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High energy Factorization, the Glasma, and the Ridge in A+A collisions.

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Factorization, the Glasma & the Ridge in A+A collisions

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VIth Int. Conf. on Perspectives in Hadronic Physics, Trieste, May 2008

Talk based on:

- ***High energy factorization in nucleus- nucleus collisions,*** **F. Gelis, T. Lappi & R. Venugopalan, arXiv:0804.2630**

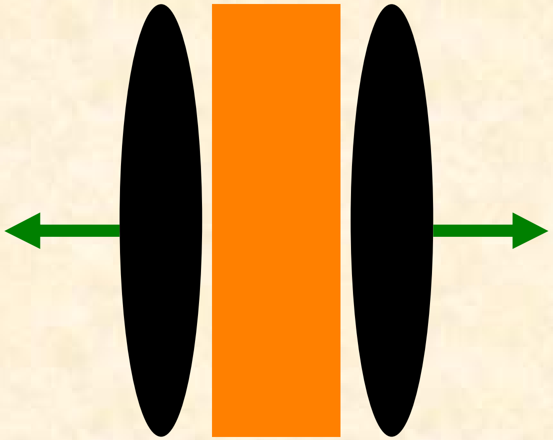
- ***Glasma flux tubes and the near side ridge phenomenon at RHIC*, A. Dumitru, F. Gelis, L. McLerran and R. Venugopalan,**

  arXiv:0804.3858

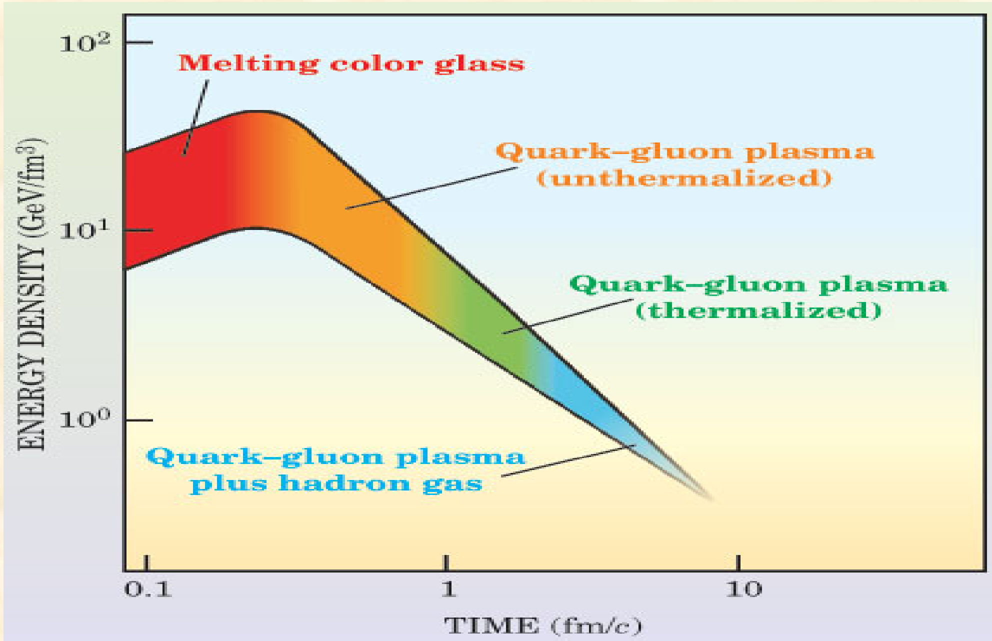
Talk Outline

- Introduction - the Glasma
- Theory framework for multi-particle production in the Glasma
- Ridgeology
- Two particle correlations in the Glasma
  - the Glasma flux tube picture

Glasma



Ludlam, McLerran, Physics Today (2003)



Glasma (\Glahs-maa\):

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

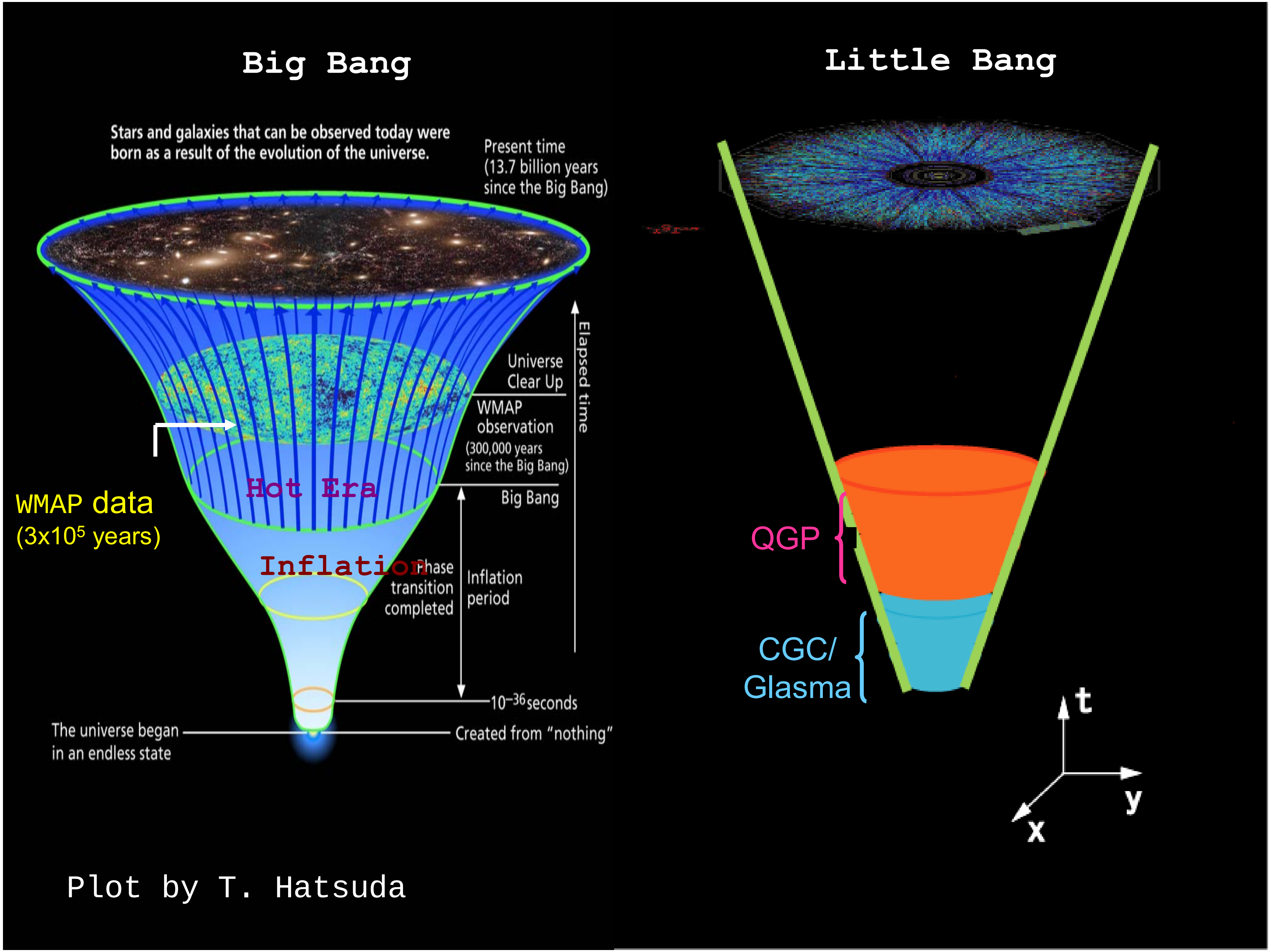
Why is the Glasma relevant ?

- *Intrinsic interest:*

  Glasma fields are among strongest Electric & Magnetic fields in nature. What are their properties ?

- *Initial conditions for the QGP:*
  - How does bulk matter flow in the Glasma influence transport in the perfect fluid ?
  - How do jets interact with the Glasma ?

The Glasma is key to quantitative understanding of matter produced in HI collisions


Big Bang
Little Bang
Stars and galaxies that can be observed today were born as a result of the evolution of the universe.
Present time (13.7 billion years since the Big Bang)
Elapsed time
Universe Clear Up
WMAP observation (300,000 years since the Big Bang)
Big Bang
Hot Era
WMAP data
(3x10^5 years)
Inflation
Phase transition completed
Inflation period
10^-36 seconds
The universe began in an endless state
Created from "nothing"
QGP
CGC/
Glasma
t
y
x
Plot by T. Hatsuda

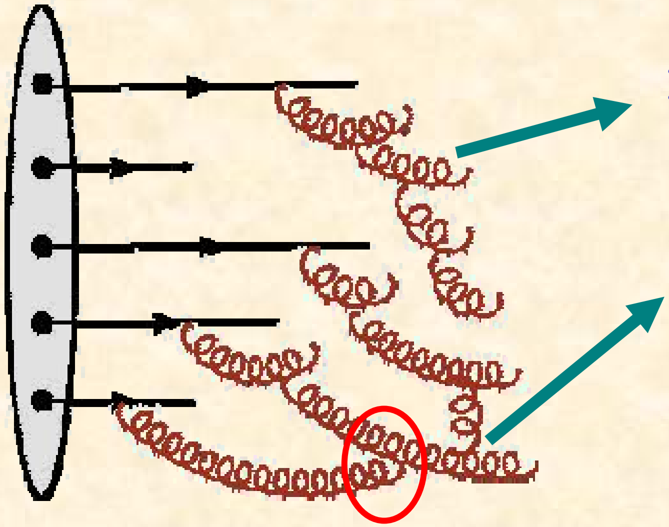
Big Bang vs. Little Bang

Big Bang		Little Bang
Decaying Inflaton field with occupation # $1/g^2$	⟷	Decaying Glasma field with occupation # $1/g^2$
Explosive amplification of low mom. small fluctuations (preheating)	⟷	Explosive amplification of low mom. small fluctuations (Weibel instability ?)
Interaction of fluct./inflaton - thermalization	⟷	Interaction of fluct./Glasma - thermalization ?

Other common features: topological defects, turbulence ?

Before the Little Bang

- Nuclear wavefunction at high energies



Bremsstrahlung $\propto \alpha_S \ln\left(\frac{1}{x}\right) \equiv \alpha_S Y$

+

Recombination $\propto \alpha_S \rho$

= Saturation: $E^2 \sim B^2 \sim \frac{1}{\alpha_S}$

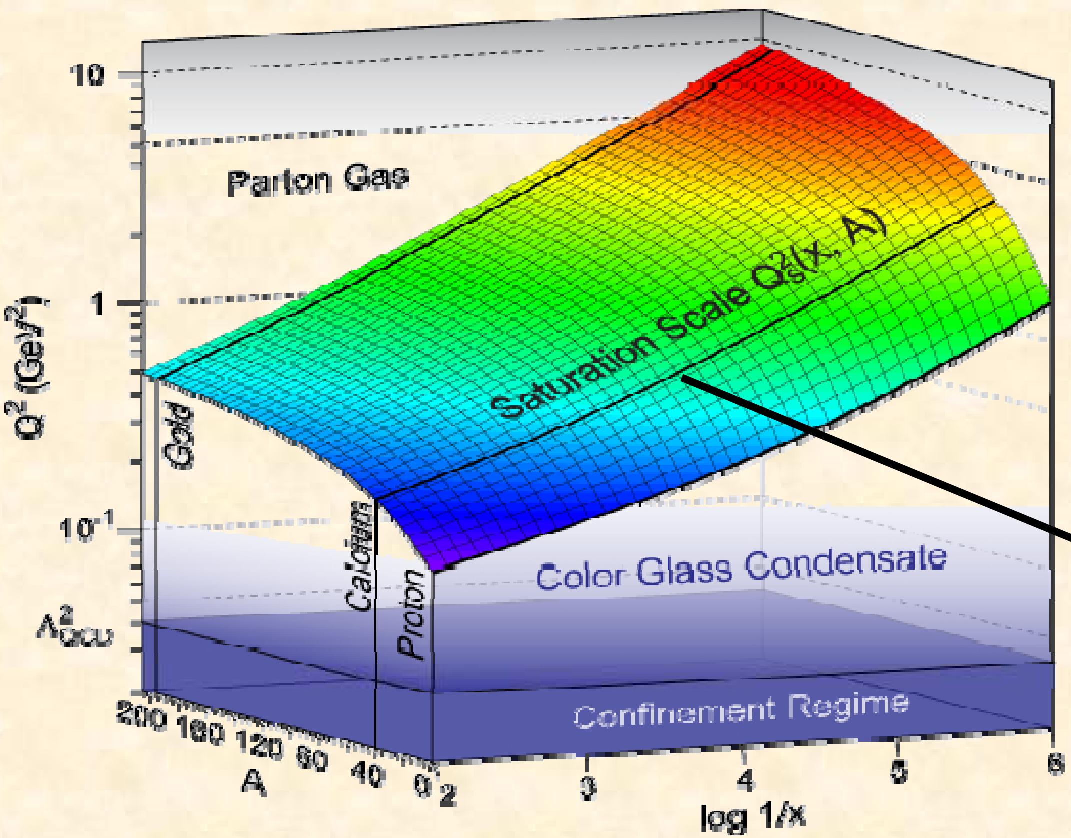
- **Renormalization Group (JIMWLK/BK) equations sum leading logs $(\alpha_S Y)^n$**

  and high parton densities

  $(\alpha_S \rho)^n$

- **Successful CGC phenomenology of HERA e+p; NMC e+A;RHIC d+A & A+A** Review: RV, arXiv:0707.1867, DIS 2007

Hadron wave-fns: universal features



CGC Effective Theory
= classic fields + strong stochastic sources

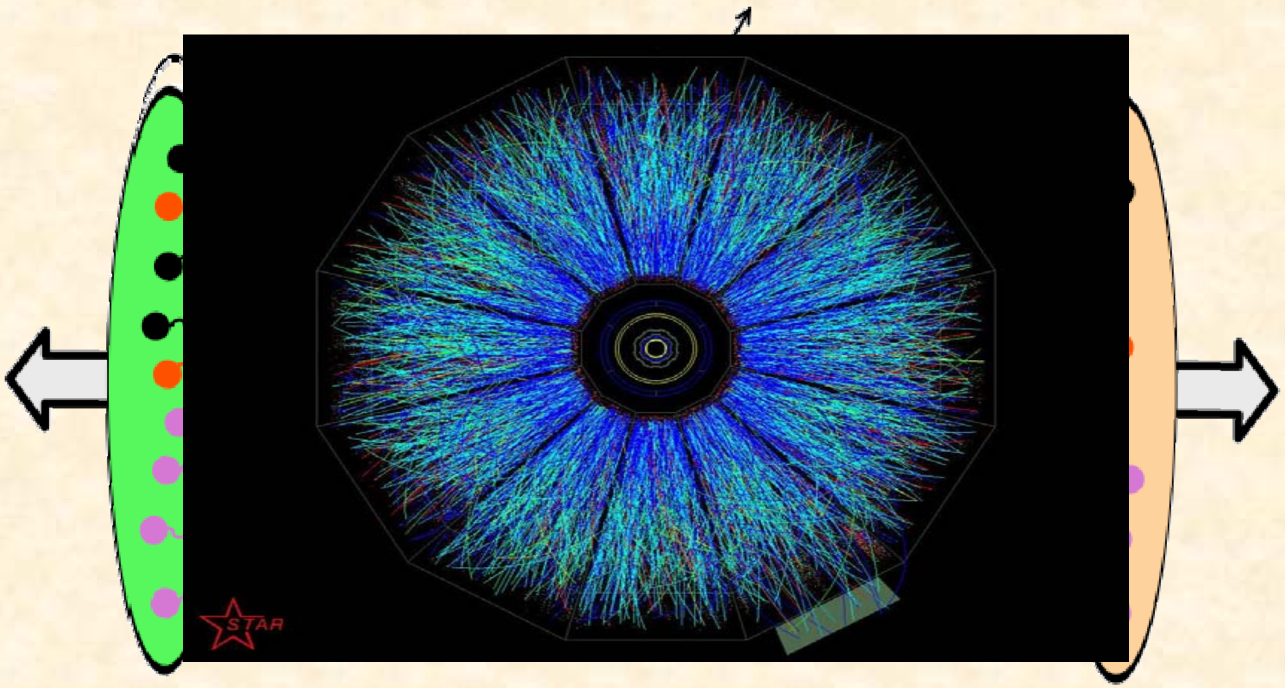
$$\rho \sim \frac{1}{g} \approx \frac{1}{\sqrt{\alpha_S}} >> 1$$

$$\times \frac{9}{4} \text{ for glue}$$

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

T. Ullrich -based on
Kowalski, Lappi, RV ; PRL 100, 022303 (2008)

How is Glasma formed in a Little Bang ?

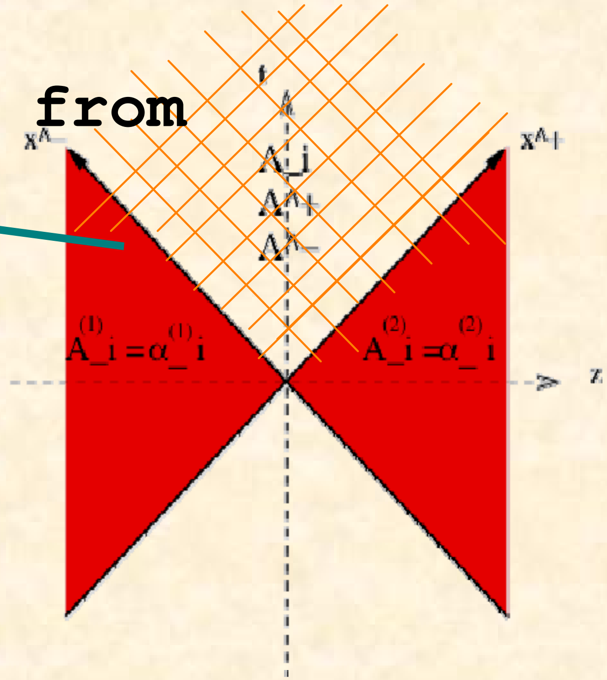


- **Problem: Compute particle production in field theories with *strong time dependent* sources**

QCD at LO: solve Yang-Mills Eqns. for two nuclei

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

Glasma initial conditions from matching classical CGC wave-fns on light cone



Kovner, McLerran, Weigert

Numerical Simulations of classical Glasma fields

Krasnitz, Nara, RVLappi

$$E_p \frac{d\langle n\rangle_{LO}}{d^3p} = \frac{1}{16\pi^3} \lim_{x^0,y^0\to\infty} \int d^3x\, d^3y e^{ip\cdot(x-y)} (\partial_{x^0} - iE_p)(\partial_{y^0} + iE_p)$$
$$\times \sum_{\text{phys.}\Lambda} \varepsilon_\mu^\lambda(p)\varepsilon^{\star\lambda}_\nu(p) A_a^\mu(x) A_c^\nu(y)$$

LO Glasma fields are boost invariant

$$\varepsilon \approx 20 - 40\,\mathrm{GeV/fm^3} \text{ at } \tau \sim 0.3 \text{ fm}$$

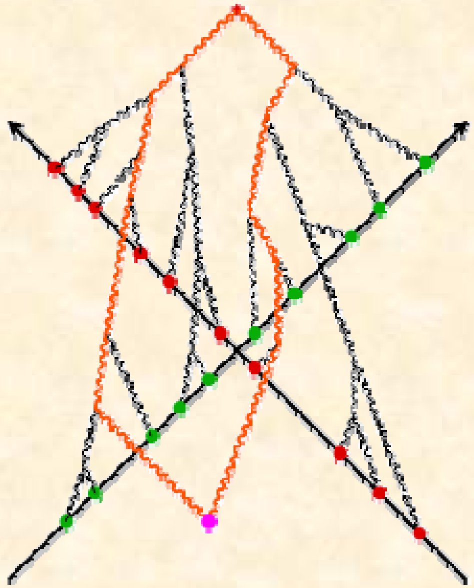
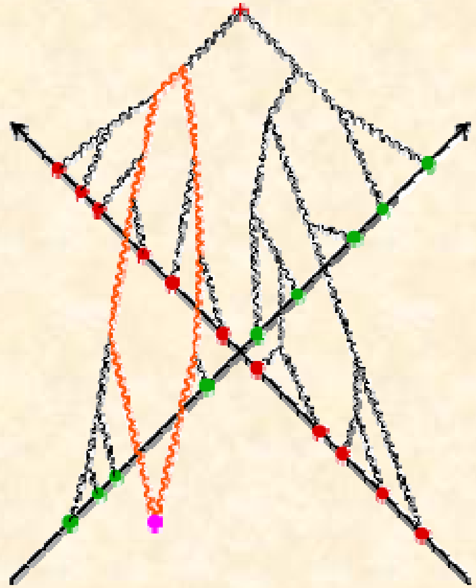
for $Q_S^A \approx 1 - 1.2\,\mathrm{GeV}$

from extrapolating DIS data to RHIC energies

Multiplicity to NLO

$\langle n \rangle_{\rm NLO}$ **(=O(1) in g and all orders in $(g\rho)^n$)**

Gelis, RV (2006)

$\langle n \rangle_{\rm NLO} =$  + 

Gluon pair production | One loop contribution to classical field

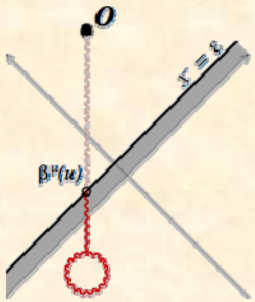
Initial value problem with retarded boundary conditions

- can be solved on a lattice in real time

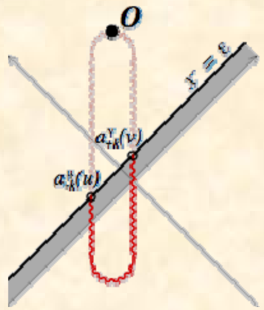
(*a la* Gelis,Kajantie,Lappi for Fermion pair production)

RG evolution for a single nucleus: JIMWLK equation

$$\mathcal{O}_{\rm NLO} = \Bigg($$



$+$



$$\Bigg)\, \mathcal{O}_{\rm LO}$$

$$= \ln\left(\frac{\Lambda^+}{p^+}\right) \mathcal{H}\, \mathcal{O}_{\rm LO}$$

(keeping leading log divergence)

$$\langle \mathcal{O}_{\rm LO} + \mathcal{O}_{\rm NLO} \rangle = \int [d\tilde{\rho}] W[\tilde{\rho}] \left[\mathcal{O}_{\rm LO} + \mathcal{O}_{\rm NLO}\right]$$

$$= \int [d\tilde{\rho}] \left\{ \left[1 + \ln\left(\frac{\Lambda^+}{p^+}\right) \mathcal{H} \right] W_{\Lambda^+} \right\} \mathcal{O}_{\rm LO}$$

LHS independent of Λ^+ => $\dfrac{\partial W[\tilde{\rho}]}{\partial Y} = \mathcal{H}\, W[\tilde{\rho}]$

JIMWLK eqn.

Correlation Functions a la JIMWLK

Brownian motion in functional space:
Fokker-Planck equation!

"diffusion coefficient"

$$=> \frac{\partial}{\partial Y} < O[\alpha] >_Y = < \frac{1}{2} \int_{x,y} \frac{\delta}{\delta \alpha_Y^a(x)} \chi_{x,y}^{ab} \frac{\delta}{\delta \alpha_Y^b(y)} O[\alpha] >_Y$$

"time"

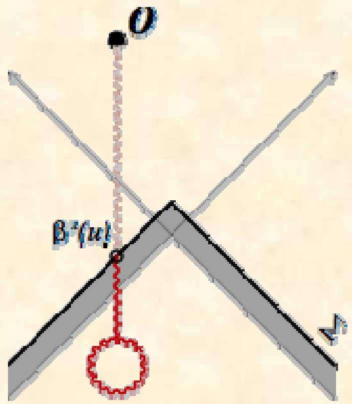
Consider the 2-point function: $< \alpha(x_\perp) \alpha(y_\perp) >_Y$

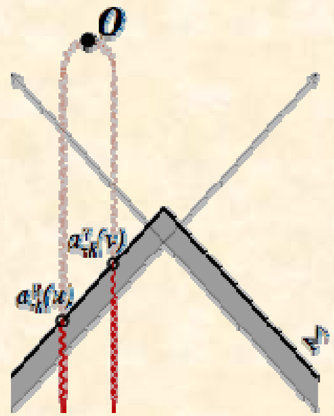
I) JIMWLK in weak field limit: $g\alpha << 1$
BFKL equation

II) In large Nc , large A limit,
recover Balitsky-Kovchegov (BK) equation

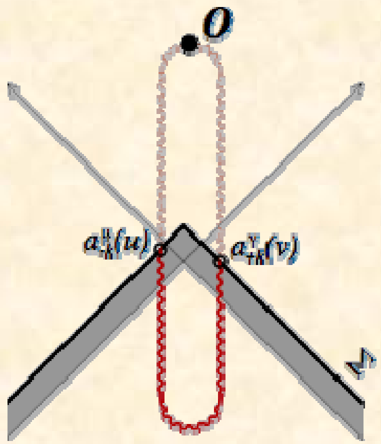
RG evolution for 2 nuclei

Log divergent contributions crossing nucleus 1 or 2:





Contributions across both nuclei are finite-no log divergences

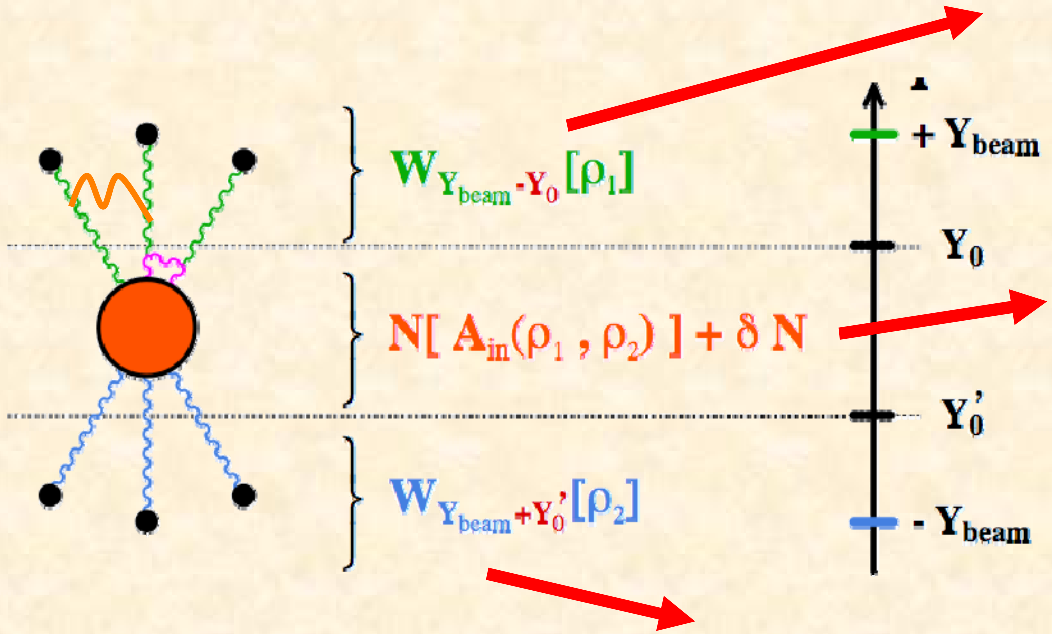


=> factorization

NLO and QCD Factorization

Gelis, Lappi, RV (2008)

What small fluctuations go into wave fn. and what go into particle production ?



Small x (JIMWLK) evolution of nucleus A
-- sum $(\alpha_S Y)^n$ & $(\alpha_S \rho_1)^n$ terms

$O(\alpha_S)$ but may grow as $\alpha_S e^{\sqrt{Q_S \tau}}$

Small x (JIMWLK) evolution of nucleus B
---sum $(\alpha_S Y)^n$ & $(\alpha_S \rho_2)^n$ terms

From Glasma to Plasma

- **NLO factorization formula:**

$$\frac{dN_{\rm LO+NLO}}{dY\,d^2p_\perp} = \int [D\rho_1]\,[D\rho_2] W_{Y_{\rm beam}-Y_0}[\rho_1] W_{Y_{\rm beam}+Y_0'}[\rho_2]$$

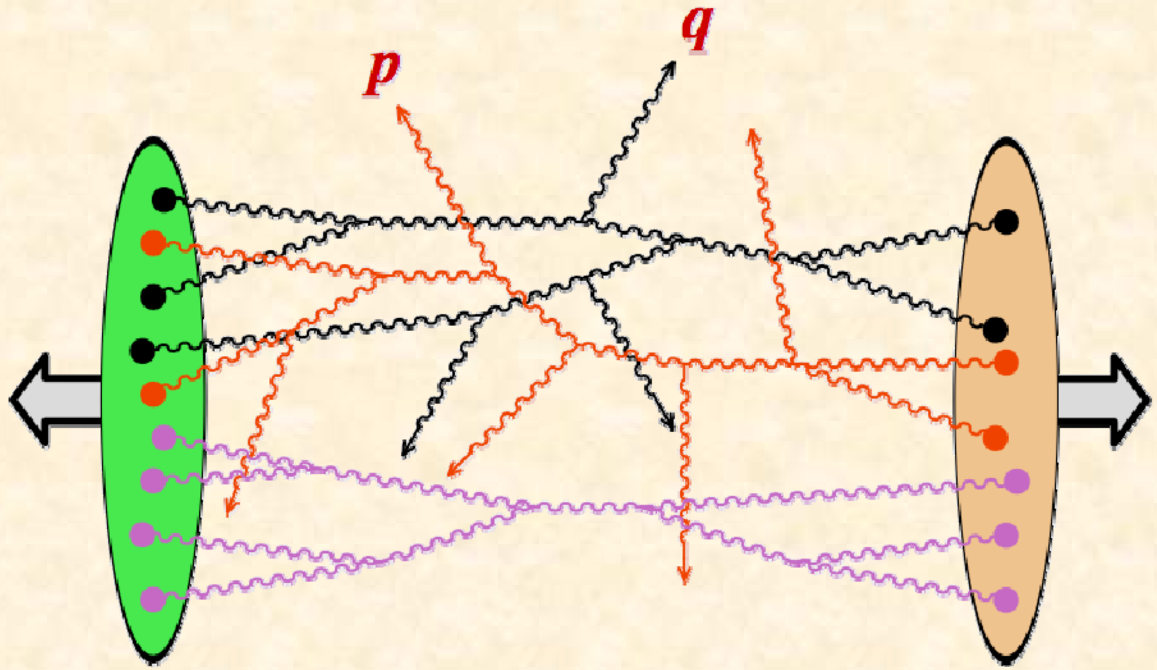
$$\times \int [Da(u)]\tilde{Z}[a] \frac{dN_{\rm LO}[\mathcal{A}(0,u)+a(u)]}{dY\,d^2p_\perp}\Big|_{\rho_1,\rho_2}$$

"Holy Grail" spectrum of small fluctuations.
First computations and numerical simulations underway

Gelis,Fukushima,McLerran
Gelis,Lappi,RV

- **With spectrum, can compute $T^{\mu\nu}$ - and match to hydro/kinetic theory**

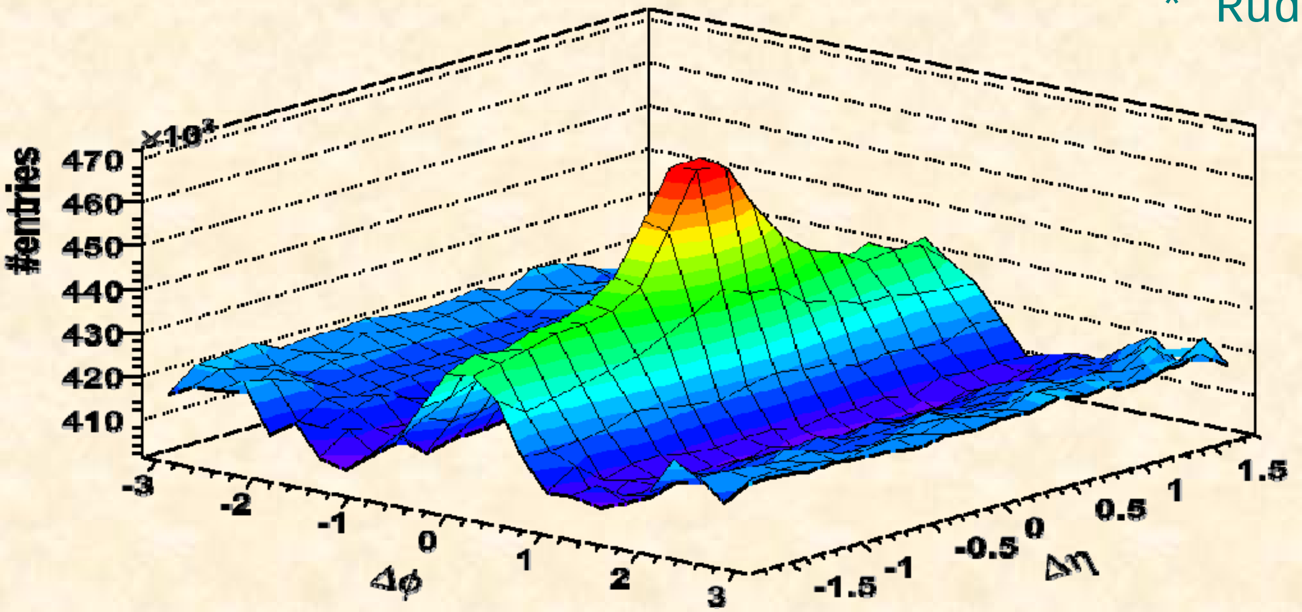
Two particle correlations in the Glasma



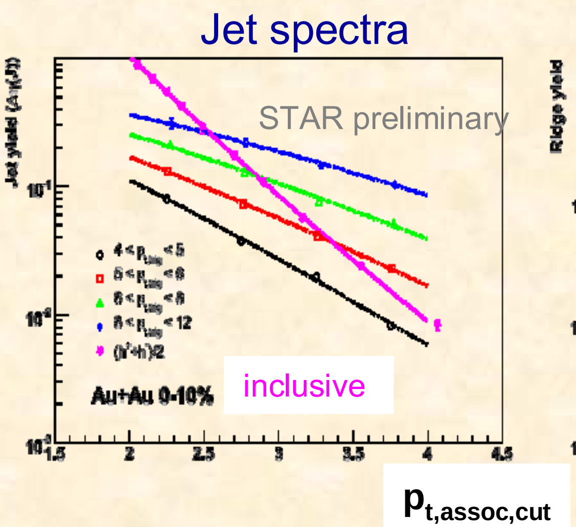
Can it explain the near side ridge ?

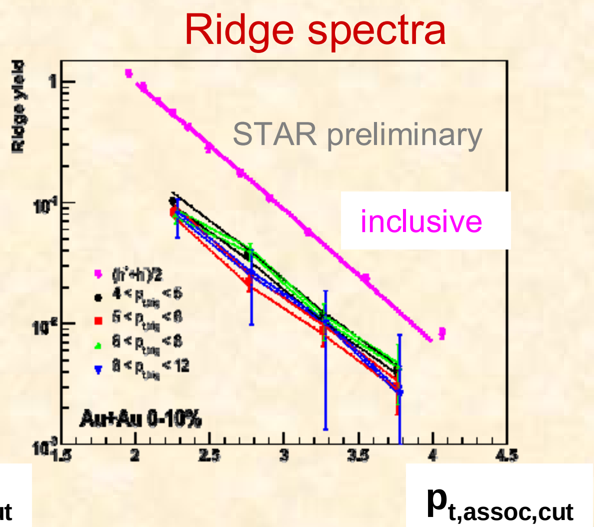
Ridgeology*

* Rudy Hwa



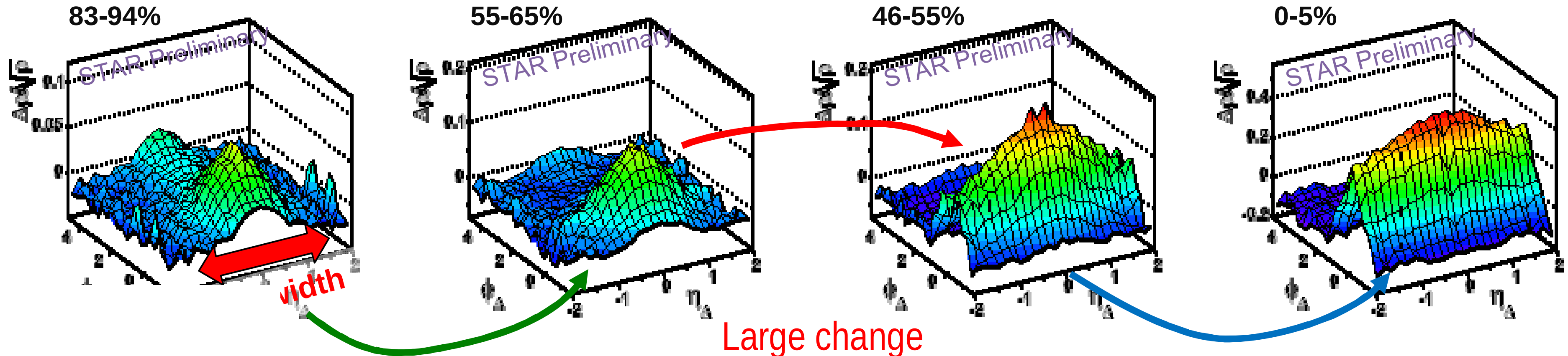
Near side peak+ ridge **(from talk by J. Putschke,STAR collaboration)**





Evolution of mini-jet with centrality

Same-side peak



Little shape change from peripheral to 55% centrality

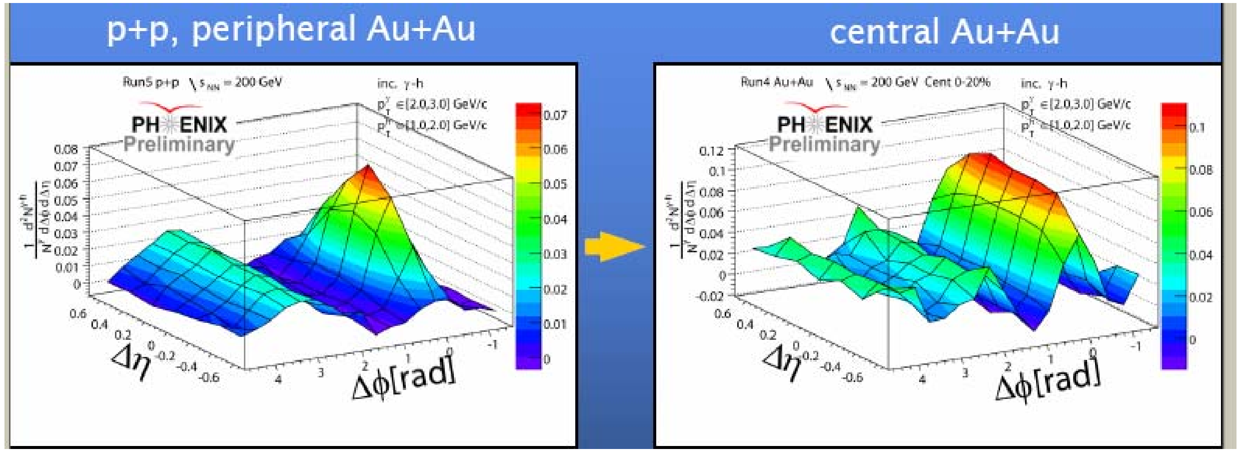
Large change within ~10% centrality

Smaller change from transition to most central

Binary scaling reference followed until sharp transition at ρ ~ 2.5

~30% of the hadrons in central Au+Au participate in the same-side correlation

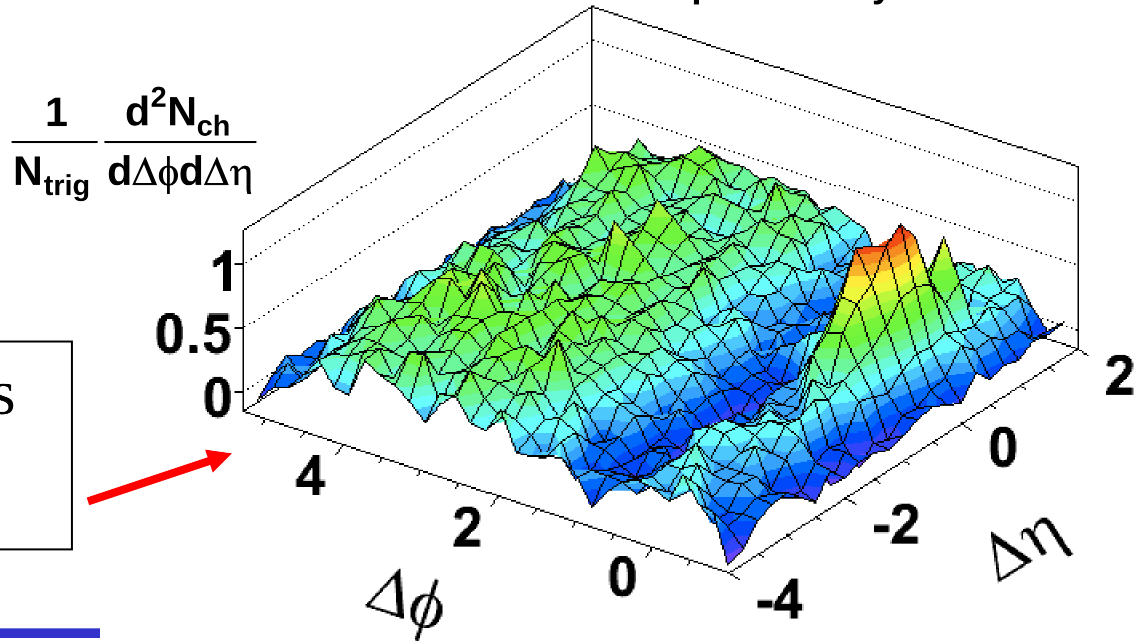
Update: the ridge comes into its own



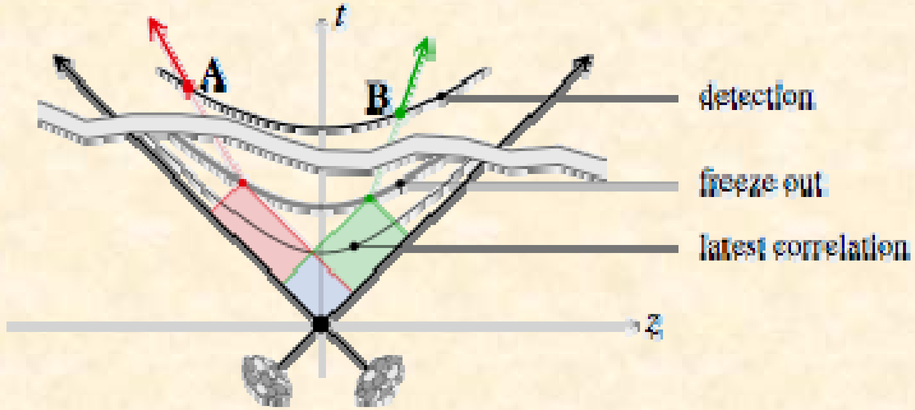
PHENIX: sees a ridge

Au+Au 200 GeV, 0 - 30%

PHOBOS preliminary



PHOBOS: the ridge extends to very high rapidity



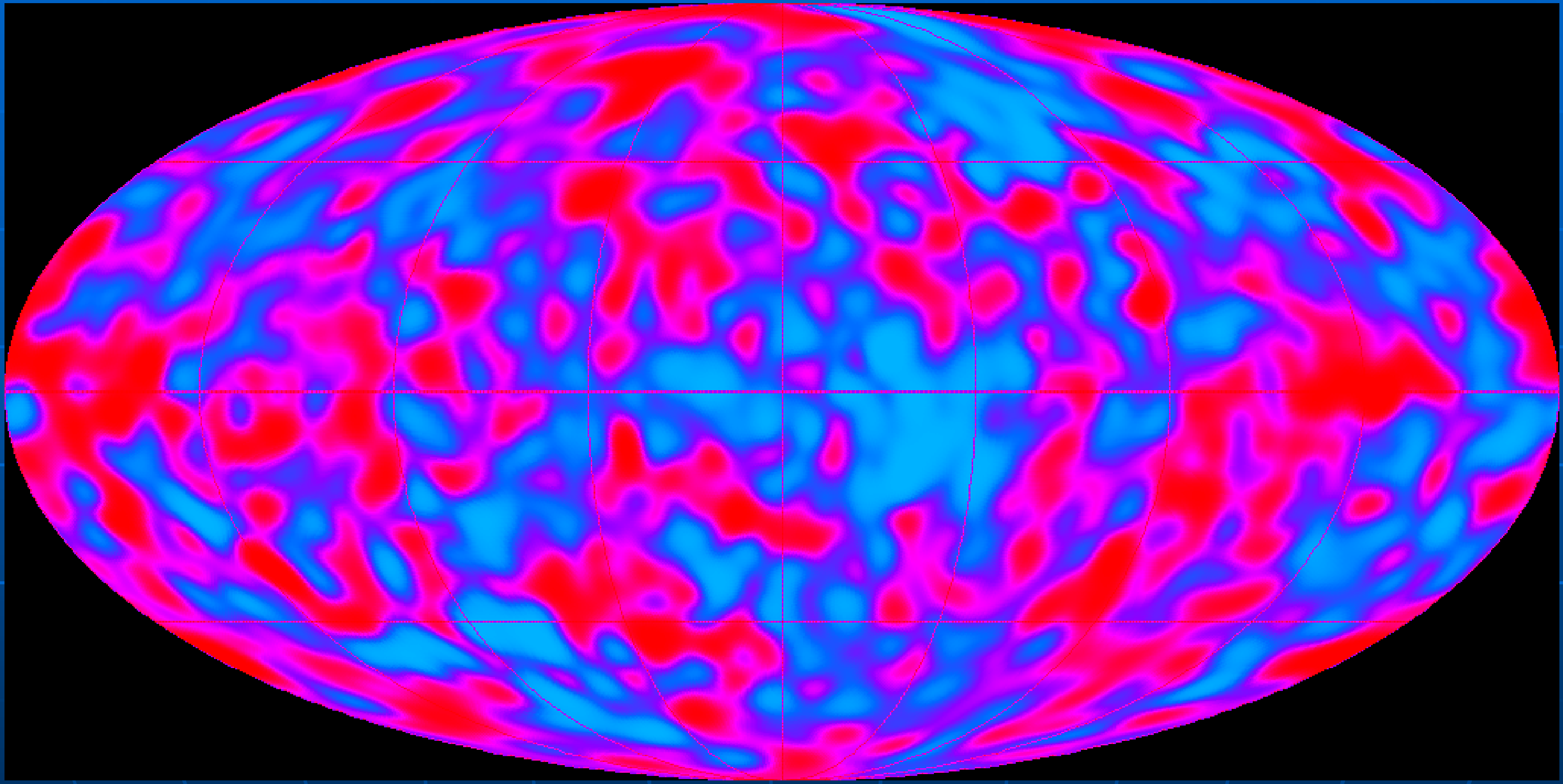
For particles to have been emitted from the same Event Horizon, causality dictates that

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

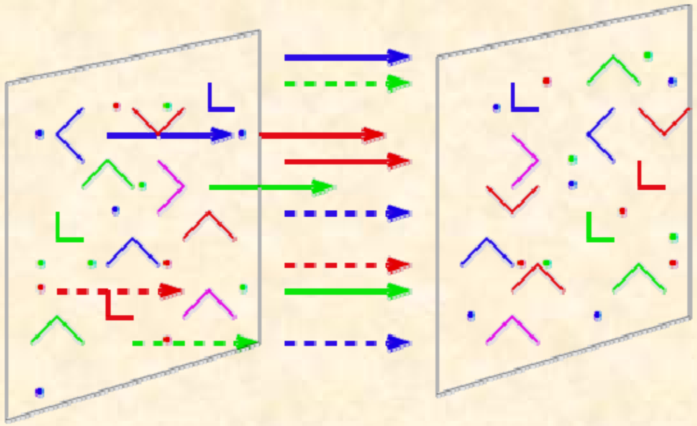
If ΔY is as large as (especially) suggested by PHOBOS, correlations were formed very early - in the Glasma…

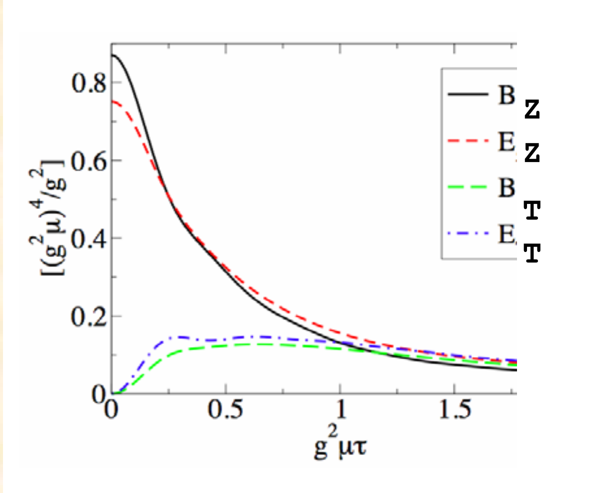
An example of a small fluctuation spectrum…

COBE Fluctuations



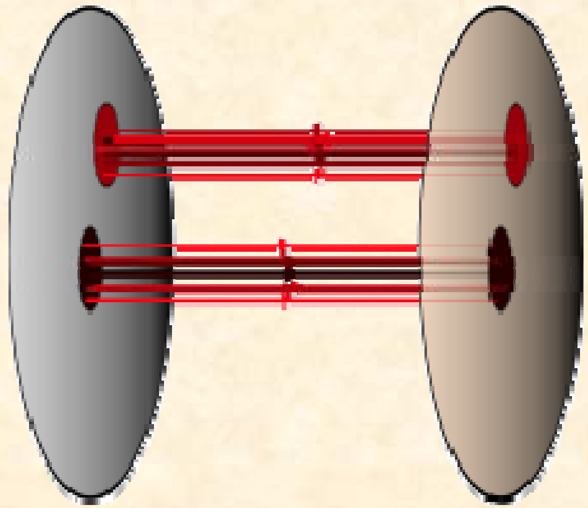
$\delta t/t < 10^{-5}$, i.e. much smoother than a baby's bottom!





After a HI collision, classical fields form a Glasma flux tube with longitudinal chromo E & B fields

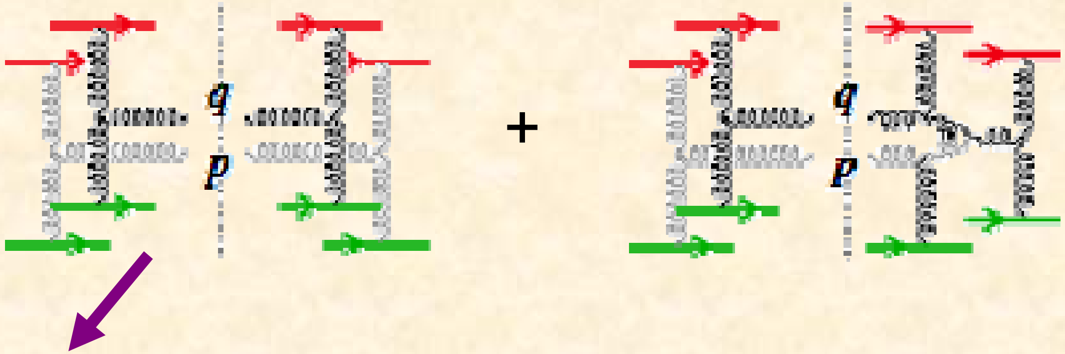
Typical size of flux tube in transverse direction is $1 / Q_S$



2 particle correlations in the Glasma (I)

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

=



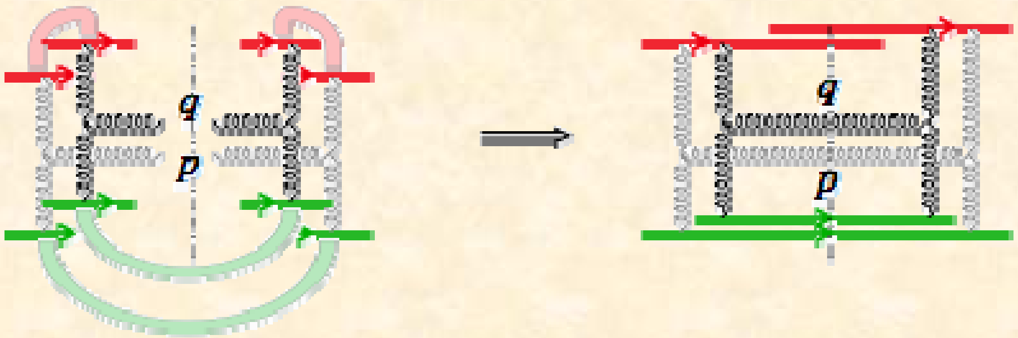
Leading (classical) contribution

Note: *Interestingly, computing leading logs at NLO, both diagrams can be expressed as the first diagram with sources evolved a la JIMWLK Hamiltonian*

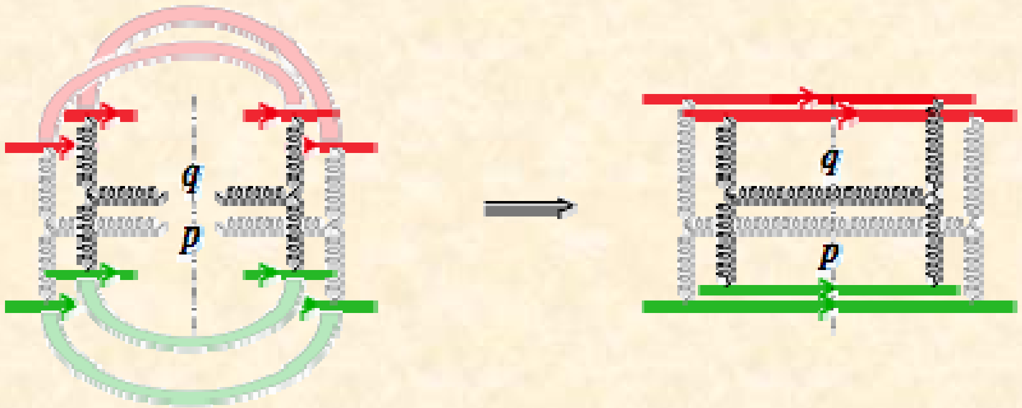
Gelis, Lappi, RV

2 particle correlations in the Glasma (II)

Leading color “topologies”:



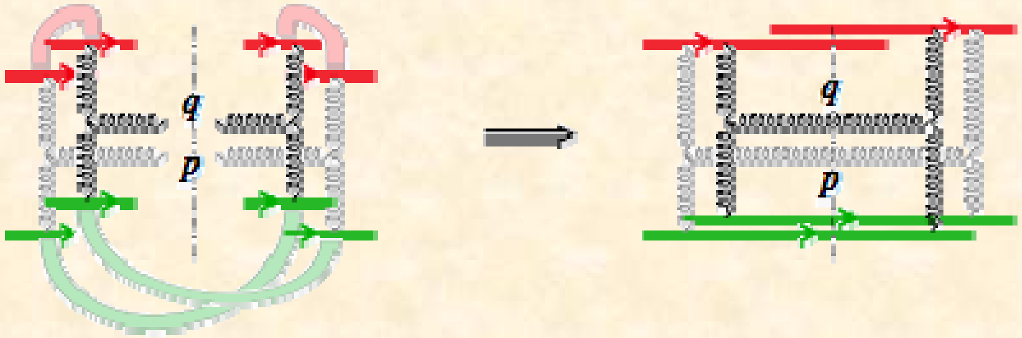
“single diffractive”



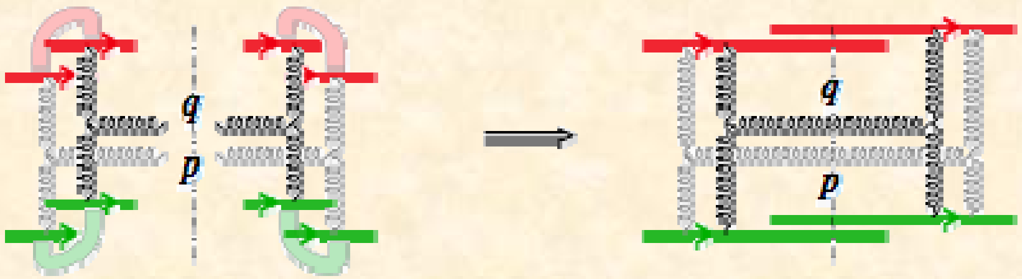
“interference” graph

2 particle correlations in the Glasma (III)

Suppressed color "topologies":



"single diffractive"
(emission from different quark lines in amp. and complex conjugate amp.)



"double diffractive"

2 particle spectrum

Simple "Geometrical" result:

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

$\kappa \approx$ 4 (more accurate result requires numerical soln. of YM eqns. - in progress.

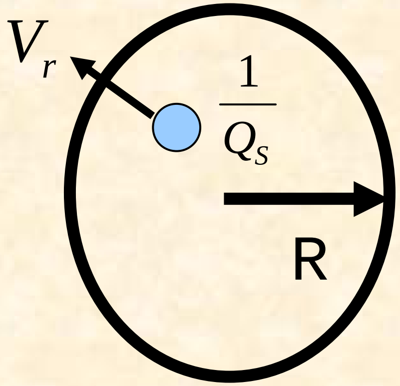
$$\frac{\Delta\rho}{\sqrt{\rho_{\rm ref}}} = \left\langle \frac{dN}{dy} \right\rangle \frac{C(\mathbf{p},\mathbf{q})}{\left\langle \frac{dN}{dy_p\, d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q\, d^2\mathbf{q}_\perp} \right\rangle} = \frac{K_N}{\alpha_S(Q_S)}$$

with K_N $\approx$ 0.3

2 particle spectrum…

Not the whole story… particle emission from the Glasma tubes is isotropic in the azimuth

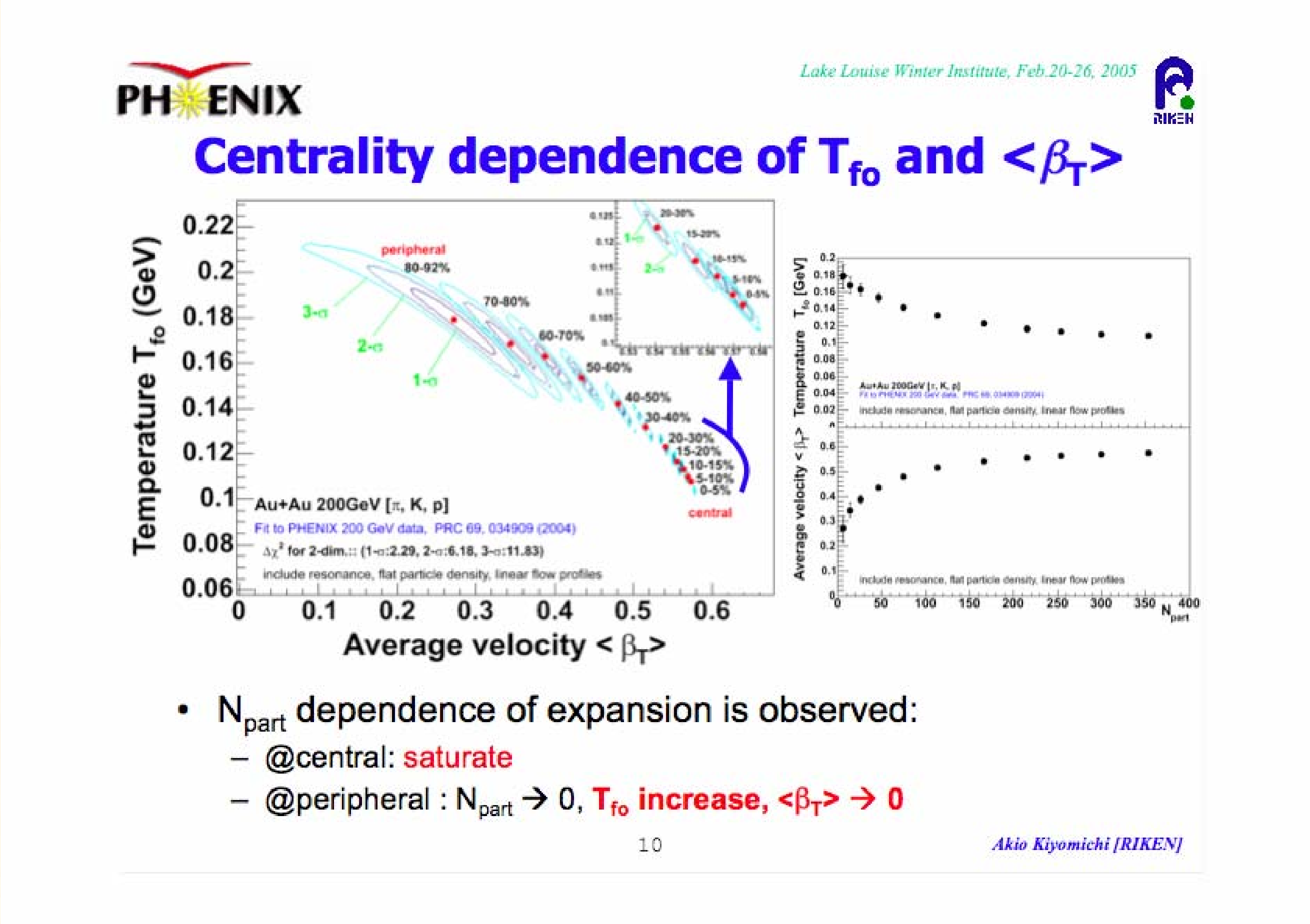
Particles correlated by transverse flow (or at high p_T by opacity effects) - are highly localized transversely, experience same transverse boost



$$\gamma_B = \cosh \zeta_B$$

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

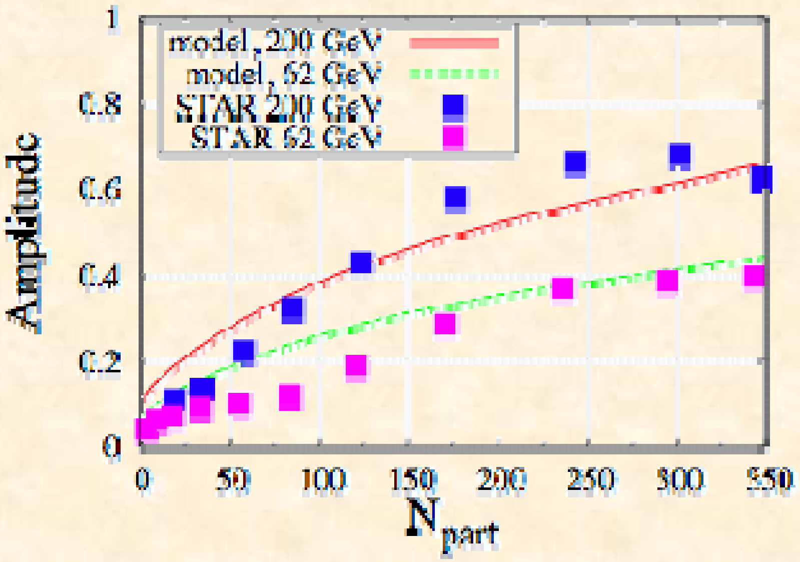
2 particle spectrum…

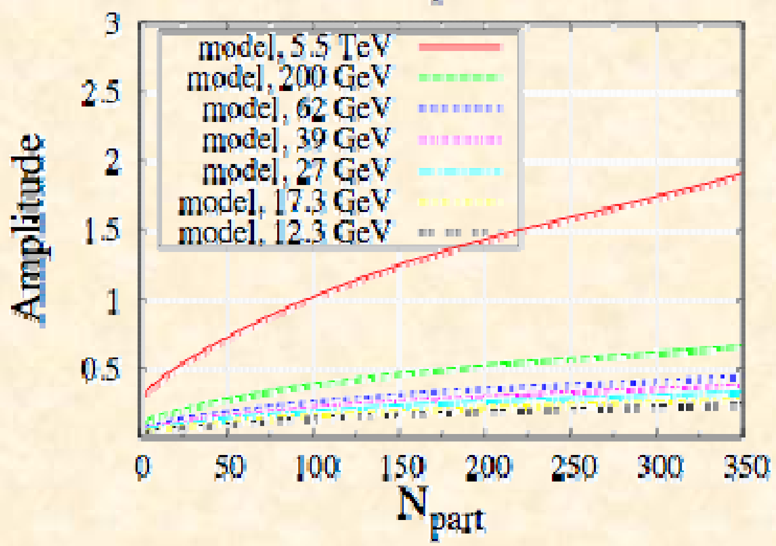


Centrality dependence of V_r from blast wave fits

Centrality dependence of Q_S a la Kharzeev-Nardi

Ridge from flowing Glasma tubes





$K_N \sim 0.1$

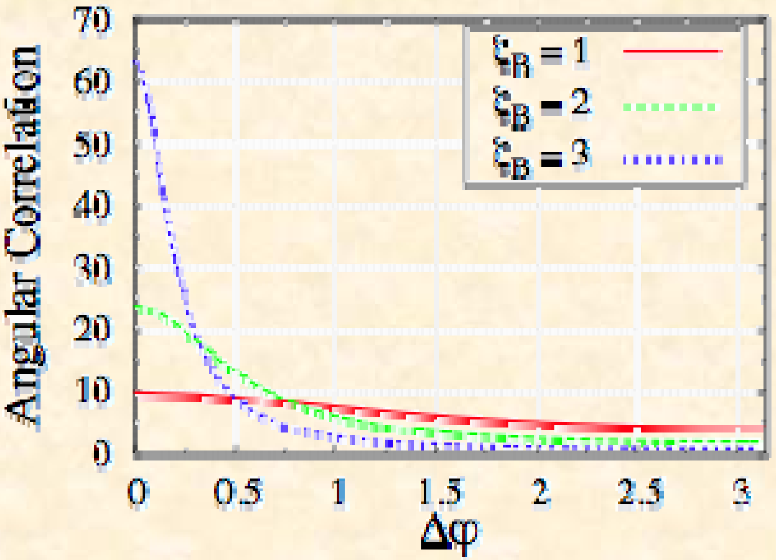
(energy & centrality dep. of flow courtesy of Paul Sorensen)

Ridge from flowing Glasma tubes

Gets many features right:

i) Same flavor composition as bulk matter
ii) Large multiplicity (1/3rd) in the Ridge relative to the bulk
iii) Ridge independent of trigger p_T-geometrical effect
iv) Signal for like and unlike sign pairs the same at large $\Delta\eta$

Caveat:



Angular dist.
appears to require larger boosts,
or absorption by medium
a la Shuryak

Conclusions

I. *Ab initio* (NLO) calculations of the initial Glasma in HI collisions are becoming available

III. Deep connections between QCD factorization and turbulent thermalization

IV. Possible explanation of interesting 2 particle correlations - the near side Ridge @ RHIC

Extra Slides

Some possible ridge explanations

QCD bremsstrahlung radiation boosted by transverse flow
S.A.Voloshin, Phys.Lett.B. 632(2007)490
E.Shuryak, hep-ph:0706.3531

In medium radiation and longitudinal flow push
N.Armesto et.al Phys.Rev.Lett. 93(2007) 242301

Broadening of quenched jets in turbulent color fields
A.Majumder et.al
Phys. Rev. Lett.99(2004)042301

Recombination between thermal and shower partons at intermediate p_T
R.C. Hwa & C.B. Chiu
Phys. Rev. C 72 (2005) 034903

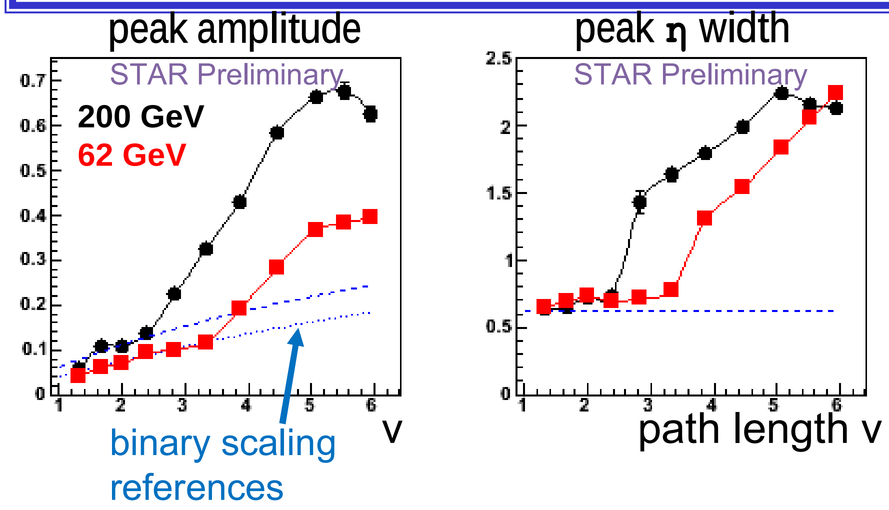
Momentum Kick Model
C.Y. Wong hep-ph:0712.3282

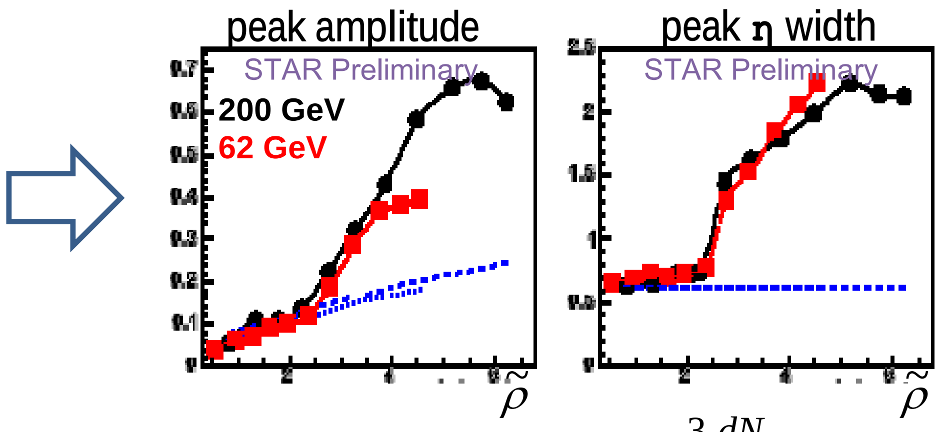
All qualitatively consistent with the features of ridge

New approaches used in to attempt to disentangle

- System size dependence
- Identified particle correlation
- Di-hadron correlation with respect to reaction plane
- 3-particle correlation

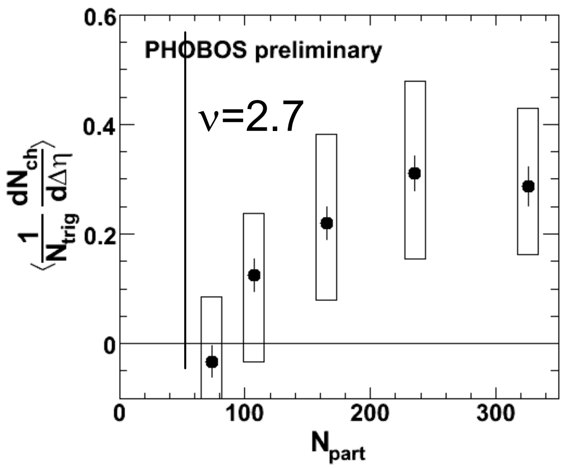
Sharp turn-on of the ridge

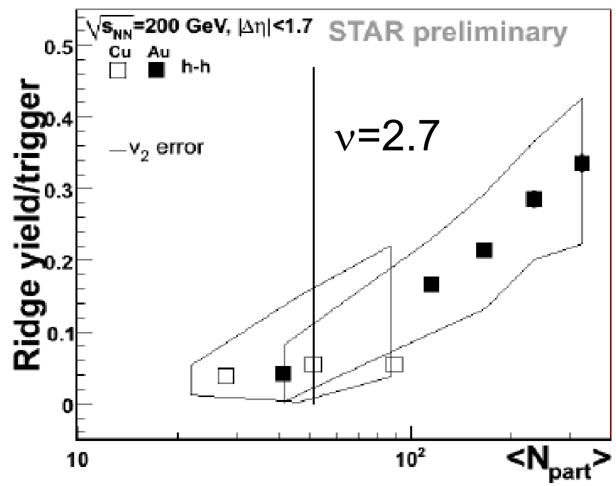




Transverse particle density $\tilde{\rho} = \frac{3}{2}\frac{dN_{ch}}{d\eta}/S$

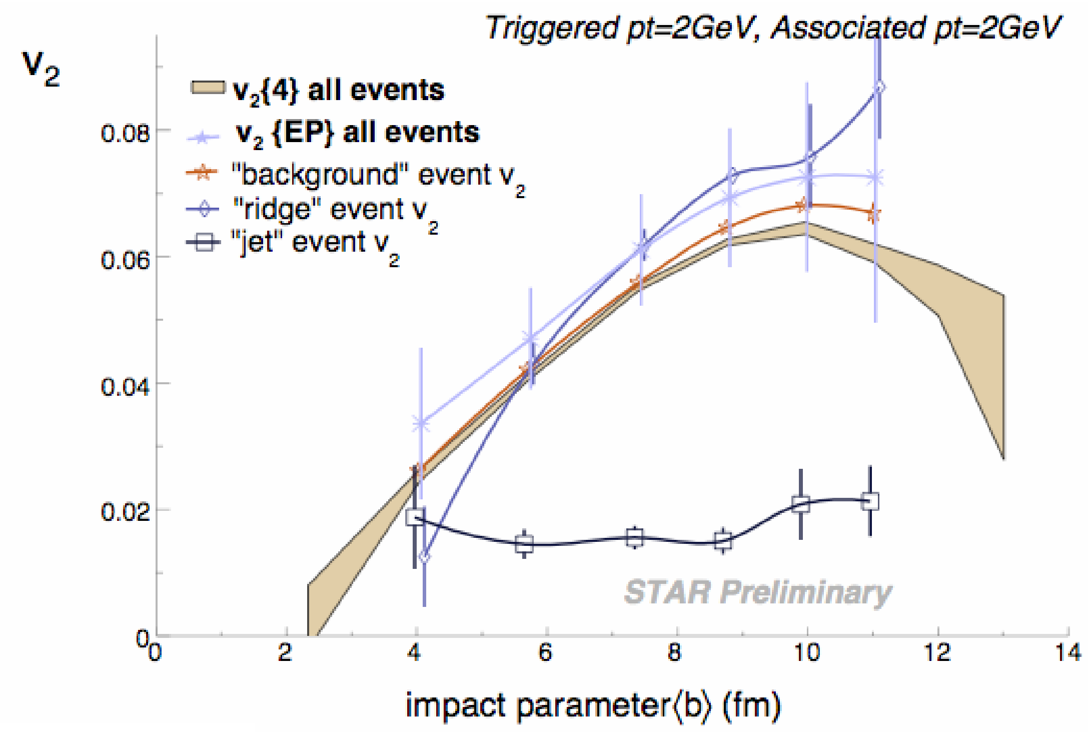
- At low p_T (untriggered), extension in Δη turns on abruptly
- Scaling between energies points to transverse particle density
- Are there signs of this in other analyses? Not clear (need to beat down v_2 effect)





Multi-particle Correlations

Small flow in “jet”-like events



T: $3<p_T<4$ GeV
A: $1<p_T<2$ GeV