Diffusion of heavy quarks in the early stages of high energy nuclear collisions

Marco Ruggieri
School of Nuclear Science and Technology
Lanzhou University, Lanzhou, China
ruggieri@lzu.edu.cn

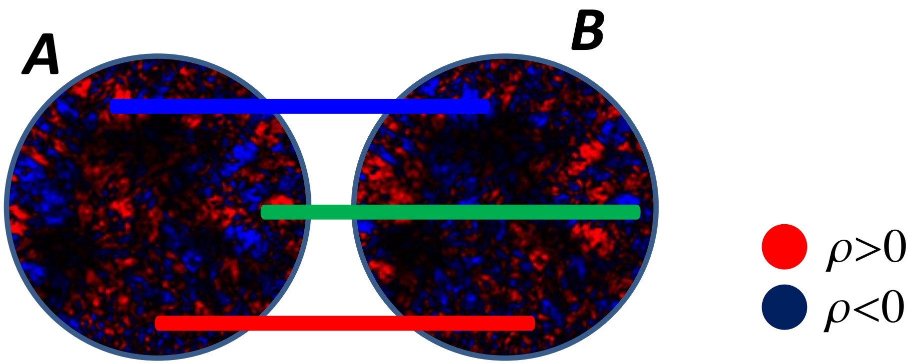
Collaborators
Pooja
Dana Avramescu
David Muller
Santosh K. Das
Vincenzo Greco
Virgil Baran
JunHong Liu
YiFeng Sun
Lucia Oliva

Plan of the talk

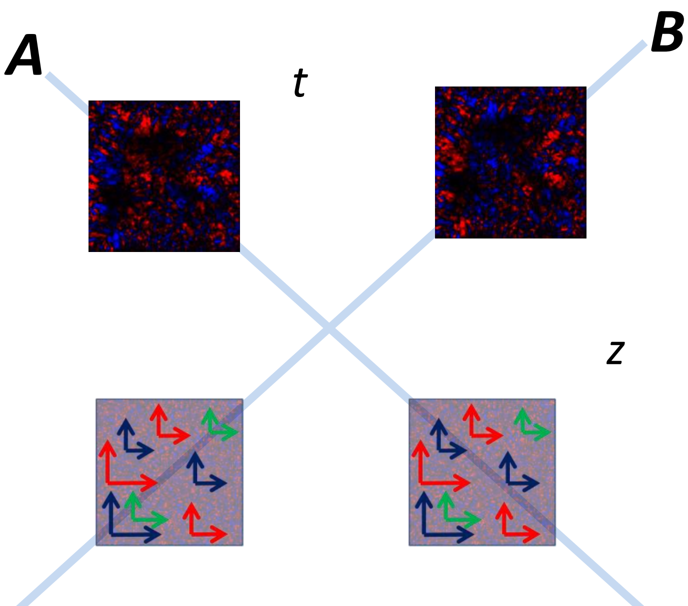
- *Early stages of heavy ion collisions: evolving Glasma (Ev-Glasma)*
- *Heavy quarks diffusion: momentum broadening, R_{AA}, v_2*
- *Conclusions and Outlook*

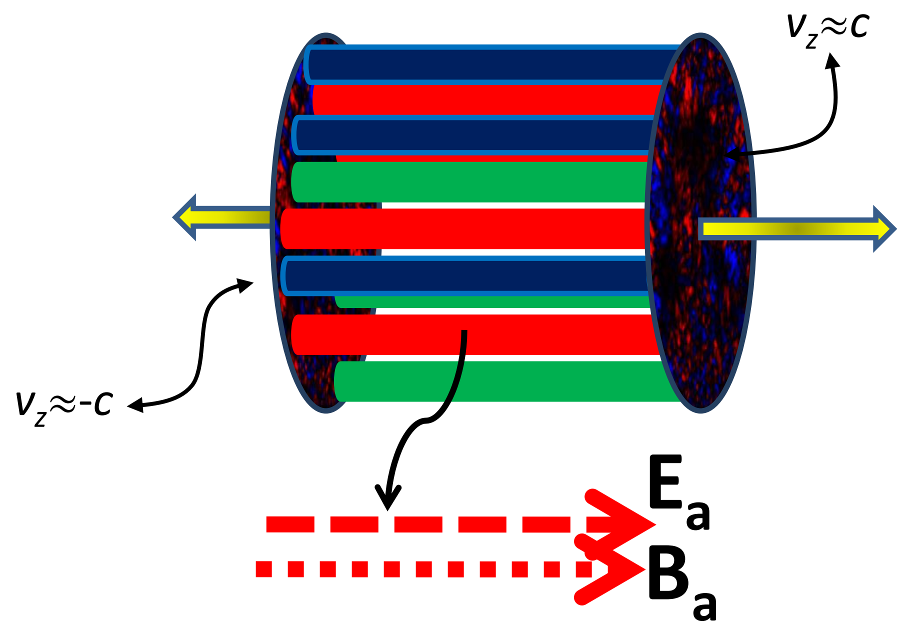
Glasma: the initial condition of RHICs

Dense gluons ***interact*** and form two sets of opposite ***effective color charges*** on the light cone of the two nuclei.



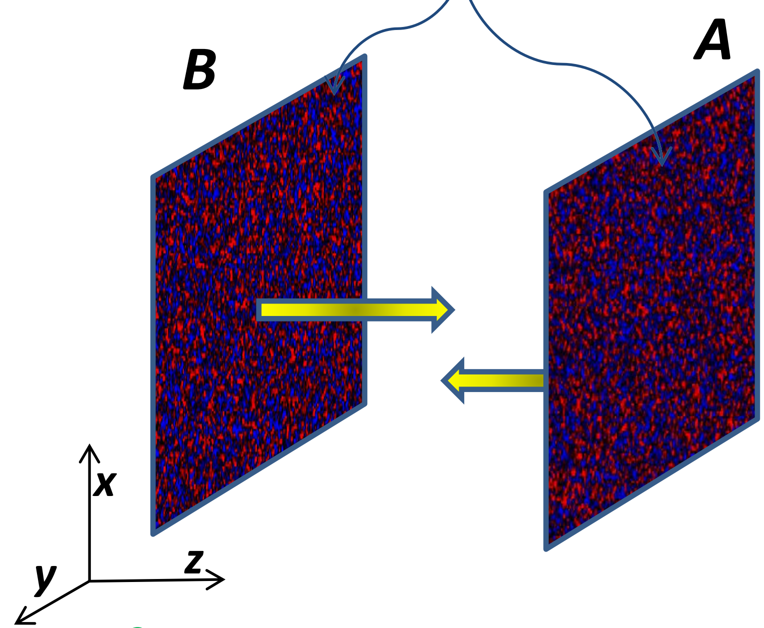
$$\nabla \cdot \boldsymbol{E} = \rho_E$$
$$\nabla \cdot \boldsymbol{B} = \rho_B$$





Lappi and McLerran (2006)

The MV model of color sources



• *Fast (large momentum) partons*

Their dynamics in the Lab frame is slowed down due to time dilation: ***static sources of color fields.***

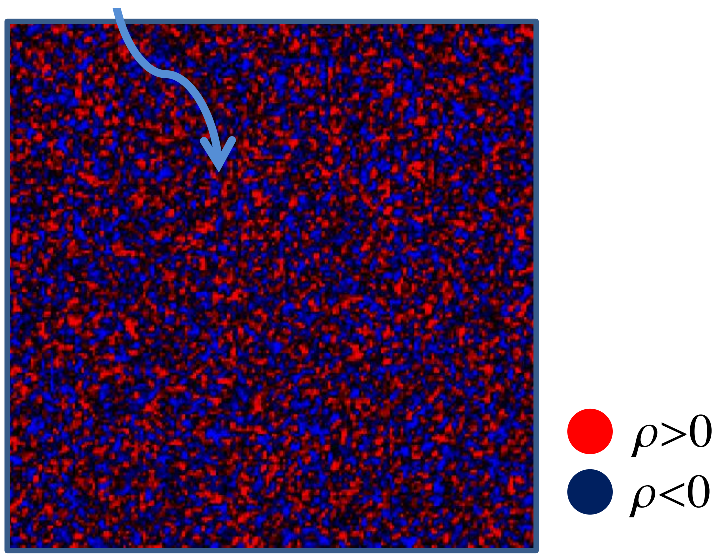
Model of static sources (MV model)

Uncorrelated color density fluctuations on the two nuclei.

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

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

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



From the correlators of Wilson lines:

$$g^2\mu = O(Q_s)$$

Lappi (2008)

***Q_s* ≈ 1 – 3 GeV**

McLerran and Venugopalan (1996)
Kovchegov (1996)

Classical Yang-Mills 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.

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

$$\boxed{\begin{aligned} \partial_\tau E_i &= \tfrac{1}{\tau}\mathcal{D}_\eta F_{\eta i} + \tau \mathcal{D}_j F_{ji}, & E_i &= \tau \partial_\tau A_i, \\ \partial_\tau E_\eta &= \tfrac{1}{\tau}\mathcal{D}_j F_{j\eta}, & E_\eta &= \frac{1}{\tau}\partial_\tau A_\eta. \end{aligned}}$$

$$\tau = \sqrt{t^2 - z^2}$$

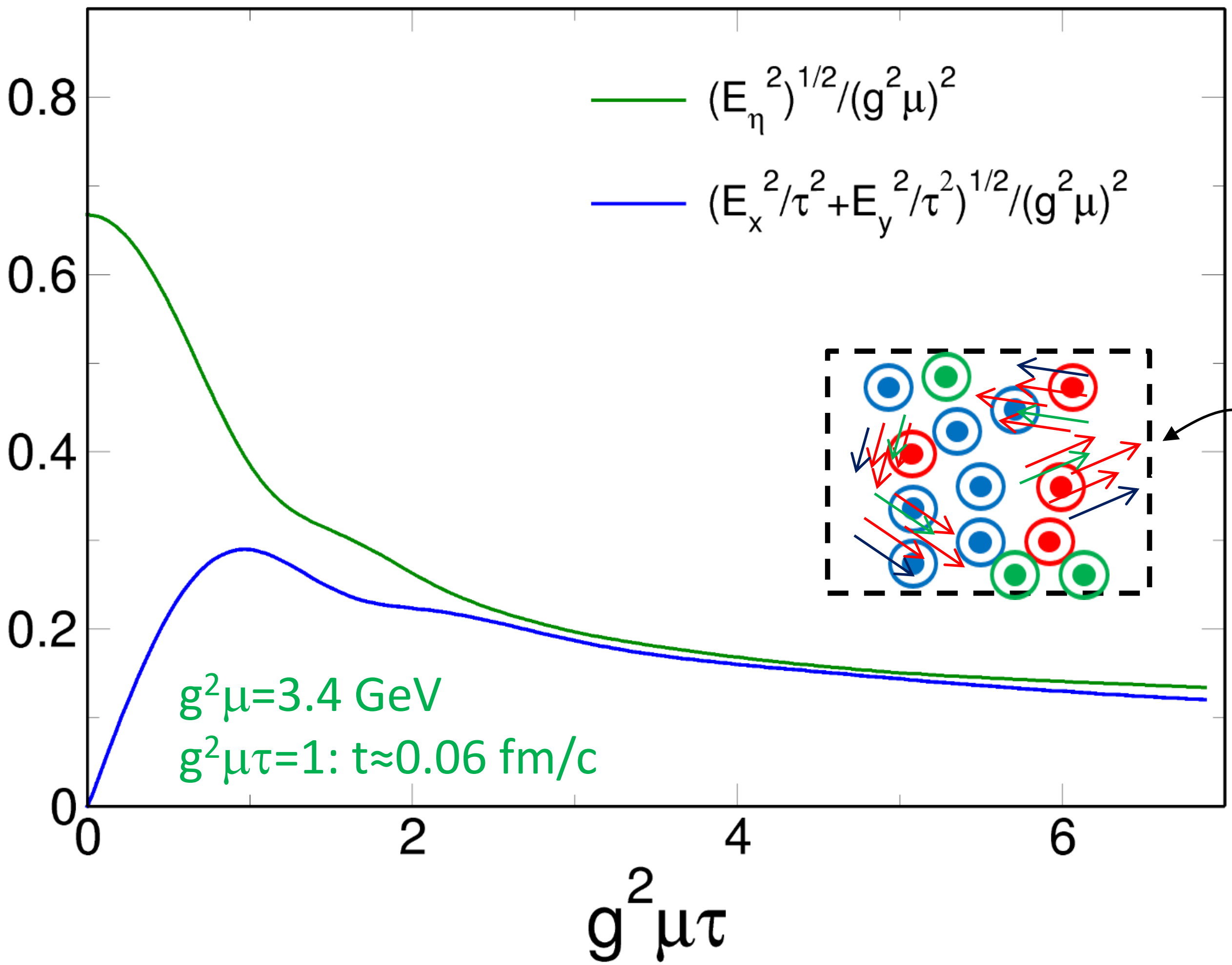
$$\eta = \frac{1}{2}\log\left(\frac{t+z}{t-z}\right)$$

and the **chromo-magnetic field** is defined as

$$B_i = -\epsilon^{ij} F_{j\eta} \qquad B_\eta = -\tfrac{1}{2}\epsilon^{ij} F_{ij}$$

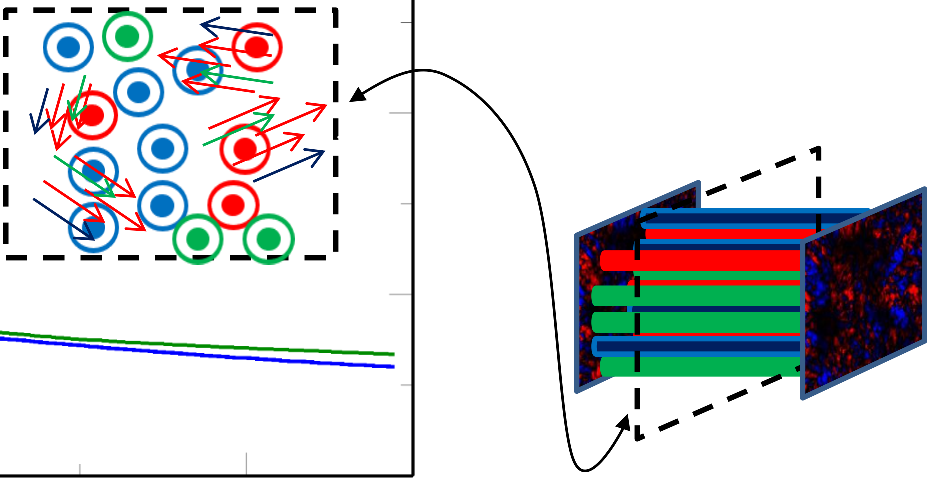
Evolution of the system is studied assuming the Glasma initial condition, and evolving this condition by virtue of the CYM equations.

Ev-Glasma: color fields



<u>*See also*</u>

M. Ruggieri *et al.* (2019)
M. Ruggieri and S. K. Das (2018)
Fukushima and Gelis (2011)
Ohnishi *et al.* (2011)
Lappi and McLerran (2006)



$$\left.\frac{dE^x_a}{dt}\right|_{t=0^+} = \partial_y B^a_z + f_{abc} A^b_y B^c_z$$

Formation time of transverse fields:

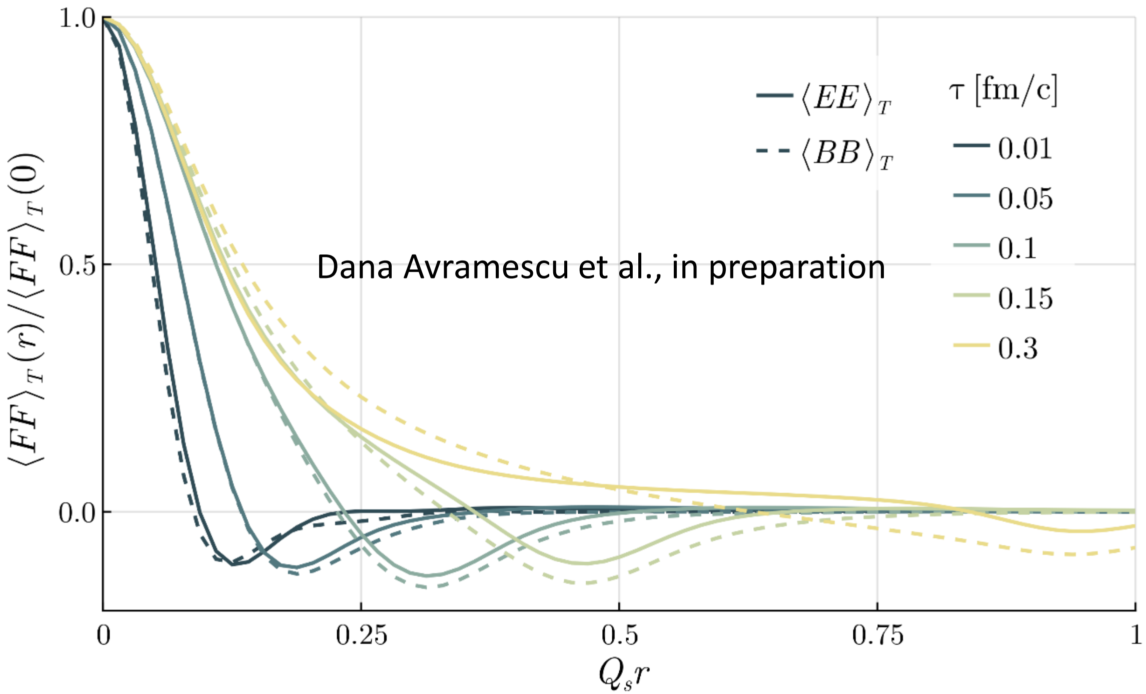
$Q_s\tau \approx 1$ namely $\tau \approx 0.1$ fm/c

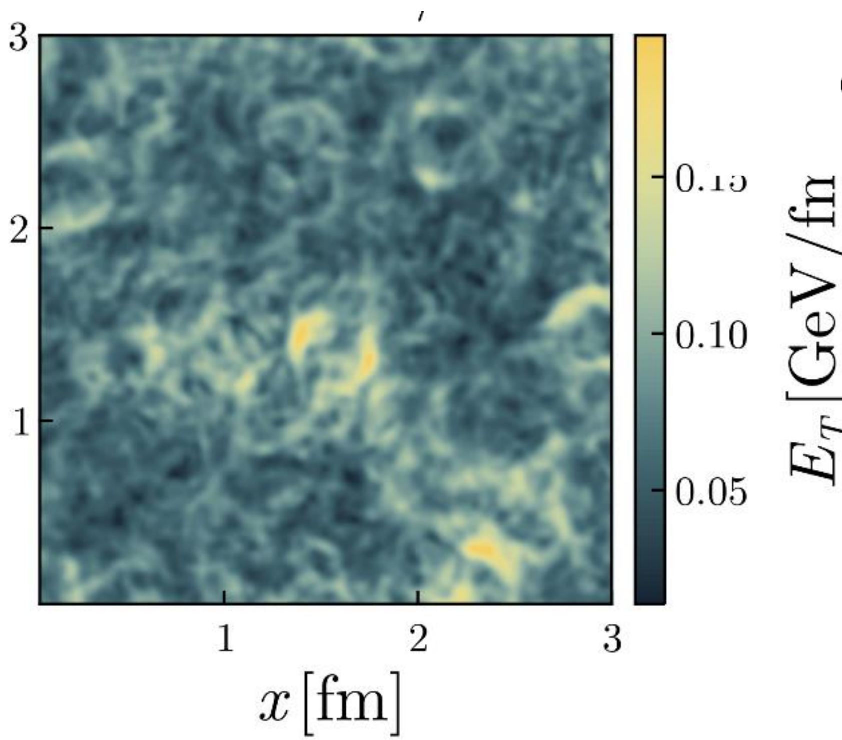
Correlator of transverse (E_x, E_y, B_x, B_y) color fields

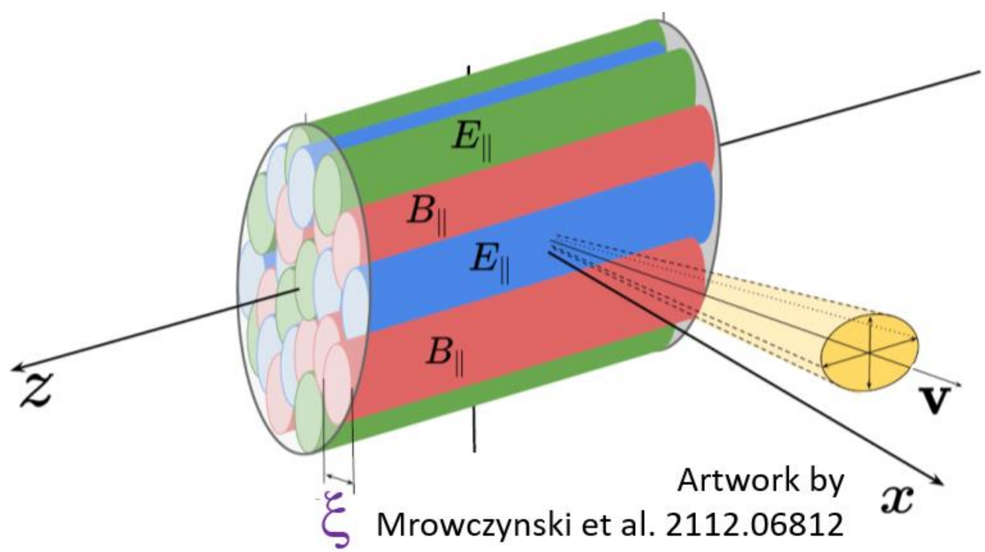
$$\langle FF \rangle_T \propto e^{-r/\xi}$$

ξ: correlation length

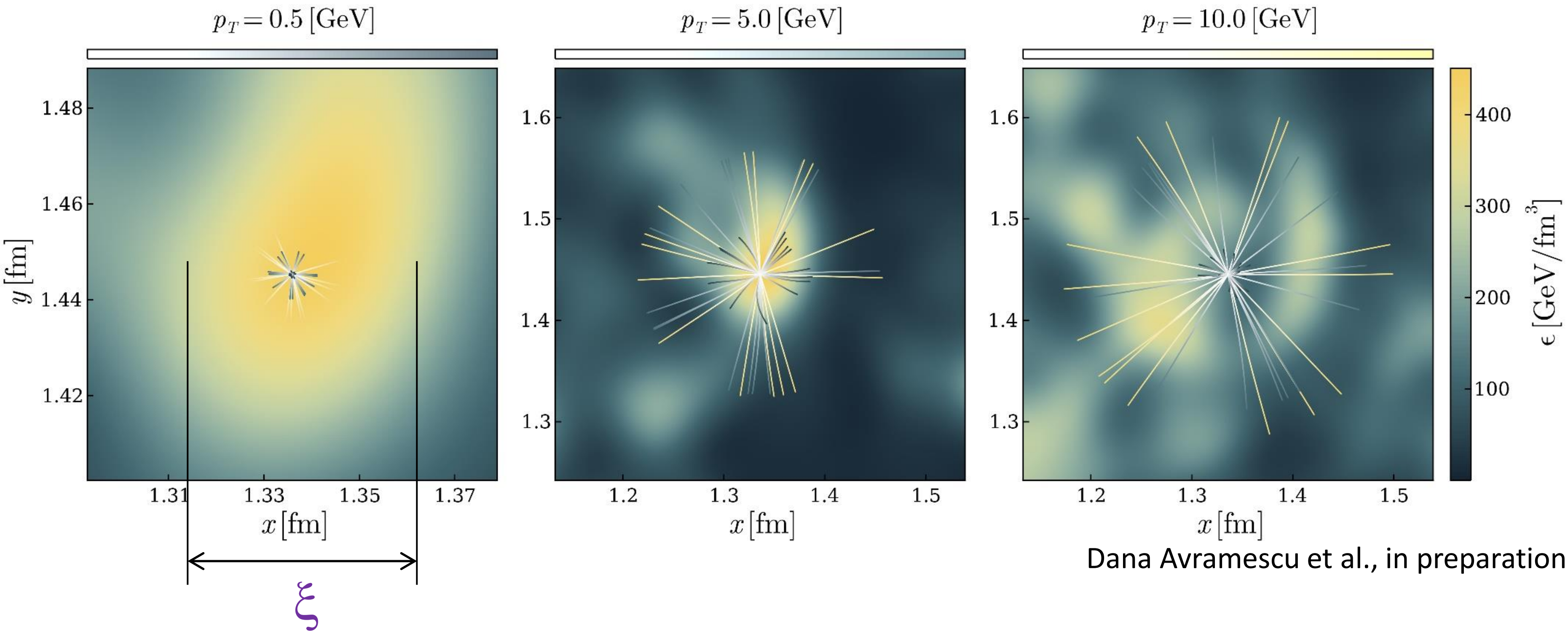
Fields arrange in
correlation domains,
(aka flux tubes, filaments) of
transverse area $\approx\xi^2 = O(1/Q_s^2)$







Color charges in the filaments

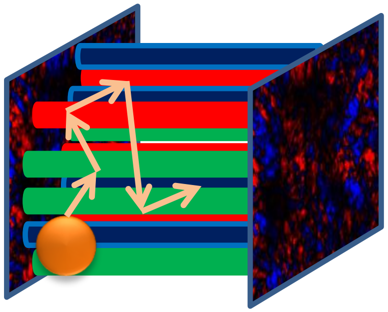


Dana Avramescu et al., in preparation

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 as probes of the evolving Glasma



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

HQs can probe the very early evolution of the Glasma fields

Equations of motion of c-quarks [Wong (1979); Heinz (1985)]:

$$\frac{dx_i}{dt} = \frac{p_i}{E} \qquad E = \sqrt{\boldsymbol{p}^2 + m^2}$$

$\boldsymbol{v} \equiv \frac{\boldsymbol{p}}{E}$ *(Relativistic) Velocity*

$$E\frac{dp_i}{dt} = gQ_a F^a_{i\nu} p^\nu$$

$\frac{d\boldsymbol{p}}{dt} = q\boldsymbol{E} + q\left(\boldsymbol{v} \times \boldsymbol{B}\right)$ *Lorentz force*

$$E\frac{dQ_a}{dt} = -gQ_c \varepsilon^{cba} \boldsymbol{A}_b \cdot \boldsymbol{p}$$

$$D_\mu J^\mu_a = 0$$

Gauge-invariant conservation of the color current carried by heavy quaks + gluons

$J^\mu_a = \bar{c}\gamma^\mu T_a c$

$$Q_a = \langle T_a \rangle$$

Correspondence between the color charges and the SU(3)-color generators, valid in the Classical Limit

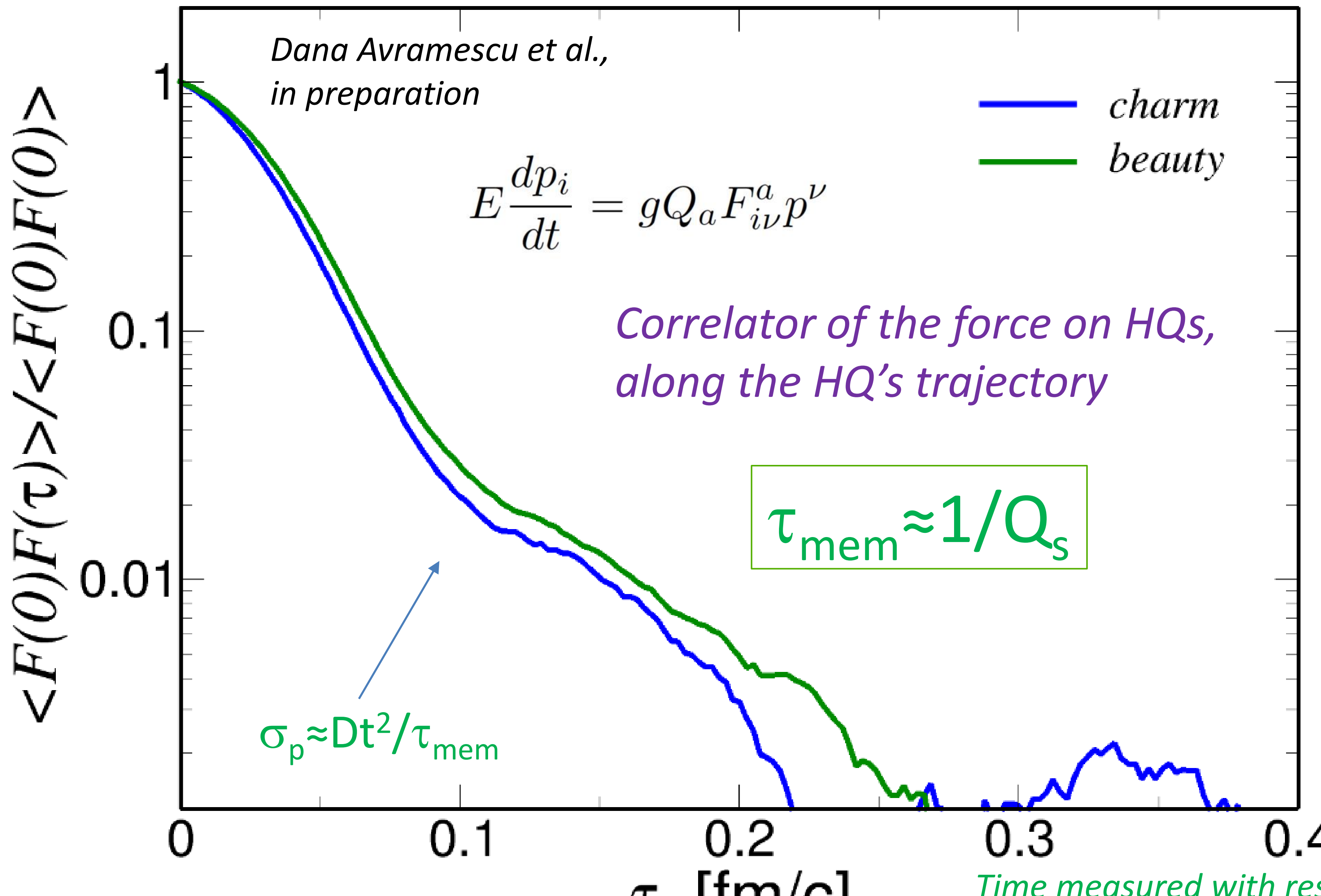
Rotation in color space

$$Q_a Q_a$$

$$d_{abc} Q_a Q_b Q_c$$

Conserved during the evolution

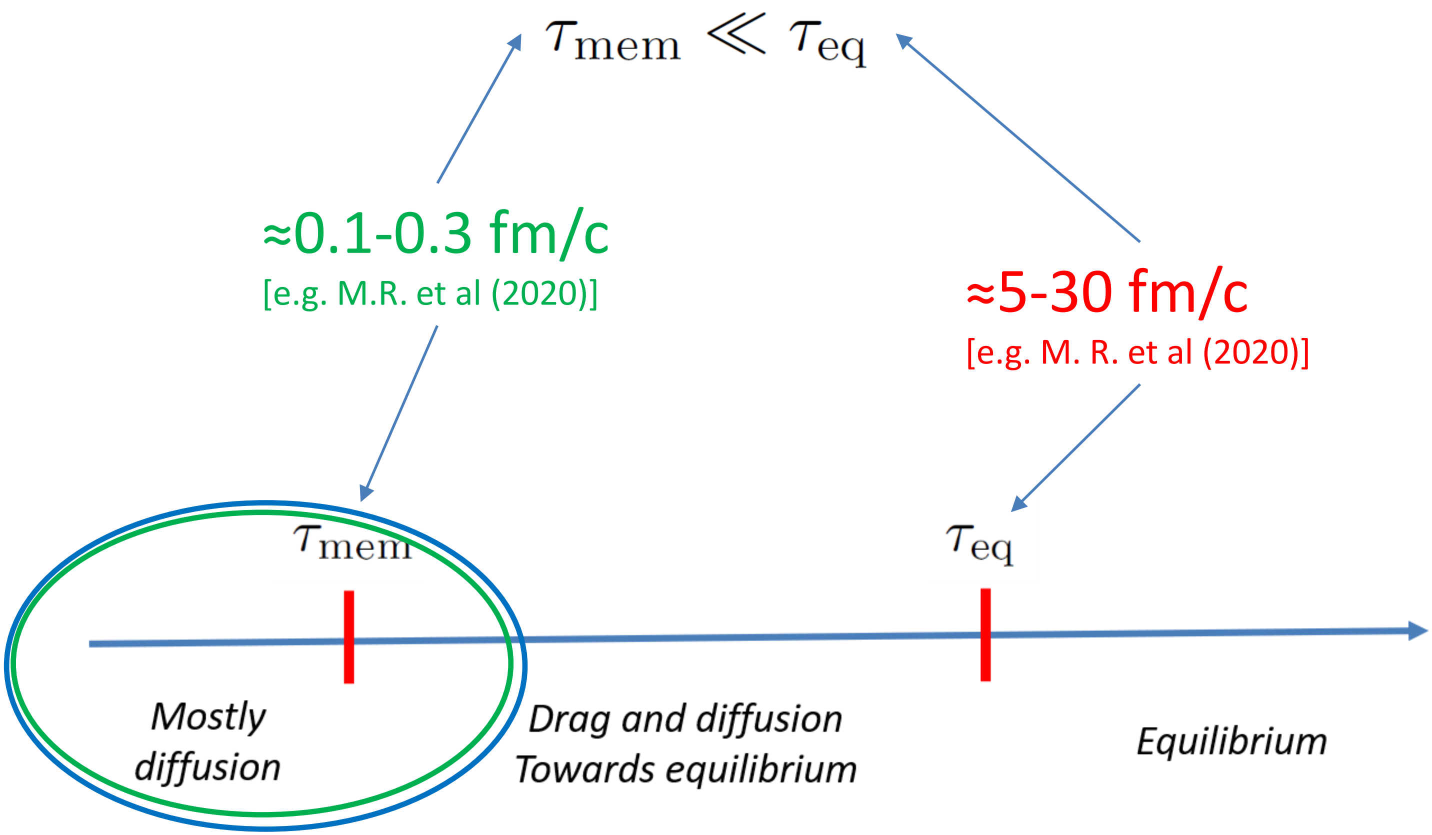
Memory for the HQs diffusion in EvGlasma



Time measured with respect to the formation time ≈ 1/2m

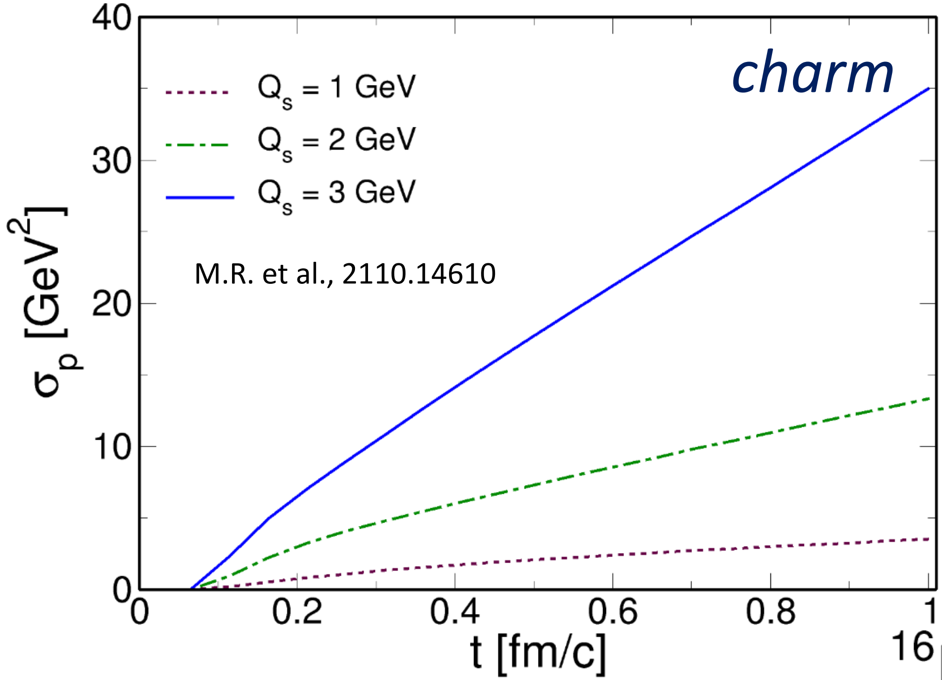
Heavy quarks in Glasma: diffusion-dominated motion

EvGlasma lifetime ≈ QGP thermalization time ≈ 0.3-0.6 fm/c



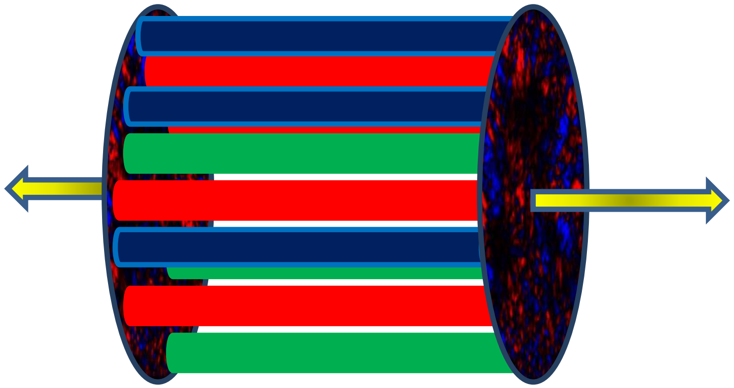
- *Diffusion dominates because memory time is much smaller than the equilibration time*
- *Memory leads to nonlinear evolution of σ_p*

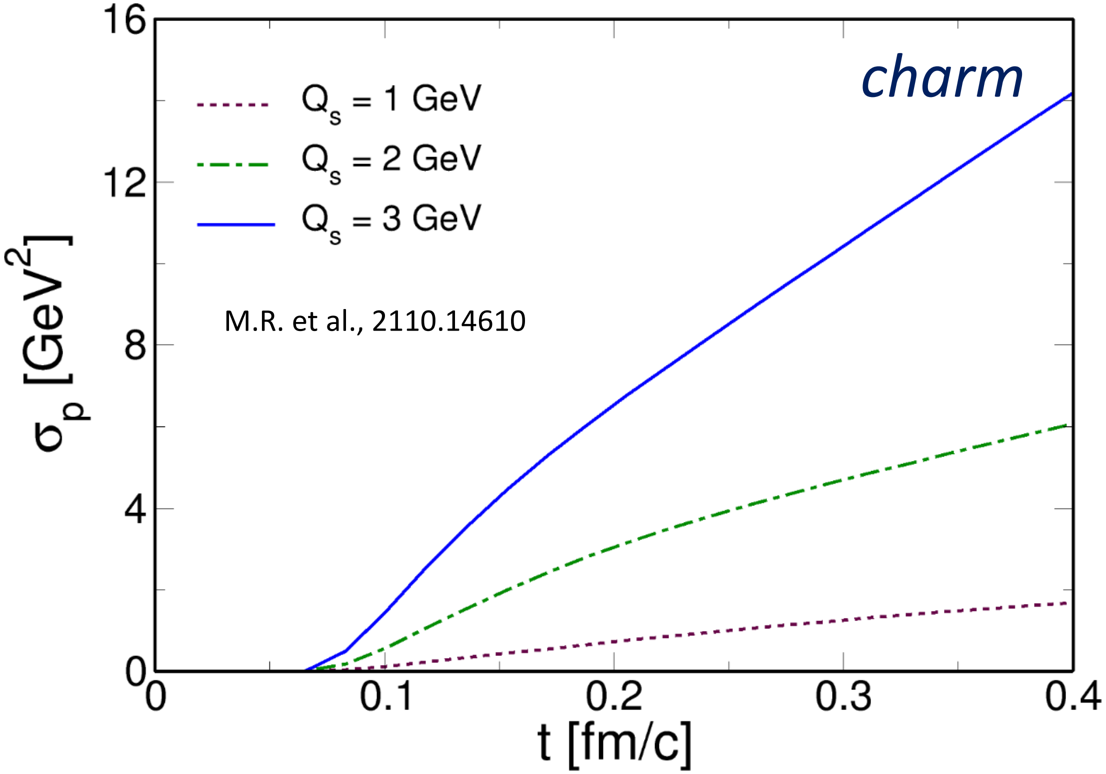
Momentum broadening



Effect of memory can be read as diffusion within a coherent flux tube as well.

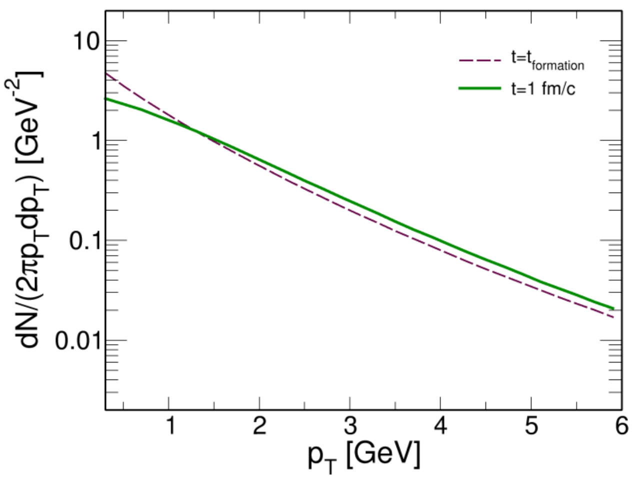
- *Early time: $\sigma_p \approx Dt^2/\tau_{mem}$*
- *Later time time: $\sigma_p \approx 2Dt$*





Impact on RAA

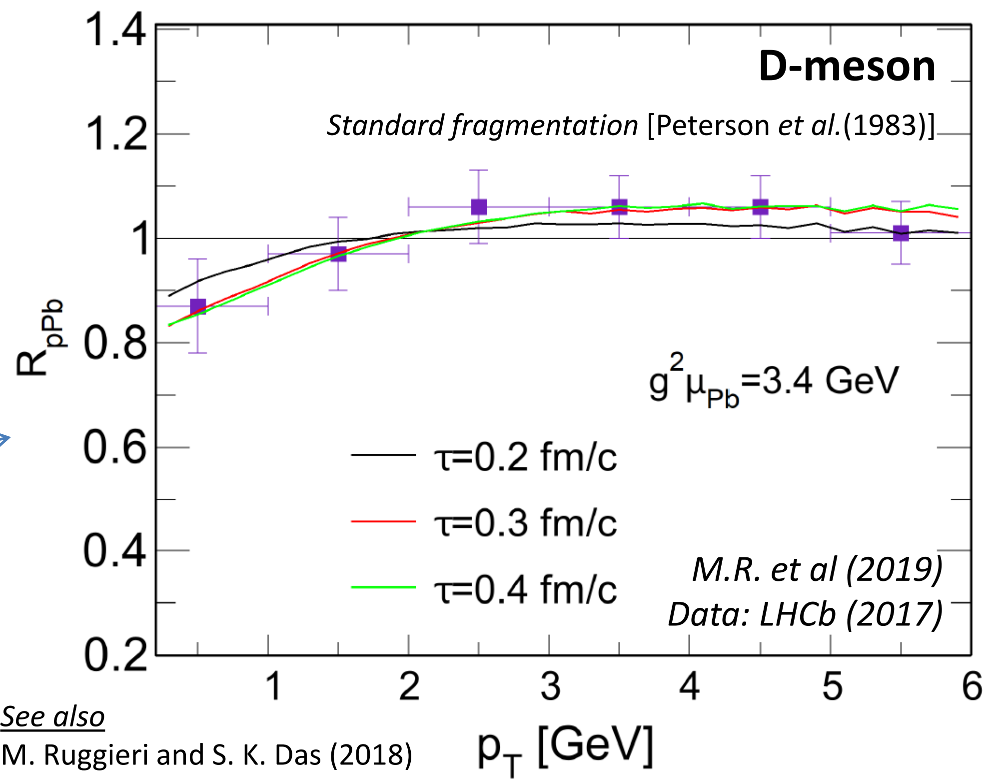
p-Pb @ 5.02 TeV



Initial distribution

From perturbative QCD, aka ***prompt*** [Scardina et al. (2017)]

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



$R_{pPb} \neq 1$

Interaction with the fields created by the collision

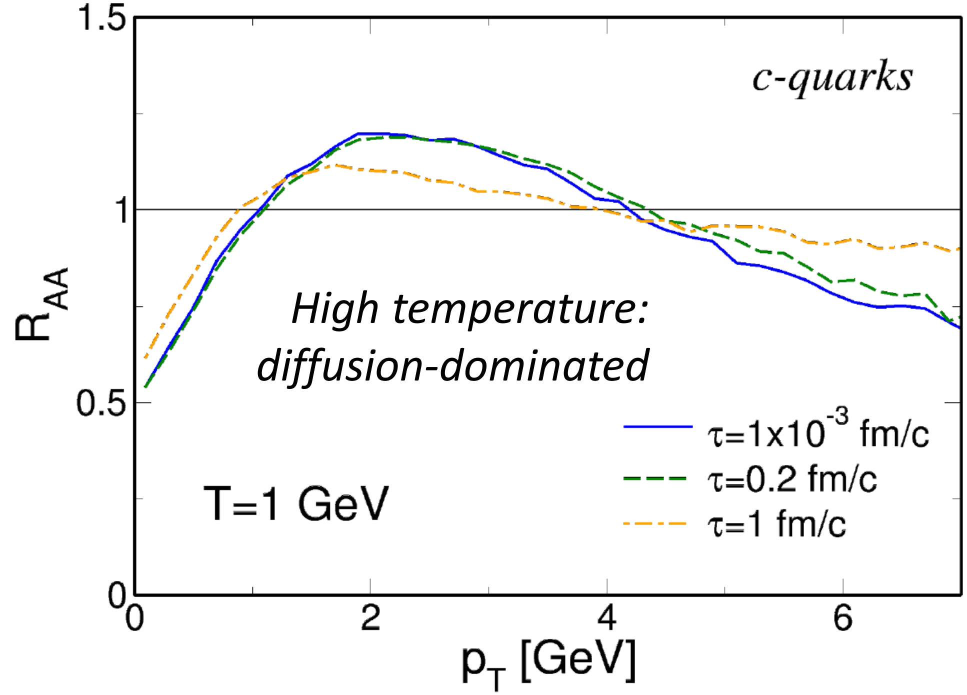
See also

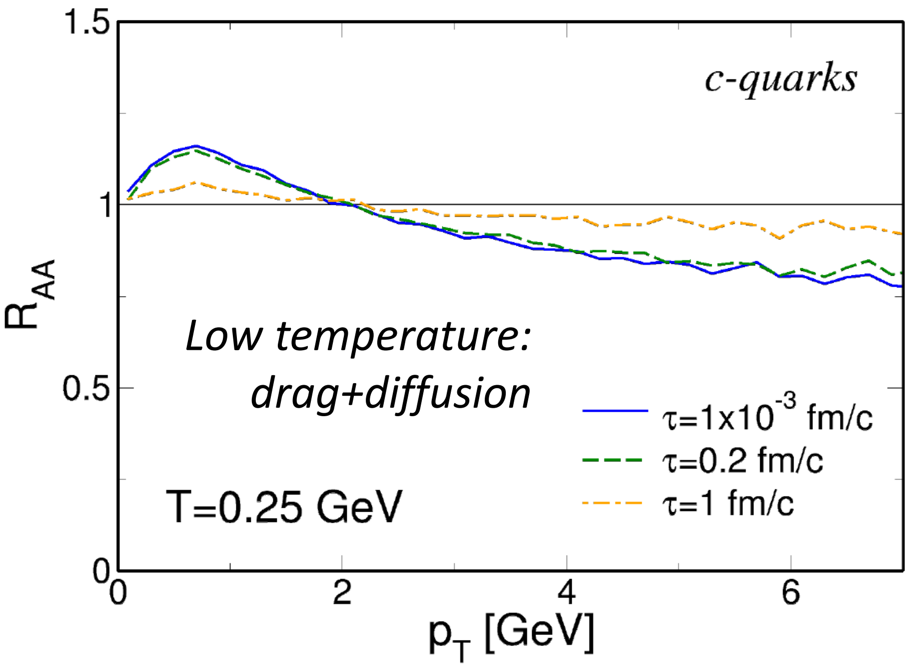
M. Ruggieri and S. K. Das (2018)

Initial spectrum is tilted by the combined effect of

- *Diffusion-dominated evolution*
- *Memory that slows down momentum broadening*

Impact on RAA

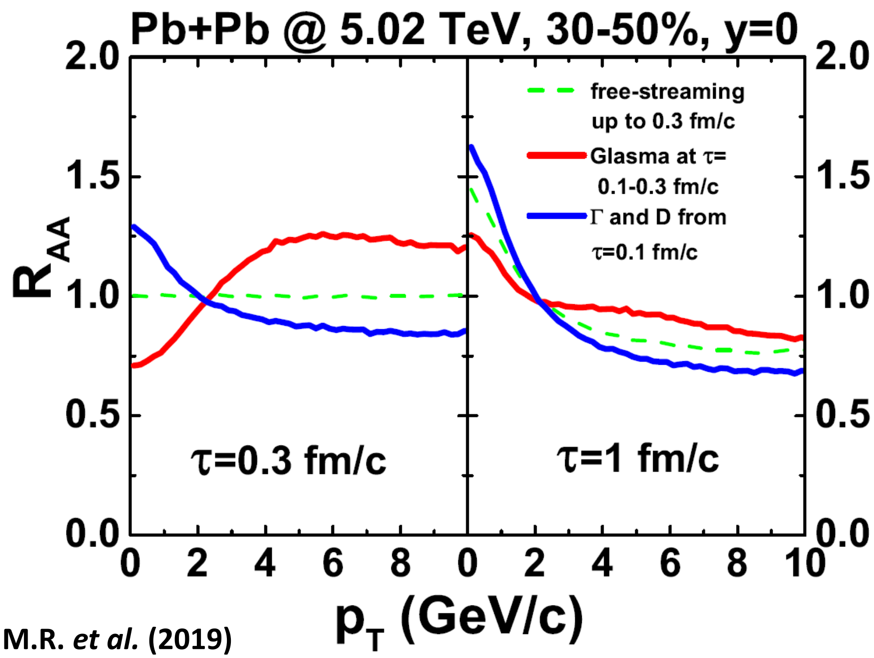




Initial spectrum is tilted by the combined effect of

- *Diffusion-dominated evolution*
- *Memory slowing down momentum broadening*

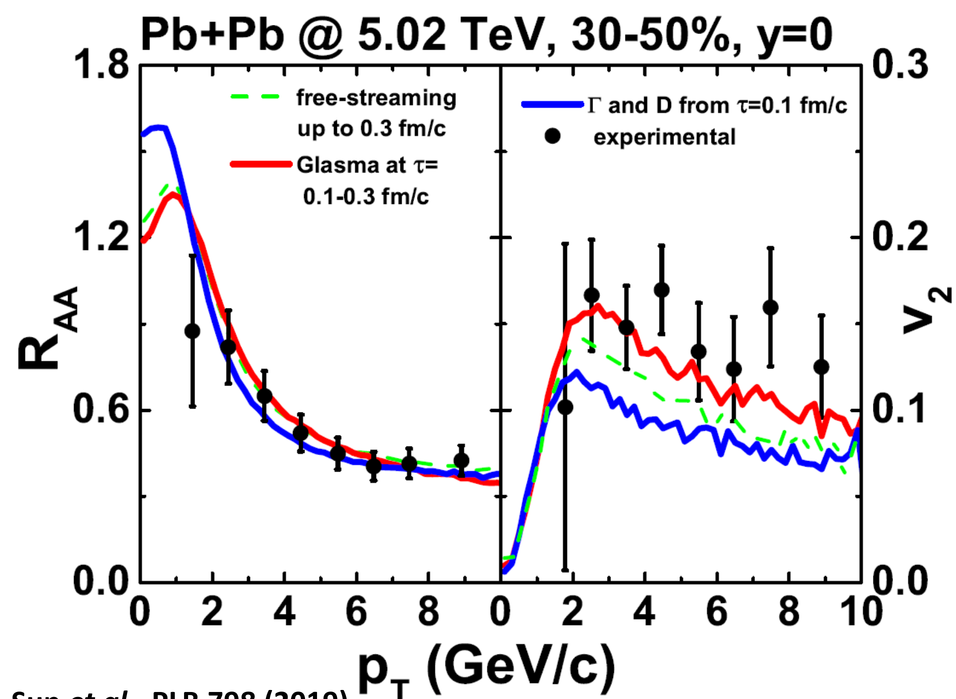
The effect on the elliptic flow in Pb-Pb



M.R. *et al.* (2019)

Data: ALICE, NPA 967 (2017), PRL 120 (2018).

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



Sun *et al.*, PLB 798 (2019)

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

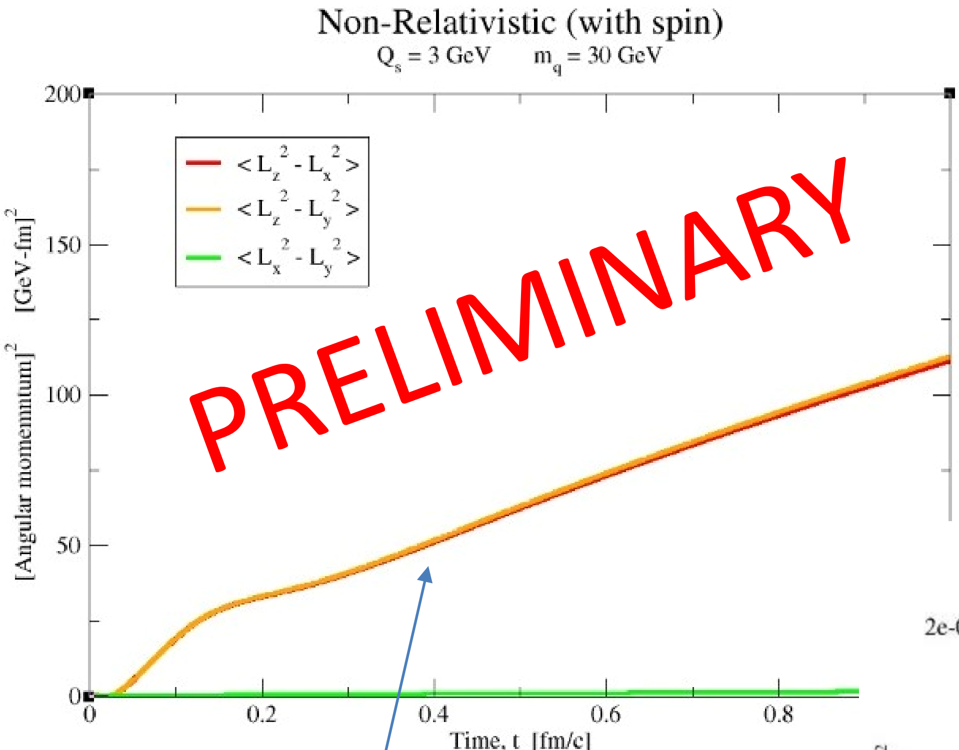
Conclusions and Outlook

- *Borrowing the CGC picture, the early stage of high energy nuclear collisions is described by a set of dense, gluon filaments called Glasma.*
- *Diffusion of HQs in the early stage of high energy collisions is affected by the strong fields: coherence/memory effects are substantial*

- ***Potential effect on observables (R_{AA}, v_n, pA and AA, 2-p correlators)***
- ***Smooth connection to kinetic theory in the early stage***
  - *Relation to quasi-particle models*
  - *Running coupling in the kinetic equations*
  - *Initial state fluctuations*
- ***Longitudinal diffusion: superdiffusion?***
- ***Fluctuation-Dissipation theorem(?)***
- ***Polarization of c-cbar and b-bbar pairs***

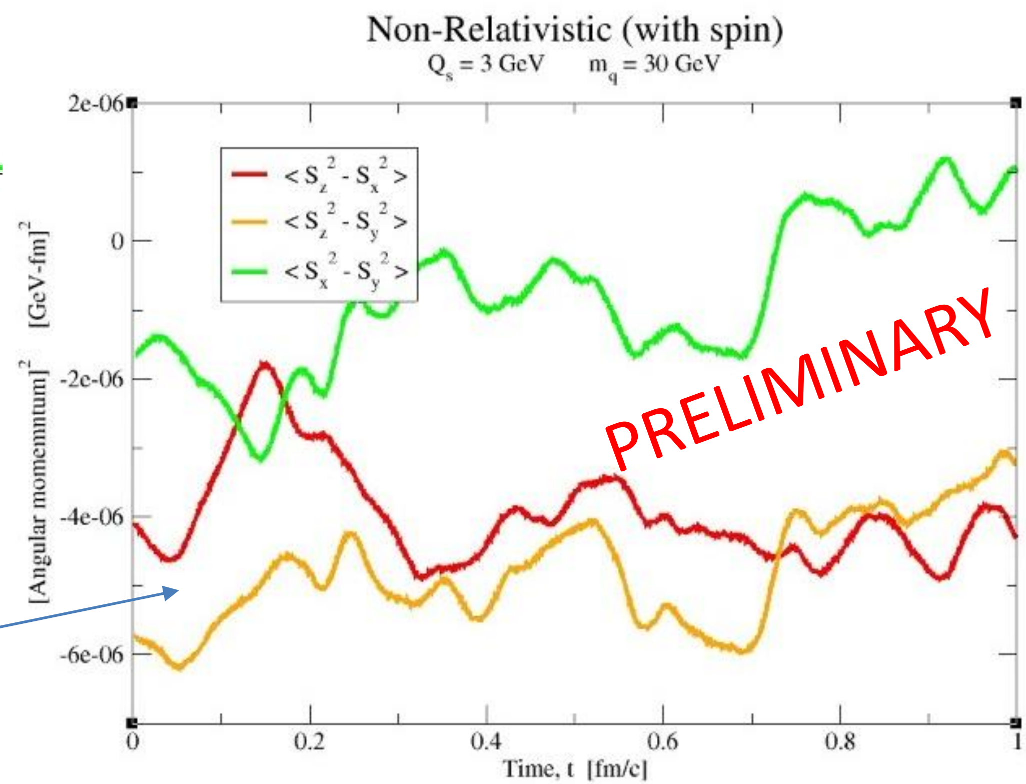
Thank you for your attention!

Polarization(?)



$$\frac{dP^i}{dt} = -\frac{g}{m} F_a^{ij} Q_a P^j + g F_a^{i0} Q_a - \frac{g}{m} Q_c (\mathcal{D}^i B_c^j) S^j,$$
$$\frac{dQ_a}{dt} = \frac{g}{m} f_{abc} A_b^j P^j Q_c + \frac{g}{m} f_{abc} S^j B_b^j Q_c,$$
$$\frac{dS^i}{dt} = -\frac{gQ_a}{m} F_a^{ik} S^k,$$
$$\frac{dL^i}{dt} = \varepsilon_{ijk} x^j \frac{dP^k}{dt}.$$

Angular momentum anisotropy



Spin unaffected