Strasbourg 2024
Strangeness in Quark Matter

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

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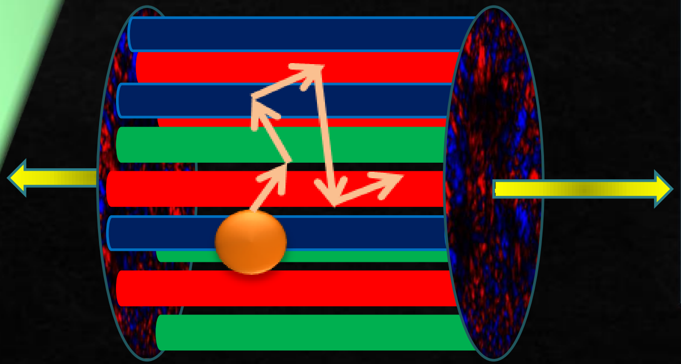
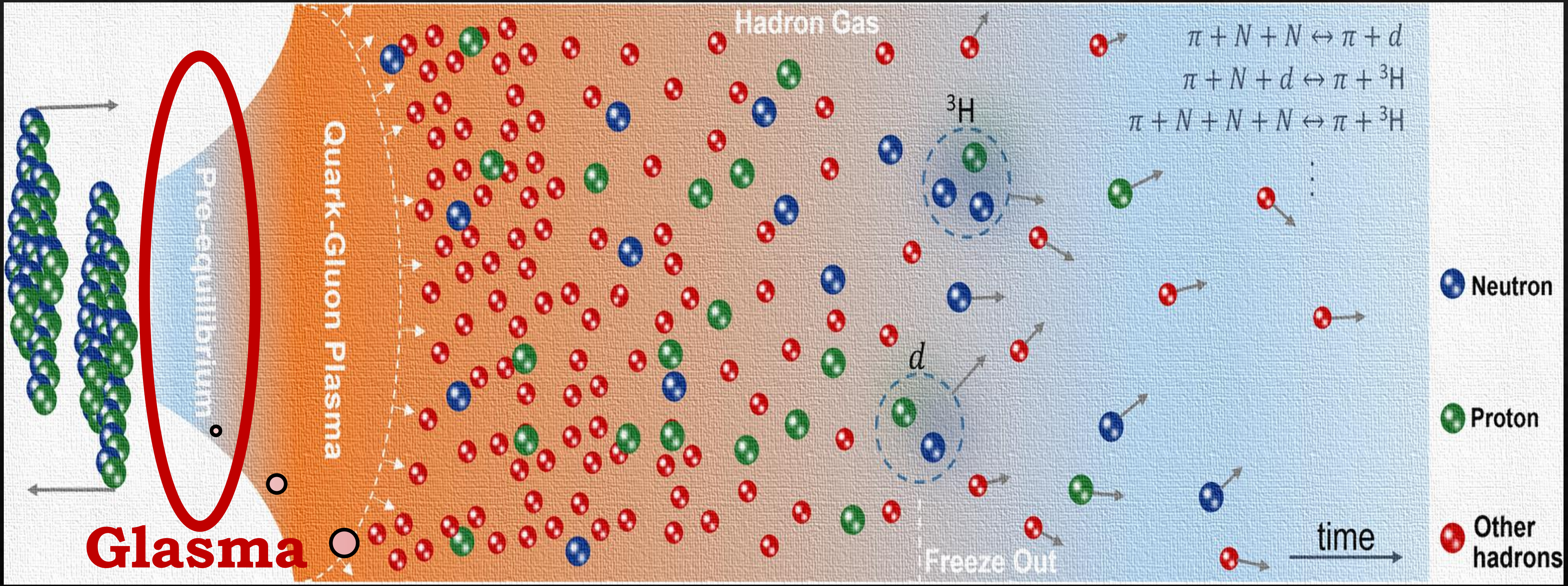


Pooja
School of Physical Sciences
Indian Institute of Technology Goa

QCD Matter produced in Heavy-Ion Collisions

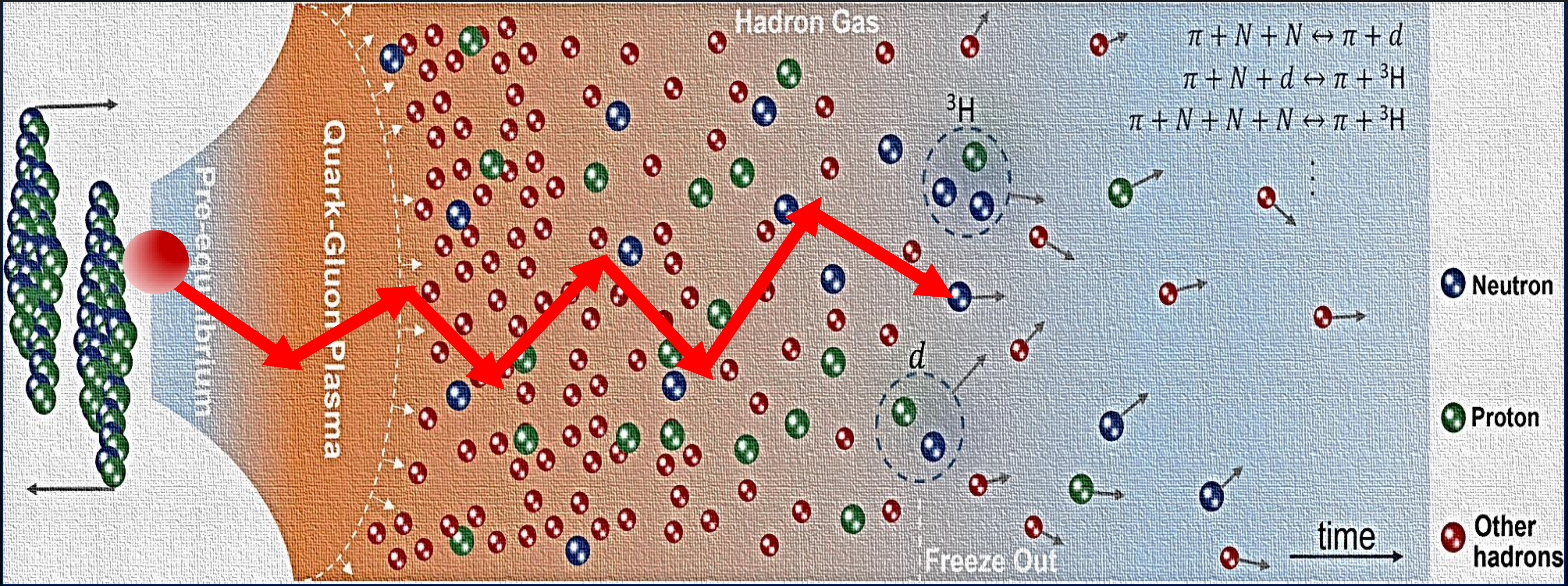


Nature Communications, 15 (2024) 1, 1074

Pre-equilibrium dynamics

- Strong longitudinal color fields (Glasma)
- Glasma to QGP conversion

Heavy quarks, c and b, in HICs



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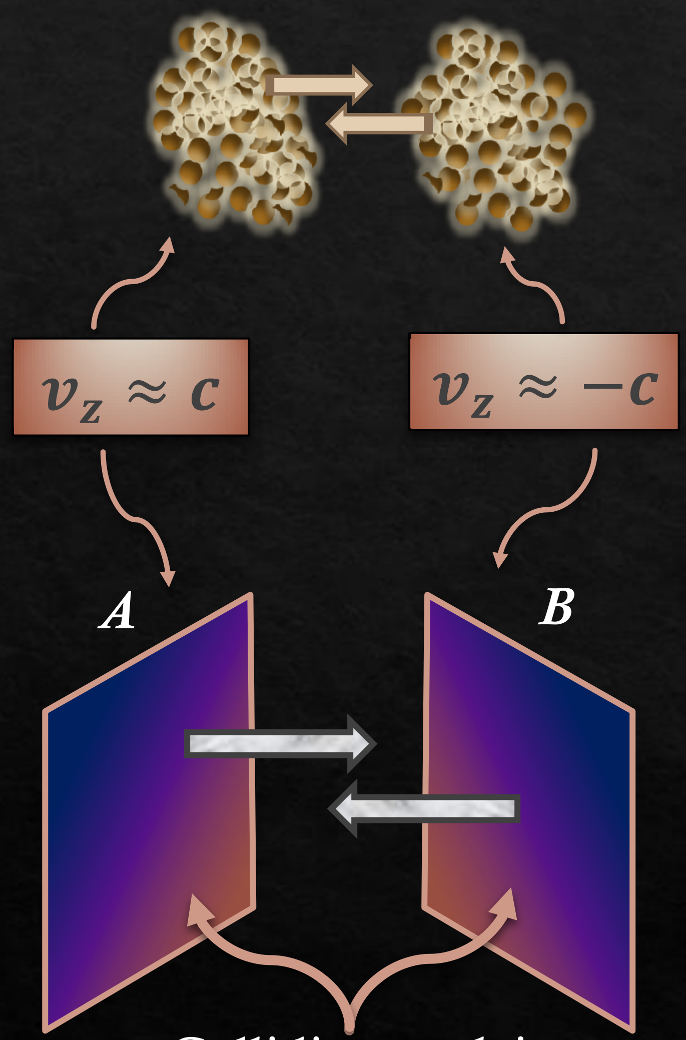
HQs can probe the entire evolution of the medium, from the early stage up to hadronization.

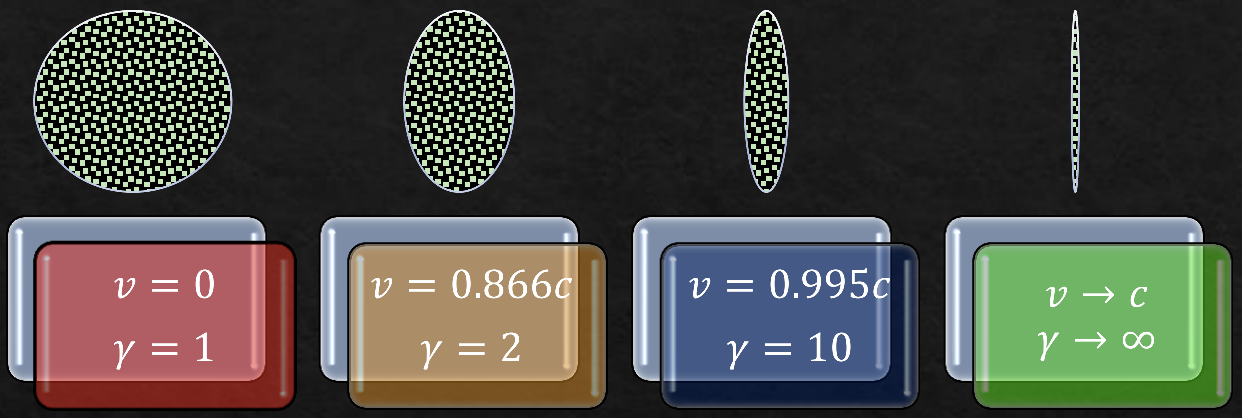
Formation of Glasma : The Initial Condition of HICs



$v_z \approx c$

$v_z \approx -c$

Colliding nuclei



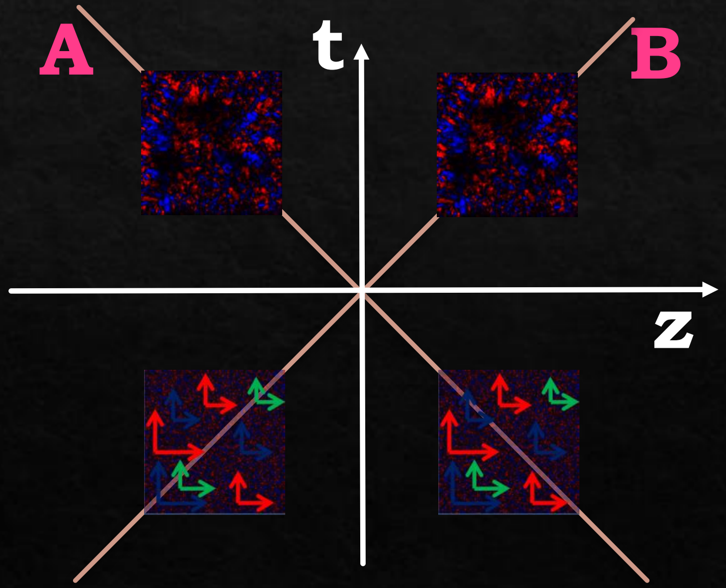
$v = 0$, $\gamma = 1$

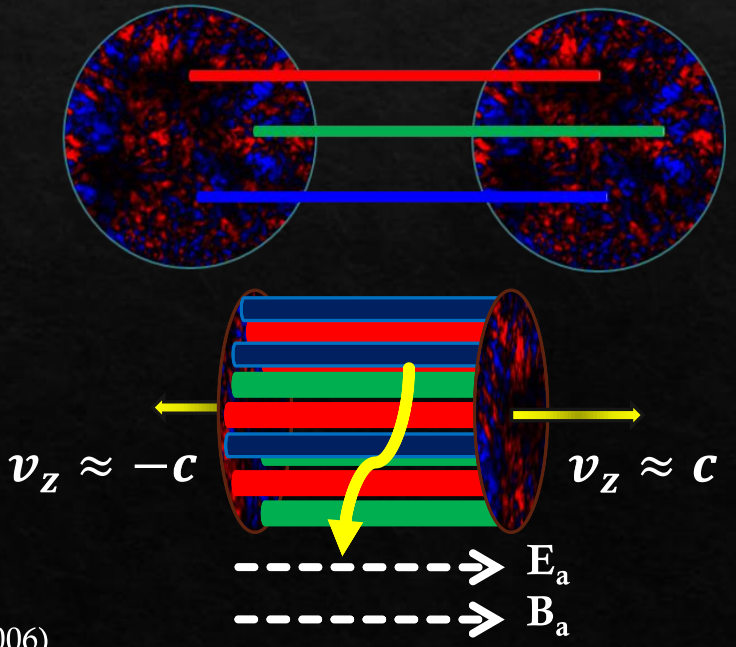
$v = 0.866c$, $\gamma = 2$

$v = 0.995c$, $\gamma = 10$

$v \to c$, $\gamma \to \infty$

Lorentz contraction along the longitudinal direction :
Two thin colliding sheets





$v_z \approx -c$

$v_z \approx c$

Lappi and McLerran (2006)

Heavy Quark : As a probe for the evolving Glasma

CYM Equations

$$\frac{dA_i^a(x)}{dt} = E_i^a(x)$$

$$\frac{dE_i^a(x)}{dt} = \partial_j F_{ji}^a(x) + g f^{abc} A_j^b(x) F_{ji}^c(x)$$

Gluon Field Strength Tensor

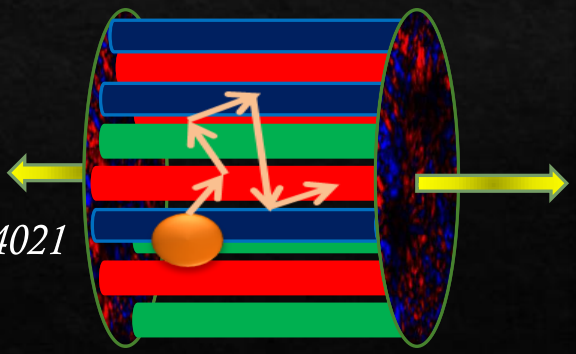
- $F_{ij}^a(x) = \partial_i A_j^a(x) - \partial_j A_i^a(x) + g f^{abc}\, A_i^b(x) A_j^c(x)$

Equations of motion of heavy quarks
(Wong Equations)

$$\frac{dx^i}{dt} = \frac{p^i}{E}, \qquad E = \sqrt{\mathbf{p}^2 + m^2}$$

$$\frac{dp^i}{dt} = g Q_a F_a^{i\mu} \frac{p_\mu}{E}$$

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

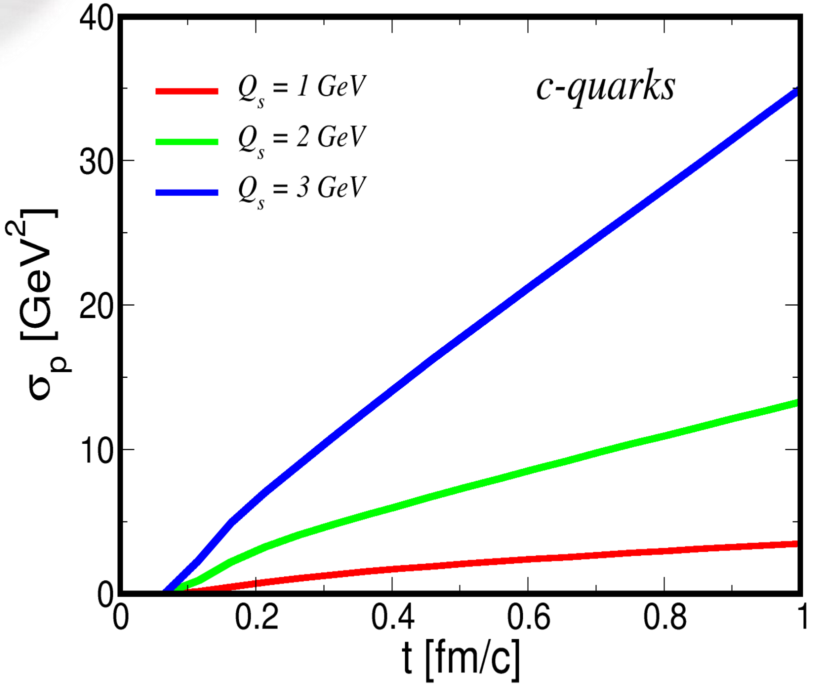


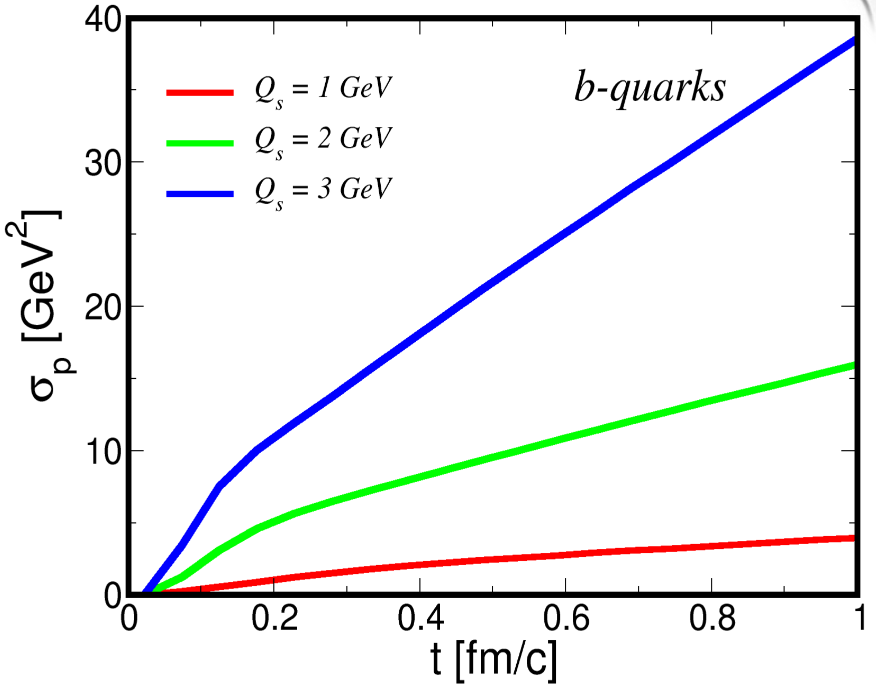
Pooja et al., *arxiv: 2404.05315*
Pooja et al., *Eur. Phys. J. Plus 137 (2022) 3, 307*
Pooja et al., *Eur. Phys. J. Plus 138 (2023) 4, 313*
D. Avramescu et al., *Phys.Rev.D 107 (2023) 11, 114021*
J. H. Liu et al., *Phys.Rev.D 103 (2021) 3, 034029*
M. Ruggieri et al., *Phys.Rev.D 98 (2018) 9, 094024*
S. K. Das et al., *J. Phys .G 44 (2017) 9, 095102*

U. W. Heinz, *Annals Phys. 161, 48 (1985)*
S. K. Wong, *Nuovo Cim. A 65, 689 (1970)*

Momentum Broadening for HQs in Glasma

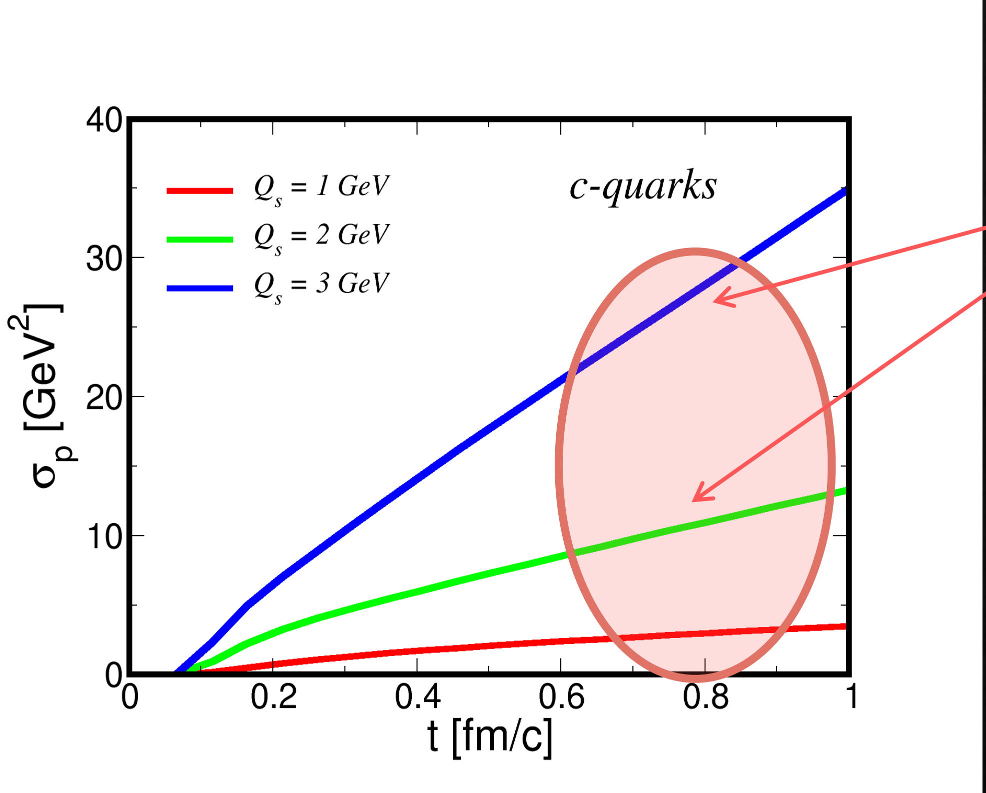
$$\sigma_p = \frac{1}{2} < (p_x(t) - p_{ox})^2 + (p_y(t) - p_{oy})^2 >$$





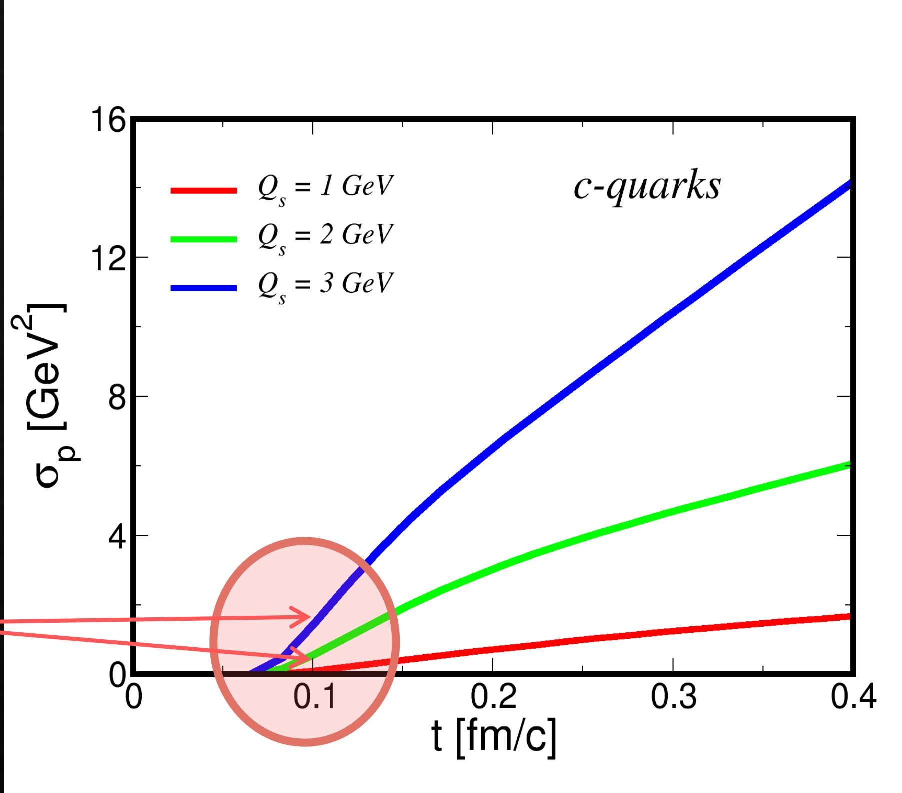
Pooja et al., *Eur. Phys. J. Plus 137 (2022) 3, 307*

Ballistic Diffusion of HQs in Glasma



Diffusion in a random medium : $\sigma_p \propto t$

Diffusion in a filament : $\sigma_p \propto t^2$

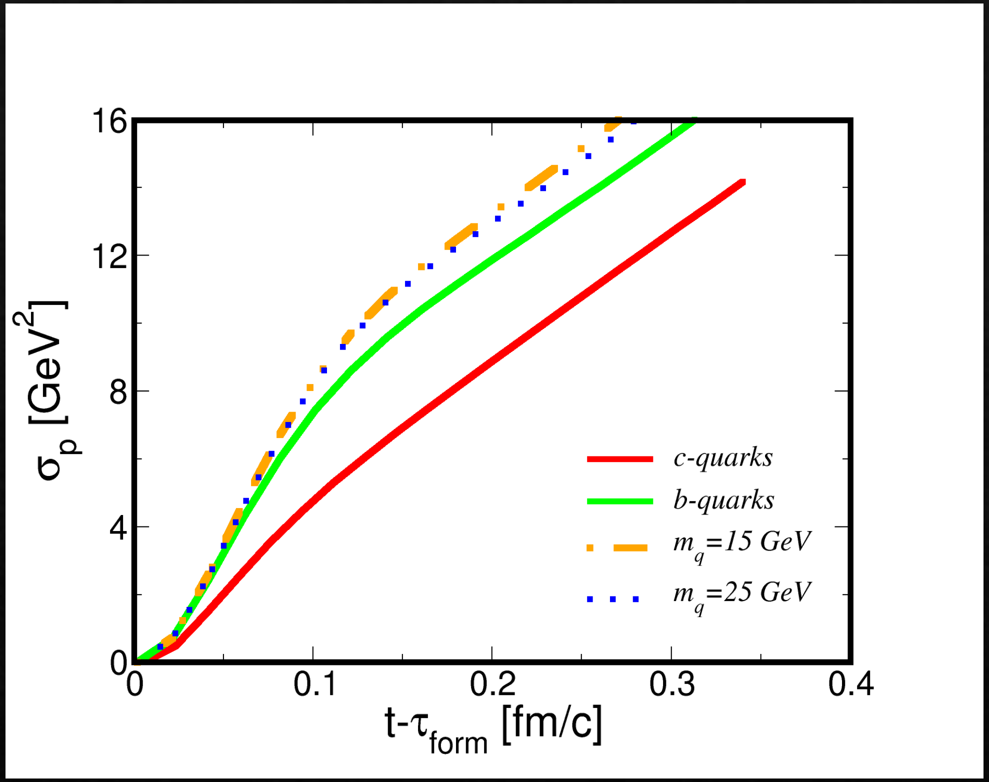


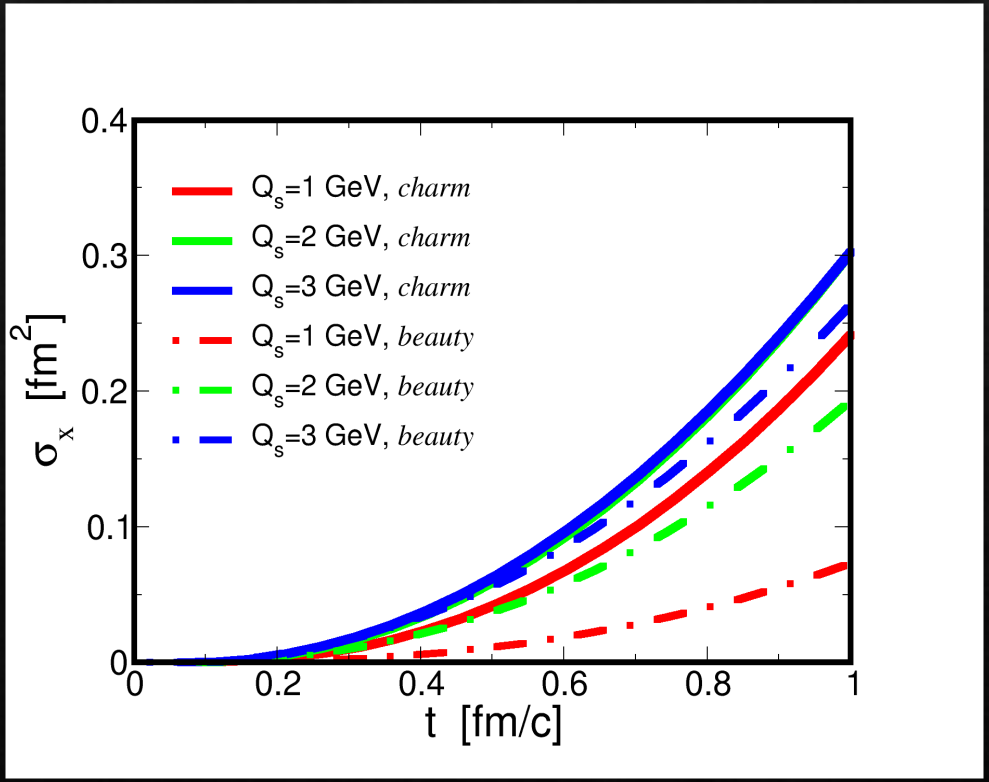
At early time : $\sigma_p \approx \frac{Dt^2}{\tau_{mem}}$

At later time : $\sigma_p \approx 2Dt$

Pooja et al., *Eur. Phys. J. Plus 137 (2022) 3, 307*
Pooja et al., *Phys. Rev. D 106 (2022) 3, 034032*
Pooja et al., *Phys.Rev.D* 108 (2023) 5, 054026

Comparison of σ_p and σ_x for Different HQs in Glasma





*Slow color charges spend some time within one single filament: diffusion in a strong gluon field, rather than in a random medium. The force exerted on these charges is time-correlated : **Memory!***

Pooja et al.,
Eur. Phys. J. Plus 137 (2022) 3, 307

In agreement with
Lappi et al., *JHEP* 09 (2020) 077

Comparison of Glasma with pQCD-Langevin

We prepare a bath of thermalized massless gluons at temperature T, with the same energy density that of the EvGlasma, and study the diffusion of HQs in this bath with Langevin equation.

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

Energy density of the Glasma fields

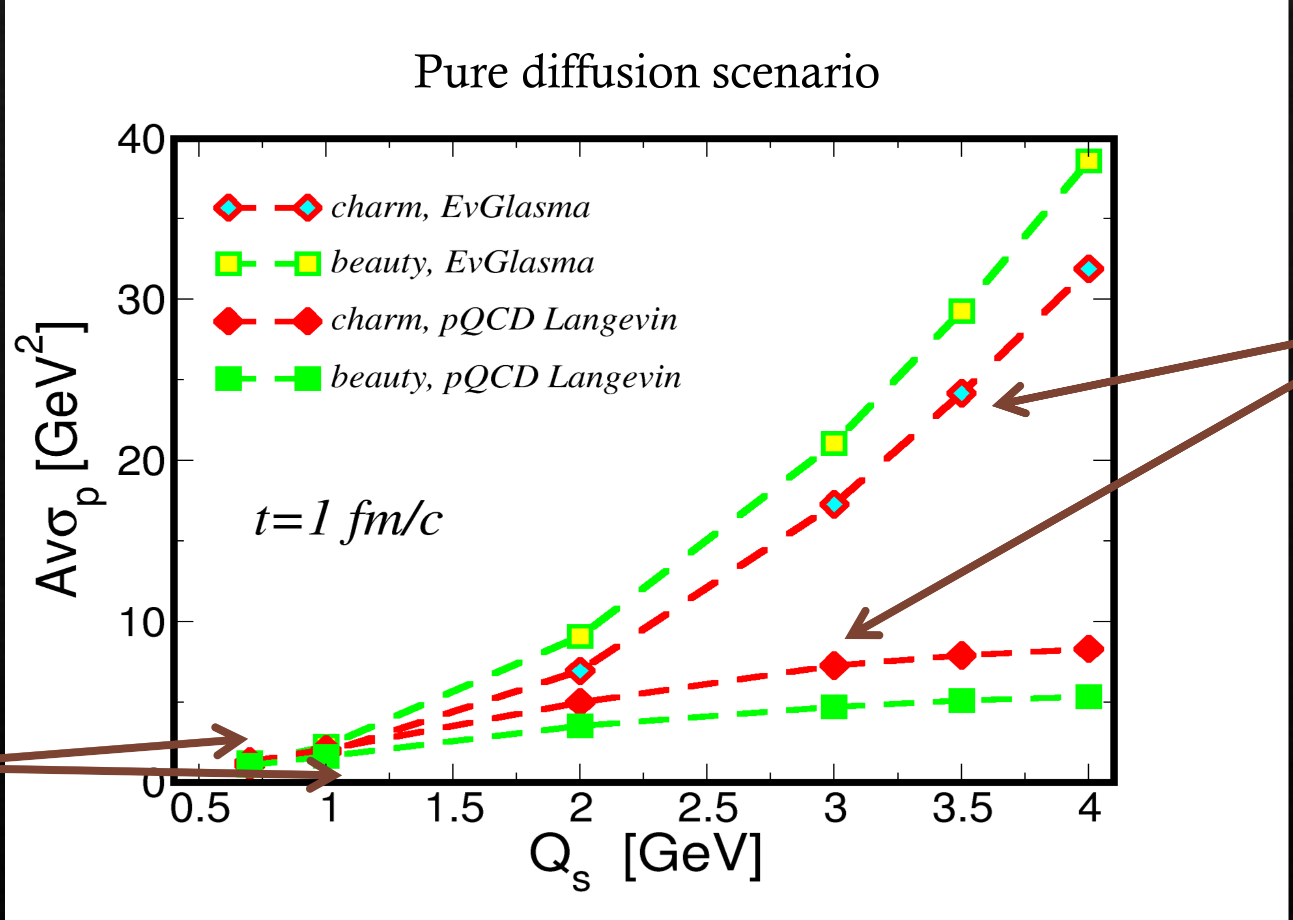
Temperature of the gluonic Plasma

Pooja et al., *Eur. Phys. J. Plus* 137 (2022) 3, 307

$\mathrm{Av}\sigma_p$ for Evolving Glasma & pQCD-Langevin

$$Av\,\sigma_p = \frac{1}{t}\int_0^t \sigma_p(t')dt'$$

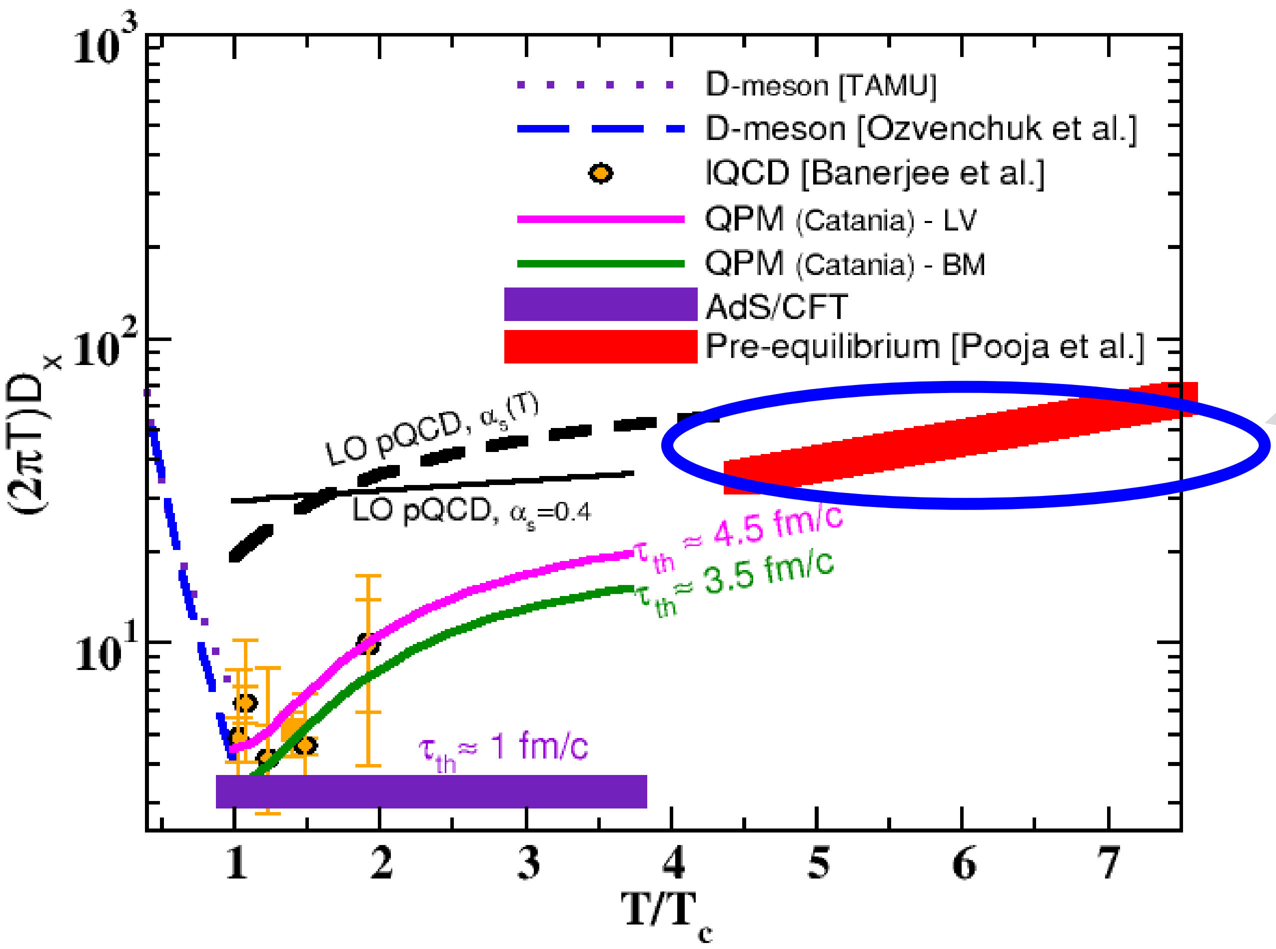
For small Q_s, the energy density of EvGlasma is small, it is closer to a dilute gluon system. So, its dynamics is closer, on average, to that of a collisional gluon plasma.



For large Q_s, HQs in the EvGlasma experience strong coherent gluon fields while the dynamics remains collisional in the Langevin case.

Pooja et al., *Eur. Phys. J. Plus* 137 (2022) 3, 307

HQ Diffusion Coefficient in Glasma



Spatial diffusion coefficient, D_x as a function of temperature

Glasma

S. K. Das (HP 2023),
arXiv : 2306.13749

Summary

- The diffusion of HQs in the pre-equilibrium Glasma phase is ballistic, $\sigma_p \propto t^2$.
- HQs dynamics in the Glasma phase can not be mimicked using the Langevin dynamics.
- HQ dynamics in Glasma is dominated by diffusion with negligible drag.
- The pre-equilibrium Glasma phase will impact experimental observables, both in AA and pA collisions.


Thank you
Tak
Kiitos
Dziękuję
Ευχαριστώ
Hvala
Obrigado
谢谢
有り難う
Danke
Merci
תודה
Tack
Gracias
Thank you
Grazie
شكرا
謝謝
감사합니다
ありがとう
Cпасибо
Cпасибі
Mulţumesc
Asante

Appendix

The MV model of color sources

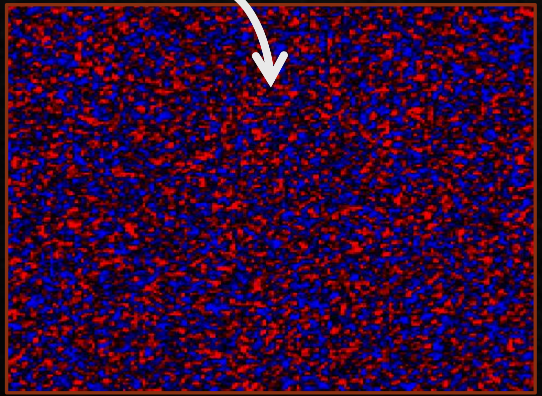
- *Fast (large momentum) partons*

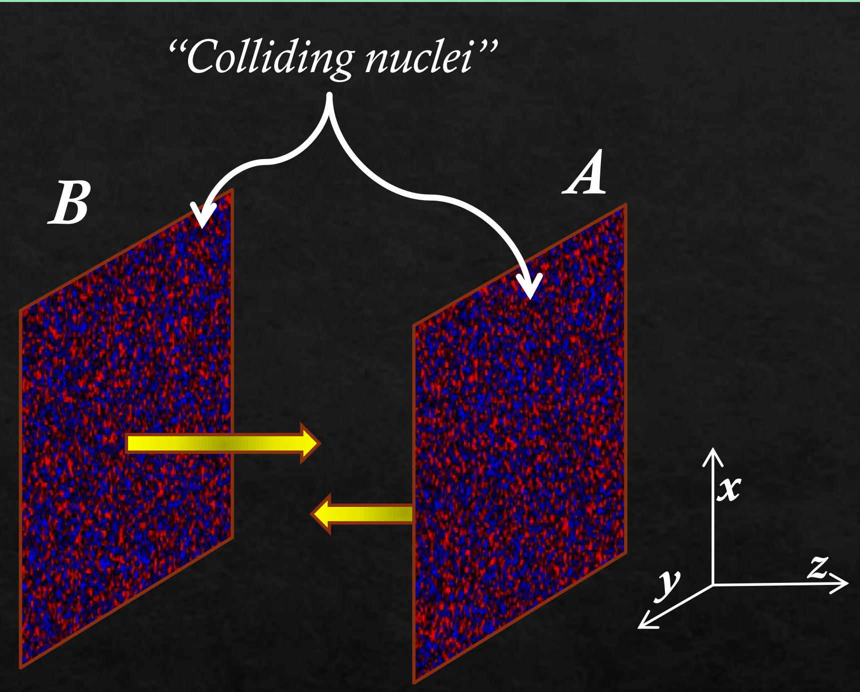
Their dynamics in the Lab frame is slowed down due to time dilation: ***static sources of color fields.***

Model of static sources (MV model)

Uncorrelated color density fluctuations on the two nuclei.

$$\langle \rho^a(\boldsymbol{x}_T) \rangle = 0,$$
$$\langle \rho^a(\boldsymbol{x}_T) \rho^b(\boldsymbol{y}_T) \rangle = (g^2\mu)^2 \delta^{ab} \delta^{(2)}(\boldsymbol{x}_T - \boldsymbol{y}_T)$$





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

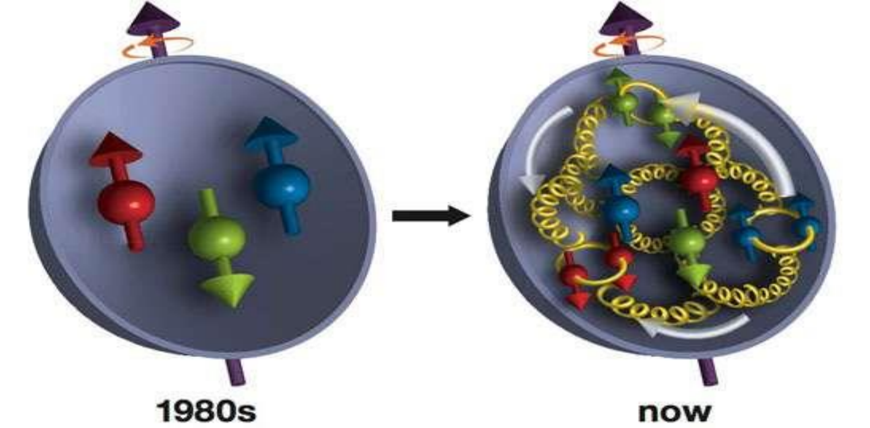
From the correlators of Wilson lines:

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

Lappi (2008)

McLerran and Venugopalan (1996)
Kovchegov (1996)

Glasma, The Initial Condition



$$x = \frac{\textit{Parton momentum}}{\textit{Nucleon momentum}}$$

Small-x content of the proton

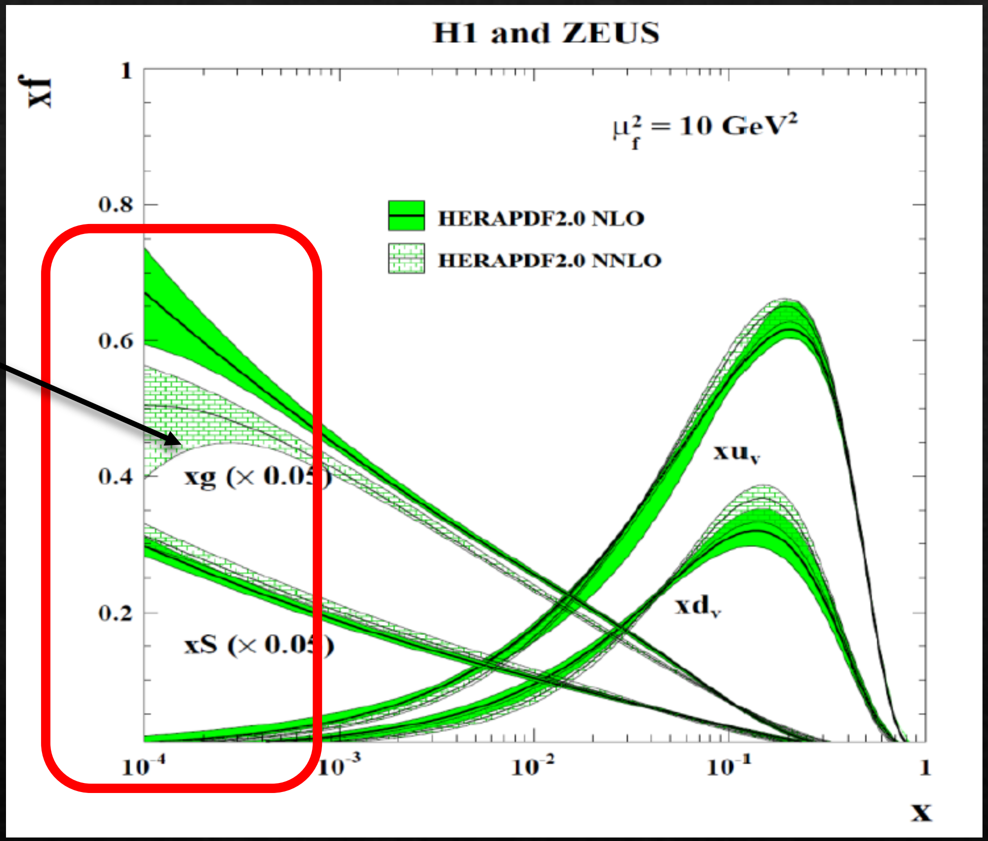
Sea quarks+antiquarks

Sea gluons

x ≈ 1

Valence quarks (uud)

The small-x proton wave function is dominated by the sea of virtual gluons



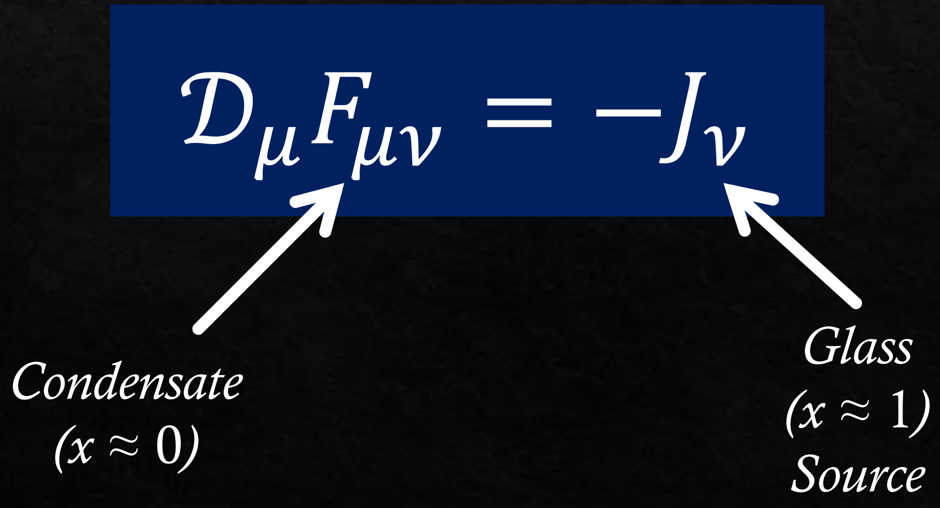
- **Slow (small momentum) partons** : ***Gluons*** (from the sea) dominate the nucleonic wave function (low momentum quarks are suppressed).
- **Fast partons** : ***Random sources*** of these classical fields.

Color-Glass Condensate

- **Color :** Gluons have “colors“
- **Glass :** Partons (quarks and gluons) with x ≈ 1 are very fast (v ≈ c). So, they appear frozen in lab, like molecules in glasses
- **Condensate :** Many small-x gluons: *classical field* like in a condensate. Gluon density is very high and saturated.

The dynamical evolution of the CGC:

Yang-Mills equation



$$\mathcal{D}_\mu F_{\mu\nu} = -J_\nu$$

Condensate
($x \approx 0$)

Glass
($x \approx 1$)
Source