

Heavy Quarks in Turbulent QGP

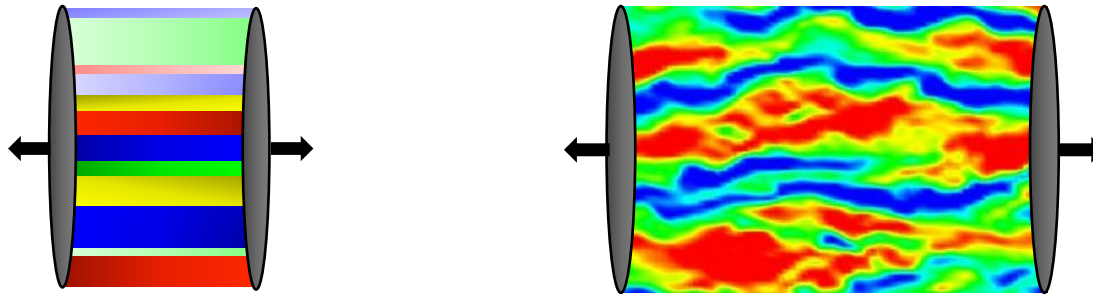
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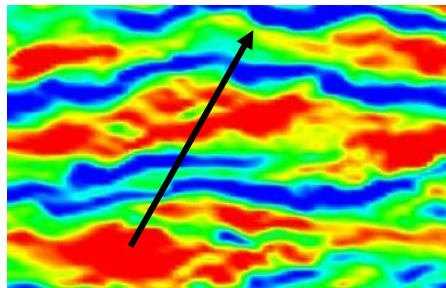
Turbulent QGP - quark-gluon plasma populated with strong classical chromodynamic fields

Motivation

- ▶ We consider the earliest stages of relativistic heavy-ion collisions.
- ▶ According to CGC, color charges confined in the colliding nuclei generate strong chromodynamic fields.



- ▶ How heavy quarks propagate through the turbulent QGP?



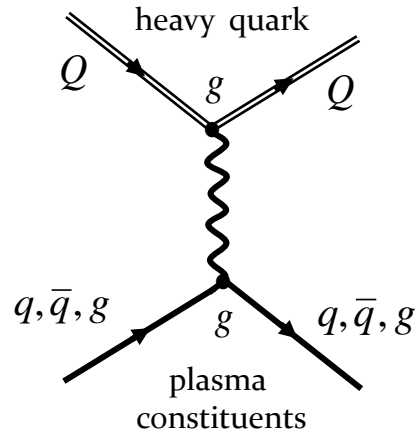
$$\frac{dE}{dx}, \hat{q} \quad ?$$

Parametric Estimates

$$\frac{dE}{dx}, \hat{q} \propto |M|^2$$



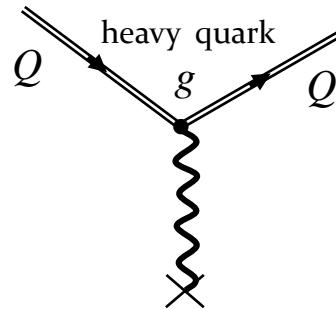
equilibrium
plasma



$$\left\{ \begin{array}{l} |M|^2 \propto g^4 \\ \frac{dE}{dx} \propto g^4 T^2 \\ \hat{q} \propto g^4 T^3 \end{array} \right.$$



turbulent
plasma



$$\left\{ \begin{array}{l} |M|^2 \propto g^2 \\ \varepsilon_{\text{plasma}} = \varepsilon_{\text{field}} \propto T^4 \\ \frac{dE}{dx} \propto g^2 T^2 \\ \hat{q} \propto g^2 T^3 \end{array} \right.$$

Fokker-Planck Equation

- Transport of heavy quarks is usually described in terms of Fokker-Planck equation.

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

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

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

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

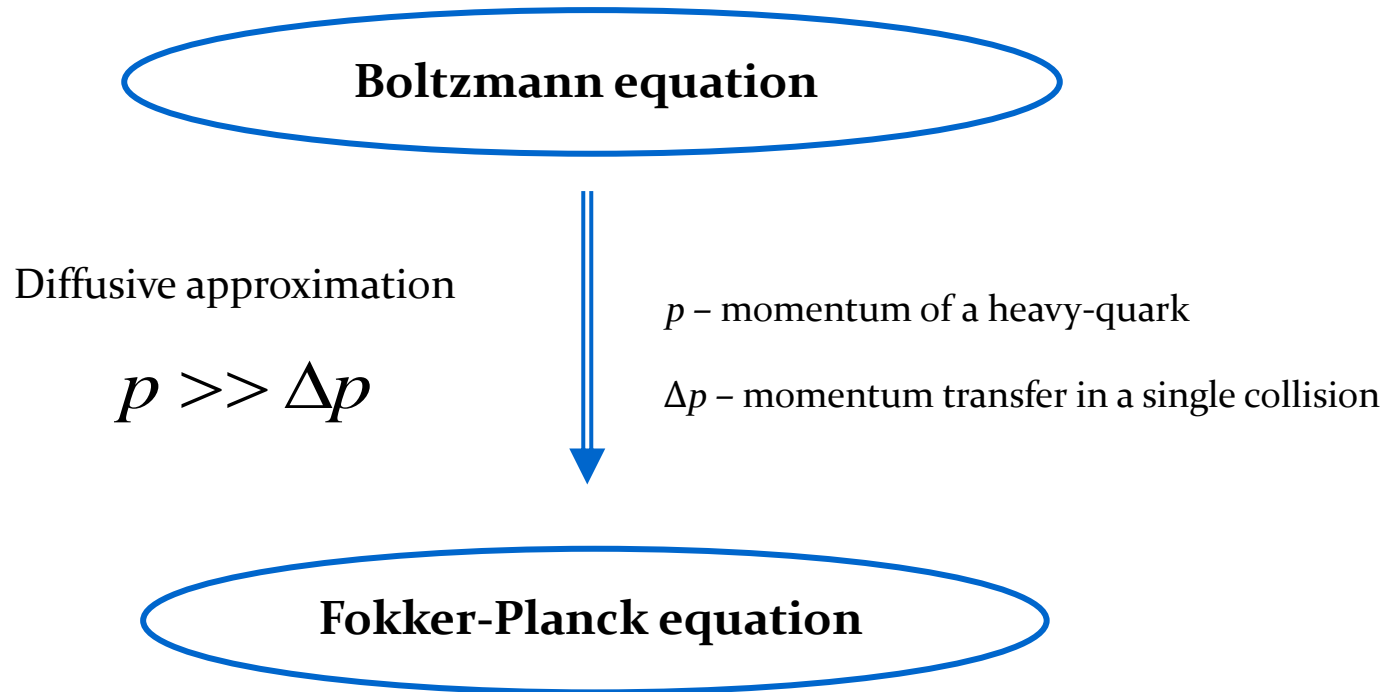
$$n(t, \mathbf{r}, \mathbf{p}) = n_{\text{eq}}(\mathbf{p}) \sim e^{-\frac{E_p}{T}}$$

solves FK equation

\Leftrightarrow

$$Y^j(\mathbf{v}) = \frac{v^i}{T} X^{ij}(\mathbf{v})$$

Origin of Fokker-Planck Equation



- ▶ How to obtain a Fokker-Planck equation for turbulent QGP?
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 heavy quarks which is the $N_c \times N_c$ matrix

$$D^\mu \equiv \partial^\mu - ig[A^\mu, \dots], \quad F^{\mu\nu} \equiv \partial^\mu A^\nu - \partial^\nu A^\mu - ig[A^\mu, A^\nu]$$

$$\{A, B\} \equiv AB + BA$$

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

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

Derivation of Fokker-Planck Equation

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

Vlasov equation

Lorentz force

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

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

ensemble averaging

$$\Downarrow \text{Tr}\langle \dots \rangle$$

collision term

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

Fluctuations provide a collision term.

Derivation of Fokker-Planck Equation

How to compute the collision term?

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

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

Vlasov equation

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

$$\begin{aligned} n &\gg |\delta Q| \\ |\nabla_p n| &\gg |\nabla_p \delta Q| \end{aligned}$$

linearization

$$\begin{aligned} \left| \frac{\partial n}{\partial t} \right| &\ll \left| \frac{\partial \delta Q}{\partial t} \right| \\ |\nabla n| &\ll |\nabla \delta Q| \end{aligned}$$

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

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

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



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

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

Derivation of Fokker-Planck Equation

- ▶ The collision term is given by field correlators

$$C \equiv \frac{1}{N_c} \text{Tr} \langle \mathbf{F} \cdot \nabla_p \delta Q \rangle \quad \text{expressed by} \quad \langle E^i E^j \rangle, \langle B^i E^j \rangle, \langle B^i B^j \rangle$$

- ▶ Gauge covariance is lost due to the linearization!

To restore gauge invariance:

$$\langle E_a^i(t, \mathbf{r}) E_a^j(t', \mathbf{r}') \rangle \rightarrow \langle E_a^i(t, \mathbf{r}) \Omega_{ab}(t, \mathbf{r} | t', \mathbf{r}') E_b^j(t', \mathbf{r}') \rangle$$

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

Fokker-Planck Equation

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

$$\left\{ \begin{array}{l} X^{ij}(\mathbf{v}) = \frac{1}{N_c} \int_0^t dt' \langle F^i(t, \mathbf{r}) F^j(t', \mathbf{r} - \mathbf{v}(t-t')) \rangle \\ Y^j(\mathbf{v}) = \frac{v^i}{T} X^{ij}(\mathbf{v}) \end{array} \right. \quad \mathbf{F} \equiv g(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Isotropic plasma

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

Field correlators in Equilibrium QGP

space-time translational invariance

flucuation spectrum

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

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

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

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

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

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

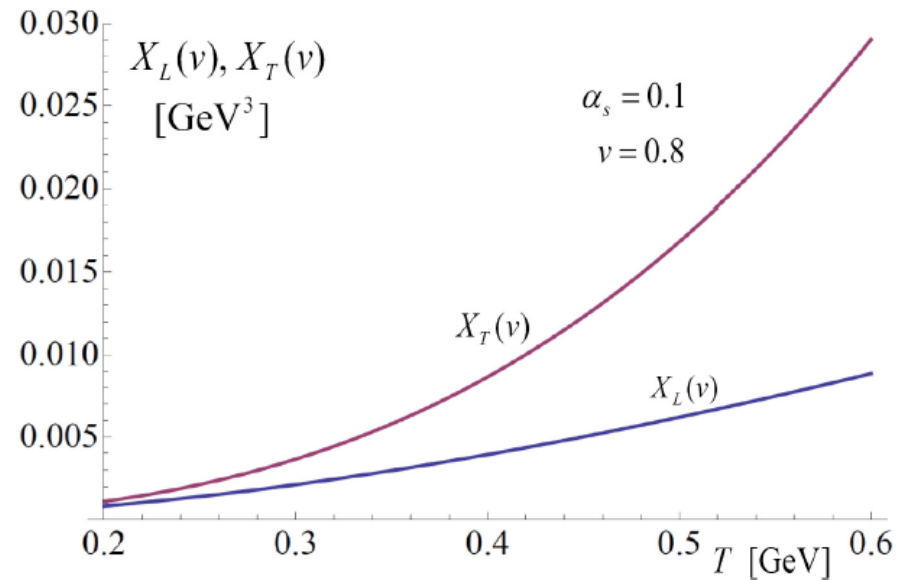
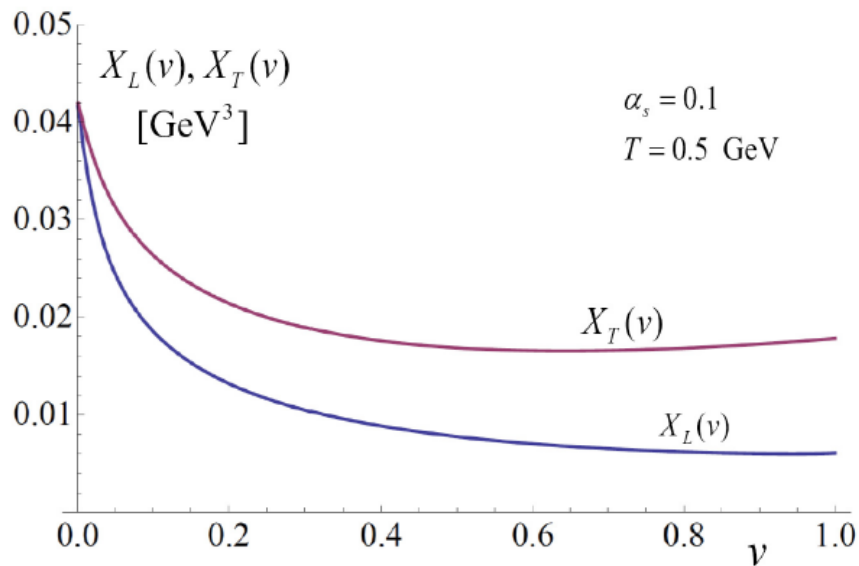
$$X^{ij}(\mathbf{v}) \equiv X_L(v) \frac{v^i v^j}{v^2} + X_T(v) \left(\delta^{ij} - \frac{v^i v^j}{v^2} \right), \quad Y^j(\mathbf{v}) = \frac{v^i}{T} X^{ij}(\mathbf{v}) = \frac{v^i}{T} X_L(v)$$

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

$$v \ll 1, \quad g \ll 1$$

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

Fokker-Planck Equation of Equilibrium QGP



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

The standard FP equation is reproduced!

Modeling of Isotropic, Homogenous & Stationary Turbulent QGP

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

'Gaussian E & B '

colorlessness

isotropy

$$\left\{ \begin{array}{l} \langle E_a^i(t, \mathbf{r}) E_b^j(0, \mathbf{0}) \rangle = \delta^{ab} \delta^{ij} M_E \exp\left(-\frac{t^2}{\tau^2} - \frac{\mathbf{r}^2}{\sigma^2}\right) \\ \langle E_a^i(t, \mathbf{r}) B_b^j(0, \mathbf{0}) \rangle = 0 \\ \langle B_a^i(t, \mathbf{r}) B_b^j(0, \mathbf{0}) \rangle = \delta^{ab} \delta^{ij} M_B \exp\left(-\frac{t^2}{\tau^2} - \frac{\mathbf{r}^2}{\sigma^2}\right) \end{array} \right.$$

$$X_L(\nu) = \sqrt{\frac{\pi}{2}} g^2 C_F \frac{M_E \tau \sigma}{\sqrt{\sigma^2 + \nu^2 \tau^2}}, \quad X_T(\nu) = \sqrt{\frac{\pi}{2}} g^2 C_F \frac{(M_E + \nu^2 M_B) \tau \sigma}{\sqrt{\sigma^2 + \nu^2 \tau^2}}$$

Modeling of Isotropic, Homogenous & Stationary Turbulent QGP

'Gaussian A'

$$\langle A_a^i(t, \mathbf{r}) A_b^j(0, \mathbf{0}) \rangle = \delta^{ab} \delta^{ij} M_A \exp\left(-\frac{t^2}{\tau^2} - \frac{\mathbf{r}^2}{\sigma^2}\right)$$

Gauge condition

$$A_a^0(t, \mathbf{r}) = 0, \quad \nabla \cdot \mathbf{A}_a(t, \mathbf{r}) = 0$$

$$\mathbf{E}_a(t, \mathbf{r}) = -\dot{\mathbf{A}}_a(t, \mathbf{r}),$$

$$\mathbf{B}_a(t, \mathbf{r}) = \nabla \times \mathbf{A}_a(t, \mathbf{r})$$

$$\langle E_a^i(t, \mathbf{r}) E_b^j(0, \mathbf{0}) \rangle, \quad \langle E_a^i(t, \mathbf{r}) B_b^j(0, \mathbf{0}) \rangle, \quad \langle B_a^i(t, \mathbf{r}) B_b^j(0, \mathbf{0}) \rangle$$

$$\left\{ \begin{aligned} X_L(v) &= \sqrt{\frac{\pi}{2}} g^2 C_F \frac{M_A \tau \sigma v^2}{(\sigma^2 + v^2 \tau^2)^{3/2}} \\ X_T(v) &= \sqrt{\frac{\pi}{8}} g^2 C_F \frac{M_A \tau v^2}{\sigma} \left[\frac{3}{(\sigma^2 + v^2 \tau^2)^{1/2}} - \frac{\sigma^2 + 3v^2 \tau^2}{(\sigma^2 + v^2 \tau^2)^{3/2}} \right] \end{aligned} \right.$$

Modeling of Isotropic, Homogenous & Stationary Turbulent QGP

'Stationary A'

$$\langle A_a^i A_b^j \rangle_{\omega, \mathbf{k}} = \delta^{ab} \delta^{ij} \frac{2\pi\delta(\omega)}{\mathbf{k}^2 + \mu^2} \Theta(|\mathbf{k}| - k_{\max}) M$$

Gauge condition

$$A_a^0(t, \mathbf{r}) = 0, \quad \nabla \cdot \mathbf{A}_a(t, \mathbf{r}) = 0$$



$$\mathbf{E}_a(t, \mathbf{r}) = -\dot{\mathbf{A}}_a(t, \mathbf{r}),$$

$$\mathbf{B}_a(t, \mathbf{r}) = \nabla \times \mathbf{A}_a(t, \mathbf{r})$$

$$\langle E_a^i(t, \mathbf{r}) E_b^j(0, \mathbf{0}) \rangle = 0, \quad \langle E_a^i(t, \mathbf{r}) B_b^j(0, \mathbf{0}) \rangle = 0, \quad \langle B_a^i(t, \mathbf{r}) B_b^j(0, \mathbf{0}) \rangle \neq 0$$

$$\left\{ \begin{array}{l} X_L(v) = 0 \\ X_T(v) \approx \frac{g^2 C_F}{16\pi} M k_{\max}^2 v \\ k_{\max} \gg \mu \end{array} \right.$$

Model Parameters

Turbulent plasma vs. equilibrium plasma at the same energy density

▶ Energy density of weakly coupled equilibrium QGP

$$\varepsilon_{\text{QGP}} = \frac{\pi^2}{60} \left(4(N_c^2 - 1) + 7N_f N_c \right) T^4$$

▶ Energy density accumulated in the fields

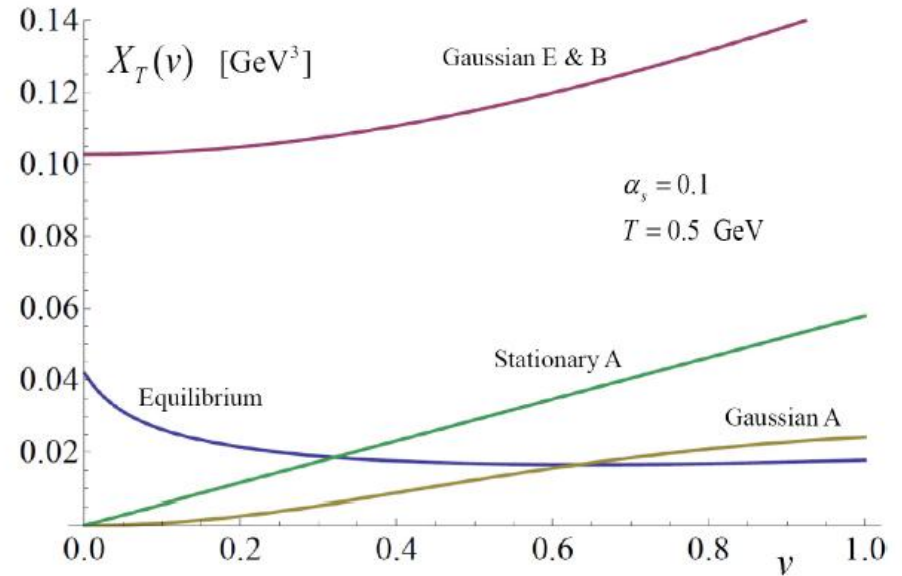
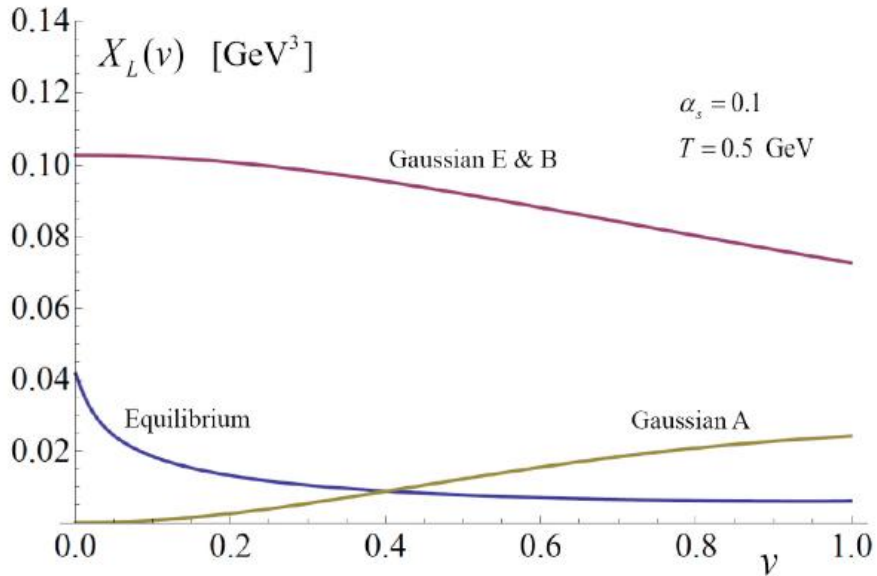
$$\varepsilon_{\text{field}} = \frac{1}{2} \left(\langle E_a^i(t, \mathbf{r}) E_a^i(t, \mathbf{r}) \rangle + \langle B_a^i(t, \mathbf{r}) B_a^i(t, \mathbf{r}) \rangle \right)$$

$$\varepsilon_{\text{QGP}} = \varepsilon_{\text{field}} = (N_c^2 - 1) \times \begin{cases} \frac{3}{2} (M_E + M_B) & \text{'Gaussian E \& B'} \\ \frac{3}{2} \left(\frac{1}{\tau^2} + \frac{2}{\sigma^2} \right) M_A & \text{'Gaussian A'} \\ \frac{M k_{\text{max}}^3}{6\pi^2} & \text{'stationary A'} \end{cases}$$

$$M_E = M_B, \quad M_A, \quad \tau = \sigma = \frac{1}{m_D}, \quad k_{\text{max}} = 5m_D$$

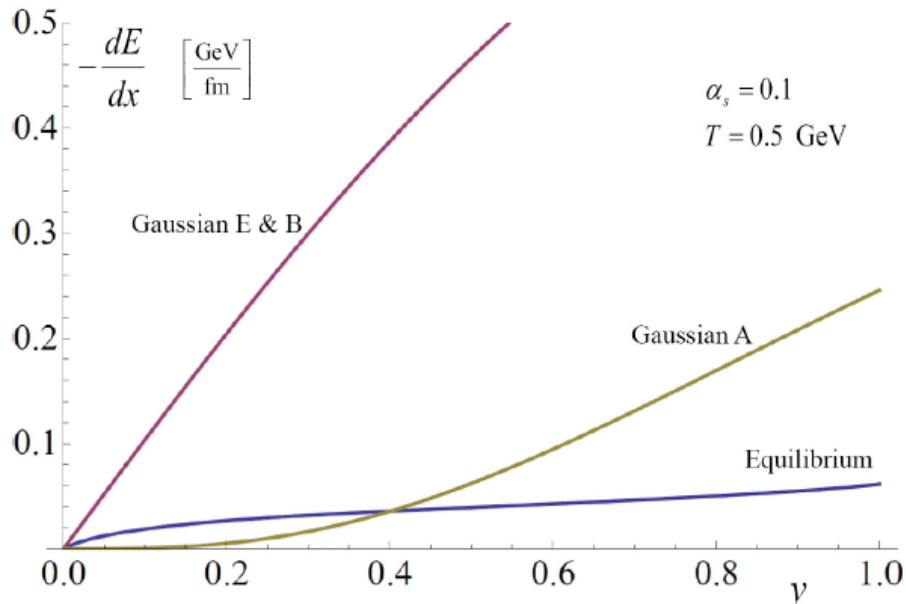
$$g, T$$

Turbulent vs. Equilibrium Plasmas



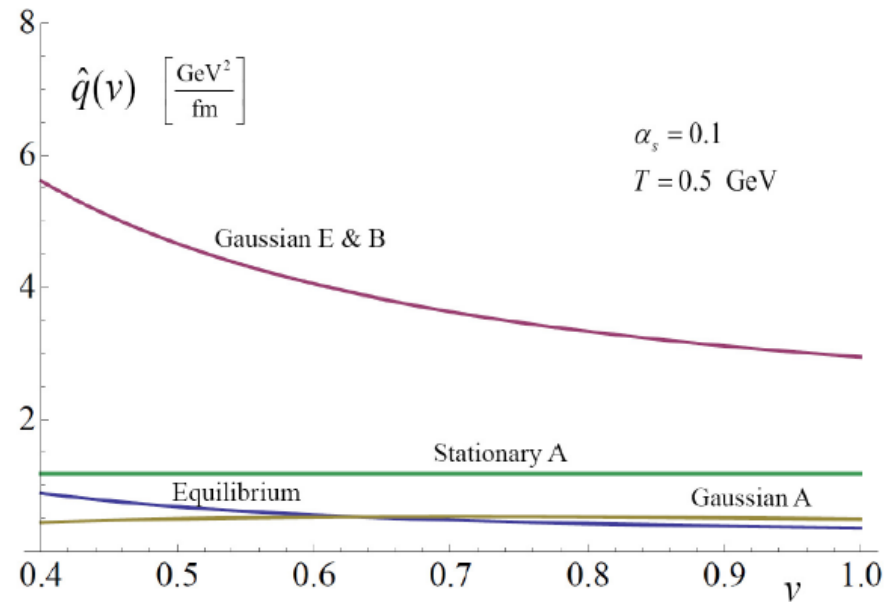
Turbulent vs. Equilibrium Plasmas

Collisional energy loss



$$\frac{dE}{dx} = -\frac{v}{T} X_L(v)$$

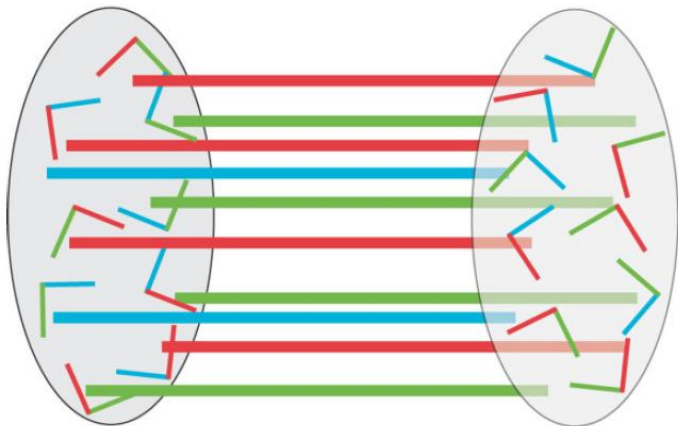
Momentum broadening



$$\hat{q} = \frac{4}{v} X_T(v)$$

Glasma

The earliest stage of relativistic heavy-ion collisions



E & B fields along the axis z

$$A_a^\mu(t, \mathbf{r}) = \left(A_a^0(t, z), A_a^x(x, y), A_a^y(x, y), A_a^z(t, z) \right)$$

Boost-invariant correlation functions

$$\left\langle E_a^z(t_1, z_1) E_b^z(t_2, z_2) \right\rangle = \delta^{ab} \Theta(t_1^2 - z_1^2) \Theta(t_2^2 - z_2^2) \tilde{M}_E \exp\left(-\frac{(\tau_1 - \tau_2)^2}{2\sigma_\tau^2} - \frac{(\eta_1 - \eta_2)^2}{2\sigma_\eta^2} \right)$$

$$\left\langle B_a^z(x_1, y_1) B_b^z(x_1, y_1) \right\rangle = \delta^{ab} \tilde{M}_B \exp\left(-\frac{x^2 + x^2}{2\sigma_T^2} \right)$$

$$\tau_i \equiv \sqrt{t_i^2 - z_i^2}, \quad \eta_i \equiv \frac{1}{2} \log\left(\frac{t_i + z_i}{t_i - z_i} \right), \quad i = 1, 2$$

Glasma

$$X^{ij}(\mathbf{v}) = \sqrt{\frac{\pi}{2}} g^2 C_F \left(\tilde{M}_E n^i n^j - \frac{V^{ij}}{v_T} \tilde{M}_B \sigma_T \right)$$

$$n^i \equiv (0,0,1), \quad V^{ij} \equiv \varepsilon^{ikl} v^k n^l \varepsilon^{jmn} v^m n^n = \begin{pmatrix} v_y^2 & -v_x v_y & 0 \\ -v_x v_y & v_x^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

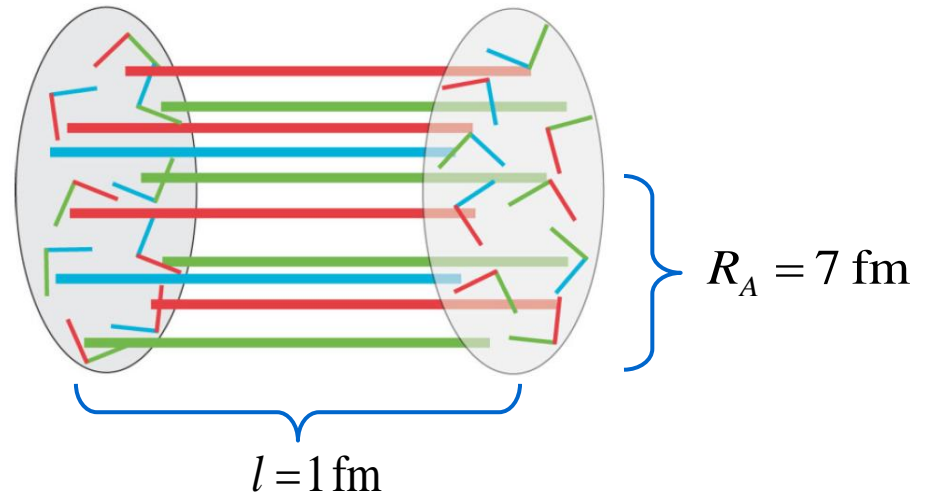
$$\left\{ \begin{array}{l} -\frac{dE}{dx} = \frac{v^i v^j}{vT} X^{ji}(\mathbf{v}) \quad \text{collisional energy loss} \\ \hat{q} = \frac{2}{v} \left(\delta^{ij} - \frac{v^i v^j}{v^2} \right) X^{ji}(\mathbf{v}) \quad \text{momentum broadening} \end{array} \right.$$

Model Parameters

Density of energy released in a central collision

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

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



$$\mathcal{E}_{\text{coll}} = \mathcal{E}_{\text{field}}$$

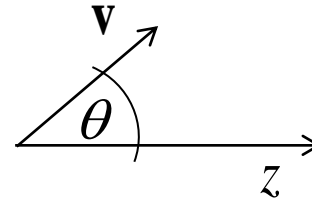
$$(T = 1.2 \text{ GeV})$$

$$\tilde{M}_E = \tilde{M}_B, \quad \sigma_T = Q_s^{-1} = 0.5 \text{ [GeV}^{-1}\text{]}$$

Energy-loss and Momentum Broadening in the Glasma

$$\left\{ \begin{array}{l} -\frac{dE}{dx} = 14 \cos^2 \theta \left[\frac{\text{GeV}}{\text{fm}} \right] \\ \hat{q} = 33(\sin^2 \theta + \sin \theta) \left[\frac{\text{GeV}^2}{\text{fm}} \right] \end{array} \right.$$

$$v=1$$



Typical values inferred from experimental data on jet quenching

$$\left\{ \begin{array}{l} -\frac{dE}{dx} = 1.0 - 3.0 \left[\frac{\text{GeV}}{\text{fm}} \right] \\ \hat{q} = 1.5 - 7.0 \left[\frac{\text{GeV}^2}{\text{fm}} \right] \end{array} \right.$$

Summary & Conclusions

- ▶ The Fokker-Planck equation of heavy quarks interacting with classical chromodynamic fields rather than with plasma constituents is derived.
- ▶ The known case of equilibrium plasma is reproduced.
- ▶ The turbulent plasma with the energy dominated by chromodynamic classical fields interacts strongly with heavy quarks.
- ▶ In spite of its short lifetime the glasma can provide a significant contribution to the collisional and radiative energy loss of heavy quarks.

more details in: St. Mrówczyński, European Physical Journal A **54**, 43 (2018)