Evidence for a Quark-Gluon Plasma at RHIC
Evidence for a Quark-Gluon Plasma at RHIC
On the “First Day”

There was light! at 10^{-34} seconds & 2 \times 10^{12} \text{ Kelvin}

Quark-to-hadron phase transition

Quark-Gluon Plasma

Rapid inflation

gravity, strong & E-W forces separate

John Harris (Yale)
Lattice QCD

\[ \epsilon / T^4 \sim \# \text{ degrees of freedom} \]

\[ \epsilon = \frac{\sqrt{\pi}^2}{30} T^4 \]

F. Karsch, et al.

\[ T_C \sim 175 \pm 8 \text{ MeV} \rightarrow \epsilon_c \sim 0.3 - 1 \text{ GeV/fm}^3 \]
Heating the vacuum modifies soft/long-wave-length processes.

**Chiral symmetry broken**, confining forces modified.

**Constituents** - Hadrons, dressed quarks, quasi-hadrons, resonances?

**Coupling strength varies** investigates confinement, hadronization, & intermediate objects.

**Heavy quark-antiquark coupling at finite T from lattice QCD**

John Harris (Yale)                             ISSP’06 Erice, Sicily, Italy, 29 Aug – 7 Sep 2006
“In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions.

In order to study the question of ‘vacuum’, we must turn to a different direction; we should investigate some ‘bulk’ phenomena by distributing high energy over a relatively large volume.”

T.D. Lee
Objective – Melt QCD Vacuum → Deconfined QGP

QCD vacuum → color dielectric!
qq̅ condensate
“confines” q,g to be in hadrons

- Compress or Heat to
- Melt the QCD vacuum
→ color conductor
→ deconfined color matter!

Thanks to Mike Lisa for animation
Phase Diagram of QCD Matter

- Early universe
- Tri-critical point
- LHC
- RHIC
- quark-gluon plasma
- color superconductor
- hadron gas
- nucleon gas
- nuclei
- Neutron stars
- CFL
- vacuum
- $\rho_0$
- baryon density

Temperature $T_c \approx 170$ MeV

see: Alford, Rajagopal, Reddy, Wilczek
Phys. Rev. D64 (2001) 074017

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Quark-Gluon Plasma (Soup)

- Standard Model → Lattice Gauge Calculations predict QCD Deconfinement phase transition at $T = 175$ MeV
- Cosmology → Quark-hadron phase transition in early Universe
- Astrophysics → Cores of dense stars (?)
- Can we make it in the lab?

- Establish properties of QCD at high $T$ (and density?)
Relativistic Heavy Ion Collider

John Harris (Yale)                             ISSP’06 Erice, Sicily, Italy, 29 Aug – 7 Sep 2006
Relativistic Heavy Ion Collider (2000 → )

Design Performance

<table>
<thead>
<tr>
<th></th>
<th>Au + Au</th>
<th>p + p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max $\sqrt{s_{nn}}$</td>
<td>200 GeV</td>
<td>500 GeV</td>
</tr>
<tr>
<td>L [cm$^{-2}$ s$^{-1}$]</td>
<td>$2 \times 10^{26}$</td>
<td>$1.4 \times 10^{31}$</td>
</tr>
<tr>
<td>Interaction rates</td>
<td>$1.4 \times 10^{3}$ s$^{-1}$</td>
<td>$3 \times 10^{5}$ s$^{-1}$</td>
</tr>
</tbody>
</table>

Ions: $A = 1 \sim 200$, pp, pA, AA, AB

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Relativistic Heavy Ion Collider and Experiments
Ultra-Relativistic Heavy Ion Collisions to Melt the Vacuum

General Orientation
Hadron (baryons, mesons) masses ~ 1 GeV
Hadron sizes ~ $10^{-15}$ meters (1 fm ≡ 1 fermi)

Gold nucleus diameter = 14 fm

RHIC Collisions
\[ E_{\text{cm}} = 200 \text{ GeV/nn-pair} \]
Total \( E_{\text{cm}} = 40 \text{ TeV} \)
Space-time Evolution of RHIC Collisions

Hard Scattering + Thermalization ($< 1$ fm/c)

QGP ($\sim$ few fm/c)

Expansion

Hadronization

Freeze-out ($\sim$ 10 fm/c)

$\gamma$, e, $\phi$, jet, p, K, $\pi$, $\mu$, $\Lambda$
Initial Observations:

Large produced particle multiplicities
ed. - “less than expected! → gluon-saturation?”

\[ \frac{dn_{ch}}{d\eta} \bigg|_{\eta=0} = 670, \ N_{\text{total}} \sim 7500 \]

> 15,000 q +\bar{q} in final state, > 92% are produced quarks

Large energy densities (\( \frac{dn}{d\eta}, \frac{dE_T}{d\eta} \))

\[ \varepsilon \geq 5 \ \text{GeV/fm}^3 \]

\[ \varepsilon \geq 5 - 15 \varepsilon_{\text{critical}} \]

30 – 100 x nuclear density

Large collective flow
ed. - “completely unexpected!”

Due to large early pressure gradients, energy & gluon densities

Requires hydrodynamics and quark-gluon equation of state

Quark flow & coalescence → constituent quark degrees of freedom!

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How do RHIC Collisions Evolve?

1) Superposition of independent p+p:

momenta random relative to reaction plane
How do RHIC Collisions Evolve?

1) Superposition of independent p+p:
   momenta random relative to reaction plane

2) Evolution as a **bulk system**
   Pressure gradients (larger in-plane) push bulk “out” → flow
   more, faster particles seen in-plane

High density pressure at center

“zero” pressure in surrounding vacuum
1) Superposition of independent p+p:

momenta random
relative to reaction plane

2) Evolution as a **bulk system**

Pressure gradients (larger in-plane)
push bulk “out” \(\rightarrow\) flow

more, faster particles
seen in-plane

**Azimuthal Angular Distributions**
On the First Day at RHIC - Azimuthal Distributions

STAR, PRL\textbf{90} 032301 (2003)

 normalized counts

- $b \approx 6.5$ fm
- $b \approx 4$ fm

Centrality collisions

Top view

Beams-eye view

John Harris (Yale)
On the First Day at RHIC - Azimuthal Distributions

STAR, PRL 90 032301 (2003)

Peripheral collisions

Top view

Beams-eye view

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Early Pressure in System
→ Elliptic Flow!

Sufficient interactions early (< 1 fm/c) in system
→ to respond to early pressure!
→ before self-quench (insufficient interactions)!
System is able to convert original spatial ellipticity
→ momentum anisotropy!
Sensitive to early dynamics of system

Hydrodynamic calculation – beam view
Elliptic Flow Saturates
Hydrodynamic Limit

• Azimuthal asymmetry of charged particles:
  \[ \frac{dn}{d\phi} \sim 1 + 2 v_2(p_T) \cos(2\phi) + \ldots \]

Mass dependence of \( v_2 \)
 Requires -

• Early thermalization (0.6 fm/c)
• Ideal hydrodynamics (zero viscosity)
  → “nearly perfect fluid”
• \( \varepsilon \sim 25 \text{ GeV/fm}^3 \) (\( \gg \varepsilon_{\text{critical}} \))
• Quark-Gluon Equ. of State
Complicated $v_2(p_T)$ flow pattern is observed for identified hadrons
\[ \frac{d^2n}{dp_Td\phi} \sim 1 + 2 v_2(p_T) \cos(2\phi) \]
**Hadron Elliptic Flow Reflects Quark Flow**

Complicated $v_2(p_T)$ flow pattern is observed for identified hadrons

$$d^2n/dp_Td\phi \sim 1 + 2 v_2(p_T) \cos (2 \phi)$$

If the flow is established at the quark level, it is predicted to be *simple*

when $p_T \rightarrow p_T/n$, $v_2 \rightarrow v_2/n$, $n = (2, 3$ quarks$)$ for (meson, baryon)

15000 quarks flow collectively
**Quark-number Scaling**

Hadronization - a soft process
- modified by changes in running coupling at low $Q^2$.

Simple hadronization model –
- quark $v_2$ related to hadron $v_2$ via

$$v_2^q = v_2^h (p_T/n)/n,$$

$n$ is number of quarks in hadron

⇒ implies $v_2$ is developed before hadronization

⇒ model implies deconfinement
If baryons and mesons form from independently flowing quarks then quarks are deconfined for a brief moment (~ $10^{-23}$ s), then hadronization!
Transport in gases of strongly-coupled atoms

RHIC fluid behaves like this – 

*a strongly coupled fluid.*

Universality of classical strongly-coupled systems?
→ Atoms, sQGP, AdS/CFT…….
Quantum lower viscosity bound: $\eta/s > 1/4\pi$  (Kovtun, Son, Starinets)

From strongly coupled $N = 4$ SUSY YM theory.

2-d Rel Hydro describes STAR $v_2$ data with $\eta/s \leq 0.1$ near lower bound!

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Ultra-low Viscosity Fluids

“A test comes from RHIC... A preliminary analysis of the e+e- experiments indicates that the collisions are creating a fluid with very low viscosity.”

Black holes have an extremely small shear viscosity - smaller than any known fluid... Strongly interacting quarks and gluons at high T should also have a very low viscosity.”

By Juan Maldacena

The Illusion of Gravity

The force of gravity and one of the dimensions of space might be generated out of the peculiar interactions of particles and fields existing in a lower-dimensional realm

By Juan Maldacena

John Harris (Yale) ISSP’06 Erice, Sicily, Italy, 29 Aug – 7 Sep 2006
“The RHIC fluid may be the least viscous non-superfluid ever seen”

The American Institute of Physics announced the RHIC quark-gluon liquid as the top physics story of 2005!

see http://www.aip.org/pnu/2005/