The Color Glass Condensate and Glasma

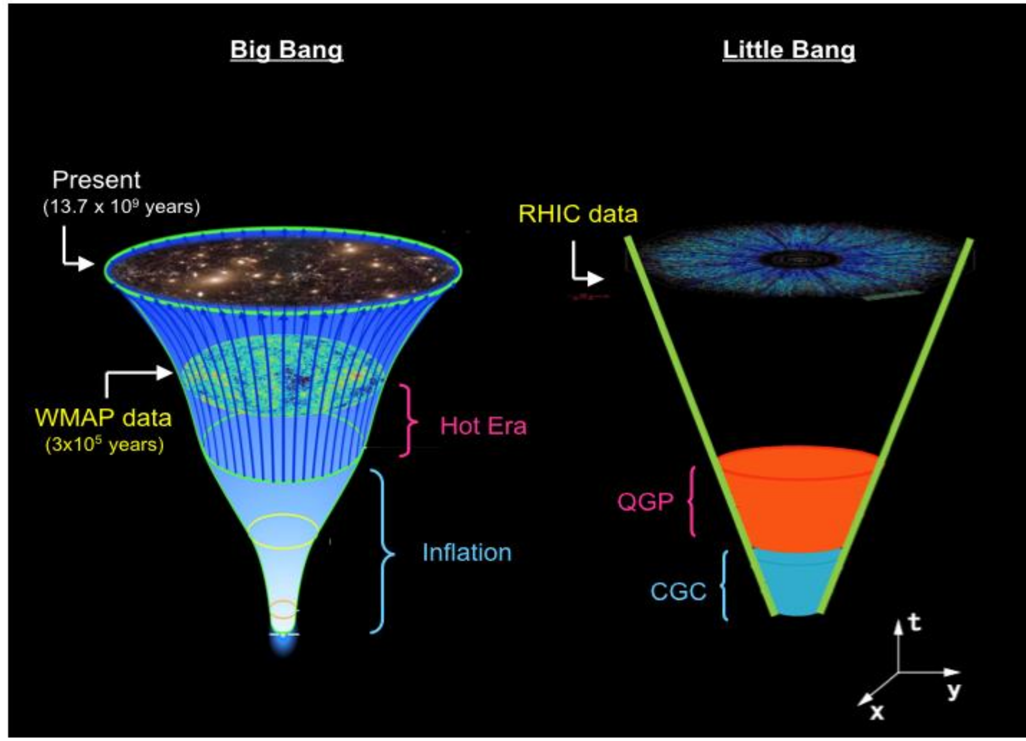
What is the high energy limit of QCD?

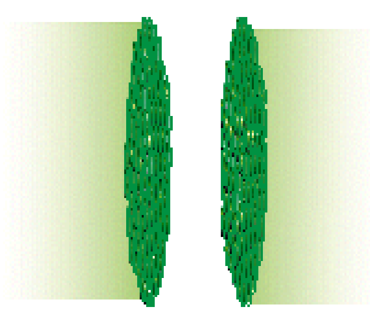
What are the possible form of high energy density matter?

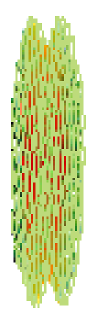
How do quarks and gluons originate in strongly interacting

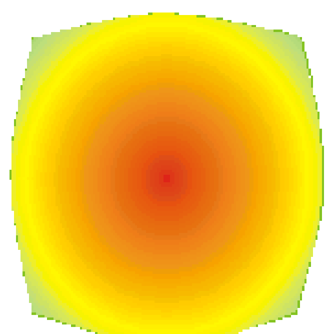
particles?

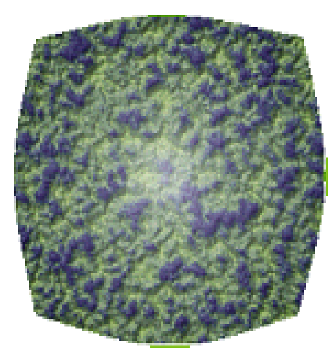
Art due to Hatsuda and S. Bass

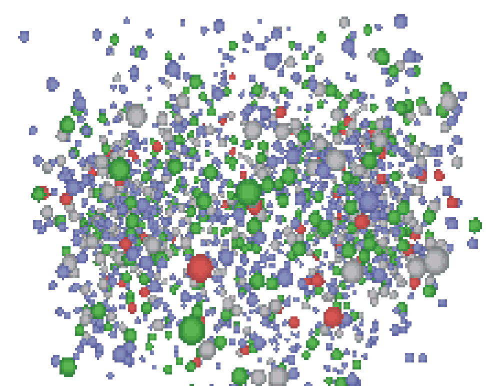


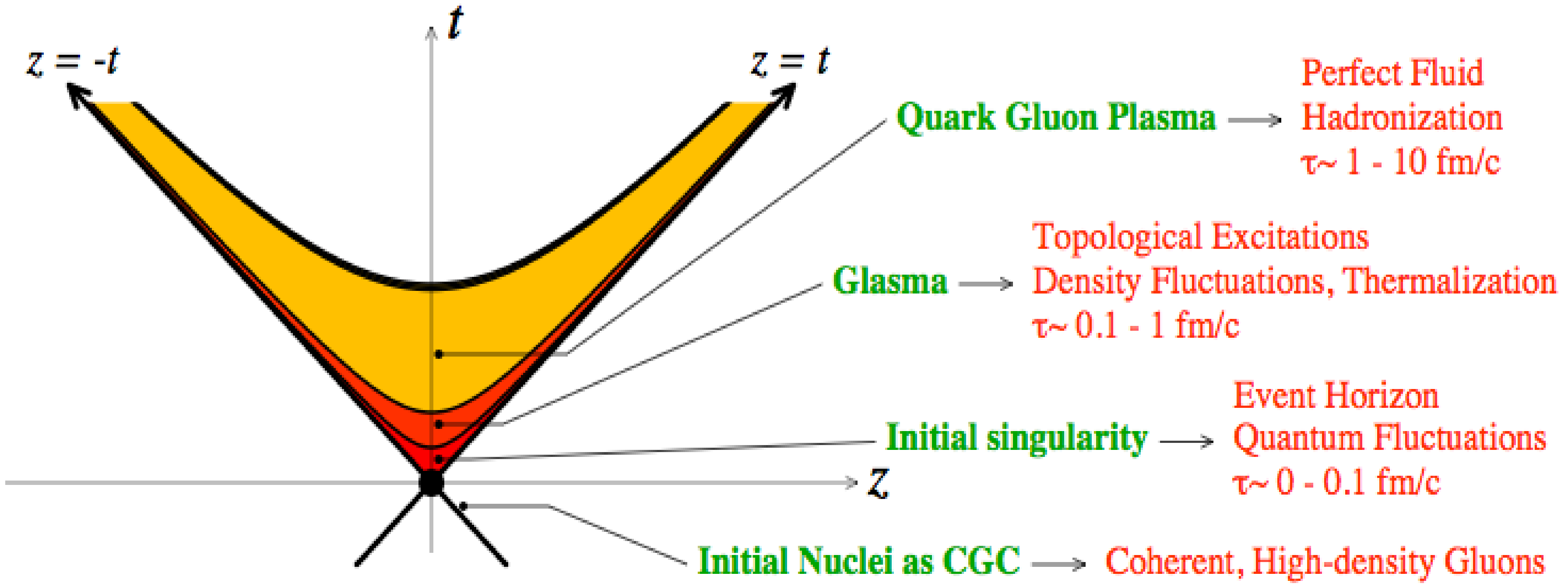

CGC


Initial Singularity


Glasma


sQGP


Hadron Gas

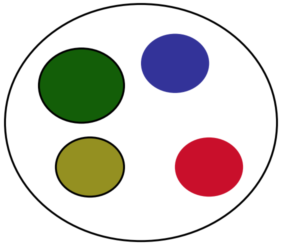


Strong correspondence with cosmology.

How can ideas be tested?

What are the new physics opportunities?

The Hadron Wavefunction at High Energy

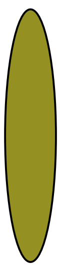


Baryon:

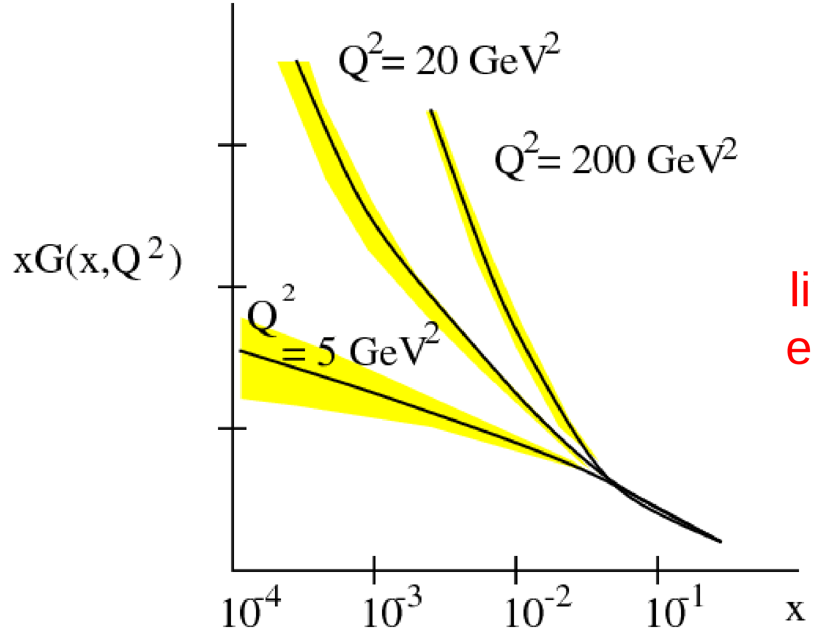
3 quarks

3 quarks 1 gluon

.....

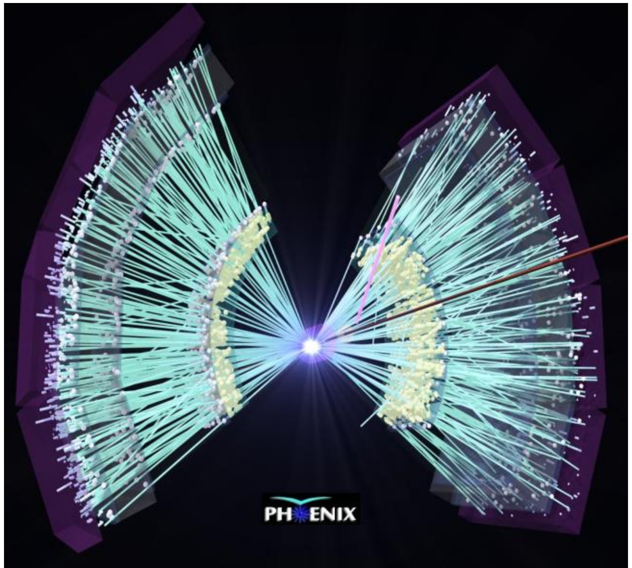


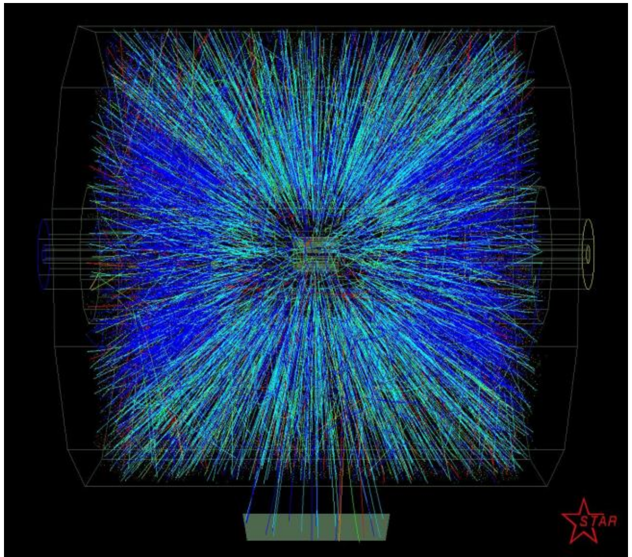
3 quarks and lots of gluons



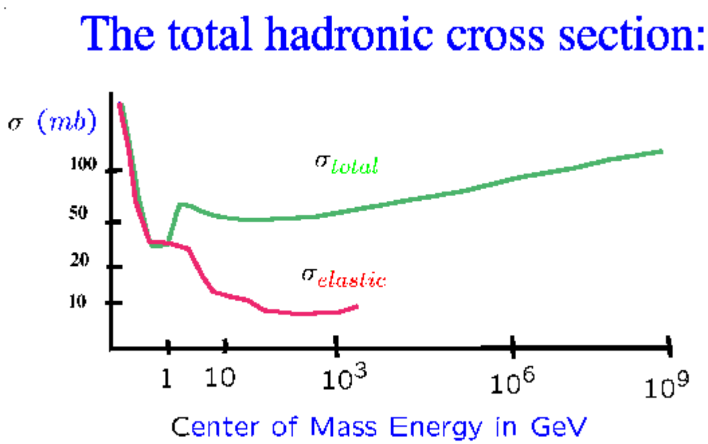
$$x = E_{gluon}/E_{hadron}$$

Small x limit is high energy limit





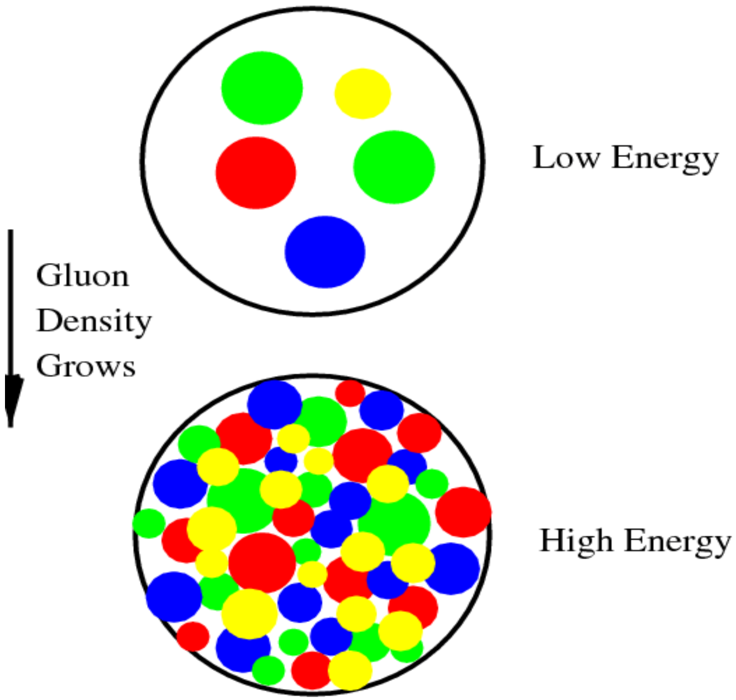
Where do all the gluons go?



Cross sections for hadrons rise very slowly with energy

$$\sigma_{tot} \sim ln^2(E/\Lambda_{QCD})$$

$$\Lambda_{QCD} \sim 200\ MeV$$



But the gluon density rises much more rapidly!

The high energy limit is the high gluon density limit.

Surely the density must saturate for fixed sizes of gluons at high energy.

What is the Color Glass Condensate?

Glue at large x generates glue at small x

Glue at small x is classical field

Time dilation -> Classical field is glassy

High phase space density -> Condensate

Phase space density: $\frac{dN}{dyd^2p_Td^2x_T} = \rho$ $\quad y = ln(1/x)$

Attractive potential $V \sim -\rho$ Repulsive interactions $\sim \alpha_{strong}\rho^2$

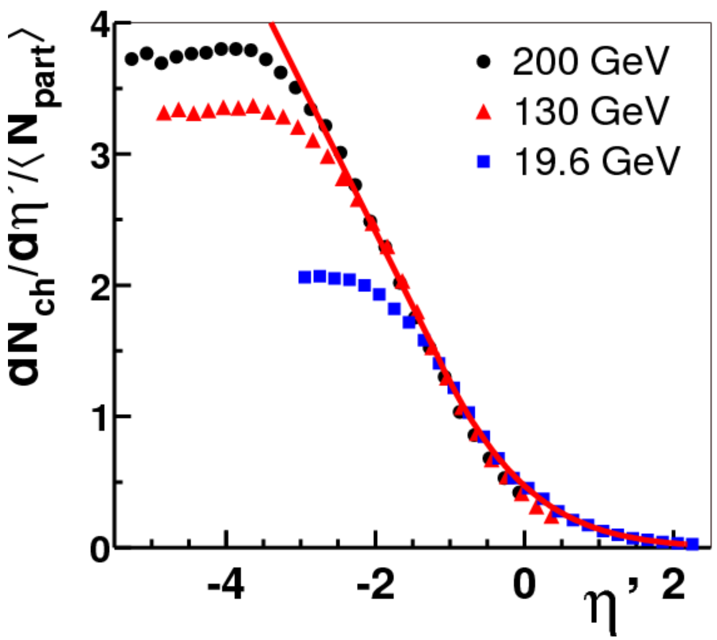
Density as high as it can be $\rho \sim 1/\alpha_{strong}$

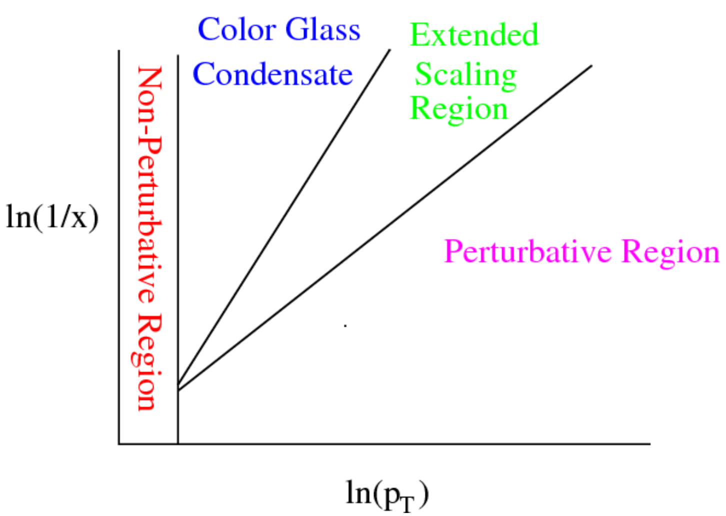
Because the density is high α_{strong} is small

ρ is big

There must be a renormalization group

The x which separates high x sources from small x fields is arbitrary





Phobos multiplicity data

High energy QCD “phase” diagram

$$\frac{dN}{dyd^2r_T} \sim \int d^2p_T \frac{dN}{dyd^2p_Td^2r_T} \sim \frac{1}{\alpha_{strong}} Q_{sat}^2$$

Why is the Color Glass Condensate Important?

It is a new universal form of matter:

Matter: Carries energy; Separation of gluons is small compared to size of system; Number of gluons is large

New: Can only be made and probed in high energy collsions

Universal: Independent of hadron, renormalization group equations have a universal solution.

Universality <=> Fundamental

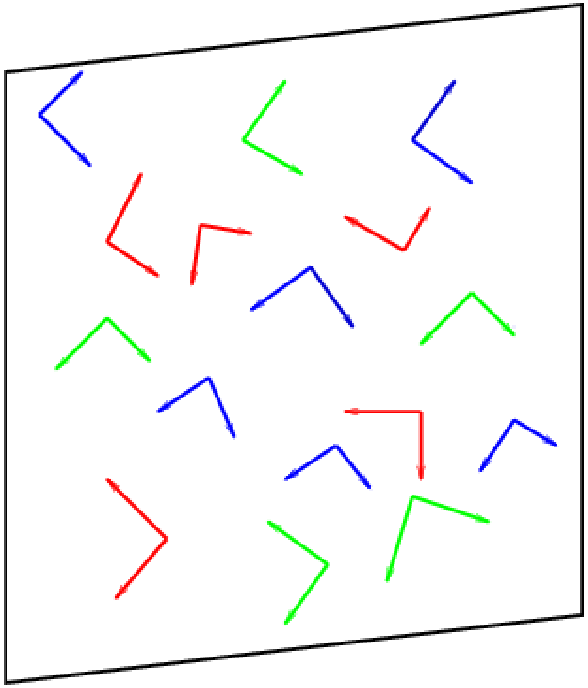
It is a theory of:

Origin of glue and sea quarks in hadrons

Cross sections

Initial conditions for formation of Quark Gluon Plasma in heavy ion collisions

What does a sheet of Colored Glass look like?



$\vec{E} \perp \vec{B} \perp \vec{z}$

On the sheet $x^- = t - z$ is small

Independent of $x^+ = t + z$

$F^{i-} = E - B$ small

$F^{i+} = E + B$

F^{ij} big

Lienard-Wiechart potentials

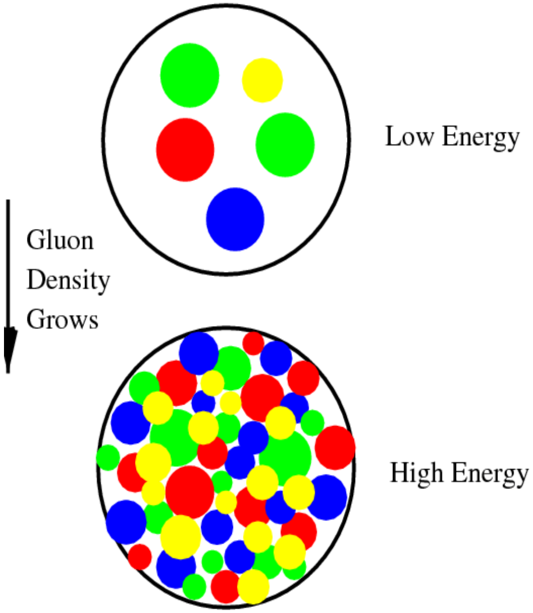
Random Color

Density of gluons per unit area $\frac{1}{\pi R^2} \frac{dN}{dy} \sim \frac{1}{\alpha_{strong}} Q^2_{sat}$

The Color Glass Condensate Explains Growth of Gluons at Small x

Renormalization group equation predicts:

$$Q^2_{sat} \sim \Lambda^2_{QCD} e^{\kappa y}$$



Gluon pile up at fixed size until

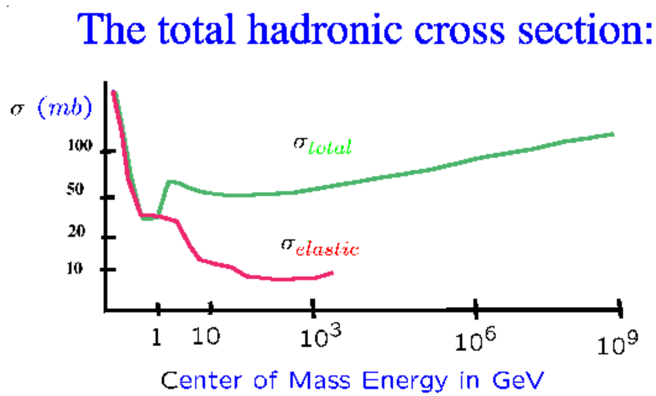
$1/\alpha$ gluons with strength α

act like a hard sphere

$$r_T p_T \sim 1$$

Once one size scale is filled
Move to smaller size scale
Typical momentum scale grows

The CGC Explains Slow Growth of Total Cross Section



Transverse distribution of gluons:

$$\frac{dN}{dy d^2 r_T} = Q^2_{sat}(y) e^{-2 m_\pi r_T}$$

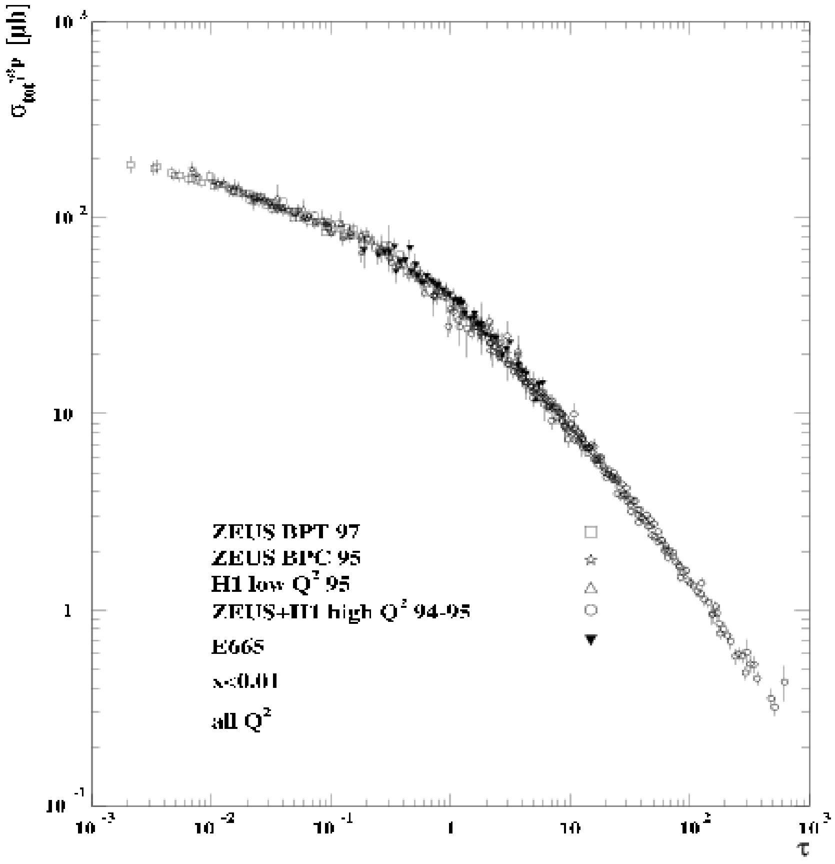
Transverse profile set by initial conditions

Size is determined when probe sees a fixed number of particles at some transverse distance

$$e^{\kappa y} e^{-2 m_\pi r_T} \sim constant$$

$$\sigma \sim r_T^2 \sim y^2 \sim ln^2(E/\Lambda_{QCD})$$

CGC Explains Qualitative Features of Electron-Hadron Scattering



Q is resolution momentum of photon, x is that of struck quark

$$\sigma_{\gamma^* p} \sim F(Q^2/Q^2_{sat}(x))$$

Function only of a particular combination of Q and x

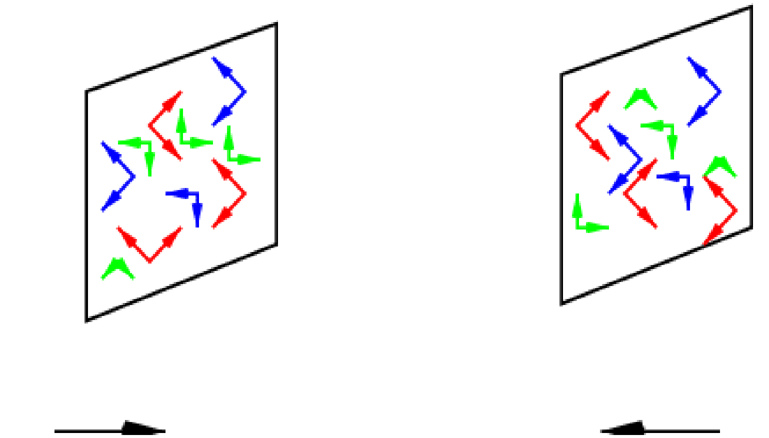
⇒Scaling relation

Works for $x < 10^{-2}$

Can successfully describe quark and gluon distributions at small x

and wide range of Q

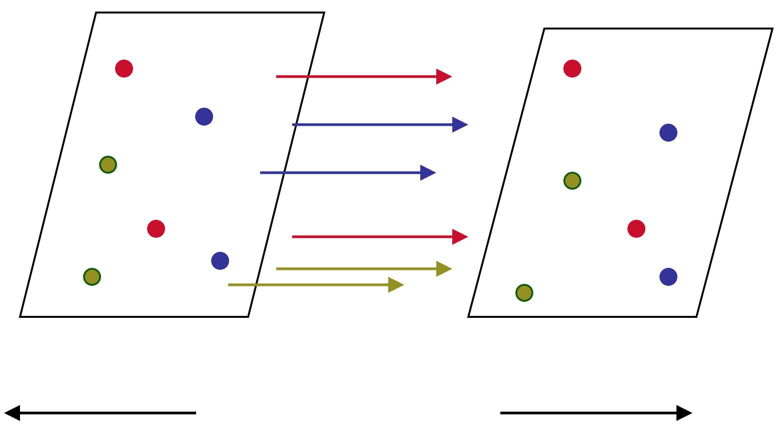
CGC Gives Initial Conditions for QGP in Heavy Ion Collisions



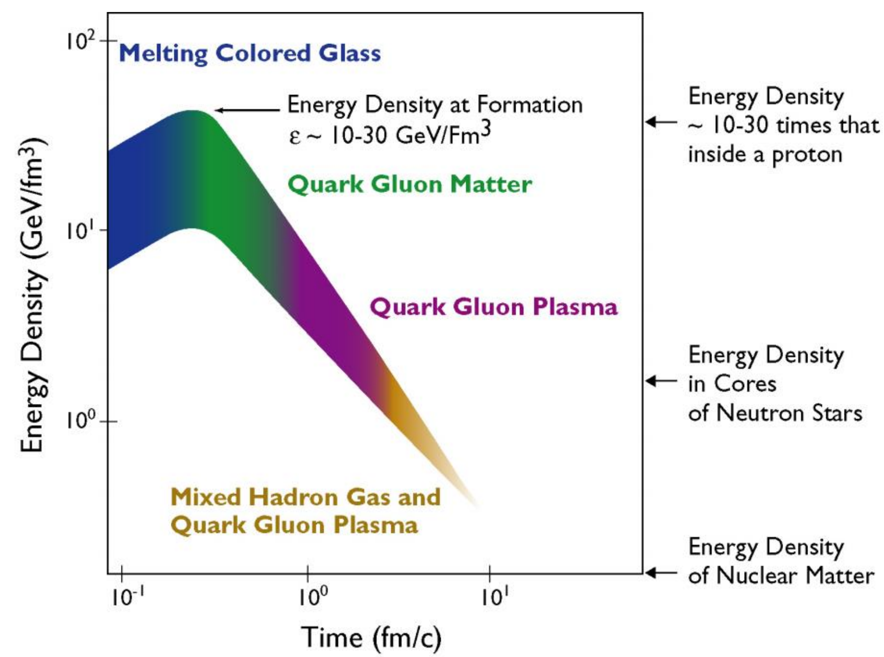
Two sheets of colored glass collide

Glass melts into gluons and thermalize

QGP is made which expands into a mixed phase of QGPand hadrons



"Instantaneously" develop longitudinal color E and B fields

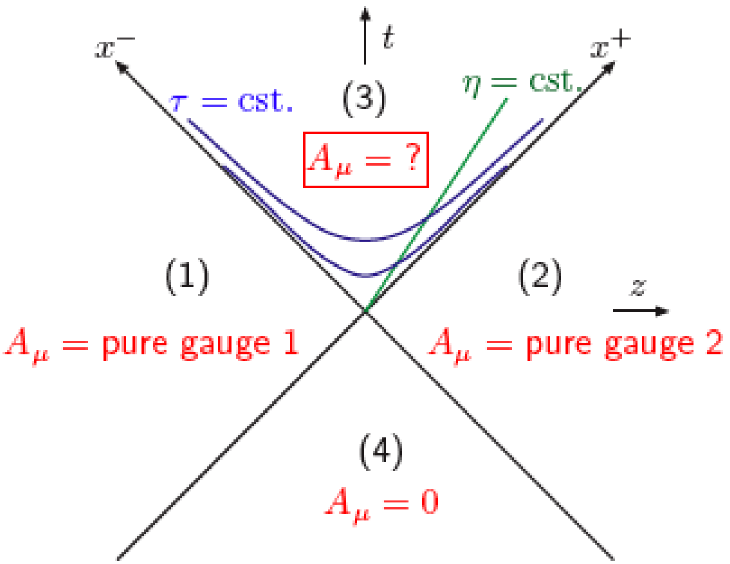


The Glasma:

Before the collision only transverse E and B CGC fields

Color electric and magnetic monopoles

Almost instantaneous phase change to longitudinal E and B



Topological charge density is maximal:

Anomalous mass generation

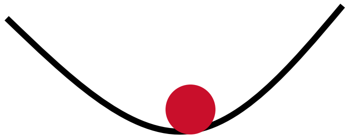
In cosmology:

Anomalous Baryogenesis

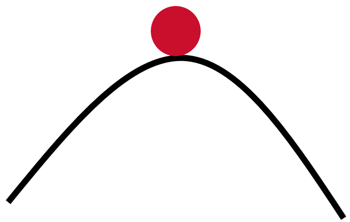
Production of gluons and quarks from melting colored glass

Interactions of evaporated gluons with classical field is g x 1/g ~ 1 is strong

Thermalization?



Before collision, stability



After collisions, unstable

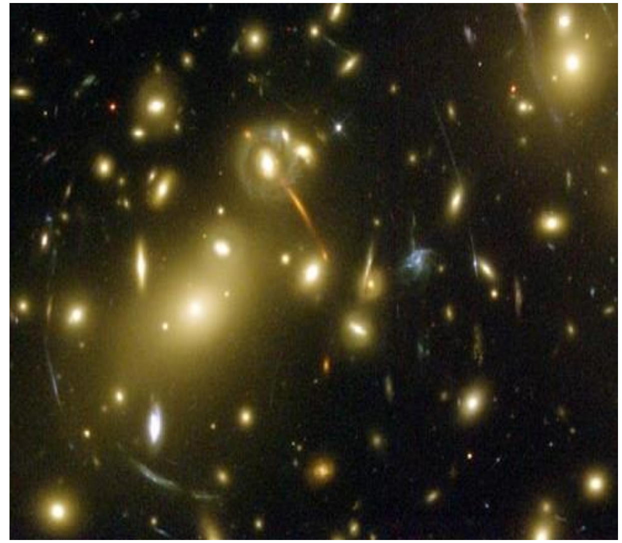
Quantum fluctuations can become as big as the classical field

Quantum fluctuations analogous to Hawking Radiation

Growth of instability generates turbulence => Kolmogorov spectrum

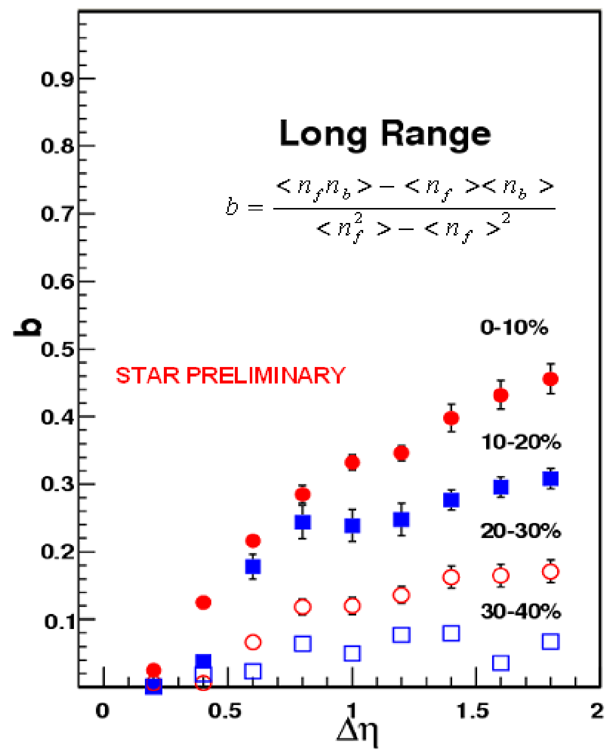
Analogous to Zeldovich spectrum of density fluctuations in cosmology

Topological mass generation



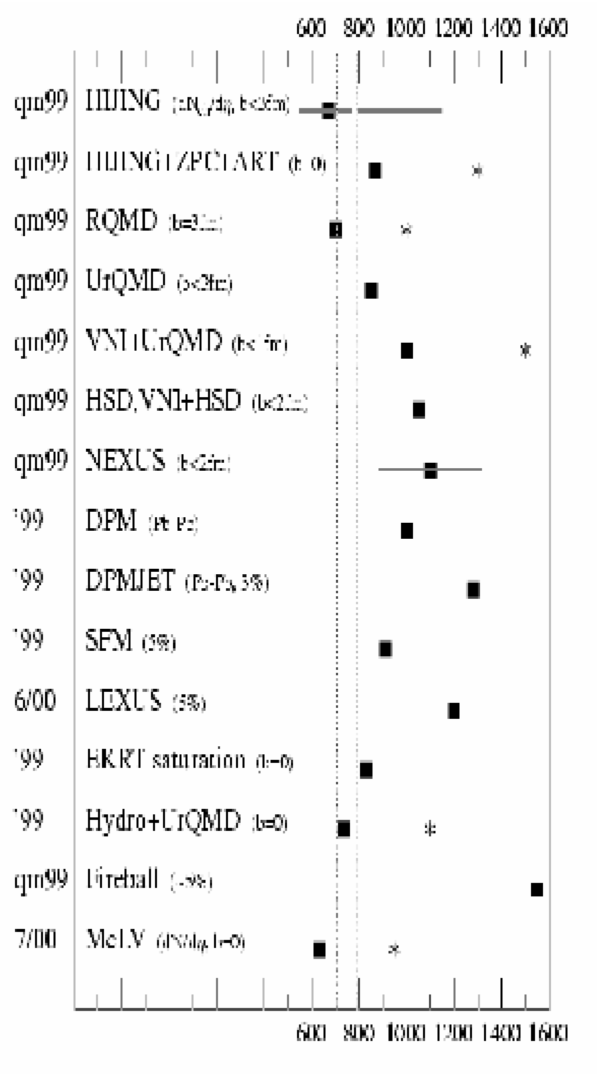
During inflation: Fluctuations on scale larger than even horizon are made

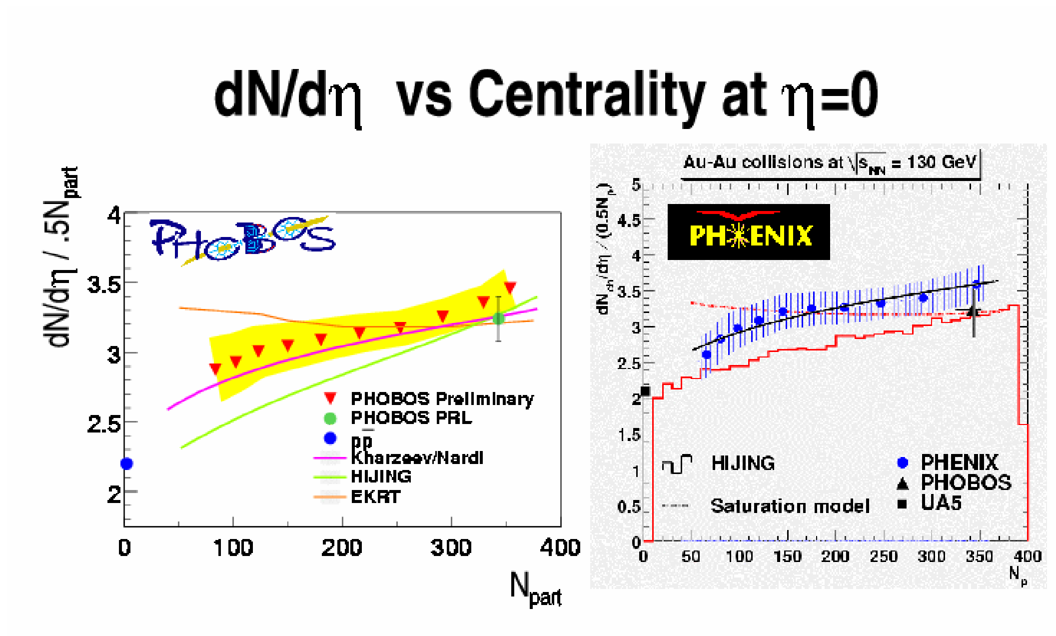
Late times: Become smaller than even horizon => Seeds for galaxy formation



Fluctuations over many units in rapidity in initial wavefunction

CGC-Glasma predicted particle production at RHIC





$$\frac{dN}{dy} \sim \frac{1}{\alpha_{strong}} \pi R^2 Q_{sat}^2 \sim A ln(A)$$

Proportionality constant can be computed.

Correctly describes suppression of particle production in forward regions of ion-ion and proton-ion collisions.

Summary

Successes:

Geometric scaling in DIS

Diffractive DIS

Shadowing in dA

Multiplicity in AA

Limiting fragmentation

Long range correlations

Total cross section

Pomeron, reggeon, odderon

At RHIC:

Systematic pA studies; Many exciting possibilities

Topological Charge?

LHC:

Can study at very small x with very high resolution

Experimental probe of CGC and Glasma

eRHIC:

Precision experiments and tests

Careful and systematic study of CGC