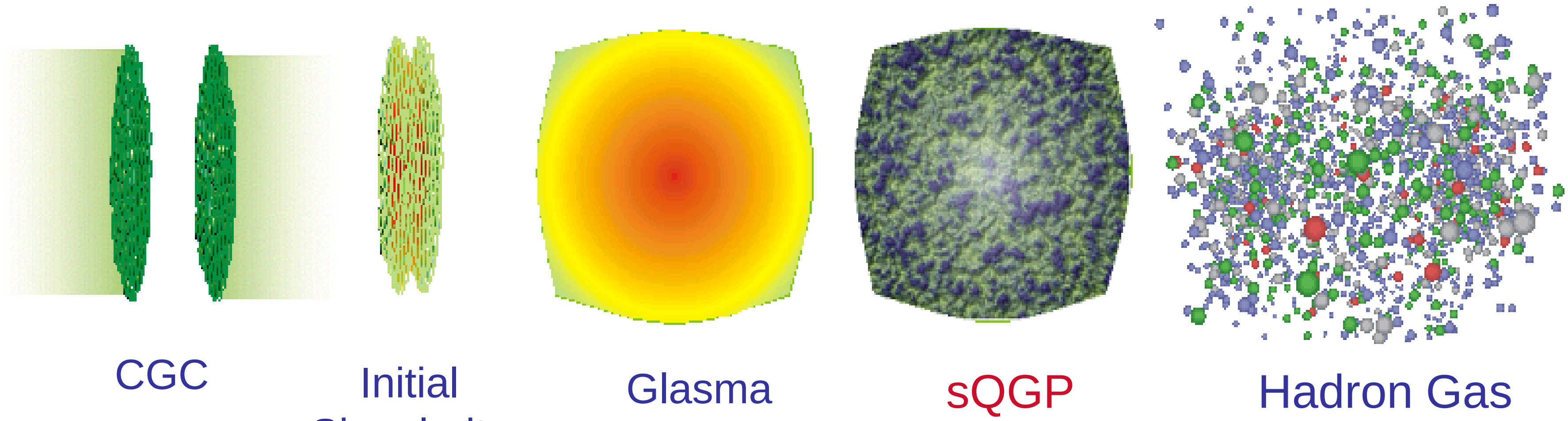
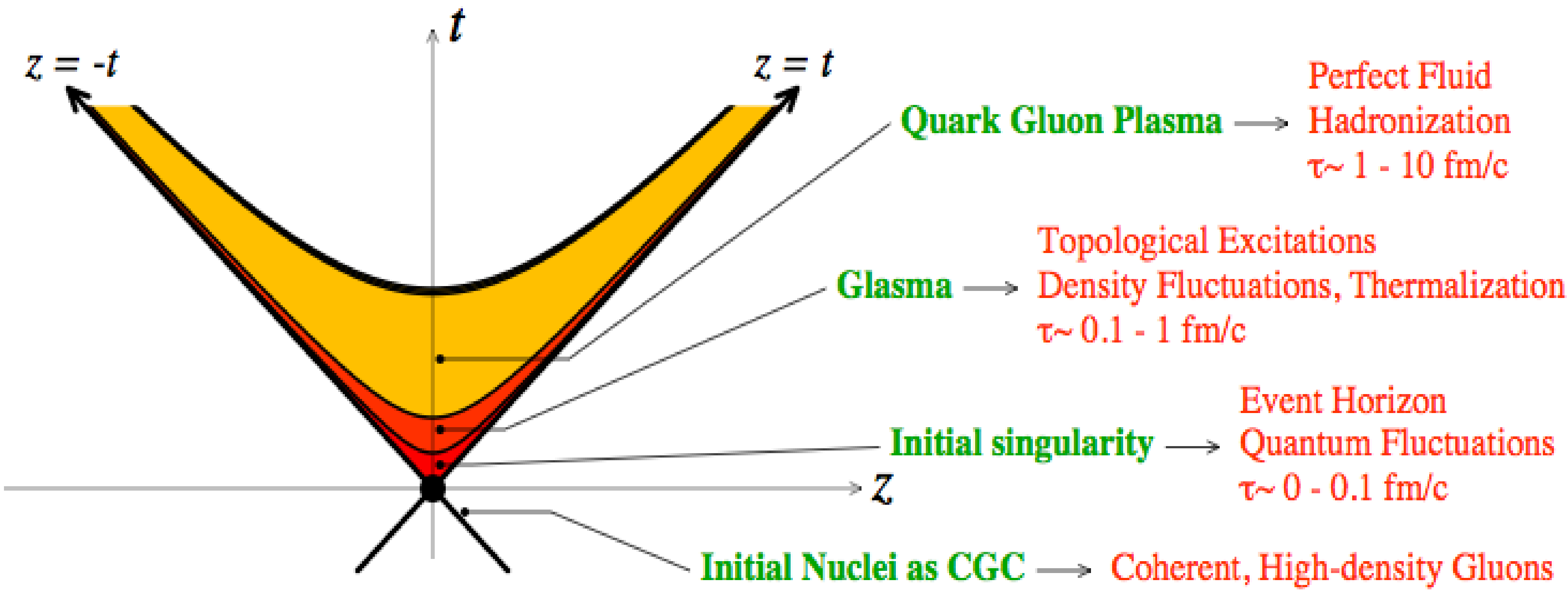
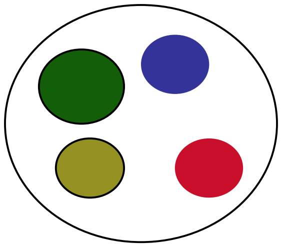
Theoretical Aspects of the Color Glass Condensate and Glasma

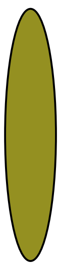
Art due to S. Bass





The Hadron Wavefunction at High Energy





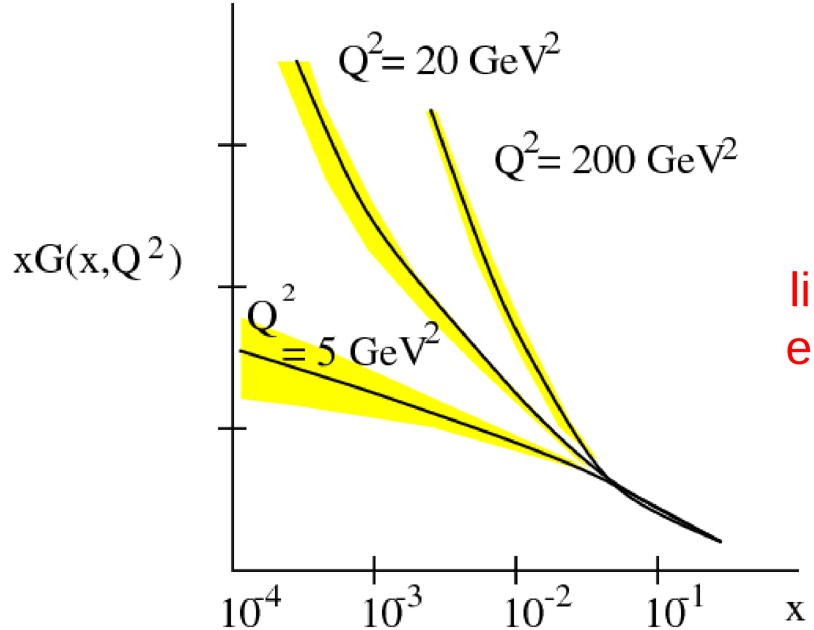
Baryon:

3 quarks

3 quarks 1 gluon

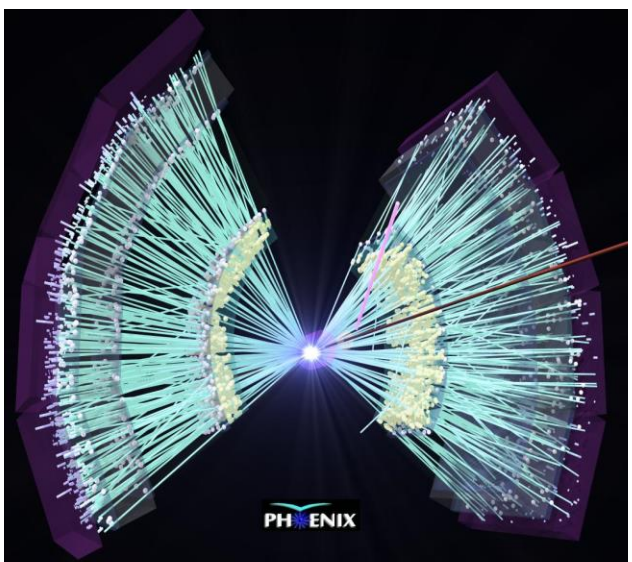
.....

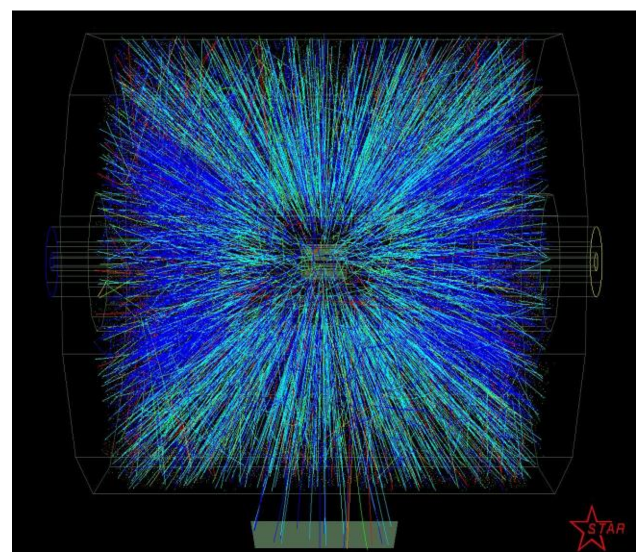
3 quarks and lots of gluons



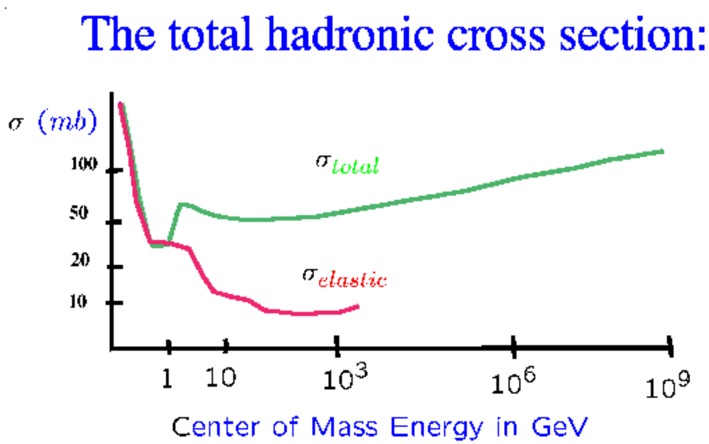
$$x = E_{gluon}/E_{hadron}$$

Small x limit is high energy limit





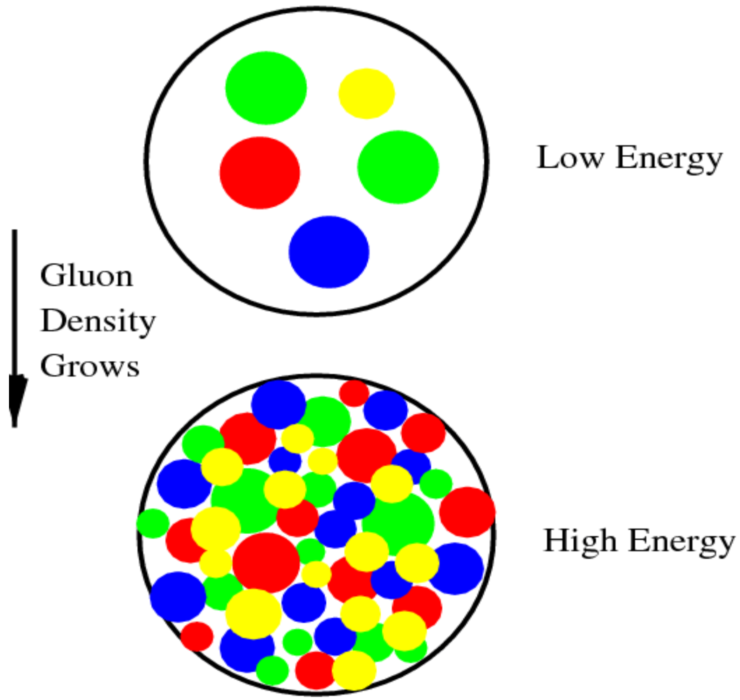
Where do all the gluons go?



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

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

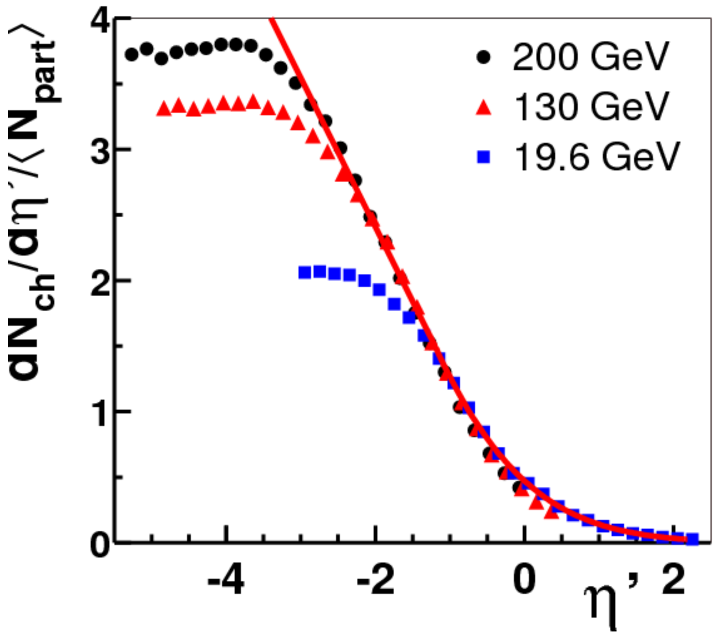
Density as high as it can be $\qquad \rho \sim 1/\alpha_{strong}$

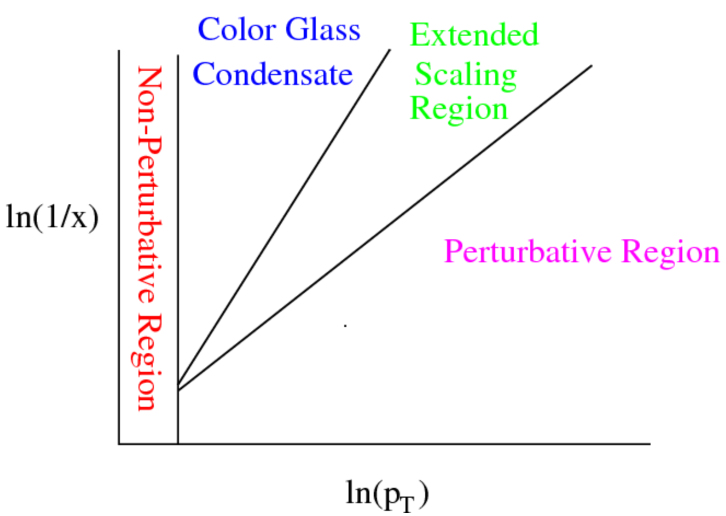
Because the density is high α_{strong} is small

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

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

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

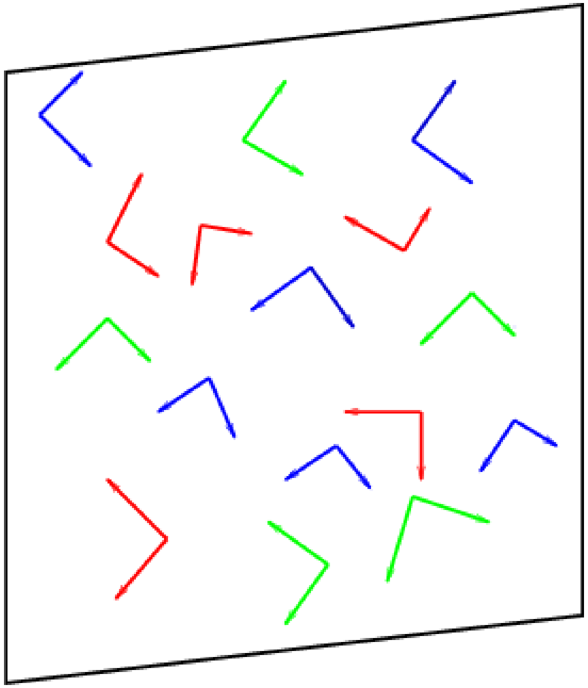
Like diffusion

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

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

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

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}

Lienard-Wiechart potentials

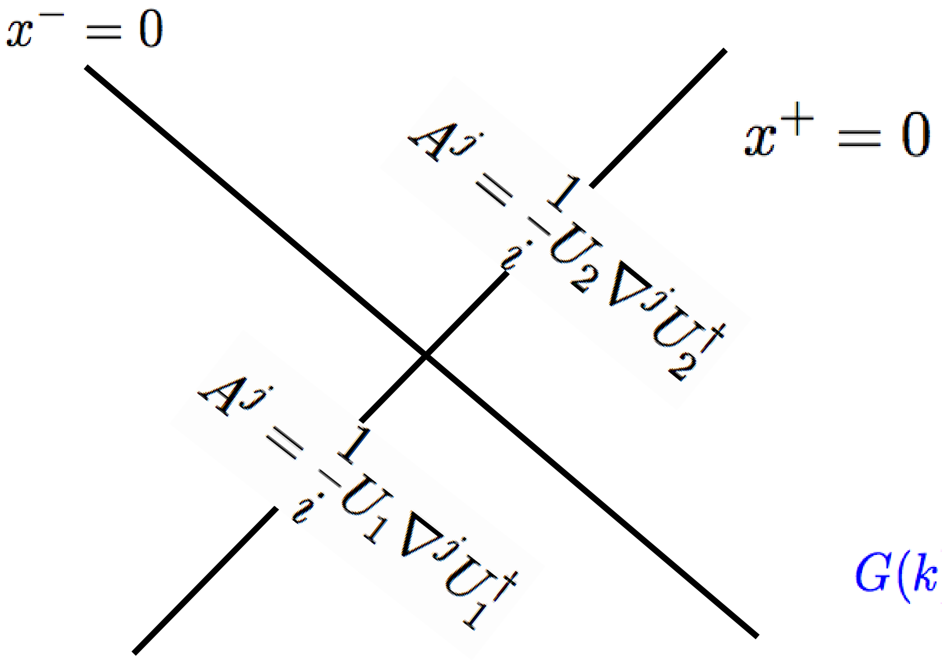
Random Color

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

Fields in longitudinal space:

$$F^{i+}$$

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

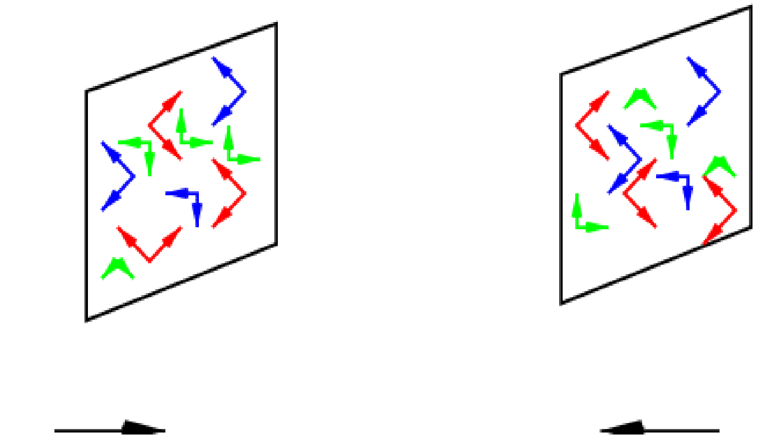


Gluon distribution is at scales larger than the cutoff

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

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

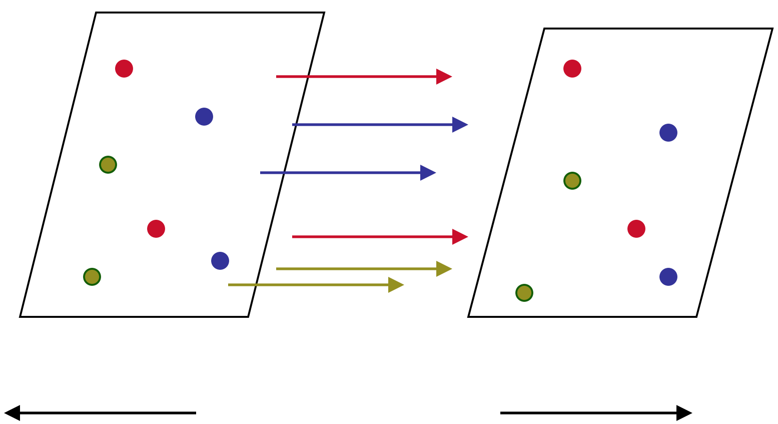
CGC Gives Initial Conditions for QGP in Heavy Ion Collisions



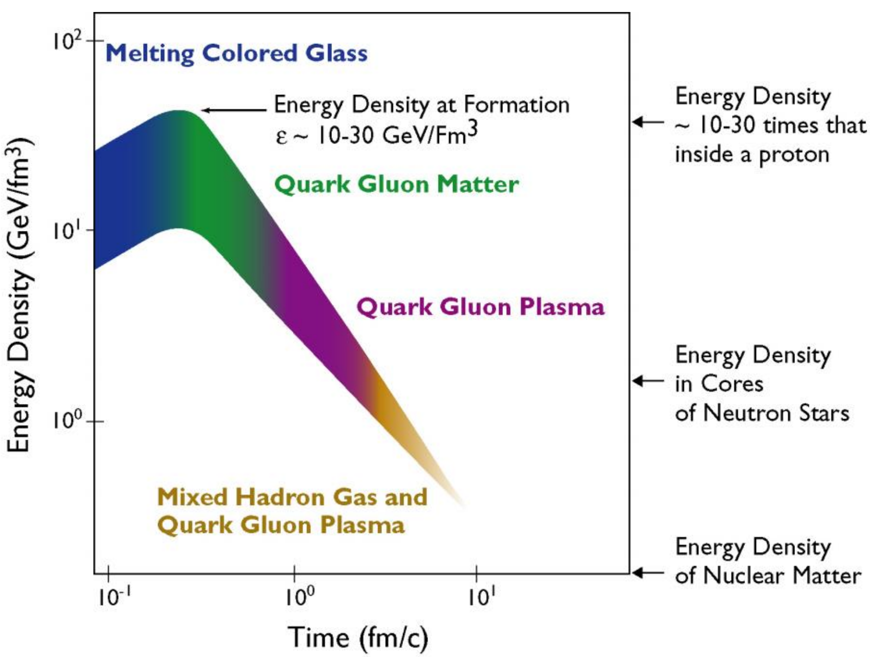
Two sheets of colored glass collide

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

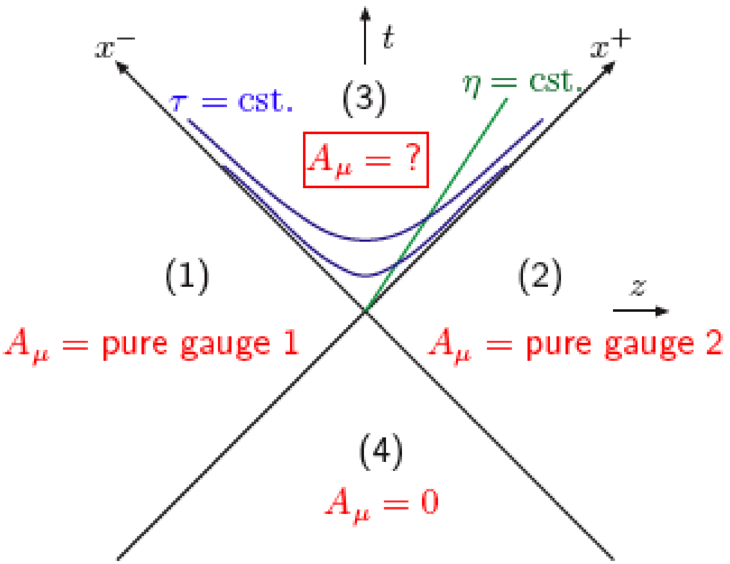


The Glasma:

Before the collision only transverse E and B
CGC fields

Color electric and magnetic monopoles

Almost instantaneous phase change
to longitudinal E and B



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!

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

Topological charge density is maximal:

Anomalous mass generation

In cosmology:

Anomalous Baryogenesis

Different signs

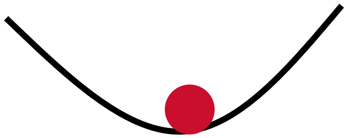
Generate different chiralities and vorticity in the fluid.

Violates P and CP on an event by event basis

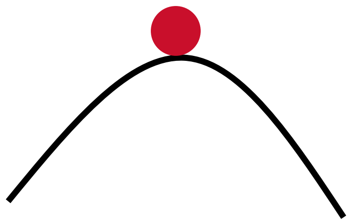
Integral vanishes initially

Classical equation do not generate net topological charge.

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



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

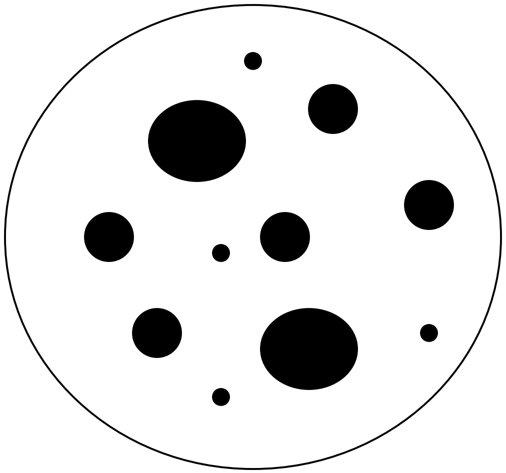
Thermalization?

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

Wigner distribution of initial wavefunction gives seeds of fluctuations.

These seeds grow when inserted into classical equations

Fluctuation in saturated regions and 2-d Quantum Gravity?



What is the distribution of the sizes of saturated spots of gluonic matter with size less than the saturation size scale?

Such fluctuations can in principle dominate the scattering out to very large momentum scales: breakdown of factorization of hadron-hadron relative to lepton hadron

How to compute scattering?

2-d field theory: Dimensionless scalar theory

$$\phi(x_T) = ln(Q^2_{sat}(x_T)/Q^2_{ave})$$

$$\nabla^2 \sim Q^2_{sat}(x_T) \sim M^2 e^{\phi(x_T)}$$

$$S = \frac{1}{g^2} \int d^2x_T \ \left((\nabla\phi)^2 + M^2 e^{\phi}\right)$$

Liouville theory: 2-d conformal invariance:

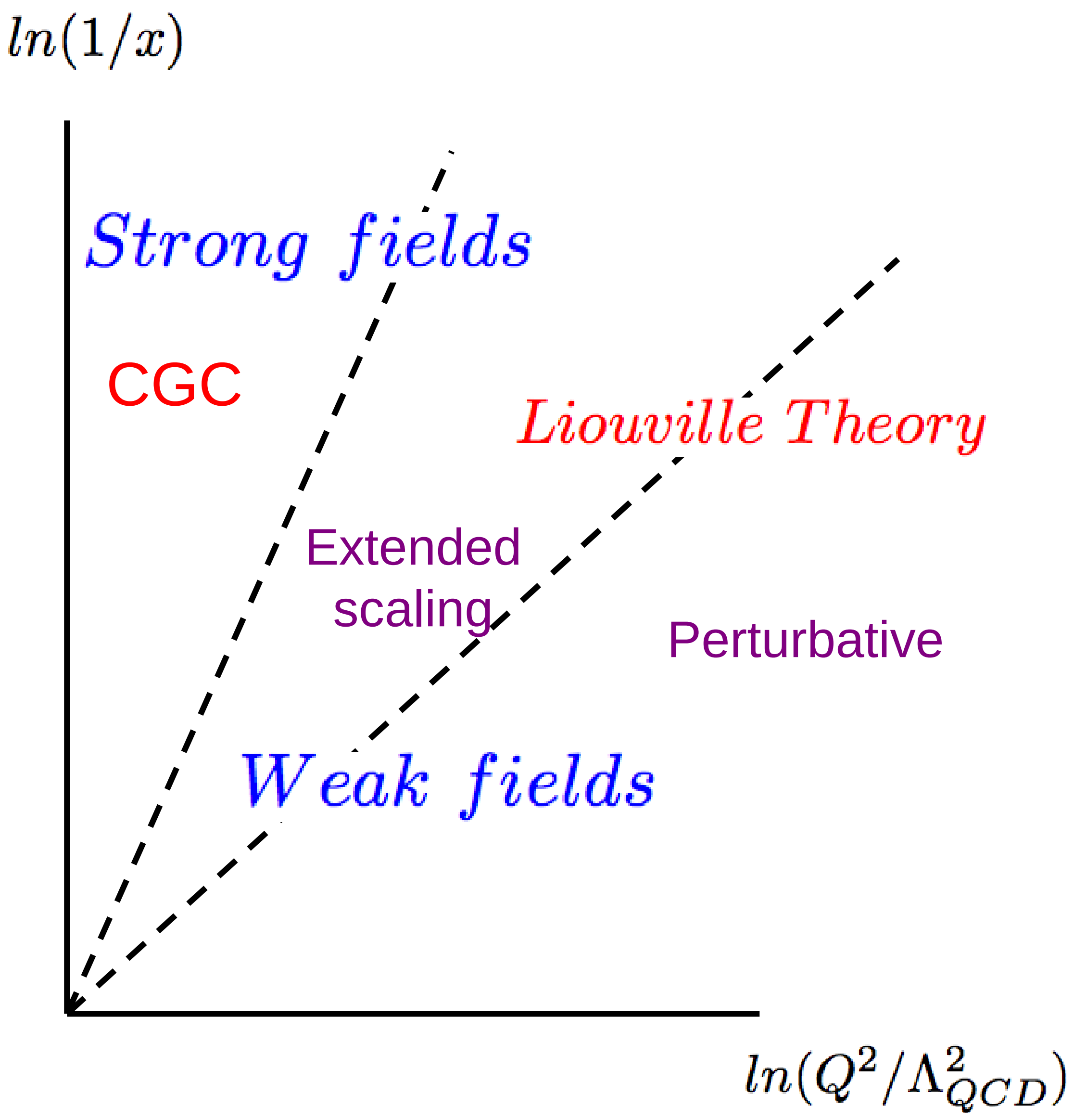
$$Q^2_{ave} = M^2 < e^{\phi} >= 0$$

Insert a source term: $-M^2\phi$

$$< e^{\phi} >= 1$$

Theory appears to be UV finite (unlike Liouville which is renormalizable) and conformal on distance scales less than the saturation scale!

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