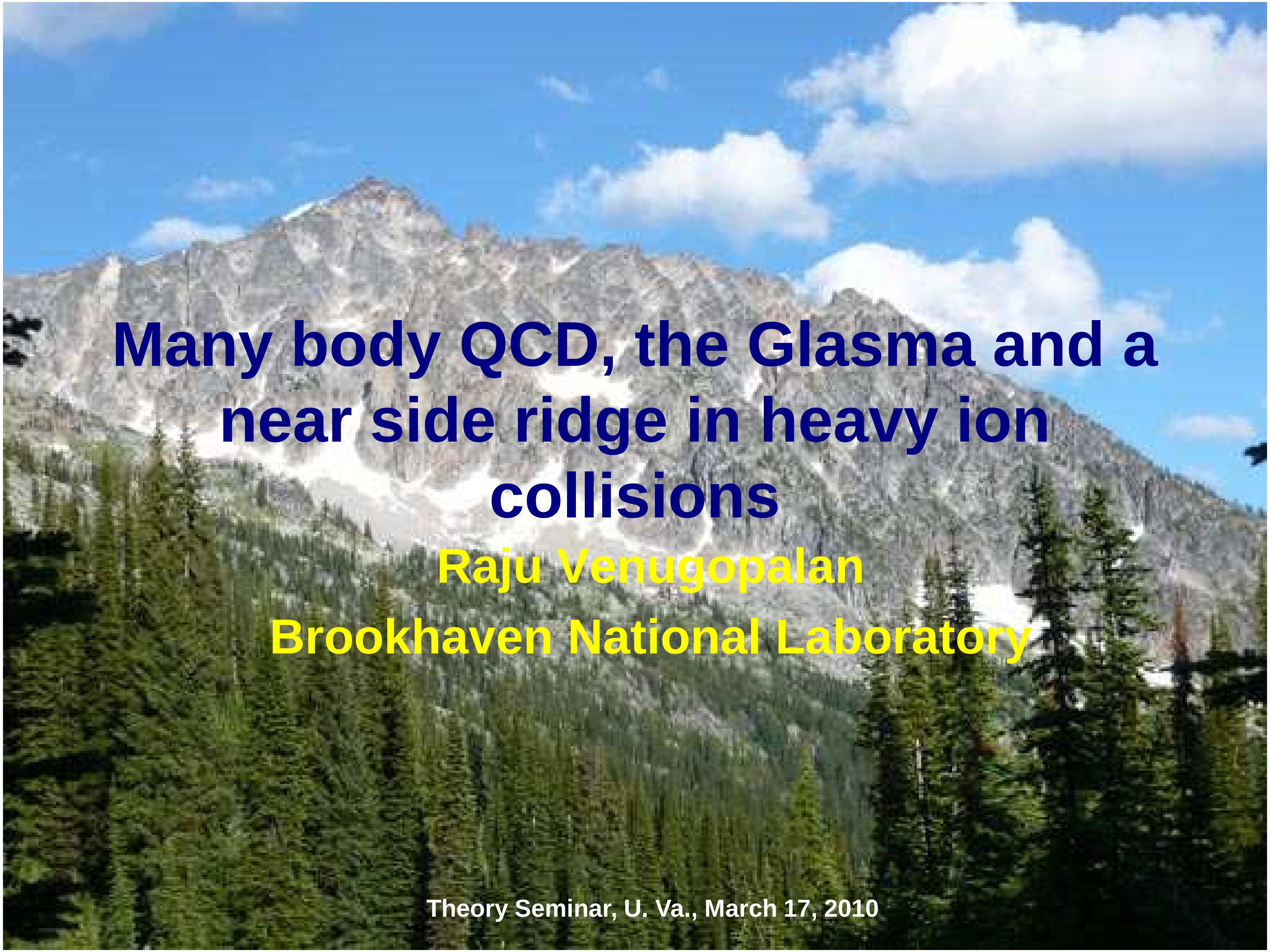


Many body QCD, the Glasma and a near side ridge in heavy ion collisions

Raju Venugopalan

Brookhaven National Laboratory

Theory Seminar, U. Va., March 17, 2010

What does a heavy ion collision look like ?

D. Nucleus-Nucleus Collisions at Fantastic Energies

Before leaving this subject it is fun to consider the collision of two nuclei at energies sufficiently high so that in addition to the fragmentation regions, a central plateau region can develop. Let us consider a central collision of a relatively small nucleus, say carbon, with a big one, say lead. Let us look at this collision in a center-of-mass frame for which the rapidities of both of the nucleus projectiles exceeds the critical rapidity. In such a frame they both possess the fur coat of wee-parton vacuum fluctuations. In such a central collision we see that the collision initially occurs between the fur of wee partons in each of the projectiles. Therefore the number of independent collisions will be of order of the area of overlap of the two projectiles; namely the cross-sectional area of the smaller nucleus.

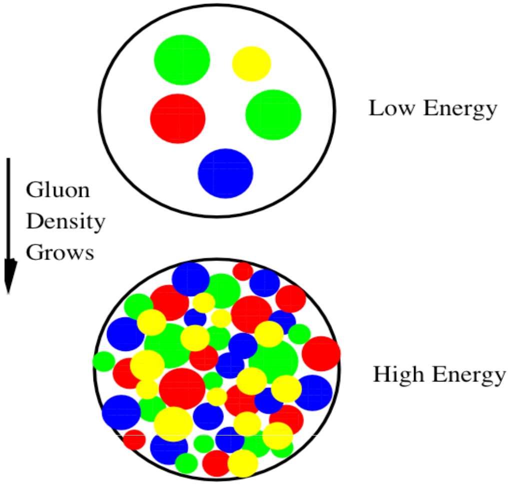
ract and produce

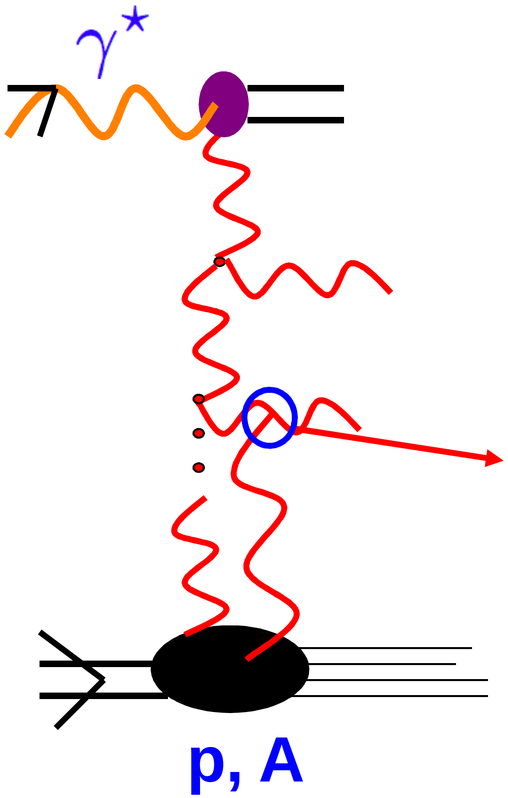
...idity distribution which is shown in Fig. 9. Much more professional studies ...ng the same line of initial assumptions can be found in the work of ... Kancheli,[32] E. Lehman and G. Winbow,[33] J. Koplik and A. Mueller,[34] and Goldhaber.[35]

Bj, DESY lectures (1975)

Gluon saturation in QCD

Gribov,Levin,Ryskin
Mueller,Qiu





Large x - bremsstrahlung
linear evolution (DGLAP/BFKL)
-sum logs in Q^2 / x to all orders

Small x -gluon recombination
non-linear evolution
(BK/JIMWLK)

Saturation scale $Q_S(x)$ - dynamical scale below which non-linear ("higher twist") QCD dynamics is dominant

In IMF, occupation # f = $1/\alpha_S$ => hadron is a dense, many body system

The nuclear wavefunction at high energies

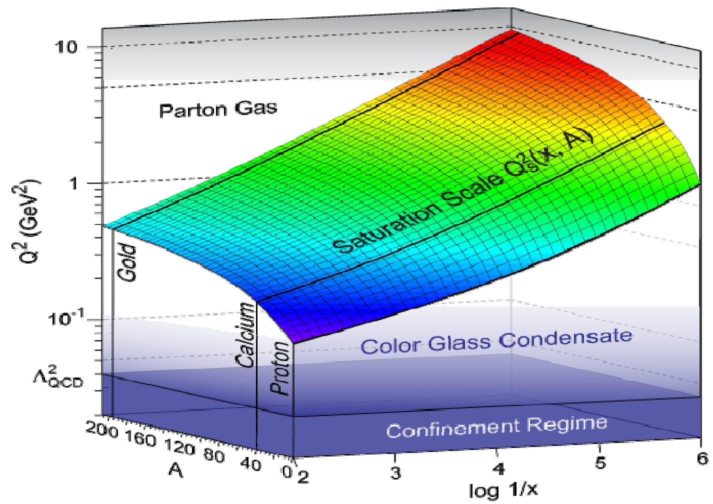
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- At high energies, interaction time scales of fluctuations are dilated well beyond typical hadronic time scales
- Lots of short lived (gluon) fluctuations now seen by probe -- proton/nucleus -- dense many body system of (primarily) gluons
- Fluctuations with lifetimes much longer than interaction time for the probe function as static stochastic color sources for more short lived fluctuations

Nuclear wave function at high energies is a Color Glass Condensate

Iancu,RV:hep-ph/0303204
Gelis,Iancu,Jalilian-Marian,RV
arXiv1002.0333

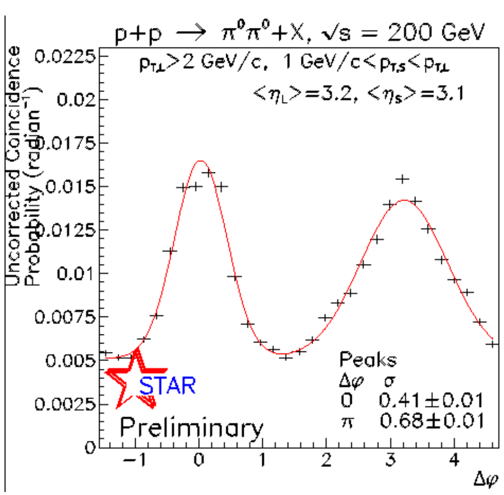
The Color Glass Condensate

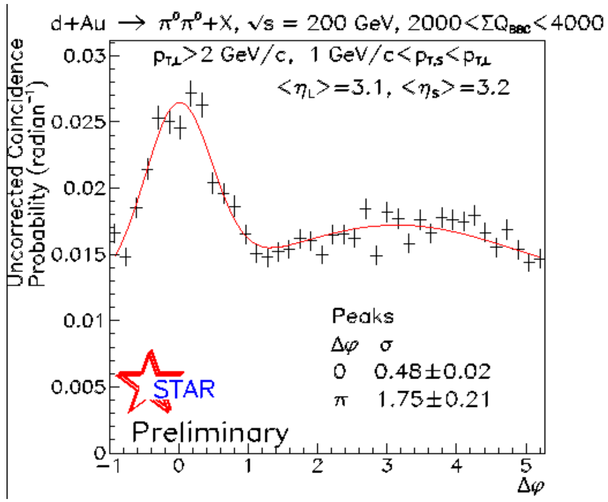


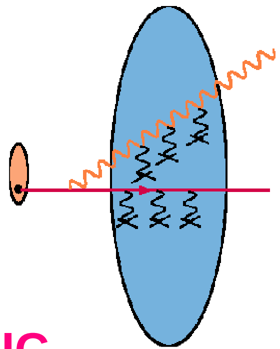
$$\alpha_S(Q_S^2) << 1$$

Q_S^2 ~ 1.2-1.4 GeV^2 (RHIC)
Q_S^2 ~ 2.6-3.9 GeV^2 (LHC)

CGC: *Classical* weak coupling effective theory of QCD of dynamical gluon fields + static color sources in non-linear regime





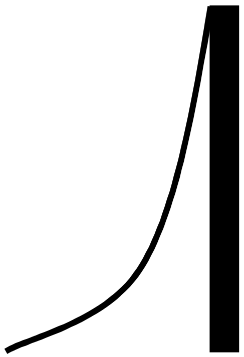


Very recent RHIC data on d+Au collisions suggests very strong color fields in Au at x =10^{-3}

Marquet; Tuchin (2010)

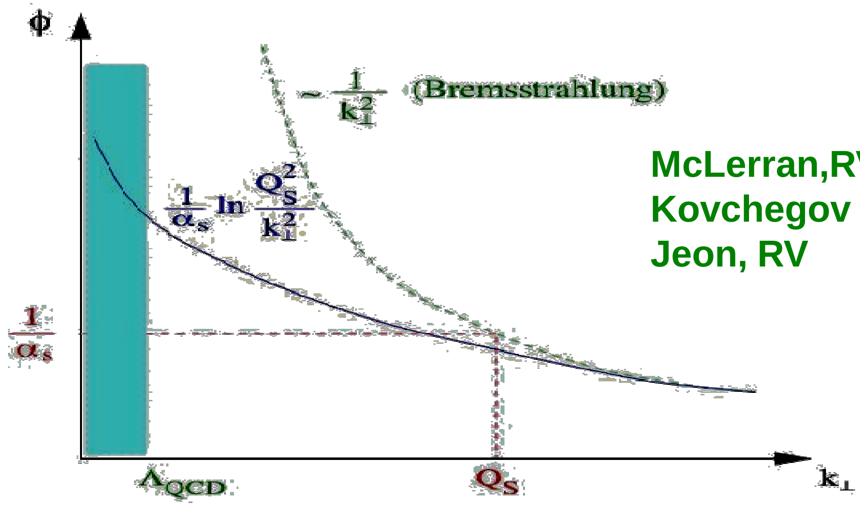
Wee fields of a large nucleus

Wee parton dist. :



$$\frac{1}{\Lambda_{\rm QCD}}\, e^{-\lambda \Delta Y/2}$$

$1/\Lambda_{\rm QCD}$ **$2R\,/\,\gamma$**



McLerran,RV
Kovchegov
Jeon, RV

$$< AA >_\rho = \int [d\rho] A_{\rm cl.}(\rho) A_{\rm cl.}(\rho) W_{\Lambda^+}[\rho]$$

"Pomeron" excitations

"Odderon" excitations

$$W_{\Lambda^+} = \exp\left(-\int d^2 x_\perp \left[\frac{\rho^a \rho^a}{2\,\mu_A^2} - \frac{d_{abc}\,\rho^a \rho^b \rho^c}{\kappa_A}\right]\right)$$

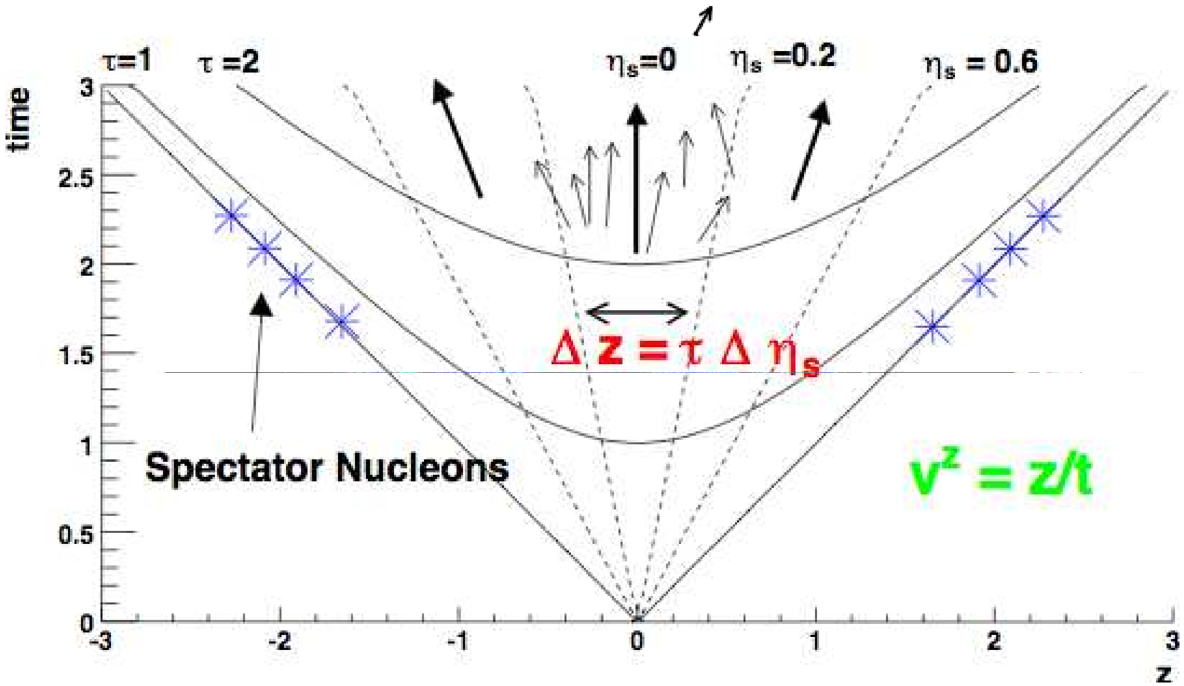
W's "universal density matrices" - obey JIMWLK RG

$$\frac{\partial\, W[\rho]}{\partial \ln(\Lambda^+)} = \mathcal{H}_{\rm JIMWLK} \otimes W[\rho]$$

Jalilian-Marian,Iancu,McLerran
Weigert,Kovner,Leonidov

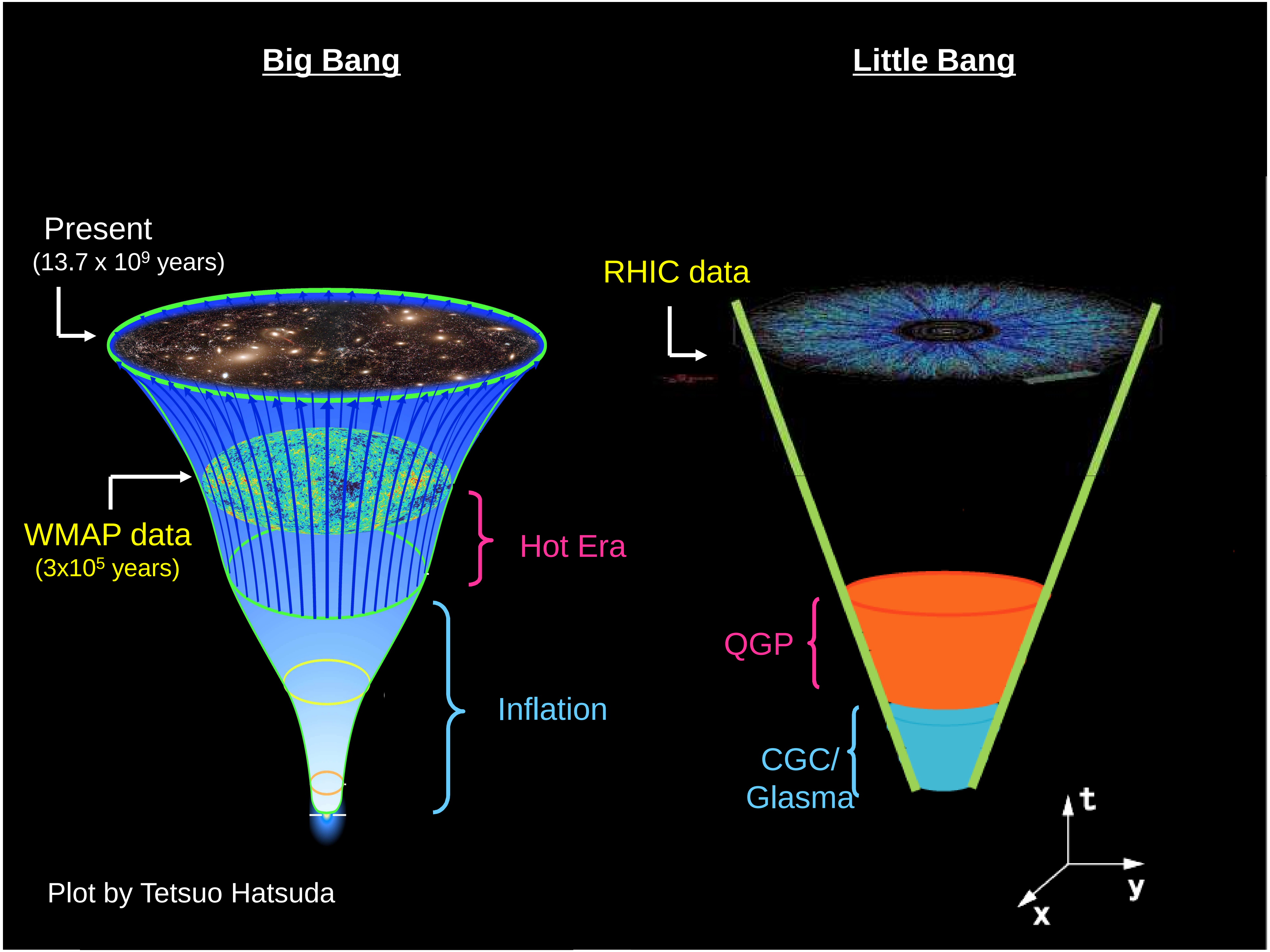
Forming a Glasma in the little Bang

Glasma (\Glahs-maa\): ***Noun:*** **non-equilibrium matter between Color Glass Condensate (CGC)& Quark Gluon Plasma (QGP)**



- **Problem: Compute particle production in QCD with** ***strong time dependent*** **sources**
- **Solution: for early times ($t \leq 1/Q_S$) -- n-gluon production computed in A+A to all orders in pert. theory to leading log accuracy**

Gelis, Lappi, RV; arXiv : 0804.2630, 0807.1306, 0810.4829

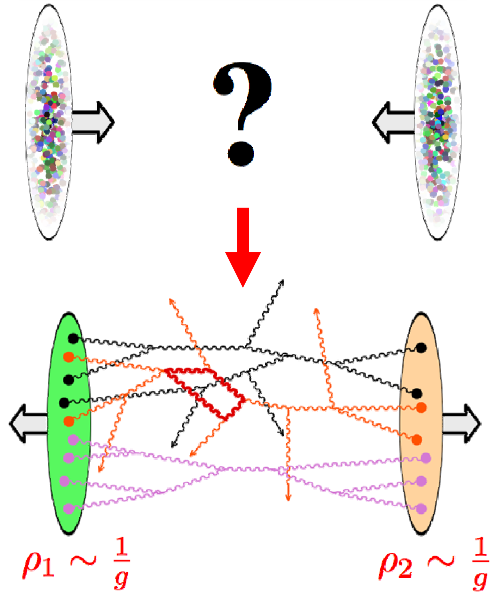

Big Bang
Little Bang
Present
(13.7 x 10⁹ years)
RHIC data
WMAP data
(3x10⁵ years)
Hot Era
Inflation
QGP
CGC/
Glasma
t
y
x
Plot by Tetsuo Hatsuda

Big Bang vs Little Bang

Decaying Inflaton with occupation # $1/g^2$	$\longleftrightarrow$	Decaying Glasma with occupation # $1/g^2$
Explosive amplification of low mom. small fluctuations (preheating)	$\longleftrightarrow$	Explosive amplification of low mom. small fluct. (Weibel instabilities)
Int. of fluctutations/inflaton -> thermalization	$\longleftrightarrow$	Int. of fluctutations/inflaton -> thermalization ?

Other common features: topological defects, turbulence ?

From CGC to Glasma



Consider $T_{\mu\nu}$: At LO, can obtain from soln. of classical Yang-Mills eqns.

$$D_\mu F^{\mu\nu,a} = \delta^{\nu+}\rho_1^a(x_\perp)\delta(x^-) + \delta^{\nu-}\rho_2^a(x_\perp)\delta(x^+)$$

$$T^{\mu\nu}_{\mathrm{LO}} = \frac{1}{4} g^{\mu\nu} F^{\lambda\delta} F_{\lambda\delta} - F^{\mu\lambda} F^{\nu}_{\lambda} \qquad \mathrm{O}\left(\frac{Q_S^4}{g^2}\right)$$

NLO terms are as large as LO for $\alpha_S \ln(1/x)$ - resum to all orders

Gelis,Lappi,RV (2008)

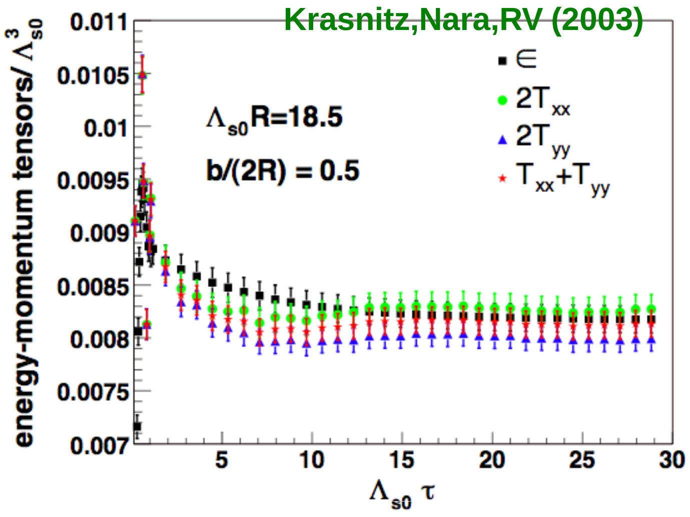
$$\langle T^{\mu\nu}(\tau, \underline{\eta}, x_\perp)\rangle_{\mathrm{LLog}} = \int [D\rho_1 d\rho_2]\, W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, T^{\mu\nu}_{\mathrm{LO}}(\tau, x_\perp)$$

$$Y_1 = Y_{\mathrm{beam}} - \eta\, ;\; Y_2 = Y_{\mathrm{beam}} + \eta$$

Glasma factorization => universal "density matrices W" ⊗ calc. "matrix element"

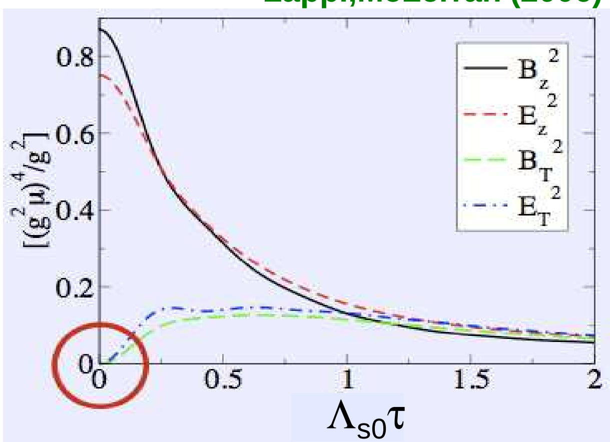
$<T_{\mu\nu}>$ in the Glasma

$$\langle T^{\mu\nu}(\tau=0^+)\rangle = \begin{pmatrix} \varepsilon_0 & 0 & 0 & 0 \\ 0 & \bar{\varepsilon} & 0 & 0 \\ 0 & 0 & \bar{\varepsilon} & 0 \\ 0 & 0 & 0 & \varepsilon_0 - 2\bar{\varepsilon} \end{pmatrix}$$



System initially very far from equilibrium!

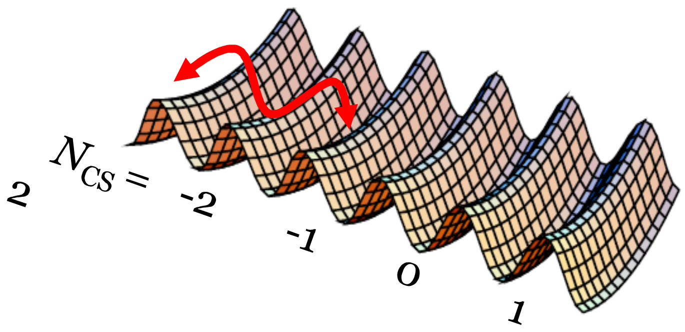
$$\langle T_{xx} + T_{yy}\rangle = 2\ \mathrm{Tr}(B_z^2 + E_z^2)$$
$$\langle T_{zz}\rangle = \mathrm{Tr}(B_j^2 + E_i^2) - \mathrm{Tr}(B_z^2 + E_z^2)$$



Initial gauge field configurations are longitudinal chromo-electric & magnetic fields

- generate Chern-Simons charge-topological flucts.

Kharzeev,Krasnitz,RV (2002)

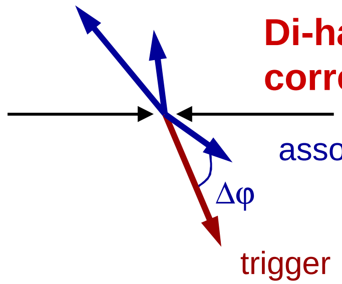


Chiral magnetic effect

Kharzeev et al.

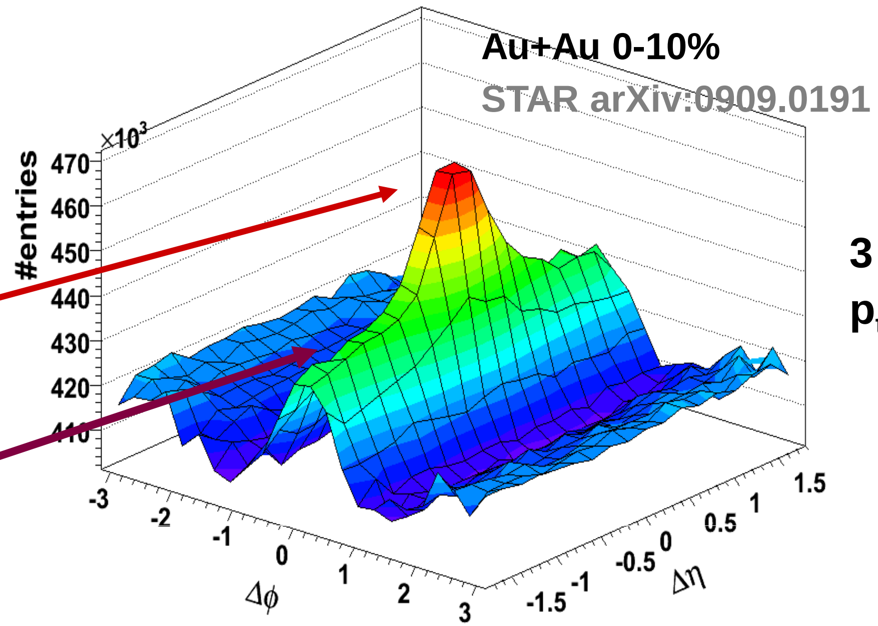
The near-side ridge

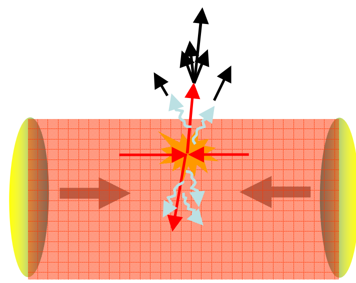
Di-hadron correlations



Near-side jet peak comparable to d+Au

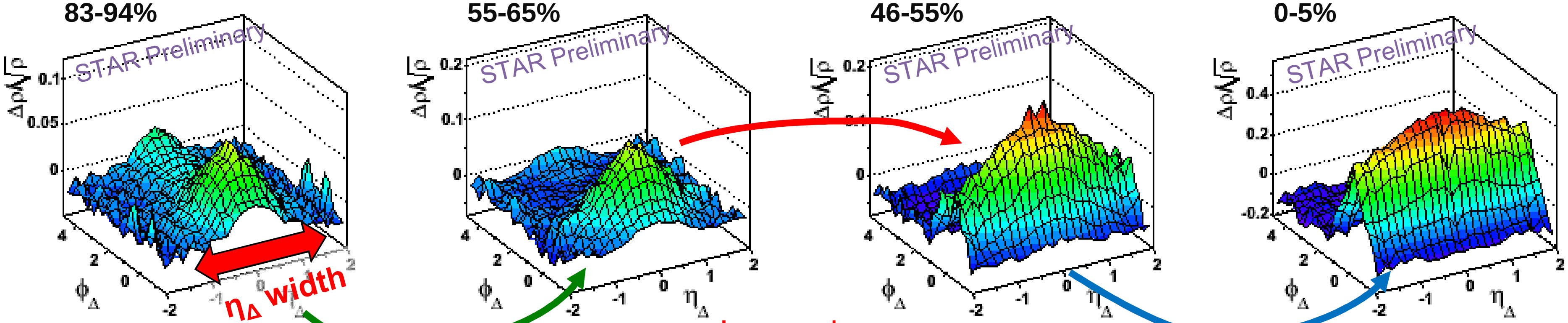
Near-side Δη independent ridge





$3 < p_{t,trigger} < 4$ GeV

$p_{t,assoc.} > 2$ GeV

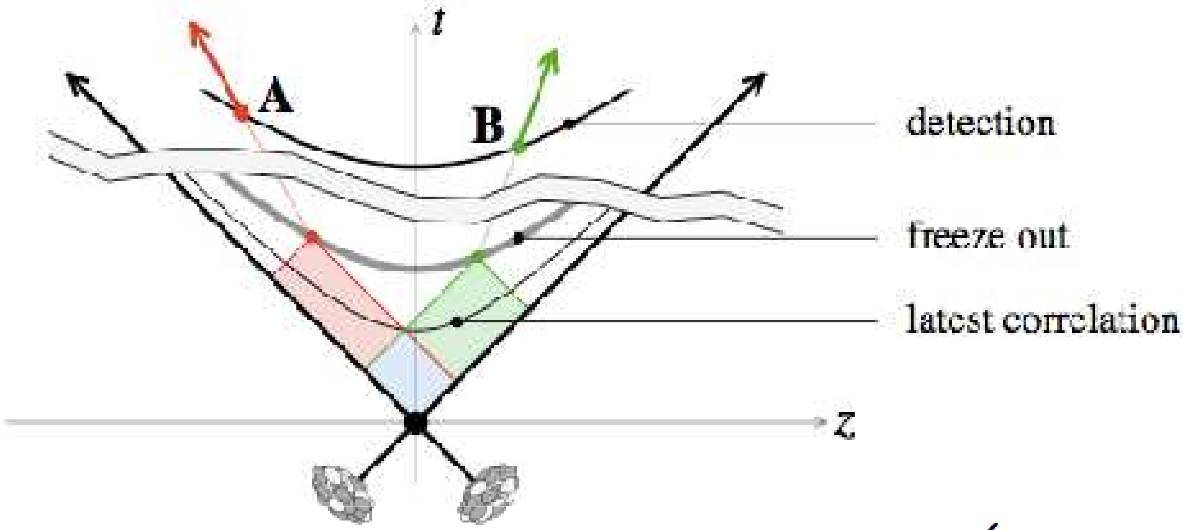


Little shape change from peripheral to 55% centrality

Large change within ~10% centrality

Smaller change from transition to most central

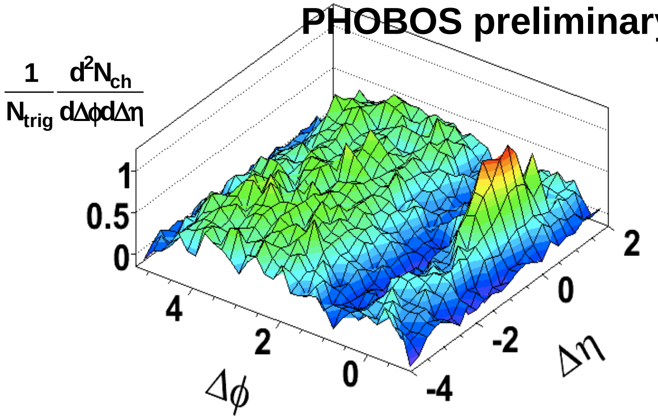
Imaging the Glasma



Causality dictates: $$\tau \leq \tau_{\mathrm{freeze-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

Au+Au 200 GeV, 0 - 30%

PHOBOS preliminary

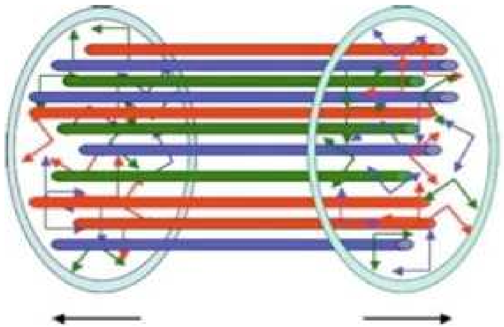


τ < 1 fm for Δy > 4

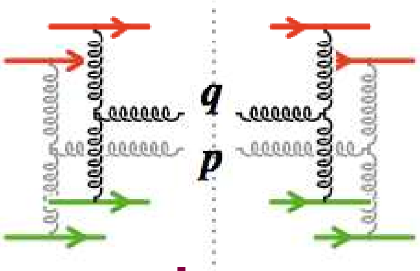
These correlations likely occur at early times…

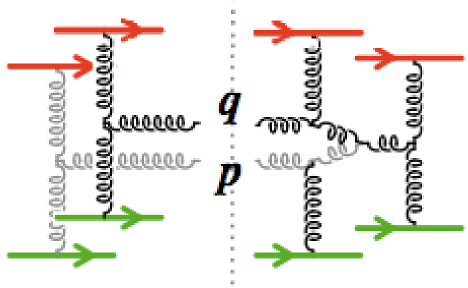
2 particle correlations in the Glasma: flux tubes

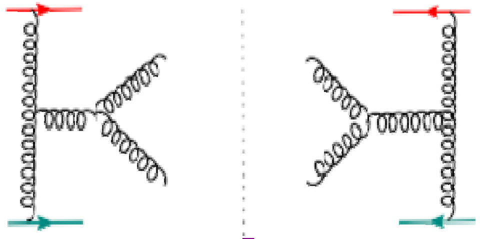
Dumitru, Gelis ,McLerran, RV, NPA (2008)
arXiv:0804.3858[hep-ph]



$$C(\mathbf{p},\mathbf{q}) = \left\langle \frac{dN_2}{dy_p\, d^2\mathbf{p}_\perp\, dy_q\, d^2\mathbf{q}_\perp} \right\rangle - \left\langle \frac{dN}{dy_p\, d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q\, d^2\mathbf{q}_\perp} \right\rangle$$







Independent gluon emission from Glasma flux tube (near-side LRC)

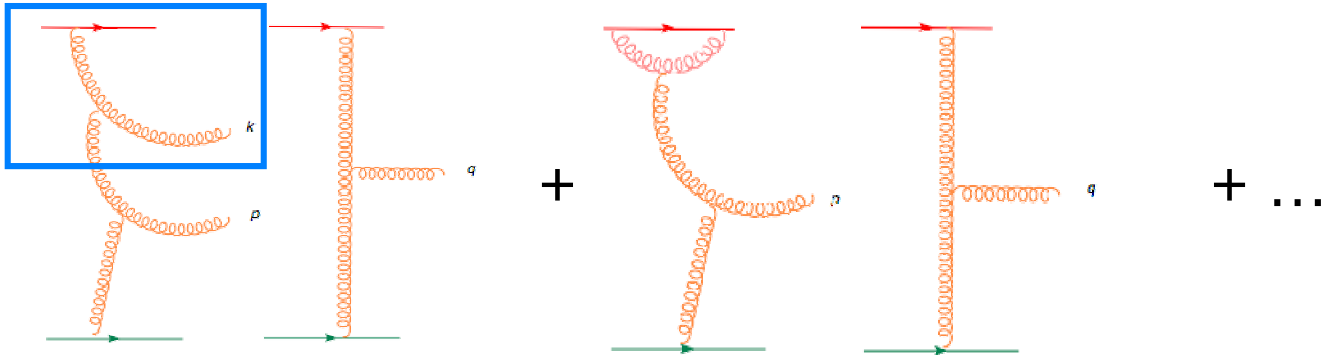
"pQCD" graphs (near-side SRC)

- **For Strong Color Sources (high energy/large nuclei/central collisions) Flux Tube Emission dominates "pQCD" by $1 / \alpha_S^2$**

2 particle correlations in the Glasma (II)

RG evolution:

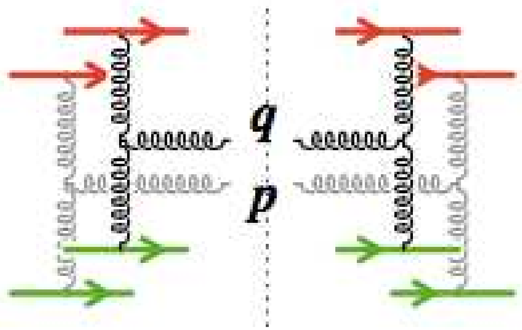
Gelis, Lappi, RV, PRD (2008)
arXiv: 0807.1306



Keeping leading logs to all orders (NLO+NNLO+…)
2-particle spectrum (for $\Delta y < 1/\alpha_S$) can be written as

$$\left\langle \frac{dN_2}{d^3p\, d^3q} \right\rangle_{\mathrm{LLogs}} = \int [d\rho_1][d\rho_2] W_{Y_1}[\rho_1]\, W_{Y_2}[\rho_2]\, \frac{dN}{d^3p}\Big|_{\mathrm{LO}} \frac{dN}{d^3q}\Big|_{\mathrm{LO}}$$

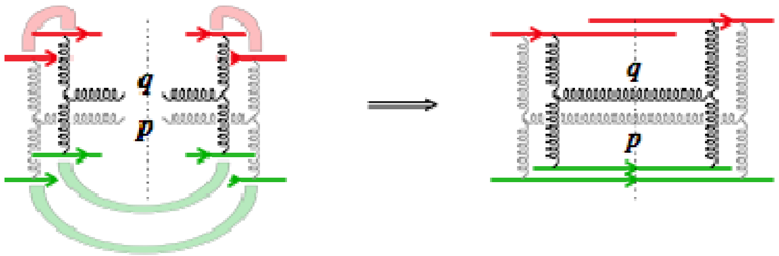
= LO graph with evolved sources
Glasma flux tubes

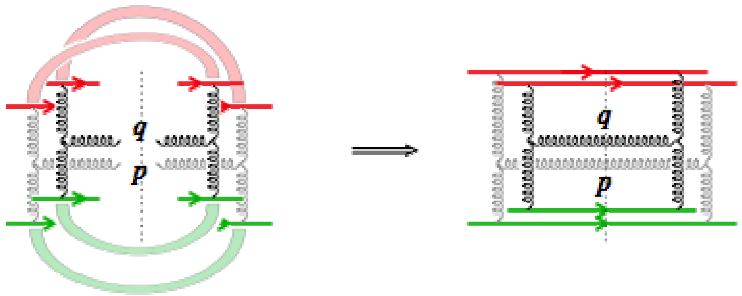


2 particle correlations in the Glasma (III)

Conjecture:

Correlations are induced by color fluctuations that vary event to event - these are local transversely and have color screening radius $1/Q_S$



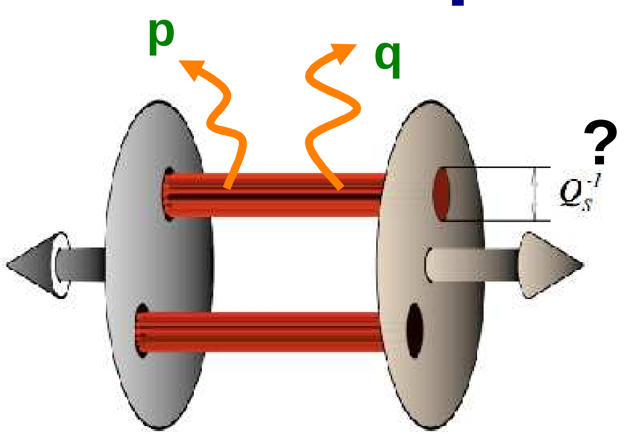


$$\frac{C(p,q)}{\langle \frac{dN}{dy_p d^2 p_\perp} \rangle \langle \frac{dN}{dy_q d^2 q_\perp} \rangle} = \frac{\kappa_2}{S_\perp Q_S^2}$$

$$\frac{\Delta\rho}{\sqrt{\rho_{\rm ref}}} = \left\langle \frac{dN}{dy} \right\rangle \frac{C(\mathbf{p},\mathbf{q})}{\left\langle \frac{dN}{dy_p\, d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q\, d^2\mathbf{q}_\perp} \right\rangle} = \frac{K_N}{\alpha_S(Q_S)}$$

Simple "Geometrical" result:
strength of correlation
= area of flux tube / transverse area of nucleus

Non-perturbative Classical QCD



If conjecture is true,
from geometry, must have $\kappa_2 \sim 1$

- Numerical solution of Yang-Mills equations for double inclusive distributions

Lappi,Srednyak,RV, JHEP (2010)
arXiv 0911.2068

Three possible scales for color screening: 1/R, m (Λ_{QCD}), Q_S

For κ_2 =1,

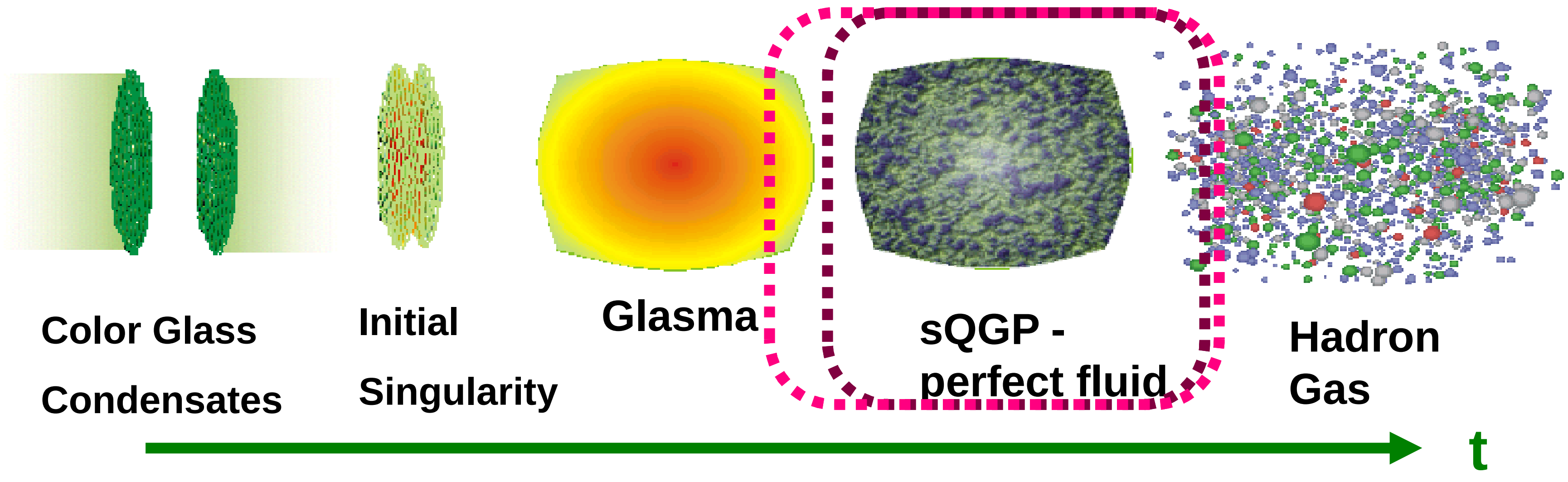
$$\frac{C(p,q)}{\langle \frac{dN}{dy_p d^2 p_\perp} \rangle \langle \frac{dN}{dy_q d^2 q_\perp} \rangle} = \frac{S_{\mathrm{F.T.}}}{S_\perp}$$

(0.5-2) / Q_S^2

Color screening radius
~ 0.7-1.4 / Q_S

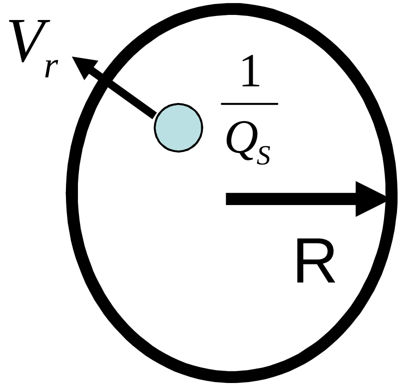
- Results confirm conjecture

The Ridge and Glasma Flux tubes
- where theory meets model



The evolution of Glasma into the perfect fluid is not understood. Initial condition for hydro evolution requires modelling…

Soft Ridge = Glasma flux tubes + Radial flow



Voloshin (2006)
Shuryak (2007)
Pruneau,Gavin,Voloshin (2008)

Pairs correlated by transverse Hubble flow in final state
- experience same boost

$$\int d\Phi \frac{\Delta\rho}{\sqrt{\rho_{\rm ref}}}(\Phi, \Delta\phi, y_p, y_q) = \frac{K_N}{\alpha_S(Q_S)} \frac{2\pi \cosh\zeta_B}{\cosh^2\zeta_B - \sinh^2\zeta_B \cos^2\Delta\frac{\phi}{2}}$$

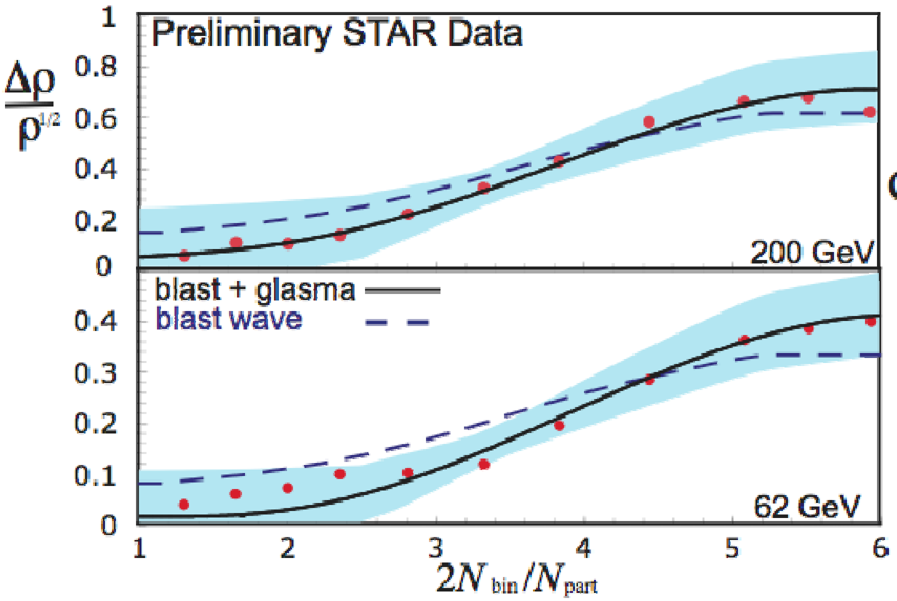
Can be computed non-perturbatively
from numerical lattice simulations

Srednyak,Lappi,RV

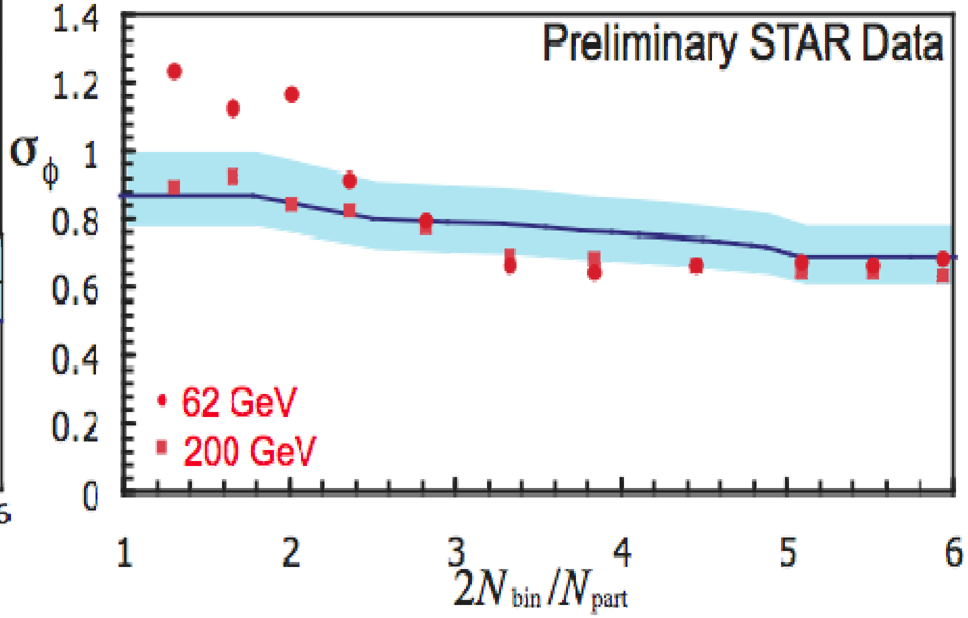
$\gamma_B = \cosh\zeta_B$ **from blast wave fits to spectra**

Q_S from centrality dependence of inclusive spectra

Ridge from flowing flux tubes



Gavin,McLerran,Moschelli, arXiv:0806.4718



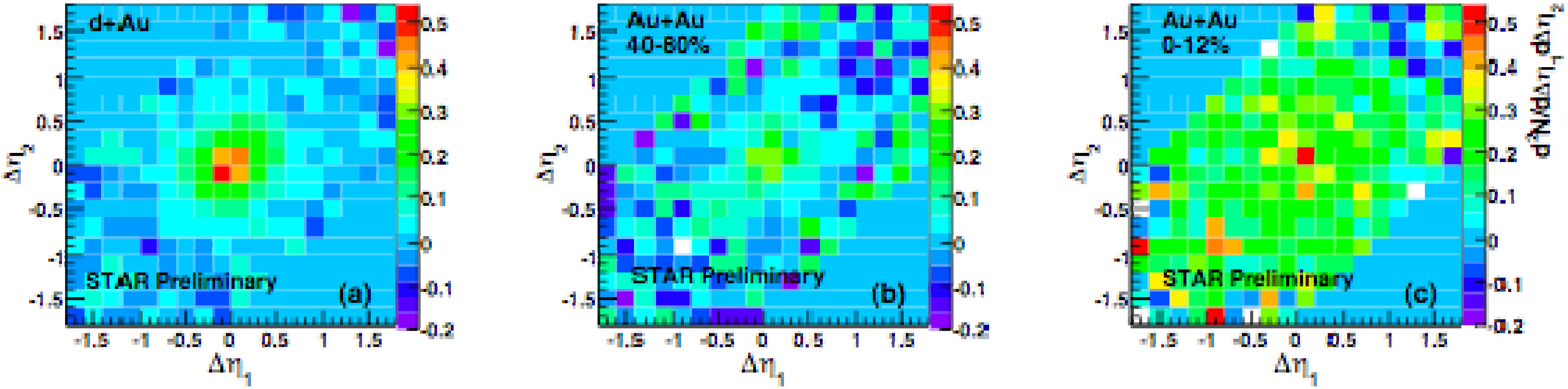
Glasma flux tubes get additional qualitative features right:

i) Same flavor composition as bulk matter
ii) Ridge independent of trigger p_T-geometrical effect
iii) Signal for like and unlike sign pairs the same at large $\Delta\eta$

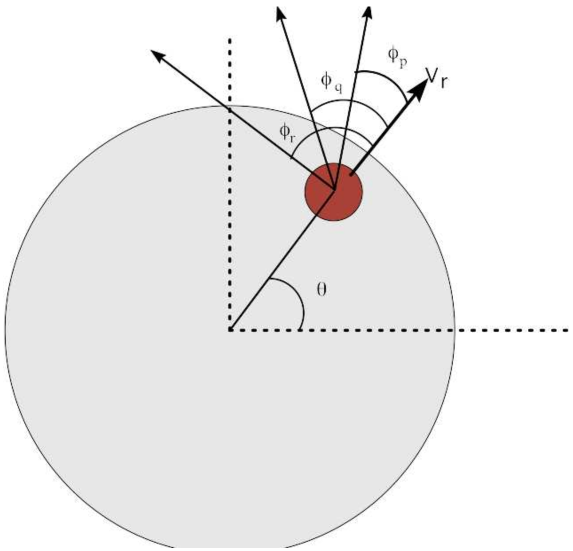
See also Lindenbaum and Longacre, arXiv:0809.3601, 0809.2286

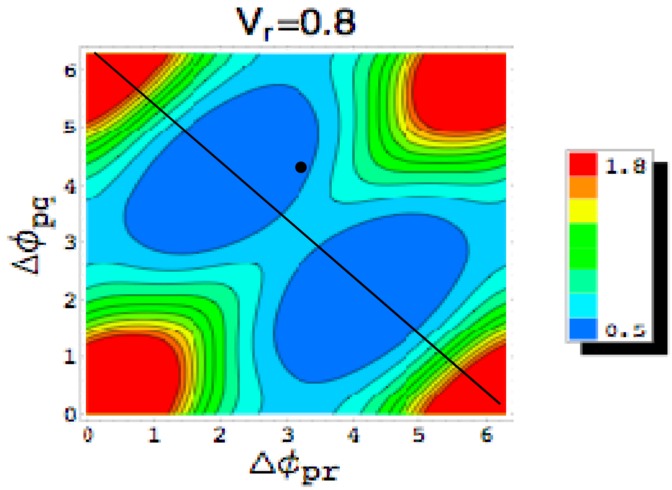
Three particle Glasma correlations

STAR, PRL 102:052302 (2009)



Prediction: flat in rapidity and angular collimation of three particle correlations · · · · · · · · · Dusling, Fernandez-Fraile, RV, NPA (2009)





"Glittering" Glasmas

Gelis,Lappi,McLerran, arXiv:0905.3234

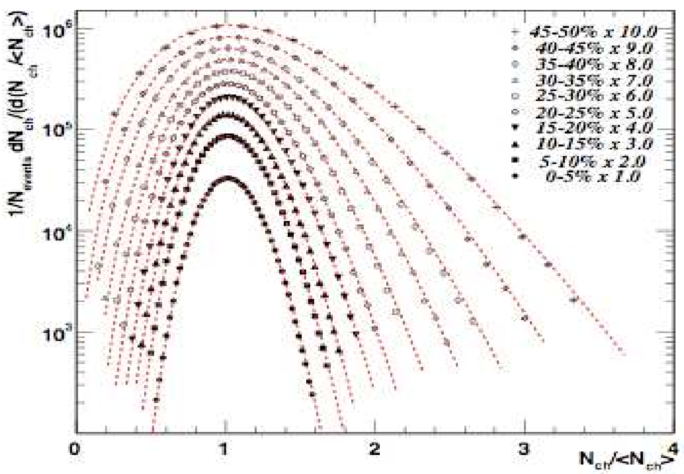
n-particle correlation can be expressed as

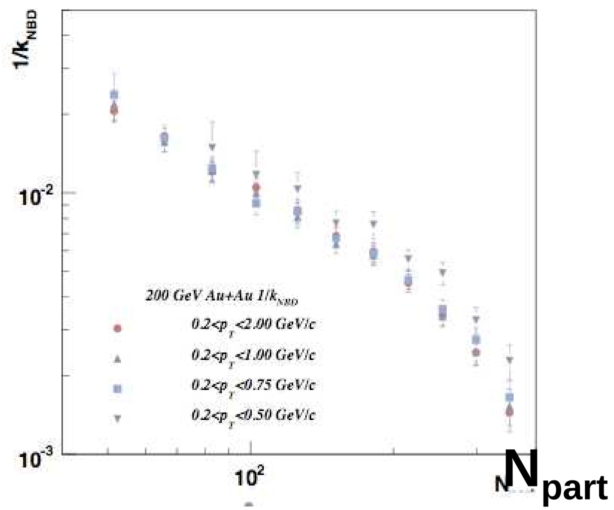
$$\left\langle \frac{d^n N}{dy_1 d^2\mathbf{p}_{\perp 1}\cdots dy_n d^2\mathbf{p}_{\perp n}} \right\rangle = \frac{(n-1)!}{k^{n-1}} \left\langle \frac{dN}{dy_1 d^2\mathbf{p}_{\perp 1}} \right\rangle \cdots \left\langle \frac{dN}{dy_n d^2\mathbf{p}_{\perp n}} \right\rangle$$

with $k = \zeta_n \dfrac{(N_c^2-1)Q_S^2 S_\perp}{2\pi}$

For k = 1, Bose-Einstein dist.
For k= ∞, Poisson Dist.

This is a negative binomial distribution which is known to describe well multiplicity distributions in hadronic and nuclear collisions

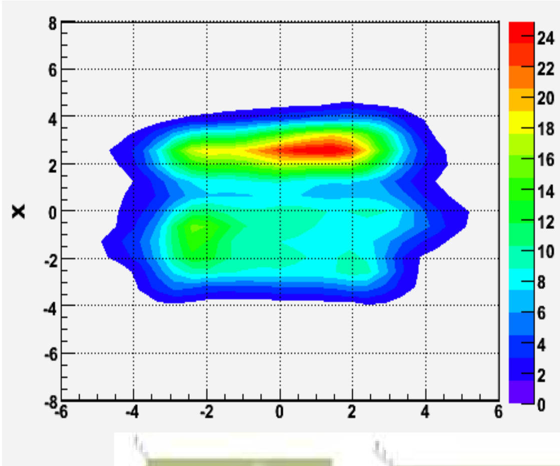




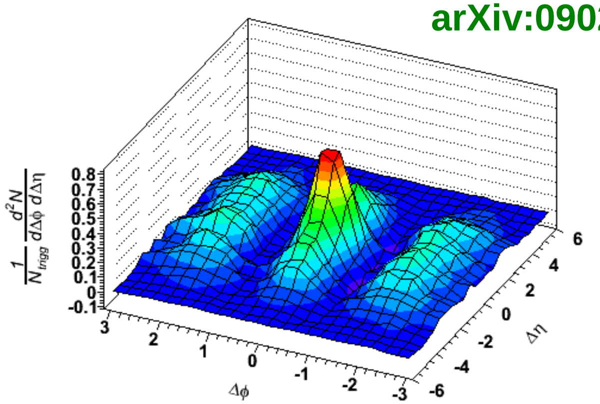
$$\sigma^2 = \bar{n} + \frac{\bar{n}^2}{k}$$

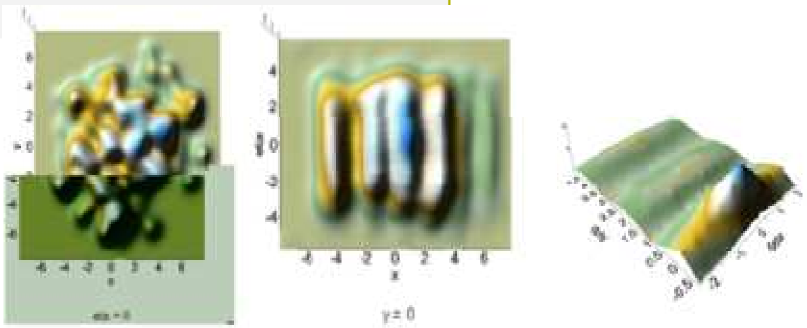
PHENIX
arXiv:0805.1521

Improving the Glasma flux tube model



Jun Takahashi et al.
arXiv:0902.4870

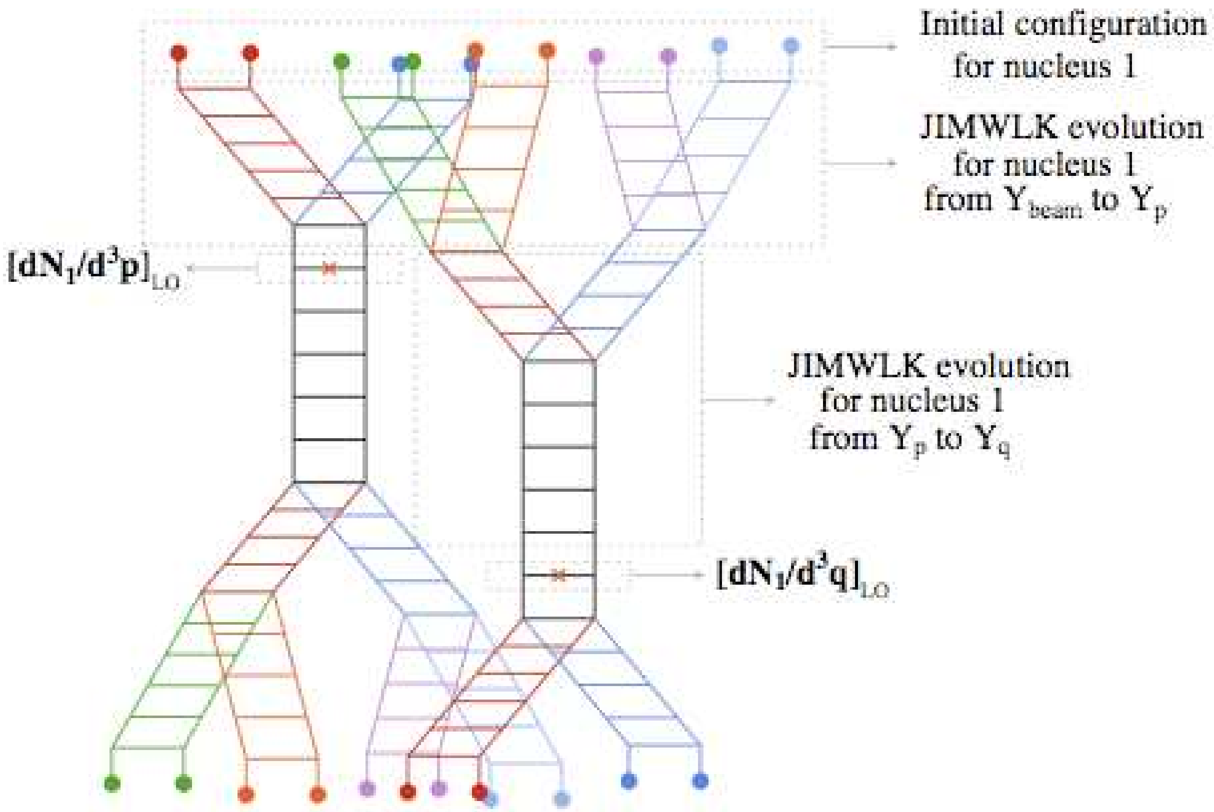




Grassi et al., arXiv:0912.0703

NEXUS initial condition / Glasma flux tube initial condition
+ SPHERIO hydro evolution
+ Cooper-Frye freezeout

ΔY dependence of 2 Part. Corr.

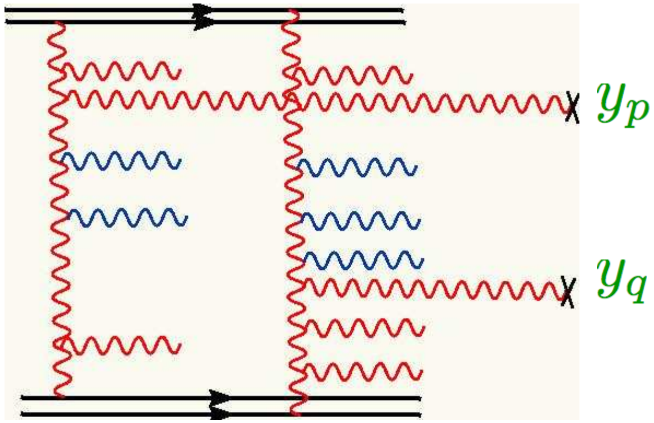


Evol. for nucl. 2

Gelis,Lappi,RV, PRD (2009)
arXiv:0810.4829

Factorization Formalism for $dN_2/d^3p\, d^3q$
ab initio **for** **arbitrary** **rapidity separation ΔY_{pq}**

From Glue Dist. to LRC



Dusling,Gelis,Lappi,RV
arXiv:0911.2720, NPA (2010)

$$\Delta y >> 1/\alpha_S \sim 3$$

unintegrated gluon dist. in nucleus obtained from solution of NLO RG (BK) eqn.

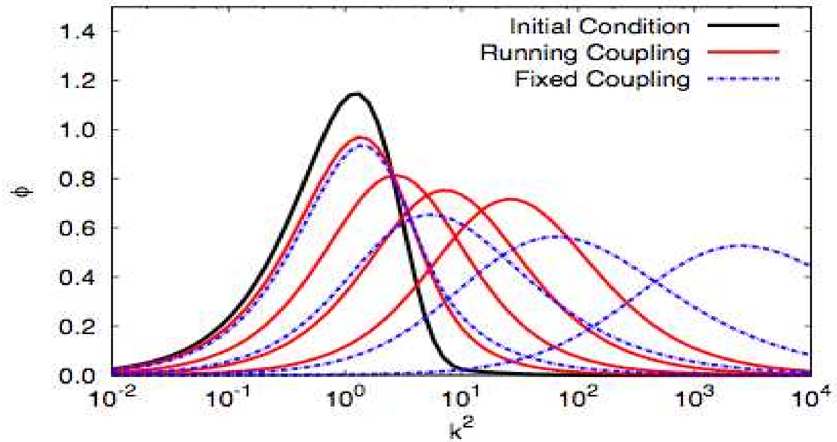
Balitsky, Chirilli
Kovchegov, Weigert
Albacete, Kovchegov

$$C(\mathbf{p},\mathbf{q}) = \frac{\alpha_s^2}{16\pi^{10}} \frac{N_c^2(N_c^2-1)S_\perp}{d_A^4\, \mathbf{p}_\perp^2 \mathbf{q}_\perp^2} \int \mathrm{d}^2\mathbf{k}_{1\perp} \times$$

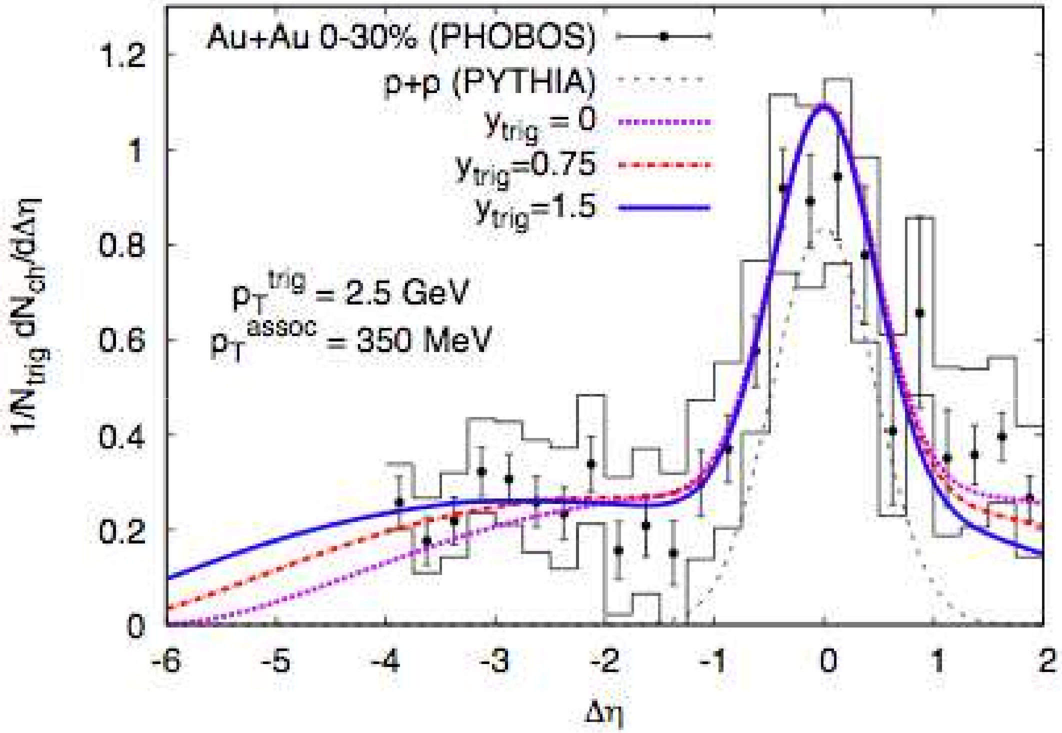
$$\Big\{ \Phi_{A_1}^2(y_p,\mathbf{k}_{1\perp})\Phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_{1\perp})\left[\Phi_{A_2}(y_q,\mathbf{q}_\perp+\mathbf{k}_{1\perp})+\Phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_{1\perp})\right]$$

$$\Phi_{A_2}^2(y_q,\mathbf{k}_{1\perp})\Phi_{A_1}(y_p,\mathbf{p}_\perp-\mathbf{k}_{1\perp})\left[\Phi_{A_1}(y_q,\mathbf{q}_\perp+\mathbf{k}_{1\perp})+\Phi_{A_1}(y_q,\mathbf{q}_\perp-\mathbf{k}_{1\perp})\right]\Big\}$$

Initial condition fixed from fits to fixed target e+A data

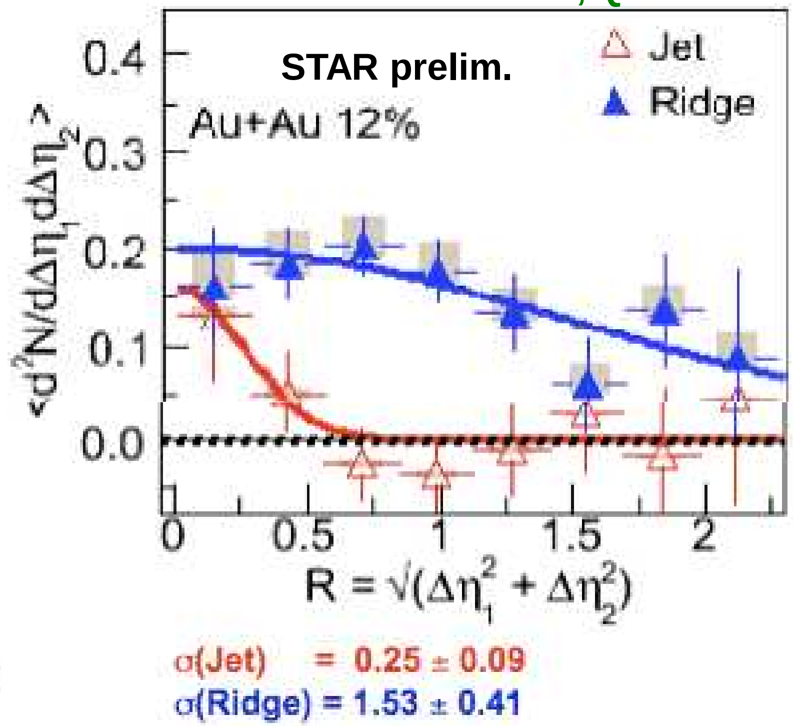


Result for RHIC LRC



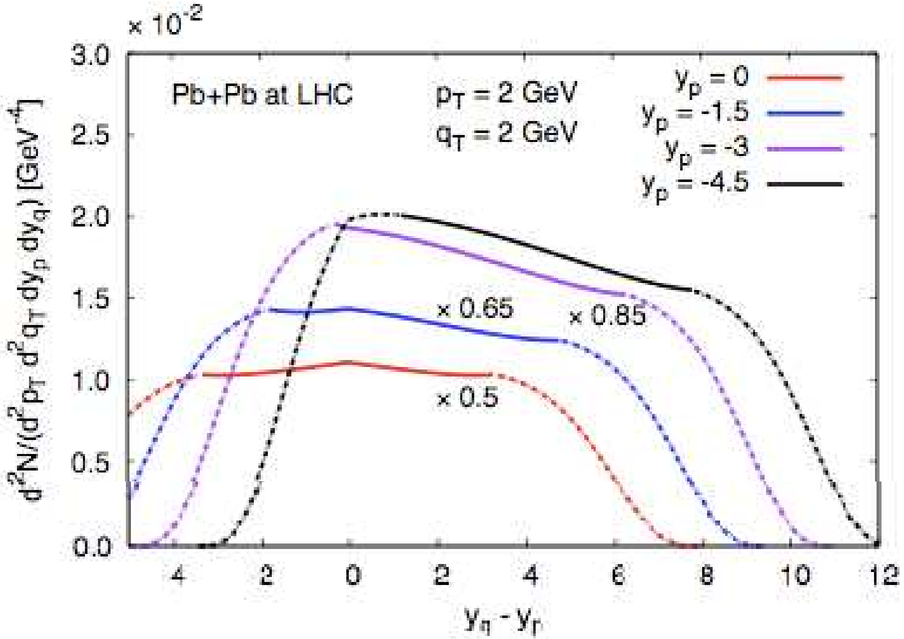
LRC seen to kinematic extent of PHOBOS

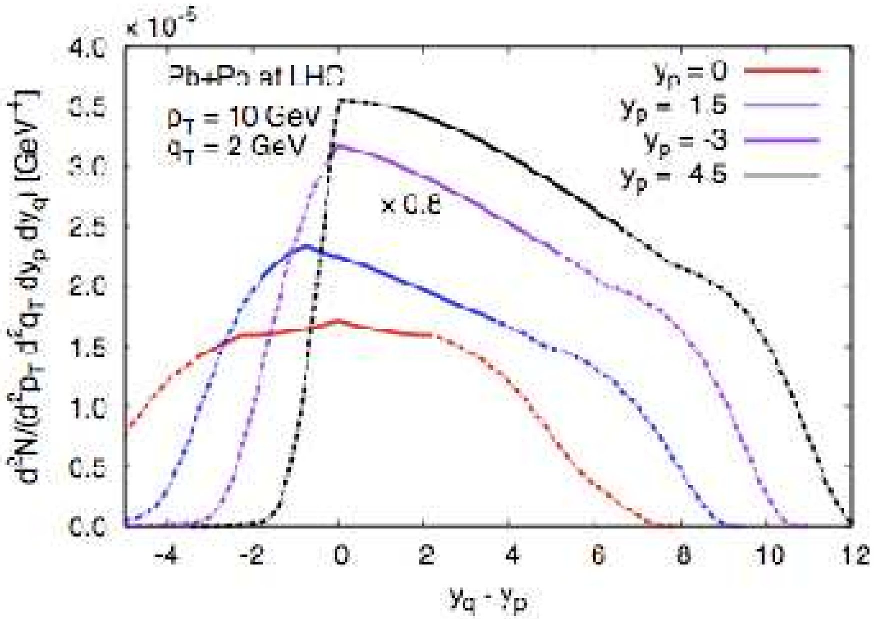
Netrakanti, QM 2009



Can also calc. STAR 3-part. Corr. - quite flat…

Projections for the LHC





LRC seen up to 10 units in rapidity
- 7 probe small x (<0.01) in both nuclei

LRC seen up to 6 units in rapidity
5 probe small x in both nuclei

Piecing it all together

Remarkable features of RHIC data

- the presence of long range correlations strikingly seen in the ridge

- topological fluctuations and charge separation

- early "isotropization" and strong flow

are sensitive to the early time strong color field (Glasma) dynamics.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Glasma flux tubes may provide a unifying explanation of all these features

These ideas will be further tested and refined in future RHIC runs and at the LHC

EXTRA SLIDES

Comparison of models by
Nagle, QM09

i) "Causation" models: purely final state models

Longitudinal collective flow, Momentum kick, Broadening in turbulent color fields,…

Difficult to get independence of trigger, width in $\Delta\eta$
Momentum kick model gets it but perhaps too wide in $\Delta\phi$

ii) "Auto-correlation" models: LRC from initial state and collimation in azimuth from boosted flow

Glasma flux tube, Parton Bubble, see also related model by Shuryak