Heavy quarks and quarkonia in the early stage of pA collisions

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Coworkers

- Vincenzo Greco
- Lucia Oliva
- Gabriele Parisi
- Binu Muraleedharan

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NextGenerationEU

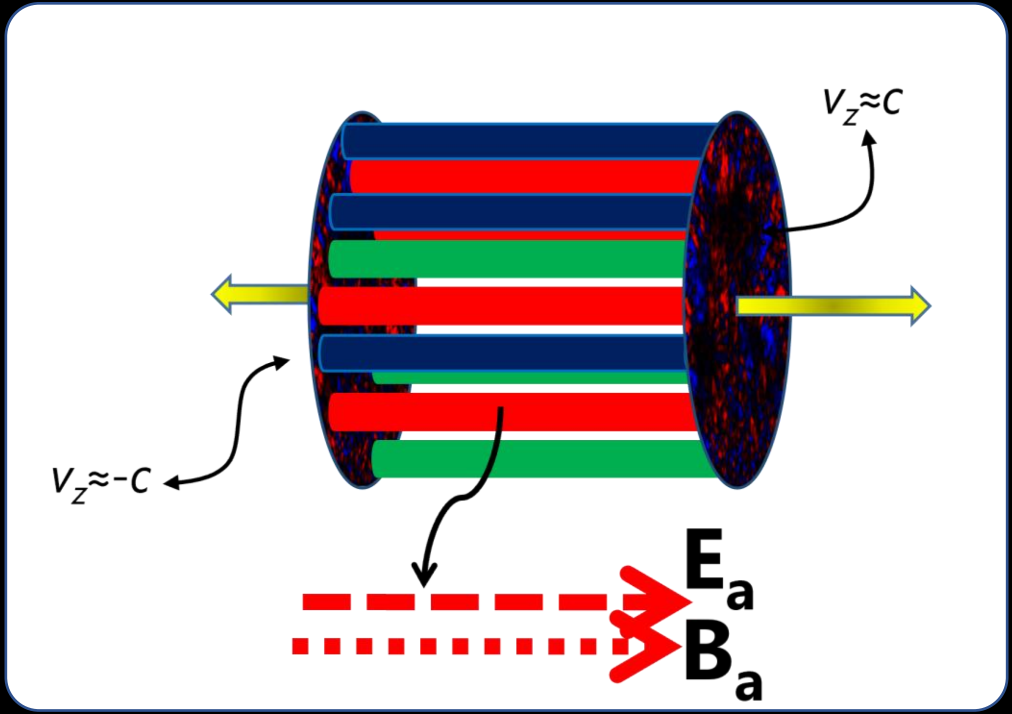
Plan of the talk

- *A user-friendly introduction to glasma and its evolution*
- *Heavy quarks in the early stage*
- *Quarkonia in the early stage*
- *Conclusions and outlook*

Glasma and its evolution

Many gluons in the early stage

Useful, easy description in terms of ***classical, intense fields***, rather than in terms of one-particle states

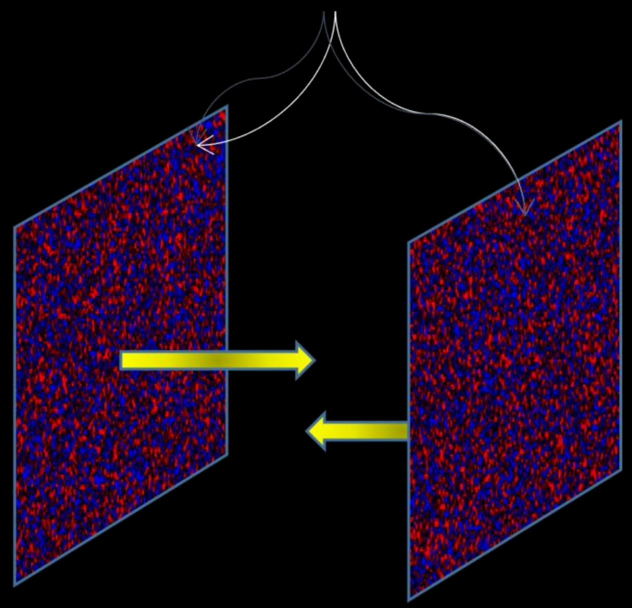


Glasma (*)

Glasma: *initial condition* for the medium produced in RHICs.

(*)Lappi and McLerran (2006)

The MV model for the color sources: portion of a large nucleus



Model of sources of the classical gluon fields (MV)

Uncorrelated color density fluctuations on the two nuclei.

McLerran and Venugopalan (1996)
Kovchegov (1996)

Gaussian distribution of color charges (*)

$$\langle \rho^a(\boldsymbol{x}_T) \rangle = 0,$$

$$\langle \rho^a_A(\boldsymbol{x}_T) \rho^b_A(\boldsymbol{y}_T) \rangle = (g\mu_A)^2 \delta^{ab} \delta^{(2)}(\boldsymbol{x}_T - \boldsymbol{y}_T)$$

$g^2\mu \approx Qs$: saturation scale

Lappi (2008)

$$Q_s \approx 1 - 3 \text{ GeV}$$

(*) Realistic Qs distribution for large nuclei: Schenke et al (2022-.....)

Hot spots model

Valence quarks act as sources for static charges that generate the CGC fields

$$T_{cq}(\boldsymbol{x}_i) = \frac{1}{2\pi B_{cq}} \exp\left(-\frac{\boldsymbol{x}_i^2}{2B_{cq}}\right)$$

Constituent quarks
[centers of hotspots
B_{cq}=(0.4 fm)^2]

$$T_p(\boldsymbol{x}_T) = \frac{1}{3}\sum_{i=1}^{3} \frac{1}{2\pi B_q} \exp\left(-\frac{(\boldsymbol{x}_T - \boldsymbol{x}_i)^2}{2B_q}\right)$$

Static color charges
[around the hotspots
B_q=(0.11 fm)^2]

$$\boxed{Q_s^2(x, \boldsymbol{x}_\perp) = \frac{2\pi^2}{N_c}\alpha_s\, xg(x, Q_0^2)\, T_p(\boldsymbol{x}_\perp)}$$

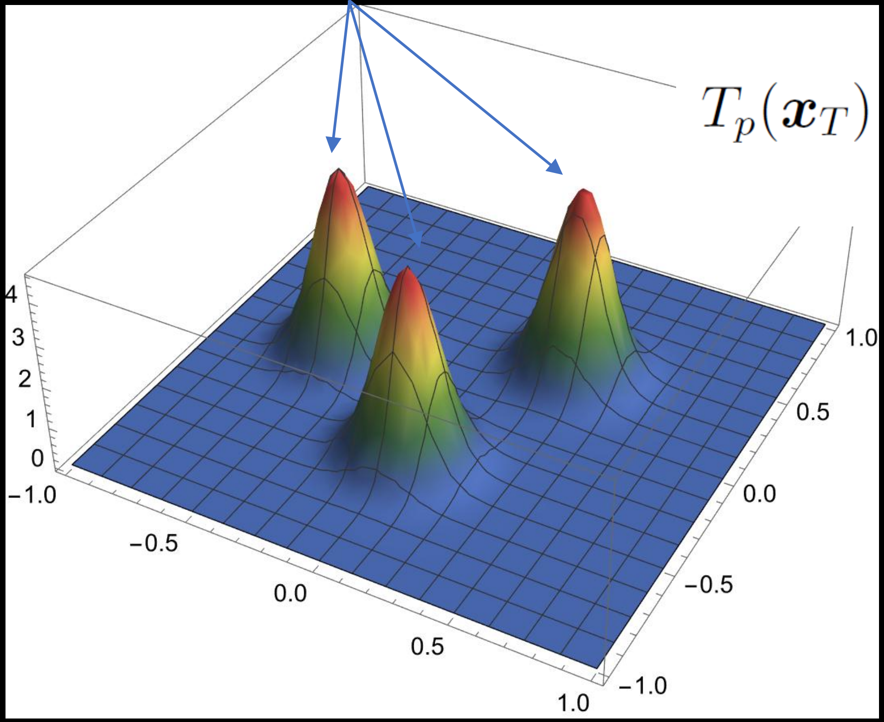
Saturation scale in the transverse plane

Simplest implementation (Q_0=1 GeV, x=10^{-4})

$$xg(x, Q_0^2) = A_g x^{-\lambda_g}(1-x)^{f_g}$$
$$A_g = 2.308, \quad \lambda_g = 0.058, \quad f_g = 5.6$$

xg≈3.94

Valence quarks (hotspots)



B. Schenke *et al.* (2022,2023)
G. Parisi *et al* (2025)
Oliva et al (2024)

Hot spots model

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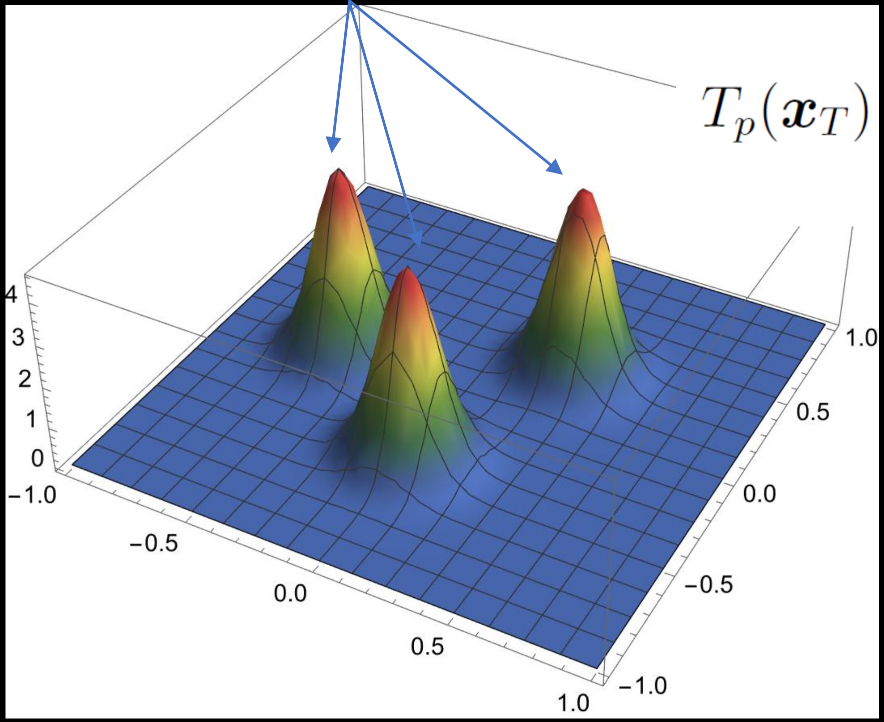
Saturation scale in the transverse plane

$$g^2\mu(x, \boldsymbol{x}_\perp) = cQ_s(x, \boldsymbol{x}_\perp)$$

(c = 1.25)

$$\langle \rho^a(\boldsymbol{x}_T)\rho^b(\boldsymbol{y}_T)\rangle = g^2\mu^2(x, \boldsymbol{x}_T)\delta^{ab}\delta^{(2)}(\boldsymbol{x}_T - \boldsymbol{y}_T)$$

Valence quarks (hotspots)



B. Schenke *et al.* (2022,2023)
G. Parisi *et al* (2025)
Oliva et al (2024)

Due to the large density the gluon field behaves like a classical field:
Dynamics is governed by classical EoMs, namely the classical Yang-Mills (CYM) equations.

$$(D^\mu F_{\mu\nu})^a = 0$$

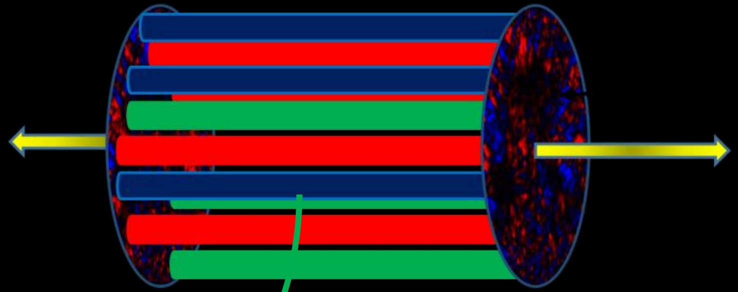
$$\tau = \sqrt{t^2 - z^2},$$
$$\eta = \frac{1}{2}\log\left(\frac{t+z}{t-z}\right)$$

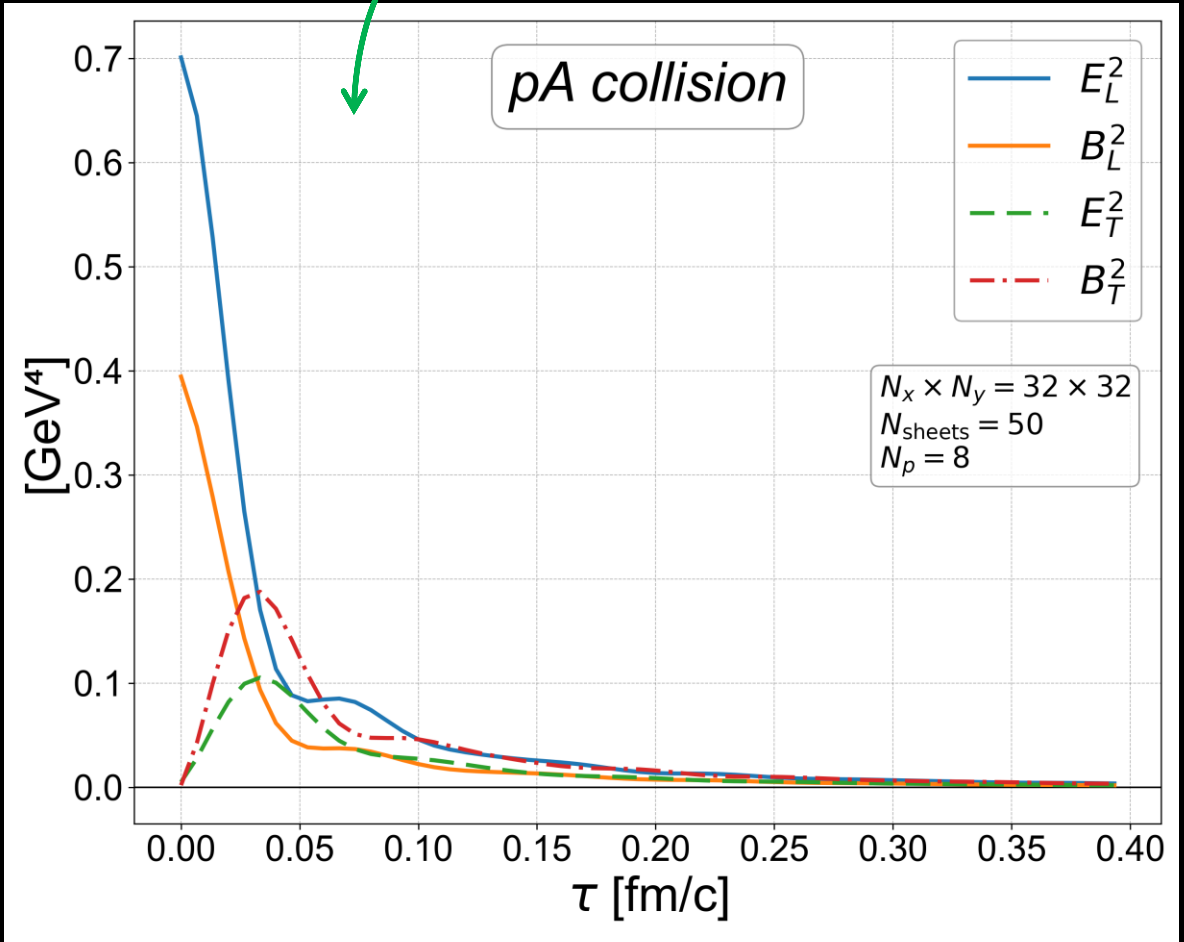
$$\boxed{\begin{aligned} \partial_\tau E_i &= \frac{1}{\tau} D_\eta F_{\eta i} + \tau D_j F_{ji}, & E_i &= \tau \partial_\tau A_i, \\ \partial_\tau E_\eta &= \frac{1}{\tau} D_j F_{j\eta}, & E_\eta &= \frac{1}{\tau}\partial_\tau A_\eta. \end{aligned}}$$

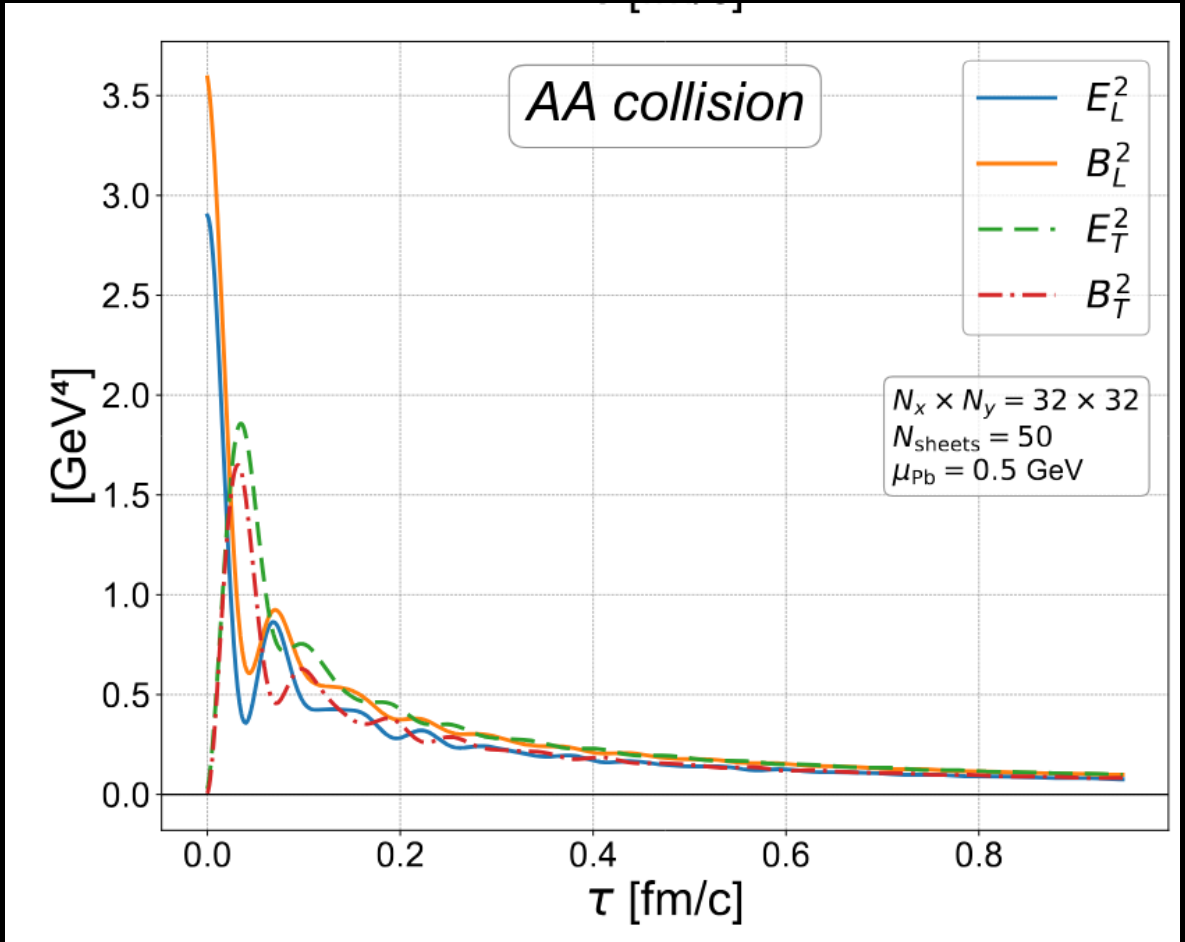
Evolution of the system is studied assuming the glasma initial condition, and evolving this condition by virtue of the CYM equations(*).

(*)These are solved in a gauge-invariant fashion on a real-time lattice.

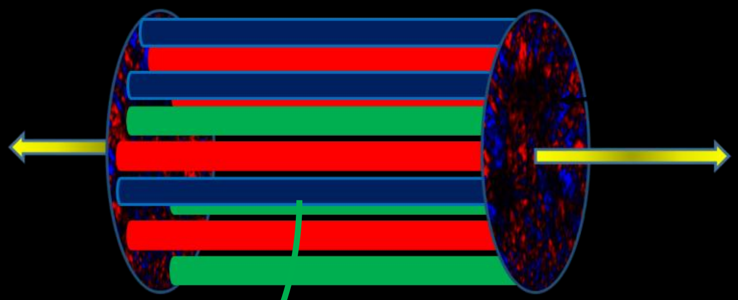
Evolution of the fields

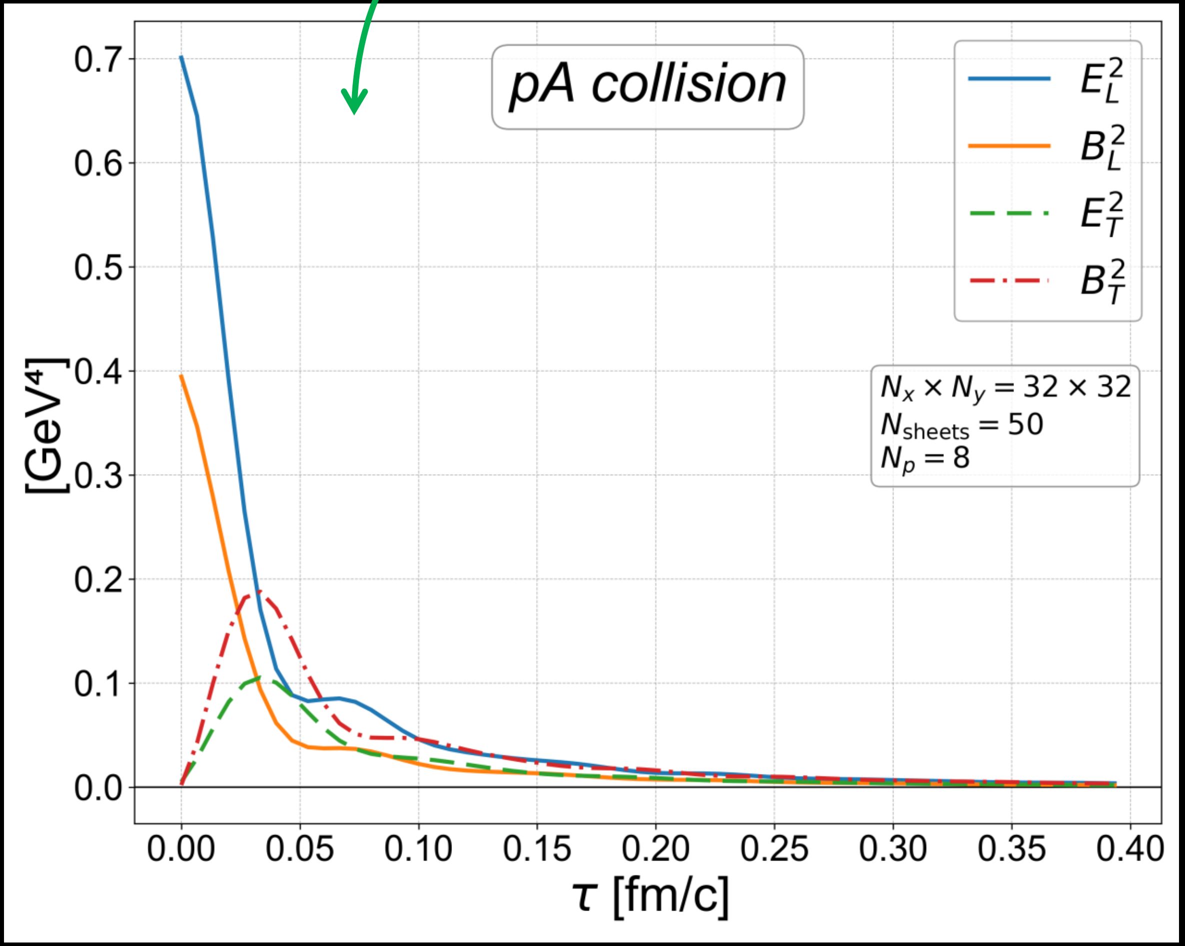






Evolution of the fields





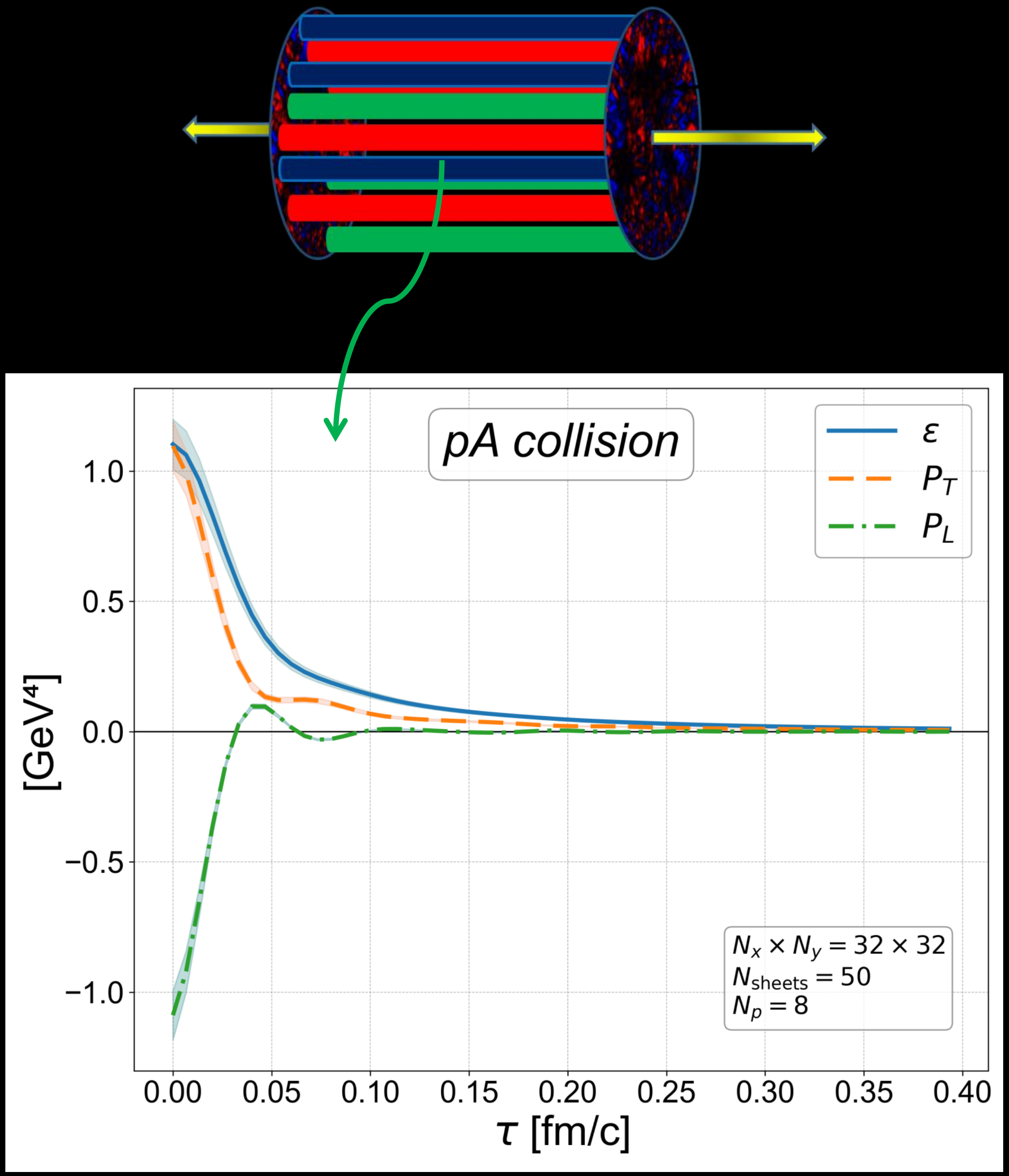
$$\left.\frac{dE_a^x}{dt}\right|_{t=0^+} = \partial_y B_z^a + f_{abc} A_y^b B_z^c$$

Formation time of transverse fields:

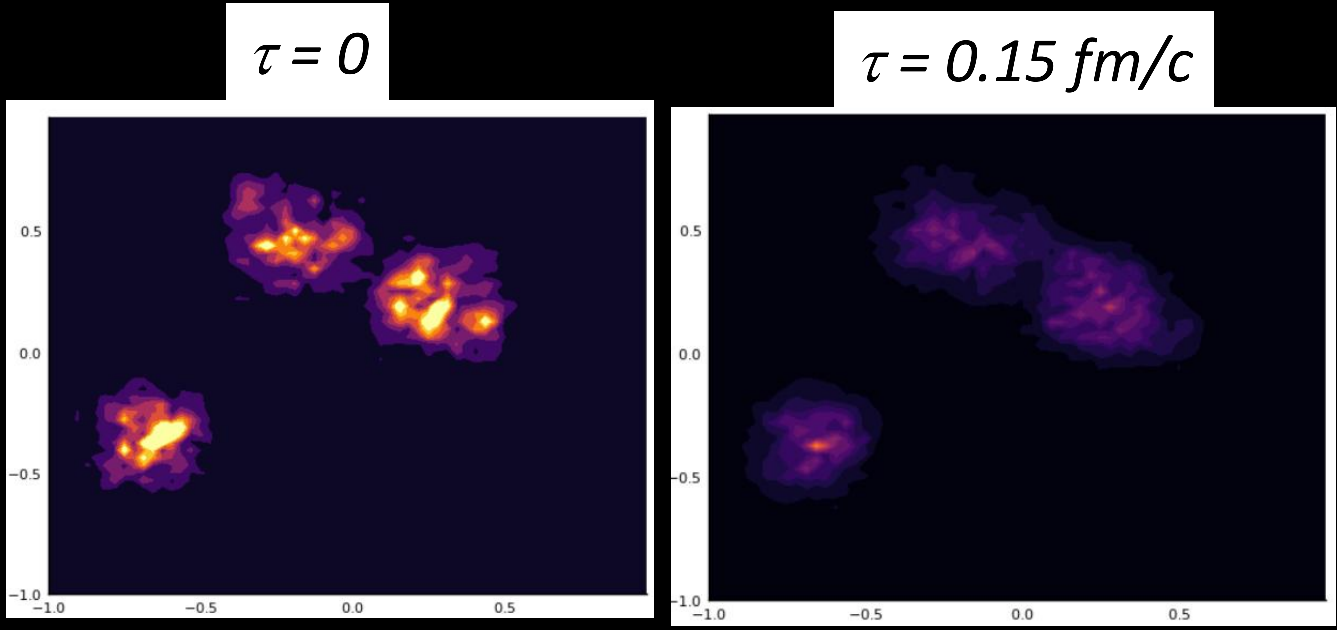
$Q_s\tau \approx 1$ namely $\tau \approx 0.1$ fm/c

See also Lappi and McLerran (2006)

Evolution of the energy density in pA collisions

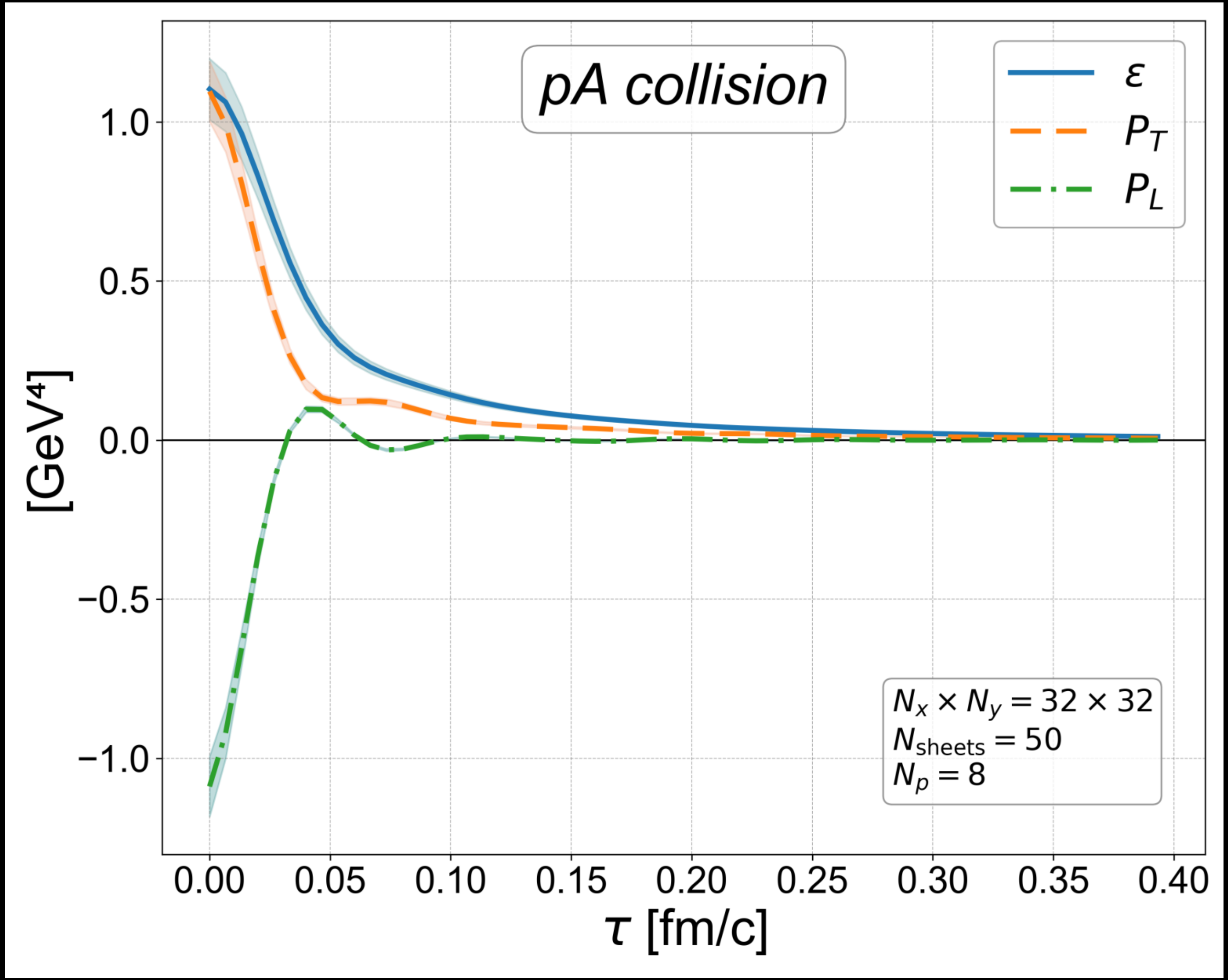


$$\varepsilon = \mathrm{Tr}\left[E_L^2 + E_T^2 + B_L^2 + B_T^2\right]$$



Energy density in the transverse plane

The free-streaming regime in pA collisions



$$\varepsilon = \mathrm{Tr}\left[E_L^2 + E_T^2 + B_L^2 + B_T^2\right],$$

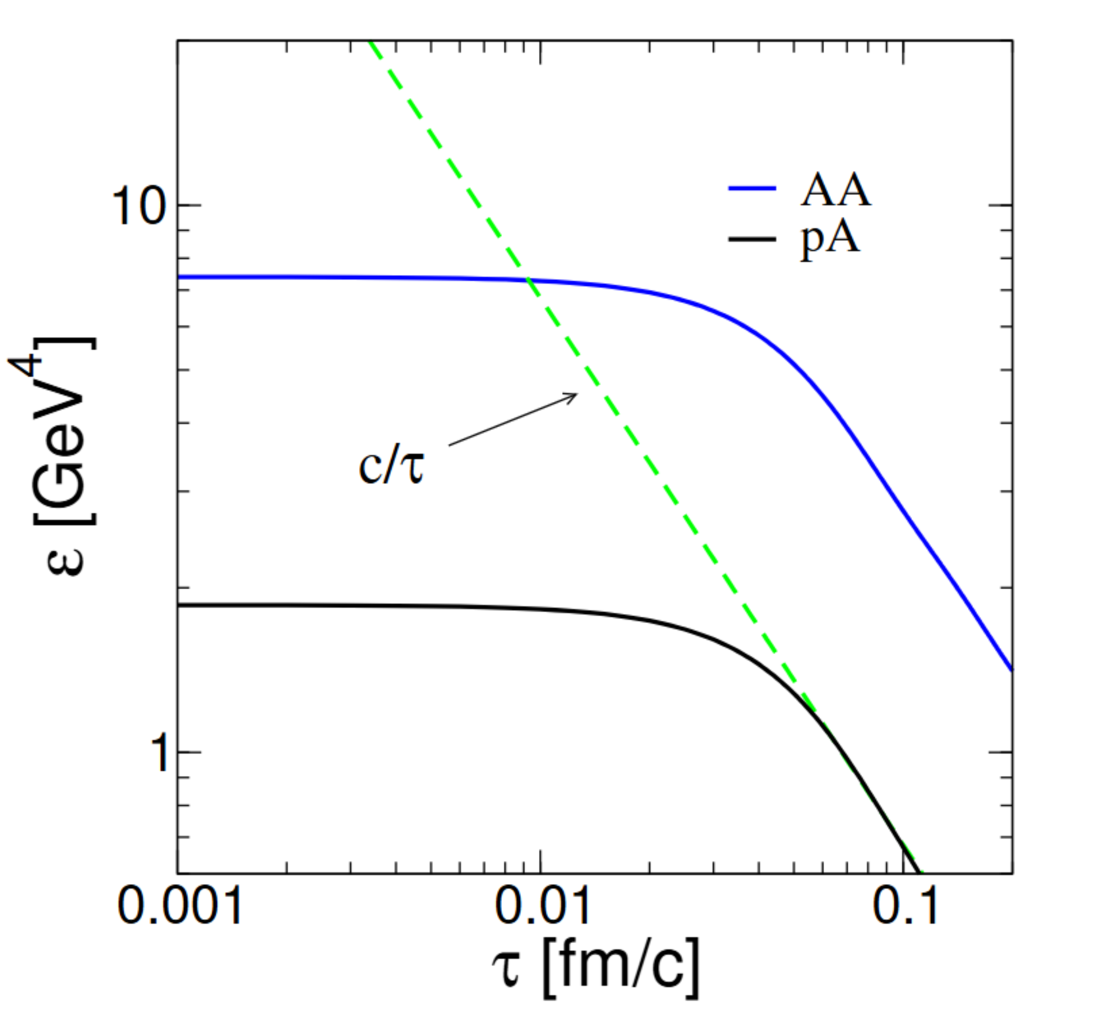
$$P_L = \mathrm{Tr}\left[-E_L^2 - B_L^2 + E_T^2 + B_T^2\right]$$

$$P_T = \mathrm{Tr}\left[E_L^2 + B_L^2\right].$$

$\tau \approx 0.2$ fm/c

Longitudinal pressure vanishes

The free-streaming in pA and AA collisions



$$\varepsilon = \mathrm{Tr}\left[E_L^2 + E_T^2 + B_L^2 + B_T^2\right]$$

Longitudinal expansion with zero pressure (aka free streaming):

$$\frac{d\varepsilon}{\varepsilon} = -\frac{d\tau}{\tau}$$

- *<u>Fields are diluted</u>: description in terms of gluons, and relativistic kinetic theory, is possible in this regime.*

Bogulavski et al. (2023, 2024)
Ruggieri et al. (2015)

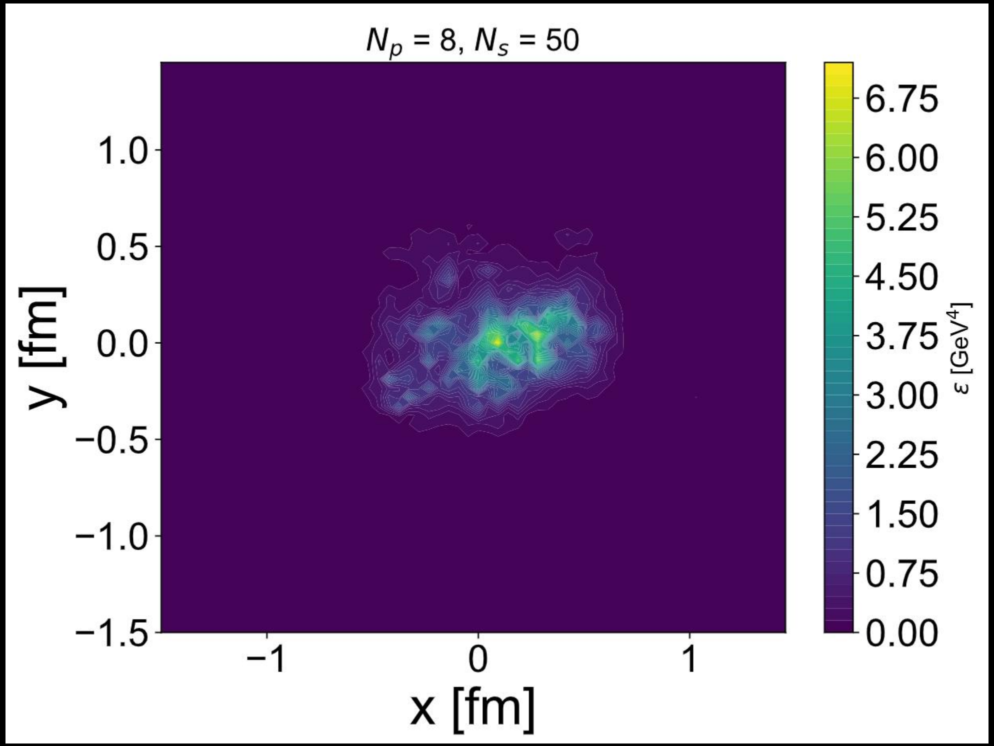
G. Parisi *et al* (2025)

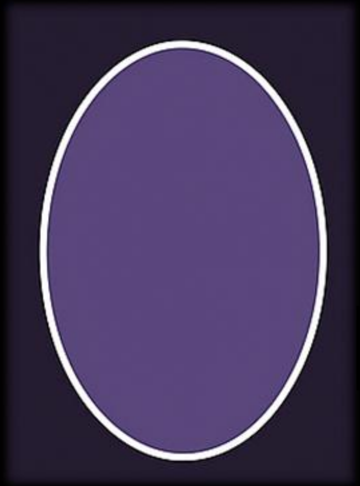
Eccentricities

$$\varepsilon_n = \frac{\langle r^n e^{in\phi} \rangle}{\langle r^n \rangle} \quad \text{with} \quad \varepsilon_n = |\varepsilon_n|\, e^{in\Psi_n}$$

Reaction plane

$$\langle f(x,y) \rangle = \frac{\int dx\, dy\, f(x,y)\, \varepsilon(x,y)}{\int dx\, dy\, \varepsilon(x,y)}$$





Symmetry: 2π/2

$\varepsilon_2,\ \varepsilon_4, \ldots$

Symmetry: 2π/3

$\varepsilon_3,\ \varepsilon_6, \ldots$

Eccentricities

$$\varepsilon_n = \frac{\langle r^n e^{in\phi} \rangle}{\langle r^n \rangle} \quad \text{with} \quad \varepsilon_n = |\varepsilon_n|\, e^{in\Psi_n}$$

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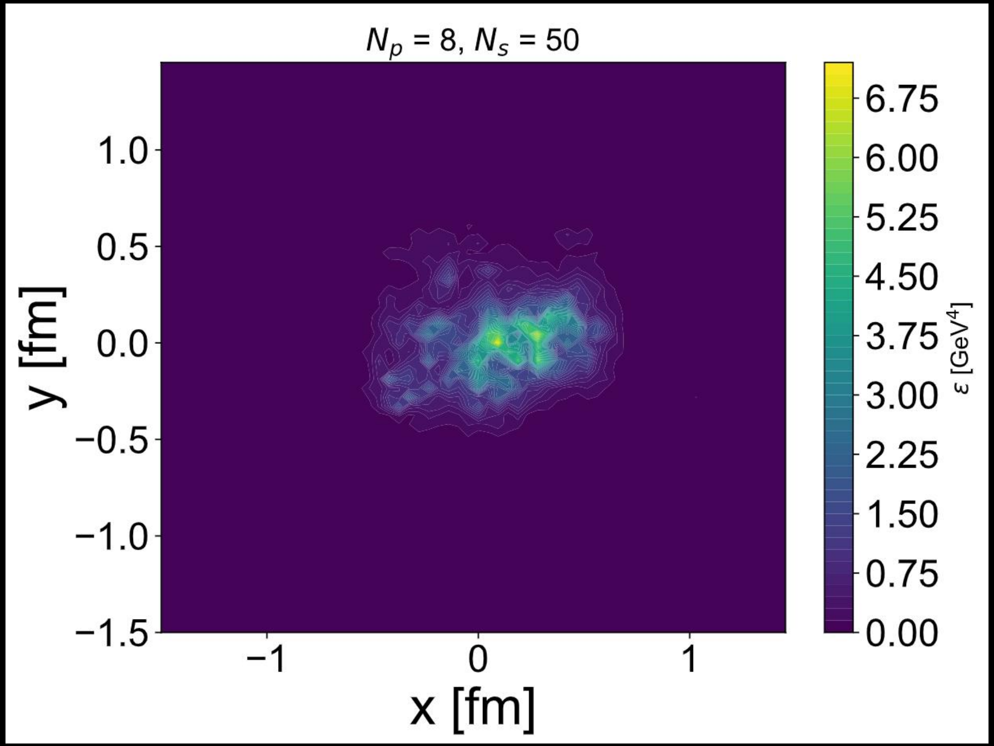
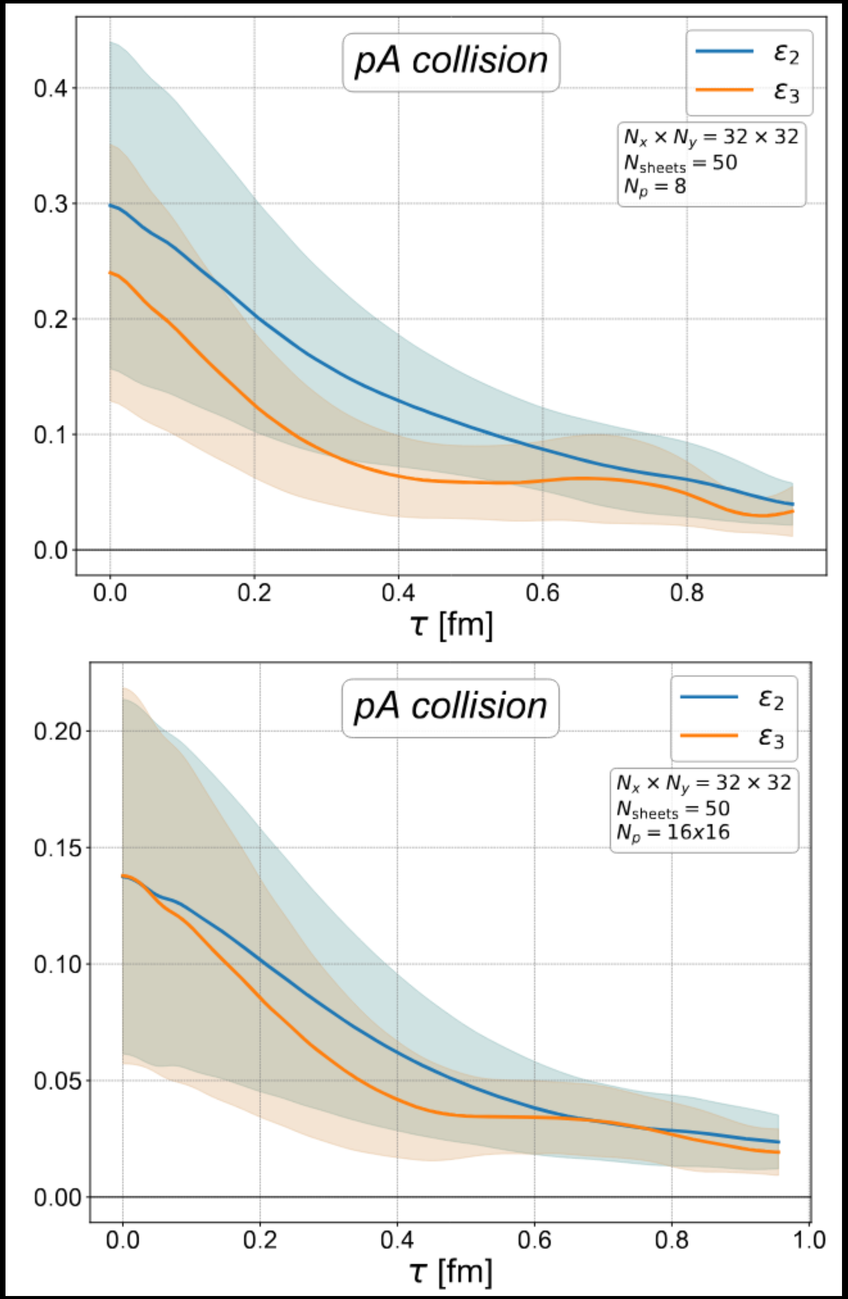




Pressure anisotropy

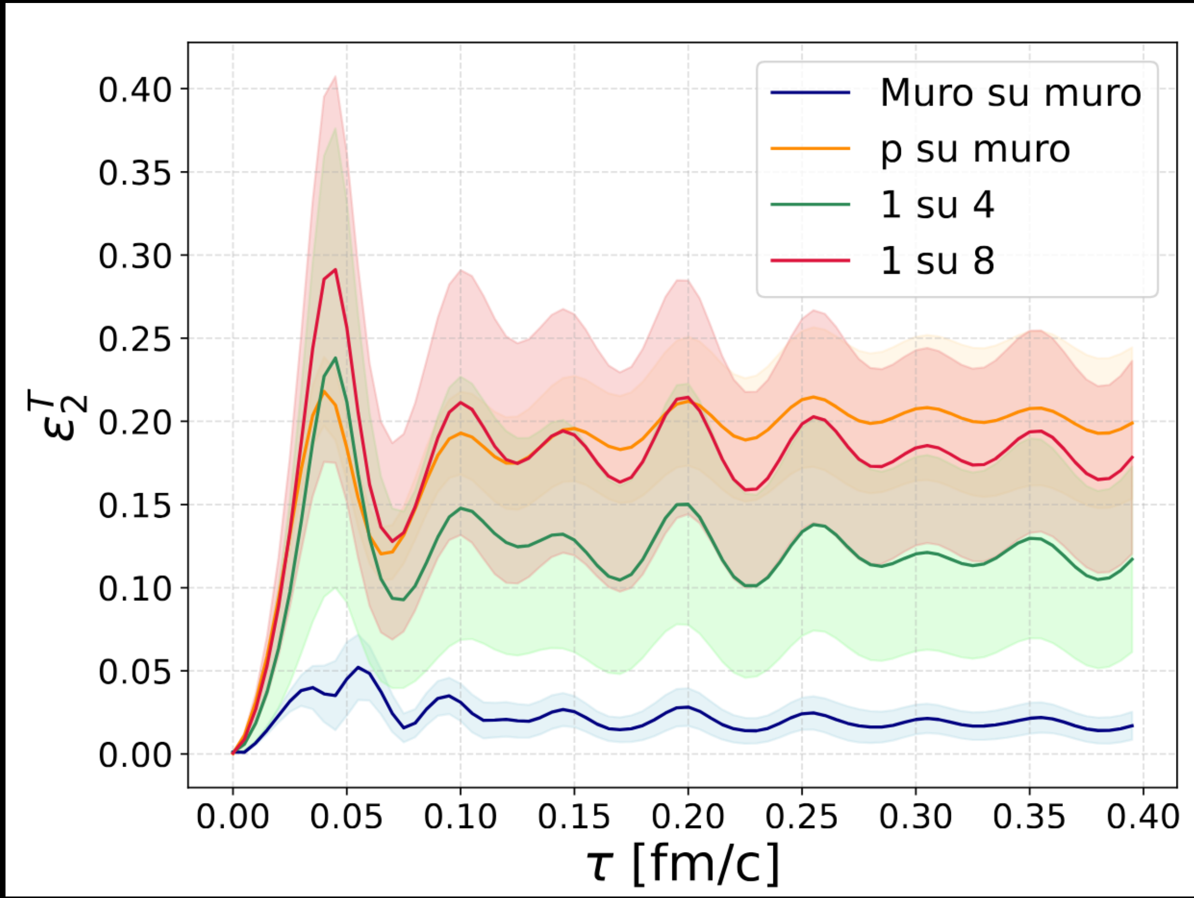
$$\varepsilon_2^{(T)} = \frac{\sqrt{\langle T^{xx} - T^{yy}\rangle_\varepsilon^2 + 4\langle T^{xy}\rangle_\varepsilon^2}}{\langle T^{xx} + T^{yy}\rangle_\varepsilon}$$

$$\langle O\rangle_\varepsilon = \frac{\int d^2x_T\ O(\boldsymbol{x}_T)\varepsilon(\boldsymbol{x}_T)}{\int d^2x_T\ \varepsilon(\boldsymbol{x}_T)}$$

$$T^{xx} = \varepsilon - \frac{2}{\tau^2}\,\mathrm{Tr}\left(E^xE^x + B^xB^x\right),$$

$$T^{yy} = \varepsilon - \frac{2}{\tau^2}\,\mathrm{Tr}\left(E^yE^y + B^yB^y\right),$$

$$T^{xy} = -\frac{2}{\tau^2}\,\mathrm{Tr}\left(E^xE^y + B^xB^y\right).$$



M.R. et al, in preparation

Elliptic flow

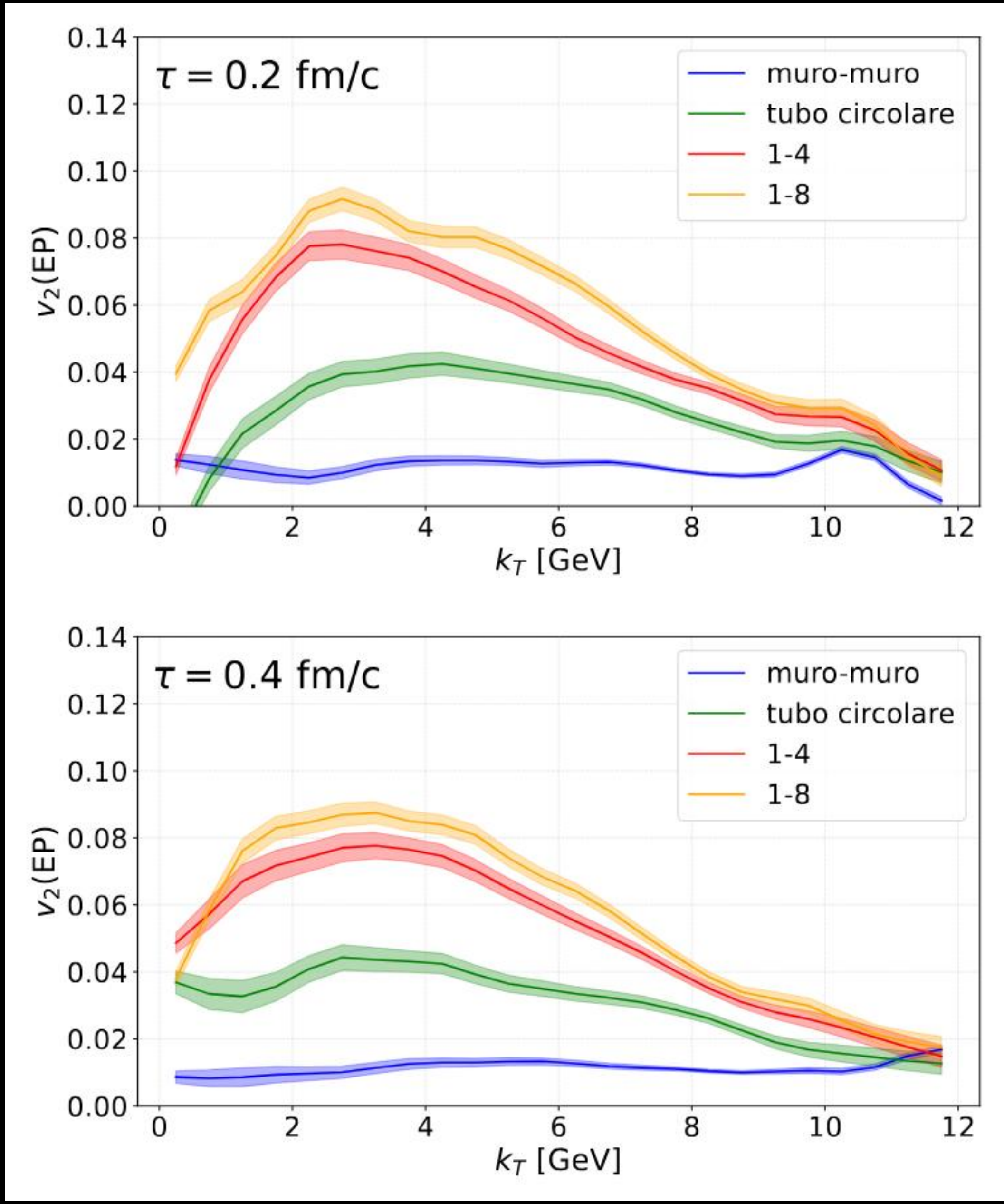
(transverse) gluon spectrum

$$v_2(\mathrm{EP}) = \left\langle \frac{\int d\phi \cos[2(\phi - \Psi_2)]\ dN/d^2k}{\int d\phi\ dN/d^2k} \right\rangle,$$

$$\Psi_2 = \frac{1}{2}\arctan\frac{S_2}{C_2},$$

$$C_2 = \int \left(\frac{k_x^2 - k_y^2}{k_T^2}\right)\frac{dN}{d^2k_T}\, d^2k_T,$$

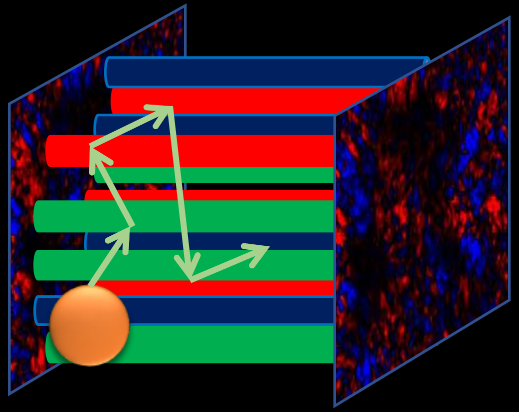
$$S_2 = \int \left(\frac{2k_xk_y}{k_T^2}\right)\frac{dN}{d^2k_T}\, d^2k_T.$$



M.R. et al, in preparation
In agreement with Schenke et al (2015)

Heavy quarks in the early stage

The pre-equilibrium stage: heavy quarks



Charm quarks

$$t_{\text{formation}} \approx \frac{1}{2m_c} \approx 0.06\ \text{fm/c}$$

Relativistic kinetic theory of HQs in Glasma *(Wong, 1979, Heinz, 1985, Pooja et al 2024)*

$$\frac{dx^i}{dt} = \frac{p^i}{E},$$

$$\frac{dp^i}{dt} = gQ_a F_a^{i\nu}\frac{p_\nu}{E} - \frac{\partial V}{\partial x^i},$$

$$E\frac{dQ_a}{dt} = g f_{abc} A_b^\mu p_\mu Q_c.$$

$$\boldsymbol{v} \equiv \frac{\boldsymbol{p}}{E} \quad \text{(Relativistic velocity)}$$

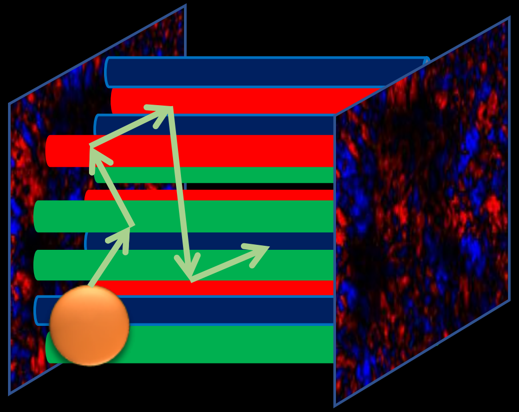
$$\frac{d\boldsymbol{p}}{dt} = q\boldsymbol{E} + q\left(\boldsymbol{v}\times\boldsymbol{B}\right) - \boldsymbol{\nabla}V \quad \text{(Lorentz force plus interquark force)}$$

$$D_\mu J_a^\mu = 0 \quad \text{(Color current conservation)}$$

$$J_a^\mu = \bar{c}\gamma^\mu T_a c$$

$$Q_a Q_a,\ \ d_{abc}Q_a Q_b Q_c \quad \text{conserved}$$

The pre-equilibrium stage: heavy quarks



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$$E\frac{dQ_a}{dt} = g f_{abc} A_b^\mu p_\mu Q_c.$$

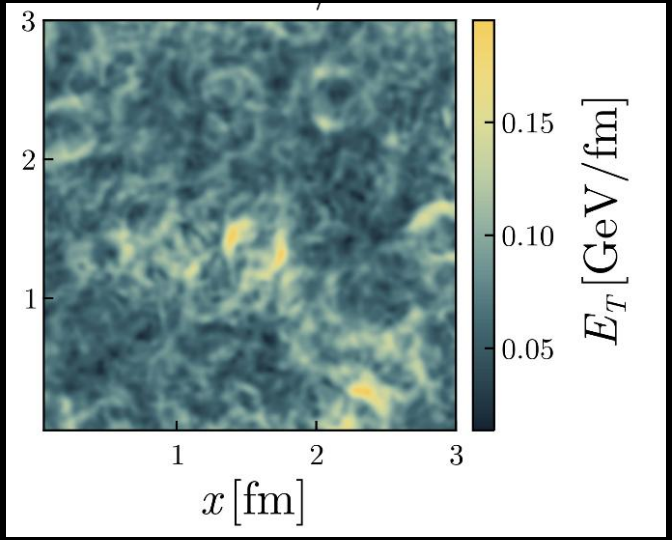
Boltzmann-Vlasov equation

$$p^\mu \partial_\mu f + gQ_a F_a^{\mu\nu} p_\nu \frac{\partial f}{\partial p^\mu} - g f_{abc} A_b^\mu p_\mu Q_c \frac{\partial f}{\partial Q_a} = 0$$

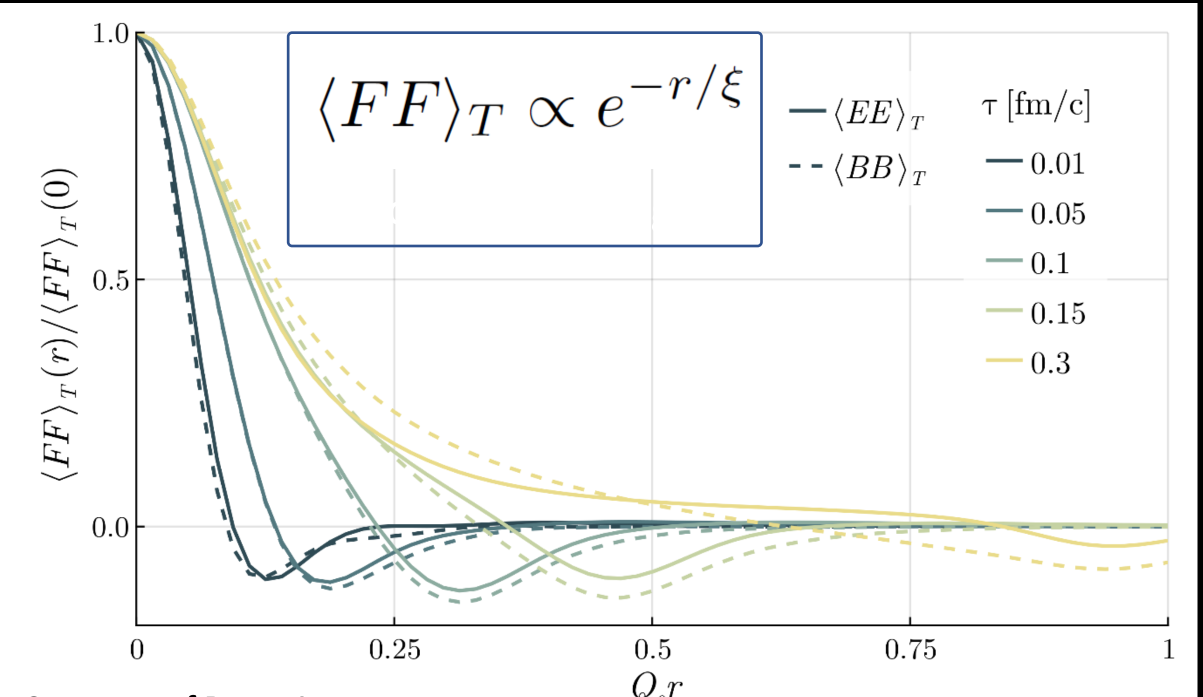
Equations of motion of heavy quarks are solved in the background given by the evolving Glasma fields

The pre-equilibrium stage: diffusion of heavy quarks in the color filaments

Fields arrange in correlation domains, aka filaments, of transverse area ≈ξ^2:
$\xi^2 = O(1/Q_s^2)$

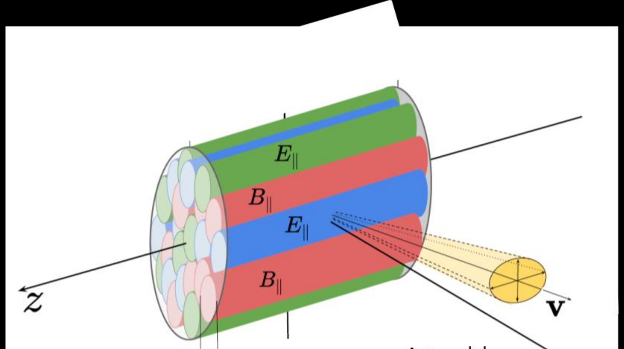


Field correlators in the transverse plane



Courtesy of Dana Avramescu

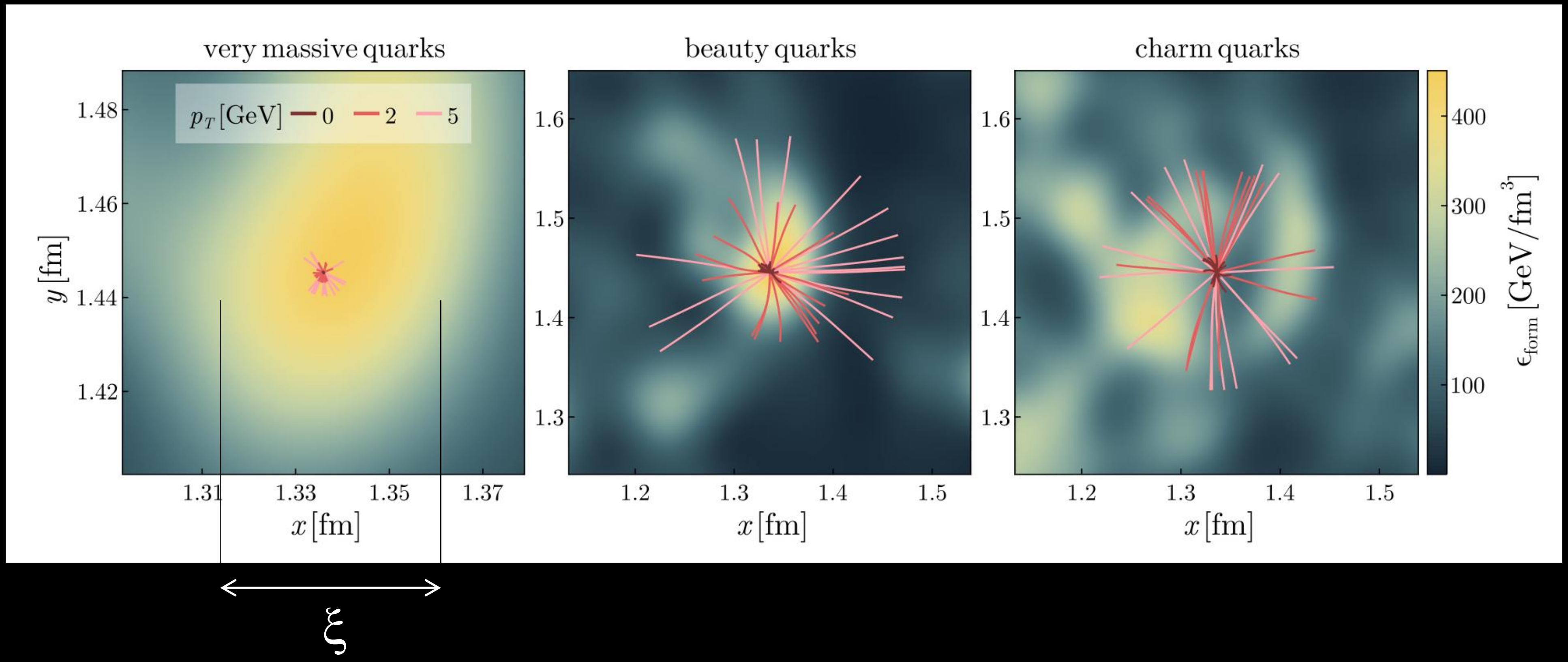
The force experienced by HQs in the pre-equilibrium stage is time-correlated: diffusion with memory.



Artwork by Mrowczynski et al. 2112.06812

The pre-equilibrium stage: diffusion of heavy quarks in the color filaments

Dana Avramescu *et al.* (2023)

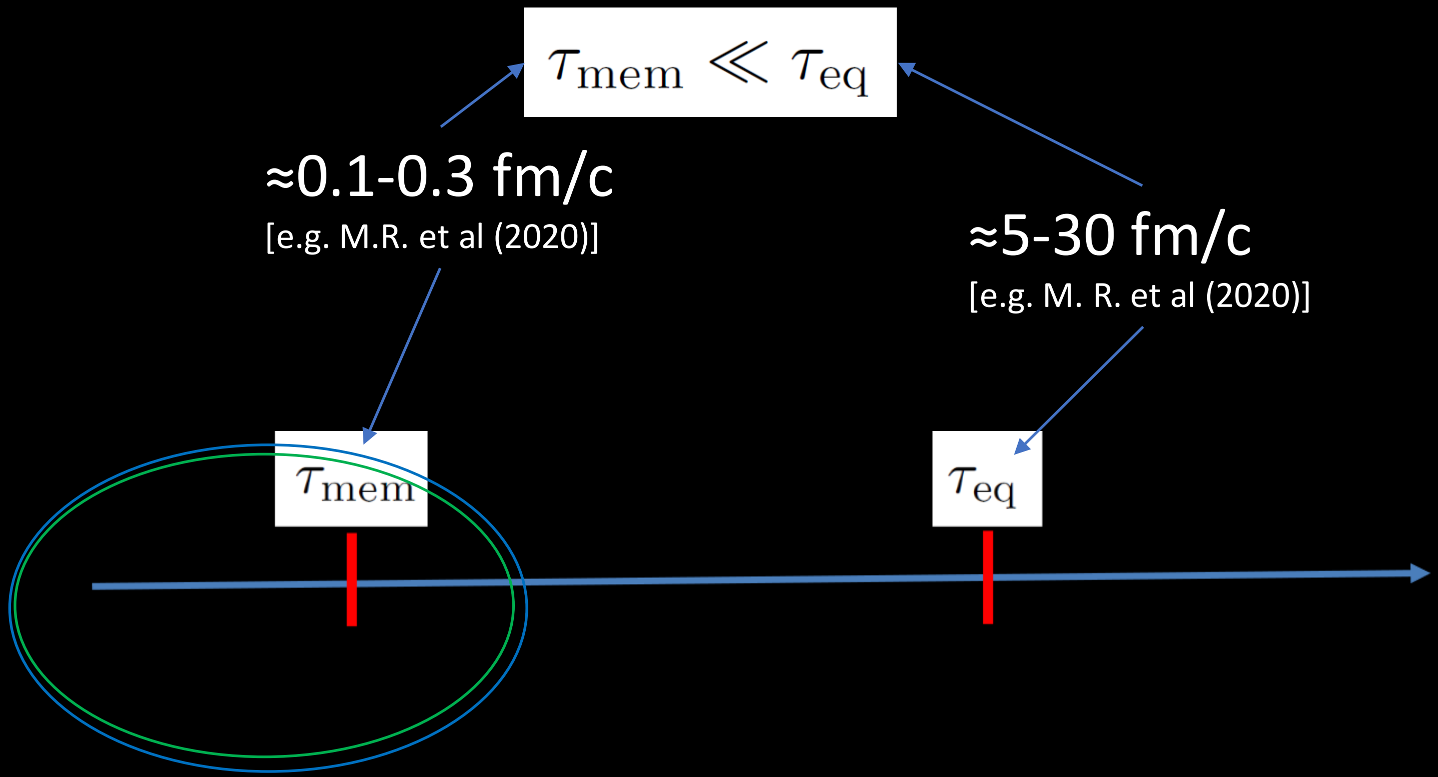


Slow color charges spend some time within one single filament: diffusion in a coherent field, rather than in a random medium.

The force exerted on these charges is time-correlated.

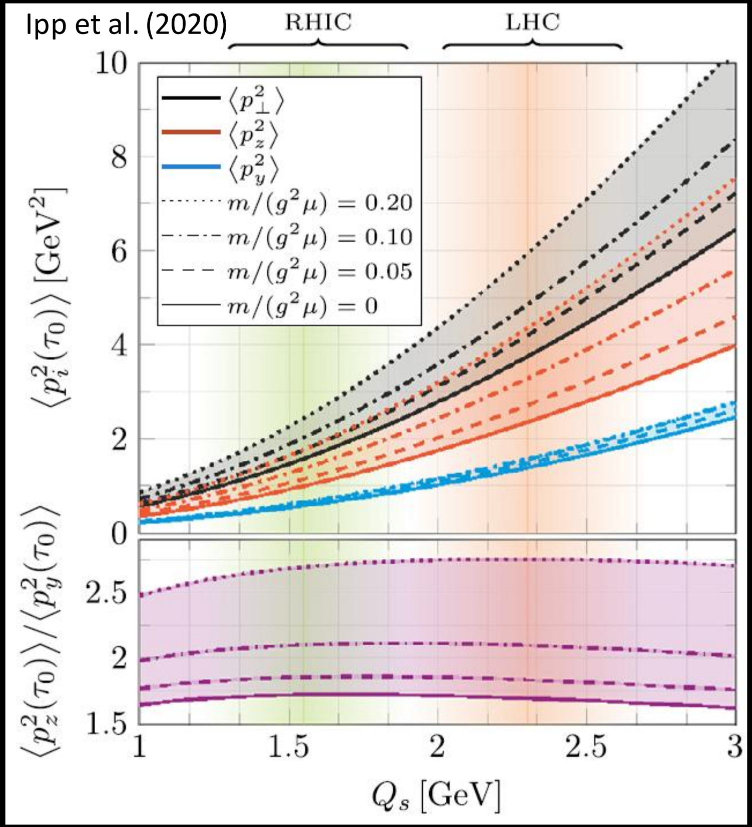
Heavy quarks inside colored filaments: diffusion dominates over energy loss for small pT

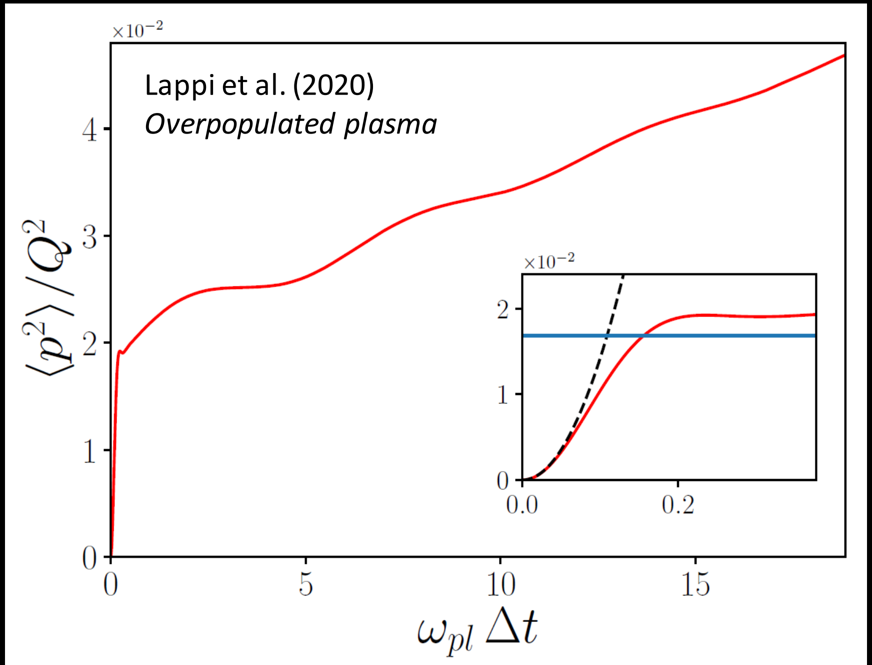
EvGlasma lifetime ≈ 0.3-0.6 fm/c

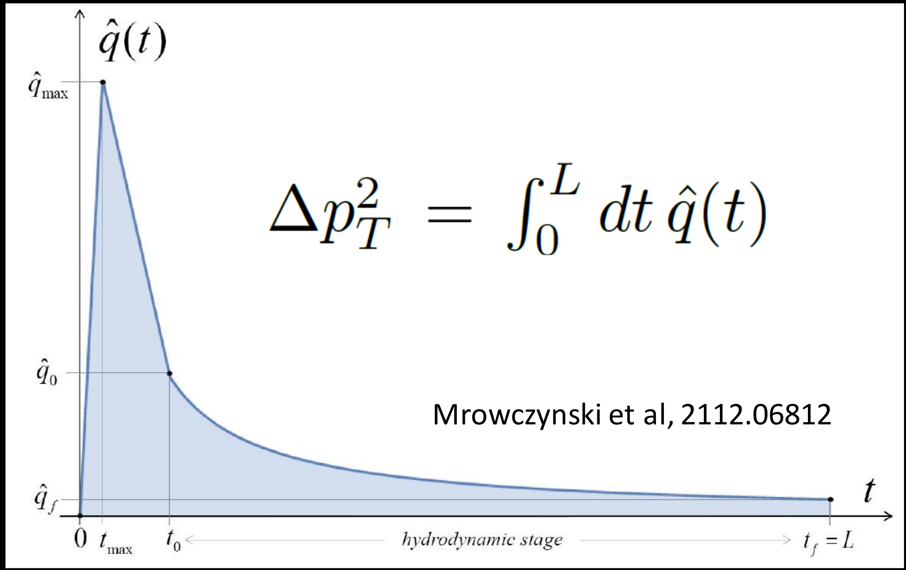


- *Diffusion dominates because of the large thermalization time*
- *Memory leads to nonlinear evolution of σ_p*

Heavy quarks in the easly stage: momentum diffusion and jet quenching



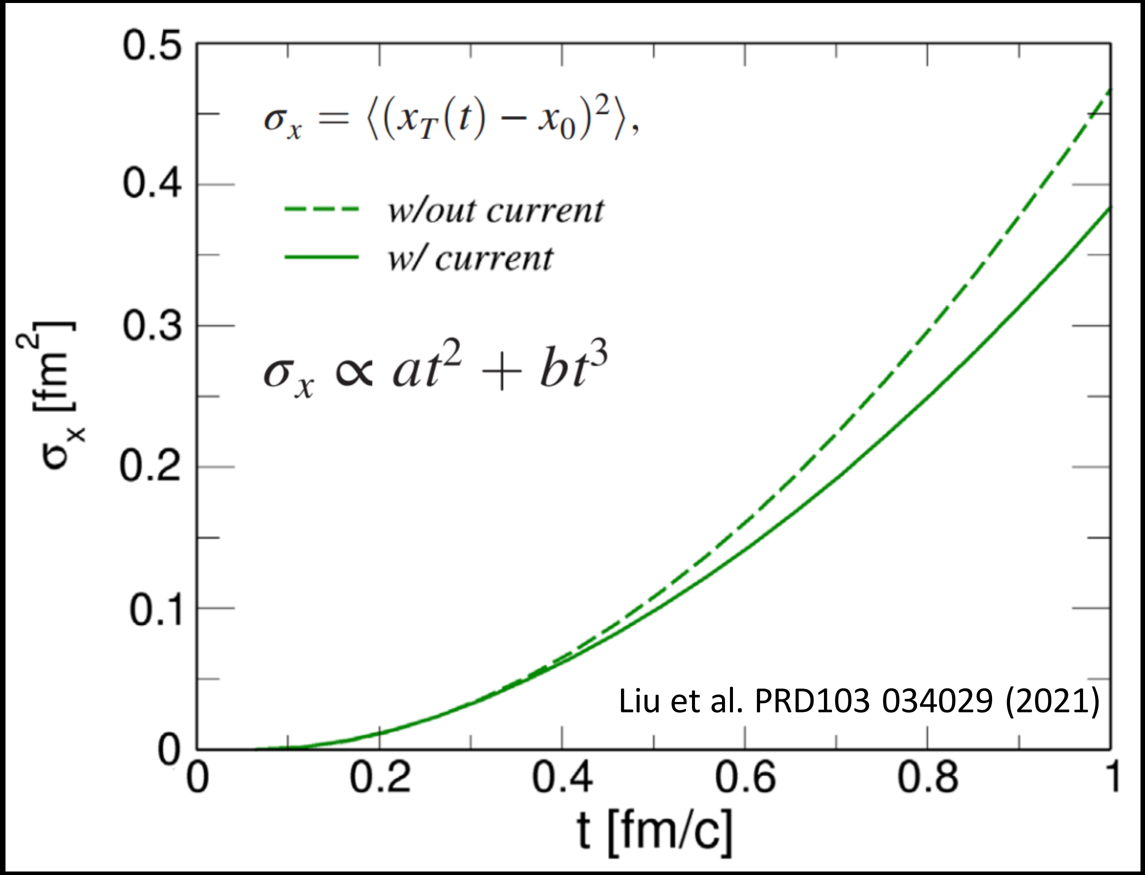


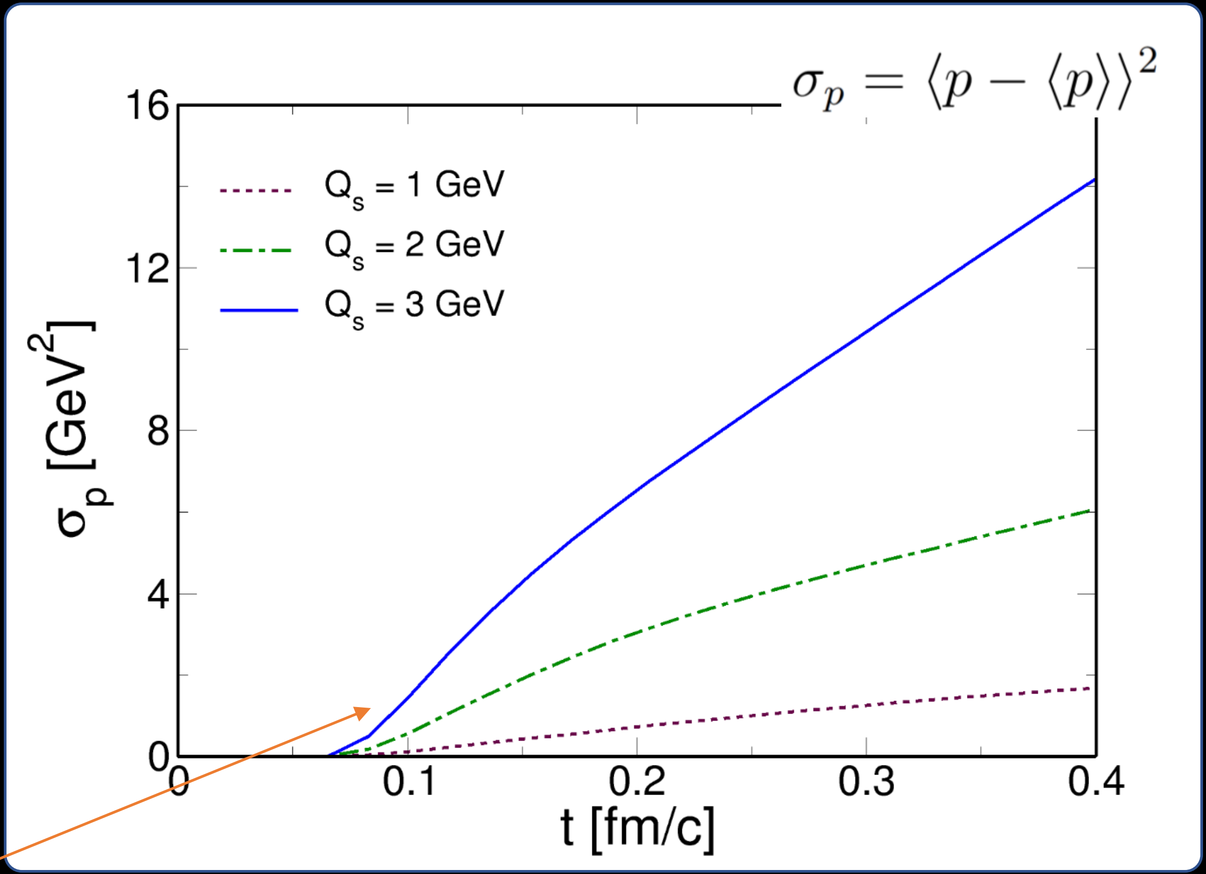


For jet quenching see also Barata *et al*, 2406.07615

For angular correlations see Avramescu *et al.*, 2409.10565

The pre-equilibrium stage: diffusion of heavy quarks in the color filaments





Diffusion in the color filament

- *Early time:* $\sigma_p \approx Q_s D t^2$

Standard Brownian motion

- *Later time:* $\sigma_p \approx 2Dt$

D: momentum diffusion coefficient

See also D. Avramescu *et al.* (2023)

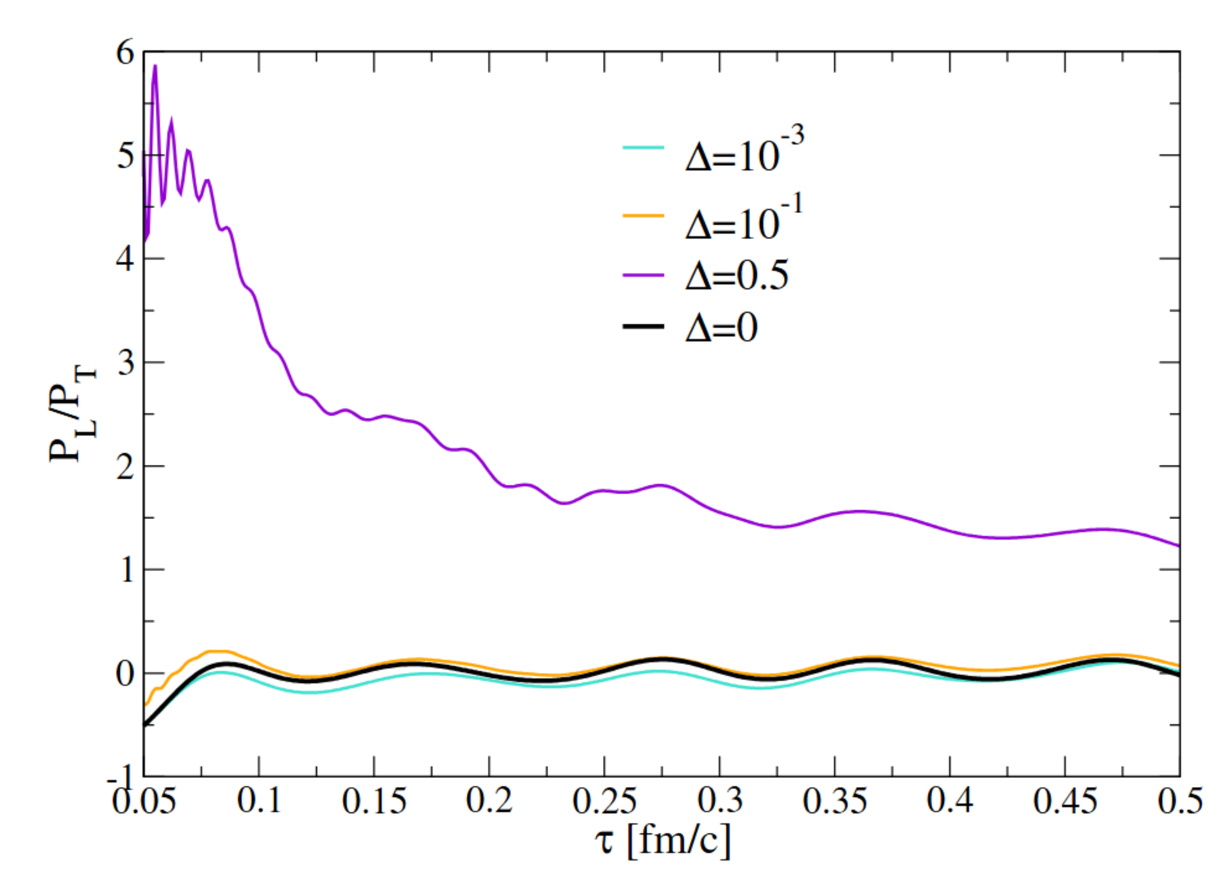
Minimal longitudinal fluctuations(*)

$$\delta E^i(\boldsymbol{x}_\perp, \eta) = -\partial_\eta F(\eta)\xi_i(\boldsymbol{x}_\perp),$$

$$\delta E^\eta(\boldsymbol{x}_\perp, \eta) = F(\eta) \sum_{i=x,y} D_i \xi_i(\boldsymbol{x}_\perp)$$

$$F(\eta) = \frac{\Delta}{N_\perp} \sum_{n \in I} \frac{1}{|I|} \cos\left(\frac{2\pi n \eta}{L_n}\right)$$

pA collisions



G. Parisi *et al* (2025)

(*)Fukushima and Gelis (2011)

Anisotropic diffusion

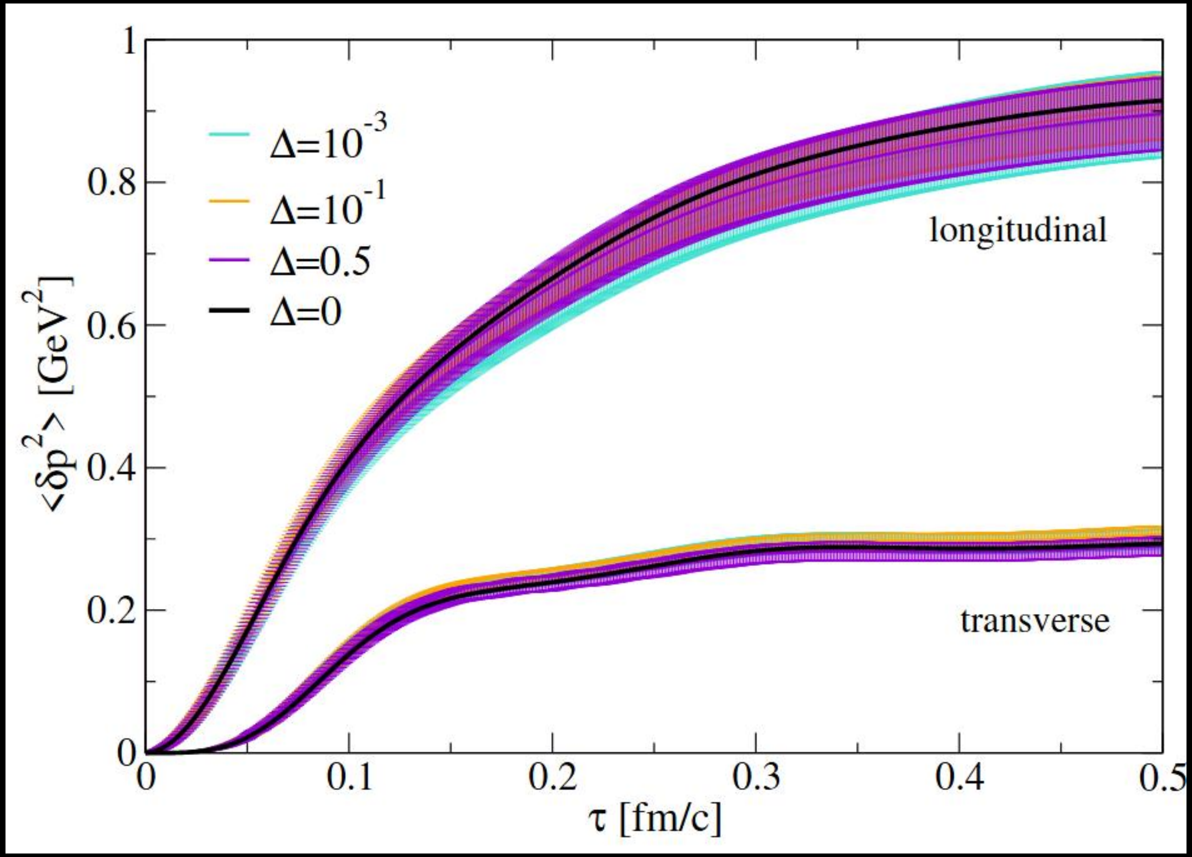
pA collisions

Minimal longitudinal fluctuations(*)

$$\delta E^i(\boldsymbol{x}_\perp, \eta) = -\partial_\eta F(\eta)\xi_i(\boldsymbol{x}_\perp),$$

$$\delta E^\eta(\boldsymbol{x}_\perp, \eta) = F(\eta) \sum_{i=x,y} D_i \xi_i(\boldsymbol{x}_\perp)$$

$$F(\eta) = \frac{\Delta}{N_\perp} \sum_{n \in I} \frac{1}{|I|} \cos\left(\frac{2\pi n \eta}{L_n}\right)$$



G. Parisi *et al* (2025)
Results without fluctuations are in agreement with D. Avramescu et al (2023), Ipp et al (2020)

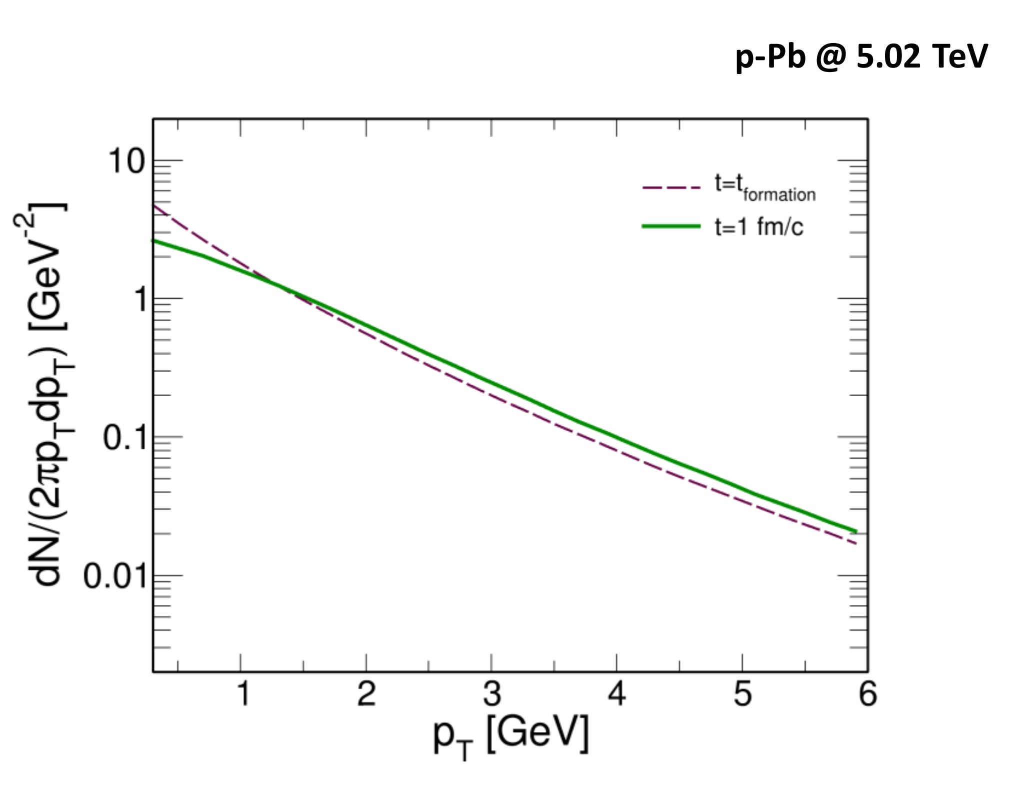
$$\begin{aligned}
\langle\langle \delta p_L^2(\tau) \rangle\rangle &= g^2 \int_0^\tau d\tau' \int_0^\tau d\tau'' \int d^2\mathbf{x}_\perp \langle \mathrm{Tr}[E_z(\tau')E_z(\tau'')] T_p(\mathbf{x}_\perp) \rangle \\
\langle\langle \delta p_T^2(\tau) \rangle\rangle &= g^2 \int_0^\tau d\tau' \int_0^\tau d\tau'' \int d^2\mathbf{x}_\perp \frac{1}{\tau'\tau''} \langle \mathrm{Tr}[E_x(\tau')E_x(\tau'') + E_y(\tau')E_y(\tau'')] T_p(\mathbf{x}_\perp) \rangle
\end{aligned}$$

(*)Fukushima and Gelis (2011)

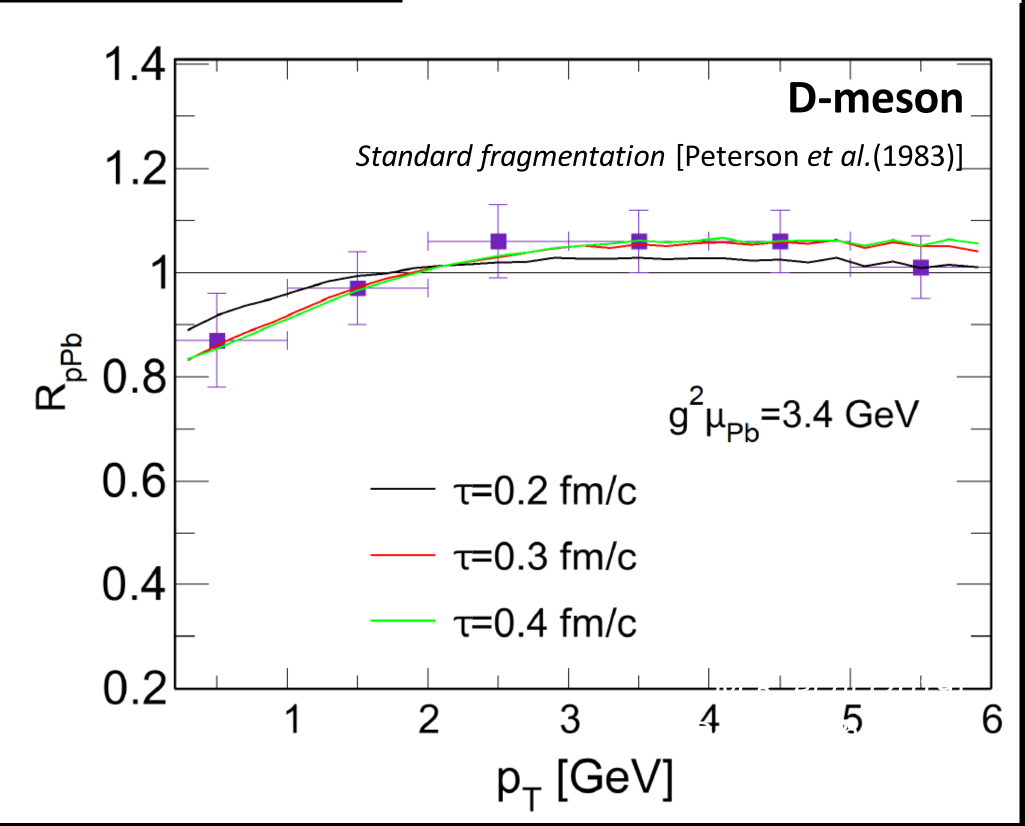
The pre-equilibrium stage: potential impact on modification factor

Initial distribution

From perturbative QCD, aka ***FONLL*** [Cacciari *et al.* (2001, 2012)]



$$R_{\rm pPb} = \frac{(dN/d^2p_T)_{\rm final}}{(dN/d^2p_T)_{\rm pQCD}}$$



$R_{pPb} \neq 1$

Interaction with the fields created by the collision

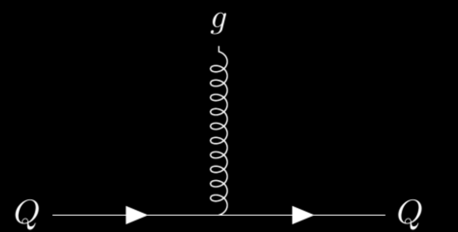
See also

M. Ruggieri and S. K. Das (2018)

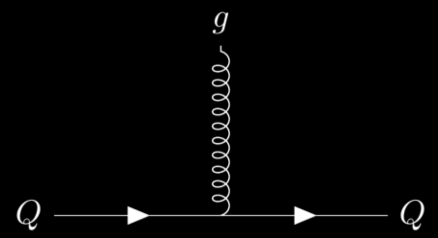
Y. Sun et al. (2019) for an estimate of the effect on the elliptic flow.

Quarkonia in the early stage

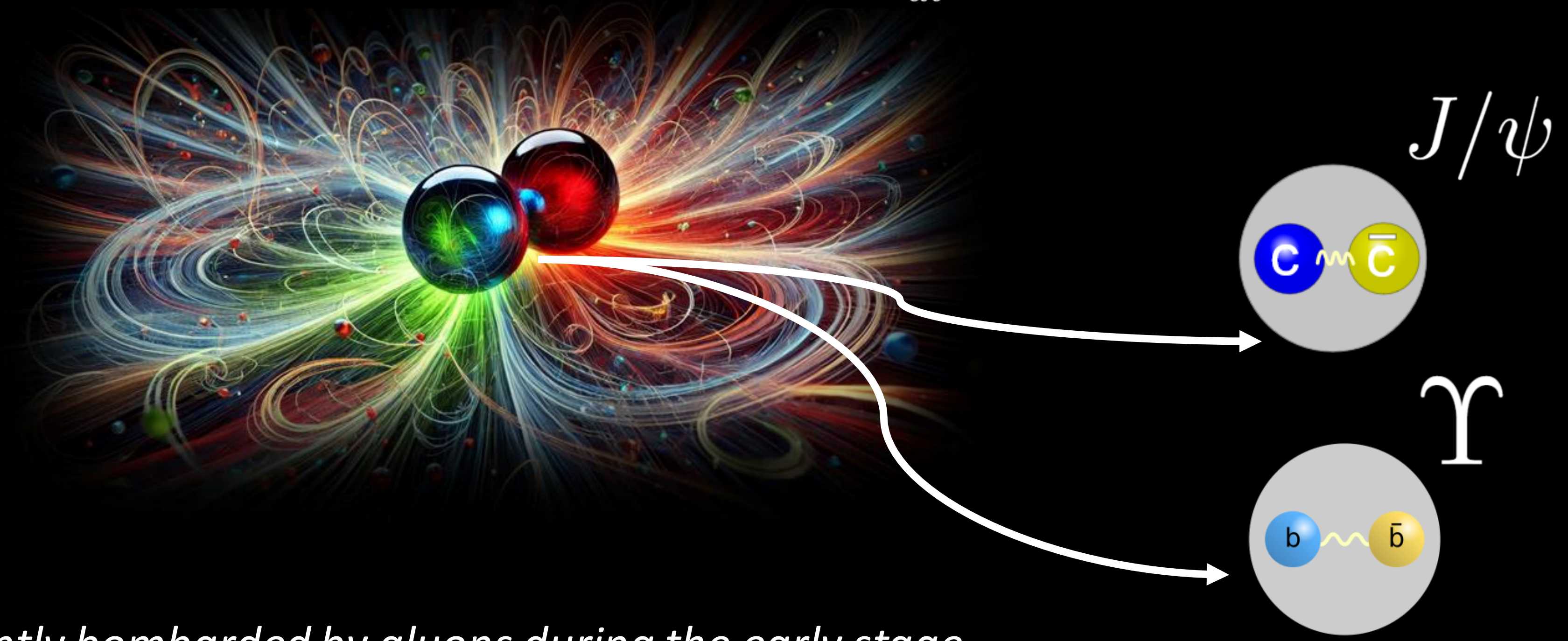
J/ψ and Υ in glasma



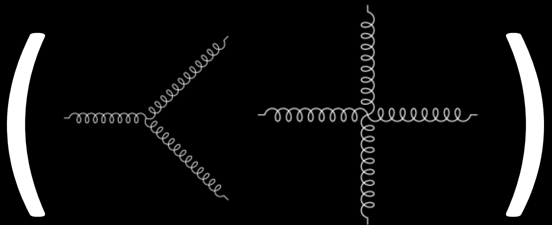
$$E\frac{d\bar{Q}_a}{dt} = g\, f_{abc} A_b^\mu p_\mu \bar{Q}_c$$



$$E\frac{dQ_a}{dt} = g\, f_{abc} A_b^\mu p_\mu Q_c$$



$$D_\mu^a F_{ab}^{\mu\nu} = 0$$



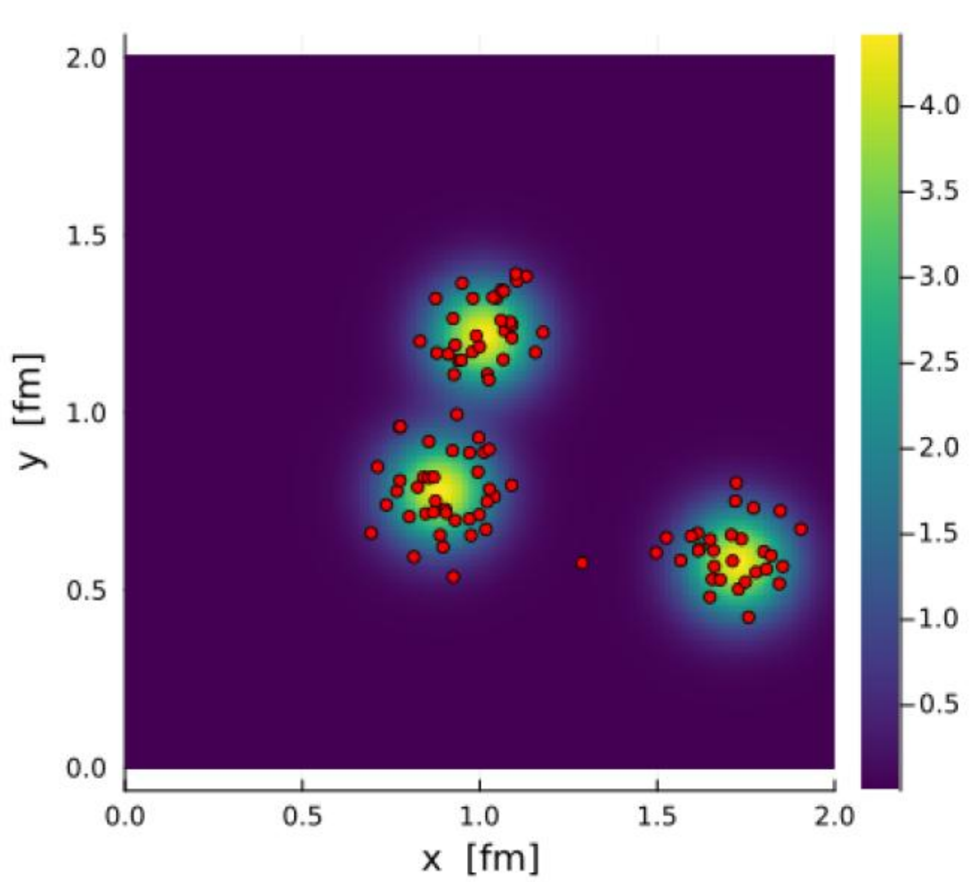
Quark-antiquark pairs are constantly bombarded by gluons during the early stage.
Their color charges fluctuate, leading to transitions to color-octet states.

More precisely

Singlet-octet transitions are induced by gauge-field fluctuations, that cause the evolution of the (traced) octet component of the density matrix of the pair.

- *Center-of-mass of the pairs is extracted near the hotspots of energy*
- *For each pair, we extract the relative distance and the relative momentum according to(*)*

Oliva et al. (2404.05315)



$$\boxed{\frac{d^4 P_{\rm HQ}}{d^2\boldsymbol{r}_{\rm rel} d^2\boldsymbol{p}_{\rm rel}} = \exp\left(-r_{\rm rel}^2/r_0^2 - p_{\rm rel}^2 r_0^2\right)}$$

$r_0 = 0.4\,\mathrm{fm}$ *c-cbar pairs*

$r_0 = 0.2\,\mathrm{fm}$ *b-bbar pairs*

- *Pairs are extracted in the color-singlet state:*

$$Q_a = -\bar{Q}_a, \quad a = 1, \ldots, N_c^2 - 1$$

(*)Zhao et al. (2025)

$$|\psi\rangle = c_S|S\rangle + \sum_{i=1}^{8} c_i|O_i\rangle \qquad \hat{V} = T^a \otimes \bar{T}^a \frac{\alpha_s}{r_{\mathrm{rel}}} \qquad V_S = -\frac{4}{3}\frac{\alpha_s}{r_{\mathrm{rel}}}, \quad V_O = \frac{1}{6}\frac{\alpha_s}{r_{\mathrm{rel}}}$$

$$P_S = -\frac{2}{3}\frac{Q^a\bar{Q}^a}{N_c} + \frac{1}{9},$$
$$P_O = \frac{2}{3}\frac{Q^a\bar{Q}^a}{N_c} + \frac{8}{9},$$

$$V \equiv \langle\psi|\hat{V}|\psi\rangle = P_S V_S + P_O V_O$$

$$\boxed{V = \frac{Q^a\bar{Q}^a}{N_c}\frac{\alpha_s}{r_{\mathrm{rel}}}}$$

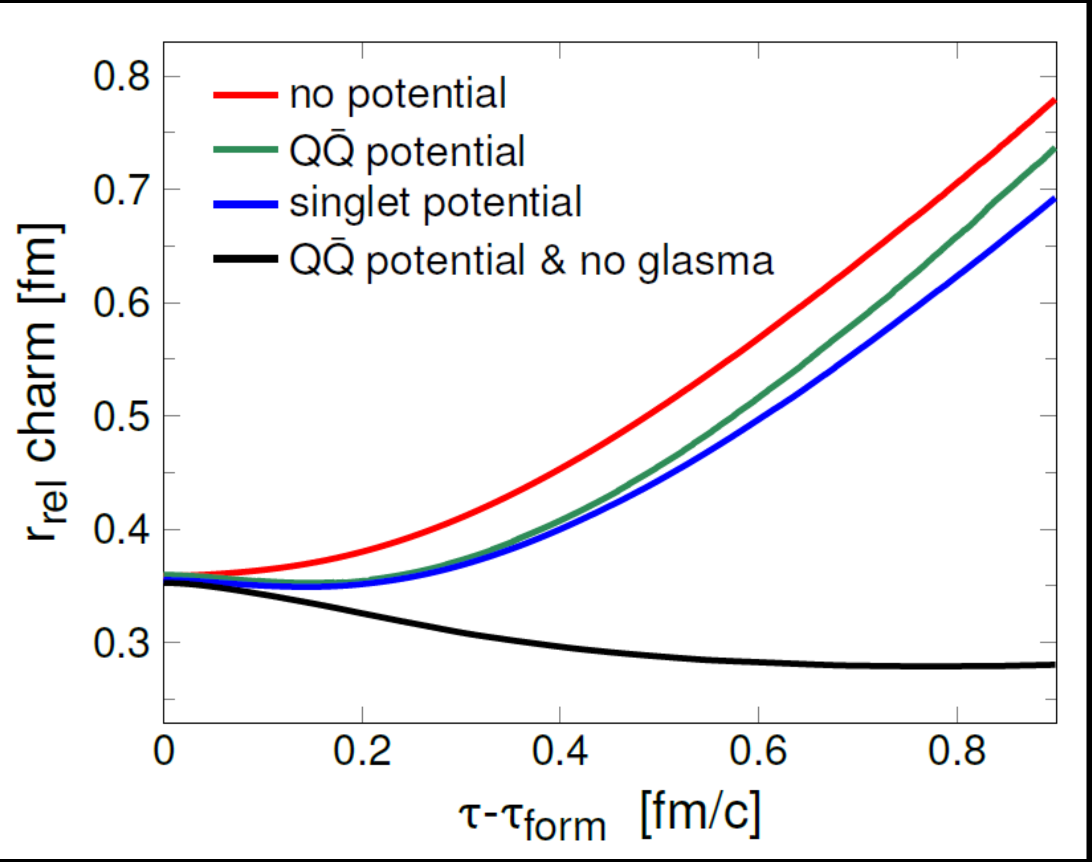
classical interquark potential

The coupling in the classical potential dynamically evolves with the pair, taking into account the formation of an octet component due to the interaction with the external gluon fields.

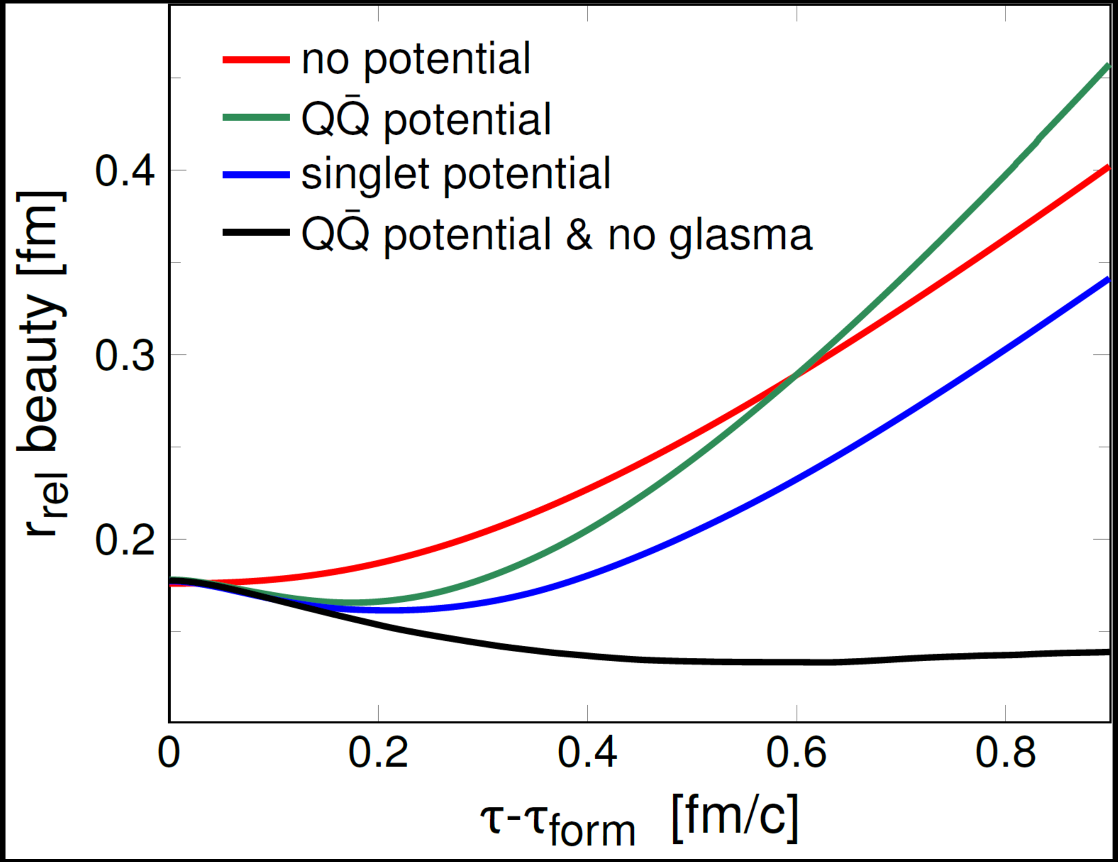
Oliva et al. (2404.05315)

J/ψ and Υ in glasma: evolution of the relative distance

c-cbar pairs



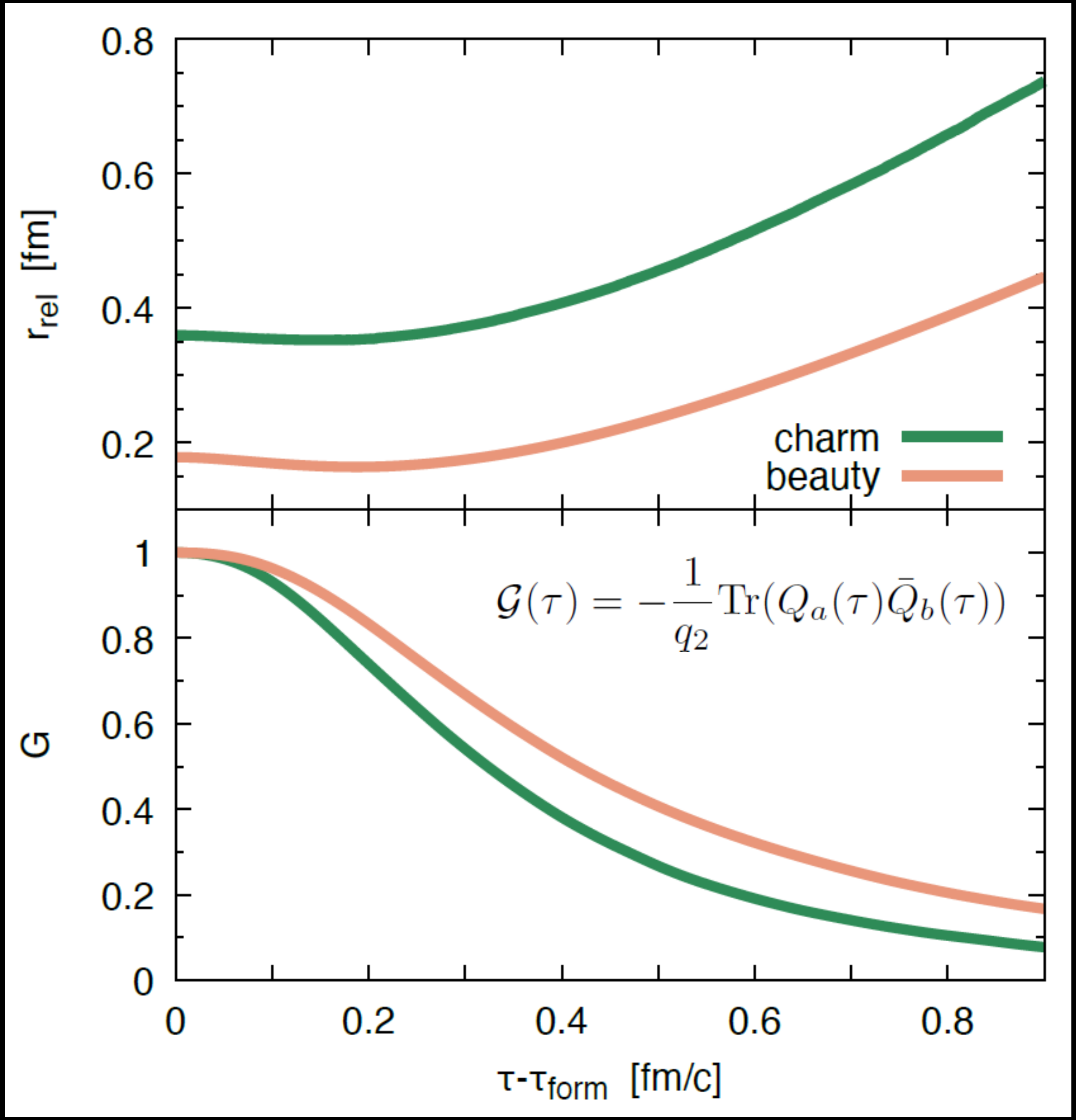
b-bbar pairs



Oliva et al. (2404.05315)

J/ψ and Υ in glasma: color decorrelation

Gauge field fluctuations induce color decorrelation in the pairs, leading to the formation of the octet component.

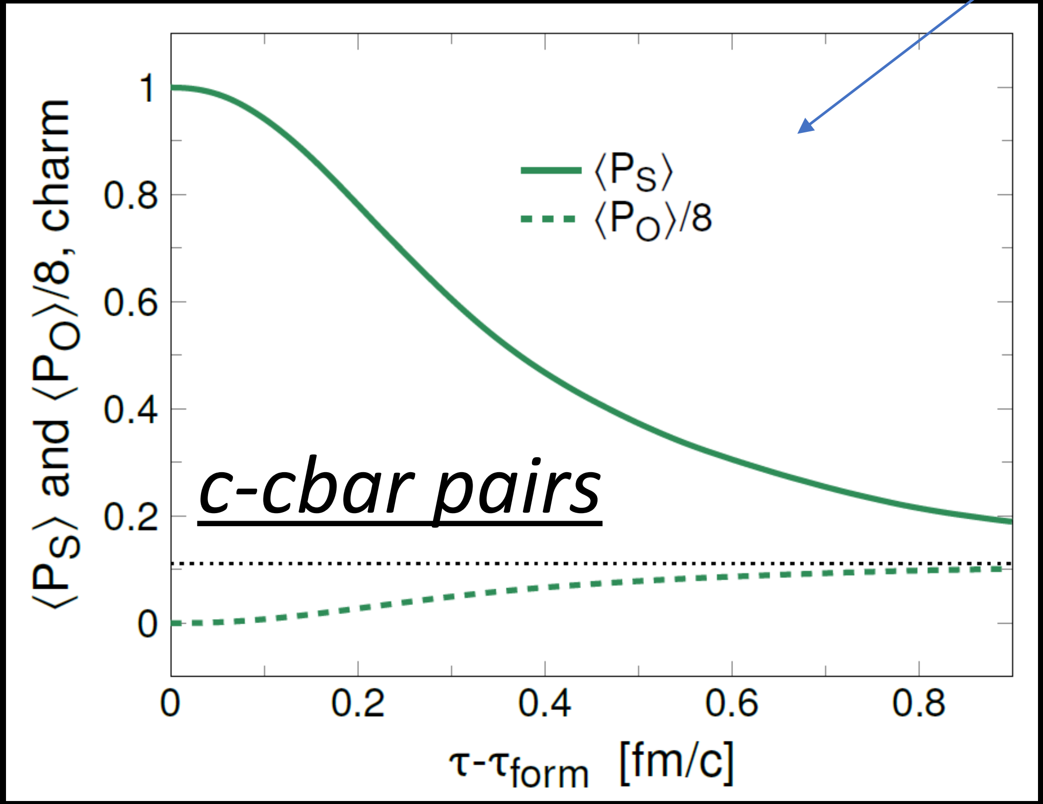


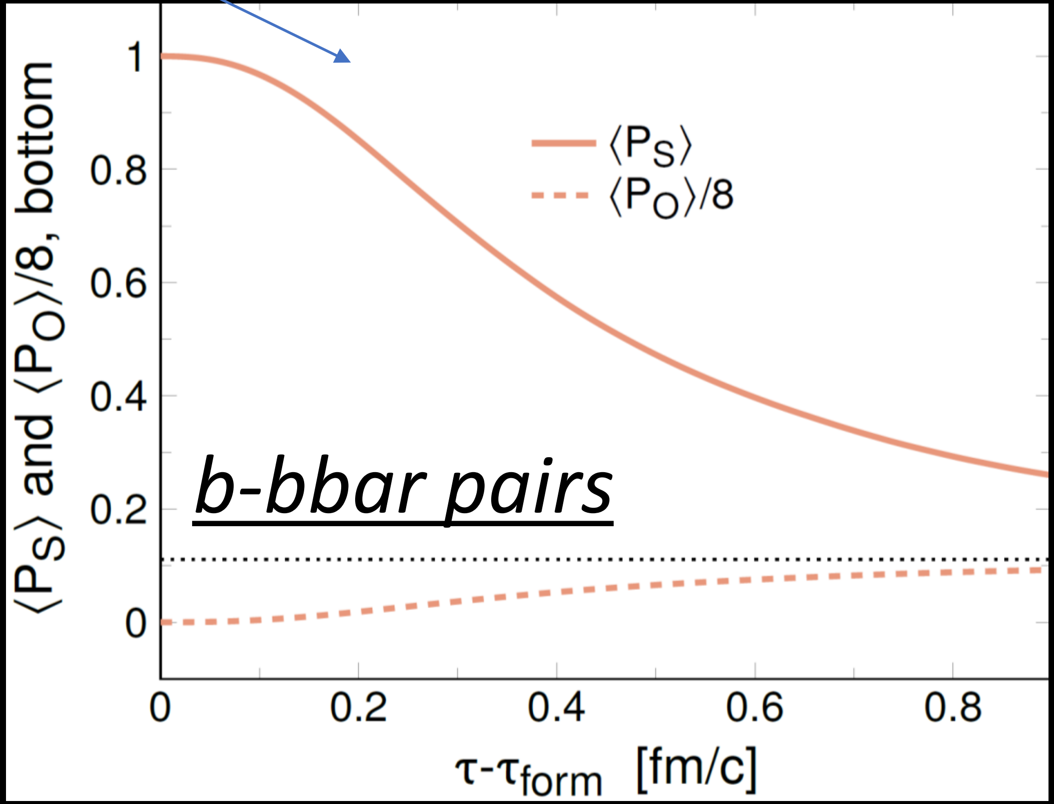
Oliva et al. (2404.05315)
See also Pooja et al. (2024)

<u>Note</u>

During the initial stage of the evolution, the relative distance remains nearly constant, while color decorrelates rapidly. Therefore, in this early phase, the primary driver of pair melting is <u>color decorrelation</u>.

Probabilities to populate the singlet and one of the octet states





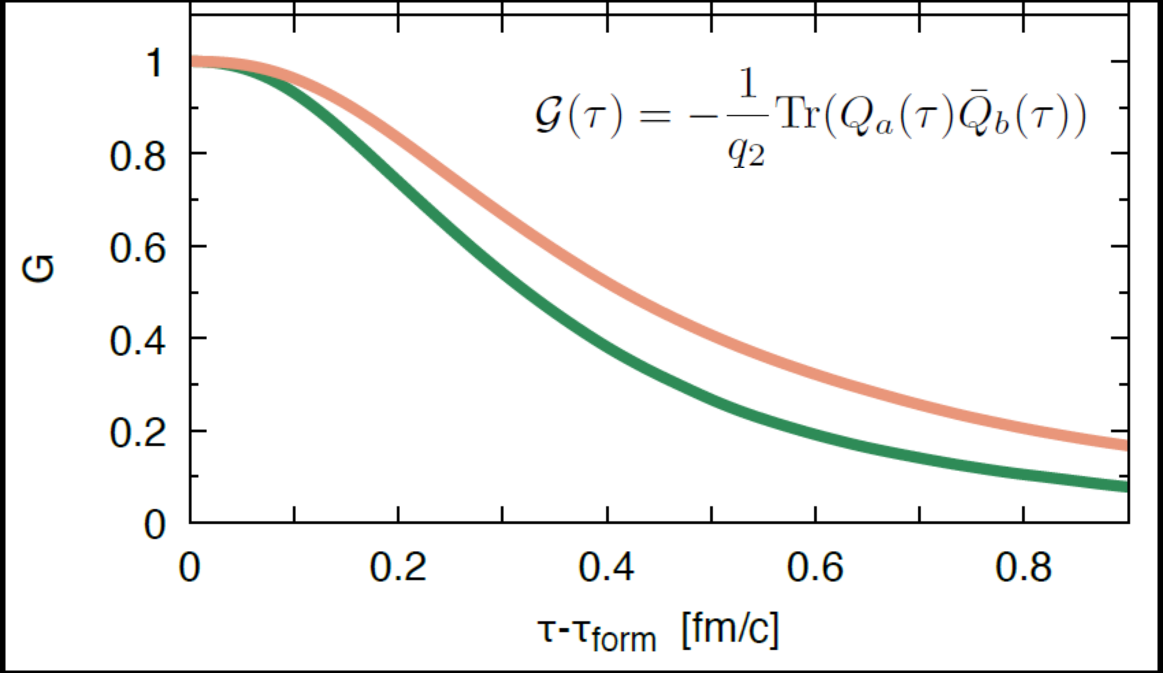
Oliva et al. (2404.05315)
See also Delorme et al. (2024)

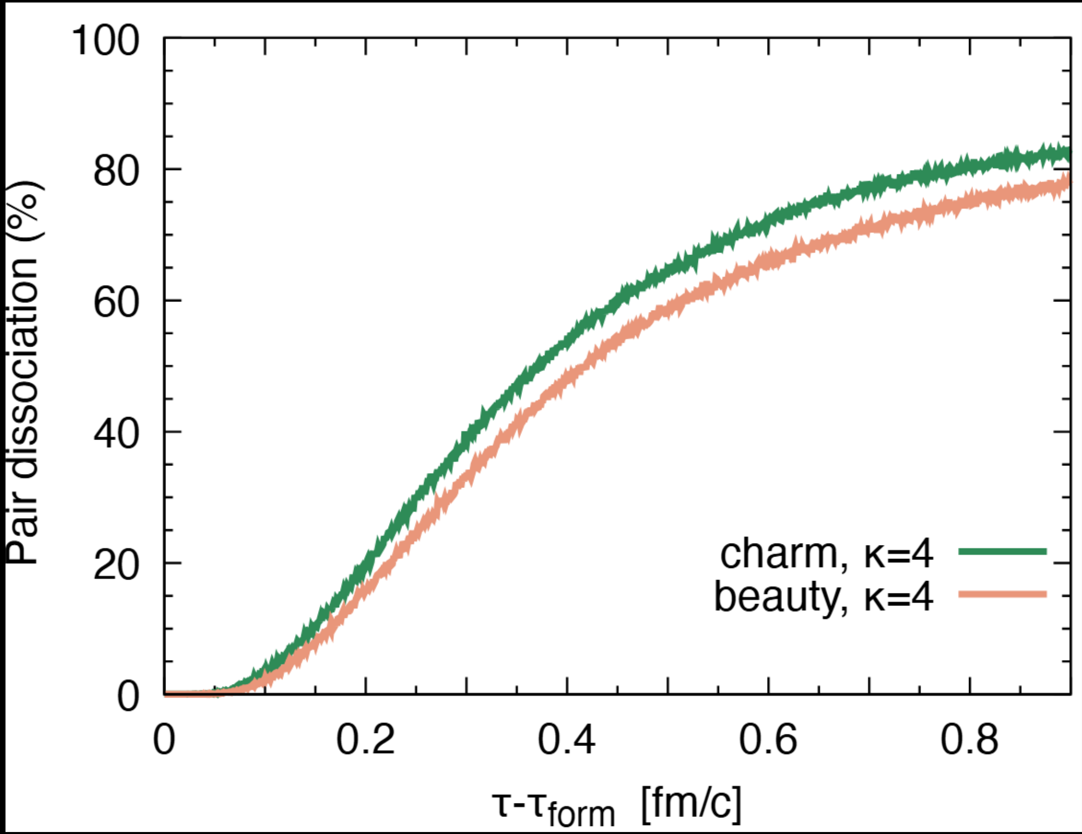
We assign a probability of survival of a pair, which is

$$\mathcal{P}_{\text{survival}} = \exp\left[-\kappa(\mathcal{G}-1)^2\right]$$

$$\mathcal{P}_{\text{melting}} = 1 - \mathcal{P}_{\text{survival}}$$

$$\mathcal{P}_{\text{color}} = \exp\left[-\kappa(\mathcal{G}-1)^2\right]$$





The melting of each pair is decided via a stochastic algorithm.

Oliva et al. (2404.05315)

- *Glasma as the initial condition in high energy nuclear collisions (pA and AA)*
- *Heavy quarks (c and b) can probe the pre-equilibrium stage, gluon-dominated, stage*
- *Interaction of HQs with evolving Glasma fields potentially affects observables (spectra, v2 and possibly more)*
- *Quarkonia melting in the early stage: rough model, which however gives indications on the amount of quark-antiquark pairs that can melt before the QGP forms*

- *Strong fluctuations can lead to a rapid turbulent behavior of the gluon fields(*) (heavy tails in field correlators) potentially enhancing the effects on HQs*
- *Quantum-transport evolution of color in the early stage, relevant for calculation of the dissociation percentage (master equation for the color density matrix)*
- *Merging the early-stage evolution (classical-statistical simulations) with the QGP (relativistic transport)*

(*)See for example Berges et al (2014)