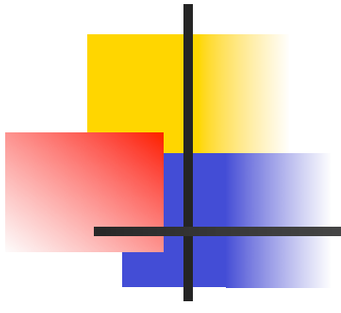
# Toward a gravity dual of RHIC collision.



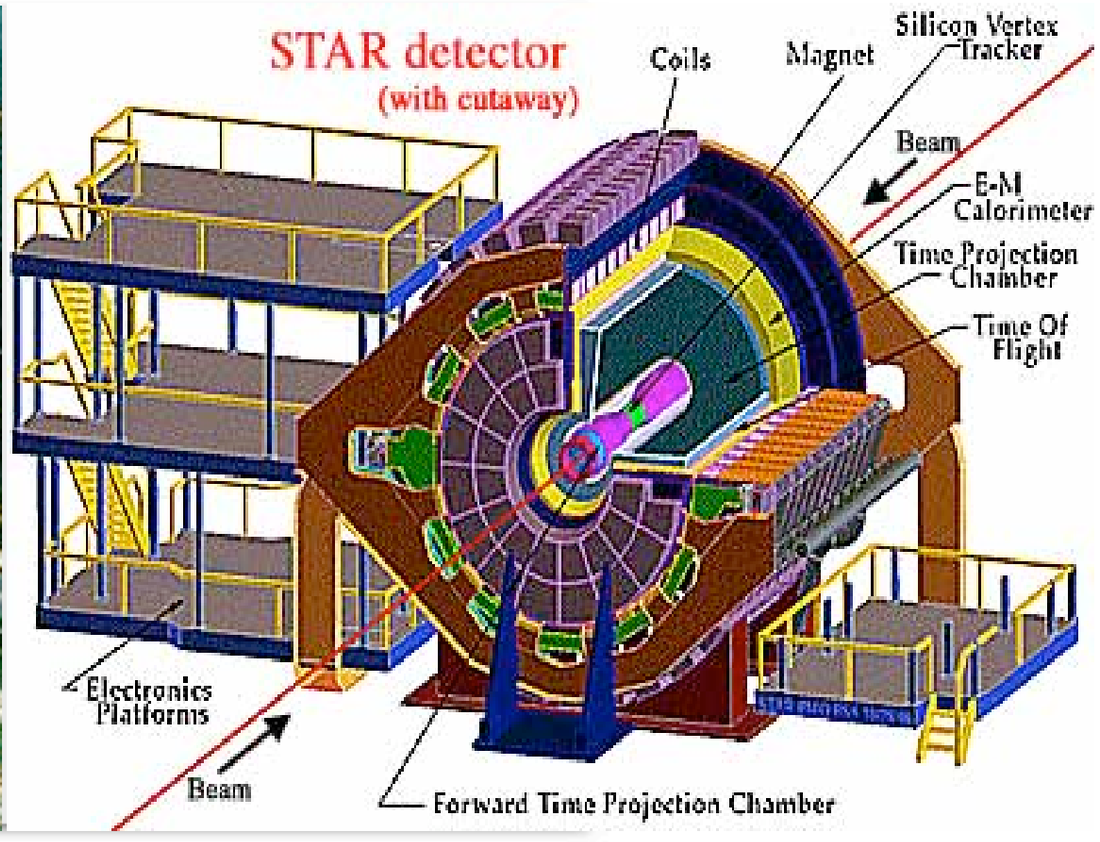

- 신상진 (HYU) @APCTP HIM 포항


  - based on hep-th/0407215(PLB608,2005)
    hep-th/0511xxx to appear

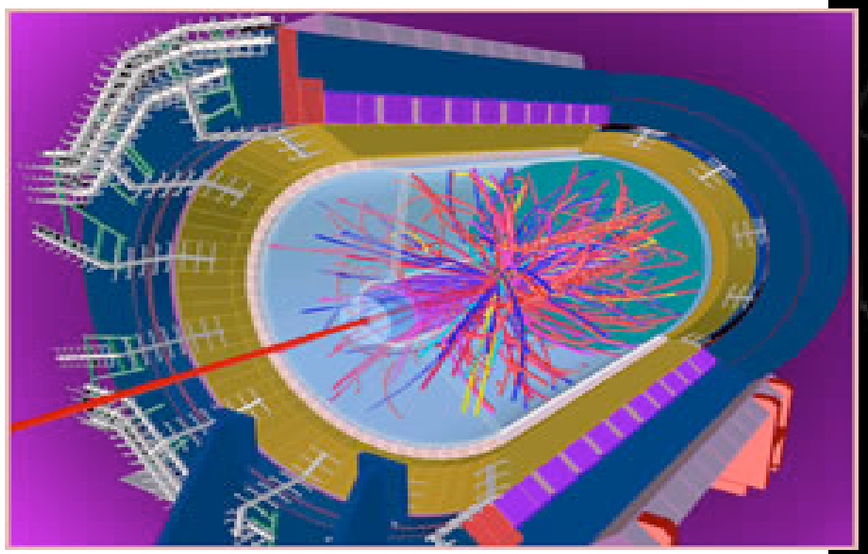
# Plan

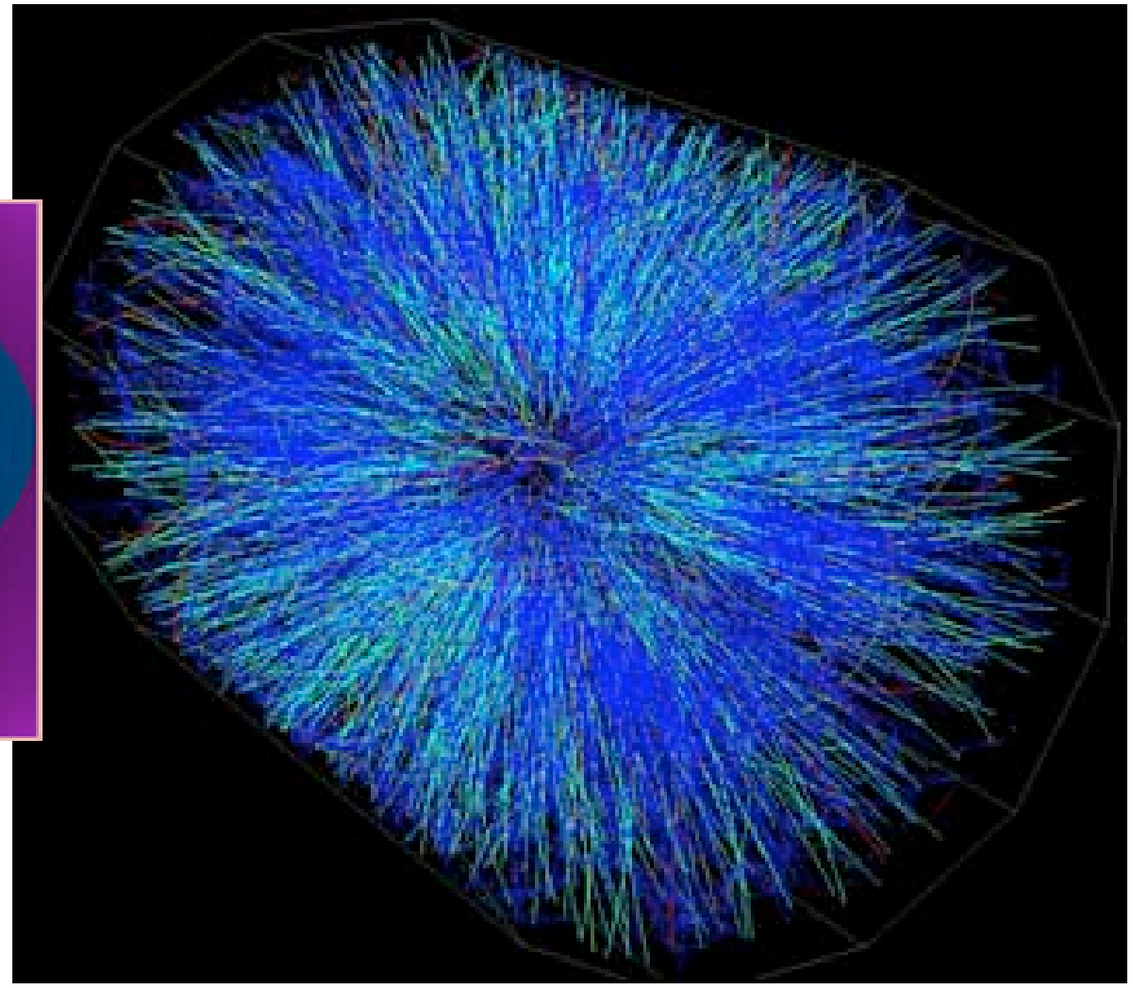
- Jet Quenching : Introduction
- Open-Closed Duality
- AdS/CFT and QCD
- Black Hole and Thermalization
- Duality of Gluon propagation
- gravity dual of RHIC collision.

# RHIC@Brookhaven NL

# Relativistic Heavy Ion Collider

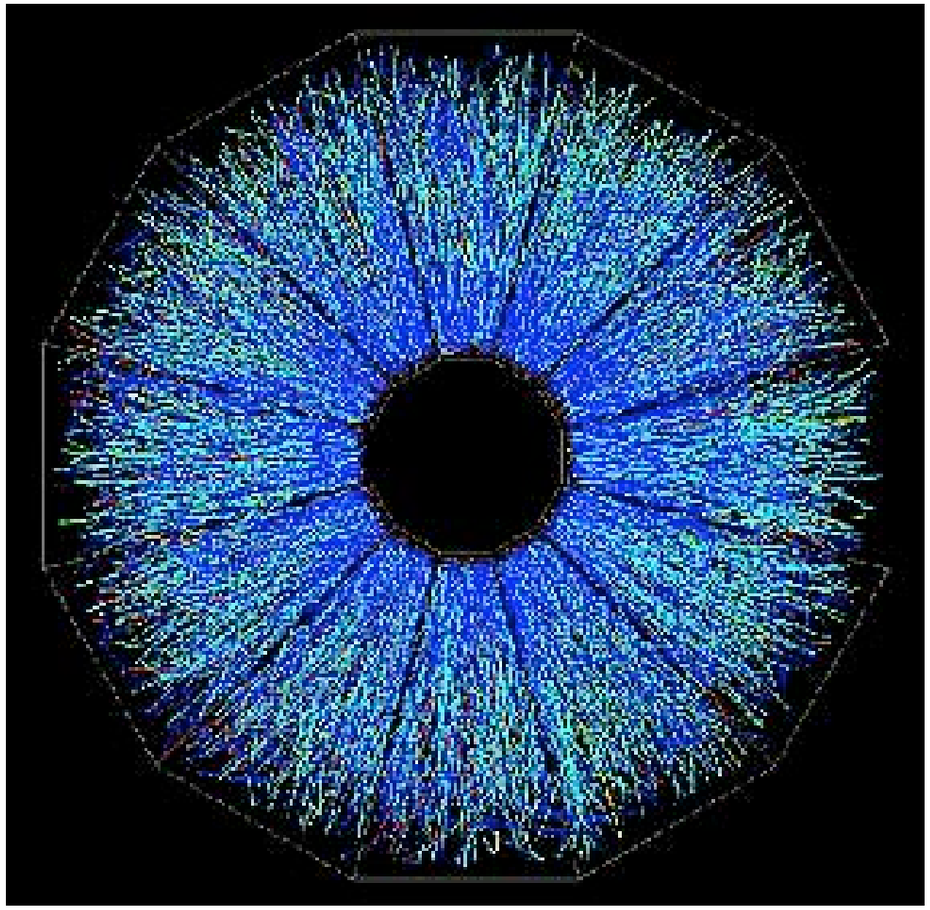




Au-Au collision

# Relativistic Heavy Ion Collider

- E~100 GeV/nucleon
- Seek QGP
- Nuclei-Nuclei collisions at high energy are very different from a simple superposition of pp/np/nn



# What is discovered?

- Original Aim: QGP,
  weakly interacting.

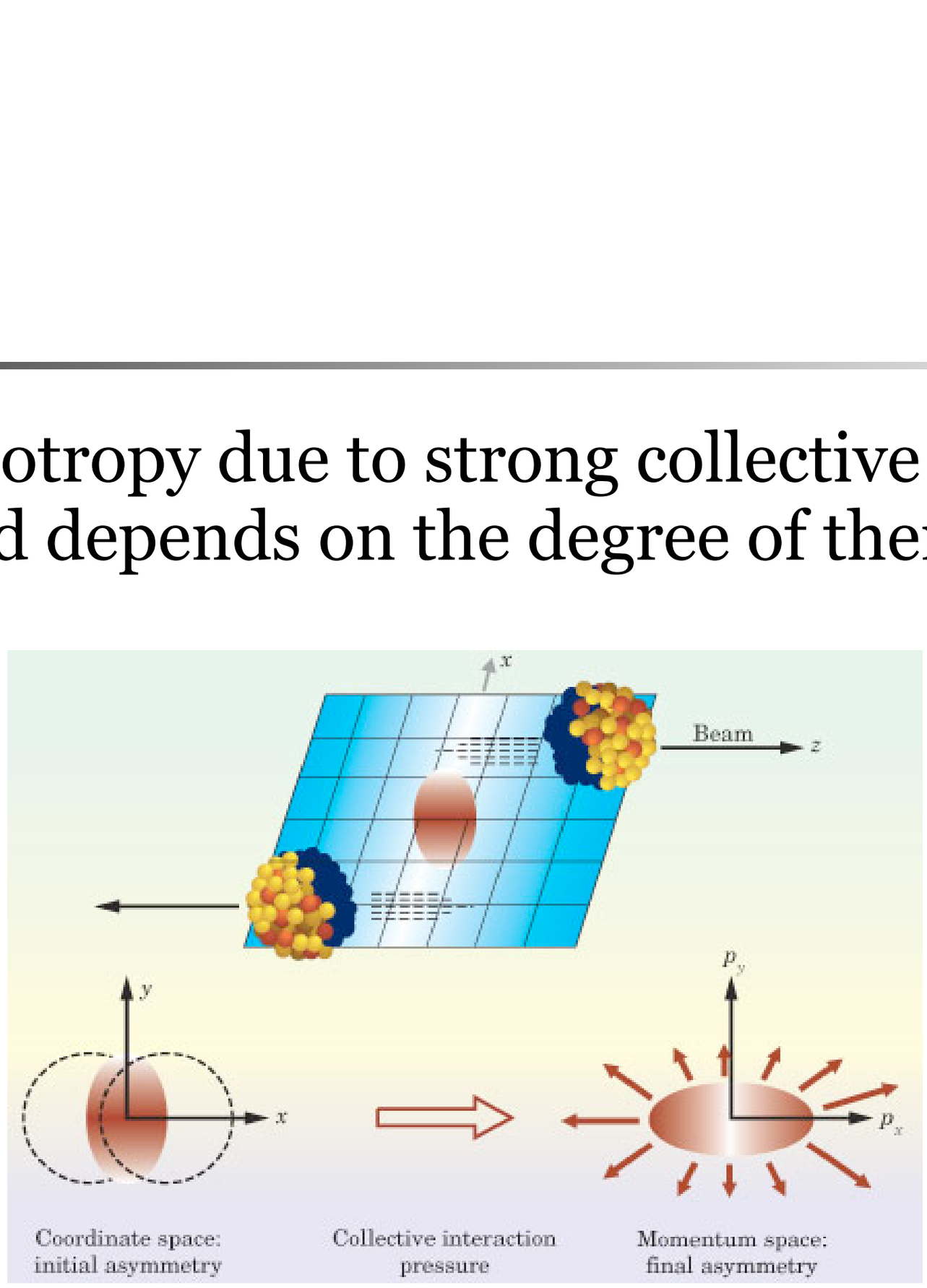
- Found something else!
  --a system with Thermal behavior

# Evidence of Thermal Equilibium

- 1. Abundance ratios for particle species shows equilibrium at freeze-out.
- 2. Flow : Evidence of collective interaction.

# Flow

Anisotropy due to strong collective interaction and depends on the degree of thermalization.



# Implication of Thermalization

- means Equilibrated
- Eqb. in such time scale

➡ Strongly interacting!

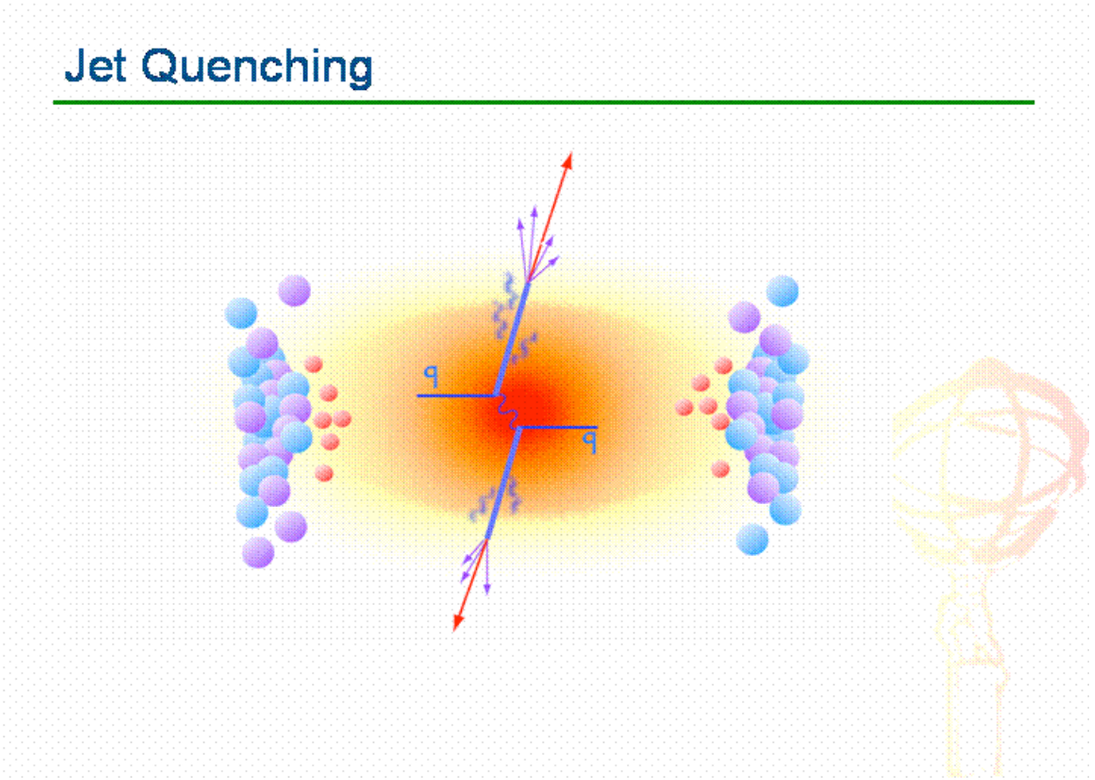
call it sQGP

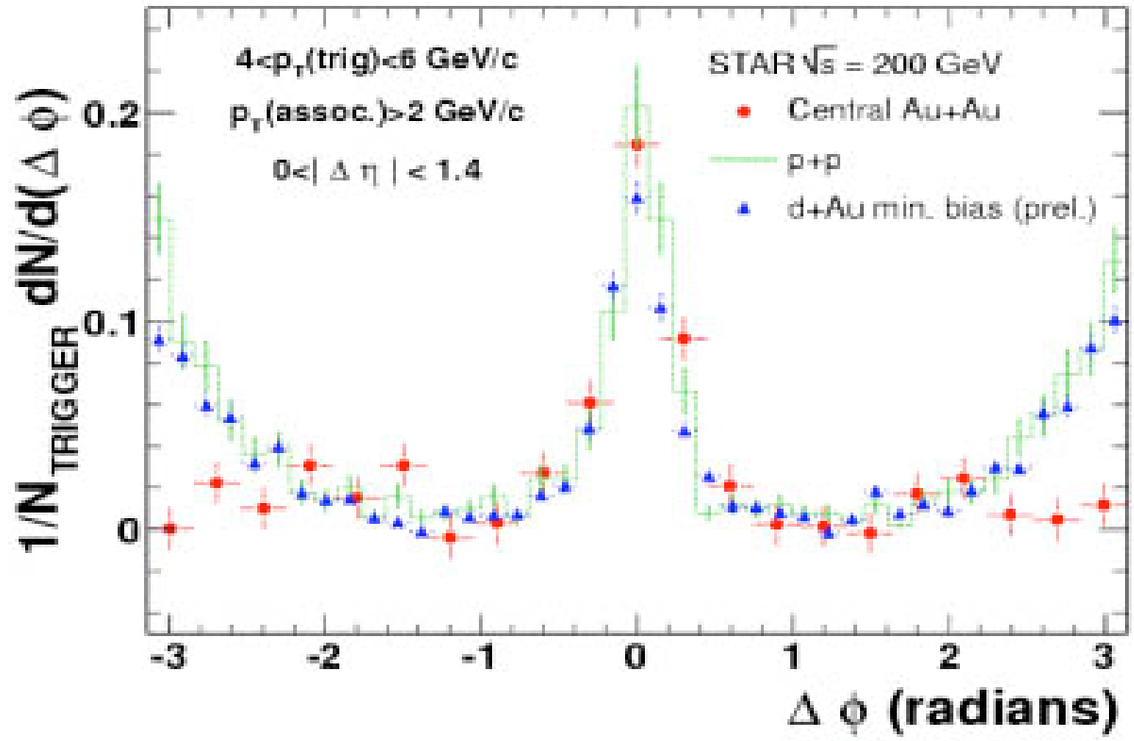
## Yet more interesting phenomena

- and Another eveidence for strong interaction character is

# Jet Quenching

# Jet quenching in RHIC




p+p and d+Au data show the existence of back-to-back pairs of jets. Central Au+Au data show the jet peak around the trigger particle, at 0 degrees, but no recoil jets. Such absence of recoil jet is expected in the case of strong energy loss in a dense medium.

# Jet quenching in RHIC

- Jets of pp
  do not appear in Au-Au collision.
- Gluon absorbed in medium by recollision,
  all by strong character → Thermalization.
  Impossible to handle in QCD.

The most dramatic observation in RHIC.

# Central Question

1. What happen to the asymptotic freedom?

Why medium has strong coupling?

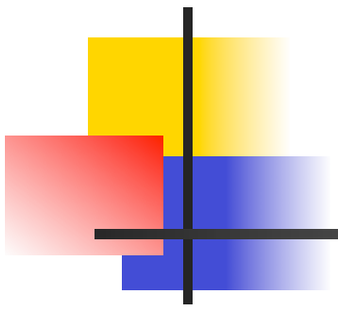
2. How to deal with strong coupling?

# In this talk, I Claim:
# Jet quenching is described by AdS-Black Hole

More specifically:

THE MEDIUM CREATED BY RHIC COLLISION is described by the dual of ADS-BLACK HOLE.

Furthermore:
The whole process of RHIC collision can be described by a CLASSICAL GRAVITY
As far as the YM-coupling is strong!



# Steps:

- What is AdS/CFT?
- What is gravity dual of thermalized YM? AdS-BH!
- What is dual of gluon propagation in deconfined phase?
- Jet-Quenching in AdS/CFT?
- Dual of collision process?

# Need

- a Digression for string theory
  by a few slides

# Low energy character of string Th:
## Massless spectrum

- Open String: $\alpha' M^2 = J - 1$ :gauge theory
- Closed string: $\frac{1}{4}\alpha' M^2 = J - 2$ : gravity

J=spin from vibration of string,

-1=12(1+2+3+…)=regulated mass from quantum fluctuation of string

# Open closed duality

unlike a point particle,

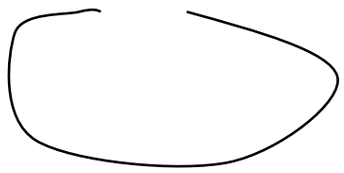
Objects with Structure like strings
→ requires Consistency.
→Various String Dualities

Among them, what we need here is

Open-closed duality

# Open-closed string connections

- Open → closed St. perturbatively

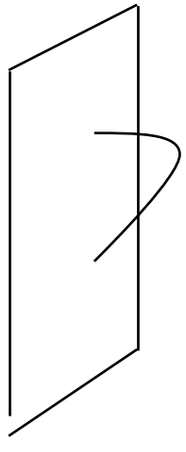


- Closed → Open sting only via D-brane

It's a nonperturbative effect
discovered only in 90'

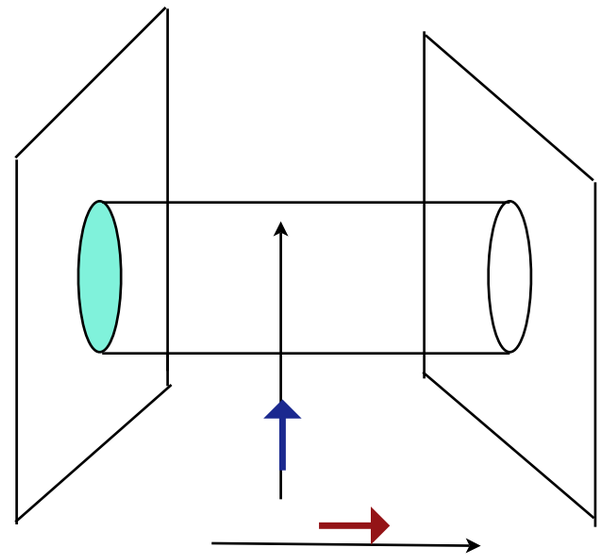
# $D_p$ -brane

- Closed string soliton- a nonperturbative object.
- That this object has dual description by dynamics of open string ending on it, is the major discovery of 90'



# Gauge-Gravity duality

- Open 1-loop(→) /Closed tree↑
  (string dynamics
  according to time direction.



- Open=gauge/Closed=gravity

- Hence gauge/gravity duality.

- Such duality is formulated by
  Maldacena exactly as
  AdS/CFT correspondence.

- From D-brane side :
  open string $\Rightarrow$ gauge theory $\Rightarrow$ SYM, N=4

- From gravity side:

$$S = \frac{1}{(2\pi)^7 l_s^8} \int d^{10}x\sqrt{-g}\left(e^{-2\phi}\left(\mathcal{R} + 4(\nabla\phi)^2\right) - \frac{2}{(8-p)!}F_{p+2}^2\right),$$

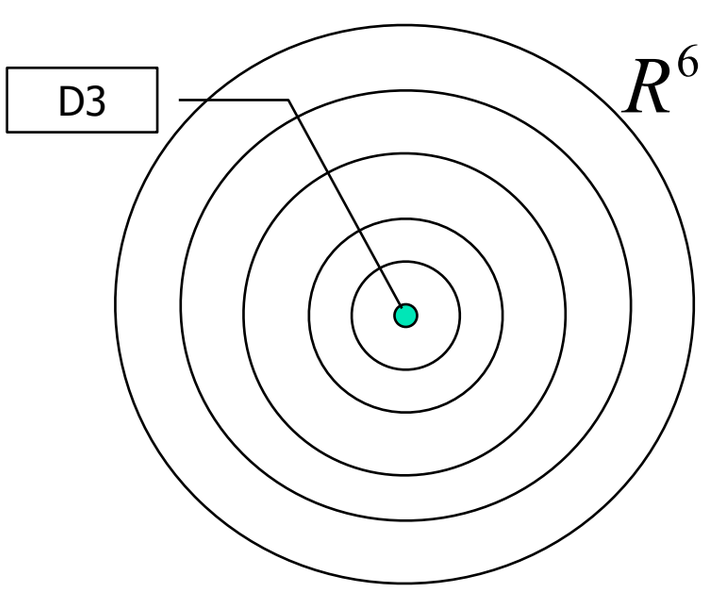
  For p=3, it has D3 solution:

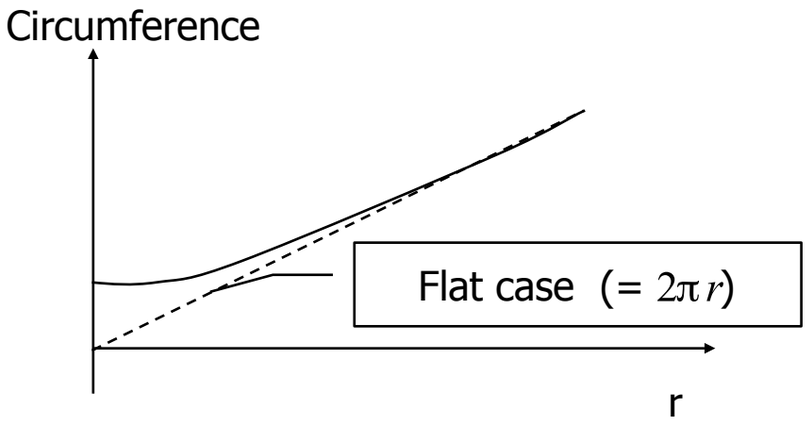
$$ds^2 = f^{-1/2}(-dt^2 + dx_1^2 + dx_2^2 + dx_3^2) + f^{1/2}(dr^2 + r^2 d\Omega_5^2) \ ,$$
$$F_5 = (1+*)dtdx_1dx_2dx_3df^{-1} \ ,$$
$$f = 1 + \frac{R^4}{r^4} \ , \qquad R^4 \equiv 4\pi g_s \alpha'^2 N \ .$$

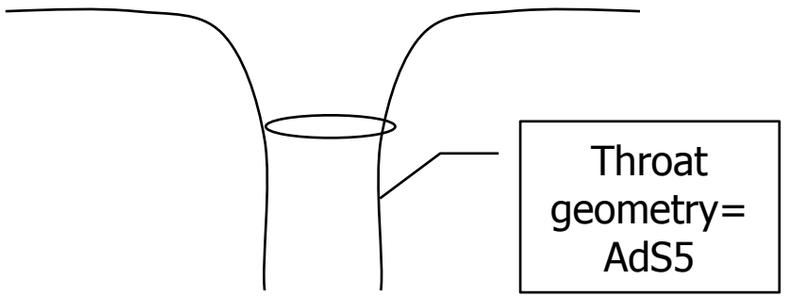
Near r~0, geometry $\Rightarrow$ $AdS_5 \times S^5$

$$ds^2 = \frac{r^2}{R^2}(-dt^2 + dx_1^2 + dx_2^2 + dx_3^2) + R^2\frac{dr^2}{r^2} + R^2 d\Omega_5^2,$$

# Near horizon geometry of D3



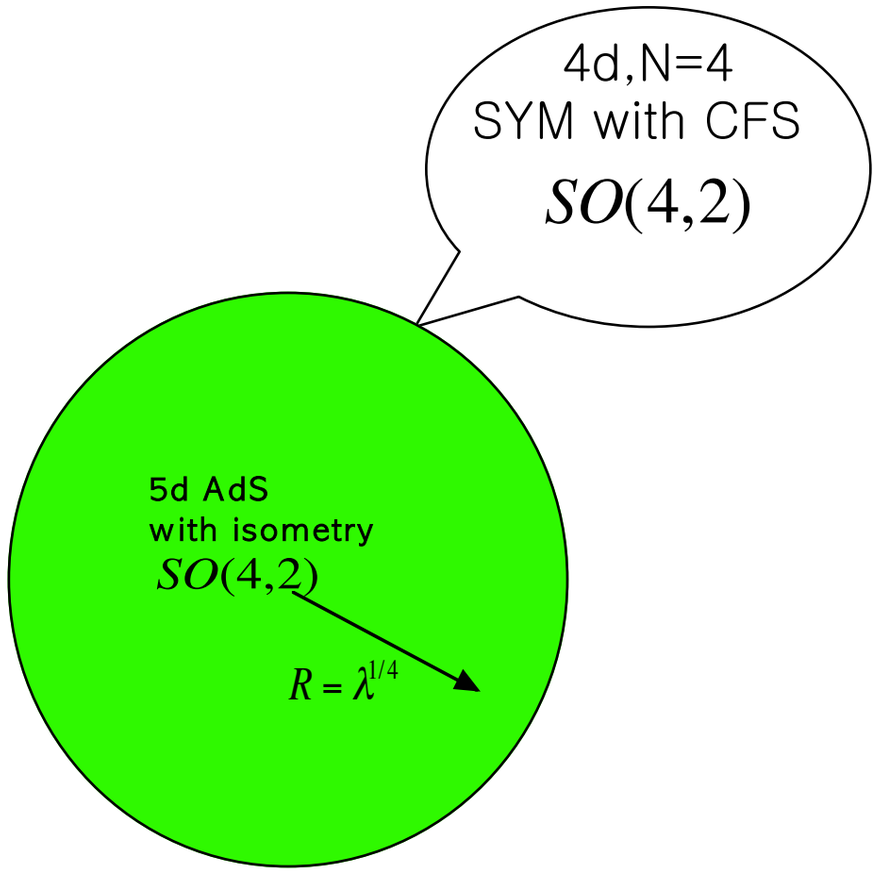




$$ds^2 = (r^2/R^2)(-dt^2 + d\vec{x}^2) + (R^2/r^2)dr^2$$

# AdS/CFT duality: Summary

1. String theory in 5d AdS is dual to $N$ =4 Super Yang Mill in 4d.



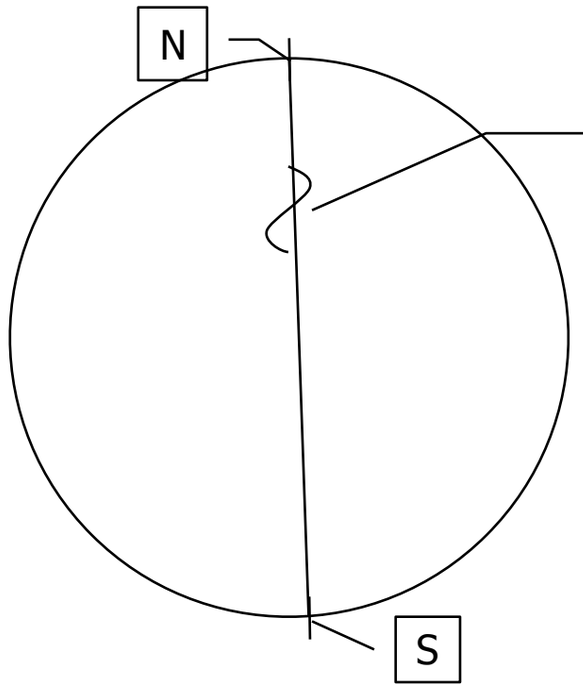

2. 5d v.s 4d $\Rightarrow$ Holographic correspondence.

3. For large t' Hooft coupling, $\lambda = g_s N_c$ ,
   string theory $\Rightarrow$ classical gravity.

4. Small coupling: hard theory.

# Gluon propagation in AdS background

- Mikhailov(hep-th/0305196)




$$E = \frac{\sqrt{\lambda}}{2\pi}\int dt \frac{\vec{a}^2 - (\vec{v}\times\vec{a})^2}{(1-\vec{v}^2)^2},$$

$$with, v = \frac{dx}{dt}, a = \frac{d^2x}{dt^2}$$

Lienard formular for the radiation apart from square root

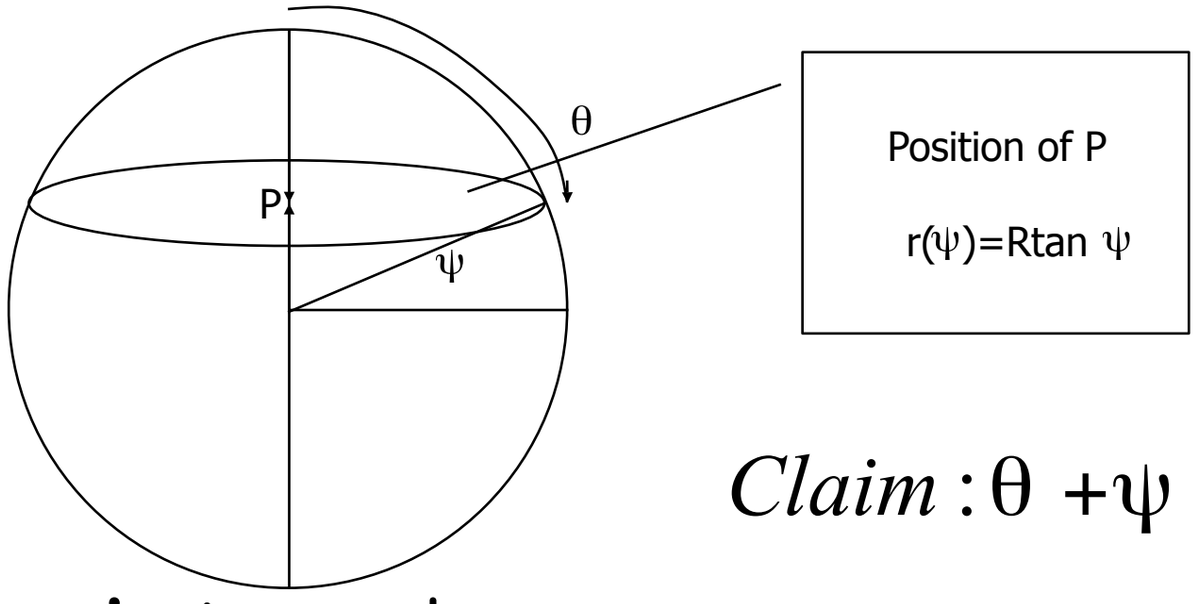
calculated energy of ripple along the string from N to S passing through the center.

$S^3$

# Holography of radiation

SJS with Zahed

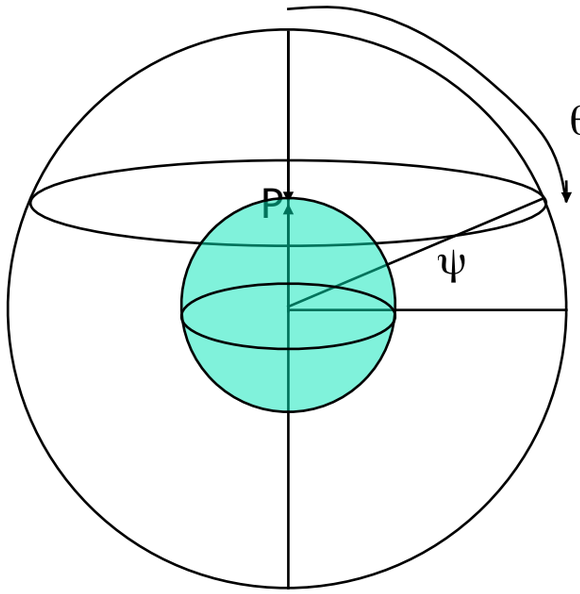
- gluon propagation at boundary v.s null geodesic along the path passing the center.




$$Claim: \theta + \psi = \pi/2$$

- We get point-sphere correspondence.

# Holography of radiation in Black hole background



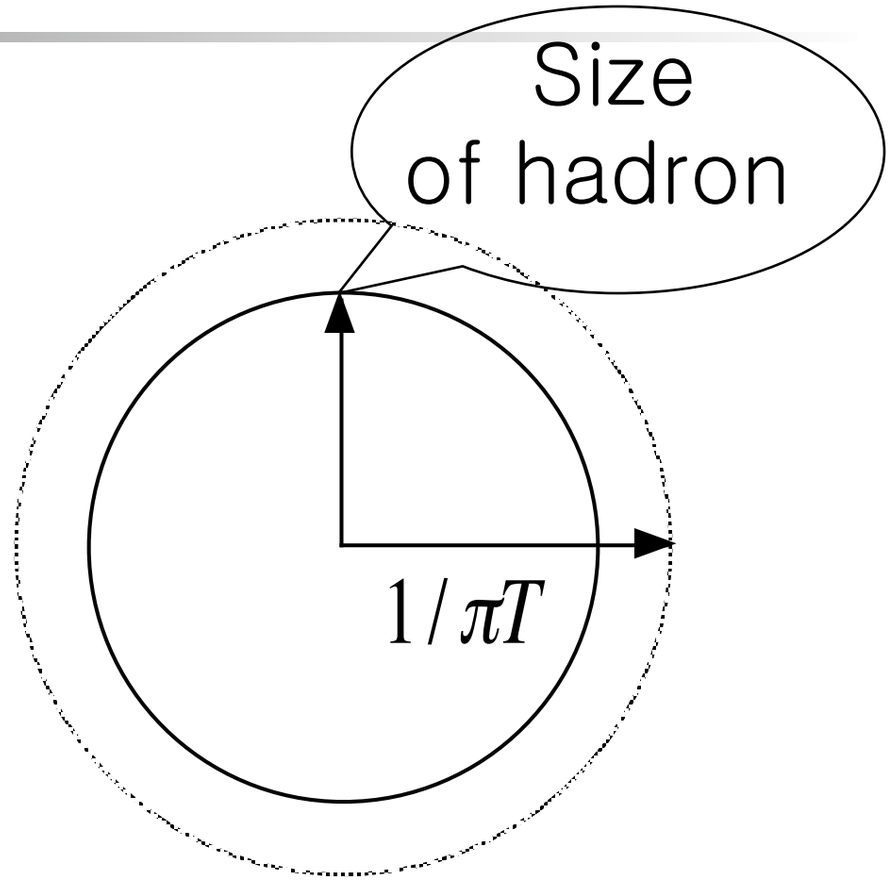

Maximal propagation distance= $1/\pi T$

P will be absorbed into the BH or never get to it according to the observer.
The dual picture to this is stopping at $1/\pi T$

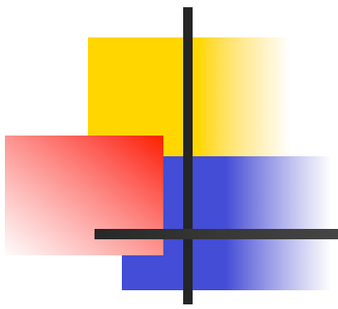
# A prediction

- At fixed temp.
  Hadrons of size less than $1/\pi T$
  will not show the Jet quenching phenomena.

  Or,
- For a fixed radius of nuclei, at low temperature, J-Q will not appear.




Situation of
No Jet Quenching



# More on

# Gravity dual of RHIC collision

# Sequence of events after mini-bang

1. Formation of High-T QGP

2. Expand and cool, at Tc : QGP to Hadrons.

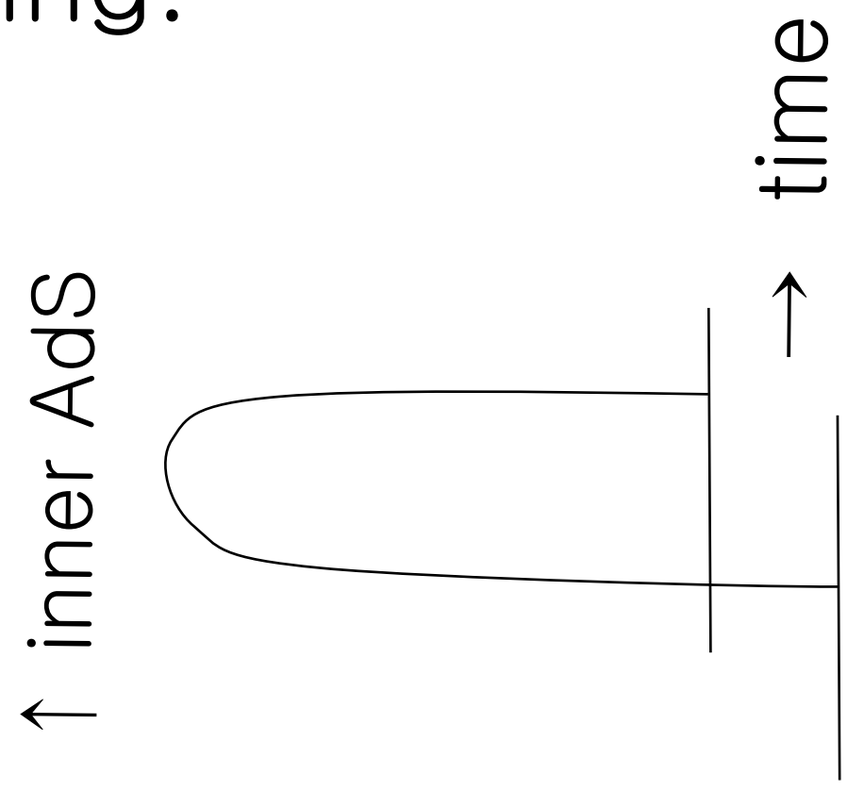
3. Freeze-out : hadrons no longer interact with each other.

# Corresponding Questions for Dual Gravity:

- Thermalization: Creation of AdS-BH
- Fireball cooling: Evolution of B.H.
- Deconfinement P.T: Hawking-Page P.T
- Fate of  the Black hole?

# Gravity description of $q\bar{q}$ dynamics

- $q\bar{q}$ dynamics is described by the AdS string.




$$Rey + Yee, Maldacena$$

$$V = -\frac{c}{L}, \quad where \quad c = 4\pi^2 (2 g_{YM}^2 N)^{1/2}$$

# String picture of scattering


$S-J.\ Sin, to\ appear$

For sufficiently small ε

$$l_{AB}+l_{CD}-l_{AD}-l_{BC}=-2\frac{c}{L}+\frac{c}{2L+\epsilon}+\frac{c}{\epsilon}>0,$$

# Closed string creation

- This process is unusual from flat space string point of view.

- The unusual effectiveness of  creation of closed string.

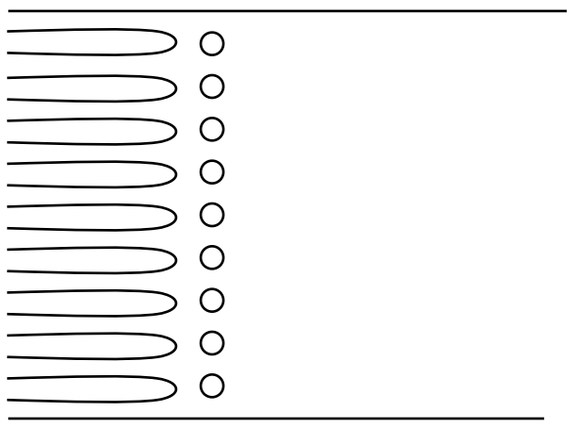
- 1 for each interaction vertex.

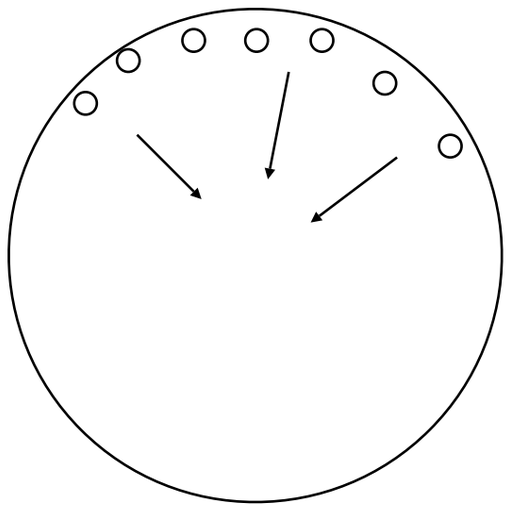
# What is gauge theory object for this?

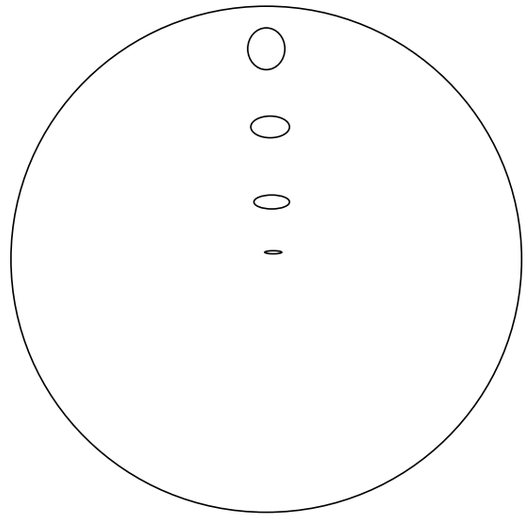
- Lots of Glue  balls!
- This unusual object is responsible to the unusual effectiveness of thermalization.
- What is then gravity picture of thermalization due to these glueballs?

# Formation of AdS-BH

- The closed strings can leave the bdry and reach the center of AdS.
- When multitudes of closed strings arrive at the same time they form ads black hole.
- Focus effect of AdS help Equilibrium.







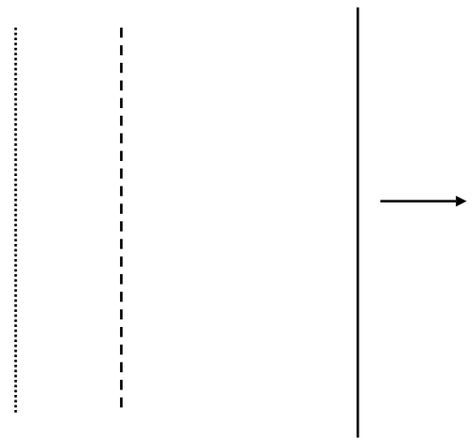
# BH formation conditions

- Let $Q_s = N/\pi R_N^2$ be the transverse density. Then the condition of BH formation is $N \geq R^{-2} G_5 Q_s^{-5}$
- Entropy, $S = T^3 V$
- Hawking temperature, $T = \frac{1}{\pi\sqrt{N_c}} \left(\frac{M}{R^3}\right)^{1/4}$
- formation time: $t = \pi R = \ldots = \pi \Lambda_{QCD}$

# Expansion and cooling

- Fixed entropy→BH size is fixed.
- Cooling→BH is moving apart from us.
- Choose co-ord. S.t we are on the probe brane in the BH b.g.

This is the set up of brane cosmology.



# Brane cosmology and cooling

- Use DBI action of probe brane as in mirage cosmology:
- Get the dynamics of the probe brane r(t) in warped back ground.
- Motion of brane → Expansion of the brane universe(=RHIC fire ball) by induced metric.

# Cooling rate

- The brane cosmology says: $a(\tau) = \tau^{1/2}$
- This is slower than the ideal fluid expansion $a(\tau) = \tau$
- Interaction, not only making the fireball fluid, it slows down the expansion.
- The Hydro. Must be replaced by GR.

# Fate of AdS BH (I)
# Hawking Page transition(Large BH)

- Deconfinement→confinement phase transition.
- AdS BH metric and double Wick rotated non-extremal D4 solution compete.

$$Z = ... + e^{-S_{AdSBH}/kT} + e^{-S_{D4}/kT} + ...$$

- One wins the other according to T.

# Fate of AdS BH (2)
# Hawking Radiation(Small BH)

- One may imagine that the black hole formed is not a large black hole but a Small BH.
- Then they are not stable under the Hawking evaporation.
- Then the final stage of the black hole is nothing but a explosive evaporation which may be dual of Hadronization.
- One may calculate the evaporation rate

$$\frac{dM}{dt} \sim -(t_0 - t)^{-2/3}$$

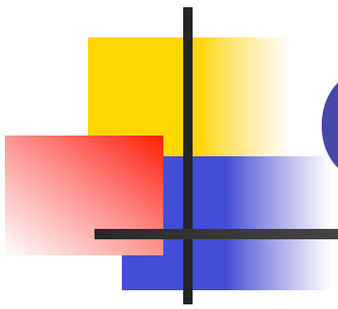
# Conclusion 1

1.Formation of ads BH→ thermalized strongly interacting firball.

2.BH horizon →Jet quenching.

3.Cooling rate→ string cosmology Hyrodynamics must be replaced by full GR.

4.Hawking-Page v.s Hawking Radiation for the freeze-out.



# Conclusion 2

If you accept sQGP, you'd

better to learn string theory