New Forms of High Energy Density Matter:

L. McLerran, December 2013, Nagoya

What are the possible forms of high energy density matter?
How might such matter be produced and studied?
How does such matter determine the high energy limit for strongly interacting particles?

Color Glass Condensate:

Very High Density States of Gluons in High Energy Hadron Wavefunction

Quark Gluon Plasma:

Glasma: Highly Coherent Gluonic Matter Produced in Collisions of High Energy Hadrons

Thermalized Quark Gluon Plasma

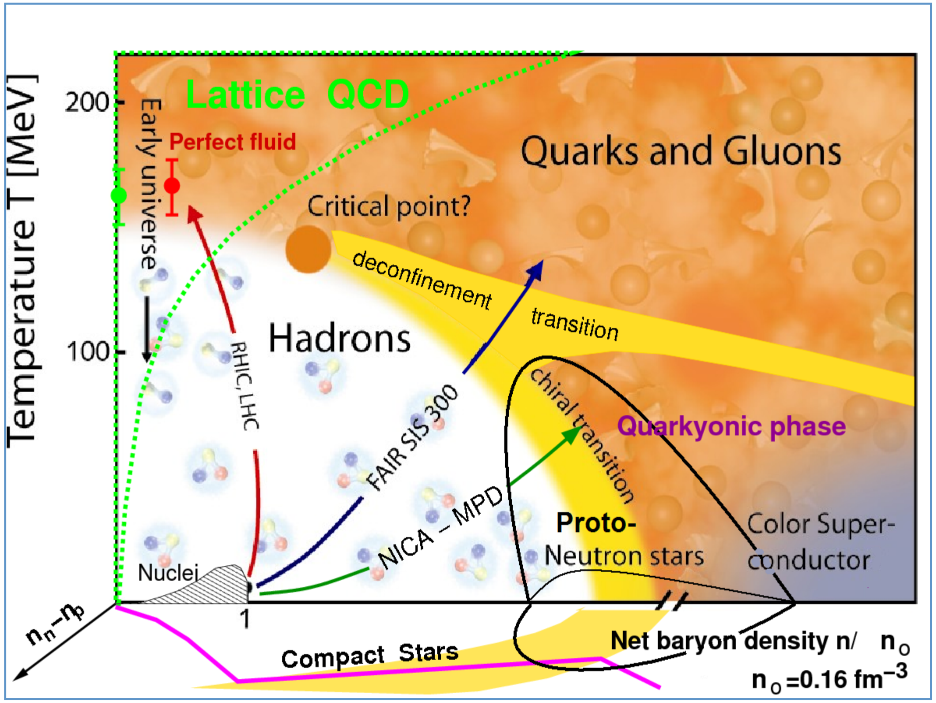
RIKEN BNL Research Center

RIKEN

RUPRECHT-KARLS-
UNIVERSITÄT
HEIDELBERG

HUAZHONG UNIVERSITY

Matter in Thermal Equilibrium



"Triple point"

Where the quark gluon plasma, quarkyonic matter and confined mesonic matter coexist

"Critical End Point"

Where first order phase transition end, assuming there is a region with first order phase transitions

"Quark Gluon Plasma"

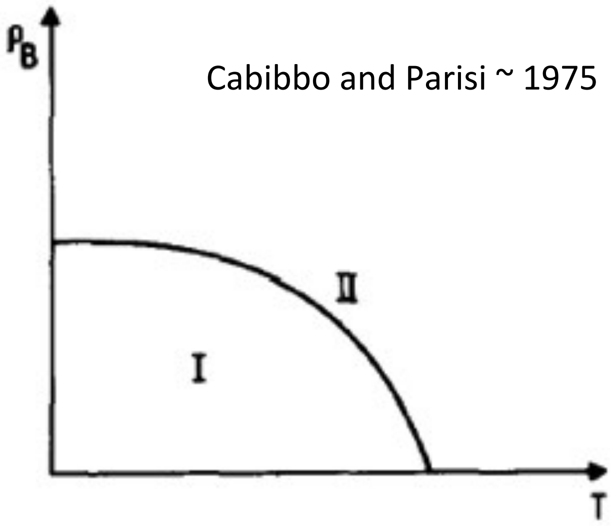
Deconfined quarks and gluons. Theoretically studied using lattice gauge theory

"Quarkyonic Matter"

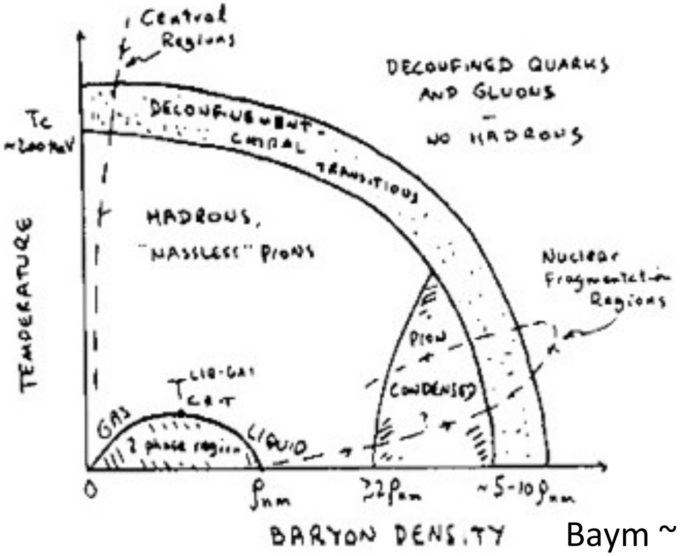
A quark Fermi sea with a confining Fermi surface and confined thermal excitations. Mass generation by chiral spirals that break translational invariance and parity. Rich phase structure associated with Fermi surface

Color Superconductivity:

At very high density and low temperature, should be colored Cooper pairs analogous to Cooper pairs of ordinary matter.



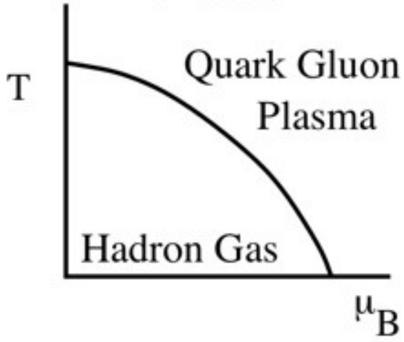
Cabibbo and Parisi ~ 1975



Baym ~ 1984

The Evolving QCD Phase Transition

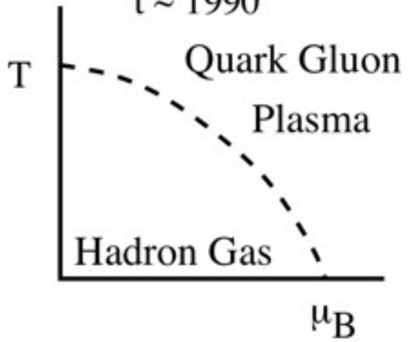
t ~ 1980



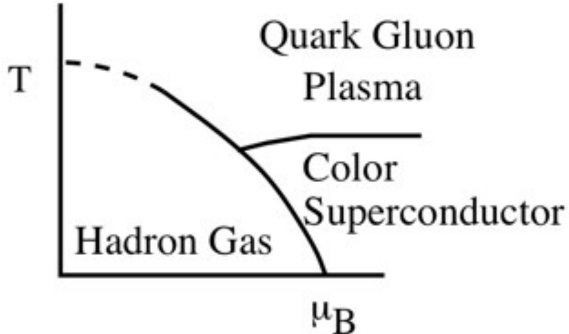
Critical Temperature 150 - 200 MeV ($\mu_B = 0$)
Critical Density 1/2-2 Baryons/Fm^3 (T = 0)

McLerran ~ 2000

t ~ 1990



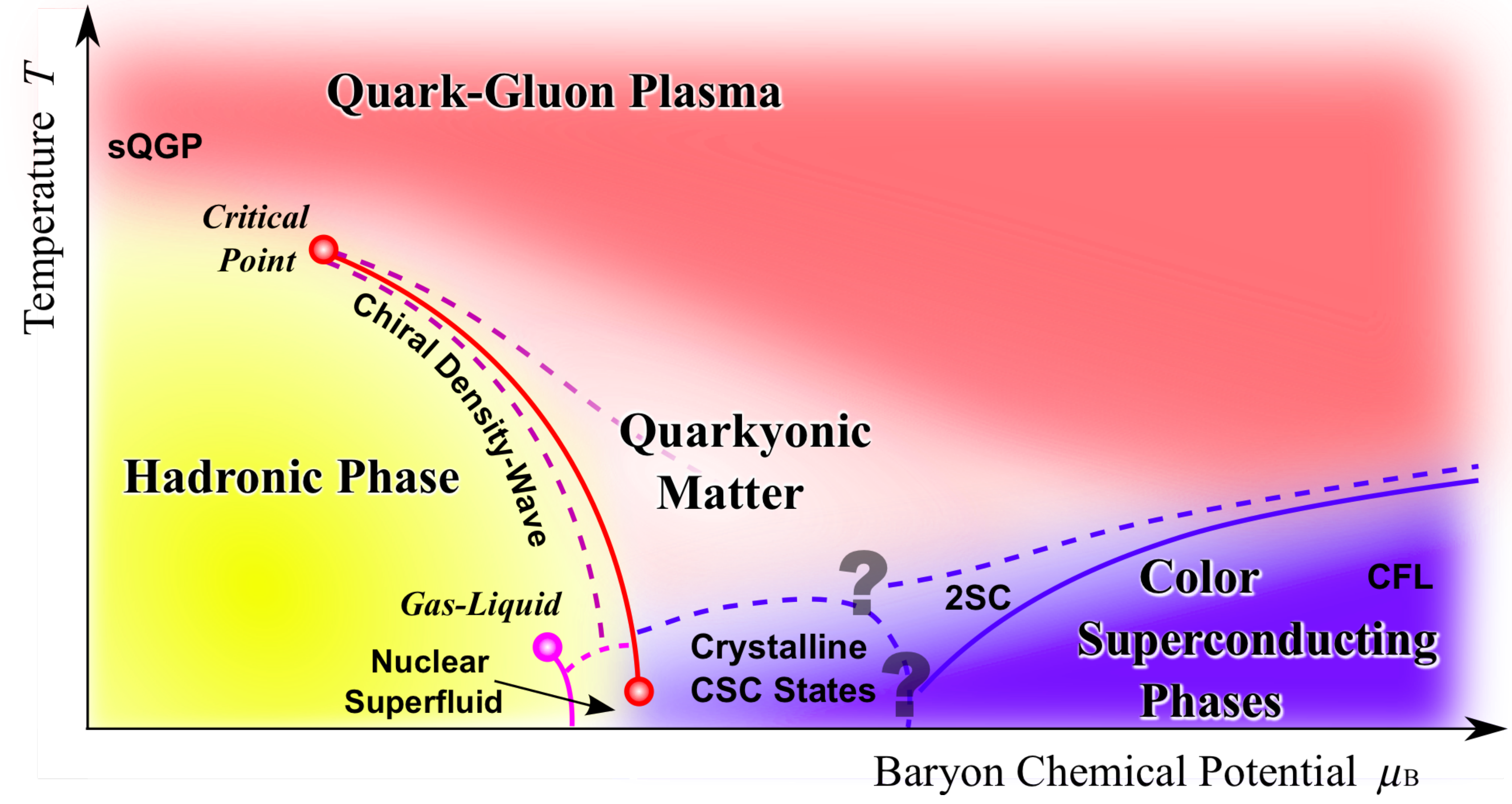
t ~ 2000



We only know:

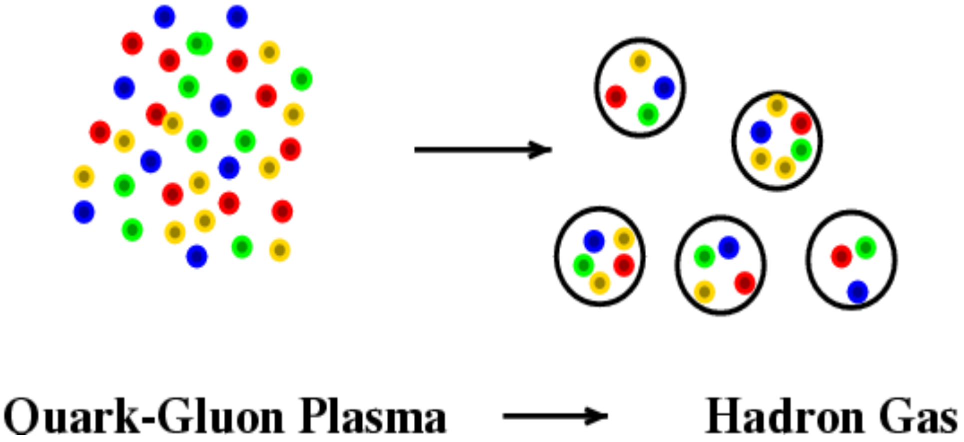
Extremely high temperature and density, low density and finite temperature

Matter at Very Baryon Density:



Recent Conception by Hatsuda and Fukushima

Matter at High Temperature and Small Baryon Density:
The Quark Gluon Plasma

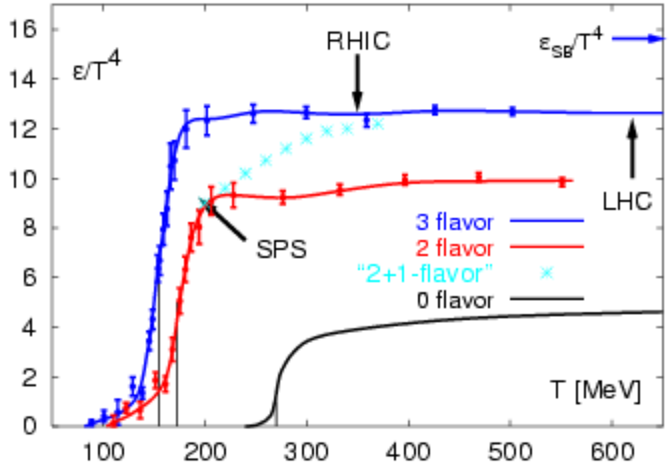


$$N_{dof} \sim 40 - 50 \sim N_c^2$$

The N_c Wall

Hagedorn Temperature

Numerical solution of QCD:
Lattice Gauge Theory



Photon Gas:

$$\epsilon = 2\ \frac{\pi^2}{30} T^4$$

Pion gas ($T >> M_{pion}$):

$$\epsilon = 3\ \frac{\pi^2}{30} T^4$$

QGP:

$$\epsilon = 40 - 50\ \frac{\pi^2}{30} T^4$$

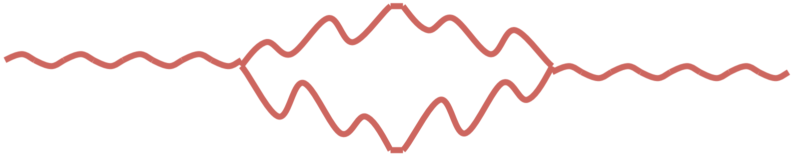
$N_{gluons} = 16$ and $N_{quarks} = 20 - 30$

A approximation:
The Large number of colors limit:

Baryons are infinitely massive compared to QCD energy scale

$$M \sim N_c \Lambda_{QCD}$$

Quarks do not affect the confining potential:
De-confinement temperature independent of density



$$g^2 N_c T^2 \sim \alpha_N T^2$$

$$g^2 \mu_Q^2 \sim \alpha_N \mu_Q^2 / N_c$$

$$\mu_Q = \mu_B / N_c$$

LM, Pisarski, Hidaka

Quark loops are always small by 1/Nc

At least 3 phases of matter:

Confined matter with no baryons
(Hadron Gas)
(low temperature and low baryon density)

$$\rho_B \sim e^{-M_B/T+\mu_B/T}$$

De-confined matter at high temperature
(Quark Gluon Plasma):
Baryon number carried by light mass deconfined quarks

High baryon density confined matter at low temperature
(Quarkyonic Matter)
Baryon density parametrically large compared to the QCD scale!
Asymptotic freedom => Weakly interacting Fermi sea of quarks
Fermi surface and thermal excitations are mesons and baryons

$$T << \Lambda_{QCD} \qquad \Lambda_{QCD} << \mu_{quark} << \sqrt{N_c}\Lambda_{QCD}$$

Quarkyonic Matter and Bulk Properties of Matter
Example of Two Flavor Matter

Hadronic Gas:
Low temperature and density

$$N_{dof} = 3$$

Quark Gluon Plasma:

$$N_{dof} = 2(N_c^2 - 1) + 8N_c \sim 40$$

Quarkyonic Matter

$$N_{dof} = 4N_c \sim 8$$

$$\epsilon_{hadron} \sim O(1) \qquad \epsilon_{Quarkyonic} \sim N_c \qquad \epsilon_{QGP} \sim N_c^2$$

Simple Model for the Phase Boundary

Deconfinement transition:

T = constant

Quarkyonic: Baryon density finite

$$\frac{M_N - \mu_B}{T} \sim constant'$$

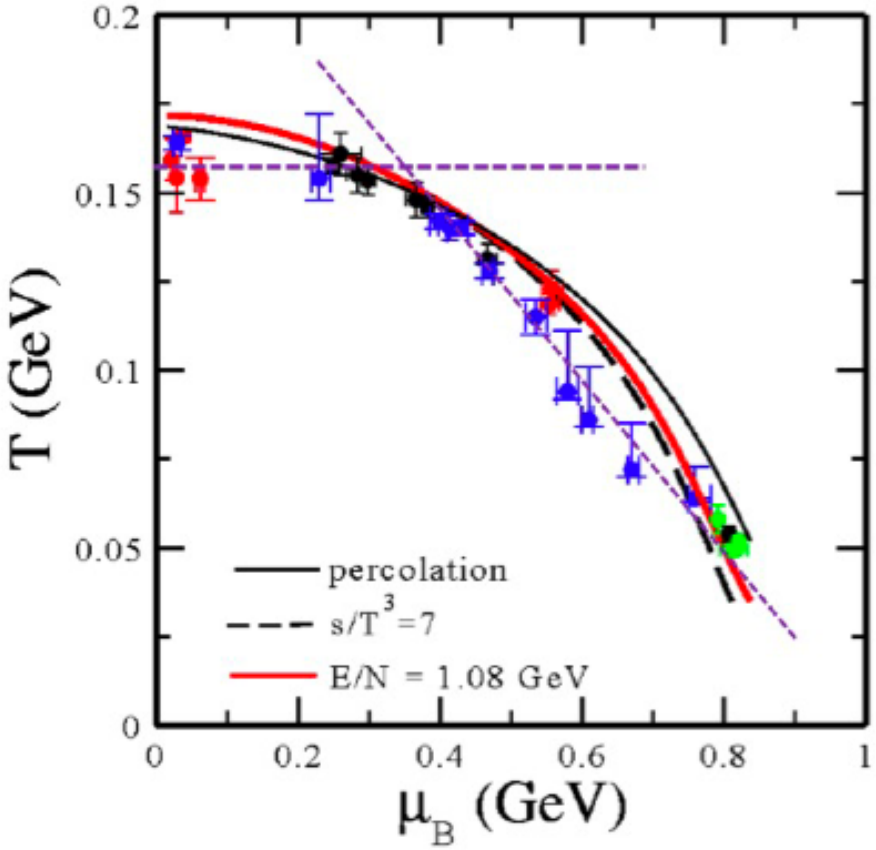
$$T \propto M_N - \mu_B$$

Triple point when the three phases meet

A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, J. Stachel,

Have we already seen the Quarkyonic phase boundary, and the Triple Point?

Reinhard Stock, Francesco Becattini, Thorsten Kollegger, Michael Mitrovski, Tim Schuster



Dashed line indicate simple models of deconfinement and quarkyonic transition

Measured abundances fall on curve with fixed baryon chemical potential and temperature at each energy: suggests a phase transition with a rapid change in energy density

High density low T points deviate from expectations of deconfinement transition

Properties of Quarkyonic Matter:

Quasi-free Fermi gas of quarks

Fermi surface of confined baryons

Thermal excitations are confined mesons and glueballs

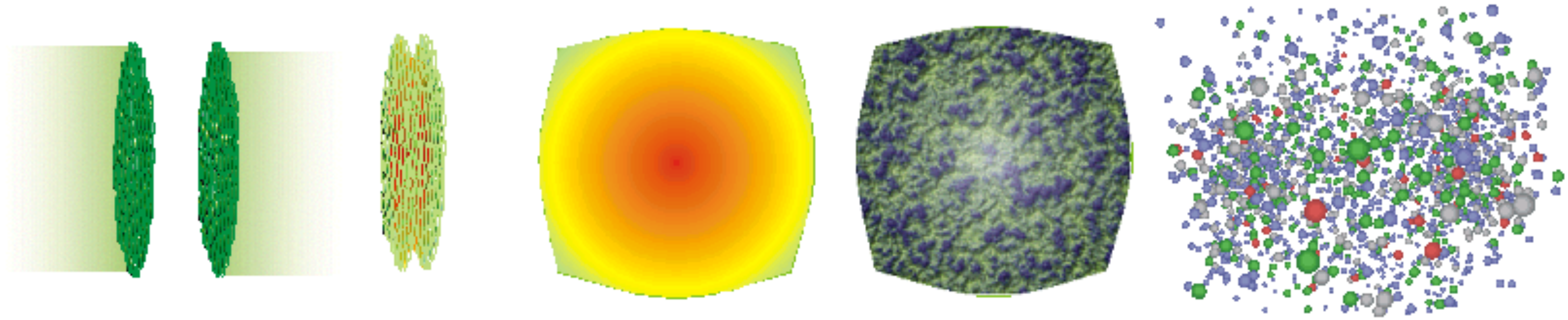
Mass generation through a condensate of scalar excitations, like in vacuum

Parting of particles to make condensate forces particle hole paris to come from near the Fermis surface => Condensate has momentum => finite wavelength => Breaks translational invariance => forms a lattice

Details of lattice structure may be complicated, and consensus lacking

Quarkyoninc matter was first conjectured from weak coupling QCD studies, but now verified in non-perturbative models based on string theory

Matter as it Appears in High Energy Collisions



CGC

Initial
Singularity

Glasma

Thermalized
QGP

Hadron Gas

← Strongly Interacting QGP →

Color Glass Condensate:
Very high energy density highly coherent gluons that form the high energy hadron wavefunction

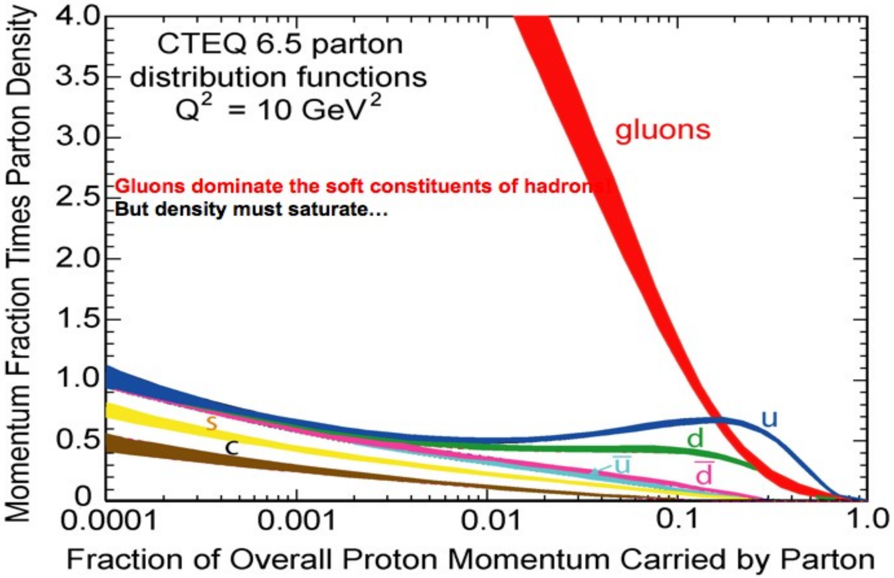
Glasma:
The matter that is formed in the collision of two sheets of Colored Glass, and eventually thermalizes into a Quark Gluon Plasma

sQGP
Strongly interacting Quark Gluon Plasma

The gluon density is high in the high energy limit:

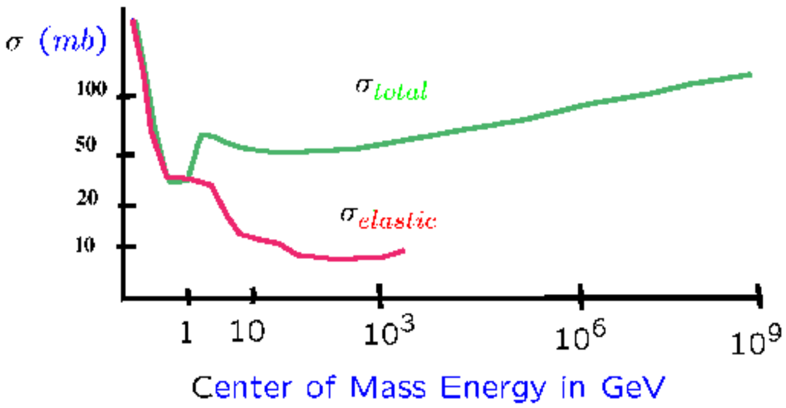
$$x = E_{gluon}/E_{hadron}$$

$$x_{min} \sim \Lambda_{QCD}/E_{hadron}$$

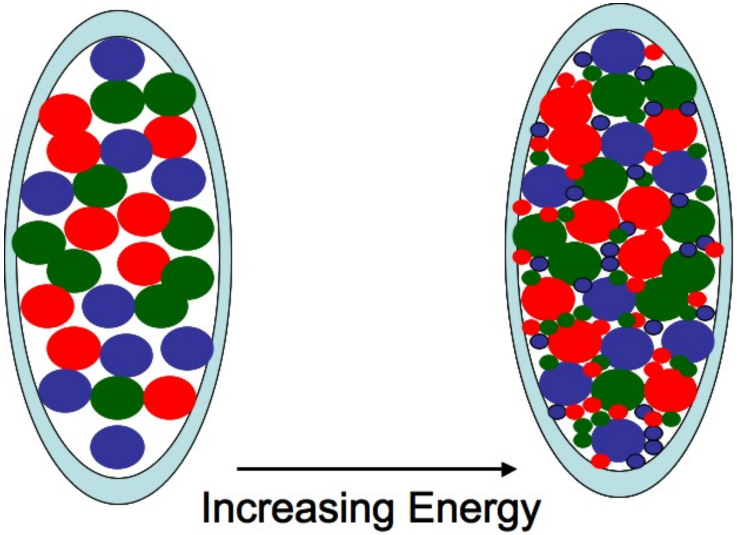


Gluons dominate the proton wavefunction

The total hadronic cross section:



Proton size grows slowly



Asymptotic Freedom: High density systems are weakly coupled because typical distances are short

$$\alpha_S << 1$$

Possible to understand from first principles

Color Glass Condensate

Color:

Gluons are colored

Condensate:

Gluon occupation number $1/\alpha_S$ **is as large as can be, like Higgs condensate or superconductor**

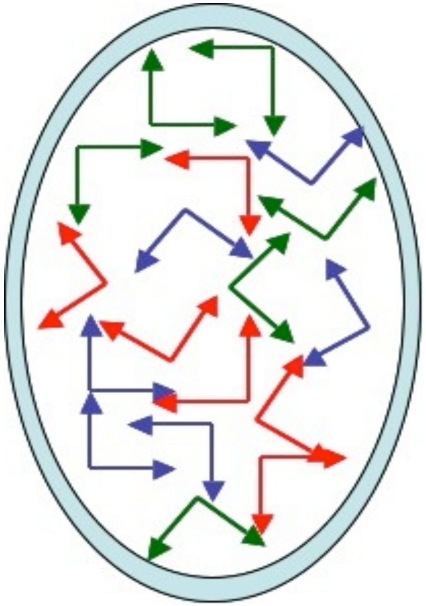
High density of gluons is self generated

Glass:

The sources of gluon field are static, evolving over much longer time scales than natural one

Resulting theory of classical field and real distribution of stochastic source is similar to spin glass

$$\frac{dN}{dy d^2 r_T d^2 p_T} \sim \frac{1}{\alpha_s}$$

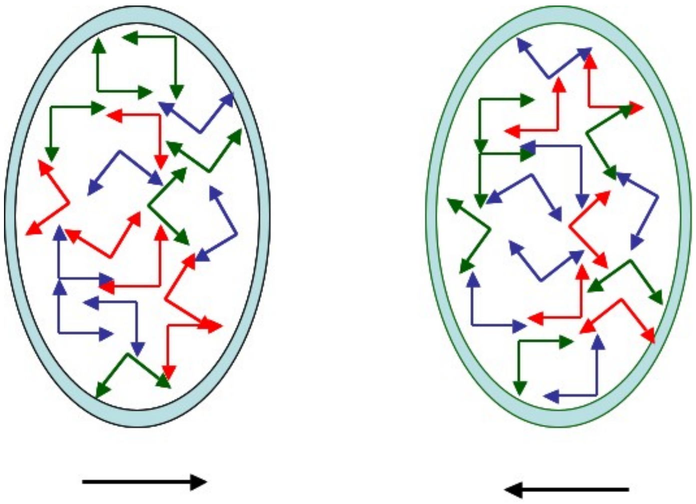


Parton distributions replaced by ensemble of coherent classical fields

Renormalization group equations for sources of these fields

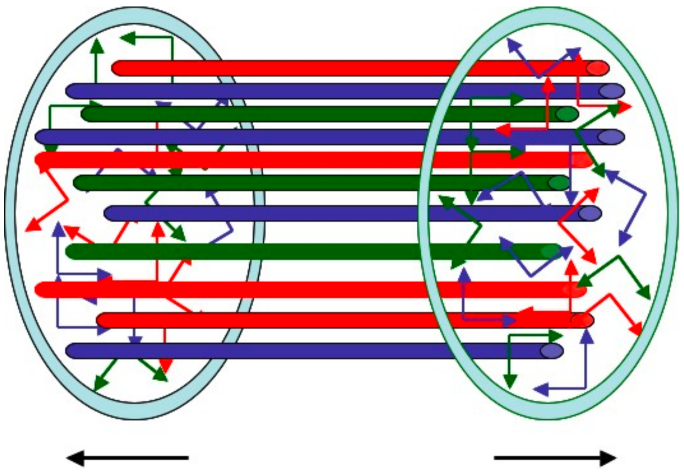
$$Q^2_{sat} >> \Lambda^2_{QCD}$$

Collisions of two sheets of colored glass



Long range color fields form in very short time

Sheets get dusted with color electric and color magnetic fields



Maximal local density of topological charge:
Large local fluctuations in CP violating

$$\vec{E} \cdot \vec{B}$$

Glasma: Matter making the transition for Color Glass Condensate to Quark Gluon Plasma

The initial conditions for a Glasma evolve classically and the classical fields radiate into gluons
Longitudinal momentum is red shifted to zero by longitudinal expansion

But the classical equations are chaotic:
Small deviations grow exponentially in time

Chaos and Turbulence:

CGC field is rapidity independent => occupies restricted range of phase space
Wiggling strings have much bigger classical phase space
A small perturbation that has longitudinal noise grows exponentially

$$A_{classical} \sim 1/g$$

$$A_{quantum} \sim 1$$

After a time

$$t \sim \frac{ln^p(1/g)}{Q_{sat}}$$

system isotropizes,

But it has not thermalized!

Recent results of Gelis and Eppelbaum using spectrum of initial fluctuations derived from QCD:

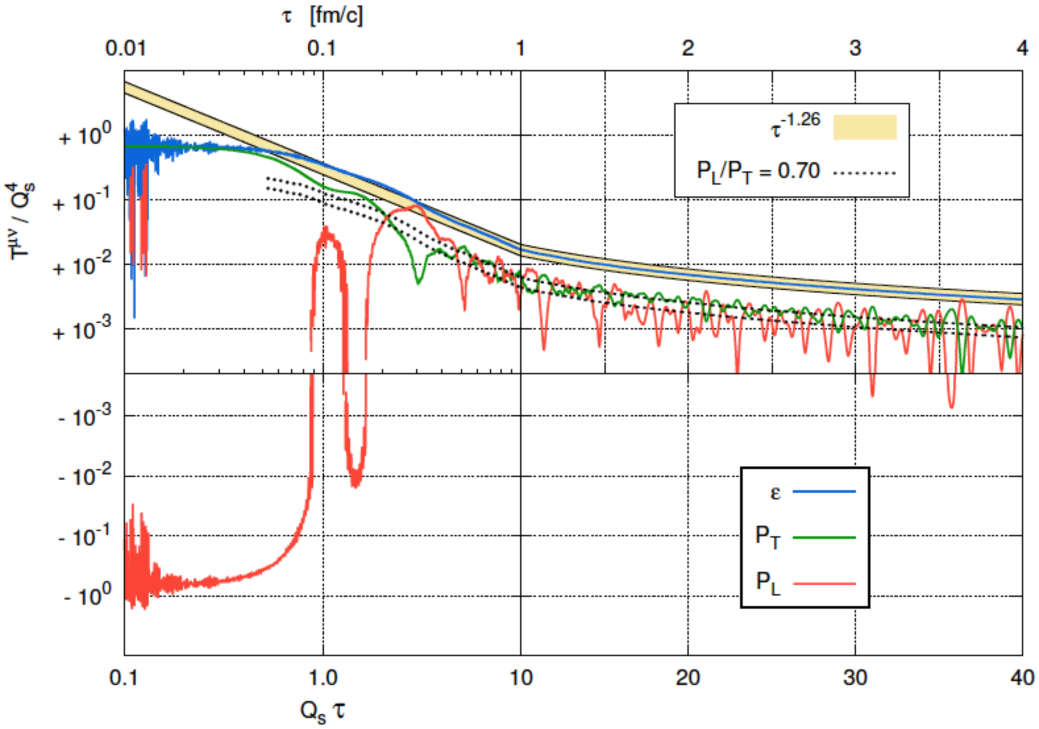
Find hydrodynamic behaviour a good approximation as coupling constant gets bigger, but even for

$$\alpha_S \sim 1/50$$

It is a good approximation.

For RHIC and LHC energy the coupling is even larger

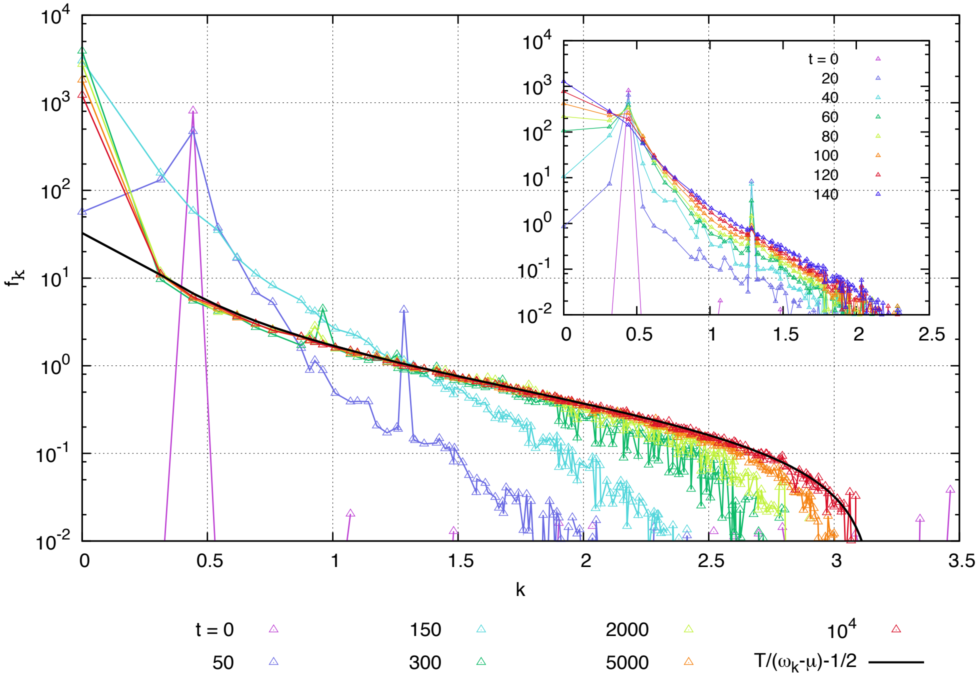
$$\eta/S \sim 0.25 \qquad t_{hydro} \sim 3/Q_{sat}$$



The perfect fluid might not be a thermally equilibrated system!

The highly occupied initial conditions for the gluons is similar to studies of cold bosonic atomic gasses

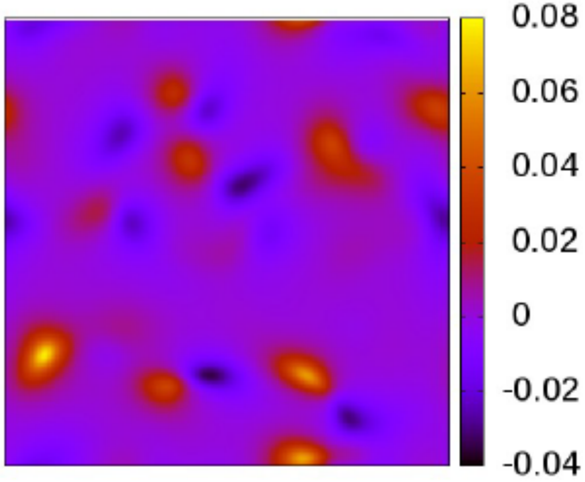
One cools the gas by removing the high energy tail of a thermal distribution so that the low energy distribution is over occupied relative to a Bose Einstein distribution
When one tries to over occupy a bosonic system one has Bose condensation



This condensation occurs in scalar theory simulations, and in simulations of the Abelian Higgs model.

Unknown whether or not this might occur in the Glasma

Glasma in the Abelian Higgs Model

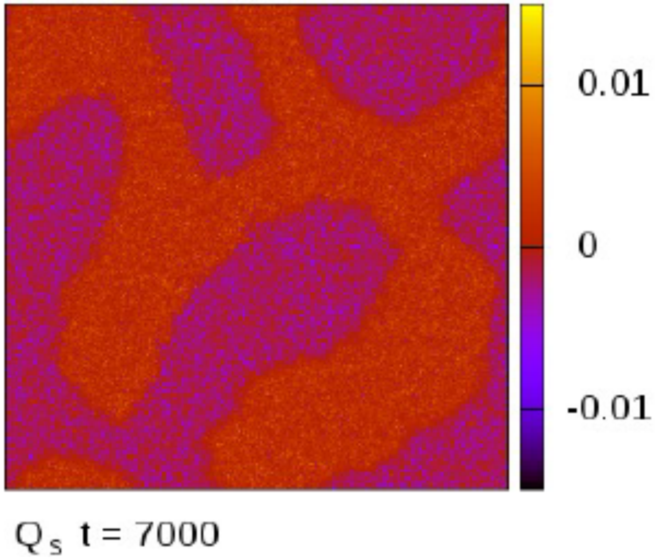


Vortices

3 phases:
Normal
Type I Superconductor
Type II Superconductor

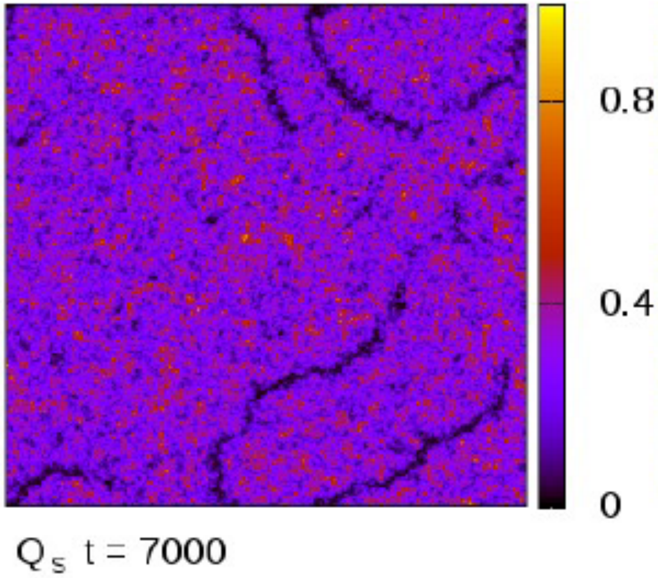
Scalar field is gauge variant but can define a gauge invariant scalar field correlation function and behavior is remarkably similar for gauged and non-gauged theories

Find interesting structures forming:
Vortices
Domain walls
Charged domains



Charged domains and domain walls

Gassenzer,
LDM,
Pawlowski,
Sexty



Future Directions for Heavy Ions

There is now the framework for a more or less complete description of heavy ion collisions from beginning to end

CGC

Initial conditions can be computed from first principles, including non trivial flow like correlations from the initial state

Glasma

Has been shown to generate hydrodynamic behaviour:
Flow generation in glasma phase?
Viscosities?
Photons?
Turbulence?
Condensation?
Thermalization?

Thermalized QGP

Chemical abundances
Flow generation?

Late times, Edge Effects, Hadronization?

pp and pA Collisions: Disentangling the Initial State from Final State Interactions

Small system size means hydro probably has large viscous correction. Glasma treatment may not suffer from treating viscous effects as an approximation.

CGC+Glasma+Hydro

Estimate limits of validity of various approaches
Determine contribution of various stages of evolution to quantities such as the ridge and photon production
Probably biggest uncertainty will be edge effects and hadronization

If we accept that there is saturation, then we must conclude that interactions among the constituents within a single hadron are strong, then for some time in a collision of two hadrons there must also be strong interactions among these constituents. Perhaps in some situations initial state or final state effect may be more important, but both are present and must play important roles.

The scientific issue is how do we properly understand, compute and probe these interactions.

eA: Isolating the Effects of the Initial State