Soft Physics in Relativistic Heavy Ion Collisions

Huichao Song
宋慧超
Peking University

Hadron and Nuclear Physics in 2017
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**little bang:** the different stage for a relativistic heavy ion collision

- **Initial state**
- **Hydro expansion of QGP or hadron gas**
- **Preequilibrium**
- **QGP**
- **Hadron Gas**
- **hadronisation**
- **Freeze-out**

**RHIC, BNL**

**LHC, CERN**
The QGP was discovered

RHIC (2000-- )

Anisotropy Parameter $v_2$

Transverse Momentum $p_T$ (GeV/c)

Hydro model

PHENIX Data

STAR Data

- $\pi$
- $\pi^+ + \pi^-$
- $K$
- $K^+ + K^-$
- $p$ + $p$
- $p + p$
RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a liquid.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain
Soft Physics for Relativistic Heavy Ion Collisions

- Hydrodynamics & hybrid model
- QGP viscosity
- multi-strange hadrons & early freeze-out
- initial state fluctuations & final state correlations
- Correlated fluctuations near the QCD critical point
Hydrodynamics & its Hybrid Model
Viscous Hydrodynamics

\[ \partial_\mu T^{\mu \nu}(x) = 0 \]

\[ \tau_\pi \Delta^{\alpha \mu} \Delta^{\beta \nu} \dot{\pi}_{\alpha \beta} + \pi^{\mu \nu} = 2\eta \sigma^{\mu \nu} - \frac{1}{2} \pi^{\mu \nu} \eta T \tau_\pi \partial_\lambda \left( \frac{\tau_\pi}{\eta T} u^\lambda \right) \]

\[ \tau_\pi \dot{\Pi} + \Pi = -\zeta (\partial \cdot u) - \frac{1}{2} \Pi \frac{\zeta T}{\tau_\Pi} \partial_\lambda \left( \frac{\tau_\Pi}{\zeta T} u^\lambda \right) \]

Heat conductivity: McGill … … on-going work

2nd order viscous hydro (I-S)


Anisotropic hydrodynamics
Frankfurt (2010), Cracow (2012), Kent, OSU (2013)

Hydrodynamics with thermal fluctuations
Sophia (2014)
Viscous Hydro + Hadron Cascade Hybrid Model

Initial conditions

viscous hydro

hadron cascade

ideal hydro (QGP & HRG)

viscous hydro (QGP & HRG)

viscous hydro (QGP)

+ URQMD (HRG)

H. Song, S. Bass, U. Heinz, PRC2011
Single shot simulations: smoothed initial conditions (before 2010)

E-b-E simulations: fluctuating initial conditions (since 2010)

QGP viscosity from flow data
VISHNU hybrid model & QGP viscosity

- Main uncertainties come from initial conditions
- Other uncertainties (much smaller)
  - Initial flow, bulk viscosity, single shot vs. e-b-e calculations
    (each of them shift $V_2$ by a few percent, partial cancellation among them)

$$1 \times (1/4\pi) \leq (\eta / s)_{QGP} \leq 2.5 \times (1/4\pi)$$
Massive Data evaluation

**Exp Observables**
- particle yields
- spectra
- elliptic flow
- triangular flow & higher order flow harmonics
- event by event $V_n$ distributions
- higher-order event plane correlations
  
**Theoretical Inputs:**
- type of initial conditions
- initial flow
- starting time
- EoS
- shear viscosity
- bulk viscosity
- relaxation times
- freeze-out/switching cond.
An quantitatively extract the QGP viscosity

- An quantitatively extraction of the QGP viscosity with iEBE-VISHNU and the massive data evaluation

- $\eta/s(T)$ is very close to the KSS bound of $1/4\pi$

An quantitatively extraction of the QGP viscosity with iEBE-VISHNU and the massive data evaluation. \(\eta/s(T)\) is very close to the KSS bound of \(1/4\pi\).

$V_2$, $V_3$, $V_4$ of identified hadrons

$V_3$ & $V_4$ shows similar mass orderings as $V_2$ for various centrality
iEBE-VISHNU (AMPT initial conditions) nicely describe the ALICE $V_n$ of pions, kaons, and protons at various centralities.

ALICE: 1606.06507
iEBE-VISHNU: Xu, Li, Song PRC 2016
Strange & Multi-strange hadrons
- Chemical & Thermal freeze-out
Chemical freeze-out for various hadrons

Statistical Model
Chemical freeze-out for various hadrons

- Earlier Chemical freeze-out of Xi and Omega!
- Different hadrons may have different effective chemical freeze-out temperature

Zhu, Meng, Song, Liu PRC 2015
Thermal freeze-out of various hadrons

- thermal freeze-out time distributions widely spread for various hadrons

- Earlier thermal freeze-out of Xi and Omega!

Zhu, Meng, Song, Liu PRC 2015
EbE-Simulations

- Initial state fluctuations and final state correlations

\[ E \frac{dN}{d^3p} = \frac{dN}{dy p_T dp_T d\phi} \]
\[ = \frac{1}{2\pi} \frac{dN}{dy p_T dp_T} \left[ 1 + 2v_1(p_T, b)\cos(\phi) + 2v_2(p_T, b)\cos(2\phi) + 2v_3(p_T, b)\cos(3\phi) \right] \]
Initialization & Pre-equilibrium

- **fluctuations of nucleon positions**: MC-Glauber, MC-KLN

- **fluctuations of color charges** (in the framework of CGC):
  

  **Correlated Fluctuation**: B. Muller & A. Schafer, Phys.Rev. D85, 114030 (2012).

- **fluctuations of local gluon numbers** (in the framework of MC-KLN):
  

- **Pre-equilibriums**:


More flow data & constraints of the initial conditions

- $V_n$ distributions
- Decorrelation of flow vector
- Correlations of Flow Harmonics
- Event Plane correlations

Gale, et al, PRL 2013

Qiu & Heinz, PLB 2012

ALICE, 1604.07663
**Vn distributions**

Vn distributions prefer the IP-Glasma initialization and ruled-out the MC-Glauber and MC-KLN initial conditions.

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**Graphs:**

- **Top Left:** ATLAS Pb+Pb, $\sqrt{s_{NN}} = 2.76$ TeV, $L_{int} = 7 \mu$b$^{-1}$
  - 10-25%
  - Data $p_T > 0.5$ GeV, $|\eta| < 2.5$
  - Glauber $0.41\varepsilon_2$
  - MC-KLN $0.29\varepsilon_2$

- **Top Right:** $p(v_2,\varepsilon_2)$, $P(v_2,\varepsilon_2)$
  - 20-25%
  - $v_2$ IP-Glasma + MUSIC
  - $v_2$ ATLAS

- **Bottom Left:** ATLAS Pb+Pb, $\sqrt{s_{NN}} = 2.76$ TeV, $L_{int} = 7 \mu$b$^{-1}$
  - 55-60%
  - Data $p_T > 0.5$ GeV, $|\eta| < 2.5$
  - Glauber $0.41\varepsilon_2$
  - MC-KLN $0.22\varepsilon_2$

- **Bottom Right:** $p(v_3,\varepsilon_3)$, $P(v_3,\varepsilon_3)$
  - 20-25%
  - $v_3$ IP-Glasma + MUSIC
  - $v_3$ ATLAS
- Hydrodynamic simulations correctly capture the sign of $SC^\nu(3,2)$ and $SC^\nu(4,2)$
- $V_2$ and $V_4$ are correlated
- $V_3$ and $V_4$ are anti-correlated
- $SC^\nu(3,2)$ and $SC^\nu(4,2)$ are sensitive to both initial conditions and $\eta/s$
- Provide strong constraint on $\eta/s(T)$
Correlated fluctuations near the QCD critical point

**Initial State Fluctuations**
- QGP fireball evolutions smear-out the initial fluctuations
- uncorrelated (in general)

**Fluctuations near the critical point**
- dramatically increase near $T_c$
- Strongly correlated
STAR BES: Cumulant ratios

Xiaofeng Luo
CPOD 2014

STAR PRL 2014

\[ \frac{S}{\sigma} \]

\[ \frac{\kappa}{\sigma^2} \]

Au+Au Collisions
Net-proton
\[ 0.4 < p_T < 2 \text{ (GeV/c)}, |y| < 0.5 \]

- 0-5%
- 5-10%
- 30-40%
- 70-80%

\[ \frac{(S \sigma)_{\text{Skellam}}}{\text{Skellam}} \]

Colliding Energy \[ \sqrt{s} \]

\[ p_T = (0.4 - 2) \text{ GeV} \]

\[ p_T = (0.4 - 0.8) \text{ GeV} \]
Theoretical predictions on critical fluctuations

\[ P[\sigma] \sim \exp\{-\Omega[\sigma]/T\}, \quad \Omega = \int d^3x \left[ \frac{1}{2} (\nabla \sigma)^2 + \frac{m^2_\sigma}{2} \sigma^2 + \frac{\lambda_3}{3} \sigma^3 + \frac{\lambda_4}{4} \sigma^4 + \ldots \right] \]

\[ \langle \sigma_0^2 \rangle = \frac{T}{V} \xi^2, \quad \langle \sigma_0^3 \rangle = \frac{2\lambda_3 T}{V} \xi^6; \quad \langle \sigma_0^4 \rangle_c = \frac{6T}{V} [2(\lambda_3 \xi)^2 - \lambda_4] \xi^8. \]

Critical Fluctuations of particles:

\[ \langle (\delta N)^2 \rangle \sim \xi^2 \]
\[ \langle (\delta N)^3 \rangle \sim \xi^{4.5} \]
\[ \langle (\delta N)^4 \rangle \sim \xi^7 \]

Finite size & finite evolution time: \( \xi < O(2 - 3 fm) \)

Static critical fluctuations vs. dynamical critical fluctuations

Stephanov PRL 2009
Static critical fluctuations on the freeze-out surface

Jiang, Li & Song, PRC 2016
Particle emissions near $T_{cr}$ with external field

**Jiang, Li & Song, PRC 2016**

**Particle emissions in traditional hydro**

$$E \frac{dN}{d^3p} = \int_{E} p_{\mu} d\sigma^{\mu}_{E} f(x, p)$$

**Particle emissions near $T_{cr}$**

$$M \longrightarrow g\sigma(x)$$

$$f(x, p) = f_0(x, p)[1 - g\sigma(x)/(\gamma T)]$$

$$= f_0 + \delta f$$

$$\langle \delta f_1 \delta f_2 \rangle_{\sigma} = f_0 f_0 f_0 f_0 \left( -\frac{g^2}{\gamma_1 \gamma_2} \frac{1}{T^3} \right) \langle \sigma_1 \sigma_2 \rangle_c ,$$

$$\langle \delta f_1 \delta f_2 \delta f_3 \rangle_{\sigma} = f_0 f_0 f_0 f_0 \left( -\frac{g^3}{\gamma_1 \gamma_2 \gamma_3} \frac{1}{T^3} \right) \langle \sigma_1 \sigma_2 \sigma_3 \rangle_c ,$$

$$\langle \delta f_1 \delta f_2 \delta f_3 \delta f_4 \rangle_{\sigma} = f_0 f_0 f_0 f_0 f_0 \left( -\frac{g^4}{\gamma_1 \gamma_2 \gamma_3 \gamma_4} \frac{1}{T^4} \right) \langle \sigma_1 \sigma_2 \sigma_3 \sigma_4 \rangle_c .$$
\[ \langle (\delta N)^2 \rangle_c = \left( \frac{g_i}{2\pi^3} \right)^2 \left( \prod_{i=1,2} \left( \frac{1}{E_i} \int d^3 p_i \int_{\Sigma_i} p_{i\mu} d\sigma_i^{\mu} d\eta_i \right) \right) \frac{f_{01} f_{02} g^2}{\gamma_1 \gamma_2 T^2} \langle \sigma_1 \sigma_2 \rangle_c, \]

\[ \langle (\delta N)^3 \rangle_c = \left( \frac{g_i}{2\pi^3} \right)^3 \left( \prod_{i=1,2,3} \left( \frac{1}{E_i} \int d^3 p_i \int_{\Sigma_i} p_{i\mu} d\sigma_i^{\mu} d\eta_i \right) \right) \frac{f_{01} f_{02} f_{03}}{\gamma_1 \gamma_2 \gamma_3} \frac{g^3}{T^3} \langle \sigma_1 \sigma_2 \sigma_3 \rangle_c, \]

\[ \langle (\delta N)^4 \rangle_c = \left( \frac{g_i}{2\pi^3} \right)^4 \left( \prod_{i=1,2,3,4} \left( \frac{1}{E_i} \int d^3 p_i \int_{\Sigma_i} p_{i\mu} d\sigma_i^{\mu} d\eta_i \right) \right) \frac{f_{01} f_{02} f_{03} f_{04} g^4}{\gamma_1 \gamma_2 \gamma_3 \gamma_4 T^4} \langle \sigma_1 \sigma_2 \sigma_3 \sigma_4 \rangle_c. \]

\[ P[\sigma] \sim \exp \{-\Omega[\sigma]/T\}, \quad \Omega[\sigma] = \int d^3 x \left[ \frac{1}{2} (\nabla \sigma)^2 + \frac{1}{4} \lambda_3 \sigma^4 \right] \]

\[ \langle \sigma_1 \sigma_2 \rangle_c = TD(x_1 - x_2), \]

\[ \langle \sigma_1 \sigma_2 \sigma_3 \rangle_c = -2T^2 \lambda_3 \int d^3 z D(x_1 - z) D(x_2 - z) D(x_3 - z), \]

\[ \langle \sigma_1 \sigma_2 \sigma_3 \sigma_4 \rangle_c = -6T^3 \lambda_4 \int d^3 z D(x_1 - z) D(x_2 - z) D(x_3 - z) \]

\[ + 12T^3 \lambda_3^2 \int d^3 u \int d^3 v D(x_1 - u) D(x_2 - u) D(x_3 - v) D(x_4 - v) D(u - v). \]

**For simplicity:** We assume that the correlated sigma field only influence the particle emissions near \( T_c \), which does not influence the evolution of the bulk matter.

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**Static critical fluctuations along the freeze-out surface**
Comparison with the experimental data

- Cumulants & cumulant ratios
- Acceptance dependence
Acceptance dependence

- Static critical fluctuations can qualitatively explain the acceptance dependence of the STAR data.
Cumulants of net protons

Net Protons 0-5%

Static critical fluctuations give positive contribution to $C_2$, $C_3$; well above the poisson baselines, can NOT explain/describe the $C_2$, $C_3$ data

Jiang, Li & Song, PRC2016

$P_T = (0.4-0.8) \, \text{GeV}$

$P_T = (0.4-2) \, \text{GeV}$
Dynamical Critical Fluctuations
Effects from dynamical evolutions

\[ \partial_\tau P(\sigma; \tau) = \frac{1}{m^2_\sigma \tau_{\text{eff}}} \left[ \partial_\sigma \left[ \partial_\sigma \Omega_0(\sigma) + V^{-1} \partial_\sigma \right] P(\sigma; \tau) \right] \]

near-equilibrium limit:

\[ \partial_\tau \kappa_2 = -2 \tau^{-1}_{\text{eff}} a_2 \delta \kappa_2 \]
\[ \partial_\tau \kappa_3 = -3 \tau^{-1}_{\text{eff}} [a_2 \delta \kappa_2 + a_3 \delta \kappa_3] \]
\[ \partial_\tau \kappa_4 = -4 \tau^{-1}_{\text{eff}} [a_2 \delta \kappa_2 + a_3 \delta \kappa_3 + a_4 \delta \kappa] \]

S. Mukherjee, R. Venugopalan, Y. Yin, PRC92 (2015)

sign of non-Gaussian cumulants can be different from equilibrium one
Dynamical critical fluctuations of the sigma field

Langevin dynamics: \[ \partial^\mu \partial_\mu \sigma(t, x) + \eta \partial_t \sigma(t, x) + V_{eff}'(\sigma) = \xi(t, x) \]

with effective potential from linear sigma model with constituent quarks

\[ V_{eff}(\sigma) = U(\sigma) + \Omega_{qq}(T, \sigma) = \frac{\lambda^2}{4} (\sigma^2 - \nu^2)^2 - h_q \sigma - U_0 - 2 d_q T \int \frac{d^3p}{(2\pi)^3} \ln \left(1 + \exp \left(-\frac{E}{T}\right)\right) \]

- The sign of \( C_3 \) is different from the equilibrium one due to the memory effects.

Work in the near future:
Coupling sigma field with particles; Study the dynamical critical fluctuations of net protons.

Jiang & Song, in preparation
Summary

**Hydrodynamics & its hybrid model**
- QGP viscosity
- initial state fluctuations & final state correlations
- chemical & thermal freeze-out

**Dynamical modeling near the QCD critical point**
- Correlated fluctuations

-Ever increasing/precise experimental data at different colliding systems provide valuable information on the properties of the QGP and the QCD phase diagram
- Sophisticated dynamical model are need to be further developed
Thank You
Massive data evaluation

(Comprehensive Heavy Ion Model Evaluation and Reporting Algorithm)

R. Soltz, et al., PRC2013
Fluctuations and Correlations in smaller systems

-p+Pb collisions at 5 TeV
Collective flow -- Experimental Observations

in p+Pb collisions at 5.02 TeV
Collective flow? -- Hydrodynamics Simulations

in p+Pb collisions at 5.02 TeV

G.-Y. Qin, B. Muller. PRC2014

K. Werner, et. Al., PRL2014

P. Bozek, W. Broniowski, G. Torrieri, PRL2013
Correlations from initial state in p+Pb collisions at 5.02 TeV

Including final state re-scattering via CYM evolution generates a positive v3 on the time scale of a single scattering.

Dusling & Venugopalan PRD 2013

Schenke, Schlichting, Venugopalan, PLB2015
Where do the correlations (collective flow) in 5.02 TeV p-Pb collisions come from?

- Initial State?
- QGP?
- Hadronic matter?

**UrQMD Baseline Calculations**

Zhou, Zhu, Li, Song, PRC 2015

Assumption: p-Pb collisions only produce hadronic systems without reaching the threshold of the QGP formation.
The UrQMD systems are largely influenced by non-flow effects.
To reproduce the flow data, effects from initial state and/or QGP are needed.
$V_2$ mass ordering in $p+Pb$ collisions at 5.02 TeV

$V_2$ mass ordering is produced by UrQMD, similar to the ALICE data.
Hadronic interactions & $v2$ mass ordering

- Hadronic interaction can generate a mass ordering for 2-particle correlations
- Additive quark model: different M-M M-B cross-sections
Fluctuations and Correlations in small systems

Many many related flow measurements for different small colliding system,

- What is the solid flow signal?
- Why hydrodynamics work well for such small system
Boltzmann approach with external field

\[ S = \int d^3x \frac{1}{2} (\partial_\mu \sigma \partial^\mu \sigma - U(\sigma)) - \int ds M(\sigma), \]

\[ \partial^2 \sigma + dU/d\sigma + (dM/d\sigma) \int p f/\gamma = 0. \]

\[ p^\mu \frac{\partial f}{\partial x^\mu} + \partial^\mu M \frac{\partial f}{\partial p^\mu} + C[f] = 0, \]

-analytical solution with perturbative expansion, please refer to Stephanov PRD 2010

Stationary solution for the Boltzmann equation with external field

\[ f_\sigma(p) = e^{\mu/T} e^{-\gamma(p)M/T}. \]

Effective particle mass: \[ M = M(\sigma) = g \sigma \]
Extracting $\eta/s$ from $V_n$ in ultra-central collisions

In most central collisions, fluctuation effects are dominant (Geometry effects are suppressed)

-can not simultaneously fit $V_2$ and $V_3$ with single $\eta/s$ (MC-Glauber & MC-KLN)
Ultracentral Collisions: bulk visc. & NN correlations

Shen, Qiu and Heinz 2013

- MC-Glauber & MC-KLN: can not simultaneously fit $V_2$ and $V_3$

- IP+Glasma + NN correlations + bulk viscosity nicely reproduces $V_n$ in ultra-central collisions

G. Denicol, QM2014

$\frac{\zeta}{s} = b \times \frac{\eta}{s} \left( \frac{1}{3} - c_s^2 \right)^2$
Event Plane Correlations

Qiu & Heinz, PLB(2012)

Pure e-b-e viscous hydro simulations:
- qualitatively reproduce the measured event plane correlations

EXP. data: [ATLAS Collaboration], CERN preprint ATLAS-CONF-2012-049
The contributions from STATIC critical fluctuations to $C_2$, $C_3$ are always positive (Both this model & early Stephanov PRL09 framework)