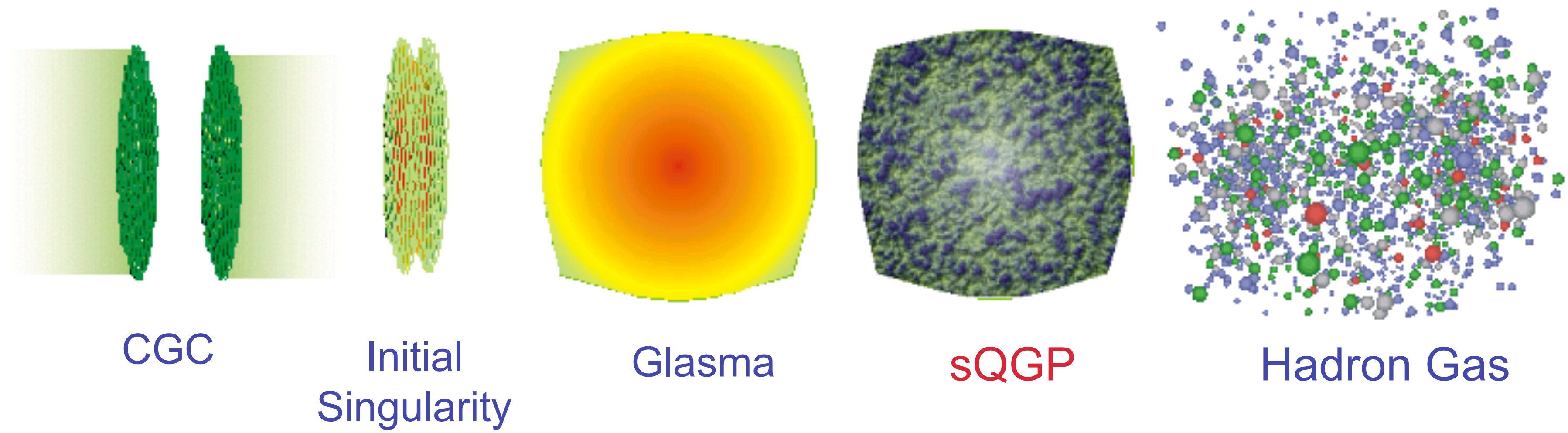
Theoretical Aspects of the Color Glass Condensate and Glasma

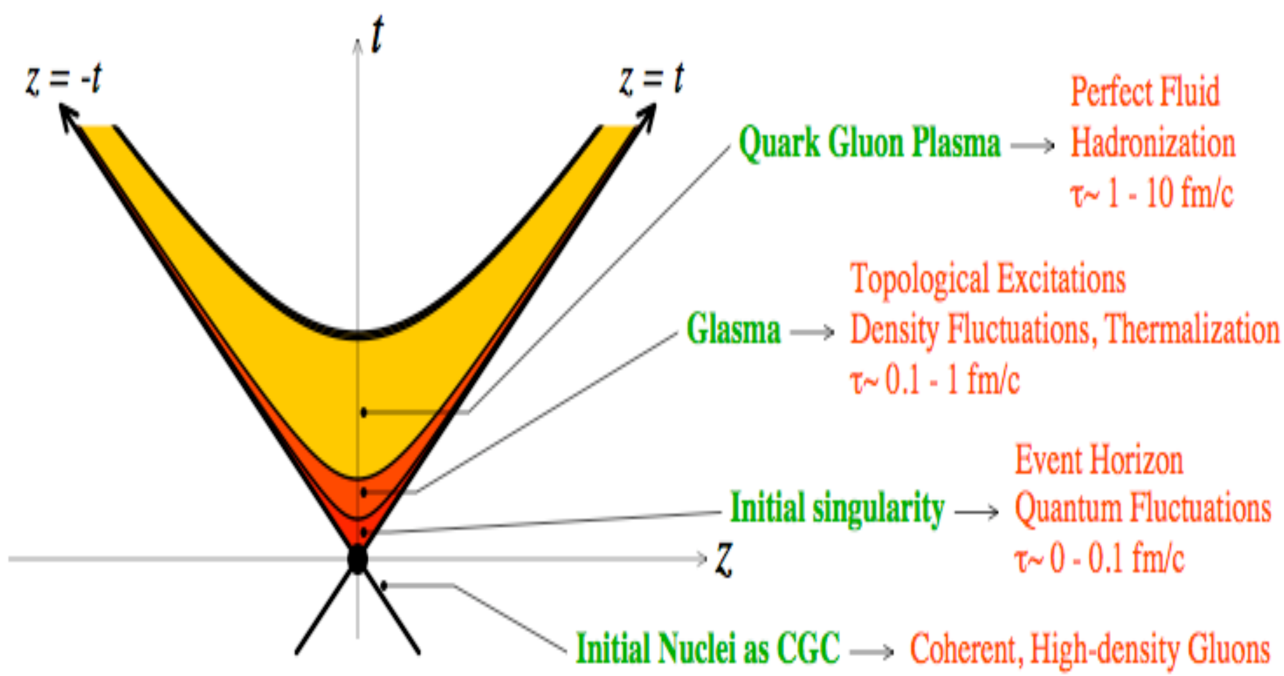
Art due to S. Bass



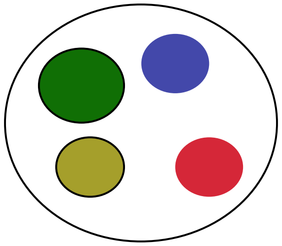
What is the high energy limit of QCD?

What are the possible form of high energy density matter?

How do quarks and gluons originate in strongly interacting particles?



The Hadron Wavefunction at High Energy

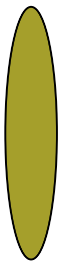


Baryon:

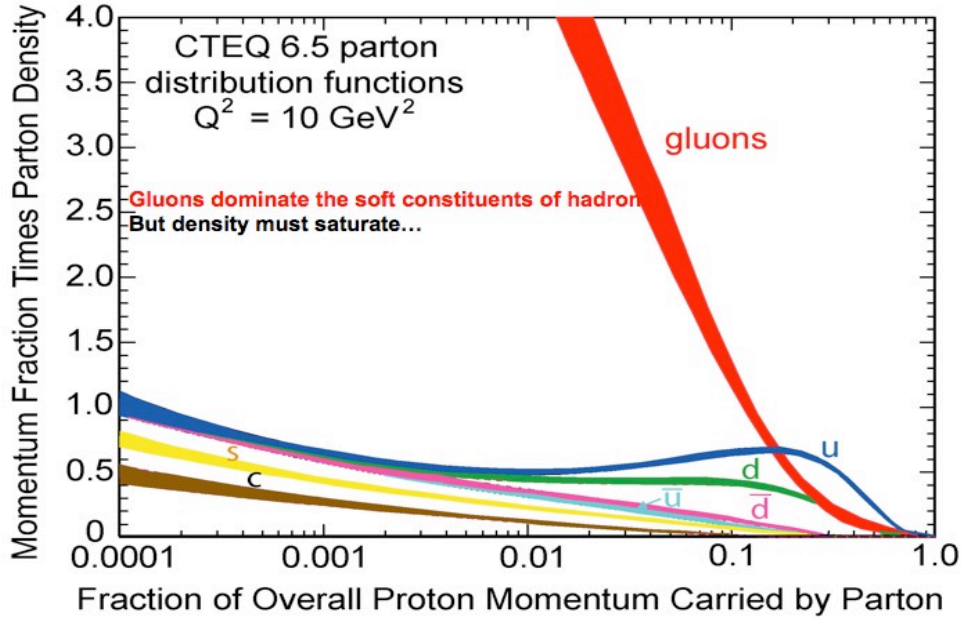
3 quarks

3 quarks 1 gluon

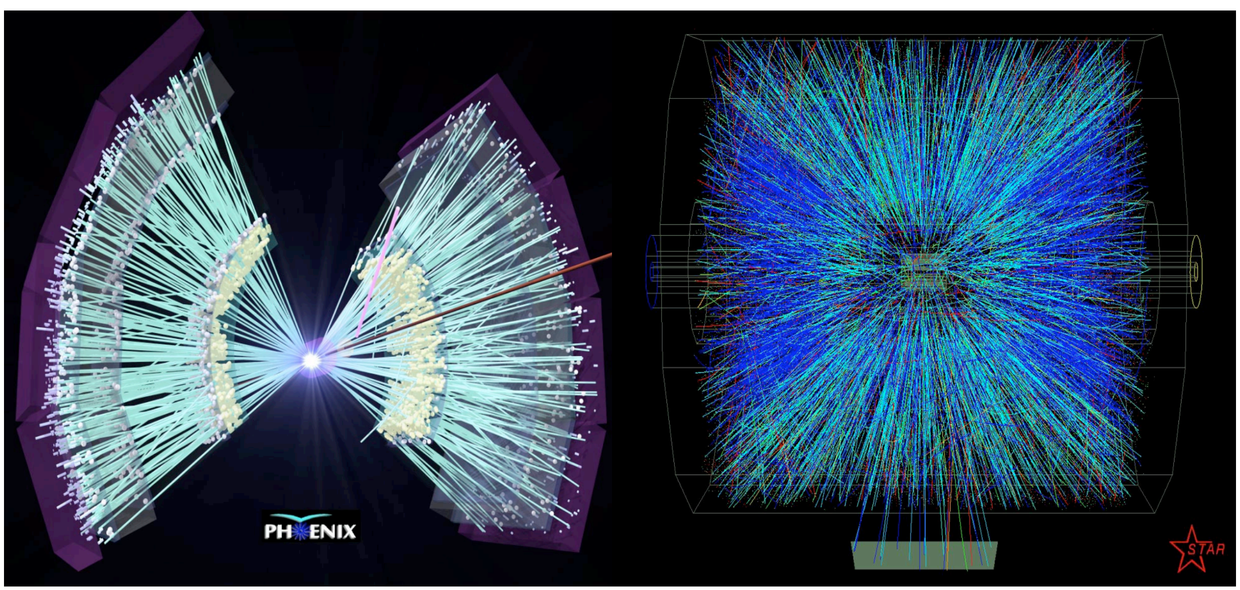
.....



3 quarks and lots of gluons



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



Small x limit is high energy limit

A Brief Aside about Rapidity in Momenta and Coordinates:

$$x^{\pm} = (x^0 \pm z)/\sqrt{2} \qquad p^{\pm} = (p^0 \pm p^z)/\sqrt{2}$$

$$x \cdot p = x_T \cdot p_T - x^+ p^- - x^- p^+$$

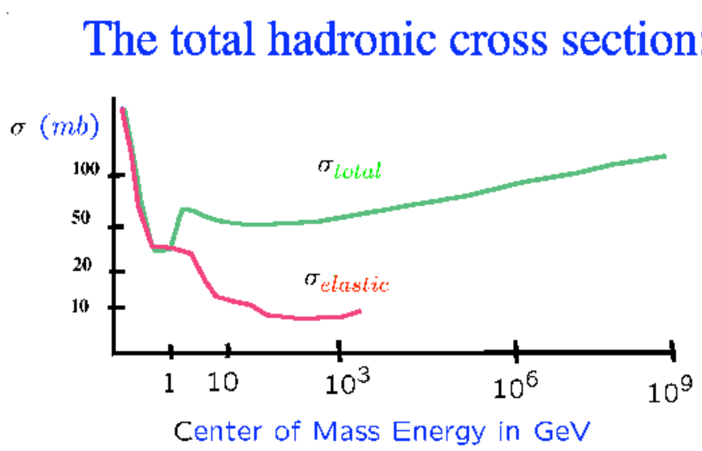
Uncertainty principle: $x^{\pm} p^{\mp} \geq 1$

$$\tau = \sqrt{t^2 - z^2} \qquad m_T = \sqrt{p_T^2 + m^2} = \sqrt{E^2 - p_z^2}$$

$$y = \frac{1}{2} ln(p^+/p^-) = ln(p^+/m_T) \sim ln(x^-/\tau) \sim \frac{1}{2} ln(x^+/x^-)$$

For a high energy right moving particle, p^+ is big, p^- is small, and vice versa for left moving

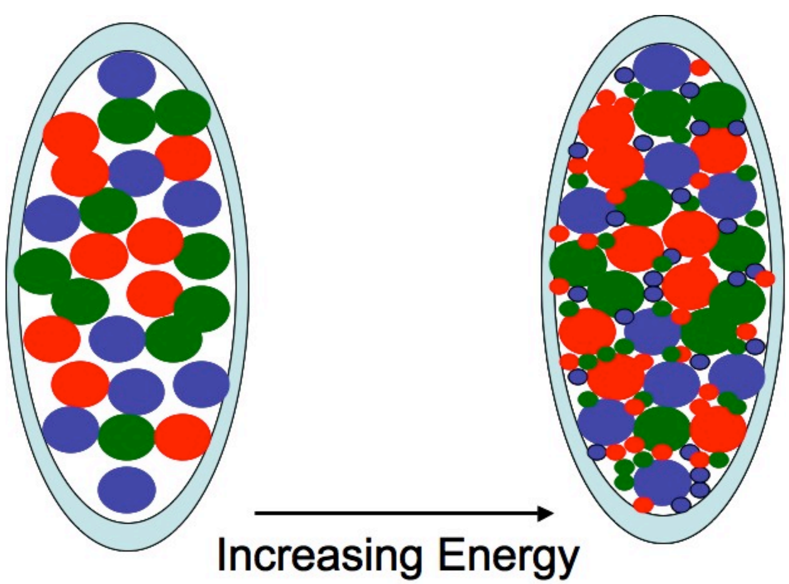
Where do all the gluons go?



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: $$\frac{dN}{dy d^2p_T d^2x_T} = \rho \qquad y = ln(1/x)$$

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

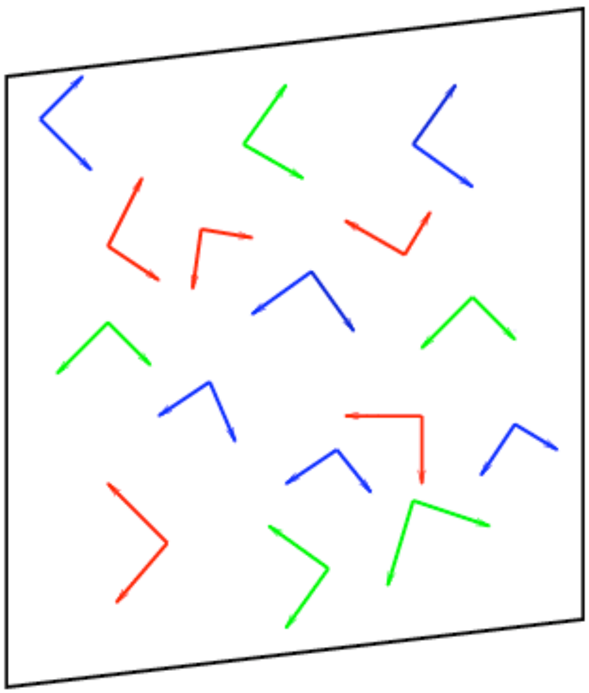
Density as high as it can be $\rho \sim 1/\alpha_{strong}$

Because the density is high α_{strong} is small

ρ is big

Classical fields which are big and coherent

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

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

F^{ij} 0(1)

Lienard-Wiechart potentials

Random Color

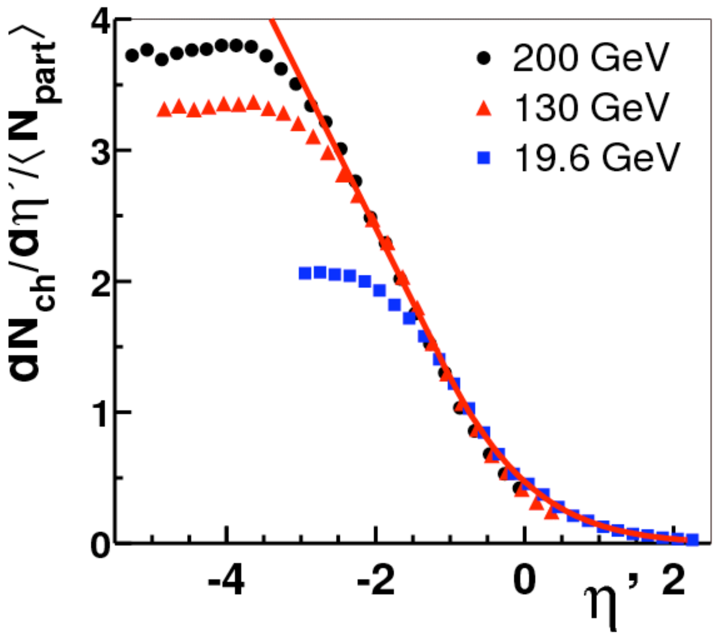
Density of gluons per unit area

(see next slide)

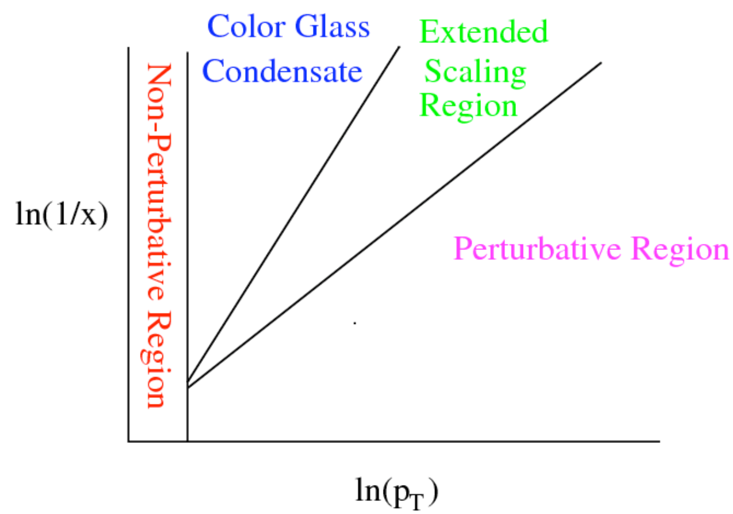
$$\frac{1}{\pi R^2} \frac{dN}{dy} \sim \frac{1}{\alpha_{strong}} Q_{sat}^2$$

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

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

The Saturation Momentum as Infrared Cutoff

At distance scales $r < 1/Q_s$ individual sources of color charge

At distance scales $r > 1/Q_s$ coherent sources of color charge

since gluon color states are multiply occupied.

On the average, the sum over color charges in a large volume will be zero, at large distances the color field is weakened

$$\frac{dN}{d^2p_T dy} \sim 1/p_T^2 \qquad p_T > Q_s$$

$$\frac{dN}{d^2p_T dy} \sim constant \qquad p_T < Q_s$$

up to logarithms

The CGC Path Integral:

$$Z = \int_\Lambda [dA][d\rho] exp\{iS[A,\rho] - F[\rho]\}$$

The current source:

$$J^\mu = \delta^{\mu +} \rho(x_T, y)$$

Rapidity:

$$y = ln(x_0^-/x^-) \sim ln(1/x) \sim \frac{1}{2} ln(p^+/p^-)$$

The separation scale is in rapidity or longitudinal momentum

$$\Lambda$$

The Renormalization Group Equation:

$$Z_0 = e^{-F[\rho]}$$

$$\frac{d}{dy}\ Z_0 = -H[d/d\rho, \rho] Z_0$$

For strong and intermediate strength fields: H is second order in

$$d/d\rho$$

It has no potential, and a non-linear kinetic energy term

Like diffusion

$$d/dt\ \psi = -p^2/2\ \psi$$

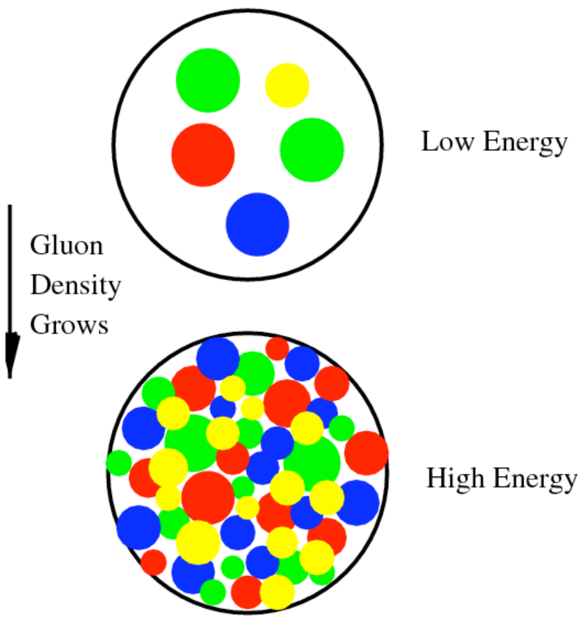
$$\psi \sim e^{-x^2/2t}$$

Wavefunction spreads for all time, and has universal limit:
Universality at high energy

The Color Glass Condensate Explains Growth of Gluons at Small x

Renormalization group equation predicts:

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



Gluons pile up at fixed size until

$1/\alpha$ gluons with strength α

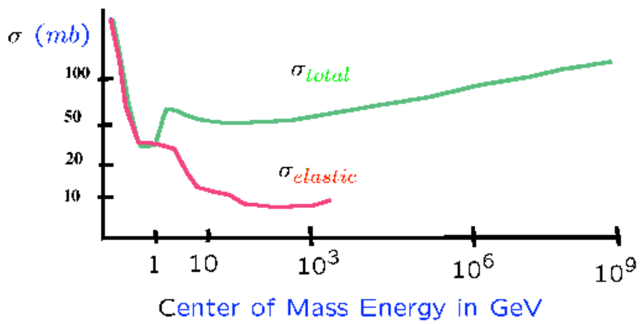
act like a hard sphere

$$r_T p_T \sim 1$$

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

The CGC Explains Slow Growth of Total Cross Section

The total hadronic cross section:



Transverse distribution of gluons:

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

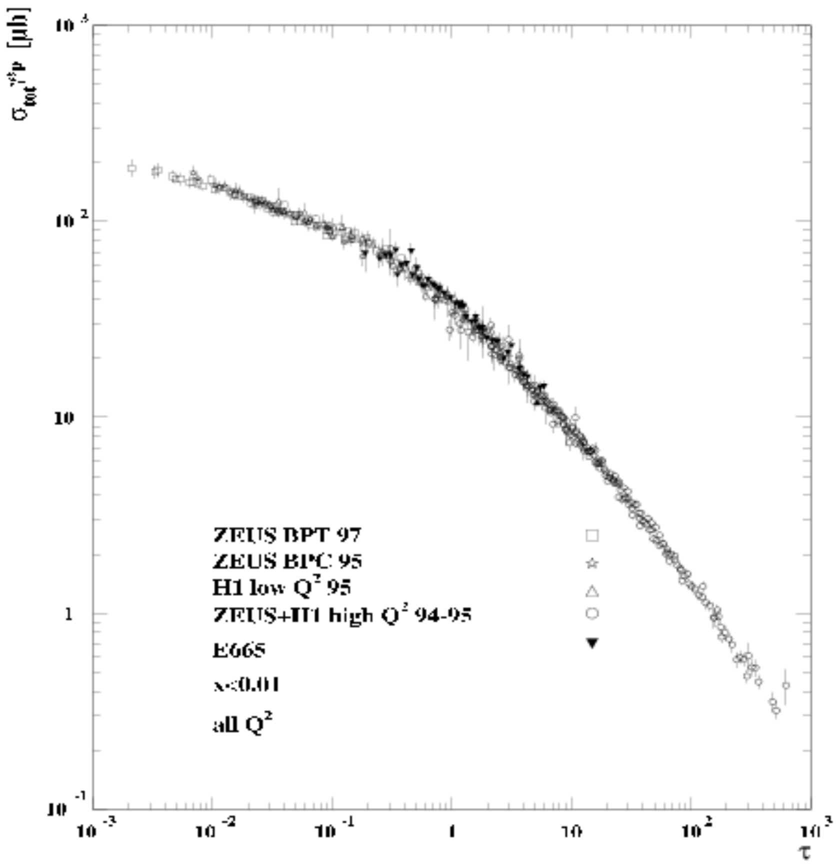
Transverse profile set by initial conditions

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

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

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

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

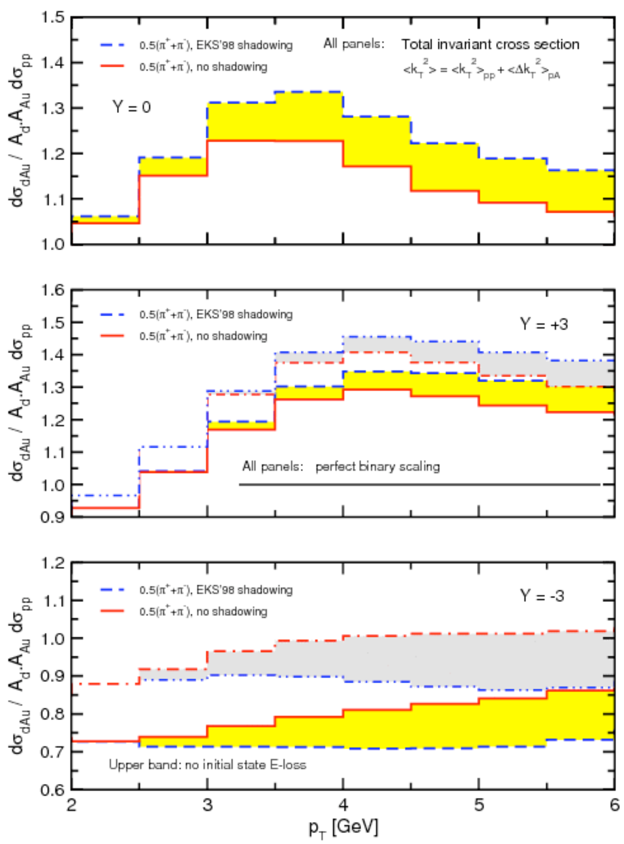
CGC provides a theory of shadowing (modification of quark and gluon distributions in nuclei)

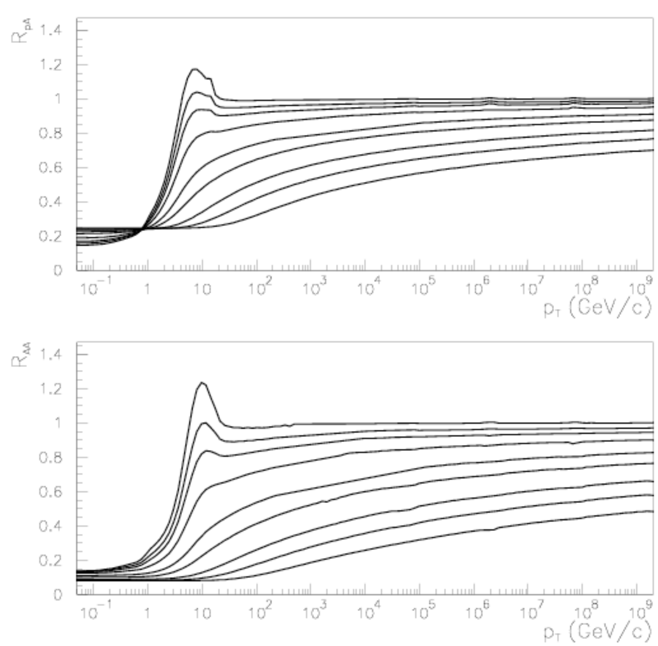
Two effects:

Multiple scattering: more particles at high pT

CGC modification of evolution equations => less particles

It also includes DGLPA or BFKL evolution

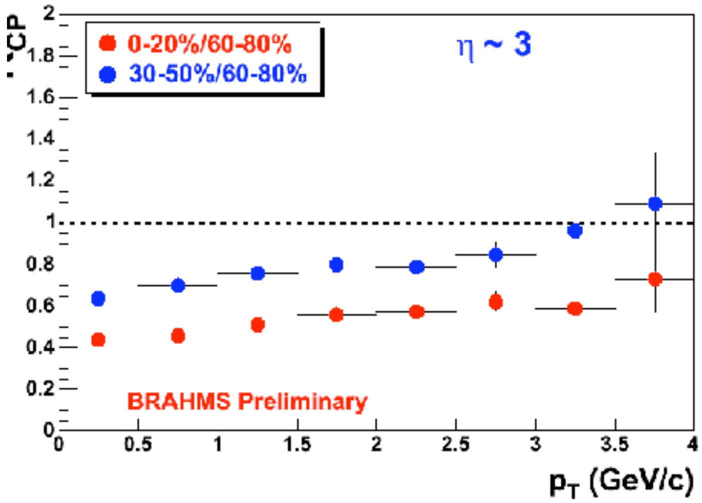




Albacete, Armesto, Kovner, Salgado, Wiedemann;

Kovchegov, Jalilian Marian, Tuchin and Kharzeev

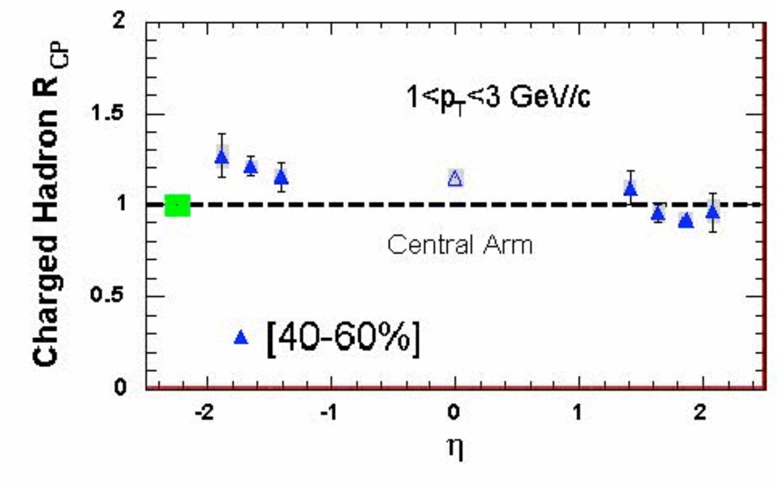
Data from dA collisions at RHIC Consistent with CGC

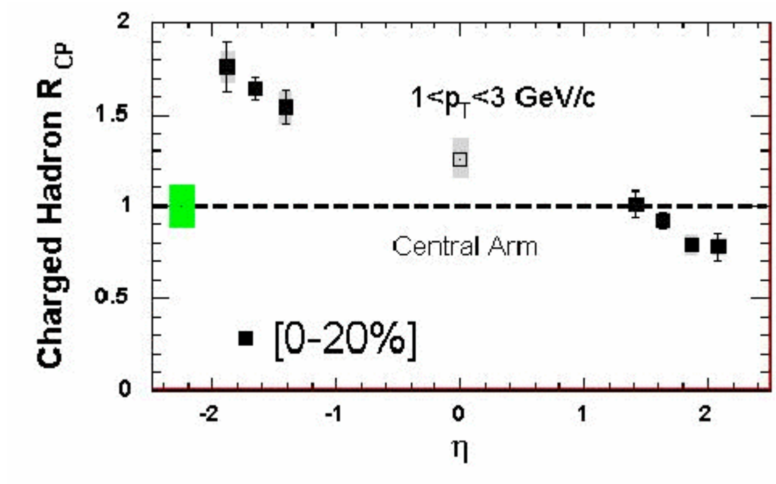


Look for fragments of deuteron since they measure them smallest x properties of the nucleus

Back to back jet correlations seen in STAR?

Detailed studies of x dependence?





Provides also a successful phenomenology of:

Limiting fragmentation

Diffractive deep inelastic scattering

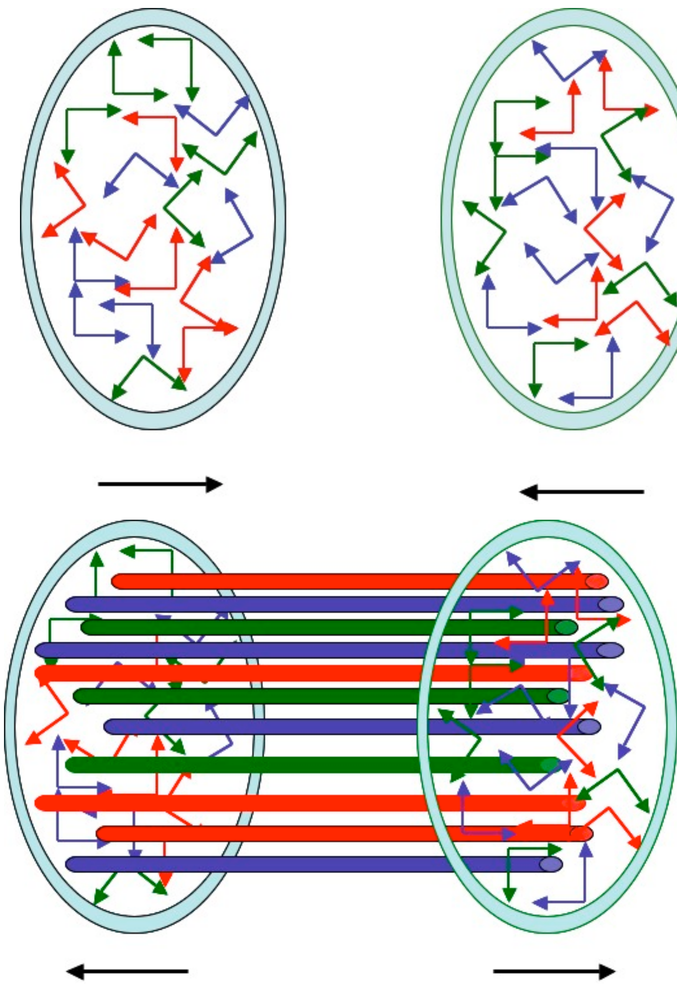
Long range correlations in rapidity

Pomerons, Reggeons, Odderons are quasi-particle excitations of the renormalization group Hamiltonian.

Also high energy nucleus-nucleus collisions,

Glasma

CGC Gives Initial Conditions for QGP in Heavy Ion Collisions

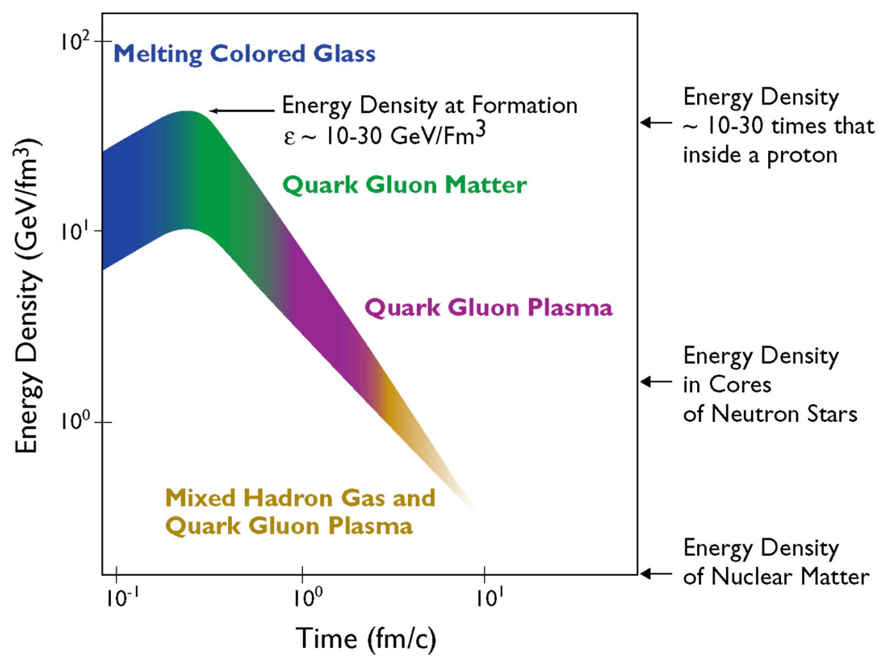


"Instantaneously" develop longitudinal color E and B fields

Two sheets of colored glass collide

Glass melts into gluons and thermalize

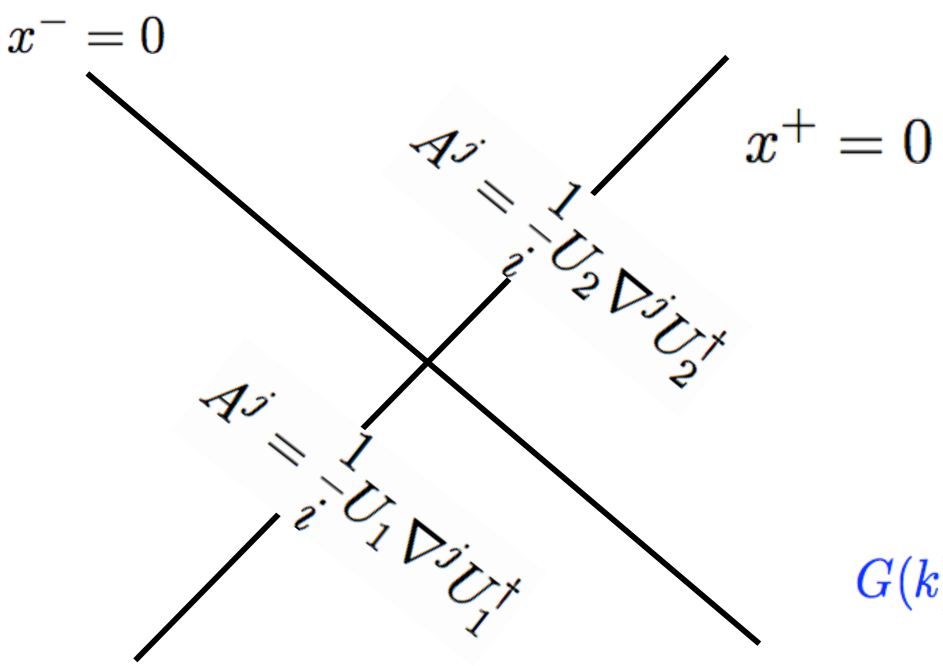
QGP is made which expands into a mixed phase of QGP and hadrons



Fields in longitudinal space:

$$F^{i+}$$

is a delta function on scales less than the inverse longitudinal cutoff



Gluon distribution is at scales larger than the cutoff

$$G(k) \sim 1/p^+$$

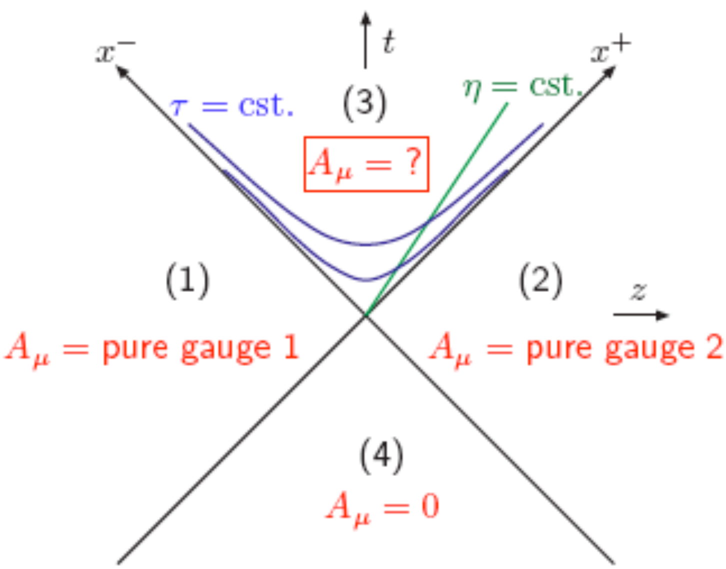
$$G(k) = < a^\dagger(k) a(k) > \sim < A(k) A(-k) >$$

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



In forward light cone

$$A_1^i + A_2^i$$

generates correct sources on the light cone

$$\nabla \cdot E = A \cdot E$$

$$\nabla \cdot B = A \cdot B$$

$$A_1 \cdot E_2$$

$$A_1 \cdot B_2$$

Equal strength for magnetic and electric charge on average!

$$\partial^\mu J_\mu^5 = \kappa\ E \cdot B + O(m_{quark})$$

Different signs

Generate different chiralities and vorticity in the fluid.

Violates P and CP on an event by event basis

Integral vanishes initially

Topological charge density is maximal:

Anomalous mass generation

In cosmology:

Anomalous Baryogenesis

Classical equation do not generate net topological charge.

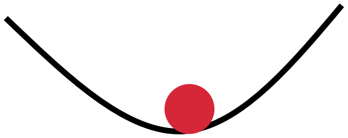
Instabilities in these solutions will generate such charge, and can themalize the system

At late times field decays into particles classically:

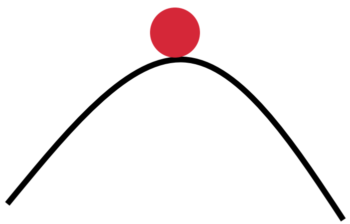
$$D^0 \vec{E} = \vec{D} \times \vec{B}$$

Because both E and B are nonzero

Longitudinal fields decay into purely transverse radiation fields



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

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

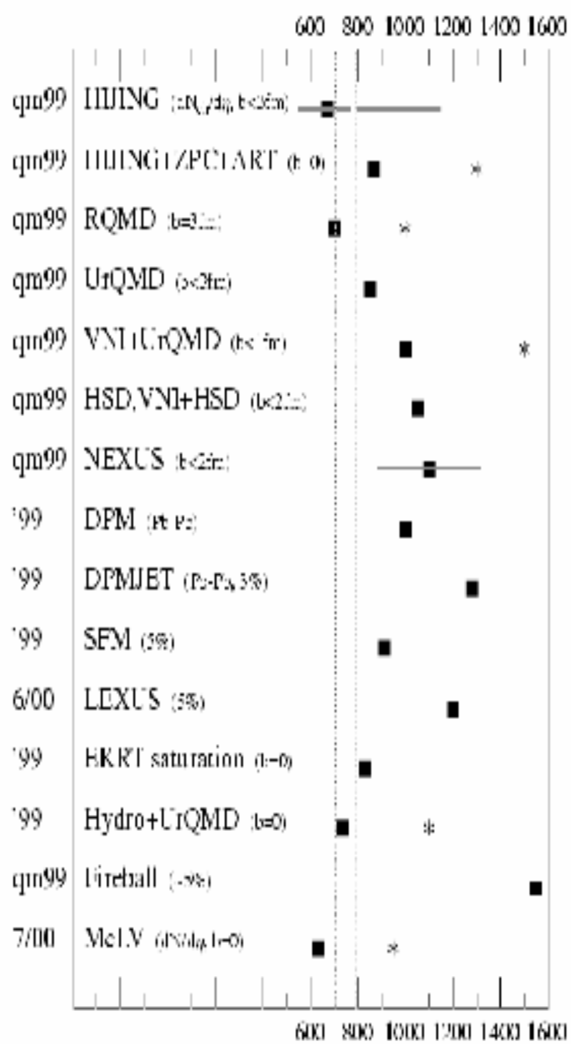
Thermalization?

$$W[p,X] = \int dz e^{-ipz} \psi^*(X+z/2)\psi(X-z/2)$$

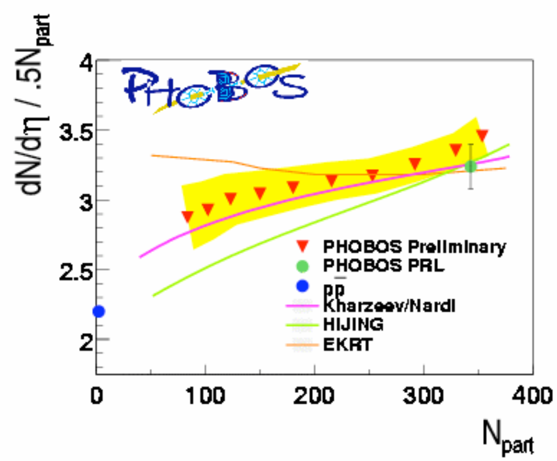
Wigner distribution of initial wavefunction gives seeds of fluctuations.

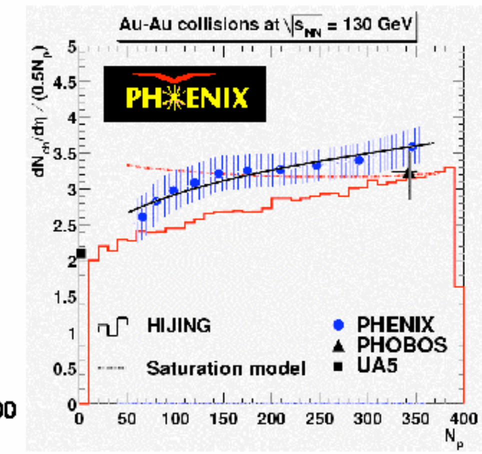
These seeds grow when inserted into classical equations

CGC-Glasma predicted particle production at RHIC



dN/dη vs Centrality at η=0

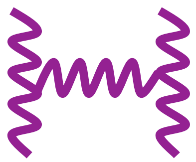




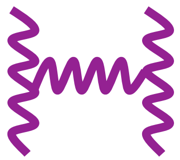
$$\frac{dN}{dy} \sim \frac{1}{\alpha_{strong}} \pi R^2 Q^2_{sat} \sim A ln(A)$$

Proportionality constant can be computed, because CGC cuts off the infrared!.

Long Range Correlations in Rapidity

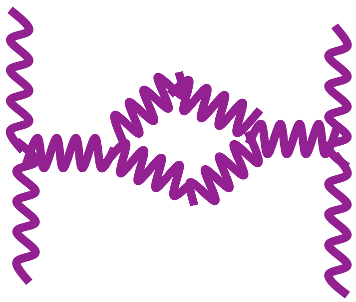


Dominant classical contribution is rapidity independent



Comes in color electric and magnetic flux tubes

Highly coherent



Next to leading order contains a correlated and a long range piece. Down by factors of strong coupling

Will be described in tomorrow's talk.

Can we see topological charge changing transitions in heavy ion collisions?

Strong sphaleron flips helicity at high temperature. Can generate net topological charge =>

Net vorticity and helicity of the fluid => correlation between spin and momentum

Strong QED magnetic field can polarize quark spins, and therefore generate net flow of the fluid, because spin is correlated with momenta.

Strong QED magnetic field perpendicular to reaction plane caused by net charge of nuclei as they collide generating net flow

Event by event CP violation

H. Warringa, D. Kharzeev and LDM