Jet transport in the Glasma

using colored particle-in-cell simulations

by $\int \mathcal{D}\mathcal{A}$vramescu

T. Lappi, H. Mäntysaari
University of Jyväskylä

A. Ipp, D. Müller
TU Wien

V. Greco, M. Ruggieri
University of Catania

Centre of Excellence
in Quark Matter

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

based on PRD 107, 114021

ECT* workshop Feb 24

Contents

- Literature highlights

Overview of hard probes in pre-equilibrium stages

- Glasma fields

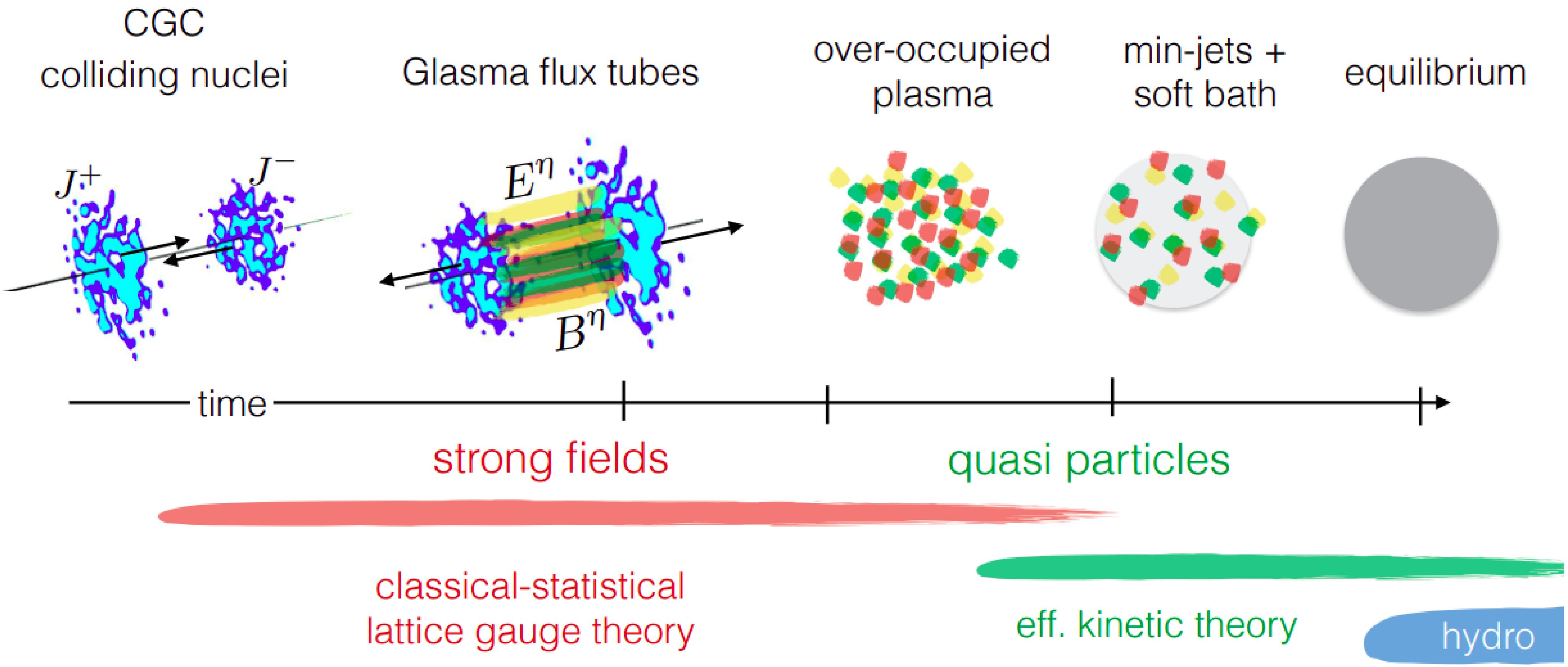
Features of the Glasma fields + numerical evolution

- Jets in Glasma fields

Classical transport of probes in Glasma + numerical solver

Heavy-ion collisions

Stitching together many theories



CGC
colliding nuclei

Glasma flux tubes

over-occupied
plasma

min-jets +
soft bath

equilibrium

time

strong fields

quasi particles

classical-statistical
lattice gauge theory

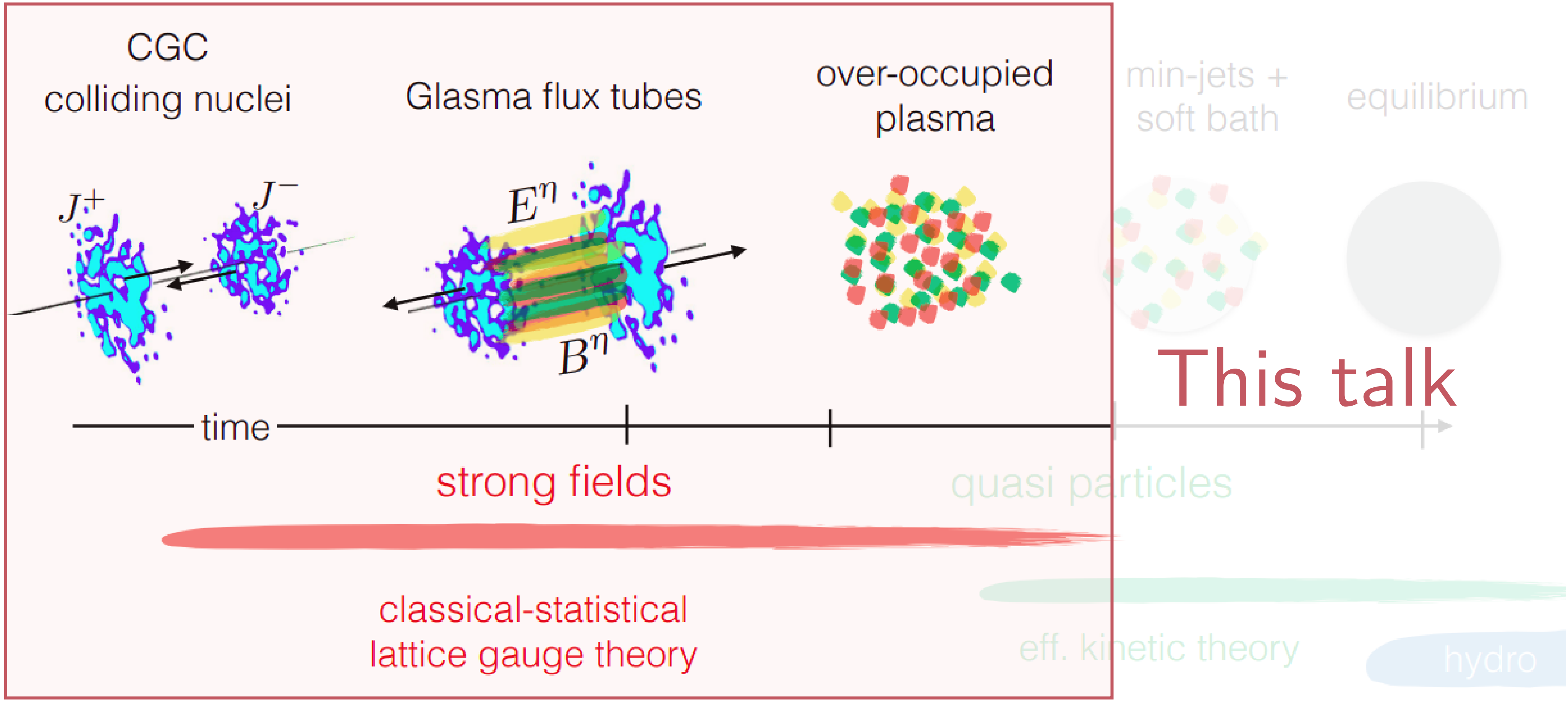
eff. kinetic theory

hydro

Figure credits to S. Schlichting

Heavy-ion collisions

Stitching together many theories



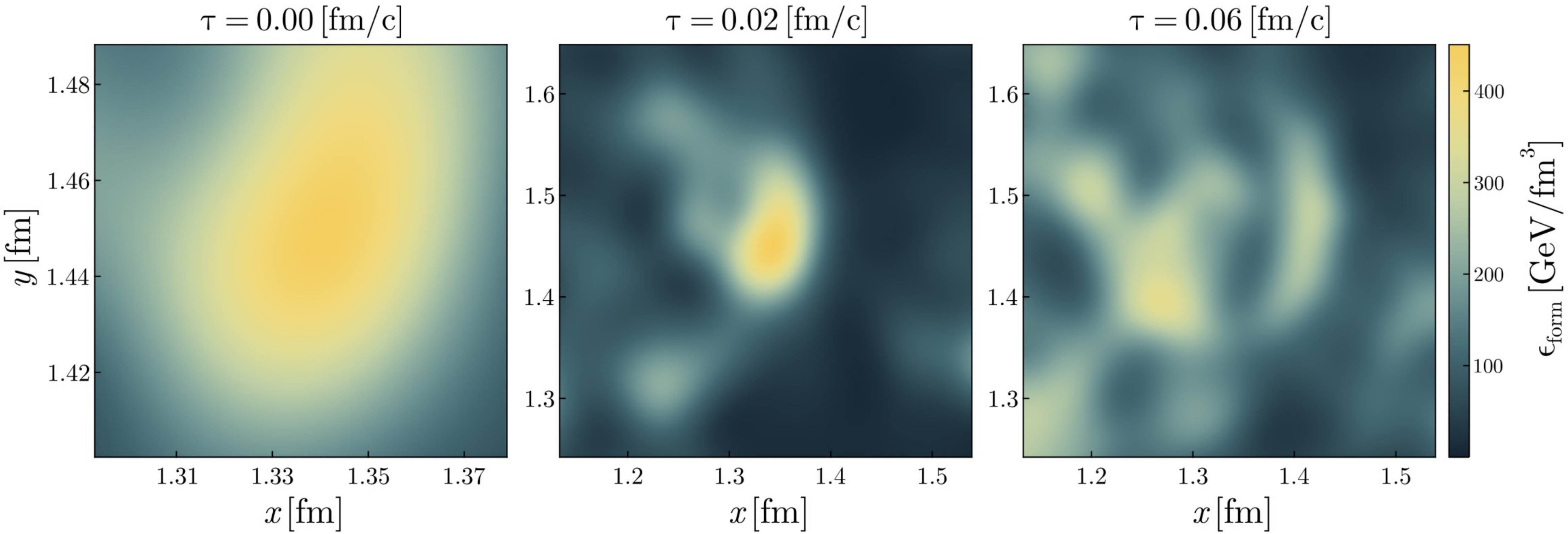
This talk

Figure credits to S. Schlichting

Approach

Prerequisite: Classical lattice gauge theory $\xrightarrow{\text{solver}}$ Glasma fields

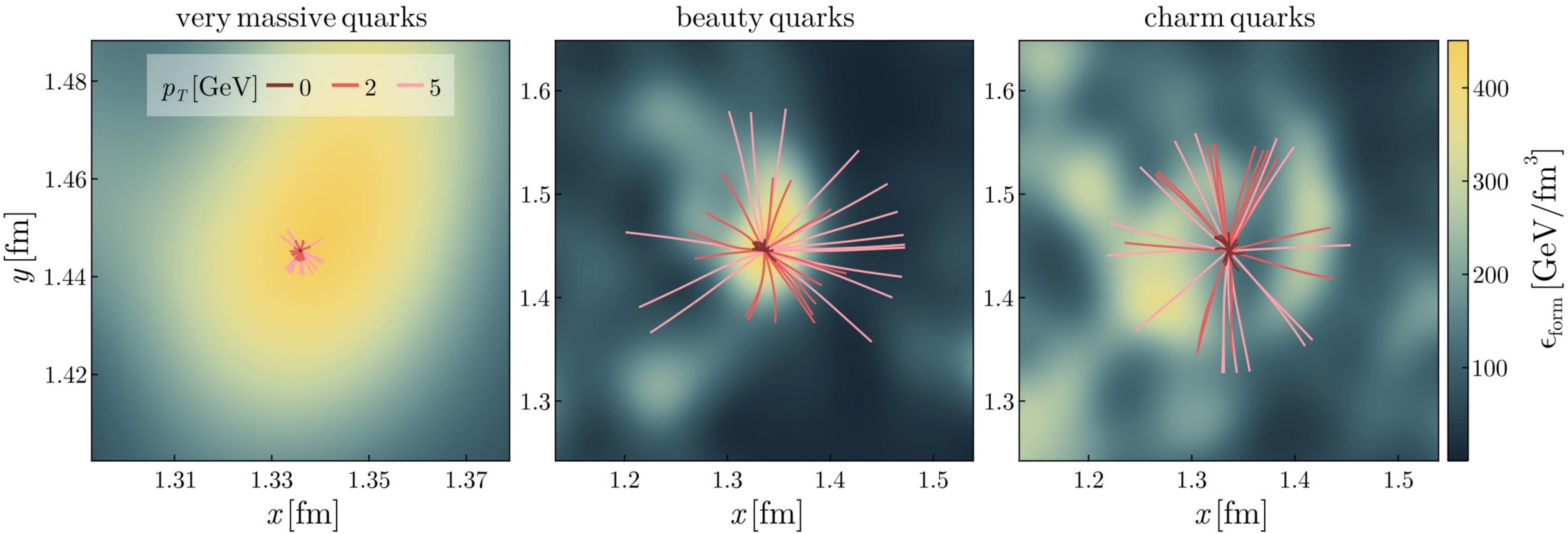
Our work: Glasma fields $\xleftrightarrow{\text{background}}$ ensemble of particles $\xrightarrow{\text{solver}}$ colored particle-in-cell



Approach

Prerequisite: Classical lattice gauge theory $\xrightarrow{\text{solver}}$ Glasma fields

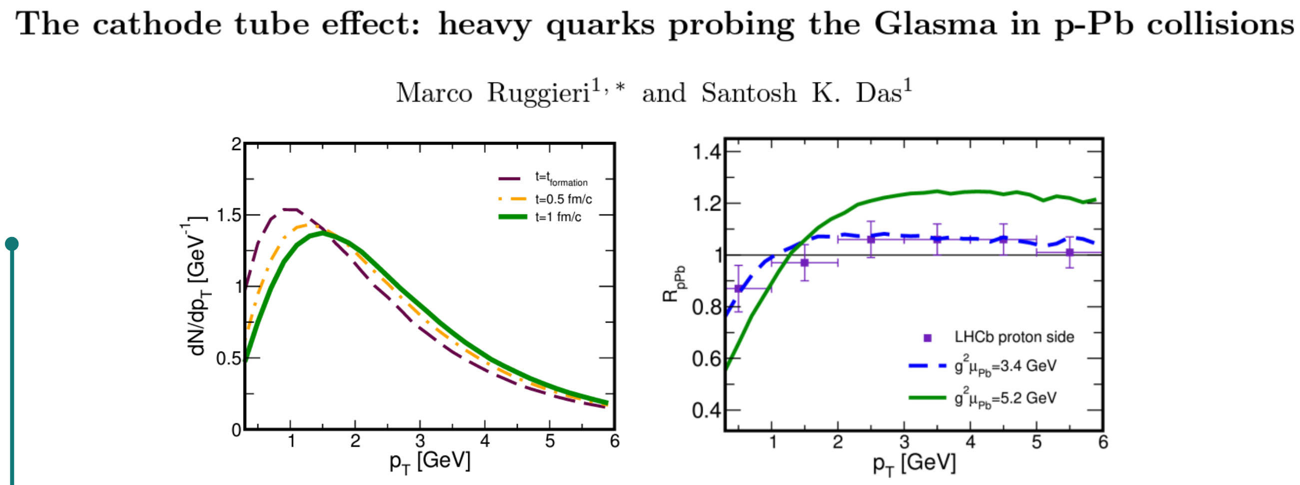
Our work: Glasma fields $\xleftrightarrow{\text{background}}$ ensemble of particles $\xrightarrow{\text{solver}}$ colored particle-in-cell



Hard probes in the pre-equilibrium stage

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



The cathode tube effect: heavy quarks probing the Glasma in p-Pb collisions

Marco Ruggieri[1,*] and Santosh K. Das[1]

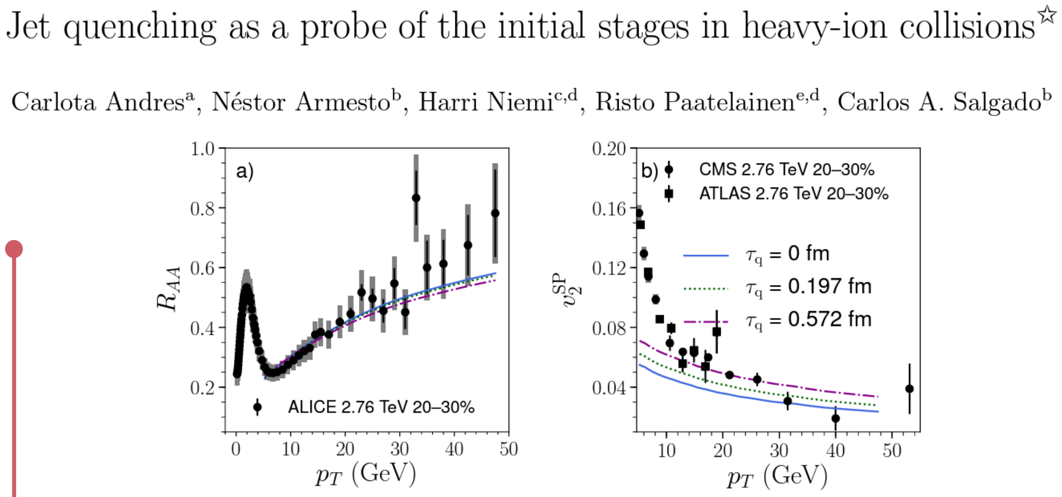
2018

[arXiV.1805.09617]

SU(2) Glasma
Classical transport

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Jet quenching as a probe of the initial stages in heavy-ion collisions☆

Carlota Andres[a], Néstor Armesto[b], Harri Niemi[c,d], Risto Paatelainen[e,d], Carlos A. Salgado[b]

2018

2019

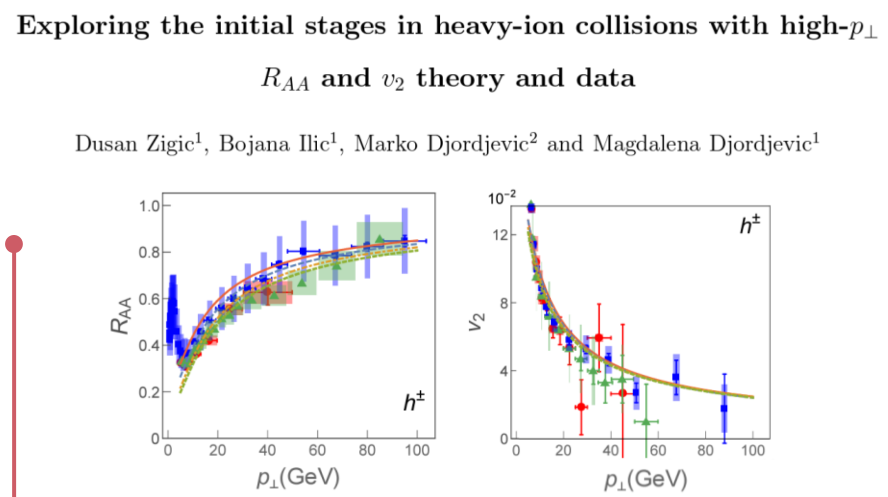
[arXiV.1902.03231]

EKRT initial conditions

BDMPS-Z energy loss

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Exploring the initial stages in heavy-ion collisions with high-$p_\perp$ R_{AA} and v_2 theory and data

Dusan Zigic[1], Bojana Ilic[1], Marko Djordjevic[2] and Magdalena Djordjevic[1]

2018

2019

[arXiV.1908.11866]

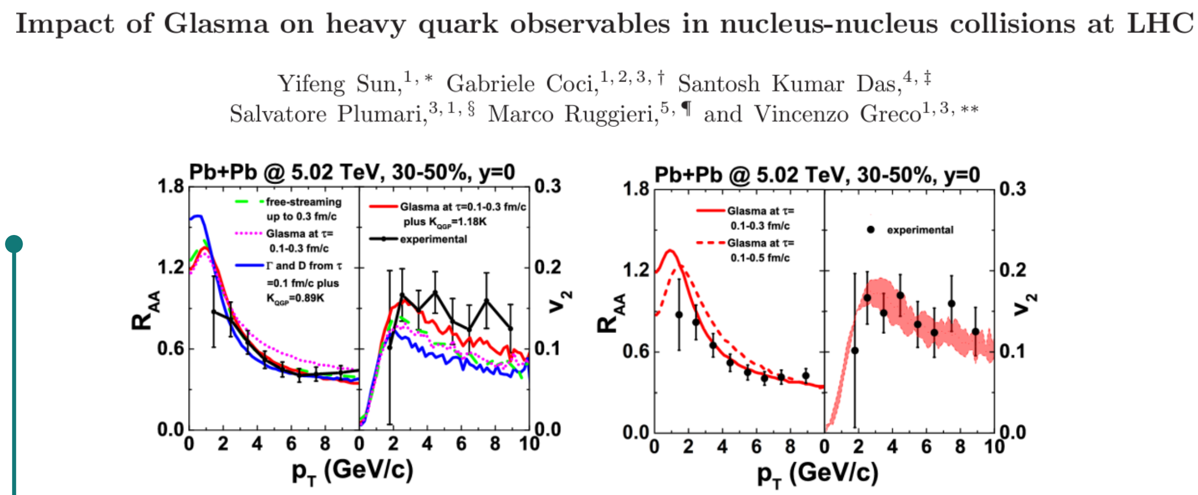
DREENA-B framework
Collisional energy loss

Magdalena's talk *Mon 16:00*

Constraining QGP properties through the DREENA framework with Bayesian inference

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Impact of Glasma on heavy quark observables in nucleus-nucleus collisions at LHC

Yifeng Sun,[1,*] Gabriele Coci,[1,2,3,†] Santosh Kumar Das,[4,‡]
Salvatore Plumari,[3,1,§] Marco Ruggieri,[5,¶] and Vincenzo Greco[1,3,**]

2018

2019

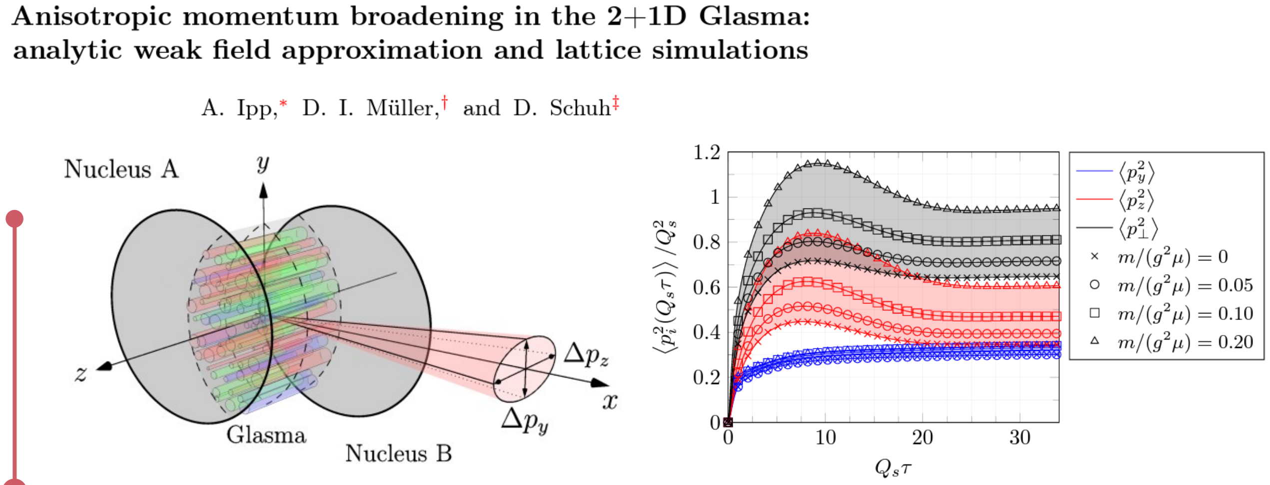
[arXiV.1902.06254]

HQs diffusion

Glasma vs. Langevin

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Anisotropic momentum broadening in the 2+1D Glasma: analytic weak field approximation and lattice simulations

A. Ipp,* D. I. Müller,† and D. Schuh‡

2018

2019

2020

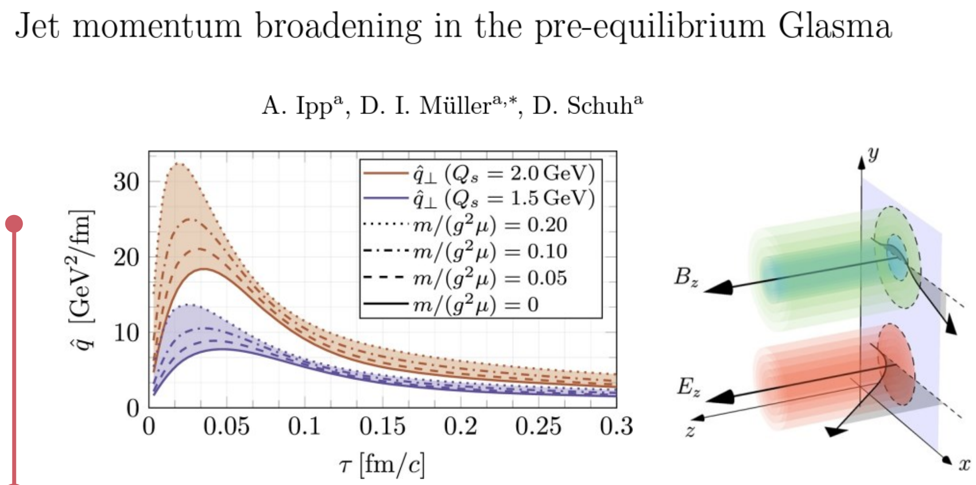
[arXiV.2001.10001]

Dilute + strong Glasma

Field correlators

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Jet momentum broadening in the pre-equilibrium Glasma

A. Ipp[a], D. I. Müller[a,*], D. Schuh[a]

2018

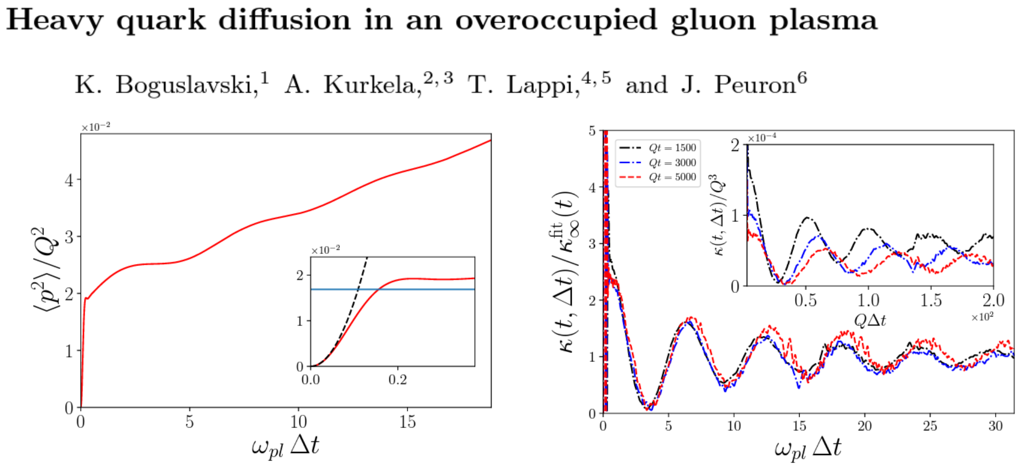
2019

2020
[arXiV.2009.14206]

Strong Glasma
Jet quenching

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Heavy quark diffusion in an overoccupied gluon plasma

K. Boguslavski,[1] A. Kurkela,[2,3] T. Lappi,[4,5] and J. Peuron[6]

2018

2019

2020

[arXiV.2005.02418]

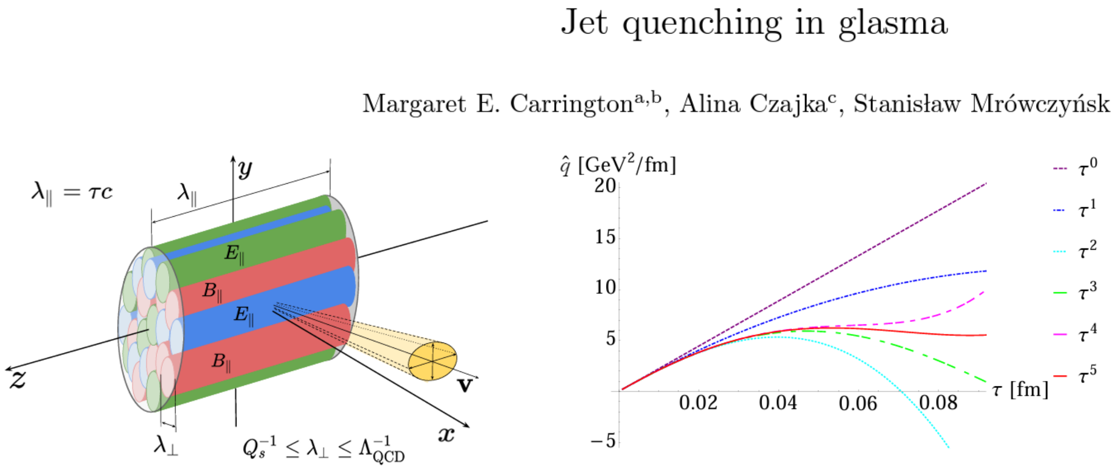
Overoccupied gluon plasma

Field correlators

HTL spectral functions

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Jet quenching in glasma

Margaret E. Carrington[a,b], Alina Czajka[c], Stanisław Mrówczyński[c,d]

2018

2019

2020

2021

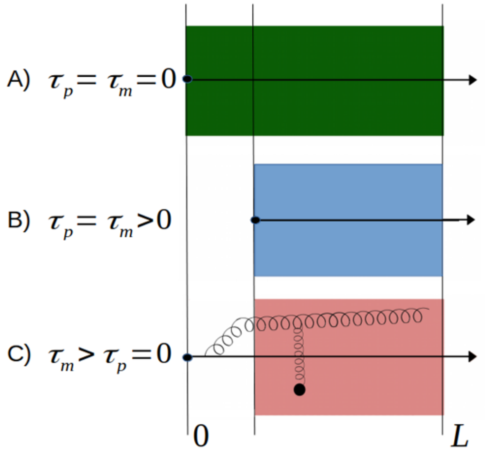
[arXiV.2112.06812]

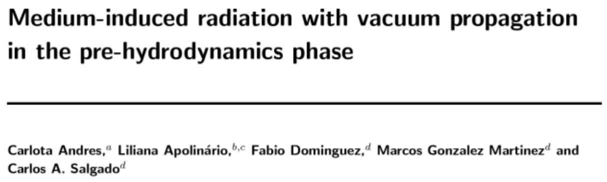
Proper time expansion Glasma

Fokker-Planck transport

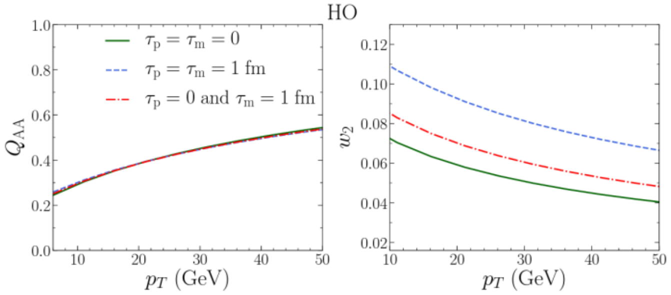
Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage




Medium-induced radiation with vacuum propagation in the pre-hydrodynamics phase

Carlota Andres,[a] Liliana Apolinário,[b,c] Fabio Dominguez,[d] Marcos Gonzalez Martinez[d] and Carlos A. Salgado[d]



2018

2019

2020

2021

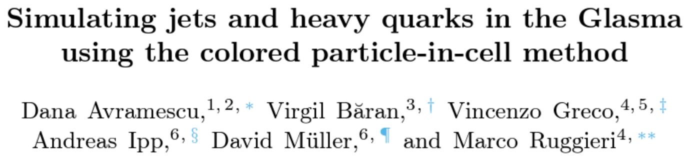
2022

[arXiV.2211.10161]

Initial stage radiation
BDMPS-Z

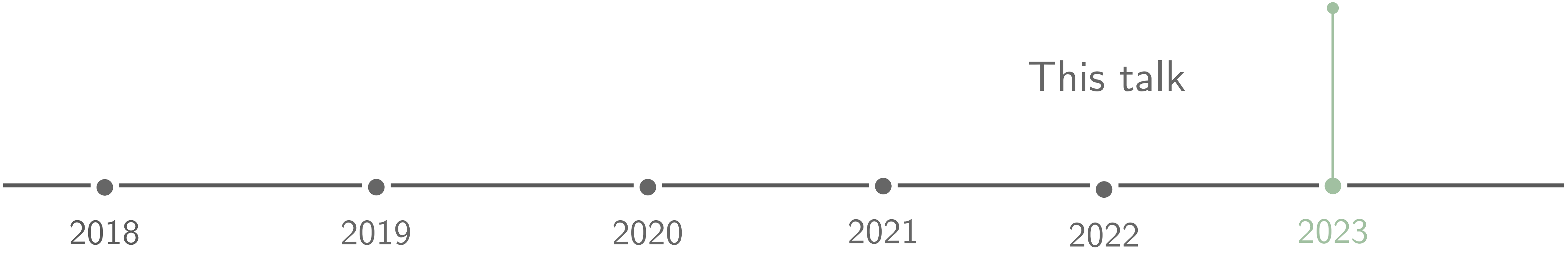
Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Simulating jets and heavy quarks in the Glasma using the colored particle-in-cell method

Dana Avramescu,[1, 2, *] Virgil Băran,[3, †] Vincenzo Greco,[4, 5, ‡]
Andreas Ipp,[6, §] David Müller,[6, ¶] and Marco Ruggieri[4, **]



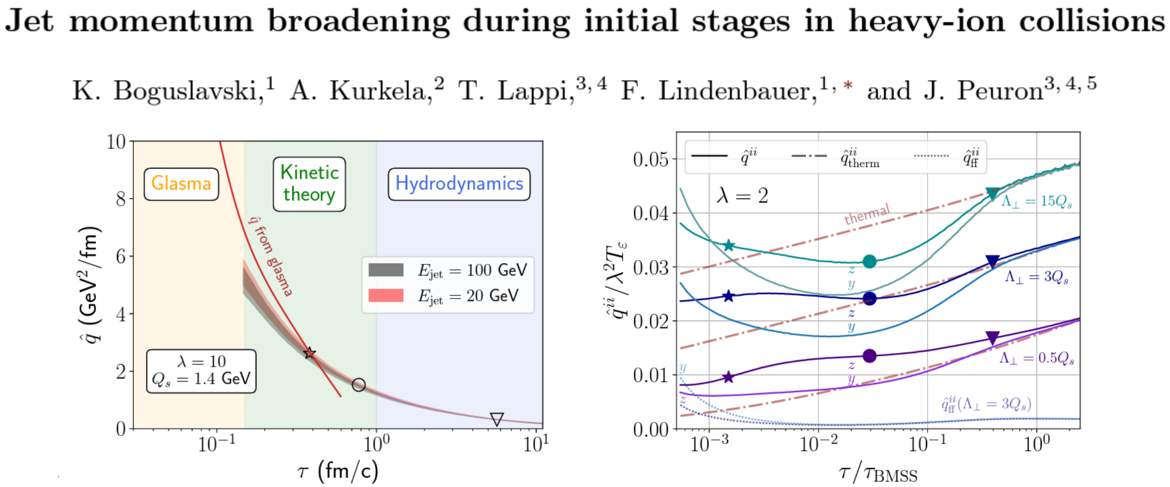
This talk

[arXiV.2303.05599]

SU(3) Glasma
Classical transport
CPIC method

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Jet momentum broadening during initial stages in heavy-ion collisions

K. Boguslavski,[1] A. Kurkela,[2] T. Lappi,[3,4] F. Lindenbauer,[1,*] and J. Peuron[3,4,5]

2018

2019

2020

2021

2022

2023
[arXiV.2303.12595]

QCD EKT
Isotropic HTL

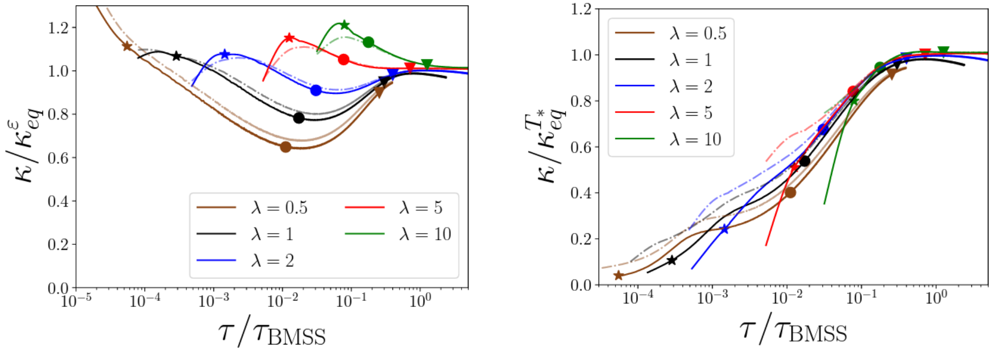
Florian's talk *Wed 11:00*
Jet quenching parameter during the initial stages

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage

Heavy quark diffusion coefficient in heavy-ion collisions via kinetic theory

K. Boguslavski,[1] A. Kurkela,[2] T. Lappi,[3,4] F. Lindenbauer,[1] and J. Peuron[3,4,5,*]



2018

2019

2020

2021

2022

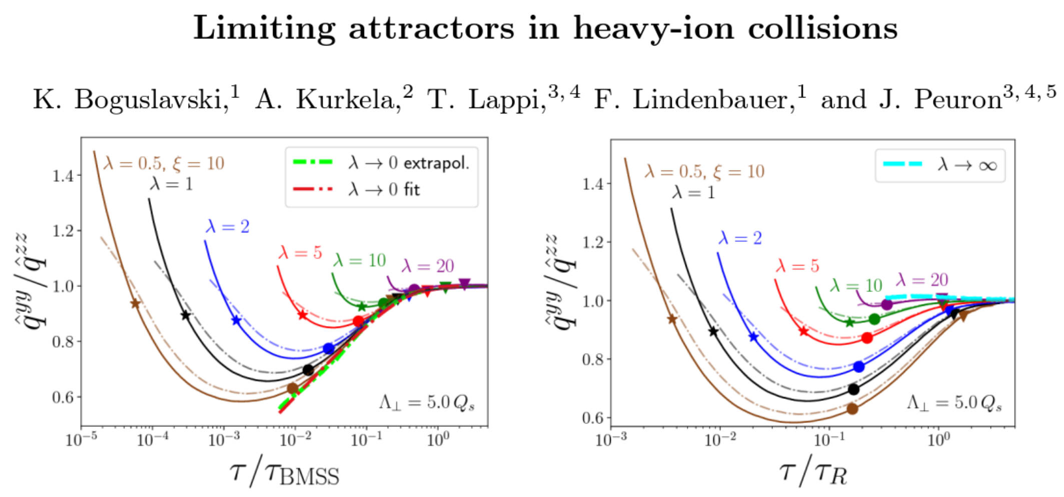
2023

[arXiV.2303.12520]

QCD EKT
Infinite mass limit

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Limiting attractors in heavy-ion collisions

K. Boguslavski,[1] A. Kurkela,[2] T. Lappi,[3,4] F. Lindenbauer,[1] and J. Peuron[3,4,5]

2018

2019

2020

2021

2022

2023

[arXiV.2312.11252]

QCD EKT

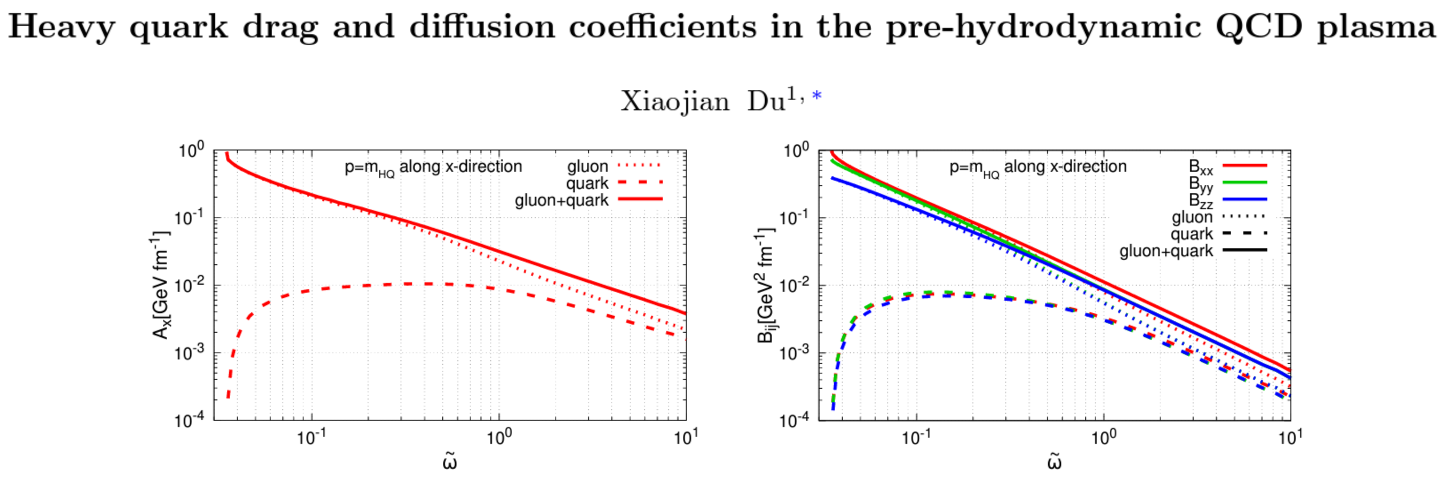
Bottom-up attractor

Tuomas' talk *Thu 09:00*

Attractor behavior of pre-equilibrium transport coefficients

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Heavy quark drag and diffusion coefficients in the pre-hydrodynamic QCD plasma

Xiaojian Du[1,*]

2018

2019

2020

2021

2022

2023

[arXiV.2306.02530]

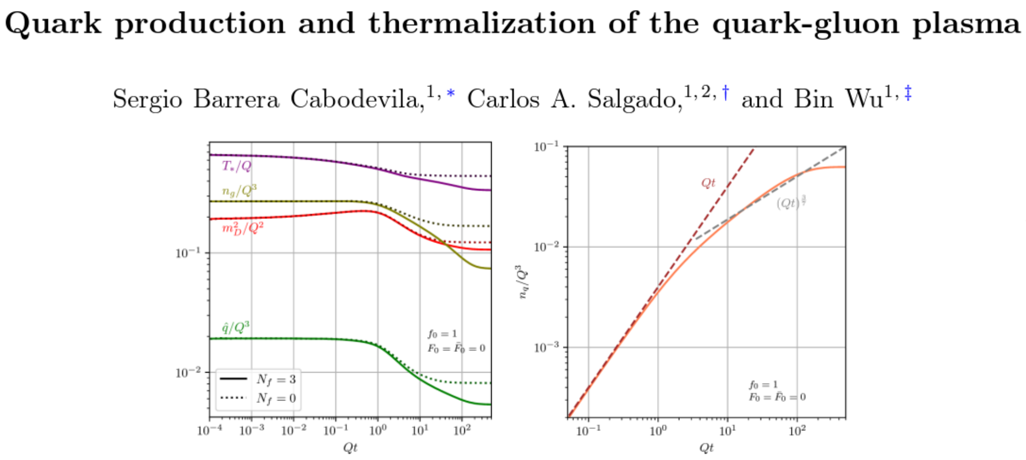
QCD EKT
HQ diffusion

Xiaojian's talk *Thu 11:00*

Heavy quark drag and diffusion coefficients in the pre-hydrodynamic QCD plasma

Legend ● heavy quarks ● jets ● hard probes

Hard probes in the pre-equilibrium stage



Quark production and thermalization of the quark-gluon plasma

Sergio Barrera Cabodevila,[1,*] Carlos A. Salgado,[1,2,†] and Bin Wu[1,‡]

2018

2019

2020

2021

2022

2023

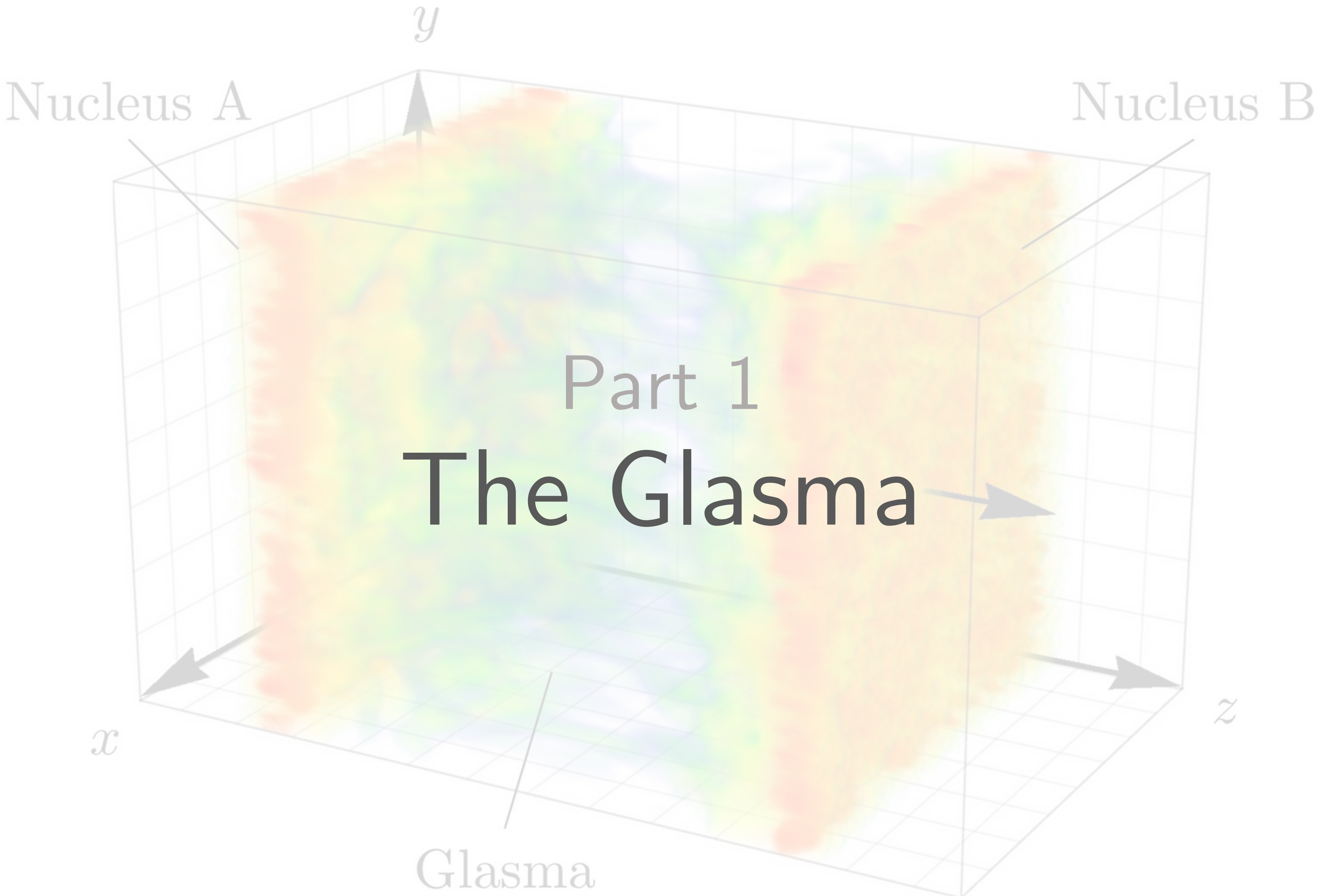
[arXiV.2311.07450]

QCD EKT
Thermalization

Sergio's talk *Thu 14:00*

Evolution of QCD jets in non-equilibrium plasma

Legend ● heavy quarks ● jets ● hard probes



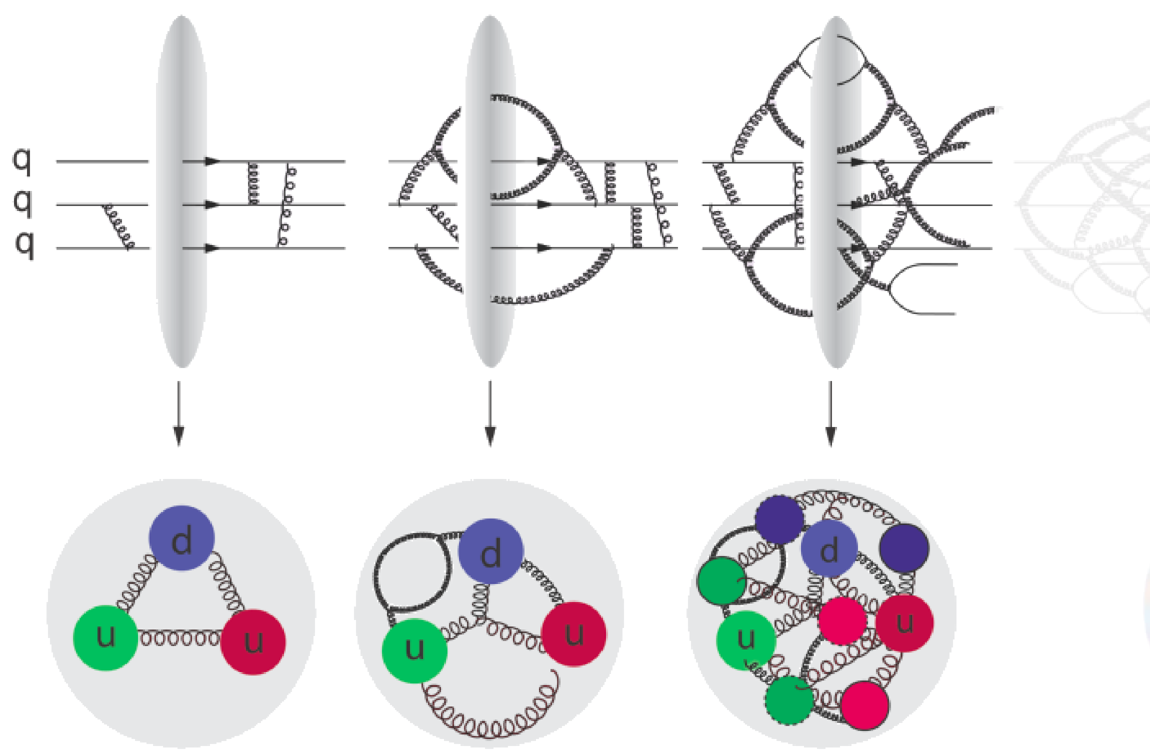
Part 1

The Glasma

Figure credits to D. Müller

High energy QCD

Gluons as main degrees of freedom



parton

$$x \overset{\text{def}}{=} \frac{p^+}{P^+}$$

nucleus

Small-x limit of QCD ↔ evolution

Figure credits to T. Ullrich

High energy QCD

Gluons as main degrees of freedom

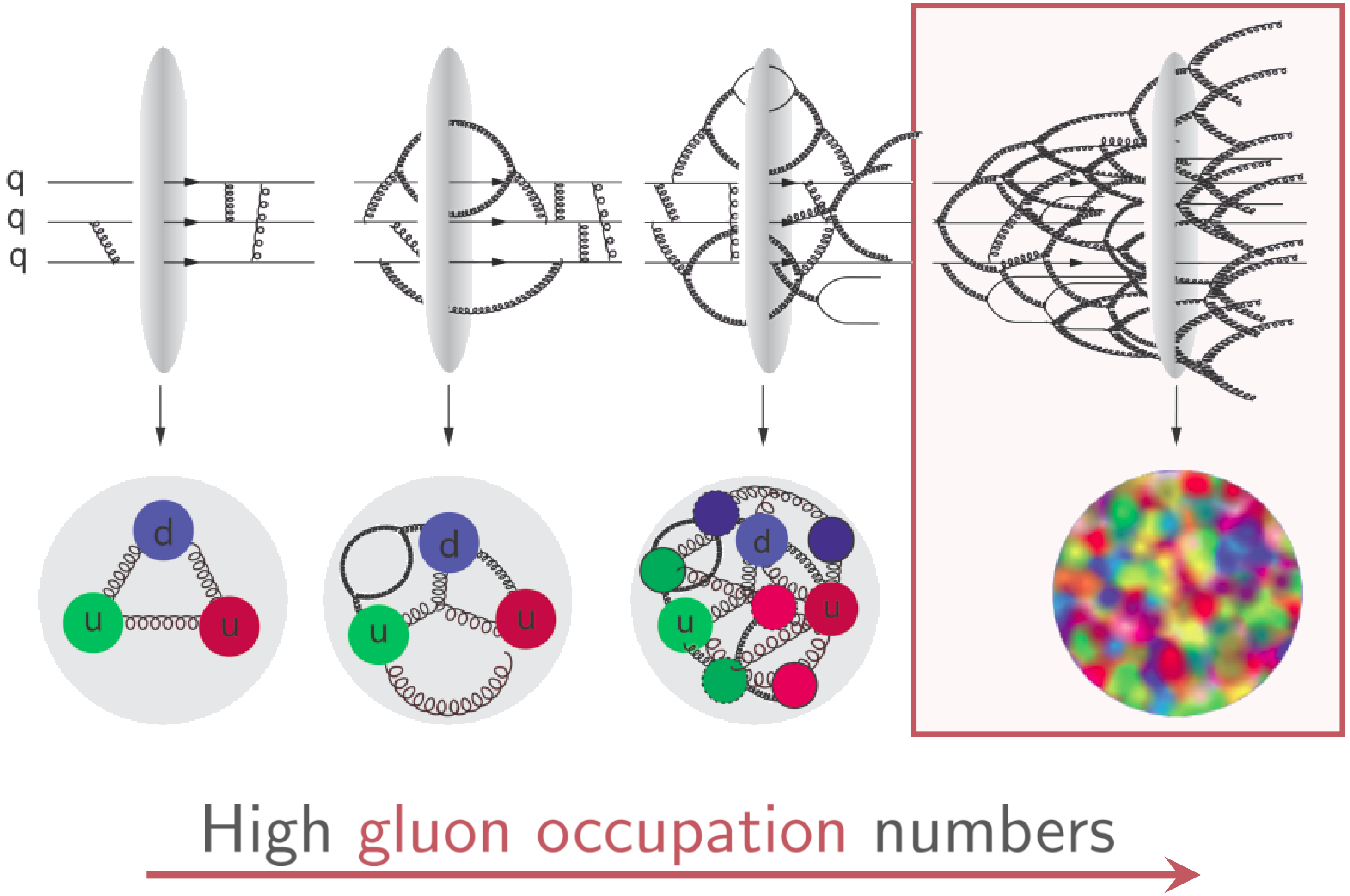


Figure credits to T. Ullrich

CGC as an EFT for small-x QCD

Classical Yang-Mills fields

- Separation of scales

$\underbrace{\text{gluons}}_{\text{gauge fields } A^\mu}$ & $\underbrace{\text{valence quarks}}_{\text{color source } J^\mu}$

- Classical Yang-Mills equations

covariant derivative

field strength tensor

$$\left(\mathcal{D}_\mu F^{\mu\nu}\right)[A^\mu] = \boxed{J^\nu}$$

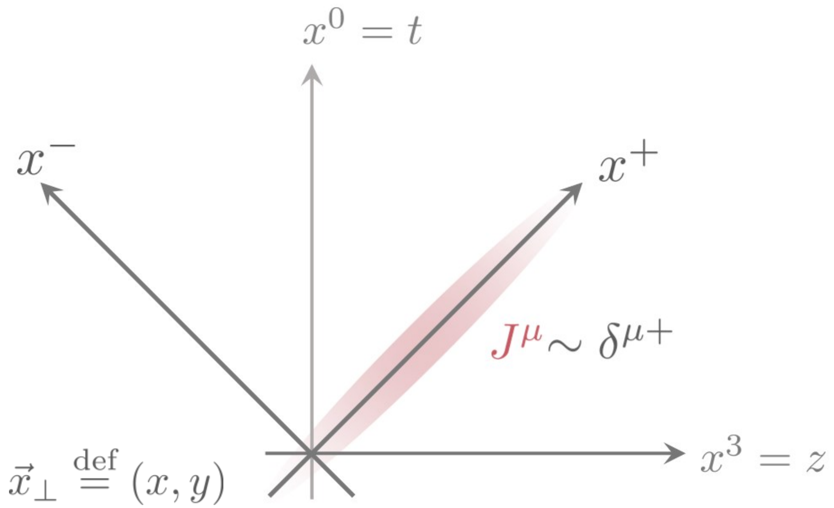
gluon gauge field

nucleus color current

- Color current $J^\mu \xleftarrow{\text{input}}$ light-cone kinematics + color charge model

CGC as an EFT for small-x QCD

Color current model



$\vec{x}_\perp \overset{\text{def}}{=} (x, y)$

$x^\pm \overset{\text{def}}{=} (x^0 \pm x^3)/\sqrt{2}$

- Light-cone current J^+

thin sheet static source

$$J^{\mu,a} = \delta^{\mu+}\delta(x^-)\boxed{\rho^a(\vec{x}_\perp)}$$

classical color charges

- Color charges for large nuclei

McLerran Venugopalan (MV) model

Saturation momentum

$$g^2\mu \propto Q_s$$

MV model parameter

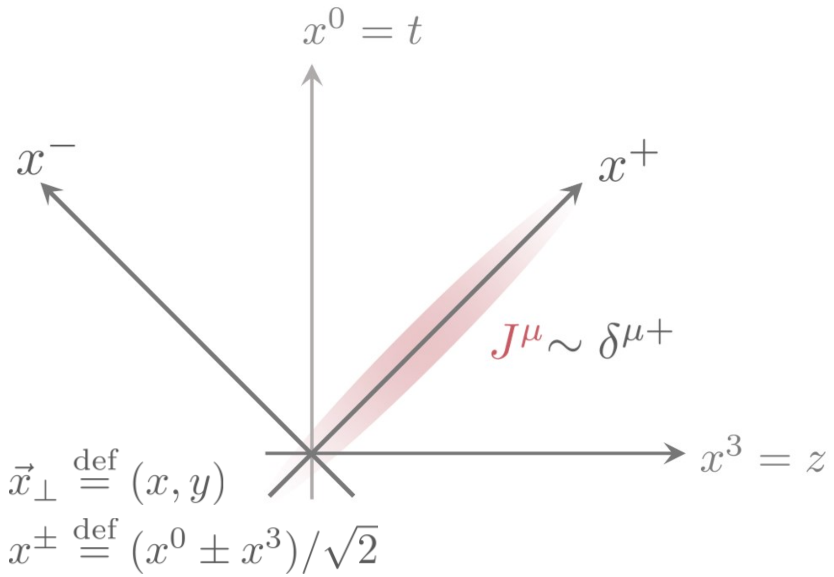
Physical parameter

$$\boxed{\begin{aligned}\langle\rho^a\rangle &= 0\\ \langle\rho^a\rho^a\rangle &\propto (g^2\mu)^2\end{aligned}}$$

Stochastic charges

CGC as an EFT for small-x QCD

Color current model



$\vec{x}_\perp \overset{\text{def}}{=} (x, y)$

$x^\pm \overset{\text{def}}{=} (x^0 \pm x^3)/\sqrt{2}$

- Light-cone current J^+

$$\textcolor{red}{J^{\mu,a}} = \underbrace{\delta^{\mu+}}_{\text{thin sheet}}\,\underbrace{\delta(x^-)}_{\text{static source}}\,\boxed{\rho^a(\vec{x}_\perp)}$$

thin sheet

static source

classical color charges

- Color charges for large nuclei

McLerran Venugopalan (MV) model

$$\boxed{\begin{aligned}\langle \rho^a \rangle &= 0 \\ \langle \rho^a \rho^a \rangle &\propto (g^2 \mu)^2\end{aligned}}$$

Stochastic charges

Physical parameter

Saturation momentum

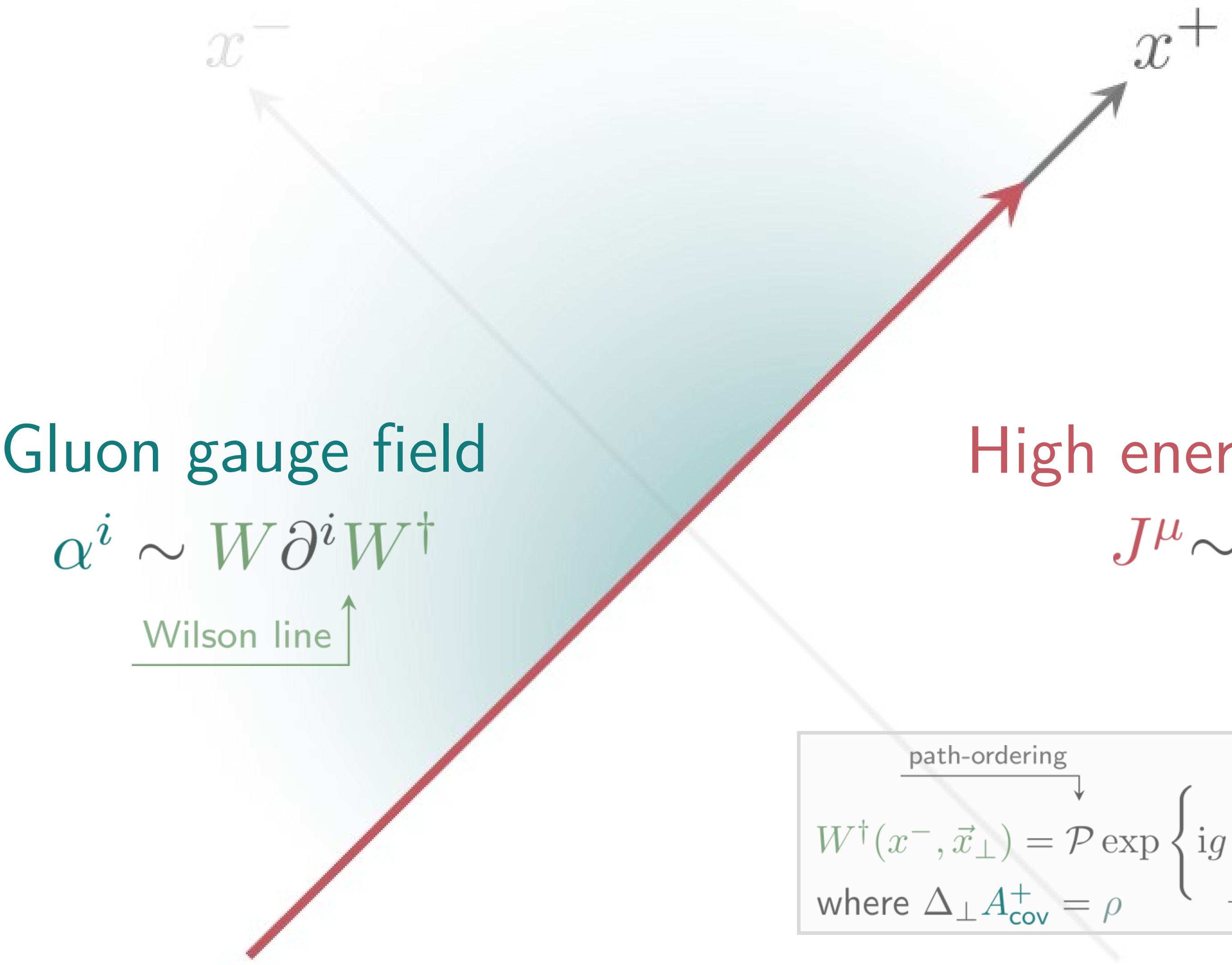
$$Q_s \approx 2\,\mathrm{GeV}$$

$$g^2 \mu \propto Q_s$$

Central LHC collisions

MV model parameter

Gauge fields before the collision



Gluon gauge field

$$\alpha^i \sim W \partial^i W^\dagger$$

Wilson line

High energy nucleus

$$J^\mu \sim \delta^{\mu+} \rho$$

color charge

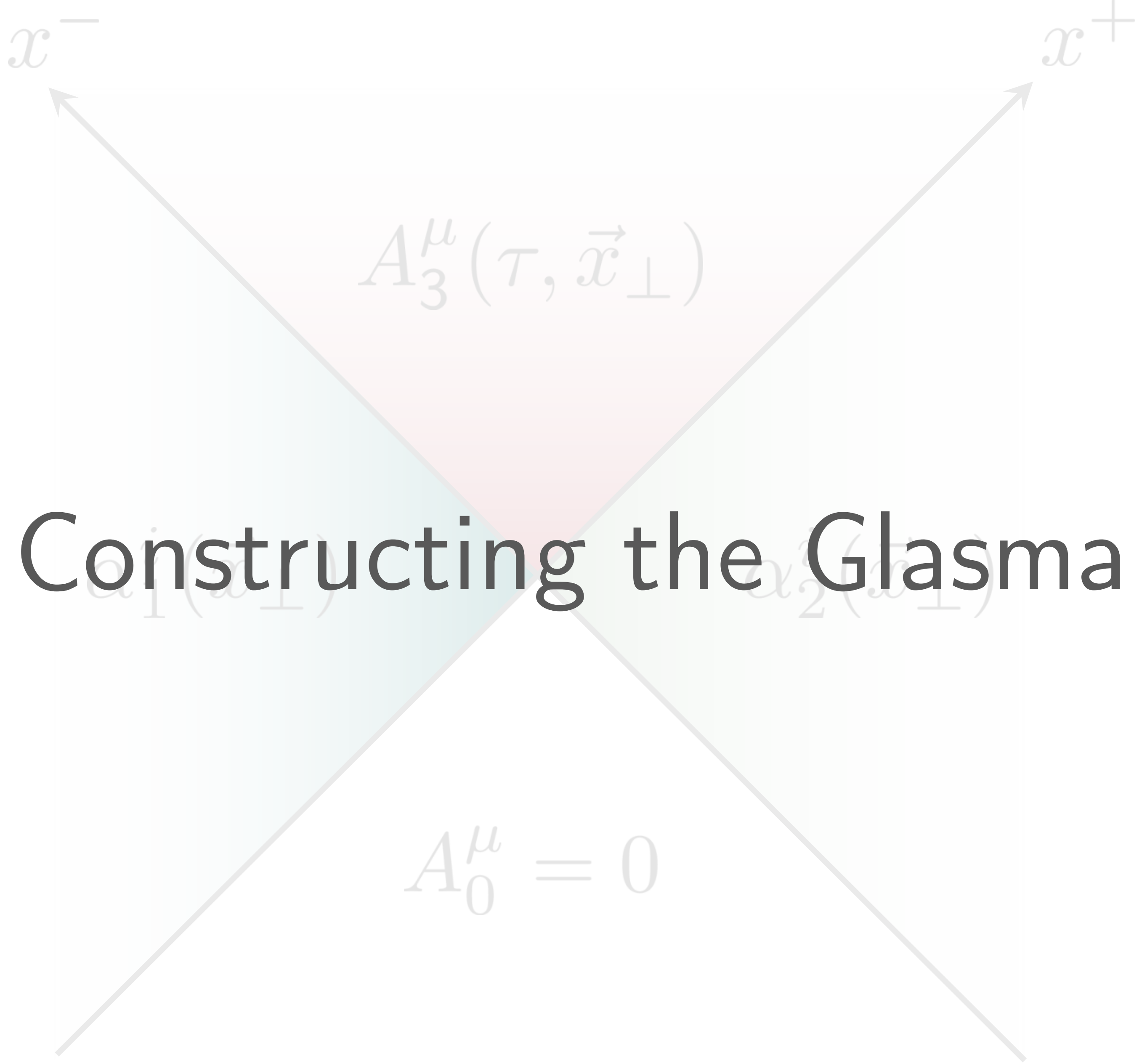
Wilson line

path-ordering

$$W^\dagger(x^-, \vec{x}_\perp) = \mathcal{P} \exp\left\{ ig \int_{-\infty}^{x^-} dz^- A^+_{\text{cov}}(z^-, \vec{x}_\perp) \right\}$$

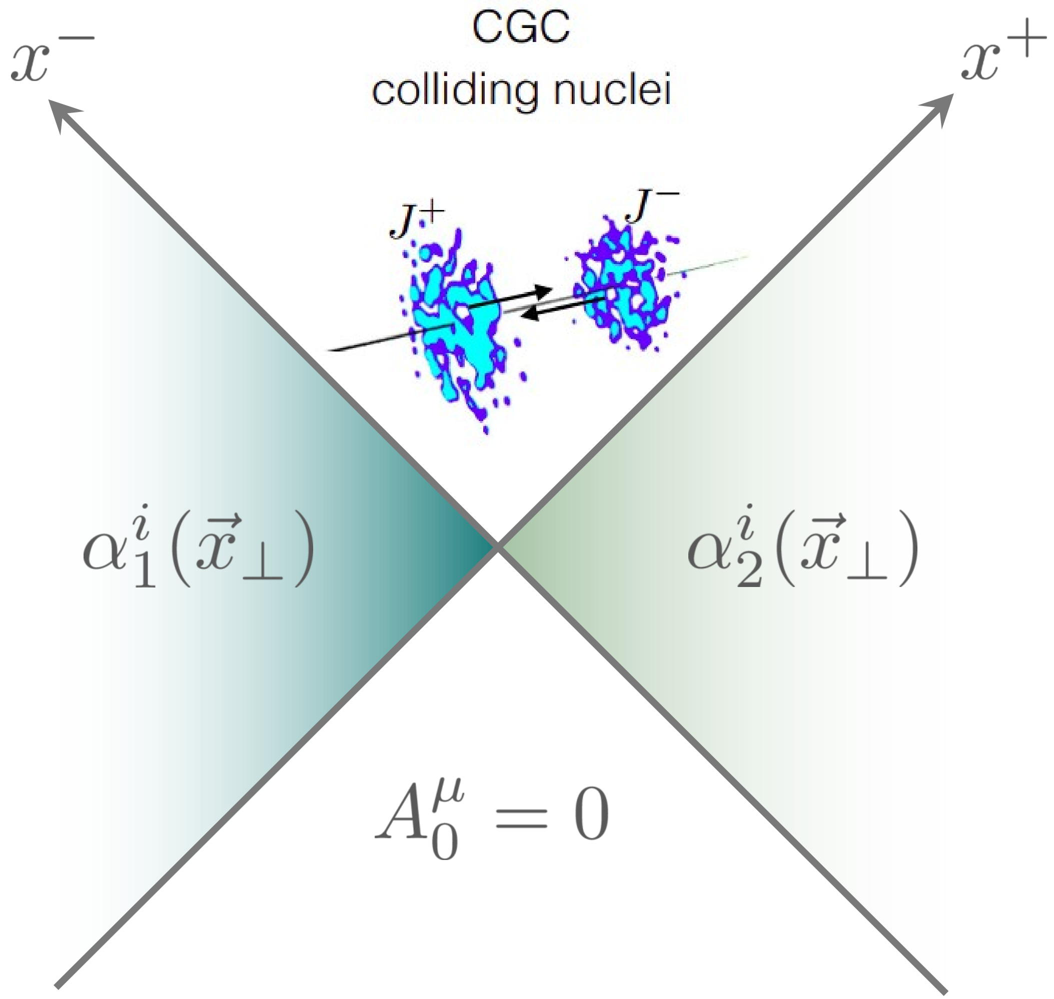
where $\Delta_\perp A^+_{\text{cov}} = \rho$

Constructing the Glasma



Collision of CGC nuclei

Light-cone diagram of collision

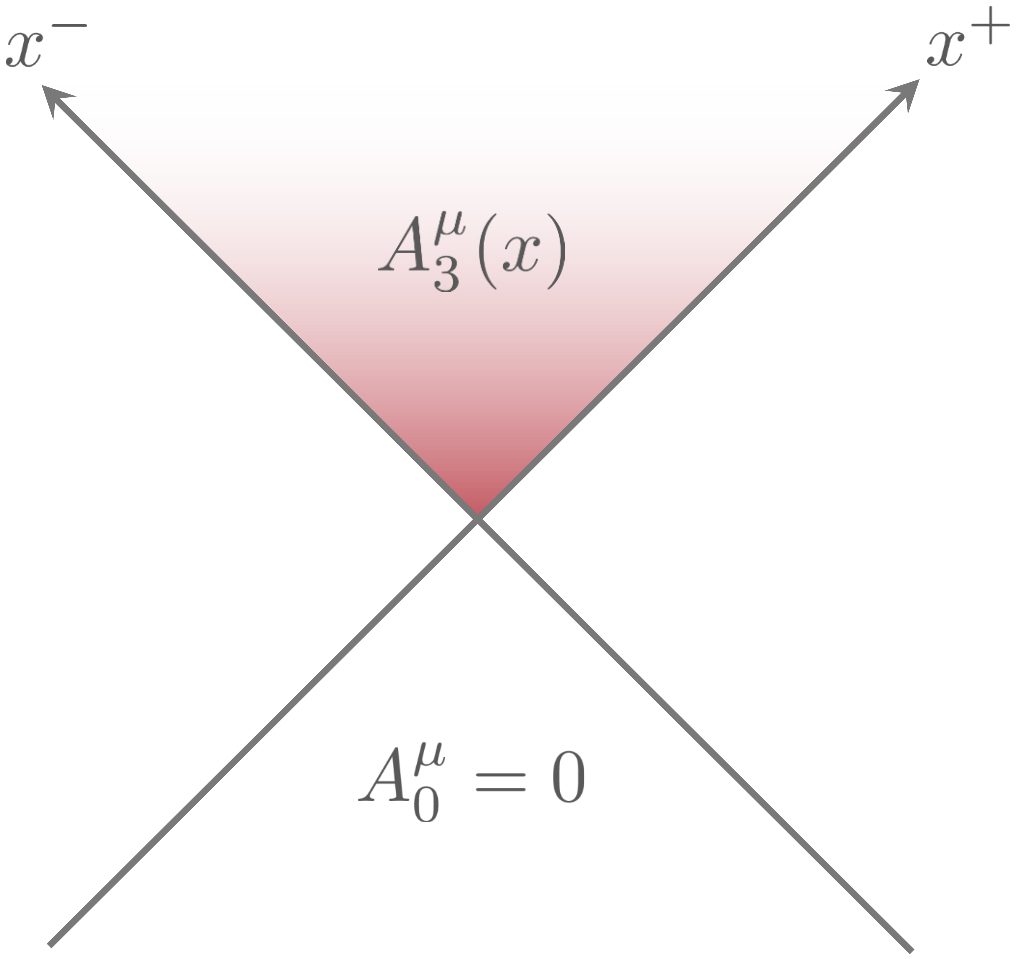


Before the collision

Known $\alpha_1^i(\vec{x}_\perp)$ and $\alpha_2^i(\vec{x}_\perp)$

Collision of CGC nuclei

Light-cone diagram of collision

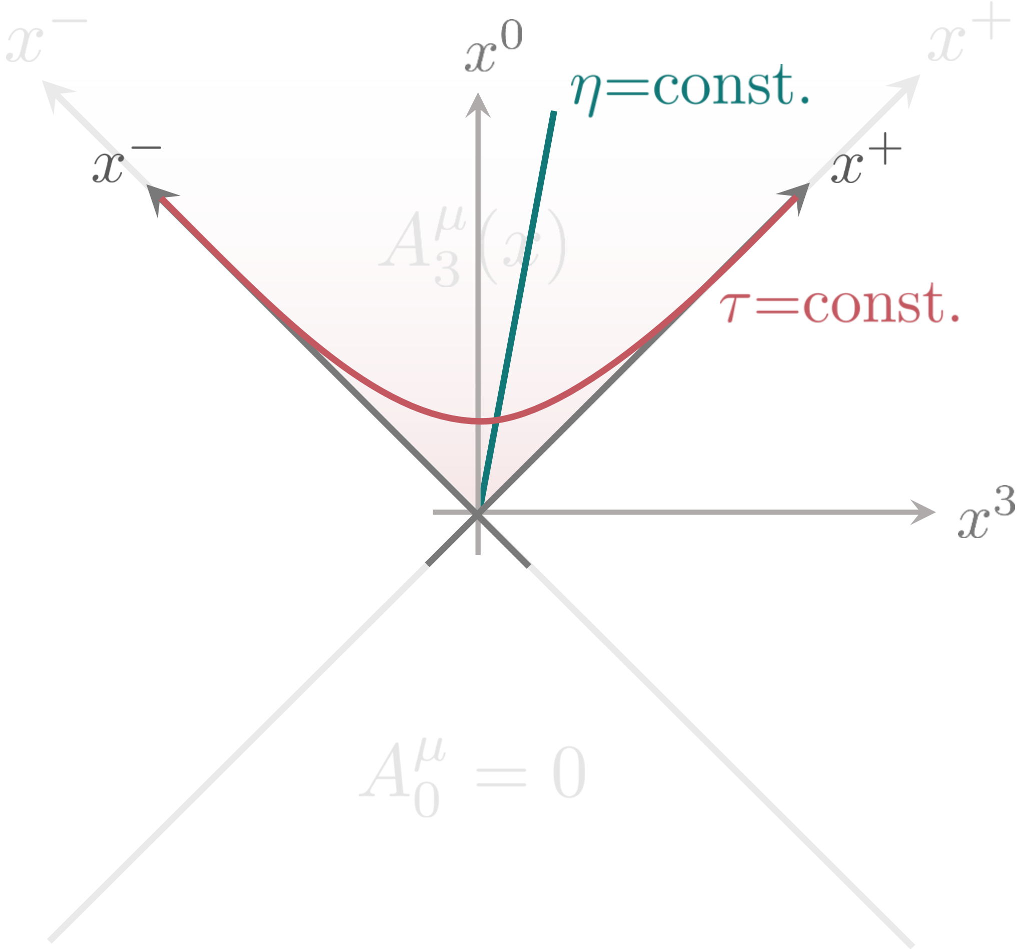


After the collision

Unknown $A_3^\mu(x)$

Collision of CGC nuclei

Light-cone diagram of collision



After the collision

Unknown $A_3^\mu(x)$

- Boost invariance

$$A^\mu(x) = A^\mu(\tau, \vec{x}_\perp, \cancel{\eta})$$

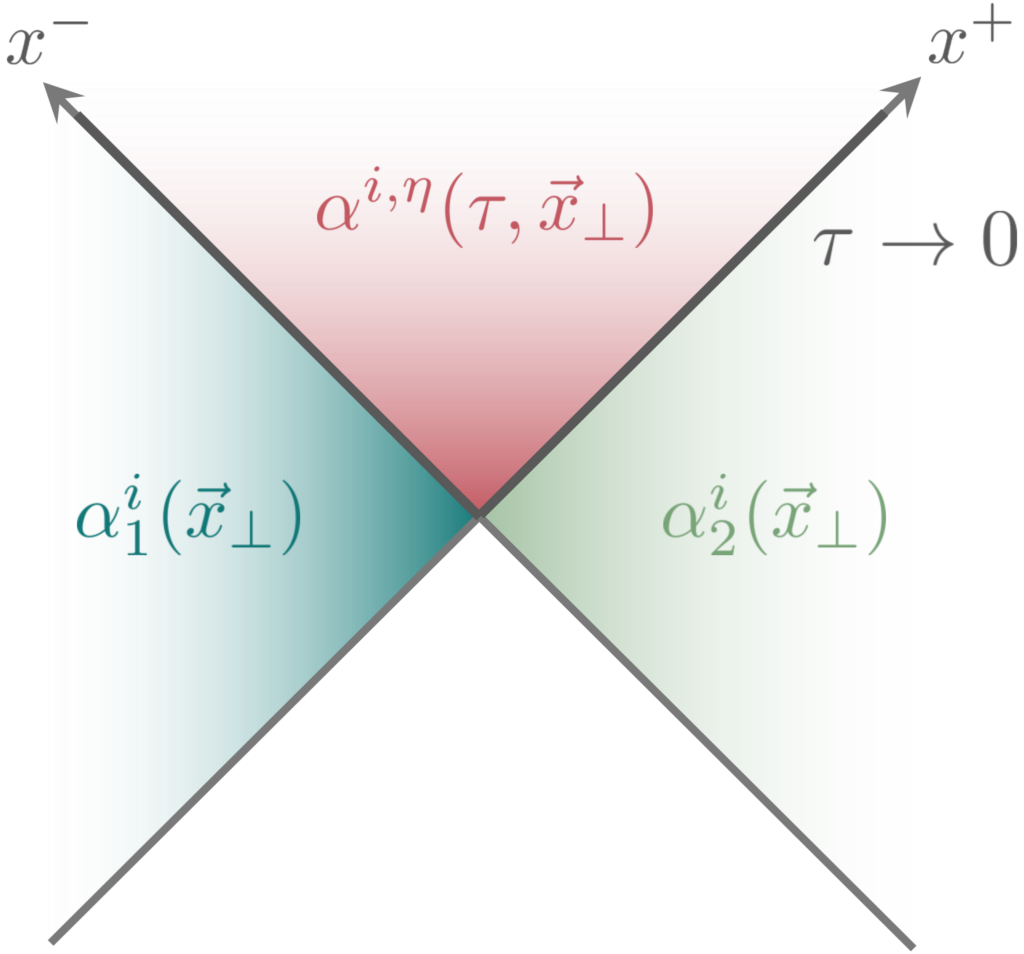
$$\eta = \ln(x^+/x^-)/2$$

Milne coordinates $(\tau, \vec{x}_\perp, \eta)$

$$\tau = \sqrt{2x^+x^-}$$

Collision of CGC nuclei

Light-cone diagram of collision



After the collision

Unknown $\alpha^{i,\eta}(\tau, \vec{x}_\perp)$

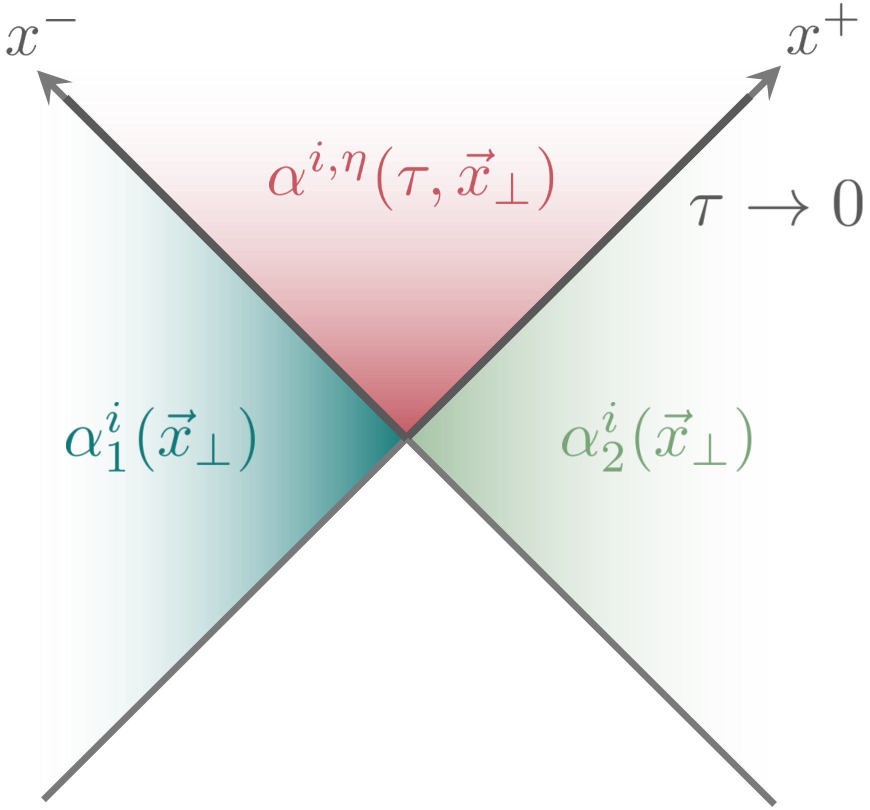
- Boost invariance
- Glasma initial condition

$$\alpha^i(\tau, \vec{x}_\perp)\Big|_{\tau\to 0} = \alpha^i_1(\vec{x}_\perp) + \alpha^i_2(\vec{x}_\perp)$$

$$\alpha^\eta(\tau, \vec{x}_\perp)\Big|_{\tau\to 0} = \frac{ig}{2}[\alpha^i_1(\vec{x}_\perp), \alpha^i_2(\vec{x}_\perp)]$$

Collision of CGC nuclei

Light-cone diagram of collision



Known $\alpha_1^i(\vec{x}_\perp)$ and $\alpha_2^i(\vec{x}_\perp)$

Unknown $\alpha^{i,\eta}(\tau, \vec{x}_\perp)$

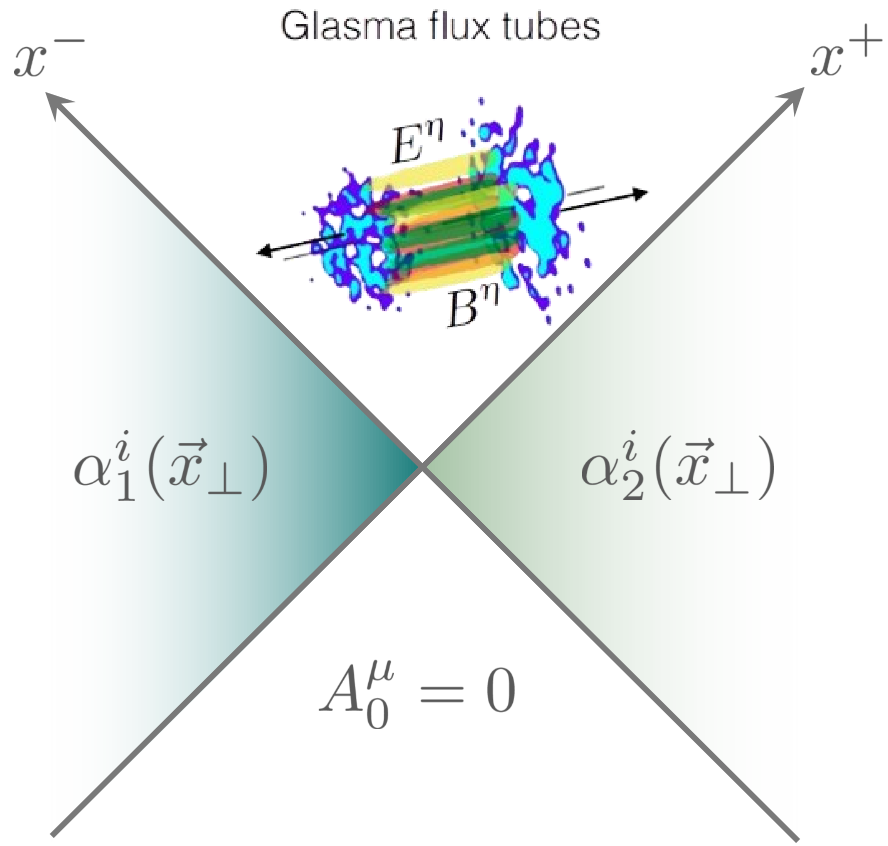
- Glasma initial condition

$$\boxed{\begin{aligned} \alpha^i(\tau, \vec{x}_\perp)\Big|_{\tau\to 0} \\ \alpha^\eta(\tau, \vec{x}_\perp)\Big|_{\tau\to 0} \end{aligned}} \begin{aligned} = \\ = \end{aligned} \boxed{\begin{aligned} &\alpha_1^i(\vec{x}_\perp) + \alpha_2^i(\vec{x}_\perp) \\ &\frac{ig}{2}[\alpha_1^i(\vec{x}_\perp), \alpha_2^i(\vec{x}_\perp)] \end{aligned}}$$

Glasma fields CGC fields

Collision of CGC nuclei

Light-cone diagram of collision



Known $\alpha_1^i(\vec{x}_\perp)$ and $\alpha_2^i(\vec{x}_\perp)$

Unknown $\alpha^{i,\eta}(\tau, \vec{x}_\perp)$

- Glasma initial condition

$$\alpha^i(\tau, \vec{x}_\perp)\Big|_{\tau\to 0} = \alpha_1^i(\vec{x}_\perp) + \alpha_2^i(\vec{x}_\perp)$$

$$\alpha^\eta(\tau, \vec{x}_\perp)\Big|_{\tau\to 0} = \frac{ig}{2}\left[\alpha_1^i(\vec{x}_\perp), \alpha_2^i(\vec{x}_\perp)\right]$$

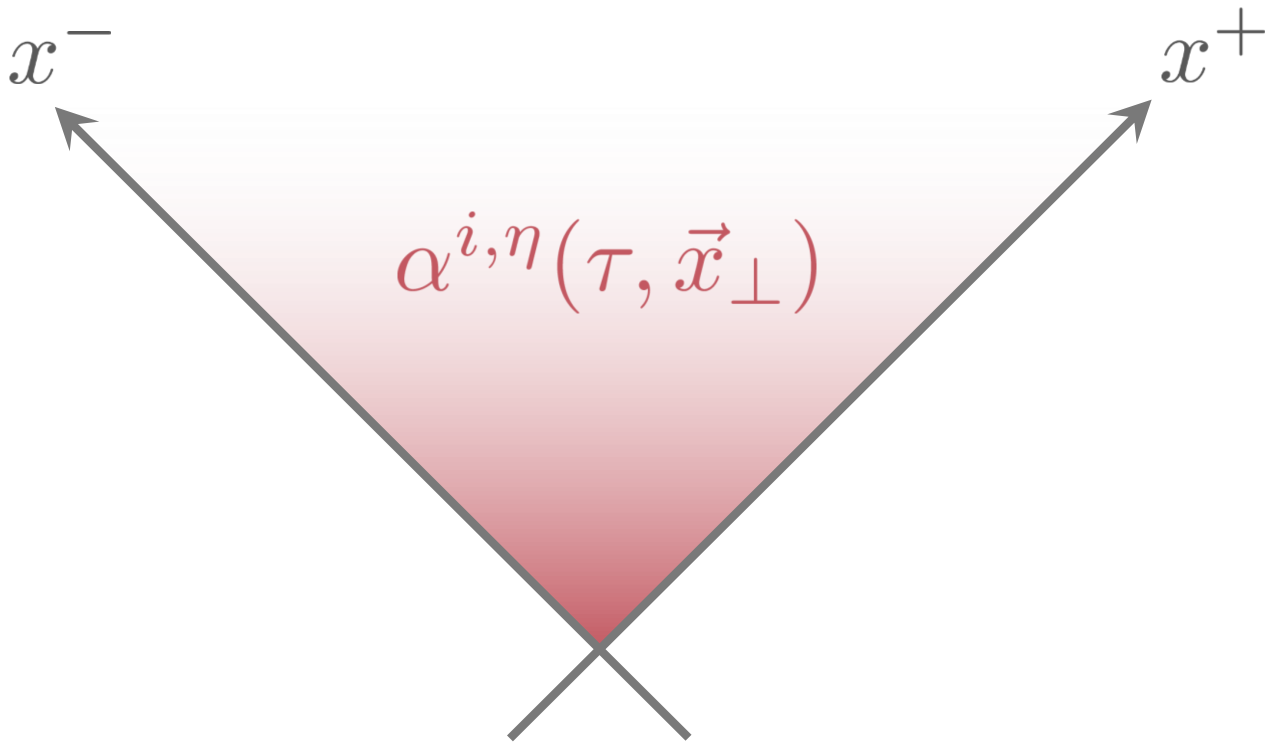
Glasma fields

CGC fields

$$\Rightarrow \begin{cases} \text{Longitudinal } E^\eta, B^\eta \\ \text{No transverse } E^i, B^i \end{cases}$$

Collision of CGC nuclei

Light-cone diagram of collision



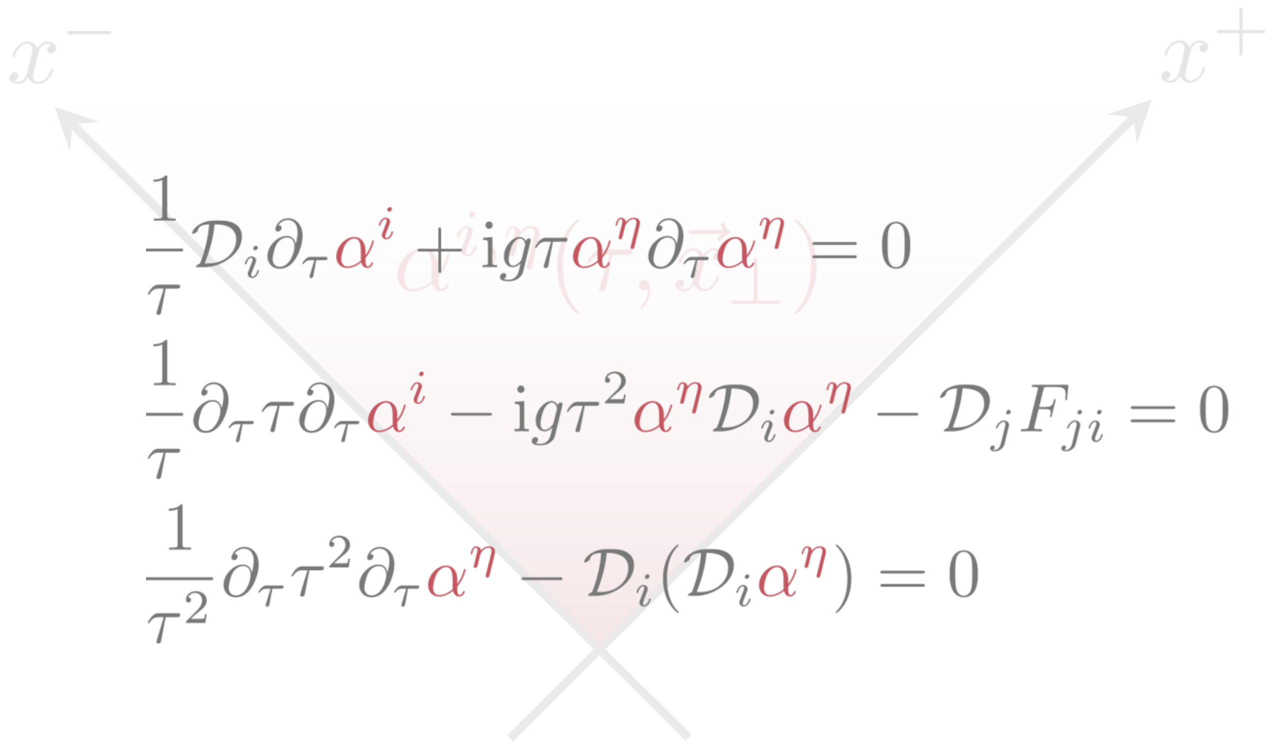
After the collision

Unknown $\alpha^{i,\eta}(\tau, \vec{x}_\perp)$

- Boost invariance
- Glasma initial condition
- Evolving Glasma

Collision of CGC nuclei

Light-cone diagram of collision



$$\frac{1}{\tau}\mathcal{D}_i\partial_\tau\alpha^i + \mathrm{i}g\tau\alpha^\eta\partial_\tau\alpha^\eta = 0$$

$$\frac{1}{\tau}\partial_\tau\tau\partial_\tau\alpha^i - \mathrm{i}g\tau^2\alpha^\eta\mathcal{D}_i\alpha^\eta - \mathcal{D}_jF_{ji} = 0$$

$$\frac{1}{\tau^2}\partial_\tau\tau^2\partial_\tau\alpha^\eta - \mathcal{D}_i(\mathcal{D}_i\alpha^\eta) = 0$$

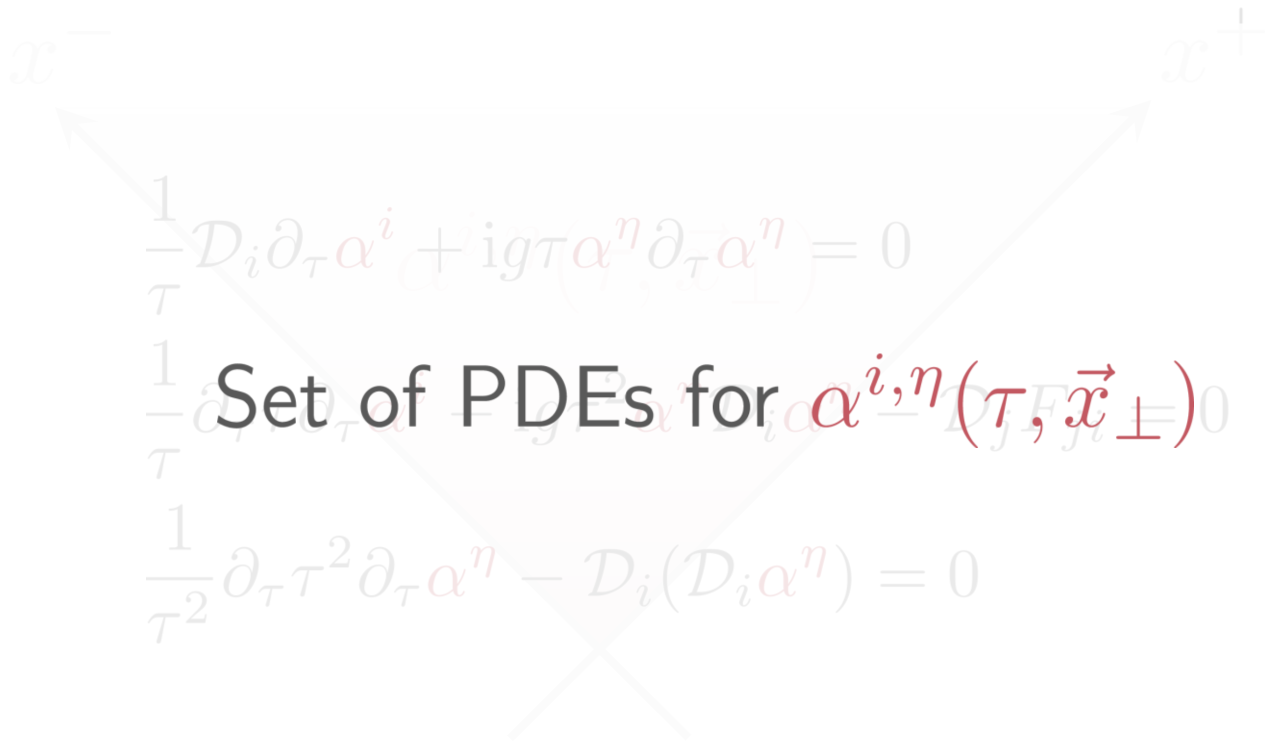
After the collision

Unknown $\alpha^{i,\eta}(\tau, \vec{x}_\perp)$

- Boost invariance
- Glasma initial condition
- Evolving Glasma

Collision of CGC nuclei

Light-cone diagram of collision



$$\frac{1}{\tau}\mathcal{D}_i\partial_\tau\alpha^i + ig\tau\alpha^\eta\partial_\tau\alpha^\eta = 0$$

$$\frac{1}{\tau}\partial_\tau\tau\partial_\tau\alpha^i - ig\tau^2\alpha^\eta\mathcal{D}_i\alpha^\eta - \mathcal{D}_jF_{ji} = 0$$

$$\frac{1}{\tau^2}\partial_\tau\tau^2\partial_\tau\alpha^\eta - \mathcal{D}_i(\mathcal{D}_i\alpha^\eta) = 0$$

Set of PDEs for $\alpha^{i,\eta}(\tau,\vec{x}_\perp)$

After the collision

Unknown $\alpha^{i,\eta}(\tau,\vec{x}_\perp)$

- Boost invariance
- Glasma initial condition
- Evolving Glasma

Lattice gauge theory

Real time lattice gauge theory

Gauge field

Wilson line

Wilson loop

Continuum

$$A_i(x)$$

$$U(x,y) = \mathcal{P}\exp\left\{ -\mathrm{i}g \int_x^y dz^i A_i(z) \right\}$$

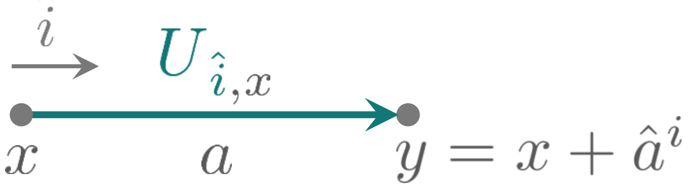
$$U_\gamma(x) = U(x,x)$$

Lattice

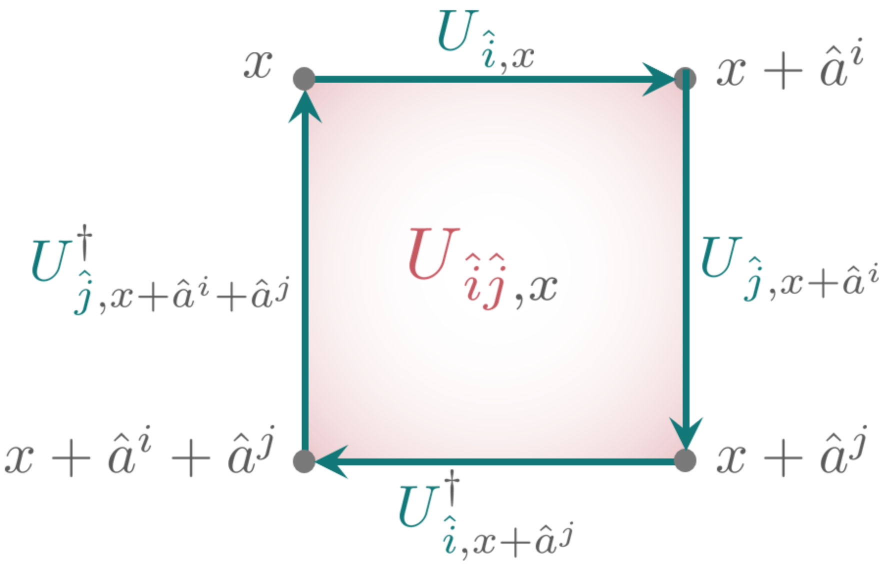
$$A_{i,x}$$

x

Gauge link



Plaquette

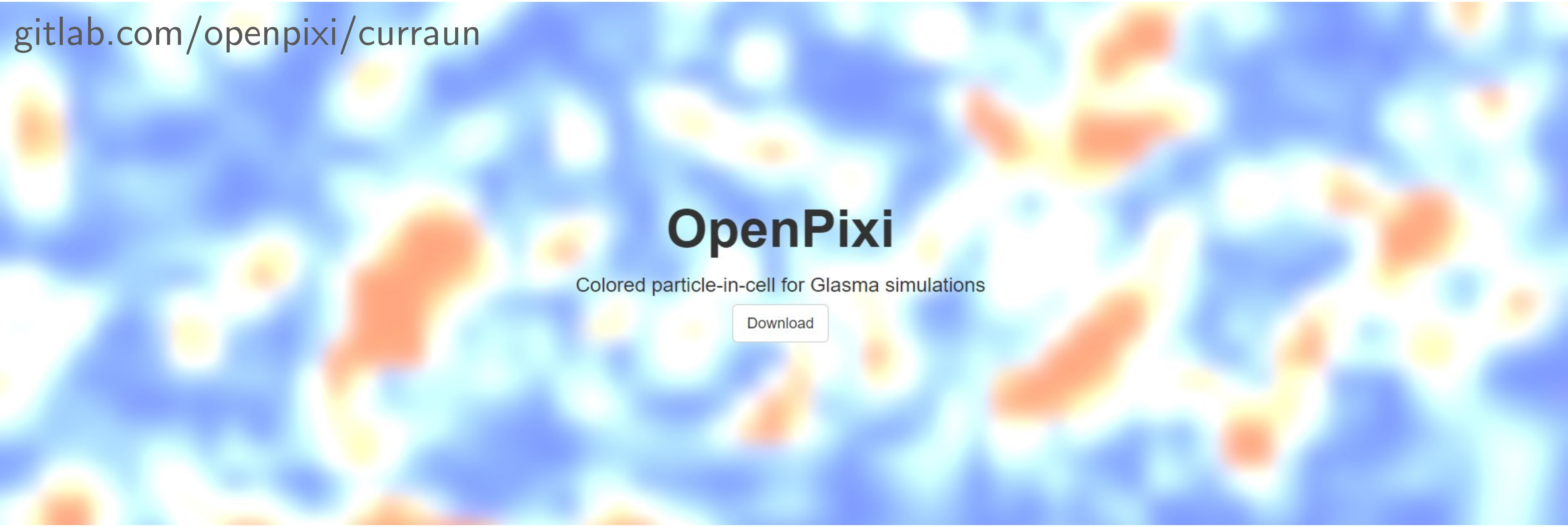


No lattice discretization in rapidity

Set of PDEs for $A_{\eta,x}$, $U_{\hat{i},x}$ and $U_{\hat{i}\hat{j},x}$

TU Wien Glasma solver

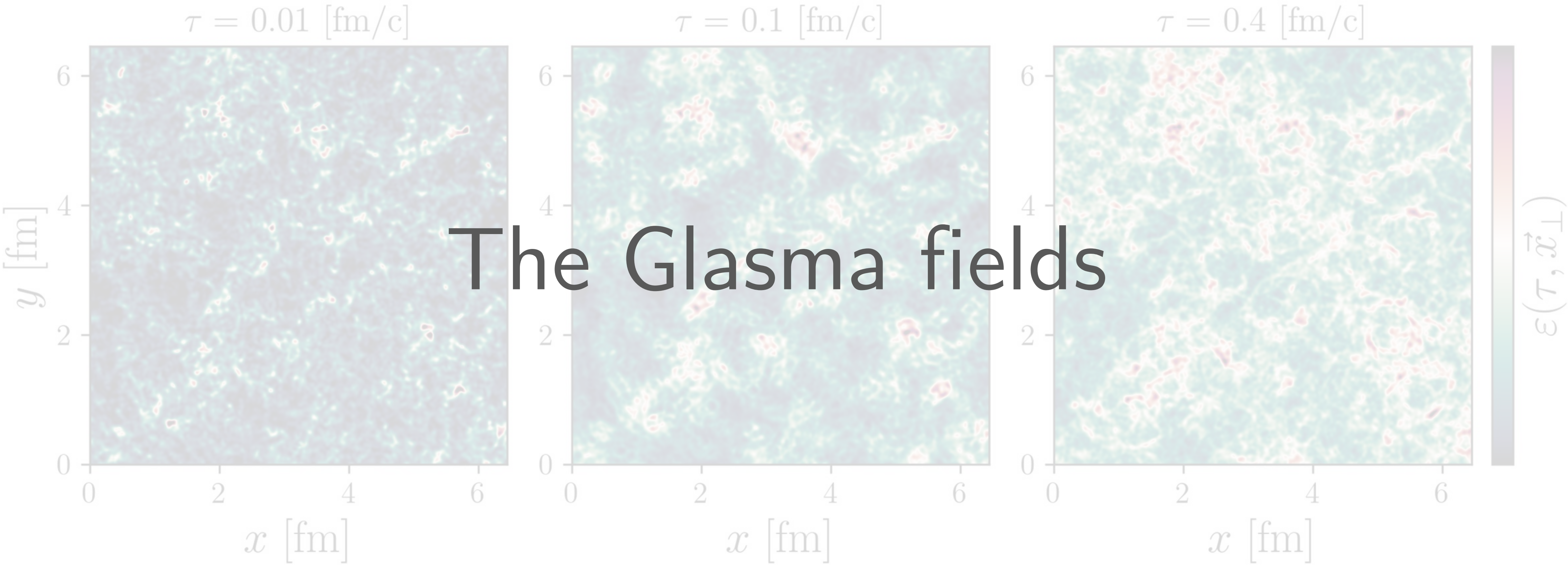
gitlab.com/openpixi/curraun



OpenPixi

Colored particle-in-cell for Glasma simulations

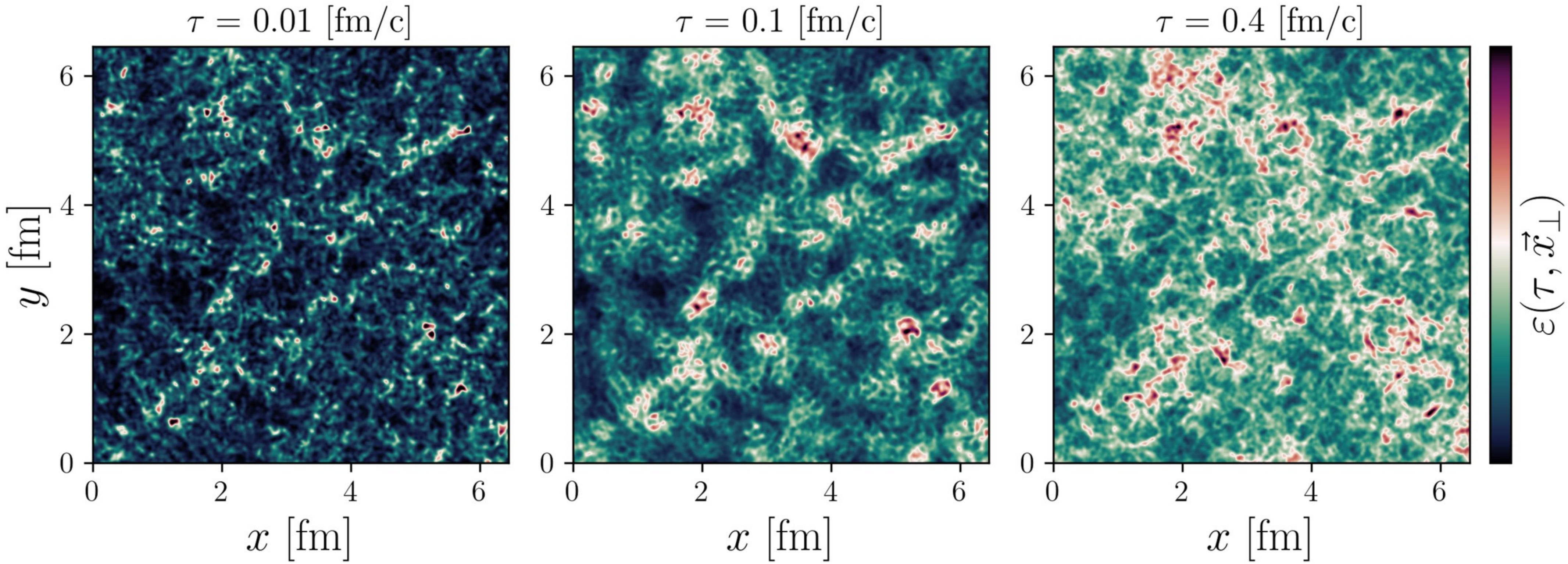
GPU solver using CUDA, SU(3) gauge group



The Glasma fields

The Glasma fields

General features

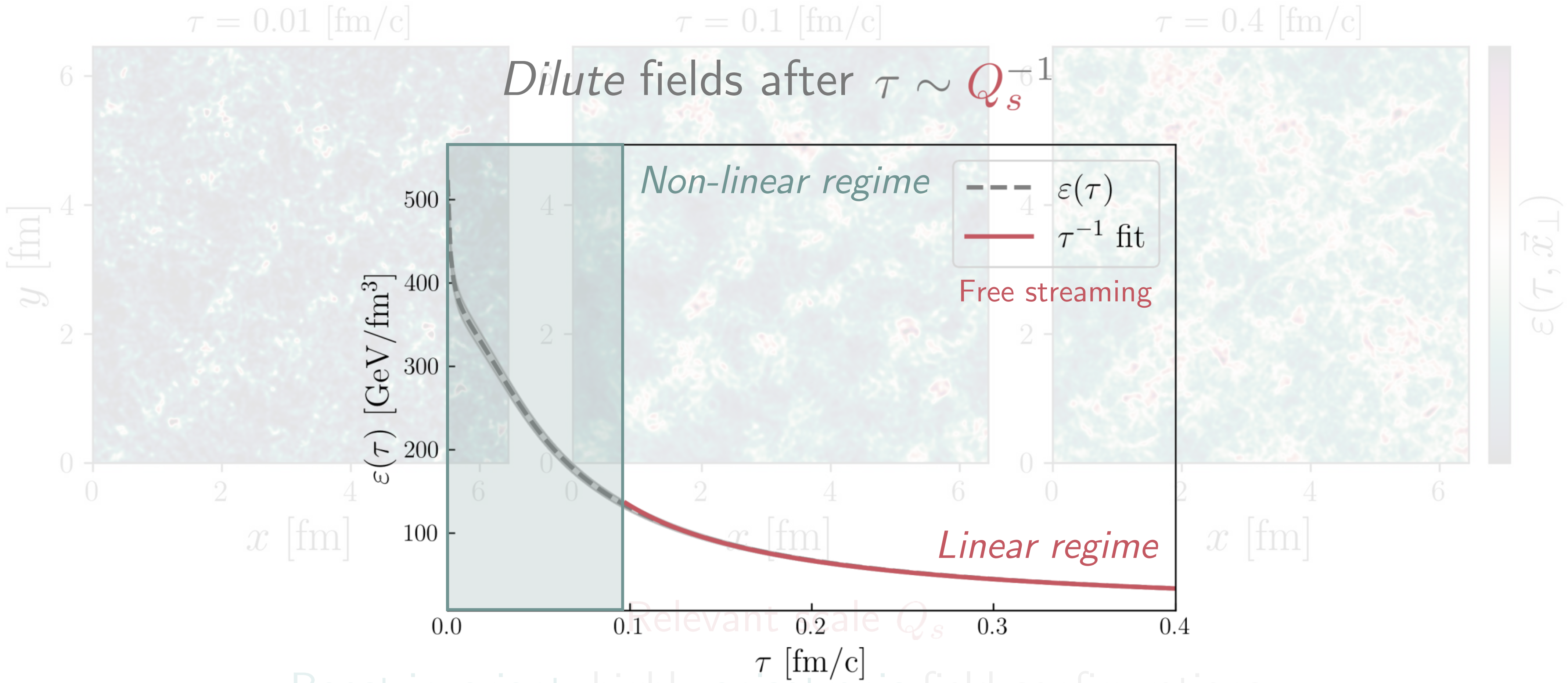


Relevant scale Q_s

Boost-invariant, highly anisotropic field configurations

The Glasma fields

Bjorken expansion



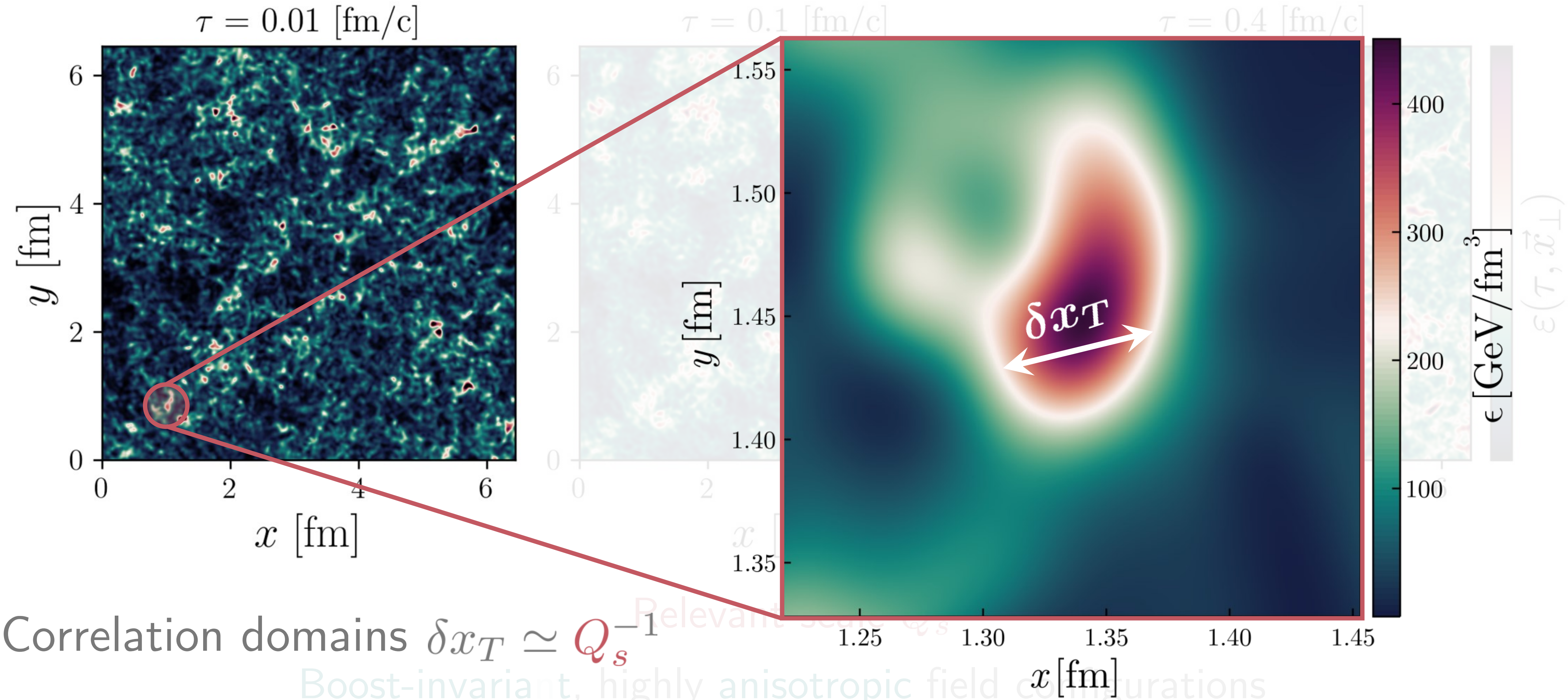
Dilute fields after $\tau \sim Q_s^{-1}$

Relevant scale Q_s

Boost-invariant, highly anisotropic field configurations

The Glasma fields

Correlation domains



Correlation domains $\delta x_T \simeq Q_s^{-1}$

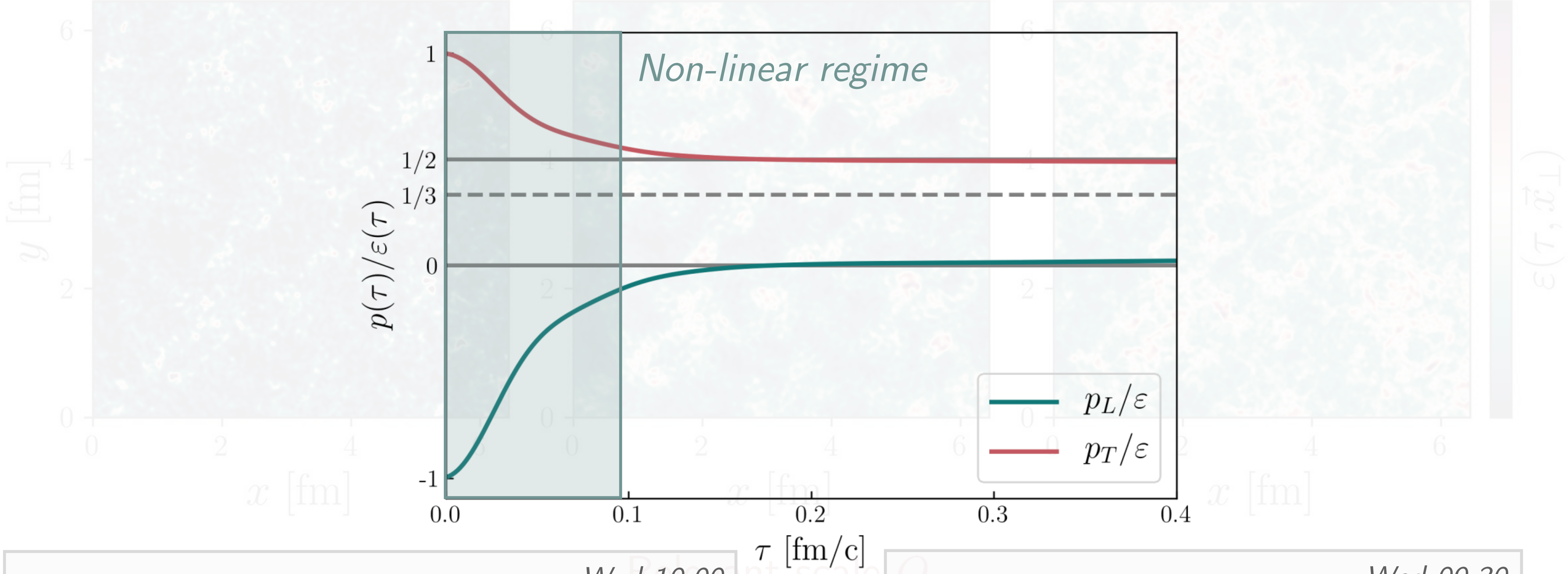
Relevant scale Q_s

Boost-invariant, highly anisotropic field configurations

The Glasma fields

Anisotropy

Longitudinal $\neq$ transverse $\Rightarrow$ anisotropy

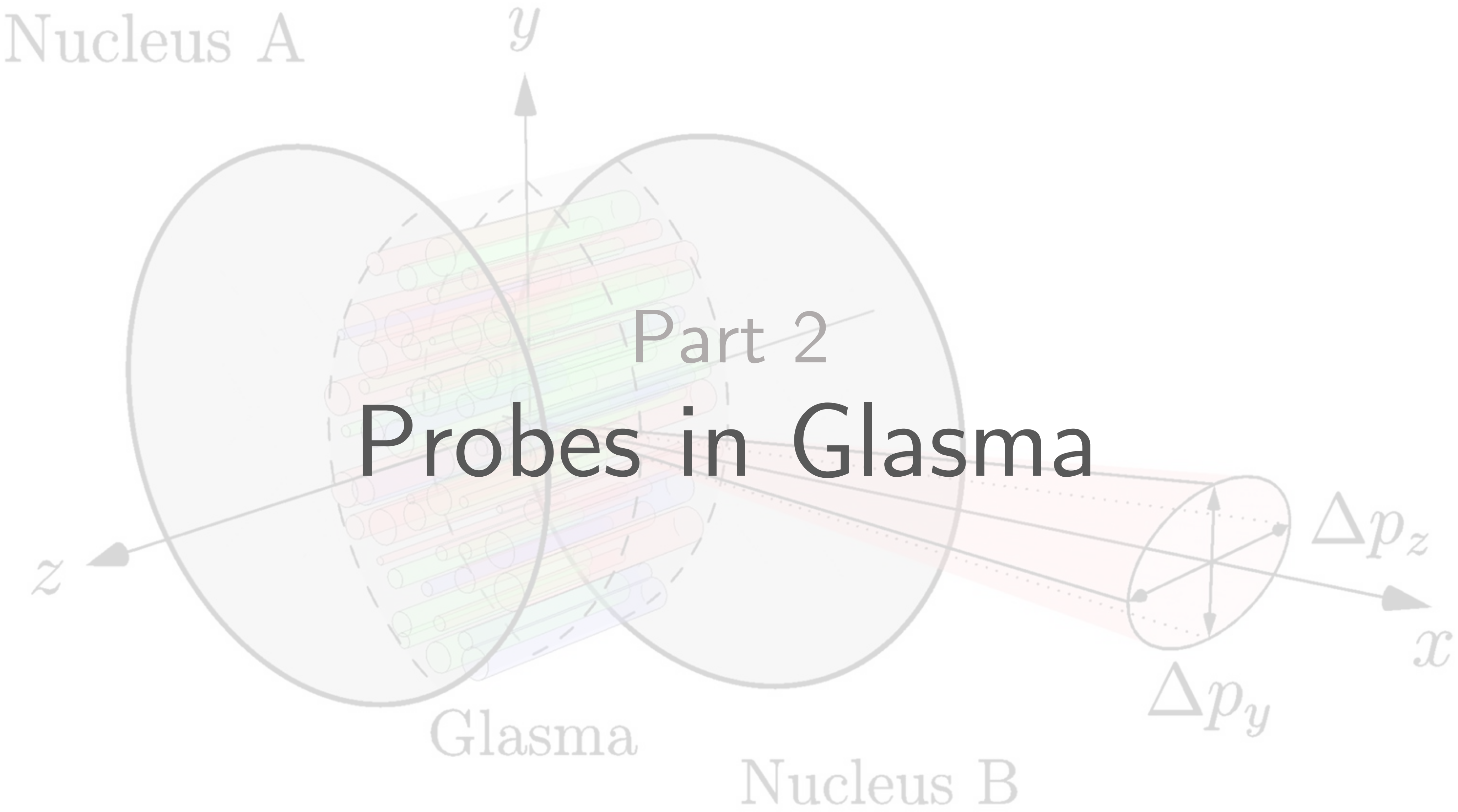


Xoan's talk *Wed 10:00*

The effect of medium flow and anisotropy on jet quenching

Sigtryggur's talk *Wed 09:30*

Polarization of jet partons in an anisotropic plasma



Part 2

Probes in Glasma

Figure credits to D. Müller

Particles in CYM fields

Wong's equations

Wong's equations ↔ classical equations of motion for particles (x^μ, p^μ, Q) evolving in Yang-Mills fields A^μ

coordinate

momentum

gauge field

color charge

$$\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}} x^\mu = \frac{p^\mu}{m} \qquad \frac{\mathrm{D}}{\mathrm{d}\boldsymbol{\tau}} p^\mu = 2g\mathrm{Tr}\left\{ Q F^{\mu\nu}[A^\mu] \right\} \frac{p_\nu}{m} \qquad \underbrace{\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}} Q = -\mathrm{i}g[A_\mu, Q]\,\frac{p^\mu}{m}}_{Q(\boldsymbol{\tau})=\mathcal{U}(\boldsymbol{\tau},\boldsymbol{\tau}_0)Q(\boldsymbol{\tau}_0)\mathcal{U}^\dagger(\boldsymbol{\tau},\boldsymbol{\tau}_0)}$$

mass

coupling constant

proper time

covariant derivative

Particles in CYM fields

Positions

Wong's equations ↔ classical equat
evolving in Yar

Hamilton equations

coordinate

$$\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}} x^{\mu} = \frac{p^{\mu}}{m}$$

proper time

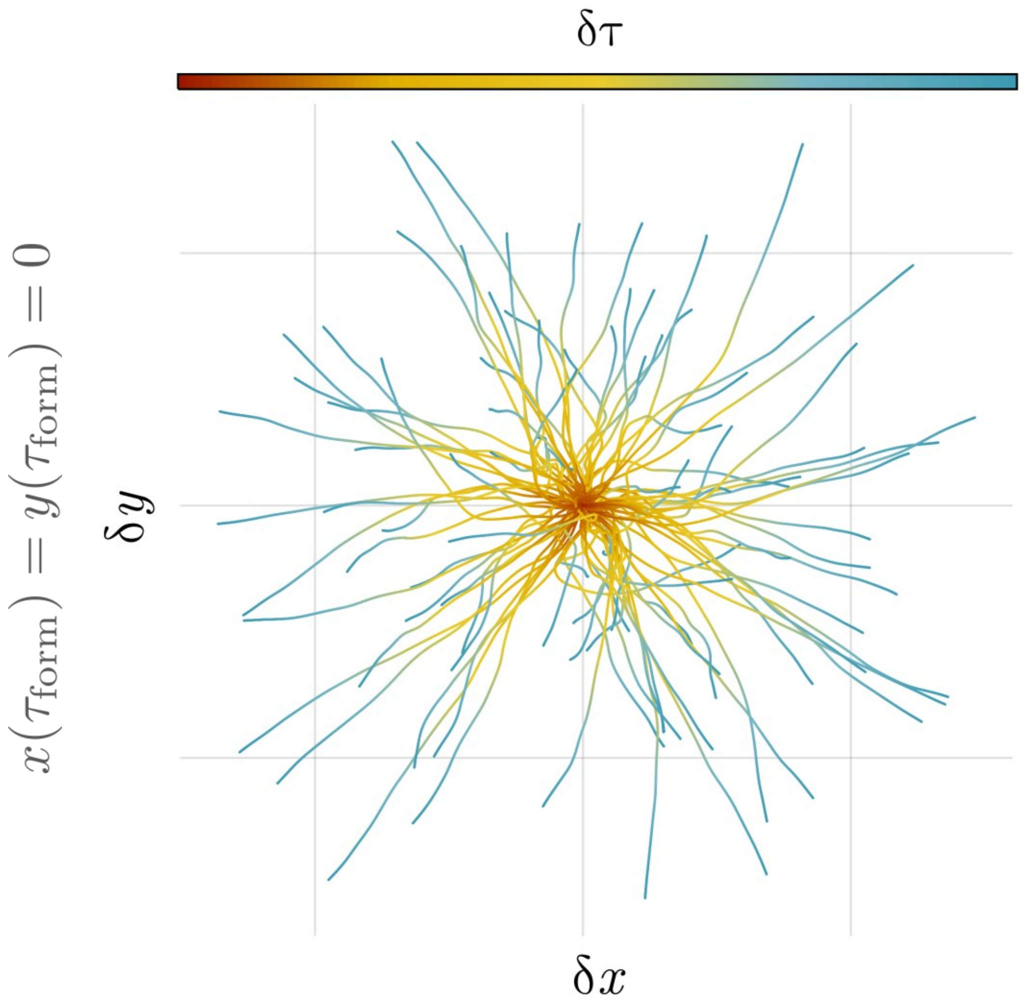
mass

momentum

$$\frac{\mathrm{D}}{\mathrm{d}\tau} p^{\mu} = 2g\mathrm{Tr}\left\{QF\right.$$

coupling consta

covariant derivative



Particles in CYM fields

Momenta

Wong's equations ↔ classical equatio

evolving in Yang-

Curvilinear color Lorentz force

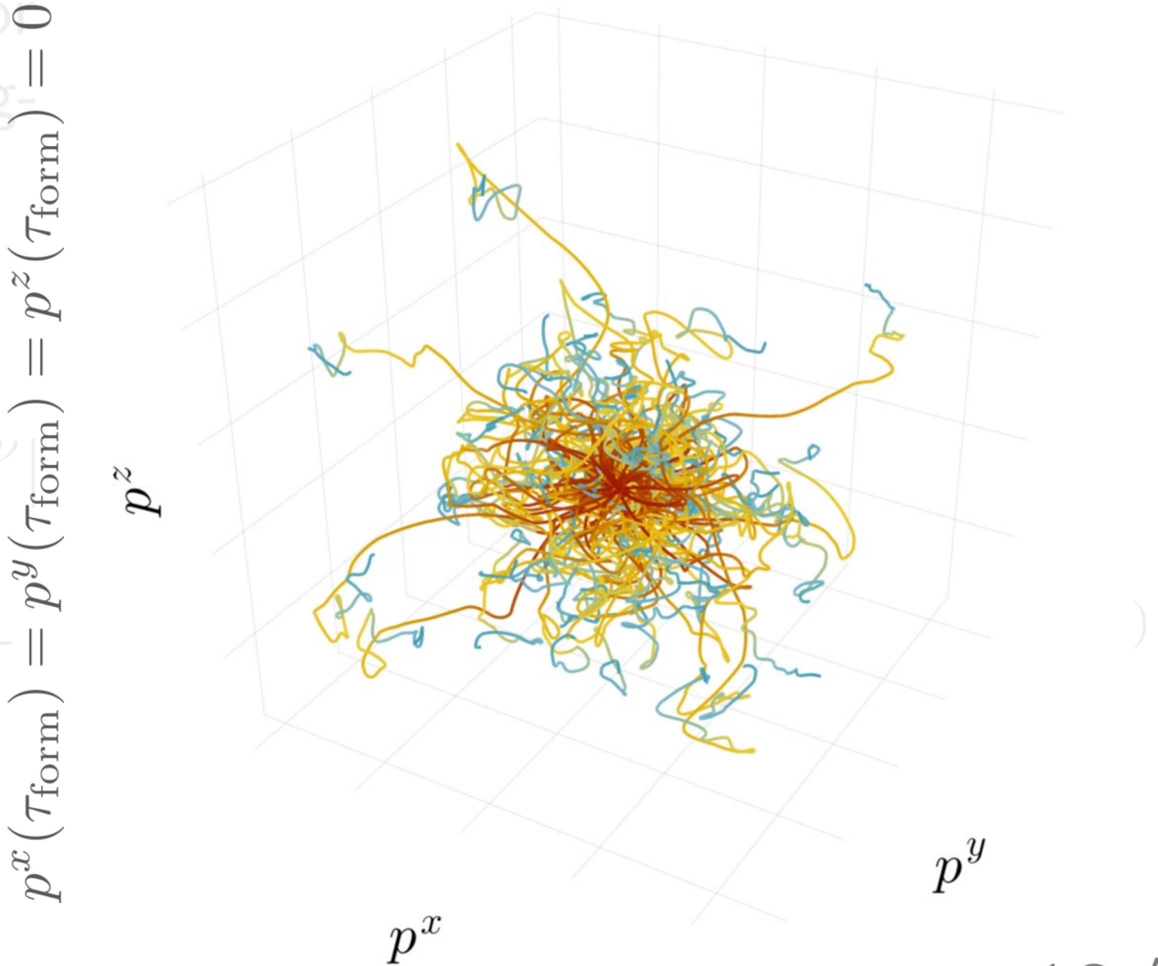
momentum

gauge field

$$\frac{\mathrm{D}}{\mathrm{d}\boldsymbol{\tau}} p^{\mu} = 2g\mathrm{Tr}\left\{ Q F^{\mu\nu}[A^{\mu}] \right\} \frac{p_{\nu}}{m}$$

coupling constant

covariant derivative



Particles in CYM fields

Color charges

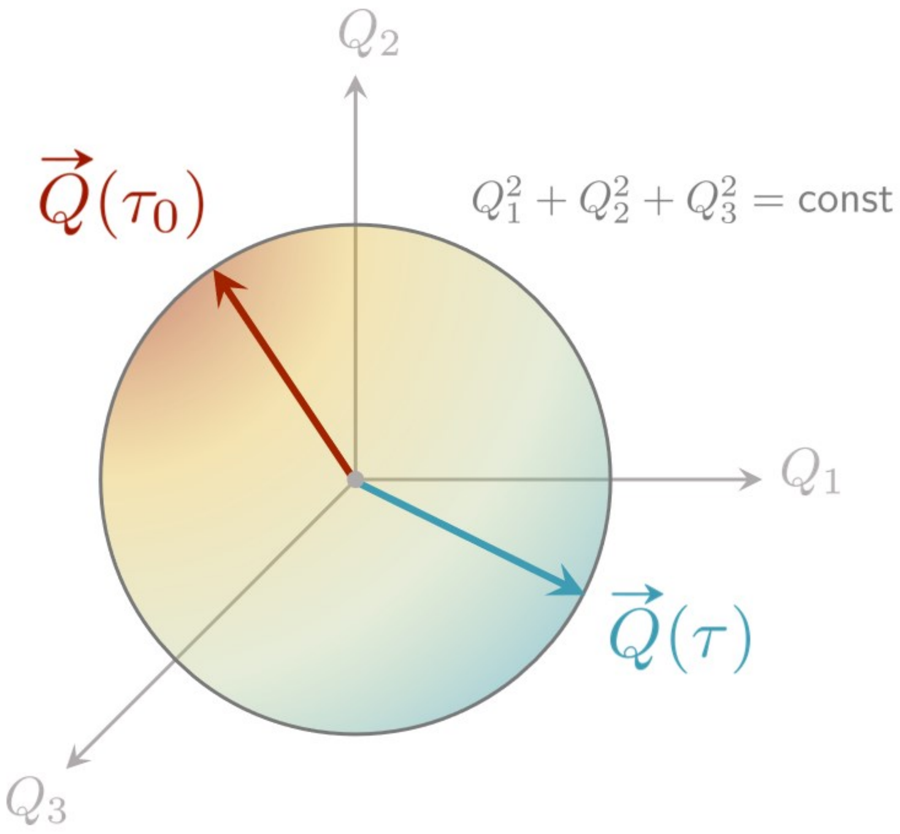
Wong … of motion for particles (x^μ, p^μ, Q)

… ills fields A^μ

coor… gauge field

$$\frac{d}{d\tau}x^\mu = \quad … u]\} \frac{p_\nu}{m}$$

proper time



Particle color rotation

color charge

$$\underbrace{\frac{d}{d\boldsymbol{\tau}}Q = -ig[A_\mu, Q]\,\frac{p^\mu}{m}}_{Q(\boldsymbol{\tau})=\mathcal{U}(\boldsymbol{\tau},\boldsymbol{\tau}_0)Q(\boldsymbol{\tau}_0)\mathcal{U}^\dagger(\boldsymbol{\tau},\boldsymbol{\tau}_0)}$$

Particles in CYM fields

Wong's equations

Wong's equations ↔ classical equations of motion for particles (x^μ, p^μ, Q) evolving in Yang-Mills fields A^μ

coordinate

momentum

gauge field

color charge

$$\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}} x^\mu = \frac{p^\mu}{m} \qquad \frac{\mathrm{D}}{\mathrm{d}\boldsymbol{\tau}} p^\mu = 2g\,\mathrm{Tr}\left\{Q F^{\mu\nu}[A^\mu]\right\}\frac{p_\nu}{m} \qquad \underbrace{\frac{\mathrm{d}}{\mathrm{d}\boldsymbol{\tau}} Q = -\mathrm{i}g[A_\mu, Q]\,\frac{p^\mu}{m}}_{Q(\boldsymbol{\tau})=\mathcal{U}(\boldsymbol{\tau},\boldsymbol{\tau}_0)Q(\boldsymbol{\tau}_0)\mathcal{U}^\dagger(\boldsymbol{\tau},\boldsymbol{\tau}_0)}$$

proper time

mass

covariant derivative

coupling constant

Colored Particle-in-Cell (CPIC) numerical solver

Particles in CYM fields

Boltzmann-Vlasov

Wong's equations ↔ classical equations of motion for particles (x^μ, p^μ, Q) evolving in Yang-Mills fields A^μ

Boltzmann-Vlasov equations

coordinate momentum gauge field color charge

$$p^\mu \left[\partial_\mu + g Q^a F^a_{\mu\nu}(x^\mu)\partial^\nu_{p^\mu} + g f^{abc} A^b_\mu(x^\mu) Q^c \partial_{Q^a}\right] \boldsymbol{f}(x^\mu, p^\mu, Q^a) = 0$$

$$\frac{\mathrm{d}}{\mathrm{d}\tau} x^\mu = \frac{p^\mu}{m} \qquad \frac{\mathrm{D}}{\mathrm{d}\tau} p^\mu = 2g\mathrm{Tr}\left\{Q F^{\mu\nu}[A^\mu]\right\}\frac{p_\nu}{m} \qquad \underbrace{\frac{\mathrm{d}}{\mathrm{d}\tau} Q = -\mathrm{i}g[A_\mu, Q]\frac{p^\mu}{m}}_{Q(\tau) = \mathcal{U}(\tau,\tau_0) Q(\tau_0)\mathcal{U}^\dagger(\tau,\tau_0)}$$

mass

proper time

coupling constant

covariant derivative

$$\boldsymbol{f}(x^\mu, p^\mu, Q^a) \xrightarrow{\text{sample}} \text{test particles } (x^\mu, p^\mu, Q^a)$$

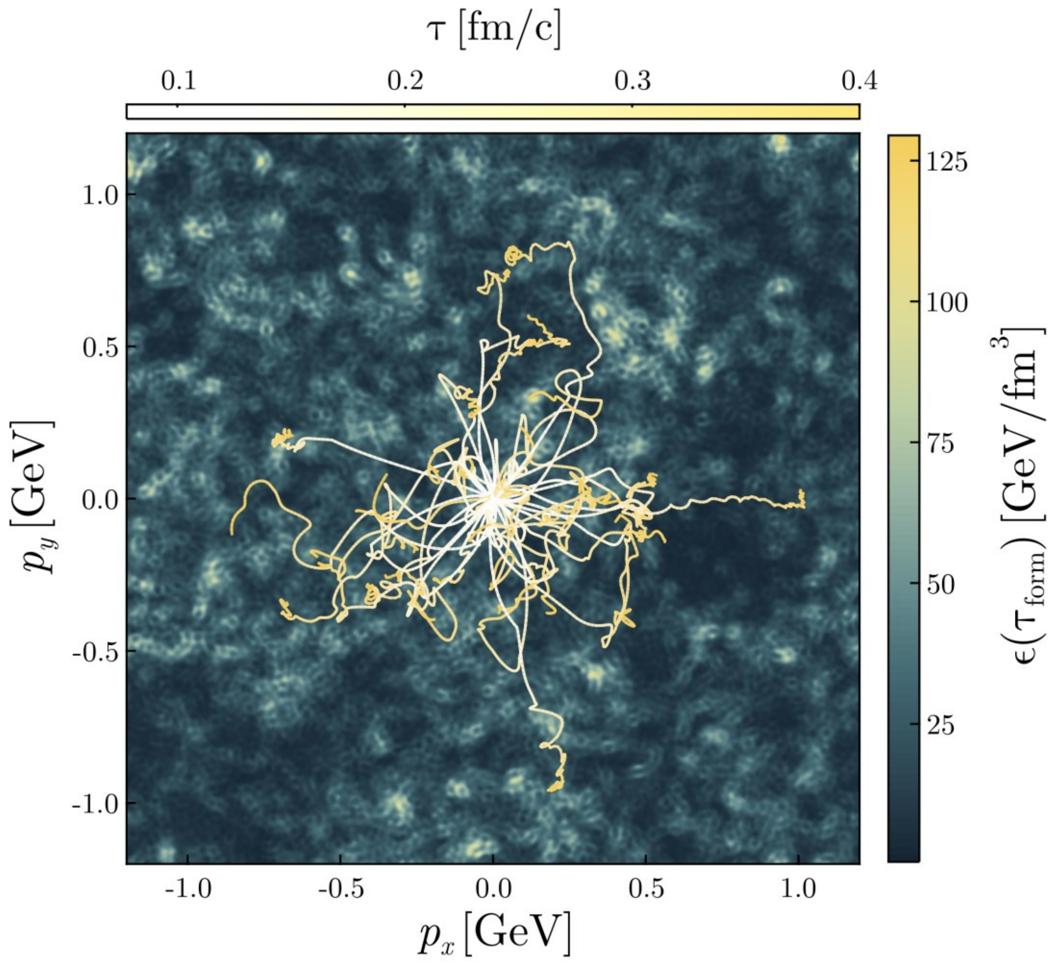
$\Rightarrow$ Wong's equations

Colored Particle-in-Cell (CPIC) numerical solver

Part 3

Jet transport in Glasma

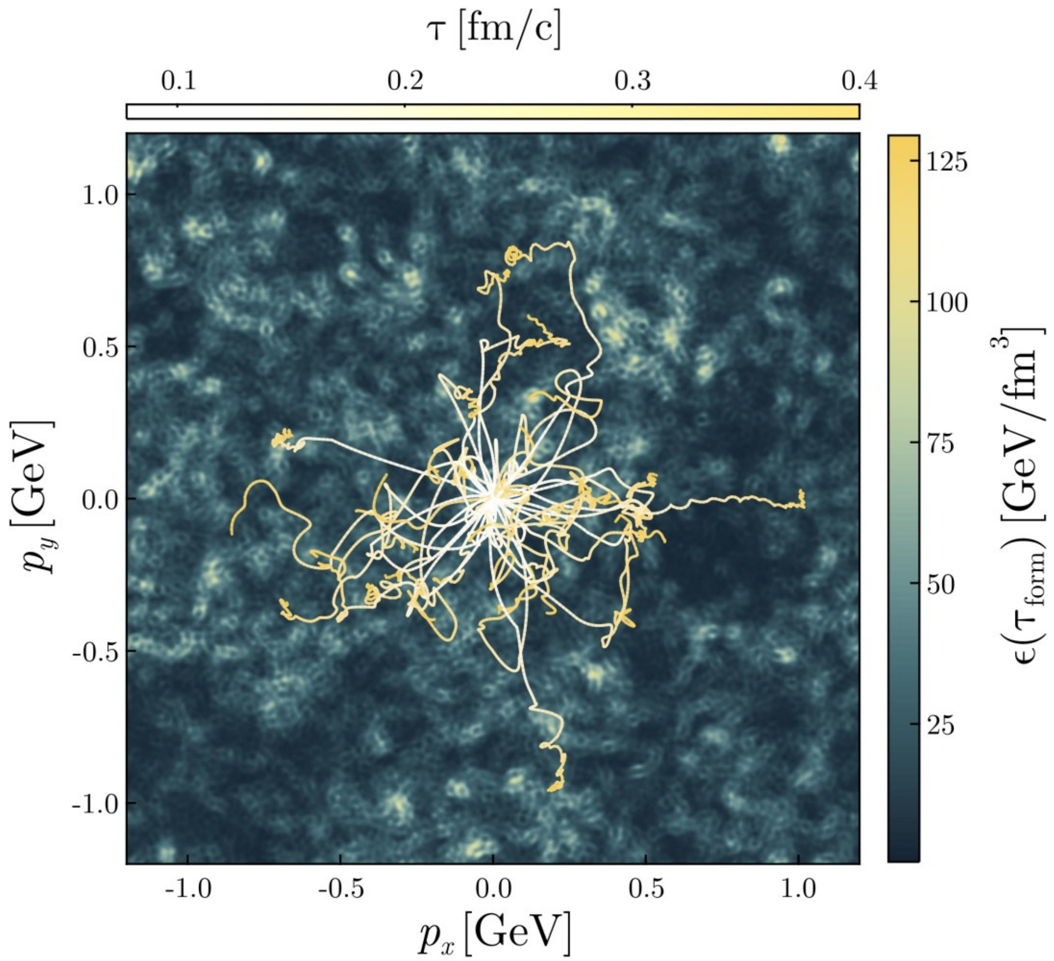
Jet momentum broadening



Momentum broadening

$$\delta p_i^2(\tau) \overset{\mathrm{def}}{=} p_i^2(\tau) - p_i^2(\tau_{\mathrm{form}})$$

Jet momentum broadening



particle trajectories

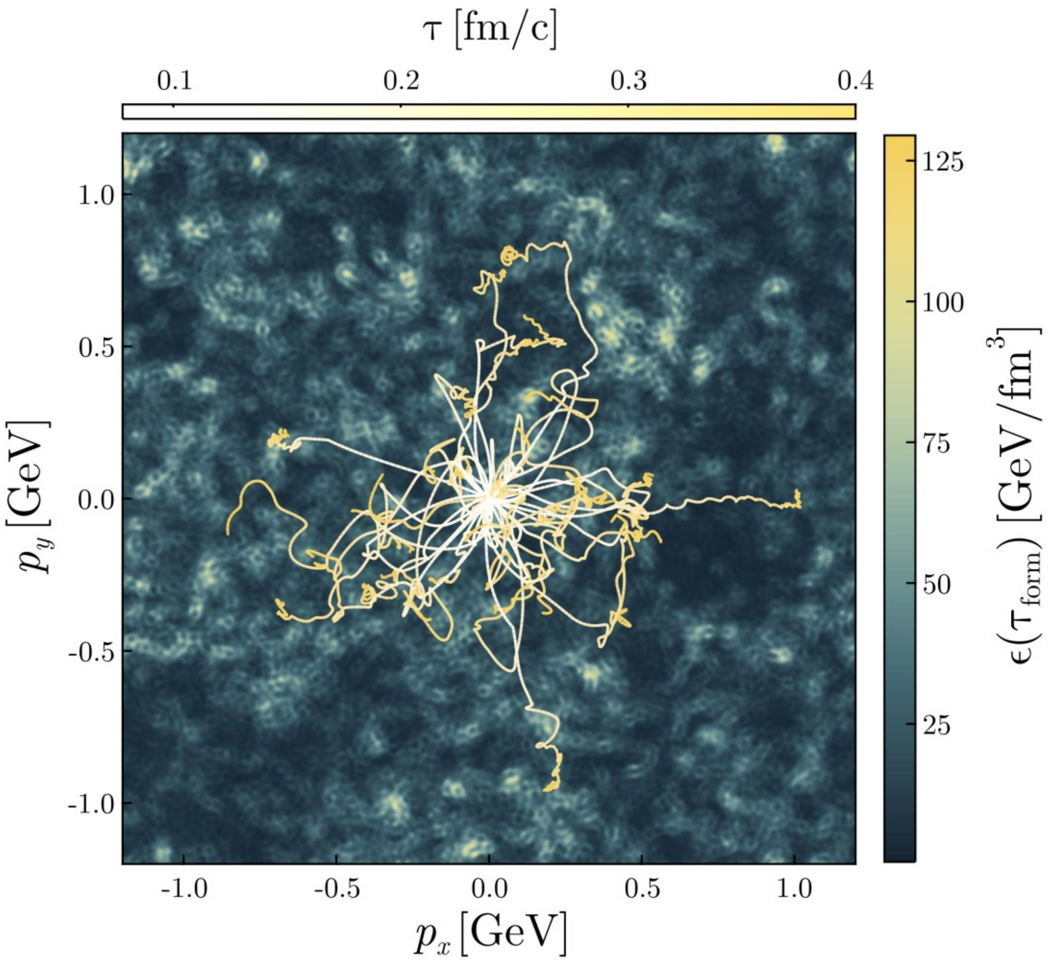
Momentum broadening

$$\left\langle \left\langle \delta p_i^2(\tau) \right\rangle \right\rangle$$

$$\delta p_i^2(\tau) \overset{\text{def}}{=} p_i^2(\tau) - p_i^2(\tau_{\text{form}})$$

background fields

Jet momentum broadening



Momentum broadening

$$\delta p_i^2(\tau) \overset{\text{def}}{=} p_i^2(\tau) - p_i^2(\tau_{\text{form}})$$

Jet quenching parameter

$$\frac{\mathrm{d}}{\mathrm{d}\tau}\langle \delta p_i^2(\tau) \rangle \overset{\text{def}}{=} \hat{q}_i(\tau)$$

Jet geometry

Initial $\vec{p} \parallel \hat{x} \Rightarrow \hat{z} \mapsto$ L and $\hat{y} \mapsto$ T

Eikonal jets from field correlators

Highly energetic light-like jets

$$\boxed{\left\langle \delta p_i^2(\tau)\right\rangle^{\mathrm{lightlike}}_{p_x\to\infty}} = g^2 \int_0^\tau \mathrm{d}\tau' \int_0^\tau \mathrm{d}\tau'' \boxed{\left\langle \mathrm{Tr}\{\widetilde{F}_i(\tau')\widetilde{F}_i(\tau'')\}\right\rangle}$$

Correlator of Glasma color fields

Eikonal jets from field correlators

Highly energetic light-like jets

$$\langle \delta p_i^2(\tau) \rangle^{\text{lightlike}}_{p_x \to \infty} = g^2 \int\limits_0^\tau \mathrm{d}\tau' \int\limits_0^\tau \mathrm{d}\tau'' \, \langle \mathrm{Tr}\{ \widetilde{F}_i(\tau') \widetilde{F}_i(\tau'') \} \rangle$$

$$\boxed{F_x = E_x , \; F_y = E_y - B_z , \; F_z = E_z + B_y} \xrightarrow{\text{parallel transport}} \boxed{\widetilde{F}_i \overset{\text{def}}{=} U_x^\dagger F_i \, U_x}$$

Glasma color electric and magnetic fields

Lattice gauge invariance

Eikonal jets from field correlators

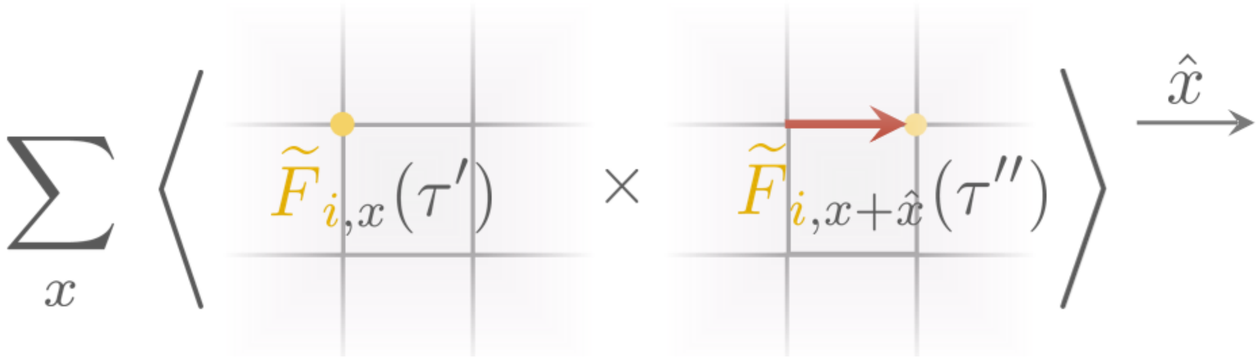
Highly energetic light-like jets

$$\langle \delta p_i^2(\tau) \rangle_{p_x \to \infty}^{\text{lightlike}} = g^2 \int_0^\tau \mathrm{d}\tau' \int_0^\tau \mathrm{d}\tau'' \, \langle \mathrm{Tr}\{ \widetilde{F}_i(\tau') \widetilde{F}_i(\tau'') \} \rangle$$

$$F_x = E_x, \; F_y = E_y - B_z, \; F_z = E_z + B_y \xrightarrow{\text{parallel transport}} \widetilde{F}_i \overset{\text{def}}{=} U_x^\dagger F_i U_x$$

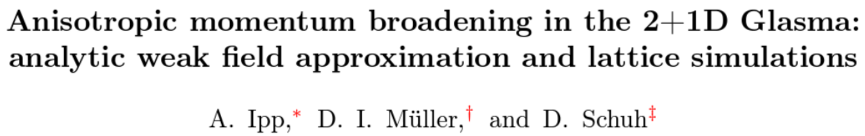
Glasma color electric and magnetic fields

Lattice gauge invariance



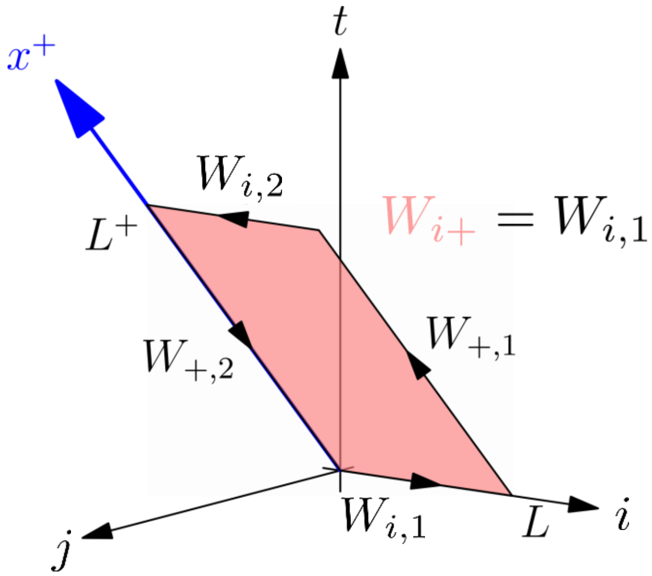
$$\sum_x \left\langle \widetilde{F}_{i,x}(\tau') \times \widetilde{F}_{i,x+\hat{x}}(\tau'') \right\rangle$$

Wilson loops and field correlators



Anisotropic momentum broadening in the 2+1D Glasma:
analytic weak field approximation and lattice simulations

A. Ipp,[*] D. I. Müller,[†] and D. Schuh[‡]



$$W_{i+} = W_{i,1} W_{+,1} W_{i,2} W_{+,2}$$

Light-like Wilson loop

$$\left\langle \mathrm{Re}\,\mathrm{Tr}[W_{i+}] \right\rangle \propto \exp\left(-\frac{L^2}{2} \langle \delta p_i^2 \rangle \right)$$

momentum broadening

Wilson loops and field correlators

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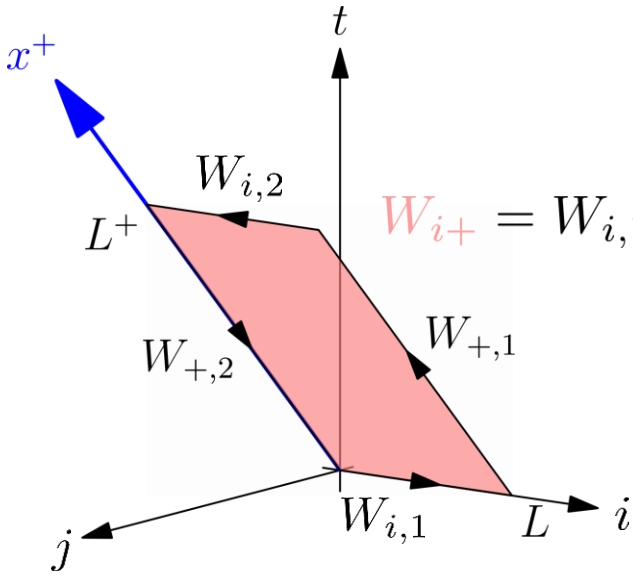


$$W_{i+} = W_{i,1}W_{+,1}W_{i,2}W_{+,2}$$

Light-like Wilson loop

$$\left\langle \mathrm{Re}\,\mathrm{Tr}[W_{i+}]\right\rangle \propto \exp\left(-\frac{L^2}{2}\langle\delta p_i^2\rangle\right)$$

momentum broadening

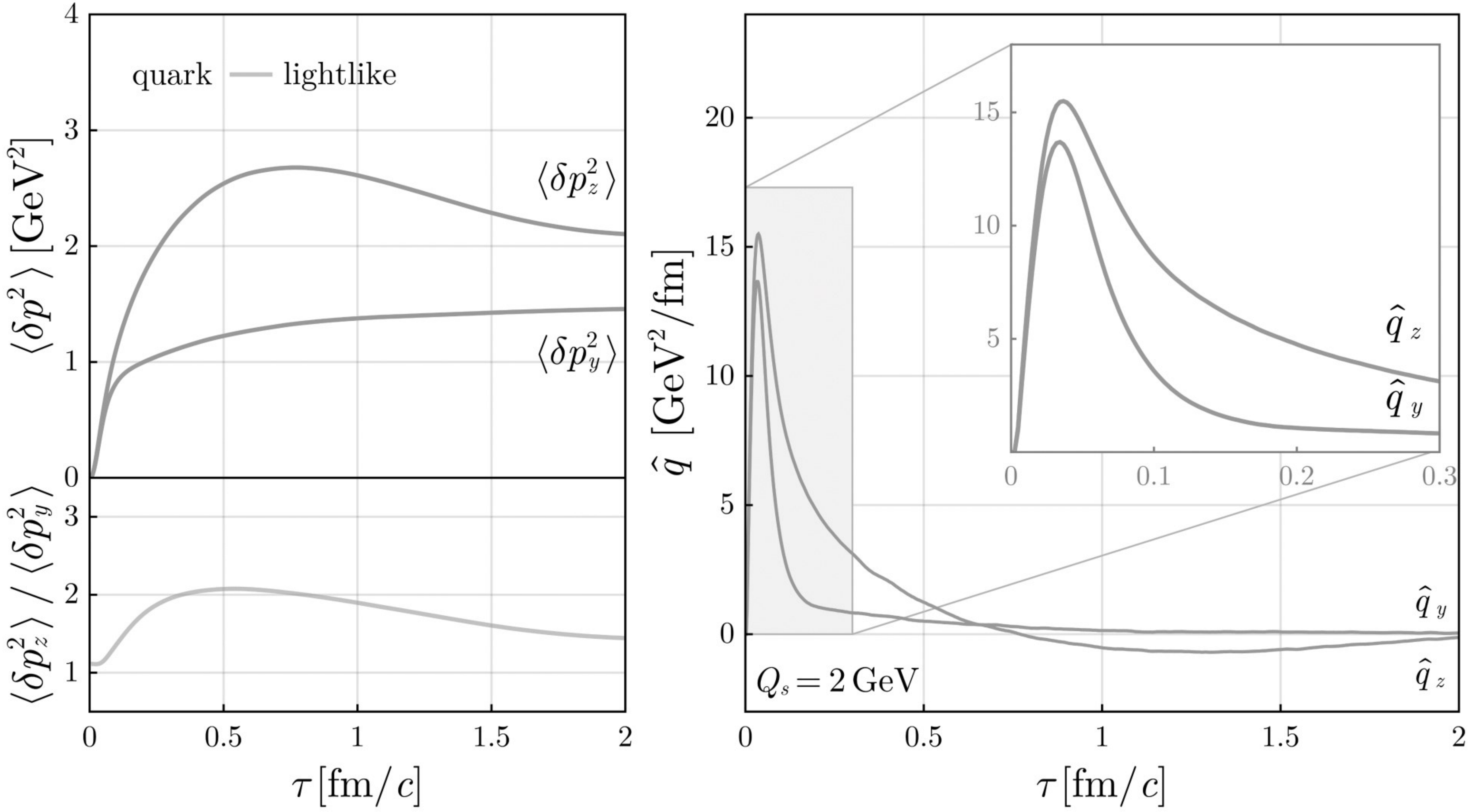
- Dipole approximation $L \ll L^+$
- Non-Abelian Stokes theorem

$$W_{i+} \approx ig\int_0^{L^+} \mathrm{d}x^+ \widetilde{F}_{i+}(x^+,0)$$

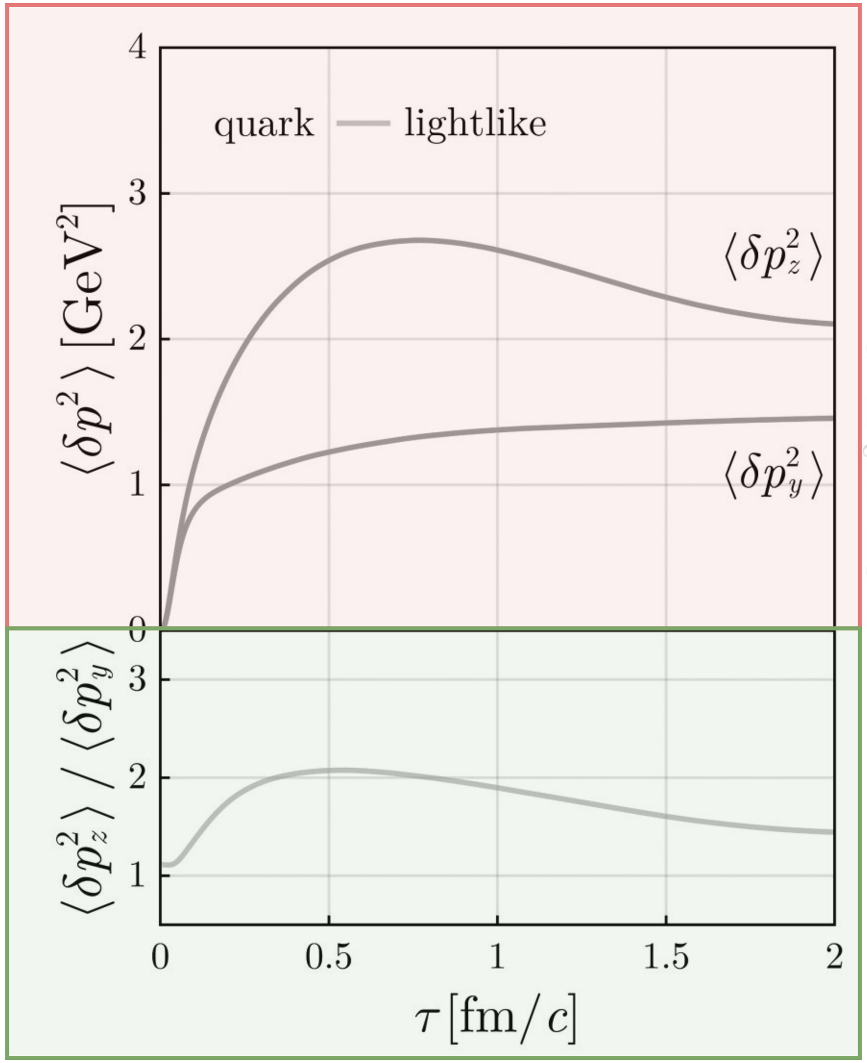
$$\langle\delta p_i^2(x^+)\rangle^{\mathrm{lightlike}} \propto g^2 \int_0^{x^+} \mathrm{d}x'_+ \int_0^{x^+} \mathrm{d}x''_+ \boxed{\langle\mathrm{Tr}\{\widetilde{F}_{i+}(x'_+)\widetilde{F}_{i+}(x''_+)\}\rangle}$$

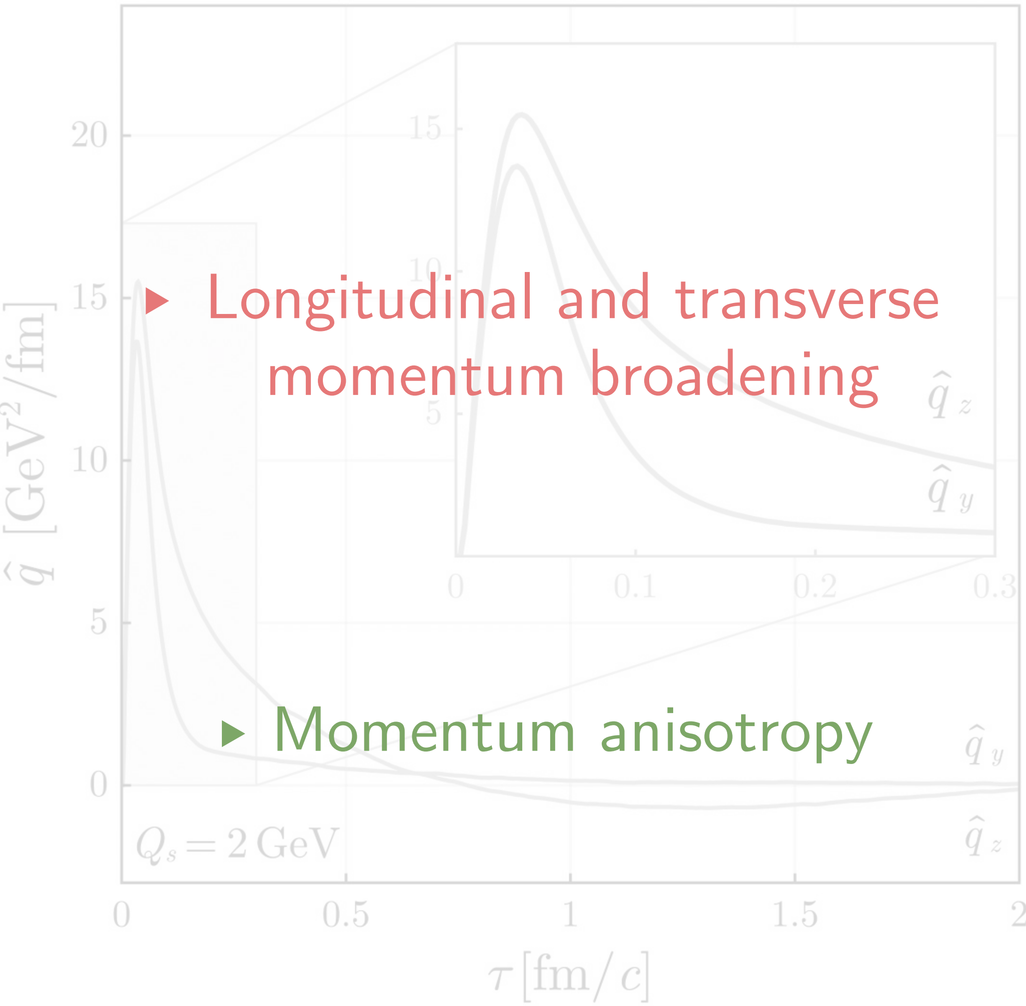
Field correlators

Eikonal jets



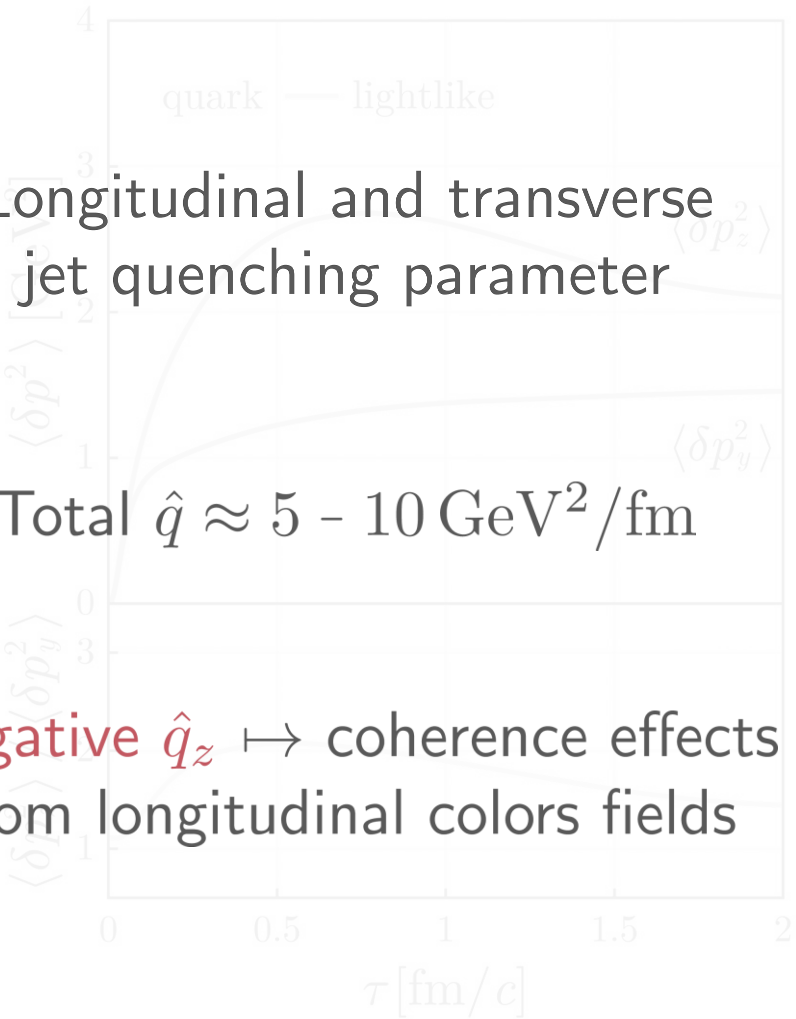
Eikonal jets



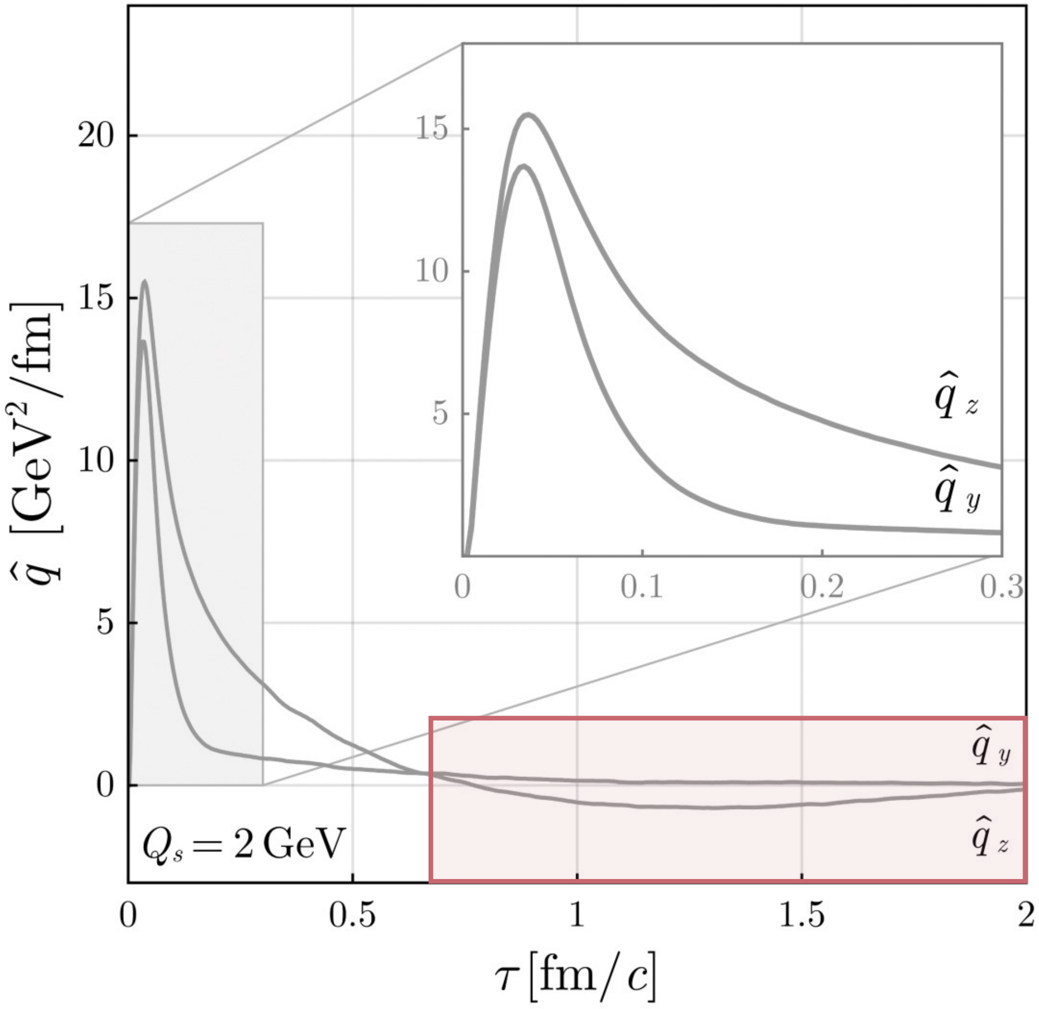


- Longitudinal and transverse momentum broadening
- Momentum anisotropy

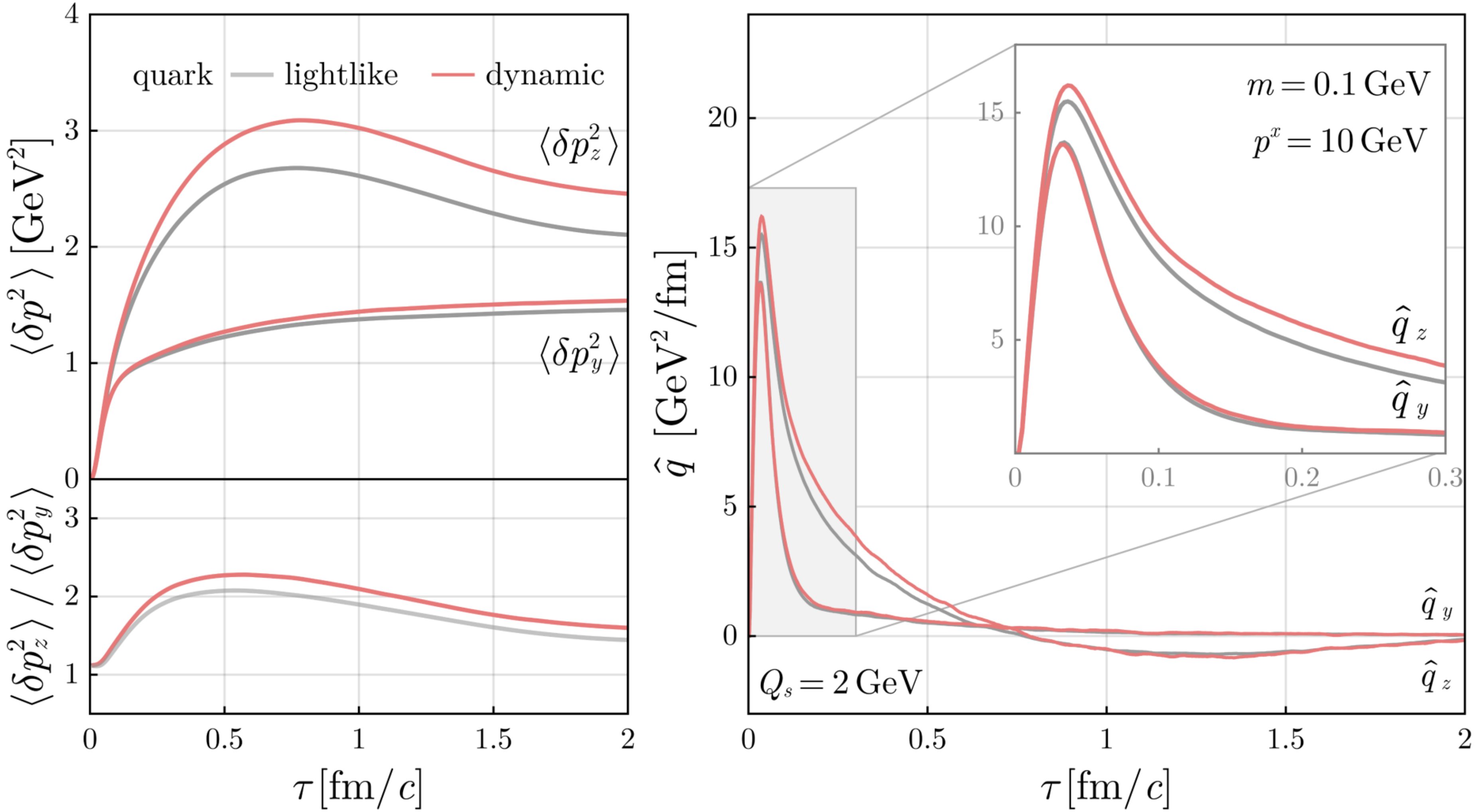
Eikonal jets



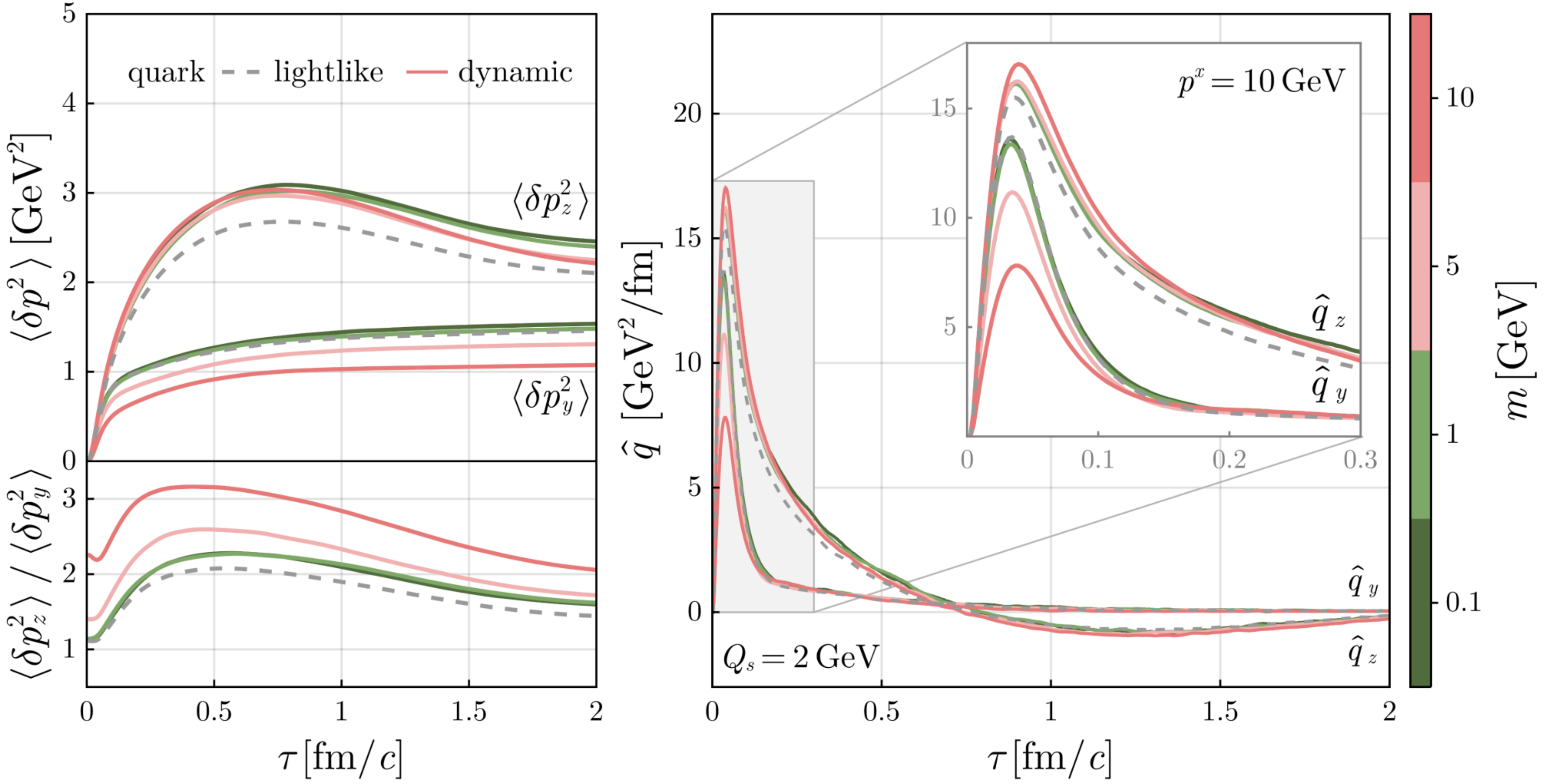
- Longitudinal and transverse jet quenching parameter
- Total $\hat{q} \approx 5$ - $10\,\mathrm{GeV}^2/\mathrm{fm}$
- Negative $\hat{q}_z \mapsto$ coherence effects from longitudinal colors fields



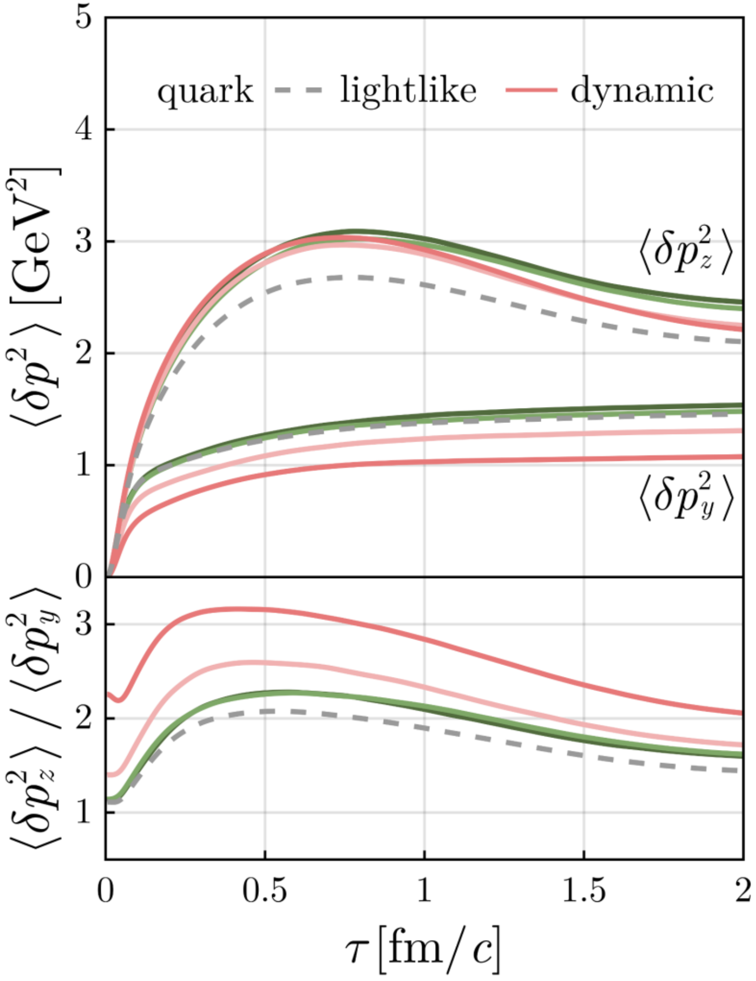
Non-eikonal jets

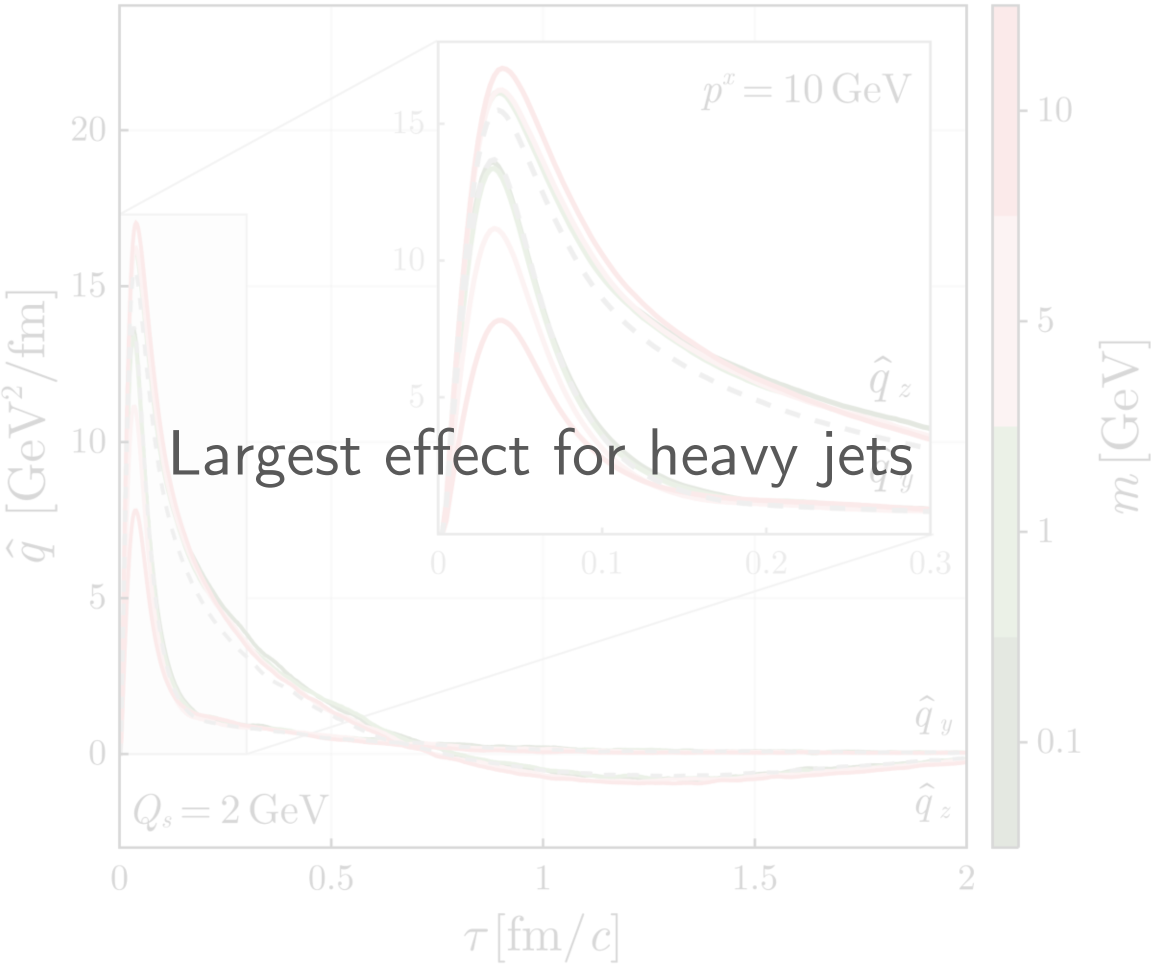


Mass dependence for non-eikonal jets



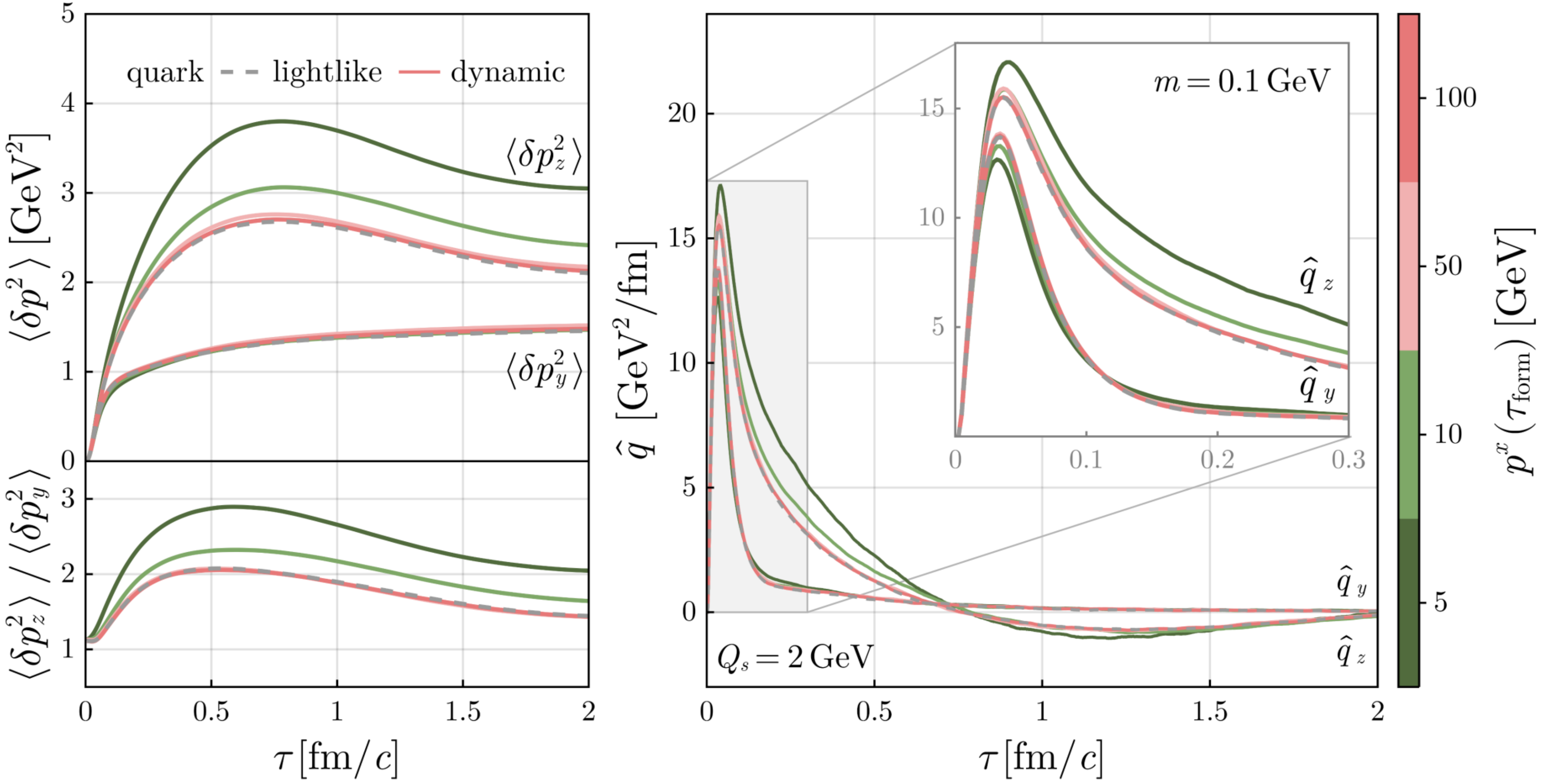
Mass dependence for non-eikonal jets



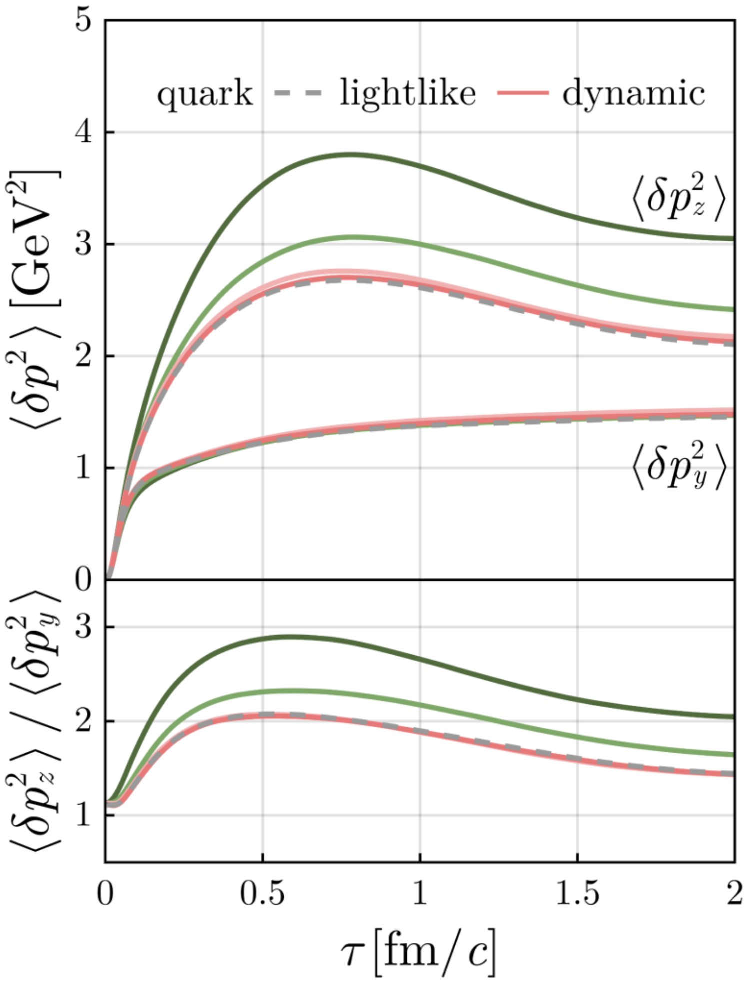


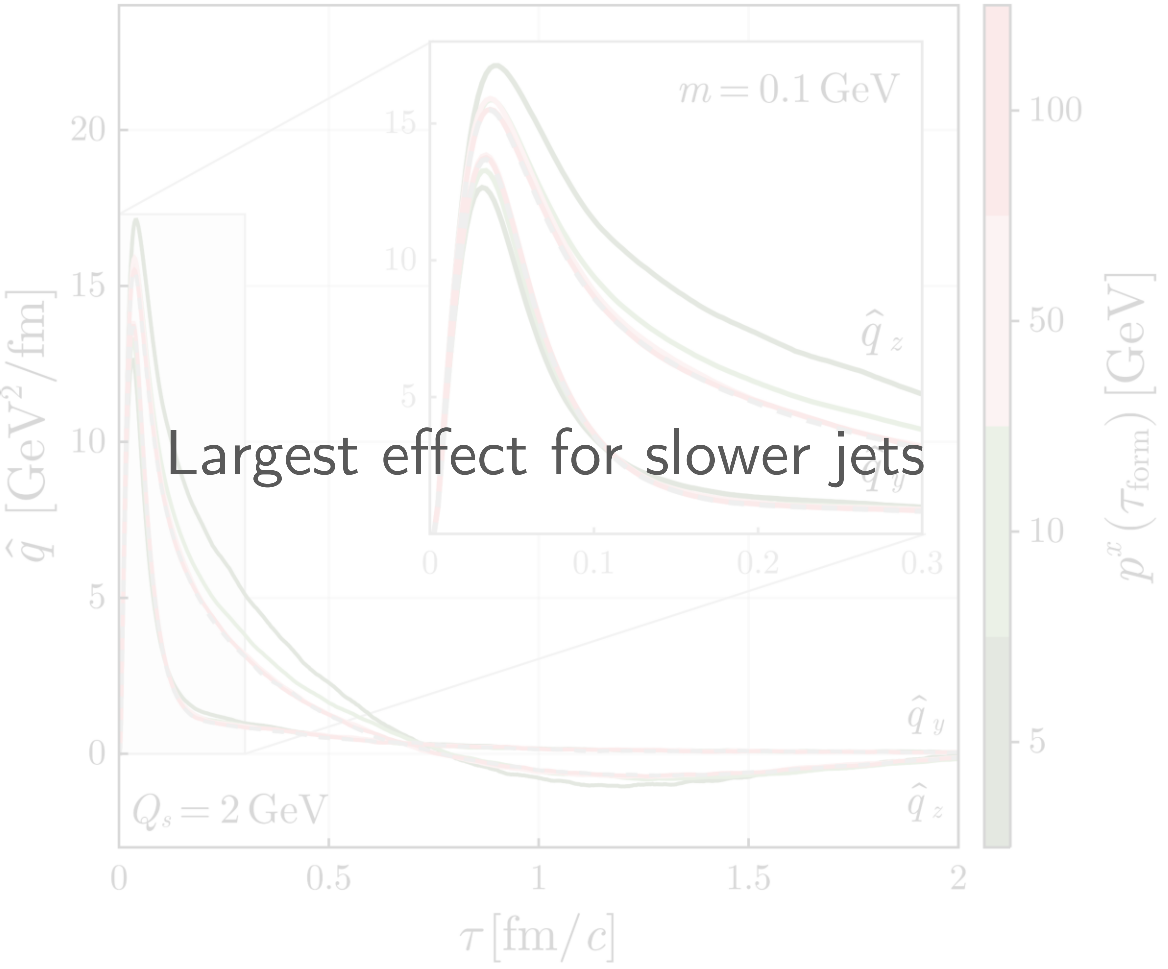
Largest effect for heavy jets

Momentum dependence for non-eikonal jets



Momentum dependence for non-eikonal jets

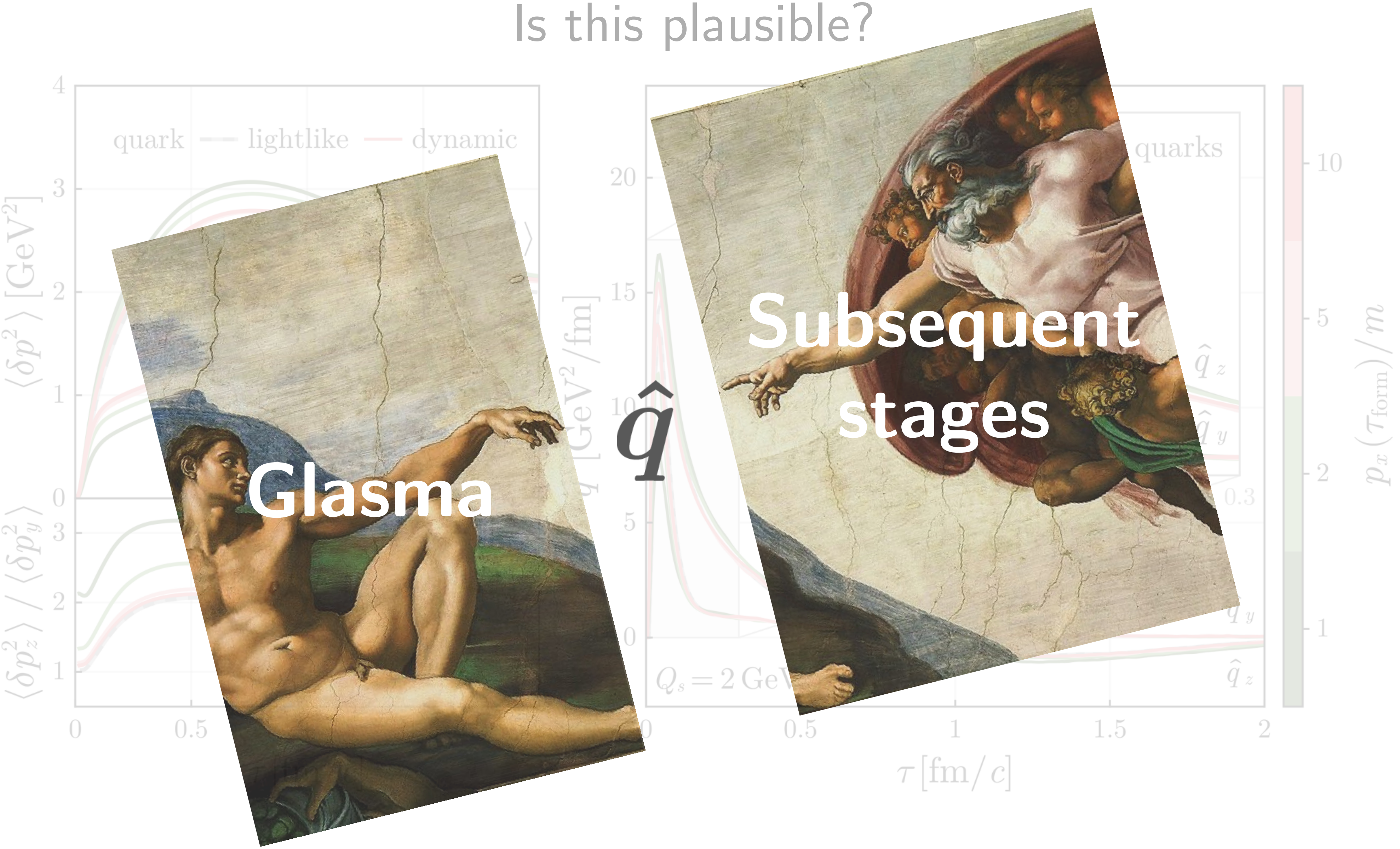




Largest effect for slower jets

Large transport coefficients

Is this plausible?



Glasma

$\hat{q}$

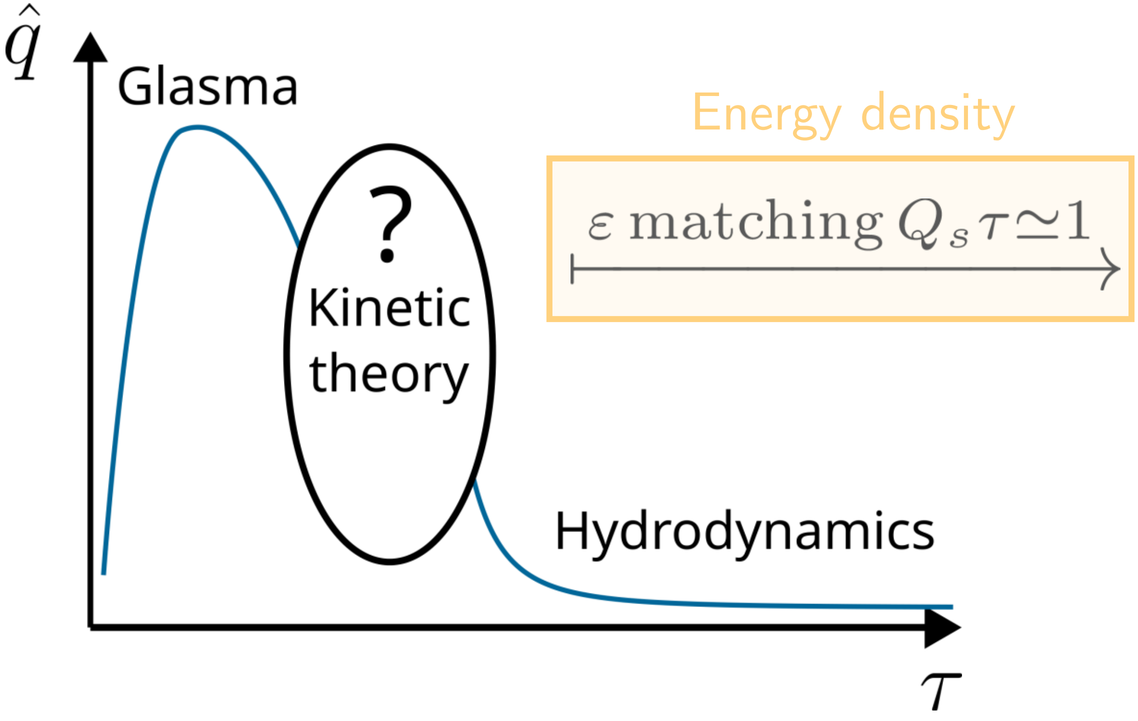
Subsequent stages

Large transport coefficients

Plausible in an EKT framework

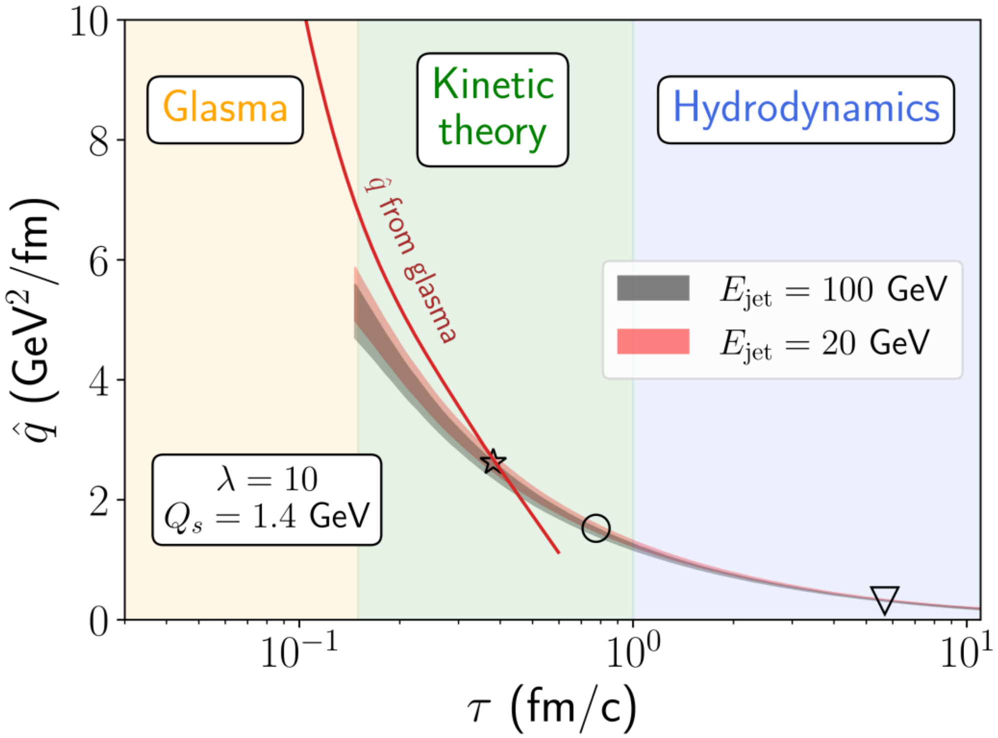
Florian's talk *Wed 11:00*

Jet quenching parameter during the initial stages



Bottom-up thermalization

using QCD EKT

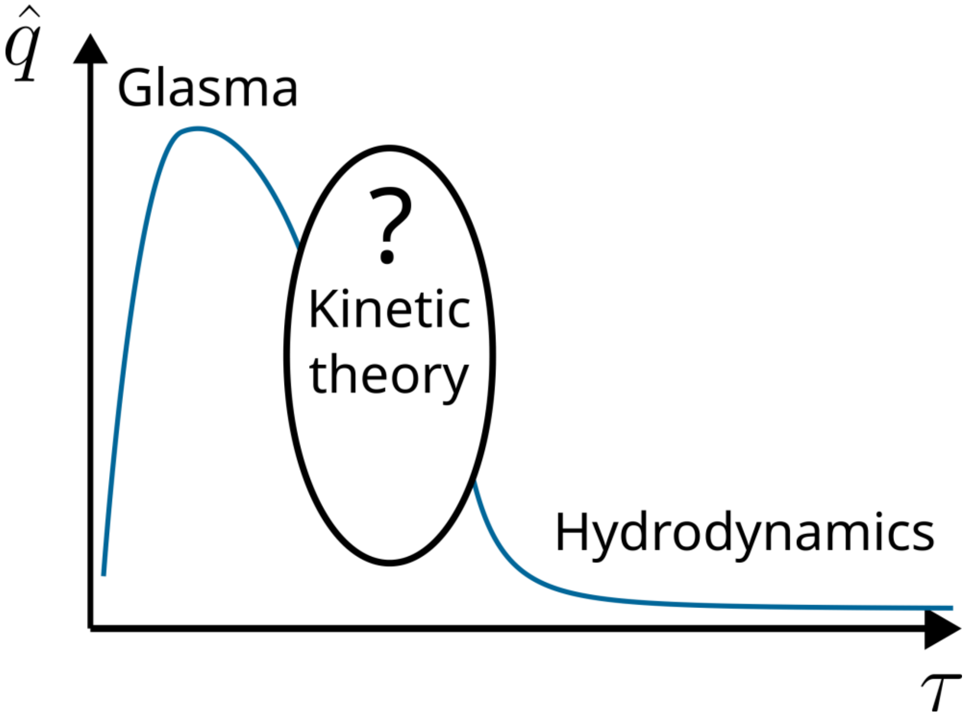


Large transport coefficients

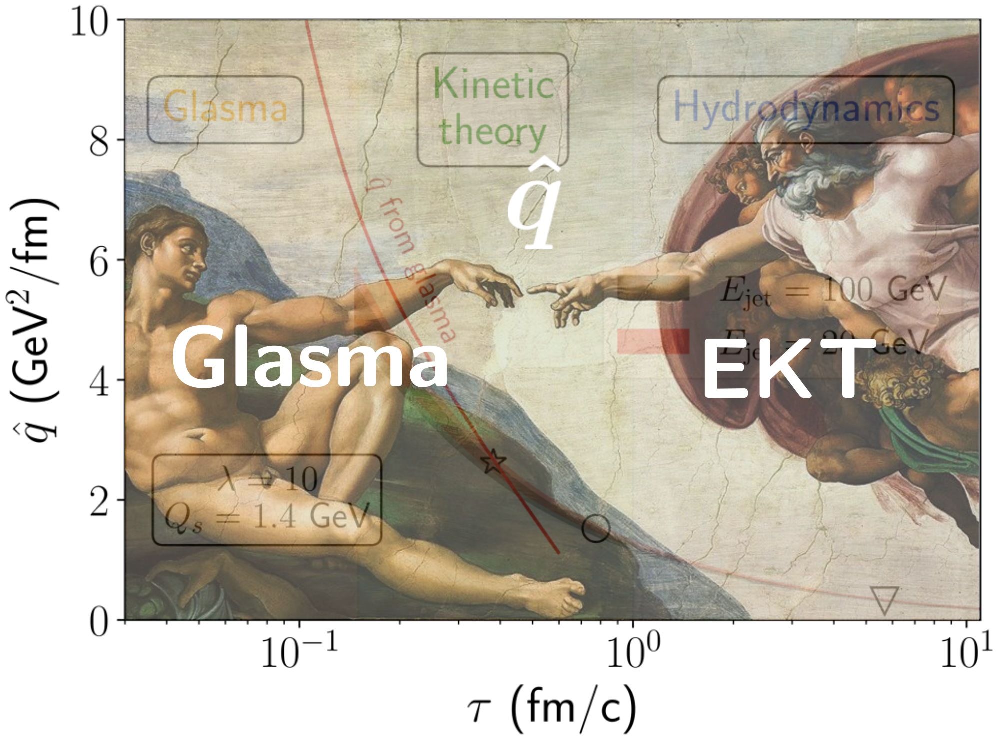
Plausible in an EKT framework

Florian's talk *Wed 11:00*

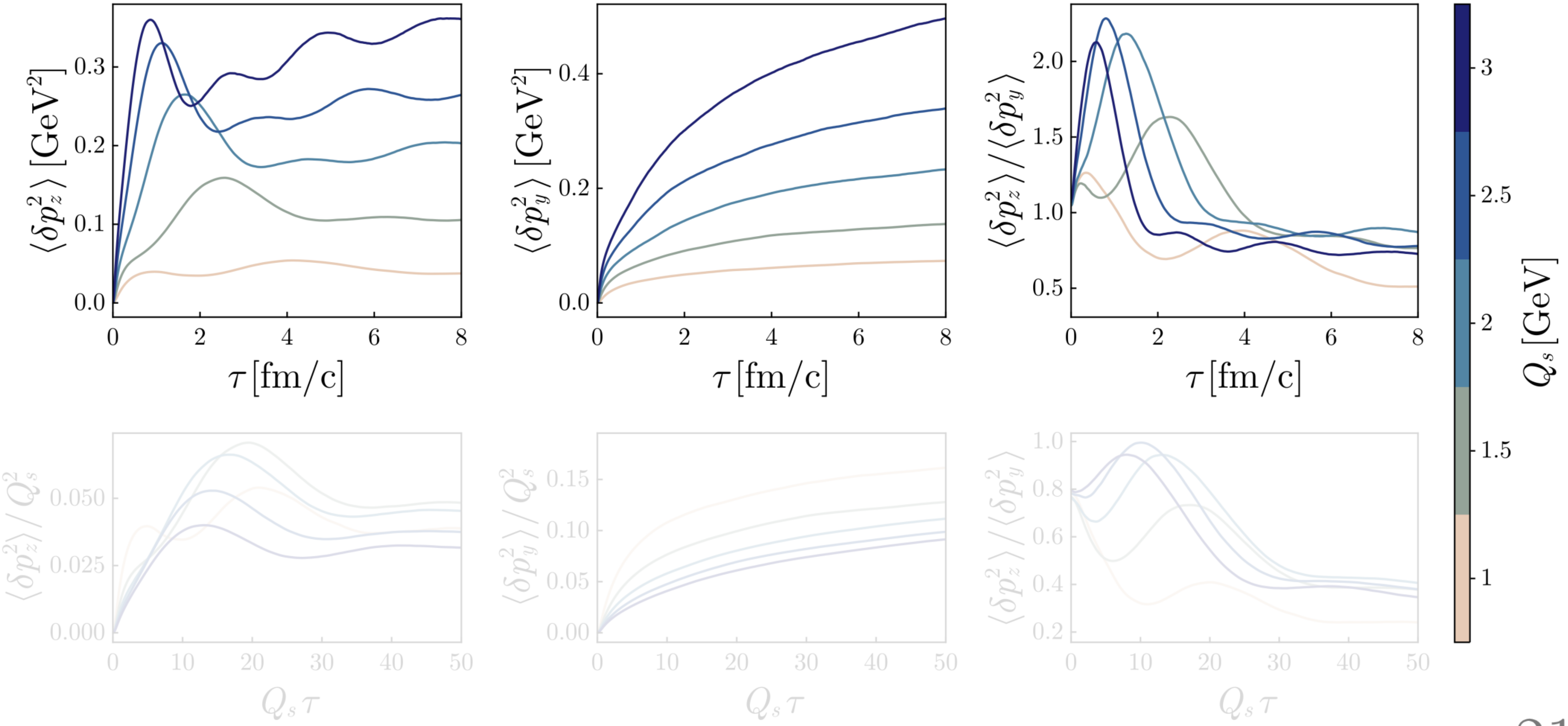
Jet quenching parameter during the initial stages



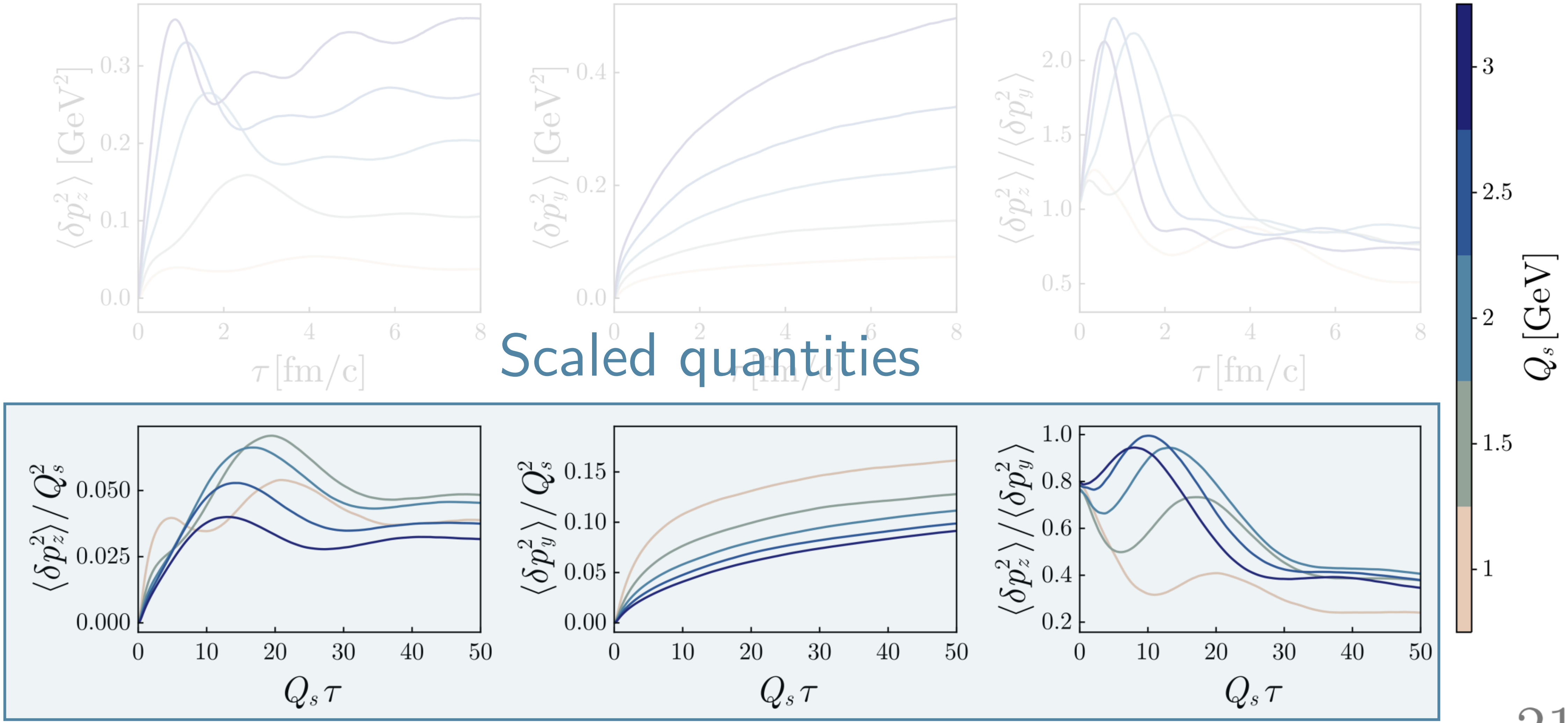
The creation of $\hat{q}$



Saturation momentum dependence



Saturation momentum dependence



Scaled quantities

Energy loss?

Possible improvements

- Classical radiation

Backreaction from particles in CYM background fields $\mathcal{D}_\mu F^{\mu\nu} = j^\mu$

CPIC Cherenkov instability $\xrightarrow{\text{cured}}$ single component j^μ

Energy loss?

Possible improvements

- Classical radiation

PIC → electromagnetic radiation reaction force ⇒ adapt to CPIC

Lorentz-Abraham-Dirac particle equations $\xrightarrow{\text{contain}}$ $\mathrm{d}^2 p_\mu / \mathrm{d}\tau^2$

Energy loss?

Possible improvements

- Classical radiation
- Glasma kinetic solver

Gluon field $A^\mu \xrightarrow[\text{cutoff}]{\text{convert}}$ gluon distribution function $\boldsymbol{f_g}$

Boltzmann-Vlasov with collision terms

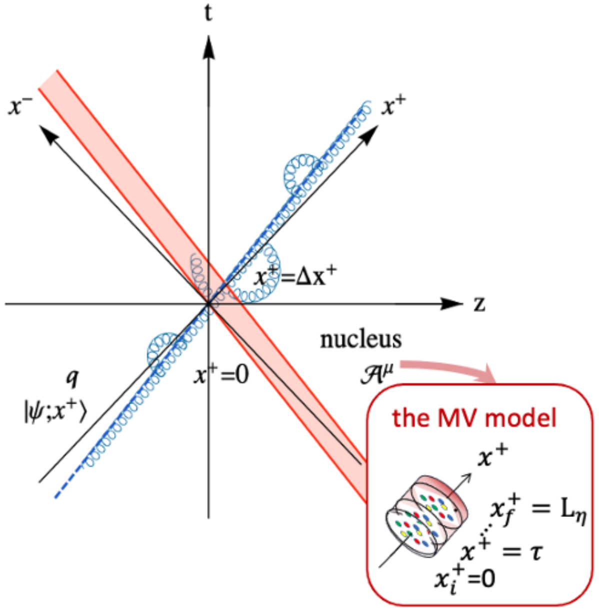
$$p^\mu \left[\partial_\mu + gQ^a F^a_{\mu\nu}(x^\mu)\partial^\nu_{p^\mu} + g f^{abc} A^b_\mu(x^\mu) Q^c \partial_{Q^a}\right] \boldsymbol{f_g}(x^\mu, p^\mu, Q^a) = \boxed{\mathcal{C}[\boldsymbol{f_g}]}$$

Collisional and radiative energy loss

Energy loss?

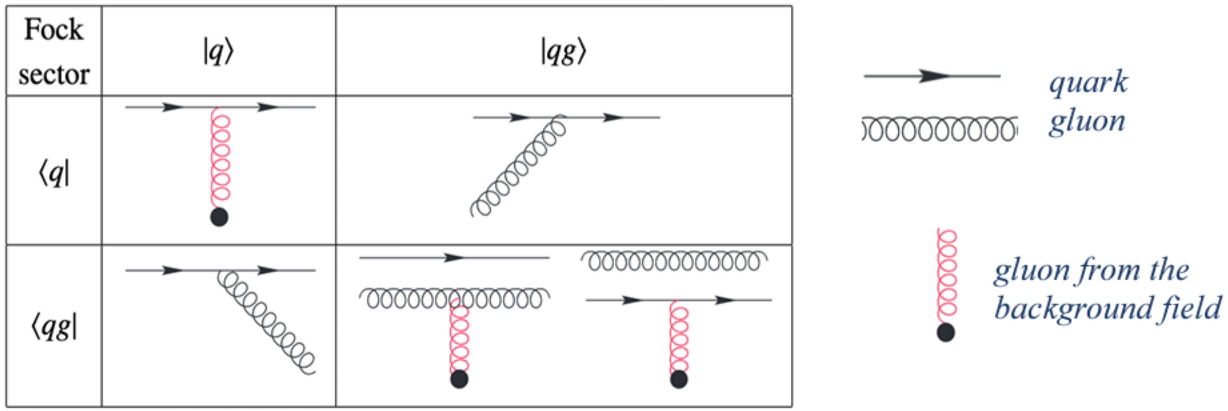
Possible improvements

- Classical radiation
- Glasma kinetic solver
- Jets in Glasma background fields



On the momentum broadening of in-medium jet evolution using a light-front Hamiltonian approach

Meijian Li,[1,2,3,*] Tuomas Lappi,[1,2,†] Xingbo Zhao,[4,5,‡] and Carlos A. Salgado[3,§]



Conclusions

- Summary

Classical transport of jets in Glasma background fields
Colored particle-in-cell numerical solver

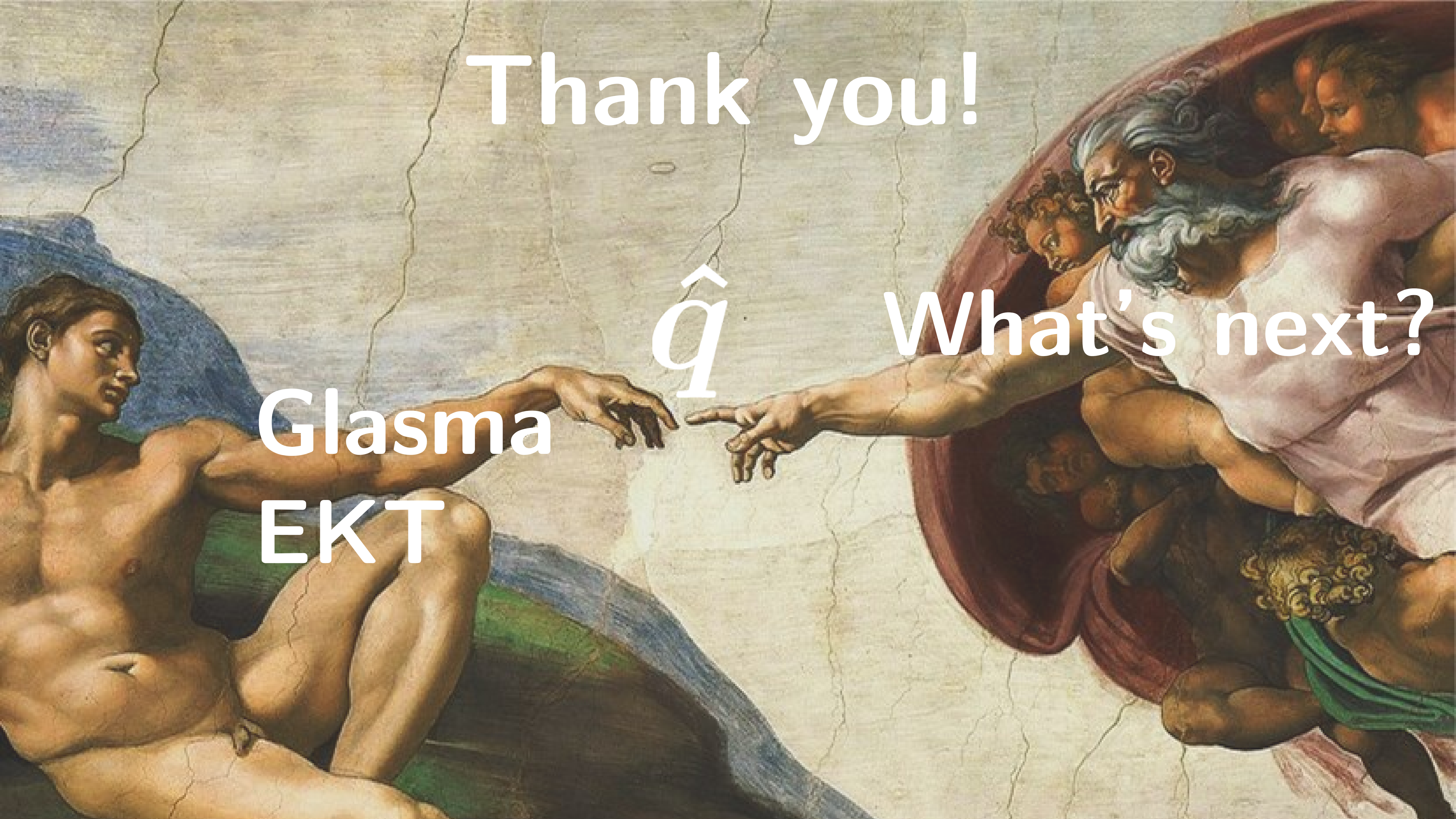
- Highlights

Transport of jets using field correlators or CPIC solver
Large transport coefficients

- Improvements

Jet energy loss in Glasma fields

Thank you!



$\hat{q}$

What's next?

Glasma
EKT