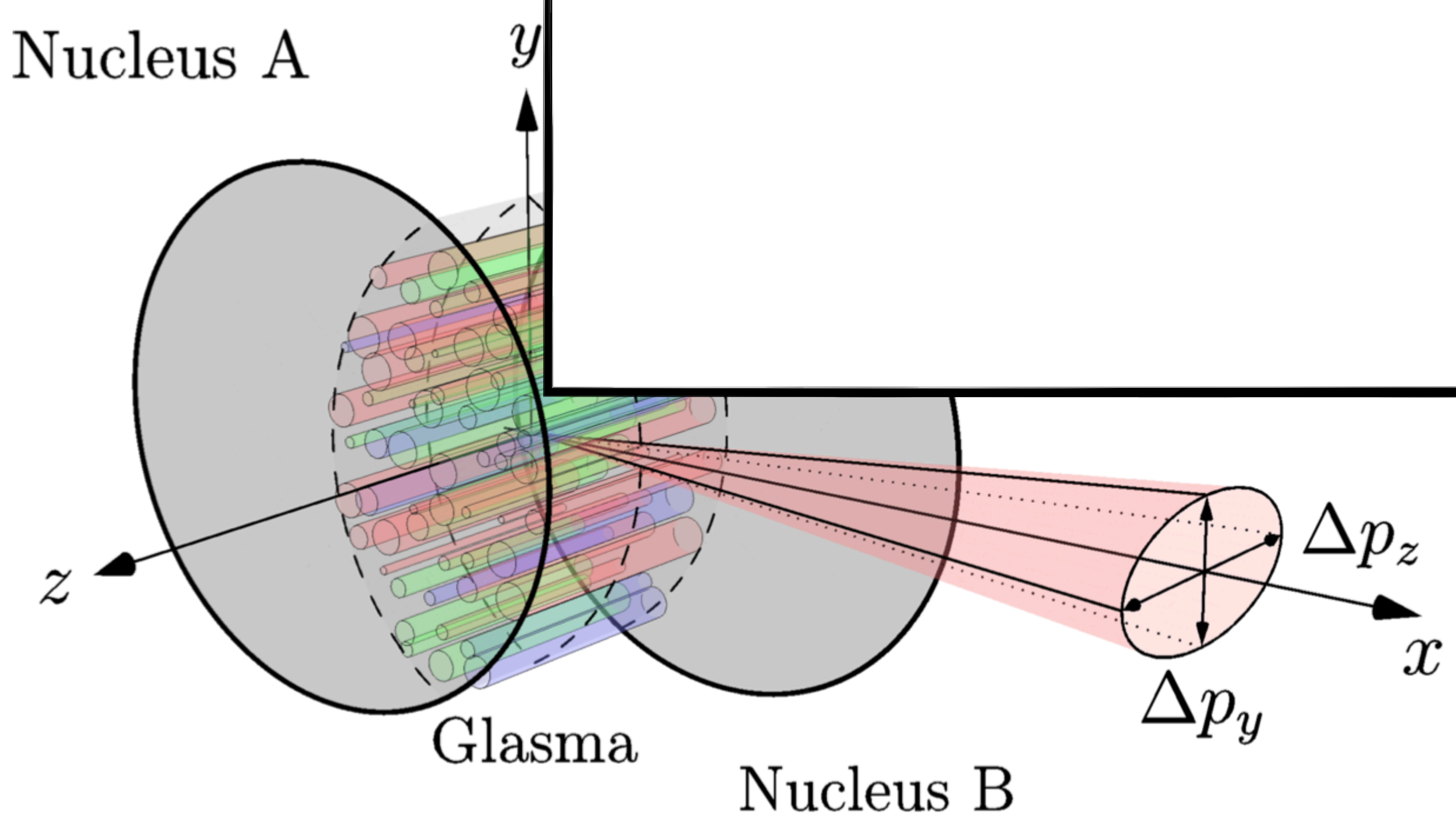
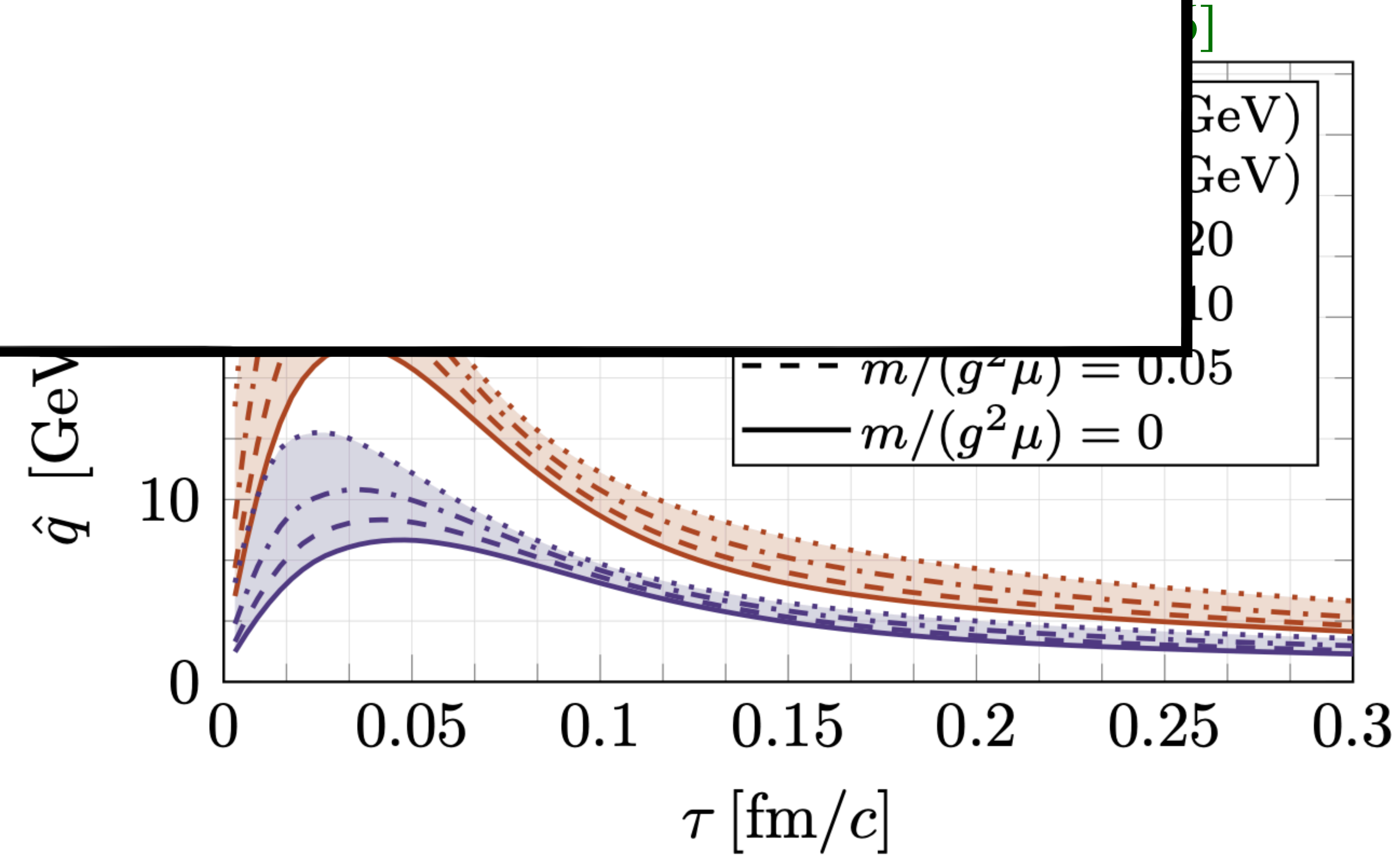
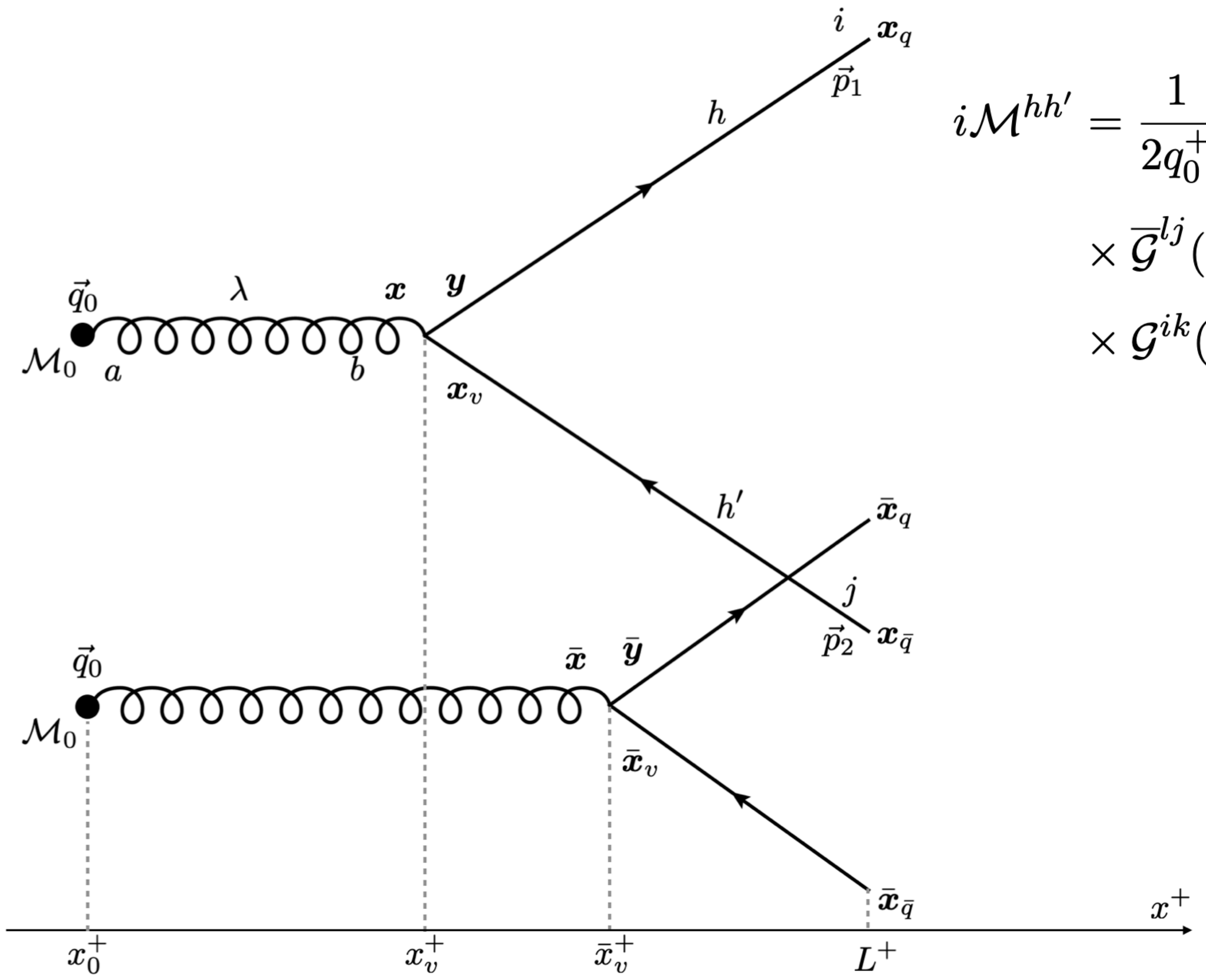




Gluon radiation in anisotropic matter

[JB, C. Salgado, J. Silva, 2407.04774]

Similar to hydro gradients, evolution in the present of anisotropic jet quenching coefficient leads to a non-trivial azimuthal structure. As an example consider g to qqbar in the presence of such a background



$$
\begin{aligned}
i\mathcal{M}^{hh'} = \frac{1}{2q_0^+} e^{i\frac{\boldsymbol{p_1}^2}{2p_1^+}L^+} e^{i\frac{\boldsymbol{p_2}^2}{2p_2^+}L^+} \sum_{\lambda=\pm1}\int_{x_v^+}\int_{\boldsymbol{x_v},\boldsymbol{x_q},\boldsymbol{x_{\bar{q}}},\boldsymbol{x_g},\boldsymbol{x},\boldsymbol{y}}\int_{x_g^+} \mathcal{M}_0^{\lambda,a}(q_0^+,x_g^+,\boldsymbol{x}_g)\, e^{-i\boldsymbol{p_1}\cdot\boldsymbol{x_q}} e^{-i\boldsymbol{p_2}\cdot\boldsymbol{x_{\bar{q}}}} \\
\times \bar{\mathcal{G}}^{lj}(L^+,\boldsymbol{x_{\bar{q}}};x_v^+,\boldsymbol{x_v}|p_2^+)\left(igt^b_{kl}V^{\lambda hh'}(z,\boldsymbol{x},\boldsymbol{y})\right)\mathcal{G}_A^{ba}(x_v^+,\boldsymbol{x_v}-\boldsymbol{x};x_g^+,\boldsymbol{x_g}|q_0^+) \\
\times \mathcal{G}^{ik}(L^+,\boldsymbol{x_q};x_v^+,\boldsymbol{x_v}-\boldsymbol{y}|p_1^+)\,,
\end{aligned}
$$

$$
V^{\lambda hh'}(z,\boldsymbol{x},\boldsymbol{y}) = 2\gamma^{\lambda h}(z)\delta_{h,-h'}\boldsymbol{\epsilon}_\lambda \cdot i(\delta(\boldsymbol{x})\delta'(\boldsymbol{y}) + z\delta'(\boldsymbol{x})\delta(\boldsymbol{y}))
$$

$$
\hat{q} = (\hat{q}_x\,,\hat{q}_y \gg \hat{q}_x)
$$

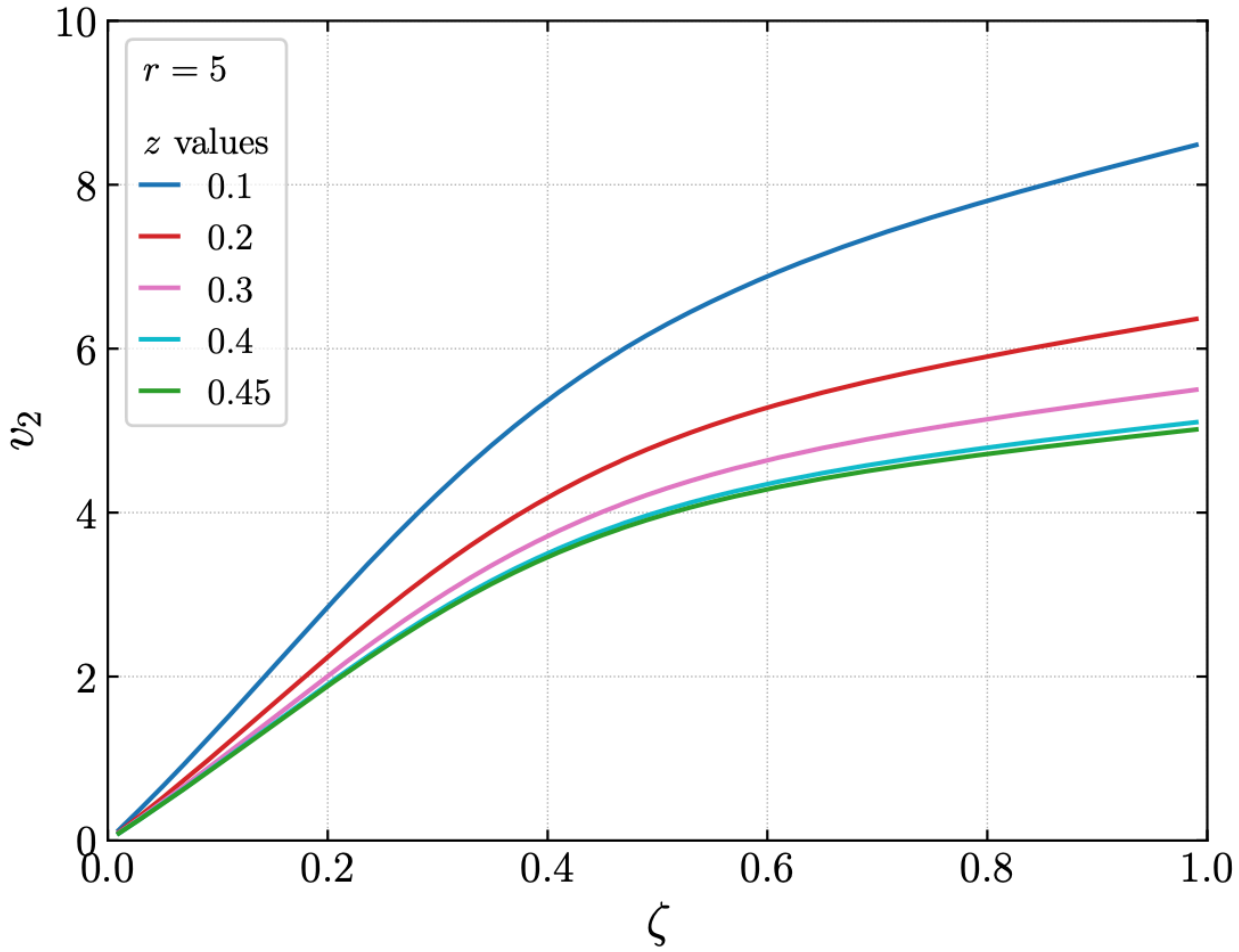
$$
\frac{2\pi}{dN^h/dz}\frac{dN^h}{dzd\phi} = 1 + \sum_{n=1}^{\infty} v_n \cos(n\phi) + \sum_{n=1}^{\infty} w_n^{(h)}\sin(n\phi)
$$

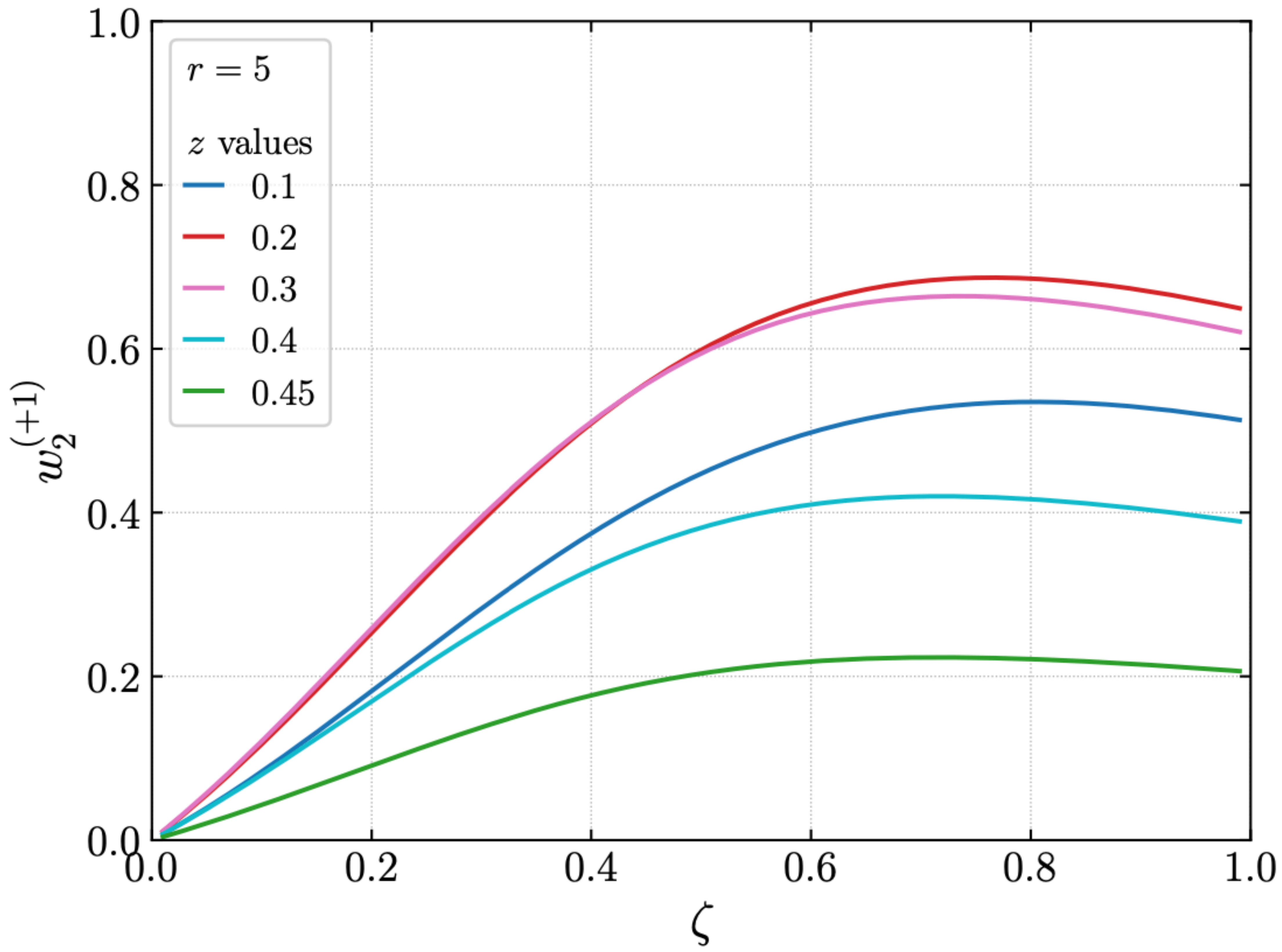
Gluon radiation in anisotropic matter

[JB, C. Salgado, J. Silva, 2407.04774]

Brookhaven National Laboratory

$$\zeta = \frac{\sqrt{\hat{q}_y} - \sqrt{\hat{q}_x}}{\sqrt{\hat{q}_y} + \sqrt{\hat{q}_x}}\,, \quad r = L^+ \frac{\left(\sqrt{\hat{q}_y} + \sqrt{\hat{q}_x}\right)}{2\sqrt{q_0^+}}$$





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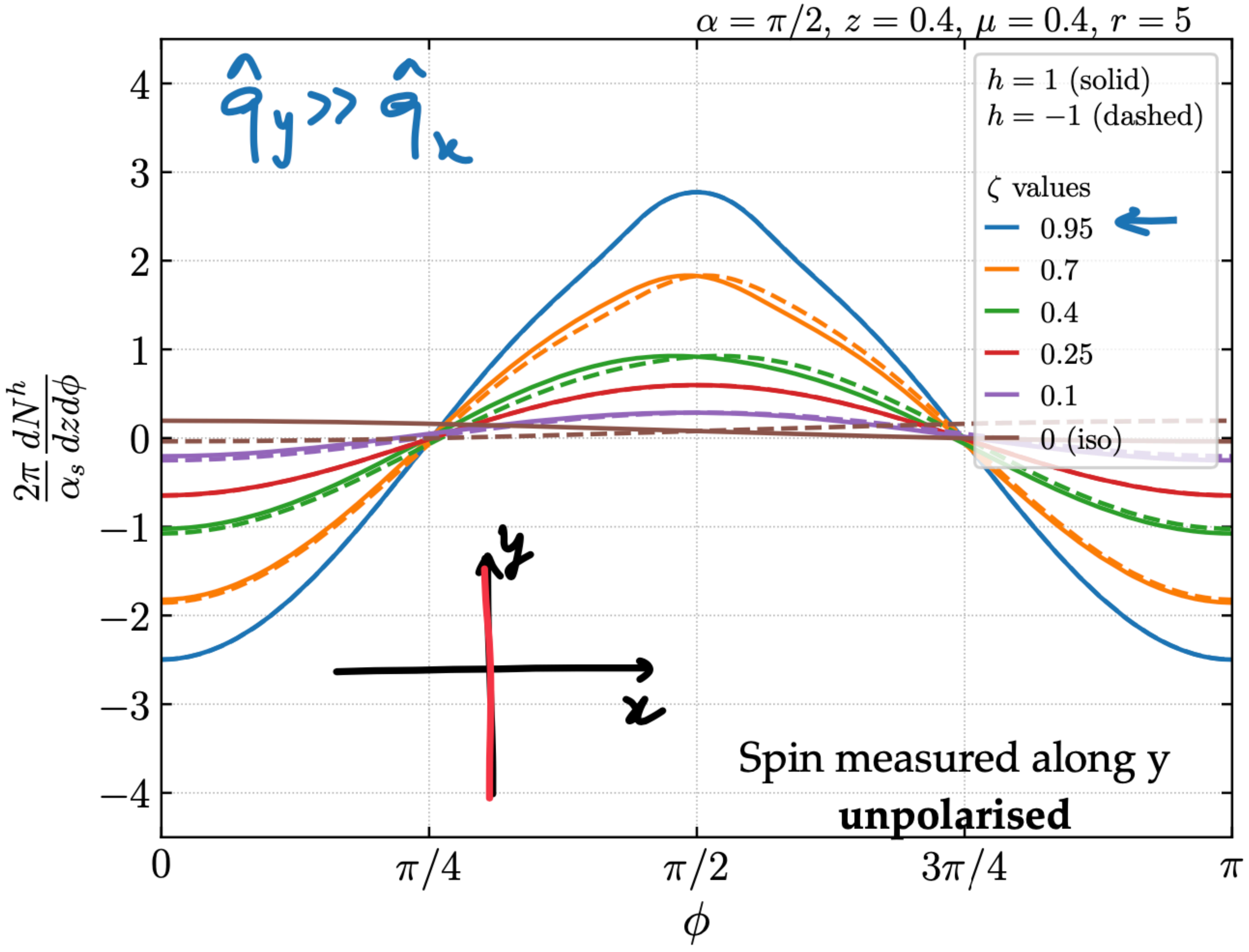
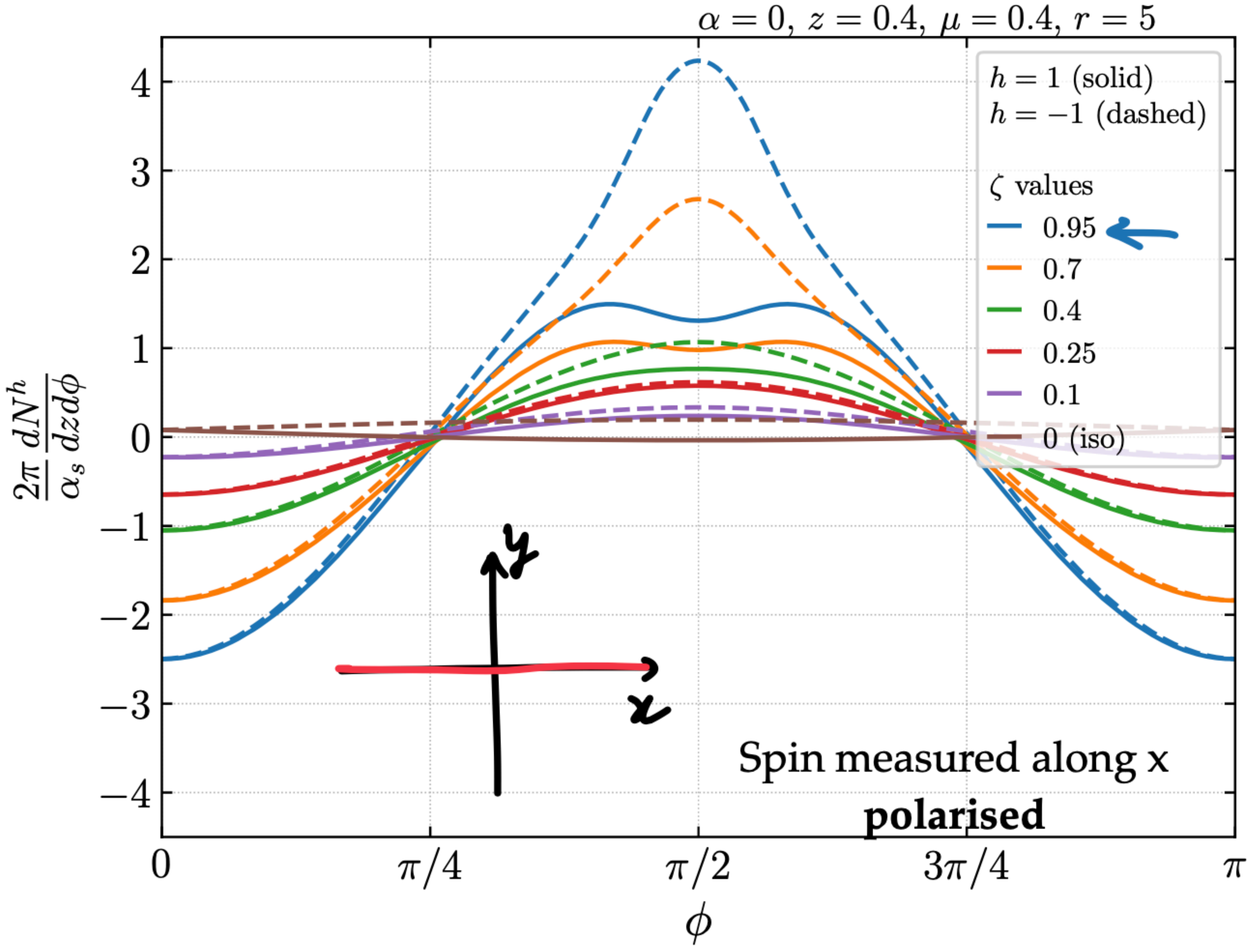
$$\zeta = \frac{\sqrt{\hat{q}_y} - \sqrt{\hat{q}_x}}{\sqrt{\hat{q}_y} + \sqrt{\hat{q}_x}}, \quad r = L^+ \frac{\left(\sqrt{\hat{q}_y} + \sqrt{\hat{q}_x}\right)}{2\sqrt{q_0^+}}, \quad \mu = \frac{\sqrt{2}m^2}{\left(\sqrt{\hat{q}_y} + \sqrt{\hat{q}_x}\right)\sqrt{q_0^+}}$$





Similar observations in [S. Hauksson, E. Iancu, 2303.03914]

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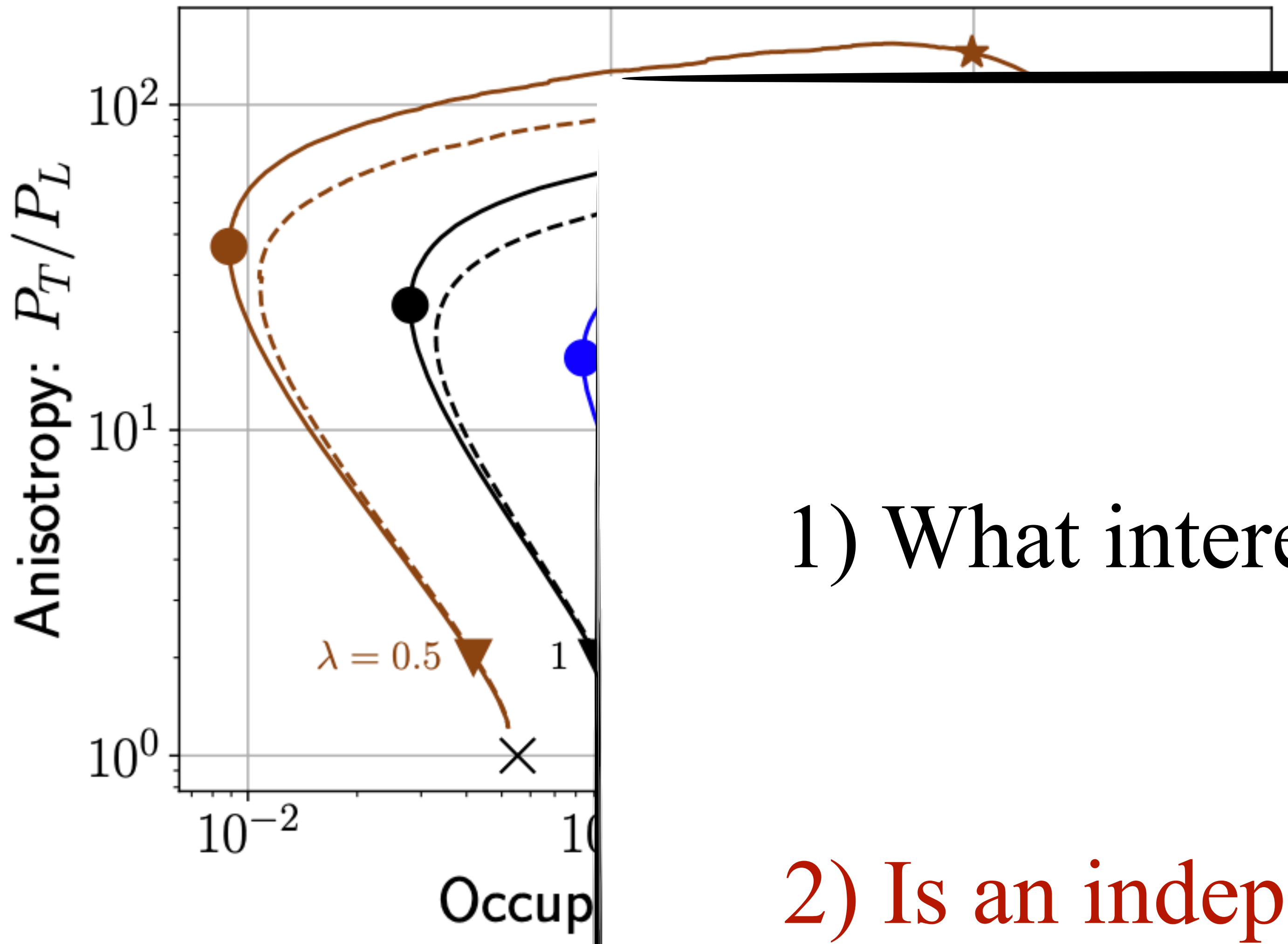

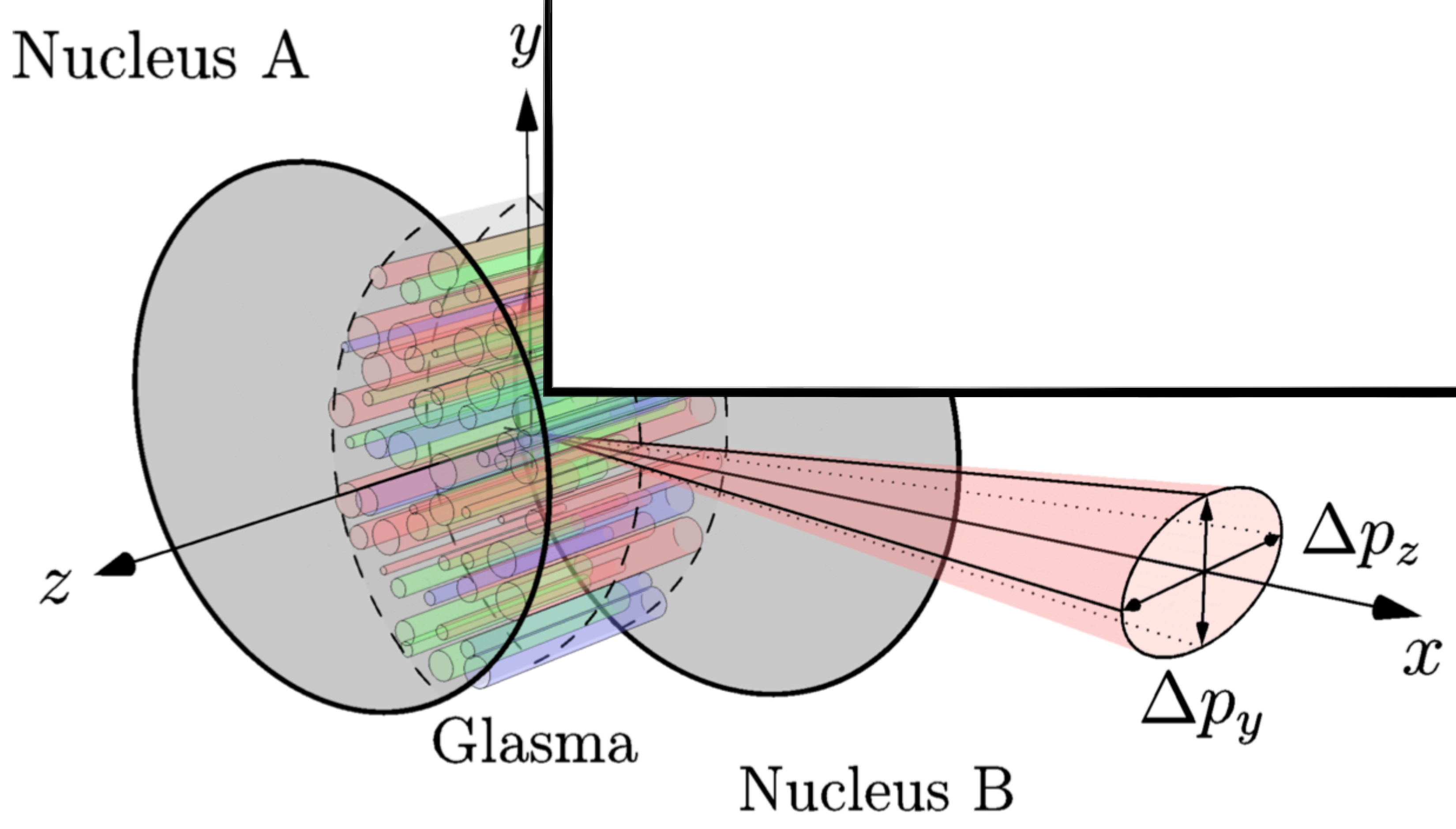

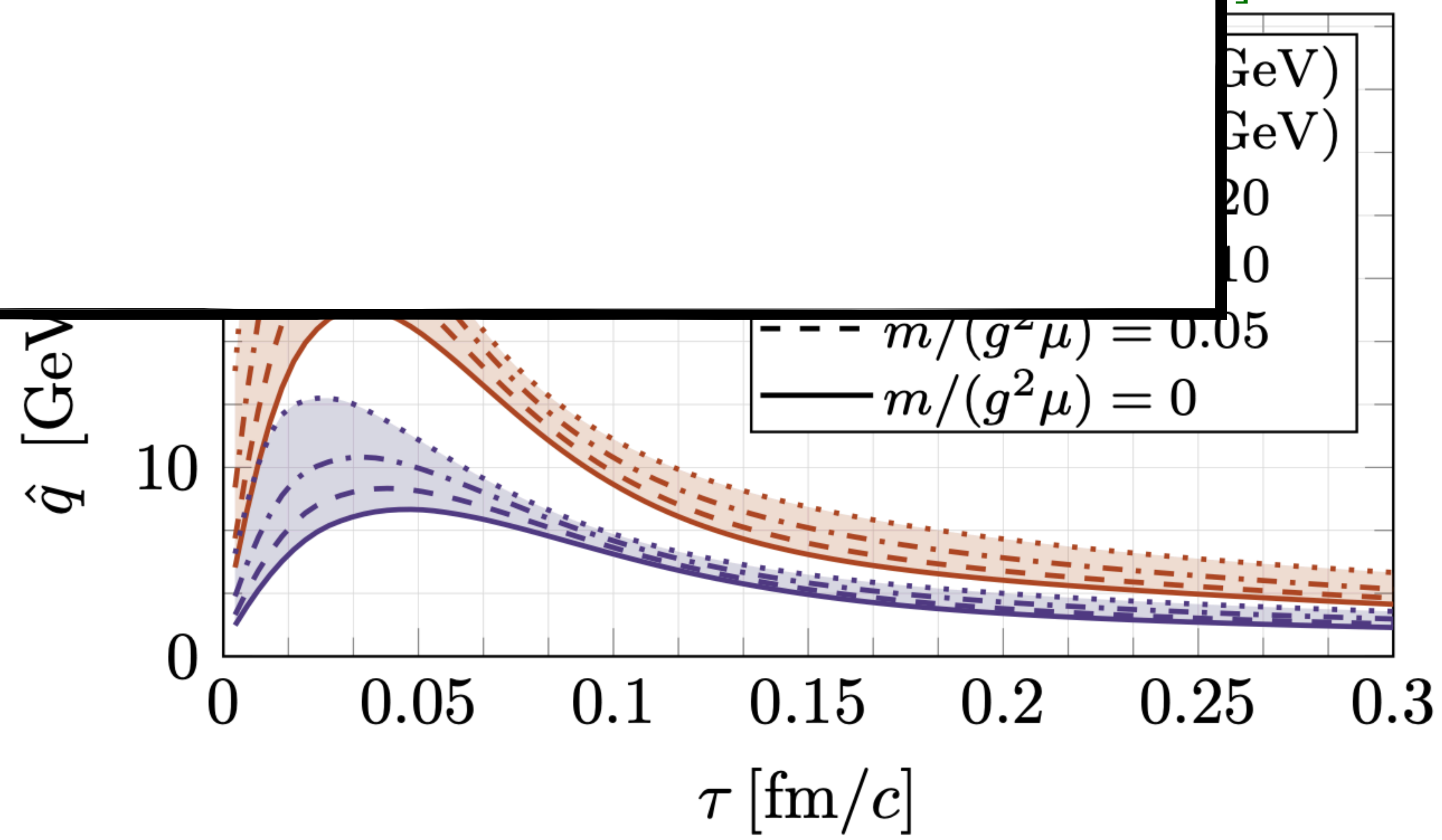

1) What interesting features can we see from early time anisotropies?

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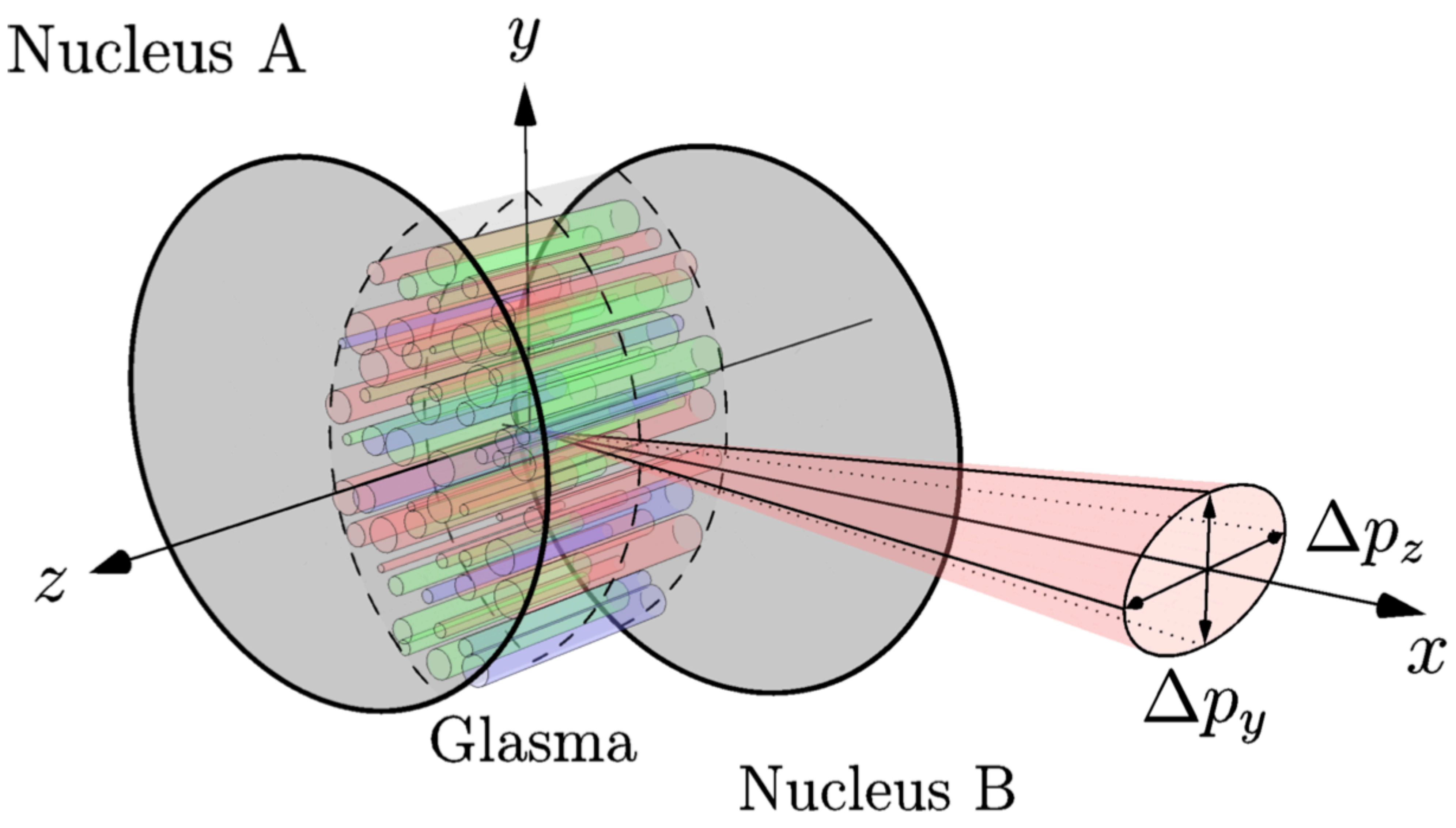
Jet evolution in the Glasma

[JB, S. Hauksson, X. Lopez, A. Sadofyev, 2406.07615]



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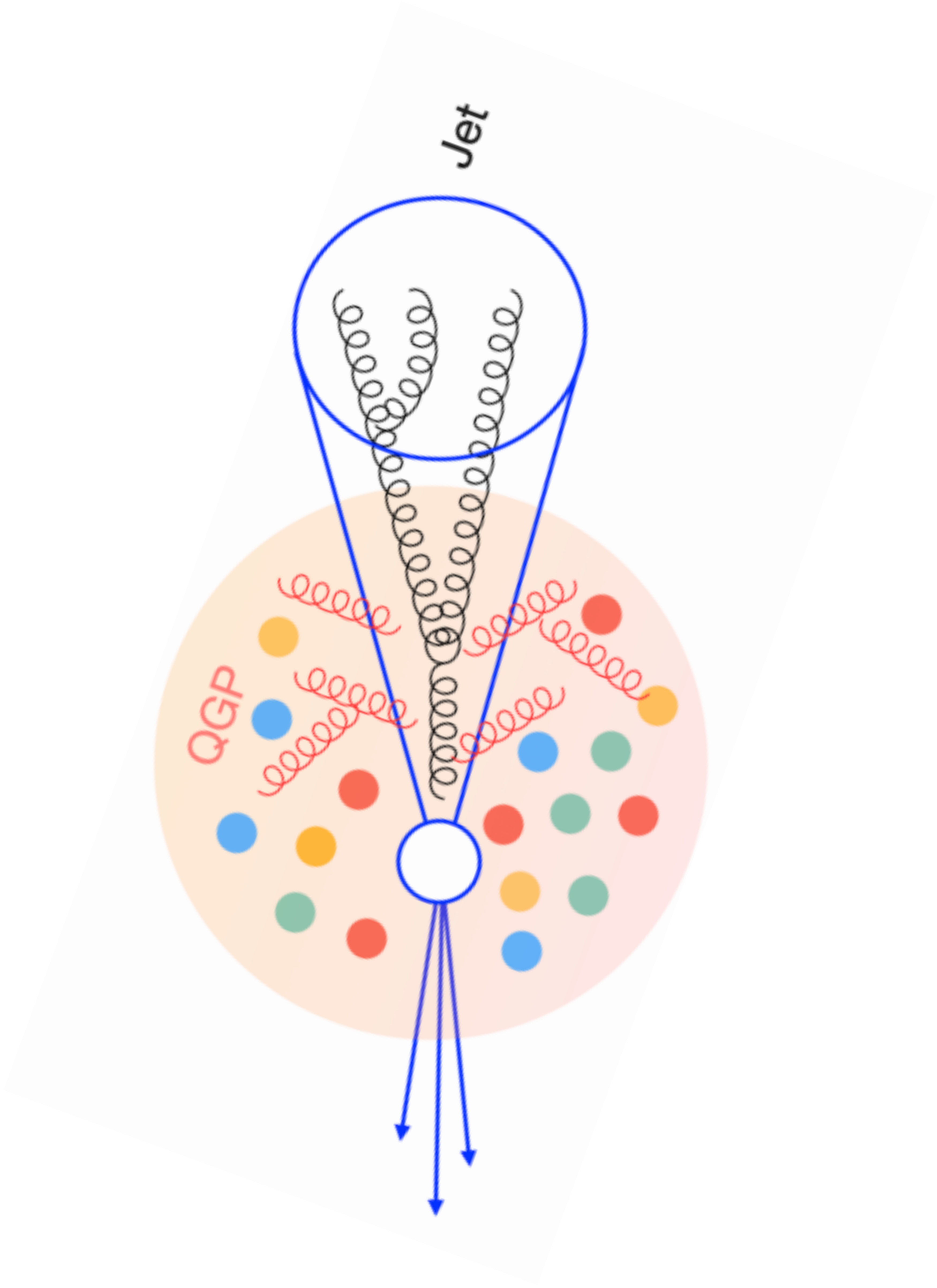

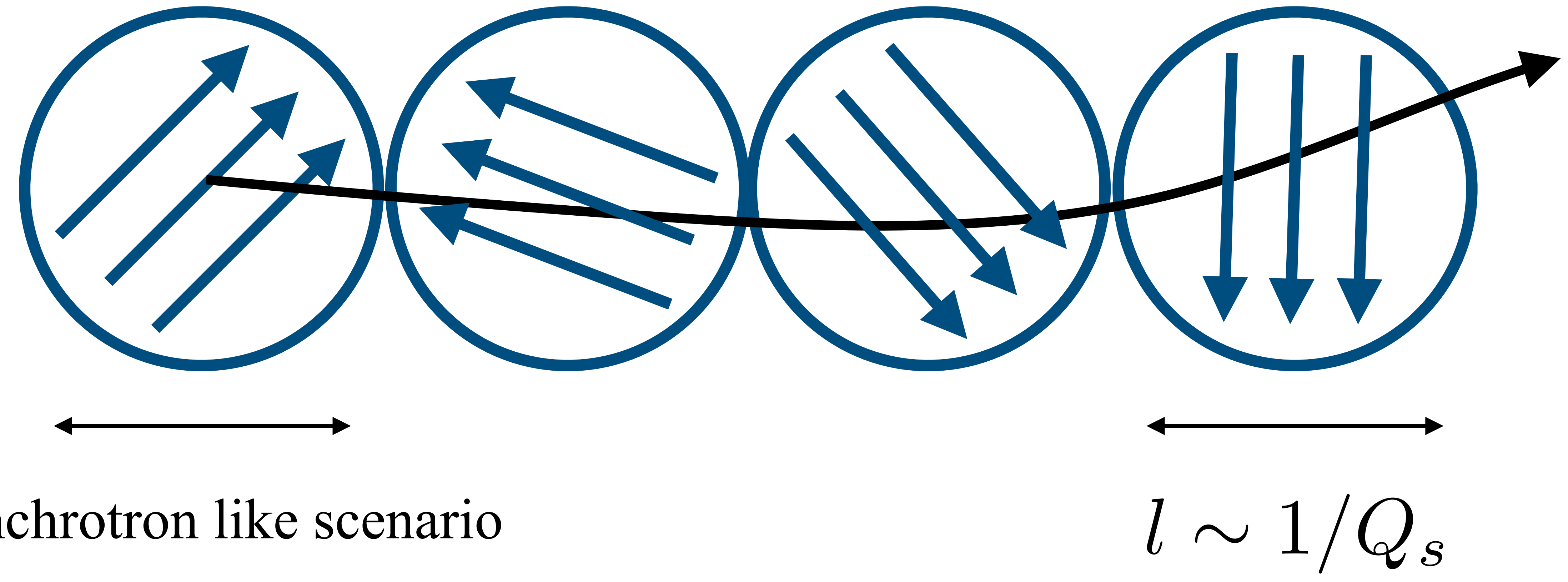

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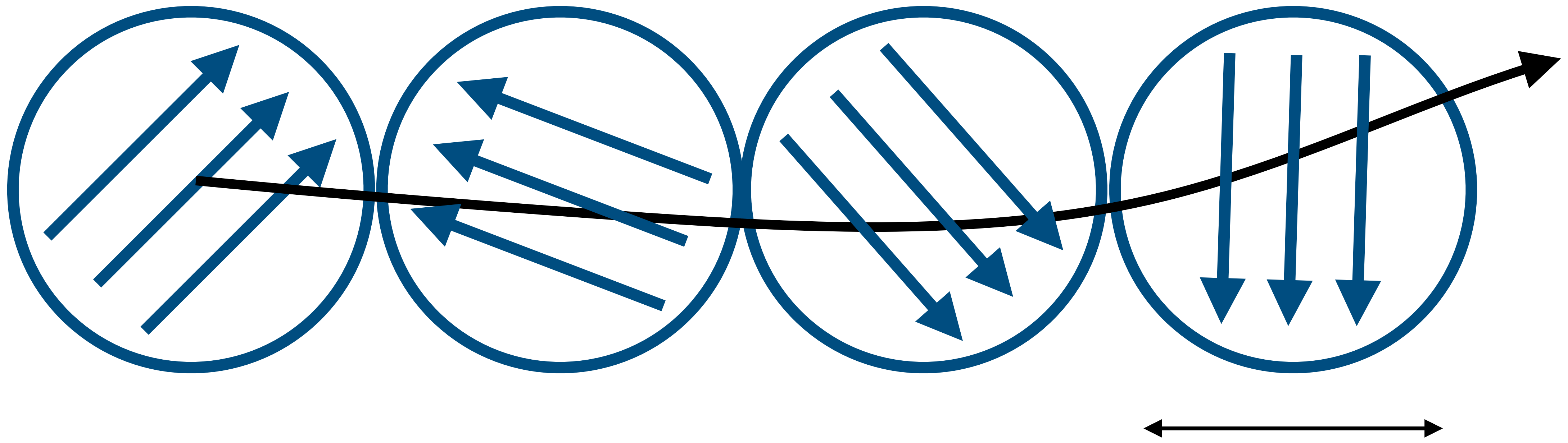


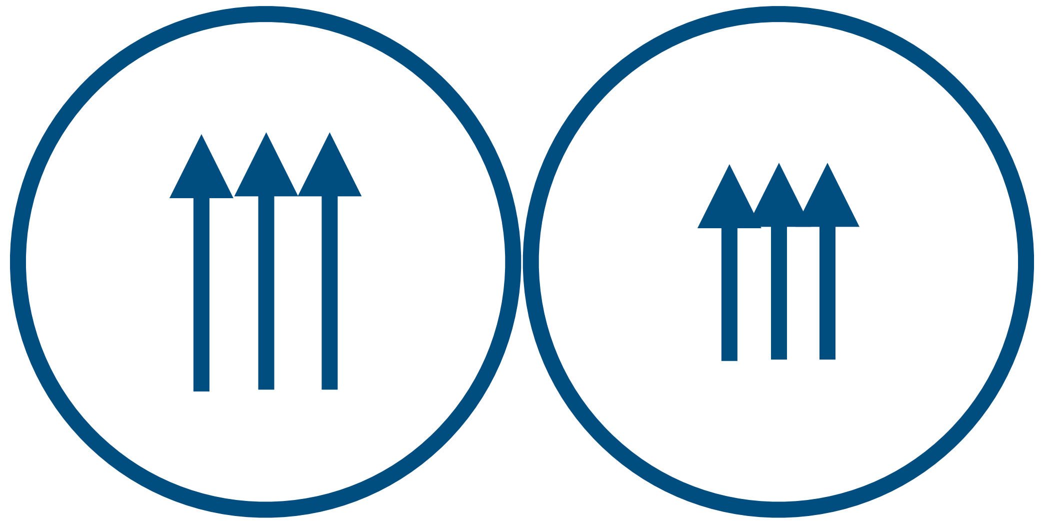
$$l \sim 1/Q_s$$

$$A^{a\mu}_{\rm coh}(\boldsymbol{x}, z) = \delta^0_\mu\, \boldsymbol{x}\cdot \mathbf{E}^a(z) = \begin{cases} \delta^{\mu 0}\boldsymbol{x}\cdot\mathbf{E}^a_1, & 0 \le z < \ell \\ \delta^{\mu 0}\boldsymbol{x}\cdot\mathbf{E}^a_2, & \ell \le z < 2\ell \\ \delta^{\mu 0}\boldsymbol{x}\cdot\mathbf{E}^a_3, & 2\ell \le z < 3\ell \\ \vdots & \end{cases}$$

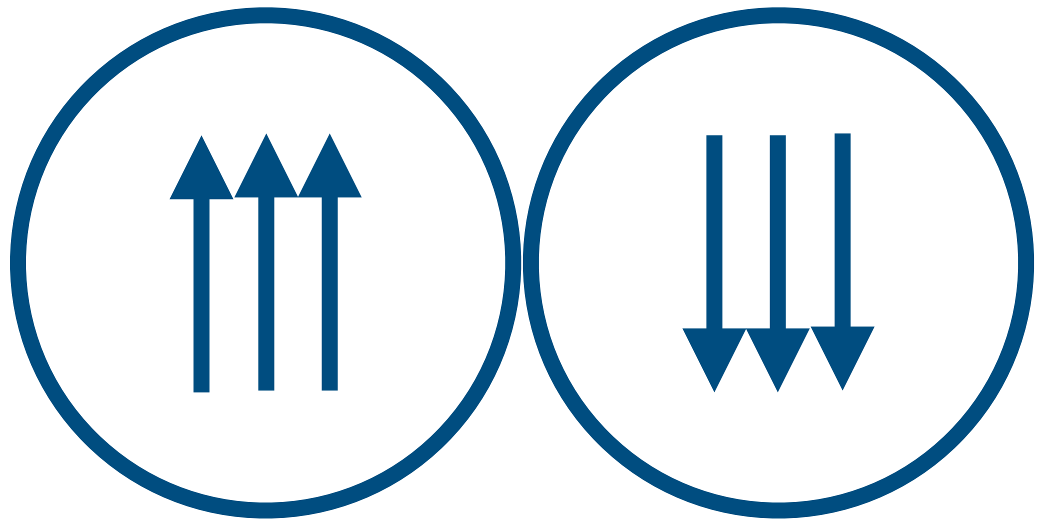
$$\langle A(x)A(y)\rangle \neq \delta(x^+ - y^+)$$

We consider two medium models:

- $$\langle f(E^a_{1x}, E^a_{2x}, E^a_{3x}, \cdots)\rangle = \int_{E_1} e^{-E^2_{1x}/E^2_0} \int_{E_2} e^{-E^2_{2x}/E^2_0} \cdots f(E^a_{1x}, E^a_{2x}, E^a_{3x}, \cdots)$$

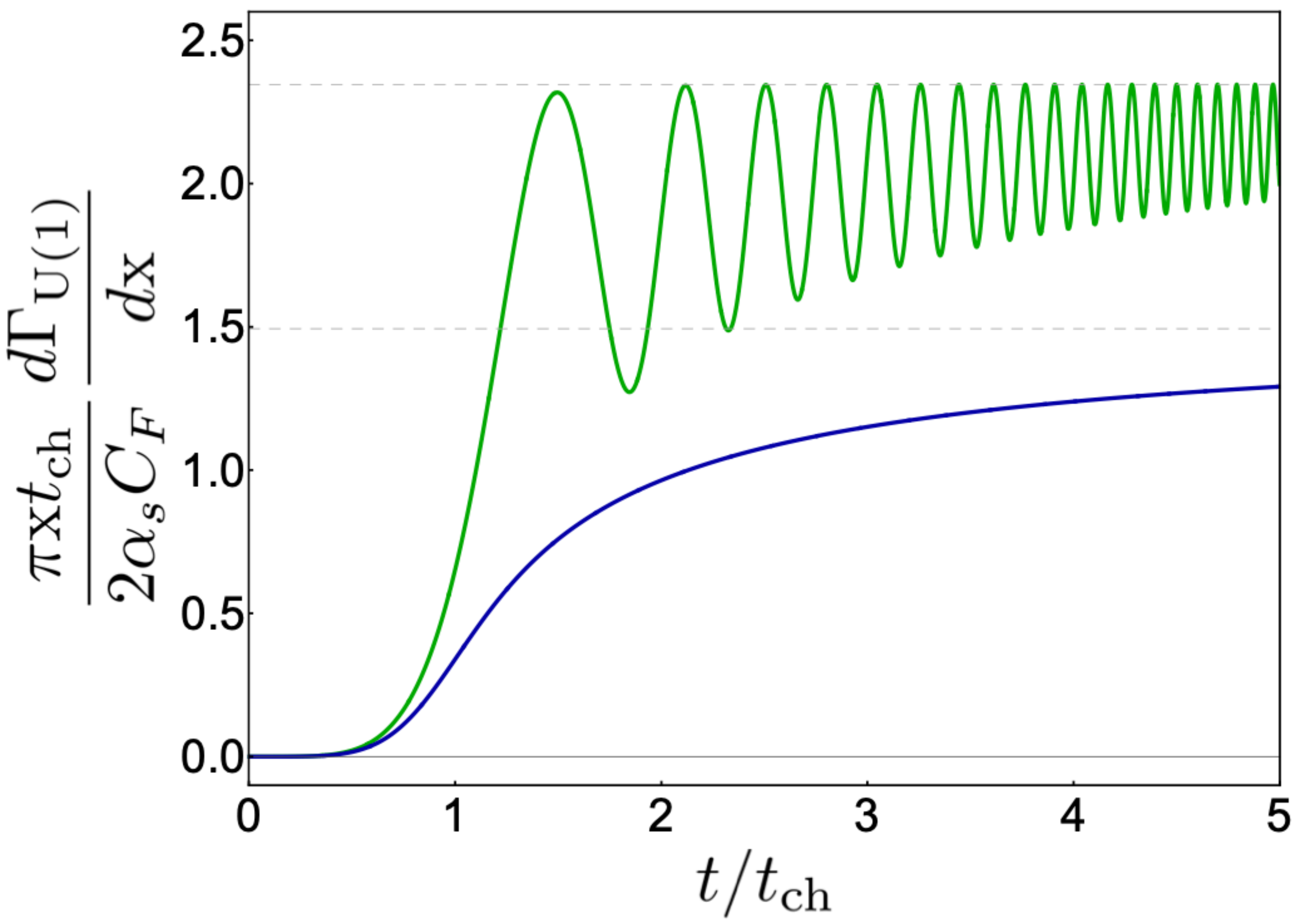


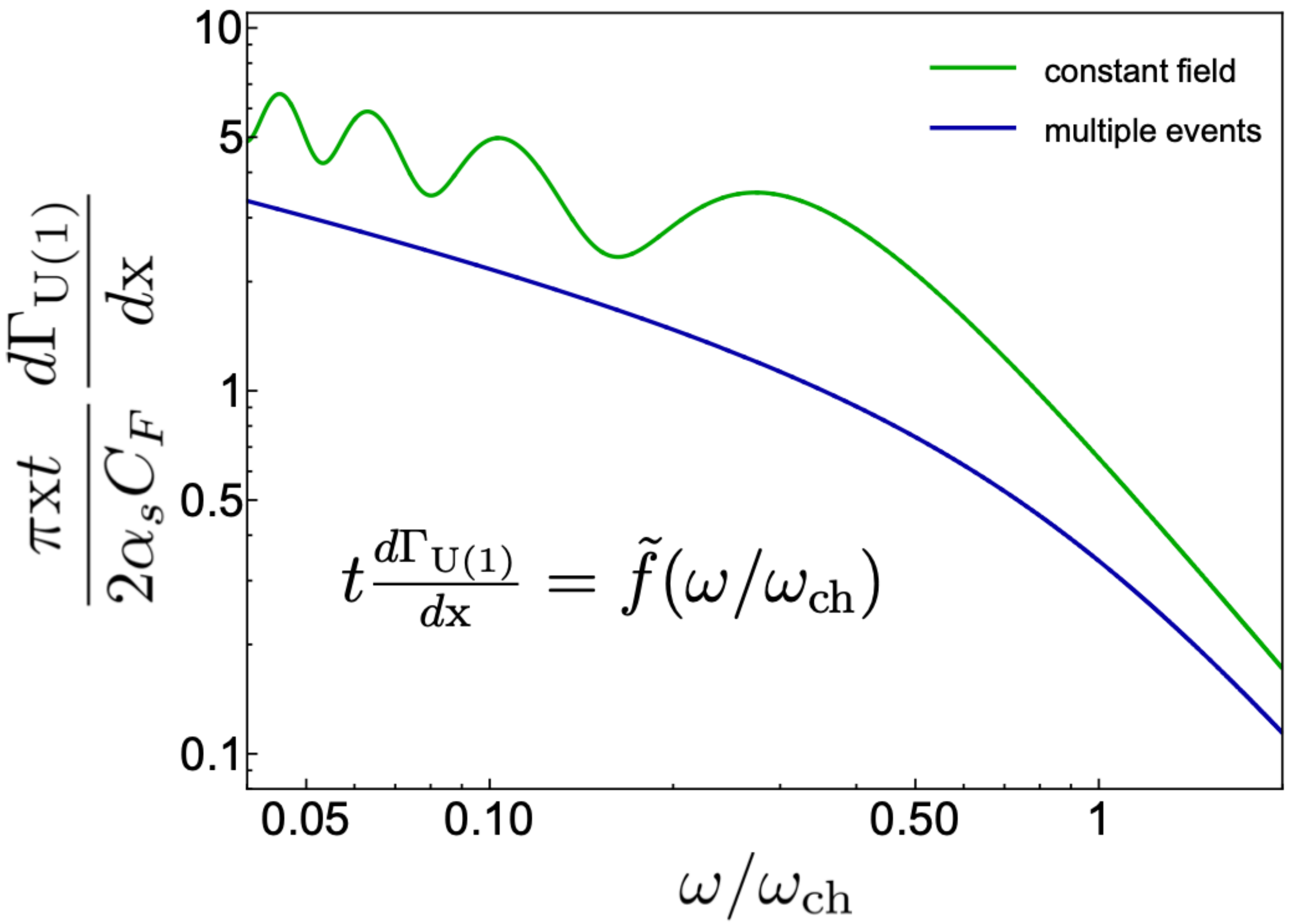
- $$\langle f(E_{1x}, E_{2x}, E_{3x}, \cdots)\rangle = \left[\prod_n \int_{E_n} \frac{dE_{nx}}{2}\left(\delta(E_{nx} - E_0) + \delta(E_{nx} + E_0)\right)\right] f(E_{1x}, E_{2x}, E_{3x}, \cdots)$$



Jet evolution in the Glasma: 1 flux tube

[JB, S. Hauksson, X. Lopez, A. Sadofyev, 2406.07615]



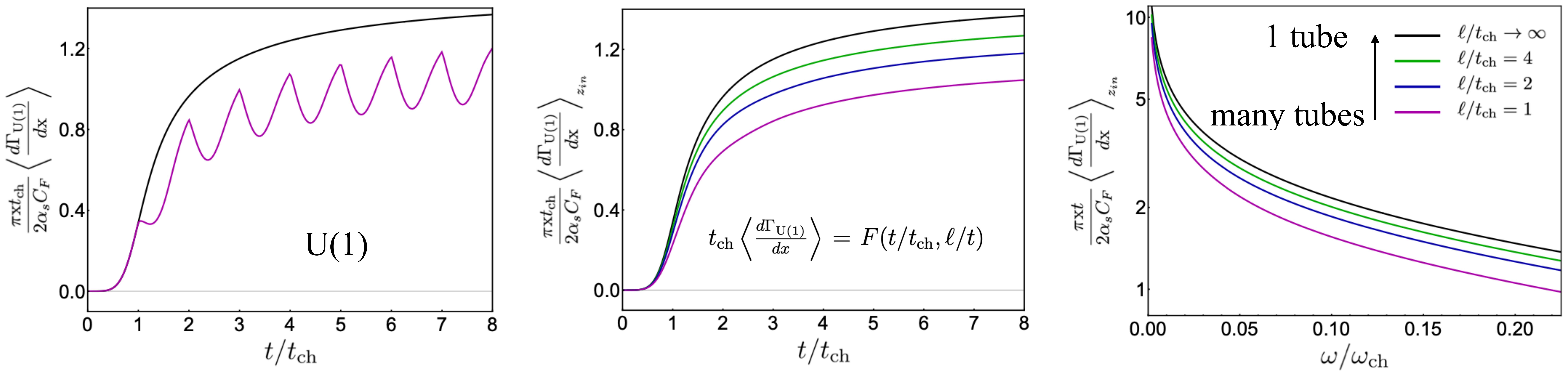


At early and late times, we find : $\frac{d\Gamma_{\rm U(1)}}{dx} \simeq \frac{7\alpha_s C_F}{24x\pi}\frac{E^4}{\omega^2}\frac{t^5}{5!}$ $\quad \frac{d\Gamma_{\rm U(1)}}{dx}\Big|_{t\to\infty} = 3^{1/6}\,\Gamma\left(\frac{2}{3}\right)\frac{\alpha_s C_F}{x\pi}E^{2/3}\omega^{-1/3}$

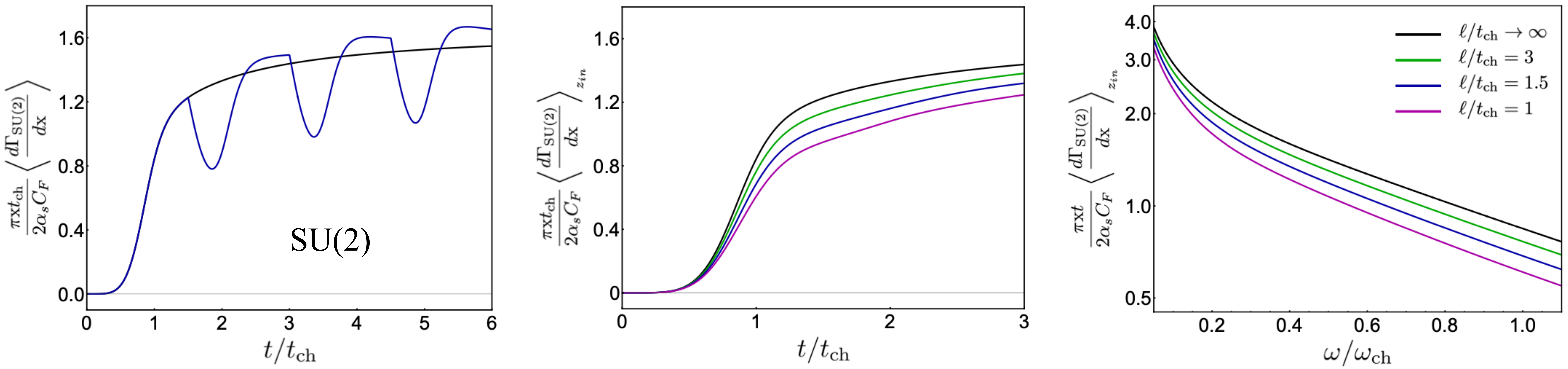
There is an emergent time scale : $t_{\rm ch} = (24\omega/E^2)^{1/3}$ which can also be obtained from $t_{\rm ch} \sim \sqrt{\omega/\hat{q}(t_{\rm ch})}$ $\quad \langle\hat{q}\rangle_{E,z_{in}} = cE_0^2 l$

Jet evolution in the Glasma: several flux tubes

[JB, S. Hauksson, X. Lopez, A. Sadofyev, 2406.07615]



More flux tubes = longer formation time = lower rate



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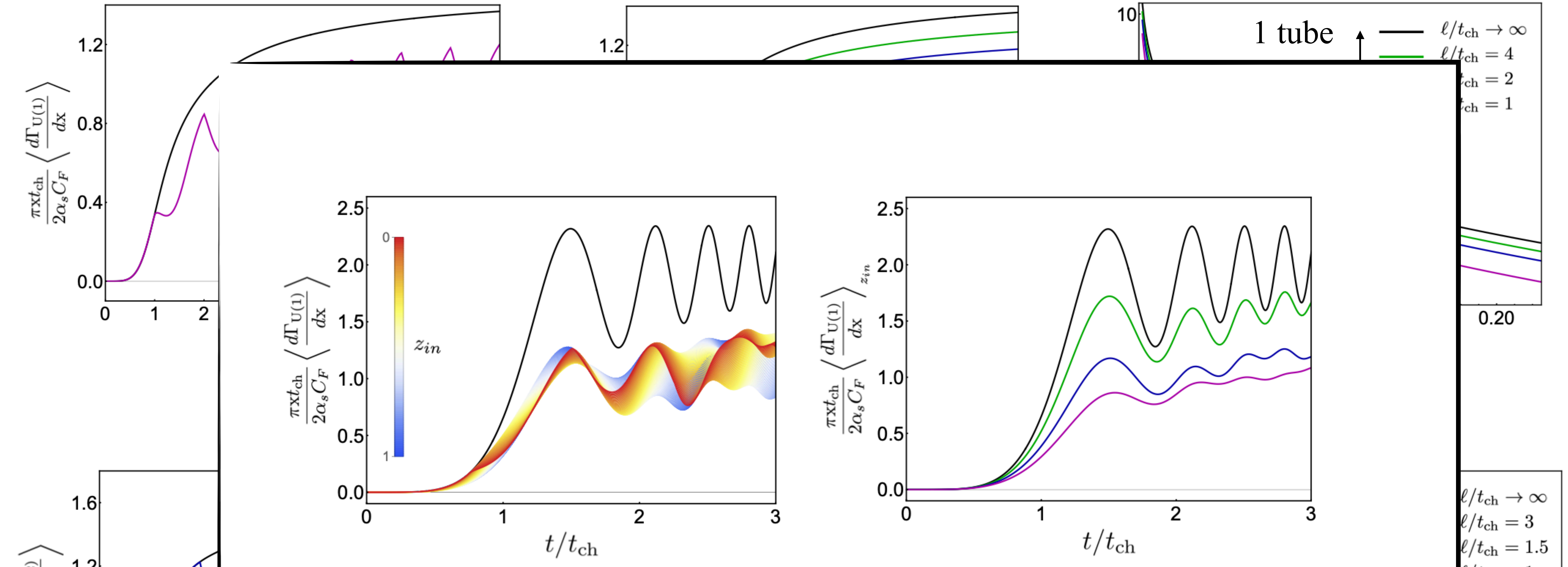
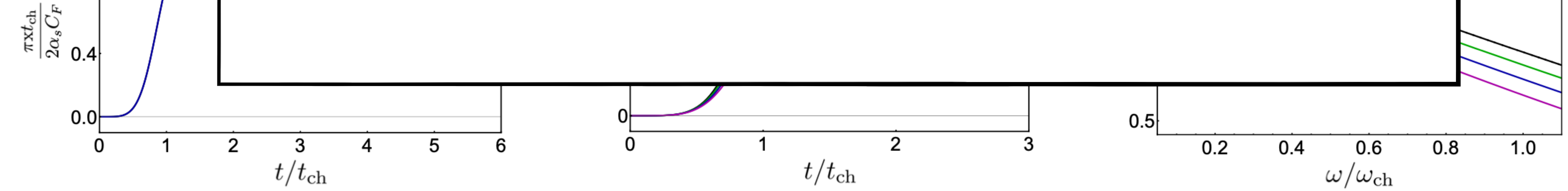
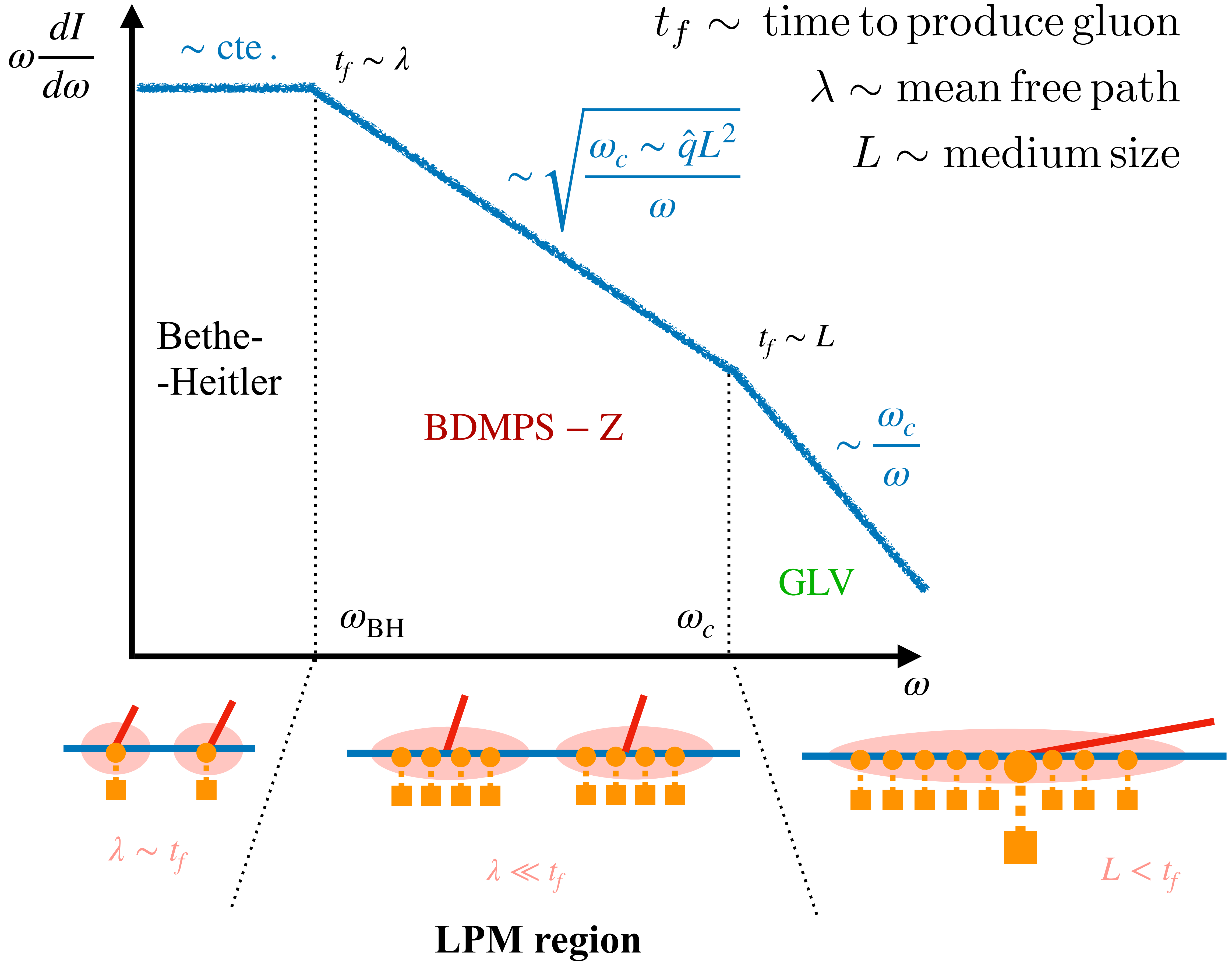


Same conclusions hold for delta function model, despite quantitative differences



Jet evolution in the Glasma: several flux tubes [JB, S. Hauksson, X. Lopez, A. Sadofyev, 2406.07615]

How different is this model from the standard multiple scattering picture ?



$t_f \sim$ time to produce gluon

$\lambda \sim$ mean free path

$L \sim$ medium size

Jet evolution in the Glasma: several flux tubes [JB, S. Hauksson, X. Lopez, A. Sadofyev, 2406.07615]

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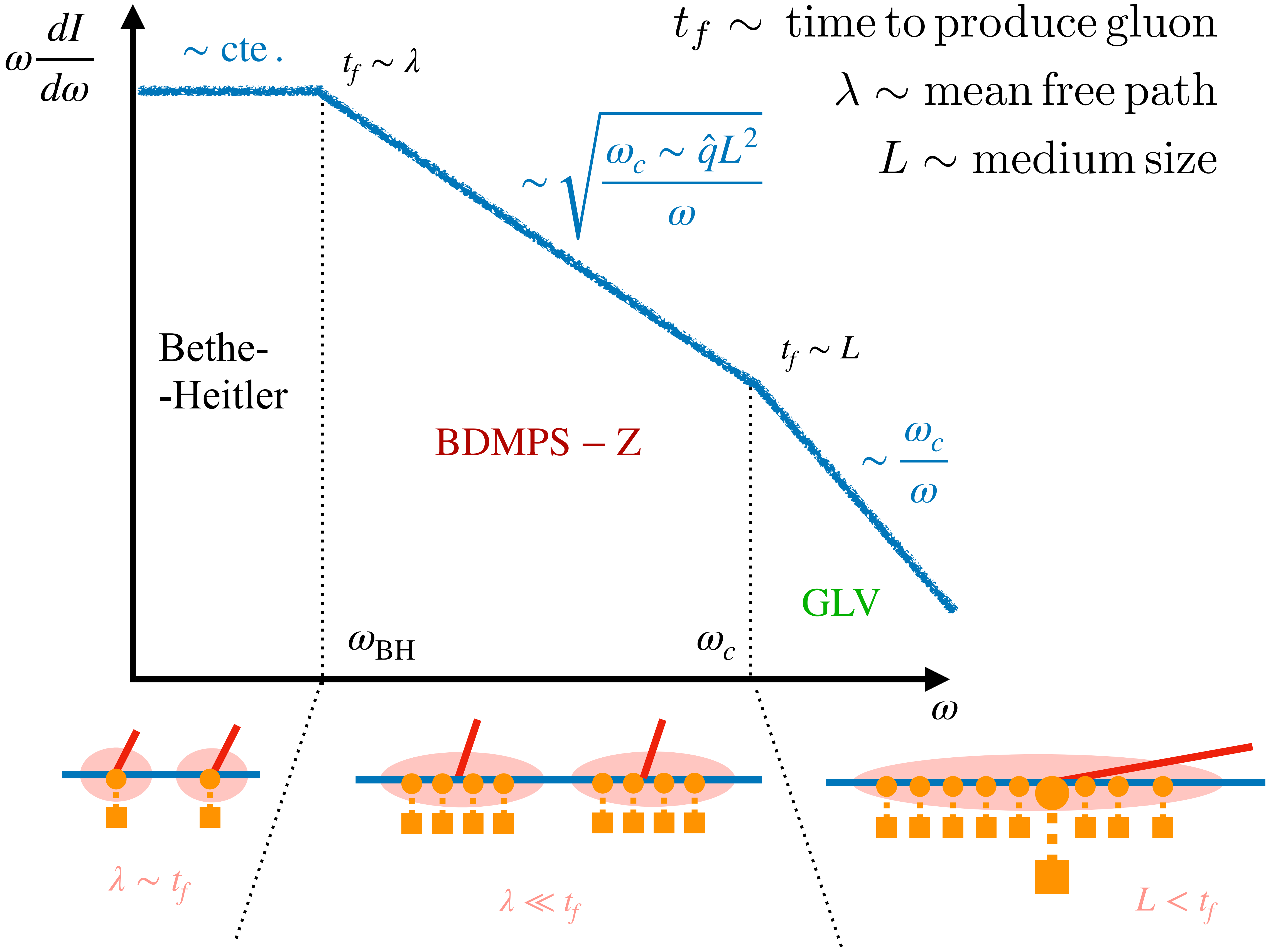
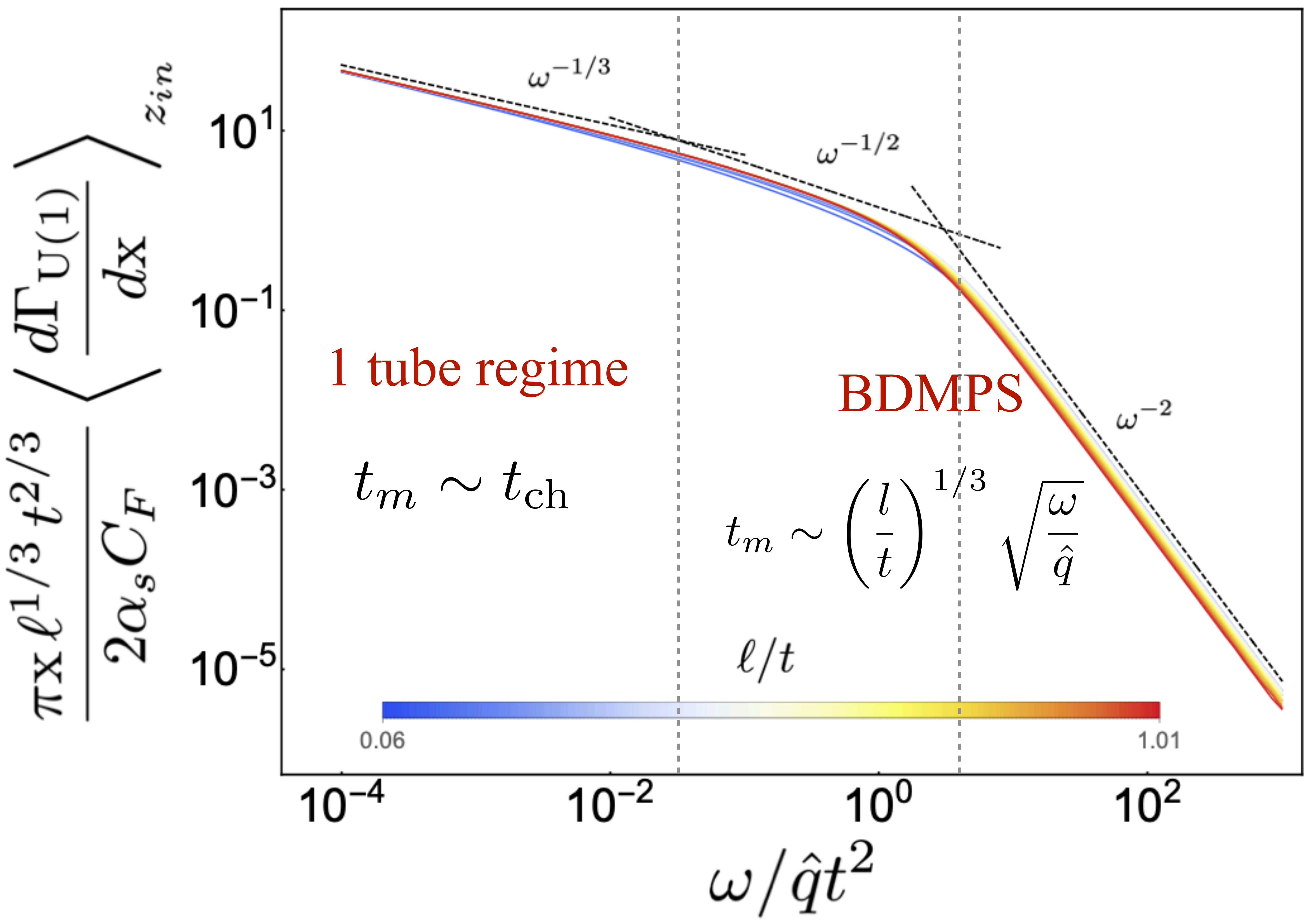


Fixed $\langle \hat{q} \rangle_{\rm U(1)} = \frac{1}{8\pi^2} E_0^2 \ell$



$$t \left\langle \frac{d\Gamma_{\rm U(1)}}{dx} \right\rangle_{z_{in}} \sim (t/\ell)^{1/3} (\hat{q}t^2/\omega)^{1/3} F(\omega/(\hat{q}t^2), \ell/t)$$

Some ideas

How about existing measurements ? What insights do they provide ? Do we need new tools ?

- Most existing jet substructure observables should be insensitive to this physics (not differential enough)
- There are proposals to go beyond, but not fully studied; can not get over full overall evolution effects

For any physical "model" what we want/need: 1) Azimuthal/polarized observable ✓
2) Picks up time constrained evolution ✓

Boosted Ws time delayed decays + azimuthal/polarized dependent observable ?