AdS/CFTからみたゲージ理論プラズマ

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Based on many people's works
and our works in collaboration w/
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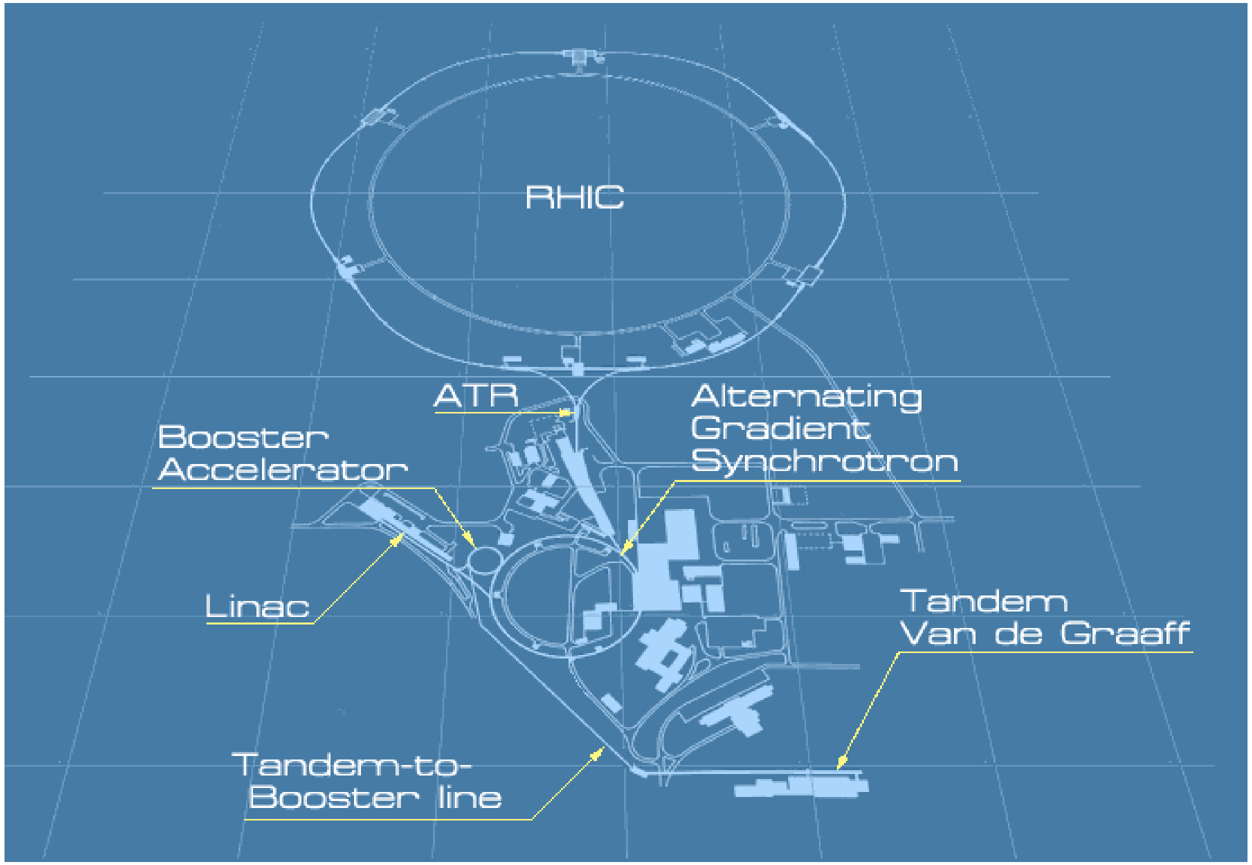
RHIC complex

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

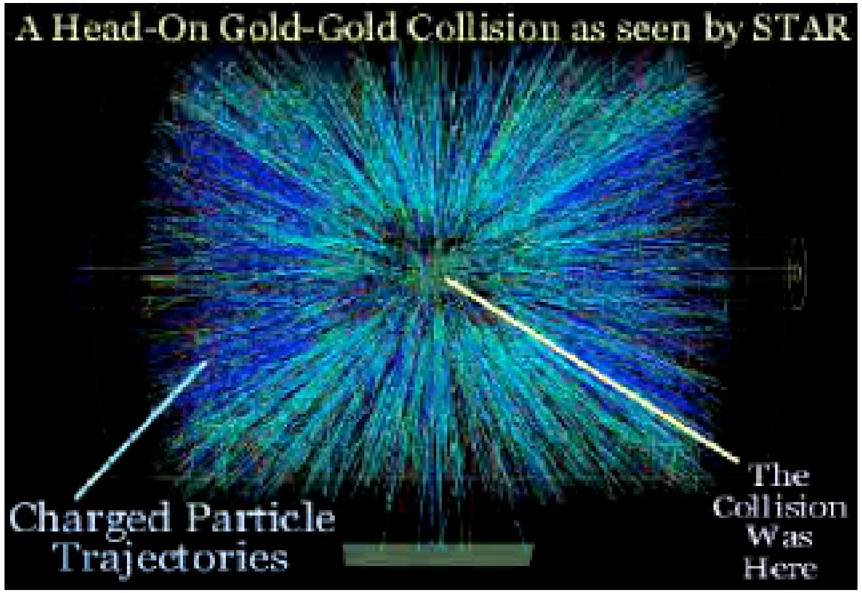
heavy ion:
e.g. ^{197}Au

Goal:
realize deconfinement transition
(quark-gluon plasma)



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

A STAR event



Animation 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

- Introduction
- Hydrodynamic issues
  - Viscosity of gauge theory plasma
  - Issue of chemical potential
- Jet quenching
- J/ψ suppression

References:
Kovtun, Son and Starinets, hep-th/0405231 and many others
Kengo Maeda, MN and Takashi Okamura, hep-th/0602010
Elena Caceres, MN and Takashi Okamura, hep-th/0607233; hep-th/0609nnn
Review: MN, 「数理科学」2006年７月号

Original AdS/CFT:

N=4 SYM ⇔ Type IIB on $\mathrm{AdS}_5\times\mathrm{S}^5$

Finite temperature AdS/CFT:

N=4 SYM at finite temp. ⇔ Type IIB on Schwarzschild-$\mathrm{AdS}_5\times\mathrm{S}^5$

thermal

thermal due to the Hawking radiation

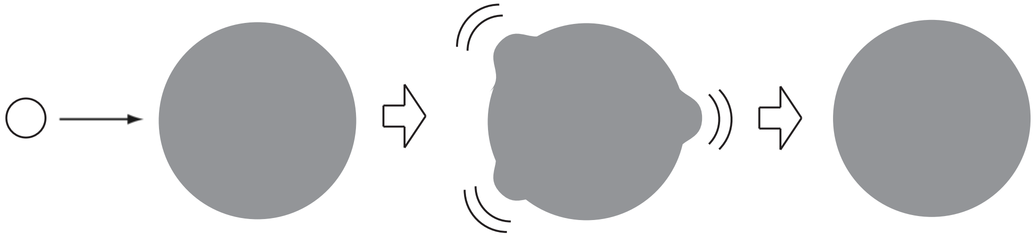
Motivated from the D3-brane

BH & hydrodynamics

BH and hydrodynamics

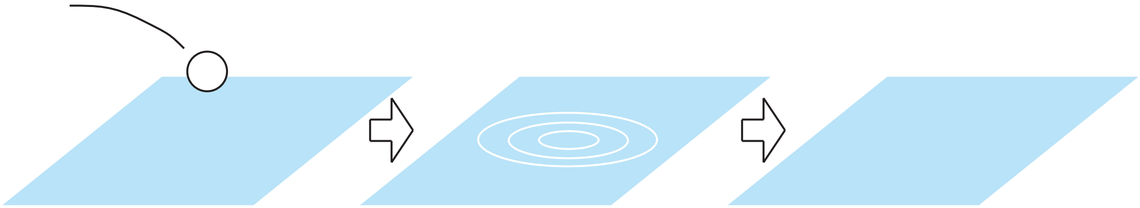
- According to RHIC experiments, QGP behaves like a liquid. AdS/CFT implies that a BH behaves like a liquid as well.
- Then, plasma viscosity must be calculable from BHs.

BH:



The diffusion: consequence of BH absorption

Water pond:



The diffusion: consequence of viscosity

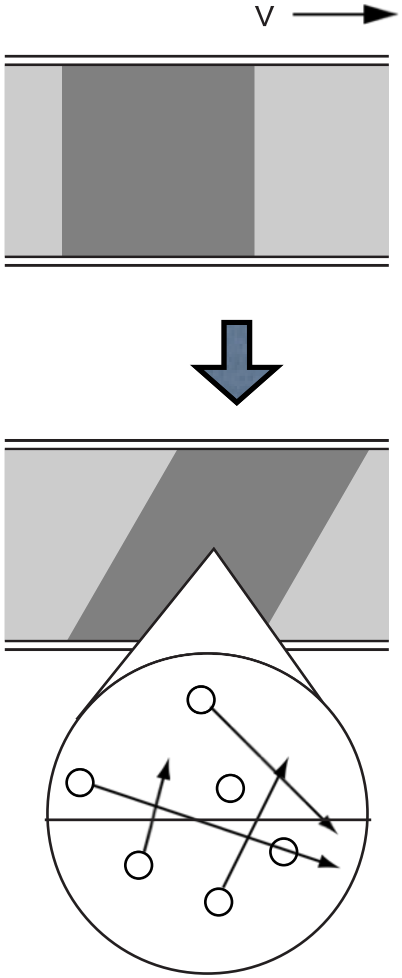
Viscosity

Fluid bet. 2 plates and move the upper plate

The lower plate experiences a force

$$\frac{F}{A} = \underset{\substack{\downarrow \\ \text{(shear) viscosity}}}{\underline{\eta}} \frac{v}{L}$$

microscopically: momentum transfer



Viscosity from AdS/CFT

Go back from SAdS to the D3
In gravity side, the diffusion occurs by BH absorption

shear viscosity ⇔ absorption cross section of graviton

(polarized parallel to brane) 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

Kovtun - Son - Starinets (2004)

A universal result

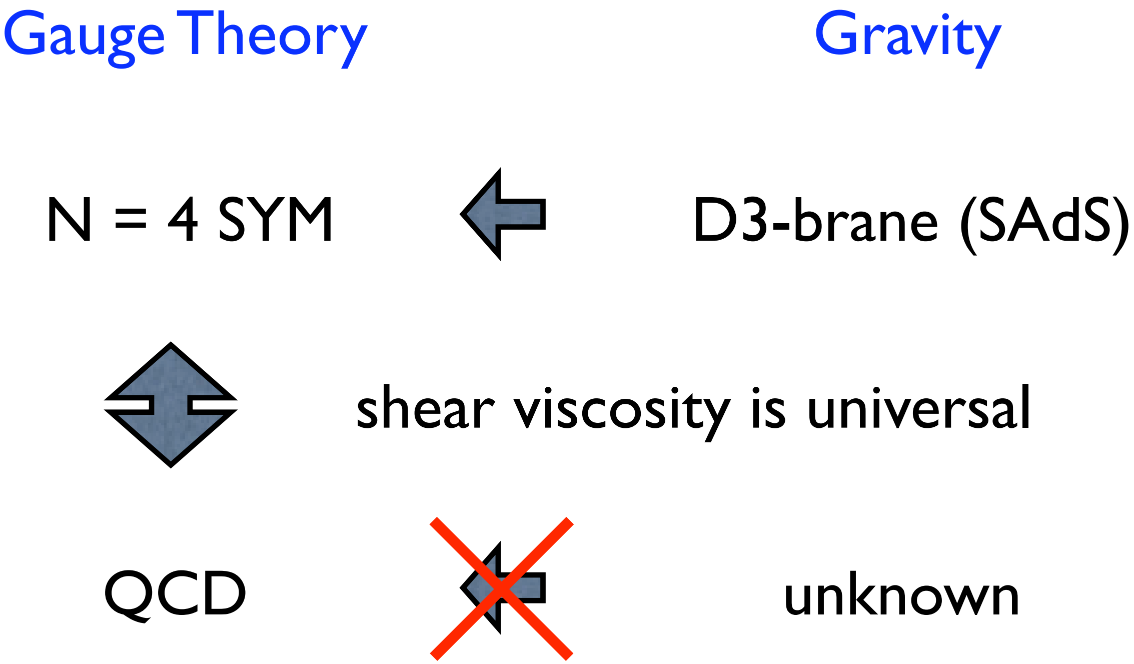
The claim:

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

indeed checked for many known gravity duals

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

unknown

→ η/s can be compared w/ experiments!

Comparison w/ Experiment

QGP experiment is underway at RHIC (Relativistic Heavy Ion Collider)

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

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

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

so the duality may be useful to analyze QGP

⚠ if they really form QGP and if hydrodynamic interpretation is correct

Behavior at weak coupling

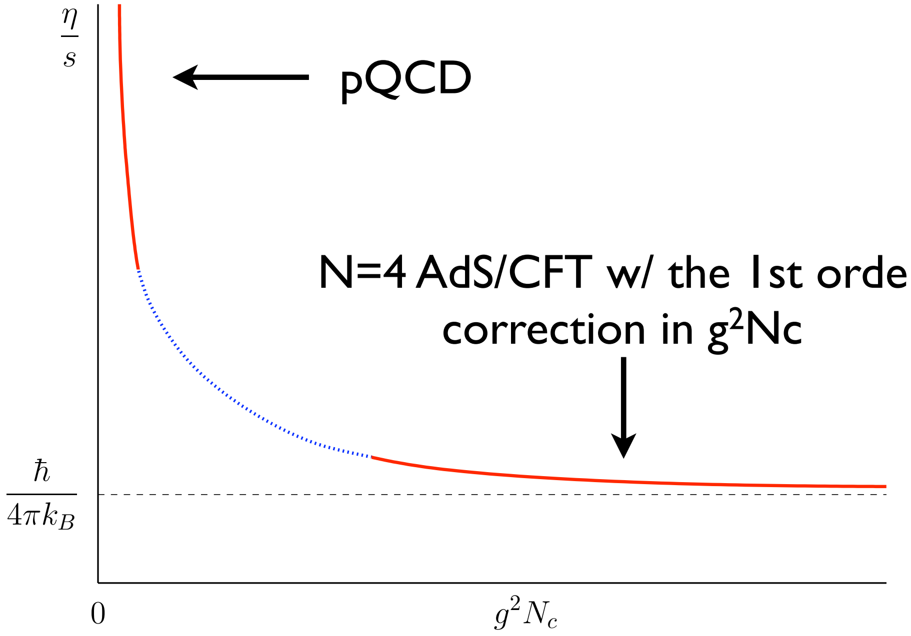
η ~ (mass density) × (mean velocity) × (mean free path)

↓ weak coupling

larger

Momentum transfer: more effective

At weak coupling $\frac{\eta}{s} >> \frac{\hbar}{4\pi k_B}$



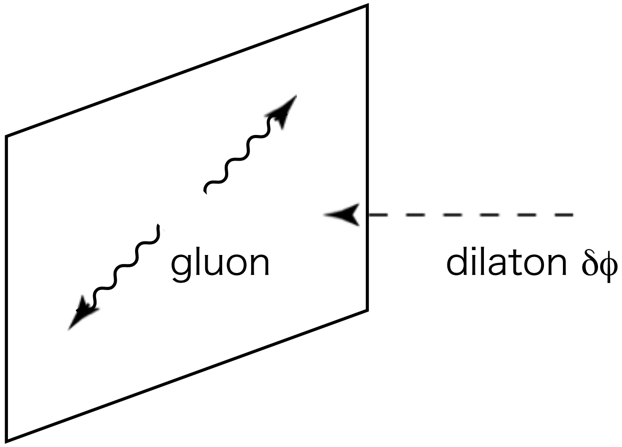
pQCD

N=4 AdS/CFT w/ the 1st order correction in g^2Nc

Adapted from hep-th/0405231

Interaction of bulk & boundary fields

Bulk & boundary fields interact



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

dilaton ↑ ↑ graviton

(e.g. expand DBI action)

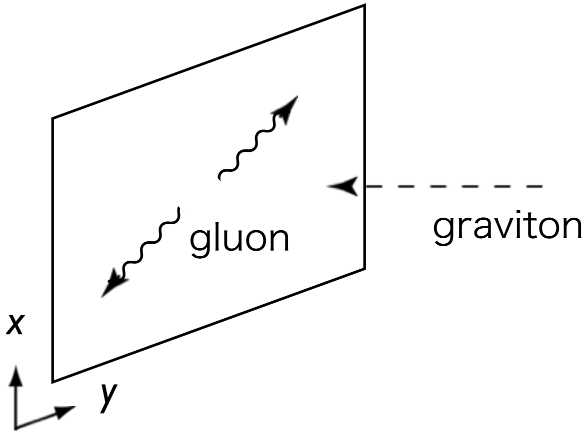
Bulk field fluctuations act as source of boundary fields

(graviton) (gluons)

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

Graviton decay rate: QFT pt. of view

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

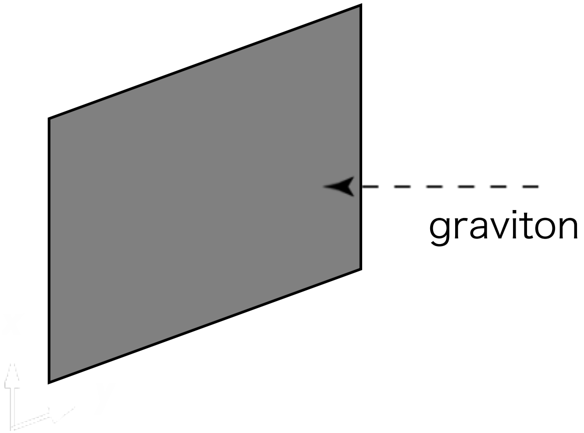


$$\sigma_{QFT} = \frac{1}{2\omega} \sum_{final} \int \frac{d^3 p_1}{(2\pi)^3 2\omega_1} \frac{d^3 p_2}{(2\pi)^3 2\omega_2} (2\pi)^4 \delta^4 (p_f - p_i) |M|^2$$

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

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

Viscosity vs absorption

Kubo formula:

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int d^4x \, e^{i\omega t} \left\langle \left[T_{xy}(t,x), T_{xy}(0,0) \right] \right\rangle$$

D3 & bulk computations yield the relation: Klebanov, 9702076

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

$$\Rightarrow \eta = \frac{\sigma_{abs}(0)}{16\pi G}$$

The relation holds for T=0 D3 (due to non-renormaliz. thm.), but is unclear for general BHs

BH: strong coupling limit of YM → strong coupling statement

We simply assume that the relation holds at strong coupling

chemical potential issue

Issue of chemical potential

Gauge theory at large 't Hooft coupling: universality of shear viscosity

But real experiments are done in finite baryon # density
(RHIC: ion - ion collision such as ^{197}Au)

How about nonzero chemical potential?

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

One simple way: charged AdS BHs instead of neutral BHs

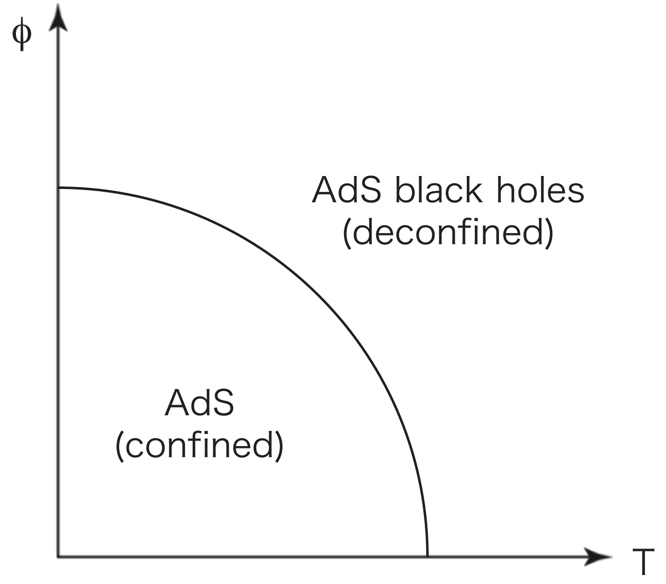
cf. 1st law of BH thermodynamics:

$$dM = TdS + \Phi dQ$$

(AdS BH) × S^5 → angular momentum along S^5
→ $U(1)_R$ charge
S^5 sym → internal sym → SYM R-sym SO(6)

3 equal charge (SO(6): rank 3) → RN-AdS BH

⚠ Not a realistic finite density



- But the phase diagram is intriguing

Chamblin - Emparan -Johnson - Myers (1999)

- The issue is universality

Shear viscosity for charged AdS BHs was computed by 4 groups

J. Mas, 0601144
Son and Starinets, 0601157
Saremi, 0601159
Maeda, Natsuume, and Okamura, 0602010

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

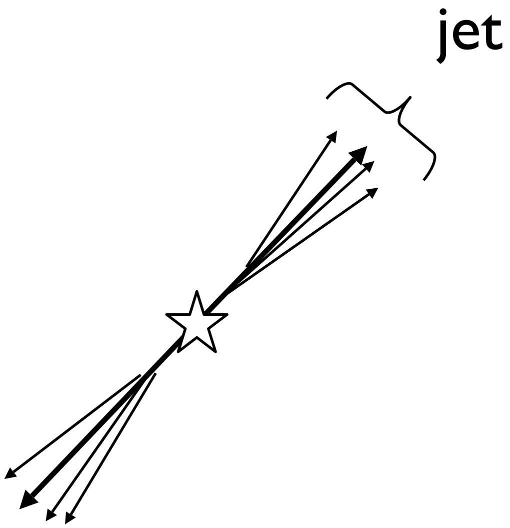
- The universality may hold even at nonzero chemical potential
  → universality even at finite baryon # density?
- η does increase but s has the same scaling (for fixed T)

Heavy quark in medium

Jet quenching

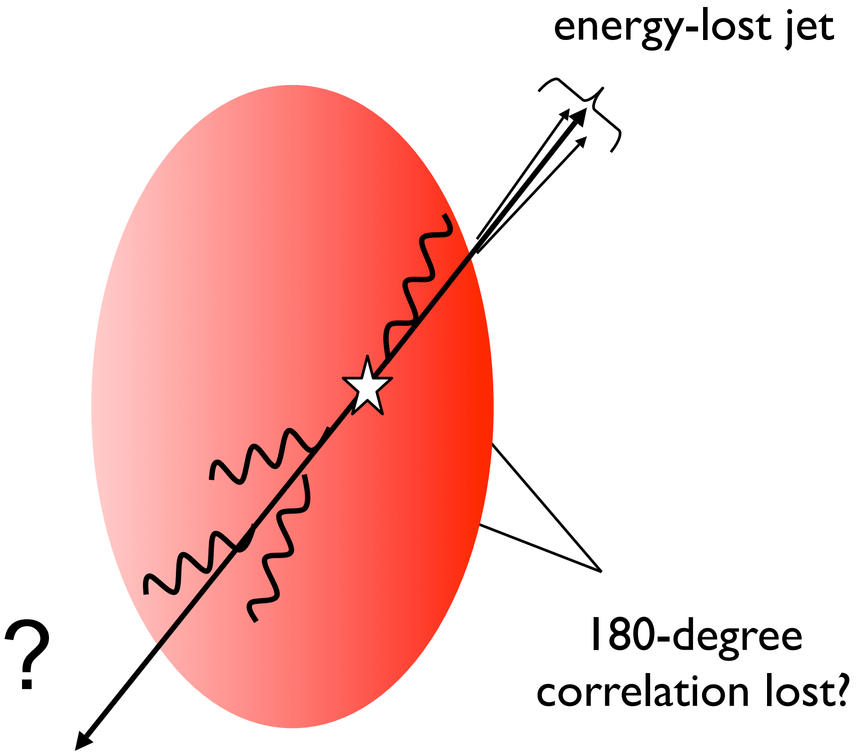
Adapted from slides by T. Hirano (Komaba)

Nucleon collision



No medium

heavy-ion collision



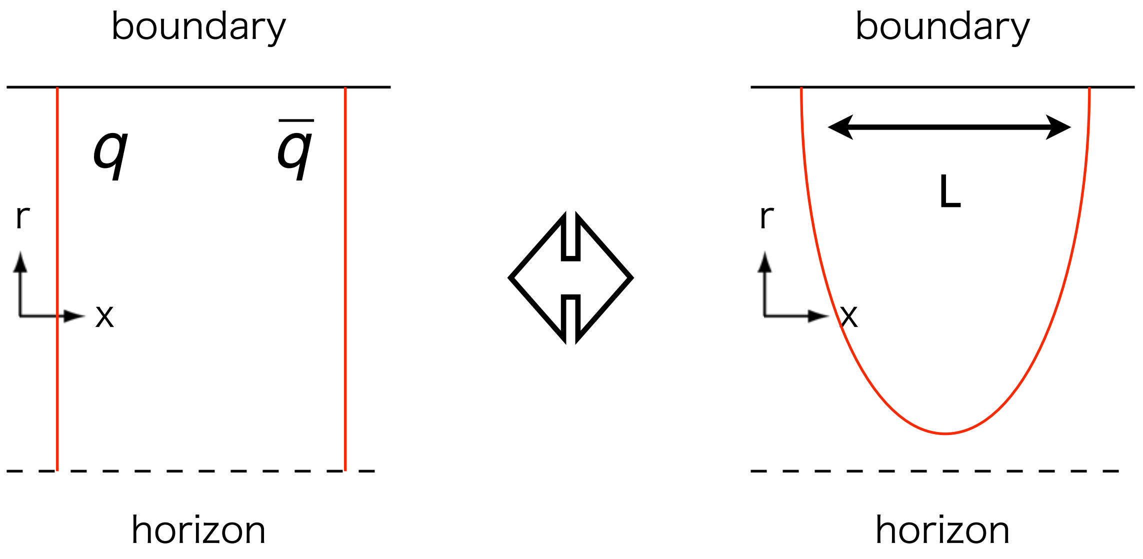
In medium

Heavy quark in AdS/CFT

Energy loss rates of heavy quark are computed in various SYM

Heavy quark: infinitely long string
Such a string has been used widely to measure heavy quark potential

Maldacena;
Rey - Yee (1998)



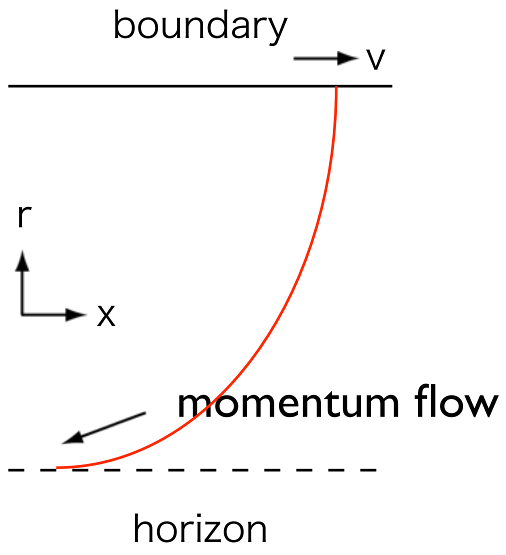
↓ not lowest energy config. ↓ energy difference: potential

Jet quenching in AdS/CFT

Now move the string

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

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



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.

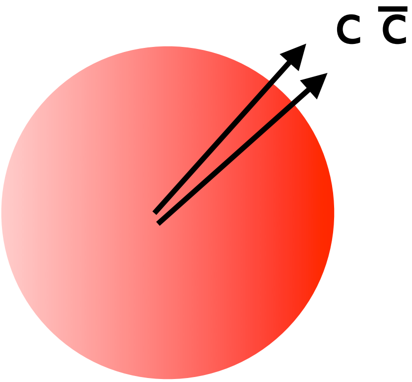
This "failure" may suggest that one has to be careful to apply AdS/CFT to QGP.

J/ψ suppression

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

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

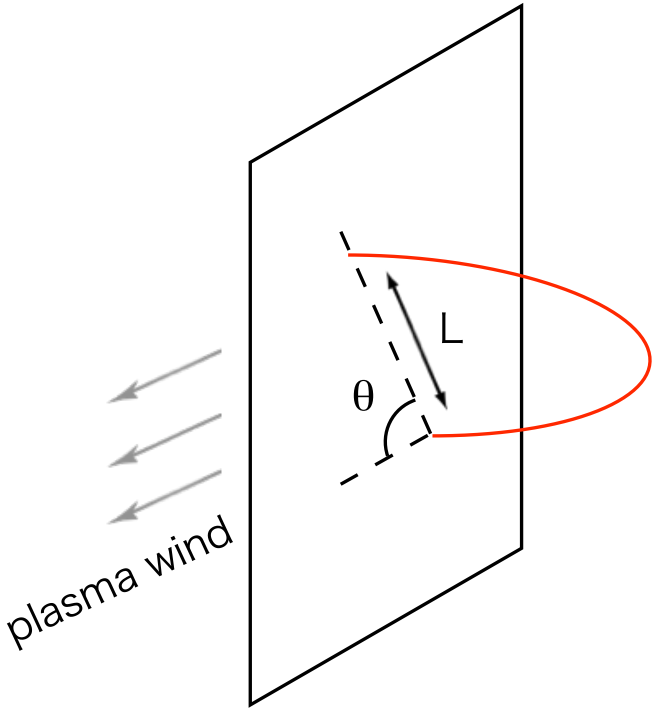
→ screening length: velocity-dependent



Screening length in AdS/CFT

At finite temp., isolated strings become energetically favorable beyond some L (Ls) → Debye screening

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



velocity dependence

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

→ boost BHs

For N=4 SYM,

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

$$L_s \propto \frac{1}{\varepsilon_0}(1-v^2)^{1/4}$$

$\sim$ (boosted plasma energy density)$^{-1/4}$

ϵ_0: unboosted density

The other gauge theories

Caceres - Natsuume - Okamura, 0607233; 0609nnn

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 → $0.22 < \Gamma < 0.25$?

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

Summary

- Hydrodynamic description of gauge theory plasma using AdS/CFT: very powerful
- 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
- Universality seems to hold even at finite chemical potential
- "Failure" of jet quenching may suggest that one has to be careful to apply AdS/CFT to QGP.