The Flavors of the Quark-Gluon Plasma

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SQM 2006
UCLA
March 27 - 30, 2006

Special thanks to M. Asakawa and S.A. Bass

Flavor in the (s)QGP Age

- Dynamics of energy and momentum tell us that medium produced at RHIC is highly opaque:
  - Jet quenching / energy loss
  - Elliptic flow
- Valence quark scaling laws tell us that flow is carried by partons
- Lattice QCD tells us that flavor quantum numbers are carried by quark-like quasiparticles
- "If it flows like a QGP, quenches like a QGP, and looks like a QGP, it probably is a *QGP* ! But what kind of QGP?

Quark flavor as probe

- Probes need to conserve original information
- Need to rely on conservation laws:
  - Energy and momentum $\rightarrow$ Jets
  - Quark flavors $\rightarrow$ *I, S, C, b*
  - Baryon number / charge $\rightarrow$ $B \Leftrightarrow Q = \frac{1}{2}(B+S+C) + I_3$
  - (Almost) no final state interactions $\rightarrow$ γ, $e^{\pm}$, $\mu^{\pm}$
- Flavor fluctuations probe carrier quantum numbers
- Light flavors (*u, d, s*): only *net* flavor conserved
- Heavy flavors (*c, b*): $C^{\pm}$, $B^{\pm}$ conserved separately
- Baryon number probes the origin of flow

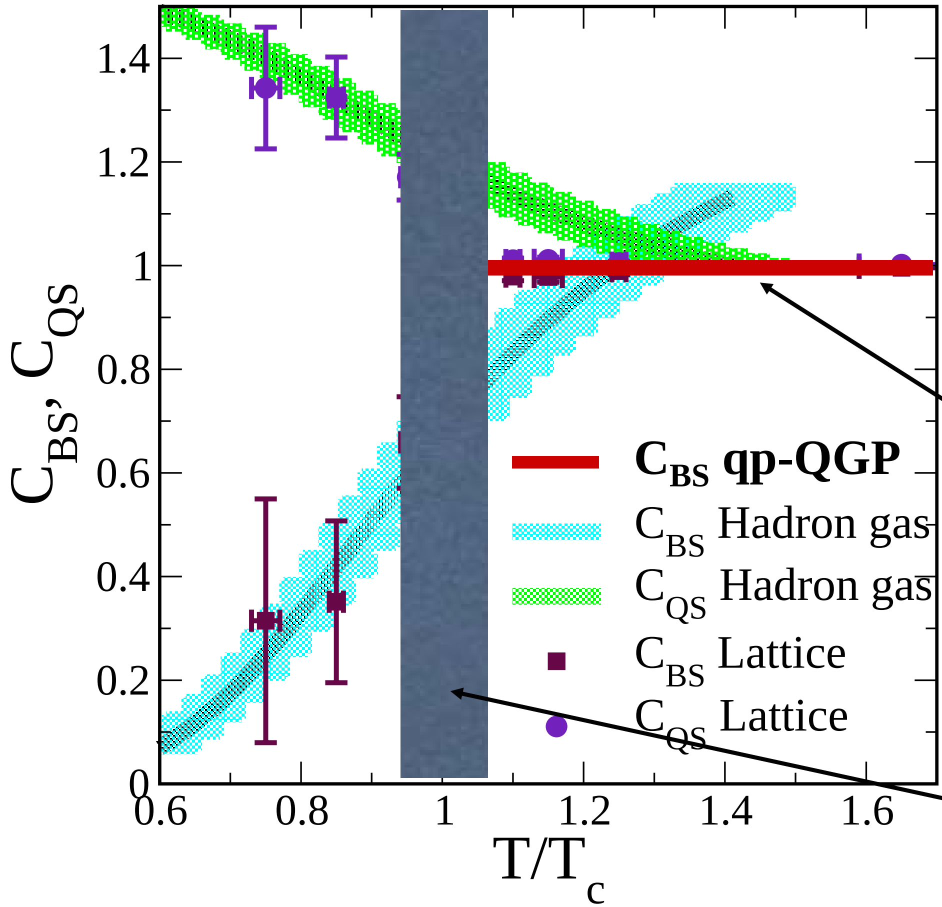
The qp-QGP

A. Majumder / R. Gavai, S. Gupta

$$\langle BS \rangle - \langle B \rangle \langle S \rangle = \sum_k B_k S_k n_k$$

$$C_{BS} = \frac{-3\left(\langle BS \rangle - \langle B \rangle \langle S \rangle\right)}{\langle S^2 \rangle}$$

$$C_{QS} = \frac{3\left(\langle QS \rangle - \langle Q \rangle \langle S \rangle\right)}{\langle S^2 \rangle}$$



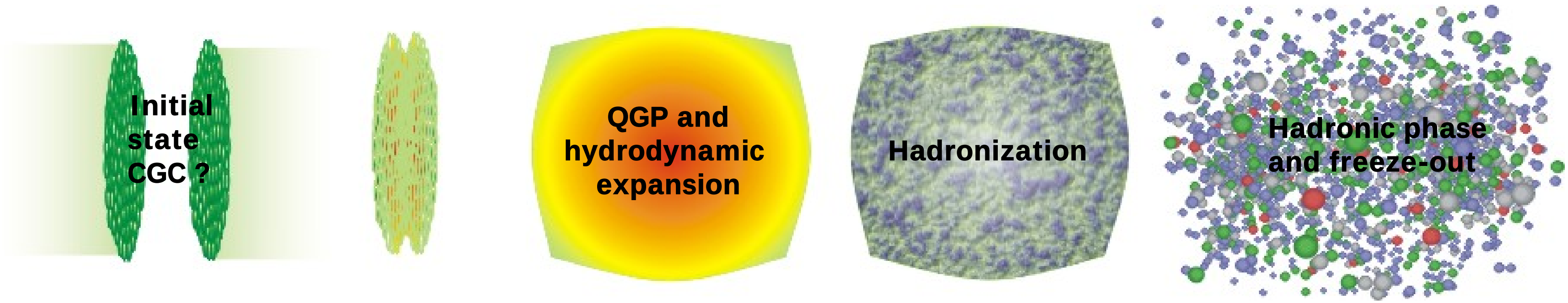
QGP behaves like quasiparticle "gas": flavor carried by quarks and antiquarks, not hadrons, diquarks, etc.

Very narrow transition region!

“It’s a Plasma, Stupid”

- But how to reconcile the apparent *quasi-particle* nature of the QGP with its extreme *opaqueness* ?
- Answer lies (may lie ?) in the peculiar properties of *turbulent* plasmas
- Plasma “*turbulence*” = random, nonthermal excitation of coherent field modes with power spectrum similar to the vorticity spectrum in a turbulent fluid [$P(k) \sim 1/k^2$]
- Plasma turbulence arises naturally in plasmas with an *anisotropic* momentum distribution (Weibel-type instabilities)
- *Expanding* plasmas (such as the QGP at RHIC) *always* have anisotropic momentum distributions
- Soft coherent fields dominate many transport properties of turbulent plasmas by generating *anomalous* transport coefficients, which give the medium the character of a nearly *“perfect” fluid*

Evolution of viscosity



viscosity:	$\eta \sim \eta_B$?	? $\eta \sim \eta_C$	$\eta \sim \eta_{HG}$

- Cross sections are additive
- □ $\eta \sim \lambda_f \sim 1/\sigma$
- ➢ Sum rule for viscosities:

$$\frac{1}{\eta} = \frac{1}{\eta_B} + \frac{1}{\eta_C}$$

➢ Smaller viscosity dominates in system with two sources of viscosity !

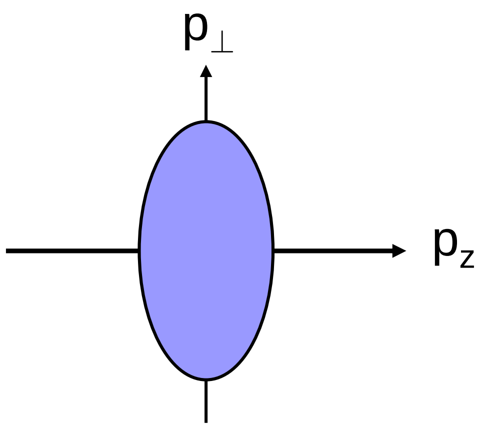
Temperature evolution

$\eta_B < \eta_C$ $\eta_B > \eta_C$ η_{HG}

η_B - the feedback loop

- Longitudinal flow induces momentum anisotropy Δ:

$$1-\frac{2T_{zz}}{T_{xx}+T_{yy}} \equiv \frac{8}{5T\tau}\Delta = \frac{8}{T\tau}\frac{\eta}{s}$$



➢ Anisotropy grows with shear viscosity η

- Soft color fields are proportional to Δ:

$$\langle B^2 \rangle \sim g^2 T^3 \Delta$$

- The anomalous viscosity is inversely proportional to ⟨B²⟩:

$$\eta_B \sim \frac{sT^3}{g^2 \langle B^2 \rangle \tau_m}$$

- Shear viscosity η stabilizes due to: $\frac{1}{\eta} = \frac{1}{\eta_B} + \frac{1}{\eta_C}$

The Münchhausen mechanism

Expansion ⇔ Anisotropy

Bjorken flow:

$$u_z(z,t) = \frac{z}{t}$$

$$1 - \frac{2T_{zz}}{T_{xx} + T_{yy}} = \frac{8}{T\tau}\frac{\eta}{s}$$

Perturbed equilibrium distribution:

$$f(p) = f_0(p)\left[1 + f_1(p)\left(1 \pm f_0(p)\right)\right]$$

$$f_0(p) = \exp[-u_\mu p^\mu / T]$$

For shear flow of ultrarelat. fluid:

$$f_1(p) = -\frac{5\eta/s}{2ET^2}\left(p^i p^j - \tfrac{1}{3}\delta_{ij}\right)\Delta_{ij}(u)$$

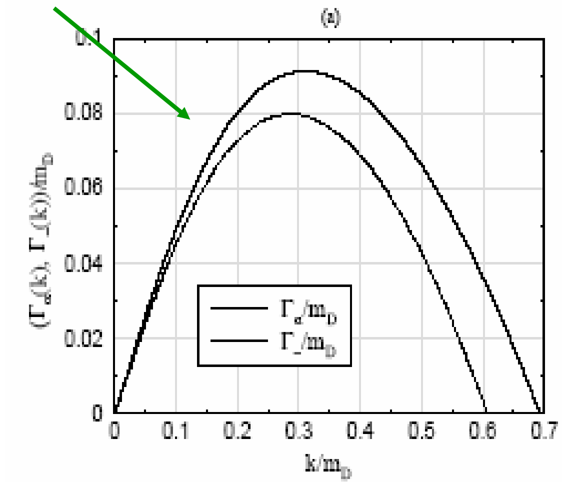
$$\Delta_{ij}(u) = \nabla_i u_j + \nabla_j u_i - \tfrac{2}{3}\delta_{ij}\nabla \cdot u$$

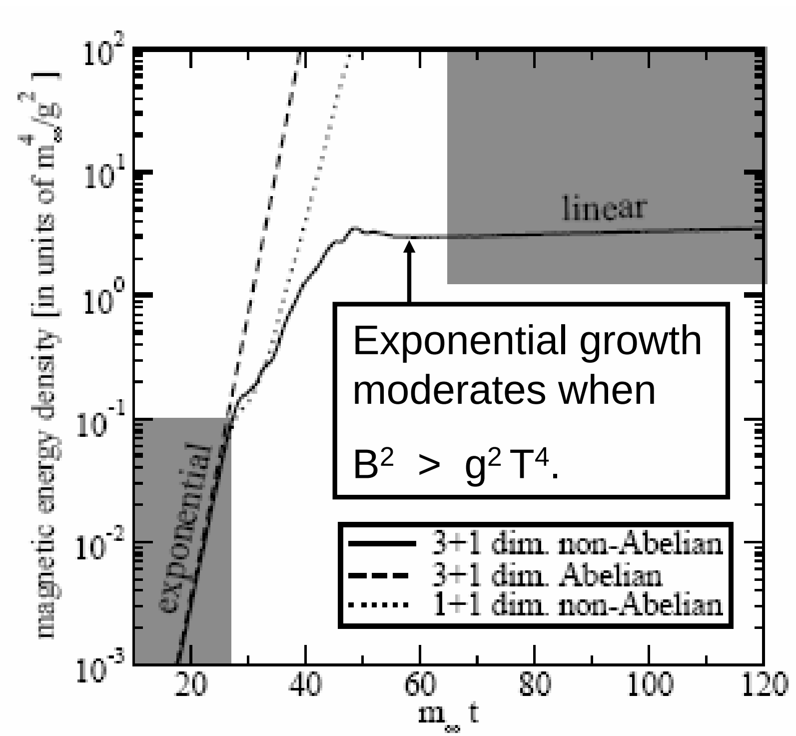
⇒ Anisotropy is governed by flow gradient and viscosity

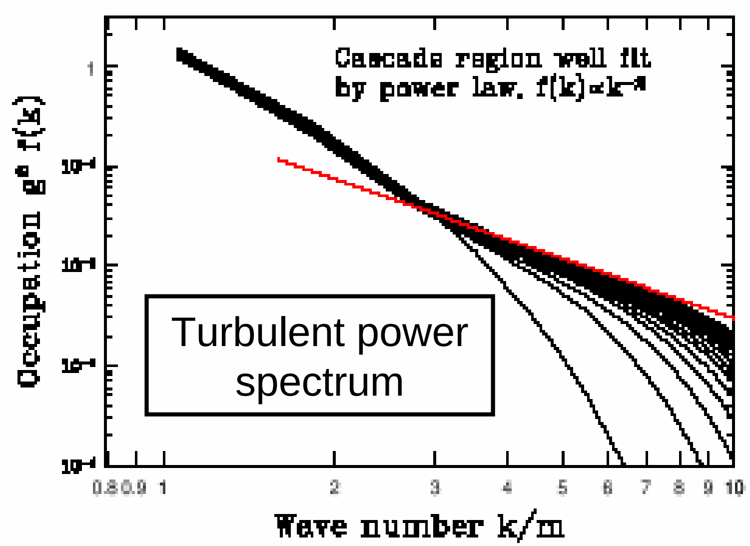
Anisotropy breeds instability

Anisotropic momentum distributions generate instabilities of *soft* ($k \sim gT$) field modes. Growth rate $\Gamma \sim f_1(p)$.

$\Rightarrow$ Shear flow *always* results in the formation of soft color fields; size controlled by $f_1(p)$, i.e. $\Delta_{ij}(u)$ and η/s.







Mrowczynski;

Strickland et al.;

Arnold et al.

Turbulence ⇒ Diffusion

V-B transport of thermal partons:

$$\left[\frac{\partial}{\partial t}+\frac{p}{E_p}\cdot\nabla_r+F\cdot\nabla_p\right]f(r,p,t)=C[f]$$

with Lorentz force

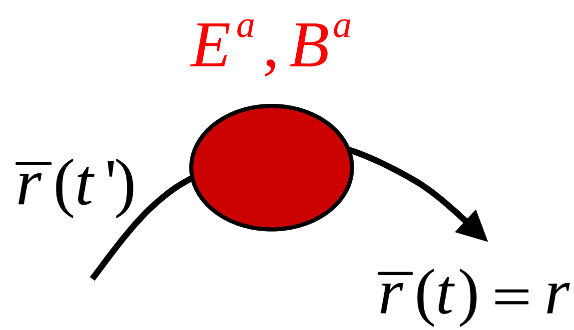
$$F=gQ^a\left(E^a+\mathrm{v}\times B^a\right)$$

Assuming E, B random, V-B eq. ⇒ F-P eq:

$$\left[\frac{\partial}{\partial t}+\frac{p}{E_p}\cdot\nabla_r-\nabla_p\cdot D(p)\cdot\nabla_p\right]\bar{f}(r,p,t)=C\left[\bar{f}\right]$$

with past trajectory $\bar{r}(t')$, so that $\bar{r}(t)\equiv r$

$$D_{ij}(p)=\int_{-\infty}^{t}dt'\left\langle F_i\left(\bar{r}(t'),t'\right)F_j(r,t)\right\rangle.$$



Most important for diffusion - chromo-magnetic fields:

$$\int dt'\left\langle B(t')B(t)\right\rangle\equiv\left\langle B^2\right\rangle\tau_m$$

$$\nabla_p\cdot D(p)\cdot\nabla_p$$
$$=\frac{g^2Q^2\left\langle B^2\right\rangle\tau_m}{2\left(N_c^2-1\right)E_p^2}\left(p\times\nabla_p\right)_\perp^2$$

Diffusion ⇒ Viscosity

Diffusion corresponds to "anomalous" viscosity:

$$\frac{\eta_B}{s} = O(1)\frac{N_c^2-1}{N_c}\frac{T^3}{g^2\langle B^2\rangle\tau_m}$$

But recall that $\langle B^2\rangle$ itself depends on anisotropy $f_1(p)$ ~ viscosity η !

In kinetic theory: $\eta \sim \rho\langle p\rangle\lambda_f \sim \langle p\rangle/\sigma \quad \rightarrow \quad \eta^{-1}$ is additive:

$$\frac{1}{\eta} = \frac{1}{\eta_B} + \frac{1}{\eta_C}$$

$\Rightarrow$ η_B dominates, if $\eta_C \gg \eta_B$.

Take $\langle B^2\rangle = 10\, b_0\, g^2 T^4 \frac{\eta / s}{T\tau}$

$\eta \rightarrow \eta_B$ and $\tau_m \sim \frac{1}{gT}$:

$$\frac{\eta_B}{s} = \left(O(1)\frac{(N_c^2-1)}{10\, b_0\, N_c}\frac{T\tau}{g^3}\right)^{1/2} \sim g^{-3/2}$$

η_B vs. η_C

Compare anomalous viscosity

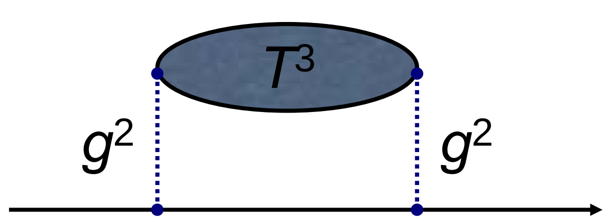
$$\frac{\eta_B}{s} = \left(O(1) \frac{(N_c^2 - 1)}{10\, b_0\, N_c} \frac{T\tau}{g^3} \right)^{1/2} \sim \frac{1}{g^{3/2}}$$

with HTL (weak coupling) result for collisional viscosity

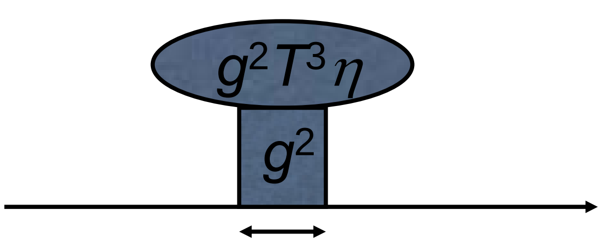
$$\frac{\eta_C}{s} \approx \frac{5}{g^4 \ln g^{-1}}$$

$\Rightarrow$ η_B indeed dominates at weak coupling !

$$\eta_C \sim g^{-4}$$



$$\eta_B{}^2 \sim g^{-3}$$



$$\tau_m \sim (gT)^{-1}$$

When even a lattice is not enough

For realistic *g* and not too late times τ, we have a quasiparticle QGP, in which transport is dominated by turbulent color fields.

At late times, shear flow from transverse flow becomes important and may keep $\eta_B < \eta_C$ for all times (depends on value of b_0).

BUT: The anomalous viscosity would not be observed in lattice QCD, because $T \neq 0$ calculations are for a plasma at rest, not a QGP with imprinted shear flow.

$\Rightarrow$ Lattice transport coefficients might not describe the real-life QGP at RHIC, even if they could be calculated reliably !

From CGC to CLP

Conclusion:

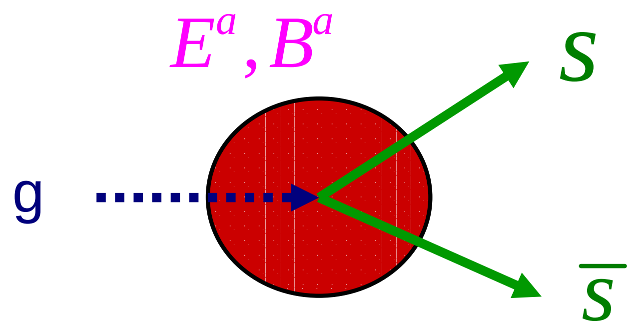
When two nuclei collide, their coherent gluons fields (the Color Glass Condensate) are shattered and melt. Because the resulting medium expands rapidly, the CGC melts into a plasma, which is a turbulent Color Liquid Plasma (the CLP). Transport phenomena, especially at early times are strongly influenced by the turbulent color fields.

- Effects on hard probes (jets, EM probes)
  - not a topic for SQM (but extremely interesting! Soft photons?)

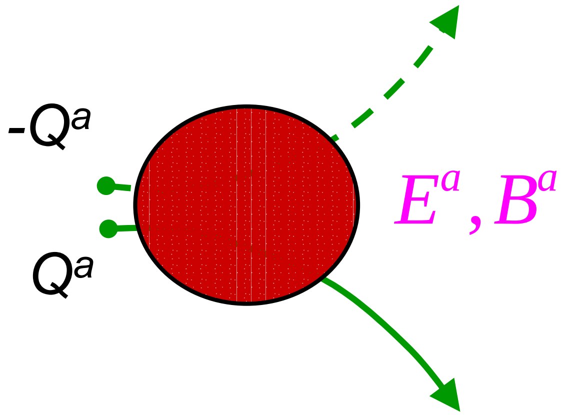
- Effects on flavor probes:
  - Quasiparticle picture of QGP is compatible with low viscosity
  - Strangeness production by a single thermal gluon
  - Field induced quarkonium dissociation
  - Anomalous diffusion of charm and bottom quarks

Two aspects of CLP

A single gluon can split into a quark pair in the presence of a color field



Coherent color field separates color charges in singlet configuration



Nothing…

…is too wonderful to be true.

Michael Faraday

(as cited on the entrance to Kinsey Hall)

The good news:

The sQGP may not be as difficult to understand as many have feared.

The challenge:

All transport processes will need to be reconsidered in the presence of soft turbulent color fields generated by the expansion of the QGP.