Some Like It Hot: Boiling the QCD Vacuum
At RHIC and LHC

Berndt Müller

Emilio Segre Lecture in Physics
Tel Aviv University - May 29, 2011
Hot, hotter, hottest …
Hot, hotter, hottest …

Hollywood
Hot, hotter, hottest …

Hell

Hollywood

“Oh, man! The coffee’s cold! They thought of everything!”
Hot, hotter, hottest …

Hollywood

“Oh, man! The coffee’s cold! They thought of everything!”

Hell

Nucleons + mesons

Quark-gluon plasma

Quark matter
Part 1

The Hottest Stuff on Earth
Heating Things Up

- What heat does to matter:
  - Increases disorder (entropy)
  - Speeds up reactions
  - Overcomes potential barriers

- States / phases of matter:
  - **Solid** [long-range correlations, shear elasticity]
  - **Liquid** [short-range correlations]
  - **Gas** [few correlations]
  - **Plasma** [free charges] (solid / liquid / gaseous)
  - **Quark matter / quark-gluon plasma** [free color charges] (liquid)
QCD phase diagram

Critical end point

1st order line

Chiral symmetry broken

Chiral symmetry restored

Color superconductor

RHIC

T

Quark-Gluon

Hadronic matter

Plasma

Nuclei

Neutron stars

μB

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QCD phase diagram

Hadronic matter

Critical end point

1st order line

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Chiral symmetry broken

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Color superconductor

LHC

RHIC

T

Nuclei

Neutron stars

μB
QCD phase diagram

- LHC
- RHIC
- RHIC beam energy scan

- Quark-Gluon
- Hadronic matter
- Plasma

- Critical end point
- 1st order line
- Chiral symmetry broken
- Chiral symmetry restored
- Color superconductor

Nuclei → Neutron stars

μB
QCD equation of state

Degrees of freedom: \[ v = \left[ (2 \times 8) + \frac{7}{4} \times (2 \times 3 \times N_f) \right] \times \left( 1 - O(g^2) \right) \]

Indication of weak or strong coupling?
QCD equation of state

Degrees of freedom:
\[ n = \left[ (2 \times 8) + \frac{7}{4} \times (2 \times 3 \times N_f) \right] \times \left( 1 - O(g^2) \right) \]

\[ \frac{\pi^2}{30} n = 16.0 \]

Lattice QCD

Indication of weak or strong coupling?

3 flavor, \( N_c = 4 \), p4 staggered

RHIC

LHC

\[ \varepsilon_{SB}/T^4 \]

\[ \frac{3p}{T^4} \]

\[ \frac{(3/4)s}{T^3} \]
Color screening

$-\nabla^2 \phi^a = g \rho^a_G(\phi^b) + g \rho^a_Q(\phi^b)$

Induced color density $\rho^a = -\mu^2 \phi^a$

with $\mu^2_G = (gT)^2$, $\mu^2_Q = \frac{N_F}{6} (gT)^2$

Static color charge (heavy quark) generates screened potential

$\phi^a = t^a \frac{\alpha_s}{r} e^{-\mu r}$
Quark masses

The diagram illustrates the mass distribution of quarks and the Higgs field. The vertical axis represents the mass in units of $10^m$, where $m$ ranges from 0 to 6. The horizontal axis lists the quark flavors: u, d, s, c, b, and t. The graph shows that the quark masses increase from u to t, with the Higgs masses being significantly lower for all flavors. The quark condensate is indicated by the notation $\langle q\bar{q} \rangle$. The Higgs field is represented by a blue circle, and the quark condensate is depicted by a yellow circle with the notation $\langle q\bar{q} \rangle$.
Quark masses

Heat “melts” the quark condensate:
QCD mass disappears above $T_c$.
(Partial) chiral symmetry restoration
Lattice QCD - 2010

Wuppertal - Budapest Coll.

Graphs showing the behavior of different parameters as a function of temperature in the context of lattice QCD.
Below $T_c$ - the HRG

Lines: Hadron resonance gas (HRG)

Data points: Lattice QCD (Wu-Bu)

LQCD lies above HRG for $T > 140$ MeV
Below $T_c$ - the HRG

Lines: Hadron resonance gas (HRG)

Data points: Lattice QCD (Wu-Bu)

LQCD lies above HRG for $T > 140$ MeV

Hadrons up to at least 2.5 GeV (maybe 3 GeV) mass contribute

$m_{cut} = 1.7$ GeV

$m_{cut} = 2.0$ GeV

$m_{cut} = 2.5$ GeV

$m_{cut} = 3.0$ GeV
When the Universe was hot...
When the Universe was hot...

Arrow of time

- Quarks gain QCD mass and become confined.
The practical path to the QGP…

…is hexagonal and 3.8 km long

Relativistic Heavy Ion Collider
The practical path to the QGP... is hexagonal and 3.8 km long

Relativistic Heavy Ion Collider
Toward higher energies...
Toward higher energies...
Space-time picture

Pre-equil. phase

Liberation of saturated low-x glue fields (CGC)

\( \tau_{eq} \approx 1 \text{ fm/c} \)

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

RHIC:
- \( s_0 \approx 33 \text{ fm}^{-3} \)
- \( T_0 \approx 275 \text{ MeV} \)

LHC:
- \( s_0 \approx 75 \text{ fm}^{-3} \)
- \( T_0 \approx 360 \text{ MeV} \)

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Chemistry

Chemical freeze-out line

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Freeze-out conditions

Kinetic freeze-out
Probes of hot QCD matter

Which properties of hot QCD matter can we hope to determine from relativistic heavy ion data (RHIC and LHC, maybe FAIR) ?

\[ T_{\mu\nu} \Leftrightarrow \varepsilon, p, s \]

**Equation of state**: spectra, coll. flow, fluctuations

\[ c_s^2 = \frac{\partial p}{\partial \varepsilon} \]

**Speed of sound**: multiparticle correlations

\[ \eta = \frac{1}{T} \int d^4x \langle T_{xy}(x)T_{xy}(0) \rangle \]

**Shear viscosity**: anisotropic collective flow

\[ \hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F^{a+i}_{-i} (y^-) F_i^{a+}(0) \rangle \]

\[ \hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle i\partial^- A^{a+}(y^-) A^{a+}(0) \rangle \]

\[ \hat{e}_2 = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F^{a+ - i} (y^-) F^{a+ - i}(0) \rangle \]

**Momentum/energy diffusion**: parton energy loss, jet fragmentation

\[ m_D = -\lim_{|x| \to \infty} \frac{1}{|x|} \ln \langle E^a(x)E^a(0) \rangle \]

**Color screening**: Quarkonium states
Probes of hot QCD matter

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Color screening: Quarkonium states

\[ m_D = - \lim_{|x| \to \infty} \frac{1}{|x|} \ln \langle E^a(x)E^a(0) \rangle \]

Easy for LQCD
Probes of hot QCD matter

Which **properties of hot QCD matter** can we hope to determine from relativistic heavy ion data (RHIC and LHC, maybe FAIR) ?

**Equation of state**: spectra, coll. flow, fluctuations

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**Shear viscosity**: anisotropic collective flow

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**Color screening**: Quarkonium states
Part 2

The Liquid QGP
Elliptic Flow ($v_2$)

$v_2 = \cos(2\phi)$

coefficient of the azimuthal distribution

Hydrodynamics:
Flow is generated by $\nabla P$

$\nabla P(\leftrightarrow) > \nabla P(\uparrow\uparrow)$
$v_2(p_T)$ vs. hydrodynamics

Hydro model

PHENIX Data

- $\pi^+ + \pi^-$
- $K^+ + K^-$
- $p+p$

STAR Data

- $K_{S0}$
- $\Lambda + \bar{\Lambda}$

Anisotropy Parameter $v_2$

Transverse Momentum $p_T$ (GeV/c)
$v_2(p_T)$ vs. hydrodynamics

Mass splitting characteristic property of hydrodynamics
$v_2(p_T)$ vs. hydrodynamics

Failure of ideal hydrodynamics tells us how hadrons form

Mass splitting characteristic property of hydrodynamics
Bulk hadronization

Fast hadrons experience a rapid transition from medium to vacuum for fast hadrons

Sudden recombination

\[ p_B \approx 3p_Q \]

\[ p_M \approx 2p_Q \]
Bulk hadronization

Fast hadrons experience a rapid transition from medium to vacuum for fast hadrons.

Sudden recombination

\[ p_B \approx 3p_Q \]
\[ p_M \approx 2p_Q \]

\[ v_2^M(p_t) = 2v_2^Q \left( \frac{p_t}{2} \right) \]
\[ v_2^B(p_t) = 3v_2^Q \left( \frac{p_t}{3} \right) \]
Quark number scaling of $v_2$

\[
\frac{1}{2}v_2^M(p_t) = v_2^Q \left( \frac{p_t}{2} \right) \quad \frac{1}{3}v_2^B(p_t) = v_2^Q \left( \frac{p_t}{3} \right)
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\]

Emitting medium is composed of unconfined, flowing quarks.
Quark number scaling of $v_2$

\[ \frac{1}{2} v_2^M (p_t) = v_2^Q \left( \frac{p_t}{2} \right) \]

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Emitting medium is composed of unconfined, flowing quarks.
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QUARK–GLUON PLASMA COOLING THROUGH PION EMISSION IN A CHIRAL BAG MODEL

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Abstract: A hypothetical quark-gluon plasma is described as a large bag, filled with quarks, antiquarks, and gluons, of radius $R \sim 2$–6 fm and temperature $T \sim 100$–250 MeV. We consider the cooling of this plasma through pion emission at the bag surface in a chiral-model approach. Comparison is made between results for a large, spherical bag and a model in the limit in which the plasma fills half of space and pion emission is across a planar interface. We find a rather low initial cooling rate per unit surface area for this mechanism, of roughly $(10$–100) $\times 10^{23}$ MeV/fm$^2$.s. This rate per unit surface becomes independent of $R$ for $R \gtrsim 3$ fm, and, because of the nature of the coupling in the chiral bag model, varies with temperature as $T^6$. 

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Initial state generated in A+A collision is grainy
event plane $\neq$ reaction plane
$\Rightarrow$ eccentricities $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$, etc. $\neq 0$

$\Rightarrow$ flows $v_1, v_2, v_3, v_4, \ldots$
2nd order relat. hydrodynamics

\[ \partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \Pi^{\mu\nu} \]

\[ \tau_{\Pi} \left[ \frac{d\Pi^{\mu\nu}}{d\tau} + \left( u^\mu \Pi^{\nu\lambda} + u^\nu \Pi^{\mu\lambda} \right) \frac{du^\lambda}{d\tau} \right] = \eta \left( \partial^\mu u^\nu + \partial^\nu u^\mu - \text{trace} \right) - \Pi^{\mu\nu} \]

\[ \eta = \text{Shear viscosity} \]

Excellent approximation of Boltzmann transport; negligible uncertainties due to:

- Bulk viscosity
- QCD Equation of state

Main input parameters:

- \( \eta/s \)
- Initial energy density profile
- Equilibration time \( \tau_0 \)
Elliptic flow “measures” $\eta_{\text{QGP}}$

Universal strong coupling limit of non-abelian gauge theories with a gravity dual:

$$\eta/s \to \frac{1}{4}\pi$$

aka: the “perfect” liquid

- $\eta/s = 0$
- $\eta/s = \frac{1}{4}\pi$
- $\eta/s = \frac{2}{4}\pi$
Elliptic flow “measures” $\eta_{\text{QGP}}$

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Consistency check:

Triangular flow
Elliptic flow “measures” $\eta_{\text{QGP}}$

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Consistency check:

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- $\eta/s = 2/4\pi$

Triangular flow
Conclusions agree almost (too ?) perfectly with RHIC.

\( v_n @ \text{LHC} \)
$v_n \ (n = 2, \ldots, 6)$

$v_n$ almost independent of rapidity
Hunting for perfection...
Hunting for perfection...

My best bet 2009

Aihong Tang [STAR] 2009
Hunting for perfection...

Present limits 2011

Aihong Tang [STAR] 2009
The scientific challenge

BY THE TIME I'M EIGHTEEN, I EXPECT THIS WORLD TO BE PERFECT!

WHY SHOULD I HAVE TO LIVE IN A WORLD SOMEBODY ELSE HAS MESSED UP?! I'LL GIVE THEM TWELVE YEARS TO GET EVERYTHING IN ORDER!

WHAT IF THEY NEED MORE TIME?

TELL THEM NOT TO BOTHER WIRING FOR AN EXTENSION... THE ANSWER WILL BE "NO!"

Sunday, May 29, 2011
The scientific challenge

By the time I’m eighteen, I expect this world to be perfect!

Why should I have to live in a world somebody else has messed up?! I’ll give them twelve years to get everything in order!

What if they need more time?

Tell them not to bother wiring for an extension... the answer will be, “No!”

No need to worry, Lucy!

We are very close to proving...

....that the world was once (13.7 x 10⁹ y ago)

a perfect liquid.
Part 3

The opaque QGP
Radiative energy loss

\[ \Delta E \sim \rho L^2 \left\langle k_T^2 \right\rangle \]

\[ \hat{q} = \rho \int q^2 \, dq^2 \, \frac{d\sigma}{dq^2} = \int dx^- \left\langle F_i^+(x^-) F^{+i}(0) \right\rangle \]
Jet quenching in Au+Au

No suppression for photons

Suppression of hadrons

Yield in A+A

\[ R_{AA}(p_T) = \frac{d^2 N_{AA} / dp_T dy}{T_{AA} \left( d^2 \sigma_{NN} / dp_T dy \right)} \]

Area density of p+p coll’s in A+A

Cross section in p+p coll’s

Without nuclear effects:

\[ R_{AA} = 1. \]
Towards measuring $\hat{q}$

Good fits for light hadrons can be obtained for all energy loss models with 3-D hydro evolution, but...

Bass, Gale, Majumder, Nonaka, Qin, Renk & Ruppert
Towards measuring $\hat{q}$

Good fits for light hadrons can be obtained for all energy loss models with 3-D hydro evolution, \textit{but}...

Transport parameter $\hat{q}$ deviates by more than factor 2 between different implementations.

Caused by differences in the cut-offs in collinear approximation used in all implementations of gluon radiation.
Towards measuring $\hat{q}$

Good fits for light hadrons can be obtained for all energy loss models with 3-D hydro evolution, but...

Transport parameter $\hat{q}$ deviates by more than factor 2 between different implementations.

Caused by differences in the cut-offs in collinear approximation used in all implementations of gluon radiation.

Is pQCD the correct theory for jet quenching?
Jet quenching at LHC

Open charm mesons are as much suppressed as light mesons
$Z^0$, photons, hadrons
$Z^0$, photons, hadrons

![Graph showing CMS Preliminary results with $PbPb \sqrt{s_{NN}} = 2.76$ TeV, $\int L \, dt = 7 \, \mu b^{-1}$]
**Di-jets**

- Dijet selection:
  - $|\eta_{\text{Jet}}| < 2$
  - Leading jet $p_{T,1} > 120\text{GeV/c}$
  - Subleading jet $p_{T,2} > 50\text{GeV/c}$
  - $\Delta \phi_{1,2} > \frac{2\pi}{3}$

- Quantify dijet energy imbalance by asymmetry ratio:

$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- Removes uncertainties in overall jet energy scale
Di-jet asymmetry

\[ A_J = \frac{(p_{T,1} - p_{T,2})}{(p_{T,1} + p_{T,2})} \]
Parton shower in matter

**Leading parton:**
Transfers energy to medium by elastic collisions
Radiates gluons scattering in the medium (*inside* and *outside* jet cone)

$$E_L(t) = E_L(t_i) - \int \hat{e}_L dt - \int \omega d\omega d\mathbf{k}_\perp^2 dt \frac{dN_{g}^{med}}{d\omega d\mathbf{k}_\perp^2 dt}$$

**Radiated gluons (vacuum & medium-induced):**
Transfer energy to medium by elastic collisions
Be kicked out of the jet cone by multiple scatterings after emission

$$\frac{df_g(\omega, k_\perp^2, t)}{dt} = \hat{e} \frac{\partial f_g}{\partial \omega} + \frac{1}{4} \hat{q} \nabla_{k_\perp}^2 f_g + \frac{dN_{g}^{med}}{d\omega d\mathbf{k}_\perp^2 dt}$$
ATLAS and CMS data differ in cuts on jet energy, cone angle, etc. ATLAS results depend somewhat on precise cuts and background corrections. Theory fits require 20% different parameters.
$\rho_T$ balance

$\rho_T$ along jet primary axis balances for whole event
Di-jet momentum difference is balanced by low-$p_T$ particles outside a wide cone.
Fragmentation

Subleading jet fragments just like a lower energy jet in $pp$ collisions: jet loses energy, but is unmodified
Part 4

QGP $\cong$ BH ?
To the rescue?

- Perturbative QCD seems to be compatible with some aspects of jet quenching, but not with others:
  - Where are the radiated gluons?
  - How is the lost energy thermalized so quickly?
  - Why do charm quarks lose energy just like light quarks?

- Perturbative QCD is incapable of explaining $\eta/s \leq 1/2\pi$

- Maybe a theory of strong coupling is needed?
  - Toy model: Strongly coupled large-$N_c$ super-Yang-Mills theory
  - Exactly solvable by holographic duality: gravity on AdS$_5$“+”
Gauge-string duality

- AdS$_5$
- String Theory
- SU($N_c$) Gauge Theory

- Exact equivalence at all energies, $N_c$ and $\lambda = g_{YM}^2 N_c$!
Thermal holography

\[
\text{AdS}_5 + \text{BH}
\]

\[
SU(N_c) \text{ Gauge Theory}
\]
Thermal holography

$\text{AdS}_5 + \text{BH}$

$\frac{\eta}{s} = \frac{\hbar}{4\pi}$

$SU(N_c)$ Gauge Theory

String Theory

Black Hole
Quark energy loss

Quark-gluon plasma

Deposited energy and momentum

Trailing string (flux tube)

Black hole
Quark energy loss

\[ \chi_h = \frac{1}{\gamma^{1/2} T} \]

\[ \chi_m = \frac{\chi_0}{\sqrt{\gamma}} = \frac{1}{\pi T \sqrt{\gamma}} \]

Upper and lower parts of the training string are causally disconnected.

Quark-gluon plasma

Deposited energy and momentum

Trailing string (flux tube)

Black hole

\[ \chi_0 = \frac{1}{T} \]
Quark energy loss

\[ \chi_h = \frac{\chi_m}{\gamma^{1/2}} \]

\[ \chi^0 = \frac{1}{T} \]

\[ \chi = \frac{\chi_0}{\sqrt{\gamma}} = \frac{1}{\pi T \sqrt{\gamma}} \]

Upper and lower parts of the training string are causally disconnected.

If quark is sufficiently massive or off-shell after scattering, it travels above the string horizon.

Soft field is continuously stripped off; quark emerges from matter in a highly virtual state with a truncated color field.

Deposited energy and momentum

Trailing string (flux tube)

Black hole

Quark-gluon plasma

Sunday, May 29, 2011
Lightning fast

Colliding shock waves create thermal matter within $\tau \approx 0.3 \text{ fm/c}$ (Chesler & Yaffe ’10)
Lightning fast

Colliding shock waves create thermal matter within $\tau \approx 0.3 \text{ fm/c}$ (Chesler & Yaffe '10)

A volume of diameter $D$ thermalizes perfectly after $\tau \approx D/2,$ i.e. at the speed of light (Balasubramanian et al. '11)
Fluctuations of conserved quantum numbers of quarks above $T_c$ behave “as if” quarks were free:

$B = \text{baryon number}$

$Q = \text{electric charge}$

$S = \text{strangeness}$

**Is this behavior compatible with strong coupling?**
Fortunately, experimental progress with several facilities (RHIC, LHC, and soon FAIR) producing data at an amazing rate, is a greater challenge than rival theories.

Main challenges for the next few years:

• Constructing a solvable model that consistently interpolates between weak and strong coupling

• Understand the initial state and thermalization

• Develop the theory of fluctuations

• Extend Lattice QCD to $\mu_B \neq 0$ and real-time response functions
Instead of a summary

```
DOES IT BOther YOU TO LIVE IN TIMES LIKE THESE, LUCY?
I MEAN, EVERYTHING IS SO UNCERTAIN AND SO CONFUSED.

DOES IT WORRY YOU OR BOTHER YOU, OR DO YOU...
WHAT ARE YOU TRYING TO DO, START AN ARGUMENT?
```
THE END