Summary and Future of Heavy Ion Physics

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10th Taro Tamura Symposium
UT Austin - 22 November 2008
The Present in the Light of the Past
Clairvoyance - NSAC style

Note what’s missing:

- Jet quenching
- Elliptic flow
- Quark recombination
- Shear viscosity
- Critical point
- .....  

If Shoji Nagamiya could not predict the future of heavy ion physics accurately, why would you expect me to do so ??
Was van Hove right?

Signal of a phase transformation:

S-shaped relationship between $<p_T>$ and energy density or entropy, where the flat region spans the domain in which frozen degrees of freedom (color) are unthawed.
QCD critical point

Critical point located near chemical freeze-out line look for signals based on hadrochemistry
Chemical tracers

Hadrochemistry is already put to good use to demonstrate that the “hard” ridge is composed of bulk matter not jet fragments.

Strange quarks are chemically equilibrated at hadronization of the quark-gluon plasma.

\[ p_T^{\text{trig}} > 4.0 \text{ GeV/c} \]
\[ 2.0 < p_T^{\text{Assoc}} < p_T^{\text{trig}} \]

Strange quark saturation

\[ \gamma_s \]

\[ \langle N_{\text{part}} \rangle \]

\[ \text{STAR Preliminary} \]

Jun Takahashi SQM 2008
Charming facts

What does $T_s(\psi) = T_s(\Omega)$ tell us?

$|y| < 0.35$

$1.2 < |y| < 2.2$

$J/\psi$ not more suppressed (at $y \approx 0$) than at SPS $\downarrow$ coalescence mechanism?
Seeing is (not?) believing

Not seeing is ... believing!
Let there be light...

**Fit results**

<table>
<thead>
<tr>
<th>Cent.</th>
<th>dN/dy(p_T&gt;1GeV/c)</th>
<th>T(MeV)</th>
<th>$\chi^2$/DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20%</td>
<td>$1.10\pm0.20\pm0.30$</td>
<td>$221\pm23\pm18$</td>
<td>3.6/4</td>
</tr>
<tr>
<td>20-40%</td>
<td>$0.52\pm0.08\pm0.14$</td>
<td>$215\pm20\pm15$</td>
<td>5.2/3</td>
</tr>
<tr>
<td>MB</td>
<td>$0.33\pm0.04 \pm0.09$</td>
<td>$224\pm16\pm19$</td>
<td>0.9/4</td>
</tr>
</tbody>
</table>
AdS/CFT

\[ L > L_{\text{max}} \]

\[ L_{s}^{SAdS}(\theta = \pi / 2) \sim \frac{1}{\pi T} (1 - v^2)^{0.22} \]
Au+Au collisions at RHIC

Entropy:

From 0 to \((dS/dy=)\) 5000 in 0.000 000 000 000 000 000 000 000 002 seconds
Final entropy

Bjorken’s formula

\[ s(\tau) \sim \frac{dN(\tau) / dy}{dV(\tau) / dy} \leq \frac{(dN / dy)_{\text{final}}}{\pi R^2 \tau} \]

Phase space analysis (Pal & Pratt):

\[ \left. \frac{dS}{dy} \right|_{\text{final}} = \sum_i \int \frac{d^3r d^3p}{(2\pi)^3 dy} \left[ -f_i \ln f_i \pm (1 \pm f_i) \ln(1 \pm f_i) \right] \]

\[ = 5600 \pm 500 \quad \text{[for 6\% central Au+Au @ 200]} \]

Chemical analysis (BM & Rajagopal):

\[ \left. \frac{dS}{dy} \right|_{\text{final}} = \sum_i (S / N)_i \frac{dN_i}{dy} = 5100 \pm 200 \quad \text{[for same cond.]} \]

Assuming isentropic expansion up to \( T_{\text{ch}} \), averaging over \( \pi R^2 \) with \( R = 7 \text{ fm} \), and using lattice EOS:

\[ s(\tau_0 = 1 \text{ fm/c}) \approx 33 \text{ fm}^{-3} \rightarrow T(\tau_0) \approx 300 \text{ MeV} \]

How is this entropy produced?
Entropic history

\[ \frac{dS}{dy} = 0 \quad 1500 \quad 4500 \quad 5100 \quad 5600 \]

- Decoherence
- Equilibration
- Isentropic expansion
- Freeze-out

\[ \tau_{\text{deco}} \quad \tau_{\text{therm}} \quad \tau_{\text{hadro}} \]

- pQCD+CGC
- pQCD+HTL
- hydrodynamics

\[ \frac{1}{Q_s} \quad 0.5-2 \text{ fm/c} \ ?! \]
Initial state

\[ \approx \frac{1}{Q^2} \]

\[ \Rightarrow Q_s^2(x, A) \]

gluon density \( \times \) area \( \sim \frac{A^{1/3} x^{-0.3}}{Q_s^2} \approx 1 \)

Universal saturated state at small \( x \): \( Q_s >> \Lambda_{QCD} \)

Gribov, Levin, Ryskin ’83
Blaizot, A. Mueller ’87
McLerran, Venugopalan ‘94

From CGC to Glassma
Inflation of complexity

- Apparent (i.e. coarse grained) entropy can be created by two main mechanisms:
  - by information loss to the “environment”;
  - by information loss due to unresolvable growth in the complexity of the system (“complexity inflation”).

- Here we are interested in the latter.

- Complexity grows due to instability and exponential growth of (quantum) fluctuations in certain directions of phase space.

- A simple example is the inverted oscillator: \( V(x) = -\frac{1}{2} \lambda x^2 \).
Decay of an unstable “vacuum state” is a common problem, e.g., in cosmology and in condensed matter physics. Paradigm case: “roll-over”.

\[
\hat{H}(t) = \frac{p^2}{2} + \frac{m(t)^2}{2} x^2
\]

with \( m^2(t) = m^2 \theta(-t) - \mu^2 \theta(t) \)
Wigner function

\( t = 0 \)

\( t = 0.5 \)

\( t = 1 \)

\( t = 2 \)
Husimi transform

- Idea (**Husimi** - 1940): Smear the Wigner function with a Gaussian minimum-uncertainty wave packet:

\[ H_\Delta(p, x; t) \equiv \int \frac{dp'}{\pi \hbar} \frac{dx'}{2\pi \hbar} \exp \left( -\frac{1}{\hbar\Delta} (p - p')^2 - \frac{\Delta}{\hbar} (x - x')^2 \right) W(p', x'; t) \]

- \( H(p, x) \) can be shown to be the square of a matrix element between the quantum state and a coherent oscillator state, and thus to be never negative!

- \( H(p, x) \) can therefore be considered as a probability density, enabling the defining of an entropy (**Wehrl** - 1978):

\[ S_{H, \Delta}(t) = -\int \frac{dp}{2\pi \hbar} \frac{dx}{2\pi \hbar} H_\Delta(p, x; t) \ln H_\Delta(p, x; t) \]
Wigner vs. Husimi

Wigner function

$t = 0$

$\text{Husimi function}$

$t = 0$

$t = 2$

$t = 2$
Several unstable modes:

\[
\frac{dS_{H,\Delta}}{dt} = \sum_k \frac{\lambda_k \sinh 2\lambda_k t}{\cosh 2\lambda_k t + (1 + \delta \delta') \sigma^{-1} \rho^{-1}} \quad \text{as } t \to \infty \quad \sum_k \lambda_k \quad \text{(independent of } \hbar \text{ !)}
\]

This is the Kolmogorov-Sinai (KS) entropy \( h_{KS} \) known from classical dynamical system theory.

KS-entropy describes the growth rate of the entropy for a coarse grained phase space density in the approach toward ergodic equilibrium.

[see e.g.: Latora & Baranger, PRL 82 (1999) 520.]

Challenge: Application to QCD.

Entropy growth starting from CGC fields.
Jets and the QGP
Energy lost

\[ \frac{\Delta E_{\text{dyn}}}{E} = \frac{C_R \alpha_s}{\pi} \frac{L}{\lambda_{\text{dyn}}} \int \frac{d^2k}{\pi} \frac{d^2q}{\pi} \frac{\mu^2}{q^2(q^2 + \mu^2)} \left( \frac{k}{k^2 + \chi} - \frac{k+q}{(k+q)^2 + \chi} \right)^2 \]

\[ = \frac{\Delta E_{\text{magnetic}}}{E} + \frac{\Delta E_{\text{electric}}}{E} \]

\[ \hat{q} \ (\text{GeV}^2/\text{fm}) \] for gluons

<table>
<thead>
<tr>
<th>scaling</th>
<th>ASW</th>
<th>HT</th>
<th>AMY</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T )</td>
<td>10</td>
<td>2.3</td>
<td>4.1</td>
</tr>
<tr>
<td>( \varepsilon^{3/4} )</td>
<td>18.5</td>
<td>4.5</td>
<td>-</td>
</tr>
</tbody>
</table>
Connecting jets with the medium

Hard partons probe the medium via the density of colored scattering centers:

\[ \hat{q} = \rho \int q^2 dq^2 \left( \frac{d\sigma}{dq^2} \right) \sim \int dx^- \left\langle F_{1+}^+(x^-) F_{1+}^-(0) \right\rangle \]

If kinetic theory applies, thermal gluons are quasi-particles that experience the same medium. Then the shear viscosity is:

\[ \eta \approx \frac{1}{3} \rho \left\langle p \lambda_f(p) \right\rangle = \frac{1}{3} \left\langle \frac{p}{\sigma_{tr}(p)} \right\rangle \]

In QCD, small angle scattering dominates:

\[ \sigma_{tr}(p) \approx \frac{2\hat{q}}{\langle p \rangle^2} \rho \]

With \( \langle p \rangle \sim 3T \) and \( s \approx 3.6\rho \)
(for gluons) one finds:

\[ \frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}} \]

“Perfect” is not what it used to be

v$_2$ still 30% below ideal hydro limit at $b = 0$ ...

... but may help resolve the RHIC HBT puzzle

<table>
<thead>
<tr>
<th>Data STAR</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta R_c/\Delta R_s$</td>
<td></td>
</tr>
<tr>
<td>C=20-30%</td>
<td>R/\lambda = 3.7</td>
</tr>
<tr>
<td>$P_T = 0.15-0.25$ GeV</td>
<td>R/\lambda = 3.1</td>
</tr>
<tr>
<td>1.17+-0.064</td>
<td></td>
</tr>
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<td>C=10-20%</td>
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</tr>
<tr>
<td>$P_T = 0.35-0.45$ GeV</td>
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</tr>
</tbody>
</table>

STAR measures $\eta/s$
Where is RHIC?

\( \frac{1.25 T^3}{\hat{q}} \approx \begin{cases} 
0.145 & \text{(AMY, HT)} \\
0.03 - 0.04 & \text{(ASW)} 
\end{cases} \)

at \( T \approx 400 \text{ MeV} \)

\( \frac{\eta}{s} = 0.134(33) \) (H.Meyer)

at \( T = 1.65 T_c \approx 300 \text{ MeV} \)

(quenched QCD)

\( \eta/s \sim \frac{\eta}{s} \approx \frac{1.25 T^3}{\hat{q}} \)

\( \frac{1}{g_{\text{eff}}} \sim \ln T \)
From rag(gednes)s to ridges

Minijets make the initial energy density distribution remarkably grainy.

Do their traces survive in correlations?
Minijets - vestigia terrent?

**Peak Amplitude**

\[ \frac{\hat{A} \bar{n}}{\sqrt{n_{\text{ref}}}} \]

STAR Preliminary

200 GeV

62 GeV

**Peak Width**

\[ \gamma \]

STAR Preliminary

constant widths

\[ N_{\text{part}} = 135 \]

\[ N_{\text{part}} = 35 \]
A question is raised

- Is the creation of collective transverse flow (including its quadrupole component $v_2$) a “bottom-up” process, i.e. the blue-shift of the thermal distribution due to the action of the internal pressure,

or

- Is the creation of collective transverse flow (including its quadrupole component $v_2$) a “top-down” process, caused by the gradual absorption of the minijet component into the tail of the thermal distribution?

- What would be an appropriate “macroscopic” description of such a (not near-equilibrium) process?
Jet-medium interaction

Mach cone

ridge

Low $p_T$

Suppressed jet + cone

Jet + ridge

Dissipation of lost energy in medium
Parton-medium coupling

\[ \left[ \frac{p^\mu}{E} \frac{\partial}{\partial x^{\mu}} - \nabla_p \cdot D(x,p) \cdot \nabla_p \right] f_0(x,p) = C \left[ f_0 \right] \]

with

\[ D_{ij}(x,p) = \int_{-\infty}^{t} dt' F_i(\vec{x},t) F_j(\vec{x} + \vec{v}(t' - t), t') . \]

\[ \frac{\partial}{\partial x^{\mu}} T^{\mu\nu} = J^{\nu} \]

Space-time distribution of collisional energy loss

with

\[ T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu} + T_{\text{diss}}^{\mu\nu} \]

\[ J^{\nu} = \int d\mathbf{p} \ p^\nu \nabla_p \cdot D(x,p) \cdot \nabla_p f(x,p) \]

Color field of moving parton interacts with the quanta of the medium
Energy density

$J^0(\rho, z)\ \text{unscreened}$

$J^0(\rho, z)\ \text{screened}$

$u = 0.99$
Linearized hydro

Linearize hydro eqs. for a weak source: \( T^{00} \rightarrow \varepsilon_0 + \delta \varepsilon, \ T^{0i} \rightarrow g^i \).

\[
\begin{align*}
\frac{\partial}{\partial t} \delta \varepsilon + \nabla \cdot \bar{g} &= J^0 \\
\frac{\partial}{\partial t} \bar{g} + c_s^2 \nabla \delta \varepsilon + \frac{\eta}{\varepsilon_0 + p_0} \frac{4}{3} 
abla (\nabla \cdot \bar{g}) &= \bar{J}
\end{align*}
\]

Solve in Fourier space for longitudinal sound:

\[
\delta \varepsilon = i \left( \frac{\omega + i \Gamma_s k^2}{\omega^2 - c_s^2 k^2 + i \Gamma_s \omega k^2} \right) J^0 + k J_L
\]

\[
g_L = i \left( \frac{c_s^2 k J^0 + \omega J_L}{\omega^2 - c_s^2 k^2 + i \Gamma_s \omega k^2} \right)
\]

\[
z\ \text{and dissipative transverse perturbation:}
\[
g_T = i \frac{J_T}{\omega + \frac{3}{4} i \Gamma_s k^2}
\]

Use: \( u = 0.99955 c, \quad c_s^2 = \frac{1}{3}, \quad \Gamma_s = \frac{1}{3\pi T} \) for \( T = 350 \text{ MeV} \).
pQCD vs. $N=4$ SYM

$u = 0.99955 \, c$

Neufeld et al.
arXiv:0802.2254

$u = 0.75 \, c$

Chesler & Yaffe
arXiv:0712.0050
The ultimate Crescendo

Radiative energy loss $>>$ collisional energy loss, but only collisions deposit energy into the plasma. However, radiated gluons contribute to the sound source:

The “soloist” becomes a chamber “orchestra”!

Gluon “swarm” grows $\sim L^2$ and dominates after $L \approx 2$ fm

This could explain why experiments only show sound velocity $c_s = 0.3$ corresponding to $T_c$. 

R.B. Neufeld
The Future is almost here!
Detector upgrade

STAR

- forward meson spectrometer
- DAQ & TPC electronics
- Time of Flight barrel
- heavy flavor tracker
- barrel silicon tracker
- forward tracker

PHENIX

- completed – hadron blind detector
- ongoing
- muon Trigger
- silicon vertex barrel (VTX)
- in preparation
- forward silicon
- forward EM calorimeter
Energy upgrade

LHC

CMS

ALICE

ATLAS
Experimental and theoretical surprises have opened a gold mine for theorists, but to extract the gold, painstaking work will be required in collaboration between theorists and experimentalists.

The first steps have been taken:

For report and details see:

https://wiki.bnl.gov/TECHQM/index.php/Main_Page

Next TECHQM workshop: LBNL 15-17 December 2008
Ultimate success of the RHIC program requires:

- precision data for key (often rare) observables;
- continued progress of our understanding of thermal QCD;
- sustained collaboration between theorists and experimentalists on precision data interpretation.

Superficially different observables (flow, jet quenching, two-particle correlations) are connected at a deep level.

Their exploration in a comprehensive framework will lead to deep insights into how bulk QCD matter behaves and, ultimately, to the fulfillment of the scientific promise of RHIC.

The LHC heavy ion program will open up new opportunities, due to its extended kinematic range for critical observables.