

Hard probes in heavy ions as open quantum systems

Hard probes in non-equilibrium QCD matter
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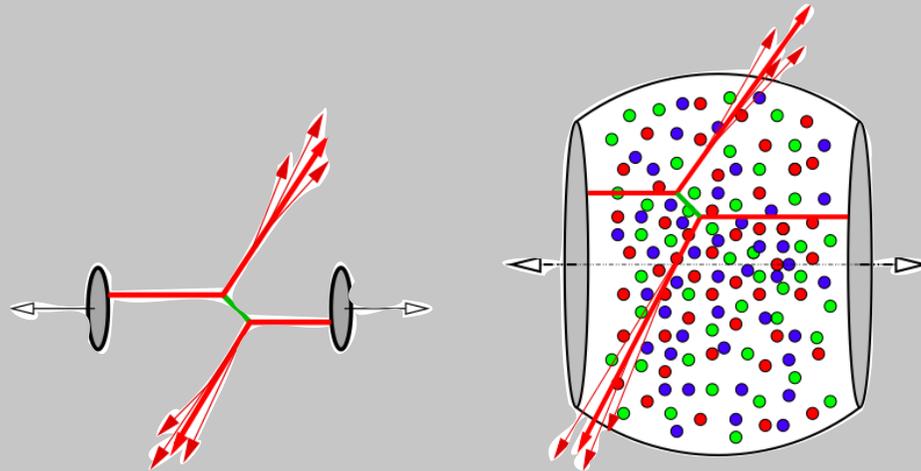


Hard probes

Hard probes are produced in hard processes on very short time scales

$$\Delta x \sim \Delta t \sim 1/M, 1/Q \quad M, Q \ll \Lambda_{\text{QCD}}$$

Thus, they are present in the early stages of heavy ion collisions



Two types of hard probes:

- "Elementary" HP: direct photons, Z and W bosons, etc.
- "Complex" HP: quarkonia, jets

Hard probes

Elementary hard probes provide information on the "initial state" (e.g. npdf): Their yield scales with the number of n-n collisions. They are weakly affected by the surrounding medium.

Complex hard probes have their own dynamics in the absence of the QGP. This dynamics can be significantly altered by the presence of the quark-gluon plasma. Understanding such modifications can yield information about the QGP properties.

Techniques from the study of **open quantum systems** are useful to understand the dynamics of complex hard probes;

- new techniques, new approximation schemes
- unifying perspective

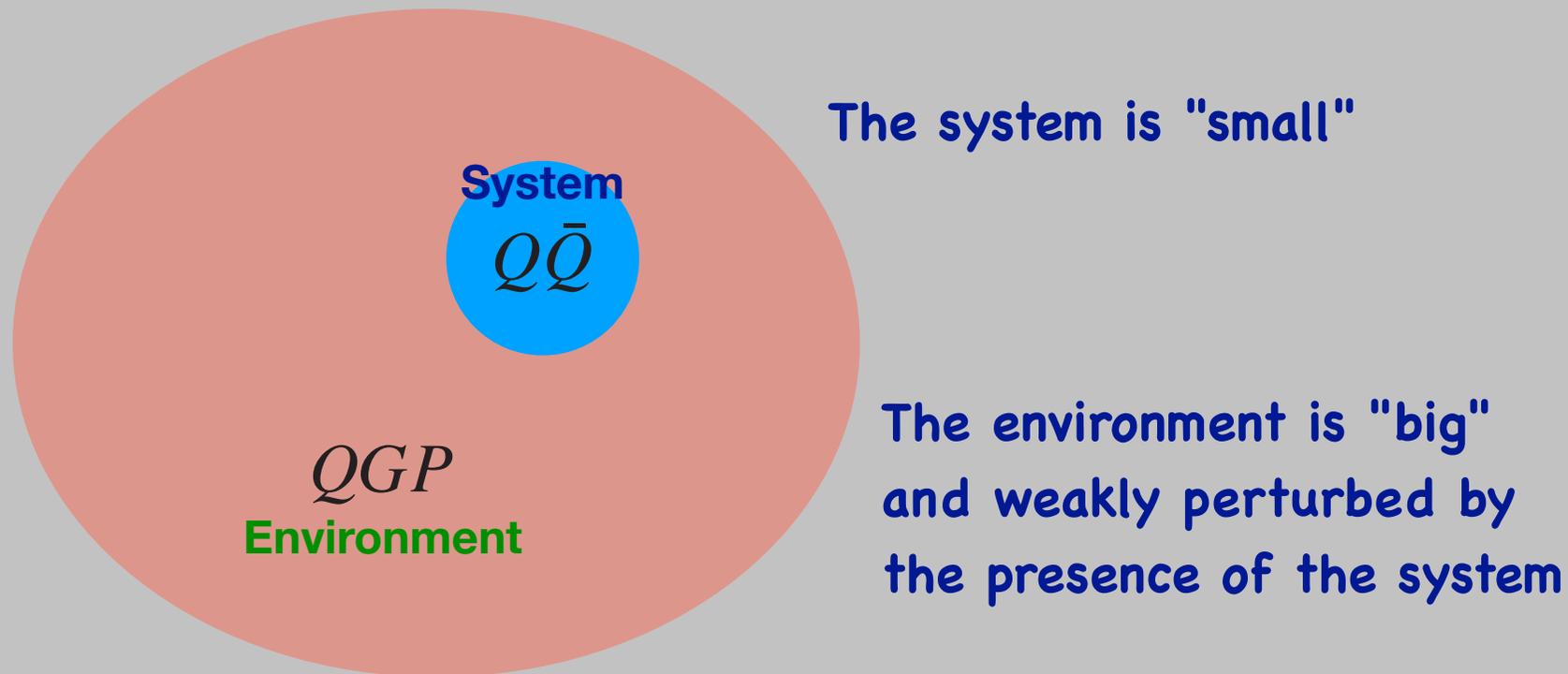
Open Quantum Systems

For recent reviews in the QCD context, see

Yukinao Akamatsu, "Quarkonium in Quark-Gluon Plasma: Open Quantum System Approaches Re-examined",
2009.10559

Xiaojun Yao, "Open Quantum Systems for Quarkonia",
2102.01736

Open quantum system (1)



The dynamics of the system is obtained after eliminating the degrees of freedom of the environment (-> effective theory). This yields in general a **non unitary evolution** (decoherence, dissipation).

The dynamics of the system is affected by the presence of the environment via simple correlation functions characterising the environment. **The system probes these correlation functions.**

Open quantum system (2)

The density matrix of total system $\mathcal{D}(t)$ obeys the equation of motion

$$i\frac{d\mathcal{D}}{dt} = [H, \mathcal{D}].$$

We need the **reduced density matrix** of the system:

$$\mathcal{D}_Q(t) = \text{Tr}_{\text{pl}} \mathcal{D}(t)$$

Equation of motion for $\mathcal{D}_Q(t)$

$$\frac{d}{dt} \mathcal{D}_Q(t) = -i[H_Q, \mathcal{D}_Q(t)] + \int_{t_0}^t dt' \mathcal{L}(t-t') \mathcal{D}_Q(t')$$

Non hamiltonian contribution

Various strategies:

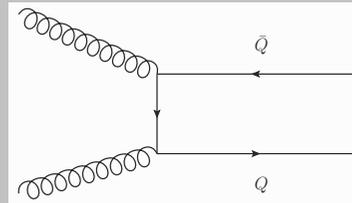
- Feynman-Vernon Influence functional
- Master equation for the density matrix, Lindblad equation,
- Schwinger-Keldysh diagrammatic techniques,
- Etc

Heavy quarkonia

[JPB, M. Escobedo-Espinosa, [1711.10812](#), [1803.07996](#), [2106.1571](#)
S.Delorme, R. Katz, T. Gousset, PB. Gossiaux, JPB, in preparation]

Heavy quarks and quarkonia as 'hard probes'

Heavy quarks are produced in pairs in the early stages of URHIC. Their number remains constant.



Formation time of a $Q\bar{Q}$ pair is small

$$\Delta t \sim \frac{1}{2M_Q}$$

$$J/\Psi \quad M_c \simeq 1.5 \text{ Gev} \quad \Delta t \simeq 0.07 \text{ fm/c}$$

$$\Upsilon \quad M_b \simeq 4.5 \text{ Gev} \quad \Delta t \simeq 0.02 \text{ fm/c}$$

Dynamics of heavy quarks is non-relativistic

$$H = \frac{P^2}{M_Q} + V(r) \quad \left(V(r) = \frac{\alpha_s}{r} + \sigma r \right)$$

The potential can be obtained using effective theory (pNRQCD)

[see N. Brambilla, A.Pineda, J. Soto, A. Vairo, NPB566 (2000) 275]

Heavy quark interaction at finite T

Initial suggestion (Matsui-Satz 86): **screening** of the potential

$$H = \frac{p^2}{M_Q} + V(r) \qquad V(r) = -\frac{\alpha}{r} e^{-r m_D(T)} + \sigma(T)r$$

Hence the "suppression" of bound states at high temperature, the most "fragile" ones (bigger, less bound) disappearing first as the temperature increases ("sequential suppression").

Hence the idea of using quarkonia to diagnose the formation of quark-gluon plasma in URHIC

However, the dynamics of the quarkonia does not reduce to a mere modification of the potential: non unitary evolution, here caused by "**collisions**" with plasma constituents.

In fact, this is a **VERY COMPLICATED MANY-BODY PROBLEM**

Typical approximations in QQS

(i) Weak coupling between HQ and the plasma

$$H_1 = -g \int_{\mathbf{r}} A_0^a(\mathbf{r}) n^a(\mathbf{r}),$$

gauge potential of plasma HQ density

$$n^a(\mathbf{x}) = \delta(\mathbf{x} - \hat{\mathbf{r}}) t^a \otimes \mathbb{I} - \mathbb{I} \otimes \delta(\mathbf{x} - \hat{\mathbf{r}}) \tilde{t}^a,$$

The presence of the heavy quarks does not modify significantly the equilibrium state of the plasma.

The influence of the plasma on the heavy quark dynamics is characterized by simple response functions (correlators)

$$\Delta(t_1, t_2) \equiv \langle A_{\text{pl}}(t_1) A_{\text{pl}}(t_2) \rangle_T = \text{Tr} \left[A_{\text{pl}}(t_1) A_{\text{pl}}(t_2) \mathcal{D}_{\text{pl}} \right]$$

No assumption of weak or strong coupling needs to be made concerning the plasma. The correlators can, in some cases, be obtained from "lattice calculations".

(ii) The response of the plasma is "fast"

plasma response is characterized by a single energy scale, the Debye mass

$$m_D = CT \quad (C \simeq 2) \quad \text{in strict weak coupling} \quad C = g$$

$$m_D \ll M$$

collisions with plasma constituents involve small energy transfer

soft gluon exchanges

$$q \lesssim m_D \ll M$$

small energy transfer

$$\frac{q^2}{M} \sim \frac{m_D^2}{M} \ll m_D$$

the relevant correlator is then generically of the form

$$\Delta(\omega = 0, \mathbf{r}) = \Delta^R(\omega = 0, \mathbf{r}) + i\Delta^<(\omega = 0, \mathbf{r})$$

$$V(\mathbf{r}) = -\Delta^R(\omega = 0, \mathbf{r}), \quad W(\mathbf{r}) = -\Delta^<(\omega = 0, \mathbf{r})$$

Screened potential

Imaginary potential

from the point of view of the HQ the interactions with the plasma are nearly instantaneous ("collisions")

$$\begin{aligned} \Delta(t_x - t_y) &= \int \frac{d\omega}{2\pi} e^{-i\omega(t_x - t_y)} [\Delta(\omega = 0) + \omega \Delta'(\omega = 0)] \\ &\simeq \delta(t_x - t_y) \Delta(\omega = 0) + i \frac{d}{dt_x} \delta(t_x - t_y) \Delta'(\omega = 0) \end{aligned}$$

**NB. Strictly valid
in QBM regime.**

Static response and "optical potential"

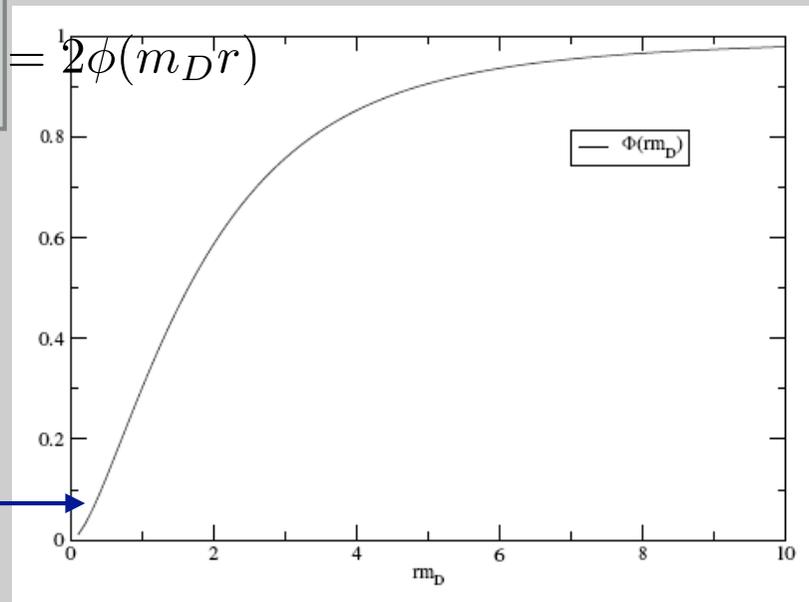
(*first obtained by M. Laine et al hep-ph/0611300)

$$\mathcal{V}(r) = V(r) + iW(r)$$

$$\Delta^R(\omega = 0, r) = -V(r)$$

$$\Delta^<(\omega = 0, r) = -W(r)$$

$$\Gamma(r) = W(r) - W(0) = 2\Phi(m_D r)$$

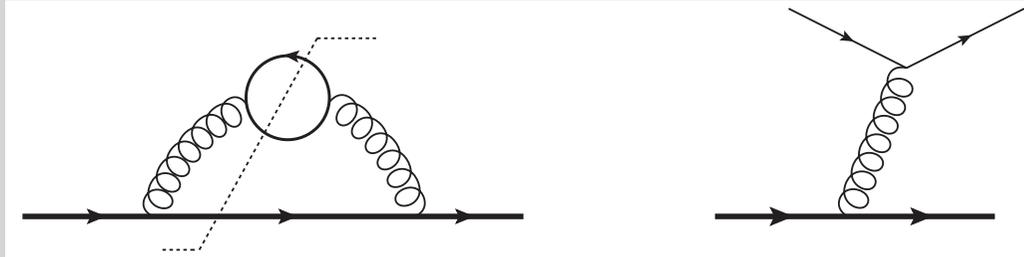


At large distance the imaginary part is twice the "damping rate" of the heavy quark

$$\Phi(x) = \frac{x^2}{3} \left(-\ln x + \frac{4}{3} - \gamma_E \right)$$

At small distance,
"color transparency"

What is the "imaginary potential" ?



HQ self energy

Collision of HQ with plasma constituent

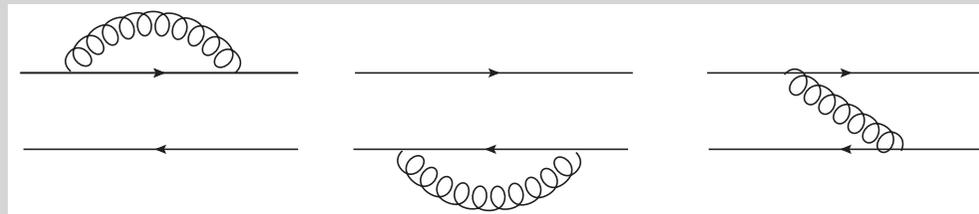
NB. The heavy quark does not "disappear" !

For one heavy quark

$$\partial_t \langle \mathbf{r} | D_Q | \mathbf{r}' \rangle = \dots - \Gamma(\mathbf{r} - \mathbf{r}') \langle \mathbf{r} | D_Q | \mathbf{r}' \rangle$$

makes density matrix nearly diagonal in coordinate space:
(collisional decoherence)

At short distance, interference produces cancellation: a small dipole does not "see" the electric field fluctuations.
(color transparency)



(iii) semi-classical approximation

$$M \gg T$$

HQ thermal wavelength $\lambda_{\text{th}} \sim \frac{1}{\sqrt{MT}} \ll \frac{1}{T}$

Density matrix becomes nearly diagonal

$$\langle \mathbf{r} | \mathcal{D}_Q | \mathbf{r}' \rangle \simeq 0 \quad \text{when} \quad |\mathbf{r} - \mathbf{r}'| \gtrsim \lambda_{\text{th}}$$

Expansion in $|\mathbf{r} - \mathbf{r}'|$  Fokker-Planck and Langevin equations

This program (i, ii, iii) can be fully realised for Abelian plasmas

J-P.B, D. de Boni, P. Faccioli and G. Garberoglio, NPA (2016)

Semi-classical expansion for heavy quark motion

- Equation for the density matrix \longrightarrow Langevin equation
- Langevin equation for the relative motion

$$\frac{M}{2} \ddot{\mathbf{r}}^i = -\gamma_{ij} \mathbf{v}^j - \nabla^i V(\mathbf{r}) + \xi^i(\mathbf{r}, t)$$

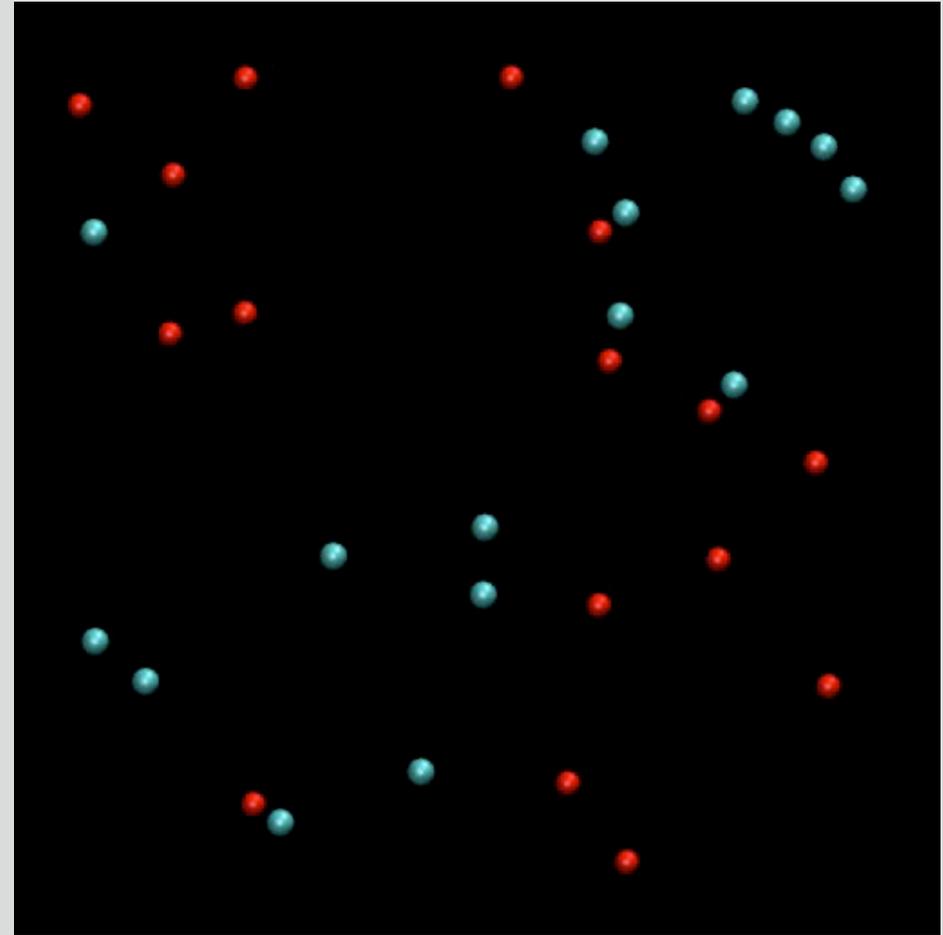
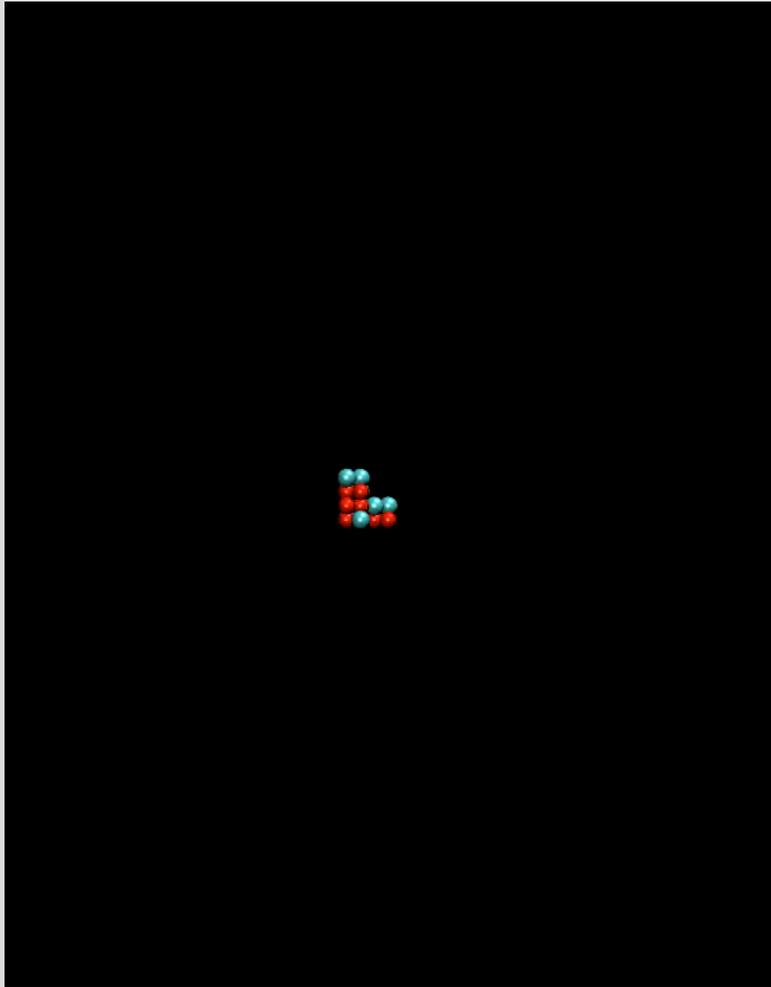
$$\gamma_{ij}(\mathbf{r}) = \frac{1}{2T} \eta_{ij}(\mathbf{r}) \quad \langle \xi^i(\mathbf{r}, t) \xi^j(\mathbf{r}, t') \rangle = \eta_{ij}(\mathbf{r}) \delta(t - t')$$

Non trivial noise

- For an isotropic plasma

$$\eta_{ij}(\mathbf{r}) = \delta_{ij} \eta(\mathbf{r}) \quad \eta(\mathbf{r}) = \frac{1}{6} (\nabla^2 W(0) + \nabla^2 W(\mathbf{r}))$$

The semi-classical approximation allows for very detailed simulations (abelian plasmas)



J-P.B, D. de Boni, P. Faccioli and G. Garberoglio, NPA (2016)

From QED to QCD

Some of the previous discussion goes through...

...but with essential differences

Force between HQ depends on color

New random force, dependent on color

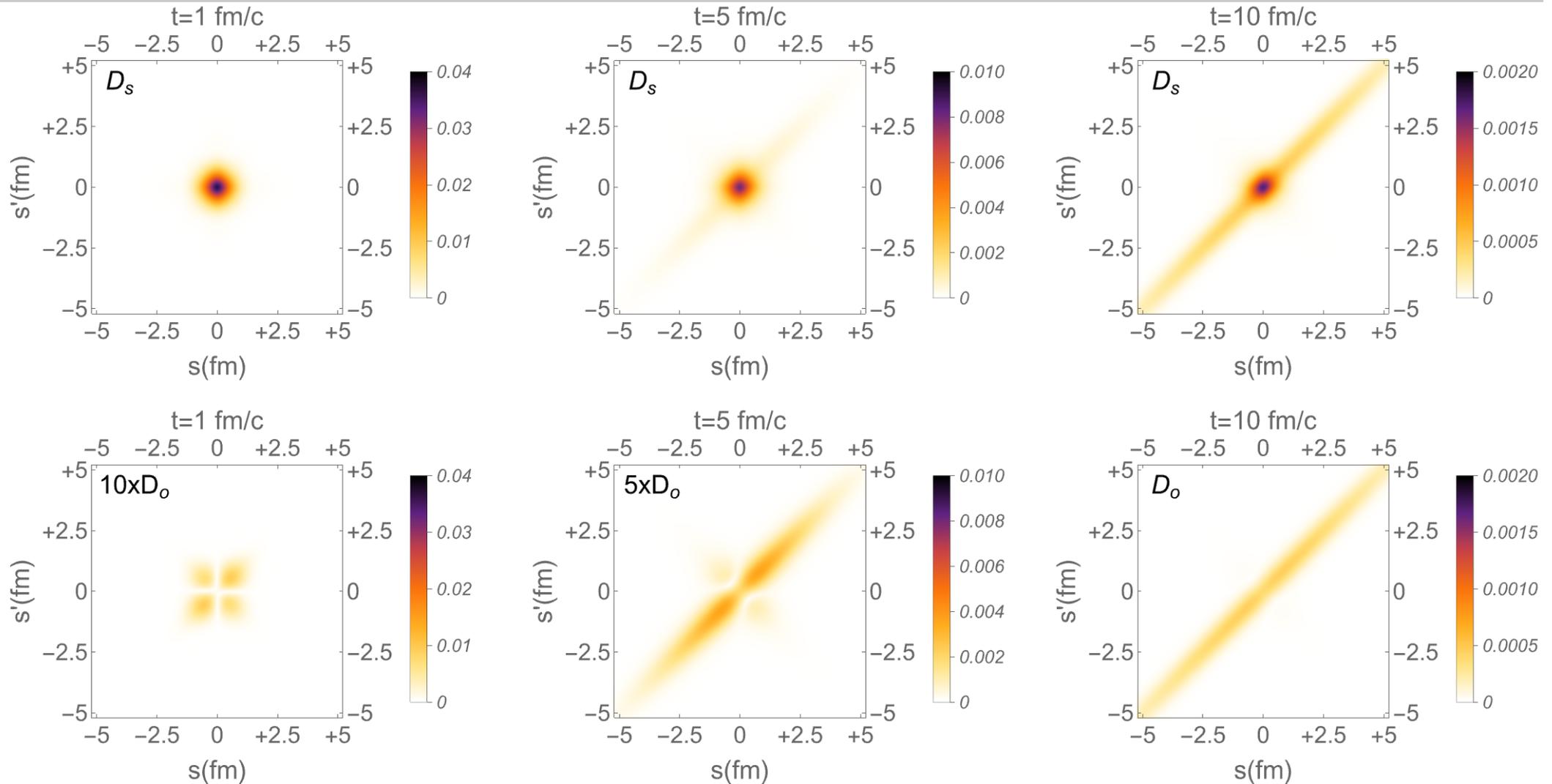
Subtle interplay between color and coordinate space dynamics -> complicates the semi-classical description

The treatment of multiple pairs is difficult

Recent progress in a one dimensional setting, see S.Delorme, R. Katz, T. Gousset, PB. Gossiaux, JPB (2023)

Collisional decoherence

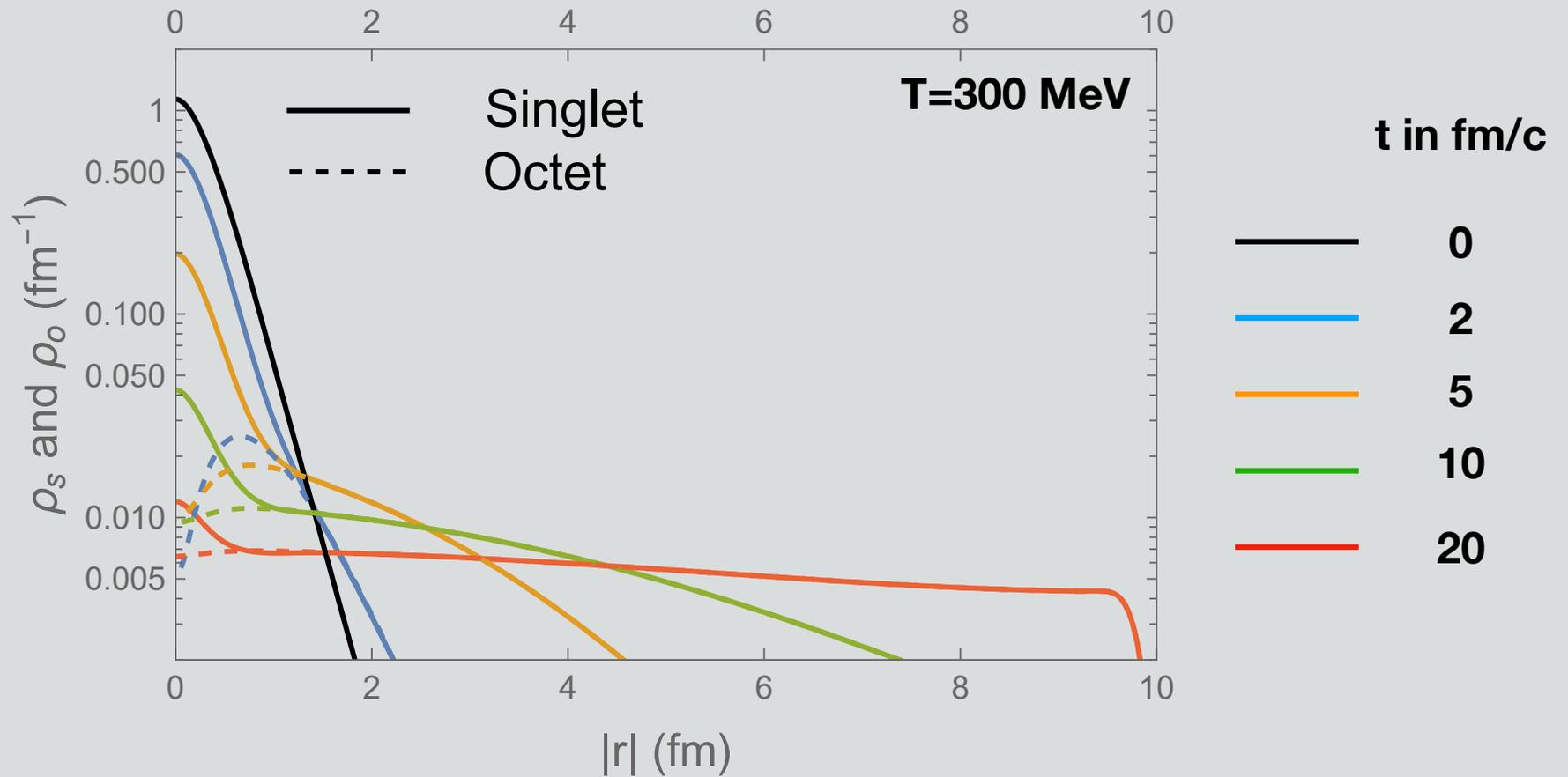
charm quark-antiquark pair at $T=300$ MeV



[From S.Delorme, R. Katz, T. Gousset, PB. Gossiaux, JPB (2023)]

Color equilibration

$$\rho_{s,o} = \langle r | \mathcal{D}_{s,o} | r \rangle$$



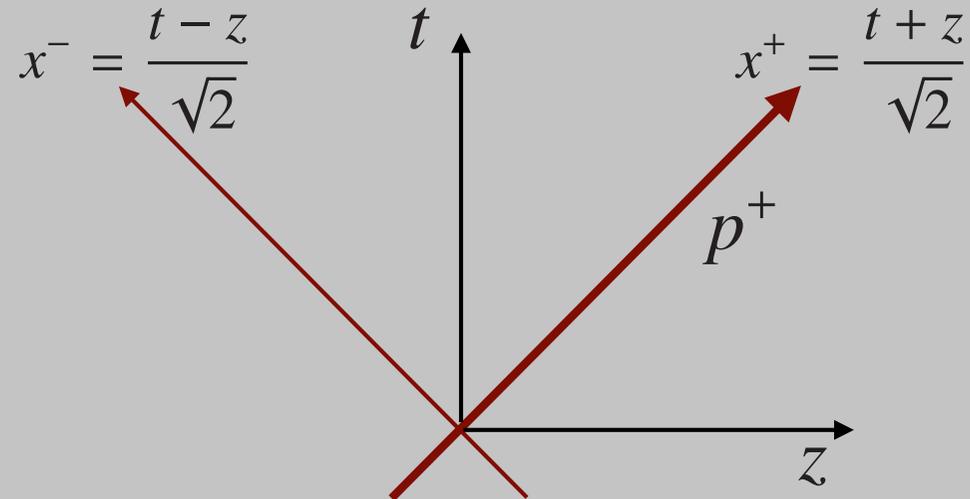
[From S.Delorme, R. Katz, T. Gousset, PB. Gossiaux, JPB (2023)]

Jet momentum broadening

[Based on J. Barata, JPB and Y. Mehtar-Tani, 2305.10476]

Momentum broadening

Consider a high energy quark propagating in the positive z-direction



The dynamics reduce to a two-dimensional non-relativistic problem in the transverse plane with $E=p^+$ playing the role of a mass and x^+ the role of time:

$$\left[i\partial_t + \frac{\partial_{\perp}^2}{2E} + gA(\mathbf{r}, t) \right] \psi(\mathbf{r}, t) = 0 \quad A \mapsto A_a^- t^a$$

$$(x^+ \mapsto t, p^+ \mapsto E)$$

The reduced density matrix

The gauge potential of the plasma is a fluctuating field with (Gaussian) correlation function

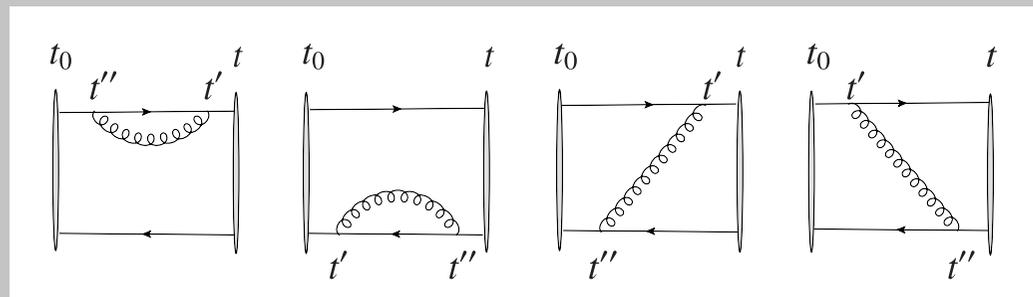
$$\langle A_a^-(x^+, \mathbf{x}) A_b^-(y^+, \mathbf{y}) \rangle = \delta_{ab} \delta(x^+ - y^+) \gamma(x^+, \mathbf{x} - \mathbf{y})$$

$$\gamma(0) - \gamma(\mathbf{r}) = g^2 n \int \frac{d^2 \mathbf{q}}{(2\pi)^2} \frac{1 - e^{i\mathbf{q} \cdot \mathbf{r}}}{(\mathbf{q}^2 + m_D^2)^2} \quad g^2 (\gamma(0) - \gamma(\mathbf{r})) = \frac{n}{2} \sigma(\mathbf{r}) \quad (r = |\mathbf{x} - \mathbf{y}|)$$

$\sigma(\mathbf{r})$ is called the dipole cross section. It is the analog of the imaginary part of the potential in the HQ problem **NB.** $\sigma(r) \propto \hat{q} r^2$

The reduced density matrix is obtained by averaging over the gauge field

$$\mathcal{D} = \text{tr}_A \mathcal{D} [A]$$



Equations for the reduced density matrix

Using the same approximations as in the HQ case, one gets

$$\frac{\partial}{\partial t} \langle r | \mathcal{D}(t) | r' \rangle = -\frac{i}{2E} \left(\frac{\partial^2}{\partial r'^2} - \frac{\partial^2}{\partial r^2} \right) \langle r | \mathcal{D}(t) | r' \rangle - \Gamma(r - r') \langle r | \mathcal{D}(t) | r' \rangle$$

Strict eikonal approximation (large mass limit, $E \gg T$)

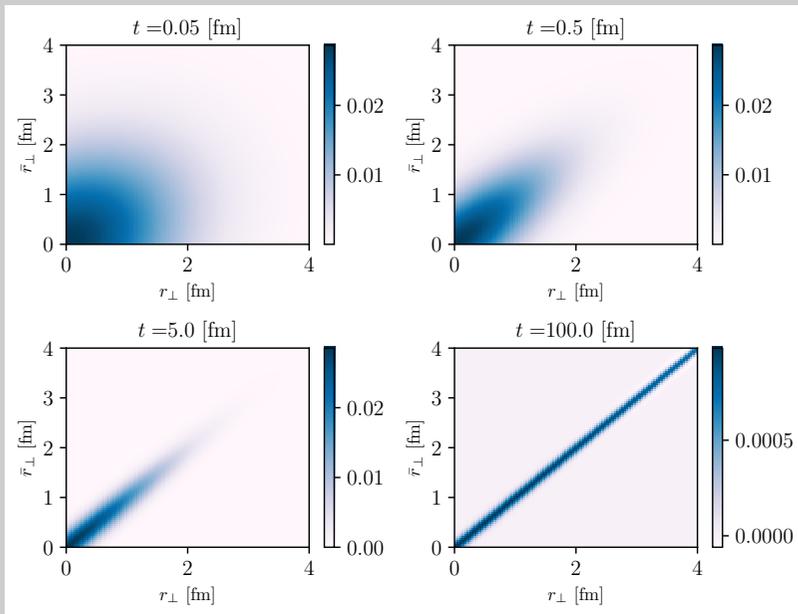
$$\langle r | \mathcal{D}(t) | r' \rangle = \langle r | \mathcal{D}(t_0) | r' \rangle e^{-t\Gamma(r-r')}$$

damping affects non diagonal matrix elements: collisional decoherence

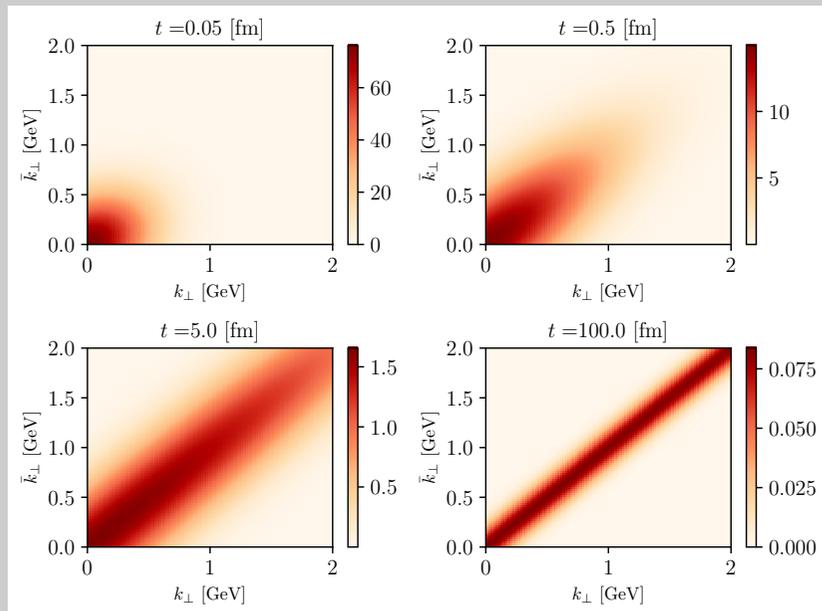
no damping at short distance (color transparency)

The reduced density matrix becomes diagonal

.... in both coordinate space and in momentum space !



$$\rho(\mathbf{b} = 0, \mathbf{x}, t) \approx \frac{1}{\pi \langle \mathbf{b}^2 \rangle_t} \exp \left\{ -\frac{\langle \mathbf{k}^2 \rangle_t \mathbf{x}^2}{4} \right\}$$



$$\begin{aligned} \rho(\ell, \mathbf{K} = 0, t) &\approx \frac{4\pi}{\mu^2 + \hat{q}t} \exp \left\{ -\frac{\ell^2 \hat{q}t^3}{48E^2} \right\} \\ &= \frac{4\pi}{\langle \mathbf{k}^2 \rangle_t} \exp \left\{ -\frac{\ell^2 \langle \mathbf{b}^2 \rangle_t}{16} \right\} \end{aligned}$$

Entropy growth

von Neumann entropy

$$S_{\text{vN}}[\rho] = -\text{Tr} \rho \ln \rho = \log \left(\frac{1-p}{4p} \right) + \frac{1}{\sqrt{p}} \ln \frac{1+p+2\sqrt{p}}{(1-p)}$$

"purity" $p \equiv \text{Tr} \rho^2$

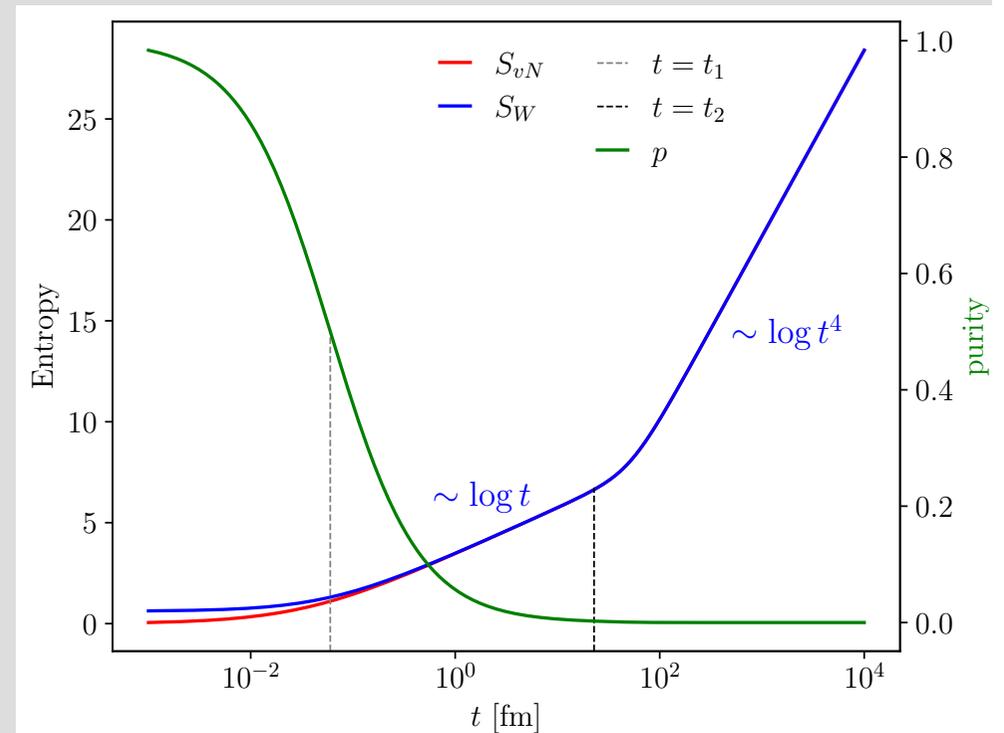
$$\frac{1}{p} = \left(1 + \frac{t}{t_1} \right) \left(1 + \frac{t^3}{12t_2^3} \frac{t+4t_1}{t+t_1} \right)$$

late time behavior

$$S_{\text{vN}} \simeq \ln \frac{1}{p} \simeq \ln \frac{\hat{q}^2 t^4}{E^2} \sim \ln \langle \mathbf{k}^2 \rangle_t \langle \mathbf{b}^2 \rangle_t$$

classical Wigner entropy

$$S_{\text{W}} \equiv - \int_{\mathbf{K}, \mathbf{b}} \rho_{\text{W}}(\mathbf{b}, \mathbf{K}) \log \rho_{\text{W}}(\mathbf{b}, \mathbf{K})$$



Summary

- The theory of open quantum systems offers a useful framework to calculate the interactions of complex hard probes with their environment.
- It also provides interesting perspectives and reveals connections between seemingly unrelated problems (examples discussed in the talk: quarkonia and (simplified) jets).
- It allows to derive many different approaches from a common starting point.