RHIC physics, AdS/CFT and string theory

Makoto Natsuume (KEK)
RHIC & String theory: 2 directions

Both directions are important to study

RHIC $\xleftarrow{}$ String Theory

Physics of QGP

RHIC $\xrightarrow{}$ String Theory

Test of AdS/CFT
Takes the pain out of string theory learning!

String Theory

A Reference for the Rest of Us!

Makoto Natsuume
KEK

Includes Black Holes, AdS/CFT, and N=4 SYM
Elements of Universe

**Force**
- Gravity
- Electromagnetic
- Weak
- Strong

**Matter**
- 6 quarks
- 6 leptons
- Higgs

In principle, all phenomena can be understood with these elements, but it is a disjointed framework.

String theory unifies these elements

General relativity (classical)
\[ \uparrow \]
Gauge theory (quantum)
Main ingredients of string theory

open string: gauge theory  closed string: gravity

cf. Length one can “see” experimentally $\sim 10^{-15}$cm

String: point particle macroscopically
Open string: gauge theory

Simplest oscillations in 4-dimensions

2 degrees of freedom $\rightarrow$ photon’s polarizations

Real superstring requires 10-dim. spacetime
Closed string: graviton

“left-moving” & “right-moving”: independent

simultaneous oscillation in 2 directions $\rightarrow$ spin 2 $h_{\mu\nu}$

String theory contains both gauge theory & gravity
“Duality”

Useful tool in string theory for the last 10 years

Various dualities appear in string theory

- Equivalence between two theories which look different
- Complementarity: Cover one theory’s hard part (strong coupling physics) by the other’s easy part (weak coupling physics)
AdS/CFT duality

QGP

Finite temperature gauge theory ⇔ Black hole at strong coupling in AdS space

thermal
thermal due to the Hawking radiation

strong coupling ⇔ “weak coupling”
(weak gravity so that General Relativity is enough)
AdS/CFT duality

Finite temperature gauge theory $\leftrightarrow$ Black hole at strong coupling in AdS space

Gauge theory $\leftrightarrow$ Gravity theory

A relation possible only for the unified theory!
What AdS/CFT stands for?

Finite temperature gauge theory $\leftrightarrow$ Black hole
at strong coupling in AdS space

AdS: anti-deSitter space
deSitter: Dutch astronomer
gauge theory: typically supersymmetric gauge theory

simplest example $\rightarrow$ $\mathcal{N}=4$ super-Yang-Mills (SYM)
$\uparrow$: # of supersym.
$\rightarrow$ scale inv.
conformal field theory (CFT)
String theory implication to RHIC
Universal value of $\eta/s$
for strongly-coupled non-Abelian plasmas

$\eta$: shear viscosity
$s$: entropy density
Comparison at Equilibrium

System at finite temperature $\rightarrow$ properties at equilibrium (thermodynamic quantities)

- **Gauge Theory**
- **Black Hole**

**Thermodynamics**
- Temp
- Energy
- Entropy

“BH thermodynamics”
- Hawking temp
- BH mass
- BH entropy

- BH has the notion of temperature due to Hawking radiation.
- BH satisfies thermodynamic-like laws (0th-3rd)
**Black hole entropy**

**BH horizon**: located at (Schwarzschild)

\[ r_0 = 2GM \]

If matter falls in, BH horizon area \( A \) increases

Nothing comes out from the horizon (classically), \( A \) is a nondecreasing quantity ↔ entropy?

\[ S_{BH} = \frac{A}{4G\hbar} \]

“BH entropy”

The formula: valid for a broad range of BHs
BH and hydrodynamics

- Next simplest situation
  → add perturbations & see how they decay

- QGP: a fluid w/ a very low viscosity according to RHIC
  → BHs and hydrodynamic systems in fact behave similarly.

Water pond:

The dissipation: consequence of viscosity

BH:

The dissipation: consequence of BH absorption
Universality of $\eta/s$

According to AdS/CFT

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

True for all known examples

- conformal plasma ($\mathcal{N}=4$ SYM) (Policastro - Son - Starinets, 0104066)
- nonconformal plasmas
- Plasmas at finite chemical potential (Kovtun - Son - Starinets, 0309213; Buchel - J.Liu, 0311175; Mas, 0601144; Son - Starinets, 0601157; Saremi, 0601159; Maeda - Natsuume - Okamura, 0602010)
- Plasmas w/ flavors
- Time-dependent plasma (Mateos - Myers - Thomson, 0610184; Janik, 0610144)
In gravity side, the dissipation occurs by BH absorption

shear viscosity $\Leftrightarrow$ absorption cross section by BH

$= \text{horizon area (for many BHs)}$

entropy $\Leftrightarrow \text{horizon area (for many BHs)}$

$$\eta = \frac{A}{16\pi G}$$

$$s = \frac{A}{4G\hbar}k_B$$

Each relation is a general result, so this must be universal result

universal nature of BH

Kovtun - Son - Starinets (2004)

Adapted from Susskind “The world as a hologram”
Gauge Theory \[ \mathcal{N} = 4 \text{ SYM} \rightarrow \text{AdS BH} \]

Gravity

“\( \eta/s \)” is universal

\[ \text{not known yet} \]

QCD

\[ \eta/s \text{ can be compared w/ experiments!} \]
Comparison

- **RHIC:**
  \[ \frac{\eta}{s} \sim O(0.1) \times \frac{\hbar}{k_B} ? \]
  Teaney, nucl-th/0301099

- **AdS/CFT:**
  \[ \frac{\eta}{s} = \frac{\hbar}{4\pi k_B} \]

- **naive extrapolation of perturbative QCD:**
  \[ \frac{\eta}{s} \sim O(1) \times \frac{\hbar}{k_B} \]

- **Lattice (pure gauge theory):**
  \[ 1 < 4\pi \frac{\eta}{s} < 2 \quad \text{for } 1.2 T_c < T < 1.7 T_c \]
  Meyer, 0704.1801 [hep-lat]
  (An early work by A. Nakamura & S. Sakai, hep-lat/0406009)

**pQCD seems inaccurate and QGP seems strongly-coupled**
QGP analysis extremely hard due to the strong coupling

genuine signatures of QGP?

- Small viscosity (elliptic flow)
- Jet quenching
- $J/\psi$ suppression

All of these are explored in AdS/CFT recently.

Liu - Rajagopal - Wiedemann, hep-ph/0605178
Herzog et al., 0605158
Casalderrey-Solana - Teaney, hep-ph/0605199
Gubser, 0605182

Liu - Rajagopal - Wiedemann, hep-ph/0607062
Chernicoff - Garcia - Guijosa, 0607089
Caceres - Natsuume - Okamura, 0607233
Natsuume - Okamura, 0706.0086 [hep-th]
Impact of RHIC on String Theory
RHIC & String theory: 2 directions

Both directions are important to study
An impact of RHIC on string theory?

- Universality of $\eta/s$ at finite chemical potential
  
  Mas, 0601144  
  Son - Starinets, 0601157  
  Saremi, 0601159  
  **Maeda - Natsuume - Okamura, 0602010**

- String theory description of “Jet quenching”
  
  Liu - Rajagopal - Wiedemann, hep-ph/0605178 (May 16)  
  Herzog et al., 0605158 (May 17)  
  Casalderrey-Solana - Teaney, hep-ph/0605199 (May 18)  
  Gubser, 0605182 (May 19)

- “Causal hydrodynamics” of gauge theory plasmas
  
  Baier - Romatschke - Son - Starinets - Stephanov, 0712.2451 [hep-th] (Dec. 18)  
  Bhattacharyya - Hubeny - Minwalla - Rangamani, 0712.2456 [hep-th] (Dec. 18)  
  **Natsuume - Okamura, 0712.2916 [hep-th] (Dec. 19)**  
  **0712.2917 [hep-th]**  
  **0801.1797 [hep-th]**

Many competitions!

08/5 RHIC & AGS Annual Users’ Meeting
You have a great opportunity to verify String Theory (AdS/CFT) experimentally
T=0 vs T≠0

Big difference bet T=0 and T≠0 for AdS/CFT \(\Rightarrow\) SUSY

- Many nice thms due to SUSY
- Many circumstantial evidences
- Most string theorists study this case

\[ \begin{align*}
T=0 & \quad \begin{align*}
\text{Many nice thms due to SUSY} \\
\text{Many circumstantial evidences} \\
\text{Most string theorists study this case}
\end{align*} \\
T≠0 & \quad \begin{align*}
\text{SUSY is broken, nice thms no longer apply} \\
\text{Few quantitative analysis, mostly qualitative} \\
\text{Few string theorists had studied this case. I myself had not considered this case seriously . . .}
\end{align*}
\]
“Unexpected connection”

But the situation changed in 2005!

RHIC experiment press release
at American Physical Society annual meeting (April 18, 2005)

"The possibility of a connection between string theory and RHIC collisions is unexpected and exhilarating,"
(Director of the DOE Office of Science)

First time string theory has been mentioned in the announcement of a major experiment

New inputs from experiments/other theoretical tools!
At finite temperature, one cannot rely on SUSY
As a result, many loose ends in AdS/CFT
Maybe hard to make progress w/ string theory alone

Check AdS/CFT results w/ experiments/other tools (e.g. Lattice)

Indirect check of AdS/CFT at finite temperature
Number of citations for 2 key papers

- Policastro - Son - Starinets, PRL87 (2001) 081601: 1st computation of $\eta/s$
- Kovtun - Son - Starinets, PRL94 (2005) 111601: universality of $\eta/s$

08/5 RHIC & AGS Annual Users’ Meeting
Let's study $\eta/s$ more generically. The ratio is universal.

String Theory

$\eta/s = 1/(4\pi)$ for $\mathcal{N}=4$ SYM

Look at RHIC results more carefully.

RHIC

“RHIC results close to the value!”

“Look at RHIC results more carefully”

Example of mutual interactions
At least 7 arXivs are involved!

- hep-lat
- nucl-th
- hep-ph
- nucl-ex
- cond-mat
- hep-th
- gr-qc

RHIC

String theory
Some possible problems

Let’s discuss if you can really take my words.

- Can we really see the small viscosity?
- Can RHIC prove String Theory?
- How serious string theorists are?
Can we really see the small viscosity?

Unclear if $\eta/s = 1/(4\pi)$ experimentally at this moment

Hydrodynamics is not enough to determine viscosity

| initial conditions of QGP | hydrodynamics | freeze-out |

Also, so small $\leftarrow$ cf. Nitrogen: $10^3$ times larger
Perfect fluid may be enough to fit experiments
In this sense, this # may not be highly important for you
But if you can see small viscosity, please obtain $\eta/s$

- $\eta/s$: Most robust prediction by AdS/CFT
  If you can confirm it, an experimental evidence of AdS/CFT

- In reality, perfect fluid should not exist

$$\eta \propto (\text{mean free path}) \propto 1/\sigma_{\text{cross}}$$
Can RHIC prove String Theory?

Not the complete proof of String Theory

- String theory has many aspects
- Only one piece of evidence of AdS/CFT

One small step for String Theory, but one giant leap for mankind

Nobody has verified string theory, nobody else can do it (for now).

String: so small
→ experimental verification by conventional methods: very hard
How serious string theorists are?

LHC will be ready soon

‘68: String theory
   Originally born as a theory of strong interaction
   Failed due to 10-dimensions, existence of graviton etc.

‘73: Asymptotic freedom $\rightarrow$ QCD established!

But string: diehard

‘74: String reincarnated as a unified theory.

Yoneya, Scherk - Schwarz

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But string theorists retained a firm belief that string theory still has something to do with strong interaction.

Works in the direction appear from time to time.

QCD: old playground for string theorists
String theorists will not give up until we solve QCD.
1974: “Annus Mirabilis”

- Grand Unified Theory
  - Georgi - Glashow, Phys. Rev. Lett. 32, 438 (74/2)

- Hawking radiation
  - Hawking, Nature, 248, 30 (74/3)

- SUSY
  - Wess - Zumino, Phys. Lett. B49, 52 (74/3)

- Large-N theory
  - 't Hooft, Nucl. Phys. B72, 461 (74/4)

- Lattice gauge theory
  - Wilson, Phys. Rev. D10, 2445 (74/6)

- String theory as the unified theory
  - Yoneya, Prog. Theor. Phys. 52, 1355 (74/10)
  - Scherk - Schwarz, Nucl. Phys. B
    Phys. Rev. Lett. 33 (74/12)

So many discoveries in different fields
Now all these discoveries are connected to each other
“My fellow heavy-ion physicists of the world: ask not what String Theory will do for you, but what together we can do for the future of physics.”
Further readings

- For English audiences
  - Son & Starinets: 0704.0240 [hep-th]
  - Mateos: 0709.1523 [hep-th]
  - Myers & Vazquez: 0804.2423 [hep-th]

- For Japanese audiences (in Japanese)
Backups
Why open & closed?

Simplest open string interactions:

Open string requires closed string

String theory contains both gauge theory and gravity
Reality of perfect fluid

In reality, perfect fluid should not exist

\[
\begin{align*}
\eta &\sim \rho \overline{v} l_{mfp} \\
\frac{s}{s} &\sim \frac{\rho}{m} \\
\frac{\eta}{s} &\sim m \overline{v} l_{mfp} > \hbar \\
\Rightarrow l_{mfp} &> \lambda_{deBroglie}
\end{align*}
\]

⇒ valid for fluids w/ quasiparticle description

So, the existence of viscosity bound itself is natural
But why the value is \(1/(4\pi)\) and why gauge theory saturates the bound?
QCD vs $\mathcal{N}=4$

QCD

- runs to weak coupling
- strongly-coupled plasma w/ fundamental matter deconfined, screening
- confinement

$\mathcal{N}=4$ SYM

- $T >> T_c$ conformal remains strong coupling
- $T > T_c$ strongly-coupled plasma w/ massive adjoint matter deconfined, screening
- $T = 0$ SUSY no confinement

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QCD: nearly conformal for $T > 2T_c$?

Conformal $\rightarrow T^\mu_\mu = 0$
$\rightarrow \varepsilon + 3p = 0$
$\rightarrow v_S^2 = 1/3$
Thermodynamics  “BH thermodynamics”

Temp  =  Hawking temp
Energy  BH mass
Entropy  BH entropy

For $\mathcal{N} = 4$ SYM

$$s_{\text{free}} = \frac{2\pi^2}{3} N_c^2 T^3$$  $s_{\text{BH}} = \frac{\pi^2}{2} N_c^2 T^3 = \frac{3}{4} s_{\text{free}}$

DOFs  Stefan-Boltzmann

Disagree? Compare the same thing!

weak coupling result (as gauge theory)  strong coupling result (as gauge theory)

strong coupling effect

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Lattice results for pure YM:

Adapted from R. Gavai, S. Gupta & S. Mukherjee, hep-lat/0506015; 0509127

Entropy

\[ S \sim (70-80\% \text{ of } S_{\text{free}}) \]

cf. \( \mathcal{N}=4 \) SYM:

\[
S_{BH} = \frac{3}{4} S_{\text{free}}
\]

Gubser - Klebanov - Peet (1996)
String theory & real life

- AdS/QCD, AdS/QGP
- String Landscape, KKLT
  - small positive cosmological constant
- Cosmic string

People study applications to have a better understanding of string theory.

AdS/CFT derivation has many loose ends. Experiments or the other theoretical tools (such as lattice gauge theory) may be useful to confirm AdS/CFT