Soft Probes Program at RHIC

Collective Flow and Fluctuations
Extracting QGP Transport Properties
Beam Energy Scan
Emergent effects of the QCD Vacuum
STAR Upgrades

Paul Sorensen
Two Features of QCD: Asymptotic Freedom and Confinement

Asymptotic Freedom:
• at short length scales coupling between charges is weak
• QCD tested with perturbative calculations at large energies

Although particle physicists tend to dwell on the energy frontier, RHIC was built to study the Confinement/Deconfinement transition (~165 MeV)

"Folks we need to stop testing QCD and start understanding it”

Y. Dokshitzer
Thermodynamics of QCD

Quantum Chromodynamics shows a rapid crossover to QGP: \( \frac{\varepsilon}{T^4} (\propto \# \text{ degrees-of-freedom}) \) plateaus when quarks and gluons start to become the relevant degrees of freedom.

Hadron Gas:
maximum T

QGP: no maximum
adding energy increases T, instead of creating heavier hadrons

The transition region (not the asymptotic limit) is of most interest
Expansion of the Little Bangs
Fireball is $\sim10^{-15}$ meters across and lives for $\sim5\times10^{-23}$ seconds
Collectivity in the Expansion

Collective expansion converts spatial asymmetries into momentum space

\[ \frac{dN}{d\varphi_n} \propto 1 + 2 \sum_n v_n \cos n \varphi_n \]

\[ v_2 = \langle \cos 2\varphi_2 \rangle \]

Discovery of a Perfect Liquid QGP at RHIC
Major Experimental Advances

First years of Au+Au
→ Perfect liquidity
→ Suppression of high $p_T$ particles

First d+Au Run
→ Opacity of the plasma phase
→ Evidence of gluon saturation

First run with Cu+Cu
→ Importance of fluctuations

Principal axis transformation

Smaller system revealed importance of fluctuations
Near perfect liquidity renders initial state quantum fluctuations experimentally accessible (the system remembers)

These are more detailed views of the initial conditions

Kowalski, Lappi and Venugopalan, Phys.Rev.Lett. 100:022303


We study the initial fluctuations the same way as cosmologists

Gluon density with subhadronic fluctuations
The Big Bang vs the Little Bangs

The Universe

- Afterglow Light Pattern 400,000 yrs.
- Inflation
- Quantum Fluctuations
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion

WMAP

1st Stars about 400 million yrs.

Big Bang Expansion 13.7 billion years

Credit: NASA

HIC

- QGP phase
- Quark and gluon degrees of freedom
- Lumpy initial energy density
- Hadronization
- Kinetic freeze-out
- Distributions and correlations of produced particles

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STAR Preliminary; QM2010

WMAP

- Multipole moment
- Temperature fluctuations [μK]

RHIC

- $v_2(n)^2 (0-2.5\% \text{ Central})$
- Charge-Independent
- $\sigma_0=0.63\pm0.02$
- $\sigma_0=0.61\pm0.01$
- Like-Sign
- $\sigma_0=1.42\pm0.1$
- $\sigma_0=0.72\pm0.07$
A Standard Model for Little Bangs

Initial state including geometric and quantum fluctuations from 1st principles

Low $\eta/s$ plasma phase modeled by hydro


Viscous damping of large n

Relativistic Viscous Hydro: effective theory studied at 1st and 2nd order, shown to converge

Hadronic phase and freezeout

Compare to experiment
With inclusion of sub-nucleonic quantum fluctuations:
→ outstanding agreement between data and model

Perfect liquidity reveals correlations in the gluon fields of size $1/Q_s$ (sub-hadronic)! How do these structures evolve with energy and rapidity?

Theory developments are still being guided by experimental discoveries.
Model doesn’t distinguish between a constant $\eta/s$ or a temperature dependent $\eta/s$ with a minimum of $1/4\pi$ at $T_C$

Temperature dependence can’t be accessed with the LHC alone.
**Requires full analysis across a range of initial energy densities**
Beam Energy Scan

Vary the initial temperature, energy density and baryon density

Search for phase boundaries, QGP turning off

Search for Critical Point and 1st order phase transition line

Study variation of transport properties, and the equation of state
An understanding of the emergent properties of QCD requires broad coverage of Temperature, and baryon density and an experimental tool box sufficient to characterize the events.
Beam Energy Scan Phase I (Tool Box)

Evidence of phase boundary at lowest energies, but full understanding is precluded by small statistics → BESII
Search for Critical Point Fluctuations

Disappearance of Evidence for Parity Violation

Drop in Momentum Fluctuations ($\delta T/T$?)

Evidence of phase boundary at lowest energies, but full understanding is precluded by small statistics → BESII
### Beam Energy Scan Phase II

We know what to measure but need more statistics

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$\mu_B^*$ (MeV)</th>
<th>BES-I</th>
<th>BES-II</th>
<th>Driving Phys.</th>
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<tr>
<td>200</td>
<td>24</td>
<td></td>
<td>0.5-2 (B)</td>
<td>Heavy flavor hadron $v_2$ &amp; $R_{AA}$</td>
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<tr>
<td>39</td>
<td>112</td>
<td>130 (M)</td>
<td></td>
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<tr>
<td>27</td>
<td>156</td>
<td>70 (M)</td>
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<tr>
<td>19.6</td>
<td>206</td>
<td>36 (M)</td>
<td>400 (M)</td>
<td>LMR di-electron**, net-p $\kappa &gt; 5\sigma$</td>
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<tr>
<td>15</td>
<td>250</td>
<td></td>
<td>100 (M)</td>
<td>$\Omega$ yield, $\phi$-meson $v_2 \leq 3$GeV/c)</td>
</tr>
<tr>
<td>11.5</td>
<td>316</td>
<td>12 (M)</td>
<td>120 (M)</td>
<td>net-p $\kappa$</td>
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<tr>
<td>7.7</td>
<td>420</td>
<td>5 (M)</td>
<td>80*** (M)</td>
<td>net-p $\kappa$</td>
</tr>
</tbody>
</table>

* Central Collisions  
** No di-electron measurements below 19.6 GeV  
*** With e-cooling, six weeks beam time allows to collect about 100M Au+Au collision events

Program requires electron cooling upgrade (x10 improvement in luminosity)  
Timescale 2017
Three Particle Correlations

Convincing description of 3-particle correlations at 200 GeV and 2.76 TeV
→overconstrains models; intricate test
→alternative extraction of viscosity and transport properties

Large data sets needed for global analysis at all beam energies
Chiral Magnetic Effect in 3-P Correlations?

Local Parity Violating Regions

The topological charge density

Animation by Derek Leinweber

Or does the charge separation occur at the phase boundary?

Major motivation for U+U collisions

Central U+U, B-Field goes away but major background sources remain

Also: varying isotopes (fix A, vary Z)

Emergent effects of the QCD Vacuum

Deformation of U enhances the sensitivity to details of the modeling → reveals the limitations of previous modeling initiating new theoretical efforts

Varying the initial geometry as a control: a scientific obligation that can only be provided by RHICs flexibility (made possible by RHICs EBIS upgrade in 2011)
STAR Upgrade Plans

Forward GEM Tracker (2013) in process
Spin physics with W’s: flavor dependence of sea quark polarization

Heavy Flavor Tracker (2014) in process
Measurement of open heavy flavor hadrons for heavy quark interactions in the QGP: QGP transport properties

Muon Telescope Detector (2014) in process
Muon trigger for Quarkonium: screening lengths in the QGP

Inner TPC Upgrade (2017) ~$3-4M
Expands coverage to higher rapidity and lower p_T
esential for studying glue (eRHIC) and major enhancement of all of STAR’s future physics programs: long range correlations

Forward Upgrades (2017 onward) ~$10-20M
Very Forward Gem Tracker, Forward Calorimetry System: studying the gluon dynamics of saturation; leading up to eRHIC

PHENIX upgrades will be discussed by Y. Akiba
A Rich Bulk Probes Program

Exploit perfect fluidity to image gluon fields, spectrum of initial quantum fluctuations, topological charge, at a variety of collision energies

Exploit flexibility of RHIC: U+U, Cu+Au, Pb+Pb, isotopes, \( \bar{p} + A \) to test models in a challenging environment

Exploit reach of RHIC to vary baryon density, energy density, isospin, Bjorken x
Conclusions

RHIC collisions create conditions similar to those present one microsecond after the Big Bang
- Near perfect liquid-like QGP discovered: un-anticipated result opened new possibility to study fluctuations in gluon fields at different scales
- Approaching a level of clarity and a standard model of heavy-ion collisions leading to well constrained parameters like viscosity etc. (*Required many data sets and working out what models and effects are most relevant*)

RHIC paradigms confirmed by LHC
- But RHIC covers the region of most interest for QCD thermodynamics
- Heavy-ion physics is not energy frontier physics: Bulk phenomena (accessible at RHIC) remain key to our field

Experimental results continue to guide theory breakthroughs
Flexibility and reach of RHIC is unique and extremely valuable
Future progress requires continued studies at RHIC: RHIC is in mid-stride