Gauge theory plasmas from string theory

M. Natsuume (KEK)

Based on many people's works
and our works in collaboration w/
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06/10 APS/JPS2: Hot & dense QCD

APS annual meeting 2005

Press release (April 18, 2005):

"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*."
"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

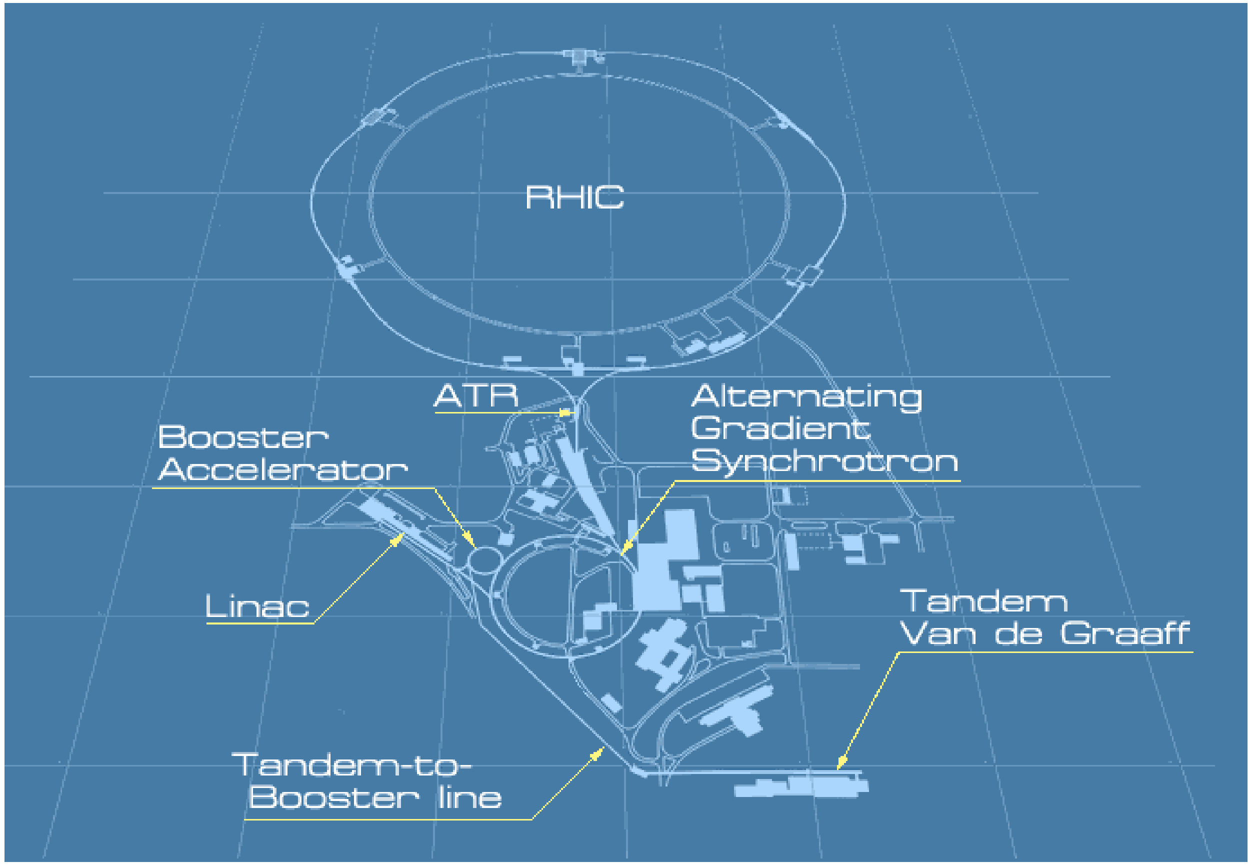
How is string theory related to quark-gluon plasma?

RHIC complex

RHIC: Relativitistic Heavy Ion Collider (Bookhaven National Nab.)

heavy ion:
  e.g. ^{197}Au

Goal:
realize deconfinement transition
(quark-gluon plasma)



http://www.bnl.gov/RHIC/RHIC_complex.htm

A STAR event

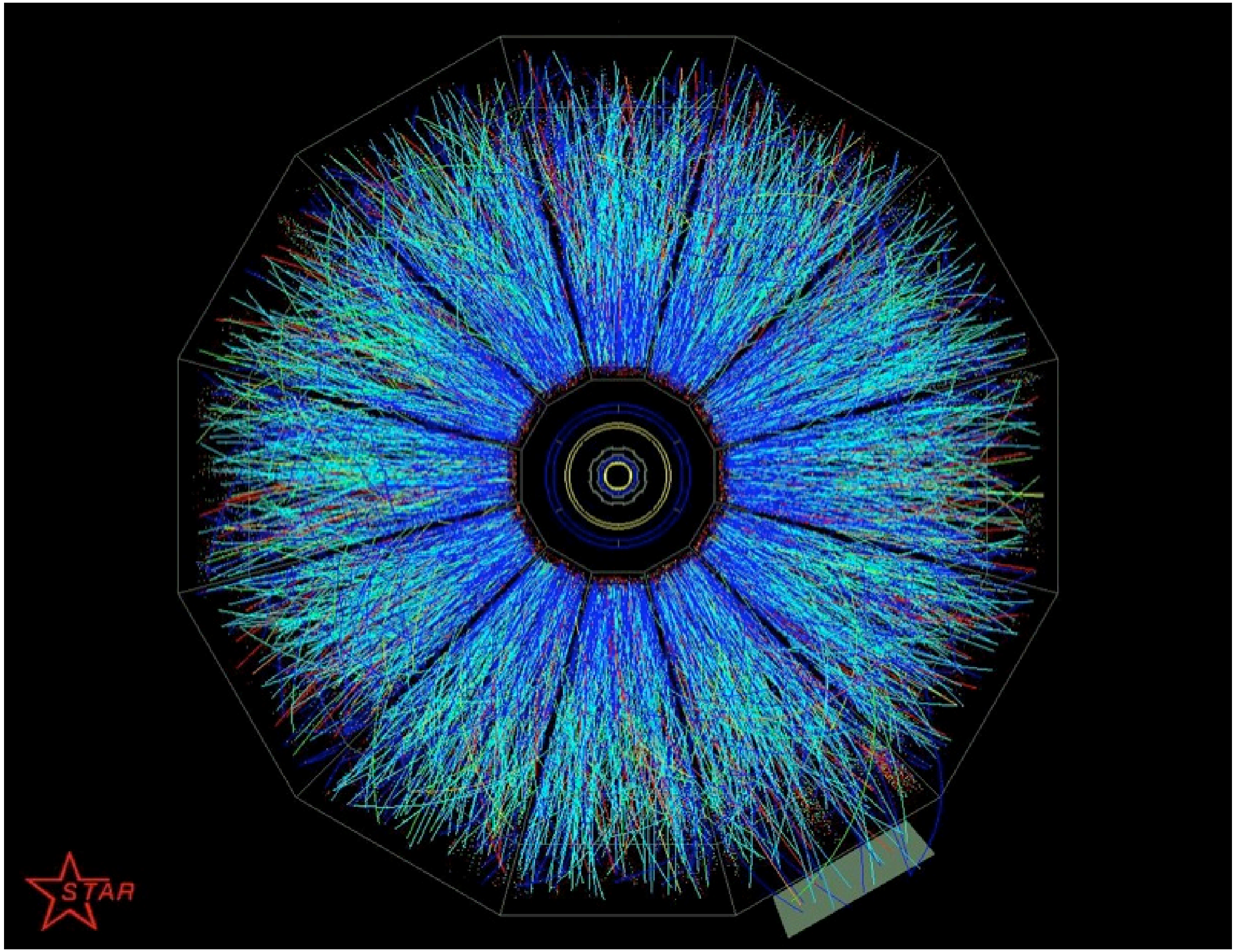


Photo courtesy of the STAR Experiment at Brookhaven National Laboratory's Relativistic Heavy Ion Collider

Difficulties

It is not an easy job to confirm QGP formation because ...

- Many particles involved, mostly strongly-interacting particles
- What we observe: only by-products
- No real theory to analyze (QCD: still strongly coupled)

⇒ genuine signatures of QGP?

- Low viscosity (elliptic flow)
- Jet quenching
- J/ψ suppression

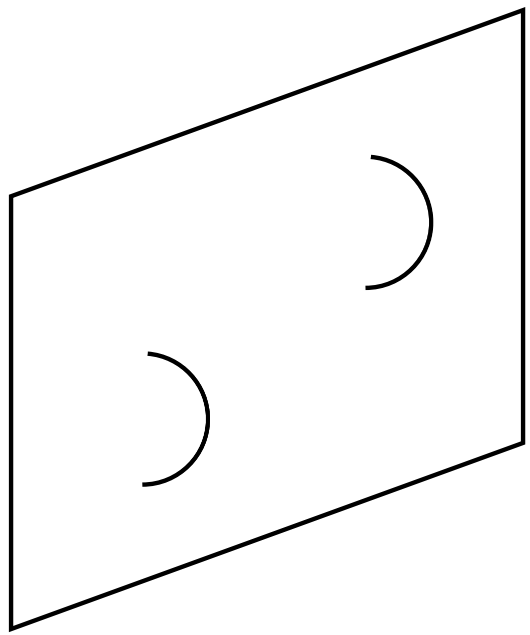
Plan

- A 10-minute course of string theory
- Small shear viscosity
- Jet quenching
- J/ψ suppression

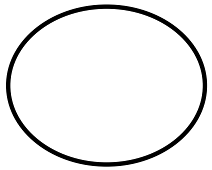
Gauge Theories
and
Black Holes

Open string and closed string

open string: gauge theory



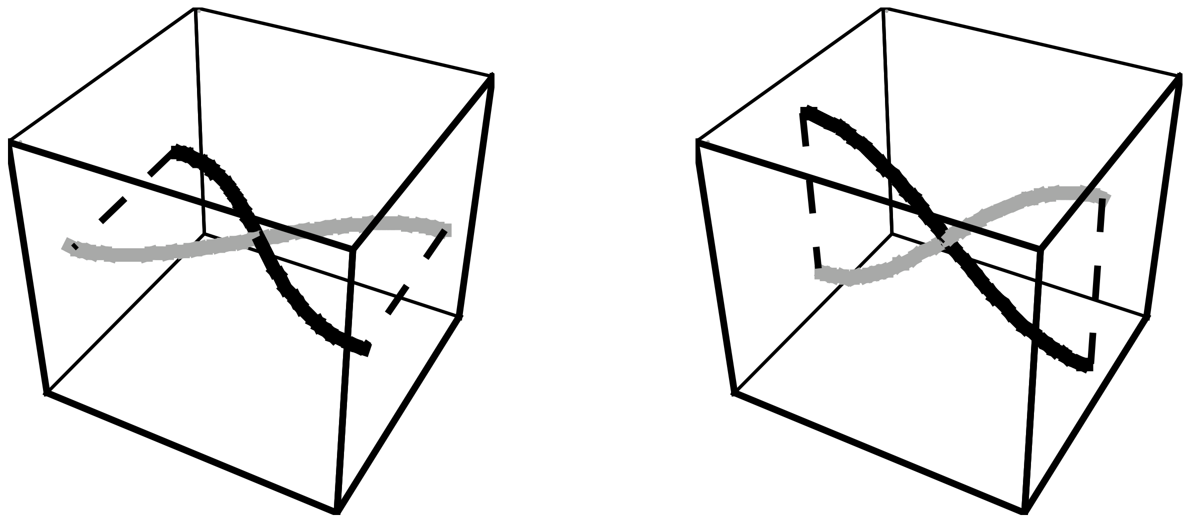
closed string: graviton



D-brane
“boundary”

“bulk”

Open string: gauge theory

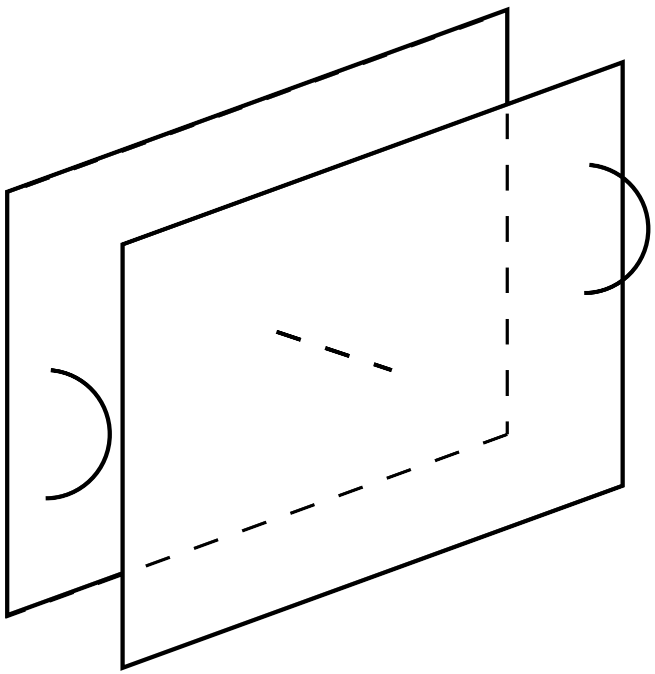


2 degrees of freedom → photon's polarizations

Yang-Mills

If there are N D-branes, open string can connect in various ways

→ SU(N)



Open string: bounded on D-brane → gauge theory localized on D-brane

p-dimensional spatial extension → Dp-brane

p=0	point-like
p=1	string-like
p=2	membrane-like
p=3	… ⇨ (1+3)-dim
…	

Consider D3-brane to mimic QCD

String theory: more than a gauge theory → gravity coupled

D-branes are described simply as a gauge theory?

D-brane and spacetime

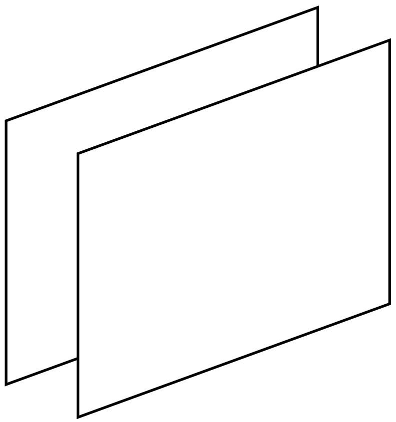
How D-branes curve spacetime?

$$\phi_{Newton} \sim \frac{GM}{r}$$

GM: measures the curvature

$$G \sim g_s^2$$

$$M \sim N / g_s \qquad \text{for D-brane}$$



$\Rightarrow \qquad GM \sim g_s N$

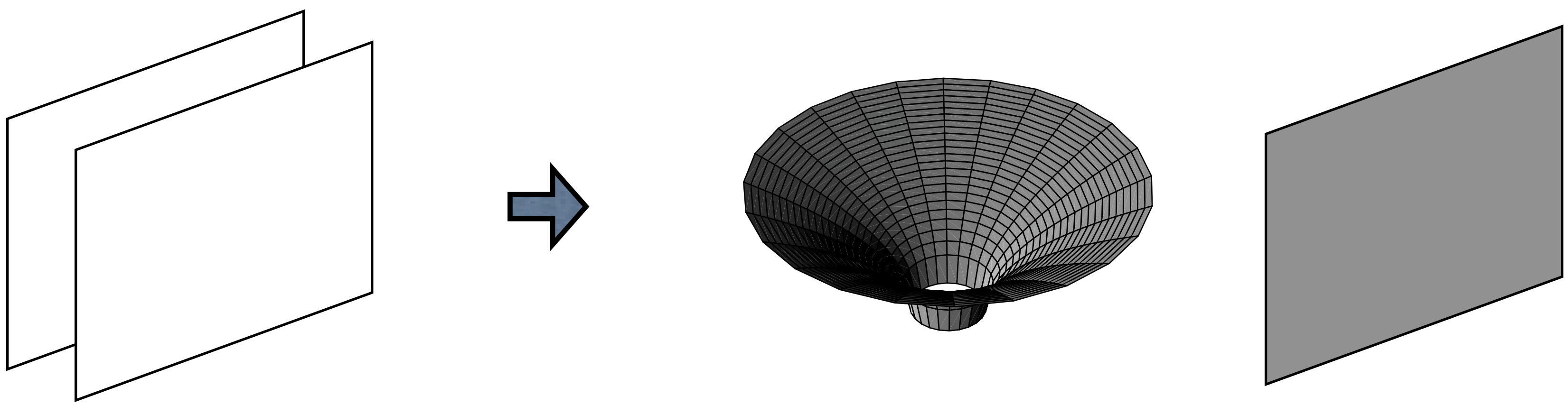
$\Rightarrow$ Spacetime remains flat as long as $g_s N << 1$

SYM is a good description

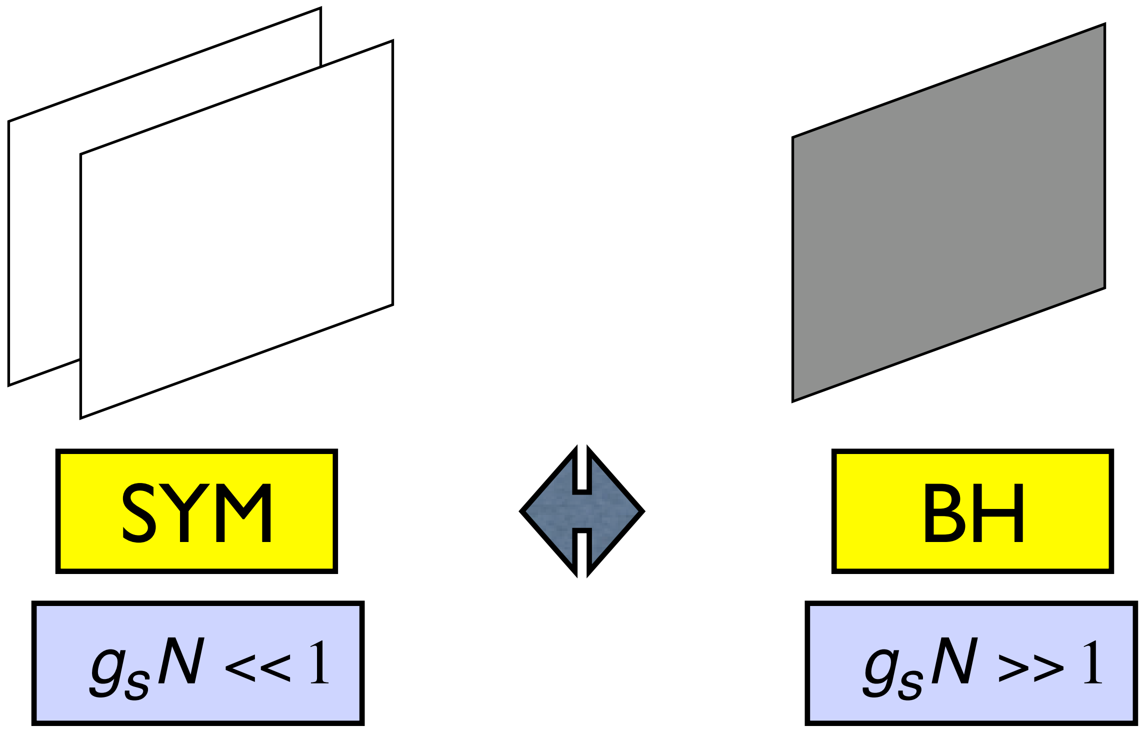
Large-N limit

When $g_s N >> 1$, D-branes strongly curve the spacetime.

BH is a good description



black hole "black brane"



$g_s \sim g_{YM}^2$ so this is just large 'tHooft coupling (strong coupling limit)

More refined version: AdS/CFT dualities

(Finite temperature) AdS/CFT:

N=4 SYM at finite temp. ⇔ Type IIB on (Schwarzschild-AdS_5 BH)×S^5

⇩ thermal

⇩ thermal due to the Hawking radiation

We use this duality & its variations
Motivated from the D3-brane

FAQs

- AdS/CFT only for CFTs?

  No. The word "gauge/gravity duality" is more proper

  N=2: N=2*, ...
  N=1: Klebanov-Strassler, Polchinski-Strassler (N=1*), ...

- Why supersymmetric gauge theories have anything to do with real QCD?

  A: universality

  Compute properties which are universal among gauge theories

- BHs here are just like usual Schwarzschild BHs?

No, at least in 2 respects

(1) BHs here are noncompact objects (often)

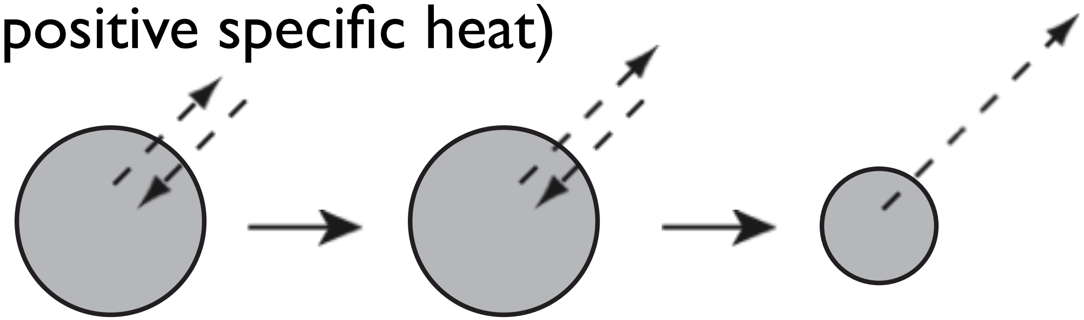
Black brane: noncompact horizon ↔ YM in noncompact space

BH: compact horizon ↔ YM in compact space

(2) impossible to keep thermal equilibrium for usual BHs

→ negative specific heat $C=dM/dT<0$
(Smaller BHs have higher temperature)

→ Reason why AdS BHs (positive specific heat)

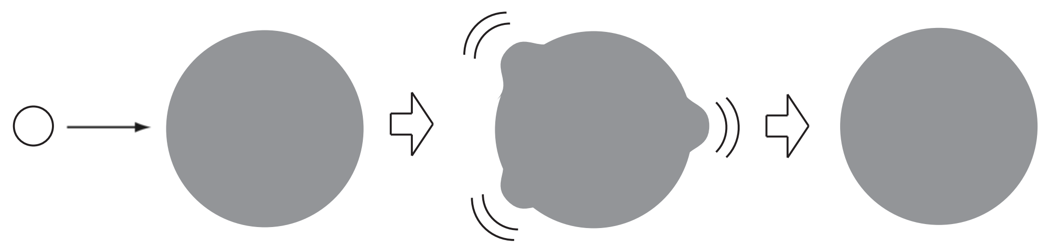


Gauge theory hydrodynamics
and
string theory

BH and hydrodynamics

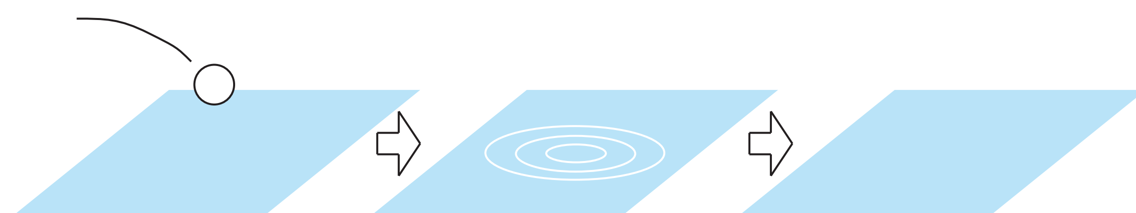
- According to RHIC experiments, QGP behaves like a liquid. AdS/CFT implies that a BH behaves like a liquid as well.
- Then, plasma viscosity must be calculable from BHs.

BH:



The diffusion: consequence of BH absorption

Water pond:



The diffusion: consequence of viscosity

Viscosity

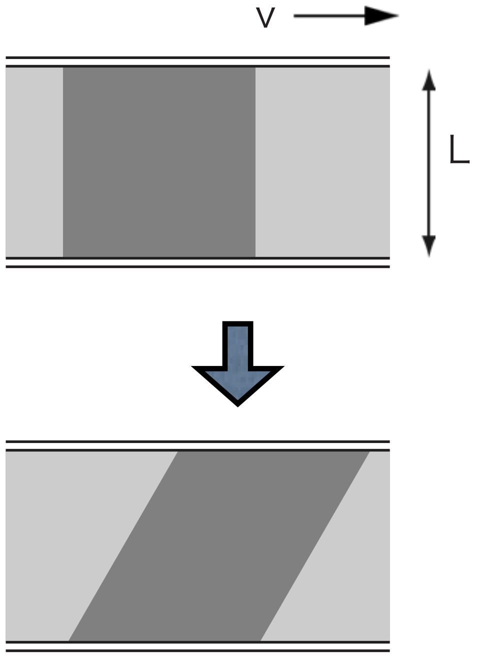
Fluid bet. 2 plates and move the upper plate

The lower plate experiences a force

$$\frac{F}{A} = \underline{\eta} \frac{v}{L}$$

↓

(shear) viscosity



Universality of shear viscosity

In Gravity, the diffusion occurs by BH absorption

shear viscosity ⇔ absorption cross section by BH

= horizon area

Das - Gibbons - Mathur (1997)

entropy ⇔ horizon area

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

Each relation is a general result, so this is

A universal result

Kovtun - Son - Starinets (2004)

The claim:

Gauge theory plasmas which have BH duals:
universal low value of shear viscosity (over s)
at large 't Hooft coupling (for zero chemical potential)

cf. Water under normal conditions: $$\frac{\eta}{s} \sim (3\times 10^3)\times\frac{\hbar}{4\pi k_B}$$

Gauge Theory		Gravity
N = 4 SYM	⇒	D3-brane (SAdS)
"shear viscosity" is universal		⇕
QCD	⇐ (dotted)	not known yet

→ η/s can be compared w/ experiments!

Comparison w/ Experiment

RHIC may suggest $\frac{\eta}{s} \sim 0.1 \times \frac{\hbar}{k_B}$? Teaney (2003)

Close to the AdS/CFT value: $\frac{\eta}{s} = \frac{\hbar}{4\pi k_B}$

cf. pQCD: $\frac{\eta}{s} \sim O(1) \times \frac{\hbar}{k_B}$

$T \sim O(\Lambda_{QCD})$: QCD still strongly-coupled

so the duality may be useful to analyze QGP

if they really form QGP and if hydrodynamic interpretation is correct

Chemical potential issue

Gauge theory at large ‘t Hooft coupling: universality of shear viscosity

However, all proofs of the universality fail w/ chemical potential

Kovtun - Son - Starinets, 0309213; 0405231
Buchel - Liu, 0311175
Buchel, 0408095

No known result for η/s

What happens to the universality?

Baryon is not easy to realize in AdS/CFT

Simple alternative

Charged BHs instead of neutral BHs

cf. 1st law of BH thermodynamics: $dM = TdS + \Phi dQ$

Not a realistic finite density → $U(1)_R$ charge: relates supercharges but the issue is universality

Shear viscosity was computed by 4 groups

Mas, 0601144
Son - Starinets, 0601157
Saremi, 0601159
Maeda - Natsuume - Okamura, 0602010

The result is $$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B}$$ again!

→ universality even at finite baryon # density?

Heavy quark in medium

Heavy quark in medium

- Jet quenching

Liu - Rajagopal - Wiedemann, hep-ph/0605178
Herzog et al., 0605158
Casalderrey-Solana - Teaney, hep-ph/0605199
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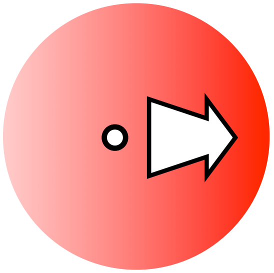
In medium, a jet is suppressed

→ energy loss rate of heavy quark



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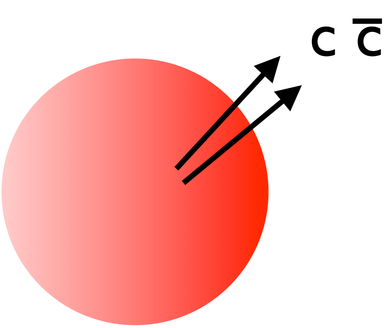
Chernicoft - Garcia - Guijosa, 0607089

In medium, charmonium formation is suppressed due to the Debye screening

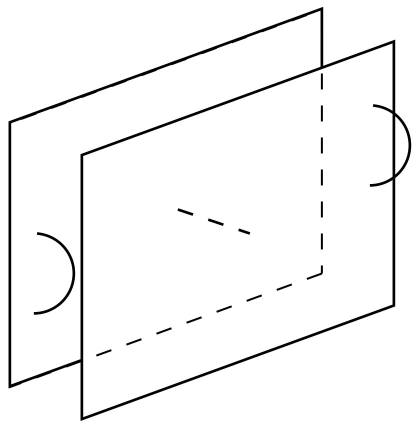
$c\bar{c}$ pair: not at rest relative to plasma

→ screening length: velocity-dependent

Chu - Matsui (1989)

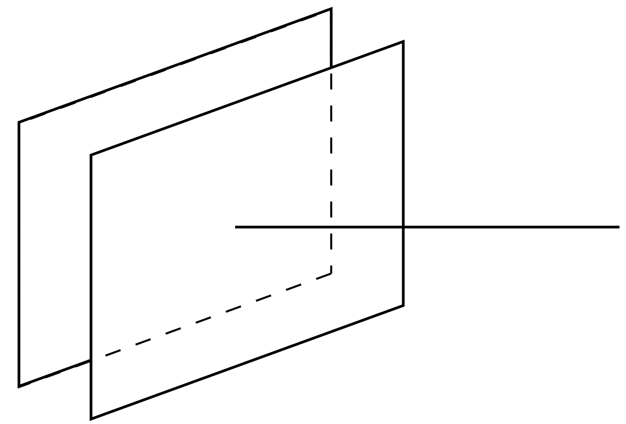


Heavy quark in AdS/CFT



→ N^2 possibilities
→ adjoint reps. of SU(N)
(e.g. gauge field)

infinitely long string



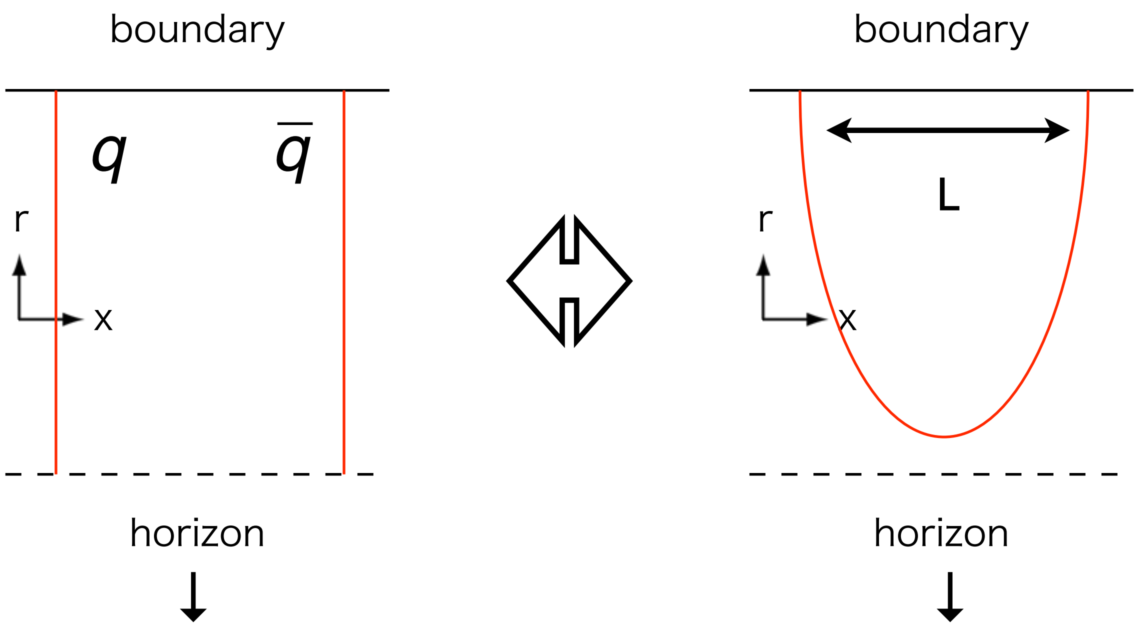
→ N possibilities
→ fundamental reps.
"quark"

Extension & tension
→ heavy quark

Heavy quark potential

Such a string has been used widely to measure heavy quark potential

Maldacena;
Rey - Yee (1998)



not lowest energy config. energy difference: potential

But at finite temp., isolated strings become favorable beyond some L
→ Debye screening

Rey - Theisen - Yee
Brandhuber - Itzhaki - Sonnenschein - Yankielowicz (1998)

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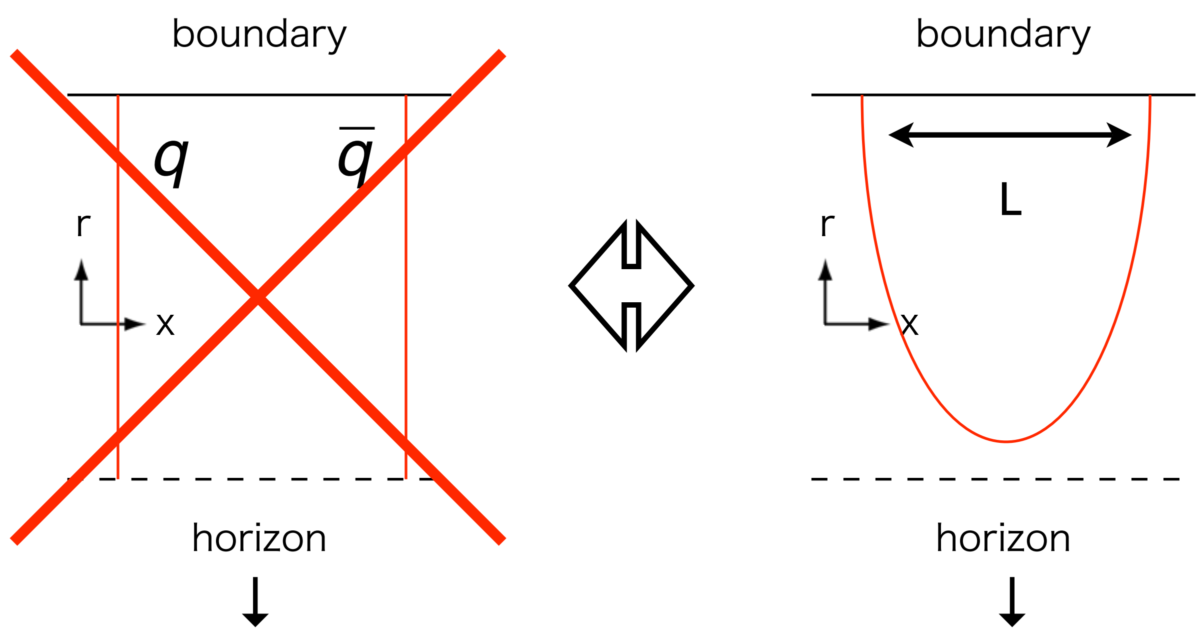

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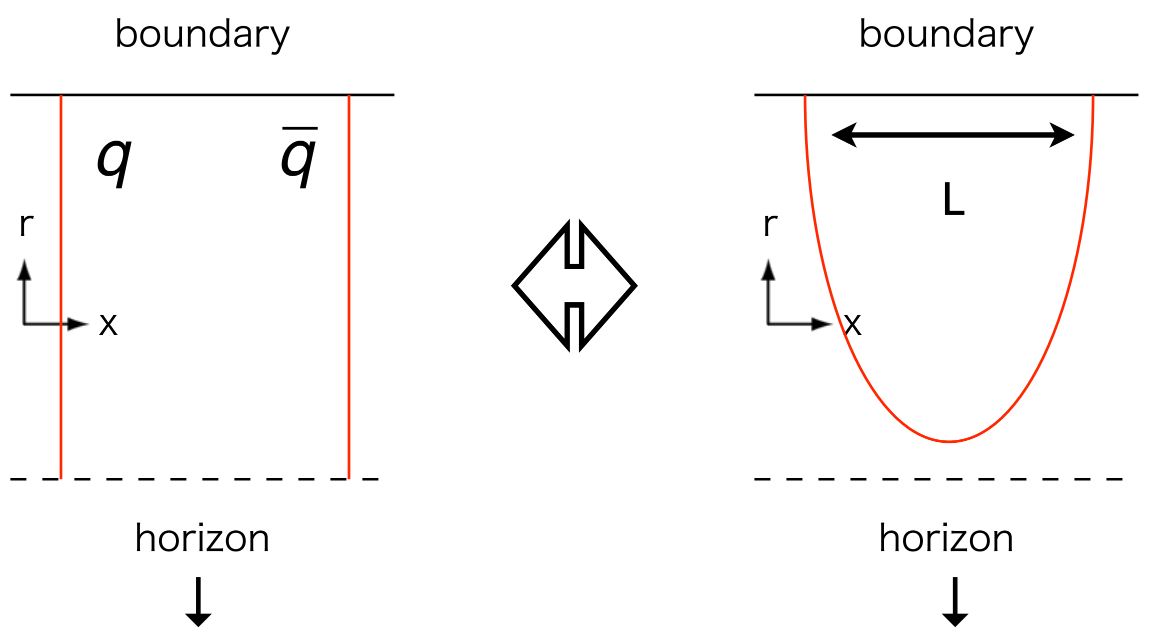

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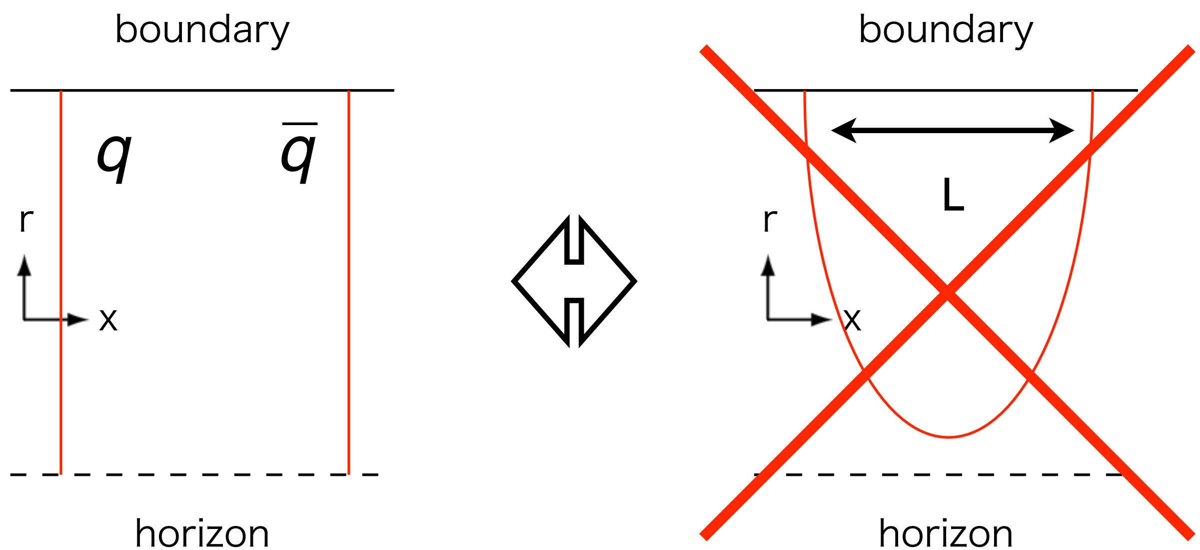

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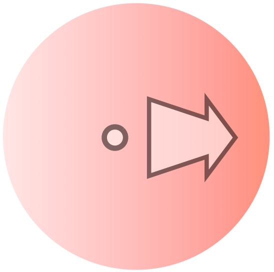

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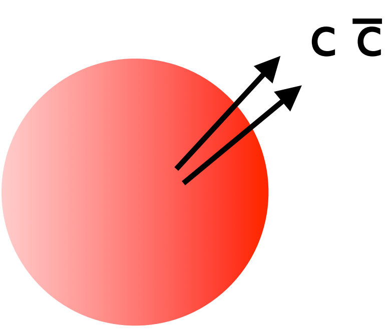


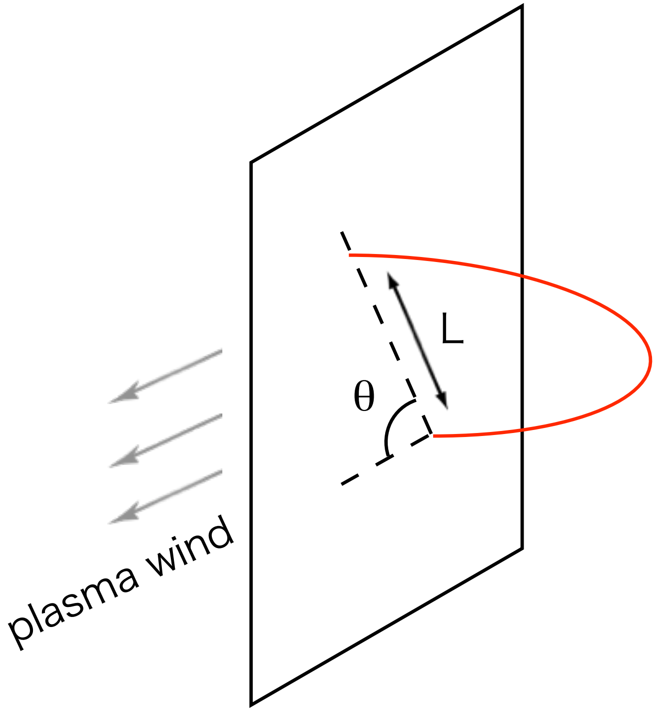
Velocity dependence of screening

Consider in the $q\bar{q}$ rest frame i.e. plasma flow → boost BHs

For N=4 SYM,

$$L_s \propto \left(\frac{1-v^2}{\varepsilon_0}\right)^{1/4} \sim \text{(boosted plasma energy density)}^{-1/4}$$

ϵ_0: unboosted density



Screening effect is stronger than v = 0 case

Ls: maximum at θ = 0, minimum at θ = π/2

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

The other gauge theories

Caceres - Natsuume - Okamura, 0607233; 0610nnn

The leading behavior in v seems universal

- In general (screening length) $\propto (1-v^2)^{\Gamma}$

  Γ determined by speed of sound: $4\Gamma = 1 - \frac{3}{4}(1-3c_s^2) + \cdots$

  conformal: $\Gamma = 1/4$

  nonconformal: $\Gamma < 1/4$

  QCD: $c_s^2 \sim 1/3 - 0.05$ (lattice) at 2Tc $\rightarrow 0.22 < \Gamma < 0.25$?

- Screening length at finite chemical potential: same as the one at zero potential for a given ϵ (at this order)

- θ-dependence: similar to N=4 SYM

Heavy quark in medium

- Jet quenching

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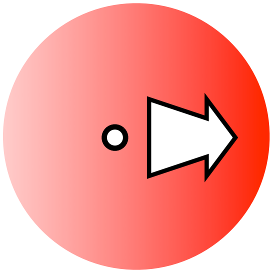

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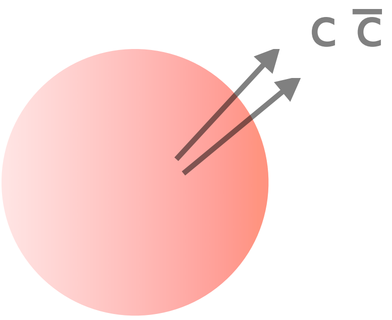
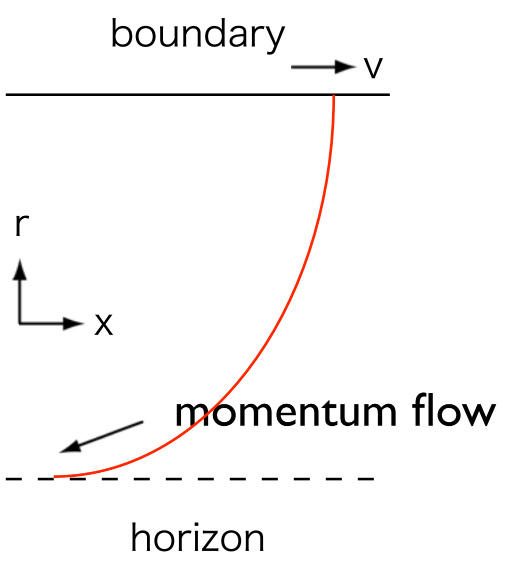


Jet quenching in AdS/CFT

Energy loss rate → move the string

$$\frac{dp}{dt} = -\frac{\pi}{2}\sqrt{\lambda}T^2 \frac{v}{\sqrt{1-v^2}} \quad \text{(for N=4 SYM)}$$



universality is lost, no finite large-λ limit (λ: ‘t Hooft coupling) ↔ η/s

Estimate w/ α_{YM} = 1/2 does not give an experimentally favored value.

This may suggest that one has to be careful to apply AdS/CFT to QGP.

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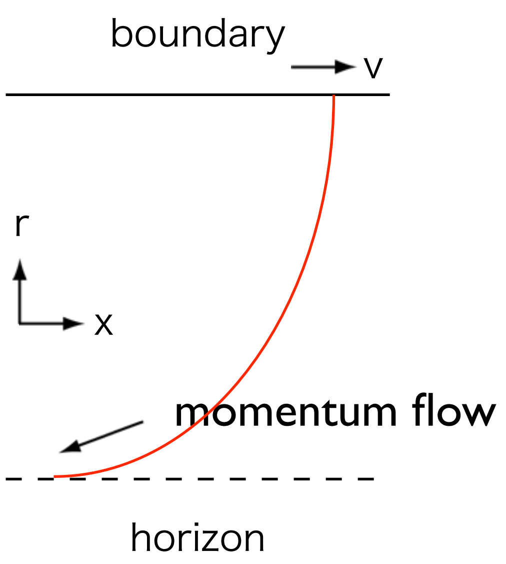

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Summary

- Currently, one can study mostly supersymmetric gauge theories from string theory. So, the connection w/ the real QCD is possible only thru

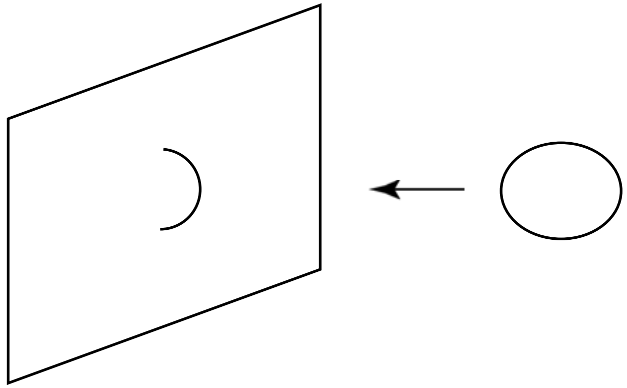
  universality

- Universality seems to hold even at finite chemical potential
- If the universality does not hold, one has to be careful (e.g. jet quenching)
- AdS/CFT may be useful to analyze experiments
  Experiments or the other theoretical tools (such as lattice) may be useful to confirm AdS/CFT
- Many loose ends

Appendix

Interaction of open & closed strings

Open & closed strings interact at boundary.



$$S_{\text{int}} \sim \int d^4x\ \phi F_{\mu\nu}^2 + h^{\mu\nu} T_{\mu\nu}^{YM} + \cdots$$

dilaton↑ ↑graviton

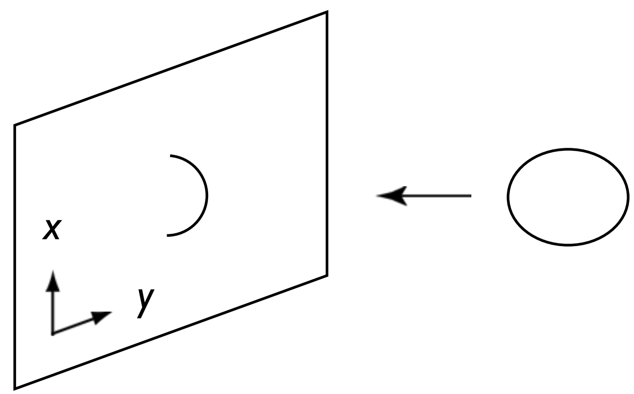
Bulk field fluctuations act as source of boundary fields

(graviton) (gluons)

⇨ GKP-Witten relation (definition of AdS/CFT)

Graviton decay rate: string pt. of view

Graviton decay rate (for h_{xy}): calculable using standard QFT formula

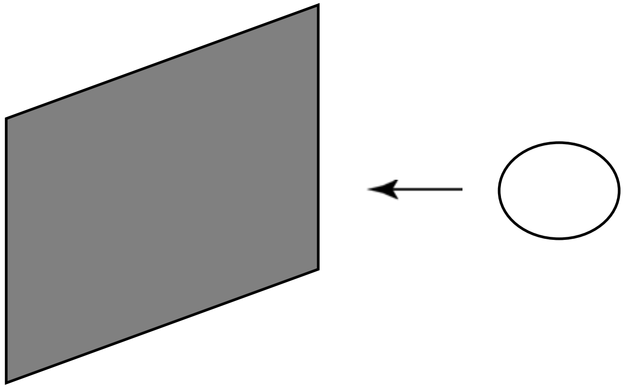


$$\sigma_{QFT} = \frac{1}{2\omega} \sum_{final} \int \frac{d^3 p_1}{(2\pi)^3 2\omega_1} \frac{d^3 p_2}{(2\pi)^3 2\omega_2} (2\pi)^4 \delta^4 (p_f - p_i) |M|^2$$

$$= \frac{8\pi G}{\omega} \int d^4 x \, e^{i\omega t} \left\langle \left[T_{xy}^{YM}(t,x), T_{xy}^{YM}(0,0) \right] \right\rangle$$

BH pt. of view

In BH description, this is absorption cross section of graviton.



Indeed (for D3 at zero temp.),

$$\sigma_{abs} = \sigma_{QFT}$$

$$\sigma_{abs} = \frac{8\pi G}{\omega} \int d^4x \, e^{i\omega t} \left\langle \left[T_{xy}^{YM}(t,x), T_{xy}^{YM}(0,0) \right] \right\rangle$$

BH↑ ↑YM