Heavy quarks as probes of the early stage of high-energy nuclear collisions

Marco Ruggieri

Dipartimento di Fisica e Astronomia, Catania University,

and INFN, Sezione di Catania

marco.ruggieri@dfa.unict.it

Coworkers

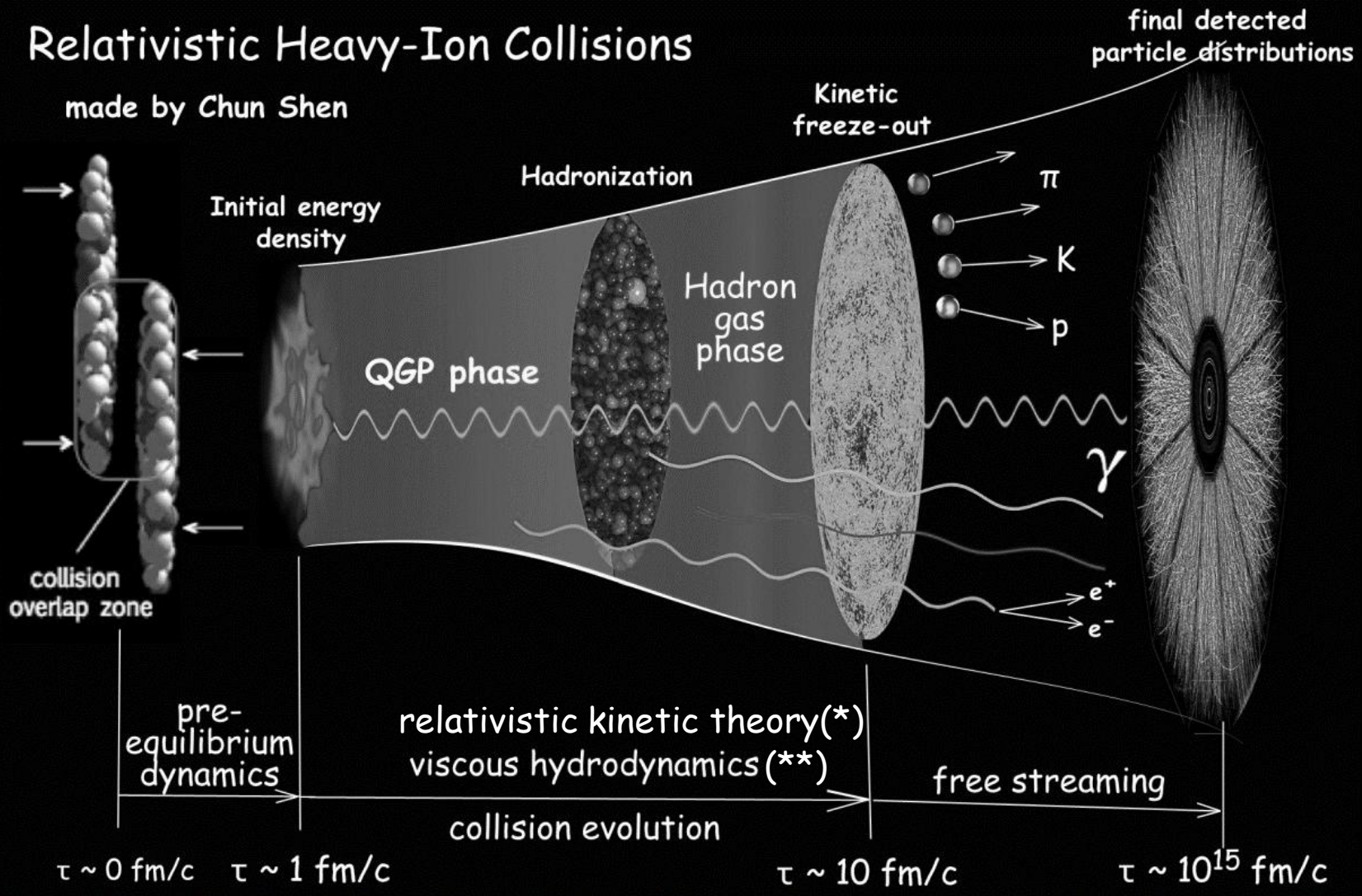
- Vincenzo Greco
- Lucia Oliva
- Fabrizio Murgana
- Gabriele Parisi
- Binu Muraleedharan

Funded by the European Union NextGenerationEU

Plan of the talk

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

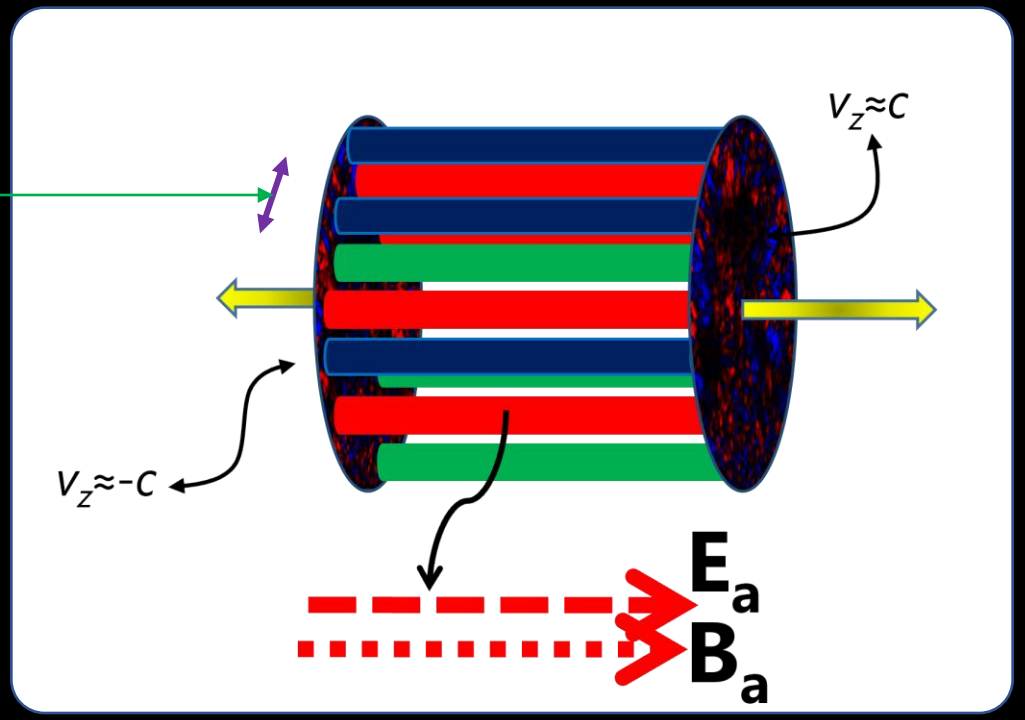
High-energy nuclear collisions



Many gluons in the early stage

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

width of each filament≈1/Qs



Glasma (*)

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

Qs = O(1 GeV)

(*)Lappi and McLerran (2006)

For a nice recent review see Carrington-Mrowczynski, 2401.13705

Hot spots model for the p in pA *(borrowed from the IP-Glasma scheme)*
Valence quarks act as sources for static charges that generate the fields.
Intensity of the fields is regulated by the saturation scale, Qs.

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

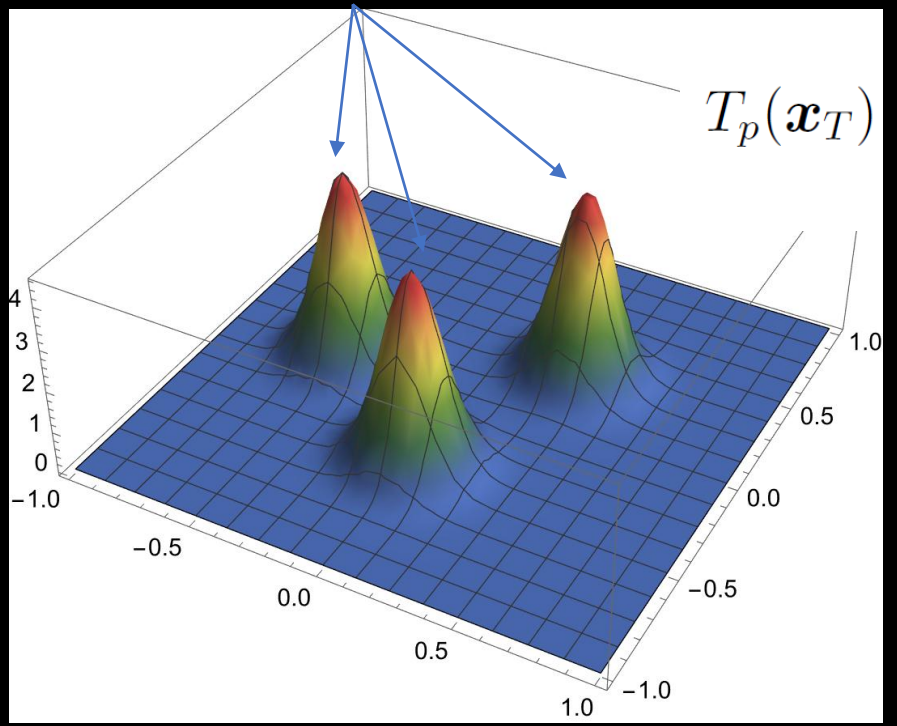
Saturation scale in the transverse plane

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

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

Qs = O(1 GeV)

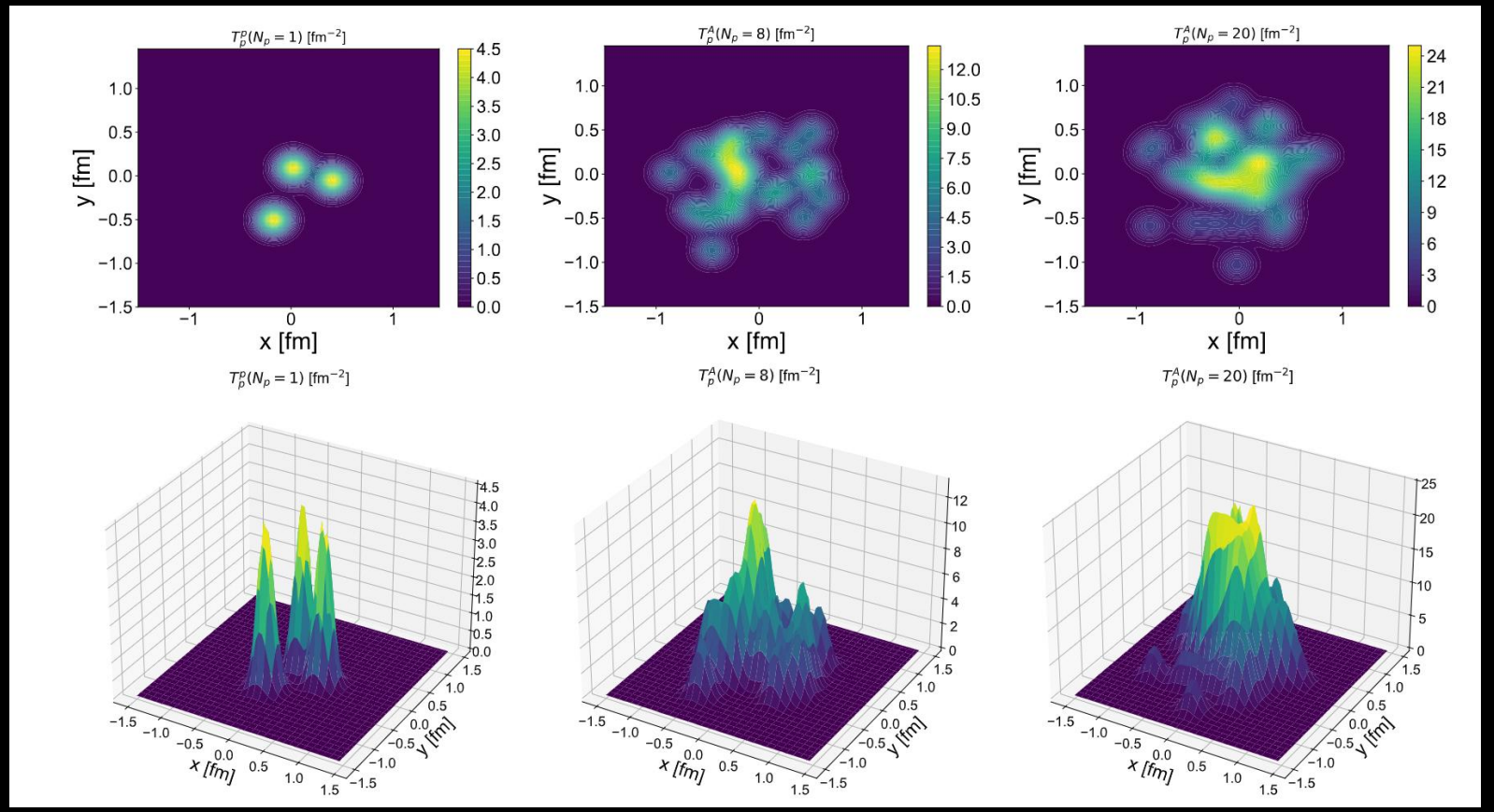
Valence quarks (hotspots)



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

Hot spots model for the A in pA *(borrowed from the IP-Glasma scheme)*

3 valence quarks per nucleon in the nucleus



proton ***8 nucleons*** ***20 nucleons***

B. Schenke *et al.* (2022,2023)
Gabriele Parisi *et al* (2025)

The pre-equilibrium stage: evolving the glasma via CYM equations

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.

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

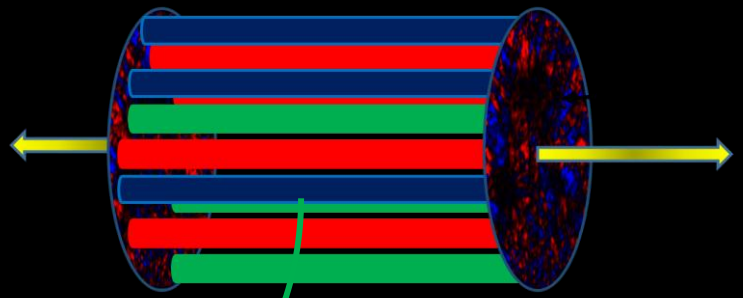
$$\tau = \sqrt{t^2 - z^2},$$
$$\eta = \frac{1}{2}\log\left(\frac{t+z}{t-z}\right)$$

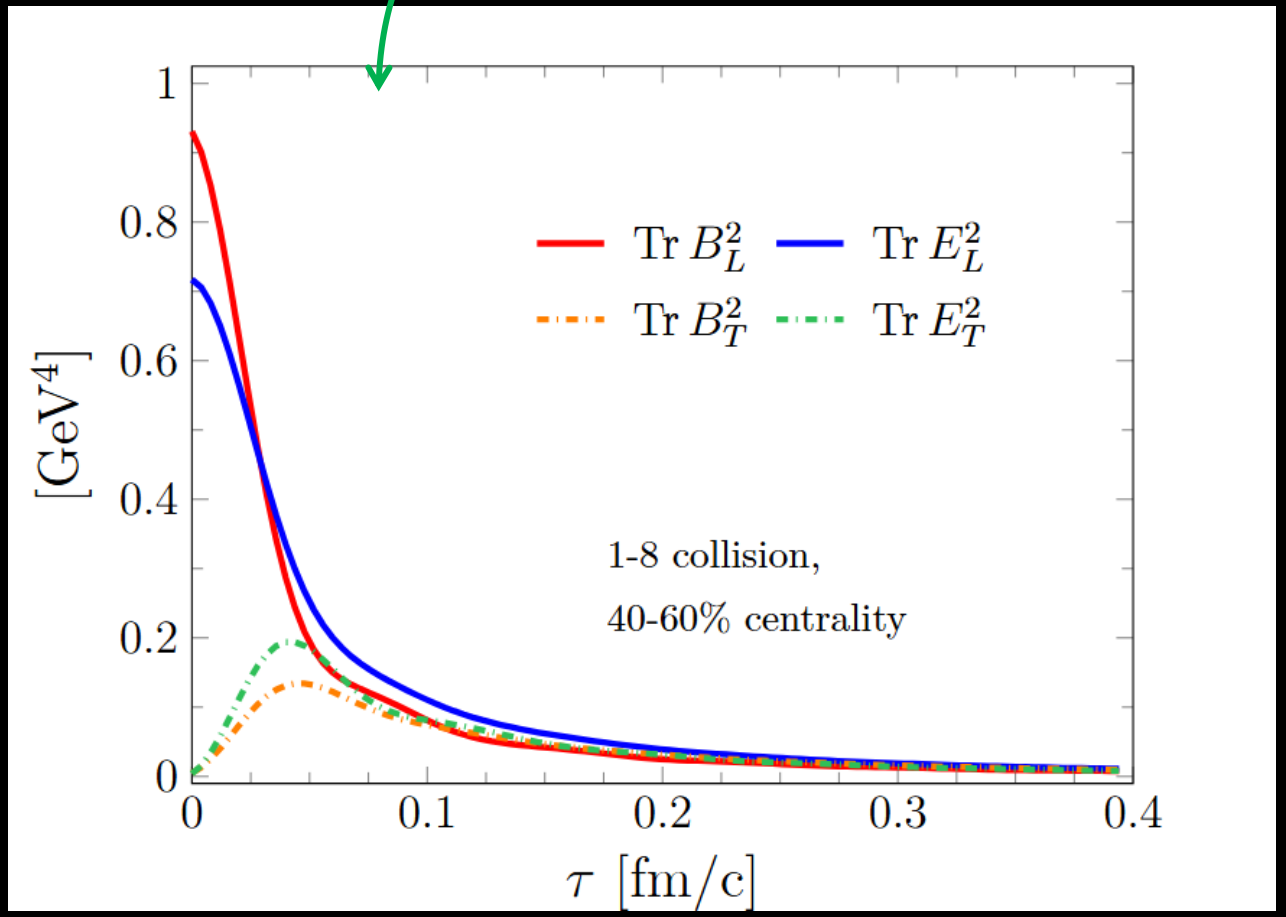
$$\partial_\tau E_i = \frac{1}{\tau} D_\eta F_{\eta i} + \tau D_j F_{ji}, \qquad E_i = \tau \partial_\tau A_i,$$
$$\partial_\tau E_\eta = \frac{1}{\tau} D_j F_{j\eta}, \qquad E_\eta = \frac{1}{\tau}\partial_\tau A_\eta.$$

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.
The code, entirely written in Python, will be made public within a few months

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)

Elliptic flow

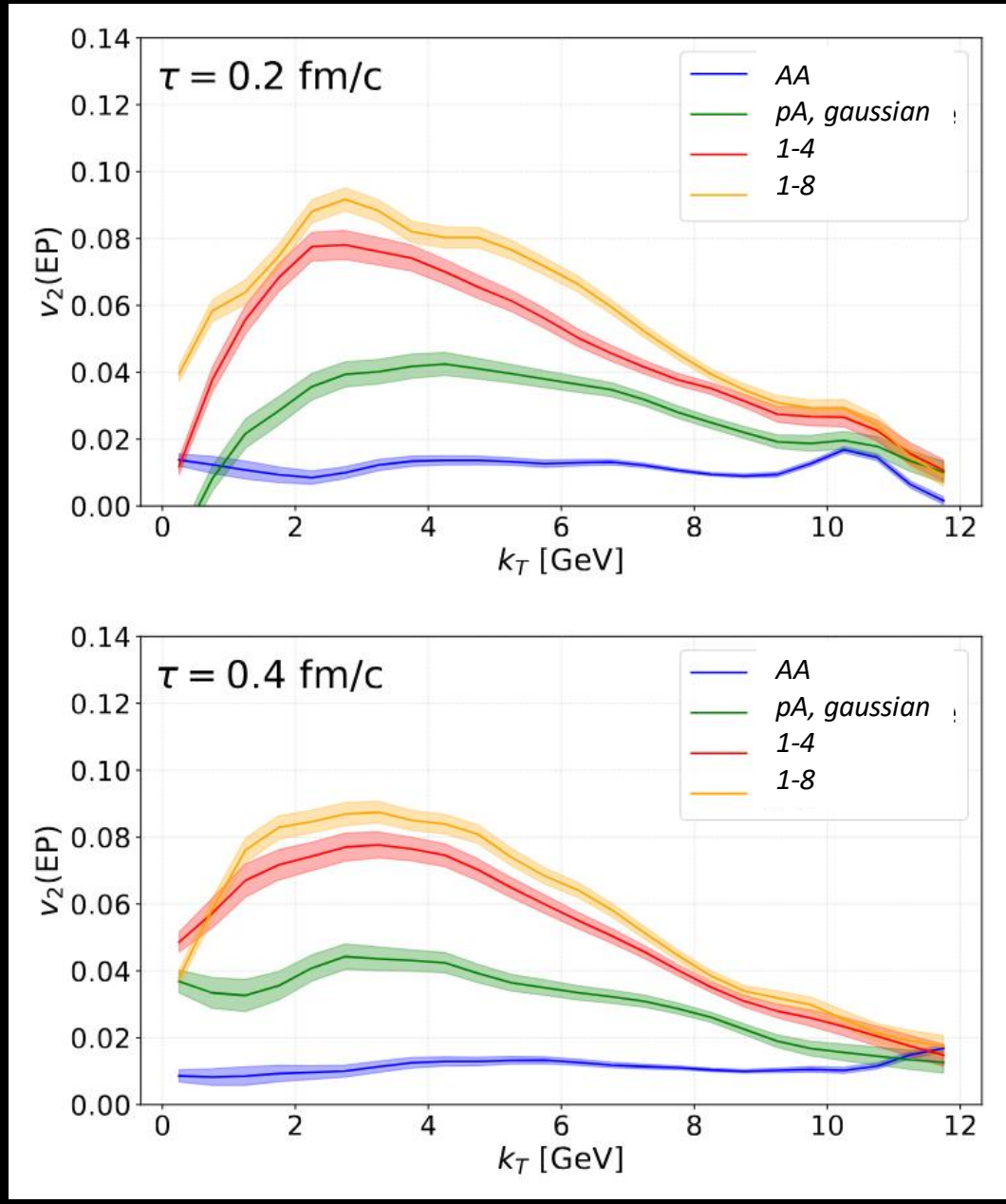
(transverse) gluon spectrum

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

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

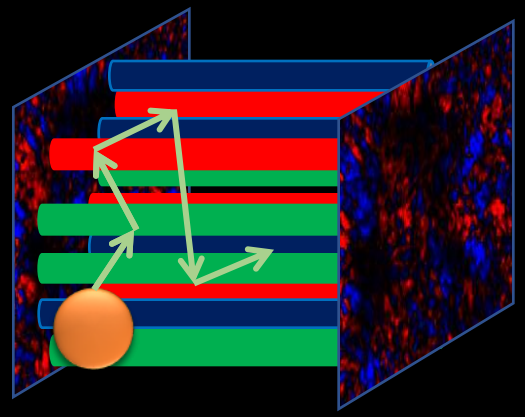
$$C_2 = \int \left(\frac{k_x^2 - k_y^2}{k_T^2} \right) \frac{dN}{d^2k_T}\, d^2k_T,$$

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



M.R. et al, in preparation
In agreement with Schenke et al (2015).
See also Carrington-Mrowczynski-Ollitrault, 2406.14463 for hydro-like behavior of the evolving glasma fields within an early-time expansion.

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)*

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

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

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

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

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

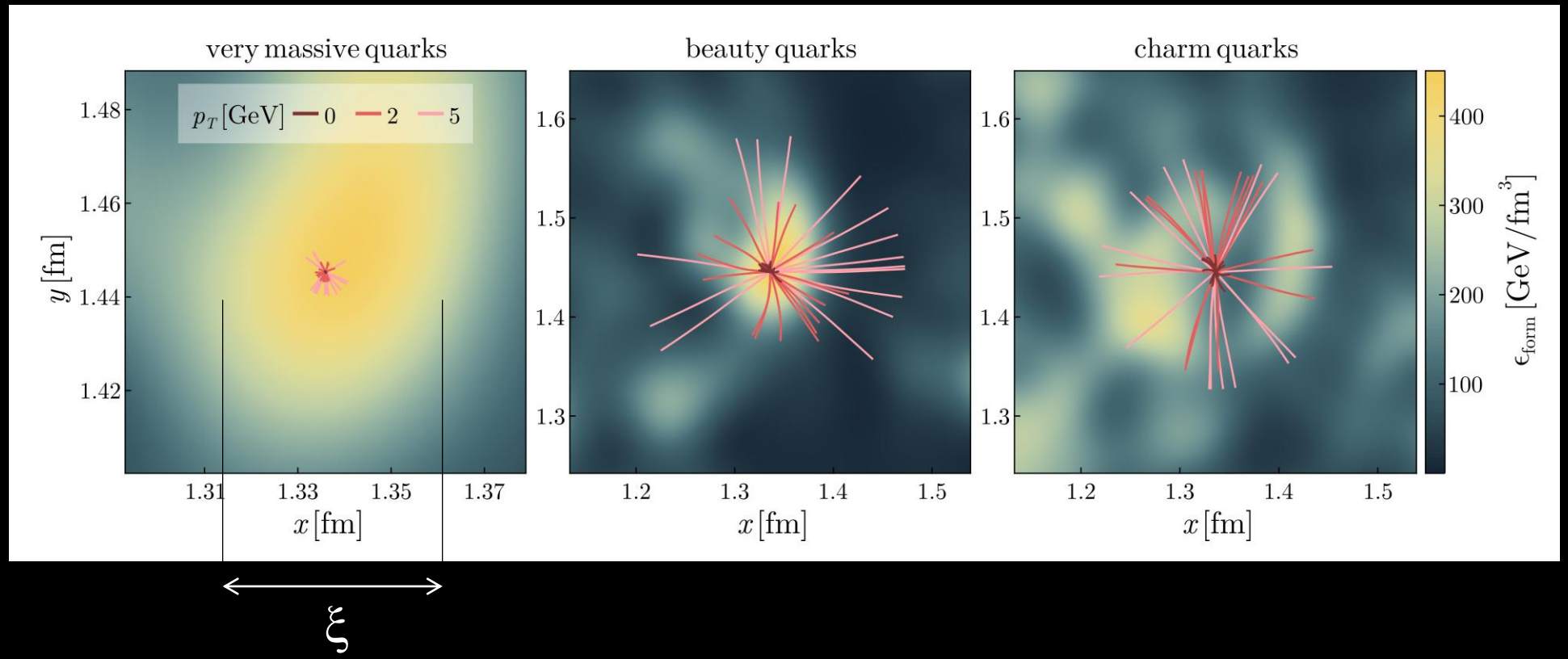
$$D_\mu J_a^\mu = 0 \quad \text{(Color current conservation)}$$

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

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

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

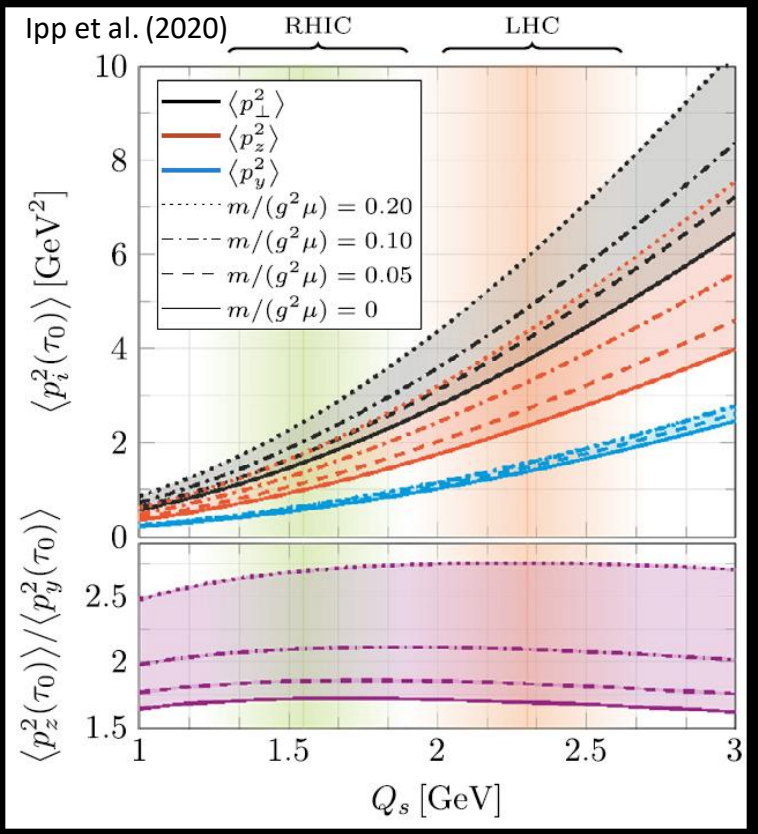
Dana Avramescu *et al.* (2023)

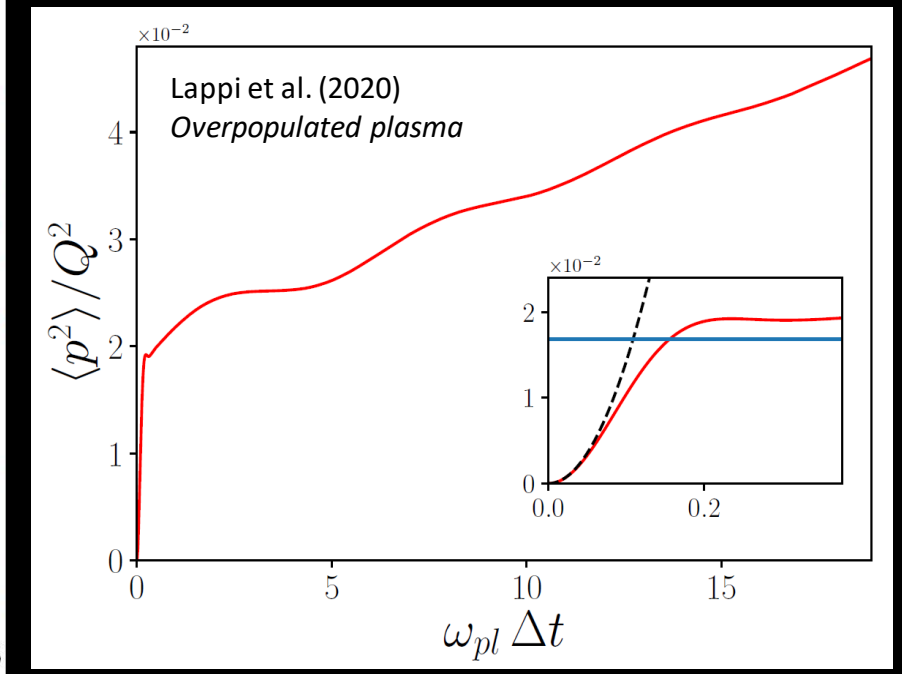


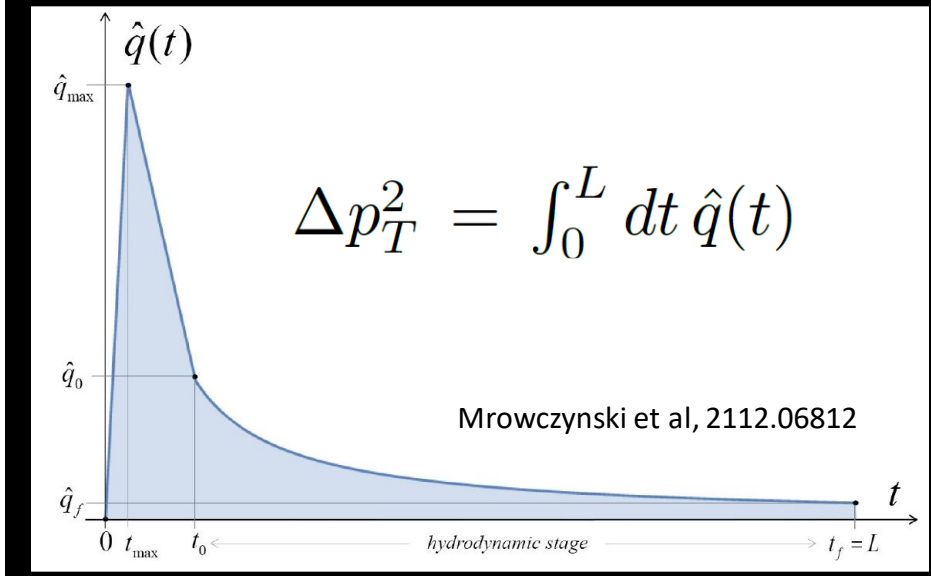
Slow color charges spend some time within one single filament: diffusion in a coherent field, rather than in a random medium.

The force exerted on these charges is time-correlated.

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







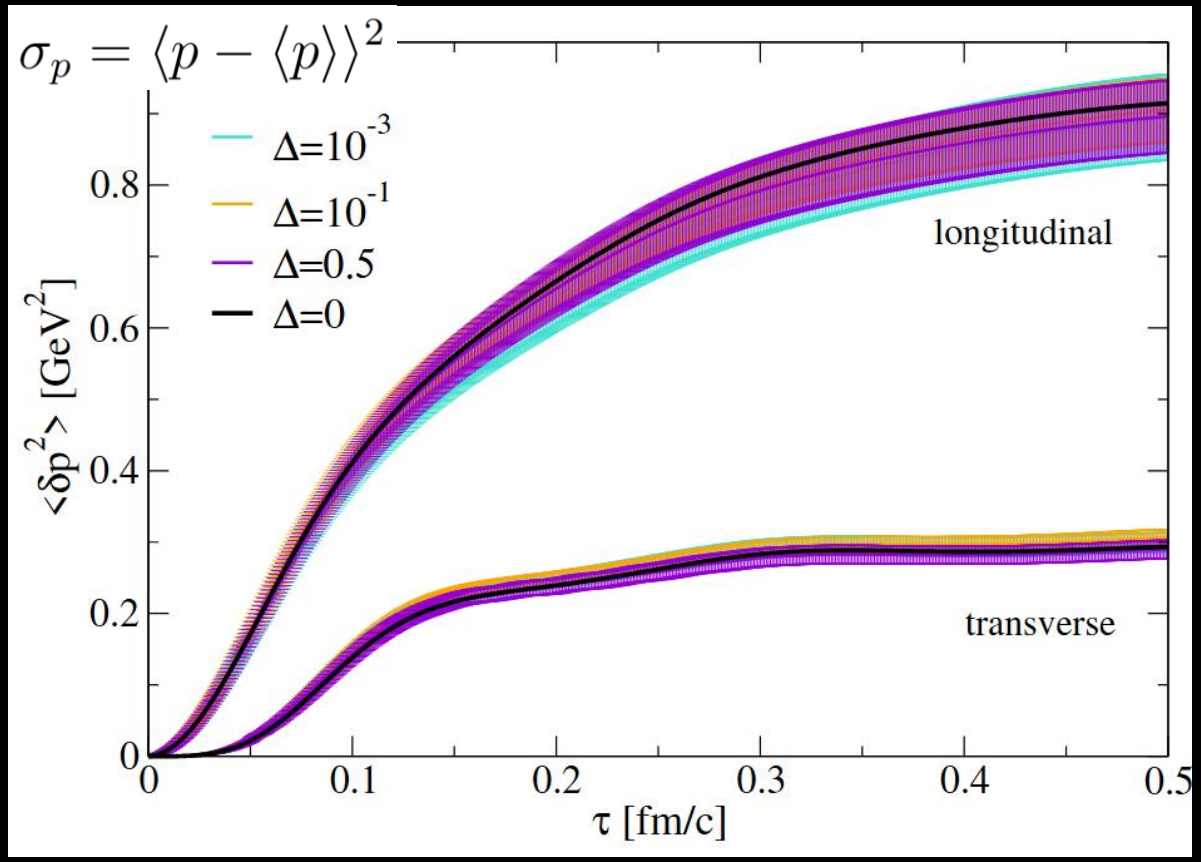
See also Mrowcznski, 1706.03127

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

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

For transport of hard probes see Carrington *et al.*, 2202.00357

pA collisions



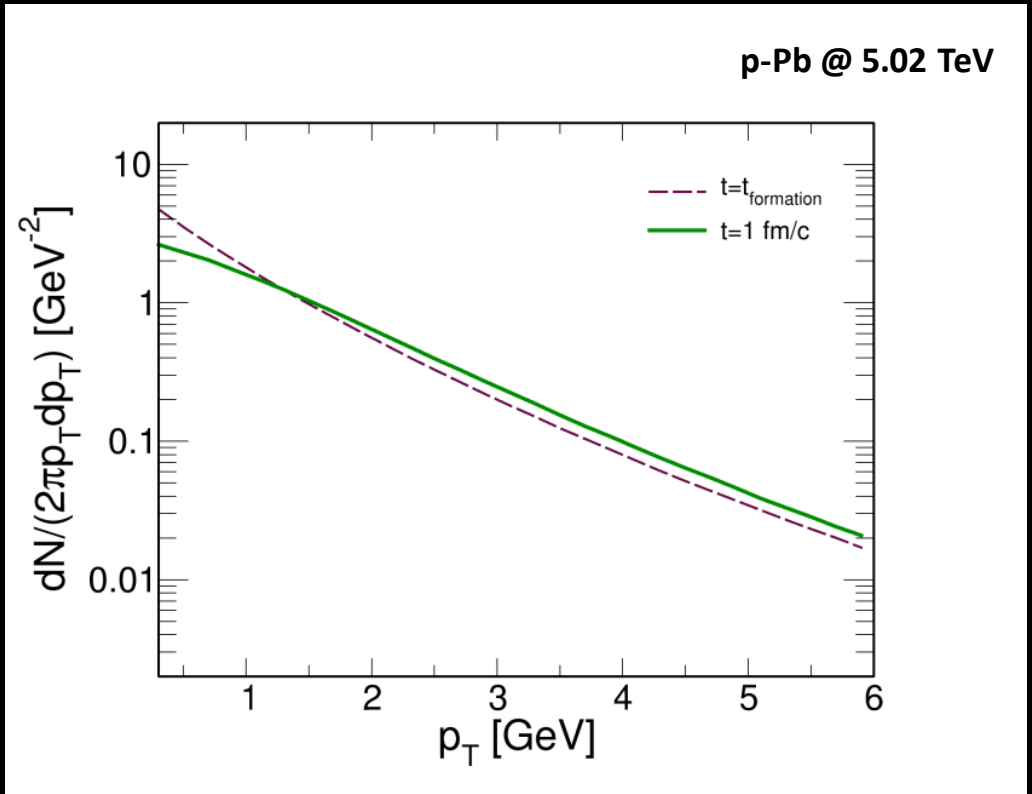
Anisotropic diffusion coefficients of HQs in evolving-glasma fields.
Adding small fluctuations does not lead to a drastic change of the results.

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

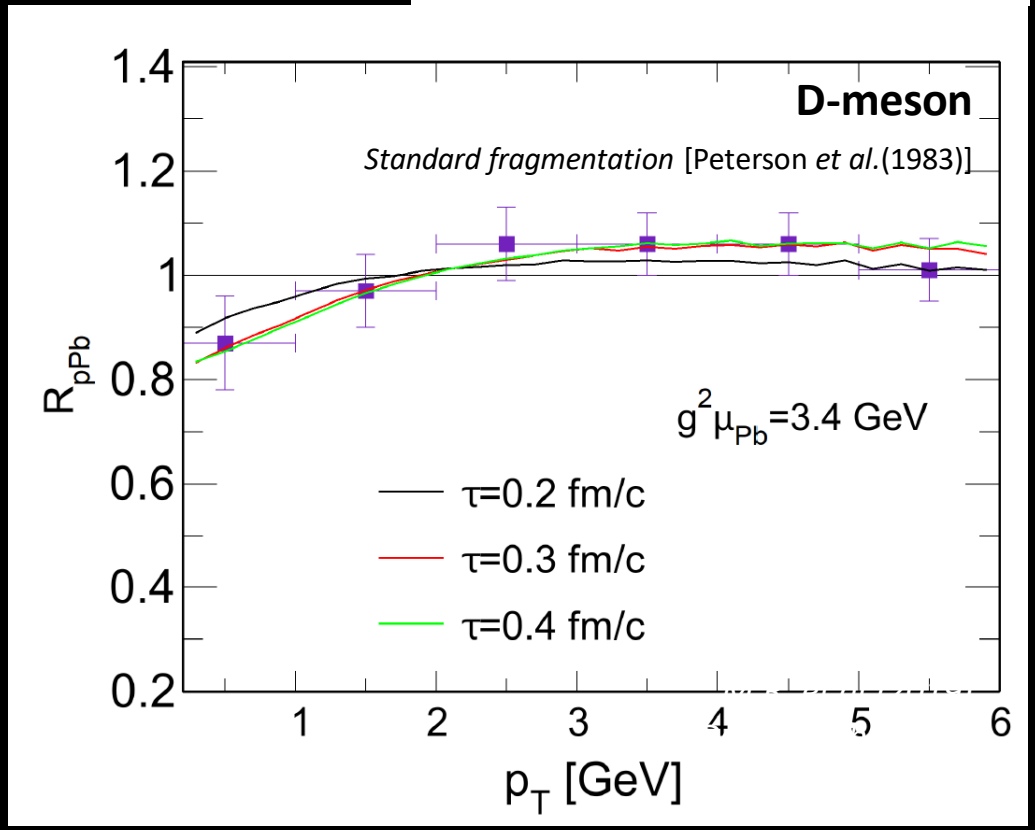
The pre-equilibrium stage: potential impact on modification factor

Initial distribution

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



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



$R_{\mathrm{pPb}} \neq 1$

Interaction with the fields created by the collision

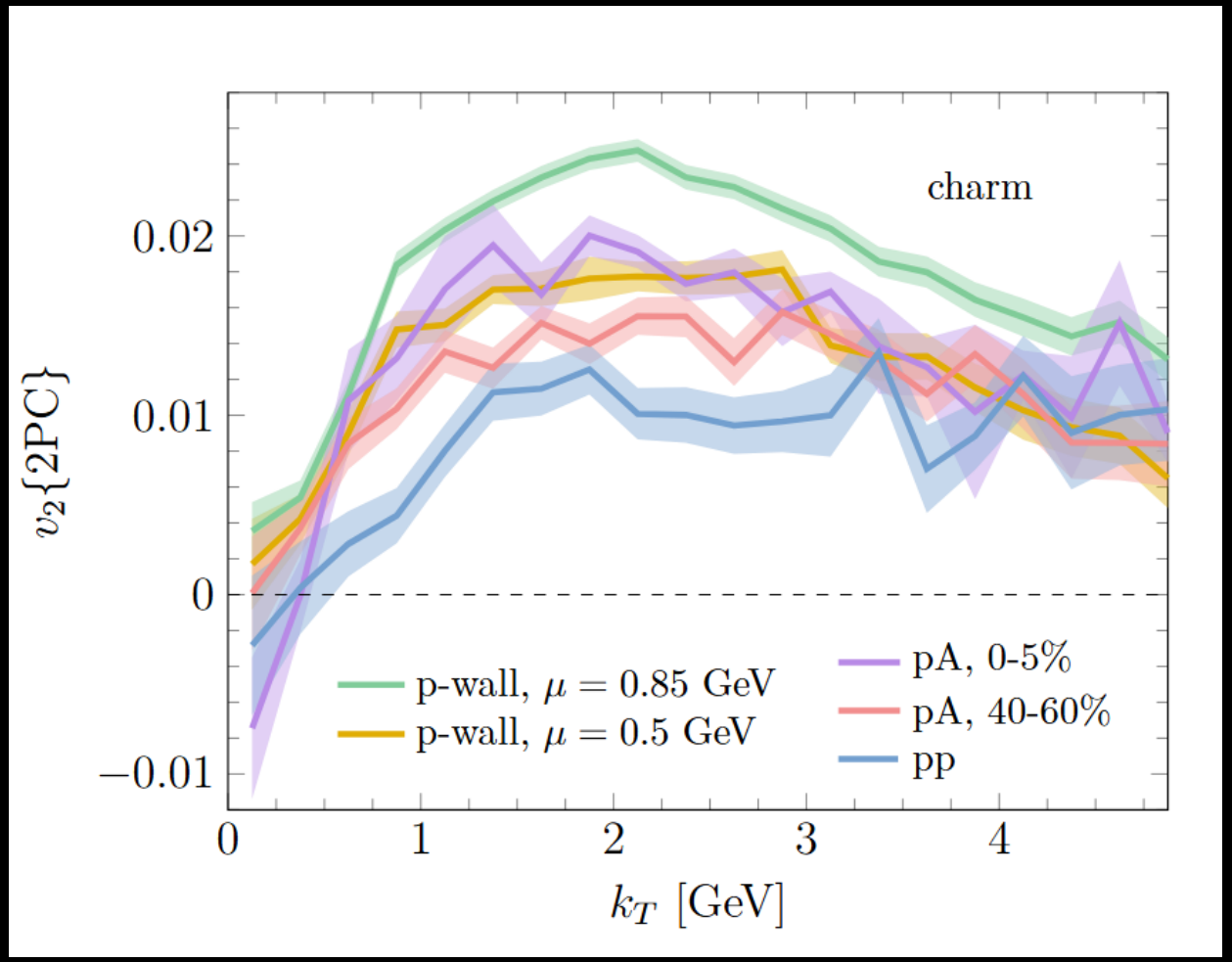
See also

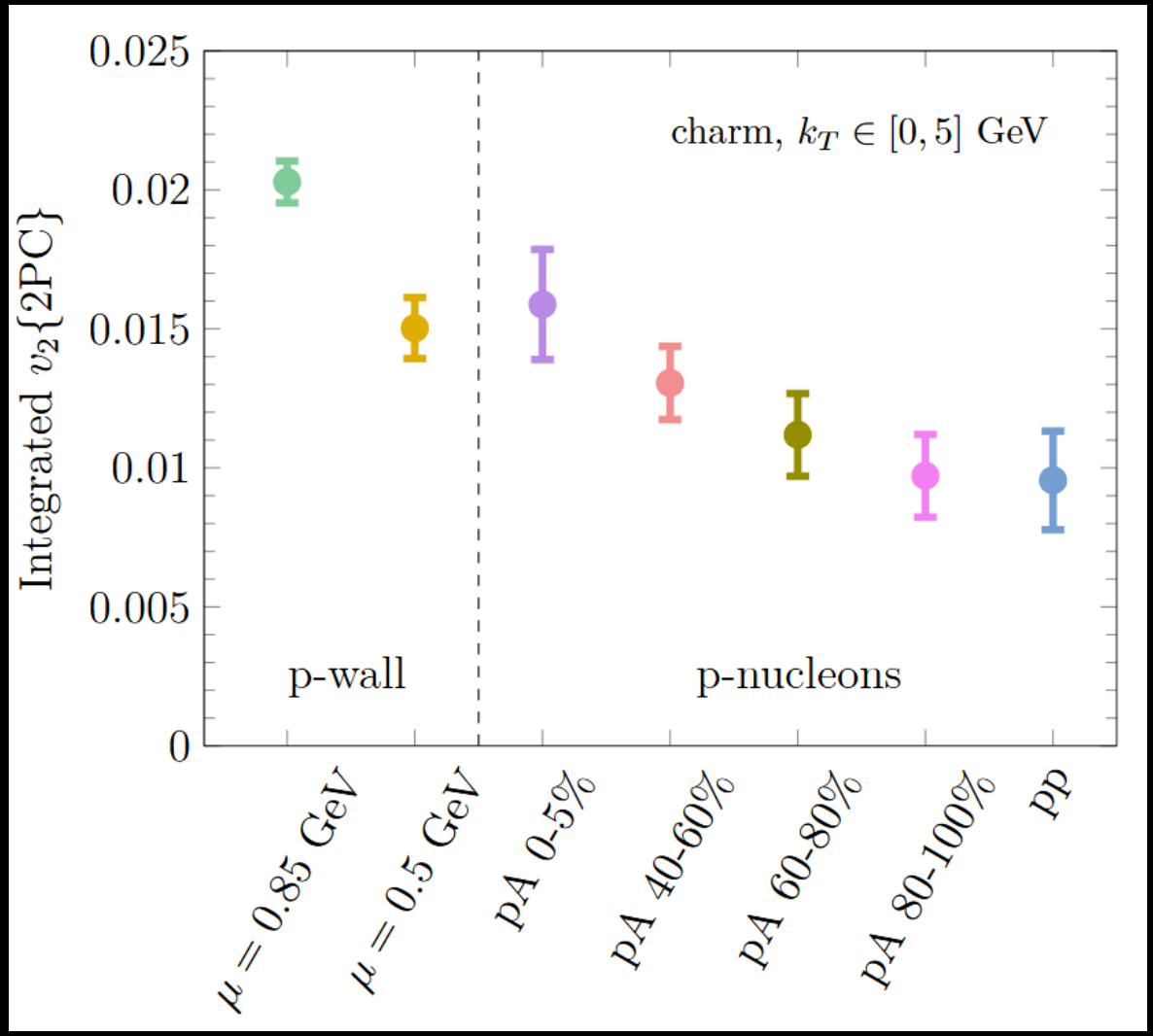
M. Ruggieri and S. K. Das (2018)

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

The pre-equilibrium stage: potential impact on elliptic flow

Charm-quark v_2 from early stage only



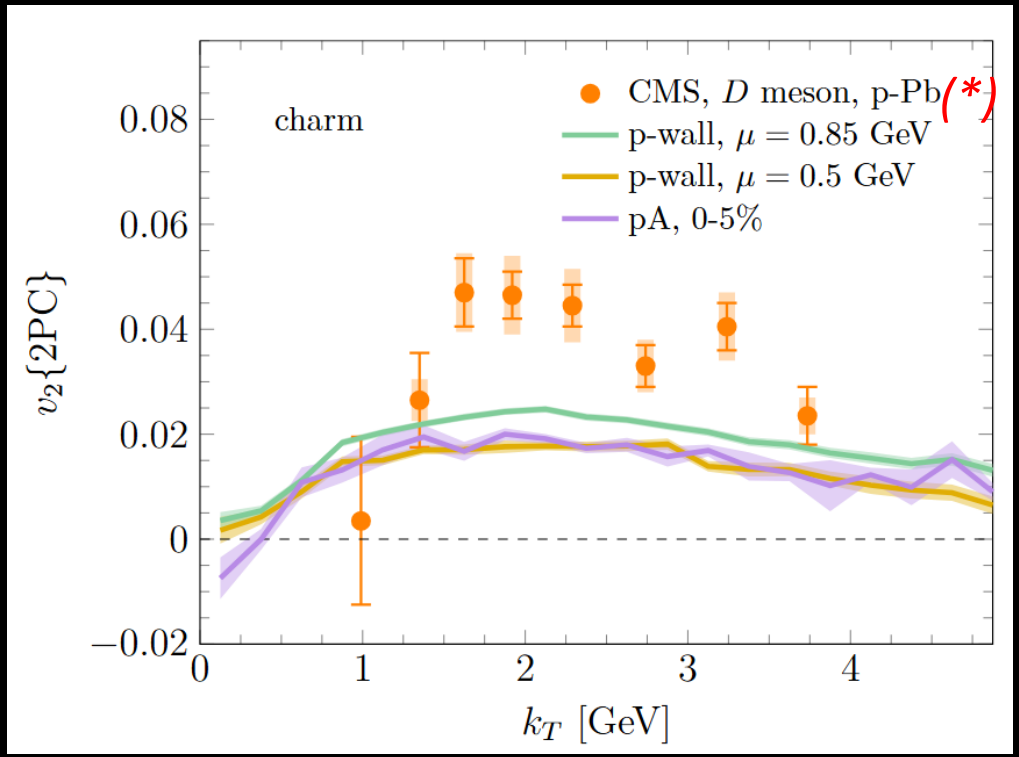


Gabriele Parisi et al, in preparation

Charm-quark integrated v_2 from early stage only

The pre-equilibrium stage: potential impact on elliptic flow

Charm-quark v_2 from early stage only



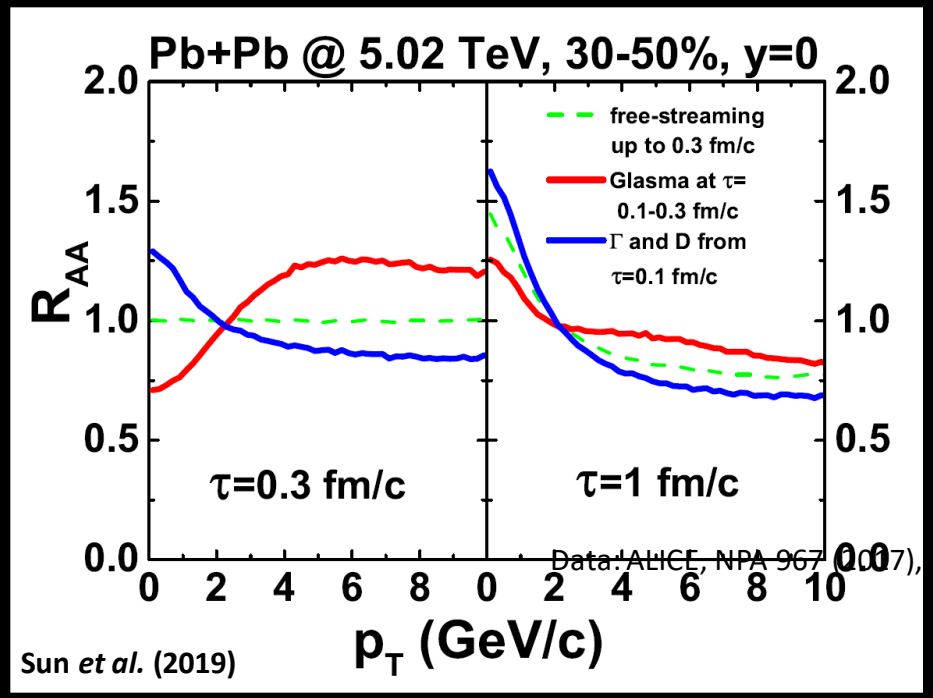
Gabriele Parisi et al, in preparation

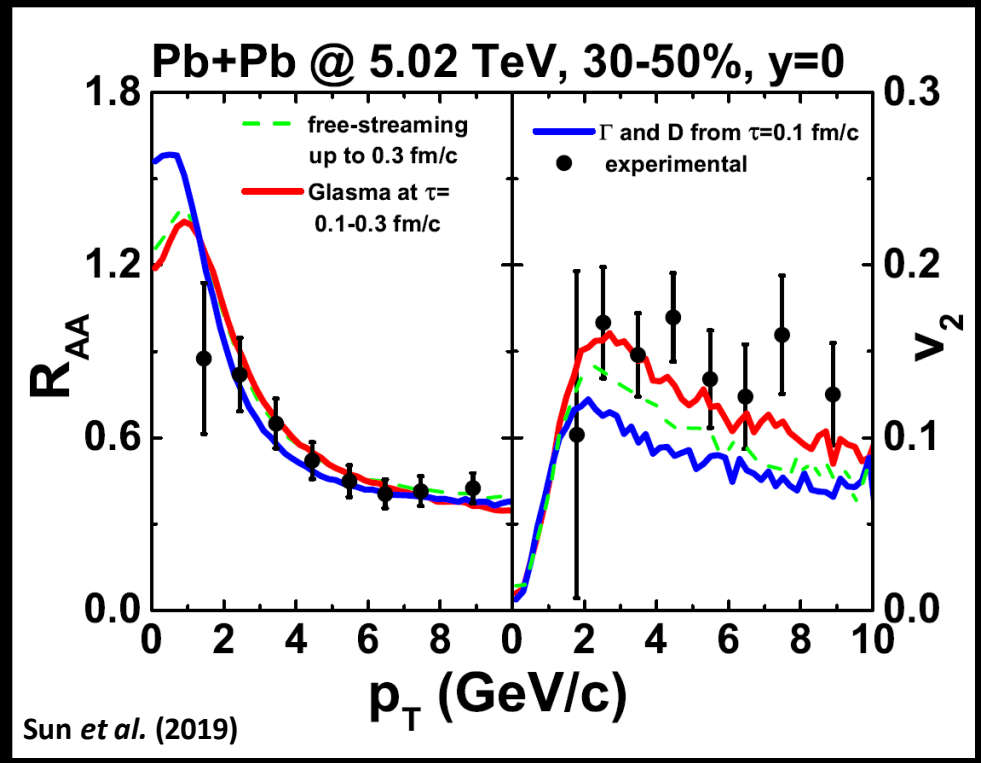
The early stage might give a substantial contribution to the v2 of charmed mesons.

(*) Experimental data shown just for guiding the eye and for establishing the order of magnitude of the v_2 measured. The v_2 and kT in the CMS data have been scaled by 2 to take into account hadronization (coalescence)

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

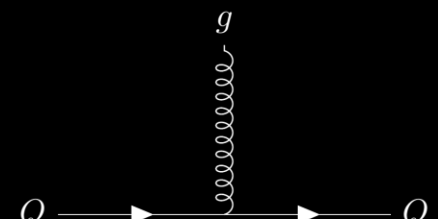
- *Diffusion in the early stage*
- *Evolution in the QGP*



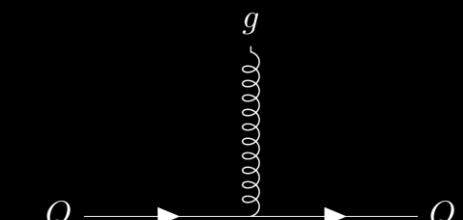


Diffusion in the early stage helps to describe simultaneously the RAA and the v2.

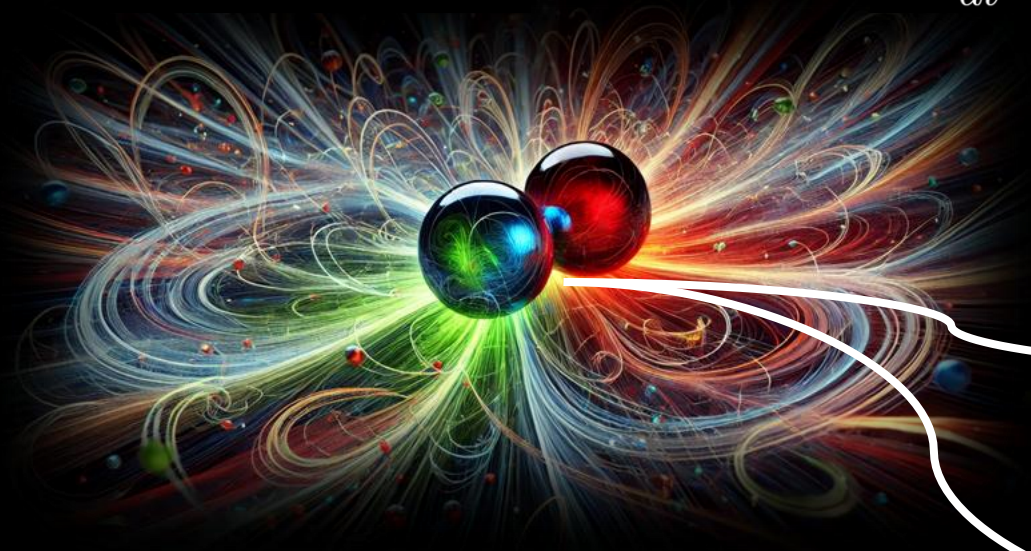
Color-singlet HQs states in the glasma



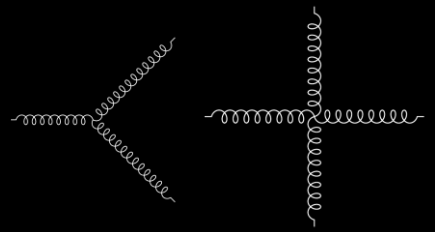
$$E\frac{d\bar{Q}_a}{dt} = g\, f_{abc} A^{\mu}_b p_\mu \bar{Q}_c$$



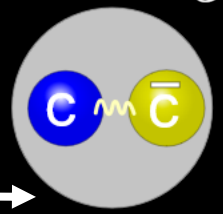
$$E\frac{dQ_a}{dt} = g\, f_{abc} A^{\mu}_b p_\mu Q_c$$



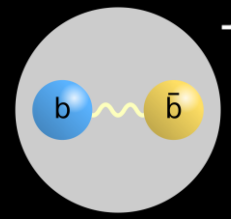
$$D^a_\mu F^{\mu\nu}_{ab} = 0$$

()

J/ψ



Υ



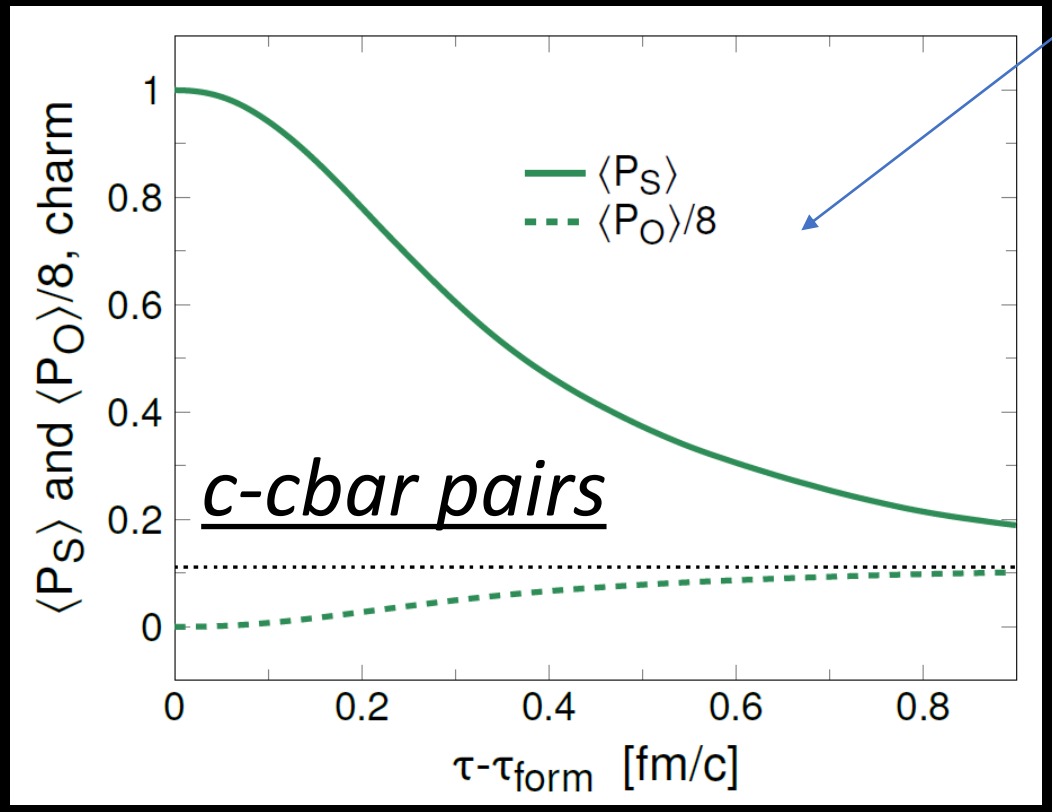
Quark-antiquark pairs are constantly bombarded by gluons during the early stage.
Their color charges fluctuate, leading to transitions to color-octet states.

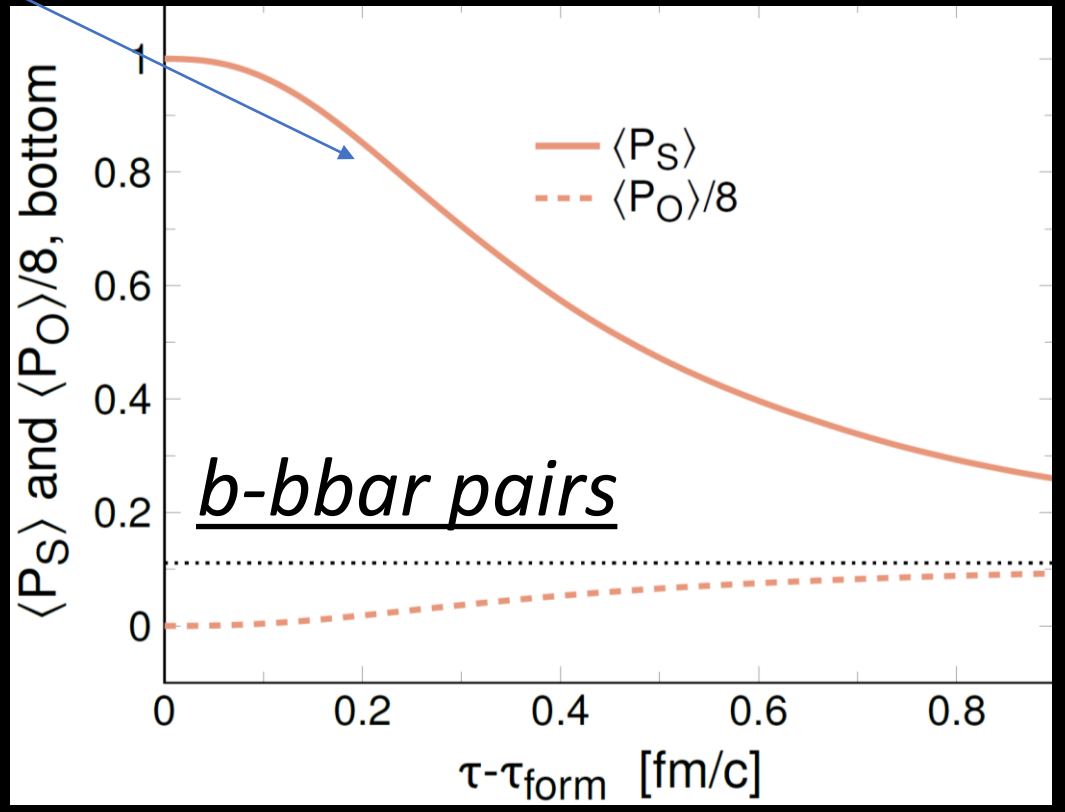
More precisely

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.

Color equilibration in evolving glasma

Probabilities to populate the singlet and one of the octet states





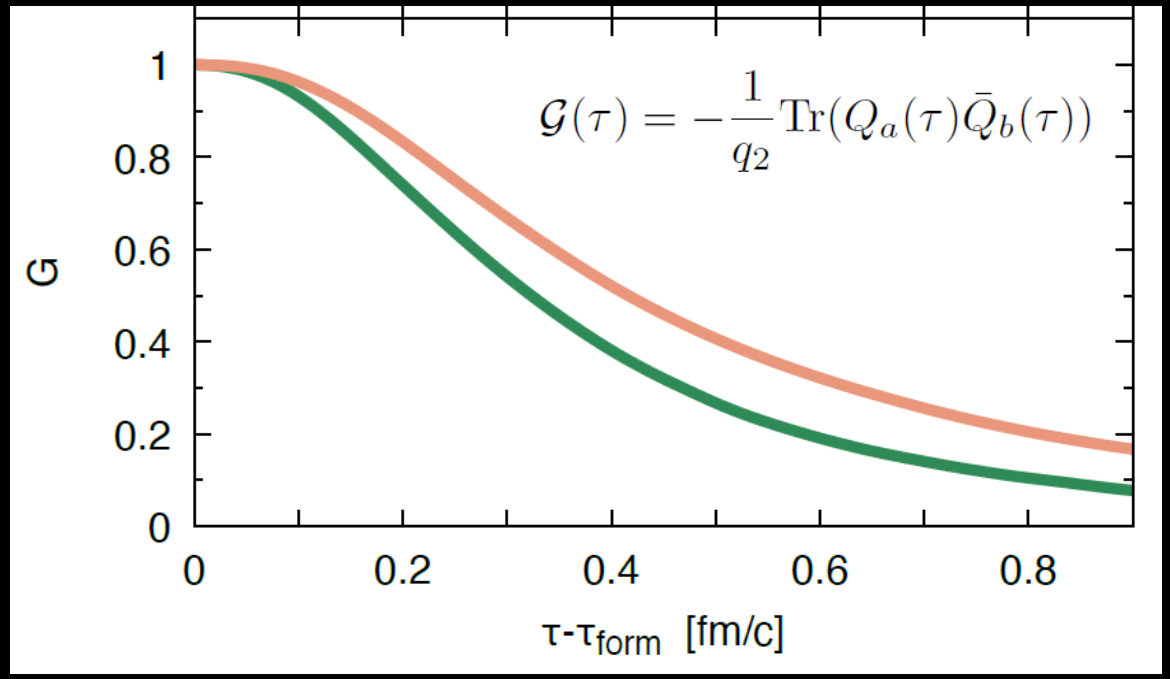
Nearly equipartition of color: it becomes equiprobable for a q-qbar state to be either in the singlet or in one of the octet states

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

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

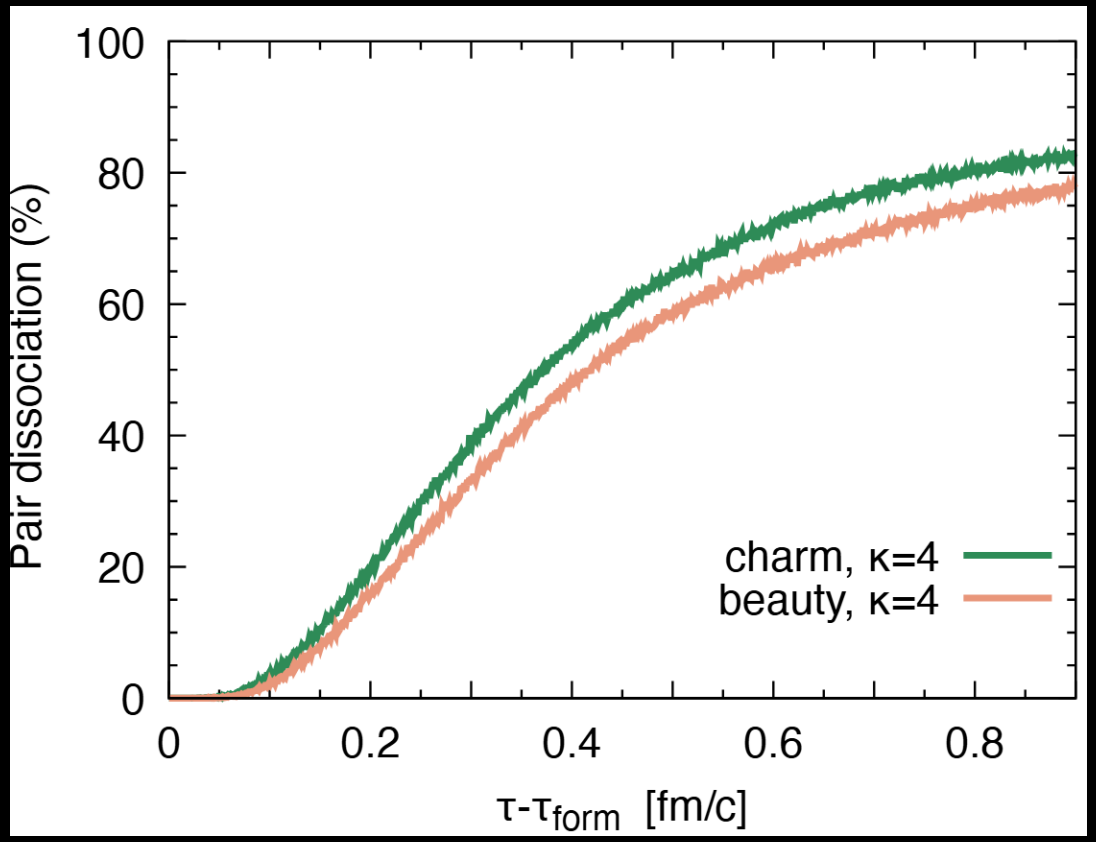
$$\mathcal{P}_{\rm survival} = \exp\left[-\kappa(\mathcal{G}-1)^2\right]$$

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



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

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



Oliva et al. (2404.05315)

Color equilibration (?) within a quantum master equation approach

Evolution of the density operator in color space (color kinetic theory) is studied within a quantum master equation approach:

$$H = H^1 + H^2$$

$$H^1 = -\frac{1}{\sqrt{2N_c}} g E_{ia} r_i \left(|S\rangle\langle O^a| + |O^a\rangle\langle S|\right)$$

$$H^2 = -\frac{1}{2} g E_{ib} r_i d_{abc} |O^a\rangle\langle O^c|$$

See Brambilla et al., 1612.07248

$$\frac{d\rho_{SS}}{dt} = \frac{2g^2 r_i^2}{2N_c\hbar^2}\int_0^t dt_1 C_i(t,t_1)\cos[\omega(t-t_1)] \left(\rho_{OO}(t_1) - d_A\rho_{SS}(t_1)\right),$$

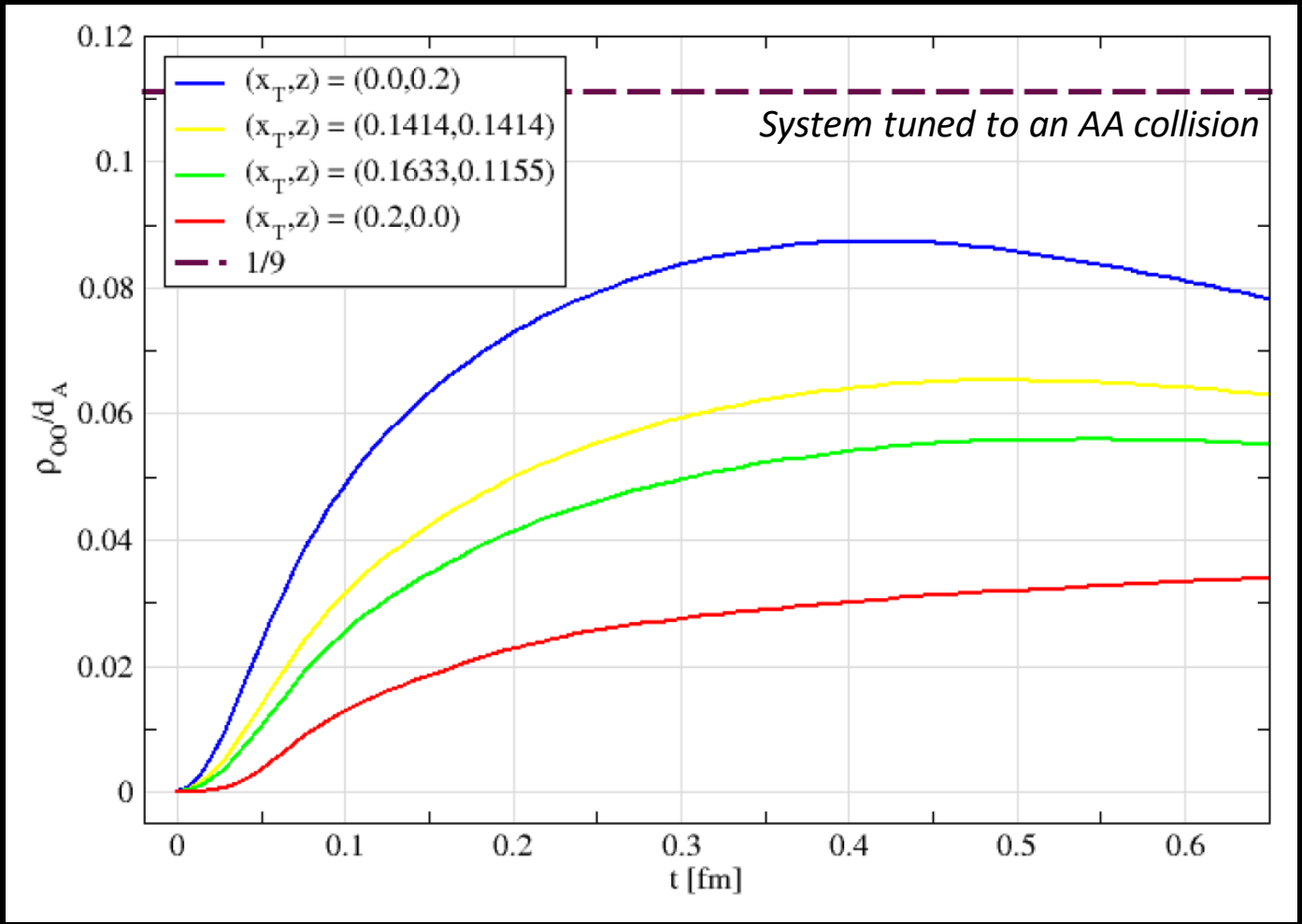
$$\frac{d\rho_{OO}}{dt} = \frac{2g^2 r_i^2}{2N_c\hbar^2}\int_0^t dt_1 C_i(t,t_1)\cos[\omega(t-t_1)] \left(d_A\rho_{SS}(t_1) - \rho_{OO}(t_1)\right)$$

$$\langle E_{ia}(t_1) E_{jb}(t)\rangle = \delta^{ij}\delta^{ab} C_i(t,t_1)$$

Muraleedharan et al., in preparation

Color equilibration (?) within a quantum master equation approach

Evolution of the density operator in color space (color kinetic theory) is studied within a quantum master equation approach:



Muraleedharan et al., in preparation

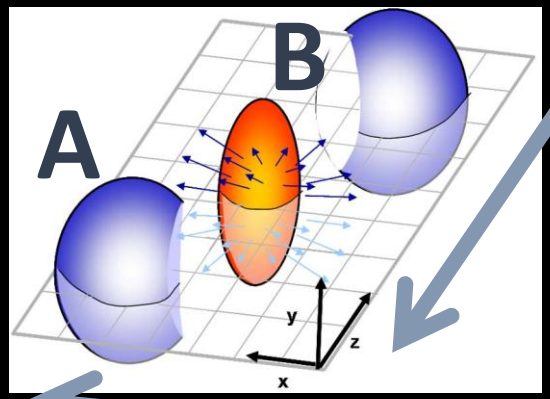
Conclusions and Outlook

- *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)

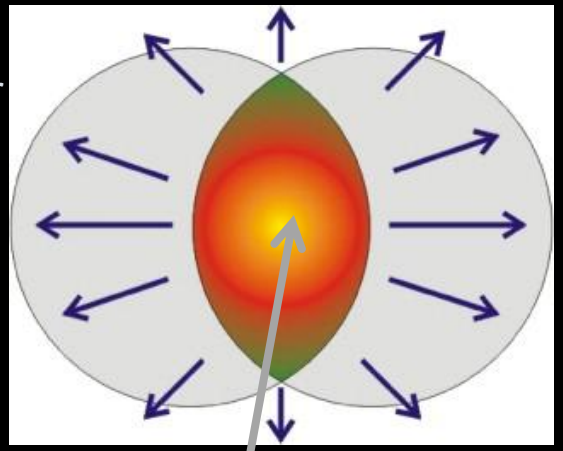
Appendix



Collision (flight) direction

Impact parameter direction

Impact parameter direction



Collision direction

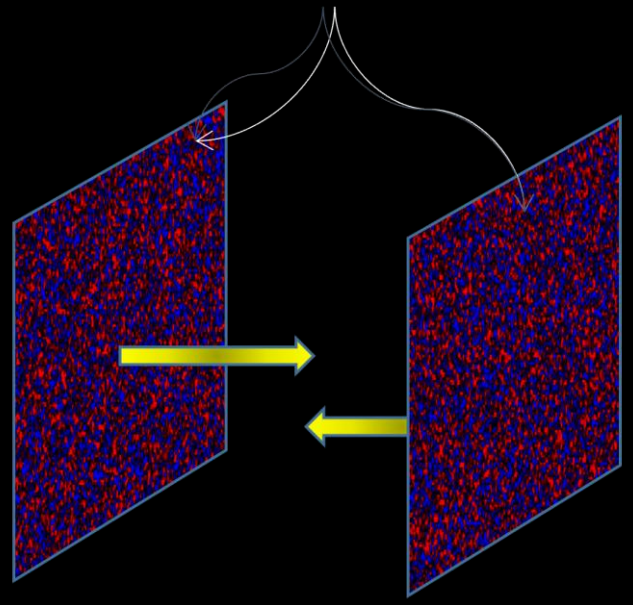
Hot and dense expanding
QUARK-GLUON-PLASMA (QGP)

Acceleratore	√s_NN [GeV]	Fattore Lorentz γ
SPS (CERN)	17.3	9.22
RHIC (BNL)	200.0	106.61
LHC (Run 1)	2760.0	1471.22
LHC (Run 2)	5020.0	2675.91
LHC (Run 3)	5460.0	2910.45
Future collider (~FCC)	100000.0	53304.9

Initial temperatures

- T_0(300,600) MeV
- *Large magnetic fields*
- *Large vorticity*
- *Small η/s*
- *Collective flows*

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 (*)

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

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

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

Lappi (2008)

$Q_s \approx 1 - 3$ 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]

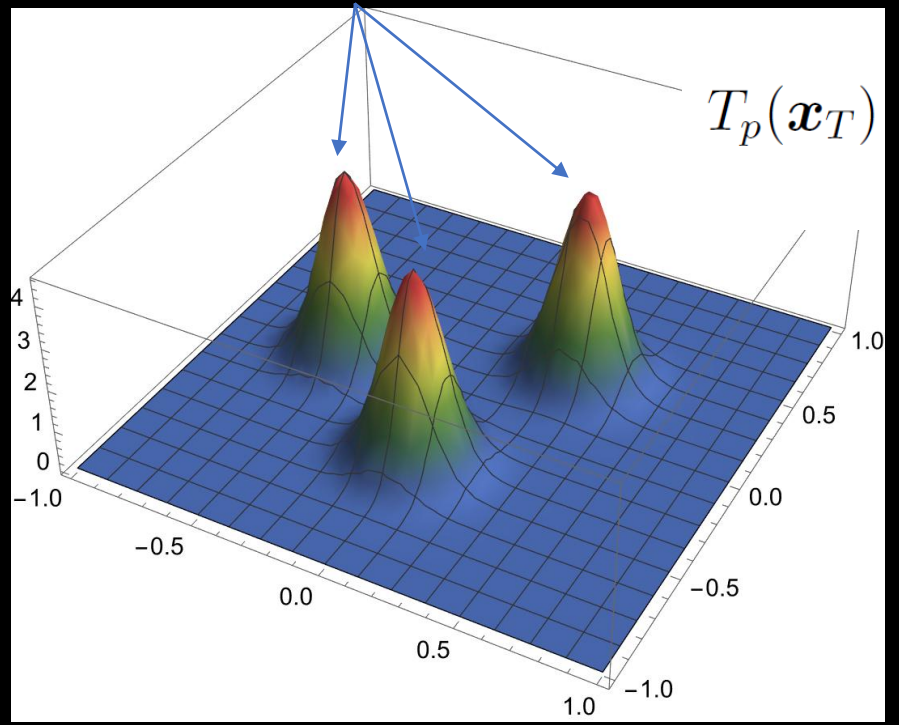
$$T_p(\boldsymbol{x}_T) = \frac{1}{3}\sum_{i=1}^{3} \frac{1}{2\pi B_q} \exp\left(-\frac{(\boldsymbol{x}_T - \boldsymbol{x}_i)^2}{2B_q}\right)$$

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

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

Saturation scale in the transverse plane

Valence quarks (hotspots)



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

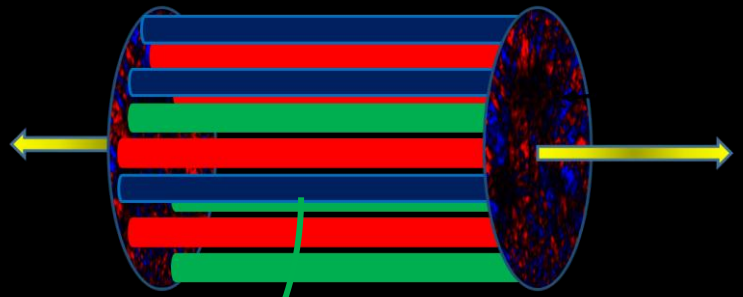
$$xg(x, Q_0^2) = A_g x^{-\lambda_g}(1-x)^{f_g}$$

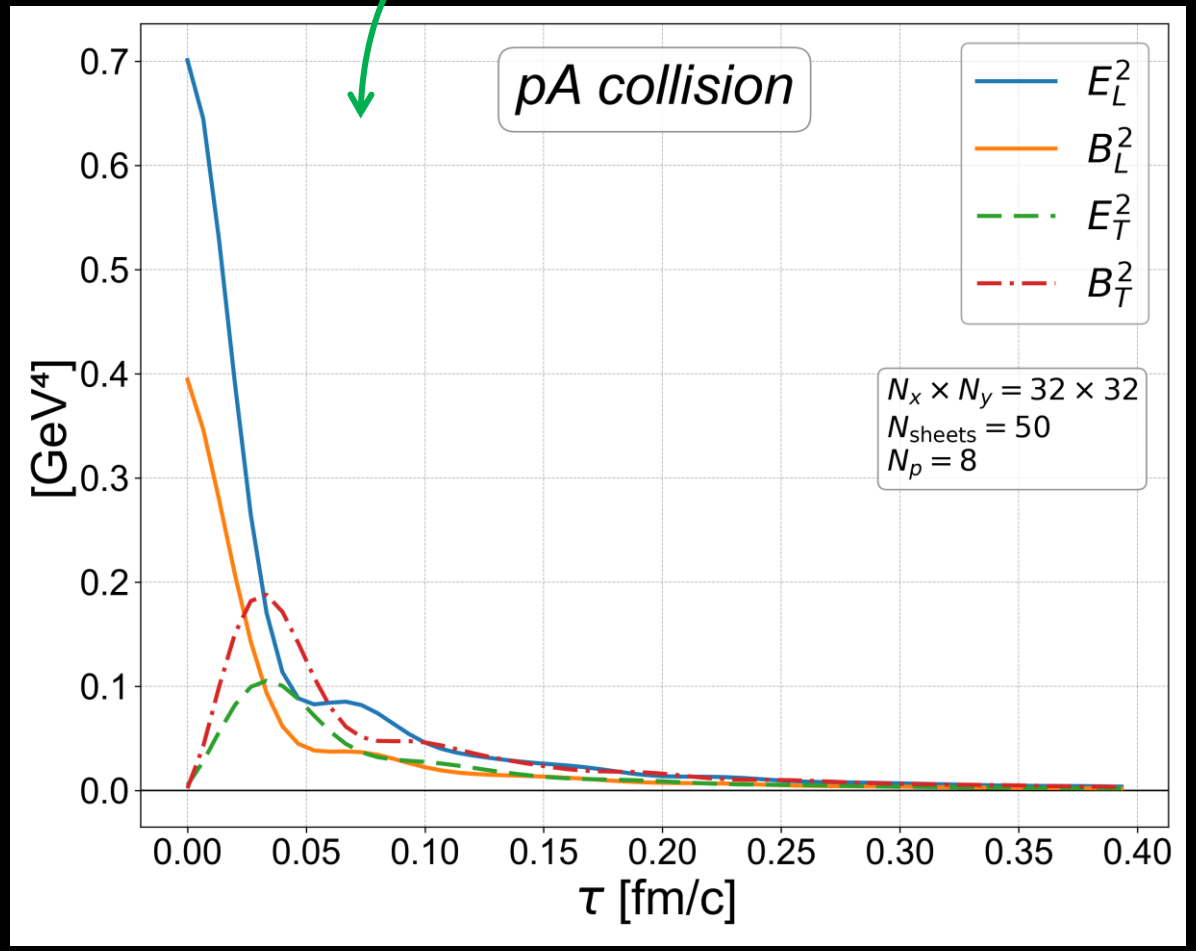
$$A_q = 2.308, \quad \lambda_q = 0.058, \quad f_q = 5.6$$

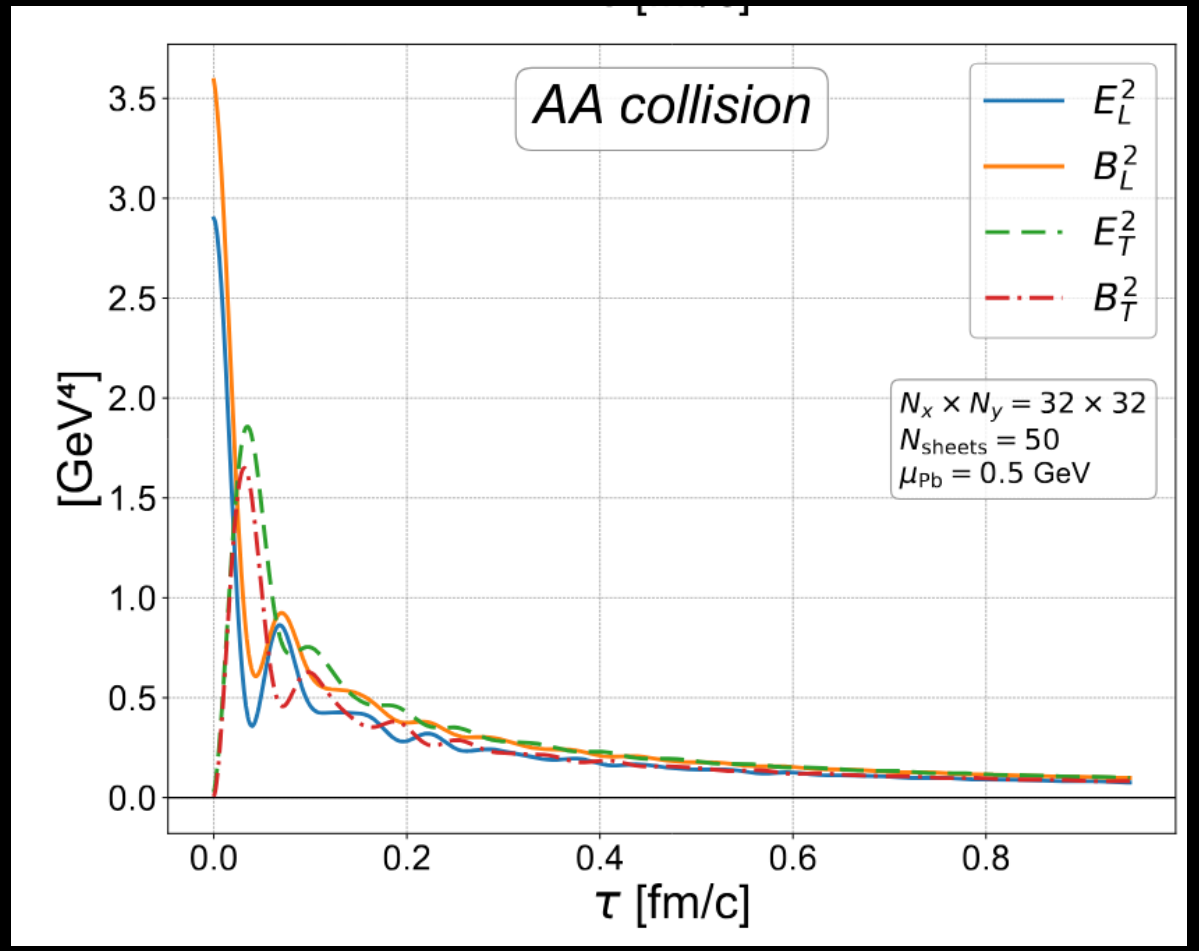
xg≈3.94

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

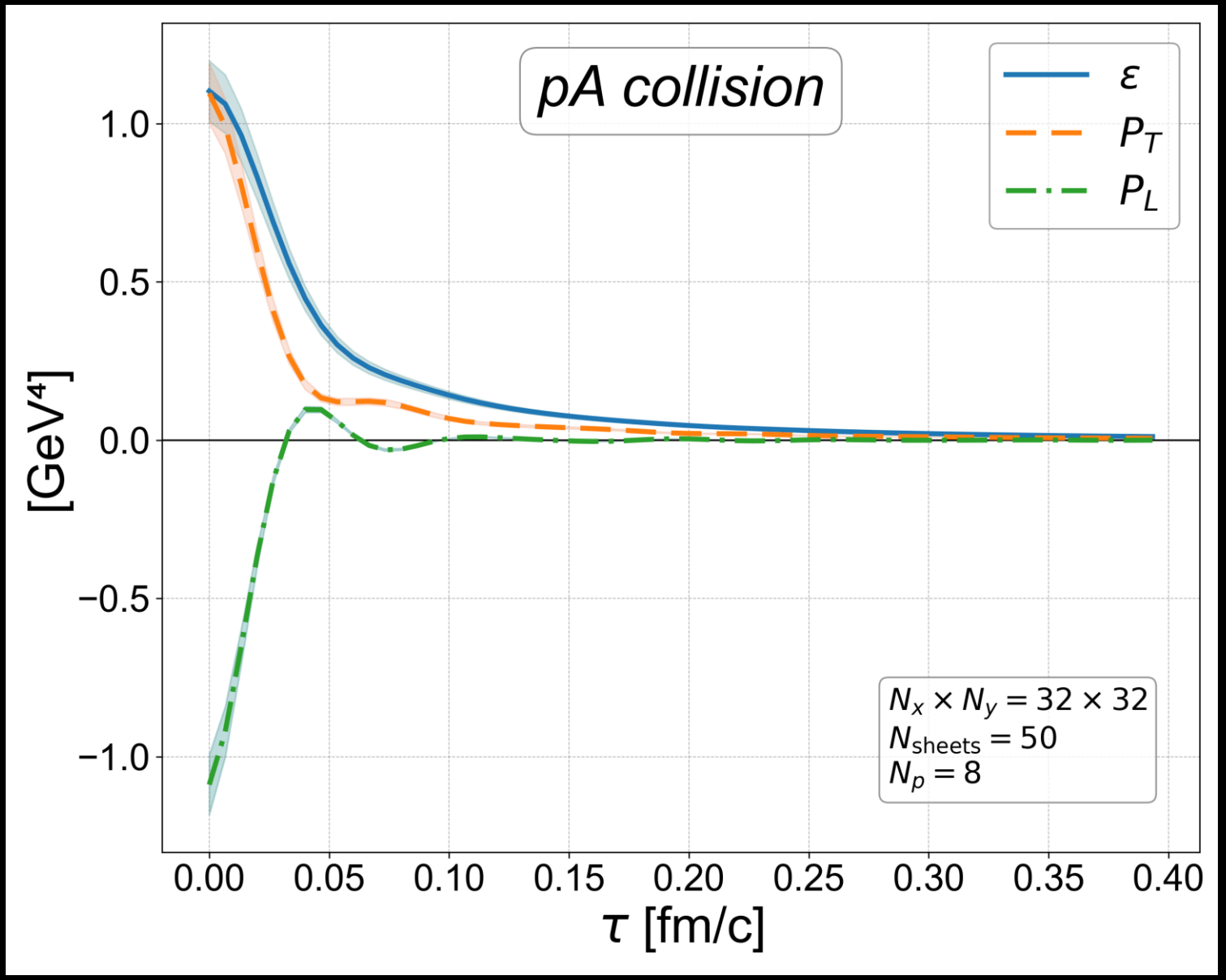
Evolution of the fields







The free-streaming regime in pA collisions



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

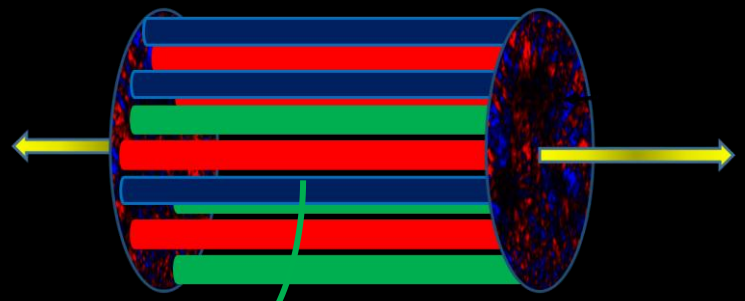
$$P_L = \mathrm{Tr}\left[-E_L^2 - B_L^2 + E_T^2 + B_T^2\right]$$

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

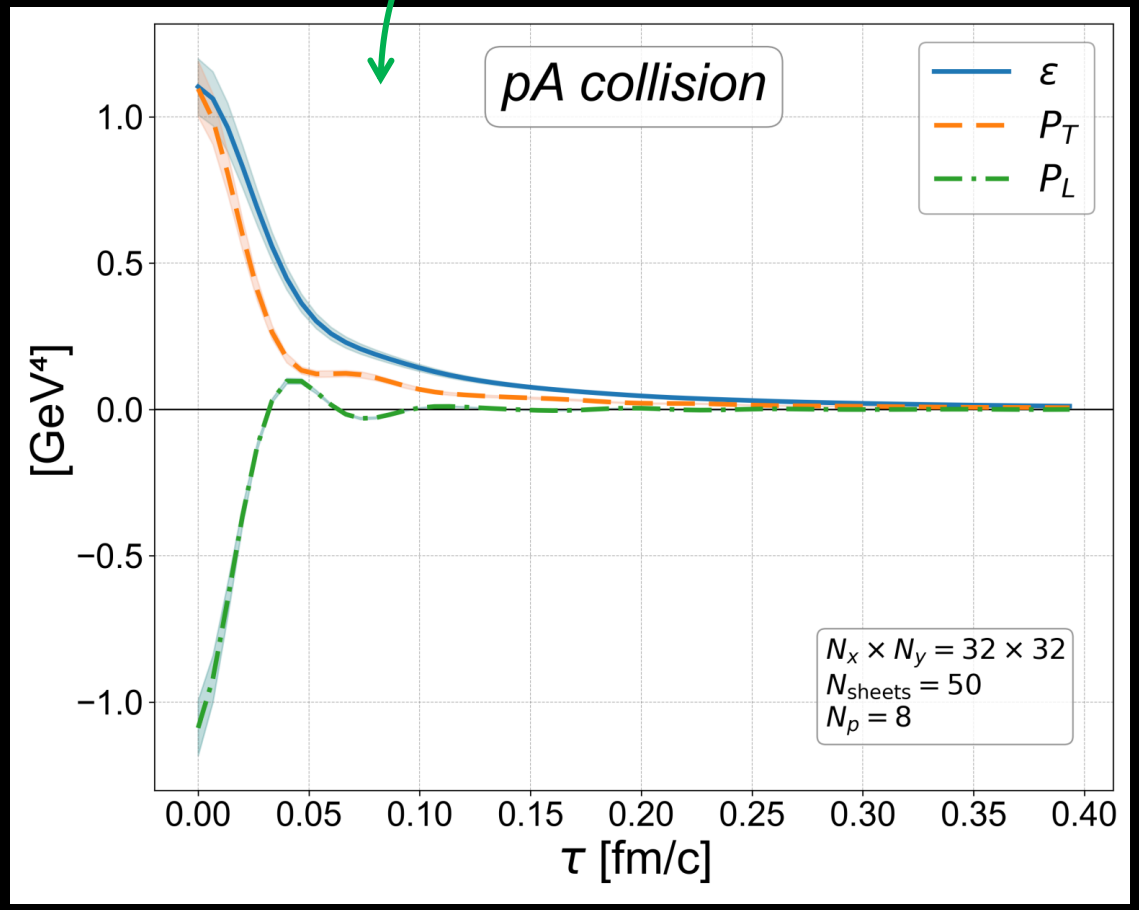
$\tau \approx 0.2$ fm/c

Longitudinal pressure vanishes

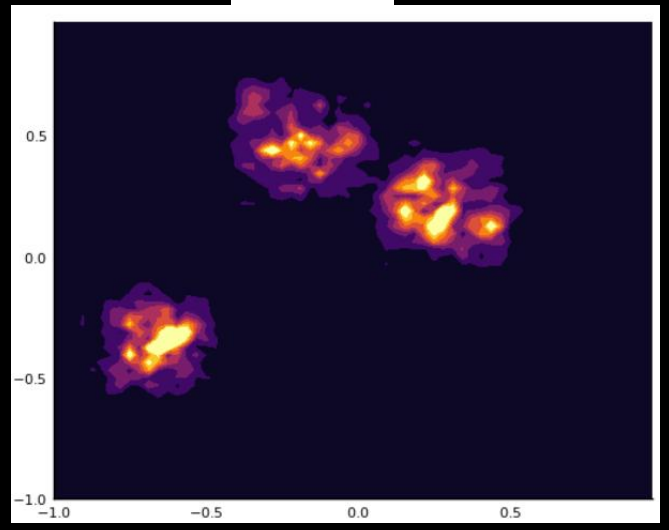
Evolution of the energy density in pA collisions



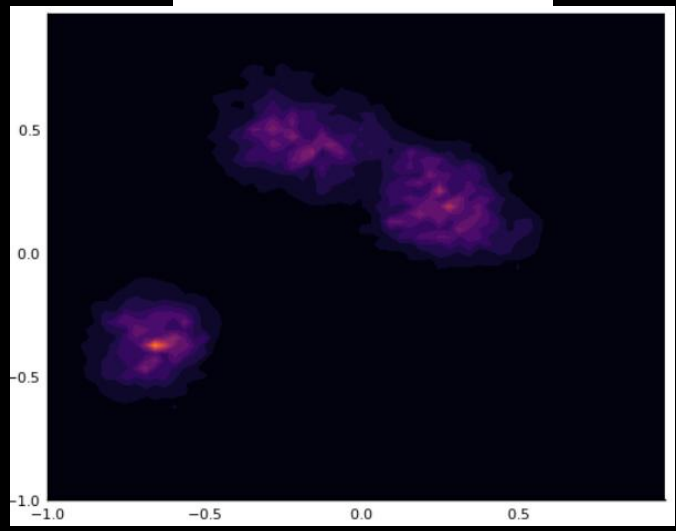
$$\varepsilon = \mathrm{Tr}\left[E_L^2 + E_T^2 + B_L^2 + B_T^2\right]$$



τ = 0

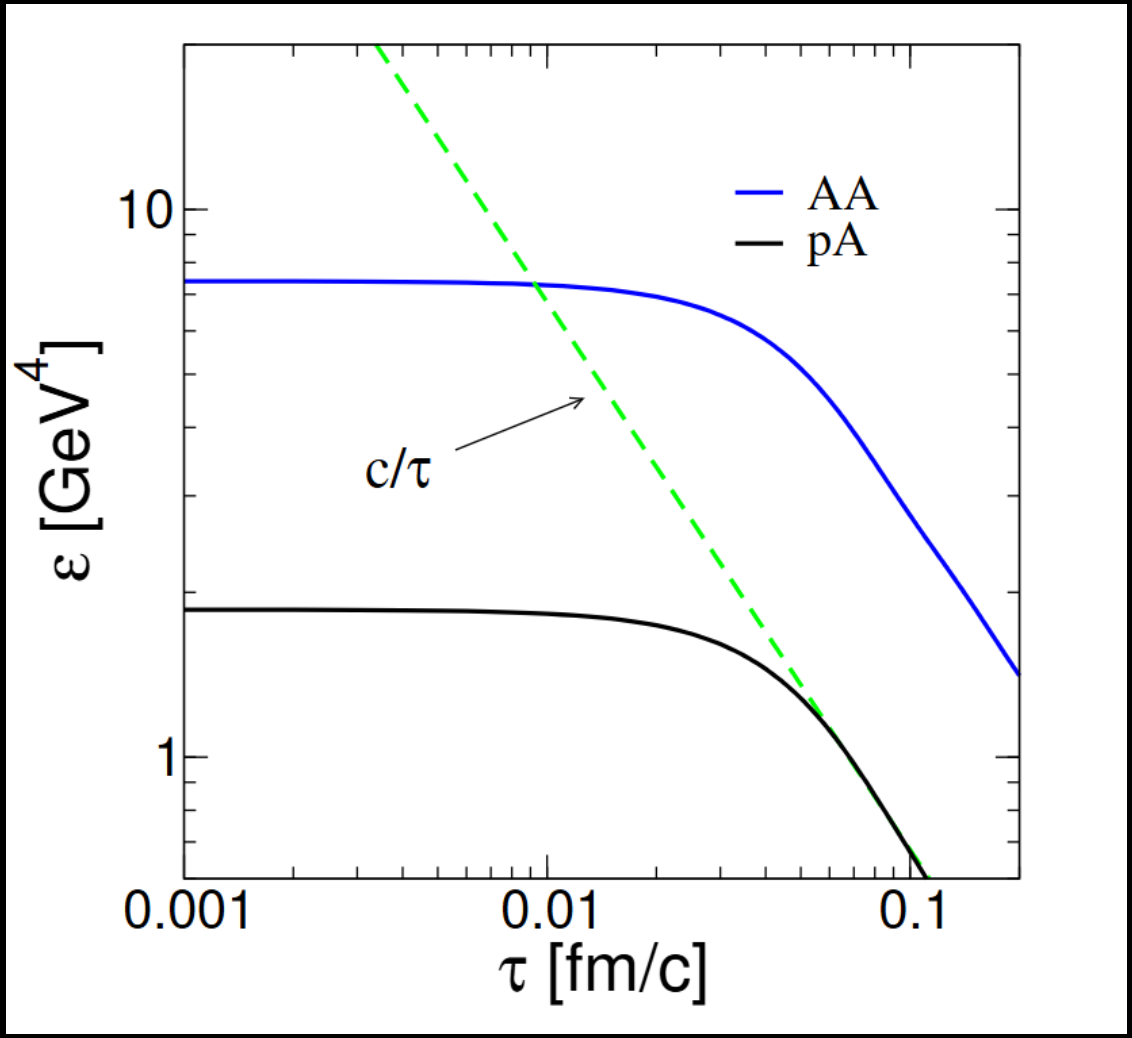


τ = 0.15 fm/c



Energy density in the transverse plane

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):

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

- *Fields are diluted: 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)

Pressure anisotropy

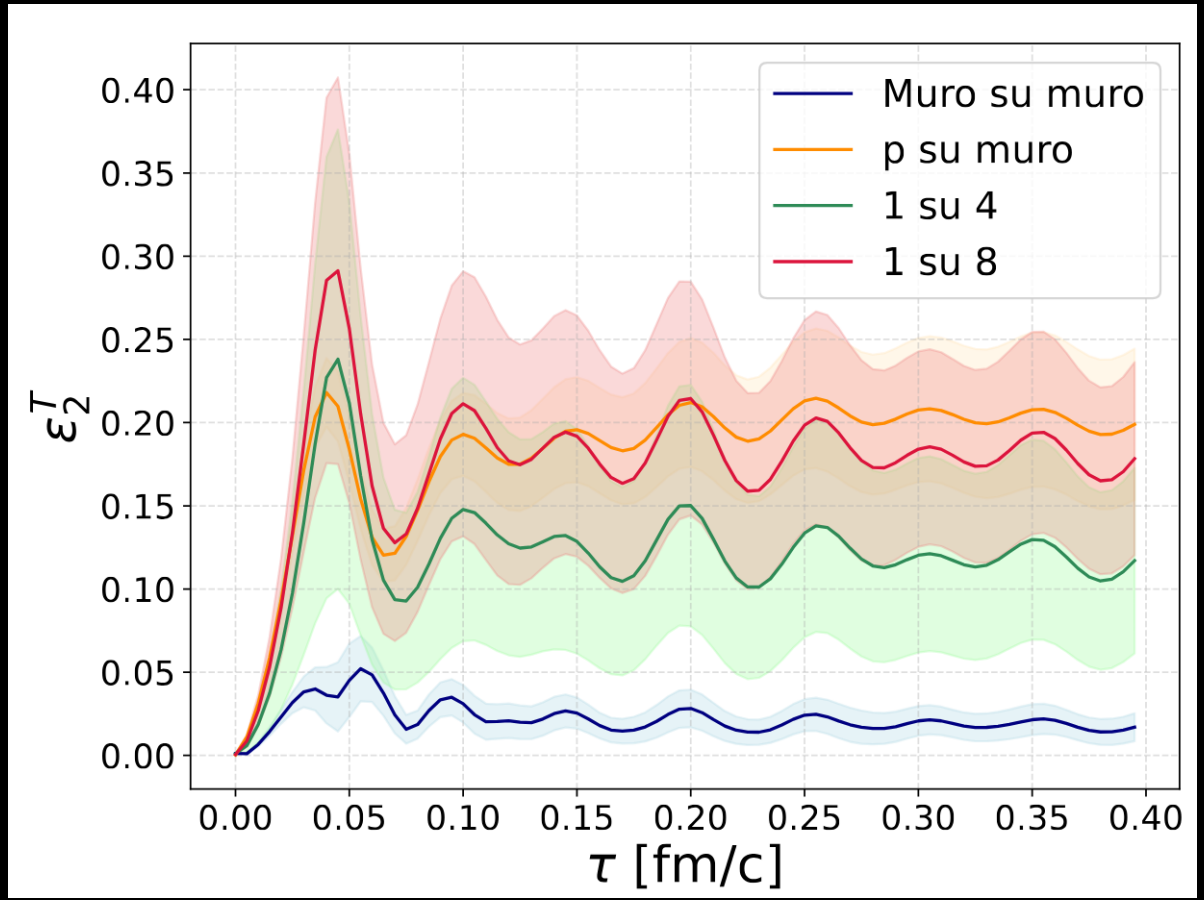
$$\varepsilon_2^{(T)} = \frac{\sqrt{\langle T^{xx} - T^{yy} \rangle_\varepsilon^2 + 4 \langle T^{xy} \rangle_\varepsilon^2}}{\langle T^{xx} + T^{yy} \rangle_\varepsilon}$$

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

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

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

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



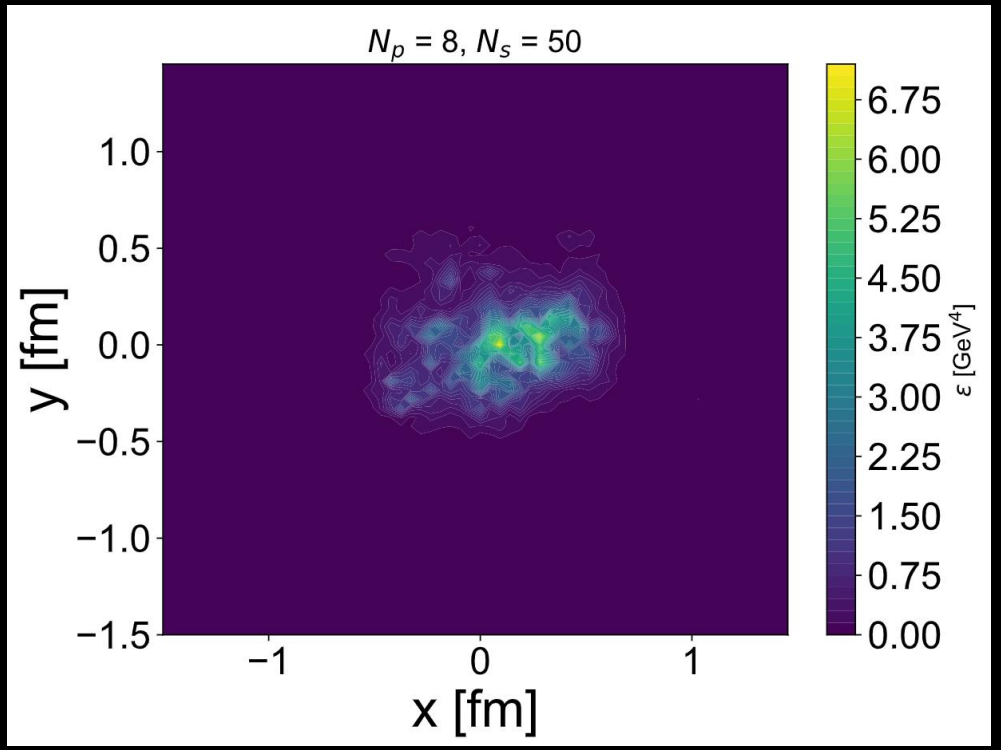
M.R. et al, in preparation

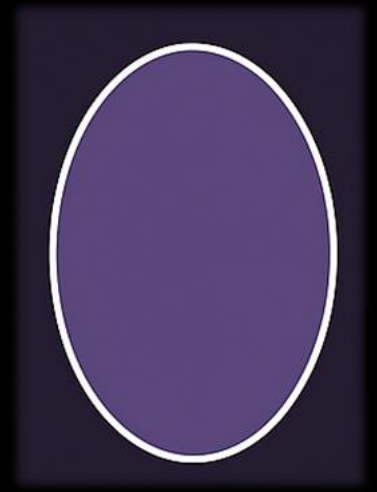
Eccentricities

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

Reaction plane

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





Symmetry: $2\pi/2$

$\varepsilon_2,\ \varepsilon_4, \ldots$

Symmetry: $2\pi/3$

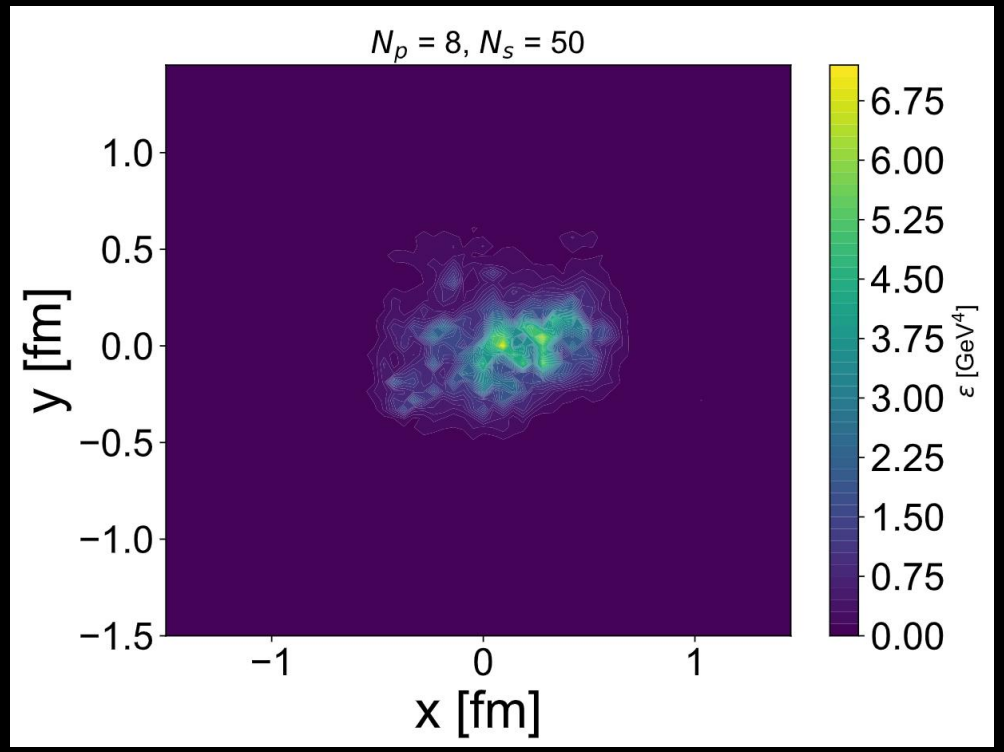
$\varepsilon_3,\ \varepsilon_6, \ldots$

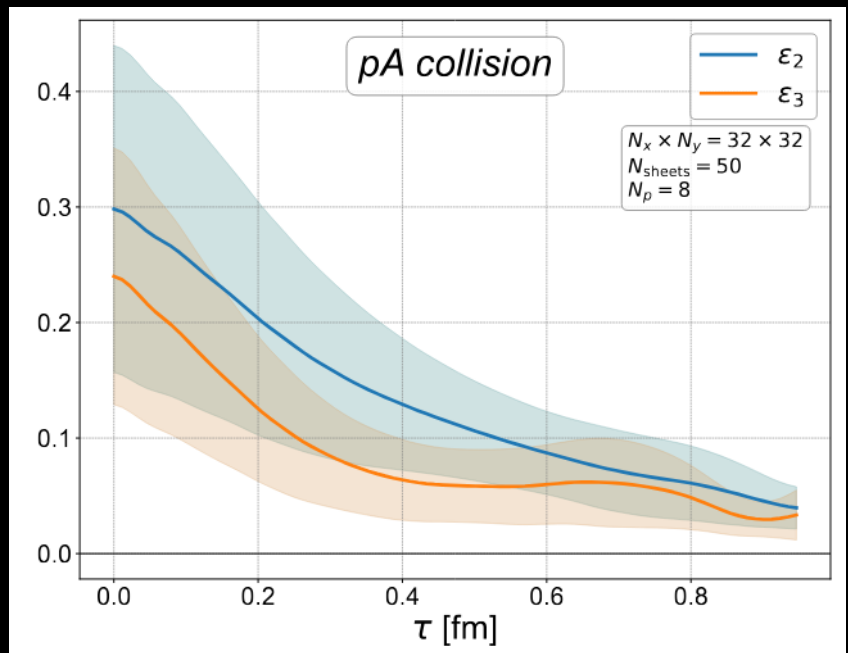
Eccentricities

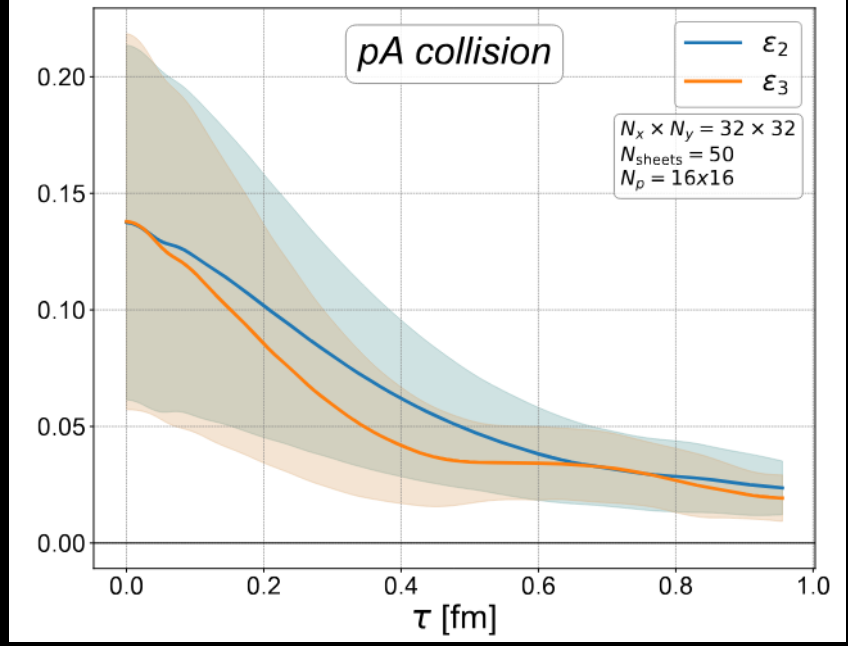
$$\varepsilon_n = \frac{\langle r^n e^{in\phi} \rangle}{\langle r^n \rangle} \quad \text{with} \quad \varepsilon_n = |\varepsilon_n| \, e^{in\Psi_n}$$

Reaction plane

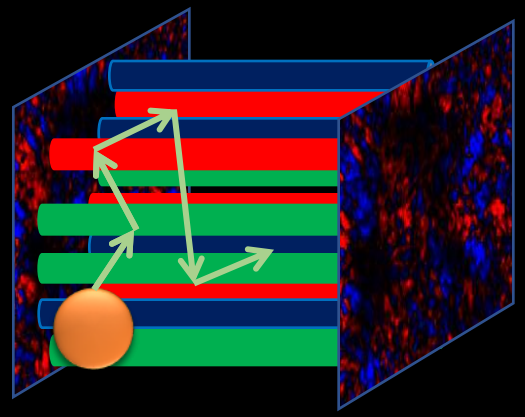
$$\langle f(x,y) \rangle = \frac{\int dx\, dy\, f(x,y)\, \varepsilon(x,y)}{\int dx\, dy\, \varepsilon(x,y)}$$







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)*

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

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

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

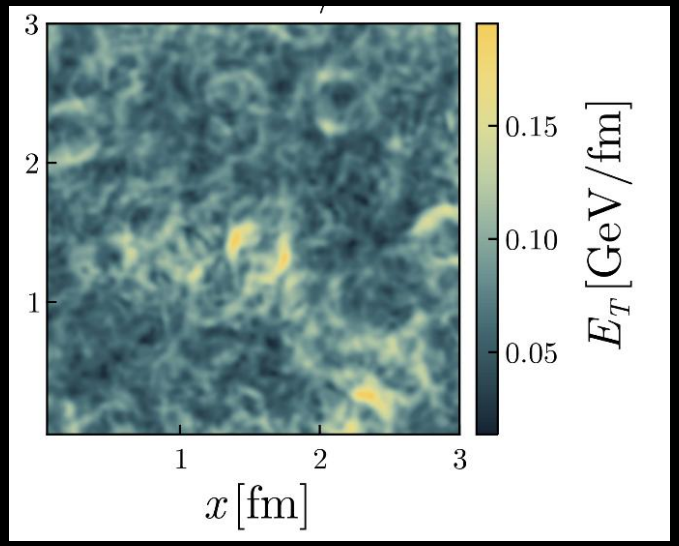
Boltzmann-Vlasov equation

$$p^\mu\partial_\mu f + gQ_aF_a^{\mu\nu}p_\nu\frac{\partial f}{\partial p^\mu} - gf_{abc}A_b^\mu p_\mu Q_c\frac{\partial f}{\partial Q_a} = 0$$

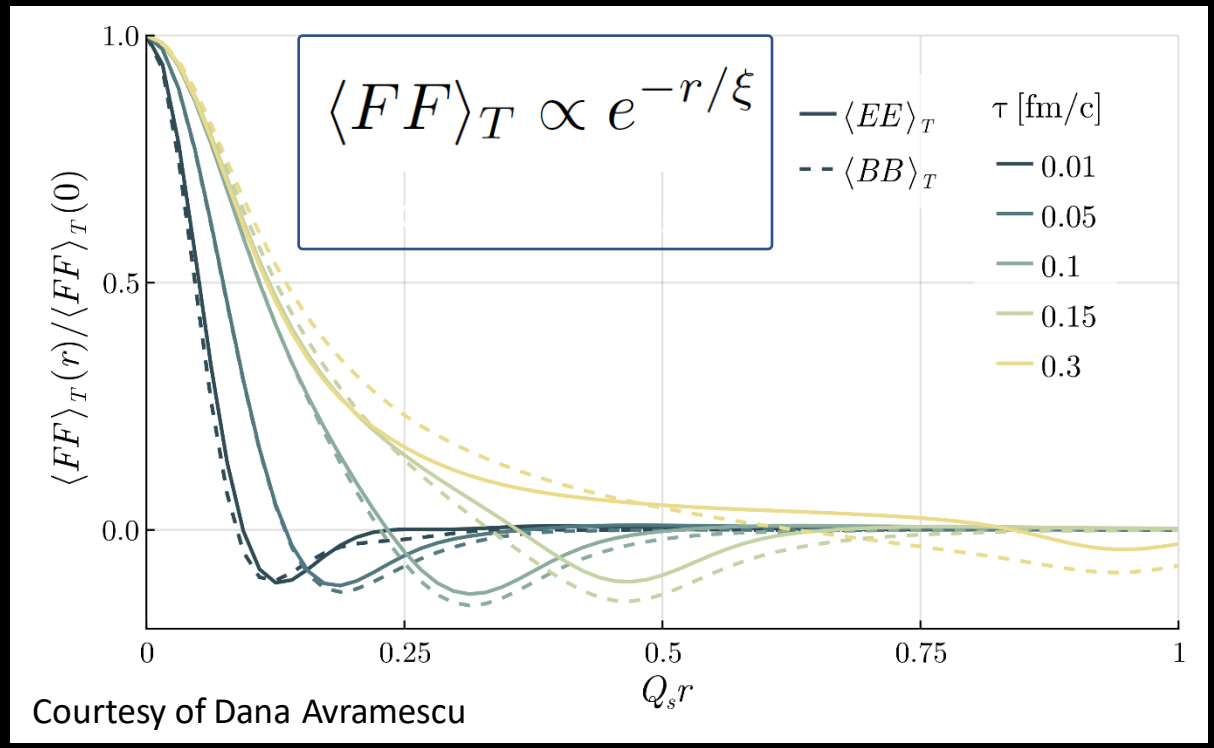
Equations of motion of heavy quarks are solved in the background given by the evolving Glasma fields

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

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

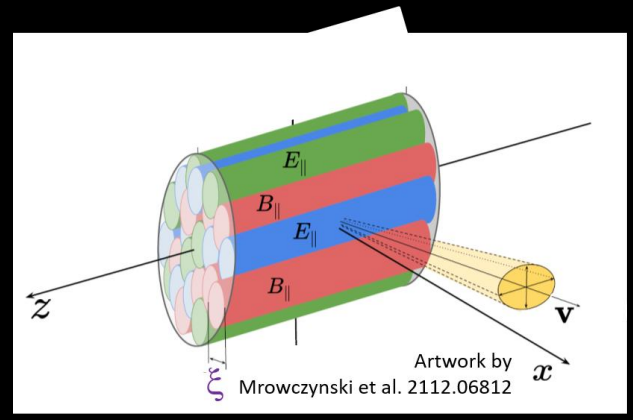


Field correlators in the transverse plane



Courtesy of Dana Avramescu

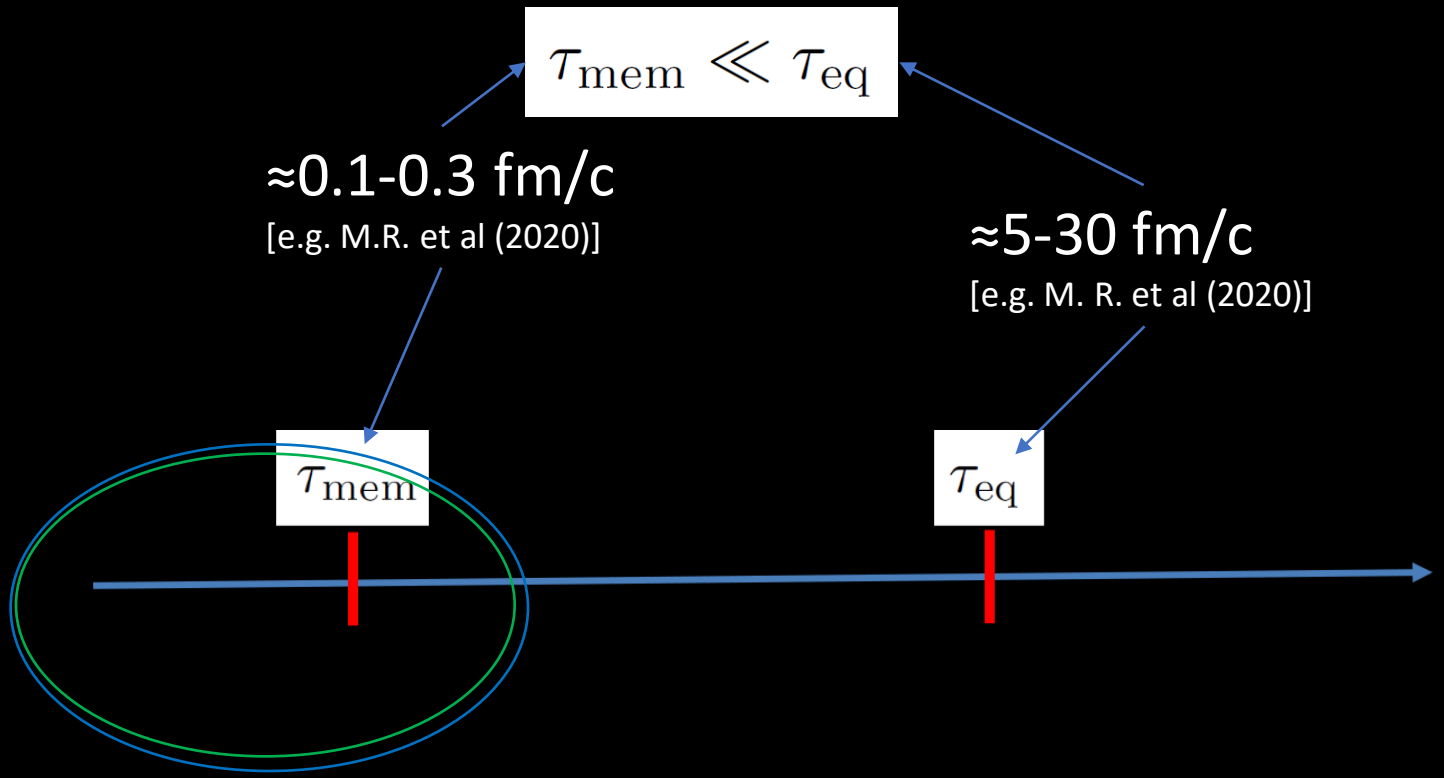
The force experienced by HQs in the pre-equilibrium stage is time-correlated: diffusion with memory.



Artwork by Mrowczynski et al. 2112.06812

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

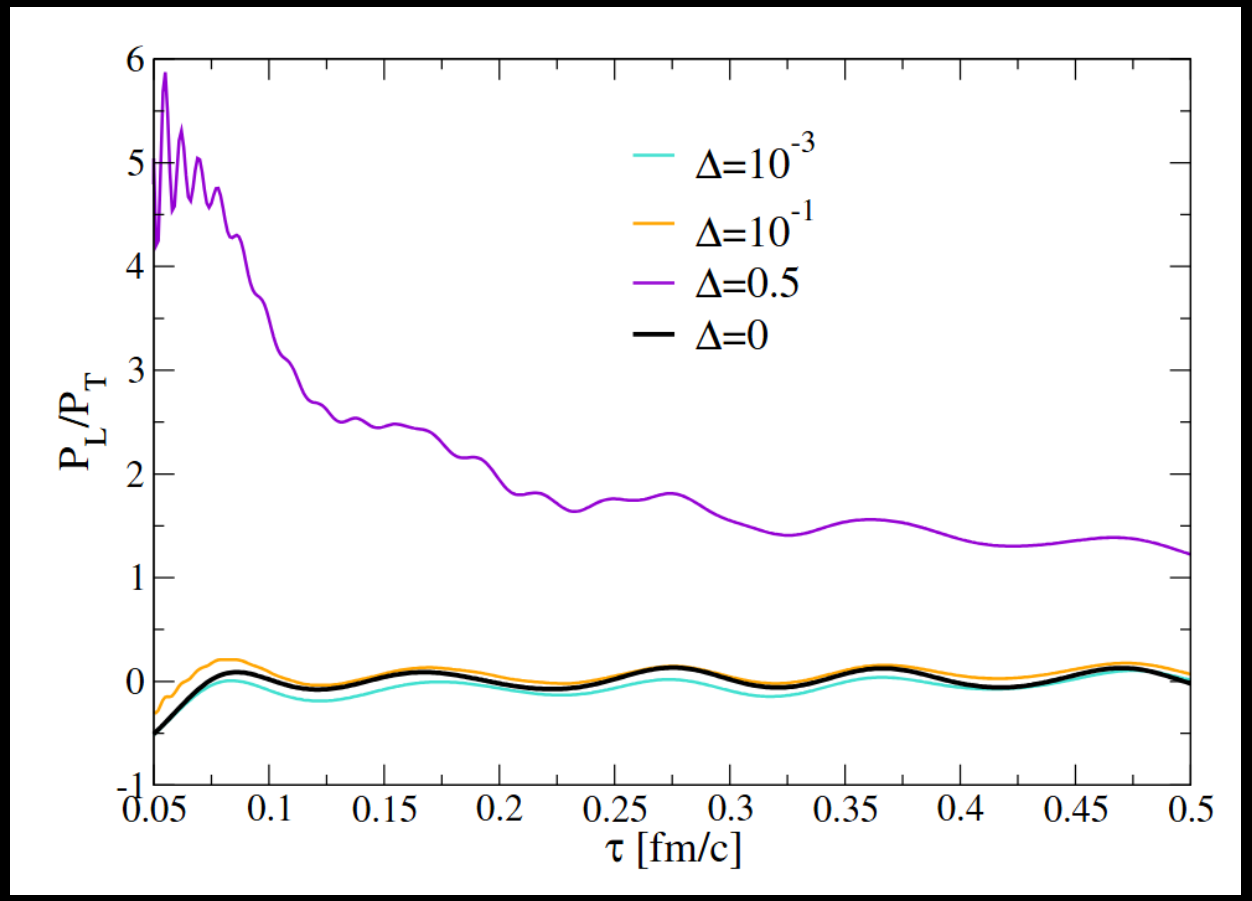
Minimal longitudinal fluctuations(*)

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

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

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

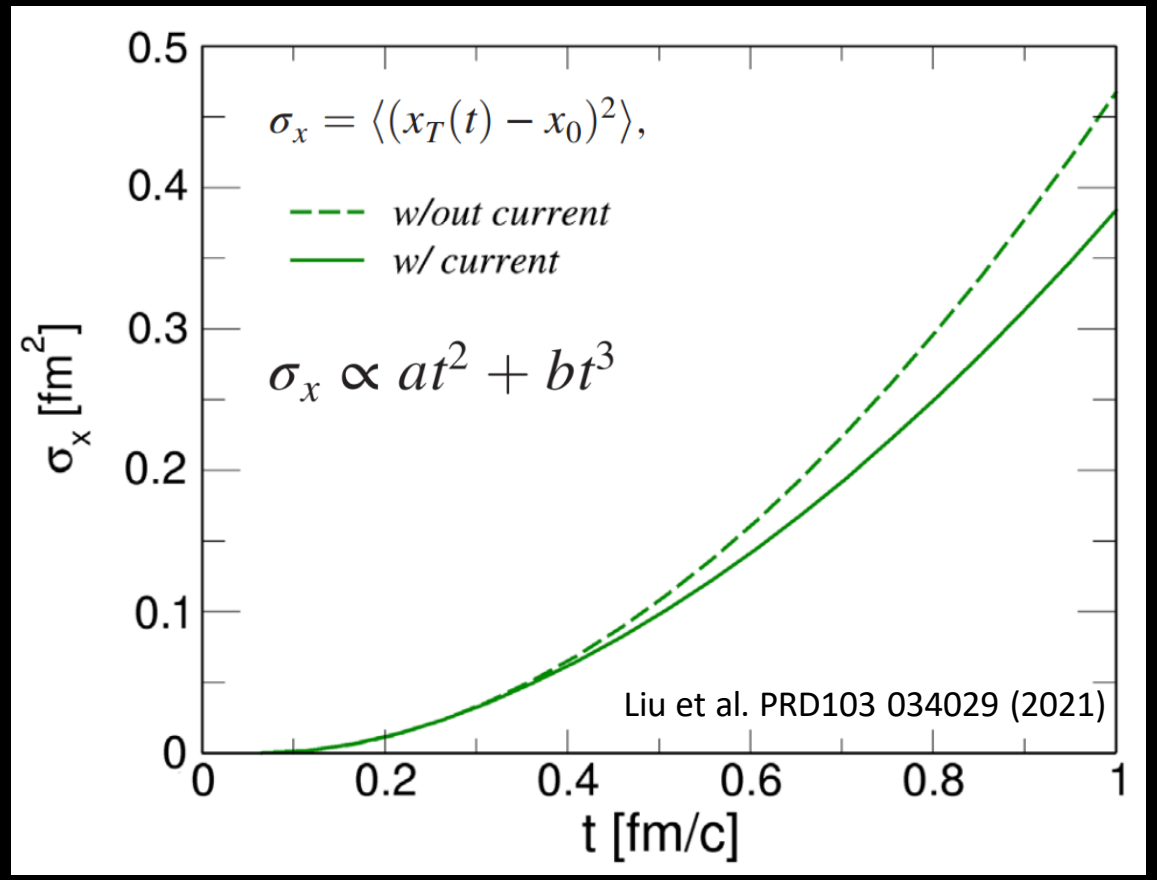
pA collisions

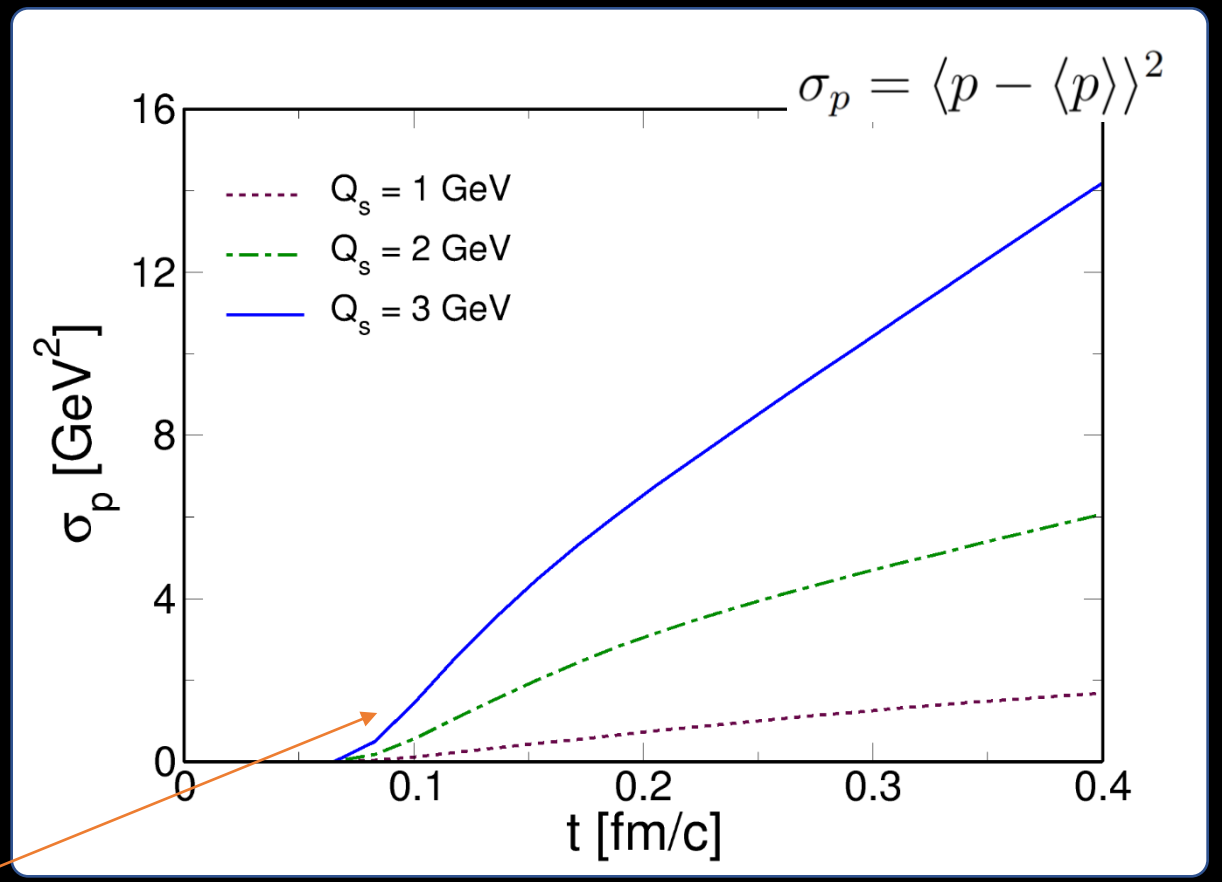


G. Parisi *et al* (2025)

(*)Fukushima and Gelis (2011)

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





Diffusion in the color filament

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

Standard Brownian motion

D: momentum diffusion coefficient

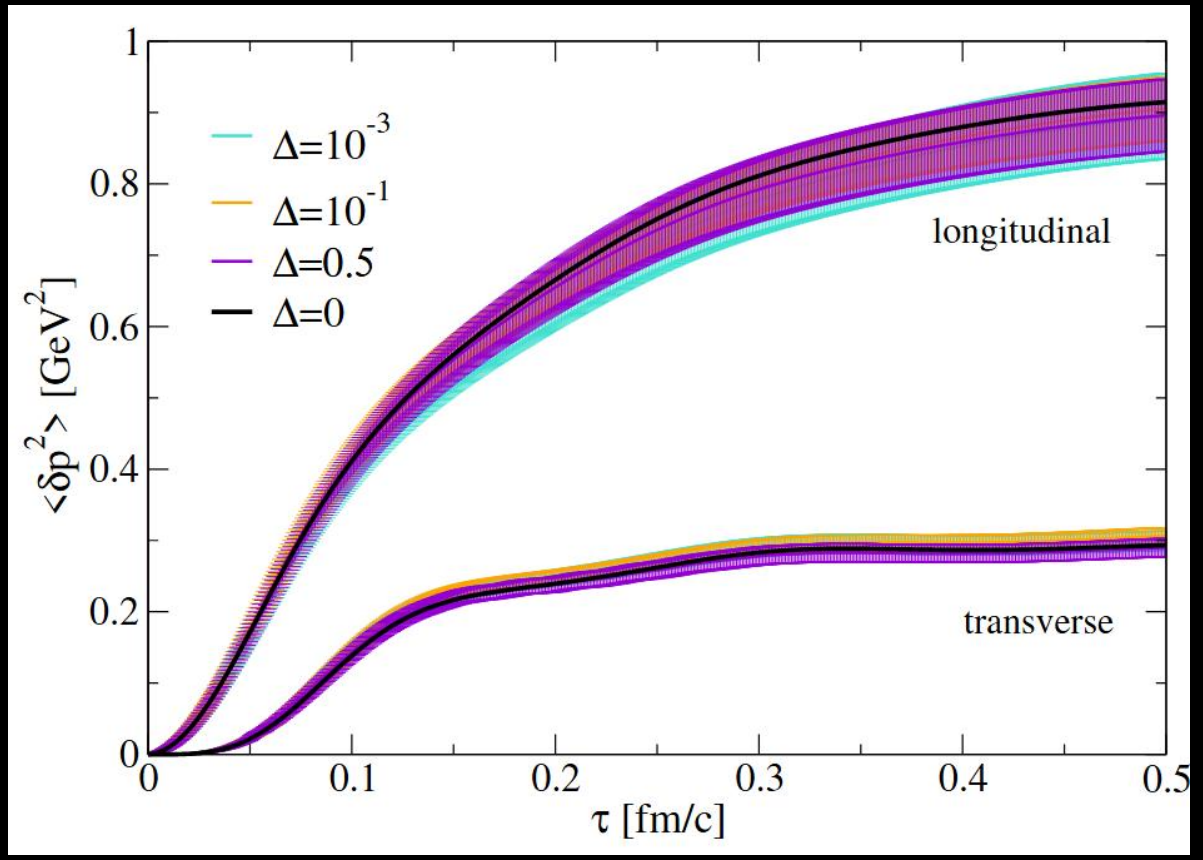
See also D. Avramescu *et al.* (2023)

Minimal longitudinal fluctuations(*)

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

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

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



G. Parisi *et al* (2025)

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

$$\langle\langle \delta p_L^2(\tau)\rangle\rangle = g^2\int_0^\tau d\tau'\int_0^\tau d\tau''\int d^2\mathbf{x}_\perp\langle \mathrm{Tr}[E_z(\tau')E_z(\tau'')]T_p(\mathbf{x}_\perp)\rangle$$

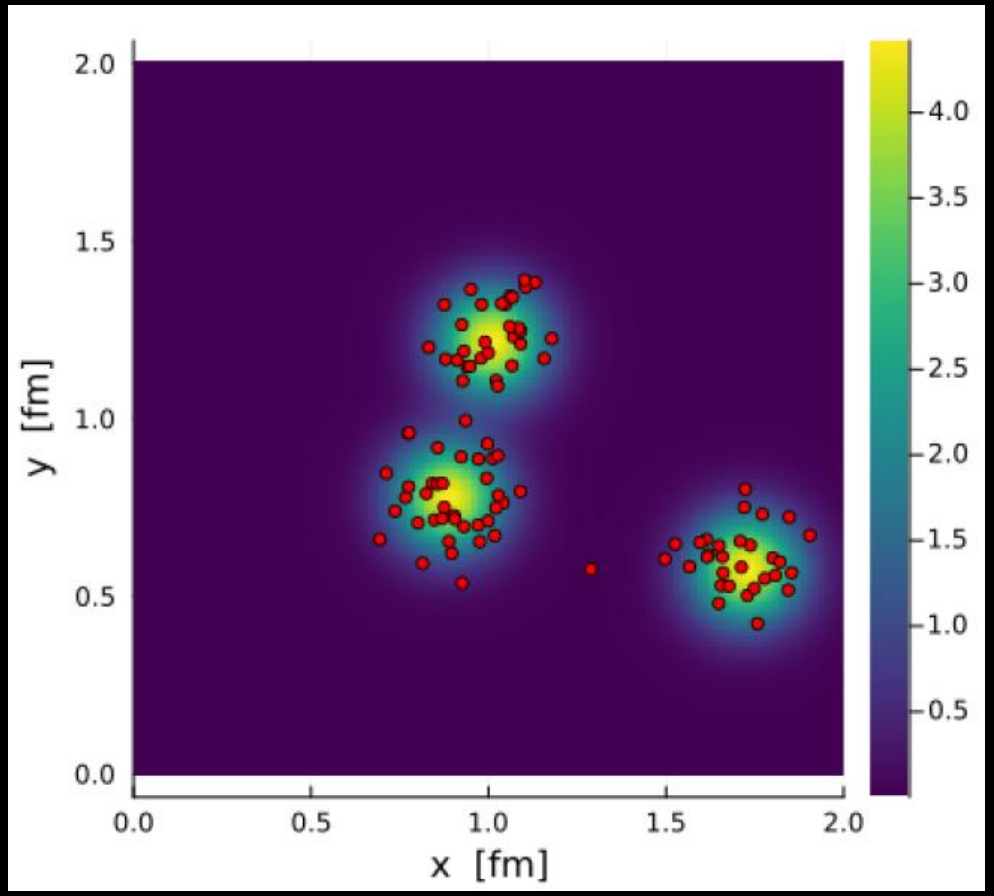
$$\langle\langle \delta p_T^2(\tau)\rangle\rangle = g^2\int_0^\tau d\tau'\int_0^\tau d\tau''\int d^2\mathbf{x}_\perp\frac{1}{\tau'\tau''}\langle \mathrm{Tr}[E_x(\tau')E_x(\tau'')+E_y(\tau')E_y(\tau'')]T_p(\mathbf{x}_\perp)\rangle$$

(*)Fukushima and Gelis (2011)

J/ψ and Υ in glasma: initialization

- *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)



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

$r_0 = 0.4\,\mathrm{fm}$ *c-cbar pairs*
$r_0 = 0.2\,\mathrm{fm}$ *b-bbar pairs*

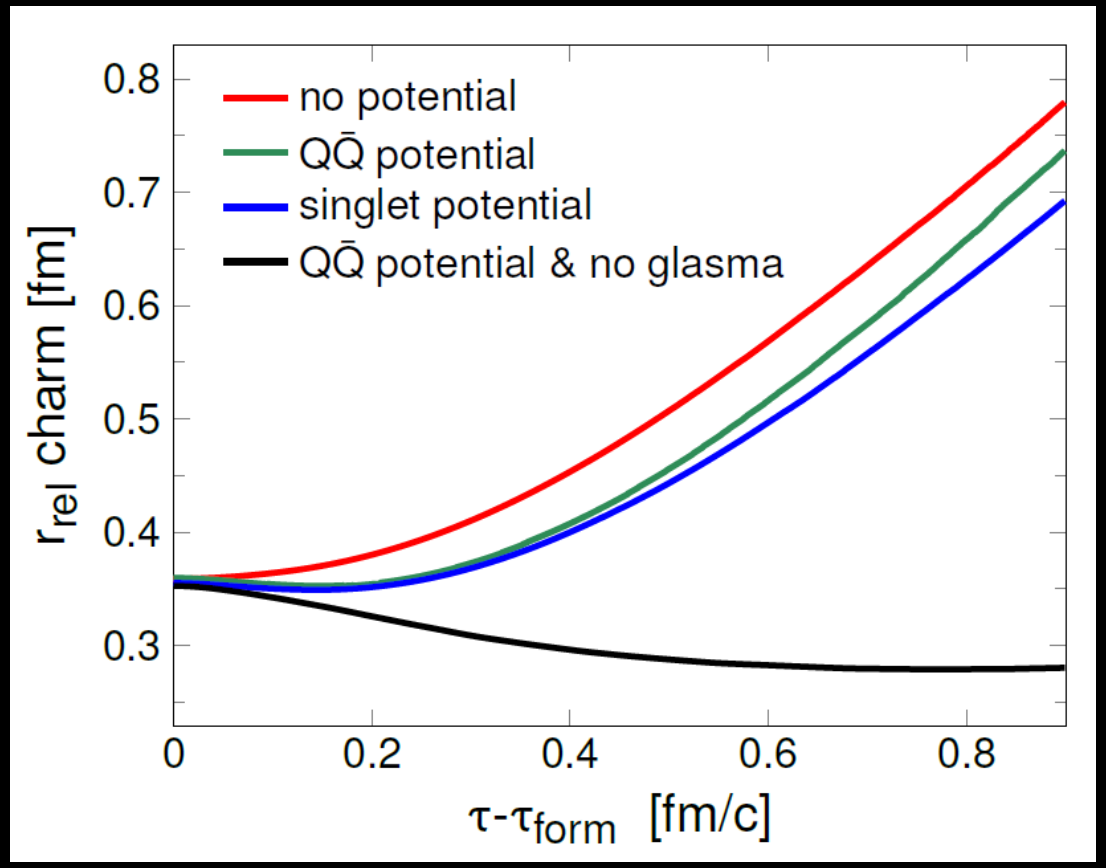
- *Pairs are extracted in the color-singlet state:*

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

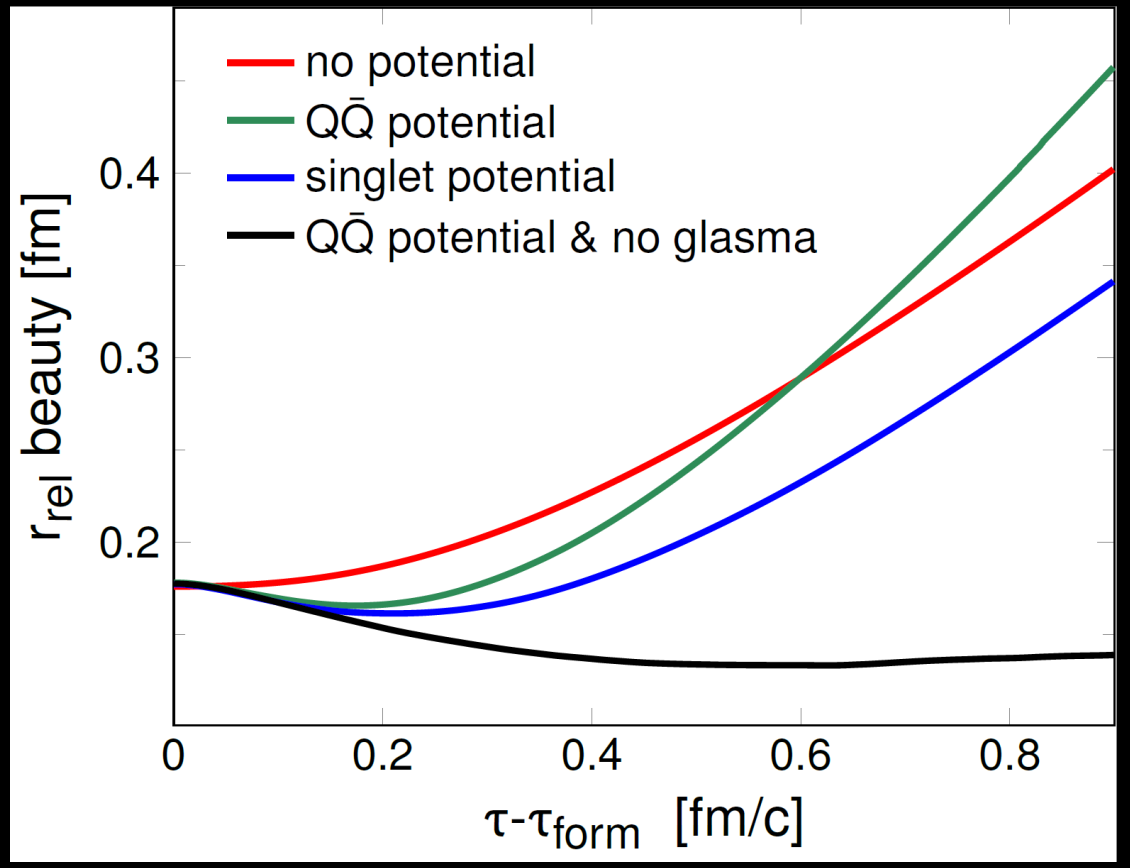
(*)Zhao et al. (2025)

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

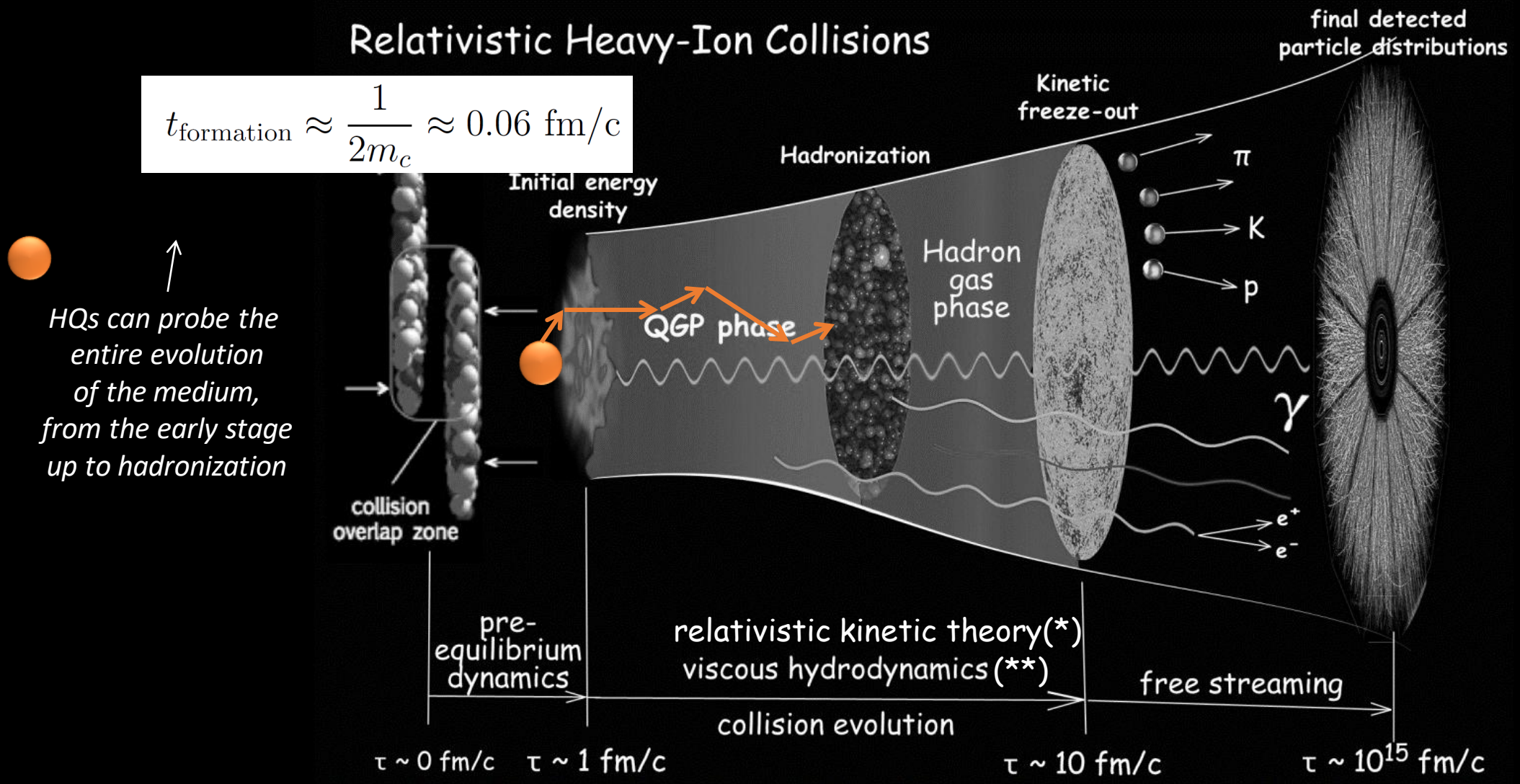
c-cbar pairs



b-bbar pairs



Oliva et al. (2404.05315)


Relativistic Heavy-Ion Collisions
$t_{\text{formation}} \approx \frac{1}{2m_c} \approx 0.06$ fm/c
HQs can probe the entire evolution of the medium, from the early stage up to hadronization
Initial energy density
Hadronization
Kinetic freeze-out
final detected particle distributions
QGP phase
Hadron gas phase
π
K
p
γ
e+
e-
collision overlap zone
pre-equilibrium dynamics
relativistic kinetic theory(*) viscous hydrodynamics (**)
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

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

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

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

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

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

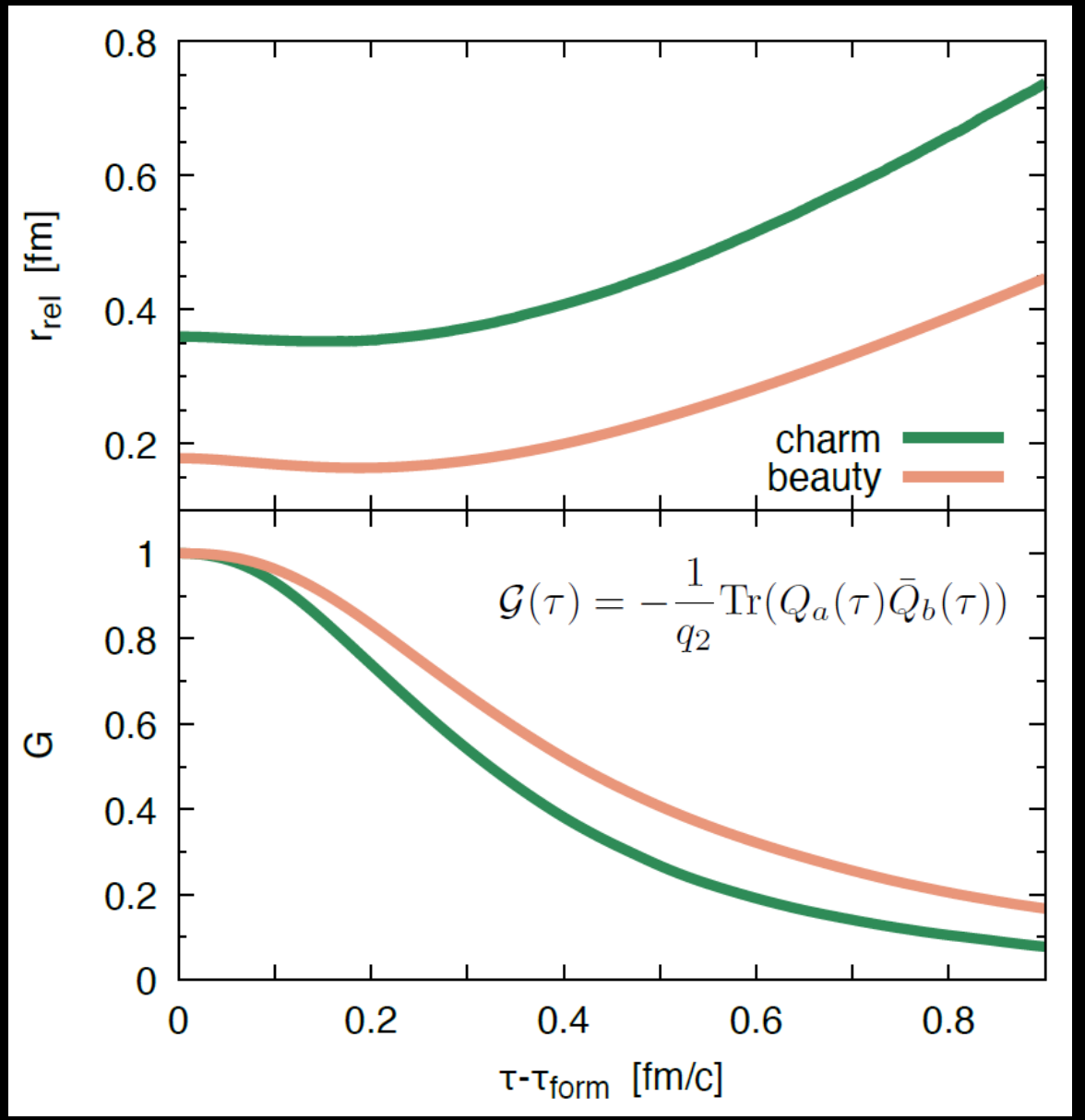
classical interquark potential

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)

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)

Note
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 color decorrelation.