The glasma initial stage of heavy ion collisions

Tuomas Lappi
BNL
tvv@quark.phy.bnl.gov

ETD-HIC, McGill, July 2007

Abstract

The initial stages of a heavy ion collision can be described as a classical color field configuration known as the glasma. I will describe how this framework enables one to relate the initial stage of heavy ion collisions to DIS measurements of the nuclear wavefunction. The glasma field configurations have been shown to be unstable already at the classical field level; I will present some preliminary results from numerical studies of these instabilities.

Outline

- Glass and glasma
- Heavy ion collisions and DIS
- Instabilities in the classical field

Glass and Glasma

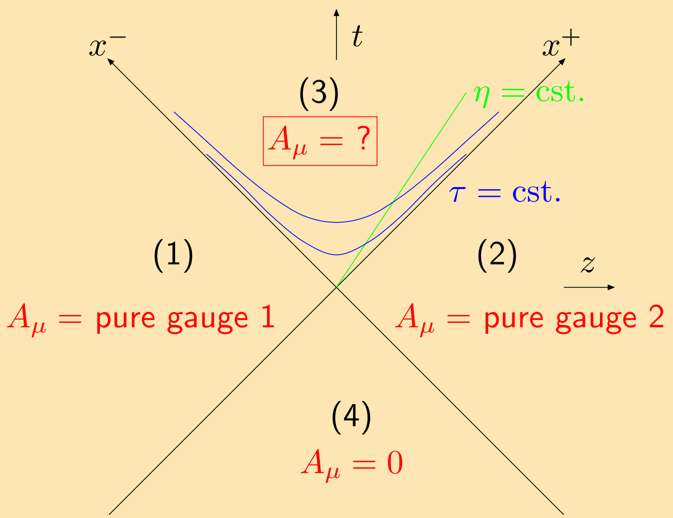
Gluon saturation: At large energies (small x) the hadron/nucleus wavefunction is characterized by saturation scale $Q_s \gg \Lambda_{QCD}$.

At $\mathbf{p}_T \sim Q_s$: strong gluon fields $A_\mu \sim 1/g$ ▶ large occupation numbers $\sim 1/\alpha_s$ ▶ classical field approximation.

CGC: The saturated wavefunction of one nucleus

Glasma:[1]

- The coherent, classical field configuration of two colliding sheets of CGC.
- Initial condition for heavy ion collision at $0 < \tau \lesssim 1/Q_s$.



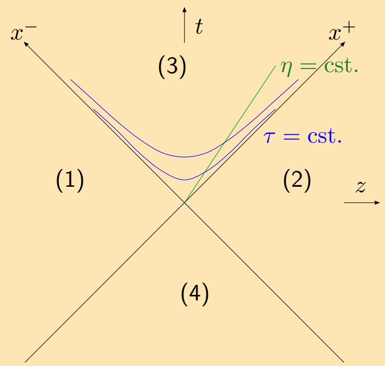
[1] T. Lappi and L. McLerran, *Nucl. Phys.* **A772** (2006) 200 [hep-ph/0602189].

MV model, Weizsäcker-Williams color field

Separation of scales: **small x = classical field,** **large x = color charge**

$$[D_\mu, F^{\mu\nu}] = J^\nu$$

$$J^\mu = \delta^{\mu +}\rho_{(1)}(\mathbf{x}_T)\delta(x^-) + \delta^{\mu -}\rho_{(2)}(\mathbf{x}_T)\delta(x^+)$$



What is the charge density $\rho(\mathbf{x}_T)$? The MV[2] model: take a Gaussian 2d noise:

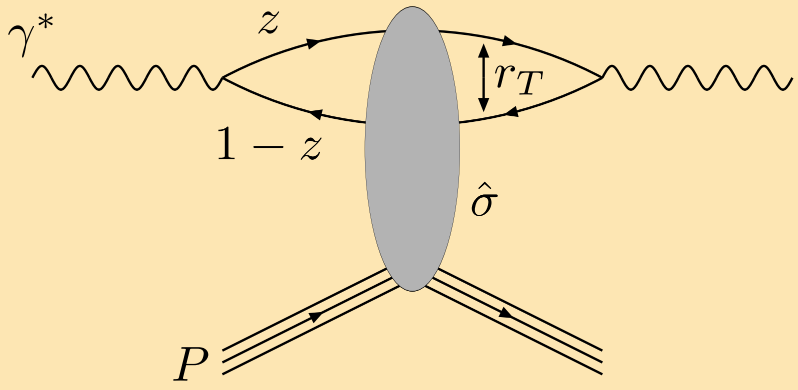
$$\langle \rho^a(\mathbf{x}_T)\rho^b(\mathbf{y}_T)\rangle = g^2\mu^2\delta^{ab}\delta^2(\mathbf{x}_T - \mathbf{y}_T)$$

and average all quantities calculated from $\rho(\mathbf{x}_T)$. Simple, leads to gluon saturation $Q_\mathrm{s} \sim g^2\mu$.

[2] L. D. McLerran and R. Venugopalan, *Phys. Rev.* **D49** (1994) 2233 [hep-ph/9309289].

Relation to DIS

DIS at high energy/small x: dipole cross section, which can be calculated from the classical field:



$$\hat{\sigma}(\mathbf{r}_T) = \int \mathrm{d}^2\mathbf{b}_T \frac{1}{N_\mathrm{c}} \left\langle 1 - U^\dagger\left(\mathbf{b}_T + \frac{\mathbf{r}_T}{2}\right) U\left(\mathbf{b}_T - \frac{\mathbf{r}_T}{2}\right)\right\rangle$$

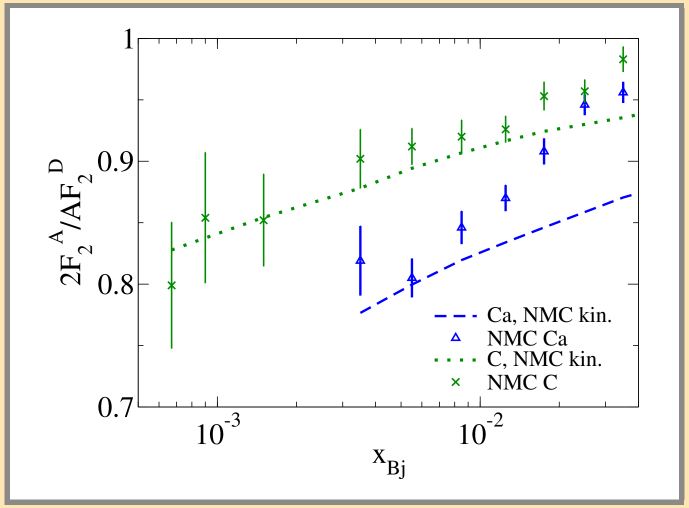
$$U(\mathbf{x}_T) = P\exp\left\{ig\int \mathrm{d}x^- A^+_{\mathrm{cov}}(\mathbf{x}_T, x^-)\right\}$$

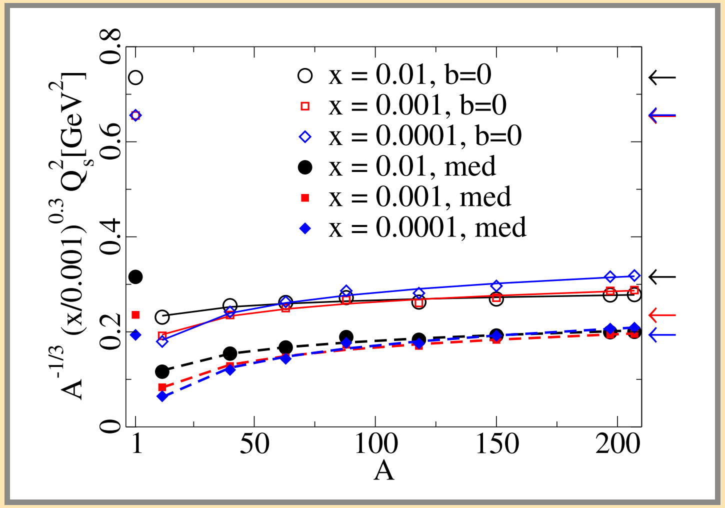
This same Wilson line gives the (LC gauge) pure gauge field in the $\tau = 0$ initial condition for the two nucleus problem.

$$A^i_{(\text{one nucleus})} = \frac{i}{g} U(\mathbf{x}_T)\partial_i U^\dagger(\mathbf{x}_T)$$

Value of Q_s from DIS, from proton to nucleus

Kowalski, Teaney [3], Kowalski, TL, Venugopalan [4]: DGLAP-improved parametrization of dipole cross section, fit to HERA data.





Result $Q_s(b_{\mathbf{med}}) \approx 1.2\mathbf{GeV}$ at RHIC, corresponding to $g^2\mu \approx 2.1\mathbf{GeV}$

▶ leads to $\mathrm{d}N/\mathrm{d}y \approx 1000$, good agreement with previous estimates.

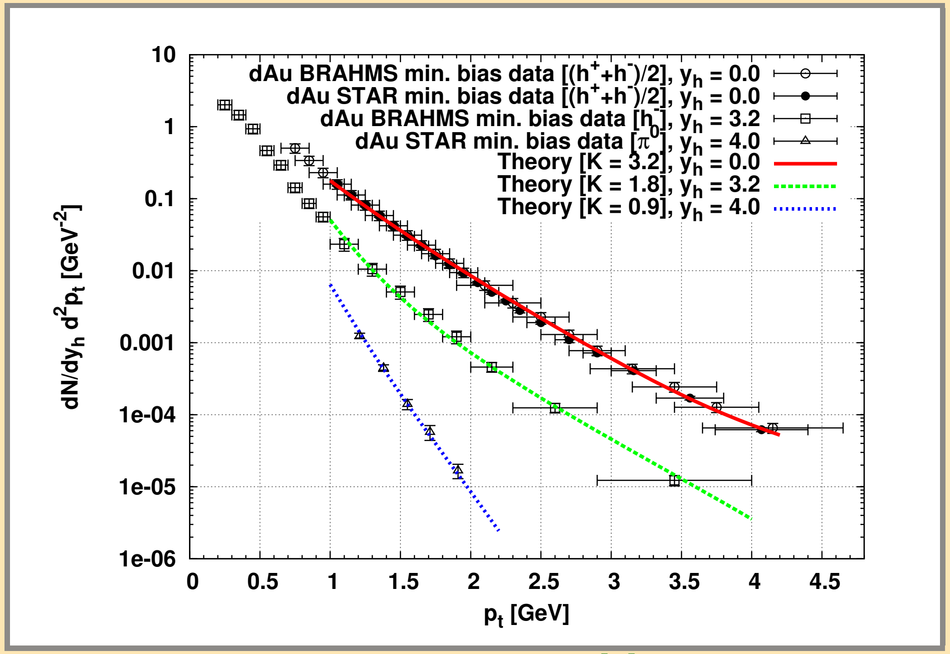
[3] H. Kowalski and D. Teaney, *Phys. Rev.* **D68** (2003) 114005 [hep-ph/0304189].

[4] H. Kowalski, T. Lappi and R. Venugopalan, arXiv:0705.3047 [hep-ph].

CGC and spectra in pA

Spectrum in (forward) pA:

- DGLAP-evolved large-x pdf for proton
- CGC description of small x nucleus (unintegrated pdf) ▶ $p_\perp$ sensitive to Q_s^A



Plot from Dumitru et al. [5]

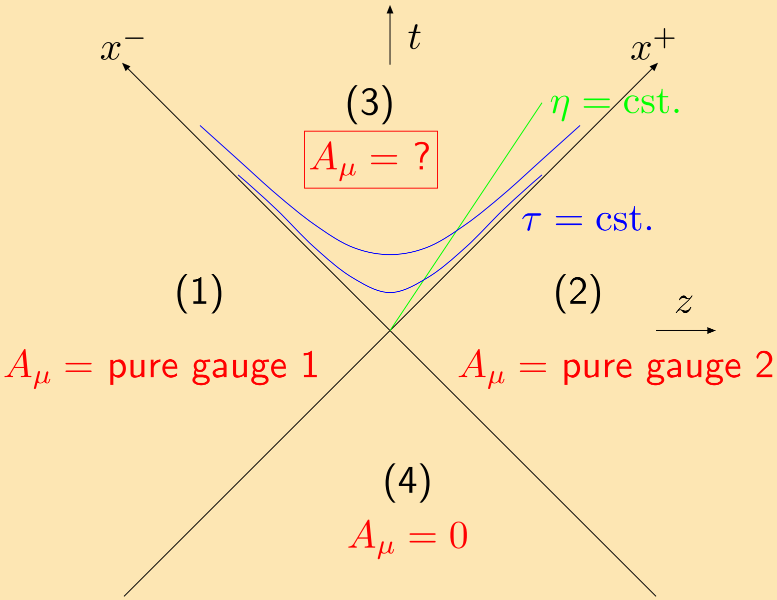
$$\frac{\mathrm{d}\sigma^{pA\to hX}}{\mathrm{d}^2\mathbf{p}_T\,\mathrm{d}^2\mathbf{b}_T\,\mathrm{d}y} = \int_{x_F}^{1} \mathrm{d}x f_{q/p}\left(x,Q^2\right) \overbrace{N_F\left(\frac{x}{x_F}\mathbf{p}_T,\mathbf{b}_T\right)}^{\text{from UU-correlator}} D_{h/q} + \{q \leftrightarrow g\}$$

[5] A. Dumitru, A. Hayashigaki and J. Jalilian-Marian, *Nucl. Phys.* **A770** (2006) 57 [hep-ph/0512129].

From glass to glasma: initial condition

Work in LC gauge: field of one nucleus only has transverse $A_i^{(m)}$

Analytical solution for regions (1) & (2) known pure gauge ▶ Gives initial condition (Kovner, McLerran, Weigert[6]) for numerical solution (Krasnitz, Nara, Venugopalan [7]) in region (3):



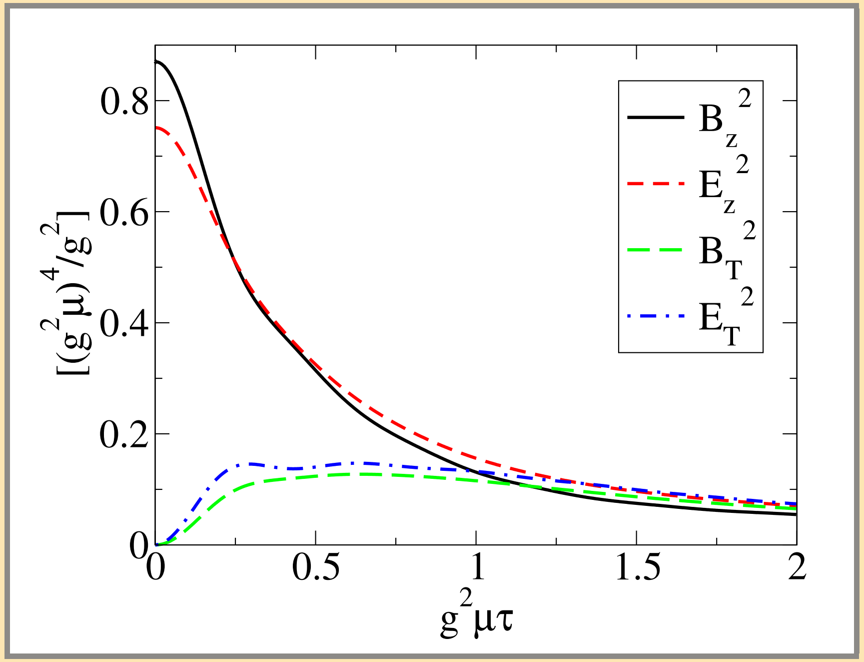
$$A_i^{(3)}|_{\tau=0} = A_i^{(1)} + A_i^{(2)}$$

$$A^\eta|_{\tau=0} = \frac{ig}{2}\left[A_i^{(1)}, A_i^{(2)}\right]$$

Gauge choice: $A_\tau = \frac{1}{\tau}(x^+A^- + x^-A^-) = 0$

[6] A. Kovner, L. D. McLerran and H. Weigert, *Phys. Rev.* **D52** (1995) 3809 [hep-ph/9505320].
[7] A. Krasnitz and R. Venugopalan, *Nucl. Phys.* **B557** (1999) 237 [hep-ph/9809433].

Glasma fields



Initially longitudinal chromoelectric and chromomagnetic fields with transverse length scale $1/Q_\mathrm{s}$.

For $Q_\mathrm{s}\tau \lesssim 1$ "longitudinal pressure" is negative

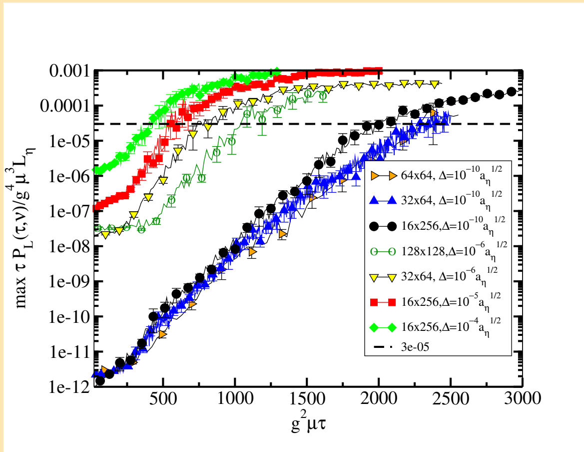
$$T_{zz} = \frac{1}{2}\left(E_T^2 - E_z^2 + B_T^2 - E_z^2\right)$$

no particle interpretation.

Instabilities in classical field

MV initial condition is boost invariant ▶ p_z redshifted $\sim 1/\tau$, anisotropic $\mathbf{p}$-distribution, ▶ Weibel instability.

- HTL, HEL, PIC simulations See talks later today
- Purely classical field



Romatschke & Venugopalan[8,9]
Allow for η-dependence of modes: plasma instability. Growth rate related to the "plasmon mass" $\Gamma \sim \sqrt{g^2\mu/\tau}$

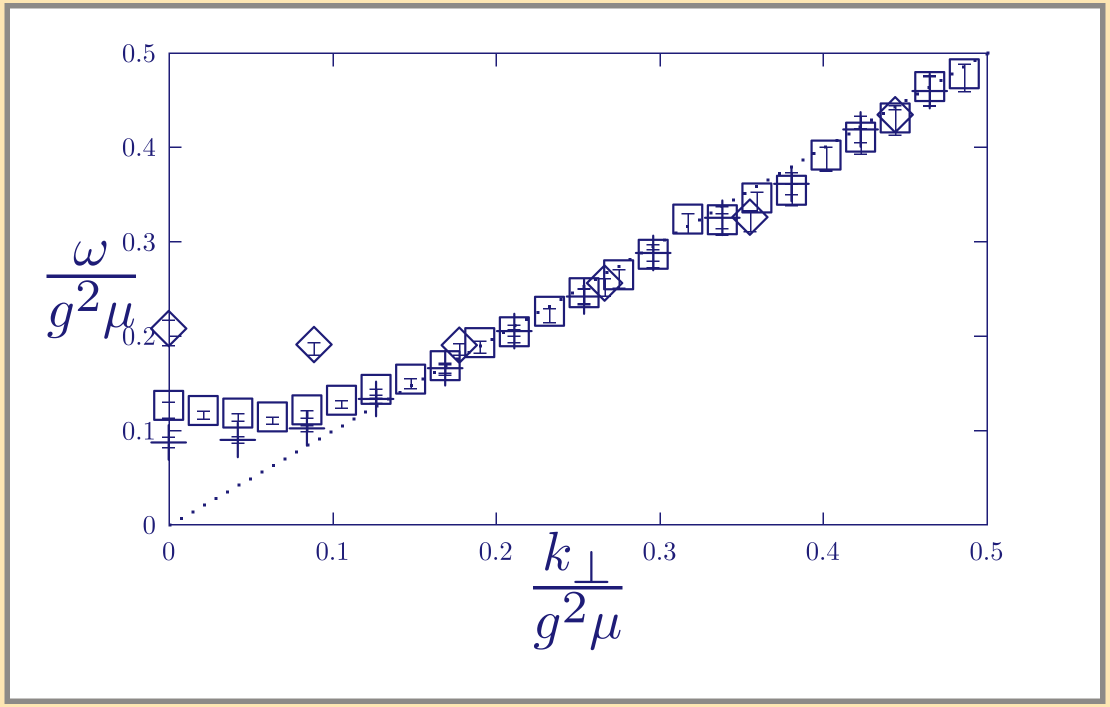
Denote ν the momentum conjugate to rapidity: $\int \mathrm{d}\eta e^{i\nu\eta} f(\eta)$

[8] P. Romatschke and R. Venugopalan, *Phys. Rev. Lett.* **96** (2006) 062302 [hep-ph/0510121].
[9] P. Romatschke and R. Venugopalan, *Phys. Rev.* **D74** (2006) 045011 [hep-ph/0605045].

Mass gap

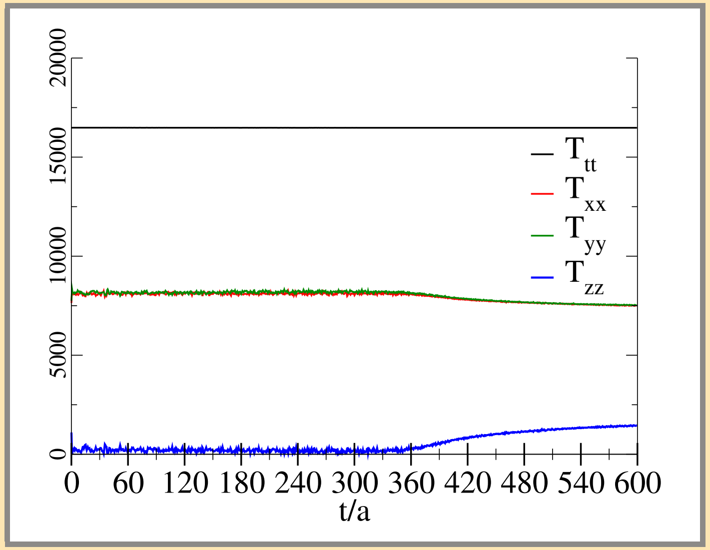
K & V [10]: There is a dynamically generated mass gap: $m^2 \sim g^2\mu/\tau$.

This is what makes the gluon spectrum IR finite. R & V: Related to the instability growth rate?



[10] A. Krasnitz and R. Venugopalan, *Phys. Rev. Lett.* **86** (2001) 1717 [hep-ph/0007108].

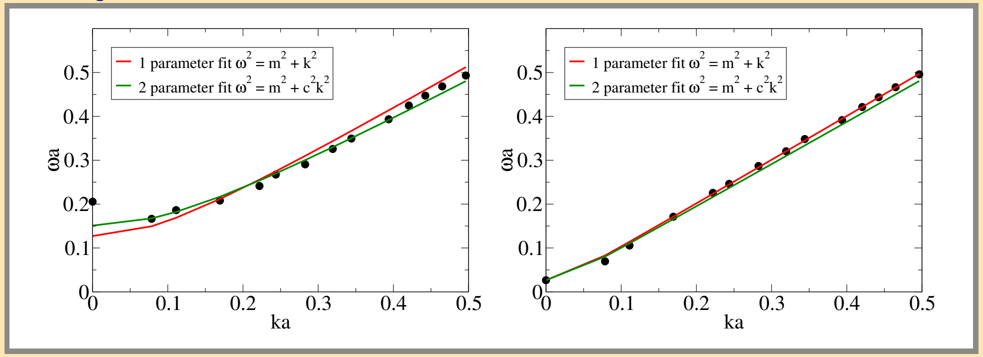
Mass gap, nonexpanding case

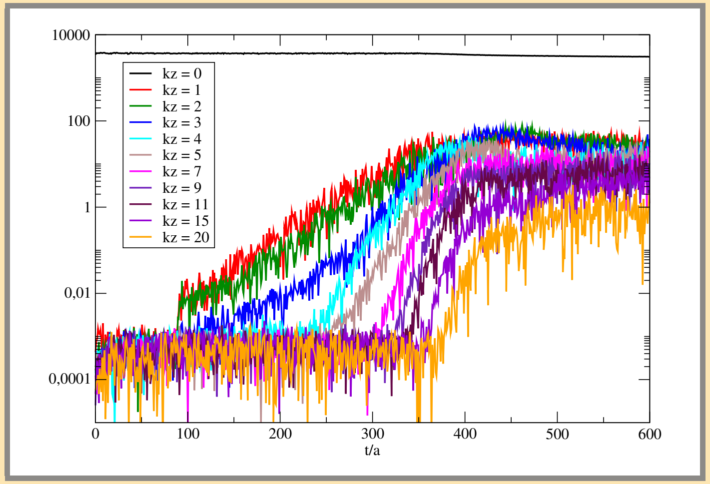


$\Longleftarrow$ $T_{\mu\nu}$ components

Dispersion relation:

Early time late time

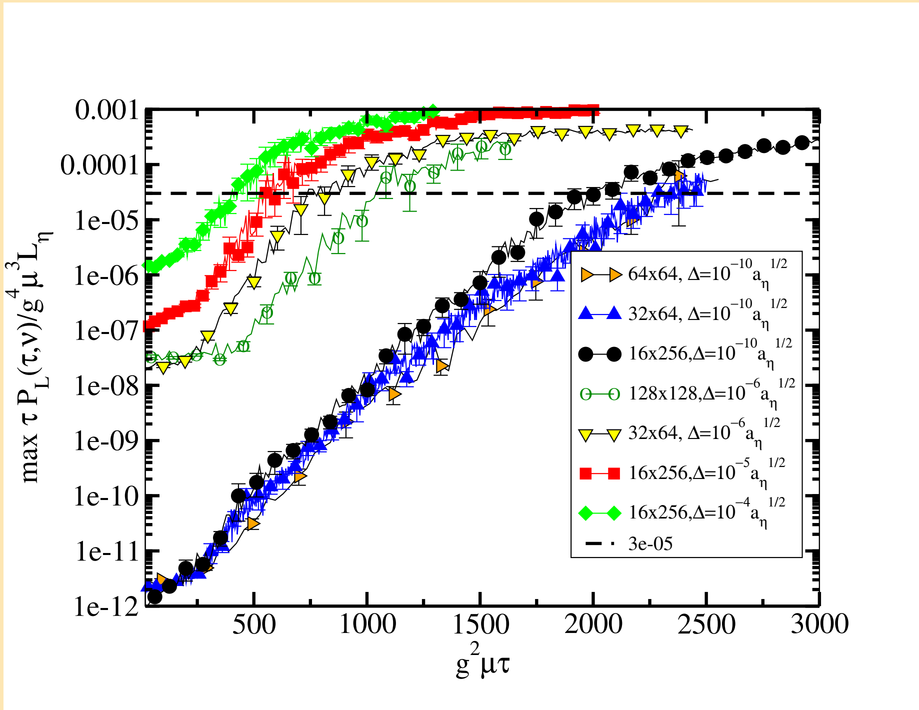




$\Longleftarrow$ Individual k_z-modes of $T_{\mu\nu}$:

Timescales

Growth as $e^{C\sqrt{g^2\mu\tau}}$.
Too little, too late for thermalization at RHIC, it seems.

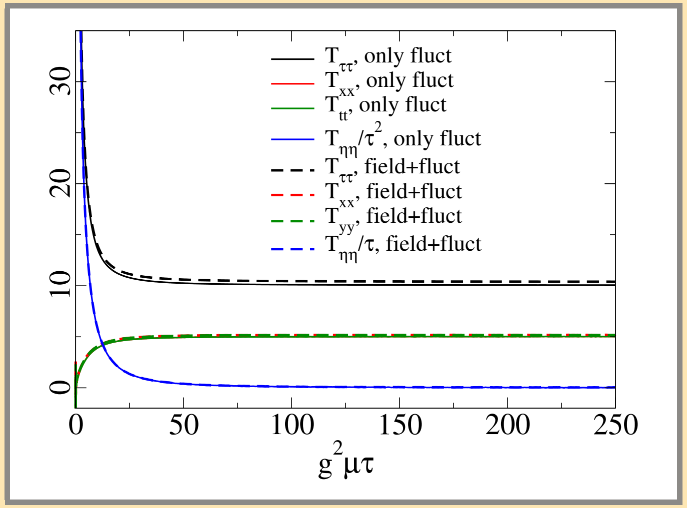


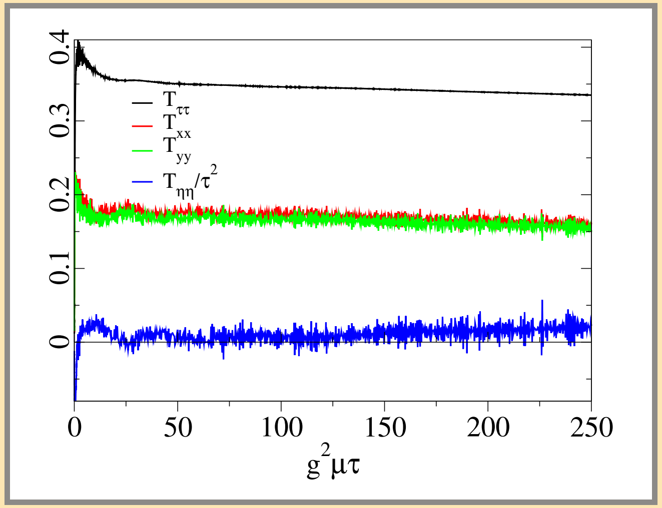
Initial condition from zero point fluctuations

Gelis, Fukushima, McLerran [11]: initial conditions from zero point fluctuations of background field. $n(\mathbf{k}) \sim |\mathbf{k}| = \sqrt{\mathbf{k}_T{}^2 + (\nu/\tau)^2}$

(Suppressed by α_s wrt. to background field $AA \sim 1/\alpha_\mathrm{s}$)

Very UV divergent spectrum: remormalize by subtracting purely fluctuation part from fluctuation + background field

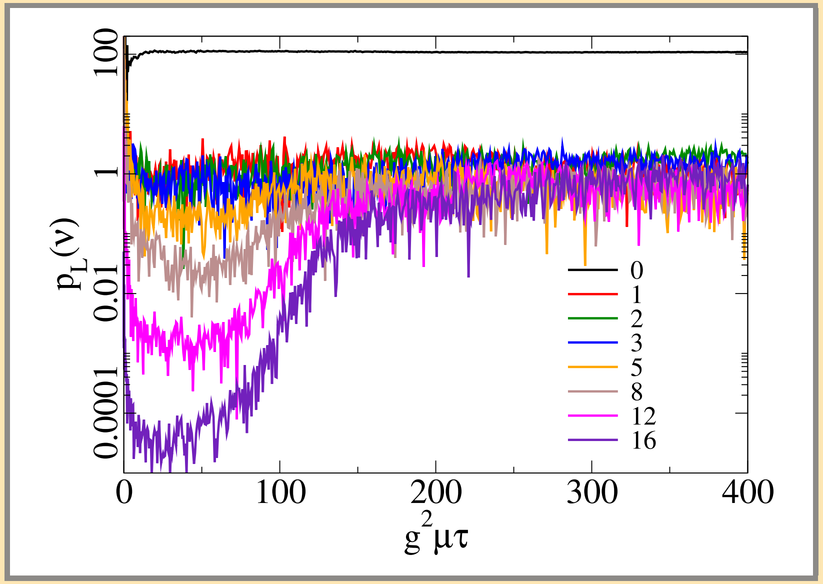


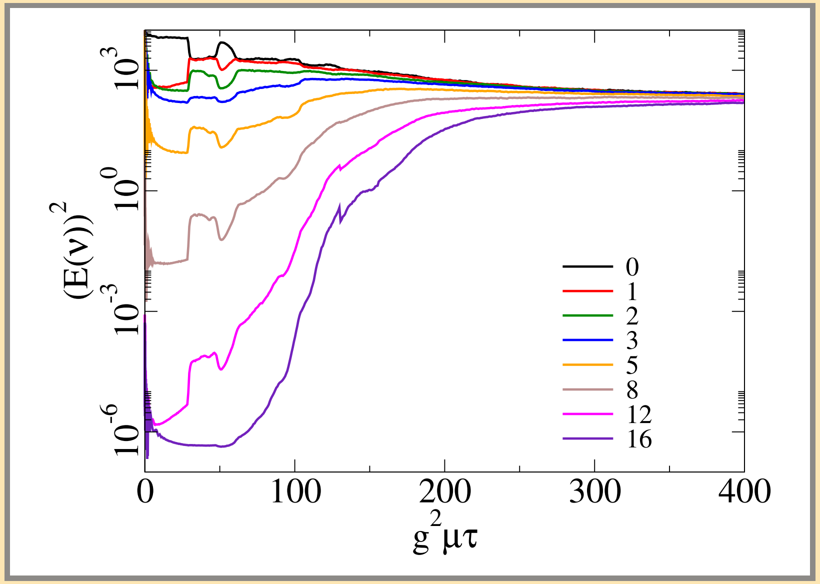


[11] K. Fukushima, F. Gelis and L. McLerran, *Nucl. Phys.* **A786** (2007) 107 [hep-ph/0610416].

Gauge fixing and spectra

Is difficult for very anisotropic field configurations, but must be done to get more detailed understanding.





Conclusions

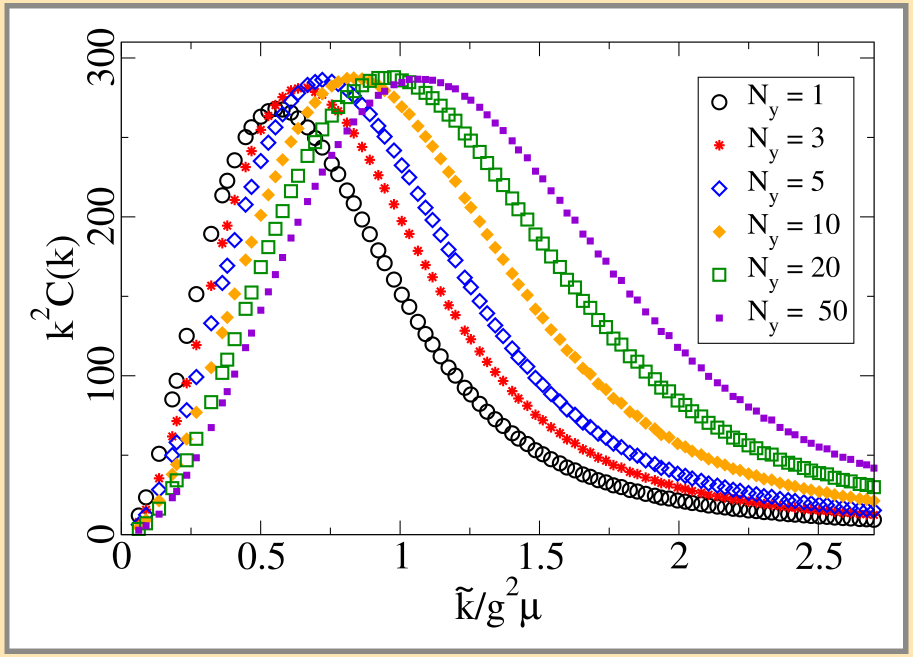
- Collision of two sheets of color glass: resulting field configuration with initially longitudinal fields ("glasma" fields).
- CGC framework: unified description of ep, eA, pA, AA . . .
- Classical field configurations are unstable
  - Dynamically generated mass gap
  - Initial conditions from zero point fluctuations renormalizable numerically
  - Gauge fixing for more detailed understanding

Backups

MV model leads to saturation

$$C(\mathbf{k}_T) = \int \mathrm{d}^2\mathbf{x}_T U^{ab}(\mathbf{b}_T + \mathbf{x}_T) U^{ab}(\mathbf{b}_T) e^{i\mathbf{k}_T\cdot\mathbf{x}_T}$$

- N_y: discretization of longitudinal x^- coordinate.
- Glasma numerics: $N_y = 1$.
- Dipole cross section has characteristic scale $Q_\mathrm{s} \sim g^2\mu$



Linearity

Explicitly linearized theory not yet solved numerically:

Not completely evident if instability is linear in the boost-invariance violating perturbation.