A Catania-Goa (with a piece of Jyvaskyla)'s tale of charm and beauty

Heavy quarks in heavy ion collisions

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Catania's group: Vincenzo Greco, Gabriele Parisi, Maria Lucia Sambataro, Salvatore Plumari, Lucia Oliva, Nugara, Minisssale, Angelo Asta
Goa's group: Santosh K. Das, Pooja, Jay Prakash, Yosouf Jamal
The Jyvaskyla's bit: Dana Avramescu

In this talk

- A user-friendly introduction to the early stage of relativistic heavy ion collisions (RHICs): the *Glasma*, and its *evolution*

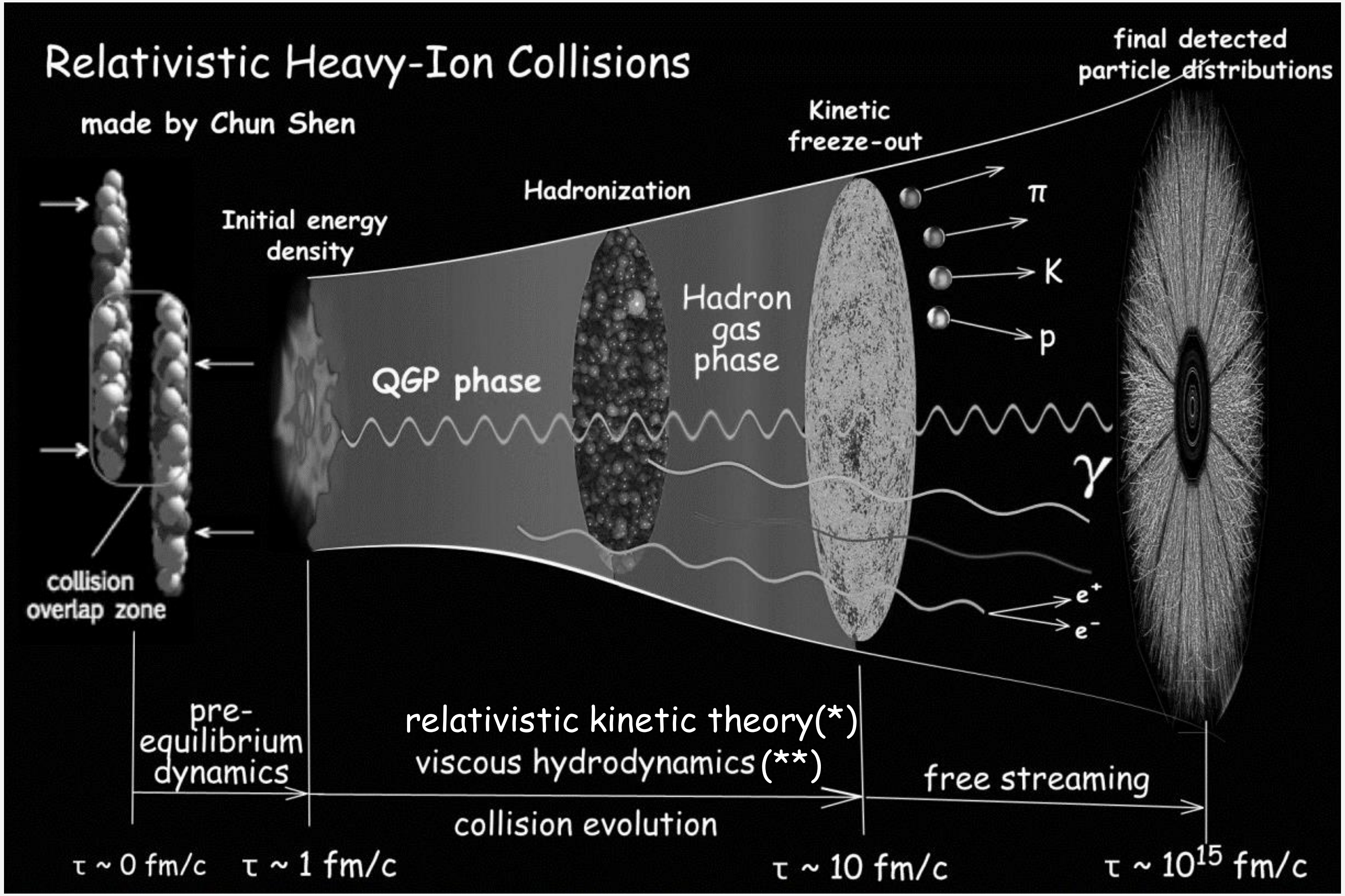
- *Heavy quarks* in the evolving Glasma

- *Heavy quarks* in the quark-gluon plasma

- *Hadronization of heavy quarks* in RHICs

- Conclusions

Medium evolution in RHICs



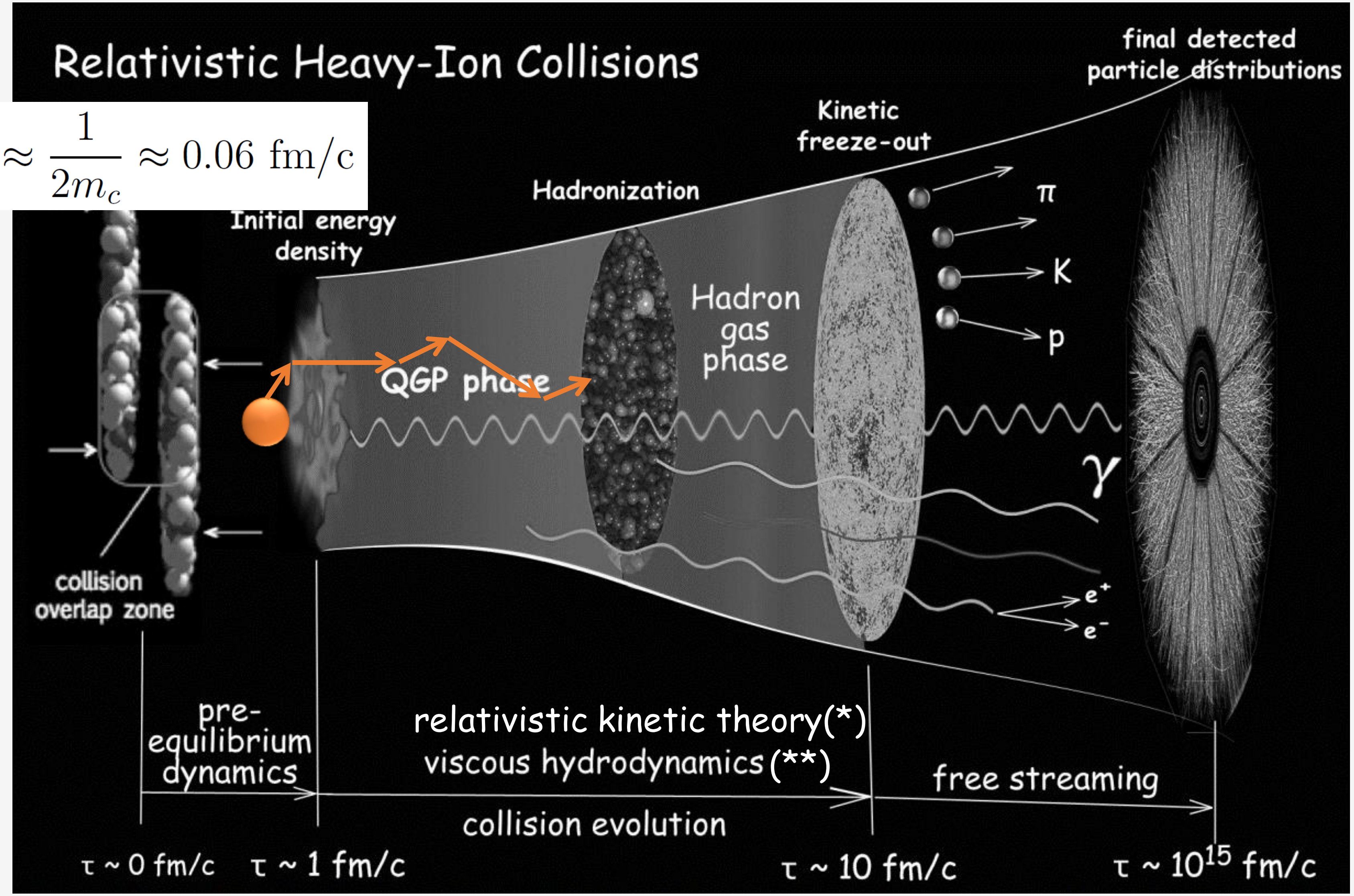
(*)Talk by Nugara

(**)Talk by Edoardo Grossi

Heavy quarks, c and b, in RHICs

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

HQs can probe the entire evolution of the medium, from the early stage up to hadronization



Heavy quarks, c and b, in RHICs

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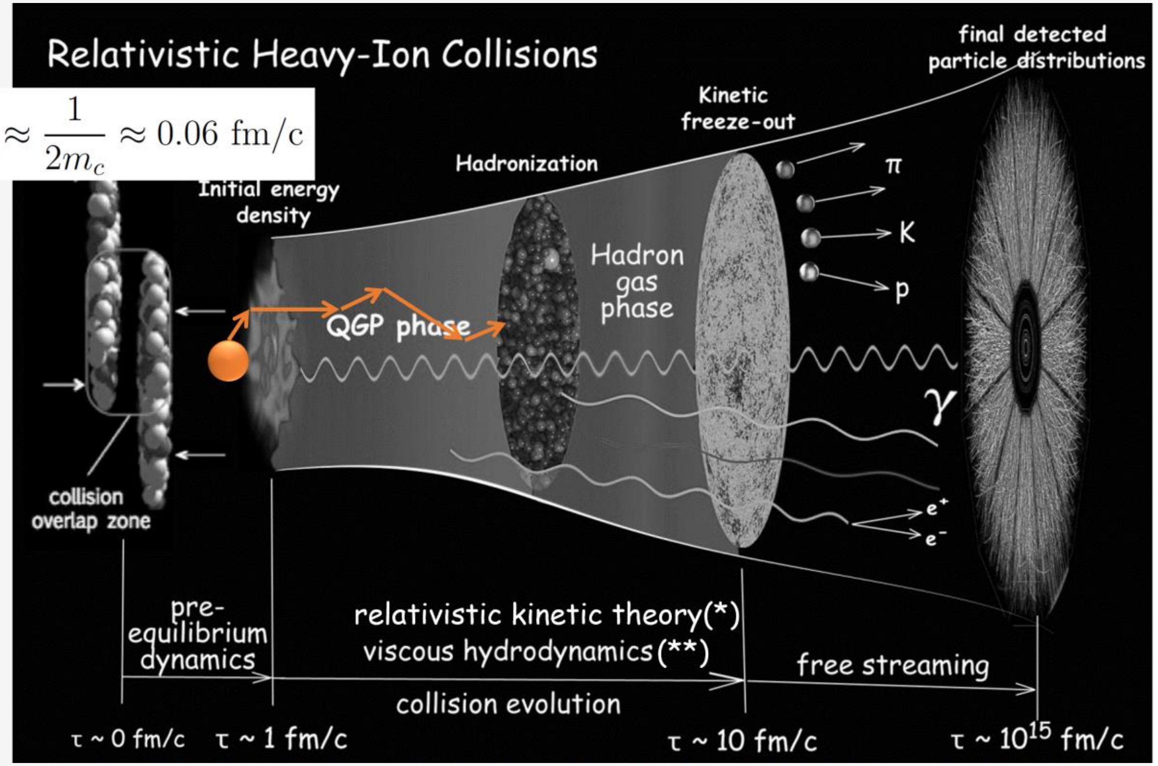


It is meaningful to study the evolution of HQs:

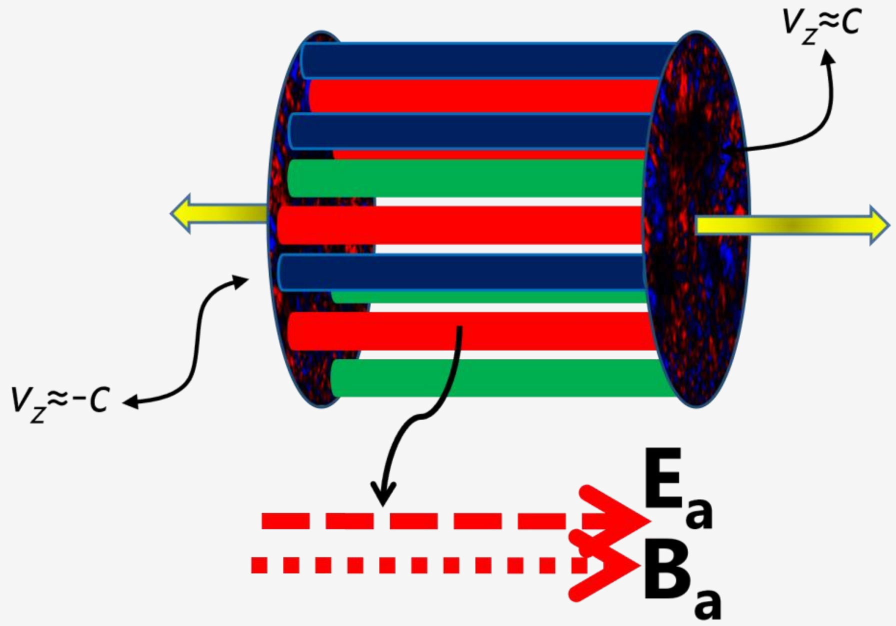
- *In the early stage (this talk)*
- *In the QGP (this talk, Martinez's talk)*

And eventually analyze the possible hadronization mechanisms

Early stage: strong gluon fields and the Glasma

<u>*Many gluons in the early stage*</u>

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

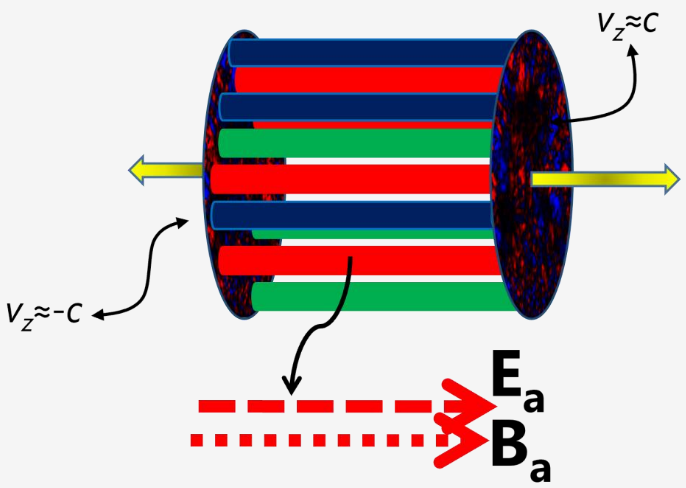


Glasma (*)

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

(*)Lappi and McLerran (2006)

Early stage: strong gluon fields and the Glasma



Strength of initial fields: $O(Q_s^2)$
Initial energy density: $O(Q_s^4)$

Q_s: saturation scale

Qs is the only energy scale in this model

$Q_s \approx 1 - 3$ GeV (*)

(*)See Parisi's talk for more details

Evolving the Glasma: classical Yang-Mills (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(*).

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

$$\partial_\tau E_i = \tfrac{1}{\tau}\mathcal{D}_\eta F_{\eta i} + \tau \mathcal{D}_j F_{ji}, \qquad E_i = \tau \partial_\tau A_i,$$

$$\partial_\tau E_\eta = \tfrac{1}{\tau}\mathcal{D}_j F_{j\eta}, \qquad E_\eta = \frac{1}{\tau}\partial_\tau A_\eta.$$

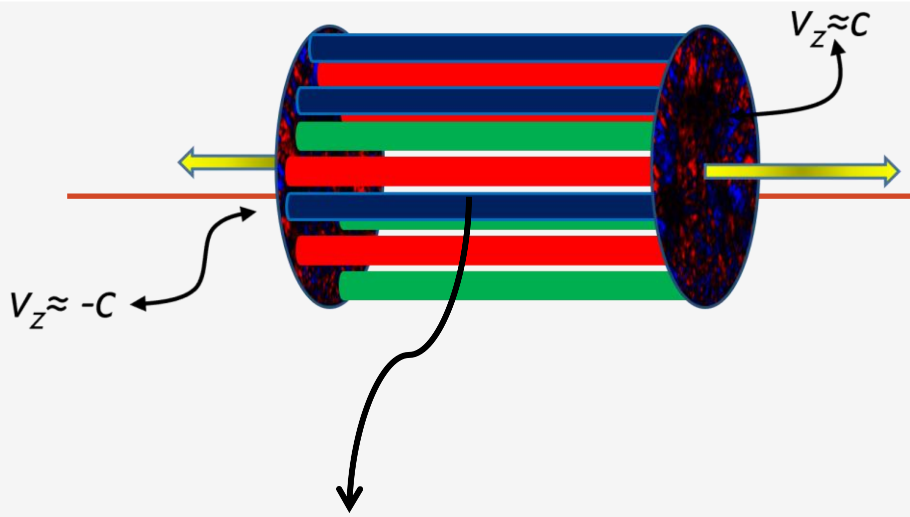
$$\tau = \sqrt{t^2 - z^2}$$

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

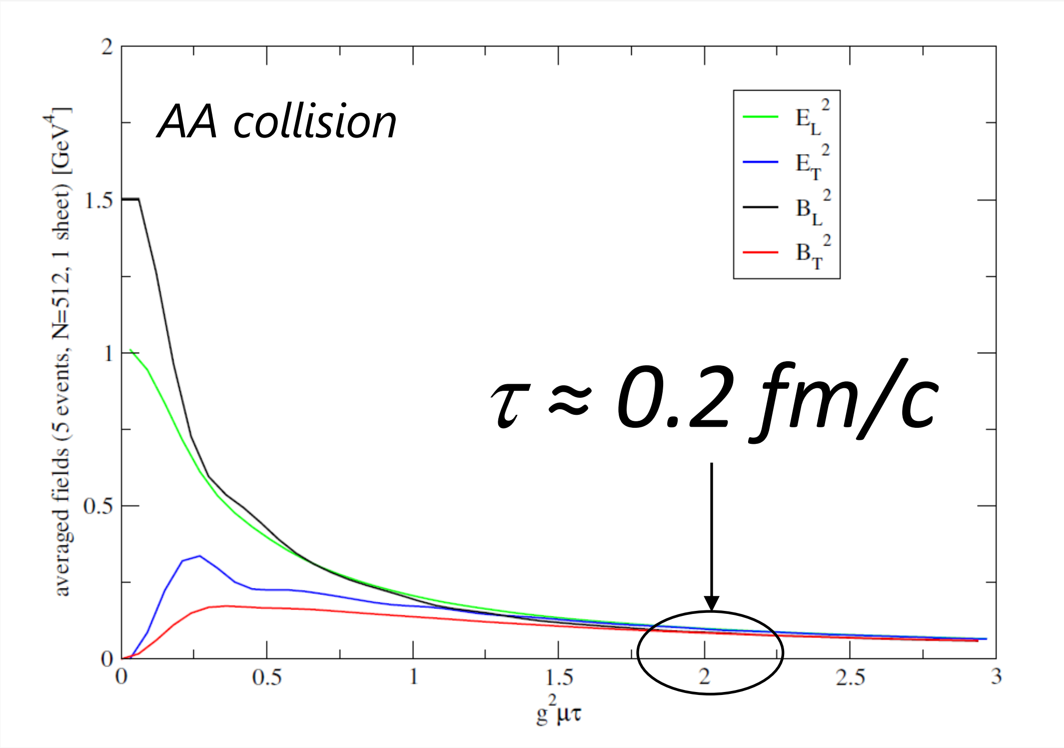
Evolution of the system is studied assuming the Glasma initial condition, and evolving this condition by virtue of the CYM equations.

(*)See the talk by Gabriele Parisi for details on how these equations are implemented and solved.

Evolving fields



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

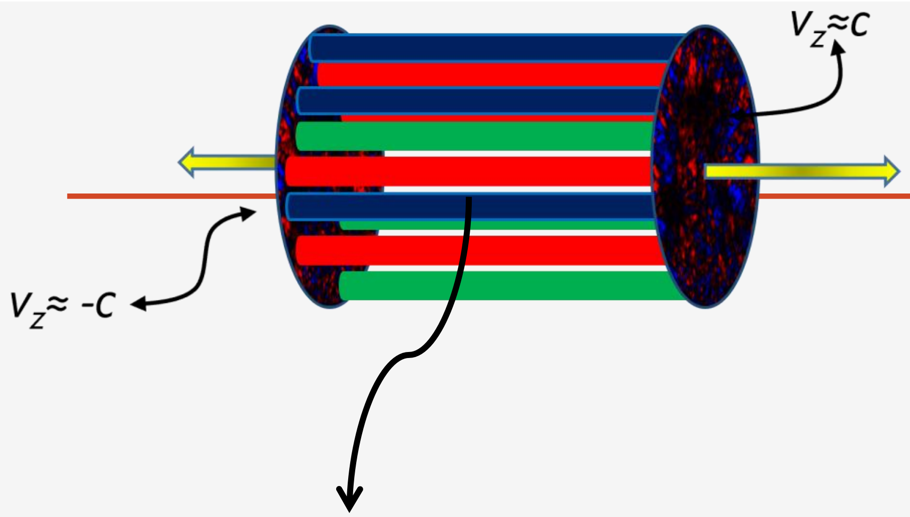


$$\left.\frac{dE_a^x}{dt}\right|_{t=0^+} = \partial_y B_z^a + f_{abc} A_y^b B_z^c$$

Formation time of transverse fields:

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

The evolution of the energy density



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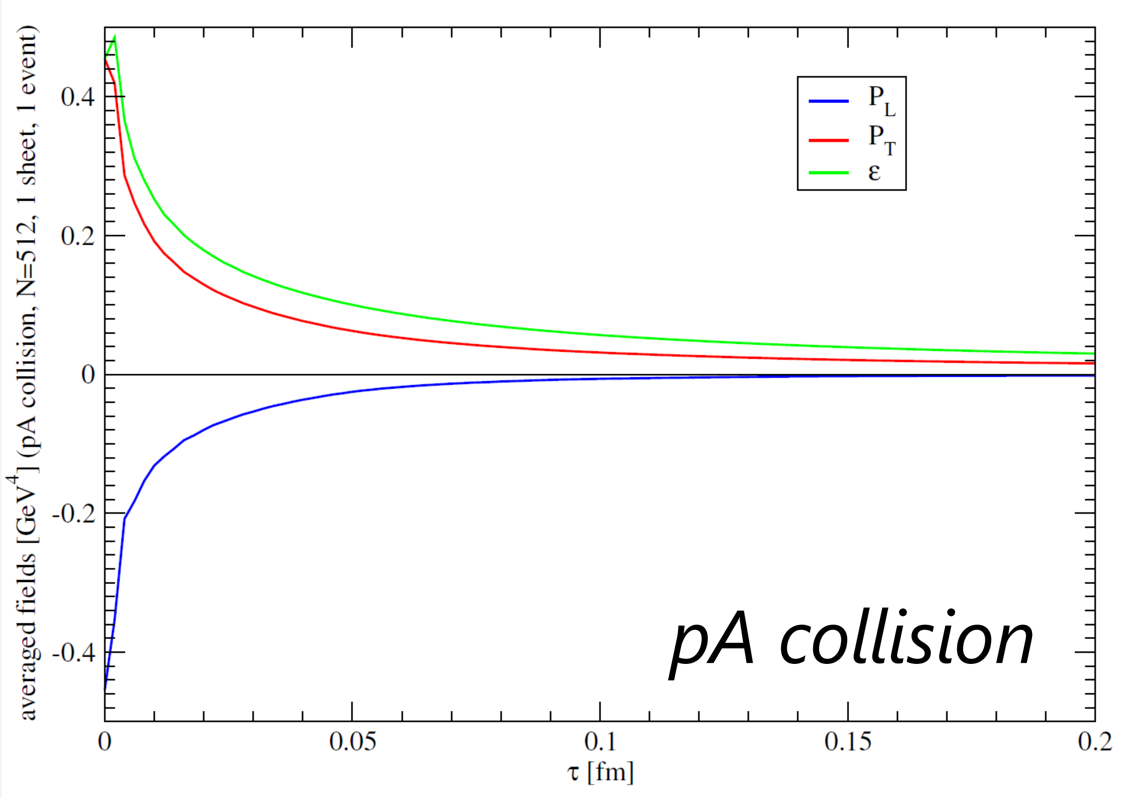
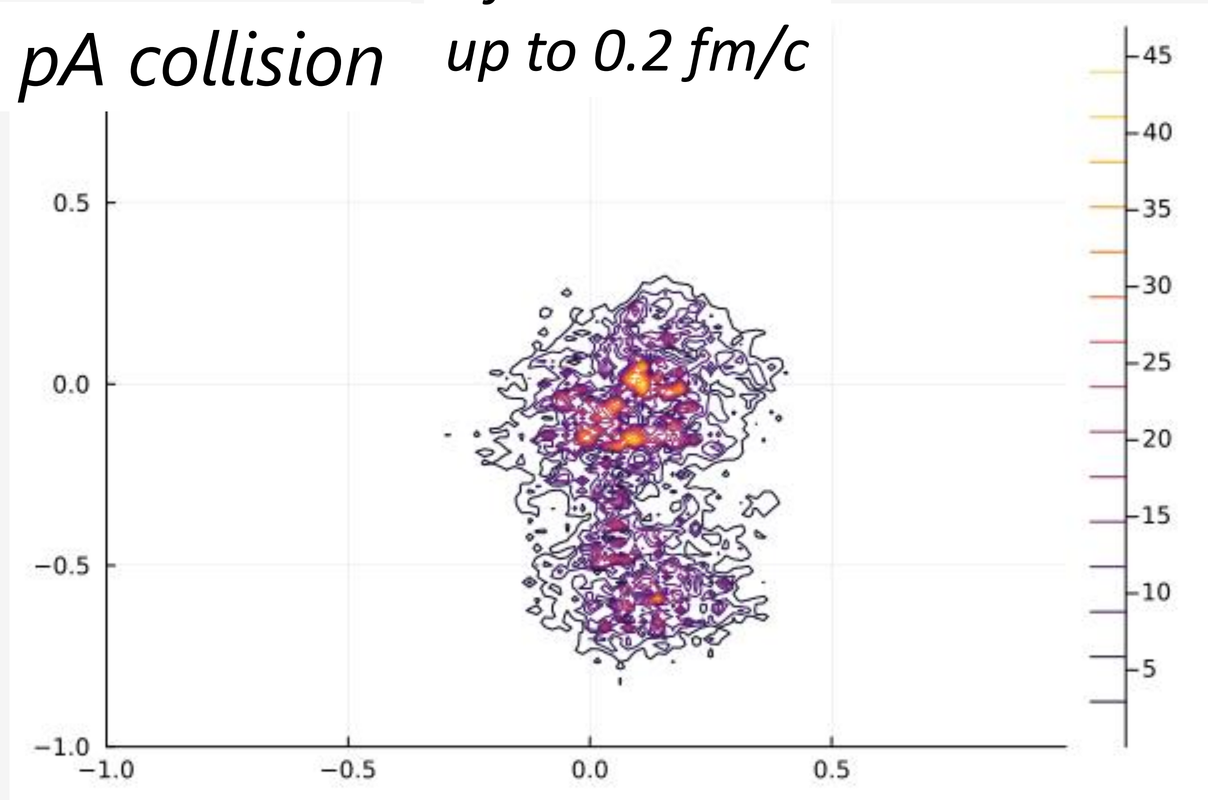
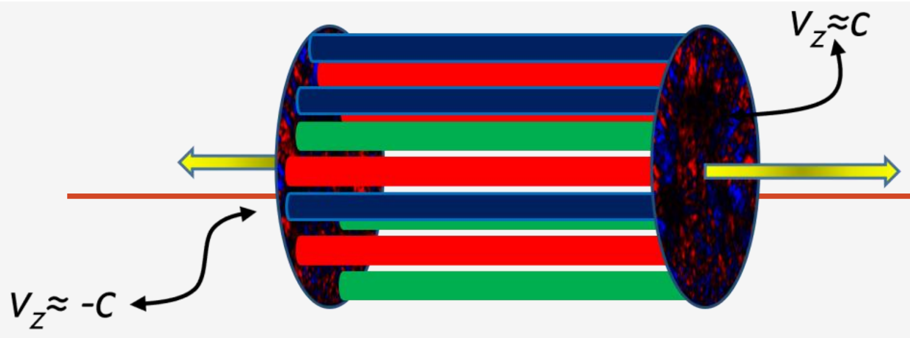


τ from 0
up to 0.2 fm/c



Animation: courtesy of Gabriele Parisi

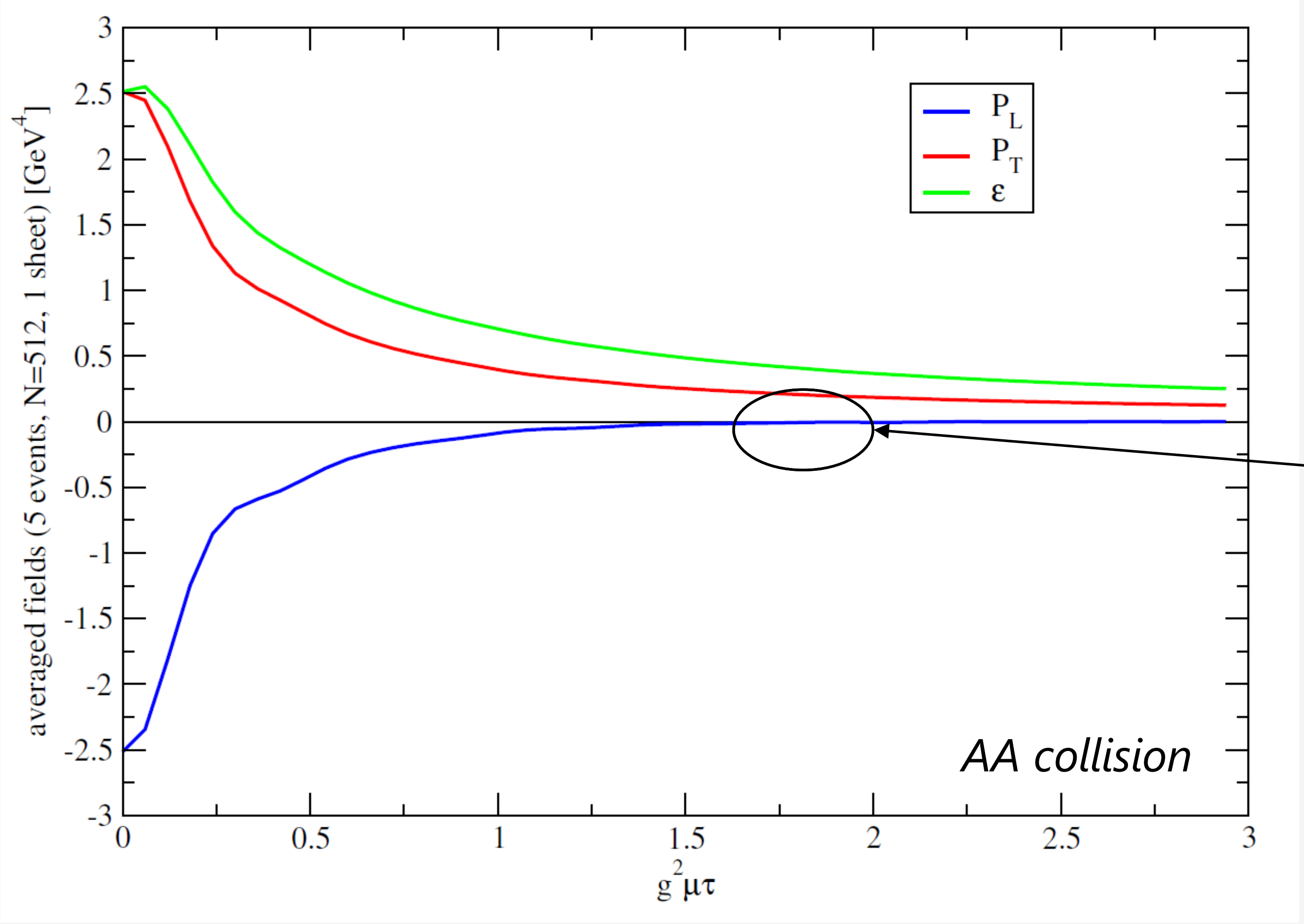
The free streaming regime, AA collisions



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

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

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



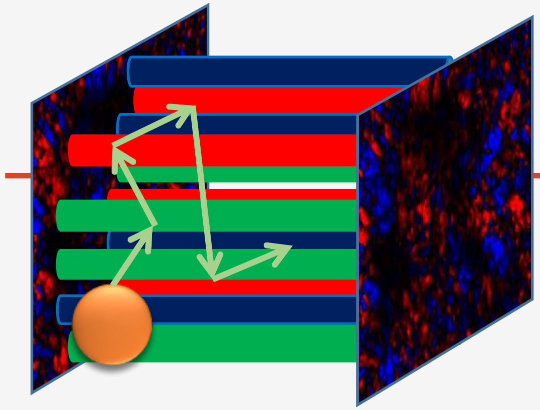
$\tau \approx 0.2$ fm/c

Longitudinal pressure vanishes(*)

$P_L \neq P_T$: the system is quite anisotropic. This anisotropy affects observables, e.g. those of the heavy quarks.

(*)Free streaming regime. See the talk by Gabriele Parisi

Heavy quarks (HQs) probing of the evolving Glasma



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

Relativistic kinetic theory of HQs in Glasma

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

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

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

Wong (1979), Heinz (1985)

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

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

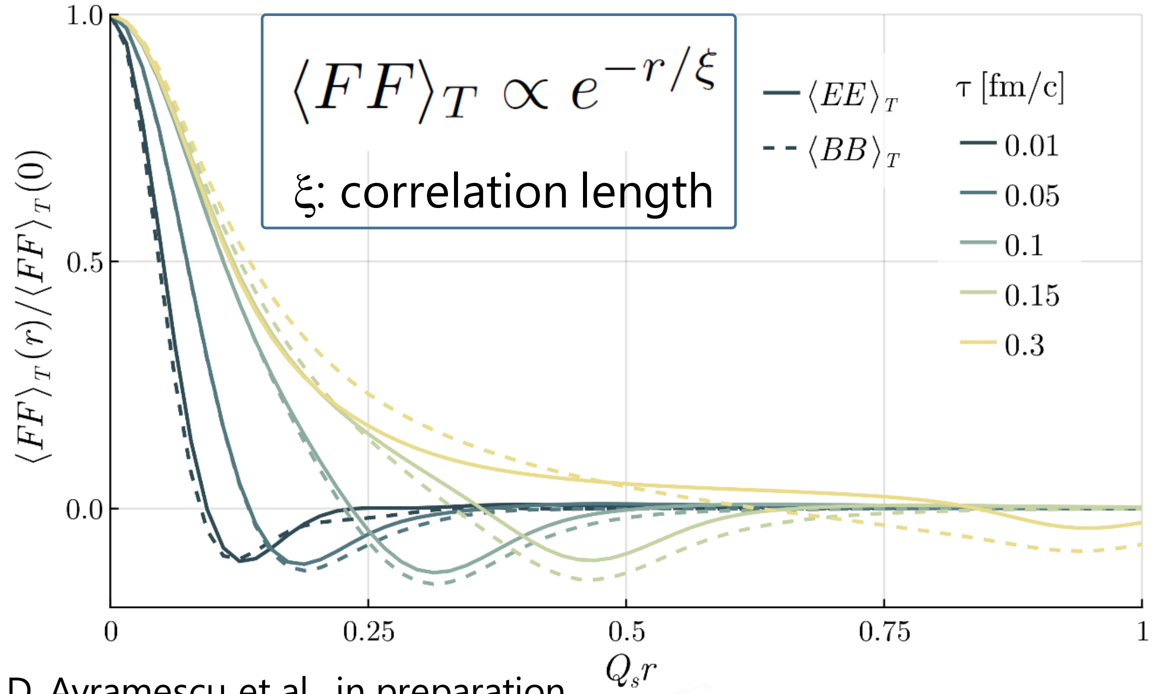
$D_\mu J^\mu_a = 0$ *Gauge-invariant conservation of the color current carried by charm quaks + gluons*

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

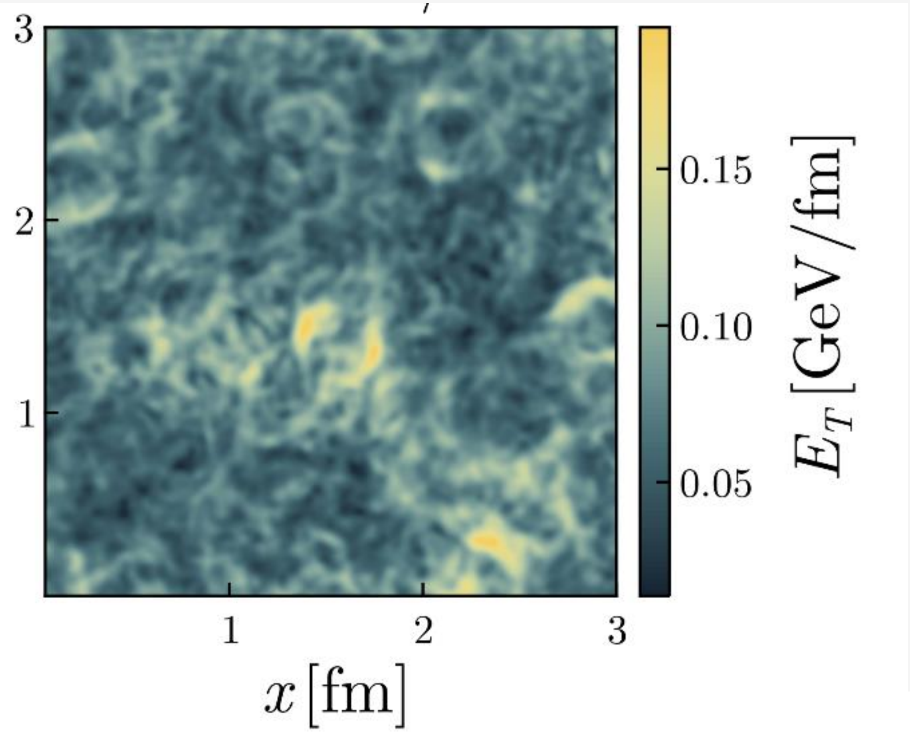
Equations of motion of heavy quarks are solved in the background given by the evolving Glasma fields

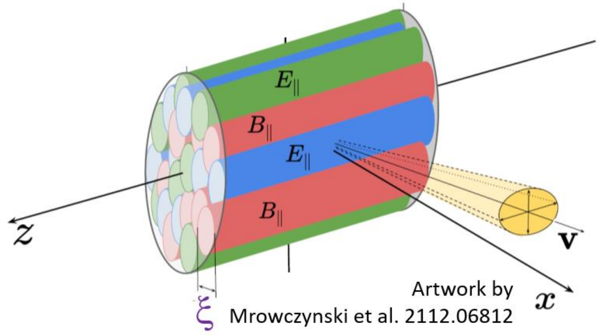
The colored filaments of the Glasma

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



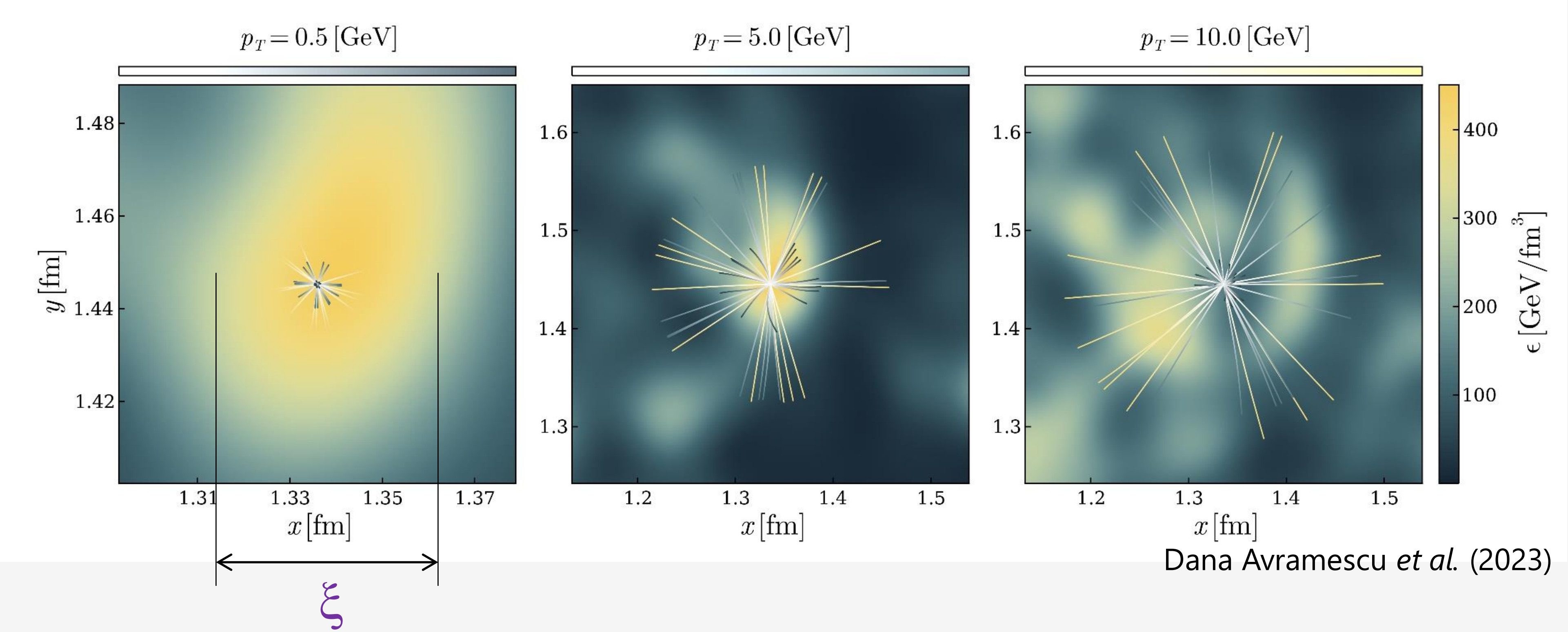
D. Avramescu et al., in preparation





Artwork by Mrowczynski et al. 2112.06812

Heavy quarks inside color filaments



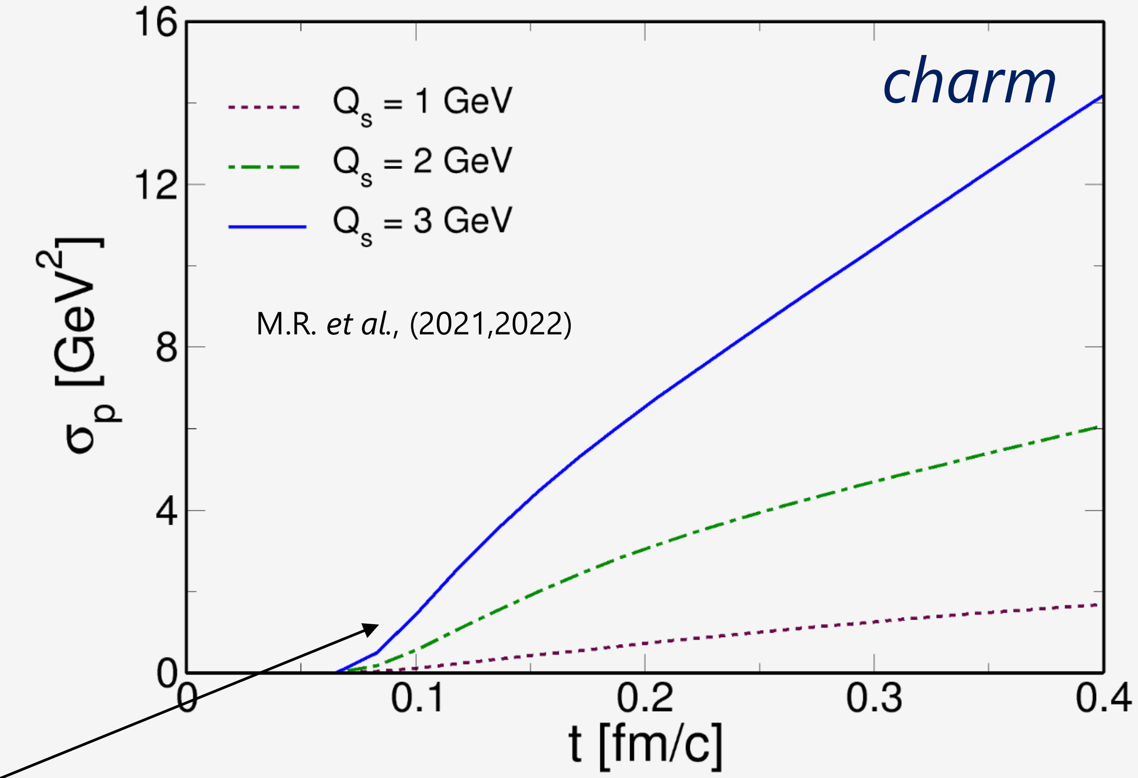
Dana Avramescu *et al.* (2023)

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.

Momentum broadening of charm quarks

$$\sigma_p = \langle p - \langle p \rangle \rangle^2$$



Diffusion in the color filament

Standard Brownian motion

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

D: momentum diffusion coefficient

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

Comparison with perturbative QCD-Langevin

Standard Brownian motion

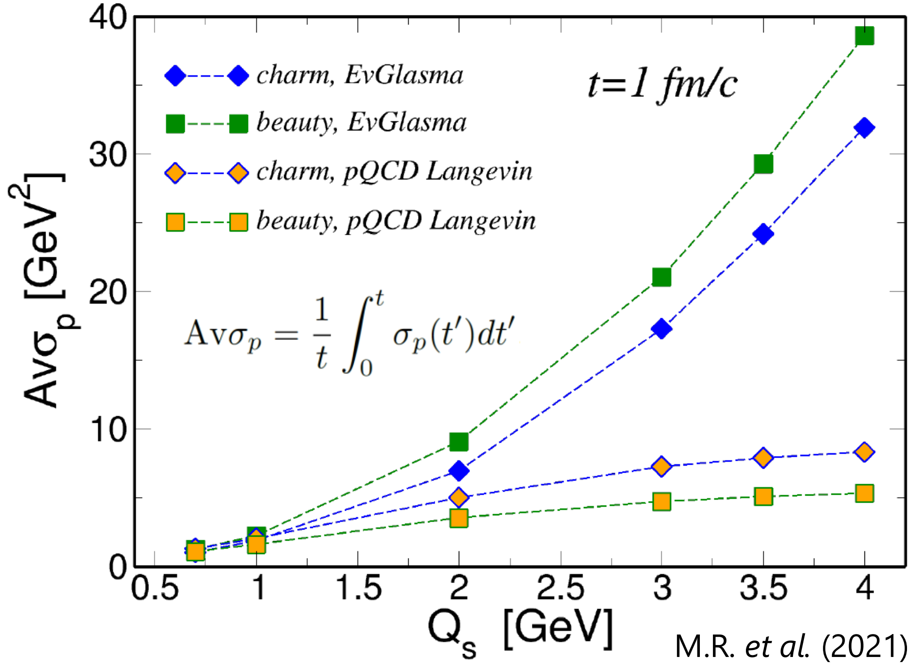
$$\frac{dp}{dt} = -\gamma p + \xi$$

$$\langle \xi(t_1)\xi(t_2)\rangle = 2D\delta(t_1 - t_2)$$

energy loss

random kicks from the medium
(momentum diffusion)

$$\sigma_p = \langle p - \langle p \rangle \rangle^2$$



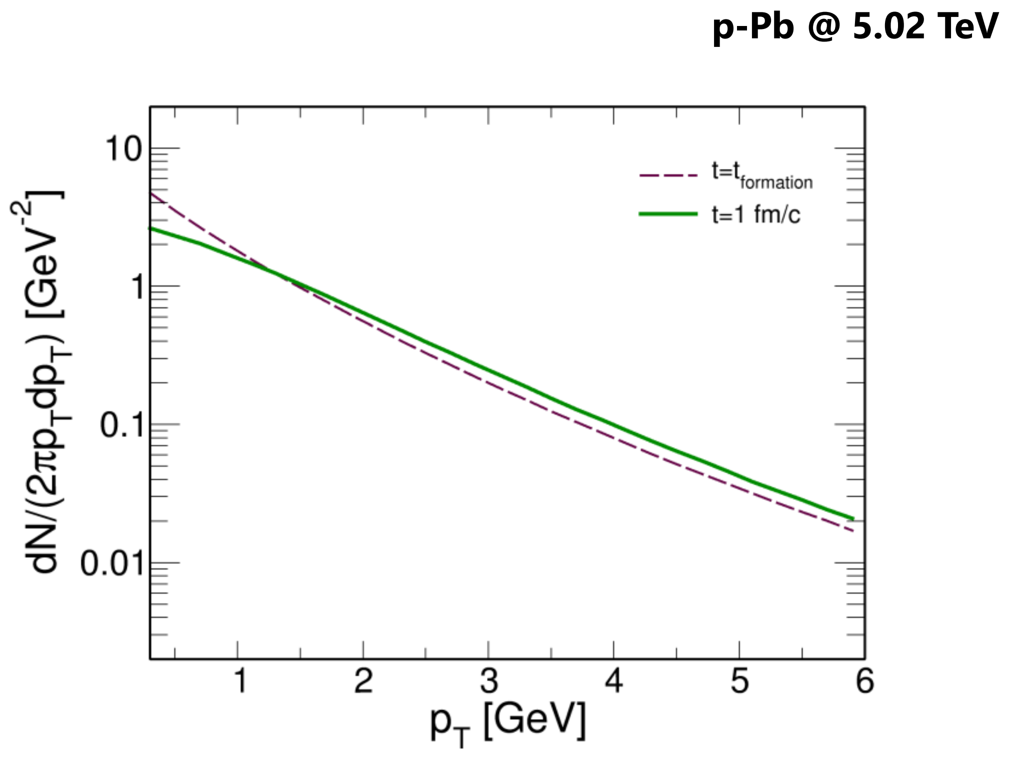
M.R. *et al.* (2021)

Average diffusion coefficient of HQs in Glasma agrees with pQCD for small values of Q_s (diluted Glasma).

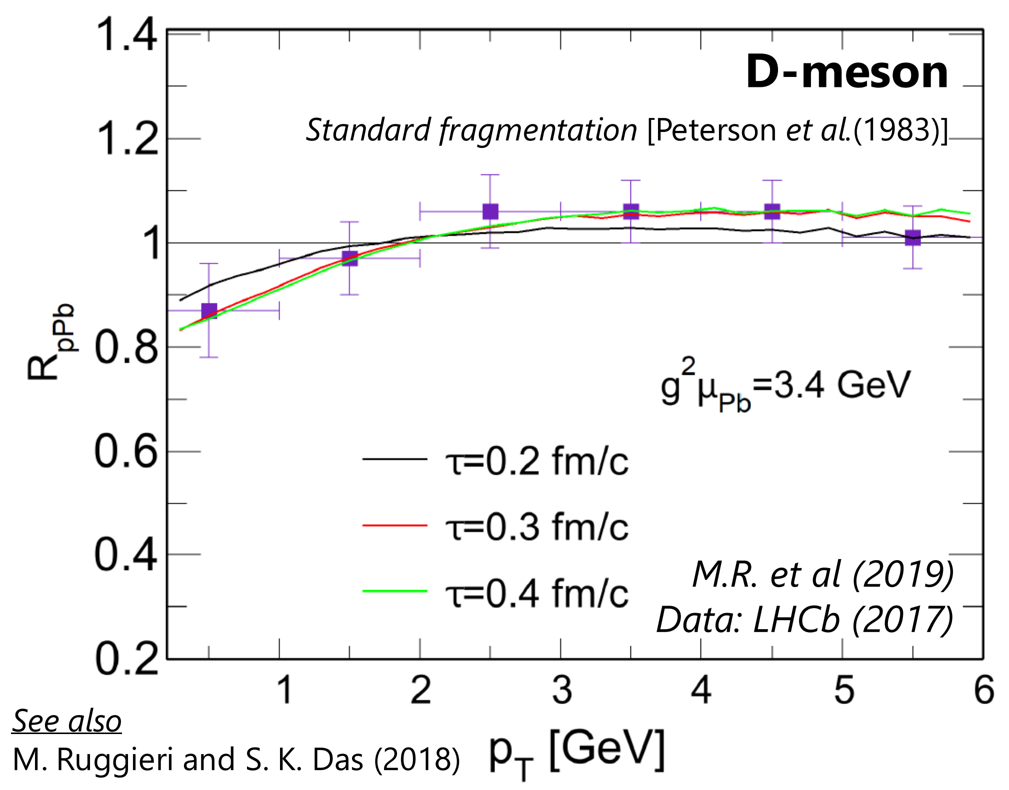
Impact on R_{AB}

Initial distribution

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



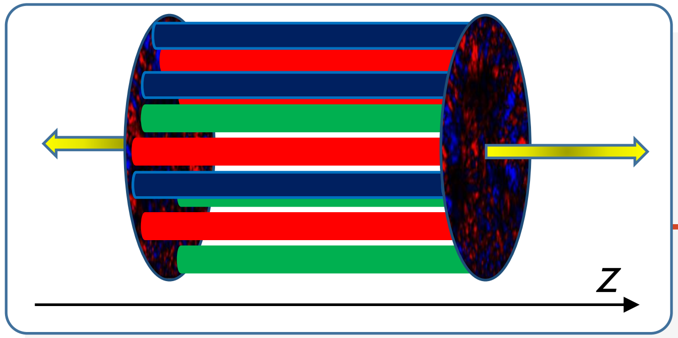
$$R_{\rm pPb} = \frac{(dN/d^2p_T)_{\rm final}}{(dN/d^2p_T)_{\rm pQCD}}$$



R_{pPb} ≠ 1

Interaction with the fields created by the collision

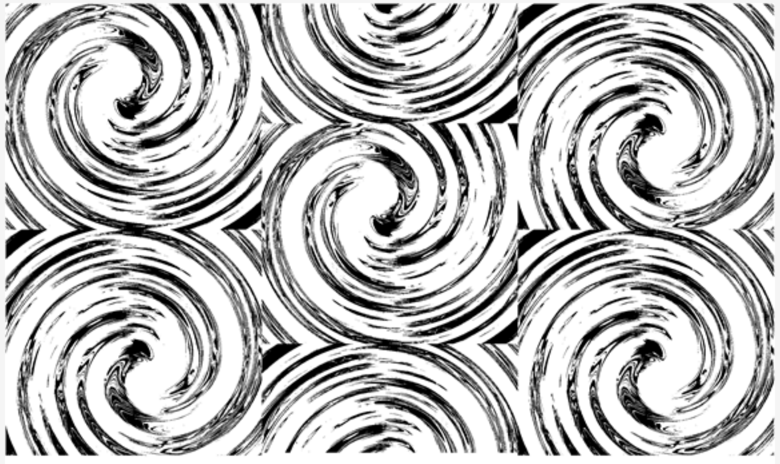
See also
M. Ruggieri and S. K. Das (2018)

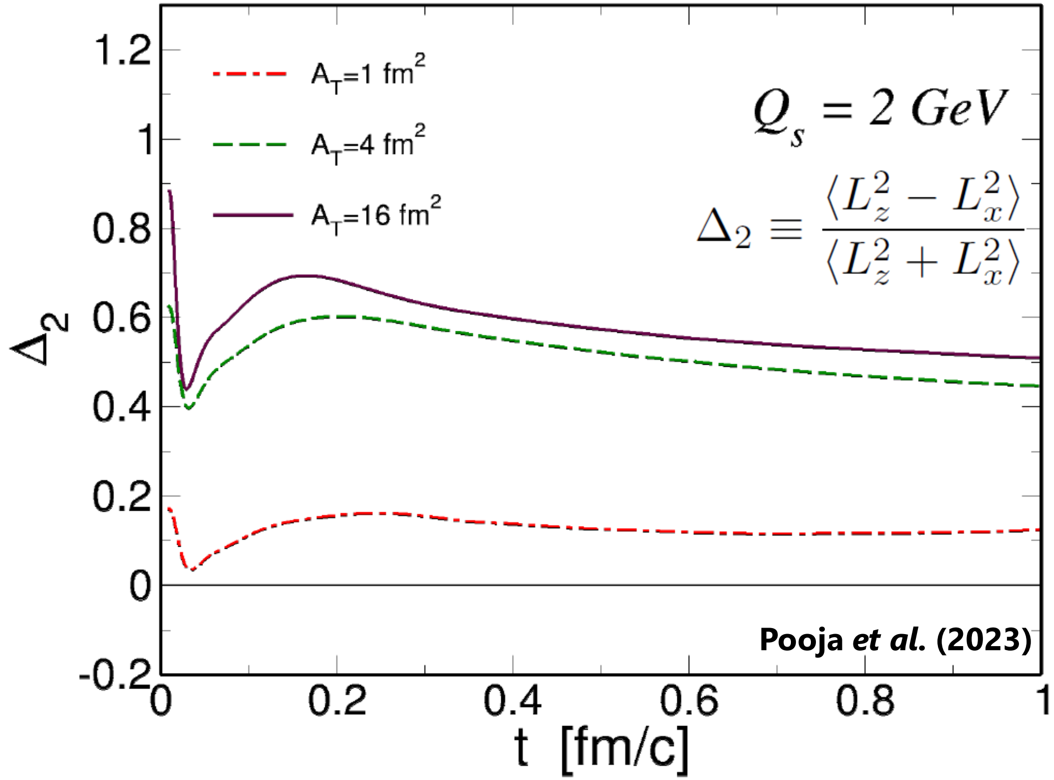


Glasma-induced polarization of c and b

Polarization of c and b, along the longitudinal direction

Anisotropic distribution of the momentum
[Pooja et al. (2023), Ipp et al. (2020), Avramescu et al. (2023)]
as well as of angular momentum [Pooja et al. (2023)]





Naively: glasma induces vortex-like motion of c and b around color filaments in the transverse plane

Heavy quarks in the quark-gluon plasma: relativistic transport theory

$$p^{\mu}\partial_{\mu}f_q(x,p)+m(x)\partial_{\mu}^{x}m(x)\partial_{p}^{\mu}f_q(x,p)=C[f_q,f_g]$$
$$p^{\mu}\partial_{\mu}f_g(x,p)+m(x)\partial_{\mu}^{x}m(x)\partial_{p}^{\mu}f_g(x,p)=C[f_q,f_g]$$

Free-streaming

field interaction
$\varepsilon - 3p \neq 0$

Collision term
gauged to some $\eta/s \neq 0$

QGP evolution

Relativistic transport theory

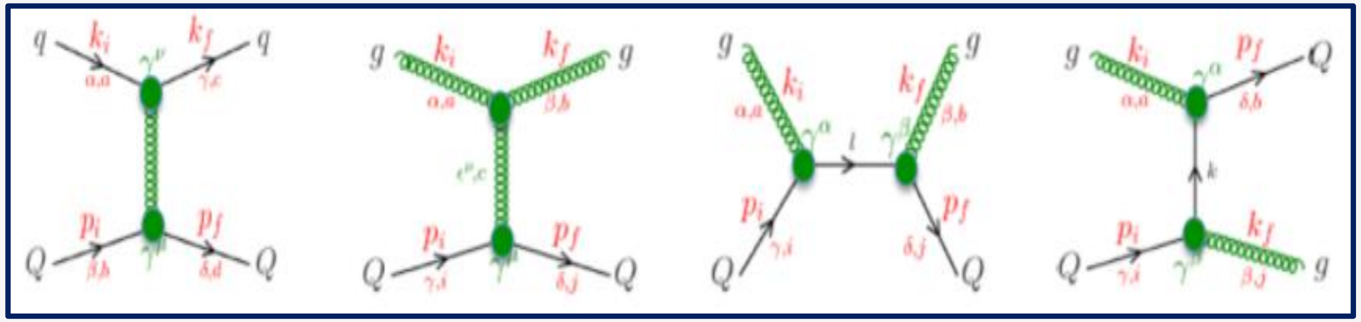
Equivalent to hydrodynamics for $\eta/s \approx 0.1$

HQs evolution in the QGP

$$p^{\mu}\partial_{\mu}f_Q(x,p)=C[f_q,f_g,f_Q]$$

$$C[f_q,f_g,f_Q]=\frac{1}{2E_1}\int\frac{d^3p_2}{2E_2(2\pi)^3}\int\frac{d^3p_1'}{2E_1'(2\pi)^3}$$
$$\times[f_Q(p_1')f_{q,g}(p_2')-f_Q(p_1)f_{q,g}(p_2)]$$
$$\times|M_{(q,g)\to Q}(p_1p_2\to p_1'p_2')|$$
$$\times(2\pi)^4\delta^4(p_1+p_2-p_1'-p_2')$$

Computed within a quasiparticles model



HADRONIZATION of HQs: hybrid Coalescence + fragmentation

The quasiparticle model (QPM) for the quark-gluon plasma

Non perturbative dynamics → M scattering matrices (q,g → Q) evaluated by Quasi-Particle Model fit to **lattice QCD thermodynamics**

N_f=2+1
Bulk:
u,d,s

$$m_g^2(T) = \frac{2N_c}{N_c^2 - 1} g^2(T)\, T^2$$
$$m_q^2(T) = \frac{1}{N_c} g^2(T)\, T^2$$

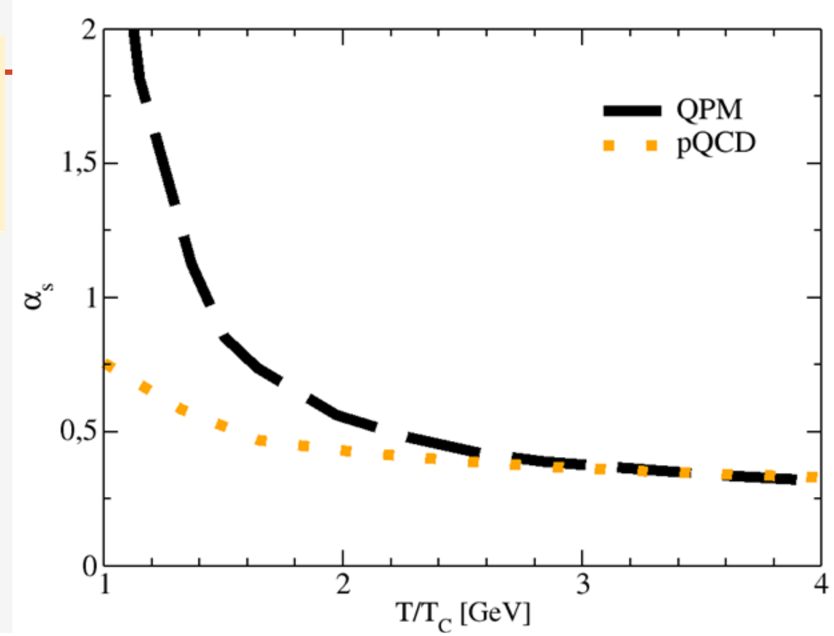
→ **Thermal masses of gluons and light quarks**

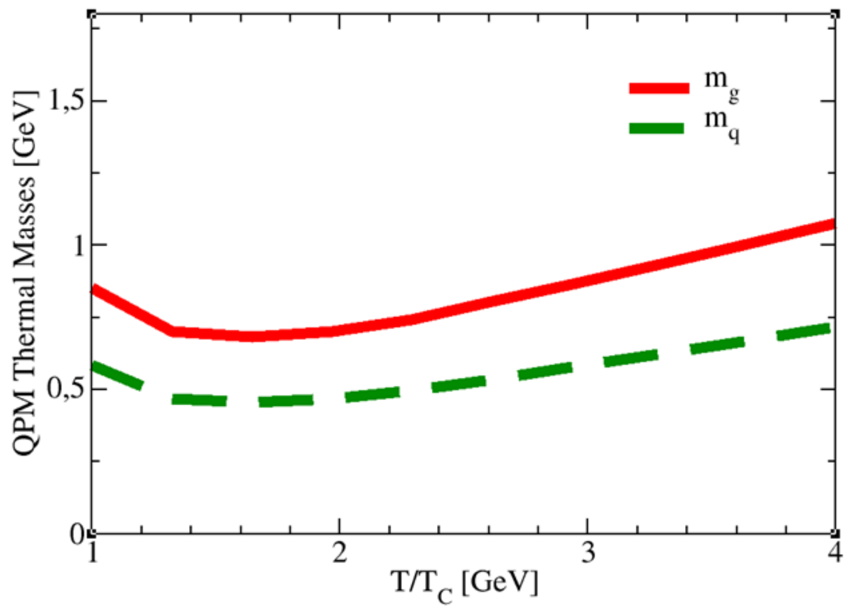
g(T) from a fit to ε from lQCD data → good reproduction of P, ε-3P

$$g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln\left[\lambda\left(\frac{T}{T_c} - \frac{T_s}{T_c}\right)\right]^2}$$

λ=2.6
T_s=0.57 T_c

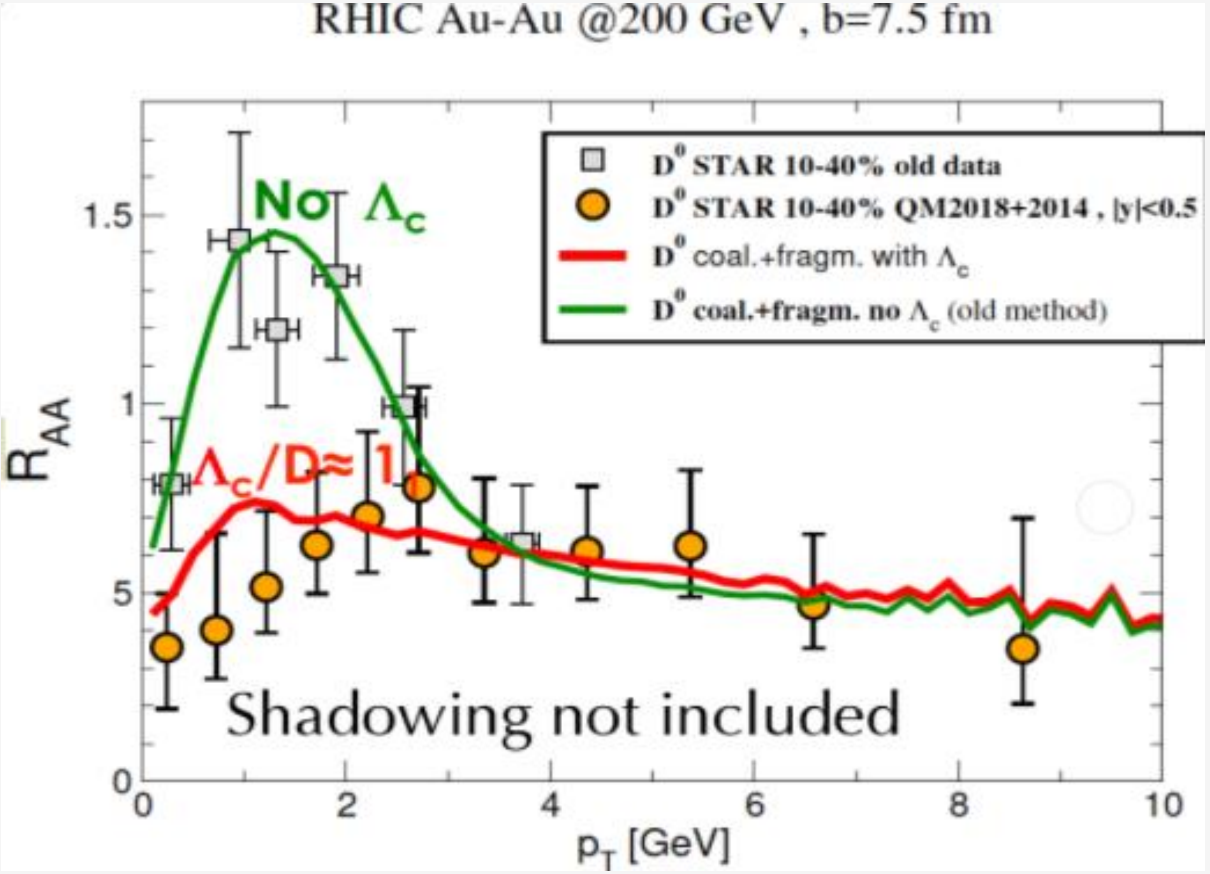
Larger than pQCD especially as T → T_c



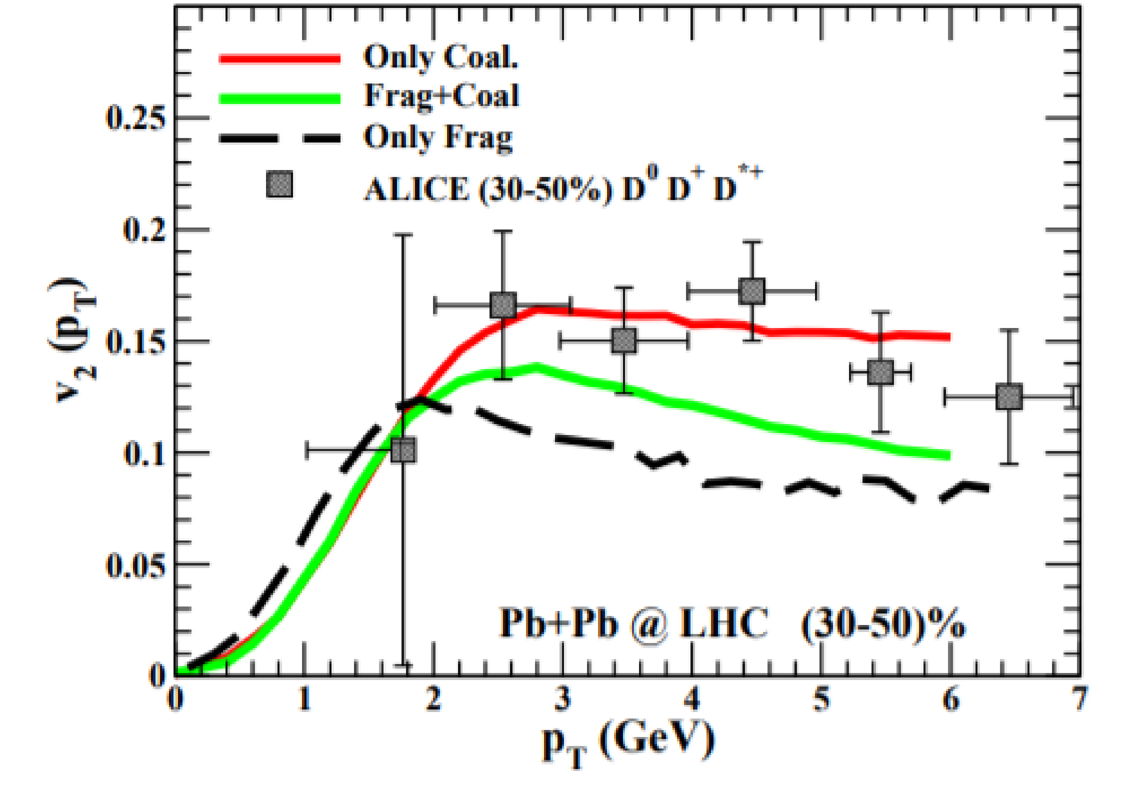


S. Plumari et al, *Phys.Rev.D* 84 (2011) 094004
H. Berrehrah,, PHYSICAL REVIEW C **93**, 044914 (2016)

Nuclear modification factor and elliptic flow of heavy mesons

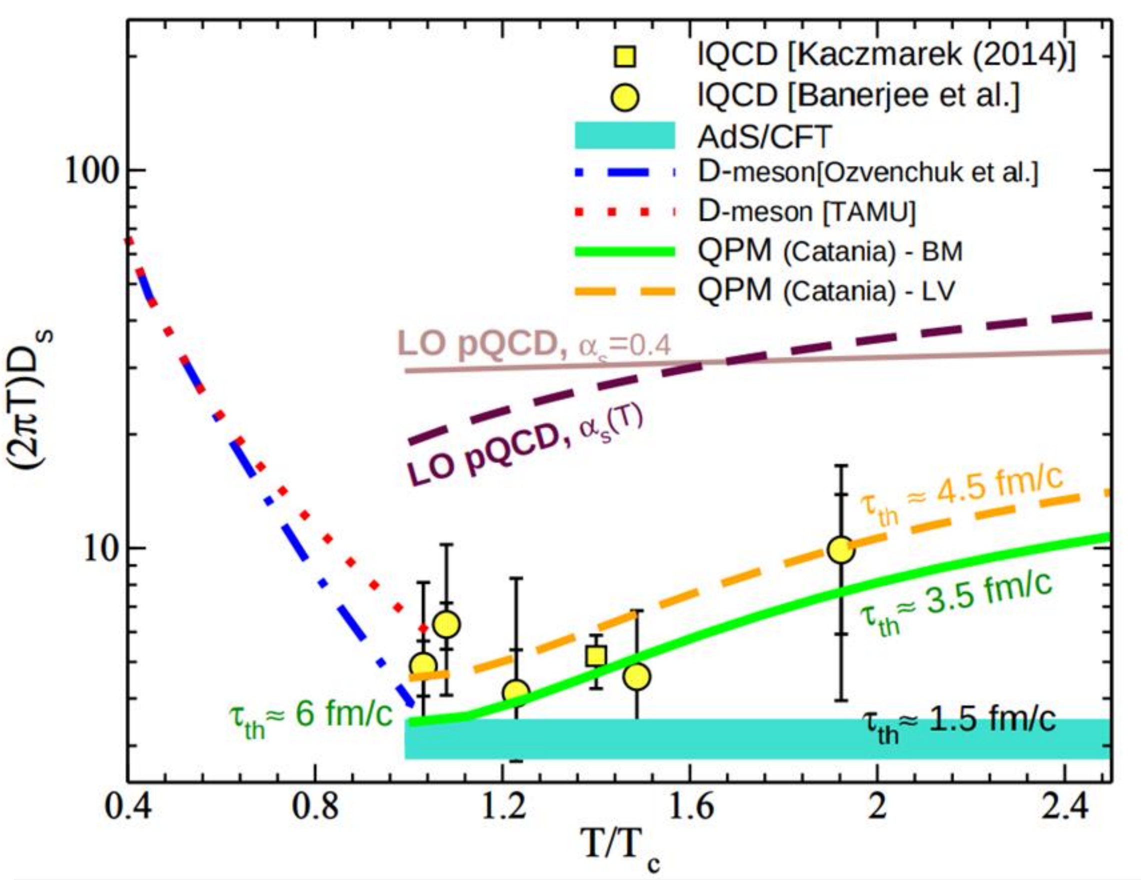


Scardina et al., PRC 97(2017)



Good description of R_{AA} and v_2 at the RHIC and the LHC energies

Spatial diffusion coefficient, Ds, of charm in QGP



R_{AA} (p_T) and v_2 (p_T) (*computed* within relativistic transport, in agreement with experimental data)

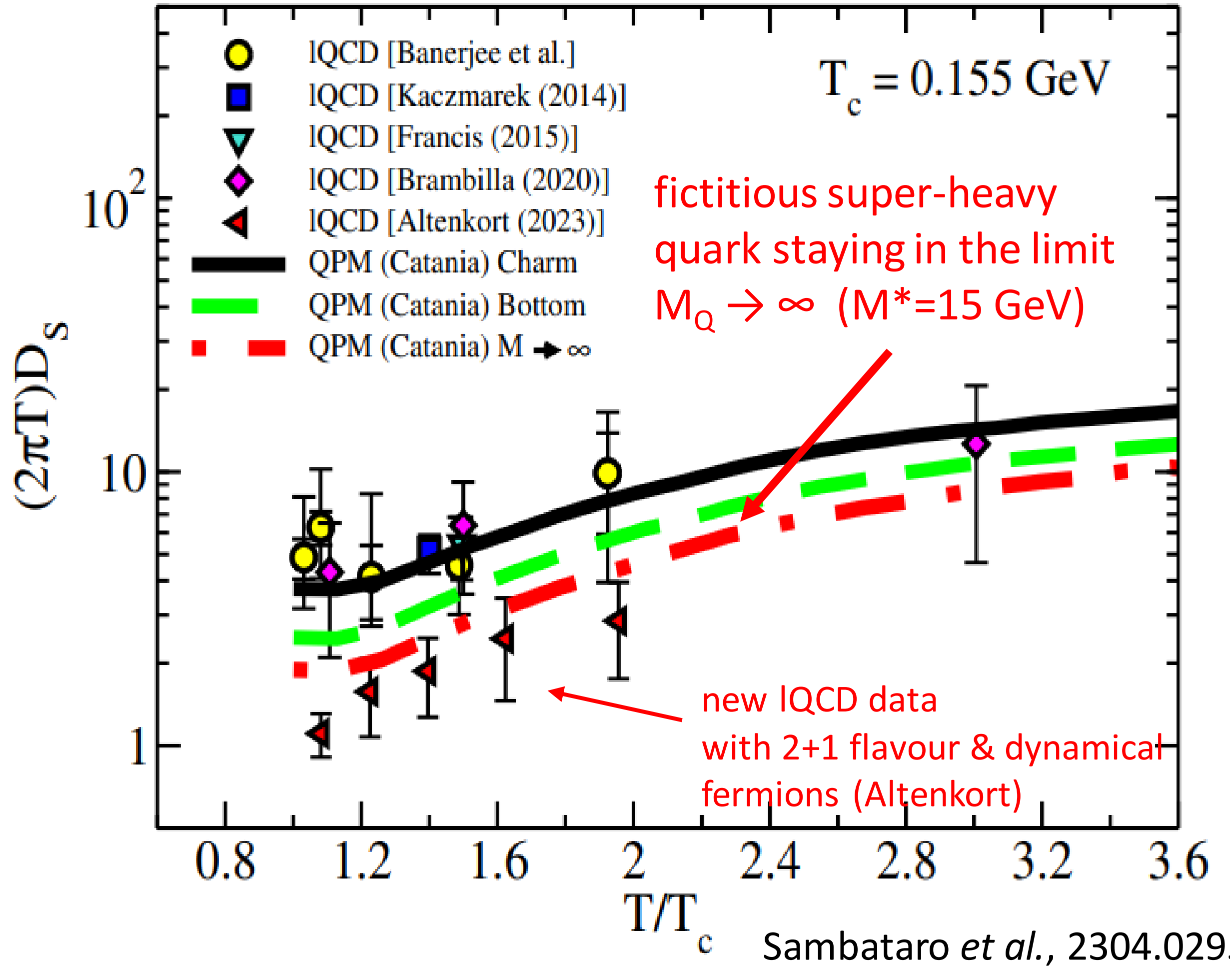
↓

thermalization time, τ_{th}, of c

$$\tau_{th} = \frac{M}{2\pi T^2}(2\pi T D_s) \cong 1.8\,\frac{2\pi T D_s}{(T/T_c)^2}\ \mathrm{fm/c}$$

Reviews:
- F. Prino and R. Rapp, JPG(2019)
- X. Dong and V. Greco, Prog.Part.Nucl.Phys. (2019)
- Jiaxing Zhao et al., arXiv:2005.08277

Spatial diffusion coefficient, Ds, of beauty in QGP

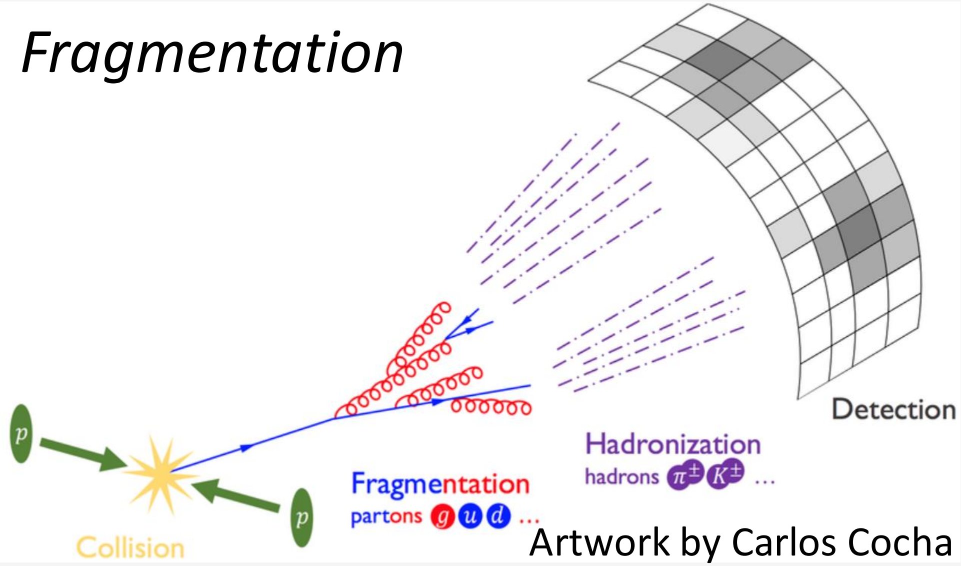


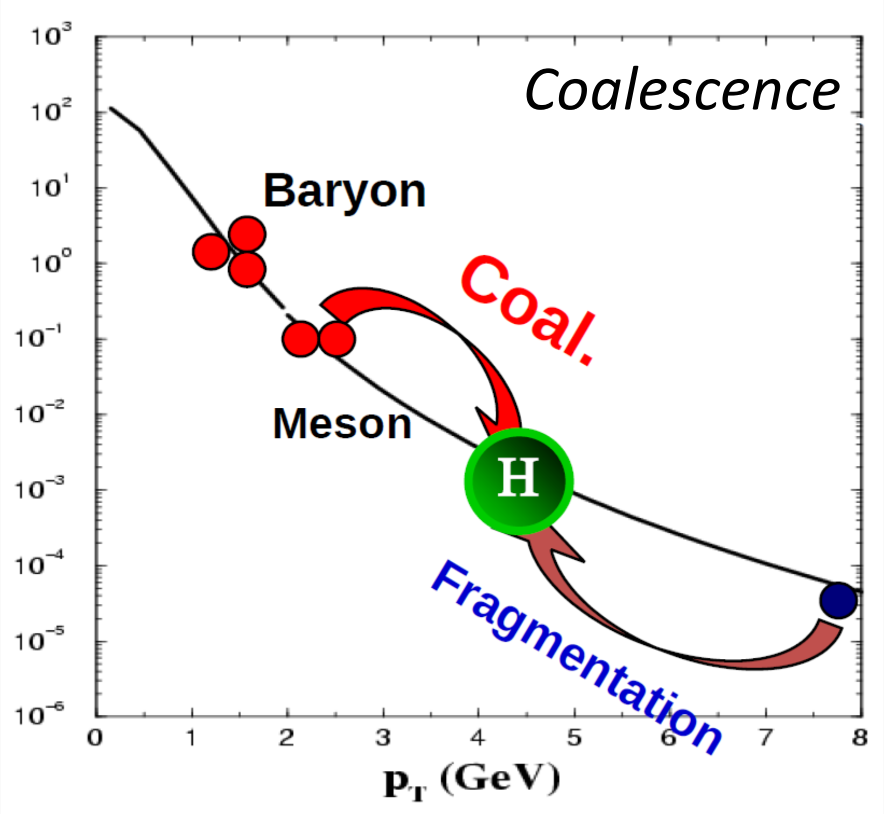
Sambataro *et al.*, 2304.02953

From D_s we obtain (T in 1-2T_c):

- $\tau_{th}(c) \sim 5$ fm/c
- $\tau_{th}(b) \sim 11$ fm/c

Hadronization of charm in heavy ion collisions: coalescence plus fragmentation



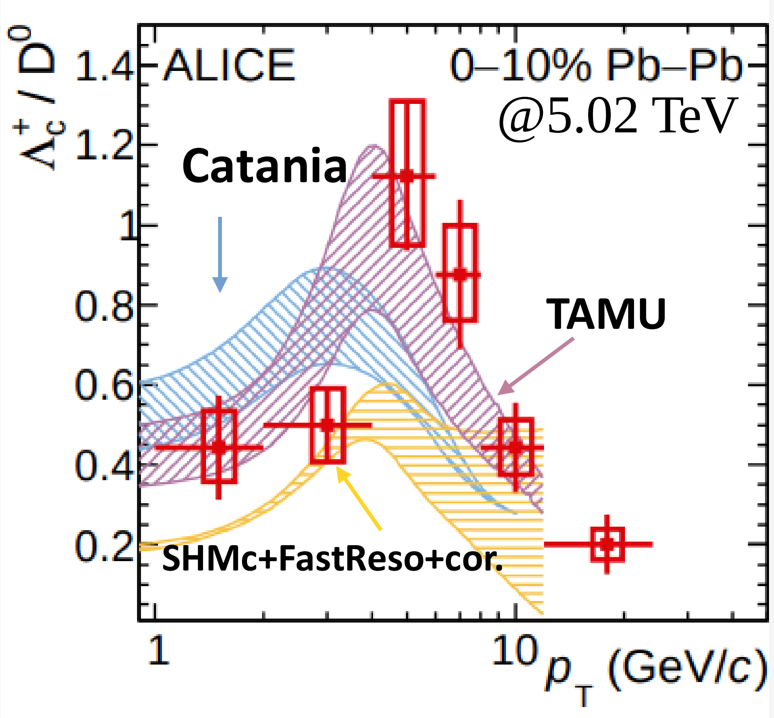


Coalescence consists in the recombination of quarks which sit close in phase space:

- *1 quark and 1 antiquark recombine to form a meson*
- *3 quarks recombine to form a baryon*

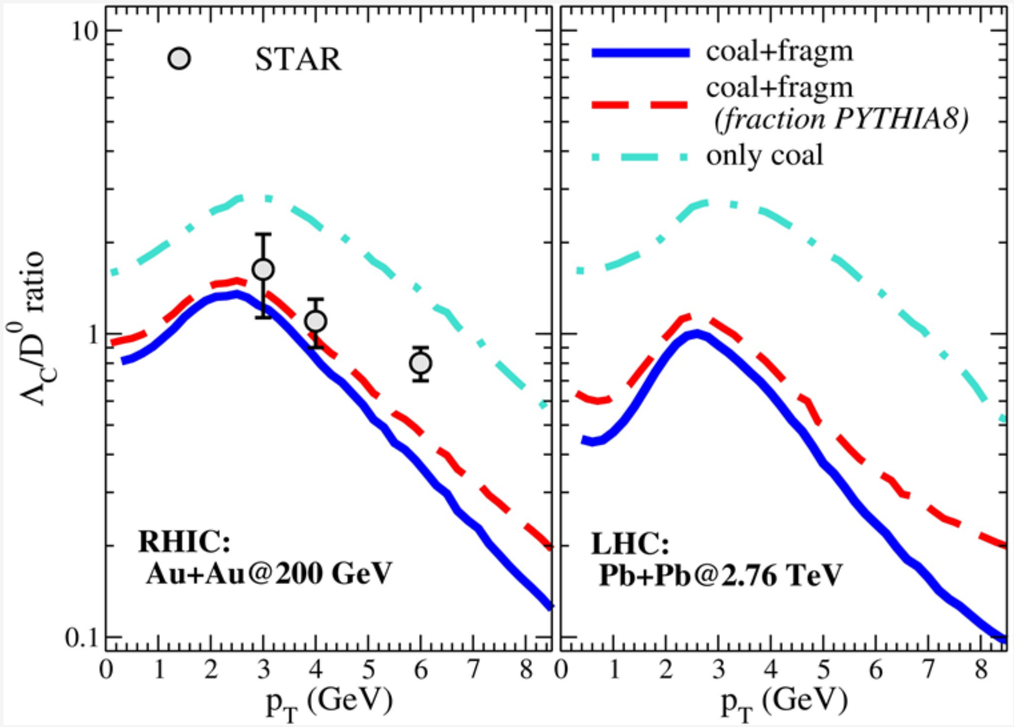
Typically coalescence enhances hadrons production at intermediate p_T.

Hadronization of charm in heavy ion collisions: coalescence plus fragmentation



ALICE Coll. arXiv:2112.08156v1

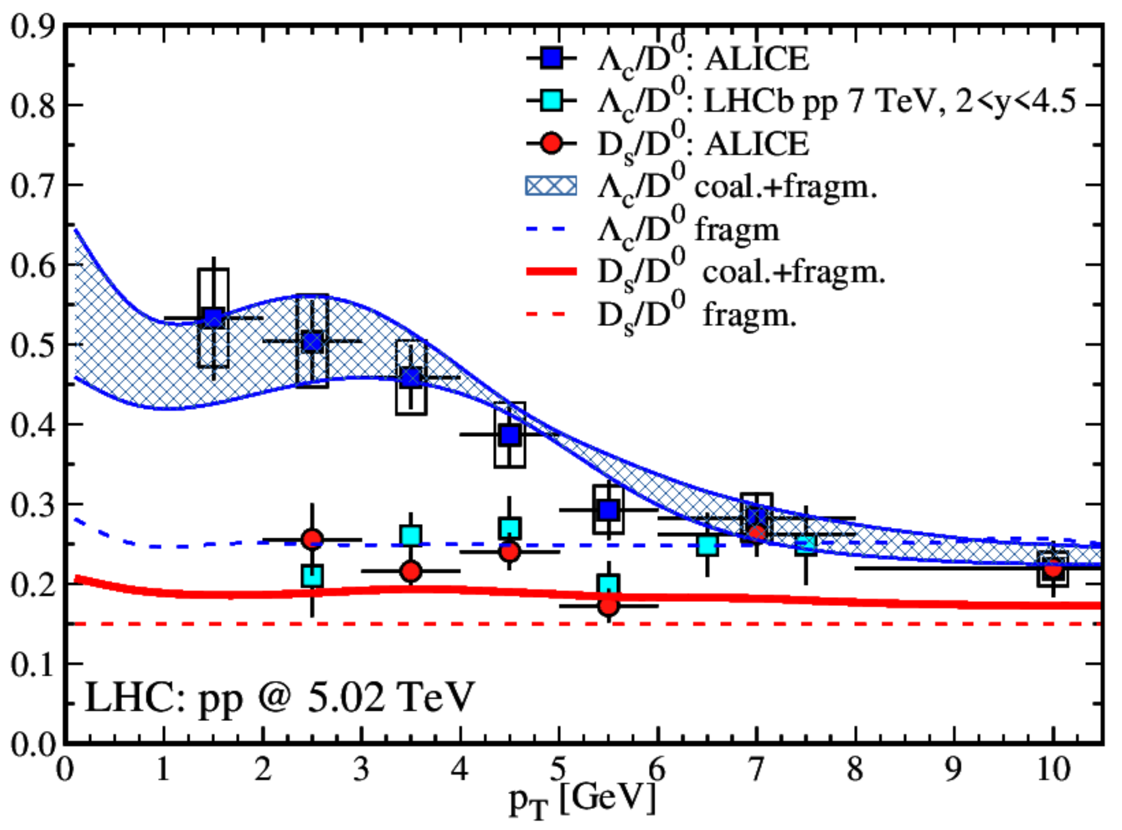
STAR Coll., Phys.Rev.Lett. 124 (2020) 17, 172301

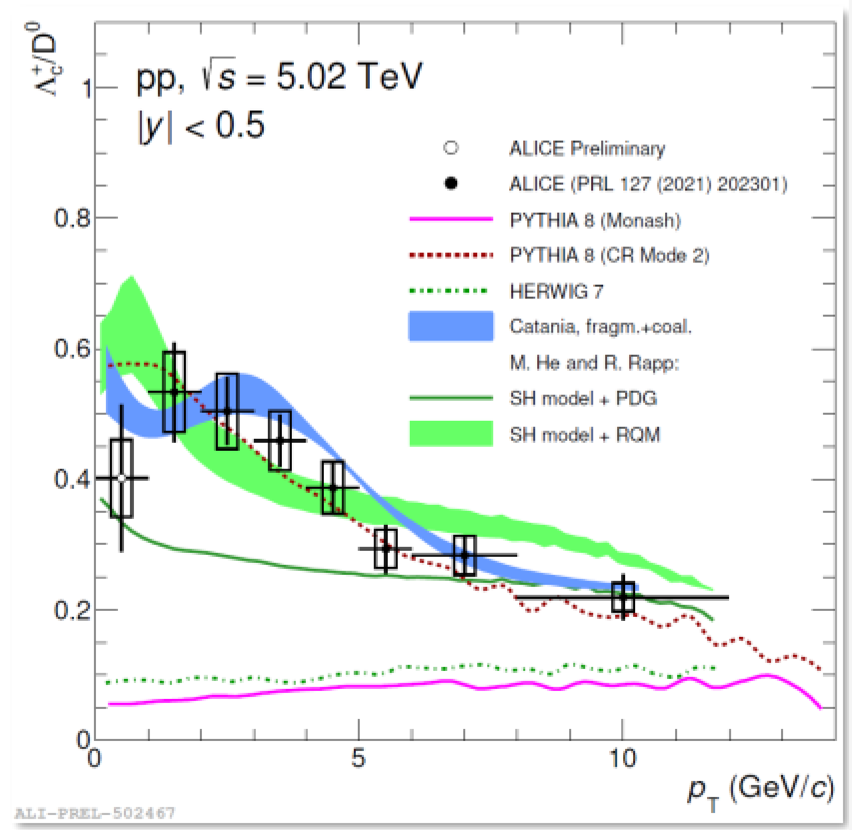


S. Plumari, V. Minissale et al., Eur. Phys. J. C78 no. 4, (2018) 348

Hadronization of charm in proton-proton collisions: coalescence plus fragmentation

V. Minissale, S. Plumari, V. Greco, Physics Letters B 821 (2021) 136622





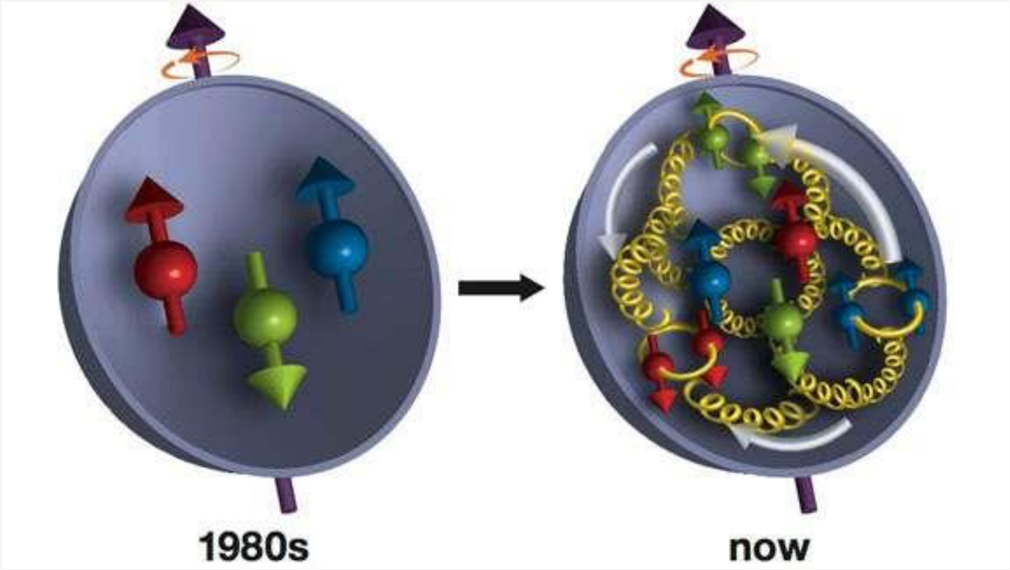
ALICE,
Phys.Rev.Lett. 127 (2021) 20, 202301

Conclusions

- Heavy quarks (HQs) excellent probes of the entire evolution of the medium created in relativistic heavy ion collisions
- *Heavy quarks* in the evolving Glasma: anomalous diffusion, anisotropic diffusion, polarization
- *Heavy quarks* in the quark-gluon plasma: relativistic transport theory, thermalization time, spatial diffusion coefficient for c and b
- *Hadronization of heavy quarks* in RHICs: coalescence plus fragmentation, effects in AA and pp collisions

Appendix

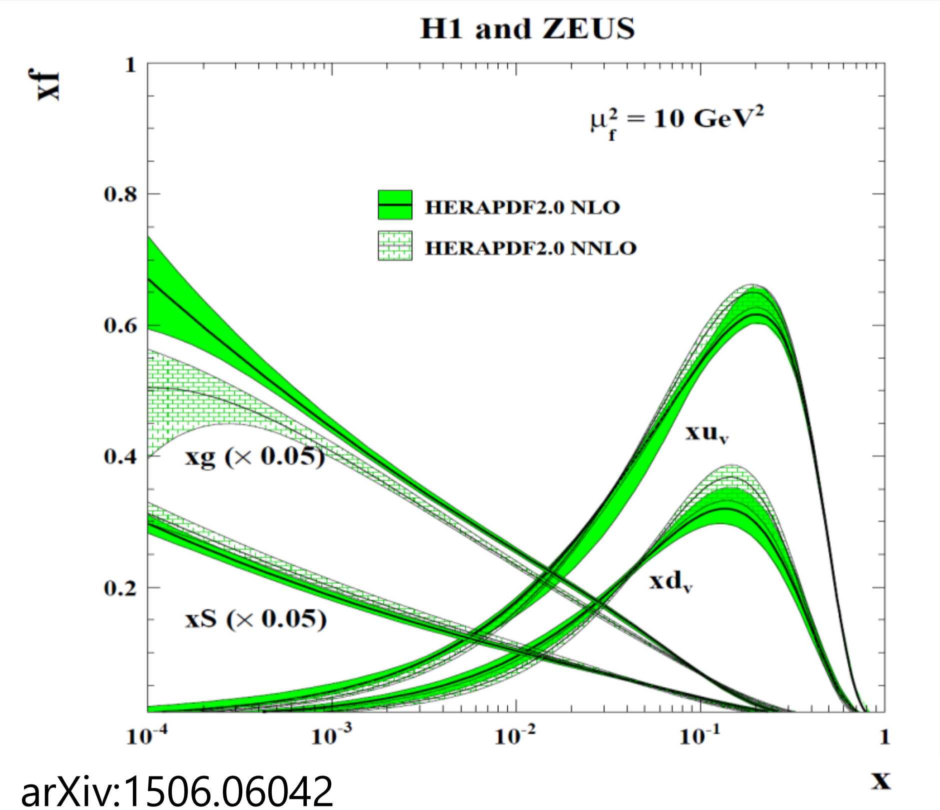
Gluons dominate the proton wave function at small x



x: parton momentum/nucleon momentum

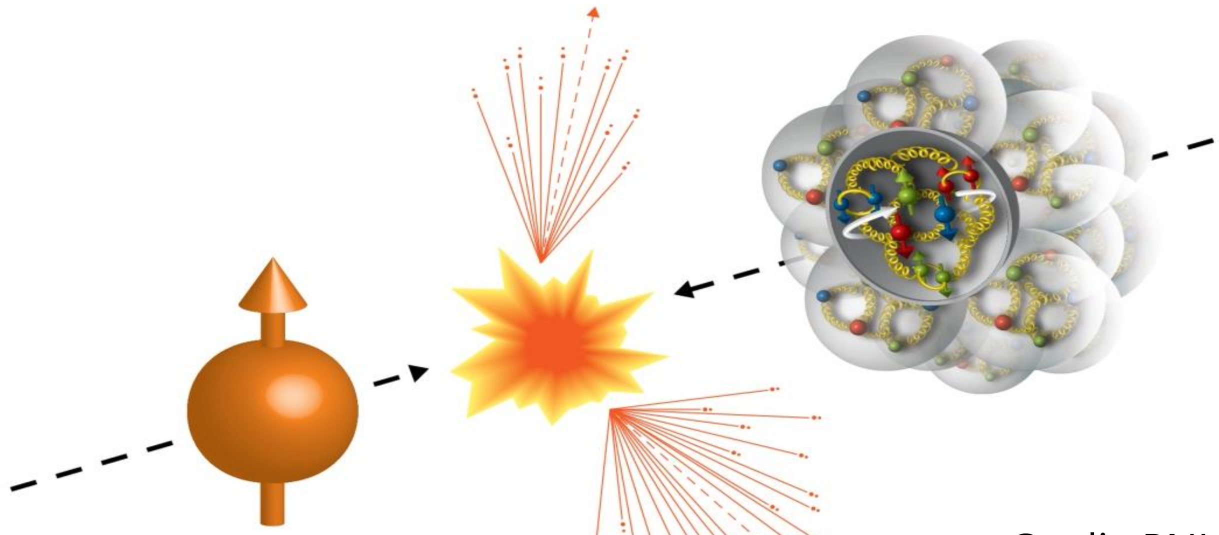
Valence quarks (uud): x ≈ 1

Small-x content of the proton
Sea quarks+antiquarks
Sea gluons



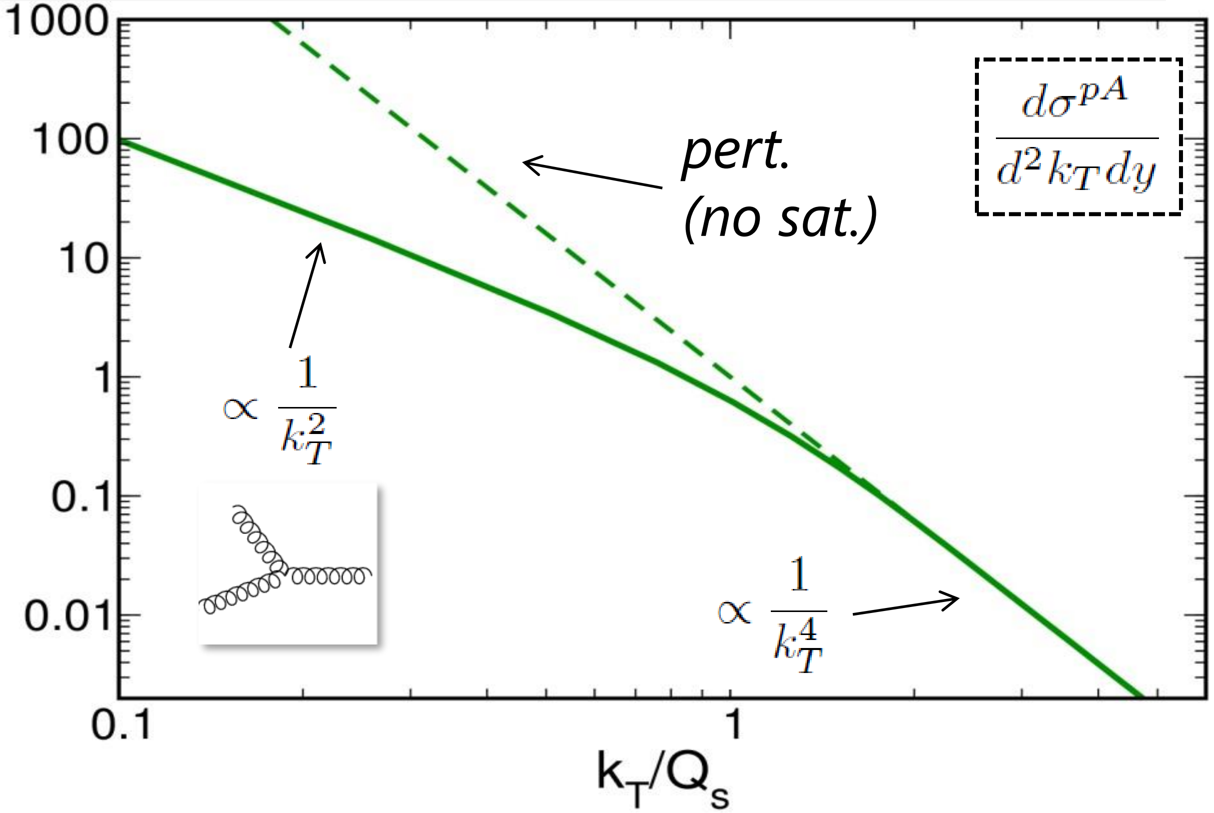
arXiv:1506.06042

Gluons dominate the proton wave function at small x



Credit: BNL
https://www.bnl.gov/rhic/news2/news.asp?a=1699&t=pr

Large gluon density: Gluon recombination



<u>Saturation</u>

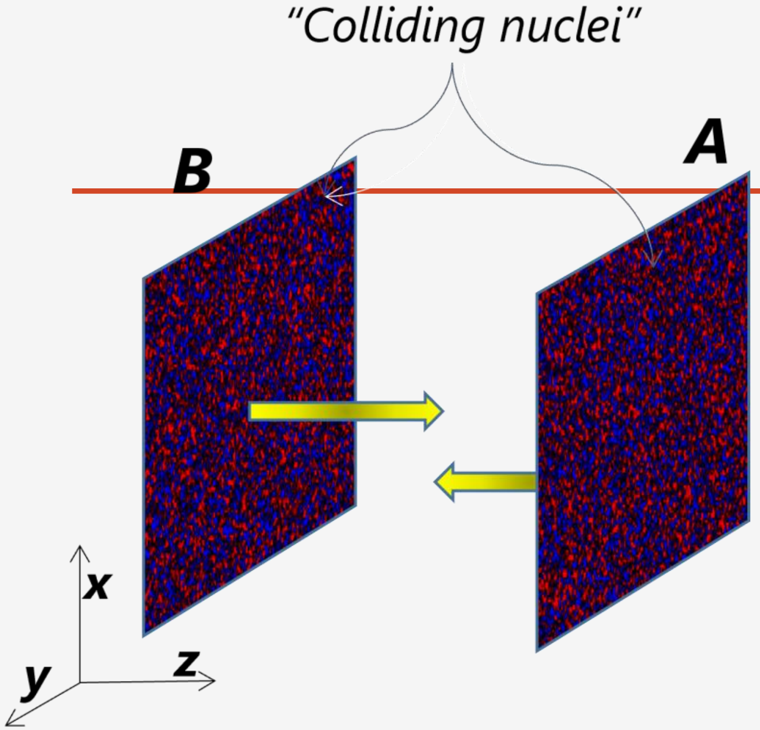
Gluon production is suppressed due to the abundance of the 2 → 1 processes.

<u>Saturation scale, **Qs**</u>

Momentum scale at which saturation becomes important

McLerran and Venugopalan (1994)

The MV model for the sources of the Glasma



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)

$Q_s \approx 1 - 3$ GeV

(*)See Parisi's talk for more details

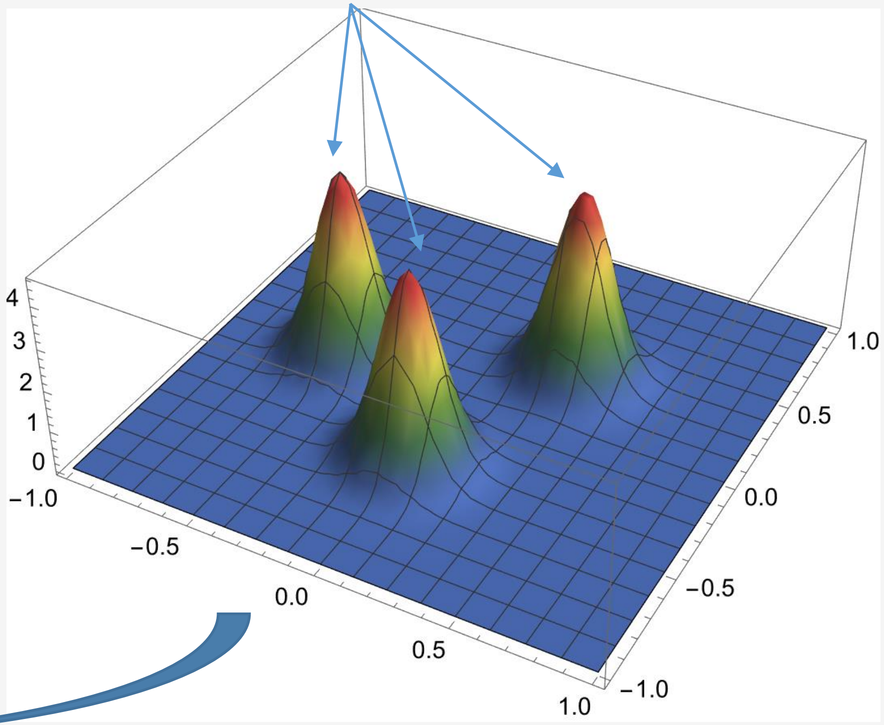
The MV model for the sources of the Glasma: the proton case

Hot spots model

Color charges mostly near the valence quarks in the proton

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

Valence quarks (hot spots)



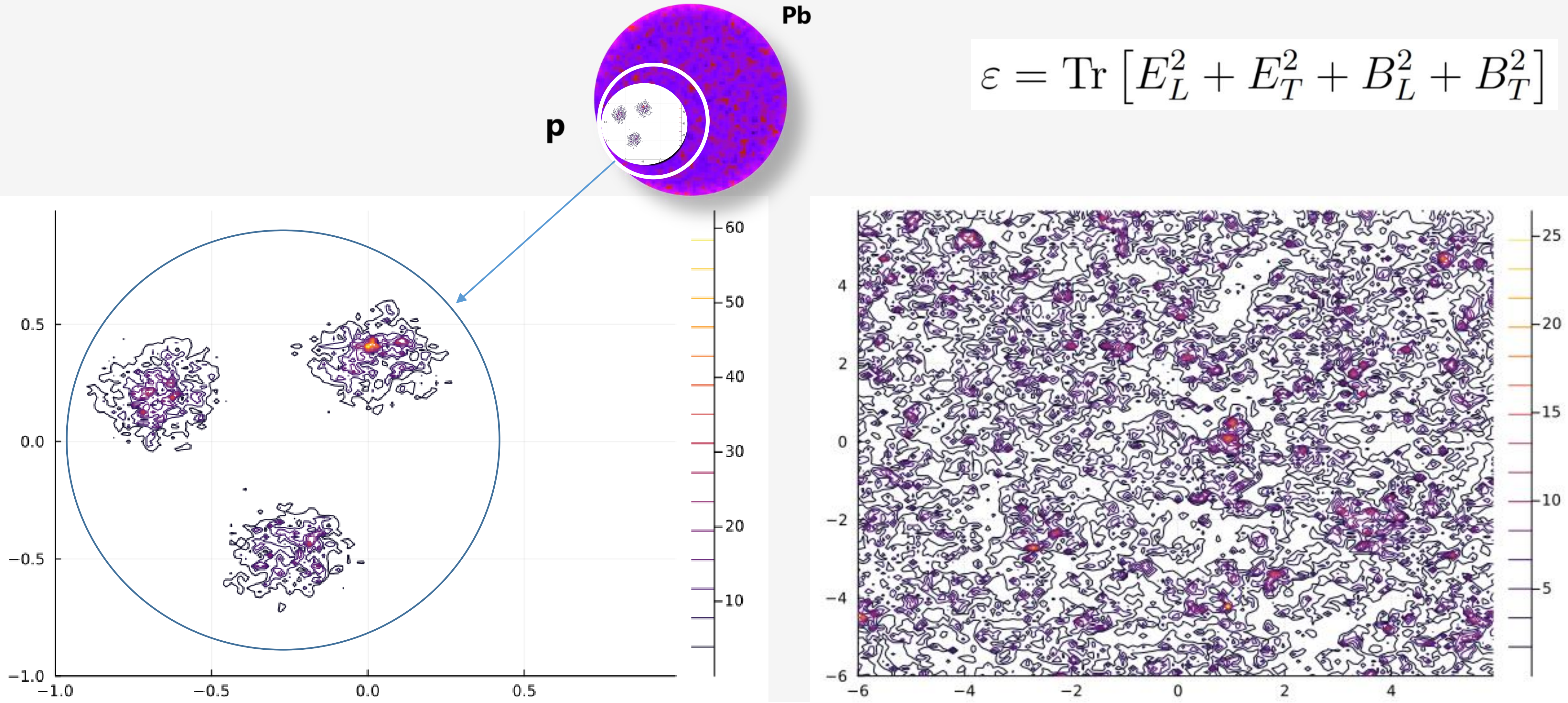
Gaussian distribution of color charges

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

B. Schenke *et al.* (2022,2023)
G. Parisi *et al*, in preparation

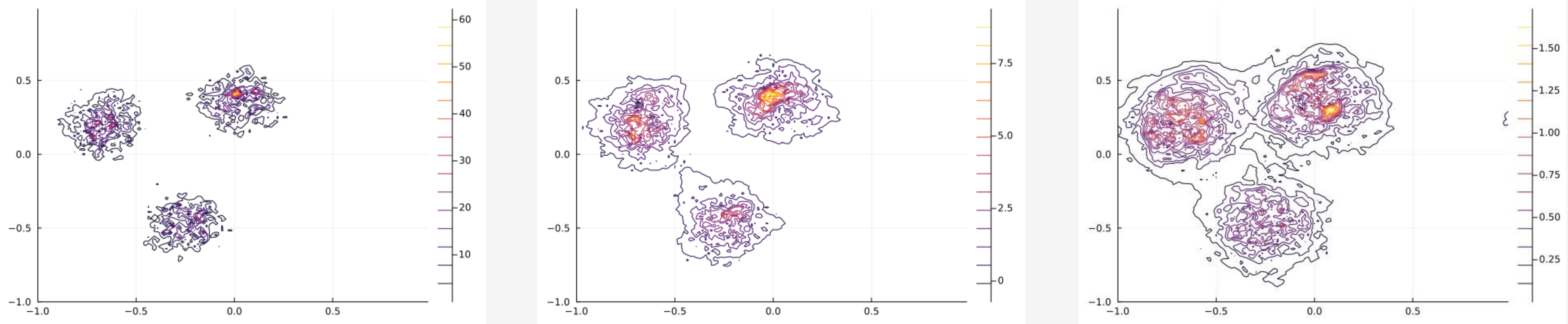
A closer look at the Glasma: the initial energy density

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

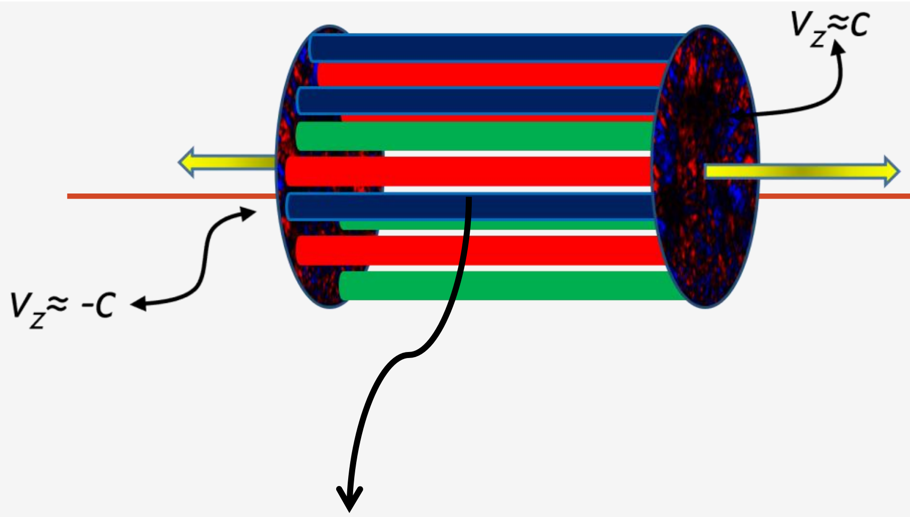


Expansion in the transverse plane: the p-Pb case

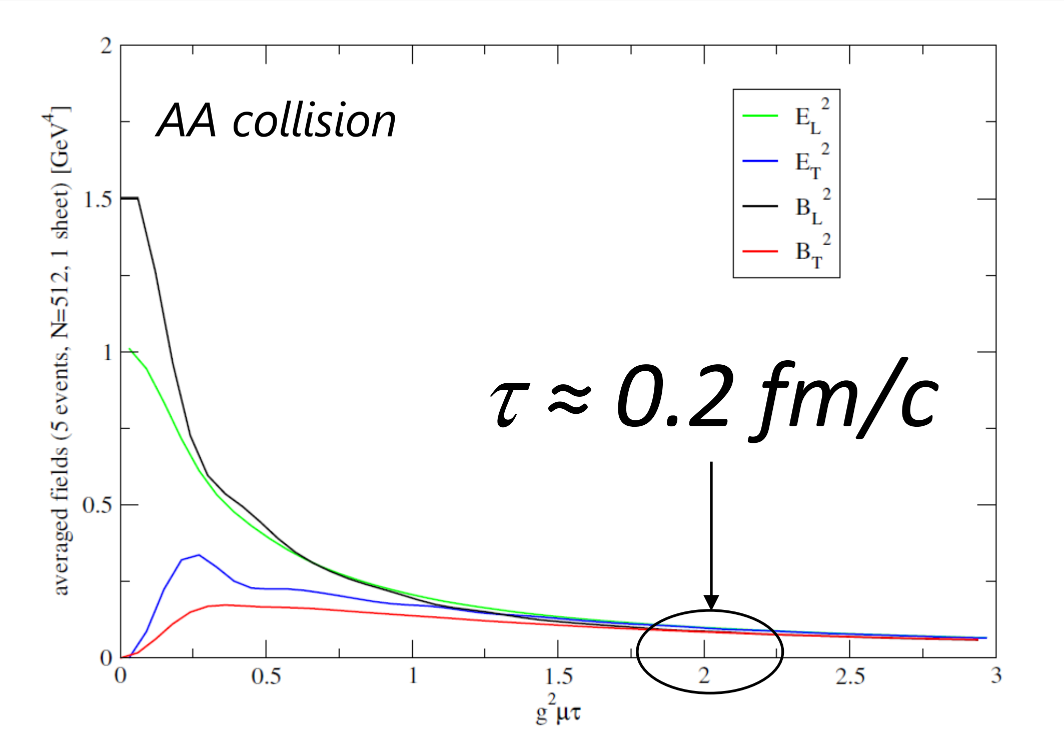
$$\varepsilon = \mathrm{Tr}\left[E_L^2 + E_T^2 + B_L^2 + B_T^2\right]$$

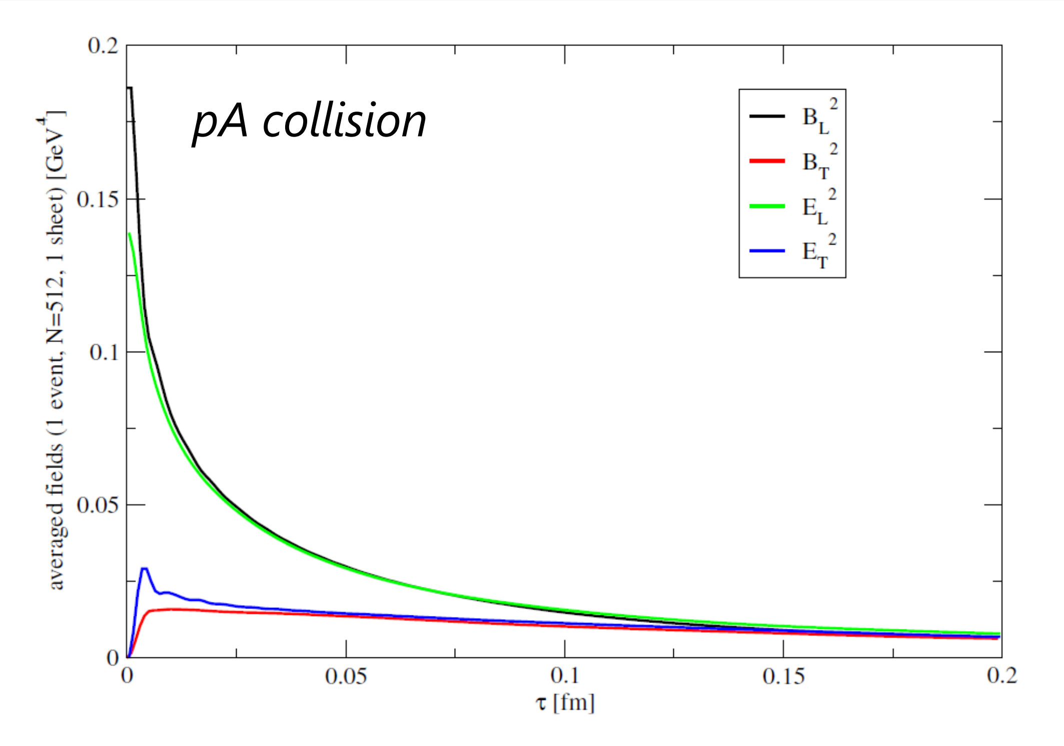


Evolving fields

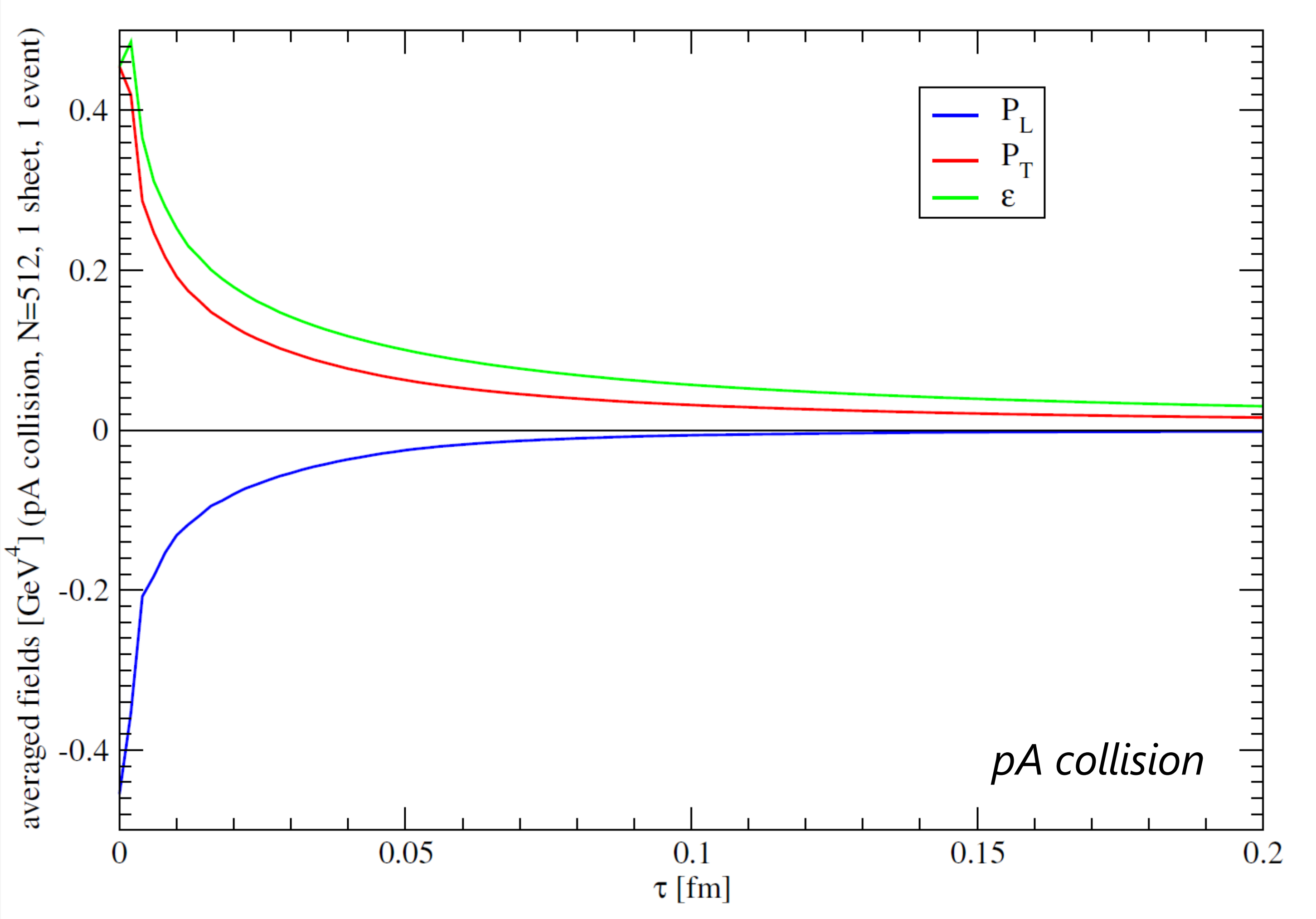


$$\varepsilon = \mathrm{Tr}\left[E_L^2 + E_T^2 + B_L^2 + B_T^2\right]$$





The free streaming regime, pA collisions



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

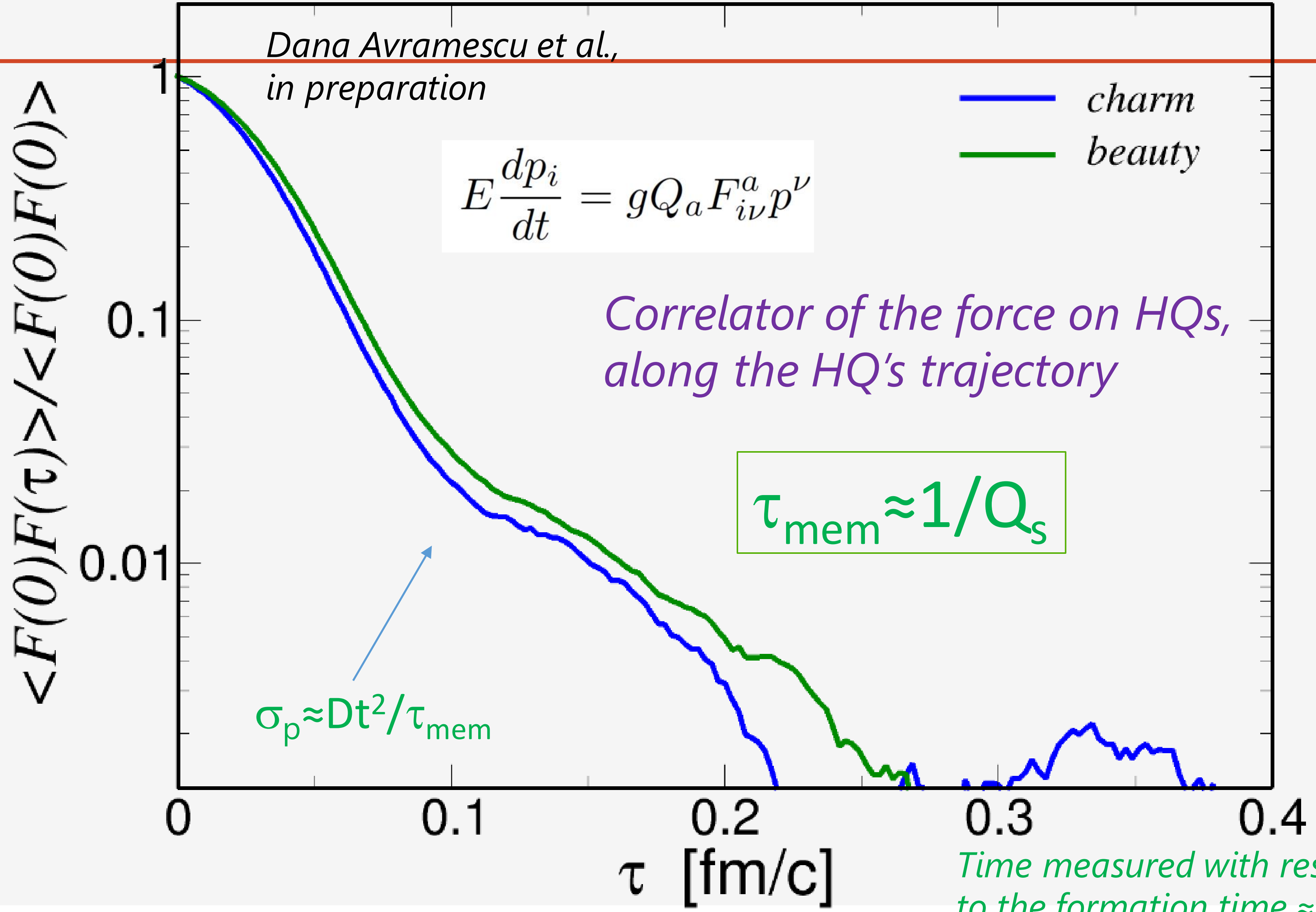
$$P_L = \mathrm{Tr}\left[-E_L^2 - B_L^2 + E_T^2 + B_T^2\right]$$

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

$\tau \approx 0.2$ fm/c

Longitudinal pressure vanishes

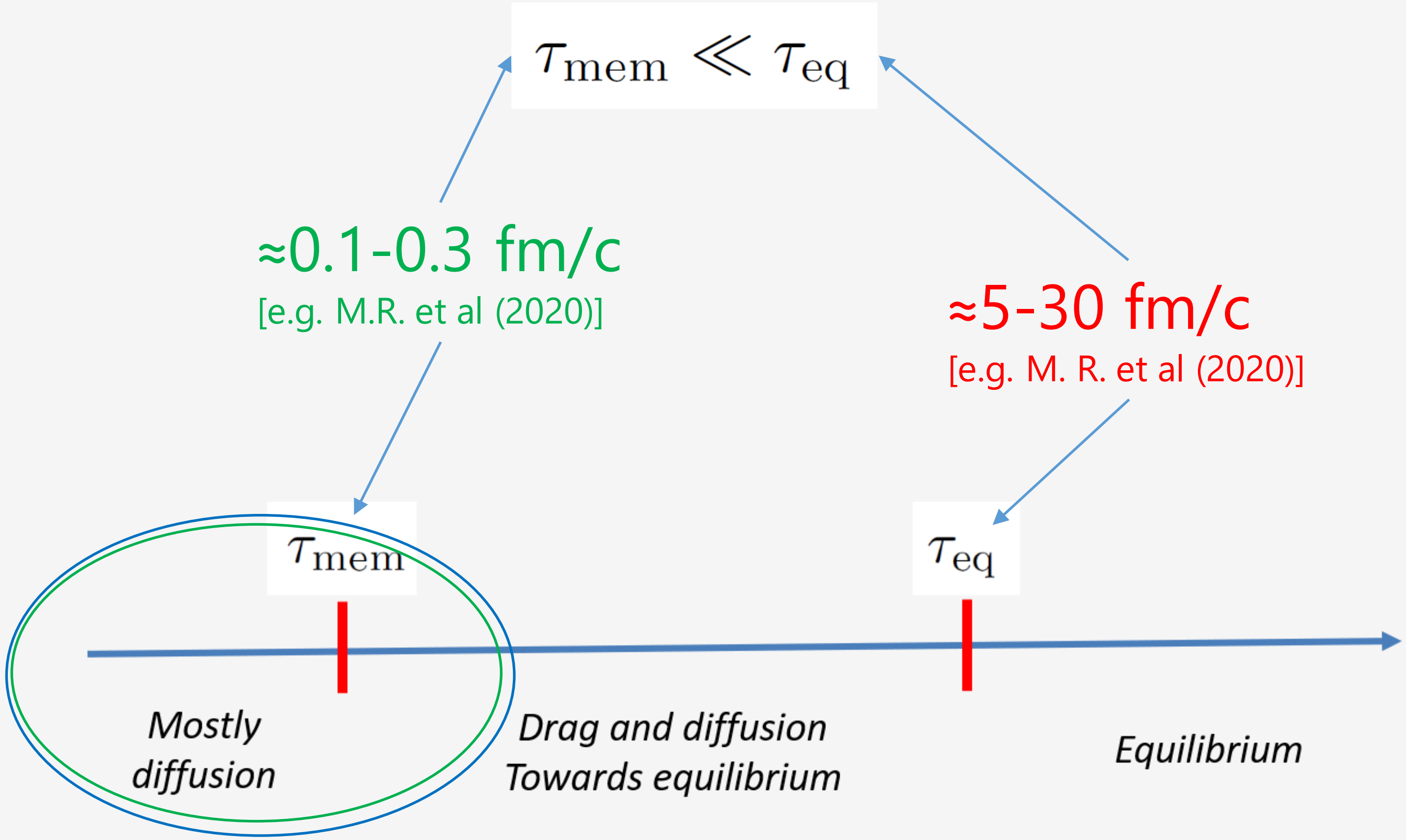
Memory for the HQs diffusion in EvGlasma



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

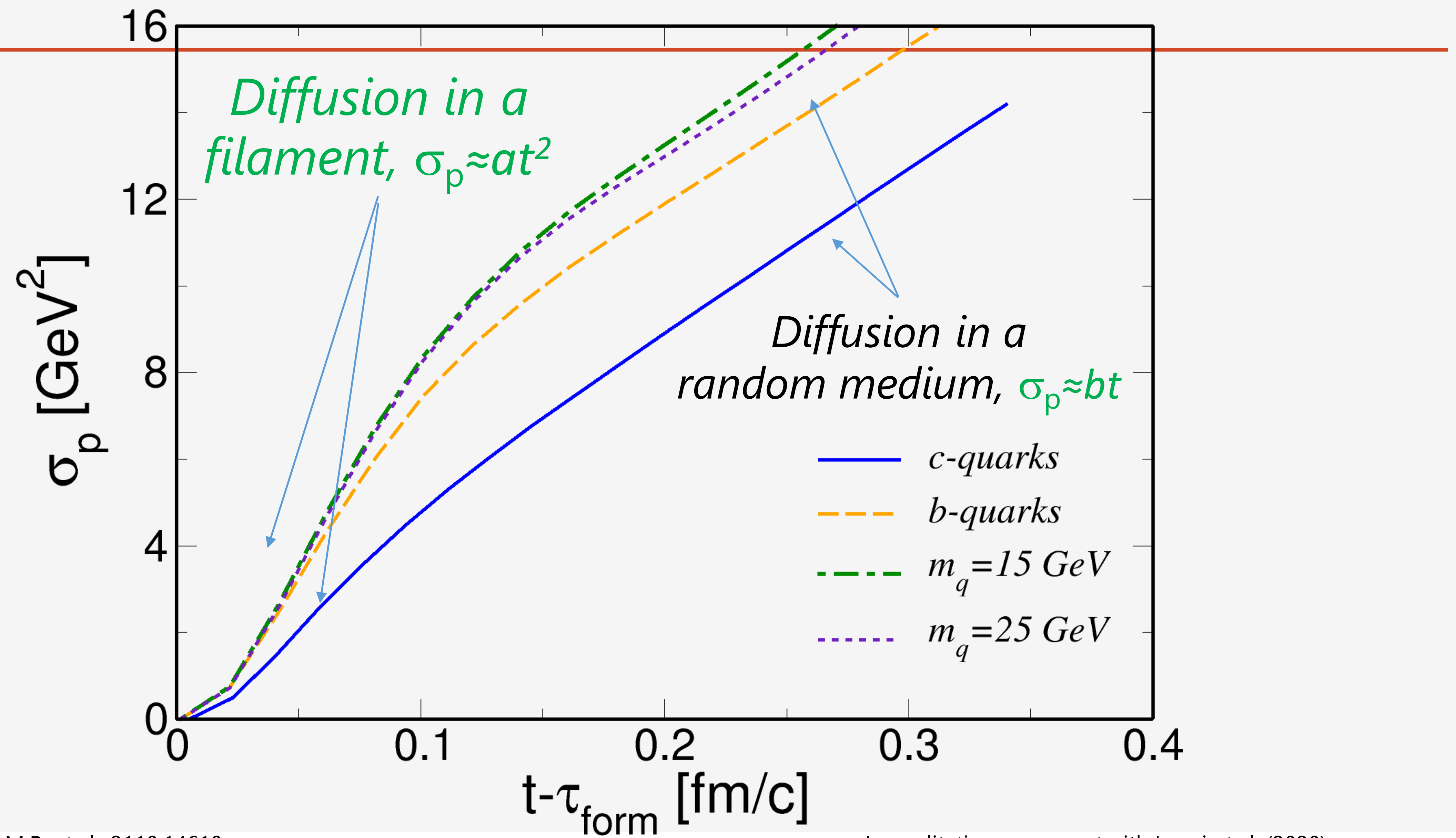
Heavy quarks in Glasma: diffusion-dominated motion

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



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

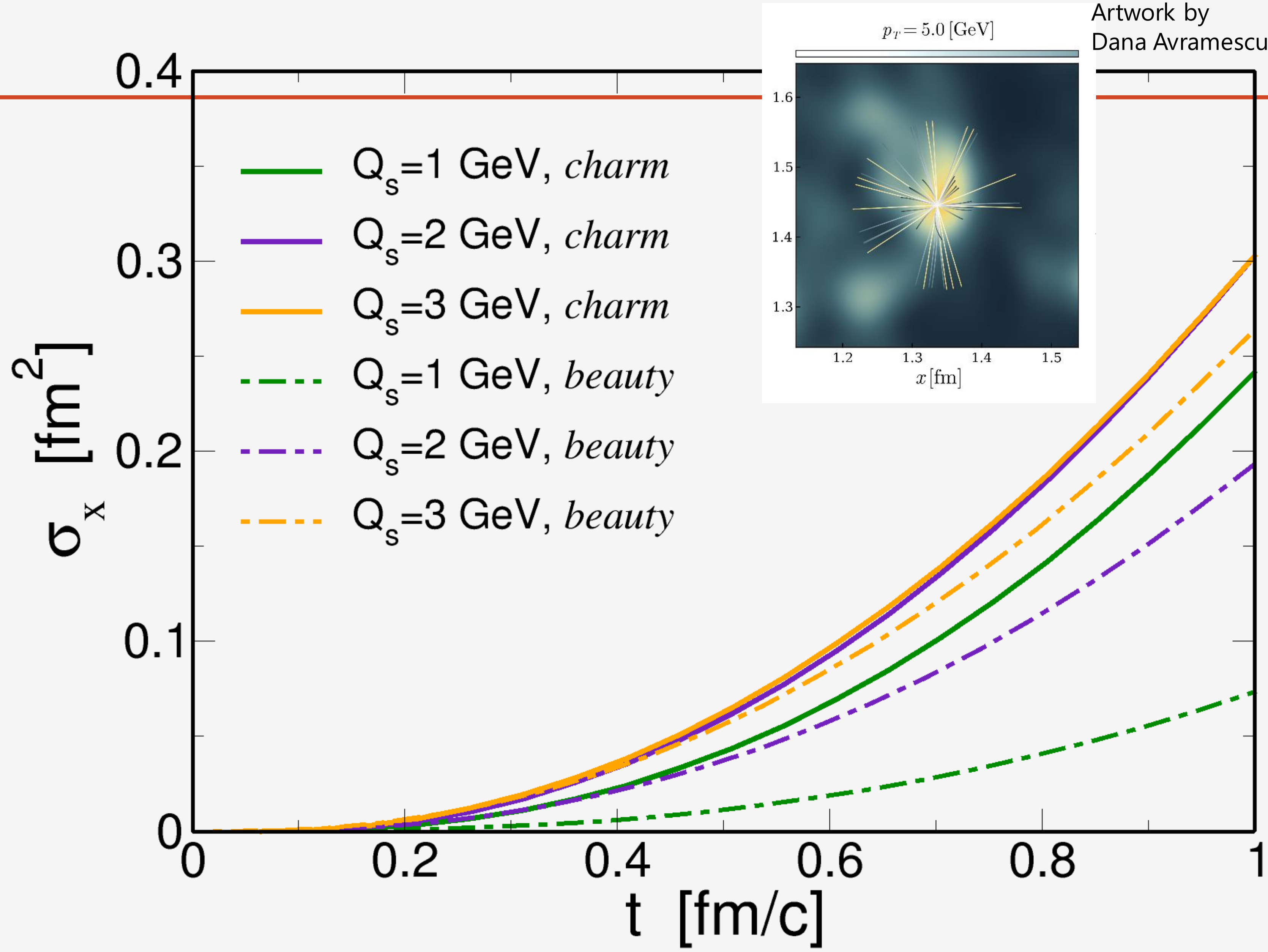
Momentum broadening: effect of HQ's mass



M.R. et al., 2110.14610

In qualitative agreement with Lappi et al. (2020)

Coordinates spreading vs HQ mass



Artwork by
Dana Avramescu

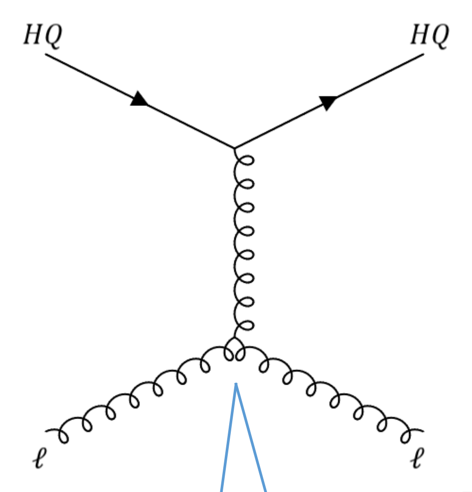
M.R. et al., 2110.14610

Comparison with pQCD-Langevin

We prepare a bath of gluons *at temperature T*, with the *same energy density* of the EvGlasma, and study the *diffusion of heavy quarks in this bath with Langevin equation*.

$$\varepsilon = 2(N_c^2-1)\int \frac{d^3p}{(2\pi)^3}\frac{p}{e^{\beta p}-1} = \frac{(N_c^2-1)\pi^2 T^4}{15}$$

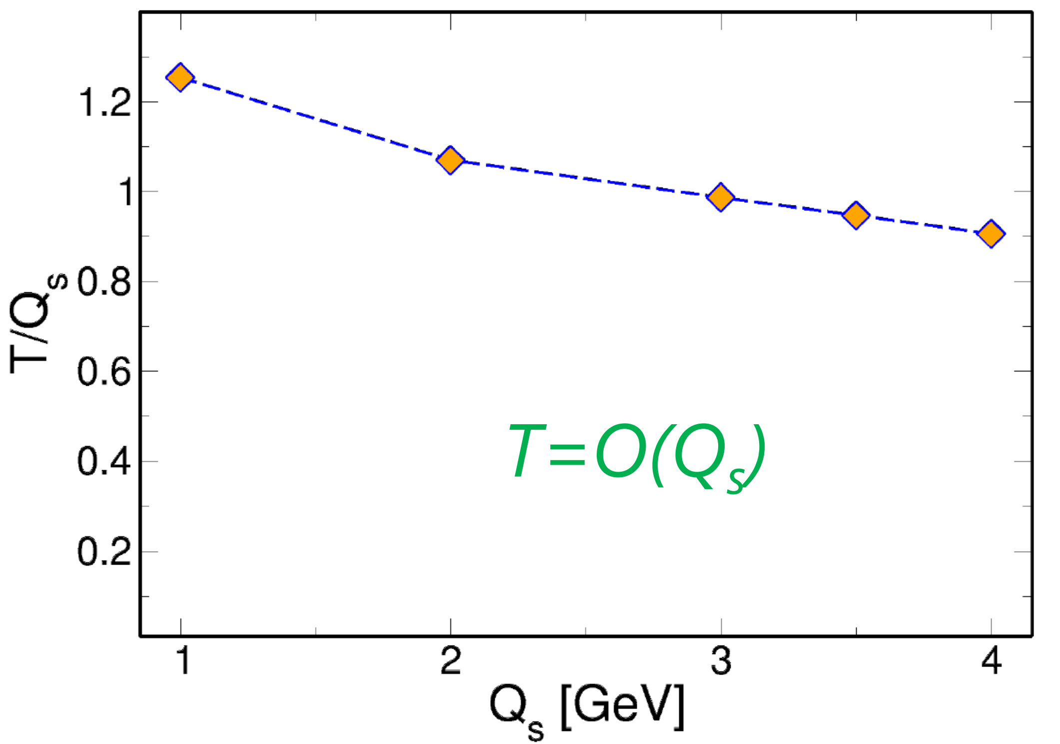
$$T = 1/\beta$$



$$\frac{dp}{dt} = -\gamma p + \xi(t)$$

$$\langle \xi(t_1)\xi(t_2)\rangle = 2\mathcal{D} f(t_1 - t_2)$$

$$f(t_1 - t_2) = \delta(t_1 - t_2)$$



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$$T = 1/\beta$$

$$\frac{dp}{dt} = -\gamma p + \xi(t)$$

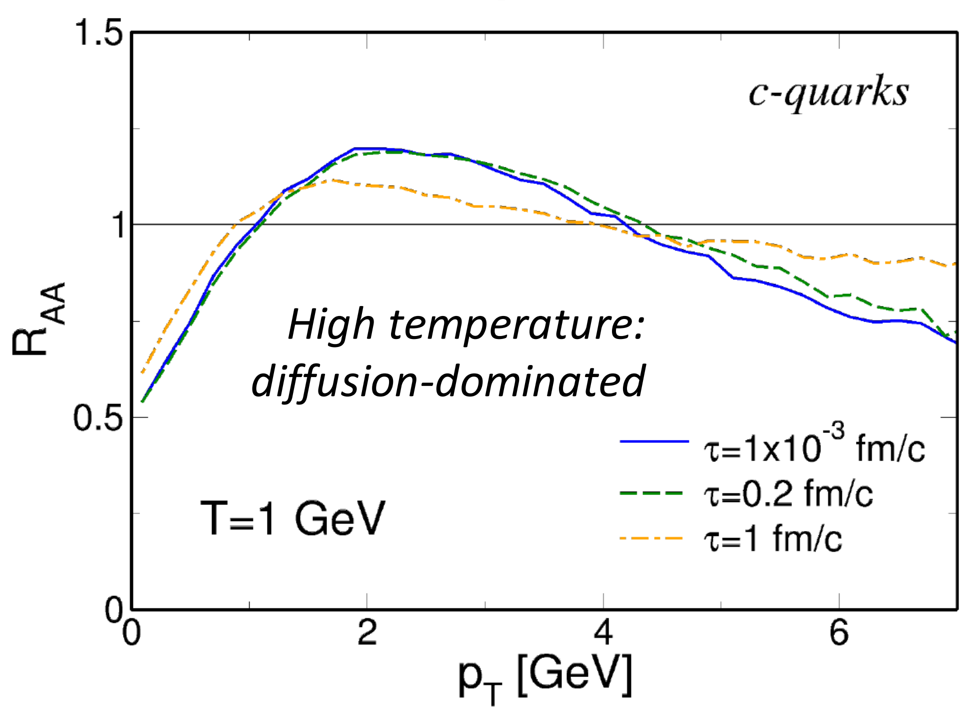
Why do we want to do this:

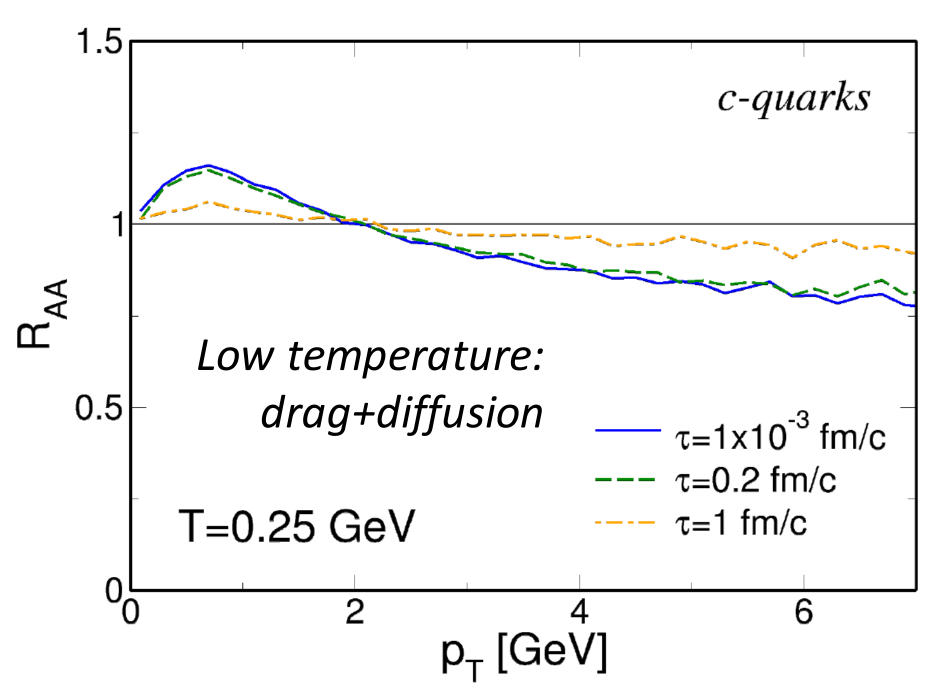
- Check if Langevin eqs, used abundantly in the HQs literature, can be used to reproduce the diffusion of HQs in the EvGlasma.

Qualitatively we already know there are differences.
Quantitatively it is worth checking if momentum broadening obtained within the two schemes is comparable.

M.R. et al., 2110.14610

Impact on RAA

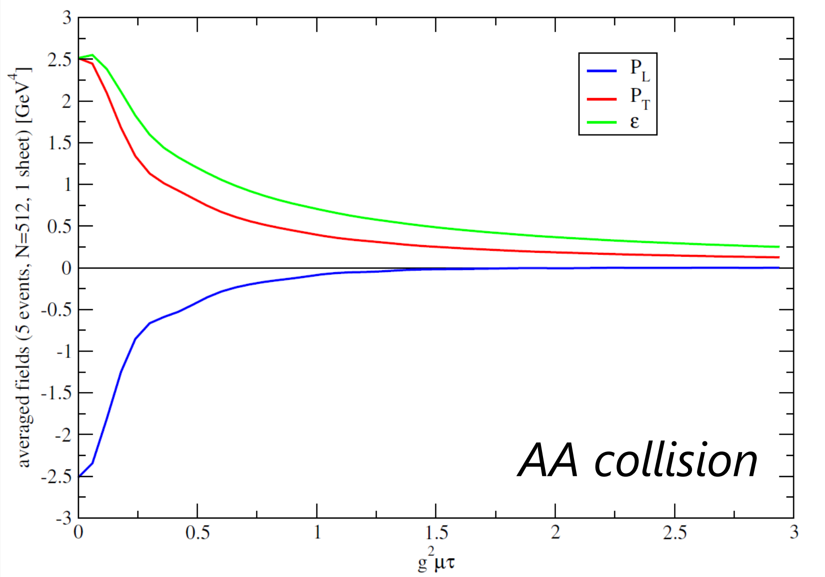


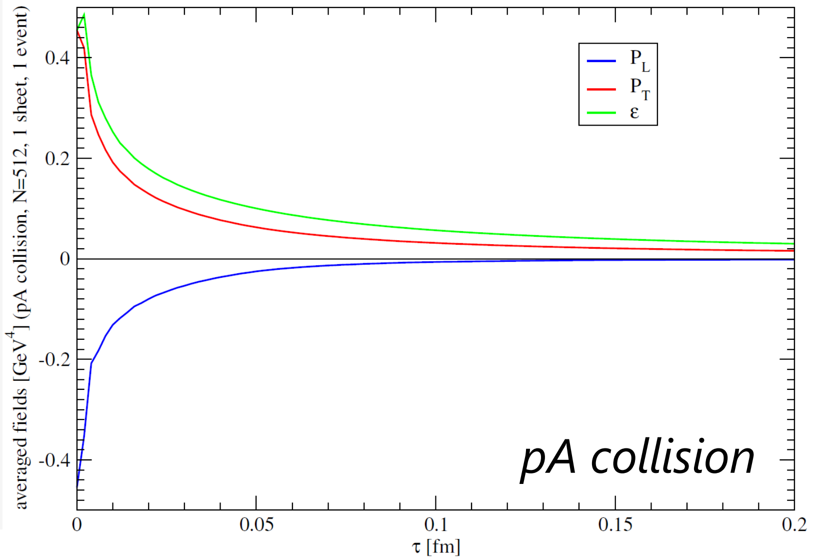


Initial spectrum is tilted by the combined effect of

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

The free streaming regime

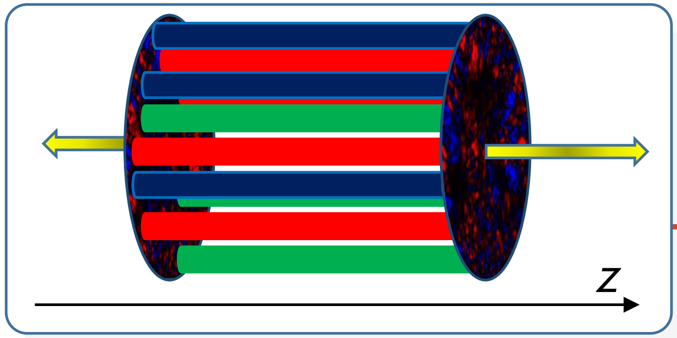




- *Fields dilute: description in terms of gluons, and relativistic kinetic theory, possible (*)*
- *$P_L \neq P_T$: the system is quite anisotropic. This anisotropy affects observables, e.g. those of the heavy quarks.*

Relativistic transport can easily handle this type of initialization.

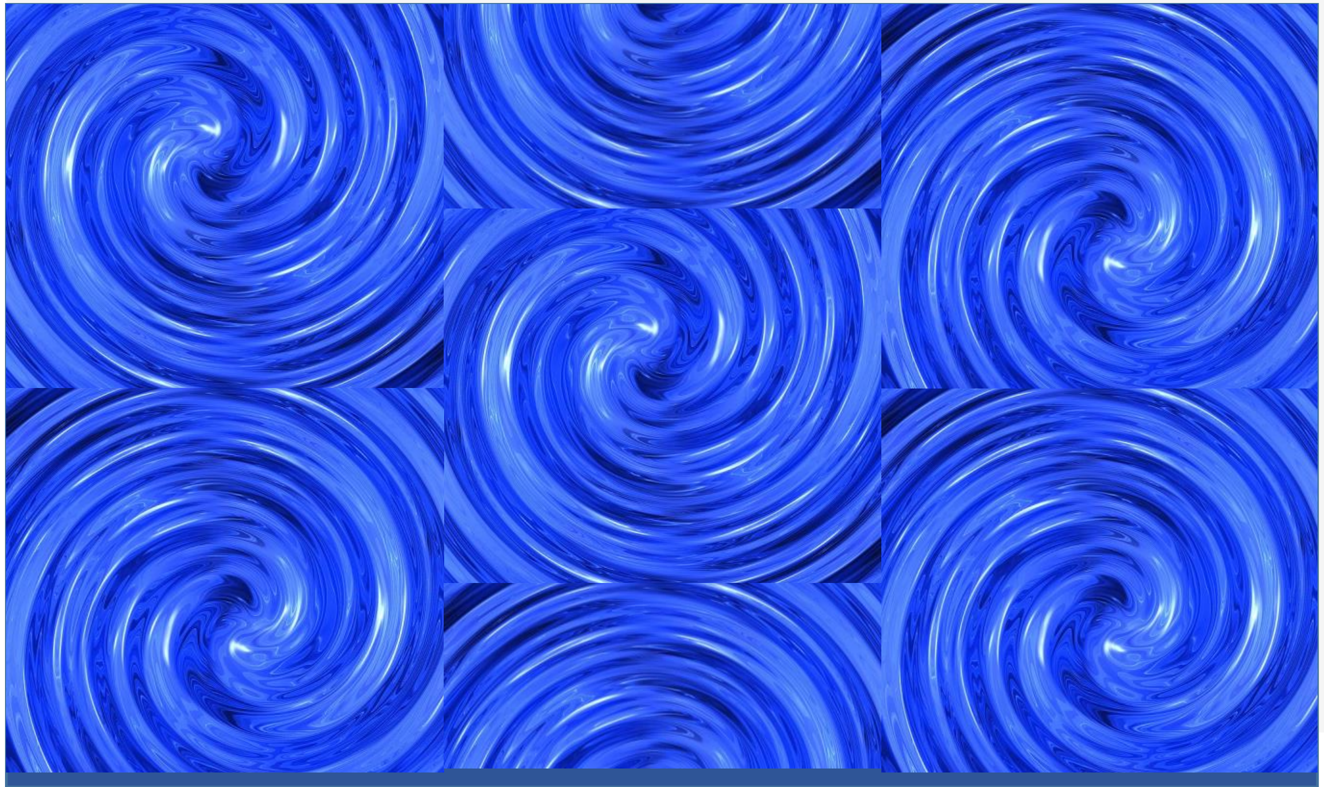
(*)See the talk by Gabriele Parisi

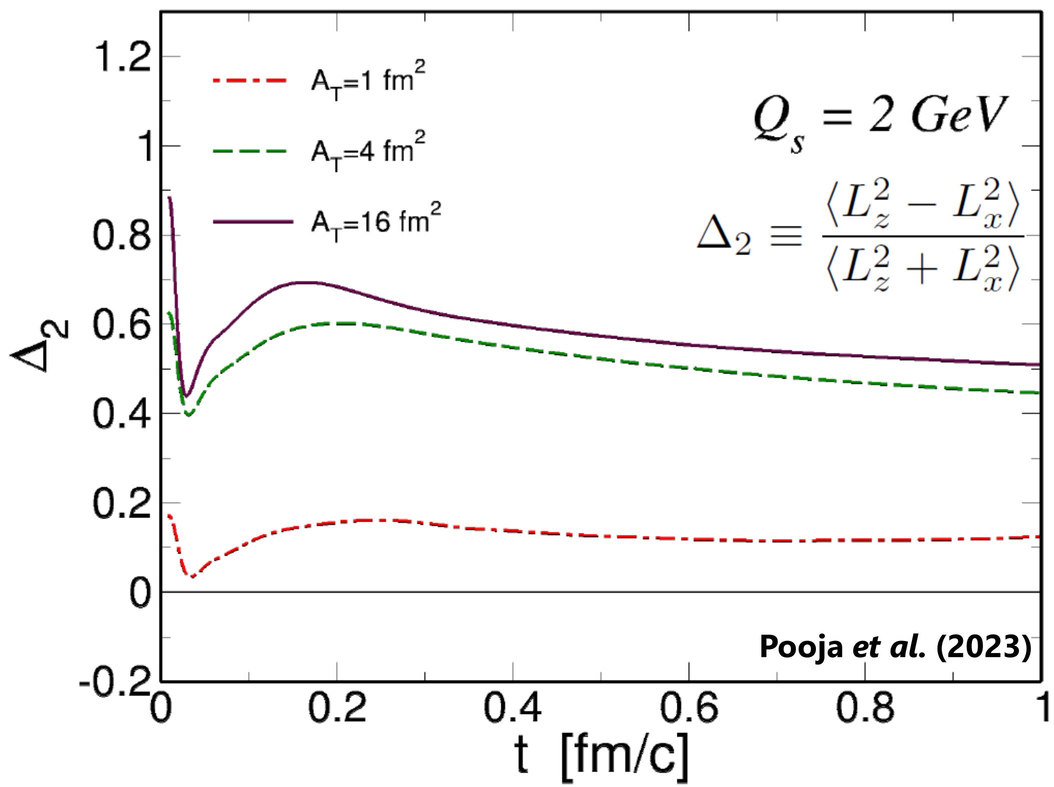


Glasma-induced polarization of c and b

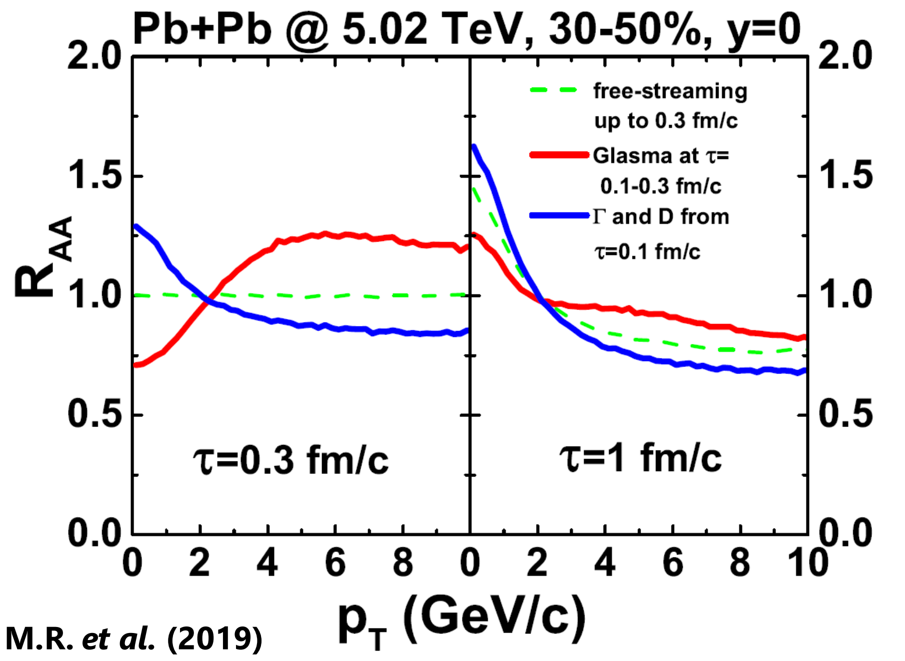
<u>Anisotropic distribution</u> of the momentum
[Pooja et al. (2023), Ipp et al. (2020), Avramescu et al. (2023)]
as well as of angular momentum [Pooja et al. (2023)]

Polarization of c and b, along the longitudinal direction



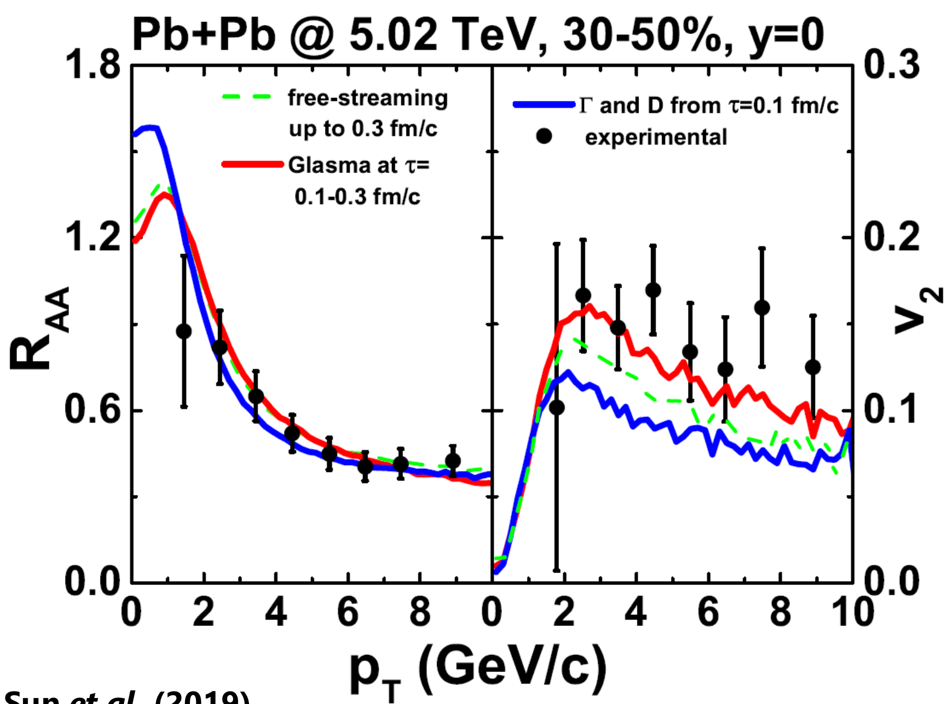


The effect on the elliptic flow in Pb-Pb



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

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

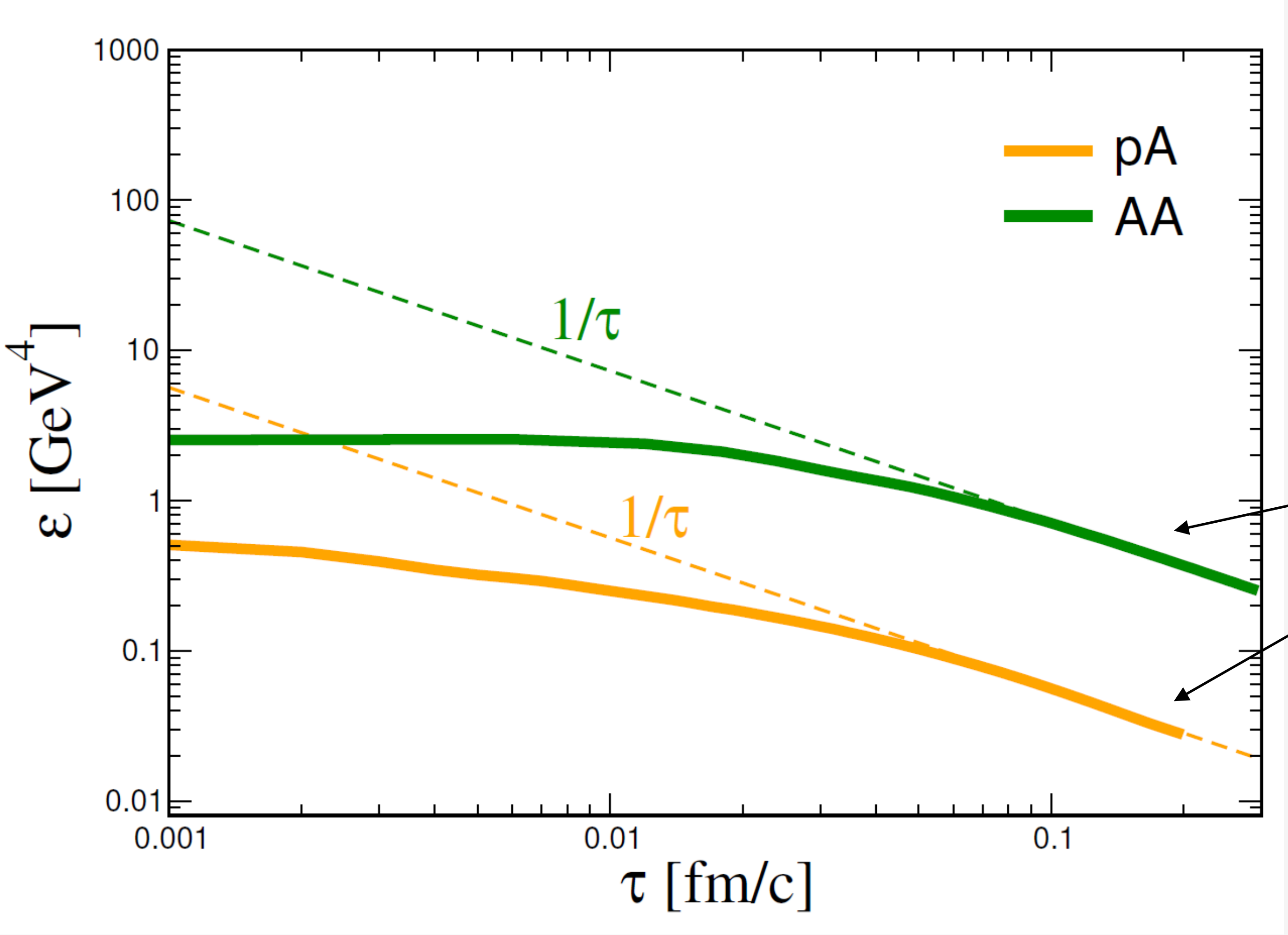


Sun *et al.* (2019)

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

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

The free streaming regime



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

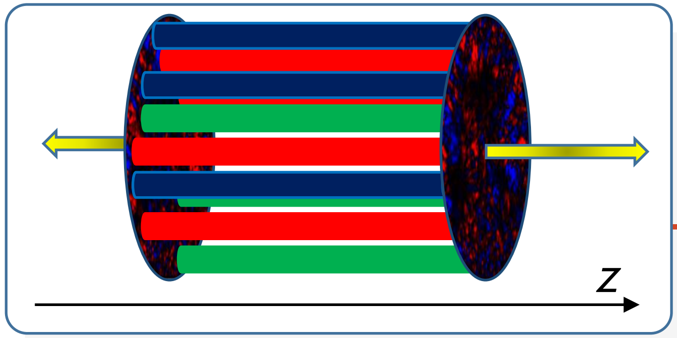
Longitudinal expansion
with zero pressure (aka free streaming):

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

- *Fields are diluted: description in terms of gluons, and relativistic kinetic theory, is possible in this regime(*)*

(*)See the talk by Gabriele Parisi

Glasma-induced polarization of c and b



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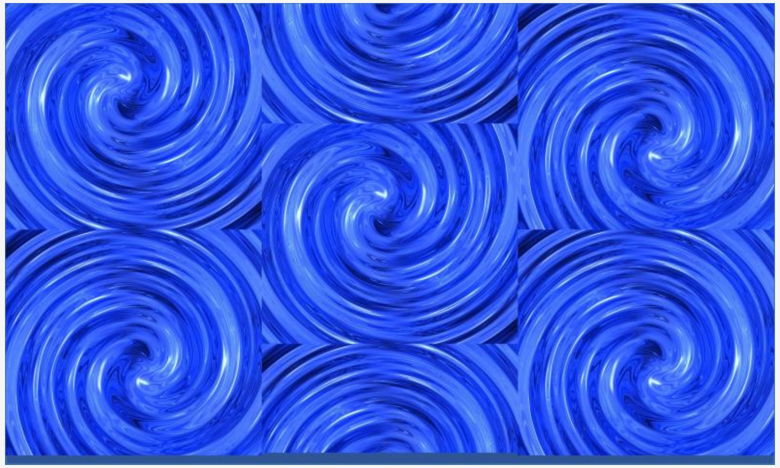

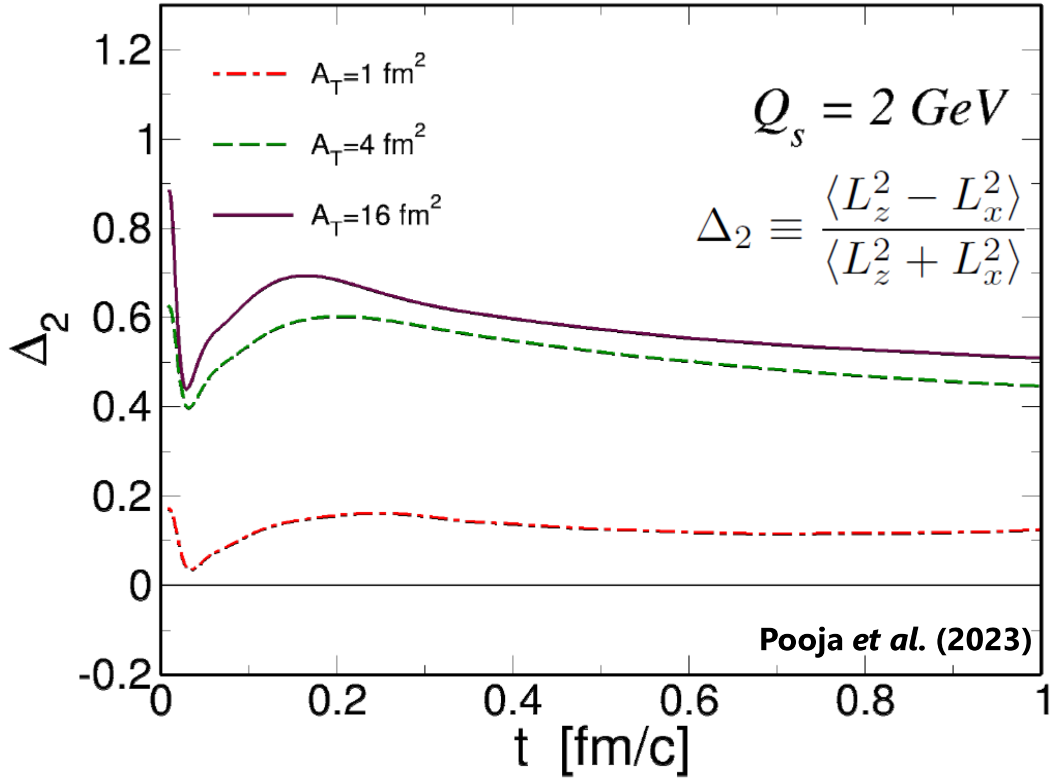

Naively: glasma induces vortex-like motion of c and b around color filaments in the transverse plane