Terrestrial Mini-Bang: Transmuting a Color Glass Condensate into a Quark Gluon Plasma

Raju Venugopalan
Brookhaven National Laboratory
- Gold-Gold collisions at $\sqrt{s} = 200 / \text{nucleon}$

- Polarized (and un-polarized) p-p collisions at $\sqrt{s} = 200 / \text{nucleon}$

- Run 4- deuteron-Gold collisions at $\sqrt{s} = 200 / \text{nucleon}$

- Future runs-other asymmetric nuclei, pp at 500 GeV, …
Where to study QCD matter

Big Bang

Only one chance…

Lattice QCD

Who wants to wait?…

RHIC

Neutron stars

Peter Steinberg
What is the QGP?

Heating QCD in a Box

\[ \alpha_s \rightarrow \alpha_s(T) \ll 1 \text{ for } T >> \Lambda_{QCD} \]

Asymptotic Freedom \implies \text{Deconfined quarks and gluons at high } T

Collins and Perry (1974)
The “Unicorn”:

Quark-Gluon Plasma =

Deconfined,
Chirally Symmetric “Phase”

Is the fabulous beast a chimera?
STATE OF THE ART PERTURBATION THEORY

Very slow convergence of finite T perturbation theory!
May be Ok at 3-5 T_c

Kajantie et al.
QCD Phase Diagram as a function of quark mass

- **Lattice QCD**: first principles computation of *static* properties of finite T QCD at $T \sim T_c$
Equation of State from Lattice QCD

May be cross-over, but still rapid change in degrees of freedom!
Static Quark Free Energy for $0.58 < T/T_c < 1.15$

- Pseudo-scalar and vector screening masses
Chiral and deconfining transitions at same temperature?

**Polyakov loop**

Deconfinement order
Parameter in pure gauge theory

**Chiral Condensate**

Chiral order parameter
Signs of deconfinement and chiral restoration on lattice

But… the picture is more complex!

Vector and pseudo-scalar spectral functions don’t change significantly for $T > T_c$

Petreczky et al. - Bielefeld Group
QCD at finite Density

\[ \alpha_s(\mu_B) \ll 1 \text{ for } \mu_B \gg \Lambda_{QCD} \]
State of the Art Lattice Results on Phase Diagram

- quark–gluon plasma
- hadronic phase
- crossover
- endpoint
- 1st order transition

Fodor & Katz, hep-lat/0402006
Back to RHIC...
HEAVY-ION EXPERIMENTS

<table>
<thead>
<tr>
<th>Facility</th>
<th>Location</th>
<th>System</th>
<th>Energy (CMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS</td>
<td>BNL, New York</td>
<td>Au+Au</td>
<td>2.6-4.3 GeV</td>
</tr>
<tr>
<td>SPS</td>
<td>CERN, Geneva</td>
<td>Pb+Pb</td>
<td>8.6-17.2 GeV</td>
</tr>
<tr>
<td>RHIC</td>
<td>BNL, New York</td>
<td>Au+Au</td>
<td>200 GeV</td>
</tr>
<tr>
<td>LHC</td>
<td>CERN, Geneva</td>
<td>Pb+Pb</td>
<td>5.5 TeV</td>
</tr>
</tbody>
</table>
Outstanding phenomenological questions

- Is high energy density bulk quark-gluon matter formed at RHIC?

- Does this matter thermalize to form a Quark Gluon Plasma? What can we learn about the properties of the QGP?

- Can we learn about “universal” properties of hadronic wavefunctions at high energies? (Color Glass Condensate)
Results from the RHIC Au-Au experiments:

Bulk features: Energy, Centrality & Rapidity dependence of inclusive hadron distributions.

Flavor: Baryon #, Strangeness, Charm.

Flow: Radial & Elliptic flow.

Hanbury-Brown-Twiss: Two particle Bose-Einstein correlations.

High p_t physics:

a) High p_t inclusive hadron spectrum relative to p-p (central/peripheral)

b) p_t dependence of azimuthal anisotropy,

c) back-to-back jet correlations.

d) direct photons & di-leptons; J/psi’s

Event-by-event physics:

p-p and d-Au “control experiments” crucial to develop consistent framework
Heavy-Ion Collisions—a violent dynamical system… Is thermalization achieved?

Require ratio of rates:

\[ \frac{\Gamma_{\text{exp.}}}{\Gamma_{\text{coll.}}} \ll 1 \]

Thermalization very sensitive to Initial Conditions
A hadron at high energies

Each wee parton carries only a small fraction of the momentum of the hadron.

\[ |h> = |qqq> + |qqqq> + \cdots + |qqq \cdots gggq\bar{q}> \]

Each wee parton carries only a small fraction of the momentum \( P^+ \) of the hadron.

What is the behavior of wee partons in a high energy hadron?
The DIS Paradigm

Kinematics:

\[ s = (p + k)^2 \]
\[ Q^2 = -q^2 = 4E_e E_{e'} \sin^2 \left( \frac{\theta}{2} \right) \]
\[ x_{\text{Bj}} = \frac{Q^2}{2M_p(E_e - E_{e'})} \equiv \frac{Q^2}{2p \cdot q} \]
\[ y = \left( 1 - \frac{E_{e'}}{E_e} \right) = \frac{p \cdot q}{p \cdot k} \]

Cross-section:

\[
\frac{d^2 \sigma^{ep \rightarrow eX}}{dx dQ^2} = \frac{4\pi \alpha_{\text{em.}}}{x Q^4} \left[ y^2 x F_1(x, Q^2) + (1 - y) F_2(x, Q^2) \right]
\]
**Born-Oppenheimer:** separation of large $x$ and small $x$ modes

Valence partons are static over wee parton life times
Phase space density grows rapidly - BFKL evolution breaks down when phase space density $f \sim 1$

Gluon density saturates at $f = \frac{1}{\alpha_s}$
The Color Glass Condensate

- Typical momentum of gluons is \( Q_s \).
- Bosons with large occupation number \( \approx \frac{1}{\alpha_s} \) form a condensate.
- Gluons are colored.
- Random sources evolving on time scales much larger than natural time scales—very similar to spin glasses.

Hadron/nucleus at high energies is a Color Glass Condensate.
Novel regime of QCD evolution at high energies

The **Color Glass Condensate**
Colliding Sheets of Colored Glass at High Energies

Initial energy and multiplicity of produced gluons depends on $Q_s$

\[
\frac{1}{\pi R^2} \frac{dE_\perp}{d\eta} = \frac{0.25}{g^2} Q_s^3 \quad \text{and} \quad \frac{1}{\pi R^2} \frac{dN}{d\eta} = \frac{0.3}{g^2} Q_s^2
\]

Classical approach breaks down at late times when $f \ll 1$

\[
\tau \gg \frac{1}{Q_s} \quad \text{but} \quad \tau \ll R
\]
Space-time evolution in heavy ion collisions

Initial conditions determined by saturation scale $Q_s \gg T_i$

$$\varepsilon \propto \frac{Q_s^4}{\alpha_s} \text{ at } \tau \sim \frac{1}{Q_s}$$

$Q_s = 1.4-2$ GeV from HERA data extrapolations and numerical simulations

Do initial state (wave fn.) effects or final state (parton re-scattering) dominate in the space-time evolution?
Emerging Consensus... final state interactions are essential.

The evidence from low p_t physics

Thermal fits to Particle ratios
Elliptic flow

Target Spectator  Projectile Spectator

Participants

\[ v_2 \equiv \cos(2\phi) = \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \]

Initial  After

Coordinate space  Momentum space

Idea: Interaction \(\Rightarrow\) convert space anisotropy to momentum anisotropy
Large elliptic flow strongly indicates collectivity in final state.
Flow of different particle species is consistent
With expectations from hydrodynamics
CGC computations don't give enough $v_2$: re-scattering essential!

Consistent with lattice estimates of viscosity by S. Gupta.

Early thermalization essential in hydro. Too much $v_2$?

Teaney: viscous effects may be important.
HBT: a major puzzle

STAR prelim.
What is the evidence from high $p_t$?

- Dramatic suppression out to 10 GeV—clearly distinct from SPS data.

D-Au data clearly establishes it as final state effect. Color Glass alone would give 25-30% suppression.

Natural explanation: partonic energy loss—not (pre-) hadron absorption.
Reconstructing Jets from Azimuthal correlations

No sign of suppression at SPS-only broadening of backward jet
Evidence of novel final state effects

- Flow at low $p_t$
- High $p_t$ suppression
- Systematics of azimuthal correlations
- Clearly distinct from cold matter probed in d–Au

All models that explain these distinct features have to assume very dense, strongly interacting matter: consistent with the QGP …many open questions remain for RHIC to explore!
Novel regime of QCD evolution at high energies

Geometrical scaling seen at HERA-small $x$ inclusive and diffractive data explained by color glass

RHIC can discover a universal Color Glass regime of QCD in hadrons at high energies
What is the CGC?

- Effective theory of QCD at high energies--small $x$
- Identifies right “universal” degrees of freedom at small $x$
- These satisfy non-linear evolutions eqns.-the JIMWLK eqns.- at small $x$

- The CGC explains saturation/shadowing in a weak coupling partonic framework.
- It is a theory of the initial conditions in heavy ion collisions.
The evidence for CGC from RHIC

**Brahms forward data qualitatively different from** $\eta = 0$

**Enhanced by STAR data showing less suppression on Gold side**

**Going forward in rapidity => smaller x in the nucleus!**
More on CGC from RHIC...

From the Phenix muon arms

Phobos plot for different $p_t$
Qualitative behavior predicted from non-linear evolution

Different from initial shadowing predictions

More quantitative studies needed!
The emerging picture from RHIC

- Central rapidities at RHIC ($x \sim 10^{-2}$) - weak initial state effects - strong final state effects
- At forward rapidities ($x \sim 10^{-3}$) - strong initial state effects

Are these effects respectively the QGP & the CGC? Likely - next few runs may be decisive
What do we need to do?

- Rare probes-photons, di-leptons, J/Psi

- Energy scan-especially interesting to establish differences with SPS as number density grows.

- Look forward--a d-Au program has great potential for new physics-may require significant detector upgrades. Tie-in with eRHIC?
Important lessons for LHC & eRHIC

- At LHC $x \approx 10^{-3}$, initial state shadowing may swamp energy loss effects.

- At eRHIC, precocious saturation effects can be studied with larger $Q^2$ lever arm.