Theoretical Review of Ultra-Relativistic Heavy Ion Physics

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Topics:

Color Glass Condensate

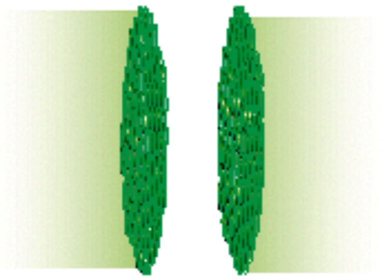
Glasma

Quark Gluon Plasma

Quarkyonic Matter

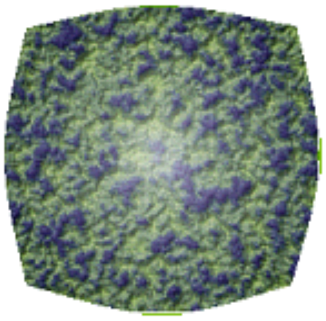
Topological Charge Fluctuations

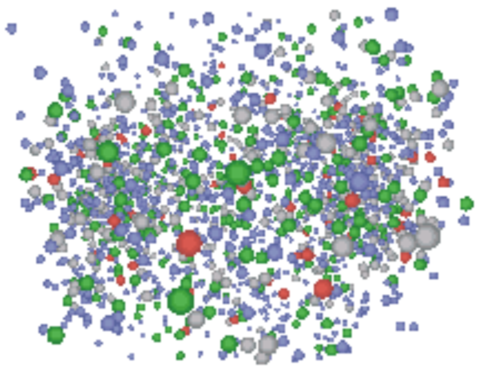
Art due to S. Bass


CGC


Initial
Singularity


Glasma

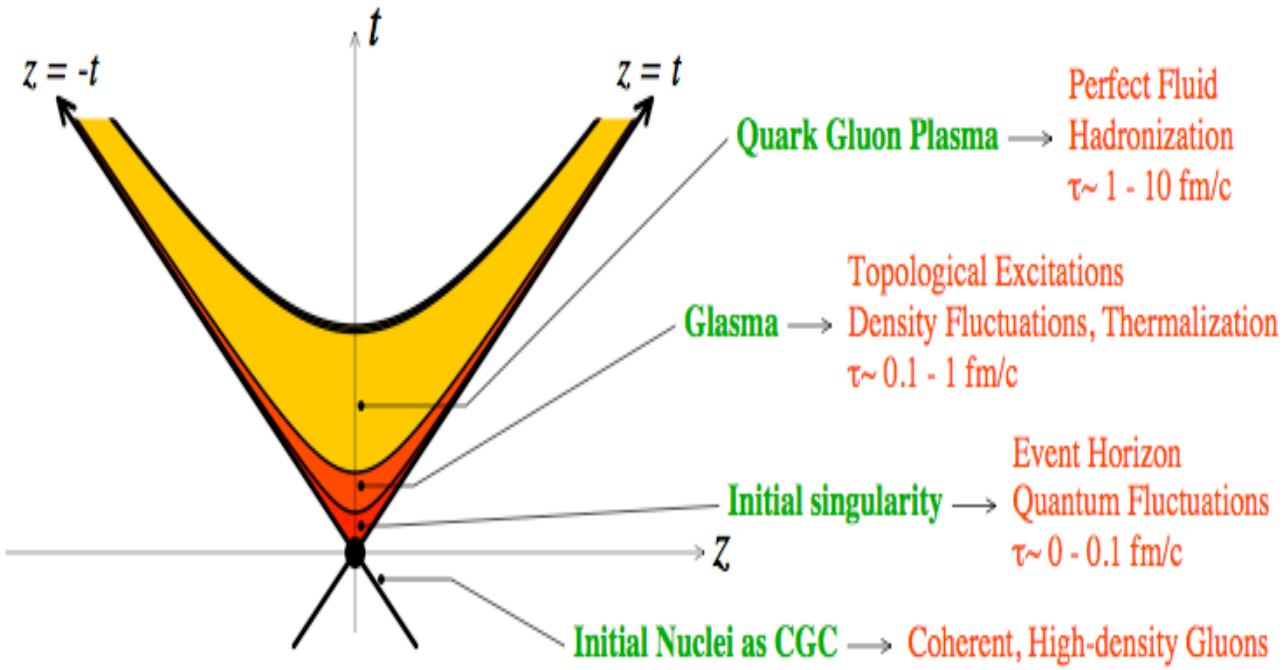

sQGP


Hadron Gas

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?

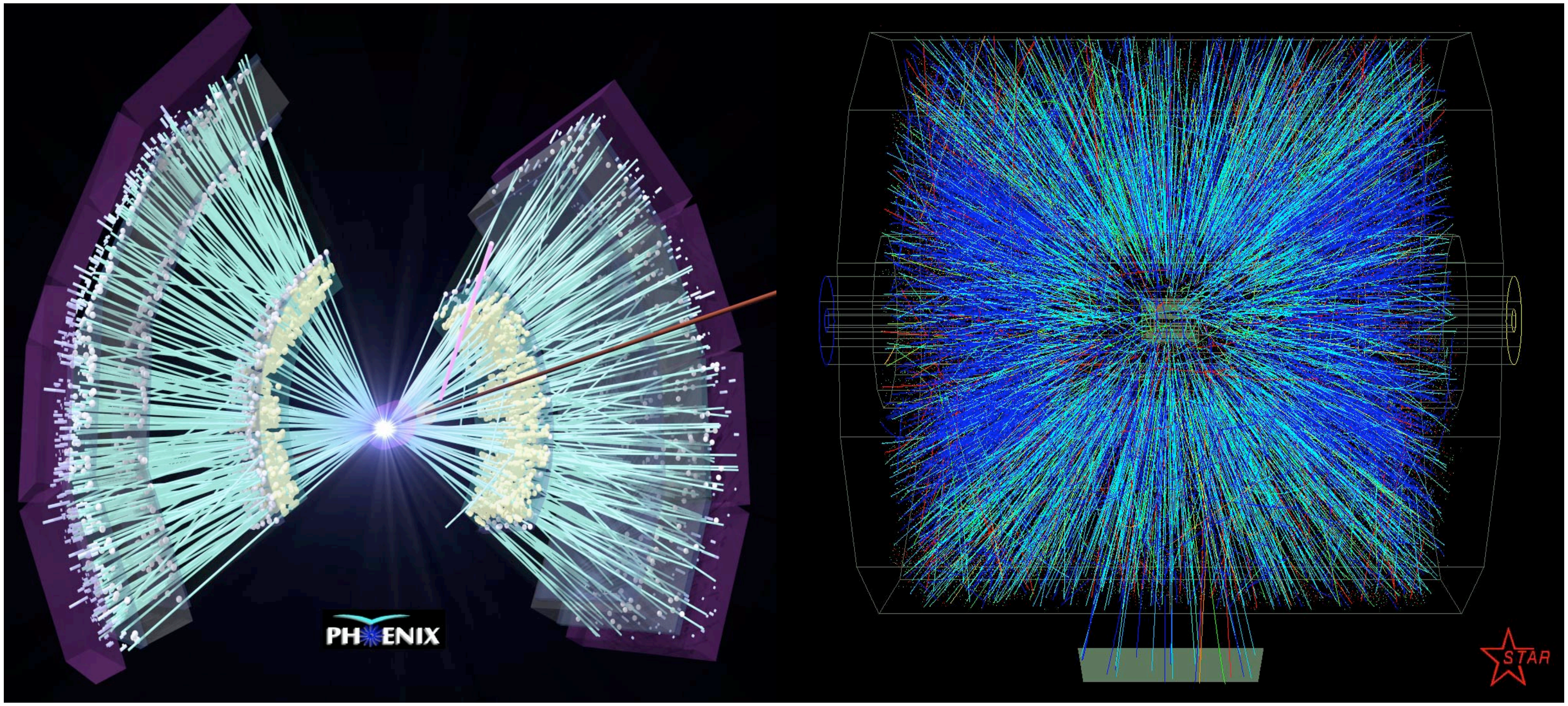


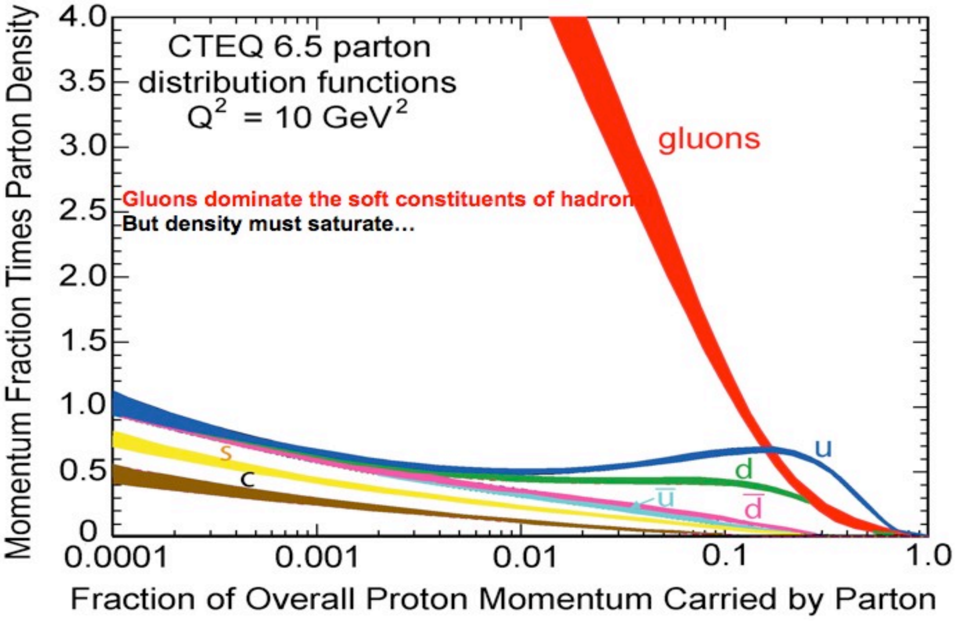
Quark Gluon Plasma → Perfect Fluid
Hadronization
τ~ 1 - 10 fm/c

Glasma → Topological Excitations
Density Fluctuations, Thermalization
τ~ 0.1 - 1 fm/c

Initial singularity → Event Horizon
Quantum Fluctuations
τ~ 0 - 0.1 fm/c

Initial Nuclei as CGC → Coherent, High-density Gluons

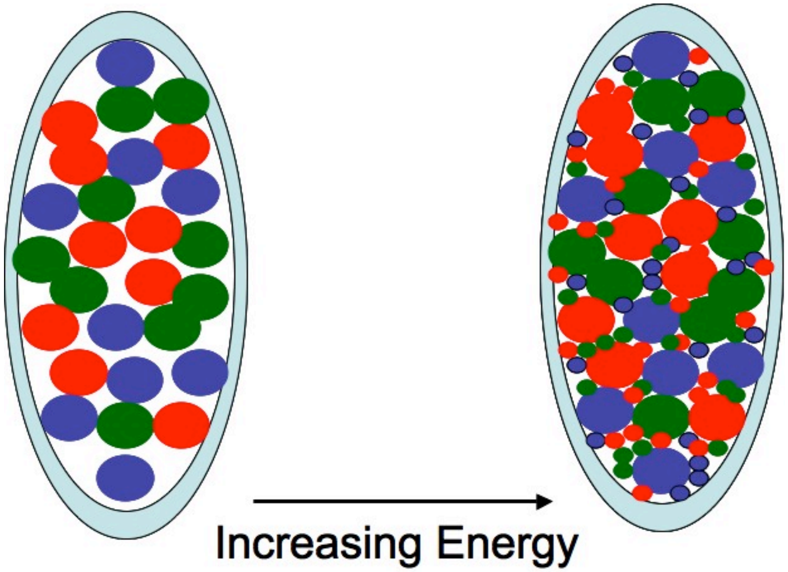




Cross sections for
hadrons rise very slowly
with energy

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

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

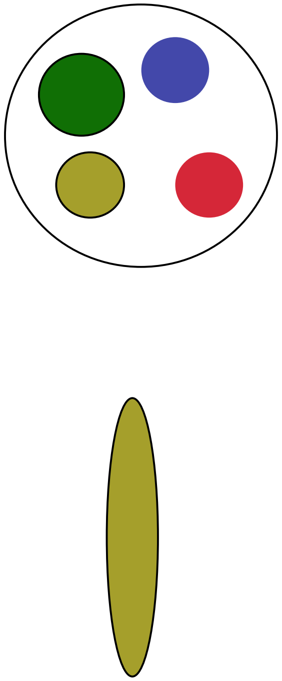


But the gluon density rises
much more rapidly!

The high energy limit is the
high gluon density limit.

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

Color Glass Condensate



Baryon:

3 quarks

3 quarks 1 gluon

.....

3 quarks and lots of gluons

Color: Gluons

Glass:

The partons which make the CGC fields are moving fast => Lorentz time dilation => fields evolve slowly compared to natural times scales

Condensate:

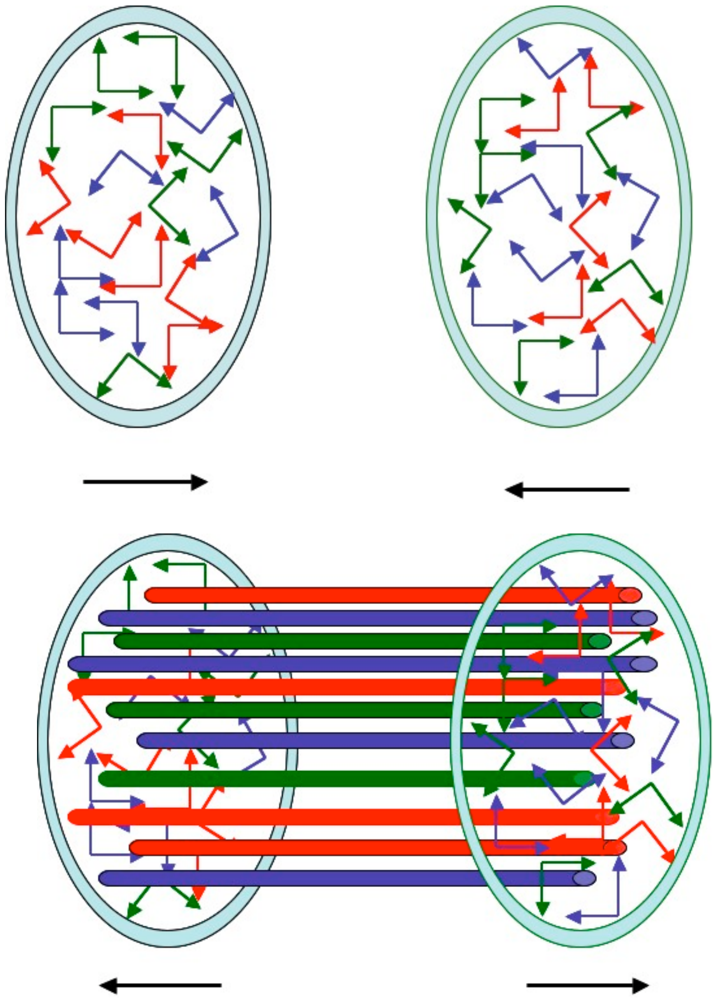
$$\frac{dN}{dy d^2p_T d^2x_T} = \rho$$ Phase space density

$$E = -\kappa\rho + \kappa'\alpha_S\rho^2 \quad \Rightarrow \quad \rho \sim 1/\alpha_S$$

Coupling weak because density is high

Fields are coherent and classical

CGC Gives Initial Conditions for QGP in Heavy Ion Collisions

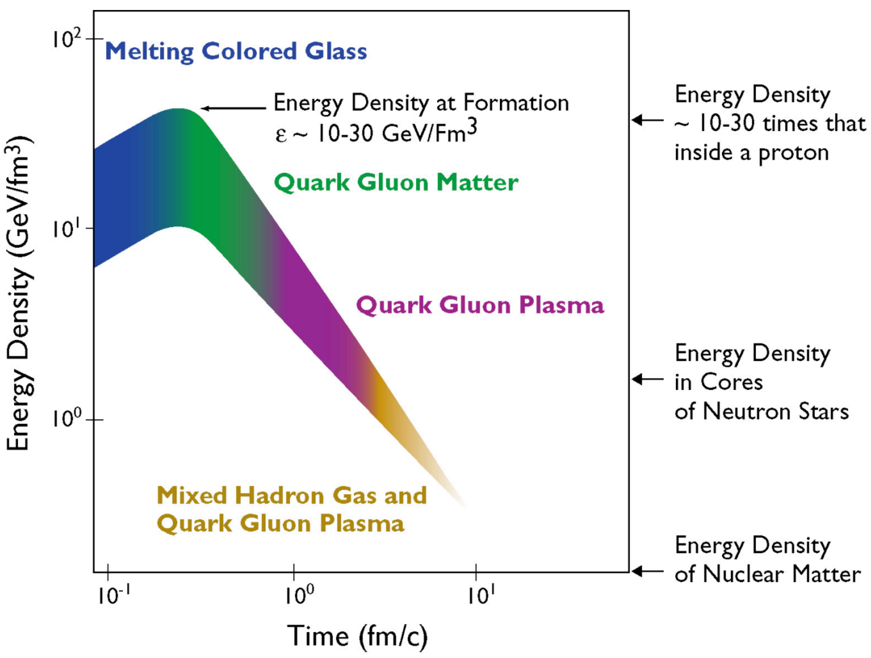


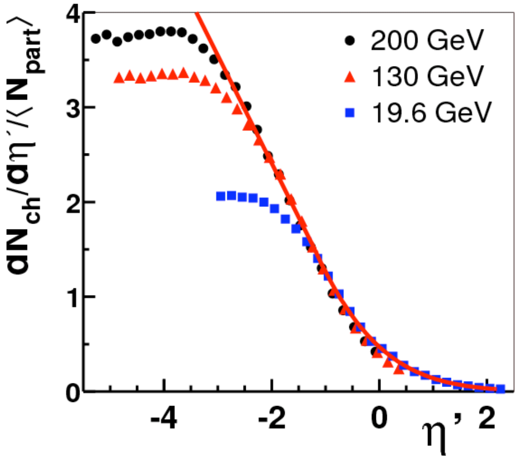
“Instantaneously” develop longitudinal color E and B fields

Two sheets of colored glass collide

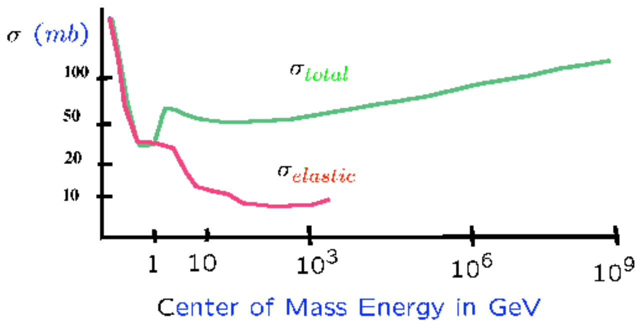
Glass melts into gluons and thermalize

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





The total hadronic cross section:



CGC Provides a Successful Phenomenology of:

Limiting Fragmentation

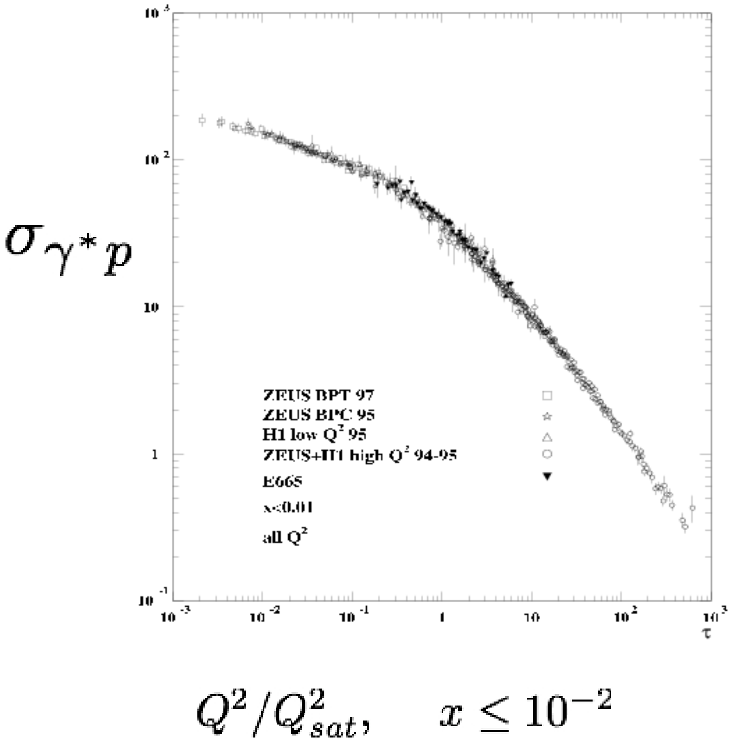
Growth and Scaling Properties of Gluon Distributions

Diffractive DIS and DIS Structure Functions

Multiplicities in Heavy Ion Collisions

Shadowing

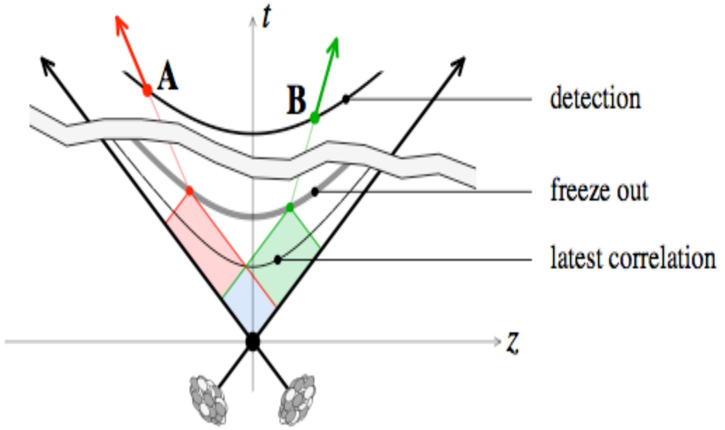
Sophisticated theoretical formalism from first principles in QCD



The Glasma, Long Range Correlations and the Ridge

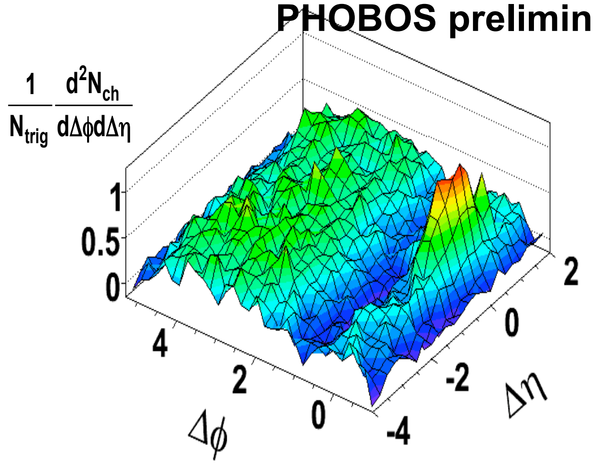
Causality dictates:

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

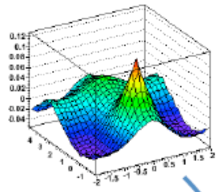


Au+Au 200 GeV, 0 - 30%

PHOBOS preliminary



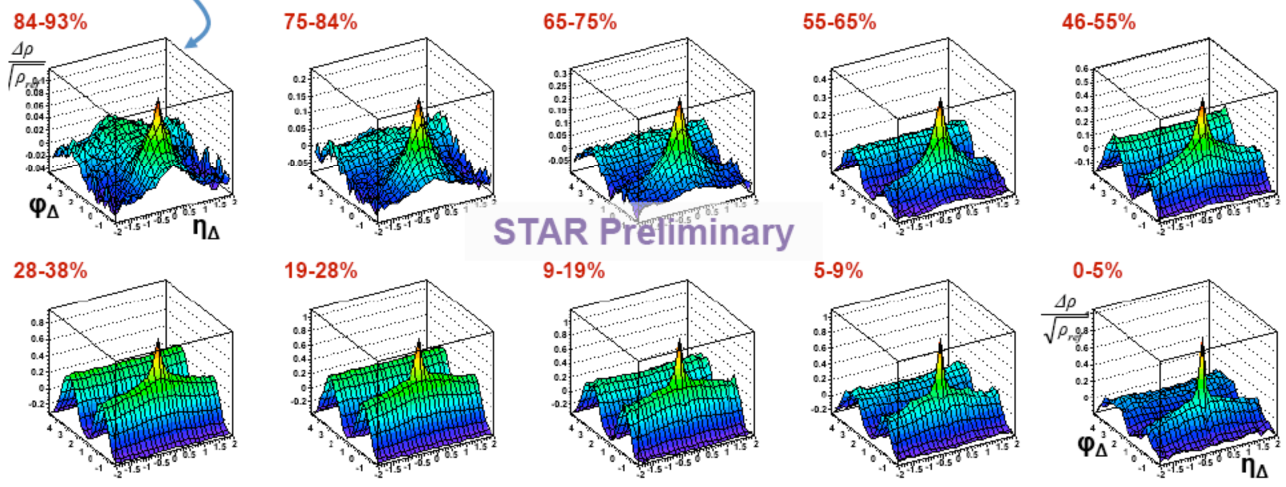
proton-proton



200 GeV Data

Analyzed 1.2M minbias 200 GeV Au+Au events, and 13M 62 GeV minbias events (not shown) Included all tracks with $p_T > 0.15$ GeV/c, $|\eta| < 1$, full φ

note: 38-46% not shown



Shuryak

Dumitru,Gavin,
Gelis, Venugopalan
Moschelli

“Glittering” Glasmas

n-particle correlation can be expressed as

Gelis,Lappi,McLerran

$$\left\langle \frac{d^n N}{dy_1 d^2\mathbf{p}_{\perp 1} \cdots dy_n d^2\mathbf{p}_{\perp n}} \right\rangle = \frac{(n-1)!}{k^{n-1}} \left\langle \frac{dN}{dy_1 d^2\mathbf{p}_{\perp 1}} \right\rangle \cdots \left\langle \frac{dN}{dy_n d^2\mathbf{p}_{\perp n}} \right\rangle$$

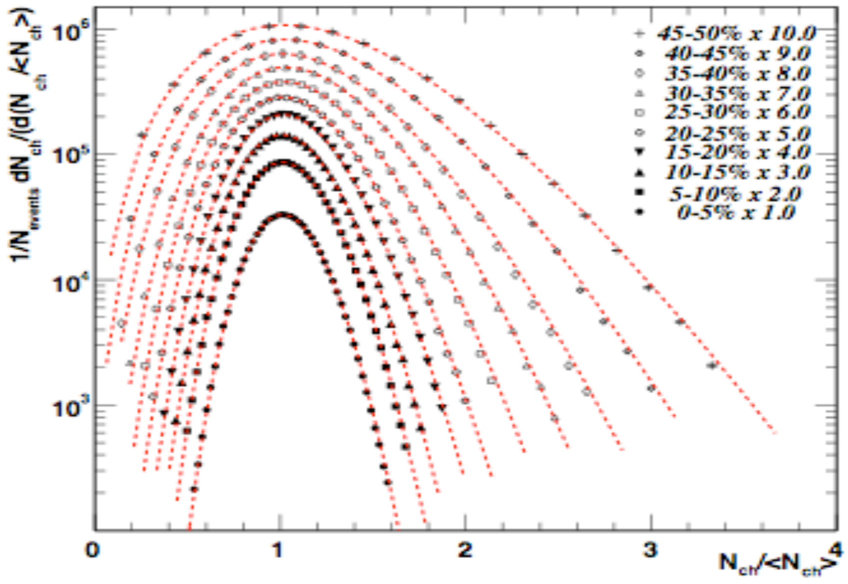
with $k = \zeta_n \frac{(N_c^2 - 1) Q_S^2 S_\perp}{2\pi}$

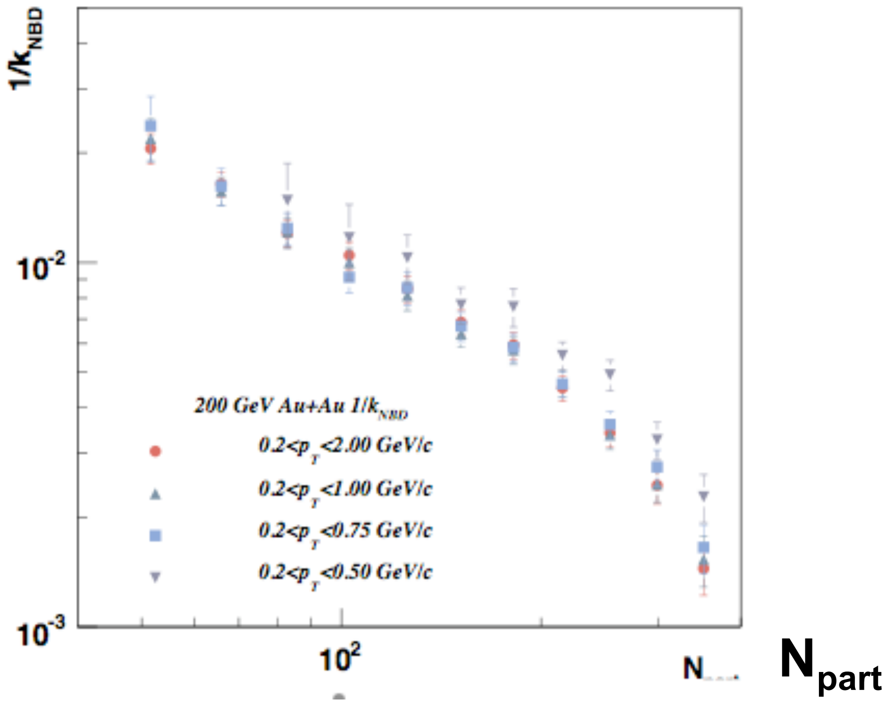
For k = 1, Bose-Einstein dist.For k= ∞, Poisson Dist.

$$\sigma^2 = \bar{n} + \frac{\bar{n}^2}{k}$$

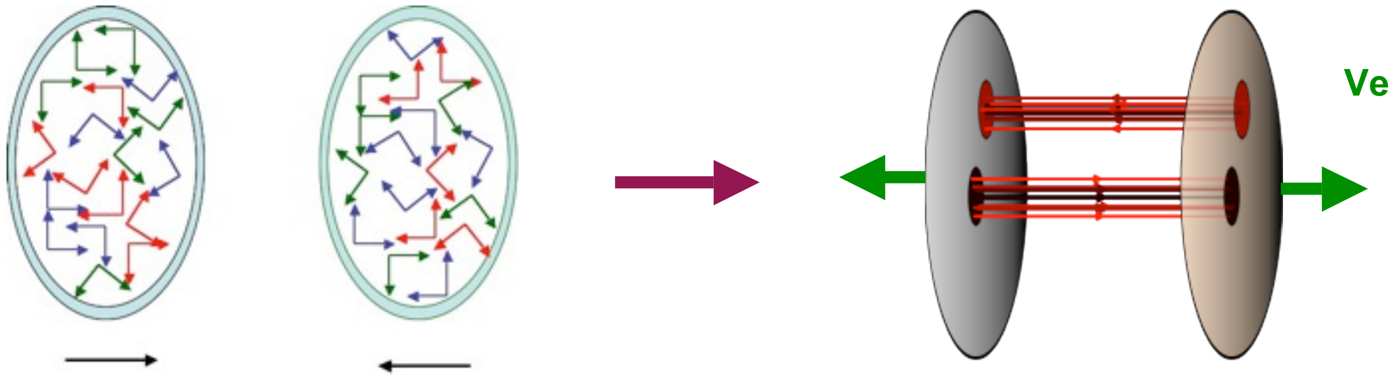
This is a negative binomial distribution which is known to describe well multiplicity distributions in hadronic and nuclear collisions

PHENIX
arXiv:0805.1521





Glasma Flux Tubes and Chern-Simons Number

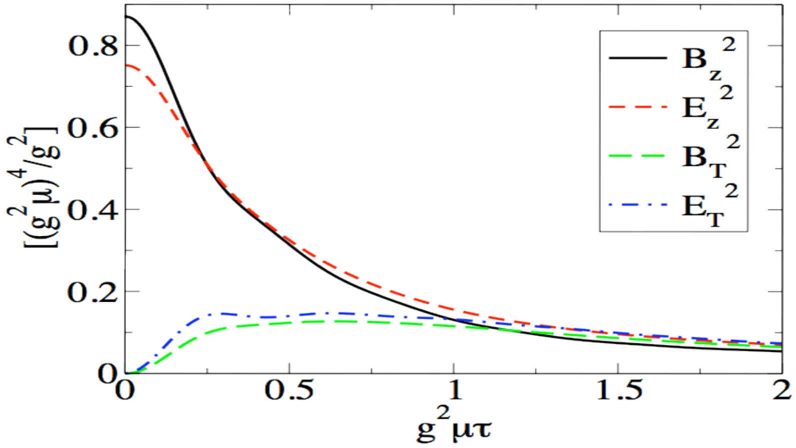


Krasnitz,Nara, Venugopalan; Lappi

Before: transverse E & B
“Weizsacker-Williams fields

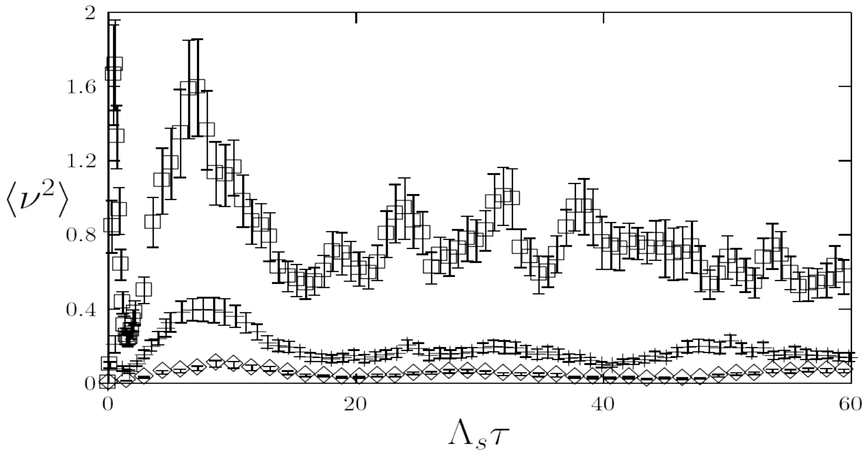
After: boost invariant flux tubes of size $1/Q_S$

Parallel color E & B fields



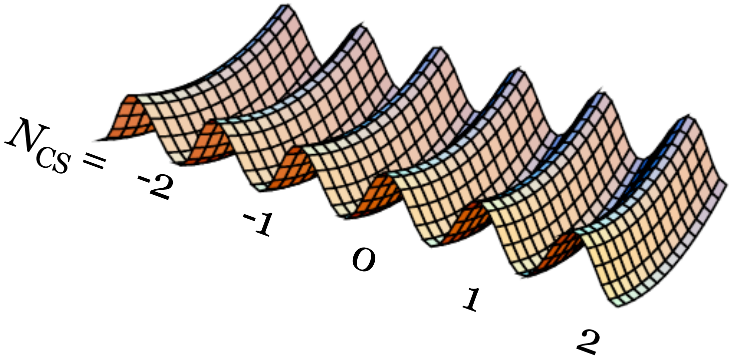
Lappi,McLerran

Chern-Simons topological charge



Kharzeev, Krasnitz, Venugopalan,

P and CP violation: Chiral Magnetic Effect



Topological fluctuations
-sphaleron transitions in Glasma

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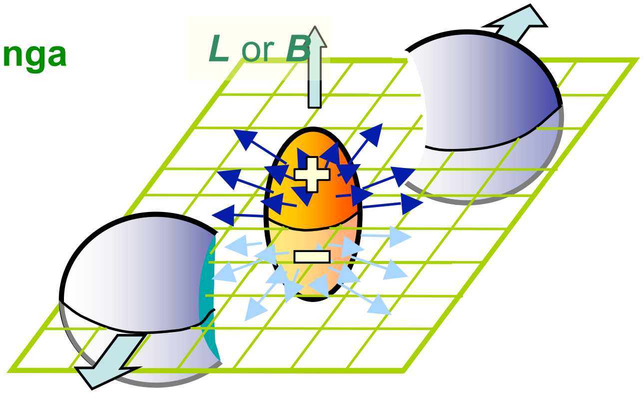
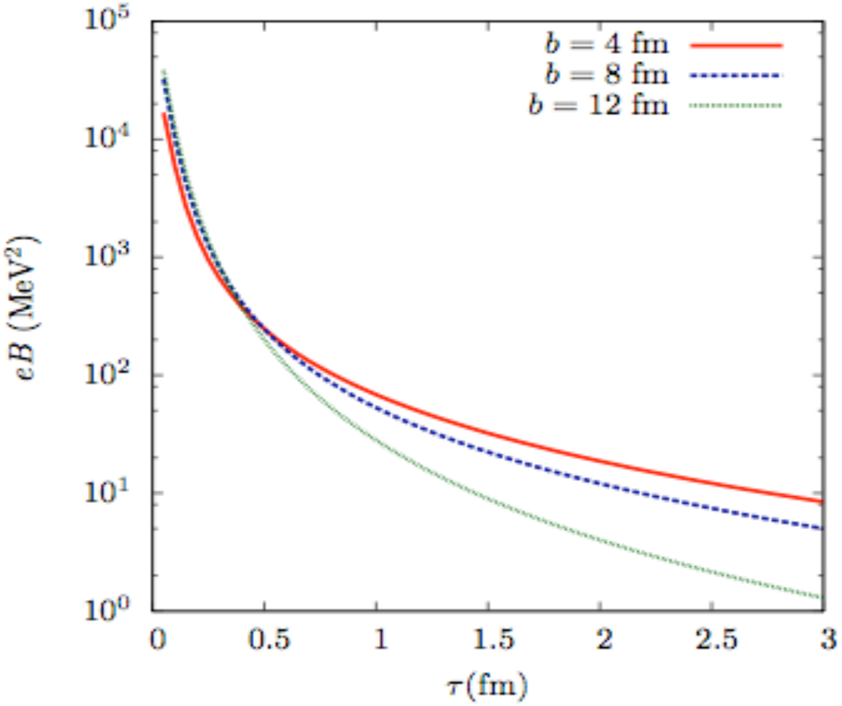
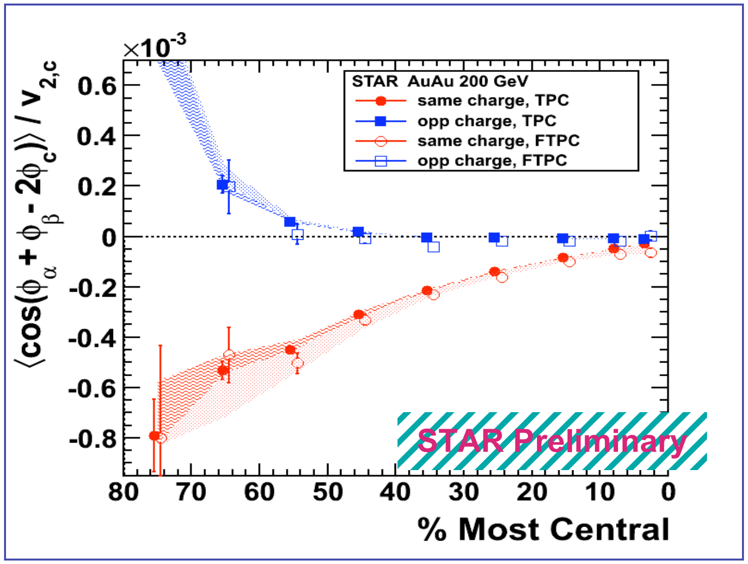
Kharzeev,McLerran,Warringa



External (QED) magnetic field





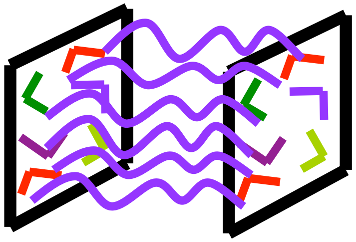
Possible experimental signal of charge separation (Voloshin)

The Unstable Glasma

Romatschke, Venugopalan

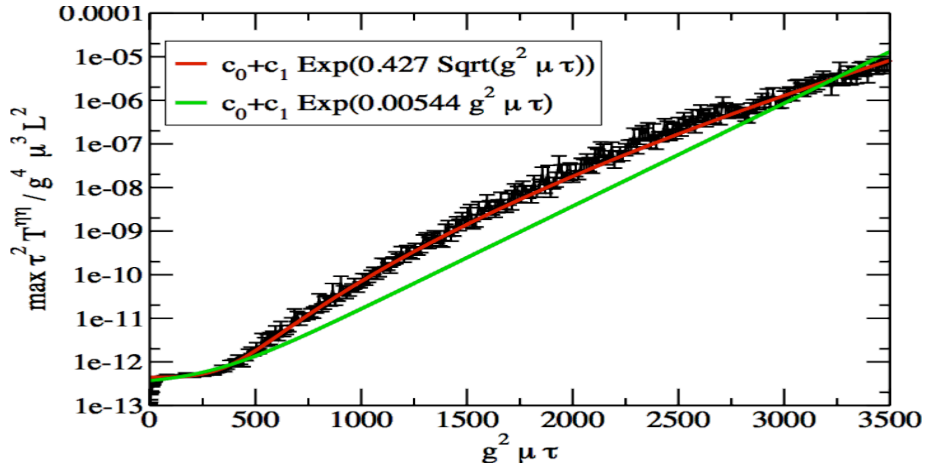
- Small rapidity dependent quantum fluctuations of the LO Yang-Mills fields grow rapidly as

$$\sim e^{\sqrt{Q_s \tau}}$$



- $E_\perp$ and $B_\perp$ fields as large as E_L and B_L at time

$$\tau \sim \frac{1}{Q_S} \ln^2\left(\frac{1}{\alpha_S}\right)$$



Possible mechanism for
rapid isotropization
Problem: collisions can't 'catch up'

- Turbulent "thermalization" may lead to "anomalously" low viscosities

Asakawa, Bass, Muller; Dumitru, Nara, Schenke, Strickland

- Significant energy loss in Glasma because of synchroton like radiation?

Shuryak, Zahed; Zakharov; Kharzeev

Thermalization:

Growth of Instabilities and Turbulance?

Strong Coupling Dynamics?

System thermalizes and makes a very good fluid: Hydrodynamic simulations of flow induced by the collisions, and of particle distributions with transverse momenta < 1-2 GeV work very well. Estimates of viscosity give very small values

$$\eta/S > 1/4\pi \qquad \chi T \sim 1/2\pi$$

Klebanov

Strongly interacting QGP paradigm.

AdSCFT Modeling for qualitative understanding of the strong coupling limit

AdSCFT has allowed insight about the form of viscous corrections to relativistic hydrodynamics that allow for a consistent theoretical formulation and numerical implementation

Danielowicz, Gyulassy

Son, Starinets, Gubser

Romatschke and Romatschke,

Muronga, Rischke

AdSCFT and Jet Quenching:

Theoretical problem: No jets in strong coupling N=4:

Electron positron annihilation

Deep inelastic Jet production

Cascade to low momentum modes occurs very quickly

A single hadron at high energy in strong coupling N=4:

Distribution of partons $\frac{dN}{dx} \sim \frac{1}{x^2}$

Saturated gluon density with phase
space occupation ~ 1, not $\frac{1}{\alpha}$

Leading twist contribution to deep
inelastic scattering vanishes

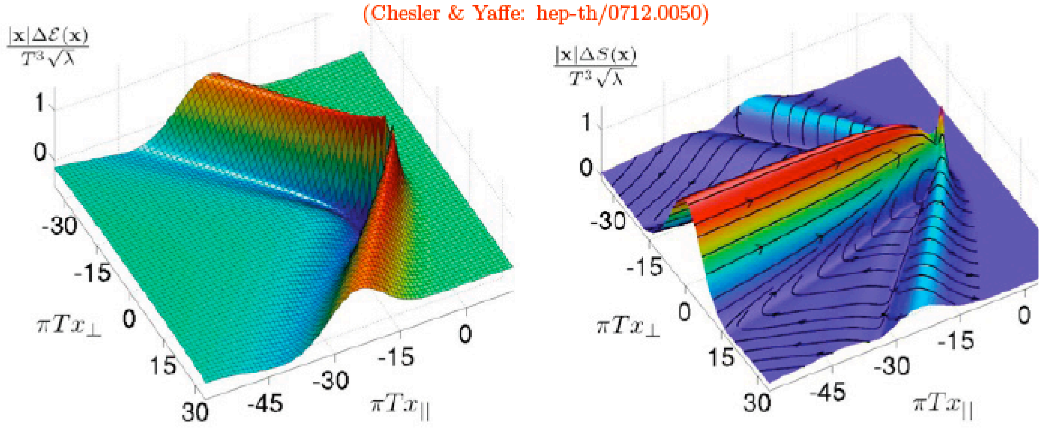
Gylassy, Vitev
Rajagopal, Wiedmann; Yaffe; Mueller, Iancu and Hatta;

Maldacena; Kovchegov

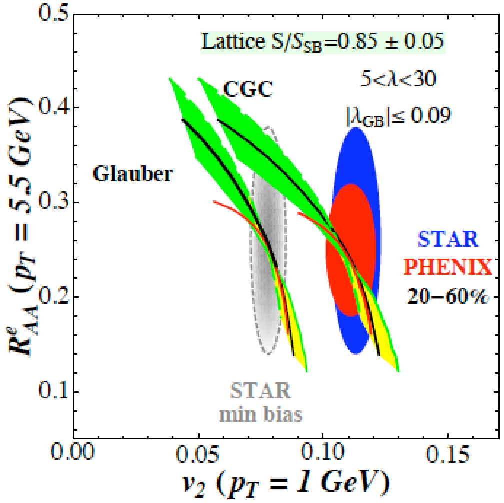
Nevertheless:

Data on jet energy loss and heavy quark flow and energy loss is so stunning:

(Chesler & Yaffe: hep-th/0712.0050)



Energy density **Energy flux**

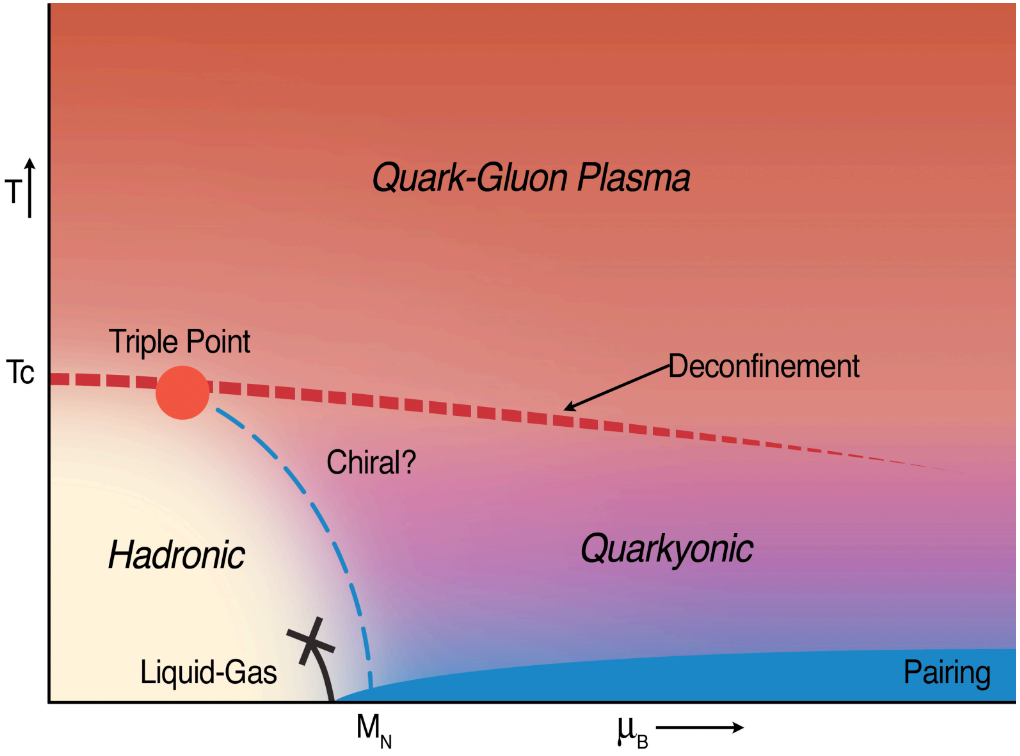


Heavy quark energy loss computations, Mach cones

Heavy quark energy loss vs v2

Chasler and Yaffe;

Betz, Gyulassy, Noronha, Torrieri, Rischke



Hadronic: mesons, glueballs and no baryons

QGP quark and gluons

Quarkyonic: net quarks, mesons and gluebals

Large Nc:

$$e^{(\mu_B - M_B)/T} = 0 \; if \;\; \mu_B < M_B$$

Quark Loops do not affect the confinement potential

Baryon mass ~ N_c,

no baryons in low density phase

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

Pisarski, Hidaka, McLerran, Redlich, Sasaki