Charm and beauty quarks in the initial stages of proton-Ion Collisions

Gabriele Parisi, Lucia Oliva, Vincenzo Greco, Marco Ruggieri

Meeting of the SIM Project, Turin
July 2, 2025

Outline

General Topic

Heavy Ion Collisions

Specific Topic

Initial Stages

of Heavy Ion Collisions

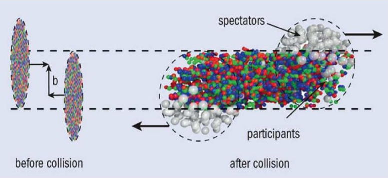
More Specific Topic

Heavy Quarks

in Initial Stages

of Heavy Ion Collisions

(my work)



D. Rashid, 2103.16899 [hep-ph]

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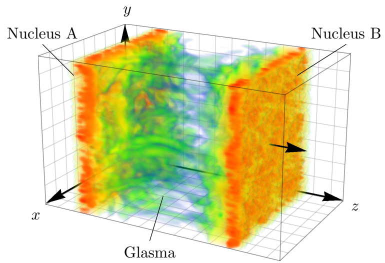

A. Ipp and D. Müller, Phys.Lett.B 771 (2017) 74-79

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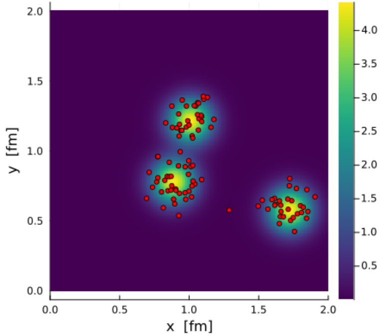
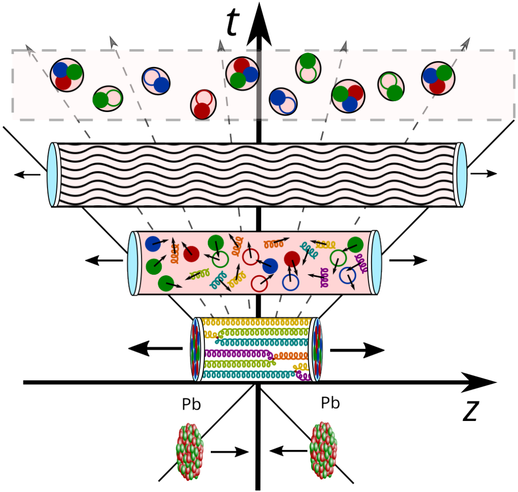


L. Oliva, G.P., V. Greco and M. Ruggieri, 2412.07967 [hep-ph], PRD accepted

Heavy-ion collisions



Final stages $\tau \geq 10\,\mathrm{fm/c}$

↑

Local equilibrium $\tau \sim 10\,\mathrm{fm/c}$

↑

QGP phase $\tau \sim 1\,\mathrm{fm/c}$

↑

Initial stage $\tau \sim 0.1\,\mathrm{fm/c}$

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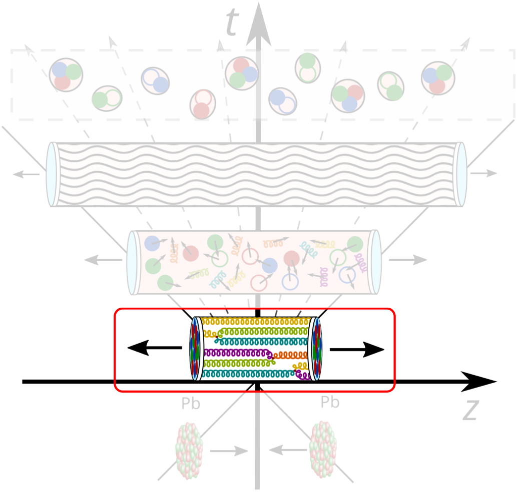
Before the collision $\tau \leq 0\,\mathrm{fm/c}$

A. Mazeliauskas: Stages of heavy ion collision

Heavy-ion collisions



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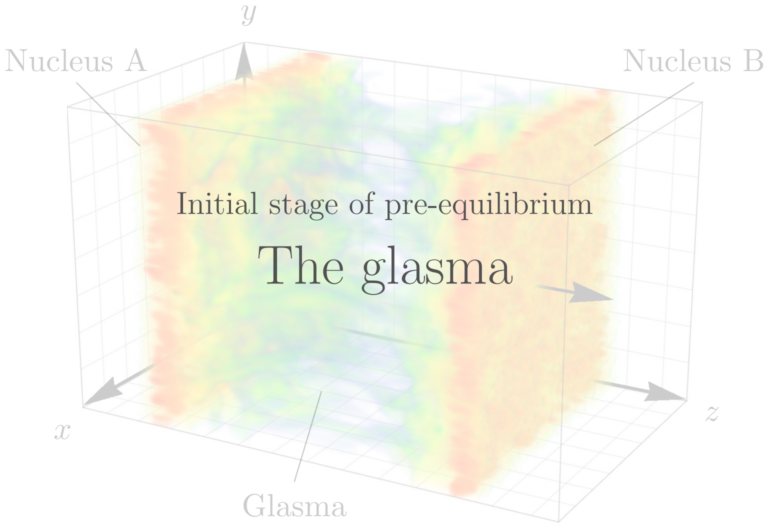
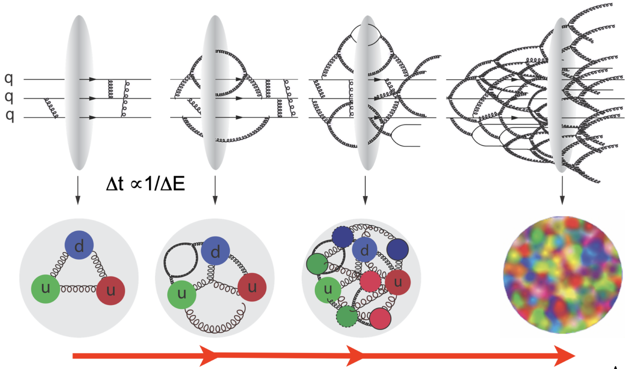
Initial stage of pre-equilibrium

The glasma



BFKL evolution



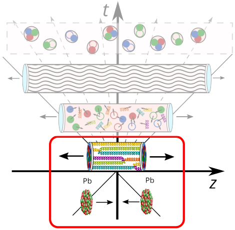
Smaller Bjorken x

At low energy,
valence quarks only

At high energy,
the nucleus contains
many soft gluons

Farid Salazar, "From Quarks and Gluons to the Internal Dynamics of Hadrons" workshop

QCD at high energy



At LHC energies, collision among **dense gluon distributions**

$\Downarrow$

Emergence of a saturation scale $Q_s \sim 2$ GeV: **Glasma**

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described by the **Color Glass Condensate** formalism

L. McLerran and R. Venugopalan, Phys.Rev.D 49 (1994) 2233-2241
Phys.Rev.D 49 (1994) 3352-3355, Phys.Rev.D 50 (1994) 2225-2233

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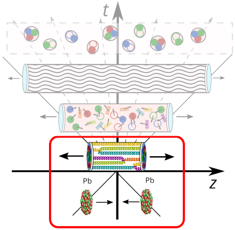

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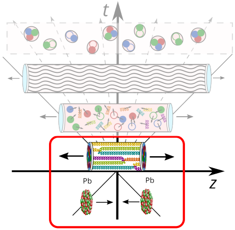

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Color Glass Condensate

Color
QCD degrees of freedom

Condensate
High-gluon density,
classical dynamics

Glass
Quarks are static sources,
due to time dilation

L. McLerran and R. Venugopalan, Phys.Rev.D 49 (1994) 2233-2241
Phys.Rev.D 49 (1994) 3352-3355, Phys.Rev.D 50 (1994) 2225-2233

Color Glass Condensate in 2+1D

McLerran-Venugopalan (MV) initial conditions

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

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

J^μ by the hard partons $\Longrightarrow$ A^μ of the soft partons

Classical dynamics of glasma, Yang Mills equations

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

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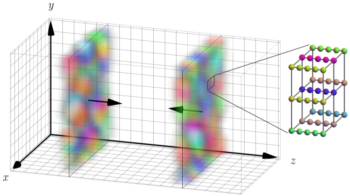
Numerical implementation



- Classical Yang-Mills discretized on lattice:

  color sheets

- Real-time lattice gauge theory techniques

Gauge links

$$V^\dagger(\mathbf{x}_T, x^-) = \mathcal{P}\exp\left[-ig\int_{-\infty}^{x^-} dz^- A^+(z^-, \mathbf{x}_T)\right]$$

Plaquettes

$$U_{x,\mu\nu} = U_{x,\mu}U_{x+\mu,\nu}U_{x+\mu+\nu,-\mu}U_{x+\nu,\nu}$$

Wilson lines

$$U_{\mathbf{x}_T,i} = V(\mathbf{x}_T)V^\dagger(\mathbf{x}_T + \Delta x_i)$$

D. Gelfand et al., Phys.Rev.D 94 (2016) 1, 014020

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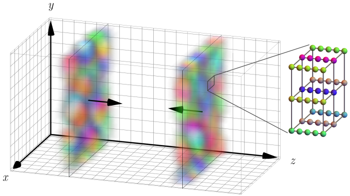

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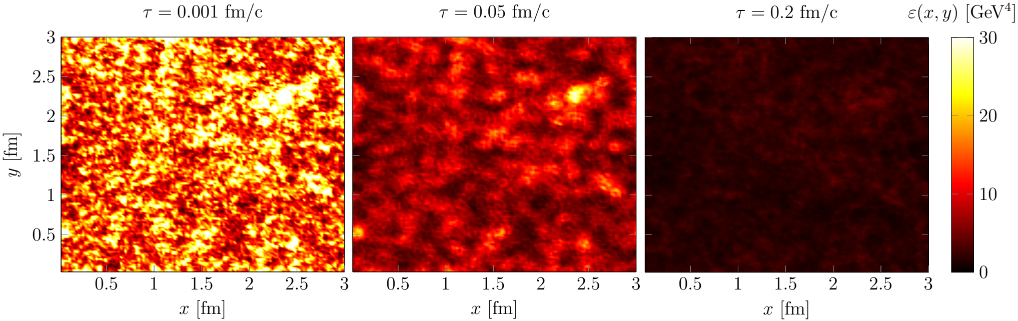
Features of the glasma

Energy density in nucleus-nucleus collisions

$$\varepsilon = \mathrm{Tr}[E_{\mathrm{L}}^2 + B_{\mathrm{L}}^2 + E_{\mathrm{T}}^2 + B_{\mathrm{T}}^2]$$



Fields dilute after $\delta\tau \sim Q_s^{-1} \sim \mathcal{O}(0.1\ \mathrm{fm/c})$

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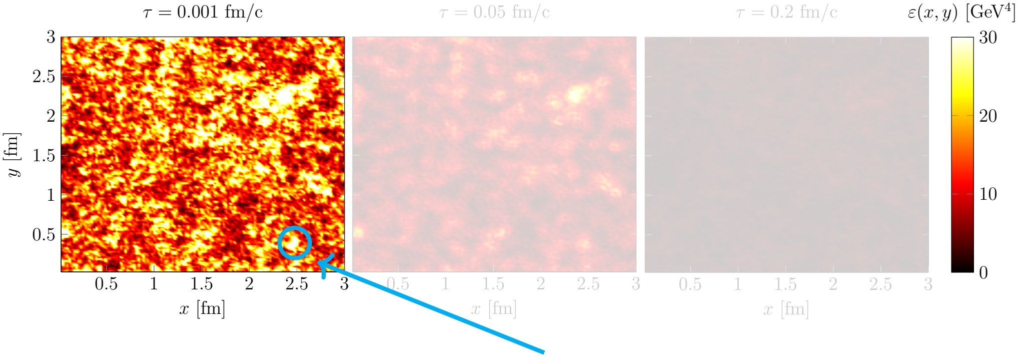
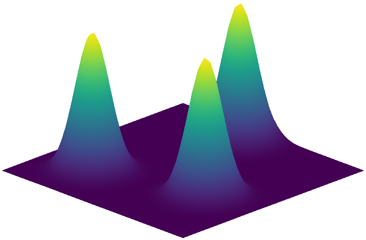


Hotspots of size $\delta x_T \sim Q_s^{-1} \sim \mathcal{O}(0.1\ \mathrm{fm})$

Color charge generation in pA

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

We can have μ space-dependent:
proton structure



- Three hotspots $\bar{\mathbf{x}}_T^i$ in a width $\sqrt{B_{qc}}$.
- Then:

$$\mu(\mathbf{x}_T) \propto \frac{1}{3}\sum_{i=1}^{3}\frac{1}{2\pi B_q}\exp\left[-\frac{(\mathbf{x}_T-\bar{\mathbf{x}}_T^i)^2}{2B_q}\right].$$

$$B_{qc} = (0.4\ \text{fm})^2, \quad B_q = (0.11\ \text{fm})^2$$

H. Mäntysaari and B. Schenke, Phys.Rev.Lett. 117 (2016) 5, 052301

B. Schenke, C. Shen and P. Tribedy, Phys.Rev.C 102 (2020) 4, 044905

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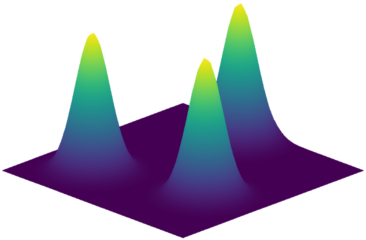

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Energy density in pA vs (x, y)

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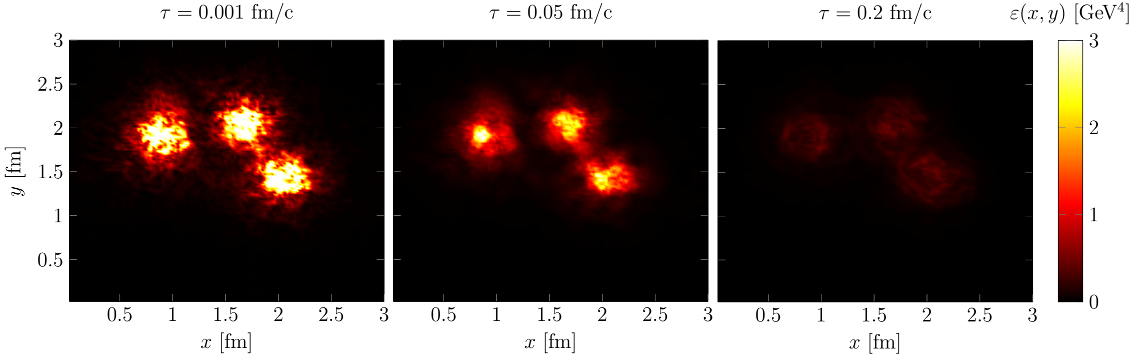
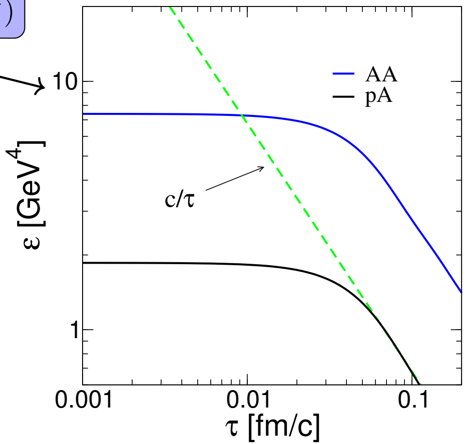


Energy density in pA vs τ

$\varepsilon_{pA}(0^+) < \varepsilon_{AA}(0^+)$



$\varepsilon \propto 1/\tau \implies$ dilute fields

32x32x32 lattice, $N_\tau = 400$

G.P., V. Greco and M. Ruggieri, 2505.08441 [hep-ph]

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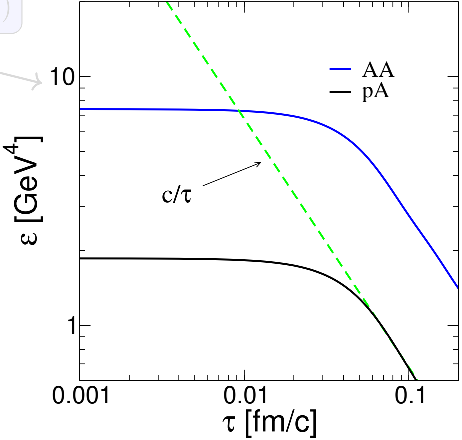

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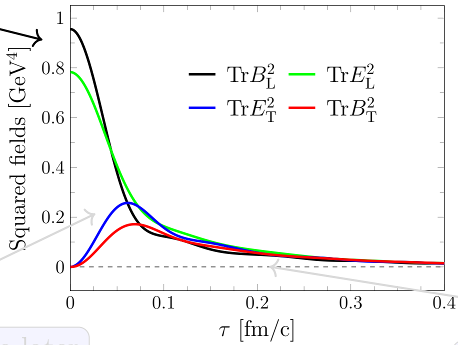
Fields in pA vs τ

Longitudinal fields $\neq 0$



Transverse fields emerge later

Dilute fields after ~ 0.1 fm/c

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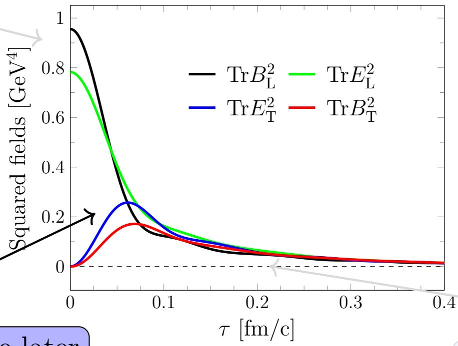

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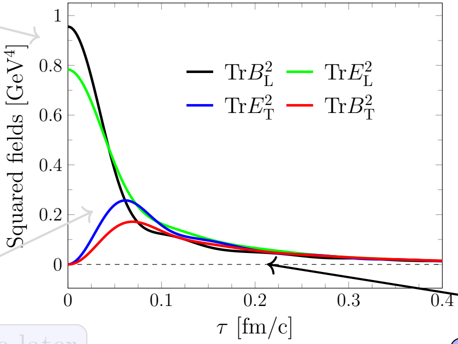

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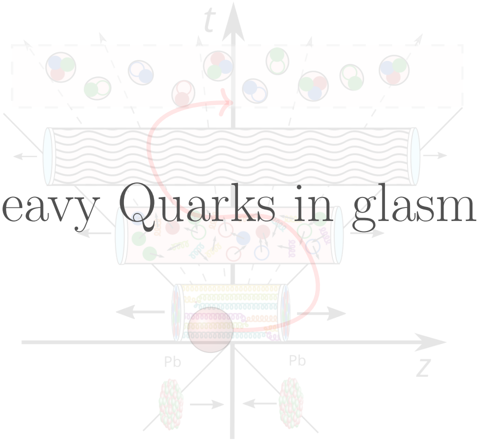
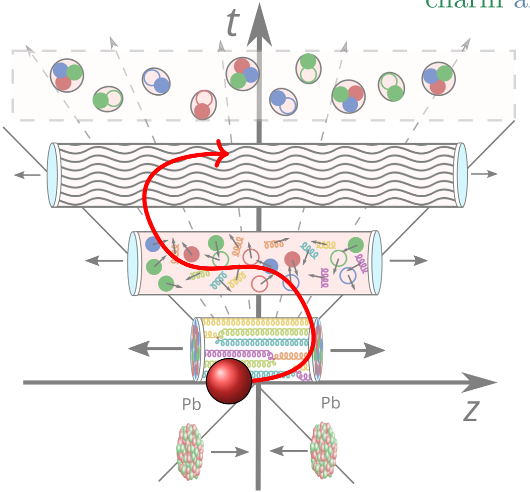
Heavy Quarks in glasma



Heavy quarks

charm and beauty



High mass: useful probes of initial stages

- $M \gg \Lambda_{QCD}$:
  early pQCD production
- $M \gg T_{QGP}$:
  no thermal production
- $\tau_{creation} \ll \tau_{QGP}$:
  probes of the collision

$$M_{\text{charm}} = 1.3\ \text{GeV},\ M_{\text{beauty}} = 4.2\ \text{GeV}$$

$$\tau_{\text{creation}} \sim 1/2M$$

A. Mazeliauskas: Stages of heavy ion collision

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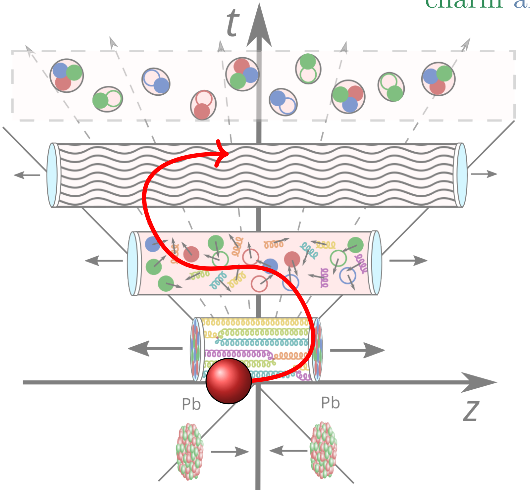

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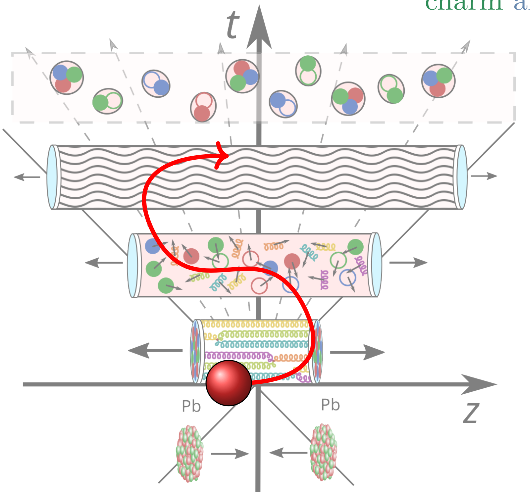

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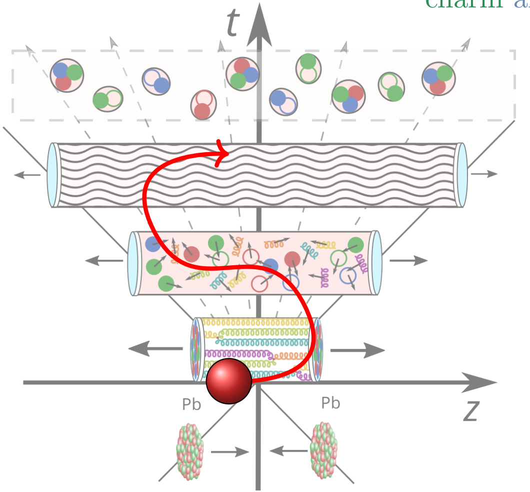

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Heavy Quarks in Yang-Mills fields

Wong equations

Classical transport in Yang-Mills background field A^μ

Coordinate evolution

$$\frac{\mathrm{d}}{\mathrm{d}\tau} x^\mu = \frac{p^\mu}{m}$$

Momentum evolution

$$\frac{\mathrm{d}}{\mathrm{d}\tau} p^\mu = \frac{1}{T_R} g \,\mathrm{Tr}\left\{ Q F^{\mu\nu} \right\} \frac{p_\nu}{m}$$

Color charge evolution

$$\frac{\mathrm{d}}{\mathrm{d}\tau} Q = -\mathrm{i} g [A_\mu, Q] \frac{p^\mu}{m}$$

S. K. Wong, Nuovo Cim. A 65 (1970) 689-694

U. W. Heinz, Annals Phys. 161 (1985) 48

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Basically $\mathbf{p} = m\mathbf{v}$

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Basically $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$

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Basically Color Rotation in SU(3)

Preserves Casimir invariants $q_2 = Q^aQ^a$ and $q_3 = d_{abc}Q^aQ^bQ^c$

S. K. Wong, Nuovo Cim. A 65 (1970) 689-694

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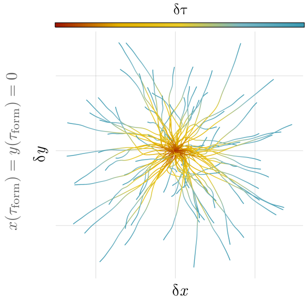
Heavy Quarks in Yang-Mills fields: trajectories

- Change in **coordinates** due to momentum kicks
- **Momentum** broadening due to color Lorentz force
- **Color charge** rotation in SU(3) with Wilson lines



D. Avramescu et al., Phys.Rev.D 107 (2023) 11, 114021

Image courtesy of Dana Avramescu

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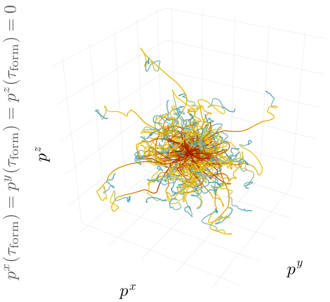

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Image courtesy of Dana Avramescu

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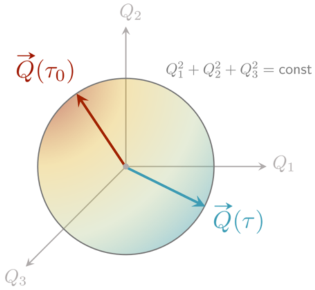


(Picture should actually be in 8 dims)

D. Avramescu et al., Phys.Rev.D 107 (2023) 11, 114021
Image courtesy of Dana Avramescu

Heavy Quarks in Yang-Mills fields: initialization

- Center of Mass position:

$$P(\mathbf{x}_\perp) \propto \mu(\mathbf{x}_\perp)$$

- Relative position:

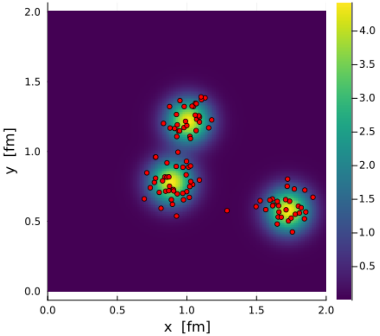
$$P(r_{\rm rel}) \propto r_{\rm rel}\, \exp\left(-r_{\rm rel}^2/\sigma^2\right)$$

- Relative momentum:

$$P(p_{\rm rel}) \propto p_{\rm rel}\, \exp\left(-p_{\rm rel}^2\sigma^2\right)$$

- Color charge:

$$\text{singlet}, \quad Q_a = -\bar{Q}_a$$



J. Zhao et al., Nuovo Cim. C 48, 5 (2025)

L. Oliva, G.P., V. Greco and M. Ruggieri, 2412.07967 [hep-ph], PRD accepted

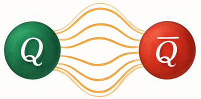
Heavy Quarks in Yang-Mills fields: pair potential

$$\frac{\mathrm{d}p^i}{\mathrm{d}\tau} = \frac{1}{T_R} g \,\mathrm{Tr}\left\{ Q F^{i\nu} \right\} \frac{p_\nu}{m} - \frac{\partial V}{\partial x^i}$$

Classical projection of pQCD potential

$$\hat{V} = T^a \otimes \bar{T}^a \frac{\alpha_s}{r_{\mathrm{rel}}} \implies V = \frac{Q_a \bar{Q}_a}{N_c} \frac{\alpha_s}{r_{\mathrm{rel}}}$$

- For $\tau = \tau_{\mathrm{form}}$, $Q_a \bar{Q}_a = -4$: attractive potential
- For $\tau > \tau_{\mathrm{form}}$: dynamic potential



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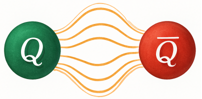

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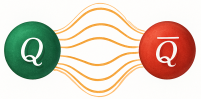

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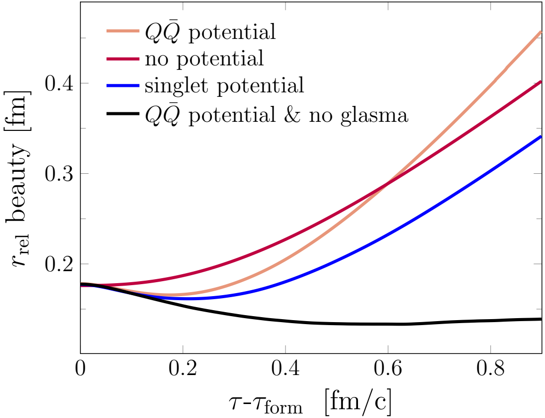
Relative distance

Effect of potential on beauty quark



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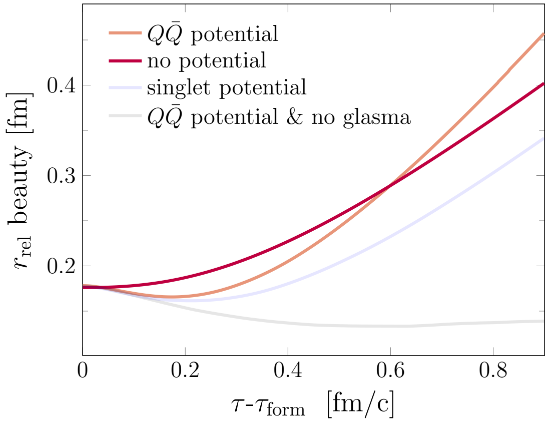

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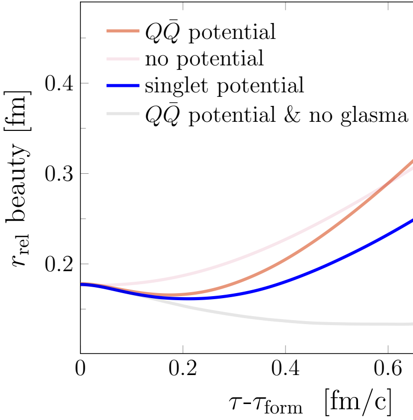

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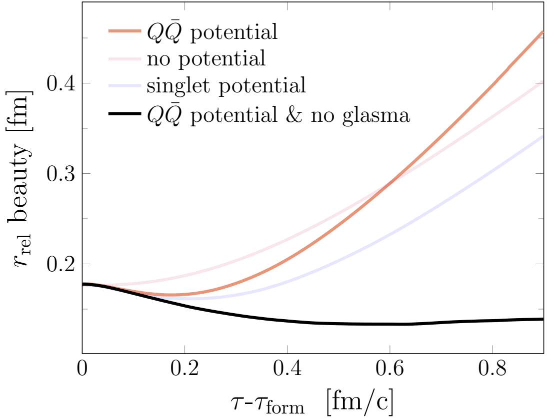

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Relative distance

charm vs beauty

- Physical input: $r_{\rm rel}^{\rm beauty} < r_{\rm rel}^{\rm charm}$
- Higher mass, lower spread
- Initial balance between:

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$\Updownarrow$

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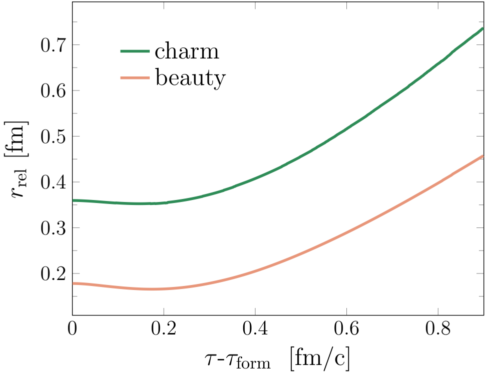

Distance not the main driver of pair decorrelation

(within glasma timescales)

L. Oliva, G.P., V. Greco and M. Ruggieri, 2412.07967 [hep-ph], PRD accepted

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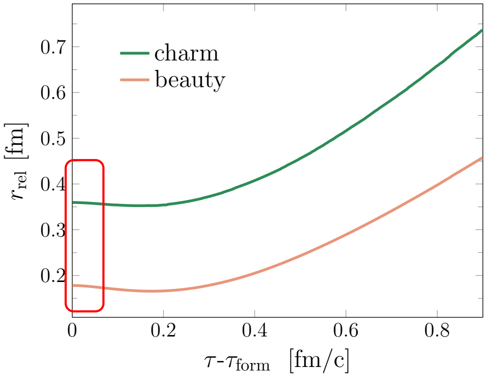

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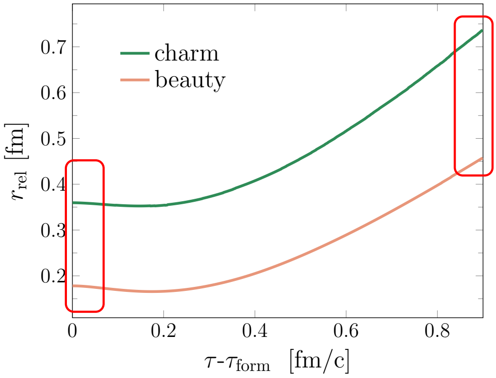

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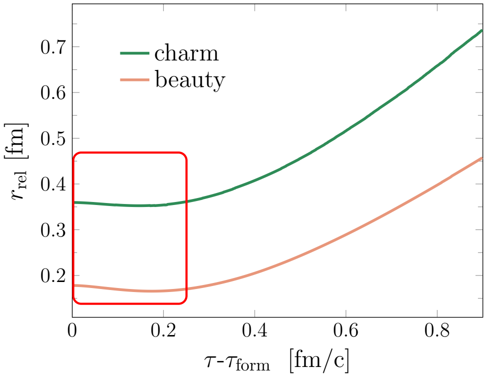

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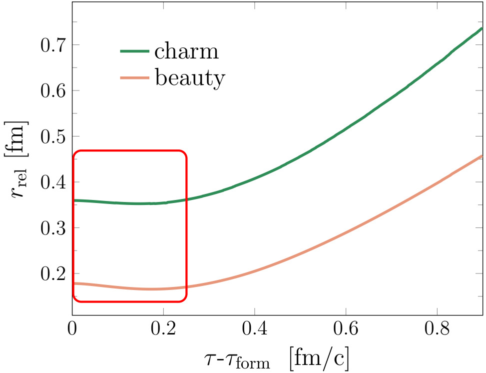

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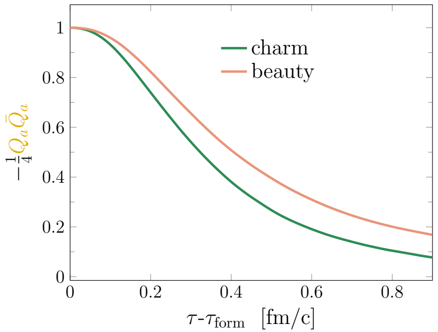
Dissociation of pairs

Melting of quarkonia due to color decorrelation



For each pair, at each time, we define:

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

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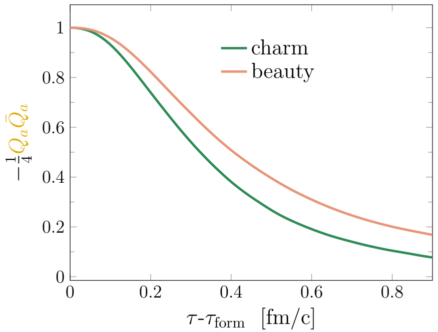

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Results: Dissociation of pairs

- Higher mass,
  implies slower diffusion,
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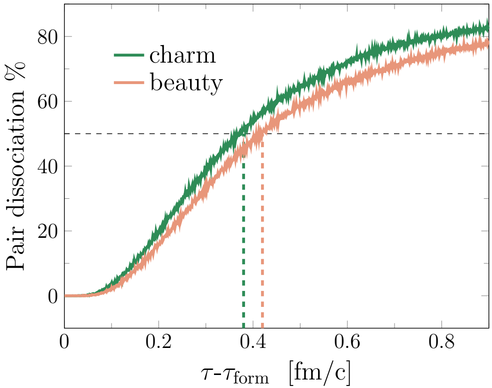
- At $\tau \sim 0.4$ fm/c, 50% of pairs melted



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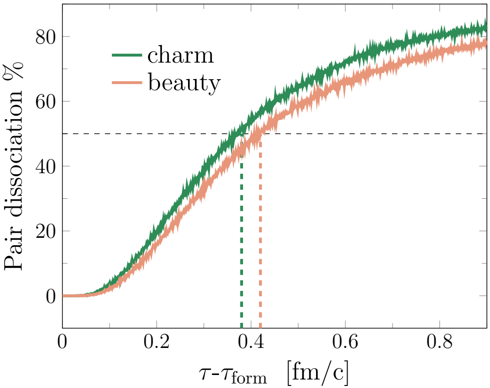

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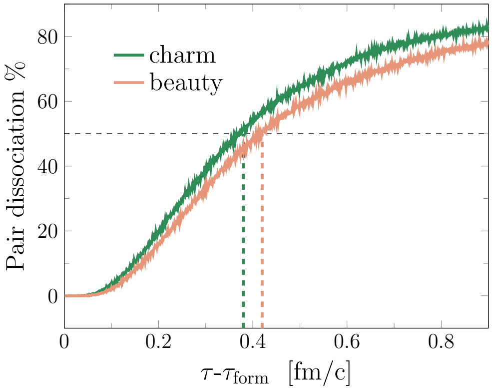

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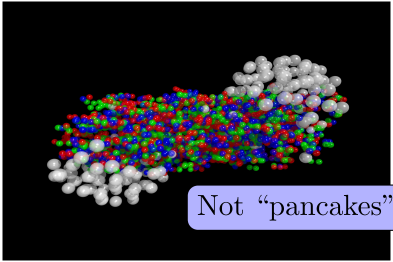
3+1D simulations

Heavy Ion Collisions are **not** boost-invariant:

rapidity-dependence to be taken into account.



Not “pancakes”

Same initial conditions + η-dependent terms such that:

$$D_i E_i(\eta) + D_\eta E_\eta(\eta) = 0 \quad \text{Gauss' Law}$$

Explicit expressions for δE in backup

https://spacegid.com/kvark-glyuonnaya-plazma.html

G.P., V. Greco and M. Ruggieri, 2505.08441 [hep-ph]

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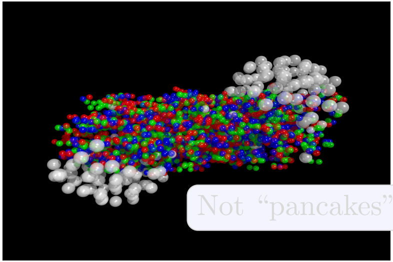

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Momentum broadening for $M_{\mathrm{HQ}} \to +\infty$

Focus on **momentum broadening**:

$$\delta p_i^2(\tau) \equiv p_i^2(\tau) - p_i^2(\tau_{\text{form}}), \qquad i = x, y, z.$$

One can prove that for $M_{\mathrm{HQ}} \to +\infty$:

$$\langle \delta p_L^2(\tau) \rangle_\infty = g^2 \int_{\tau_0}^{\tau} d\tau' \int_{\tau_0}^{\tau} d\tau'' \langle \mathrm{Tr}[E_z(\tau')E_z(\tau'')] \rangle$$

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D. Avramescu et al., Phys.Rev.D 107 (2023) 11, 114021

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D. Avramescu et al., Phys.Rev.D 107 (2023) 11, 114021

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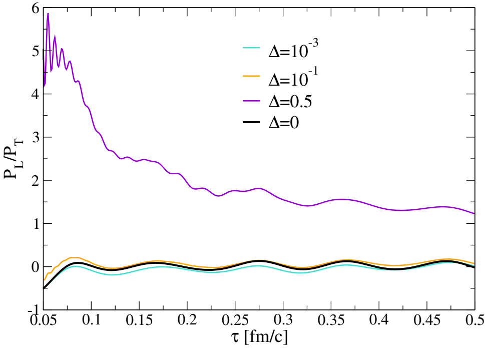
Results: 3+1D simulations

Pressures Ratio

Fluctuations scaling as $\delta E_i \sim \Delta$



Significant effect on pressure for high Δ

So, maybe fluctuations favor isotropization...

G.P., V. Greco and M. Ruggieri, 2505.08441 [hep-ph]

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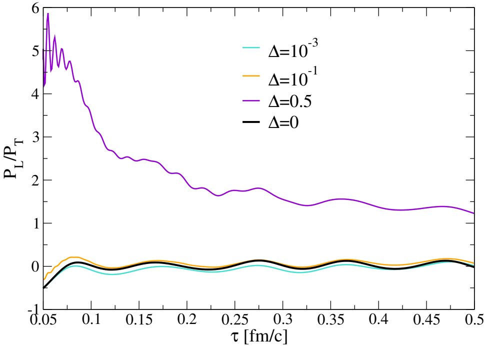

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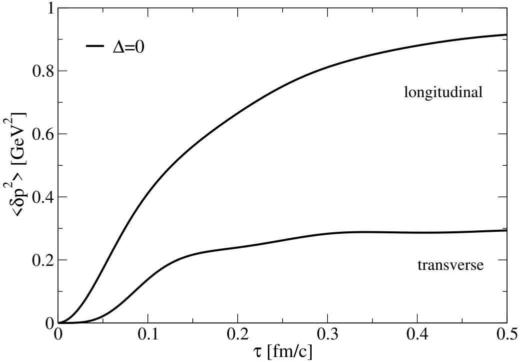
... or maybe not. Effect on momenta shifts irrelevant



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Need different initial conditions to favor isotropization

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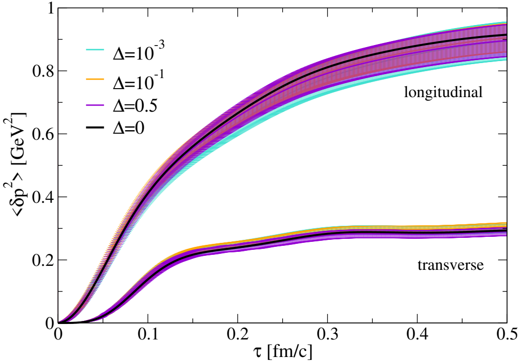

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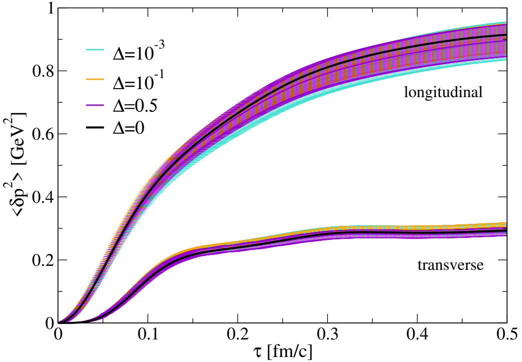

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Outro

Conclusions

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- Around 50% dissociation, due to color decorrelation
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Outlook

- Anisotropic flows v_n of gluons and Heavy Quarks in Glasma
- Coupling to later stages of Heavy Ion Collisions

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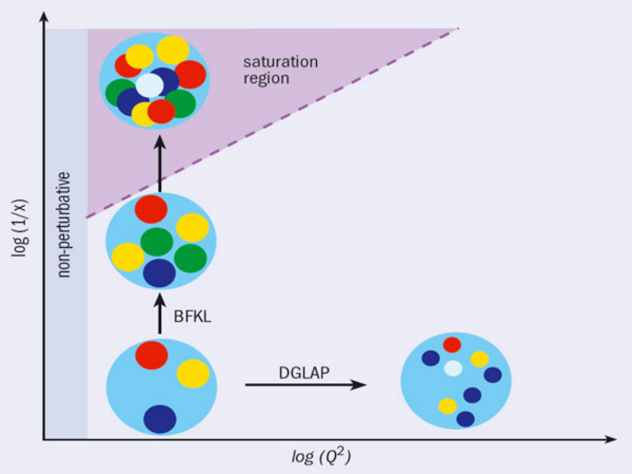
Thank you!

Any questions?

https://siciliamare.info/etna/

Back-up

BFKL and DGLAP evolutions



https://cerncourier.com/a/qcd-scattering-from-dglap-to-bfkl/

CYM on lattice

After gauge choice, YM equations reduce to:

$$\Delta_\perp \alpha(\mathbf{x}_\perp) = -\rho(\mathbf{x}_\perp) \implies \tilde{\alpha}^a_{n,k} = \frac{\tilde{\rho}^a_{n,k}}{\tilde{k}^2_\perp + m^2}$$

where

$$\tilde{k}^2_\perp = \sum_{i=x,y} \left(\frac{2}{a_\perp}\right)^2 \sin^2\left(\frac{k_i a_\perp}{2}\right).$$

CYM on lattice

Solve previous eq. for A^+_a in each nucleus (at $\tau = 0^-$). For $\tau = 0^+$?

$$A^+_{\text{tot}} = A^+_1 + A^+_2 \overset{?}{\Longrightarrow} U_{\text{tot}} \propto \exp\left[iA^+_{\text{tot}}\right] = U_1 \cdot U_2 \quad \text{NO!!}$$

In SU(3) no exact formula for U_{tot}, rather we iteratively solve:

$$\text{Tr}[t_a(U^A_{x,i} + U^B_{x,i})(\mathbb{I} + U_{x,i}) - \text{h.c.}] = 0.$$

Those U are needed for the magnetic fields:

$$B^2_L = \frac{2}{g^2 a^4_\perp}\text{Tr}(\mathbb{I} - U_{xy}), \qquad B^2_T = \frac{2}{(g a_\eta a_\perp \tau)^2}\sum_{i=x,y}\text{Tr}(\mathbb{I} - U_{\eta i}).$$

M. C. Cautun, Master Thesis (2009)

CYM on lattice

- **Initial conditions:**

$$E_x = E_y = 0, \quad U_\eta = \mathbb{I}, \quad U_{x/y} = U_{\mathrm{tot},x/y} \text{ as in previous slide}$$

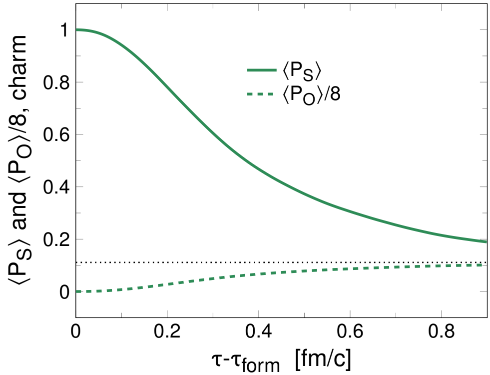
$$E^\eta = -\frac{i}{4ga_\perp^2} \sum_{i=x,y} \Big[(U_i(\mathbf{x}_\perp) - \mathbb{I})(U_i^{B,\dagger}(\mathbf{x}_\perp) - U_i^{A,\dagger}(\mathbf{x}_\perp)) + (U_i^\dagger(\mathbf{x}_\perp - \hat{i}) - \mathbb{I})(U_i^B(\mathbf{x}_\perp - \hat{i}) - U_i^A(\mathbf{x}_\perp - \hat{i})) - h.c. \Big].$$

- **Eqs of motion:**

$$\partial_\tau U_i(x) = \frac{-iga_\perp}{\tau} E^i(x) U_i(x), \qquad \partial_\tau U_\eta(x) = -iga_\eta \tau E^\eta(x) U_\eta(x).$$

Octet and Singlet projectors

$$P_S = -\frac{2}{3}\frac{Q_a\bar{Q}_a}{N_c} + \frac{1}{9}, \quad P_O = \frac{2}{3}\frac{Q_a\bar{Q}_a}{N_c} + \frac{8}{9},$$



At late times

$$\langle P_S \rangle \approx \langle P_O \rangle / 8 \approx 1/9.$$

Qualitative agreement with other approaches:

Brownian motion in QGP

L. Oliva, G.P., V. Greco and M. Ruggieri, 2412.07967 [hep-ph], PRD accepted

S. Delorme et al., JHEP 06 (2024) 060

Explicit expressions for δE

$$\delta E^i = a_\eta^{-1}[F(\eta - a_\eta) - F(\eta)]\xi_i(\mathbf{x}_\perp),$$
$$\delta E^\eta = -a_\perp^{-1} F(\eta) \sum_{i=x,y} [U_i^\dagger(\mathbf{x}_\perp - \hat{i})\xi_i(\mathbf{x}_\perp - \hat{i})U_i(\mathbf{x}_\perp - \hat{i}) - \xi^i(\mathbf{x}_\perp)],$$

where ξ such that:

$$\langle \xi_i(\mathbf{x}_\perp)\xi_j(\mathbf{y}_\perp)\rangle = \delta_{ij}\delta^{(2)}(\mathbf{x}_\perp - \mathbf{y}_\perp).$$

P. Romatschke and R. Venugopalan, Phys.Rev.D 74 (2006) 045011

K. Fukushima and F. Gelis, Nucl.Phys.A 874 (2012) 108-129

Explicit expressions for δE

Actual shape of the fluctuation given by $F(\eta)$. We can choose:

- Random gaussian function in η.
- Oscillating function $F(\eta) = \frac{\Delta}{N_\perp} \cos\left(\frac{2\pi\eta}{L_\eta} \cdot \nu_0\right)$ for some ν_0.
- Superposition of oscillating functions:

$$F(\eta) = \sum_\nu \frac{\Delta}{N_\perp} \cos\left(\frac{2\pi\eta}{L_\eta} \cdot \nu\right).$$

The 'seed' Δ regulates the amplitude.

P. Romatschke and R. Venugopalan, Phys.Rev.D 74 (2006) 045011

K. Fukushima and F. Gelis, Nucl.Phys.A 874 (2012) 108-129