Jet quenching in glasma

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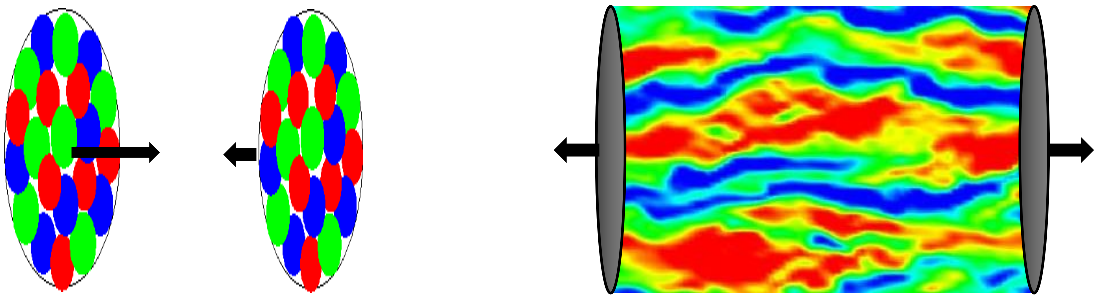
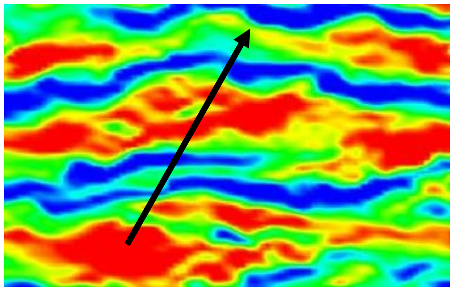
Motivation

- We consider the earliest stages of relativistic heavy-ion collisions.

- According to CGC, color charges confined in the colliding nuclei generate **glasma** – the system of strong mostly classical chromodynamic fields.



- How hard probes propagate through the glasma?



$$\frac{dE}{dx}, \ \hat{q} \ \ ?$$

Fokker-Planck Equation

- Transport of hard probes can be described using the Fokker-Planck equation.

drift — collisions

$$\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)n(t,\mathbf{r},\mathbf{p})=\left(\nabla_p^i X^{ij}(\mathbf{v})\nabla_p^j+\nabla_p^i Y^i(\mathbf{v})\right)n(t,\mathbf{r},\mathbf{p})$$

$n(t,\mathbf{r},\mathbf{p})$ - distribution function of hard probes

$$\mathbf{v}\equiv\frac{\mathbf{p}}{E_\mathbf{p}},\quad \nabla_p^i\equiv\frac{\partial}{\partial p_i}$$

$$X^{ij}(\mathbf{v}),\ Y^i(\mathbf{v}) \Rightarrow \begin{cases} \dfrac{dE}{dx}=-\dfrac{\mathrm{v}^i}{\mathrm{v}}Y^i(\mathbf{v}) & \text{collisional energy loss} \\ \hat{q}=\dfrac{2}{\mathrm{v}}\left(\delta^{ij}-\dfrac{\mathrm{v}^i\mathrm{v}^j}{\mathrm{v}^2}\right)X^{ji}(\mathbf{v}) & \text{momentum broadening} \end{cases}$$

$$n(t,\mathbf{r},\mathbf{p})=n_{\mathrm{eq}}(\mathbf{p})\sim e^{-\frac{E_\mathbf{p}}{T}} \Leftrightarrow Y^j(\mathbf{v})=\frac{\mathrm{v}^i}{T}X^{ij}(\mathbf{v})$$

solves FK equation

Origin of Fokker-Planck Equation

Boltzmann equation

Diffusive approximation

$$p >> \Delta p$$

p – momentum of a hard probe

Δp – momentum transfer in a single collision

Fokker-Planck equation

- How to obtain a Fokker-Planck equation for glasma?

  Apply the *quasilinear* method known in plasma physics.

Derivation of Fokker-Planck Equation

The dynamics is assumed to be dominated by strong classical fields.

Vlasov equation

$$p_\mu D^\mu Q(t,\mathbf{r},\mathbf{p}) - \frac{g}{2} p^\mu \{F_{\mu\nu}(t,\mathbf{r}), \partial_p^\nu Q(t,\mathbf{r},\mathbf{p})\} = 0$$

free streaming

mean-field force

$Q(t,\mathbf{r},\mathbf{p})$ - exact distribution function of hard probes which is the $N_c \times N_c$ matrix

$$D^\mu \equiv \partial^\mu - ig[A^\mu, ...]$$

chromodynamic strength tensor

$$\{A, B\} \equiv AB + BA, \qquad F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu - ig[A^\mu, A^\nu]$$

St. Mrówczyński, European Physical Journal A **54**, 43 (2018)

Derivation of Fokker-Planck Equation

Regular and fluctuating quantities

fluctuating part

$$Q(t,\mathbf{r},\mathbf{p}) = \langle Q(t,\mathbf{r},\mathbf{p})\rangle + \delta Q\,(t,\mathbf{r},\mathbf{p})$$

regular colorless part

$$\langle Q(t,\mathbf{r},\mathbf{p})\rangle = n(t,\mathbf{r},\mathbf{p})I$$

$n(t,\mathbf{r},\mathbf{p})$ - averaged distribution function

- $|n| >> |\delta Q|, \quad |\nabla_p n| >> |\nabla_p \delta Q|$
- $|\frac{\partial n}{\partial t}| << |\frac{\partial \delta Q}{\partial t}|, \qquad |\nabla n| << |\nabla \delta Q|$
- $\langle \mathbf{E}\rangle = 0, \quad \langle \mathbf{B}\rangle = 0, \quad \mathbf{E}, \mathbf{B}, A^\mu \sim \delta Q$

Derivation of Fokker-Planck Equation

$$Q(t,\mathbf{r},\mathbf{p}) = n(t,\mathbf{r},\mathbf{p})I + \delta Q\,(t,\mathbf{r},\mathbf{p})$$

Lorentz force

$$\mathbf{F} \equiv g\left(\mathbf{E} + \mathbf{v}\times\mathbf{B}\right)$$

Vlasov equation

$$\left(D^0 + \mathbf{v}\cdot\mathbf{D}\right)Q - \mathbf{F}\cdot\nabla_p Q = 0$$

ensemble averaging $\mathrm{Tr}\langle\ldots\rangle$

collision term

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)n(t,\mathbf{r},\mathbf{p}) = \frac{1}{N_c}\mathrm{Tr}\left\langle \mathbf{F}(t,\mathbf{r})\cdot\nabla_p \delta Q(t,\mathbf{r},\mathbf{p})\right\rangle$$

Fluctuations provide a collision term.

Derivation of Fokker-Planck Equation

How to compute the collision term?

$$C \equiv \frac{1}{N_c} \mathrm{Tr} \left\langle \mathbf{F} \cdot \nabla_p \delta Q \right\rangle = ?$$

$$Q(t, \mathbf{r}, \mathbf{p}) = n(t, \mathbf{r}, \mathbf{p}) I + \delta Q\,(t, \mathbf{r}, \mathbf{p})$$

Vlasov equation

$$\left(D^0 + \mathbf{v} \cdot \mathbf{D} \right) Q - \mathbf{F} \cdot \nabla_p Q = 0$$

$$n \gg |\delta Q|$$

$$|\nabla_p n| \gg |\nabla_p \delta Q|$$

linearization

$$\left|\frac{\partial n}{\partial t}\right| \ll \left|\frac{\partial \delta Q}{\partial t}\right|$$

$$|\nabla n| \ll |\nabla \delta Q|$$

$$\left(\frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \delta Q = \mathbf{F} \cdot \nabla_p n$$

Derivation of Fokker-Planck Equation

Solution of the linearized transport equation

$$\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\delta Q(t,\mathbf{r},\mathbf{p})=\mathbf{F}(t,\mathbf{r})\cdot\nabla_p n(\mathbf{p})$$

initial value

$$\delta Q(t,\mathbf{r},\mathbf{p})=\int_0^t dt'\,\mathbf{F}(t',\mathbf{r}-\mathbf{v}(t-t'))\cdot\nabla_p n(\mathbf{p})+\delta Q_0(\mathbf{r}-\mathbf{v}t,\mathbf{p})$$

$$C\equiv\frac{1}{N_c}\mathrm{Tr}\left\langle\mathbf{F}(t,\mathbf{r})\cdot\nabla_p\delta Q(t,\mathbf{r},\mathbf{p})\right\rangle=\left(\nabla_p^i X^{ij}(\mathbf{v})\nabla_p^j+\nabla_p^i Y^i(\mathbf{v})\right)n(\mathbf{p})$$

$$\begin{cases} X^{ij}(\mathbf{v})=\dfrac{1}{N_c}\displaystyle\int_0^t dt'\left\langle F^i(t,\mathbf{r})F^j(t',\mathbf{r}-\mathbf{v}(t-t'))\right\rangle \\ Y^i(\mathbf{v})=\dfrac{1}{N_c}\left\langle F^i(t,\mathbf{r})\delta Q_0(\mathbf{r}-\mathbf{v}t,\mathbf{p})\right\rangle\dfrac{1}{n(\mathbf{p})} \end{cases}$$

Fokker-Planck Equation

$$\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)n(t,\mathbf{r},\mathbf{p})=\left(\nabla_p^i X^{ij}(\mathbf{v})\nabla_p^j+\nabla_p^i Y^i(\mathbf{v})\right)n(t,\mathbf{r},\mathbf{p})$$

$$\begin{cases} X^{ij}(\mathbf{v})=\dfrac{1}{N_c}\displaystyle\int_0^t dt'\left\langle F^i(t,\mathbf{r})F^j(t',\mathbf{r}-\mathbf{v}(t-t'))\right\rangle \\ Y^j(\mathbf{v})=\dfrac{\mathrm{v}^i}{T}X^{ij}(\mathbf{v}) \end{cases}$$

$$\mathbf{F}\equiv g\left(\mathbf{E}+\mathbf{v}\times\mathbf{B}\right)$$

- The collision term is given by field correlators $\left\langle E^iE^j\right\rangle,\left\langle B^iE^j\right\rangle,\left\langle B^iB^j\right\rangle$
- Gauge covariance is lost due to the linearization!

  To restore gauge covariance: $\left\langle E_a^i(t,\mathbf{r})E_a^j(t',\mathbf{r}')\right\rangle \rightarrow \left\langle E_a^i(t,\mathbf{r})\Omega_{ab}(t,\mathbf{r}\,|\,t',\mathbf{r}')\,E_b^j(t',\mathbf{r}')\right\rangle$

$$\Omega(t,\mathbf{r}\,|\,t',\mathbf{r}')\equiv P\exp\left[ig\int_{(t',\mathbf{r}')}^{(t,\mathbf{r})}ds_\mu A^\mu(s)\right]$$

Field correlators in Equilibrium QGP

space-time translational invariance

flucuation spectrum

$$\left\langle E_a^i(t,\mathbf{r}) E_b^j(t',\mathbf{r}')\right\rangle = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} \int \frac{d^3k}{(2\pi)^3} e^{-i(\omega(t-t')-\mathbf{k}(\mathbf{r}-\mathbf{r}'))} \underbrace{\left\langle E_a^i E_b^j \right\rangle_{\omega,\mathbf{k}}}_{\text{flucuation spectrum}}$$

- $$\left\langle E_a^i E_b^j \right\rangle_{\omega,\mathbf{k}} = 2\delta^{ab} \frac{\omega^4}{e^{\beta|\omega|}-1} \left[\frac{k^i k^j}{\mathbf{k}^2} \frac{\mathrm{Im}\, \varepsilon_L(\omega,\mathbf{k})}{|\omega^2 \varepsilon_L(\omega,\mathbf{k})|^2} + \left(\delta^{ij} - \frac{k^i k^j}{\mathbf{k}^2}\right) \frac{\mathrm{Im}\, \varepsilon_T(\omega,\mathbf{k})}{|\omega^2 \varepsilon_T(\omega,\mathbf{k}) - \mathbf{k}^2|^2} \right]$$

- $$\left\langle B_a^i B_b^j \right\rangle_{\omega,\mathbf{k}} = 2\delta^{ab} \frac{\omega^2 \mathbf{k}^2}{e^{\beta|\omega|}-1} \left(\delta^{ij} - \frac{k^i k^j}{\mathbf{k}^2}\right) \frac{\mathrm{Im}\, \varepsilon_T(\omega,\mathbf{k})}{|\omega^2 \varepsilon_T(\omega,\mathbf{k}) - \mathbf{k}^2|^2}$$

- $$\left\langle B_a^i E_b^j \right\rangle_{\omega,\mathbf{k}} = \left\langle E_a^j B_b^i \right\rangle_{\omega,\mathbf{k}} = 2\delta^{ab} \frac{\omega^3}{e^{\beta|\omega|}-1} \varepsilon^{imj} k^m \frac{\mathrm{Im}\, \varepsilon_T(\omega,\mathbf{k})}{|\omega^2 \varepsilon_T(\omega,\mathbf{k}) - \mathbf{k}^2|^2}$$

$\varepsilon_{L,T}(\omega,\mathbf{k})$ - chromodielectric functions

St. Mrówczyński, Physical Review D **77**, 105022 (2008)

Fokker-Planck Equation of Equilibrium QGP

$$\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)n(t,\mathbf{r},\mathbf{p})=\left(\nabla_p^i X^{ij}(\mathbf{v})\nabla_p^j+\nabla_p^i Y^i(\mathbf{v})\right)n(t,\mathbf{r},\mathbf{p})$$

Isotropy

$$X^{ij}(\mathbf{v})\equiv X_L(\mathrm{v})\frac{\mathrm{v}^i\mathrm{v}^j}{\mathbf{v}^2}+X_T(\mathrm{v})\left(\delta^{ij}-\frac{\mathrm{v}^i\mathrm{v}^j}{\mathbf{v}^2}\right),\qquad Y^j(\mathbf{v})=\frac{\mathrm{v}^i}{T}X^{ij}(\mathbf{v})=\frac{\mathrm{v}^i}{T}X_L(v)$$

$$\begin{cases} X_L(\mathrm{v})=\dots \\ X_T(\mathrm{v})=\dots \end{cases}$$

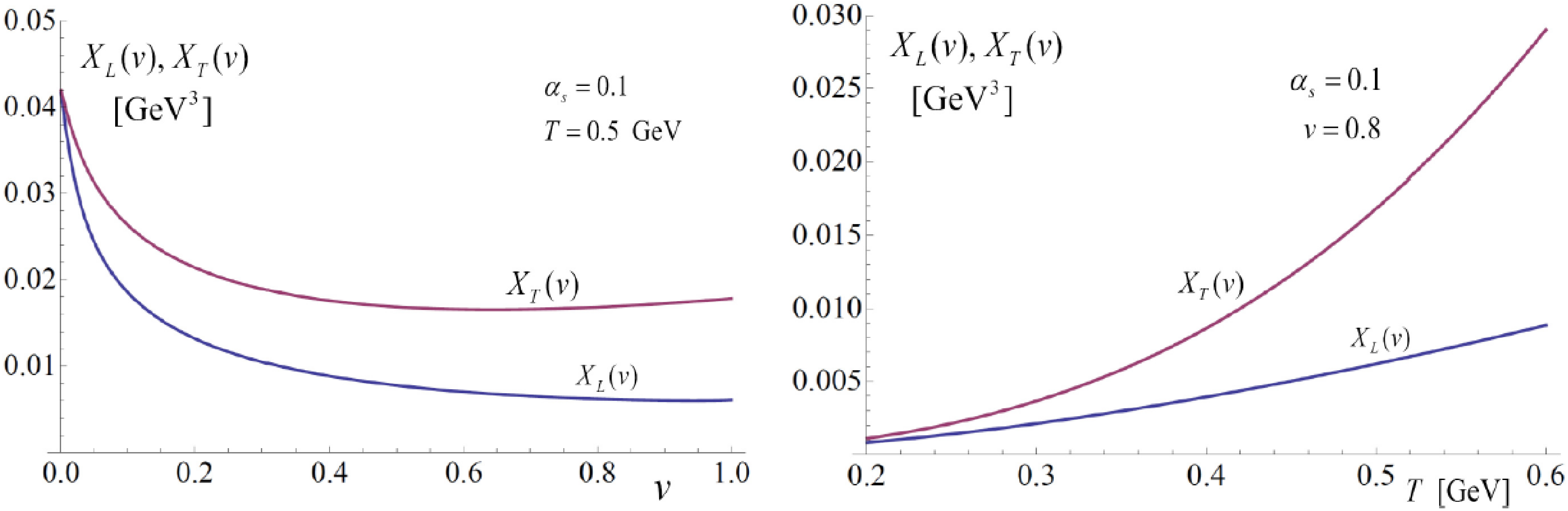
For heavy quarks

$$\mathrm{v}<<1,\quad g<<1$$

$$X_L(\mathrm{v})=X_T(\mathrm{v})\approx\frac{g^2C_F}{12\pi}m_D^2T\log\left(\frac{T}{m_D}\right)\qquad C_F\equiv\frac{N_c^2-1}{2N_c}$$

G. D. Moore and D. Teaney, Physical Review D **71**, 064904 (2005)

Fokker-Planck Equation of Equilibrium QGP



Quantitative agreement with $X_L(\mathrm{v})$ & $X_T(\mathrm{v})$ obtained from the Boltzmann collision term by means of the diffusive approximation.

The standard FP equation is reproduced!

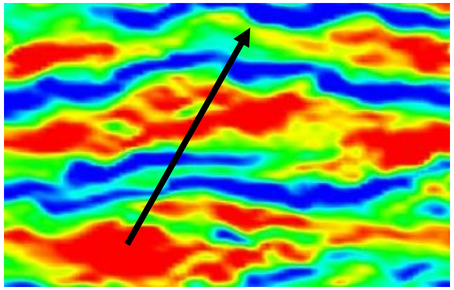
B. Svetitsky, Physical Review D **37**, 2484 (1988)

Transport of hard probes in glasma

$$X^{ij}(\mathbf{v}) = \frac{g}{N_c}\int_0^t dt'\Big\{\big\langle E^i(t,\mathbf{r})E^j(t',\mathbf{r}')\big\rangle + \varepsilon^{jkl}\mathrm{v}^k\big\langle E^i(t,\mathbf{r})B^l(t',\mathbf{r}')\big\rangle + \varepsilon^{ikl}\mathrm{v}^k\big\langle B^l(t,\mathbf{r})E^j(t',\mathbf{r}')\big\rangle + \varepsilon^{ikl}\varepsilon^{jmn}\mathrm{v}^k\mathrm{v}^m\big\langle B^l(t,\mathbf{r})B^n(t',\mathbf{r}')\big\rangle\Big\}$$

$$\mathbf{r}' \equiv \mathbf{r} - \mathbf{v}(t-t')$$

$$\begin{cases} \hat{q} = \dfrac{2}{\mathrm{v}}\left(\delta^{ij} - \dfrac{\mathrm{v}^i\mathrm{v}^j}{\mathrm{v}^2}\right)X^{ji}(\mathbf{v}) \\[2ex] \dfrac{dE}{dx} = -\dfrac{\mathrm{v}^i\mathrm{v}^j}{\mathrm{v}T}X^{ij}(\mathbf{v}) \end{cases}$$

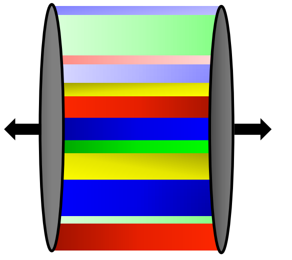


Rough estimate

Density of energy accumulated in the fields

$$\varepsilon_{\text{field}} = \frac{1}{2}\left(\left\langle E_a^i E_a^i \right\rangle + \left\langle B_a^i B_a^i \right\rangle\right)$$

E & *B* fields along the axis *z*



Density of energy released in a central collision

$$\varepsilon_{\text{coll}} = \frac{c_{\text{inel}} A \sqrt{s}}{\pi R_A^2 l}$$

$$\varepsilon_{\text{coll}} = \varepsilon_{\text{field}} \Longrightarrow \begin{cases} -\dfrac{dE}{dx} \sim (0 \div 10) \quad \left[\dfrac{\text{GeV}}{\text{fm}}\right] \\ \hat{q} \sim 10 \quad \left[\dfrac{\text{GeV}^2}{\text{fm}}\right] \end{cases}$$

$c_{\text{inel}} = 0.5, \quad A = 200, \quad \sqrt{s} = 5\,\text{TeV}, \quad l = 1\,\text{fm}$

St. Mrówczyński, European Physical Journal A **54**, 43 (2018)

Realistic calculations in proper time expansion

R. J. Fries, J. I. Kapusta, and Y. Li, arXiv:nucl-th/0604054
G.Chen, R.J. Fries, J.I. Kapusta and Y. Li, Physical Review D **92**, 064912 (2015)

Proper time τ is treated as a small parameter $\tau << Q_s^{-1}$

Fully analytic approach

M. Carrington, A. Czajka & St. Mrówczyński, Nuclear Physics A **1001**, 121914 (2020)

M. Carrington, A. Czajka & St. Mrówczyński, European Physical Journal A **58**, 5 (2022)

M. Carrington, A. Czajka & St. Mrówczyński, Physical Review C **106**, 034904 (2022)

M. Carrington, A. Czajka & St. Mrówczyński, Physics Letters B **834**, 137464 (2022)

M. Carrington, A. Czajka & St. Mrówczyński, Physical Review C **106**, 034904 (2022)

M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, arXiv:2304.032

Glasma from AA collisions

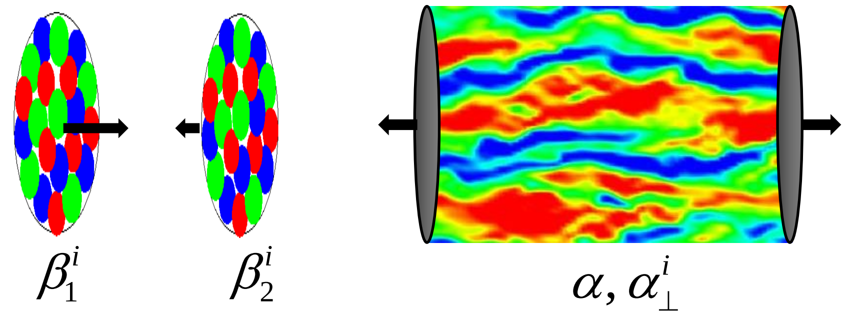
The earliest stage of relativistic heavy-ion collisions

Classical Yang-Mills equation

$$D_\mu F^{\mu\nu}(x) = j^\nu(x)$$

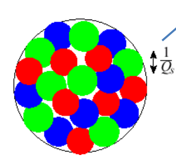
$$j^\mu(x) = j_1^\mu(x) + j_2^\mu(x)$$

$$j_{1,2}^\mu(x) = \pm\delta^{\mu\mp}\delta(x^\pm)\rho_{1,2}(\mathbf{x}_\perp)$$



Ansatz of gauge potentials

$$\begin{cases} A^+(x) = \Theta(x^+)\Theta(x^-)x^+\alpha(\tau,\mathbf{x}_\perp) \\ A^-(x) = -\Theta(x^+)\Theta(x^-)x^-\alpha(\tau,\mathbf{x}_\perp) \\ A^i(x) = \Theta(x^+)\Theta(x^-)\alpha_\perp^i(\tau,\mathbf{x}_\perp) \\ \qquad + \Theta(-x^+)\Theta(x^-)\beta_1^i(\mathbf{x}_\perp) + \Theta(x^+)\Theta(-x^-)\beta_2^i(\mathbf{x}_\perp) \end{cases}$$



Boundary condition

$$\begin{cases} \alpha(0,\mathbf{x}_\perp) = \beta_1^i(\mathbf{x}_\perp) + \beta_2^i(\mathbf{x}_\perp) \\ \alpha_\perp^i(0,\mathbf{x}_\perp) = -\frac{ig}{2}[\beta_1^i(\mathbf{x}_\perp), \beta_2^i(\mathbf{x}_\perp)] \end{cases}$$

Gauge condition

$$x^+A^+ + x^-A^- = 0$$

E. Iancu, R. Venugopalan, in *Quark-Gluon Plasma 3*,
ed. by R.C. Hwa, X.-N. Wang (World Scientific, Singapore, 2004

Proper time expansion

$$\alpha(\tau,\mathbf{x}_\perp)=\sum_{n=0}^{\infty}\tau^n\alpha_{(n)}(\mathbf{x}_\perp), \qquad \alpha_\perp^i(\tau,\mathbf{x}_\perp)=\sum_{n=0}^{\infty}\tau^n\alpha_{\perp(n)}^i(\mathbf{x}_\perp)$$

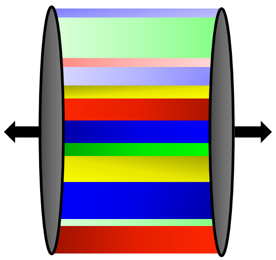
The Yang-Mills equations for the expanded potentials are solved recursively.

$$E^i=F^{i0}, \quad B^i=\frac{1}{2}\varepsilon^{ijk}F^{kj}$$

0th order

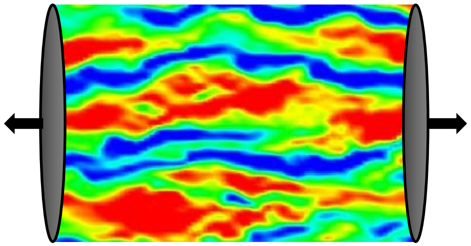
$$\mathbf{E}_{(0)}=(0,0,E^z), \qquad \mathbf{B}_{(0)}=(0,0,B^z)$$

$$E^z_{(0)}(\mathbf{x}_\perp)=-ig[\beta_1^i(\mathbf{x}_\perp),\beta_2^i(\mathbf{x}_\perp)],$$
$$B^z_{(0)}(\mathbf{x}_\perp)=-ig\varepsilon^{zij}[\beta_1^i(\mathbf{x}_\perp),\beta_2^j(\mathbf{x}_\perp)],$$



E & *B* fields along the axis *z*

At higher orders transverse fields show up



G.Chen, R.J. Fries, J.I. Kapusta and Y. Li, Physical Review D **92**, 064912 (2015)

Field correlatos

The correlators

$$\left\langle E_a^i(t,\mathbf{r})E_b^j(t',\mathbf{r}')\right\rangle, \quad \left\langle E_a^i(t,\mathbf{r})B_b^j(t',\mathbf{r}')\right\rangle, \quad \left\langle B_a^i(t,\mathbf{r})B_b^j(t',\mathbf{r}')\right\rangle$$

are expressed through

$$\sum \partial^i \partial^j \left\langle \beta_a^k(\mathbf{x}_\perp)\beta_b^l(\mathbf{y}_\perp)\dots\beta_c^m(\mathbf{z}_\perp)\right\rangle$$

IR regulator $m = \Lambda_{\text{QCD}}$

In covariant gauge $\partial_\mu \beta^\mu = 0$

$$-\nabla^2 \beta^+(\mathbf{x}_\perp) = \rho(\mathbf{x}_\perp) \quad \Rightarrow \quad \beta^+(\mathbf{x}_\perp) = \frac{1}{2\pi}\int d^2x'_\perp K_0(m|\mathbf{x}_\perp - \mathbf{x}'_\perp|)\rho(\mathbf{x}'_\perp)$$

The potentials are transformed from the covariant to light-cone gauge

Wick theorem

$$\left\langle \rho_a^k(\mathbf{x}_\perp)\rho_b^l(\mathbf{y}_\perp)\dots\rho_c^m(\mathbf{z}_\perp)\right\rangle = \sum\prod\left\langle \rho_a^i(\mathbf{x}_\perp)\rho_b^j(\mathbf{y}_\perp)\right\rangle$$

Glasma graph approximation

$$\left\langle \beta_a^k(\mathbf{x}_\perp)\beta_b^l(\mathbf{y}_\perp)\dots\beta_c^m(\mathbf{z}_\perp)\right\rangle = \sum\prod\left\langle \beta_a^i(\mathbf{x}_\perp)\beta_b^j(\mathbf{y}_\perp)\right\rangle = \sum\prod B_{ab}^{ij}(\mathbf{x}_\perp - \mathbf{y}_\perp)$$

Basic correlator

$$B_{ab}^{ij}(\mathbf{x}_\perp,\mathbf{y}_\perp) \equiv \left\langle \beta_a^i(\mathbf{x}_\perp)\beta_b^j(\mathbf{y}_\perp)\right\rangle = \int d^2x'_\perp\, d^2y'_\perp \cdots\cdots \left\langle \rho_a^i(\mathbf{x}'_\perp)\rho_b^j(\mathbf{y}'_\perp)\right\rangle$$

$$\left\langle \rho_a^i(\mathbf{x}_\perp)\rho_b^j(\mathbf{y}_\perp)\right\rangle = g^2\mu\,\delta^{ab}\delta^{(2)}(\mathbf{x}_\perp-\mathbf{y}_\perp)$$

color charge surface density

$$\mu = g^{-4}Q_s^2$$

$$B_{ab}^{ij}(\mathbf{x}_\perp,\mathbf{y}_\perp) \equiv \delta^{ab}\left(\delta^{ij}C_1(r) - \hat{r}^i\hat{r}^jC_2(r)\right)$$

$$\mathbf{r} \equiv \mathbf{x}_\perp - \mathbf{y}_\perp, \quad r \equiv |\mathbf{r}|, \quad \hat{r}^i \equiv \frac{r^i}{r}$$

$$\begin{cases} C_1(r) \equiv \dfrac{m^2K_0(mr)}{g^2N_c\left(mrK_1(mr)-1\right)}\left\{\exp\left[\dfrac{g^4N_c\mu\left(mrK_1(mr)-1\right)}{4\pi m^2}\right]-1\right\} \\[2ex] C_2(r) \equiv \dfrac{m^3rK_1(mr)}{g^2N_c\left(mrK_1(mr)-1\right)}\left\{\exp\left[\dfrac{g^4N_c\mu\left(mrK_1(mr)-1\right)}{4\pi m^2}\right]-1\right\} \end{cases}$$

$$\underset{r<<m^{-1}}{\approx} \quad \#\log(mr)$$

UV regularization required

$$r > Q_s^{-1}$$

J. Jalilian-Marian, A. Kovner, L. D. McLerran and H. Weigert, Physical Review D **55**, 5414 (1997)

Fokker-Planck Equation

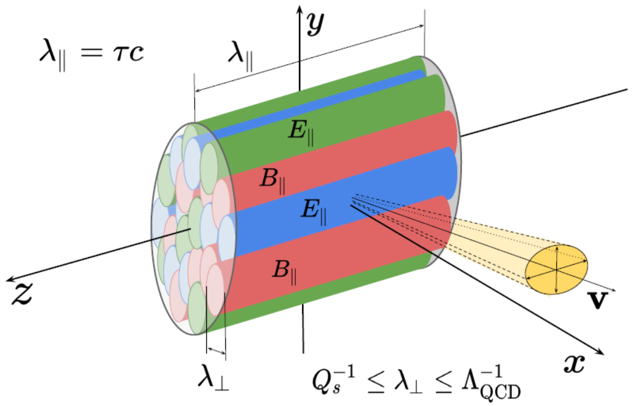
$$\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)n(t,\mathbf{r},\mathbf{p})=\left(\nabla_p^i X^{ij}(\mathbf{v})\nabla_p^j+\nabla_p^i Y^i(\mathbf{v})\right)n(t,\mathbf{r},\mathbf{p})$$

$$\begin{cases} X^{ij}(\mathbf{v})=\dfrac{g}{N_c}\displaystyle\int_0^t dt'\Big\{\left\langle E^i(t,\mathbf{r})E^j(t',\mathbf{r}')\right\rangle+\varepsilon^{jkl}\mathrm{v}^k\left\langle E^i(t,\mathbf{r})B^l(t',\mathbf{r}')\right\rangle \\ \qquad +\varepsilon^{ikl}\mathrm{v}^k\left\langle B^l(t,\mathbf{r})E^j(t',\mathbf{r}')\right\rangle+\varepsilon^{ikl}\varepsilon^{jmn}\mathrm{v}^k\mathrm{v}^m\left\langle B^l(t,\mathbf{r})B^n(t',\mathbf{r}')\right\rangle\Big\} \\ Y^j(\mathbf{v})=\dfrac{\mathrm{v}^i}{T}X^{ij}(\mathbf{v}) \end{cases}$$

The correlators are computed order by order.

$$\begin{cases} \hat{q}=\dfrac{2}{\mathrm{v}}\left(\delta^{ij}-\dfrac{\mathrm{v}^i\mathrm{v}^j}{\mathrm{v}^2}\right)X^{ji}(\mathbf{v}) \\ \dfrac{dE}{dx}=-\dfrac{\mathrm{v}^i}{\mathrm{v}}Y^i(\mathbf{v}) \end{cases}$$

Hard probes in glasma - $\hat{q}$



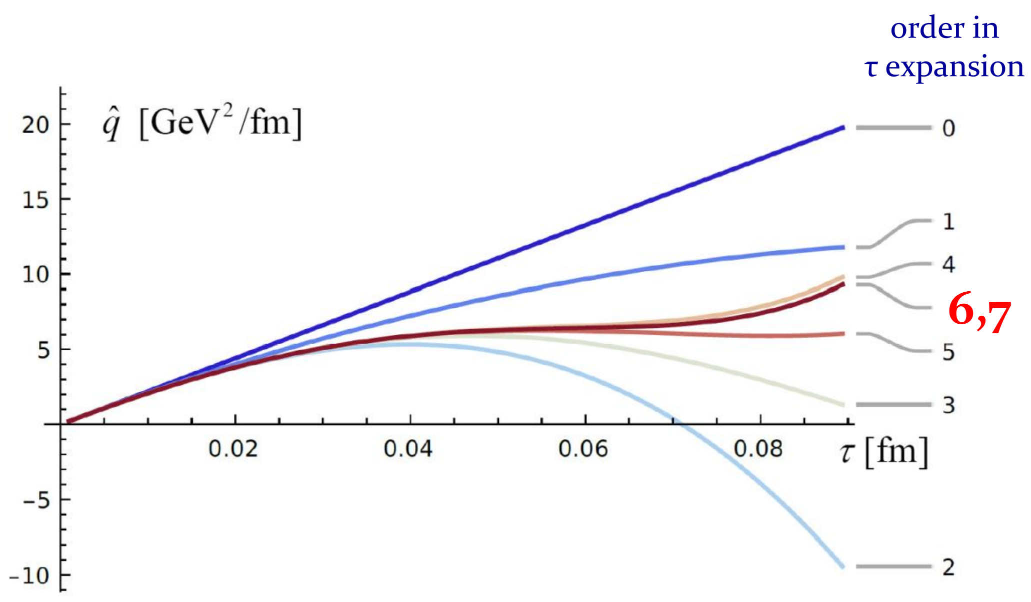
$$\hat{q} = \frac{2}{\mathrm{v}}\left(\delta^{ij} - \frac{\mathrm{v}^i \mathrm{v}^j}{\mathrm{v}^2}\right) X^{ji}(\mathbf{v})$$

$N_c = 3, \quad g = 1$

$Q_s = 2$ GeV

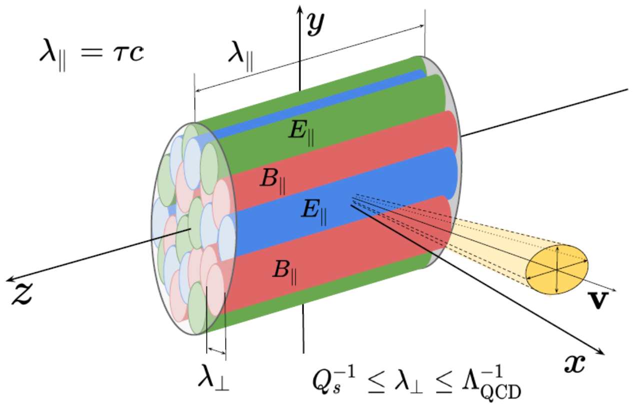
$m = 0.2$ GeV

$\mathrm{v} = \mathrm{v}_\perp = 1$

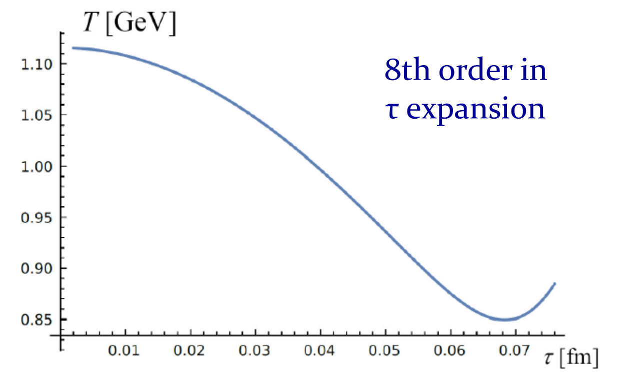


M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, arXiv:2304.032

Hard probes in glasma - $\frac{dE}{dx}$



$$\frac{dE}{dx} = -\frac{1}{T}\frac{\mathrm{v}^i \mathrm{v}^i}{\mathrm{v}} X^{ij}(\mathbf{v})$$

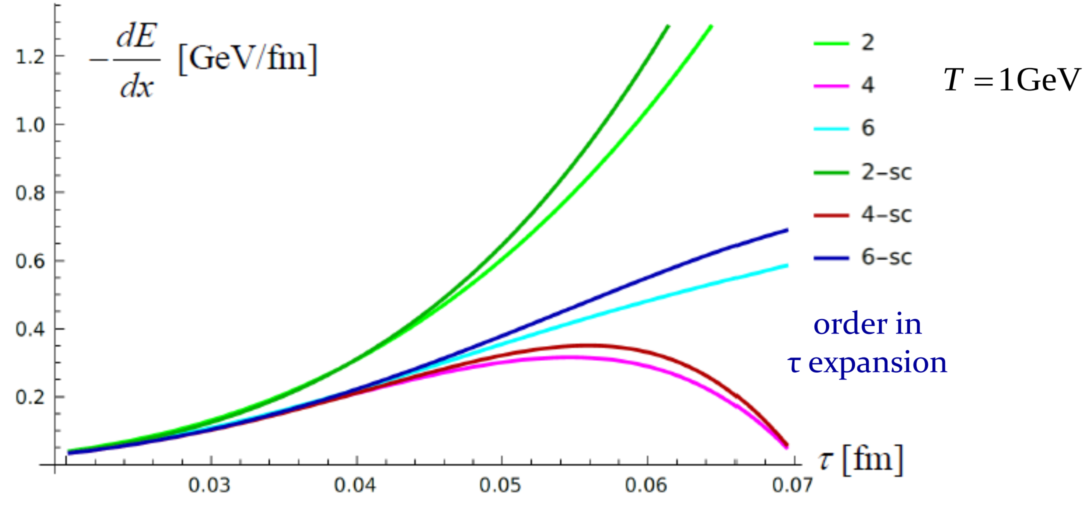


$N_c = 3, \quad g = 1$

$Q_s = 2$ GeV

$m = 0.2$ GeV

$\mathrm{v} = \mathrm{v}_\perp = 1$



M. Carrington, W. Cowie, B. Friesen, St. Mrówczyński & D. Pickering, arXiv:2304.032

Glasma impact on jet quenching

Glasma

$\hat{q}_{\max} = 6 \;\; \mathrm{GeV}^2 / \mathrm{fm}$

$t_{\max} = 0.06 \;\; \mathrm{fm}$

Equilibrium QGP

$\hat{q} = 3T^3$

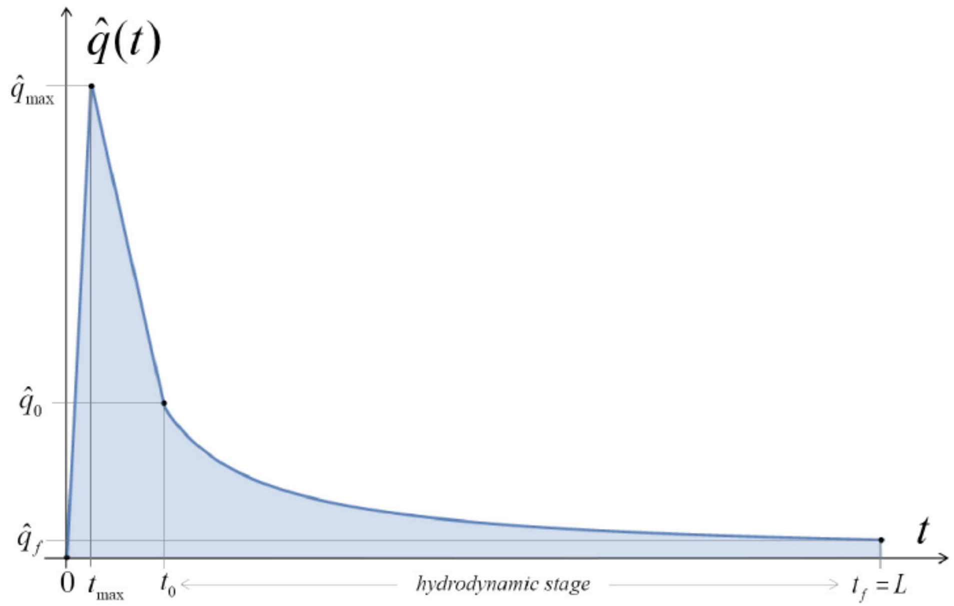
$t_0 = 0.6 \; \mathrm{fm}$

$T_0 = 450 \; \mathrm{MeV}$

$\hat{q}_0 = 1.4 \;\; \mathrm{GeV}^2 / \mathrm{fm}$

$T = T_0 \left(\frac{t_0}{t} \right)^{1/3}$

$L = 10 \; \mathrm{fm}$



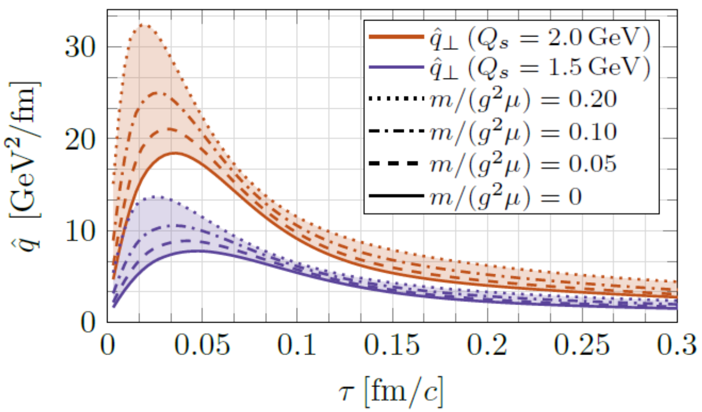
$$\Delta p_T^2 \Big|^{\text{non-eq}} = \int_0^{t_0} dt\, \hat{q}(t)$$

$$\Delta p_T^2 \Big|^{\text{eq}} = \int_{t_0}^{L} dt\, \hat{q}(t)$$

$$\frac{\Delta p_T^2 \Big|^{\text{non-eq}}}{\Delta p_T^2 \Big|^{\text{eq}}} = 0.93$$

S. Cao et al. [JETSCAPE], Physical Review C **104**, 024905 (2021),
C. Shen, U. Heinz, P. Huovinen and H. Song, Physical Review C **84**, 044903 (2011).

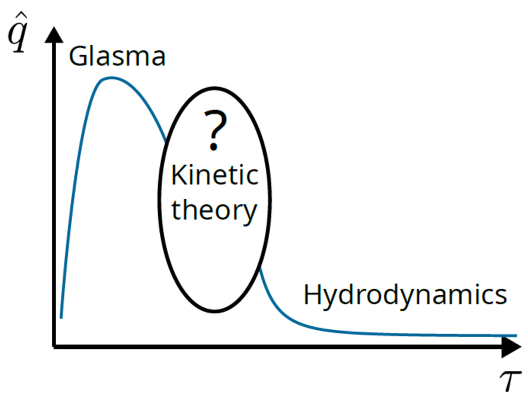
Glasma impact on jet quenching cont.



Full simulations of glasma

A. Ipp, D.I. Műller and D. Schuh, Phys. Lett. B **810**, 135810 (2020)

D. Avramescu, V. Băran, V. Greco, A. Ipp, D.I. Műller & M.Ruggieri, Phys. Rev. D **107**, 114021 (2023)



Kinetic theory interpolates between glasma and equilibrium QGP

K. Boguslavski, A. Kurkela, T.Lappi, F. Lindenbauer & J.Peuron, arXiv:2303.12595

Summary & Conclusions

- The Fokker-Planck equation of hard probes interacting with classical chromodynamic fields rather than with plasma constituents is derived.
- The known case of equilibrium plasma is reproduced.
- The field correlators are computed up to τ^7 or τ^8.
- The momentum broadening and energy loss in the glasma are significantly bigger than in equilibrated QGP.
- In spite of its short lifetime the glasma provides a significant contribution to the jet quenching.