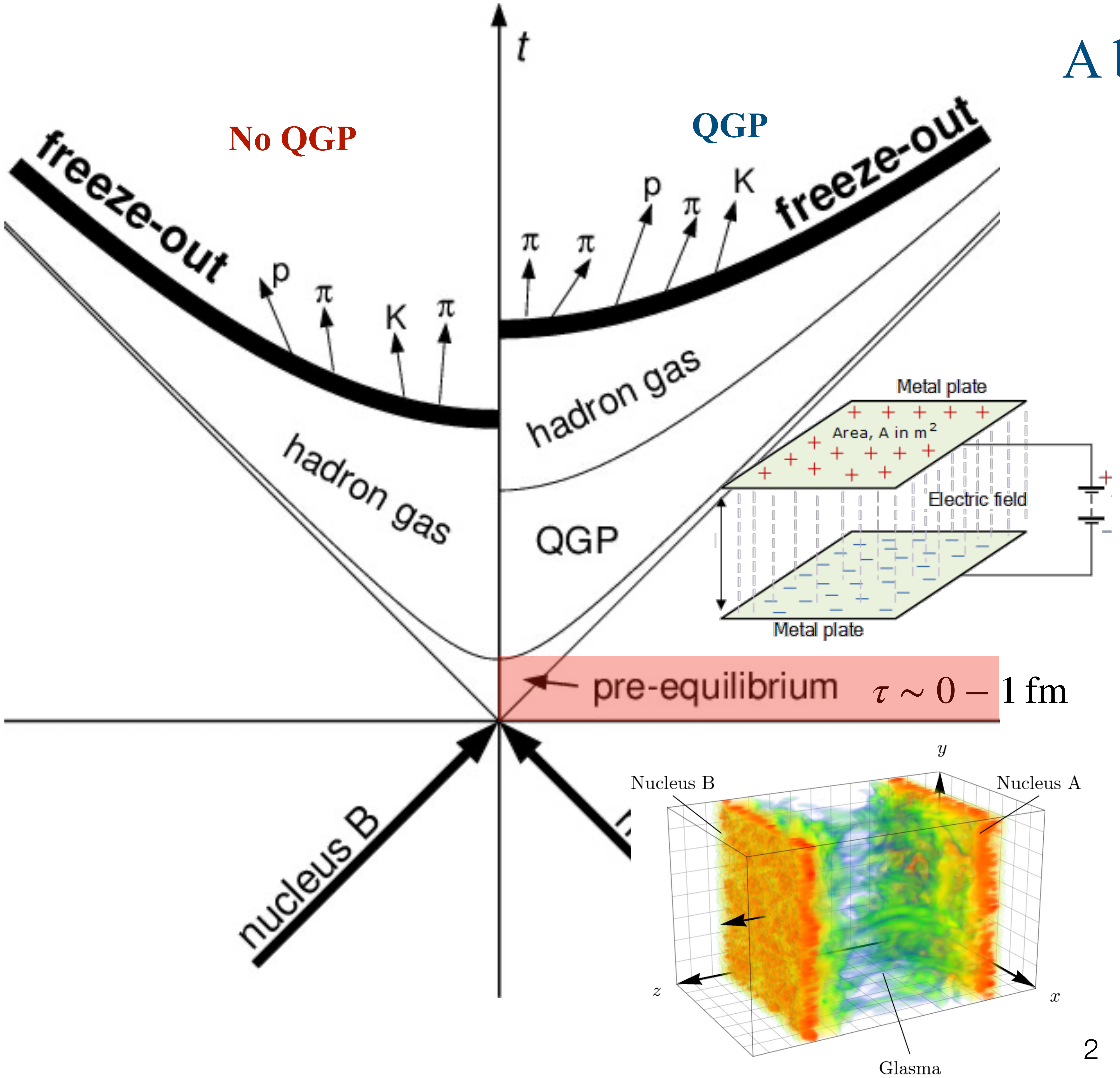
Jet evolution in structured matter

8th August 2024, HI physics in the EIC era

João Barata, BNL

The spacetime picture of HICs



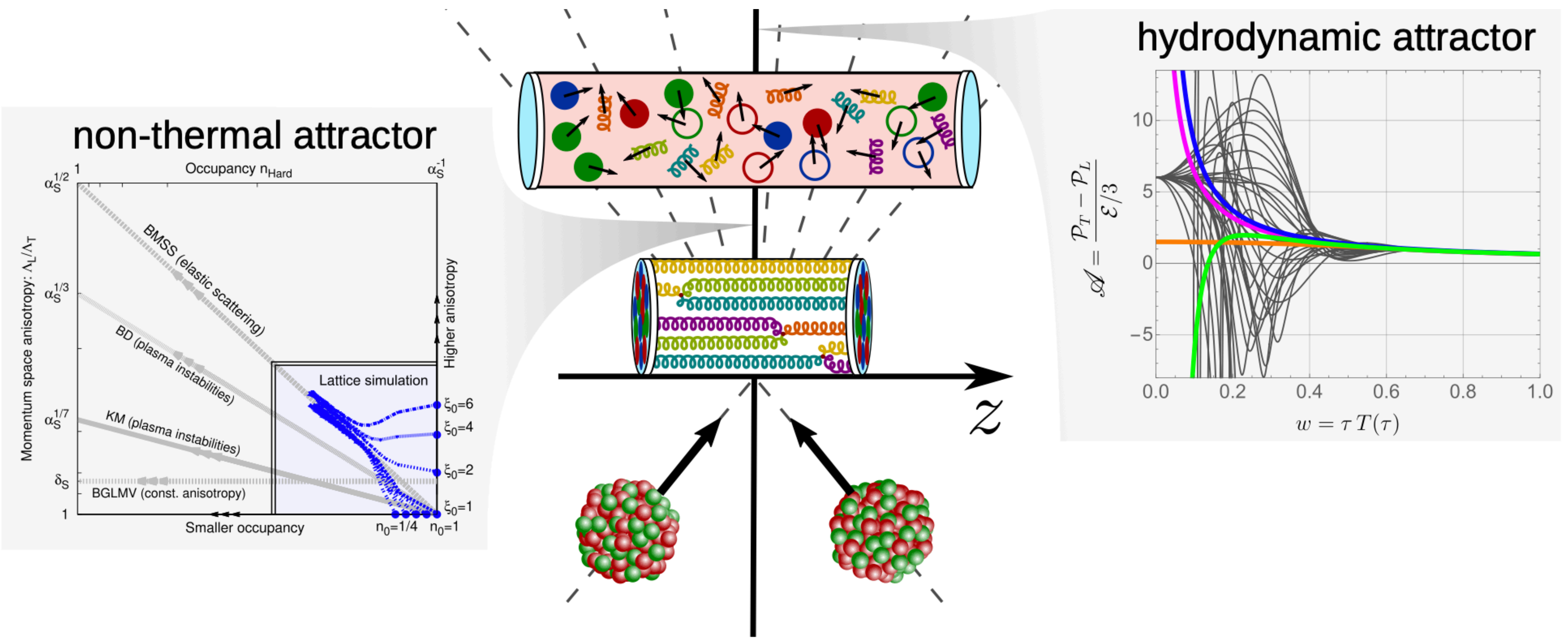
$1\,\mathrm{fm} \sim 10^{-24}\,\mathrm{s}$

A brief summary of the different epochs in HICs

Early times: Out of equilibrium matter (Glasma)

Short lived and dominated by classical configurations

Followed by pre-equilibrium stage, typically described using EKT [See Tuomas' talk]



[Berges, Heller, Mazeliauskas, Venugopalan, 2005.12299]

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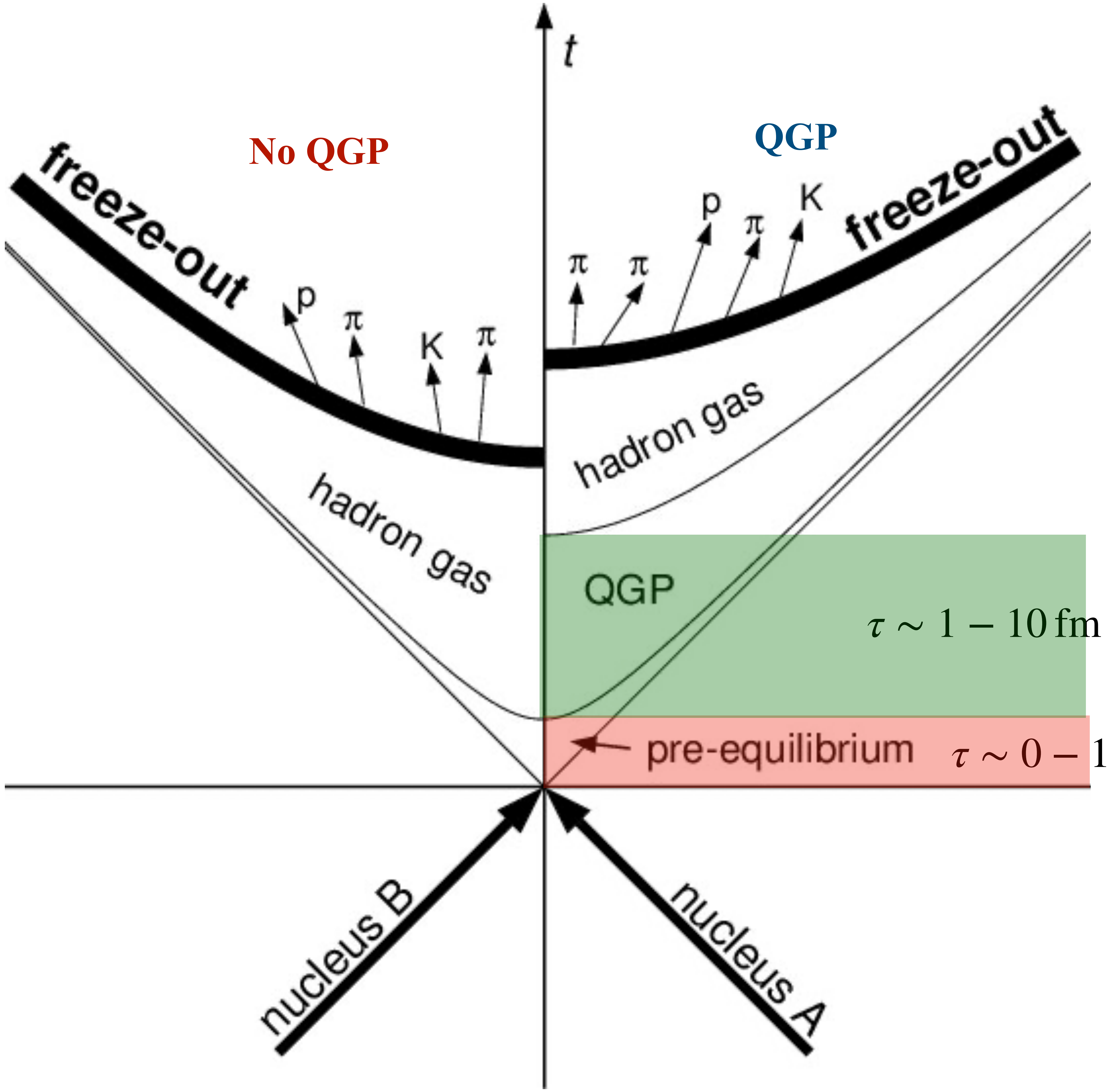

$\tau \sim 1 - 10\,\mathrm{fm}$

$\tau \sim 0 - 1\,\mathrm{fm}$

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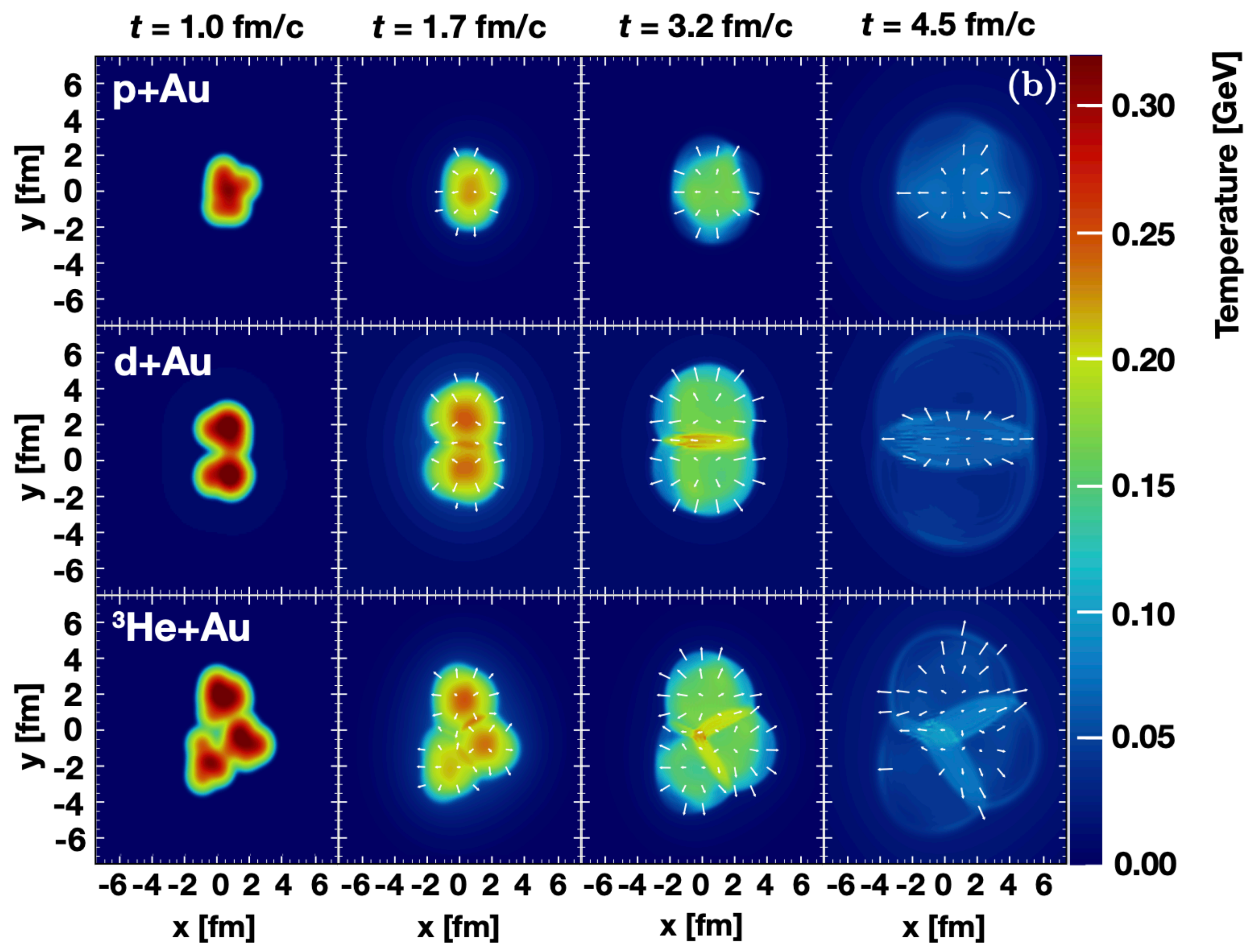
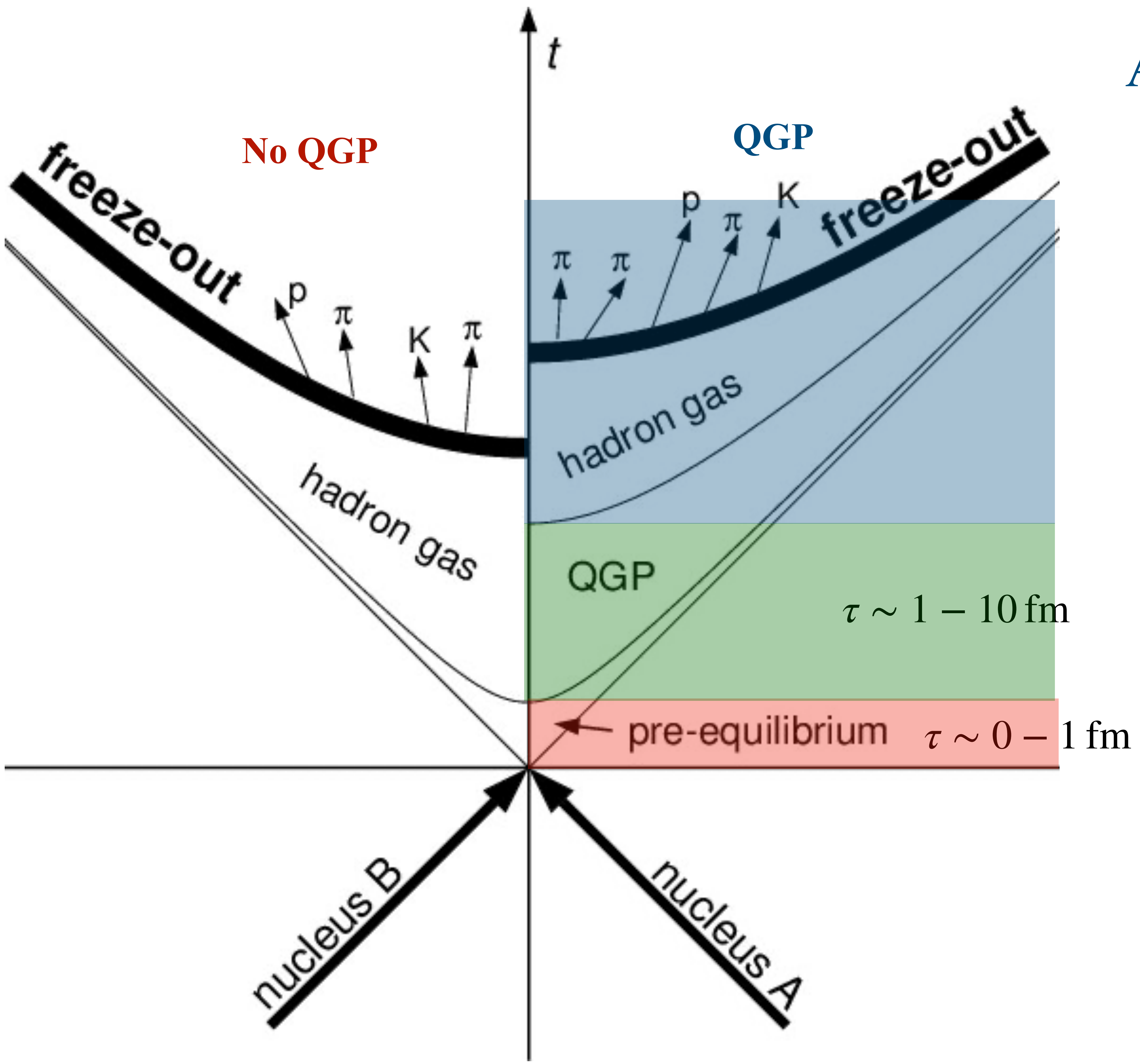
Intermediate times: Quark Gluon Plasma phase

Long lived, expanding hydro system where quarks and gluons are not confined inside hadrons



[PHENIX collaboration, 2018]

The spacetime picture of HICs



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Early times: Out of equilibrium matter (Glasma)

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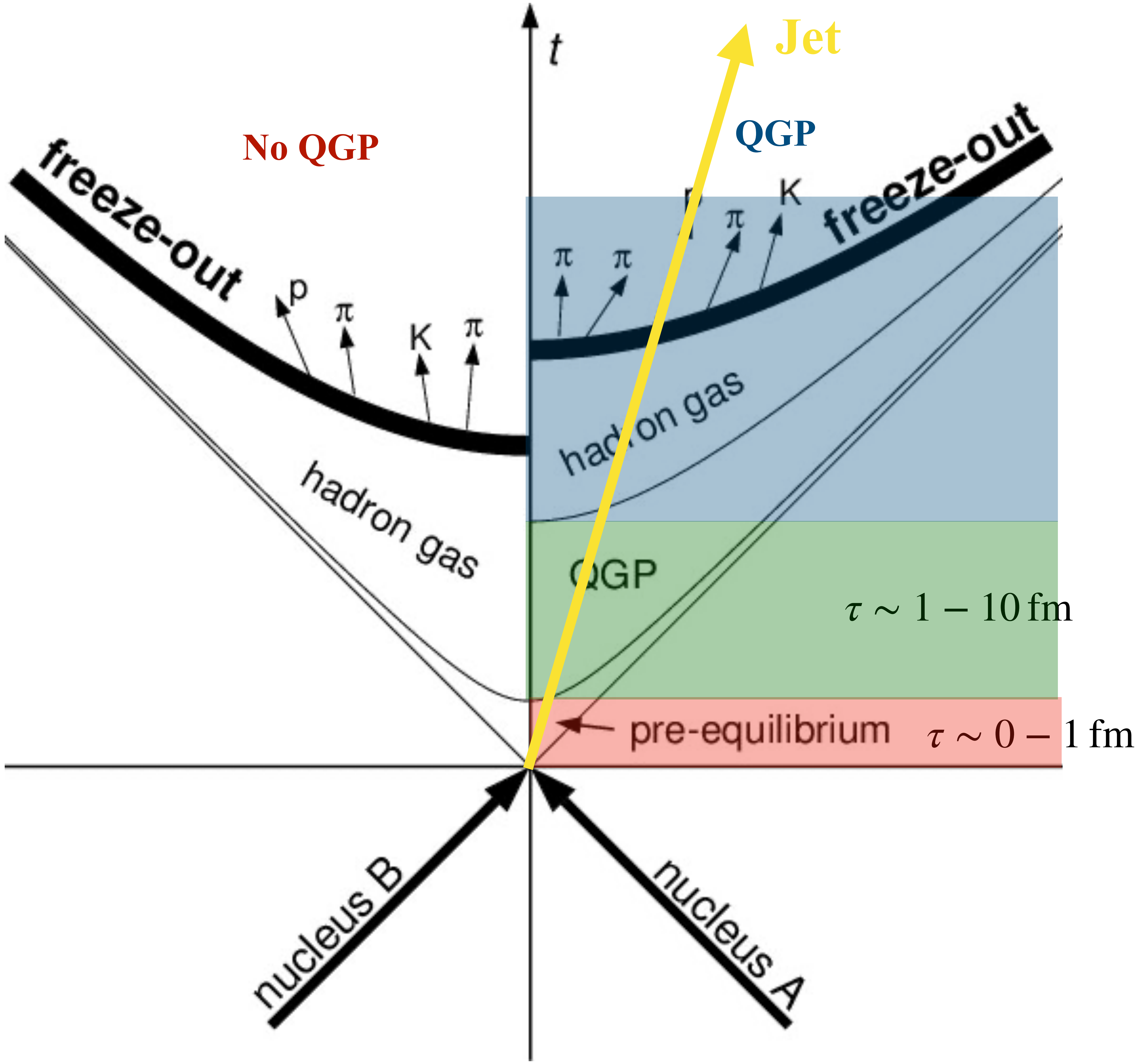
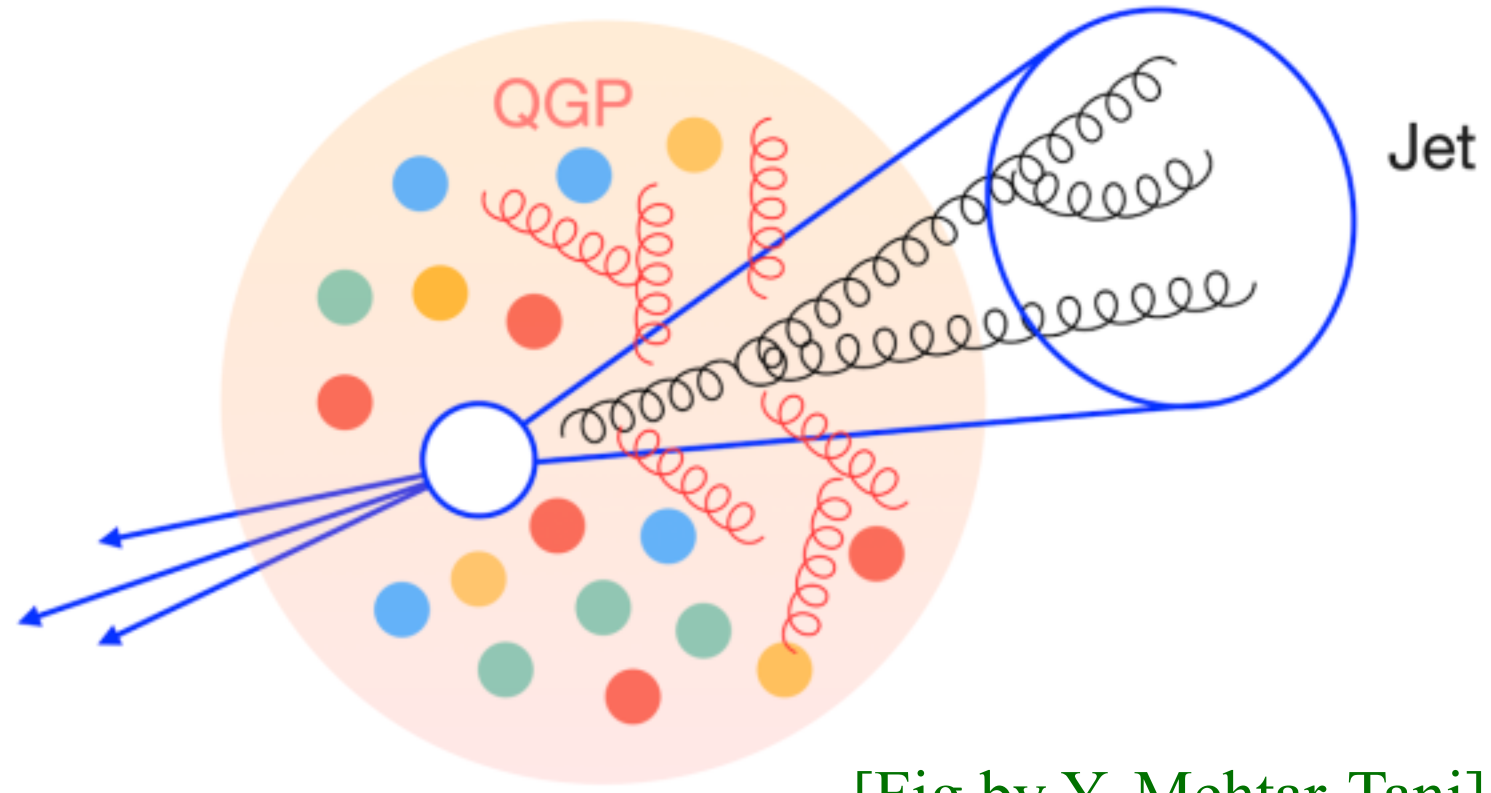
Hadronic phase: Temperature below critical value

Gas of hadrons, which eventually free streams to the detectors

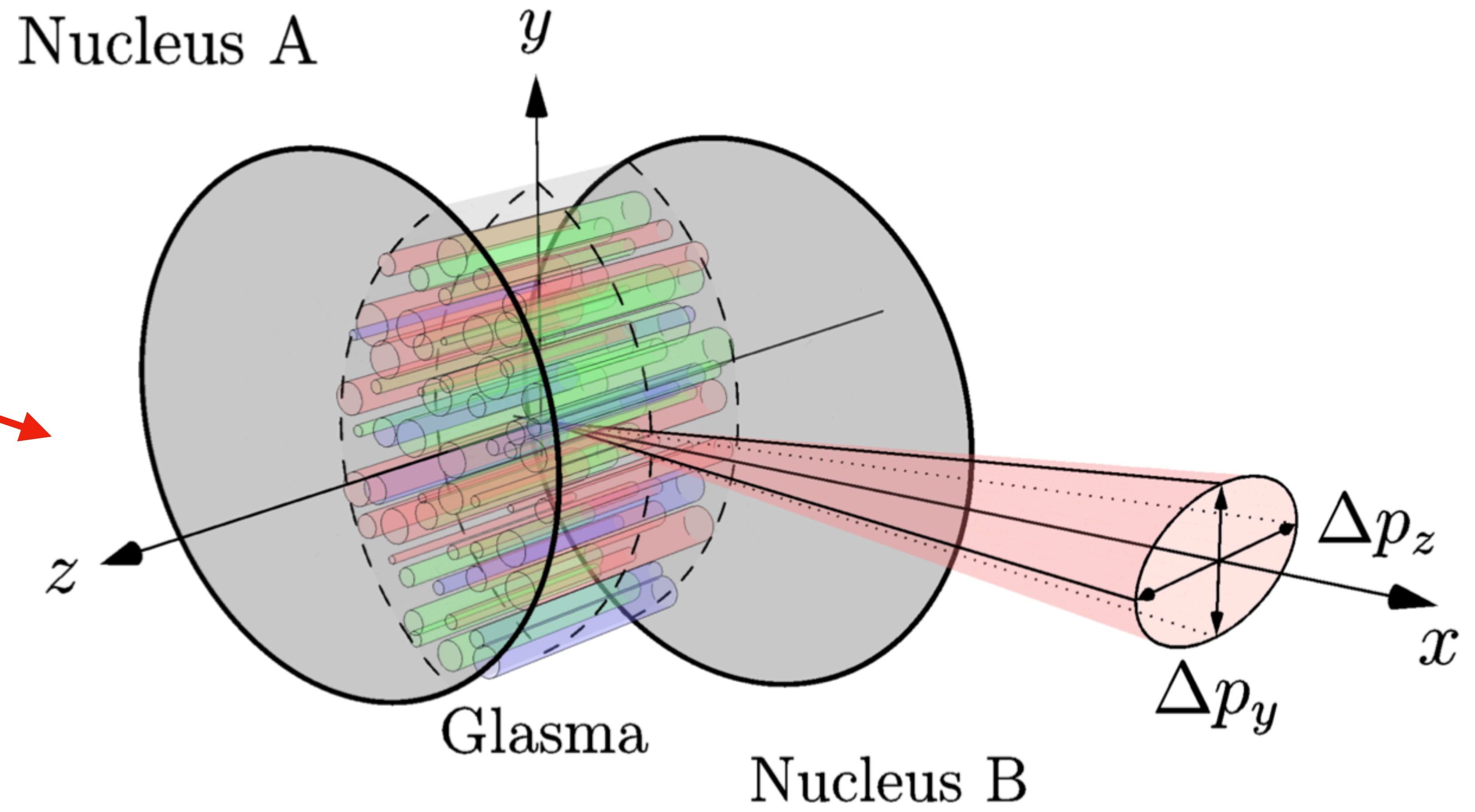
The spacetime picture of HICs



An ideal probe: QCD jets



[Fig by Y. Mehtar-Tani]



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

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, see Jo's talk], 2308.01294 [Jet substructure], DREENA [see Bithika's and Magdalena's talks], …

Jet evolution in the early stages

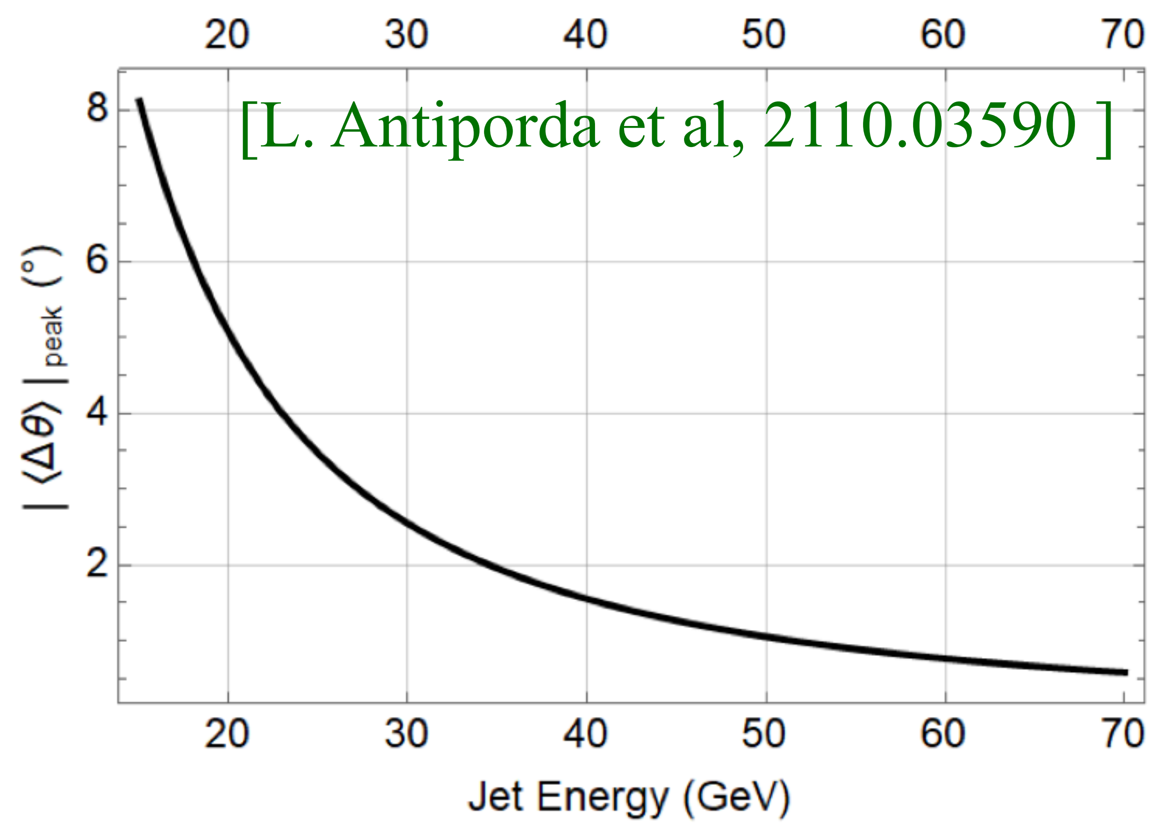
Momentum broadening in early stages: See Tuomas' talk + works by D. Muller et al + works by A. Czajka et al

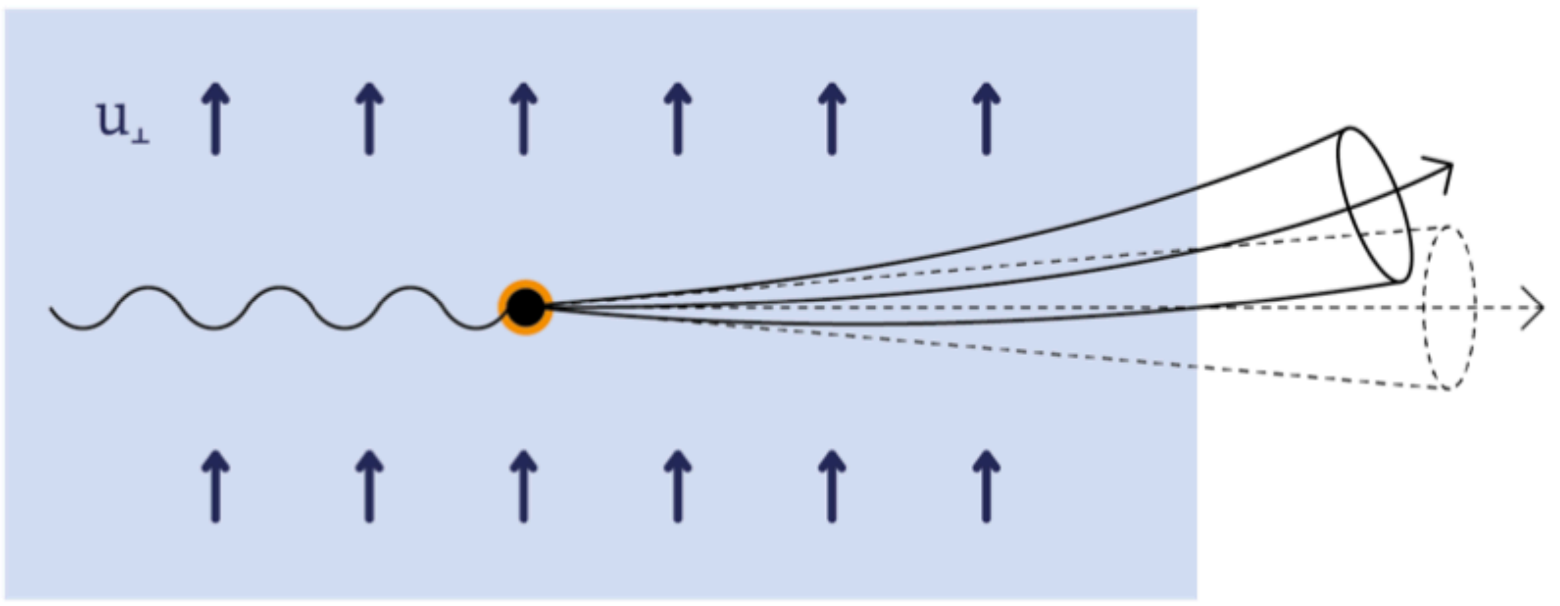
Radiative spectrum in "glasma": 2306.20307 [Photons], 2303.03914 [Gluon branching], 2407.04774 [Quark antenna], 2406.07615 [Spatial correlations]

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

The Landscape

Jet evolution in hydrodynamical phase





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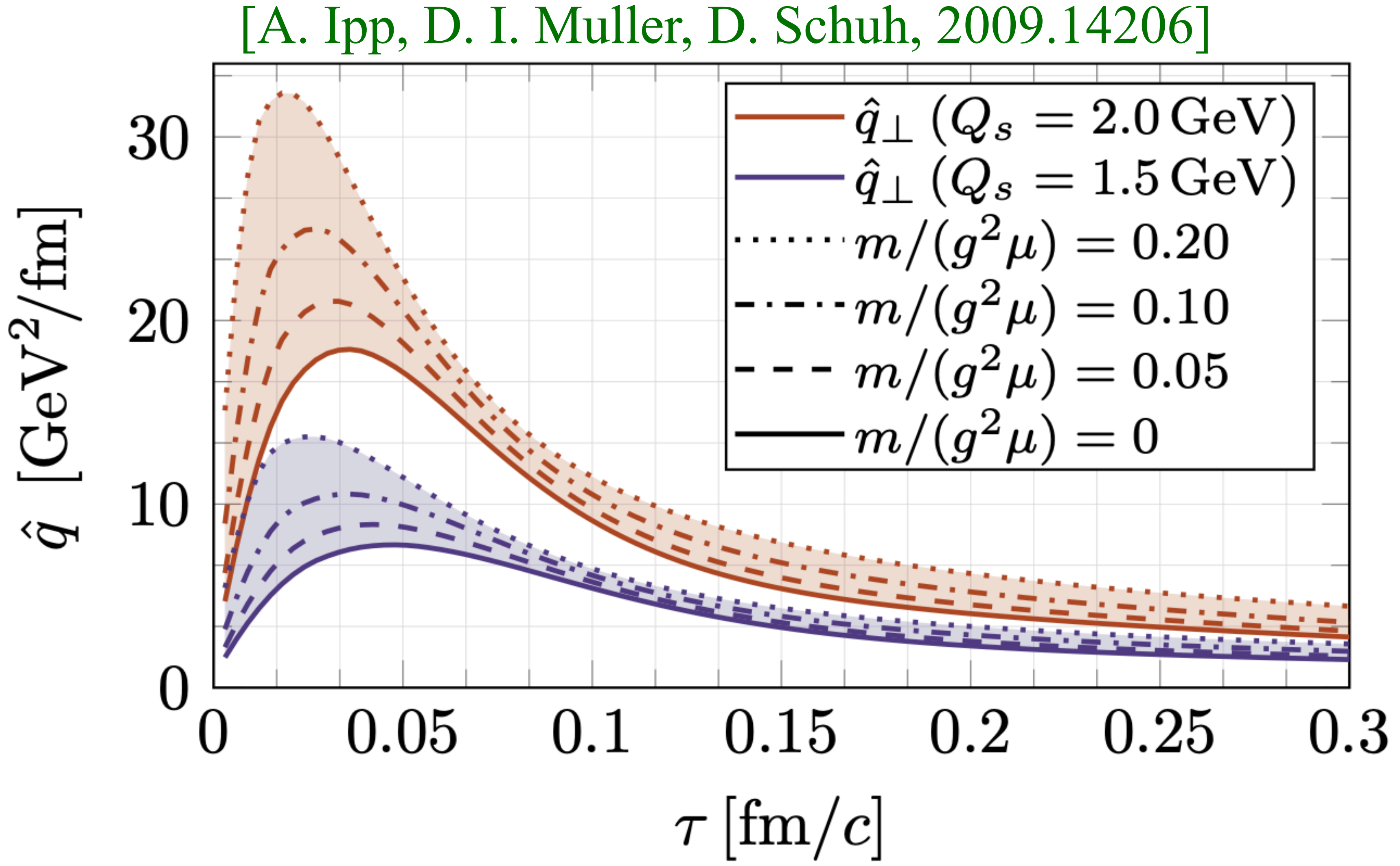

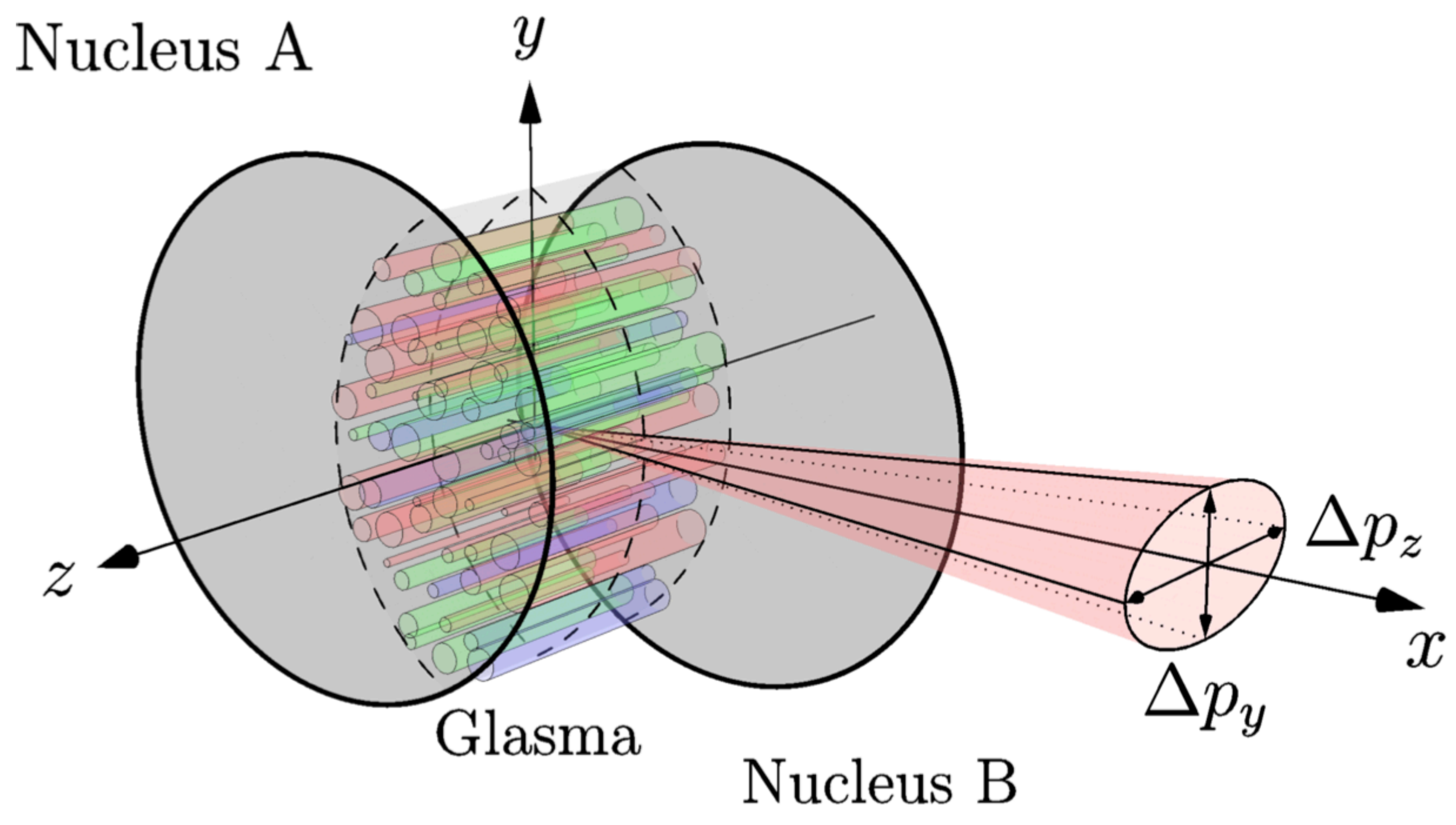

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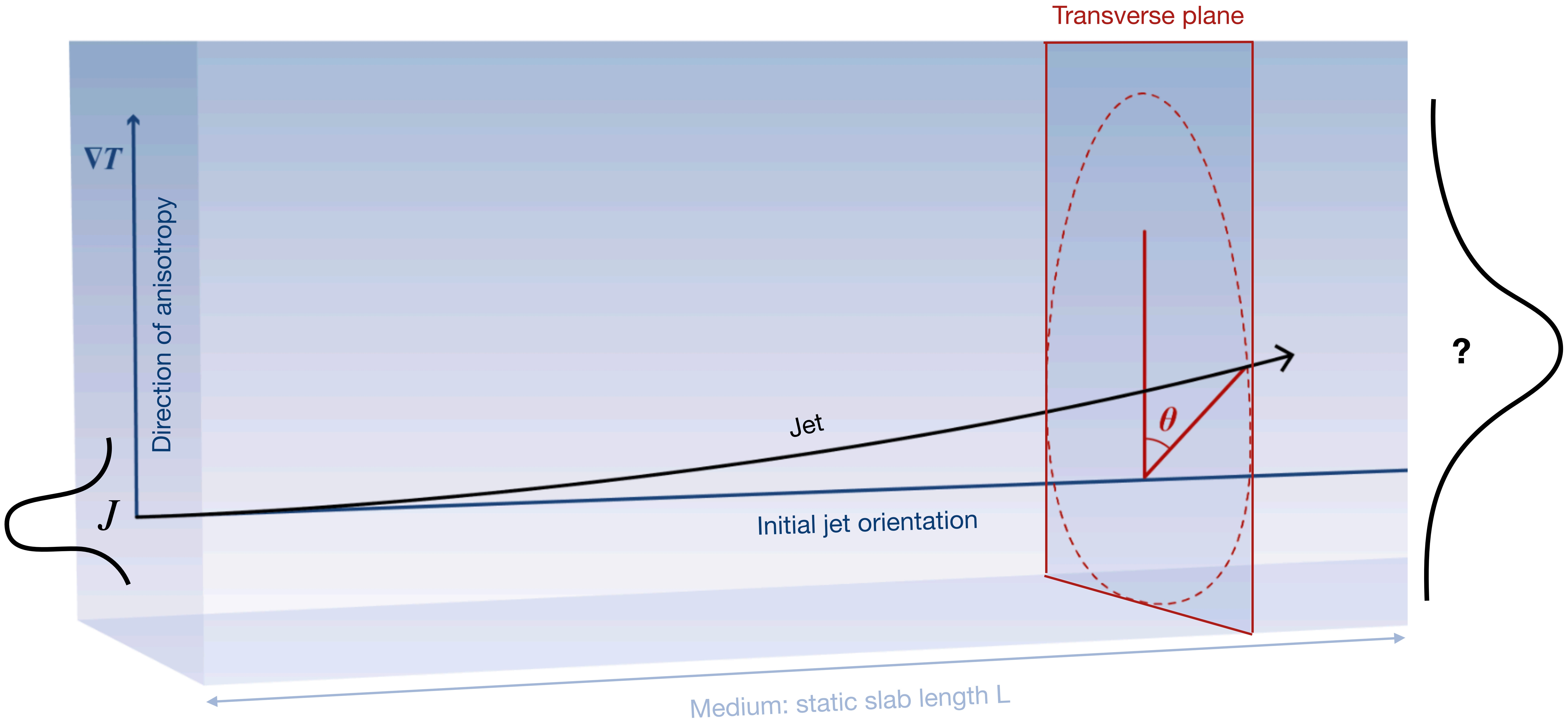
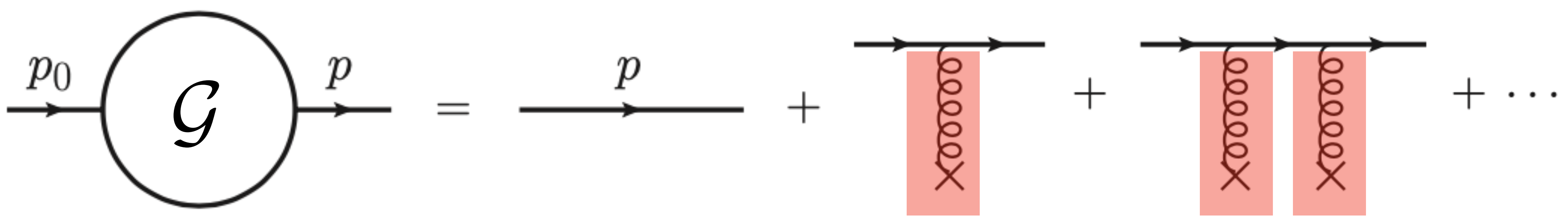
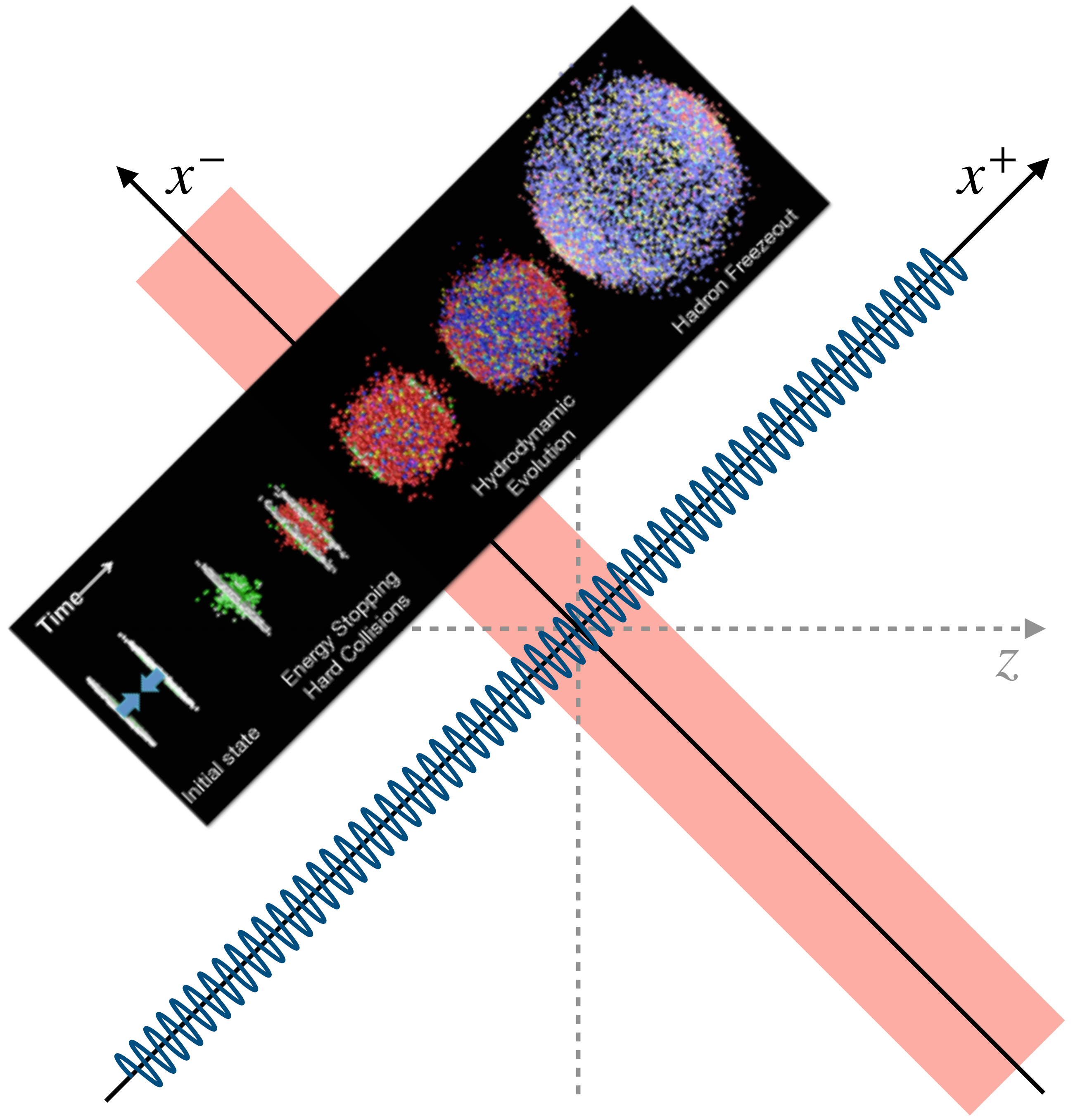
Gradient corrections to parton evolution



Jets in AA

In the medium, one needs to account for interactions with the QGP:





For very energetic particles there is a simple solution:

$$\mathcal{G}(\boldsymbol{x}_2, t_2; \boldsymbol{x}_1, t_1) = \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} \mathcal{D}\boldsymbol{r} \exp\left(\frac{i\omega}{2} \int_{t_1}^{t_2} dt\, \dot{\boldsymbol{r}}^2 \right) \mathcal{W}_{\boldsymbol{r}}$$

Wilson line along forward light-cone

[BDMPS-Z, early 2000s]

Any process reduces to computing correlators of these objects

QCD vertices

$$d\sigma \sim \langle \mathcal{T} \prod \{\mathcal{G}, \Gamma\} \rangle_{\text{matter}}$$

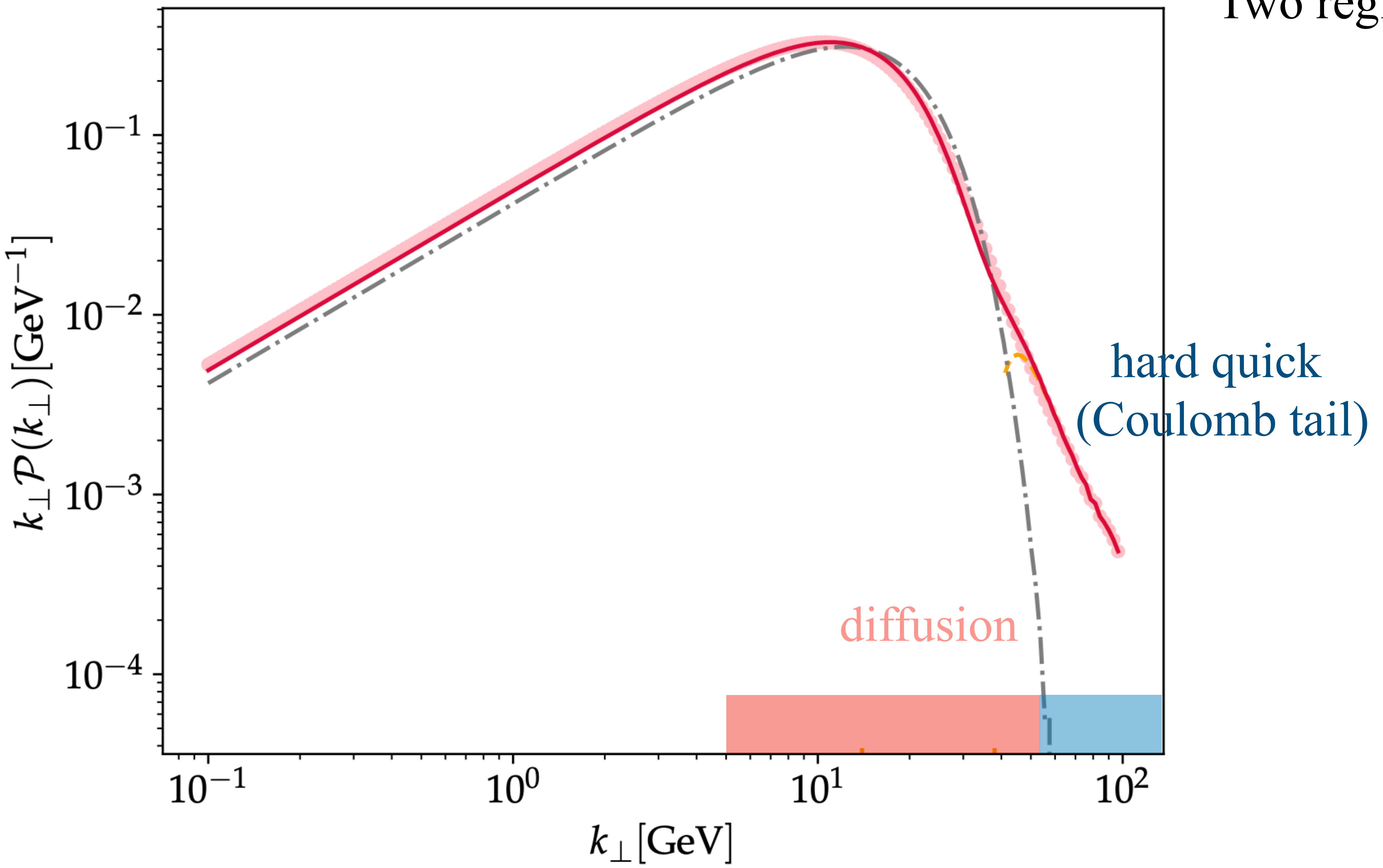
In general, one assumes a Gaussian form for the average

$$\langle A^{-,a}(x) A^{-,b}(y) \rangle \propto f(\boldsymbol{x} - \boldsymbol{y}) \delta^{ab} \delta(x^+ - y^+)$$

Momentum broadening

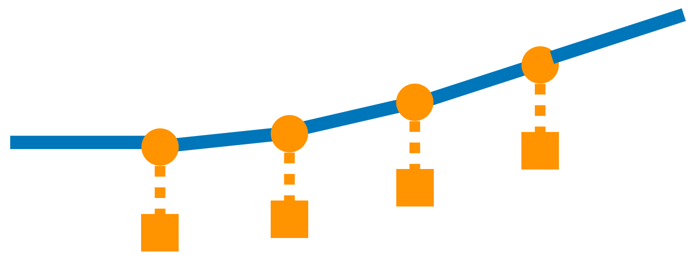
Simplest case: single parton evolution in the medium

$$\langle \mathcal{G}(\boldsymbol{x})\mathcal{G}^\dagger(0)\rangle \overset{\text{F.T.}}{\rightarrow} \mathcal{P}(\boldsymbol{k})$$



Two regimes :

Diffusive broadening

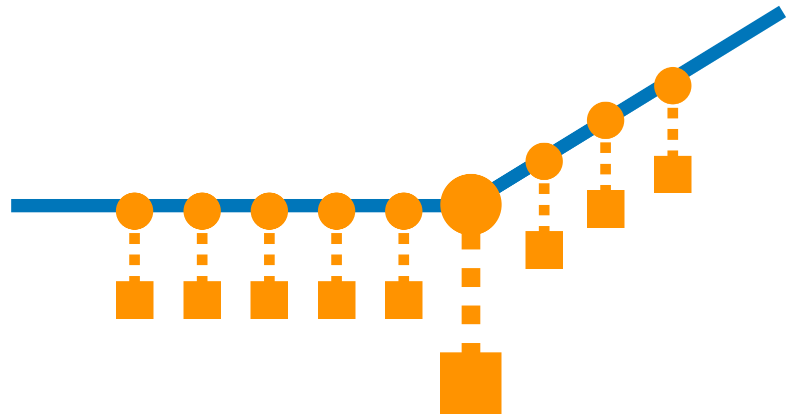


= many soft kicks

jet quenching parameter

$$\partial_t \mathcal{P}(\boldsymbol{k}) = -\frac{\hat{q}}{4}\partial^2_{\boldsymbol{k}}\mathcal{P}(\boldsymbol{k})$$

Single hard interaction



= one hard kick

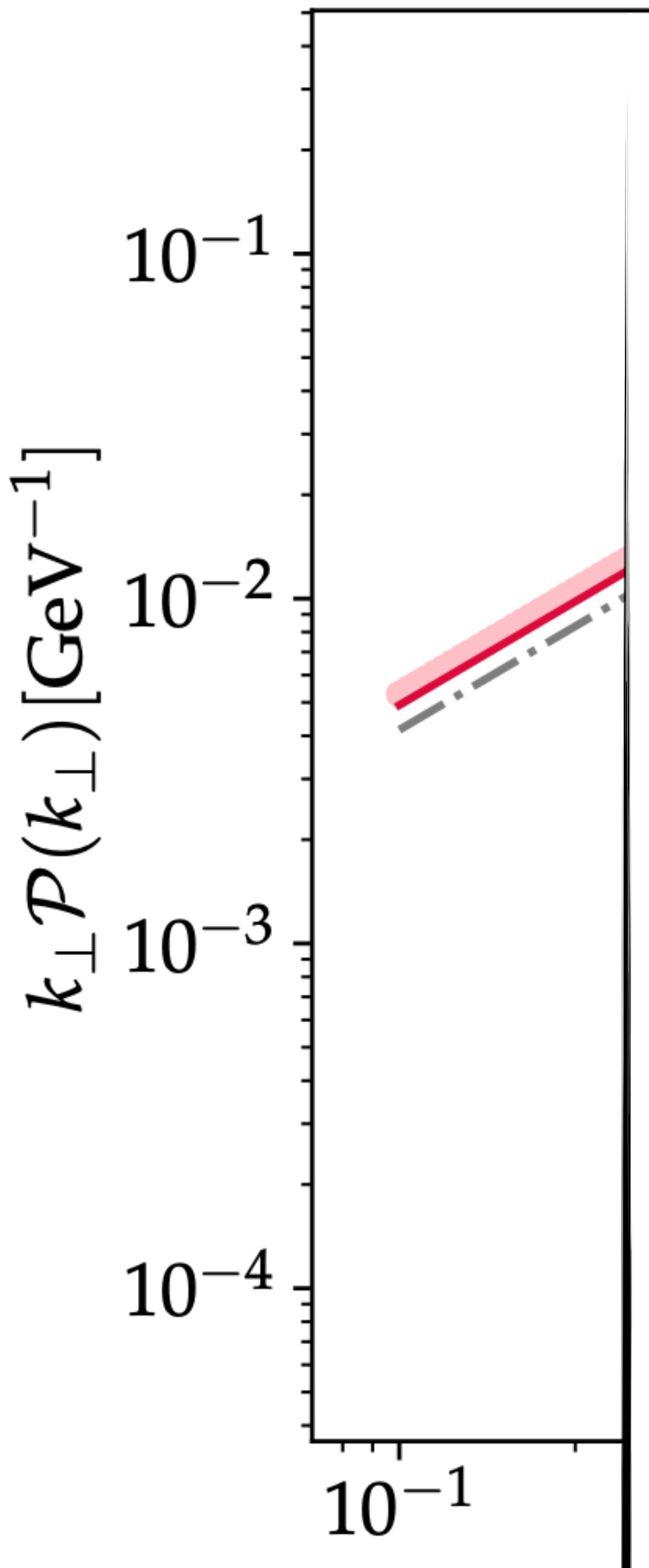
$$\mathcal{P}(\boldsymbol{k}) \propto \frac{1}{\boldsymbol{k}^4}$$

Momentum broadening

Simplest case: single parton evolution in the medium

$$\langle \mathcal{G}(\boldsymbol{x})\mathcal{G}^\dagger(0)\rangle \xrightarrow{\text{F.T.}} \mathcal{P}(\boldsymbol{k})$$

Two regimes :



If the medium has structure (gradients) can we still write :

$$\partial_t \mathcal{P}(\boldsymbol{k}) = -\frac{\hat{q}}{4}\partial^2_{\boldsymbol{k}}\mathcal{P}(\boldsymbol{k}) \quad ?$$

Is it enough to make the diffusion constant space dependent ?

Gradient Tomography of Jet Quenching in Heavy-Ion Collisions

Yayun He,[1] Long-Gang Pang,[1] and Xin-Nian Wang[1,2,*]

$$\frac{\partial f_a}{\partial t} + \frac{\vec{k}_\perp}{\omega}\cdot\frac{\partial f_a}{\partial \vec{r}_\perp} = \frac{\hat{q}_a}{4}\vec{\nabla}^2_{k_\perp} f_a(\vec{k},\vec{r})$$

$$\hat{q} \sim T^3 \to T^3(t,\vec{x})$$

ft kicks

quenching parameter

n

hard kick

$\mathcal{P}(\boldsymbol{k}) \propto \frac{\quad}{\boldsymbol{k}^4}$

Gradient corrections to broadening

[JB, A. Sadofyev, X.-N. Wang, 2210.06519]

Brookhaven National Laboratory

We first derive the probability for a quark to acquire transverse momentum at leading order in hydro gradients

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

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

To answer the previous question, we go and compute the evolution equation for the relevant correlator

$$W_L(\boldsymbol{Y},\boldsymbol{p}) \equiv \int_{\boldsymbol{y},\boldsymbol{x},\boldsymbol{X},\boldsymbol{p}_0} e^{-i(\boldsymbol{p}\cdot\boldsymbol{y}-\boldsymbol{p}_0\cdot\boldsymbol{x})} W_0(\boldsymbol{X},\boldsymbol{p}_0) \times \left\langle \mathcal{G}\left(\boldsymbol{Y}+\frac{\boldsymbol{y}}{2};\boldsymbol{X}+\frac{\boldsymbol{x}}{2}\right)\mathcal{G}^\dagger\left(\boldsymbol{Y}-\frac{\boldsymbol{y}}{2};\boldsymbol{X}-\frac{\boldsymbol{x}}{2}\right)\right\rangle$$

Easy to generalize from before

Gradient corrections to broadening

[JB, A. Sadofyev, X.-N. Wang, 2210.06519]

Brookhaven National Laboratory

This allows to (partially) resum all gradients; this is only possible assuming a local and Gaussian background

$$\left\langle \mathcal{G}^\dagger(\bar{\boldsymbol{k}}, L+\epsilon; \bar{\boldsymbol{k}}_0, 0)\, \mathcal{G}(\boldsymbol{k}, L+\epsilon; \boldsymbol{k}_0, 0)\right\rangle = \int_{\boldsymbol{l},\bar{\boldsymbol{l}}} \left\langle \mathcal{G}^\dagger(\bar{\boldsymbol{k}}, L+\epsilon; \bar{\boldsymbol{l}}, L)\, \mathcal{G}(\boldsymbol{k}, L+\epsilon; \boldsymbol{l}, L)\right\rangle \times \left\langle \mathcal{G}^\dagger(\bar{\boldsymbol{l}}, L; \bar{\boldsymbol{k}}_0, 0)\, \mathcal{G}(\boldsymbol{l}, L; \boldsymbol{k}_0, 0)\right\rangle$$

Using this property and the explicit form for the leading distribution, we find

$$\partial_L W(\boldsymbol{k}, \bar{\boldsymbol{k}}) = -i\,\frac{\boldsymbol{k}^2 - \bar{\boldsymbol{k}}^2}{2E} W(\boldsymbol{k}, \bar{\boldsymbol{k}}) - \int_{\boldsymbol{q},\bar{\boldsymbol{q}},\boldsymbol{l},\bar{\boldsymbol{l}}} \mathcal{K}(\boldsymbol{q}, \bar{\boldsymbol{q}}; \boldsymbol{l}, \bar{\boldsymbol{l}}) W(\boldsymbol{l}, \bar{\boldsymbol{l}})$$

$$\mathcal{K}(\boldsymbol{q}, \bar{\boldsymbol{q}}; \boldsymbol{l}, \bar{\boldsymbol{l}}) = -(2\pi)^4\, C\, v(\boldsymbol{q}) v(\bar{\boldsymbol{q}}) \times \left\{ \rho(\boldsymbol{q}-\bar{\boldsymbol{q}})\, \delta^{(2)}(\boldsymbol{k}-\boldsymbol{q}-\boldsymbol{l})\delta^{(2)}(\bar{\boldsymbol{k}}-\bar{\boldsymbol{q}}-\bar{\boldsymbol{l}}) - \frac{1}{2}\rho(\boldsymbol{q}+\bar{\boldsymbol{q}})\, \delta^{(2)}(\boldsymbol{k}-\boldsymbol{l})\delta^{(2)}(\bar{\boldsymbol{k}}-\boldsymbol{q}-\bar{\boldsymbol{q}}-\bar{\boldsymbol{l}}) - \frac{1}{2}\rho^\dagger(\boldsymbol{q}+\bar{\boldsymbol{q}})\, \delta^{(2)}(\boldsymbol{k}-\boldsymbol{q}-\bar{\boldsymbol{q}}-\boldsymbol{l})\delta^{(2)}(\bar{\boldsymbol{k}}-\bar{\boldsymbol{l}}) \right\}$$

Gradient corrections to broadening

[JB, A. Sadofyev, X.-N. Wang, 2210.06519]

Brookhaven National Laboratory

To understand where the evolution gets modified, we expand order by order in gradients

0th order: Boltzmann + diffusion ✓

1st order: Boltzmann + diffusion + $\hat{q}(\boldsymbol{Y})$ ✓

2nd order: Boltzmann + diffusion + $\hat{q}(\boldsymbol{Y})$ + quantum corrections

$$\kappa = 2\pi^2 C \int_{\boldsymbol{q}} v^2$$

$$\left(\partial_L + \frac{\boldsymbol{p}\cdot\boldsymbol{\nabla}_{\boldsymbol{Y}}}{E} - \frac{\hat{q}(\boldsymbol{Y})}{4}\partial_{\boldsymbol{p}}^2\right) W(\boldsymbol{Y},\boldsymbol{p}) = \boxed{\nabla_i\nabla_j\rho \times \int_{\boldsymbol{q}} \left[\kappa \frac{\partial^2}{\partial p_i \partial p_j}\delta^{(2)}(\boldsymbol{q}) - V_{ij}(\boldsymbol{q})\right] W(\boldsymbol{Y},\boldsymbol{p}-\boldsymbol{q})}$$

$$V_{ij}(\boldsymbol{q}) = \frac{C}{2}\left(\left\{2q_iq_j\left[vv'' - v'v'\right] + vv'\delta_{ij}\right\} - (2\pi)^2\delta^{(2)}(\boldsymbol{q})\int_{\boldsymbol{l}}\left\{2l_il_j\left[vv'' - v'v'\right] + vv'\delta_{ij}\right\}\right)$$

Evolution is now sensitive the scattering rate and corrections inherited from LPM phases; includes non-local terms

Gradient corrections to broadening

[JB, A. Sadofyev, X.-N. Wang, 2210.06519]

What do the new terms generate ?

$$\hat{q} = \frac{1}{L}\int_{\boldsymbol{p}} \boldsymbol{p}^2 W(\boldsymbol{p}, \boldsymbol{Y}, L)$$

A simple calculation gives

Coef. homogenous case

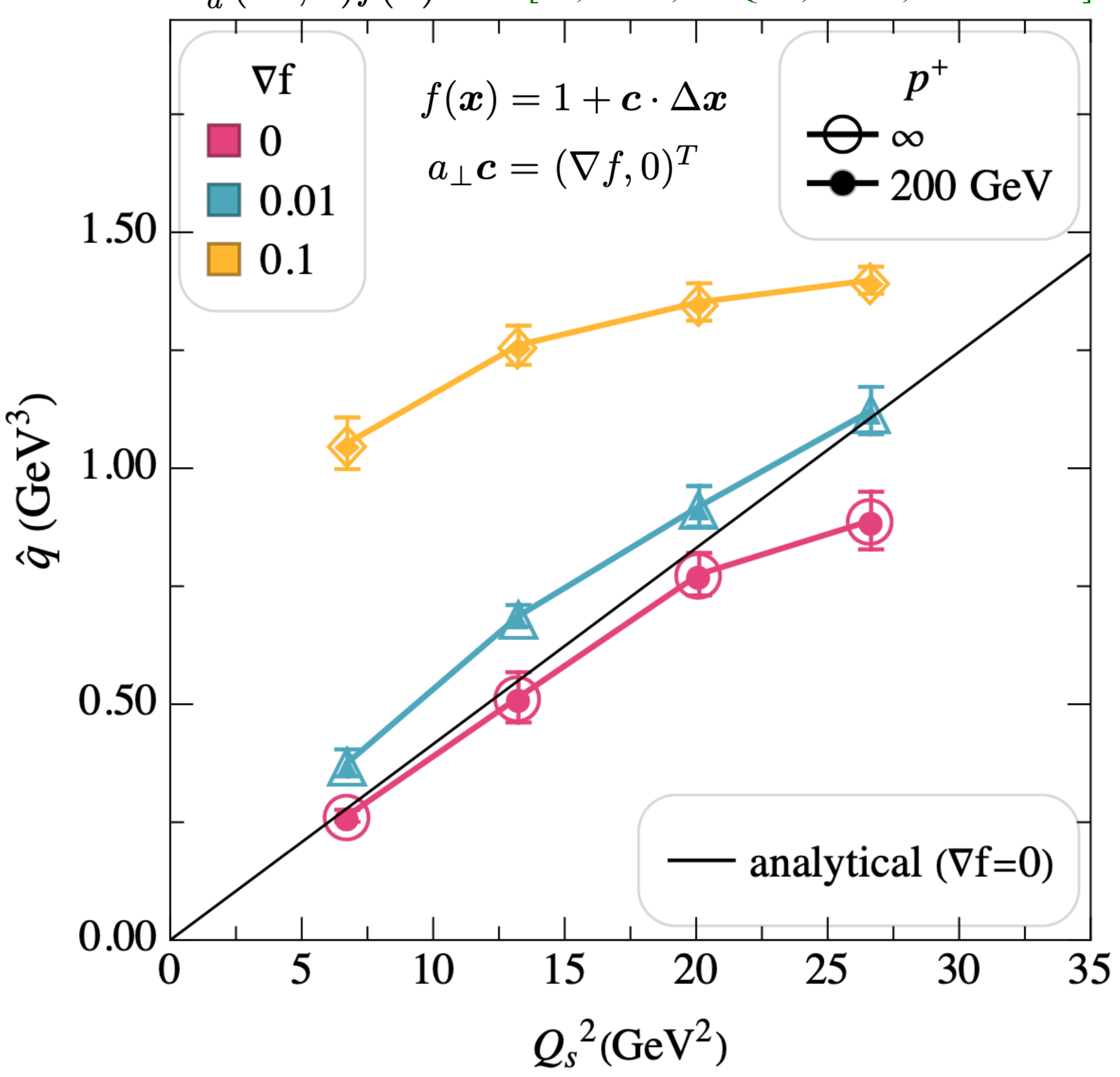
$$\hat{q}_r = \hat{q} + \nabla^2 \hat{q}\left(\frac{\hat{q}L^3}{12E^2} + \eta\right)$$

Full coeff.

Coef. due to anisotropy effects

with $\eta = \rho\,\kappa/(2\pi^2\hat{q}) + \frac{C\rho}{2\hat{q}}\int_{\boldsymbol{q}} \boldsymbol{q}^2 v^2[\boldsymbol{q}^2 v'/v]'$

[JB, M. Li, W. Qian, X. Du, 2208.06750]



Gradient corrections to broadening

[JB, A. Sadofyev, X.-N. Wang, 2210.06519]

What do the new terms generate ?

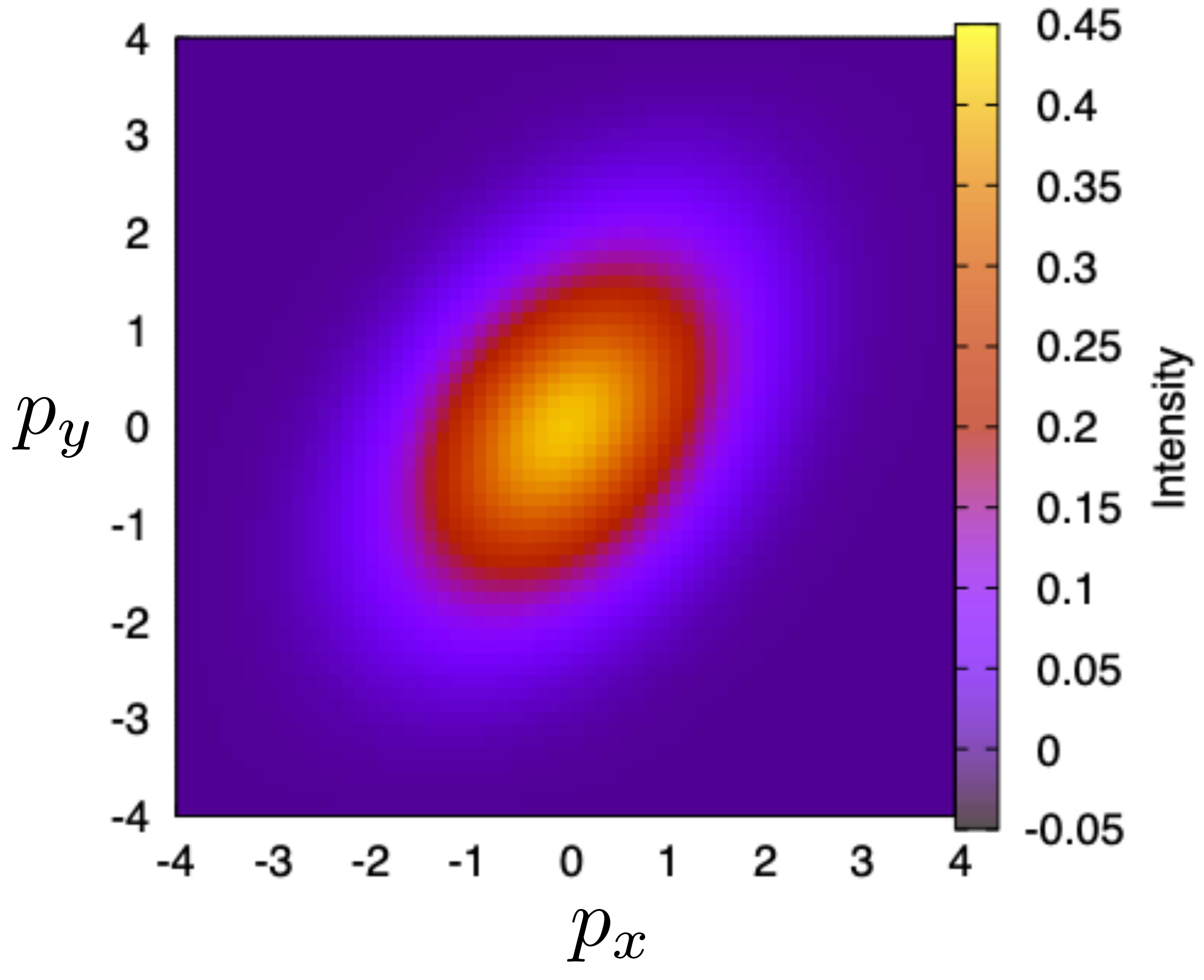
$A_a^-(x^+, \boldsymbol{x}) f(\boldsymbol{x})$ [JB, M. Li, W. Qian, X. Du, 2208.06750]

A simple ca

Full coeff

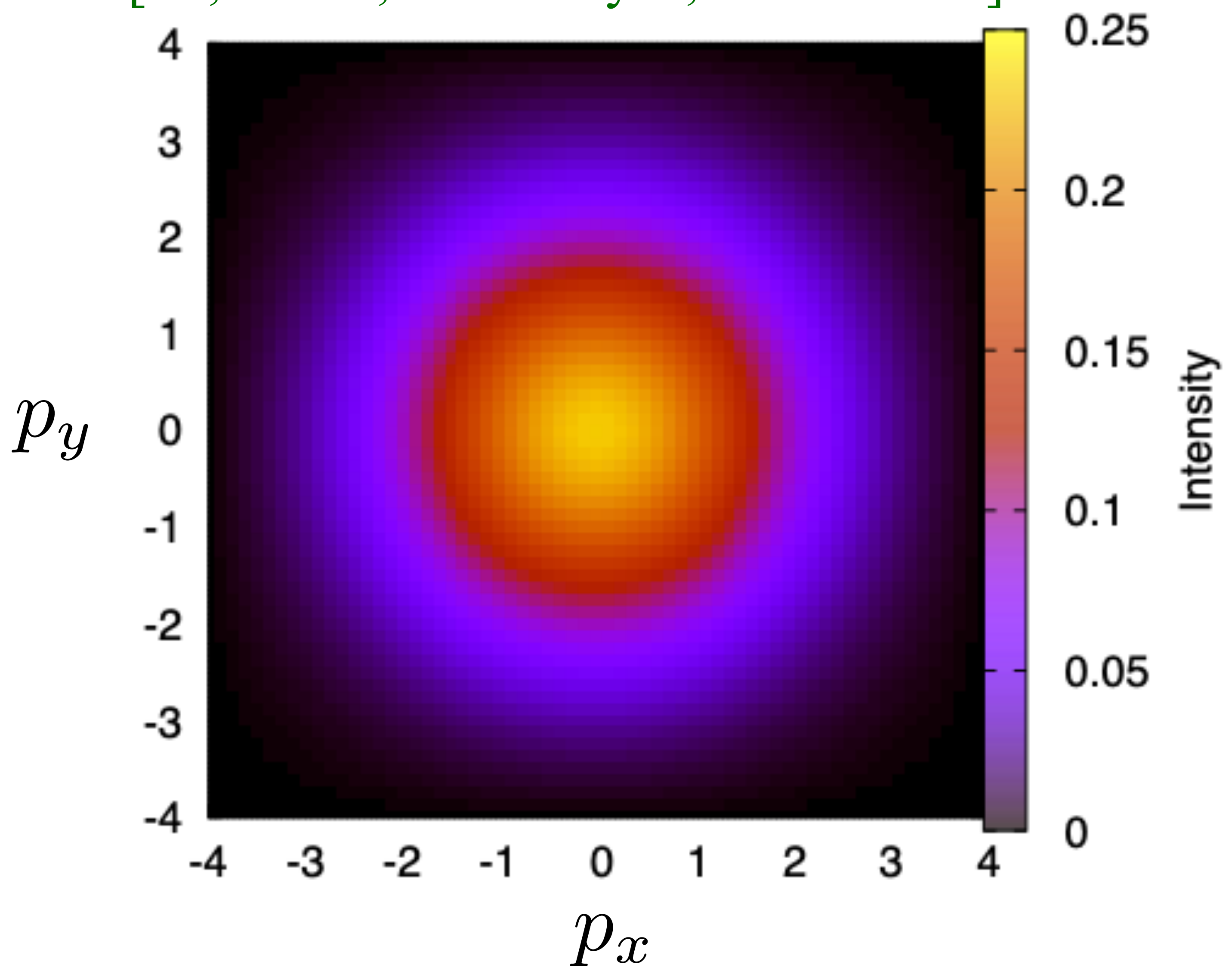
with $\eta =$

Numerical evaluation for isotropic diffusion coefficient at fixed Y



With RHS

[JB, X. Du, A. Sadofyev, 24xx.xxxxx]



No RHS

GeV

∇f=0)

30 35

$Q_s{}^2(\mathrm{GeV}^2)$

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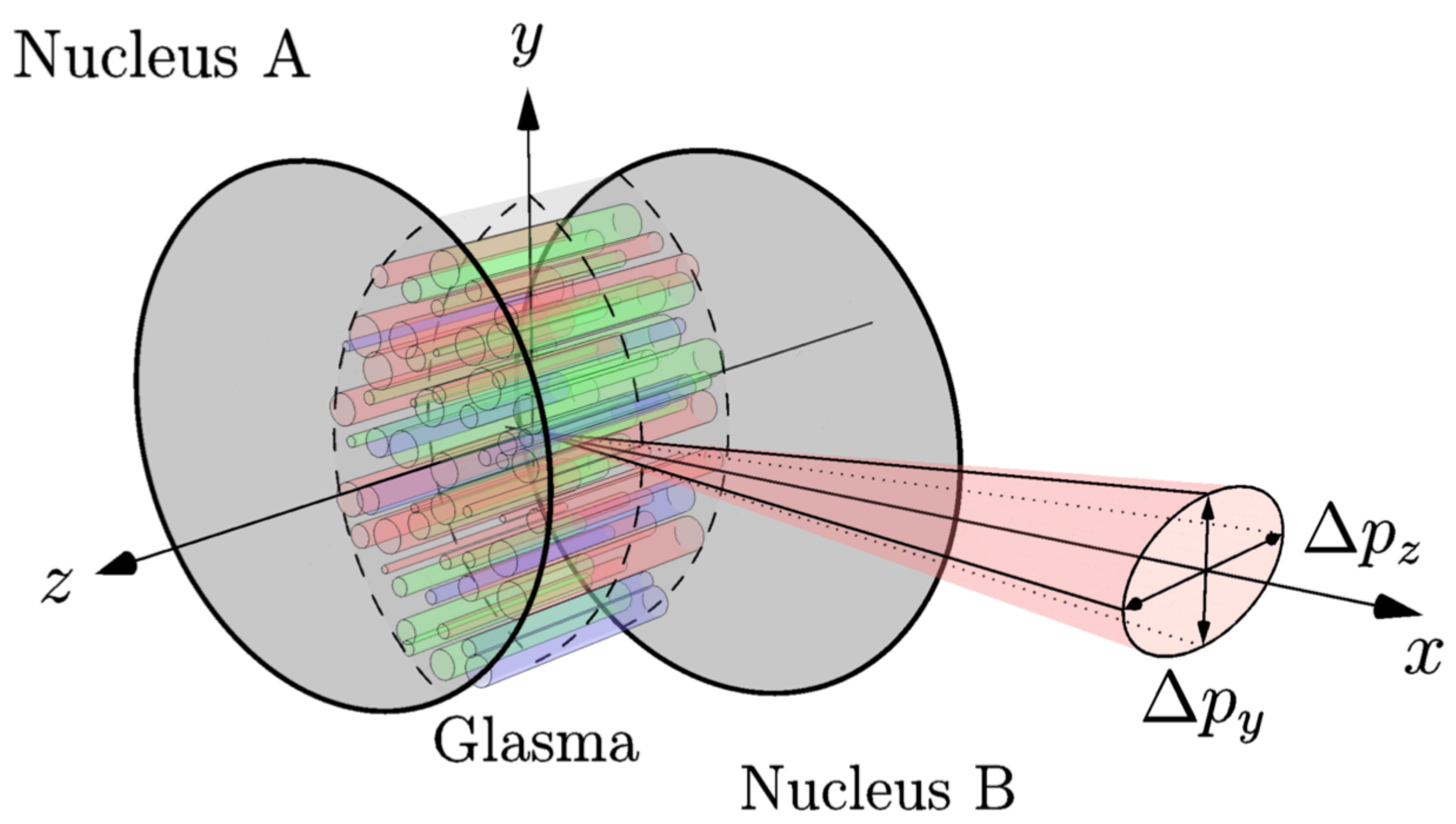
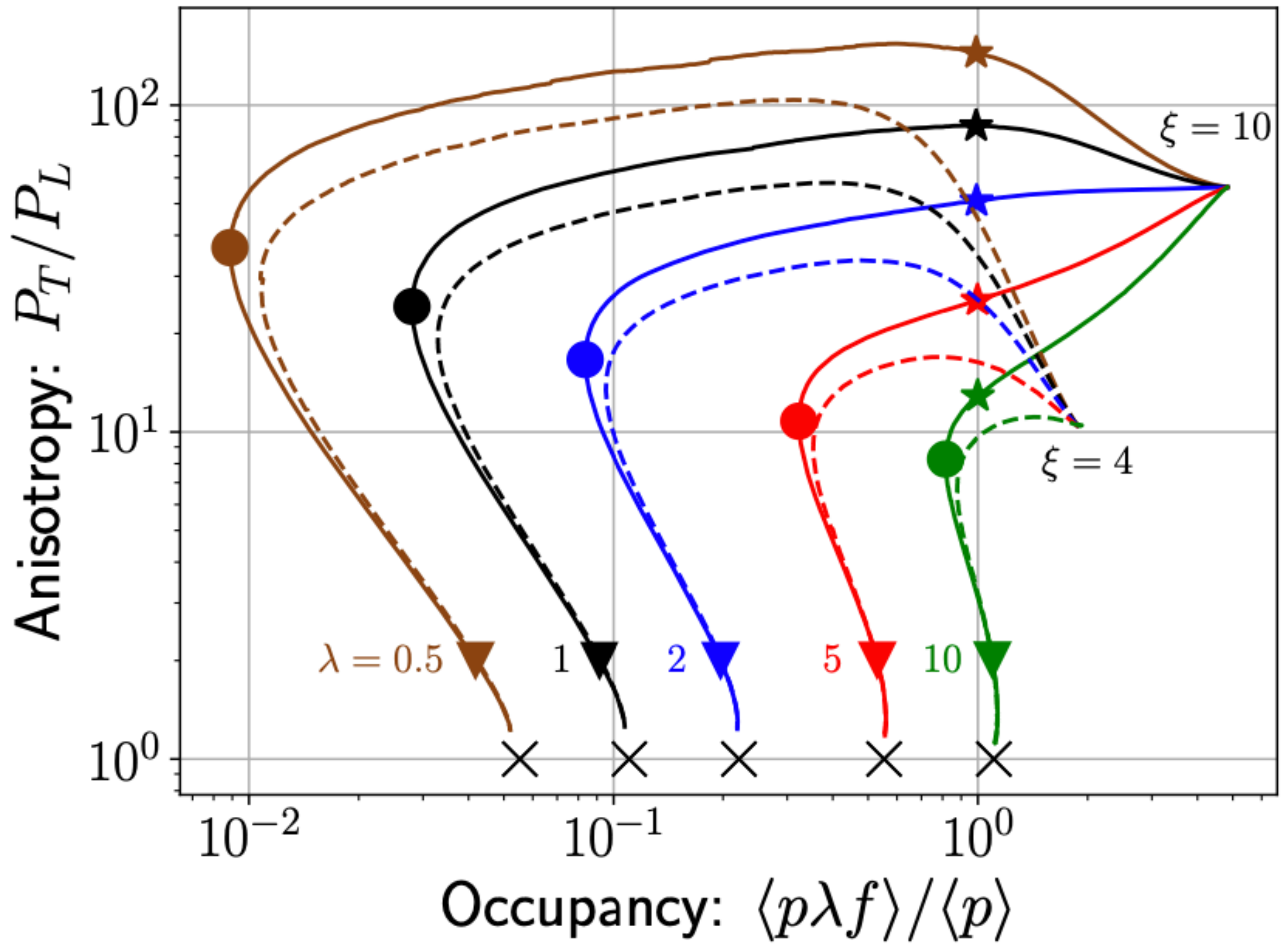
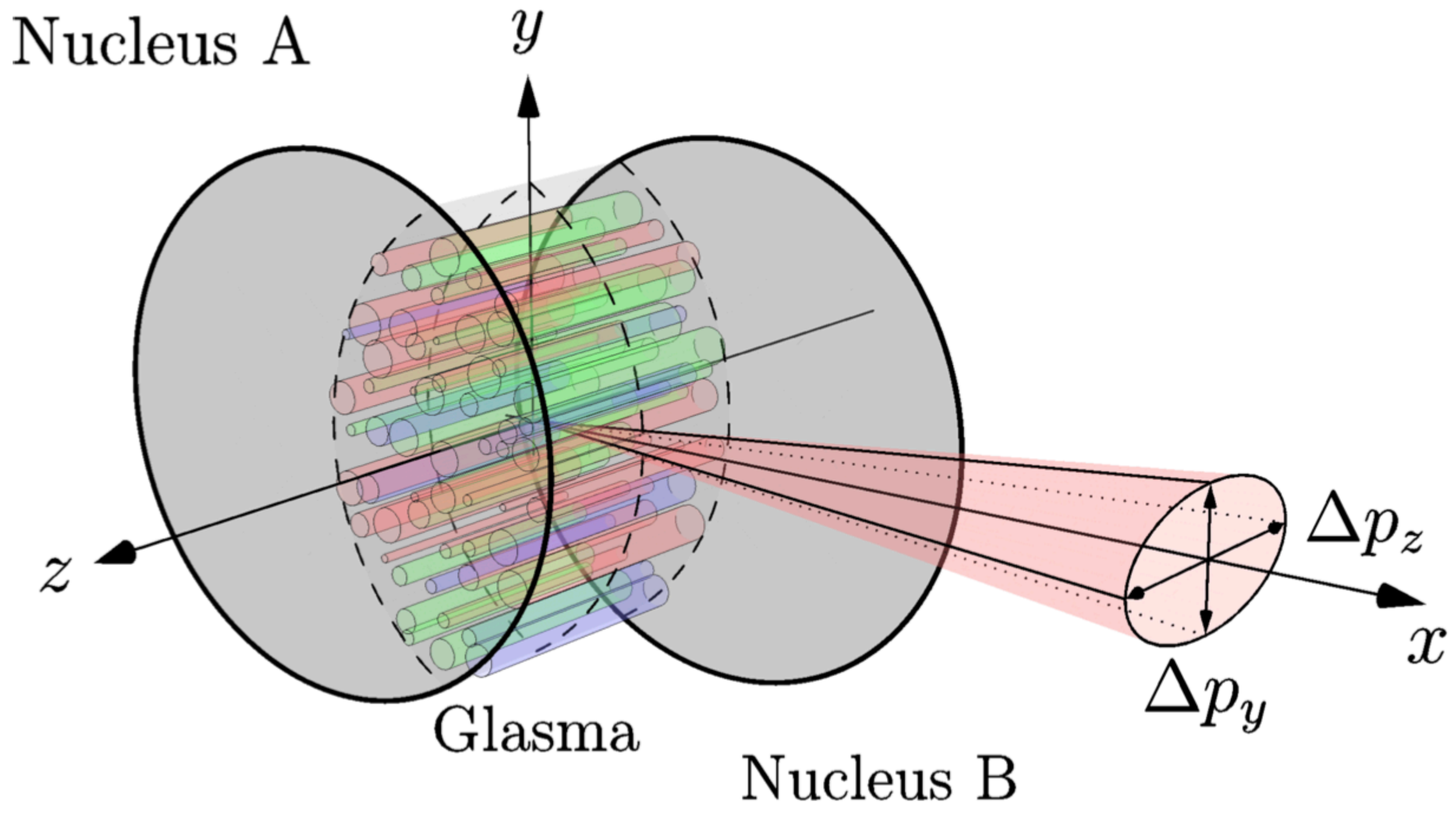


Why are the early stages “different”





- At early times there is a big pressure anisotropy
- This reflects in an anisotropic transport coefficient

[Can be washed out by hydro expansion]

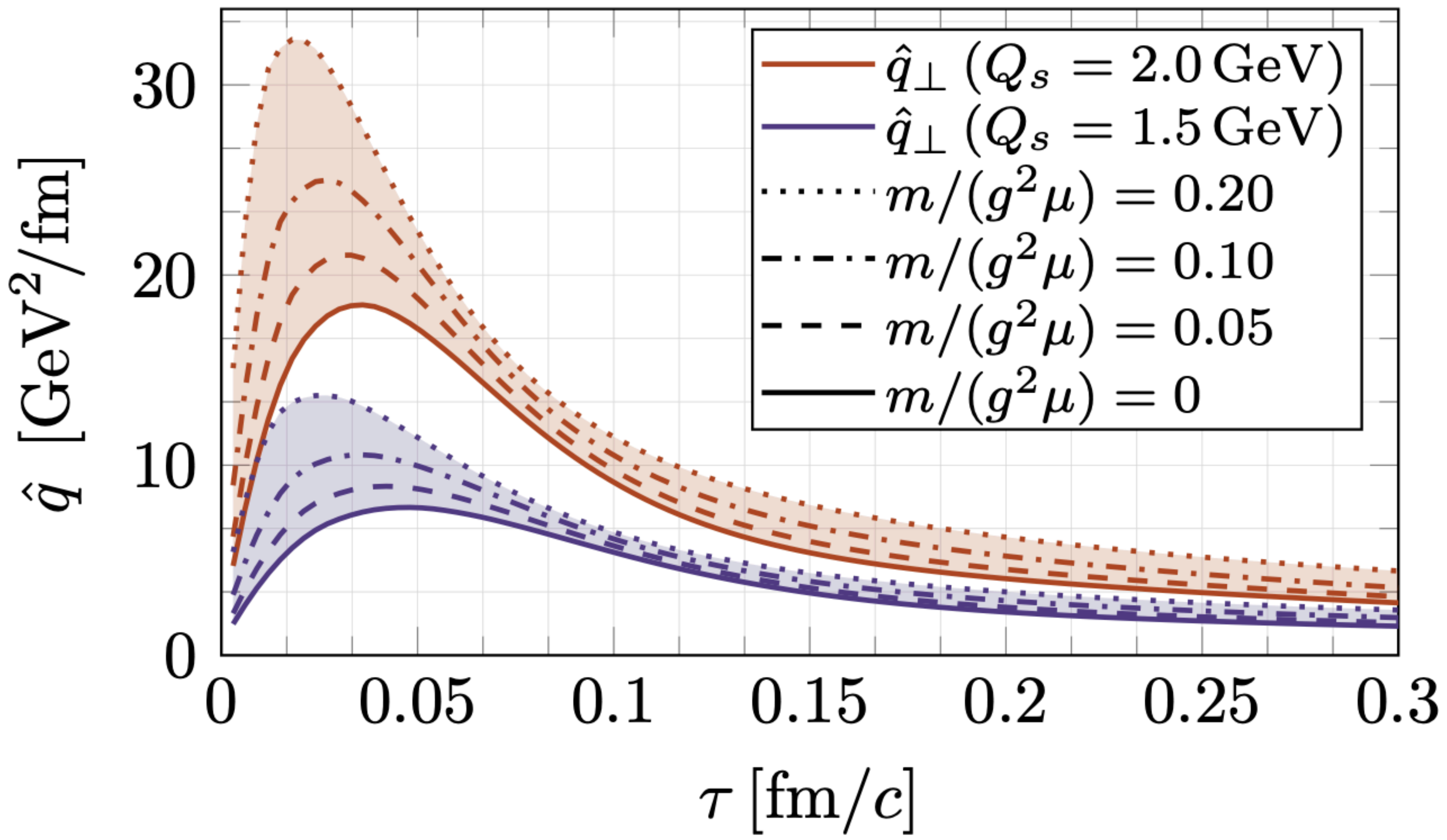
$$\hat{q}_x \gg \hat{q}_y$$

- 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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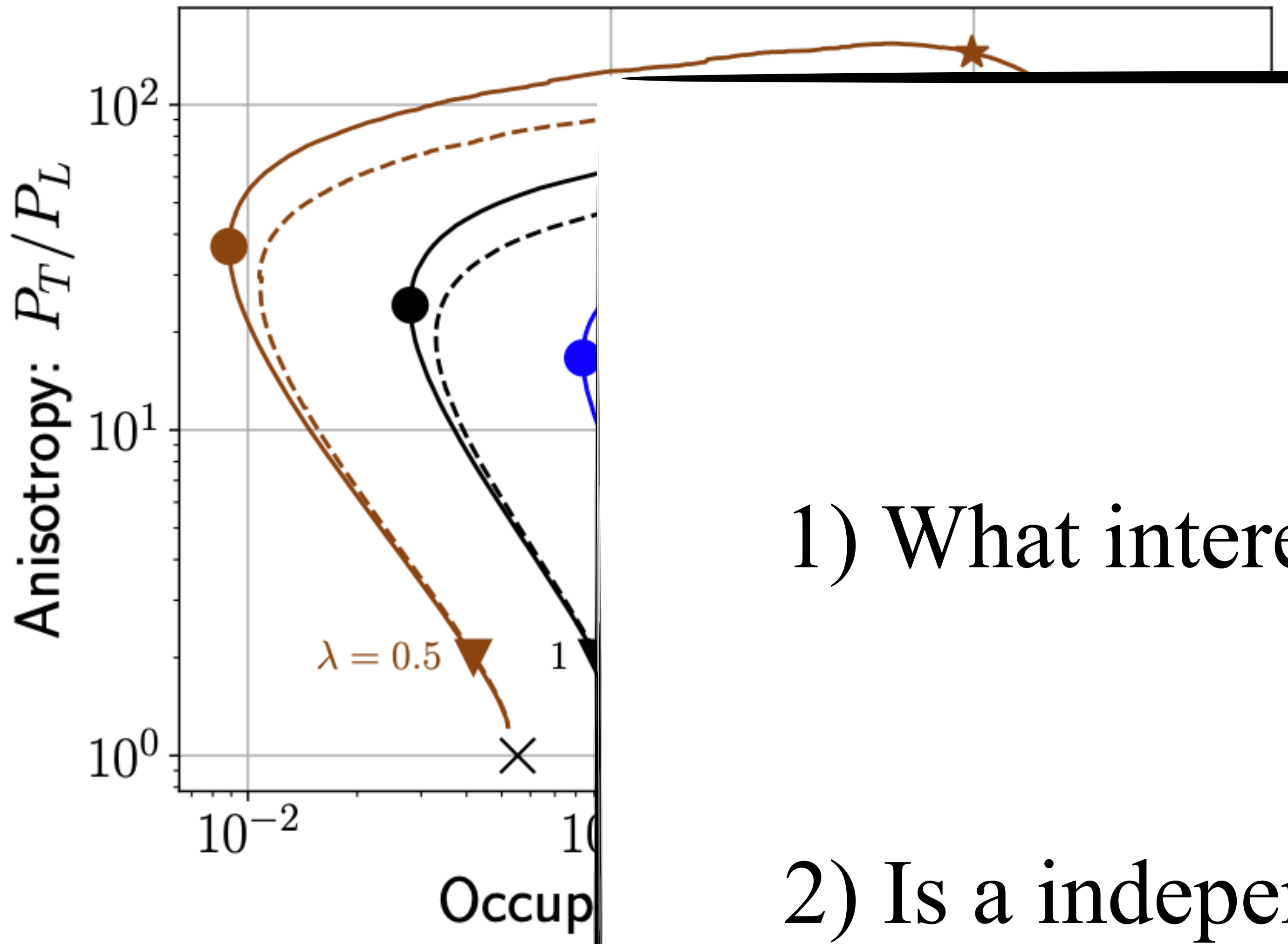
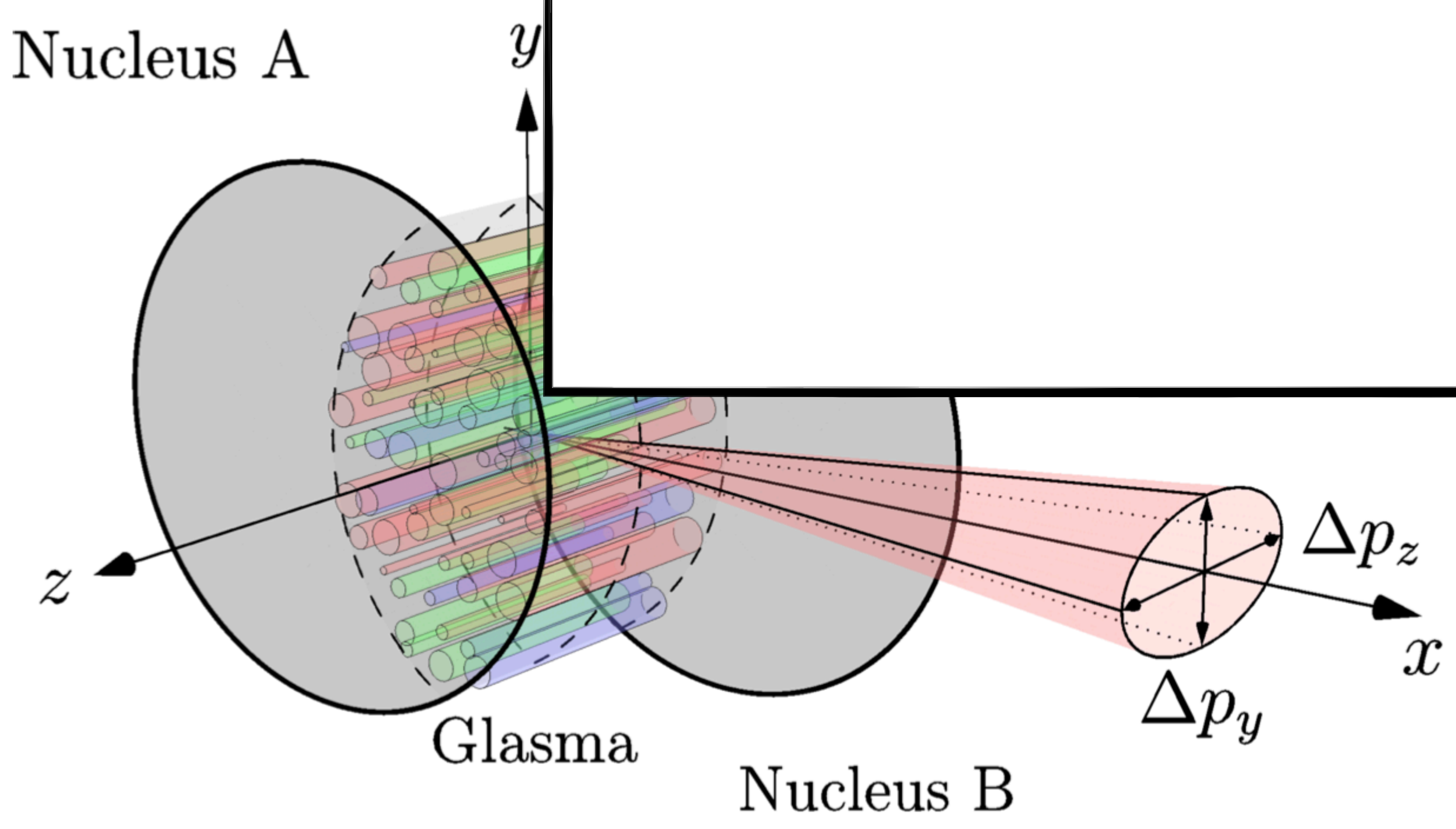
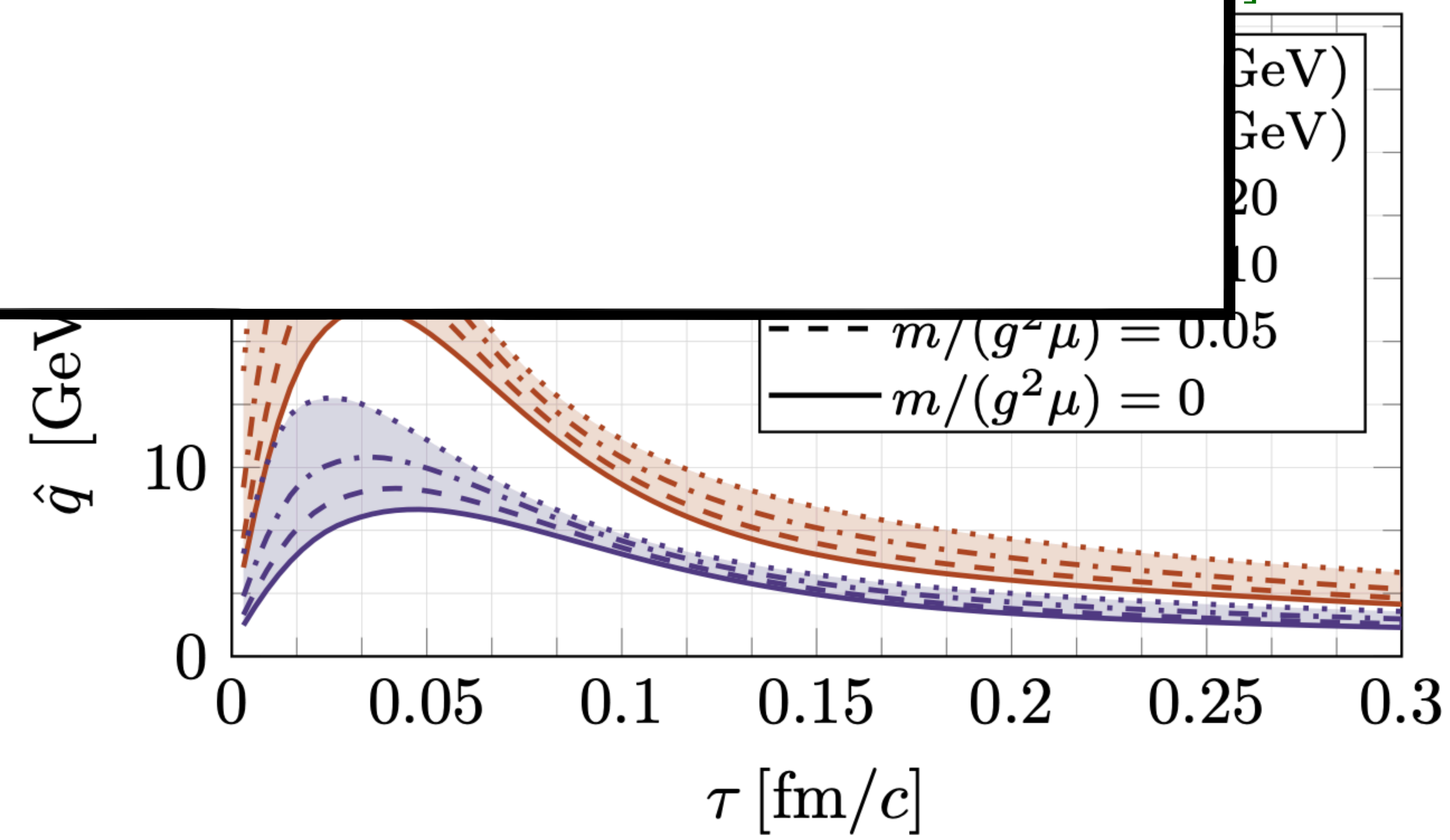


1) What interesting features can we see from early time anisotropies?

2) Is a independent multiple scattering picture still meaningful ?





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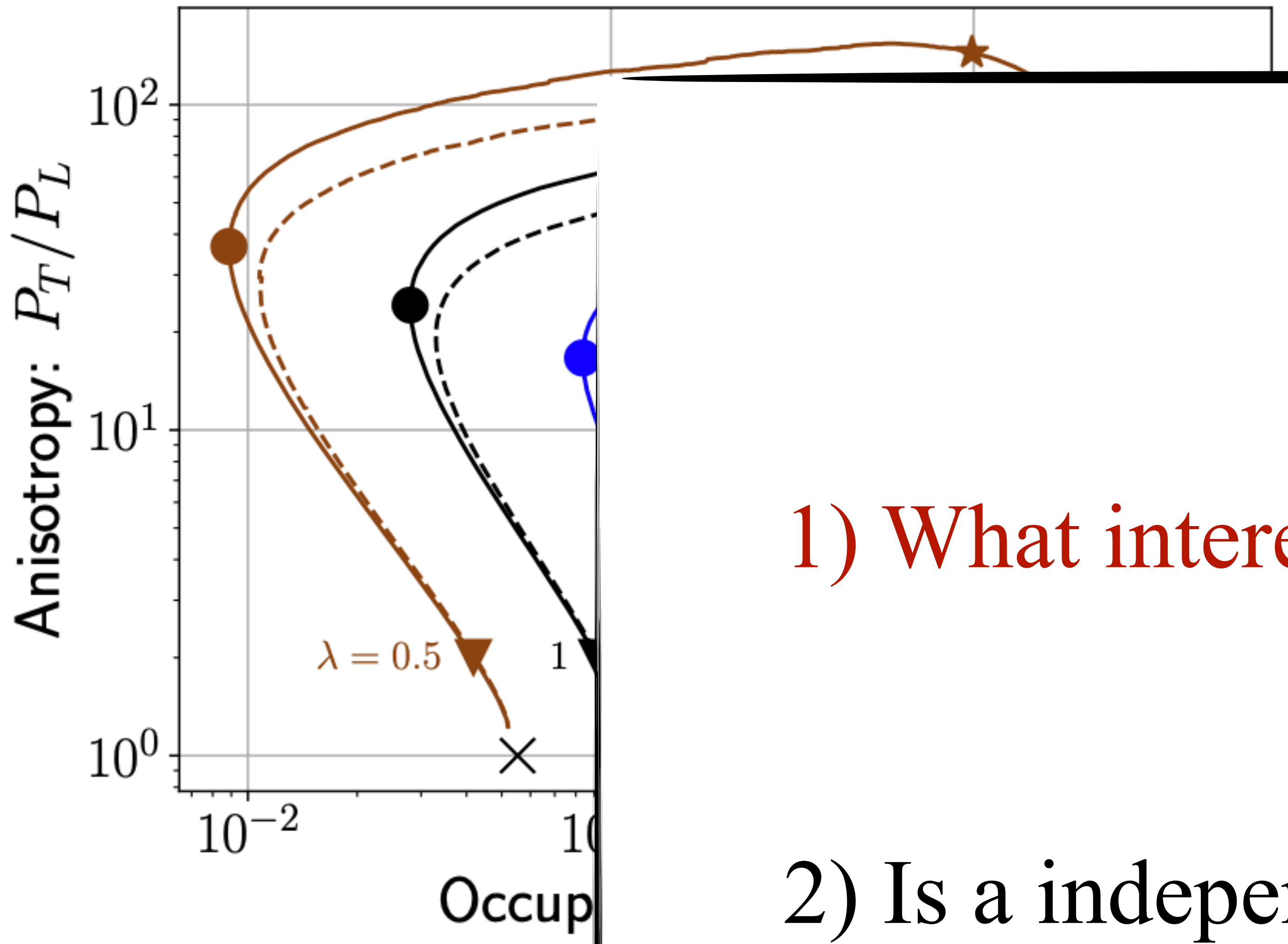

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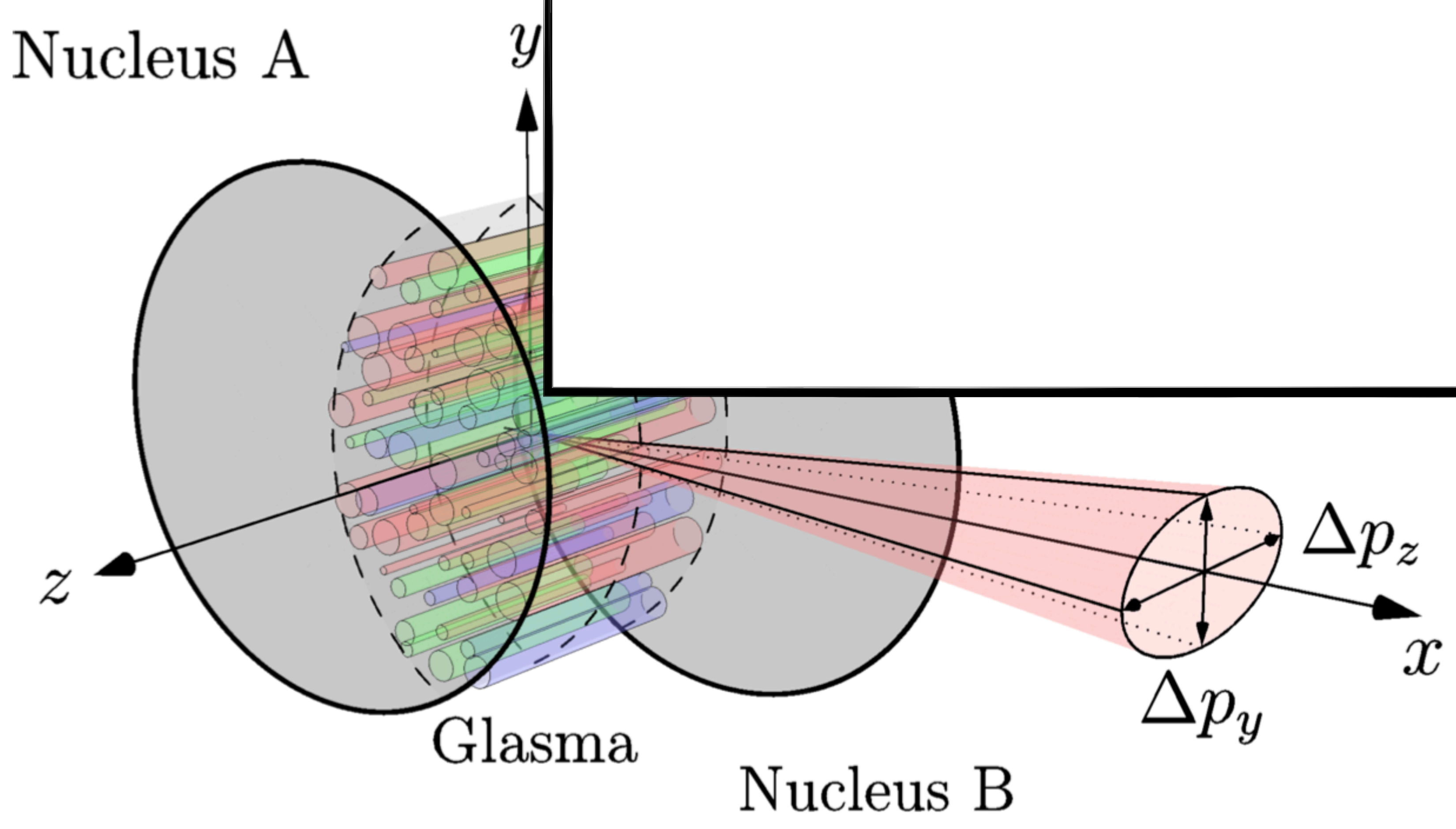
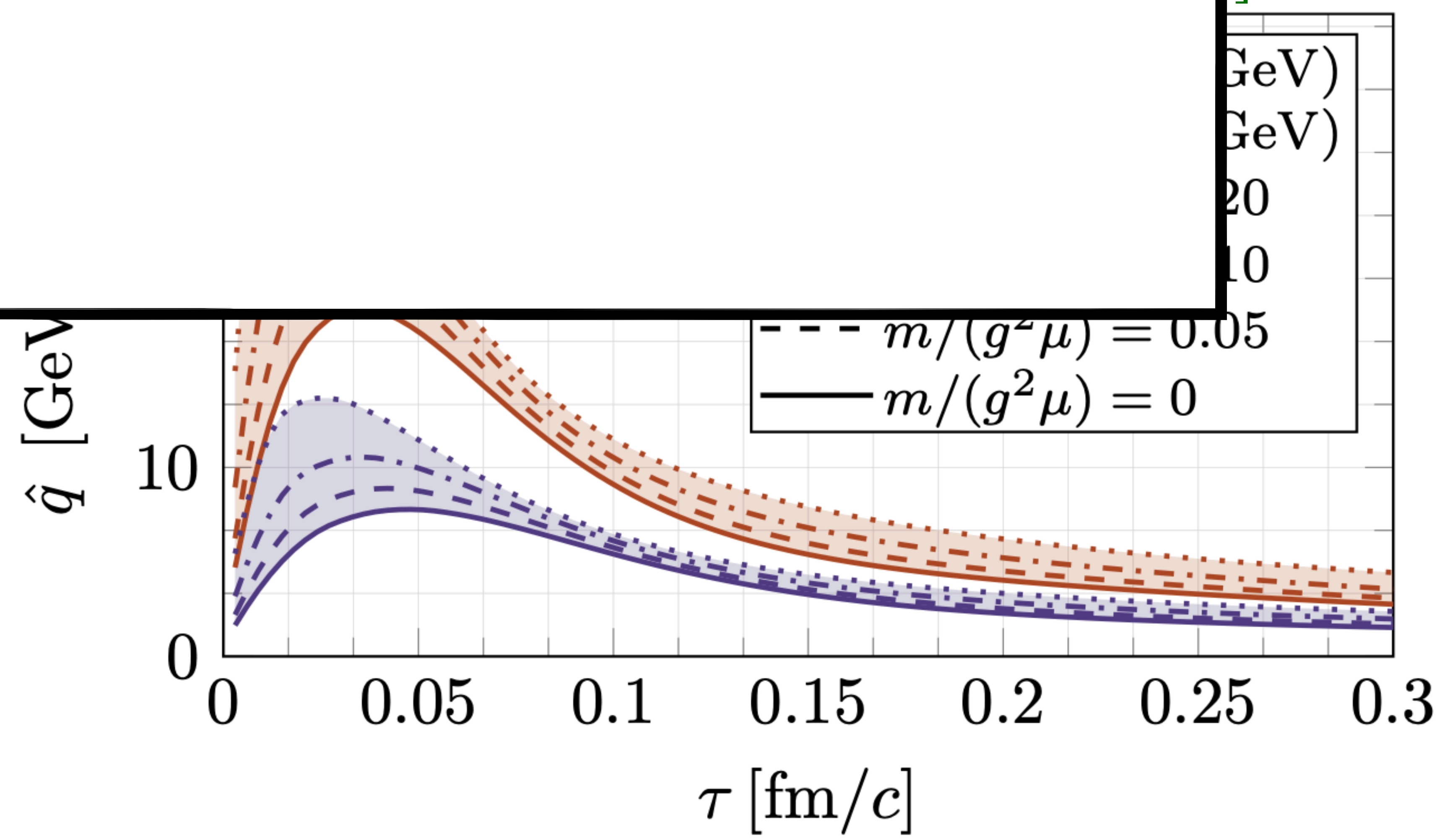


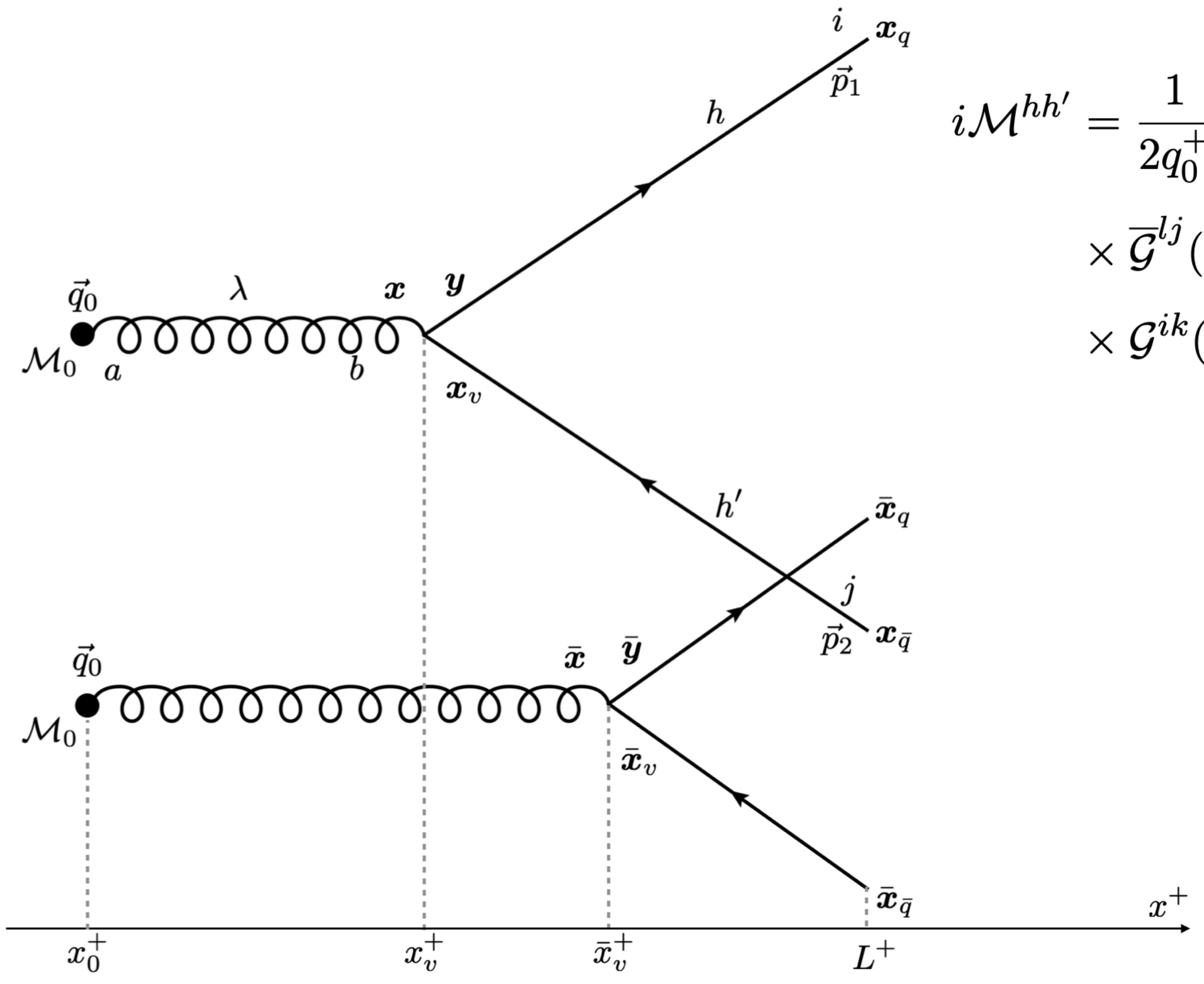


Gluon radiation in anisotropic matter

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

Brookhaven National Laboratory

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



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

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

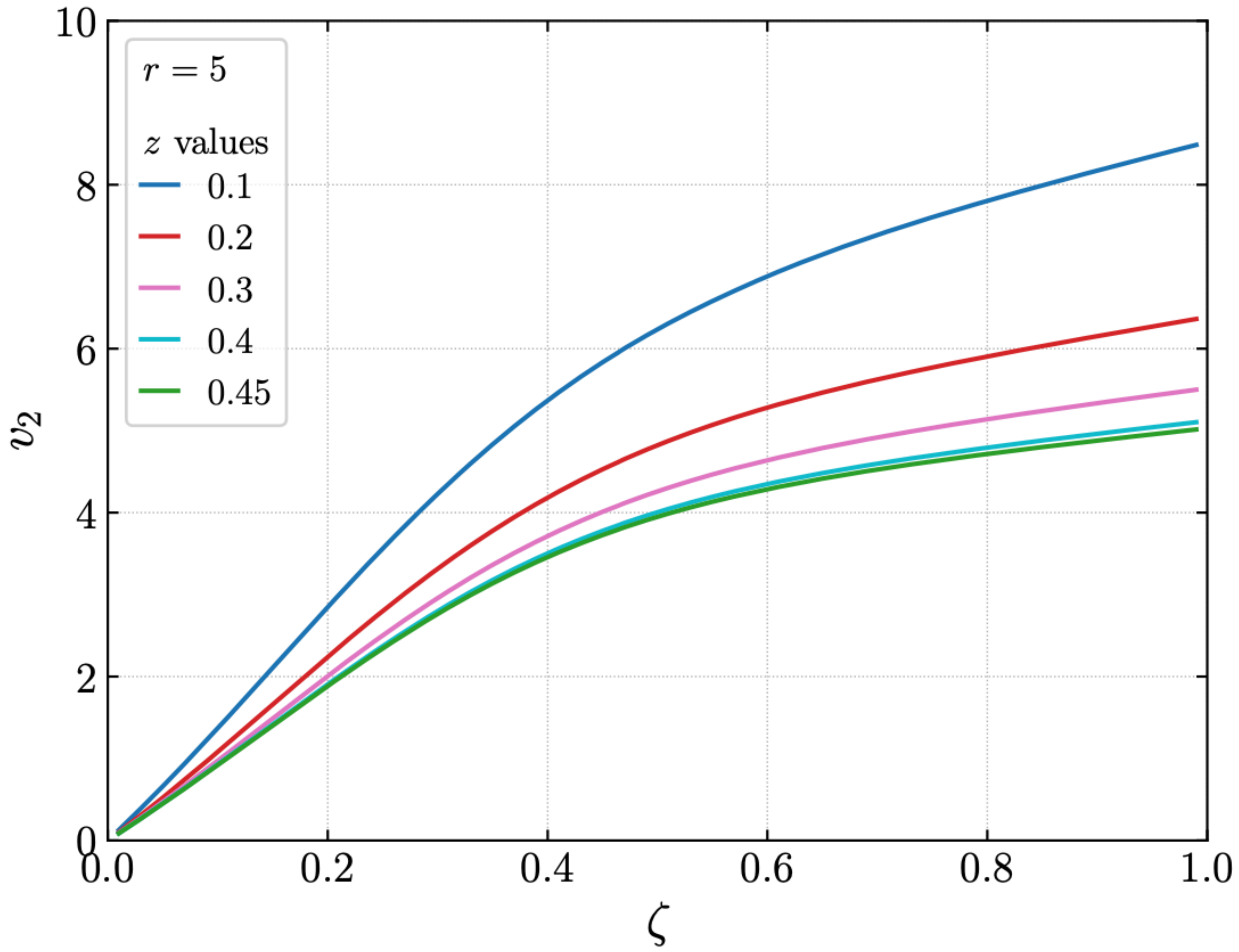
↓

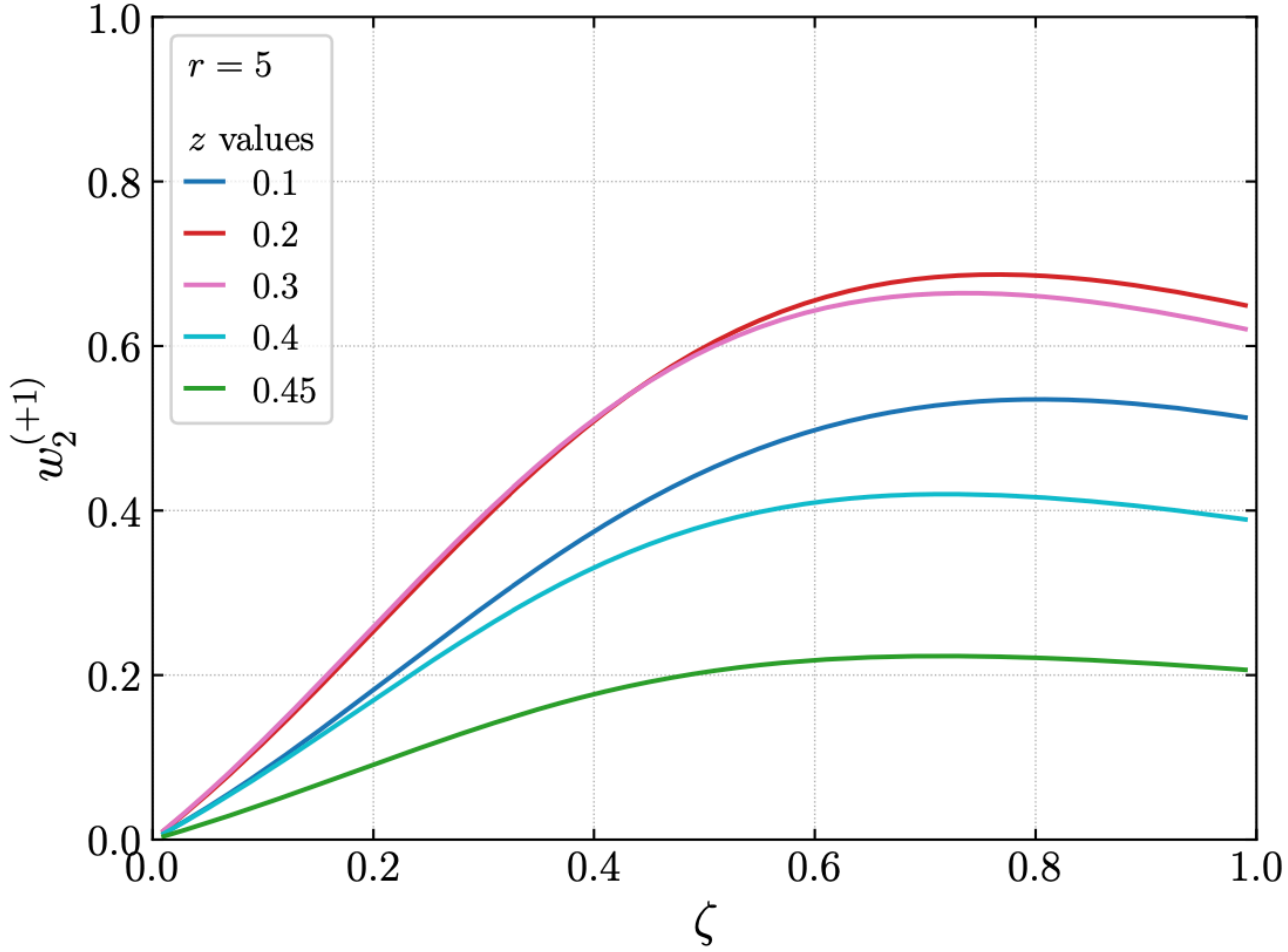
$$
\frac{2\pi}{dN^h/dz}\frac{dN^h}{dzd\phi} = 1 + \sum_{n=1}^{\infty} v_n^{(h)}\cos(n\phi) + \sum_{n=1}^{\infty} w_n^{(h)}\sin(n\phi)
$$

Gluon radiation in anisotropic matter

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

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





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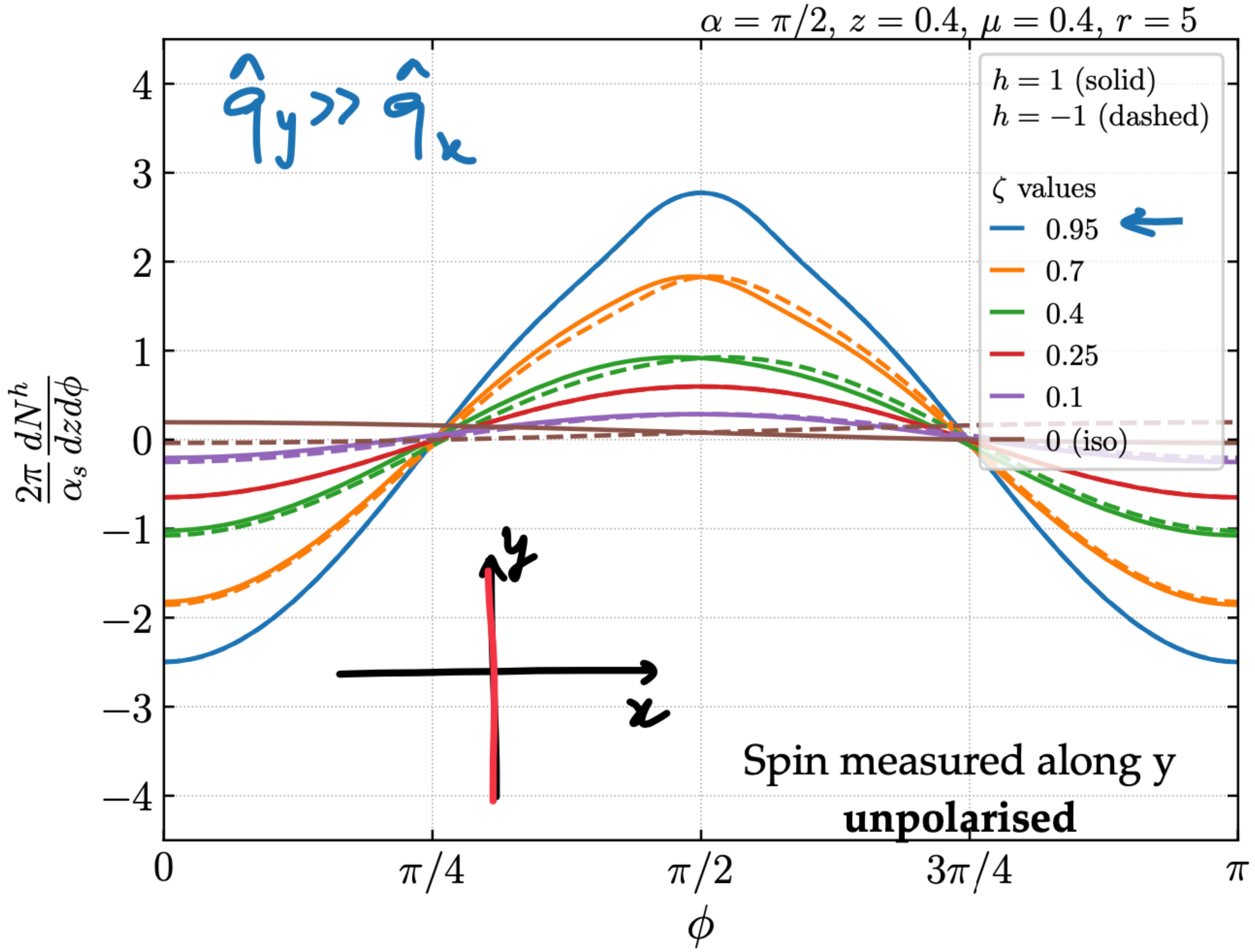
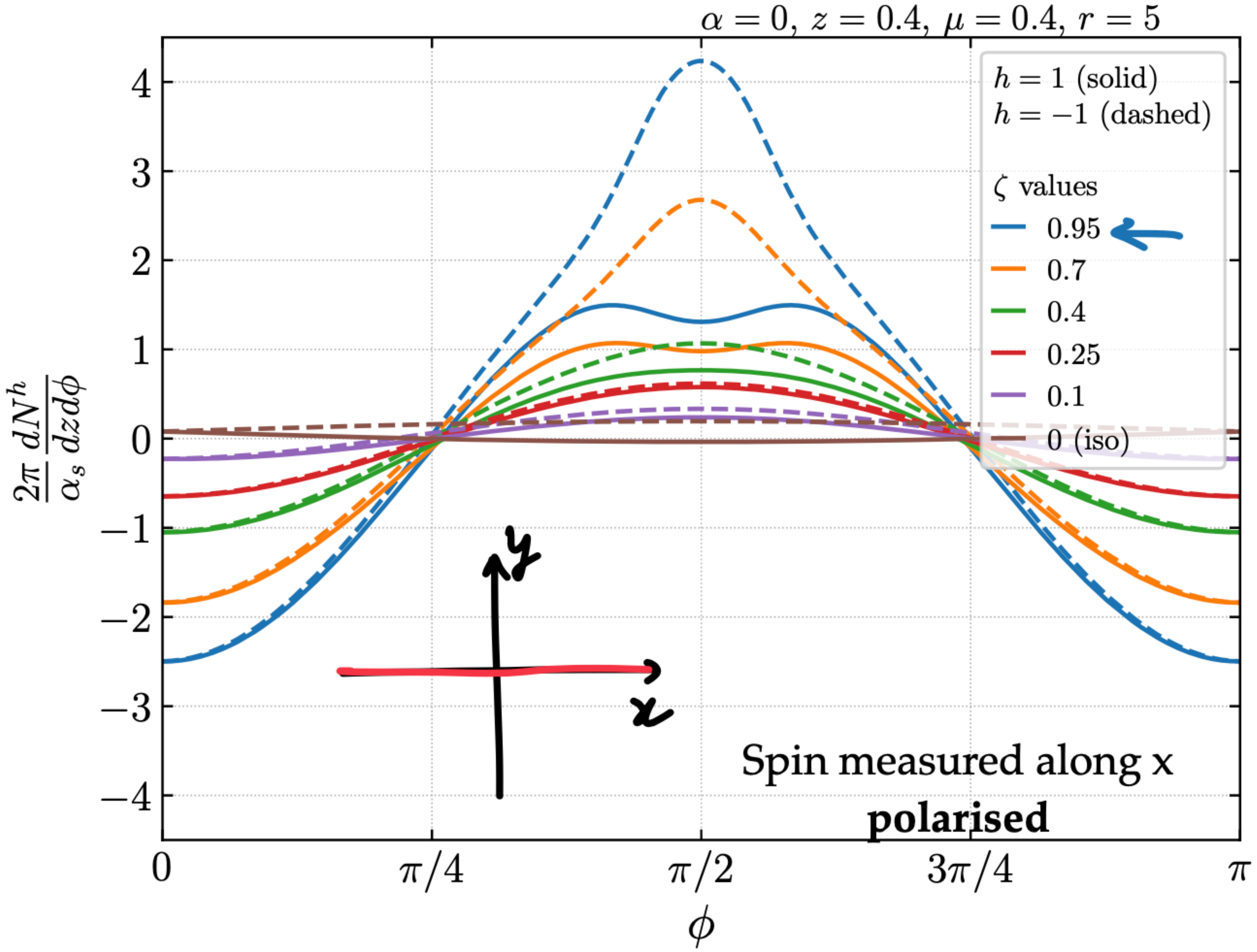




Similar observations in [S. Hauksson, E. Iancu, 2303.03914]

Why are the early stages “different”

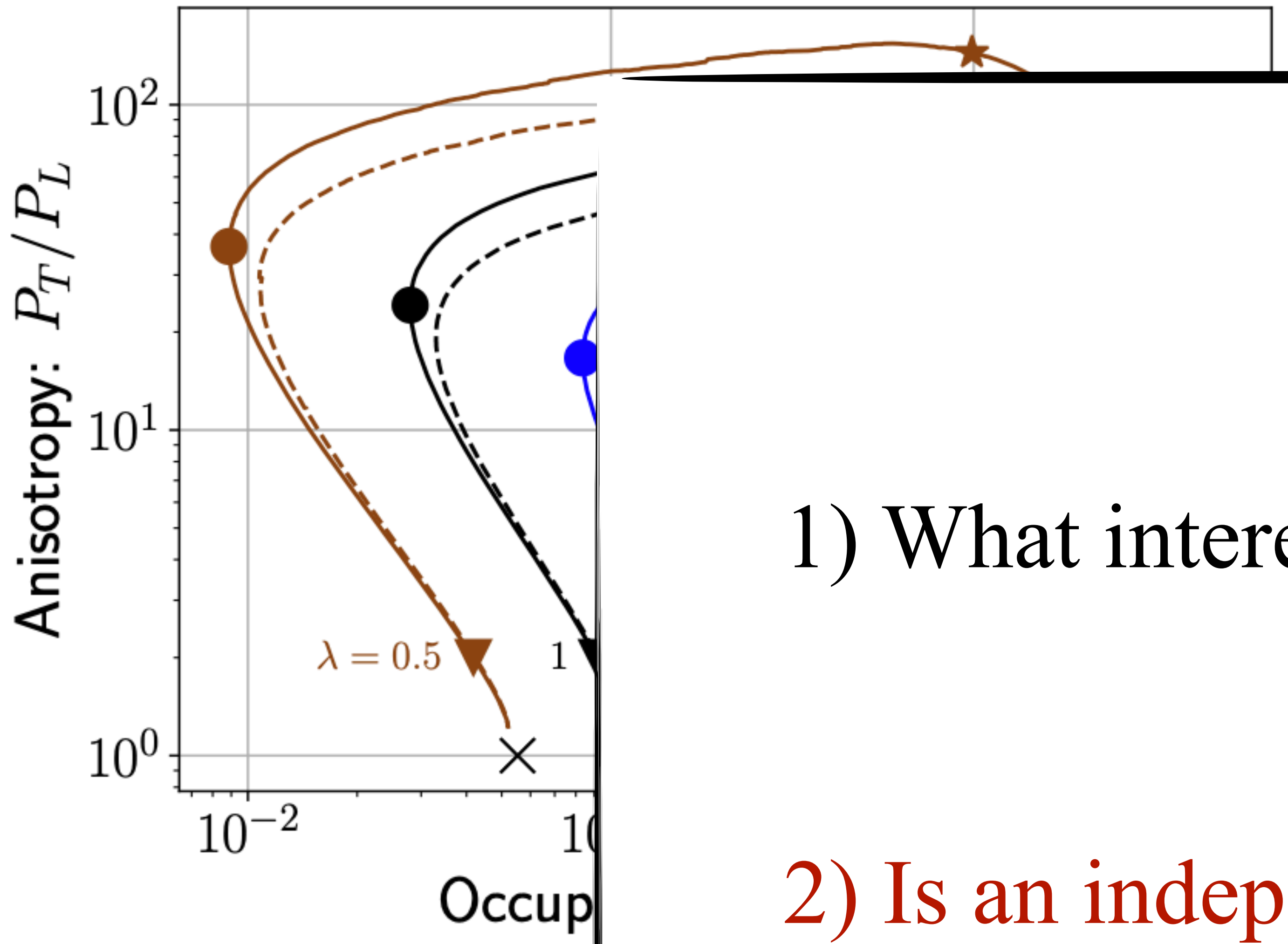
- At early times there is a big pressure anisotropy

oefficient
d out by hydro expansion]

coefficient

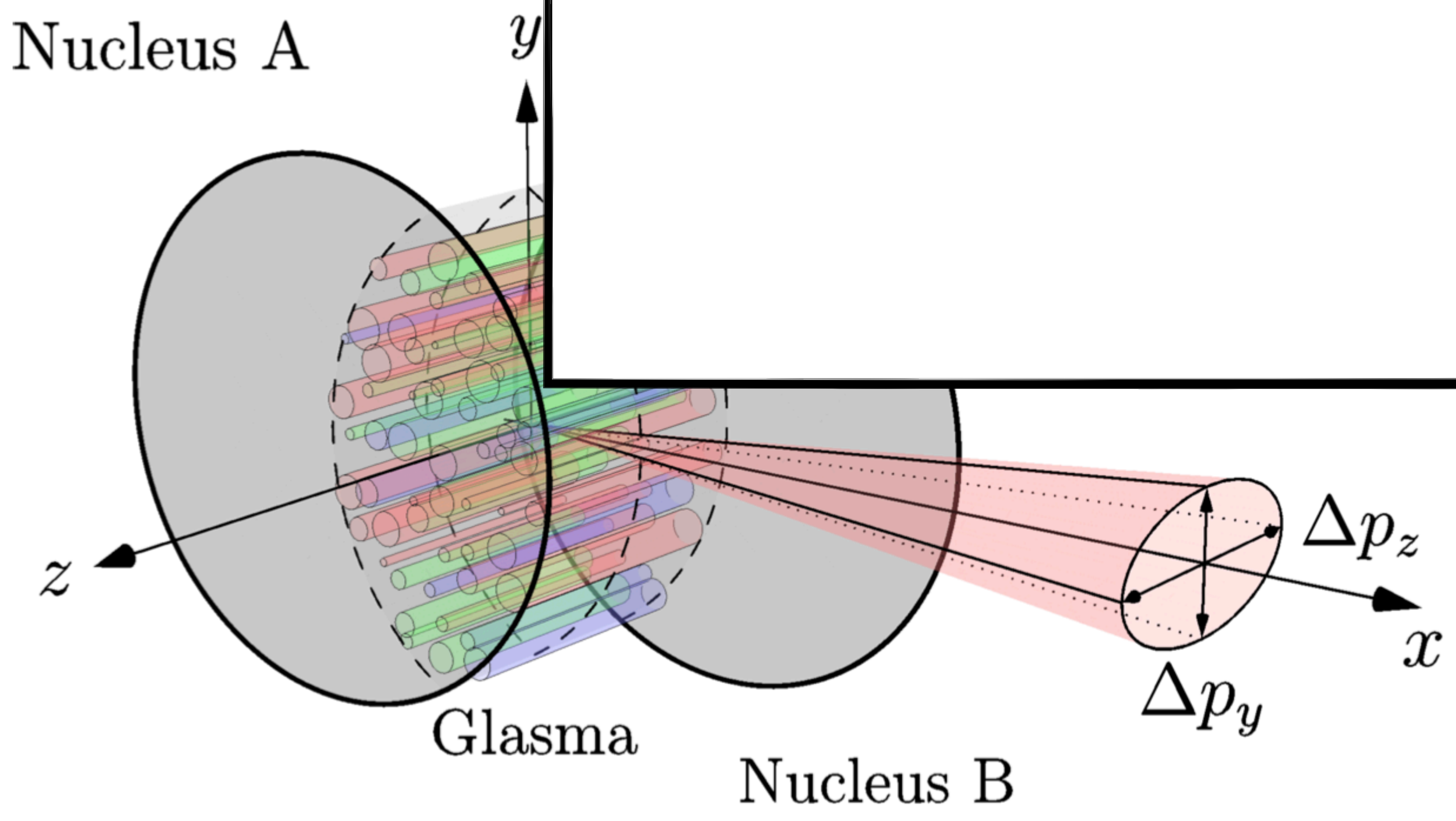
bservables integrate over jet path]

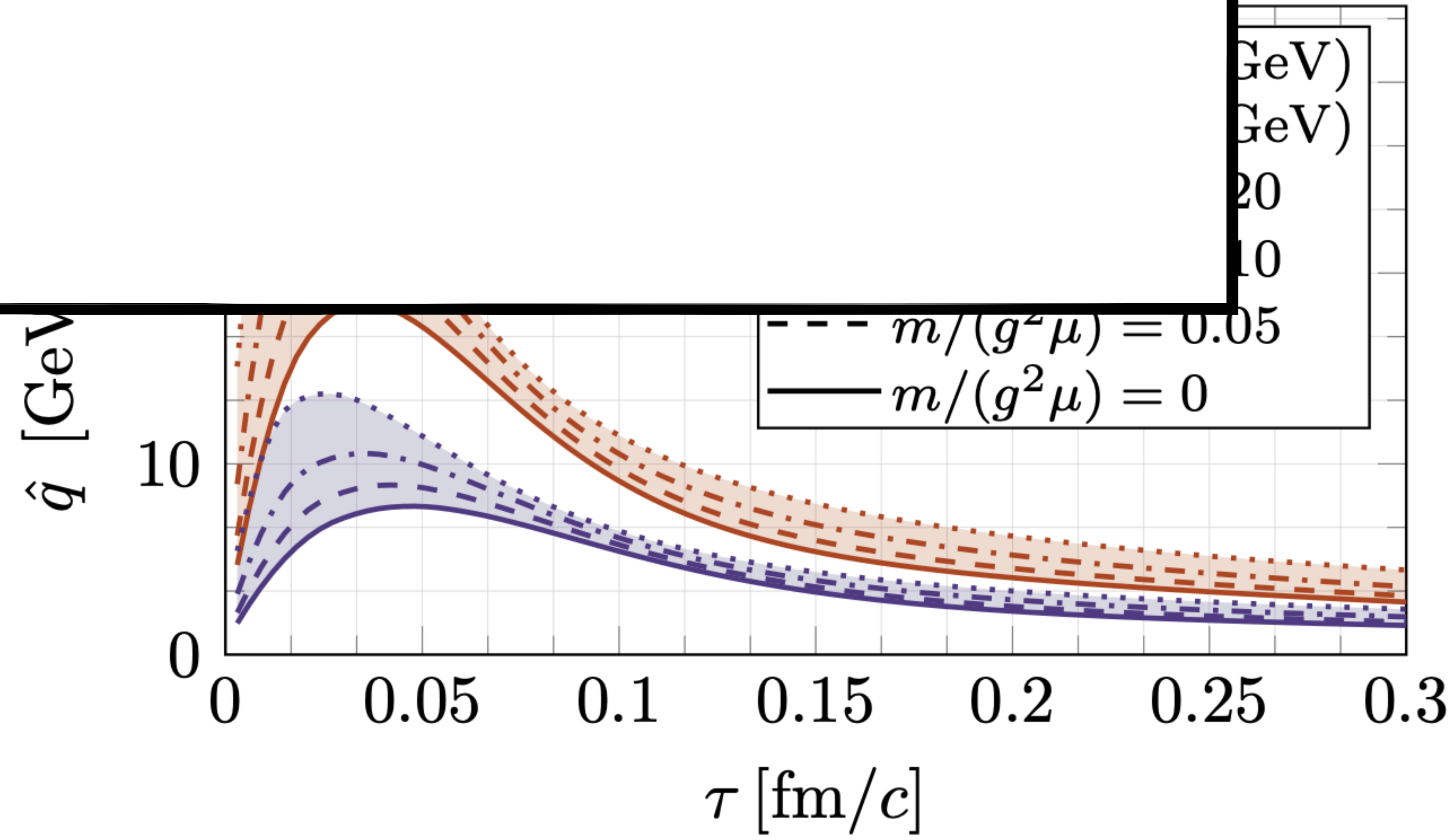
early



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

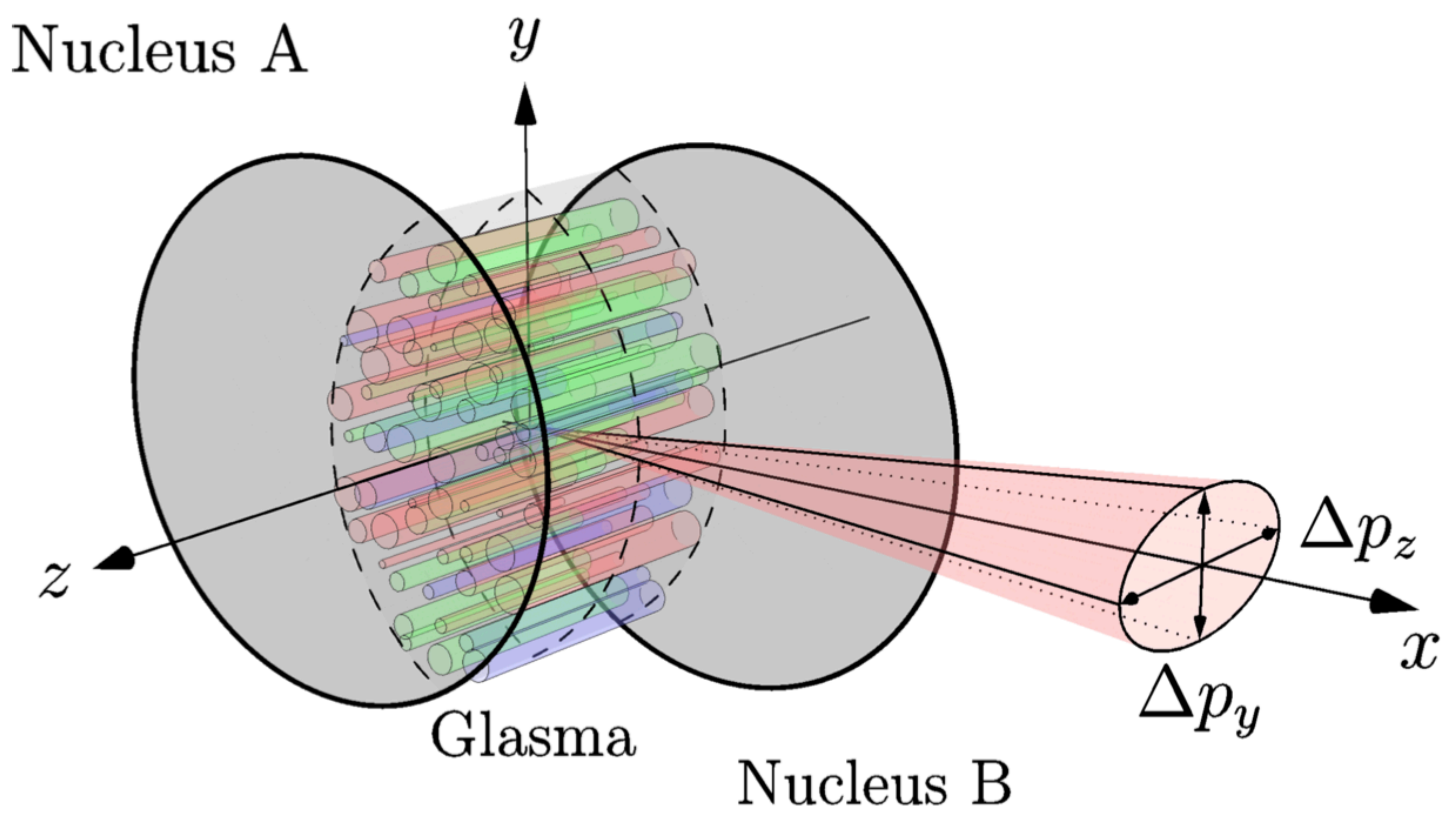
2) Is an independent multiple scattering picture still meaningful ?

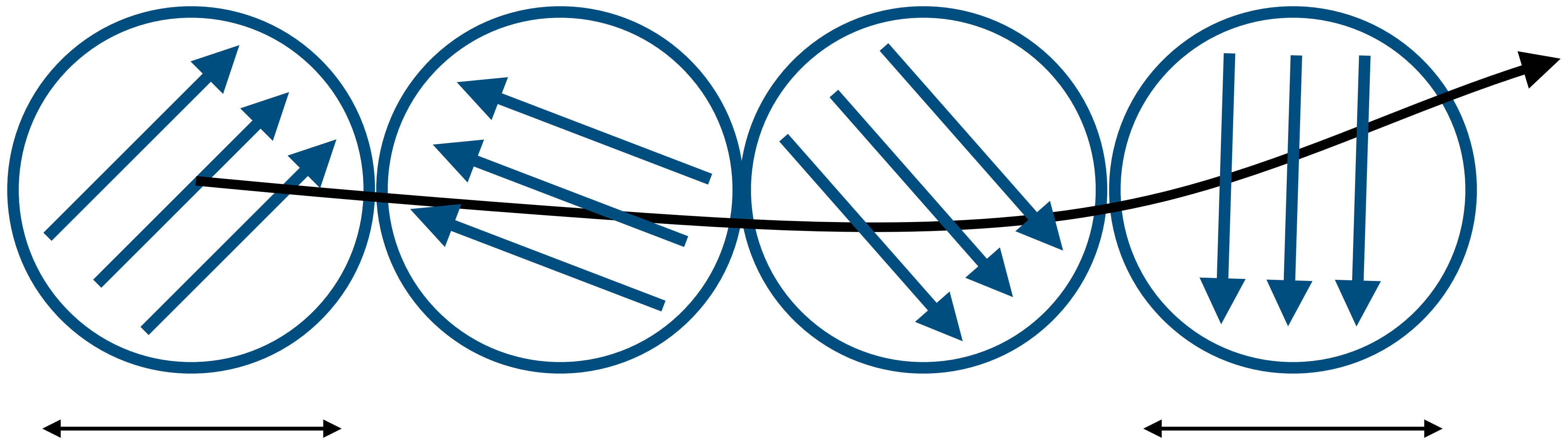




Jet evolution in the Glasma

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

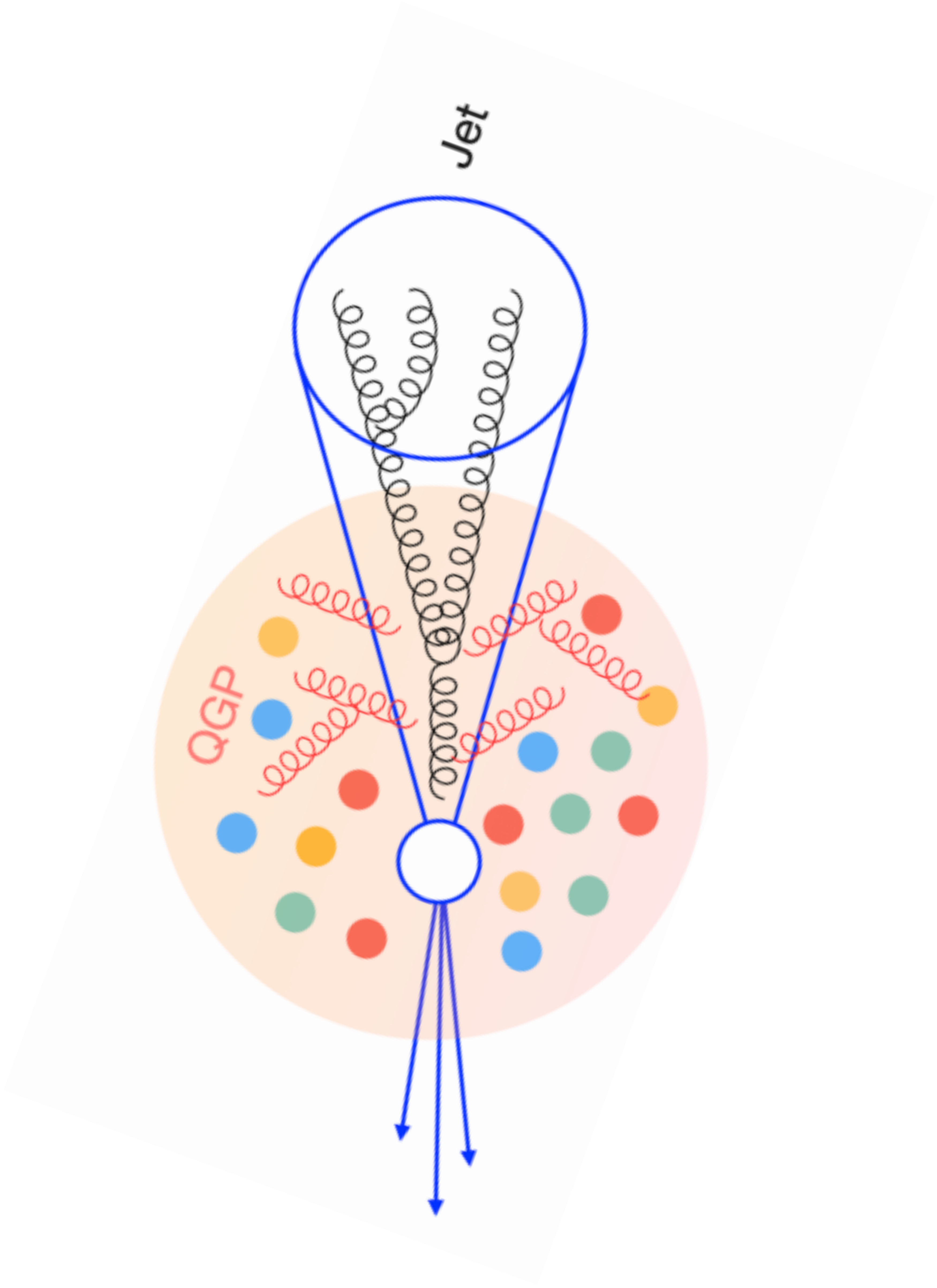




Synchrotron like scenario

$l \sim 1/Q_s$

$\overset{??}{=}$



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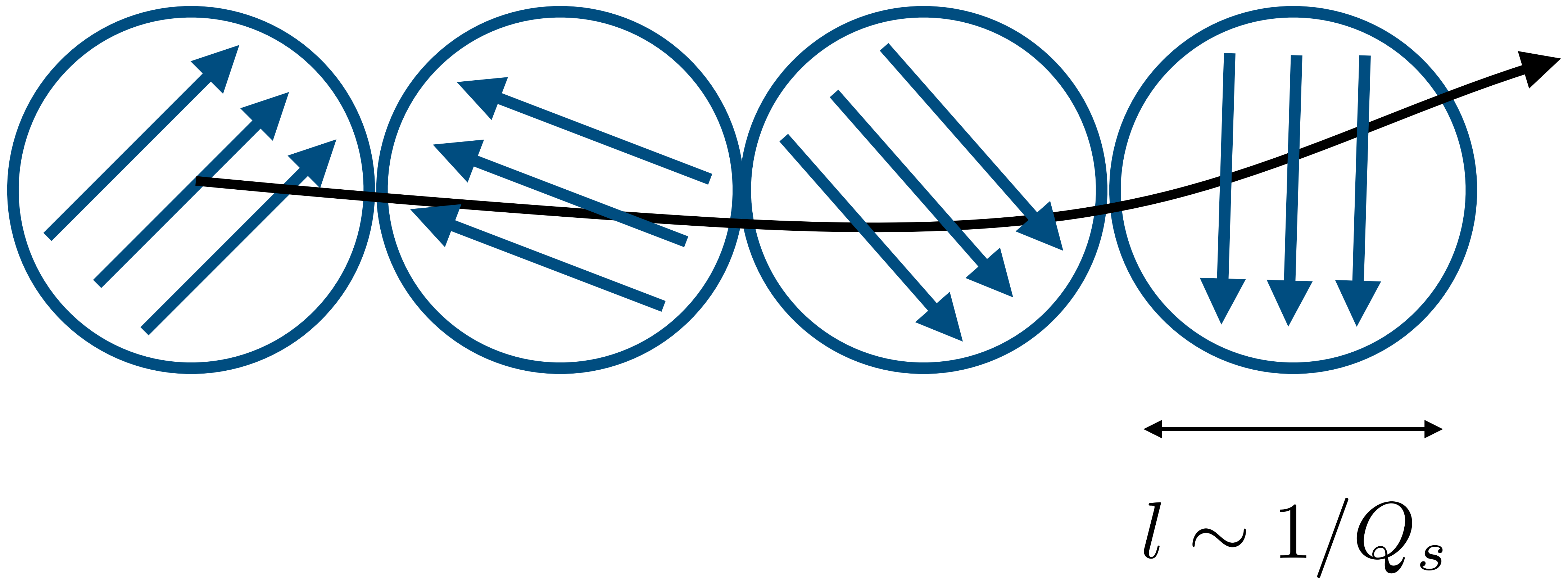
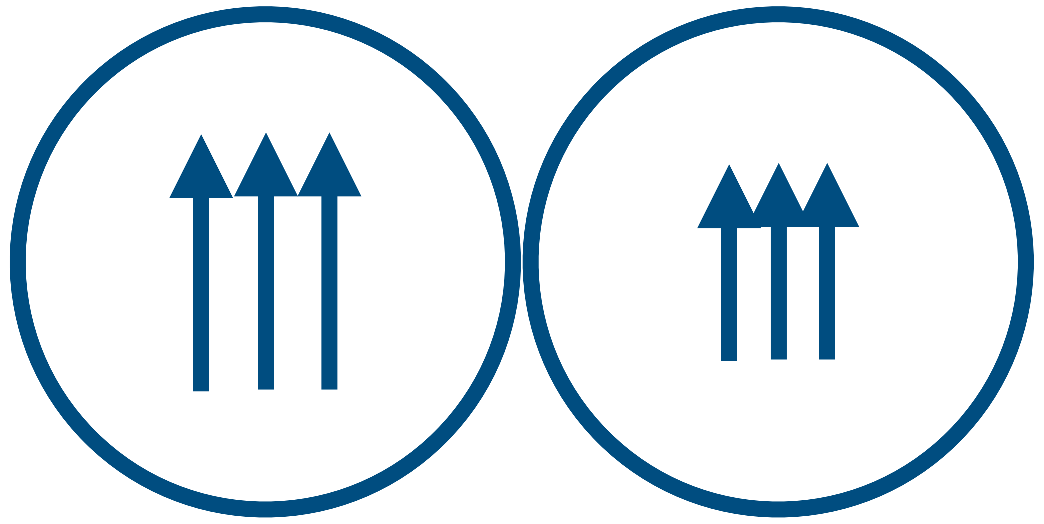


$$A^{a\mu}_{\text{coh}}(\boldsymbol{x}, z) = \delta^0_\mu\, \boldsymbol{x} \cdot \mathbf{E}^a(z) = \begin{cases} \delta^{\mu 0} \boldsymbol{x} \cdot \mathbf{E}^a_1, & 0 \leq z < \ell \\ \delta^{\mu 0} \boldsymbol{x} \cdot \mathbf{E}^a_2, & \ell \leq z < 2\ell \\ \delta^{\mu 0} \boldsymbol{x} \cdot \mathbf{E}^a_3,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

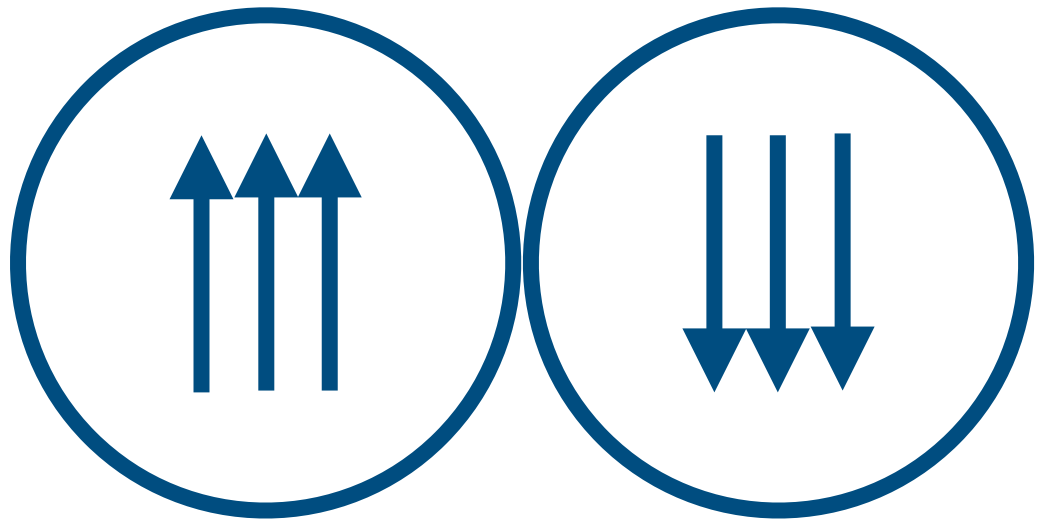
$$\langle A(x)A(y)\rangle \neq \delta(x^+ - y^+)$$

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

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

With these elements, we can redo the previous calculations. First let us consider momentum broadening

$$\hat{q} = -\frac{1}{2(2\pi)^3\mathcal{N}}\frac{\partial}{\partial L}\int_{\boldsymbol{x}} \boldsymbol{\nabla}^2_{\boldsymbol{x}-\bar{\boldsymbol{x}}}\Big(J^\dagger(\bar{\boldsymbol{x}})\mathcal{W}^\dagger(\bar{\boldsymbol{x}})\mathcal{W}(\boldsymbol{x})J(\boldsymbol{x})\Big)_{\bar{\boldsymbol{x}}=\boldsymbol{x}} \qquad \mathcal{P}\exp\left\{i\int_0^L d\tau\, t^a\mathbf{E}^a\cdot\boldsymbol{x}\right\}$$

To perform averaging it is convenient to further simplify expressions using

$$\frac{\partial}{\partial L}\mathcal{W}(\boldsymbol{x})\mathcal{W}^\dagger(\bar{\boldsymbol{x}}) = i\mathbf{E}^a(L)\cdot\left[\boldsymbol{x}\,t^a\mathcal{W}(\boldsymbol{x})\mathcal{W}^\dagger(\bar{\boldsymbol{x}}) - \bar{\boldsymbol{x}}\,\mathcal{W}(\boldsymbol{x})\mathcal{W}^\dagger(\bar{\boldsymbol{x}})t^a\right]$$

$$\tilde{\mathcal{W}}(\mathbf{Y};z,\bar{\tau}) = \tilde{\mathcal{W}}(\mathbf{Y};z,z_n)\,\tilde{\mathcal{W}}(\mathbf{Y};z_n,z_{n-1})\,\tilde{\mathcal{W}}(\mathbf{Y};z_{n-1},z_{n-2})\cdots\tilde{\mathcal{W}}(\mathbf{Y};z_{k+1},\bar{\tau})$$

This results in a simple result for any gauge group **before** and **after** averaging

$$\hat{q}(z) = \frac{w^2}{2\pi^3}\int_{\mathbf{Y}}\int_0^z d\bar{\tau}\,\tilde{\mathcal{W}}^{ab}(\mathbf{Y};z,\bar{\tau})\,E^a_x(z)E^b_x(\bar{\tau})e^{-2w^2\mathbf{Y}^2} \qquad \langle\hat{q}\rangle_{E,z_{in}} = cE_0^2 l$$

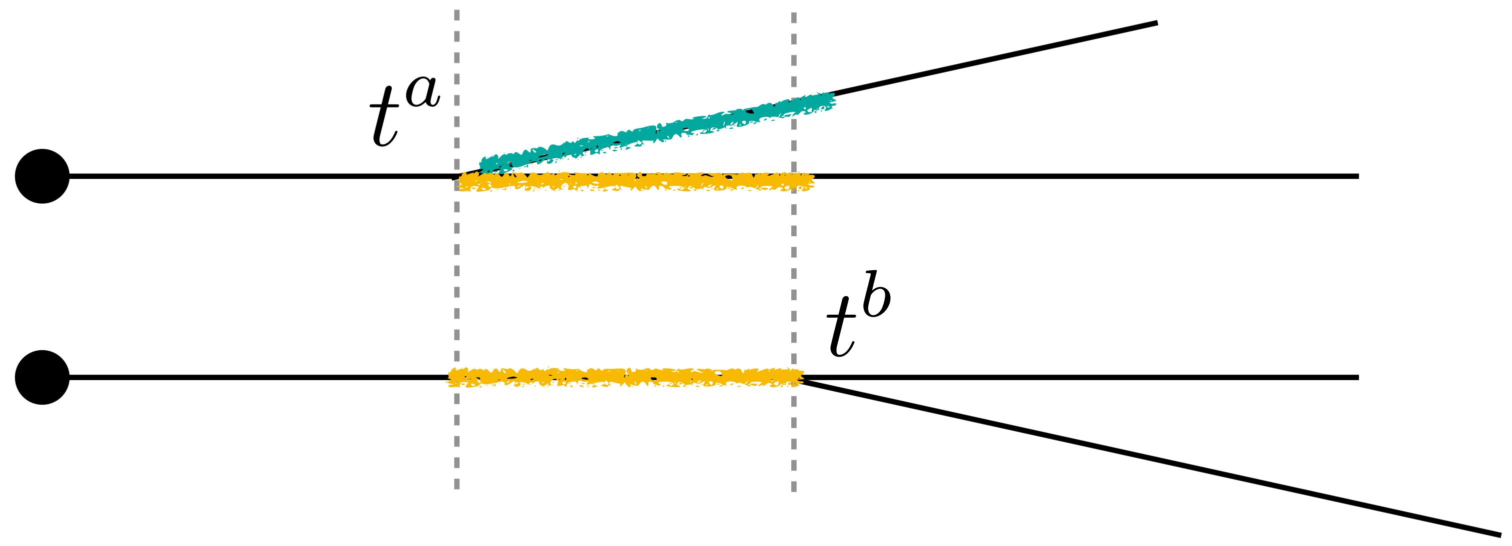
Jet evolution in the Glasma

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

The one-gluon radiation cross-section is harder to compute; focus on radiative rate

$$\frac{d\Gamma}{dx} = \frac{2\alpha_s C_F}{x\omega^2}\mathrm{Re}\int_0^t ds\, \boldsymbol{\nabla}_{\boldsymbol{x}} \cdot \boldsymbol{\nabla}_{\boldsymbol{y}} \Big(\mathcal{K}(\boldsymbol{x},t;\boldsymbol{y},s) - \mathcal{K}_0(\boldsymbol{x},t;\boldsymbol{y},s)\Big)_{\boldsymbol{x}=\boldsymbol{y}=0}$$

$$\mathcal{K}(\boldsymbol{x},t;\boldsymbol{y},s) = \frac{1}{N_c^2-1} G^{ab}(\boldsymbol{x},t;\boldsymbol{y},s)\tilde{\mathcal{W}}^{\dagger ba}(0;t,s)$$

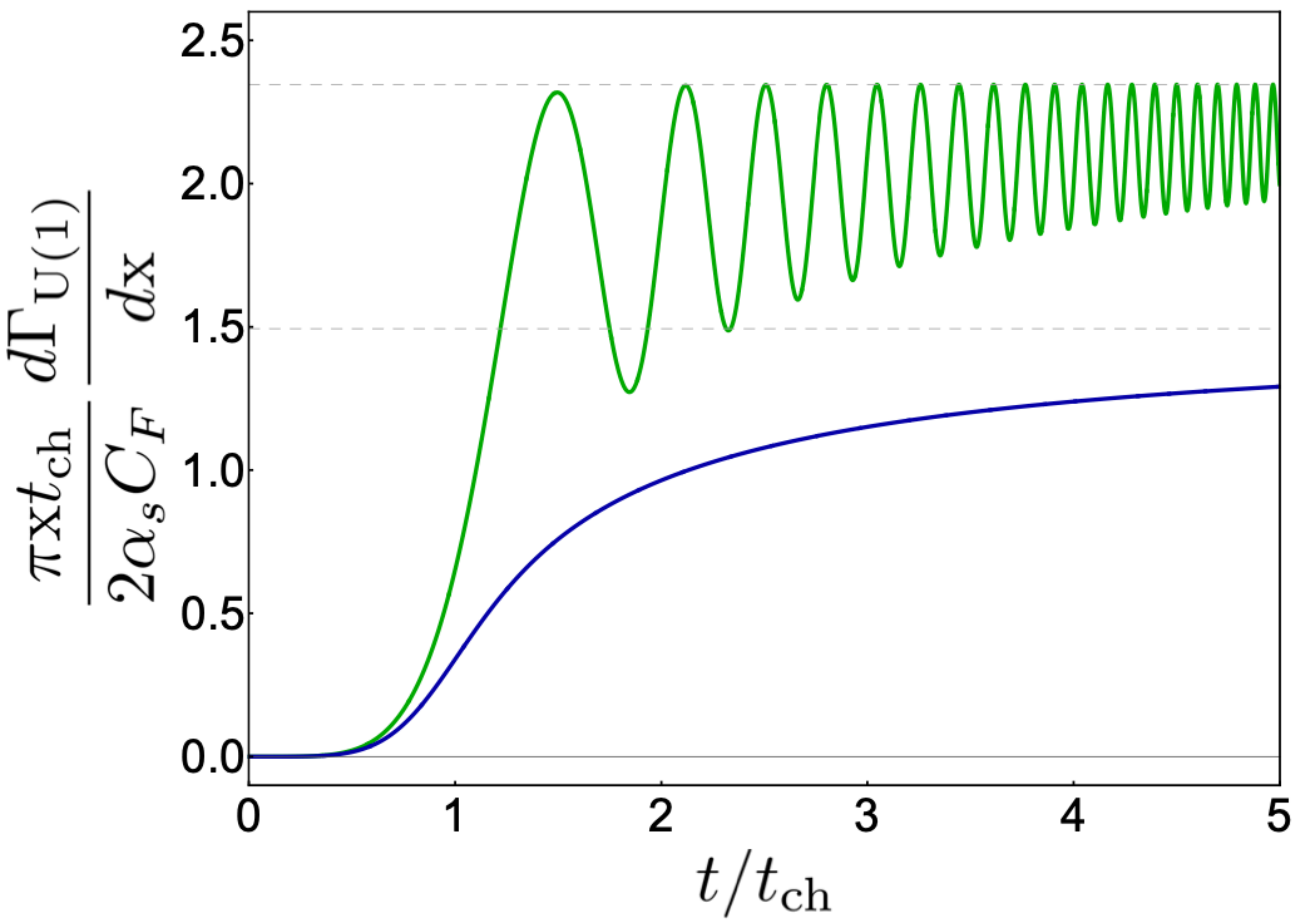


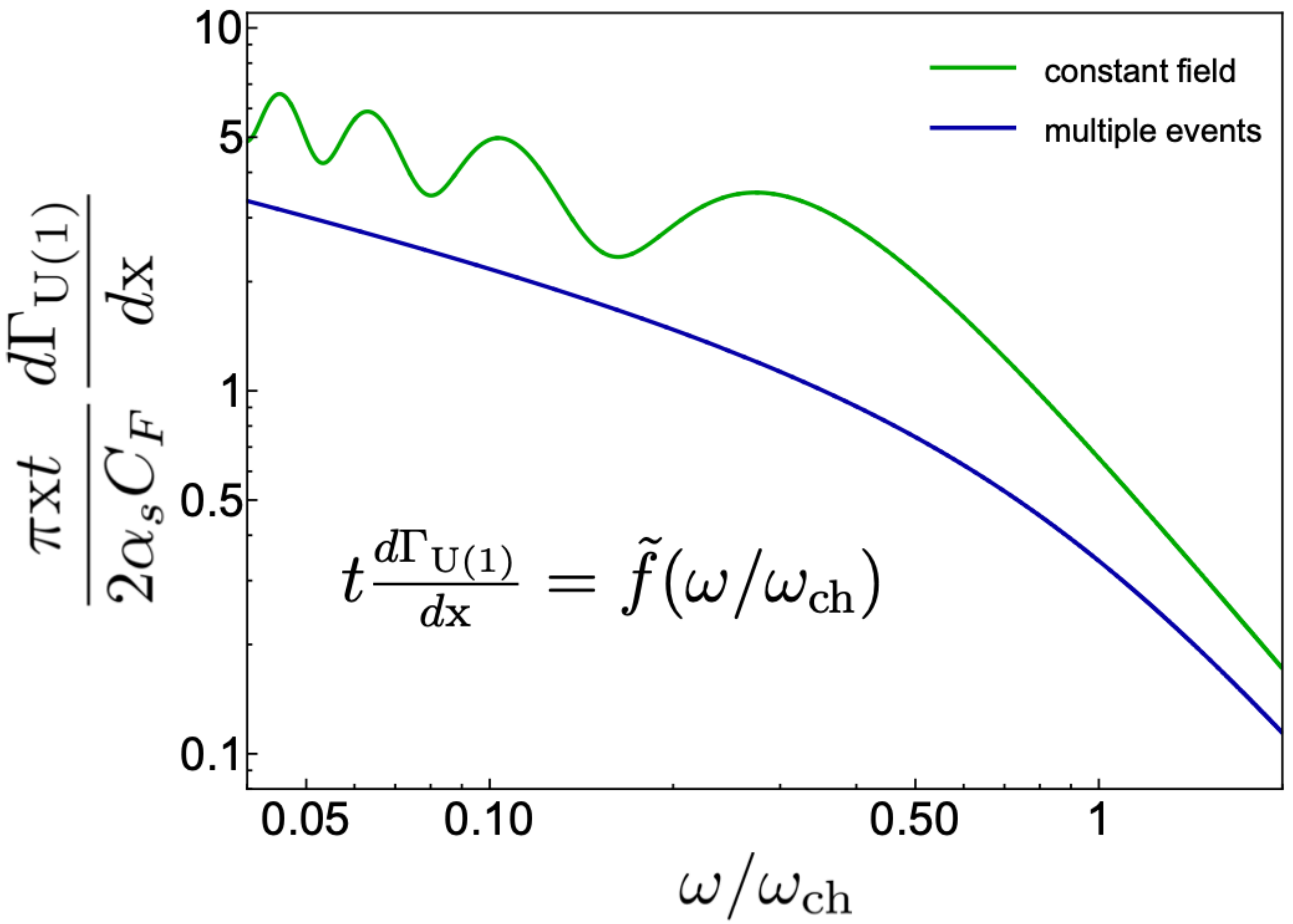
Explicitly, for a U(1) case with a single flux tube we find

$$\frac{d\Gamma_{\mathrm{U}(1)}}{dx} = \frac{2\alpha_s C_F}{x\pi}\mathrm{Re}\int_0^t ds\,\frac{1}{s^2}\left(1 - \left(1 - i\frac{E^2 s^3}{8\omega}\right) e^{-i\frac{E^2 s^3}{24\omega}}\right)$$

Jet evolution in the Glasma: 1 flux tube

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





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

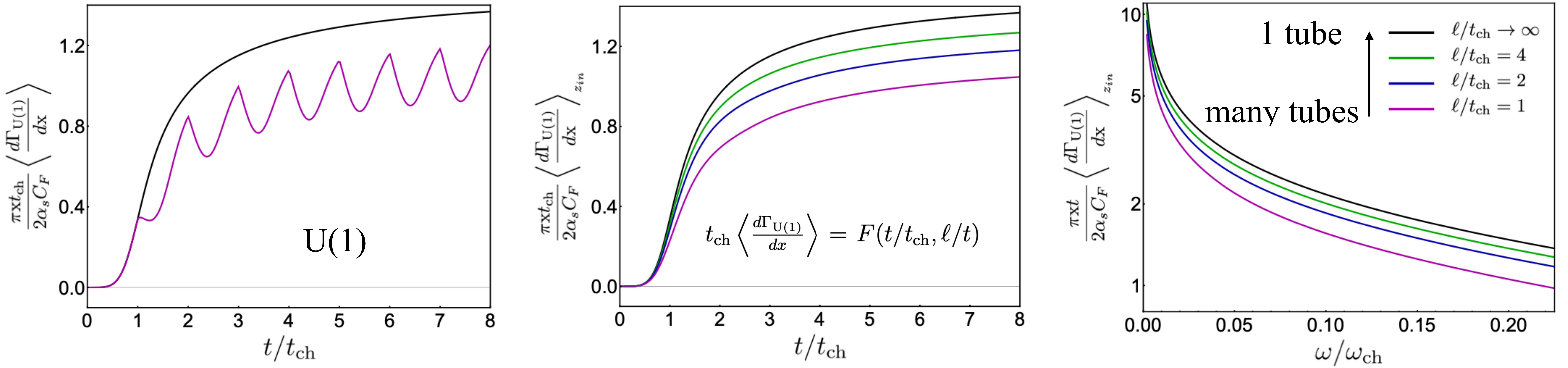
There is an emergent time scale : $t_{\rm ch} = (24\omega/E^2)^{1/3}$ which can also be obtained from

$$t_{\rm ch} \sim \sqrt{\omega/\hat{q}(t_{\rm ch})}$$

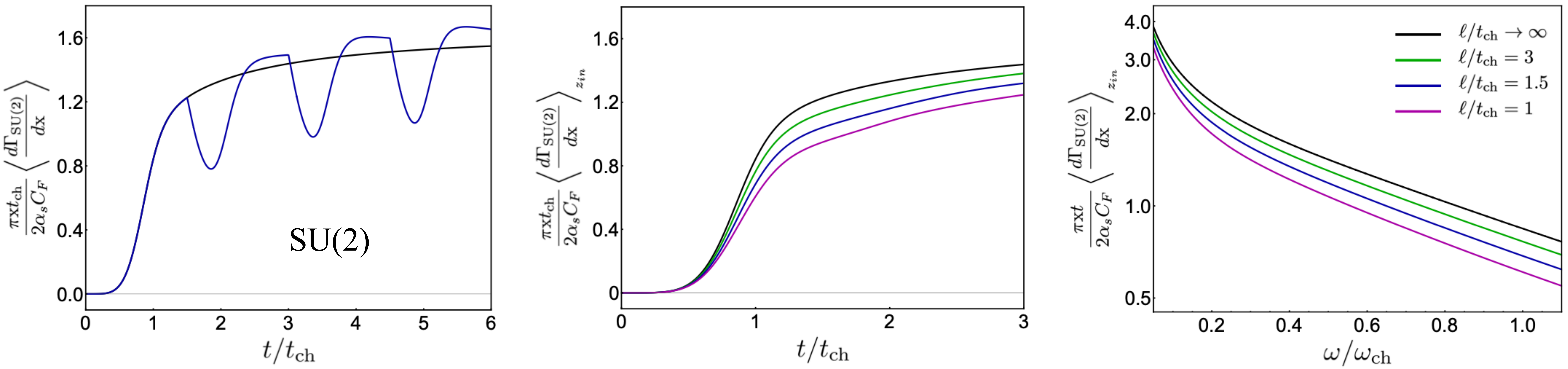
$$\langle\hat{q}\rangle_{E,z_{in}} = cE_0^2 l$$

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

Brookhaven National Laboratory

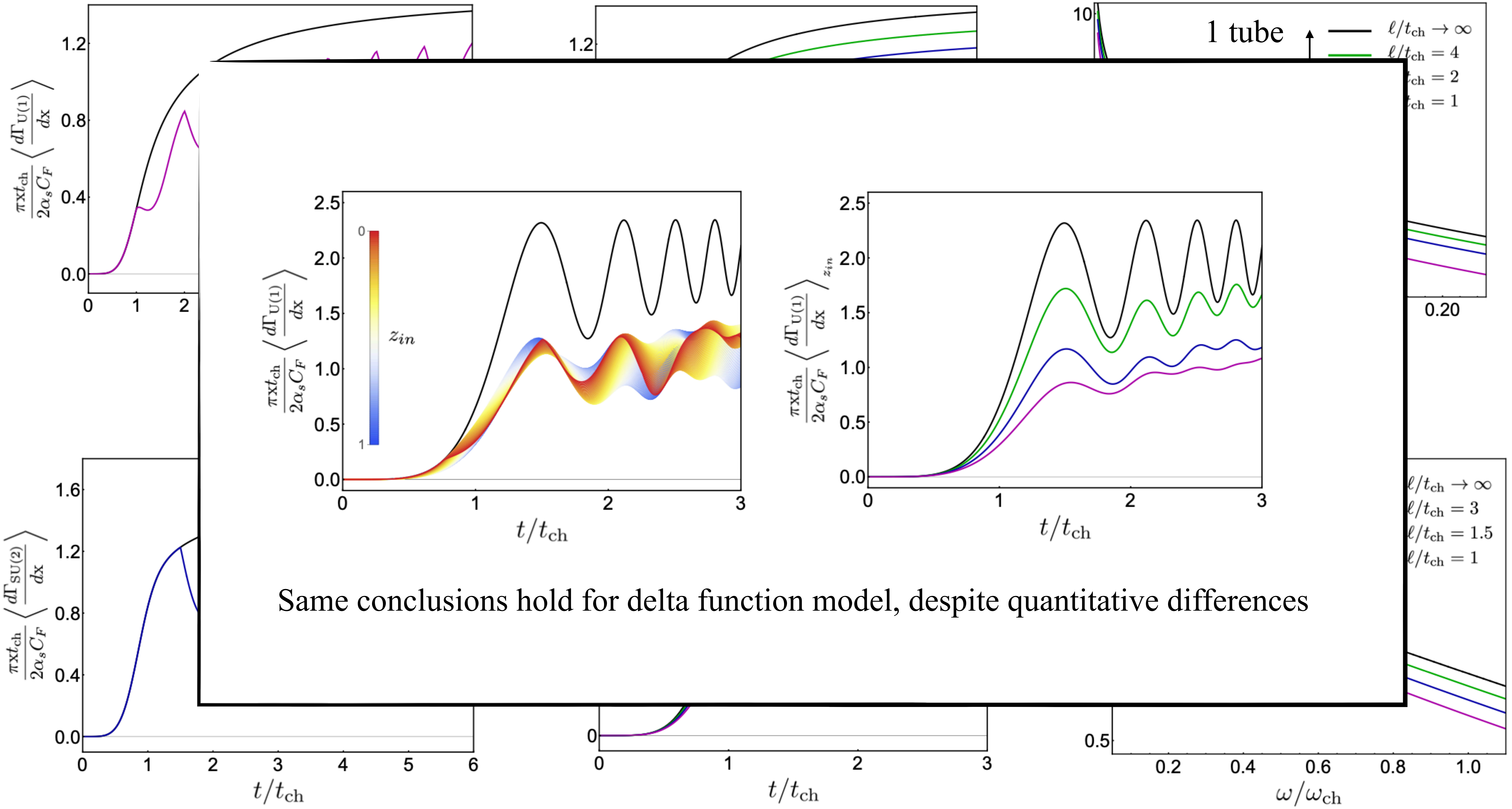


More flux tubes = longer formation time



Jet evolution in the Glasma: several flux tubes

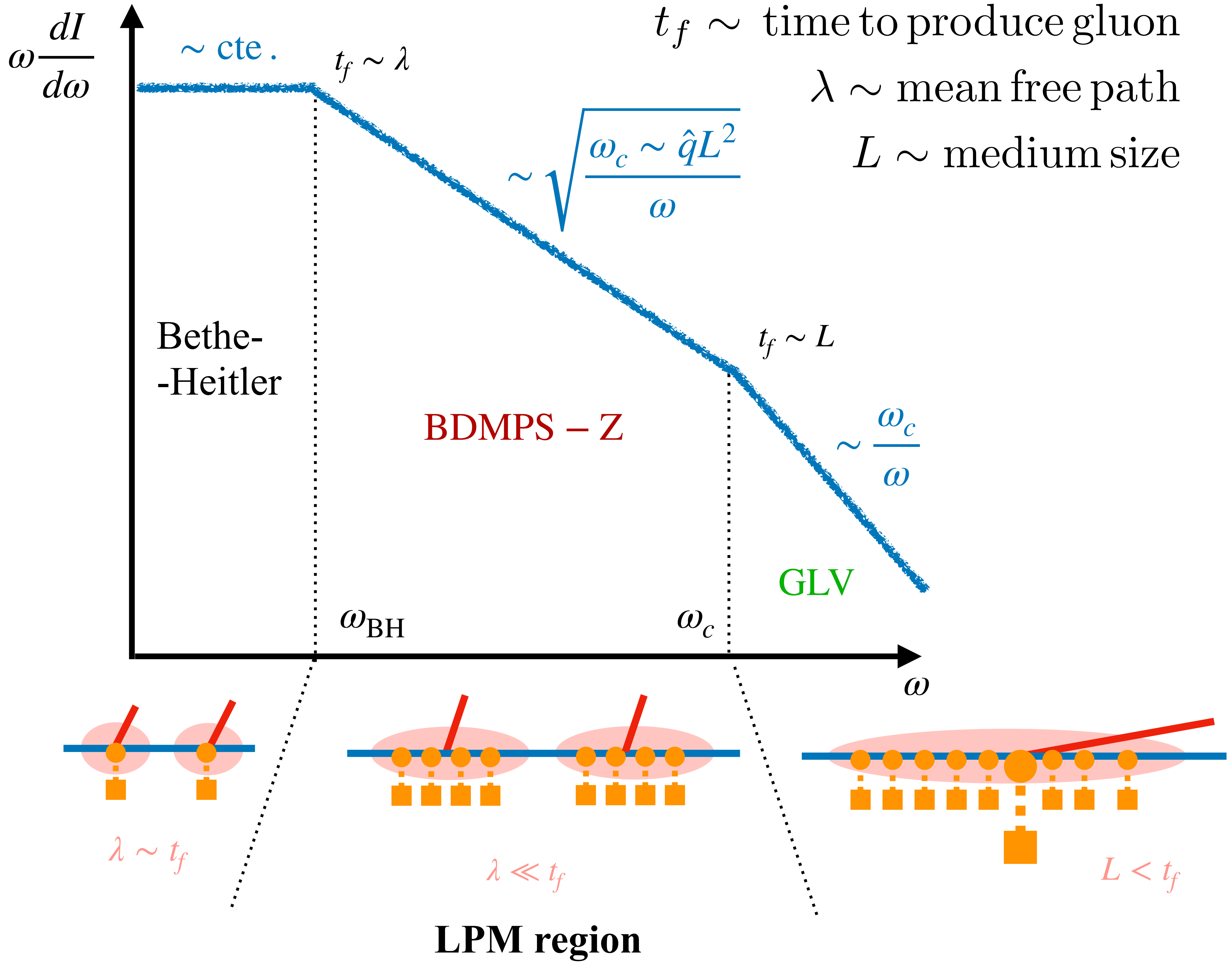
[JB, S. Hauksson, X. Lopez, A. Sadofyev, 2406.07615]



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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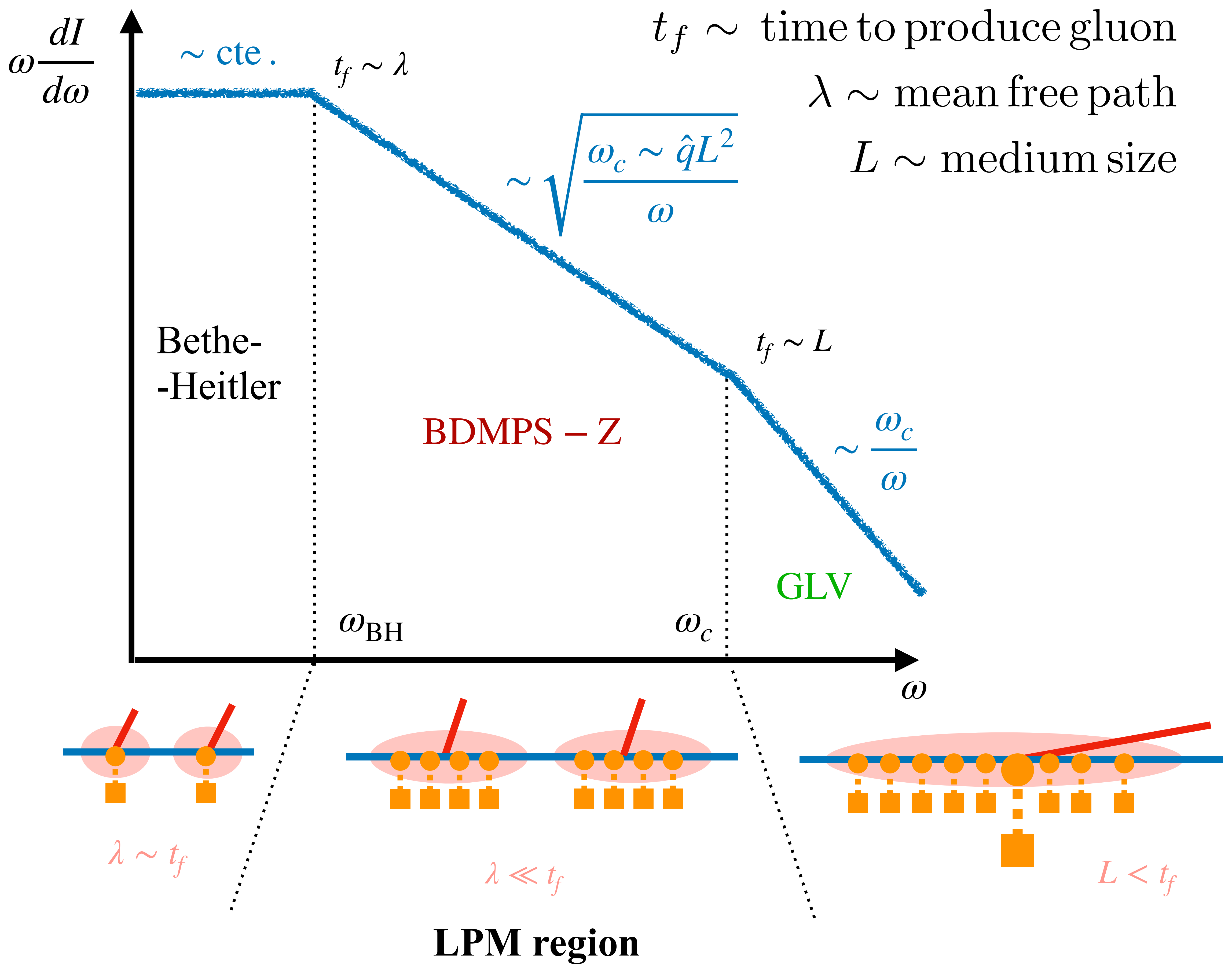
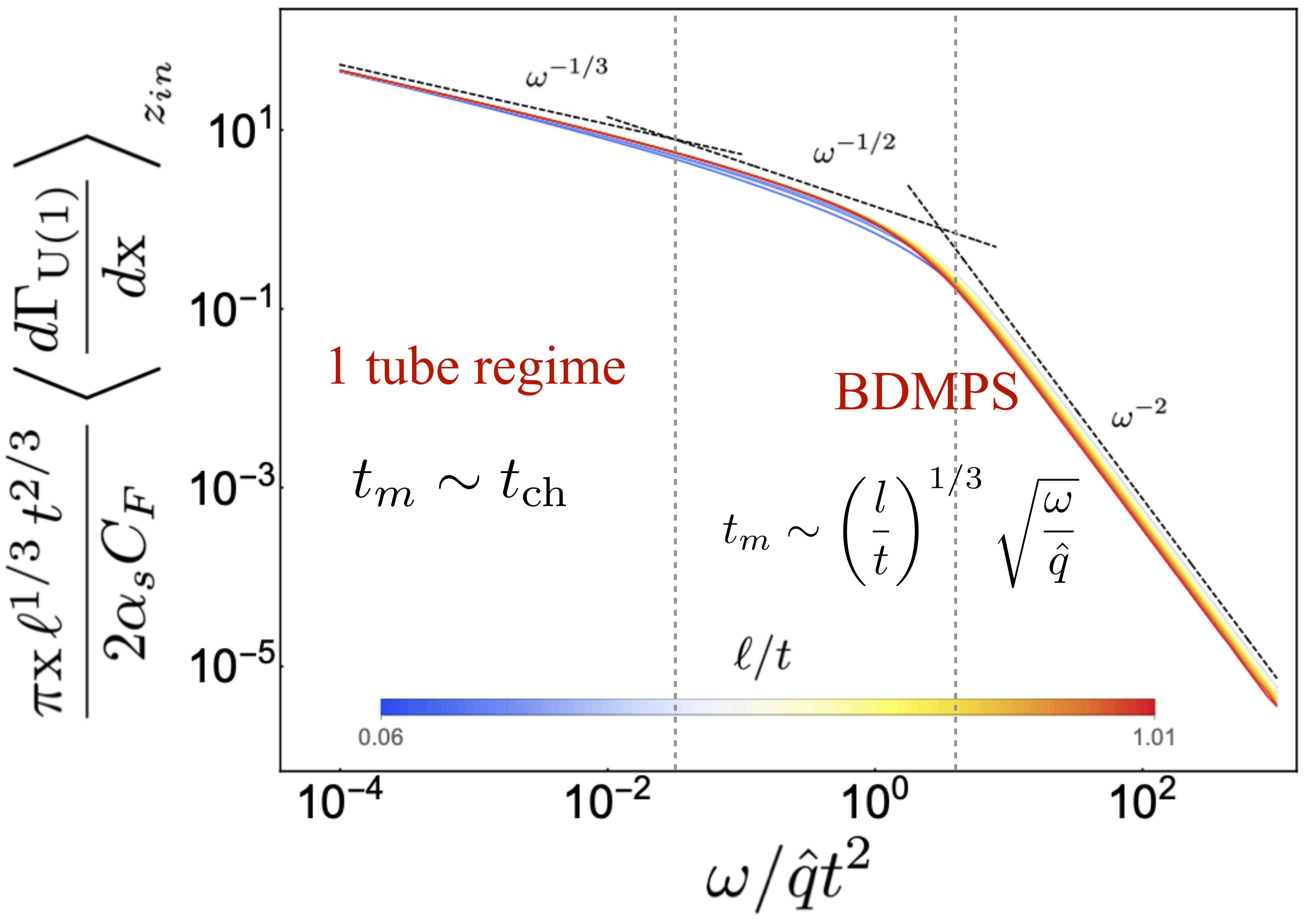


Fixed $\langle \hat{q} \rangle_{\rm U(1)} = \frac{1}{8\pi^2} E_0^2 \ell$



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

Summary

→ **Hydro gradient corrections to jet evolution**

Evolution in non-trivial backgrounds requires revisiting old calculations;

In general, it is not equivalent to using standard jet quenching results in non-trivial backgrounds

→ **Jet evolution in the Glasma**

Evolution in Glasma phase requires rethinking the standard approach to jets in HIC

The presence of matter anisotropy generate new effects (i.e. polarization) which have not been fully explored in pheno studies

At the end of the day, these effects might be too small or wash out, but they need to be studied from the theory side