RHIC physics, AdS/CFT and string theory

Makoto Natsuume (KEK)

08/5 RHIC & AGS Annual Users' Meeting

RHIC & String theory: 2 directions

RHIC ⇐ String Theory

Physics of QGP

RHIC ⇒ String Theory

Test of AdS/CFT

Both directions are important to study

Takes the pain out of string theory learning!

String Theory

FOR DUMMIES®

A Reference for the Rest of Us!

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

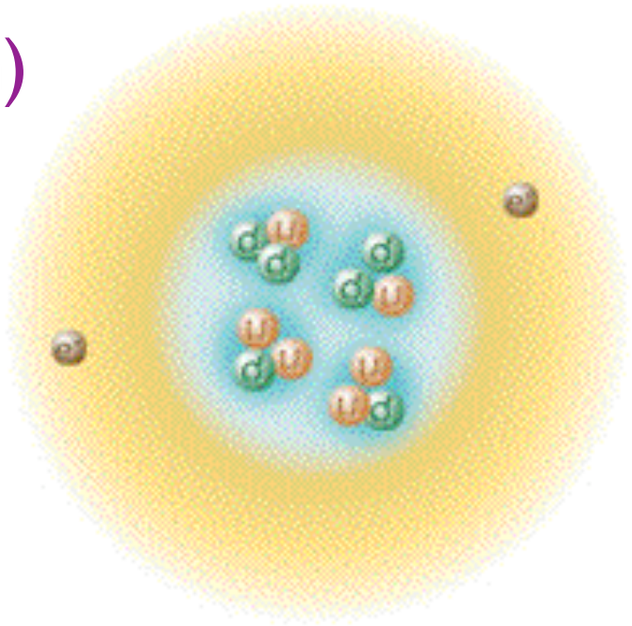
Makoto Natsuume
KEK

Elements of Universe

- Force

  Gravity
  Electromagnetic
  Weak
  Strong

  } General relativity (classical) ⇕ Gauge theory (quantum)



- Matter

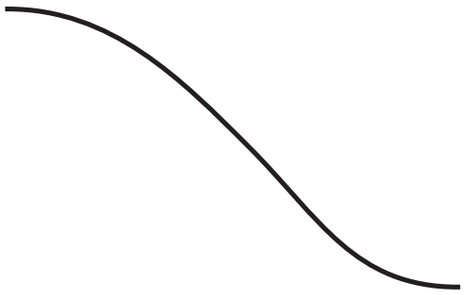
  6 quarks
  6 leptons
  Higgs

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

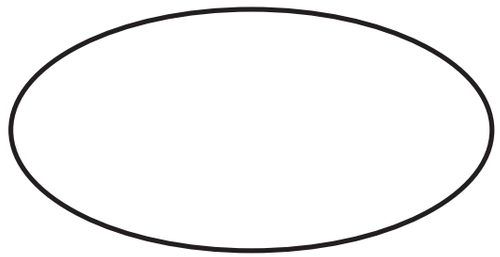
String theory unifies these elements

Main ingredients of string theory

open string: gauge theory



closed string: gravity



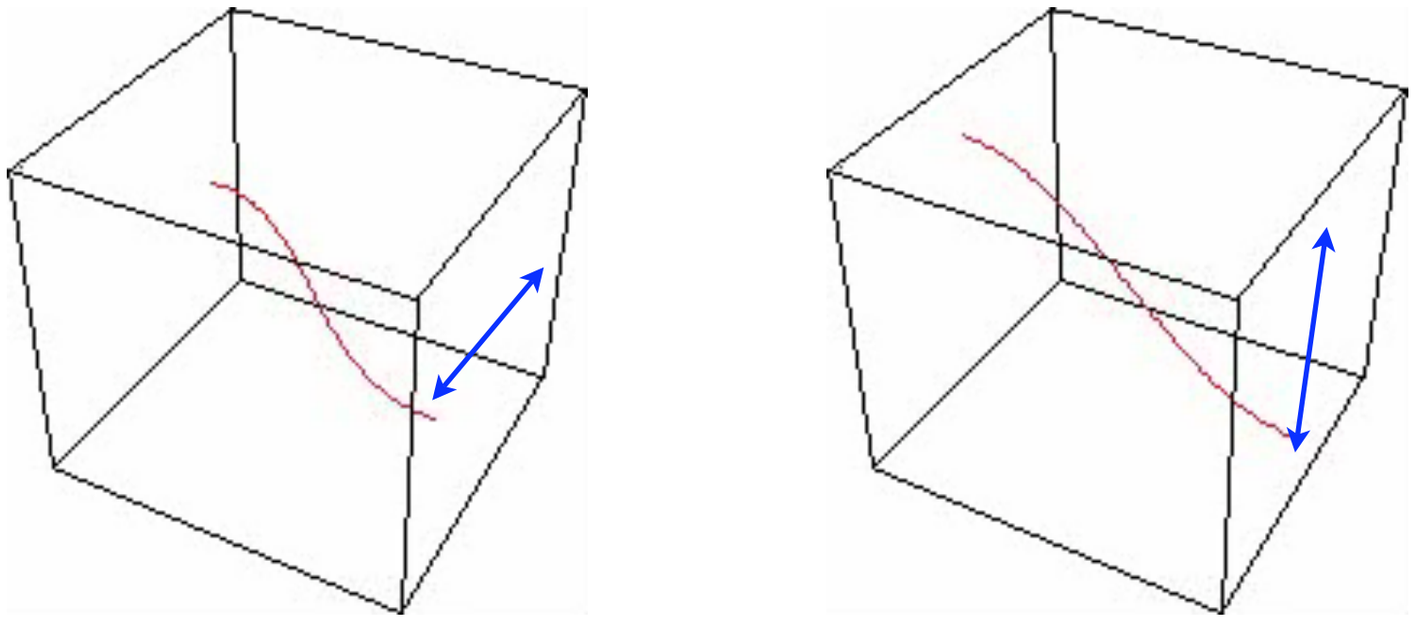
10^{-32} cm

cf. Length one can "see" experimentally ~ 10^{-15}cm

String: point particle macroscopically

Open string: gauge theory

Simplest oscillations in 4-dimensions



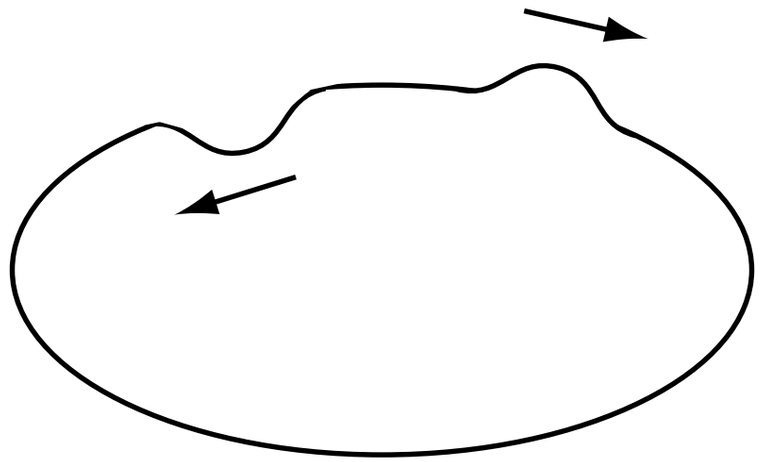
2 degrees of freedom → photon's polarizations

Real superstring requires 10-dim. spacetime

Closed string: graviton

"left-moving" & "right-moving": independent

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



String theory contains
both gauge theory & gravity

"Duality"

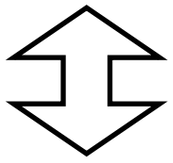
Useful tool in string theory for the last 10 years

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 ⇔ Black hole
at strong coupling in AdS space

Gauge theory ⇔ Gravity theory

A relation possible only for the unified theory!

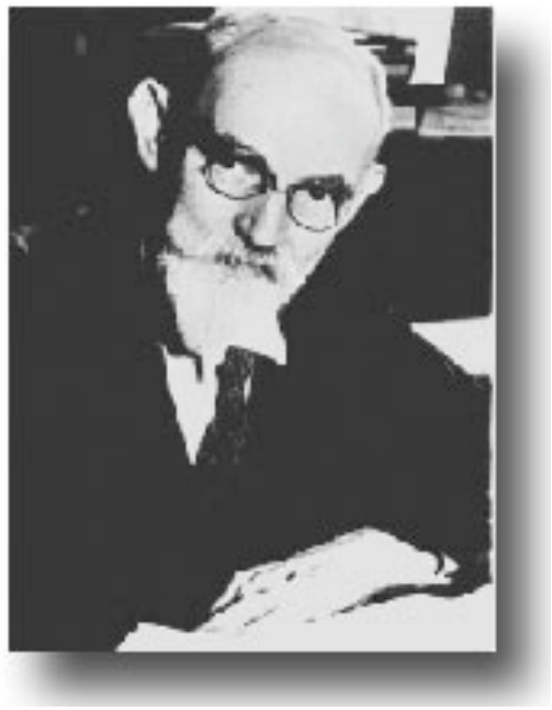
What AdS/CFT stands for?

Finite temperature gauge theory ⇔ Black hole

at strong coupling in AdS space

AdS: anti-deSitter space

deSitter: Dutch astronomer



gauge theory: typically supersymmetric gauge theory

simplest example → $\mathcal{N}$=4 super-Yang-Mills (SYM)

↑: # of supersym.

→ scale inv.

conformal field theory (CFT)

String theory implication to RHIC

Universal value of η/s
for strongly-coupled non-Abelian plasmas

η: shear viscosity
s: entropy density

Comparison at Equilibrium

System at finite temperature → properties at equilibrium
(thermodynamic quantities)

Gauge Theory	⇔	Black Hole
Thermodynamics		"BH thermodynamics"
Temp		Hawking temp
Energy		BH mass
Entropy		BH entropy

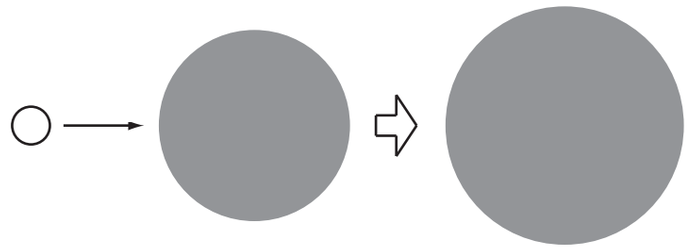
- BH has the notion of temperature due to Hawking radiation.
- BH satisfies thermodynamic-like laws (0th-3rd)

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"

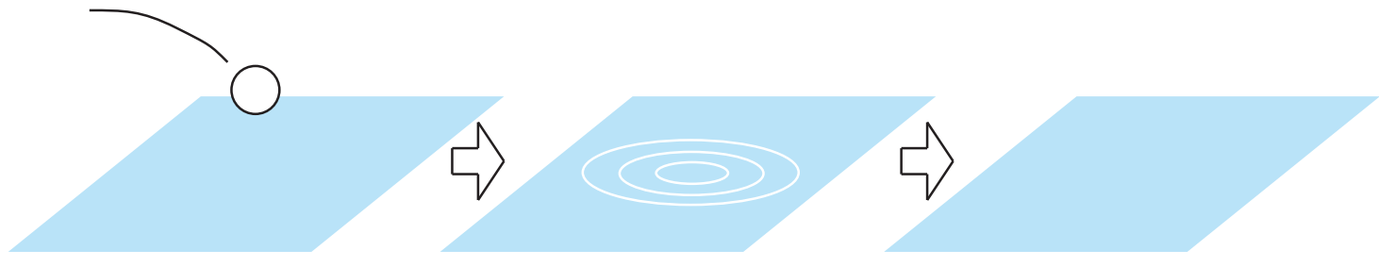
The formula: valid for a broad range of BHs

BH and hydrodynamics

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

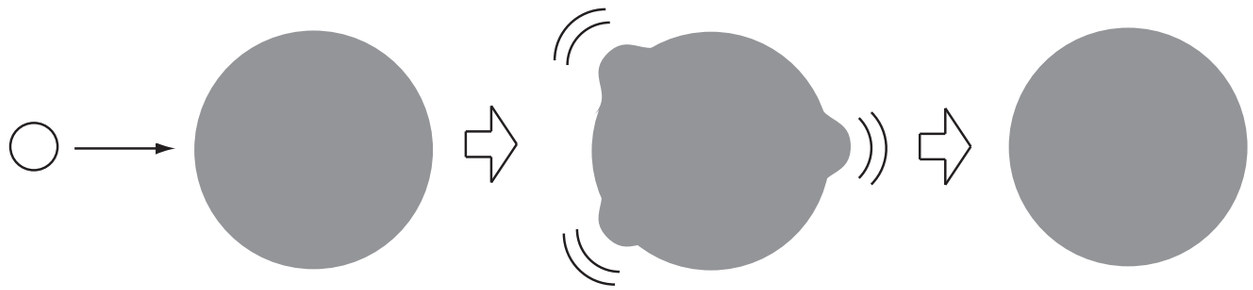
- QGP: a fluid w/ a very low viscosity according to RHIC
  → BHs and hydrodynamic systems in fact behave similarly.

Water pond:



The dissipation: consequence of viscosity

BH:



The dissipation: consequence of BH absorption

Universality of η/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 — Kovtun - Son - Starinets, 0309213; Buchel - J.Liu, 0311175
- ☑ Plasmas at finite chemical potential — Mas, 0601144; Son - Starinets, 0601157; Saremi, 0601159; **Maeda - Natsuume - Okamura, 0602010**
- ☑ Plasmas w/ flavors — Mateos - Myers - Thomson, 0610184
- ☑ Time-dependent plasma — Janik, 0610144

Why universal?

In gravity side, the dissipation occurs by BH absorption

shear viscosity ⇔ absorption cross section by BH

= horizon area (for many BHs)

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

entropy ⇔ horizon area (for many BHs)

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

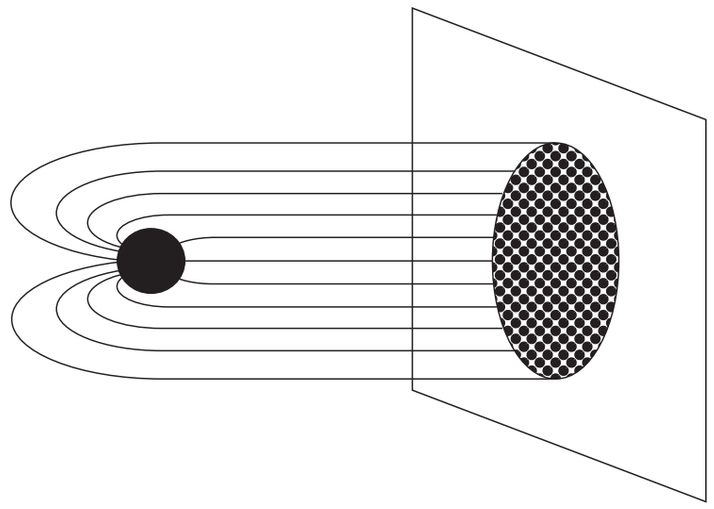
$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B}$$

Each relation is a general result, so this must be

Kovtun - Son - Starinets (2004)

universal result

→ universal nature of BH



Adapted from Susskind
"The world as a hologram"

Gauge Theory		Gravity
$\mathcal{N}$ = 4 SYM	⇨	AdS BH
"η/s" is universal	⇕	
QCD	⇦	not known yet

→ η/s 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): $1 < 4\pi \frac{\eta}{s} < 2$ for 1.2 Tc < T < 1.7 Tc

  Meyer, 0704.1801 [hep-lat]
  (An early work by A. Nakamura & S. Sakai, hep-lat/0406009)

pQCD seems inaccurate and QGP seems strongly-coupled

Other topics

QGP analysis extremely hard due to the strong coupling

⇒ genuine signatures of QGP?

☑ Small viscosity (elliptic flow)

☑ Jet quenching

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

☑ J/ψ suppression

Liu - Rajagopal - Wiedemann, hep-ph/0607062
Chernicoft - Garcia - Guijosa, 0607089
Caceres - Natsuume - Okamura, 0607233
Natsuume - Okamura, 0706.0086 [hep-th]

All of these are explored in AdS/CFT recently.

Impact of RHIC on String Theory

RHIC & String theory: 2 directions

RHIC ⇐ String Theory

Physics of QGP

RHIC ⇒ String Theory

Test of AdS/CFT

Both directions are important to study

An impact of RHIC on string theory?

- Universality of η/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

Benincasa - Buchel - Heller - Janik, 0712.2025 [hep-th] (Dec. 13)
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!

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 ⇒ SUSY

T=0
- Many nice thms due to SUSY
- Many circumstantial evidences
- Most string theorists study this case

T≠0
- SUSY is broken, nice thms no longer apply
- Few quantitive analysis, mostly qualitative
- Few string theorists had studied this case. I myself had not considered this case seriously . . .

“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

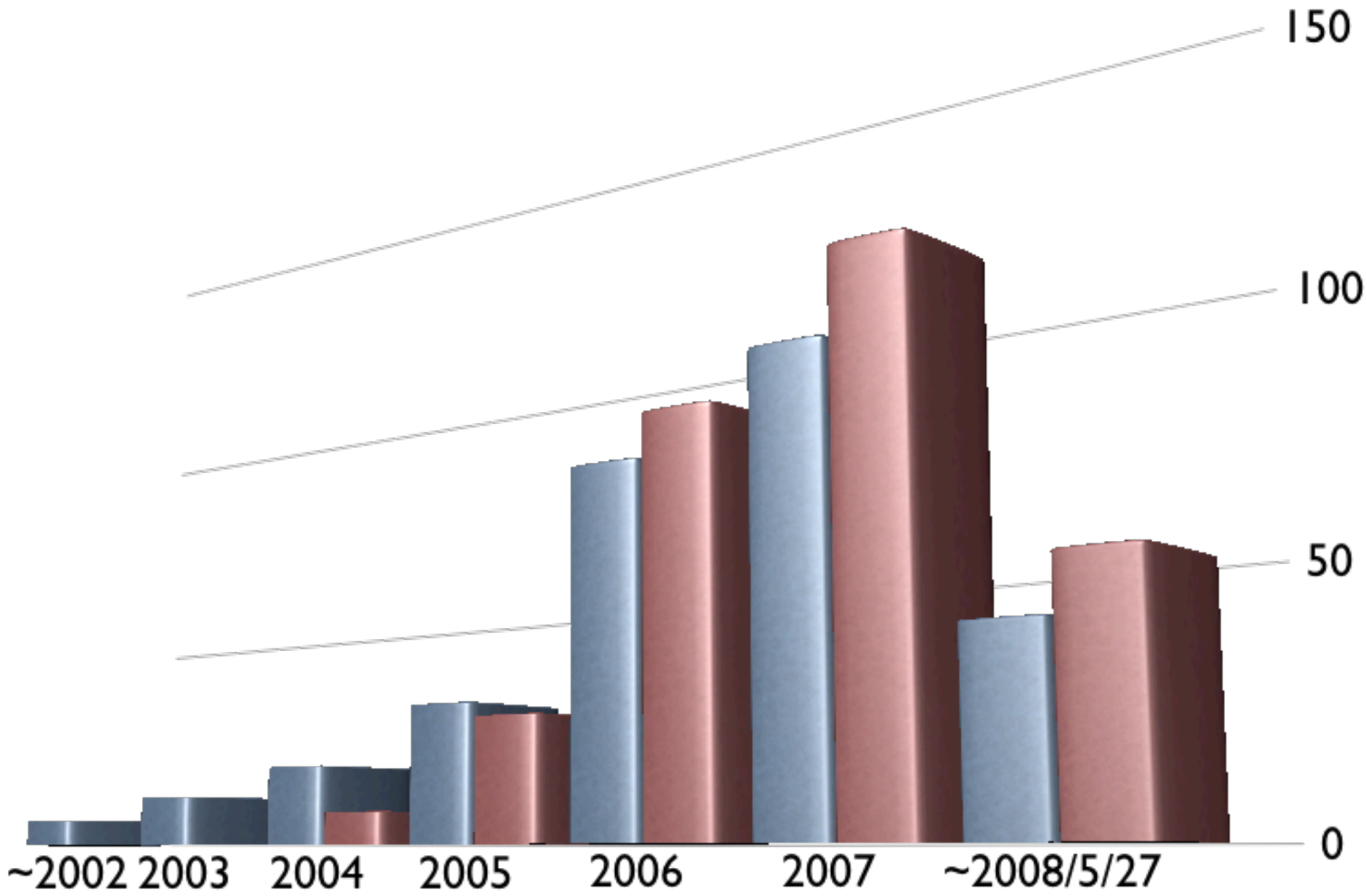
⇨ New inputs from experiments/other theoretical tools!

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 η/s
- Kovtun - Son - Starinets, PRL94 (2005) 111601: universality of η/s

Example of mutual interactions

String Theory
"η/s = 1/(4π) for $\mathcal{N}$=4 SYM"

RHIC
"RHIC results close to the value!"

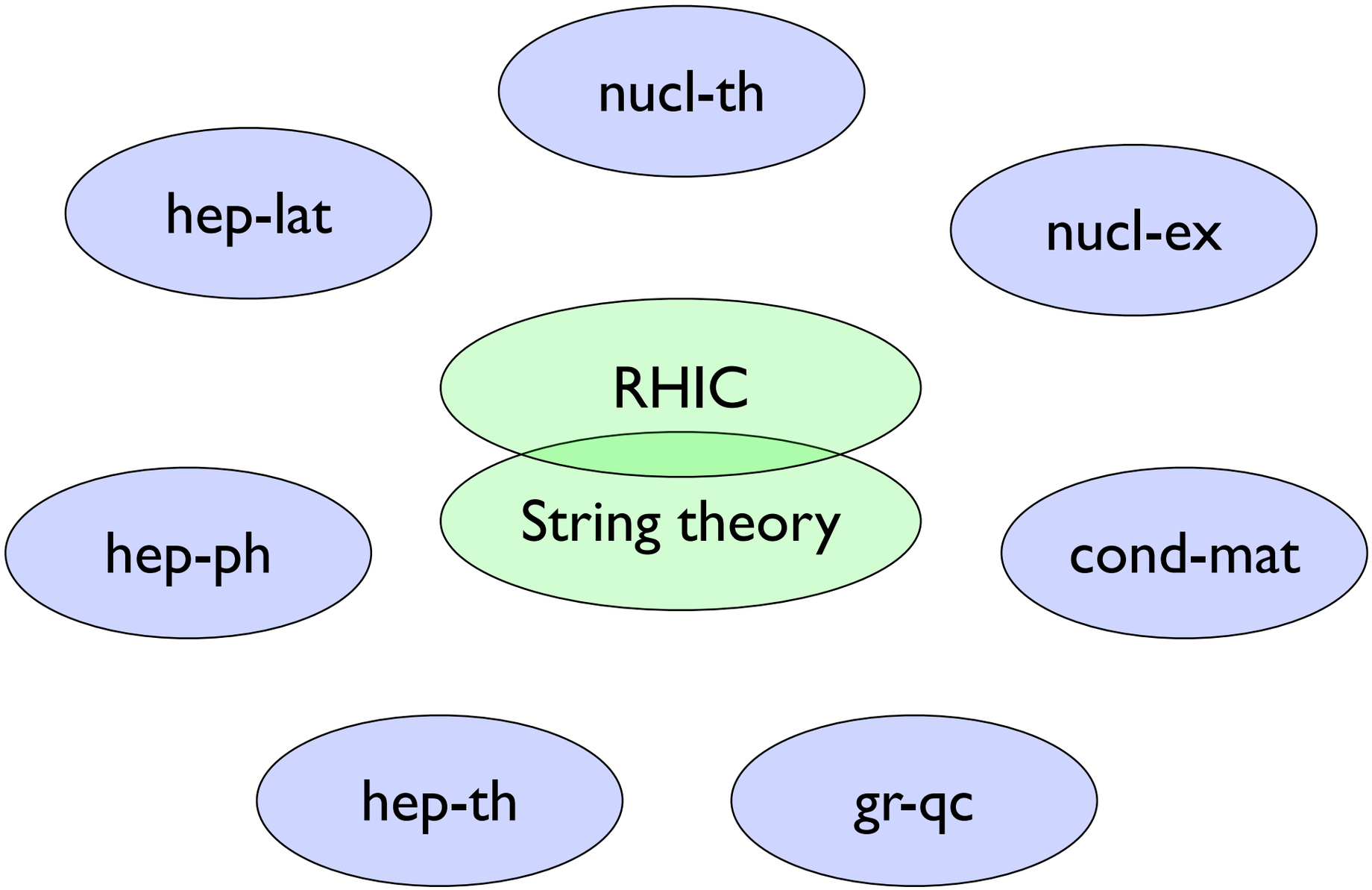
String Theory
"Let's study η/s more generically"
"The ratio is universal"

RHIC
"Look at RHIC results more carefully"

?

String Theory

At least 7 arXivs are involved!



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 ← 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 η/s

- η/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

$$\eta \propto (\text{mean free path}) \propto 1/\sigma_{cross}$$

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

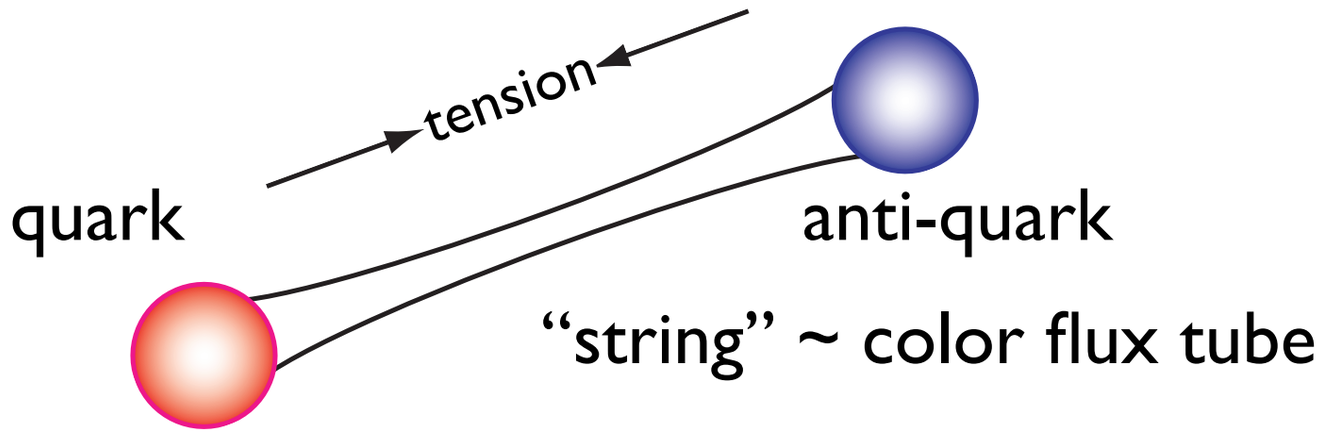
Failed due to 10-dimensions, existence of graviton etc.

'73: Asymptotic freedom → QCD established!

But string: diehard

'74: string reincarnated as a unified theory.

Yoneya, Scherk - Schwarz



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

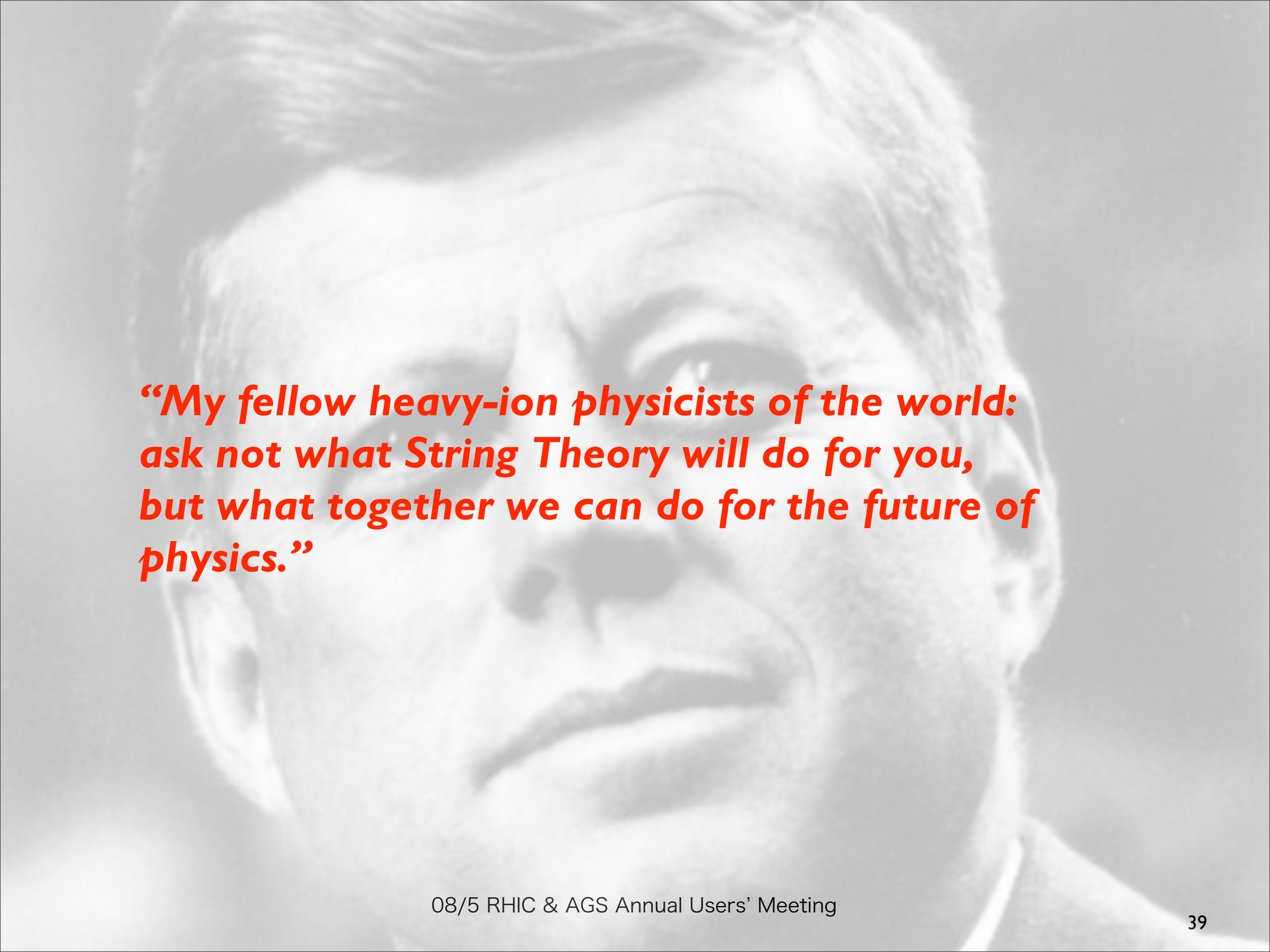
Works in the direction appear from time to time.

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
- "November revolution" J/ψ — 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."

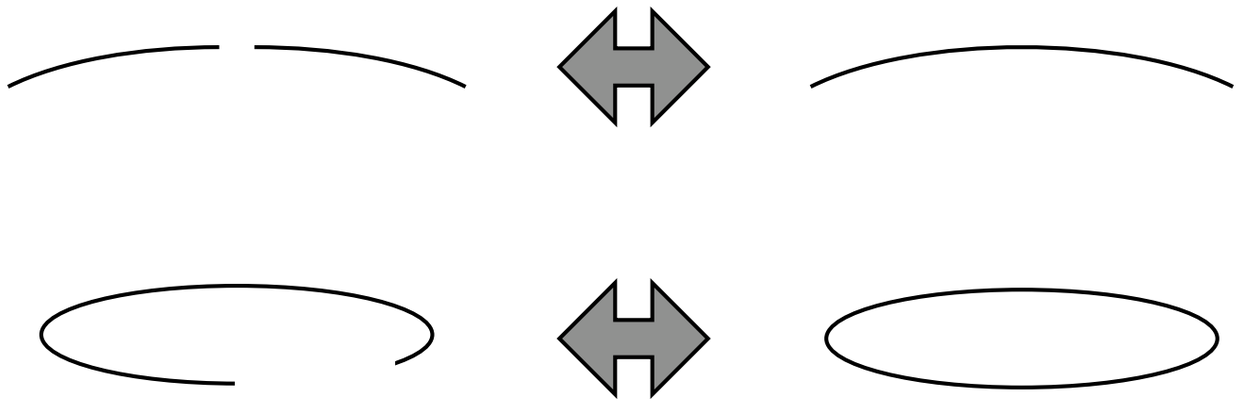
Further readings

- For English audiences
  - My reviews: hep-ph/0701201, *Nature Physics* (May 2007)
  - Son & Starinets: 0704.0240 [hep-th]
  - Mateos: 0709.1523 [hep-th]
  - Myers & Vazquez: 0804.2423 [hep-th]
- For Japanese audiences (in Japanese)
  - My book: *Invitation to String Theory* (June 2008, in press)
  - My reviews: *Butsuri* (Sep. 2007), *Suuri Kagaku* (July 2006, Feb 2008)
  - *Parity* magazine special issue (Aug. 2008, in press)

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

$$\begin{cases} \eta \sim \rho \bar{v} l_{mfp} \\ s \sim \dfrac{\rho}{m} \end{cases}$$

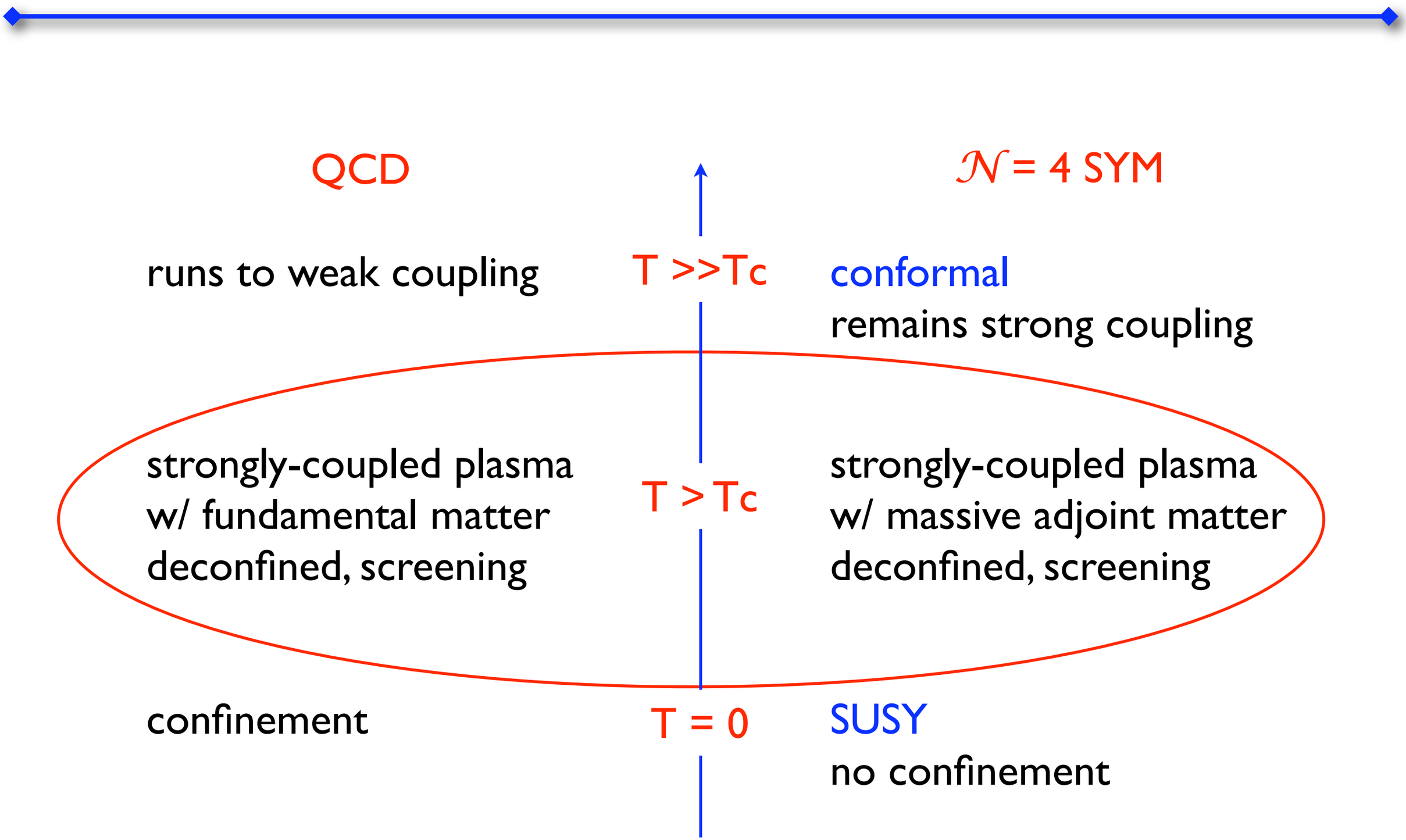
$$\frac{\eta}{s} \sim m \bar{v} l_{mfp} > \hbar$$

$$\Rightarrow l_{mfp} > \lambda_{deBroglie}$$

⇒ valid for fluids w/ quasiparticle description

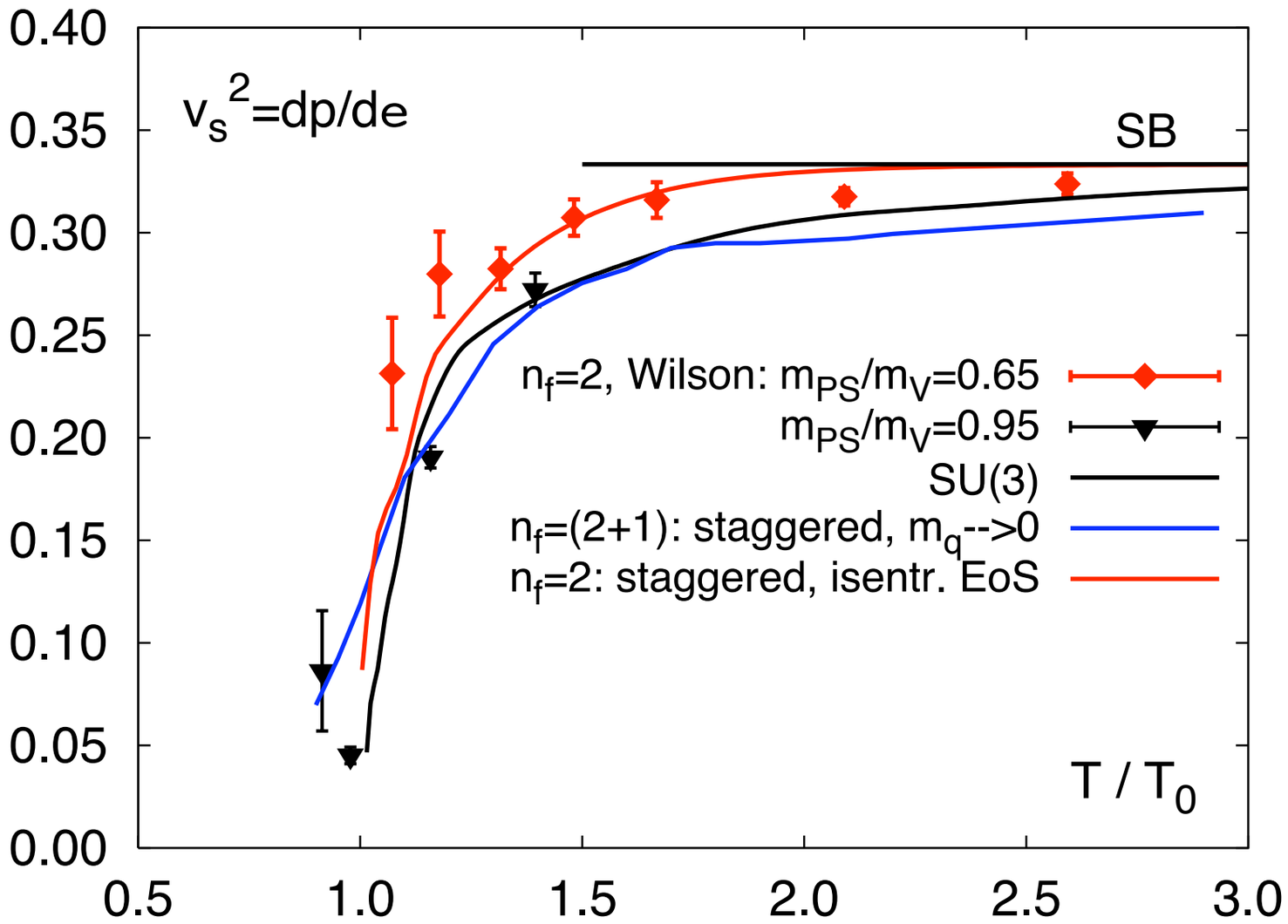
So, the existence of viscosity bound itself is natural
But why the value is 1/(4π) and why gauge theory saturates the bound?

QCD vs $\mathcal{N}$=4



Speed of sound

Adapted from F. Karsch, hep-lat/0601013



nf=2: Ali Khan et al. hep-lat/0103028
pure SU(3): Boyd et al. (1996)
staggered: Aoki et al. hep-lat/0510084
Ejiri et al. hep-lat/0512040

QCD: nearly conformal for T>2Tc?

conformal → $T^\mu{}_\mu=0$
→ $\varepsilon+3p=0$
→ $v_s^2 = 1/3$

SYM ⇔ BH

Thermodynamics "BH thermodynamics"

Temp	=	Hawking temp
Energy		BH mass
Entropy		BH entropy

For $\mathcal{N}=4$ SYM

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

DOFs Stefan-Boltzmann

Disagree? Compare the same thing!

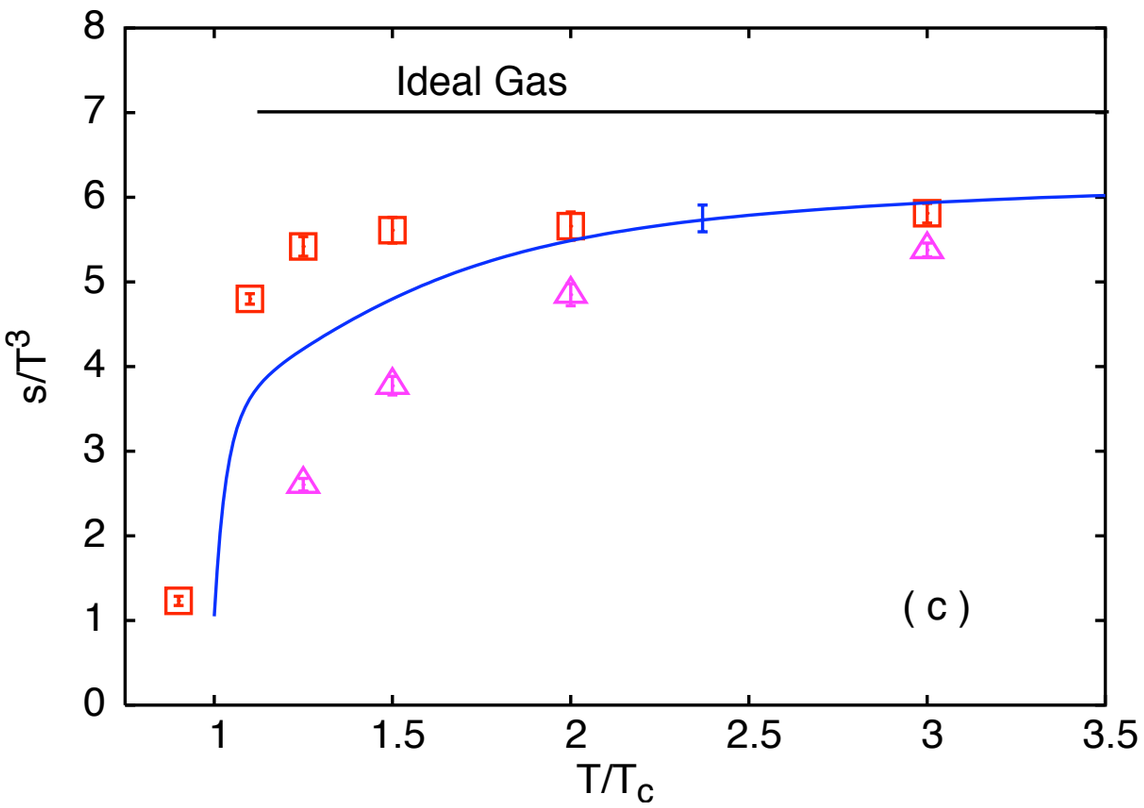
weak coupling result (as gauge theory) strong coupling result (as gauge theory)

strong coupling effect

Entropy

Lattice results for pure YM:

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



S ~ (70-80% of S_{free})

cf. $\mathcal{N}$=4 SYM:

$$S_{BH} = \frac{3}{4} S_{free}$$

Gubser - Klebanov - Peet (1996)

String theory & real life

- AdS/QCD, AdS/QGP
- String Landscape, KKLT

  ⇦ small positive cosmological constant

  Bousso - Polchinski (2000)
  Kachru - Kallosh - Linde - Trivedi (2003)
  Susskind (2003)

- Cosmic string

  Copeland - Myers - Polchinski (2003)

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