

Gravity, Particle Physics

and

their Unification

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Lepton-Photon 99

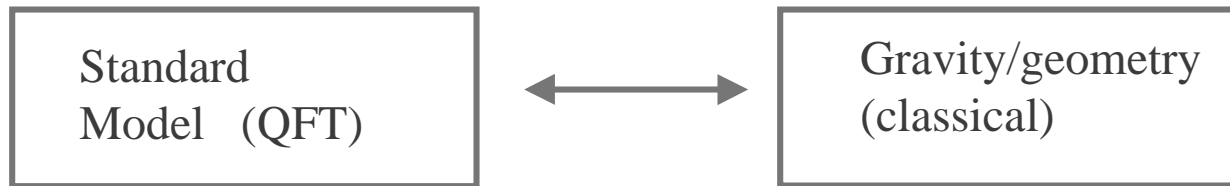
# Outline

- Why strings? Quantum gravity
- What is string theory, D-branes
- Going down to 4 dimensions
- Dualities
- Black hole entropy, evaporation
- QCD & strings, the large N limit
- Anti-de-Sitter spacetimes, Holography

## References:

- “Superstring Theory” by Green, Schwartz and Witten
- “String theory” by Polchinski
- Black hole entropy: Strominger and Vafa hep-th/9601029
- AdS/CFT : J.M. hep-th/9711200. Review: Aharony, Gubser, J.M., Ooguri and Oz, hep-th/9905111

## Our present world picture



Not valid up to very high energies, it certainly breaks down at  $E_{\text{Pl}} \sim 10^{19}$  GeV  
(or not valid to high accuracy)

It is mathematically inconsistent, (Puzzles about black hole evaporation)

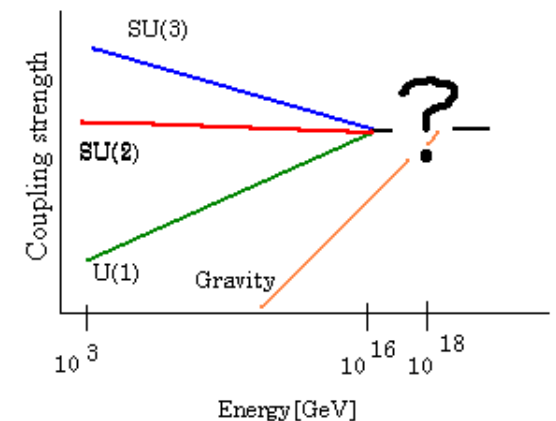
It does not explain the most important “experiment” : The Big Bang

The Big Bang theory links, at early times, high energy physics and cosmology

Unification:

Could we explain the parameters of the Standard Model?

It is suggestive that the scale where the couplings would unify,  $10^{16}$  GeV, is close to the Planck scale.



# Challenges

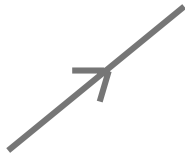
- I) Formulate an internally consistent theory of quantum gravity
  - Ia) Understand the puzzles of black hole thermodynamics
- II) Be capable of incorporating the Standard Model
- III) Explain the Big Bang and the parameters of the Standard Model

String theory does I. Many aspects of Ia and II are fairly well understood.

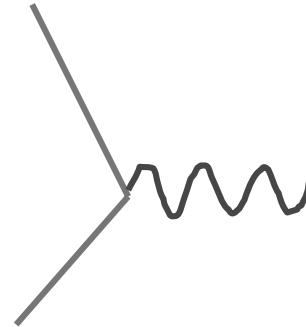
III is not done yet...

# Particle theory (quantum field theory)

Free particles



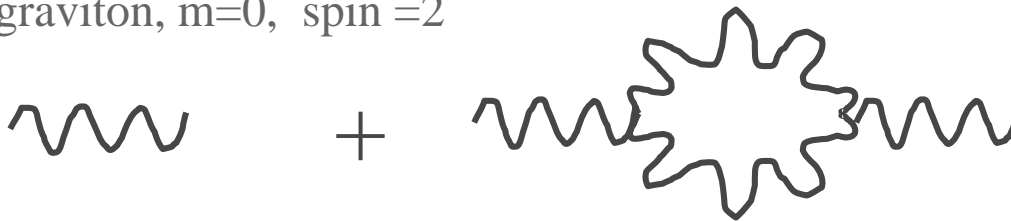
Particle interactions



$g =$  coupling constant

Gravity

graviton,  $m=0$ ,  $\text{spin}=2$



Quantum corrections give infinities that one cannot eliminate

# String Theory

## Free strings



$$\text{Tension} = T = \frac{1}{l_s^2}, \quad l_s = \text{string length}$$

Relativistic, so  $T = (\text{mass})/(\text{unit length})$



Excitations along a stretched string travel at the speed of light

## Closed strings



Can oscillate  $\longrightarrow$  Normal modes  $\longrightarrow$  Quantized energy levels

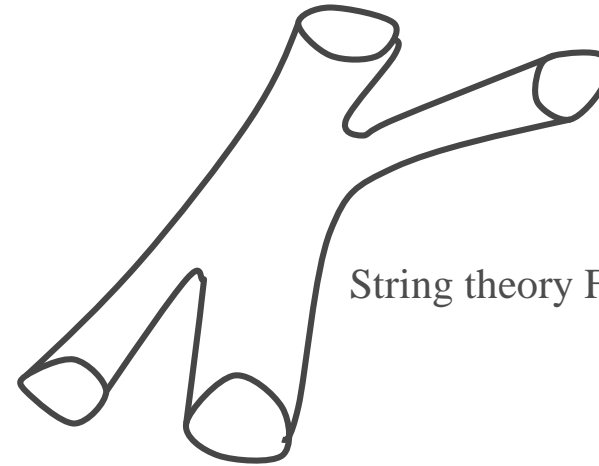
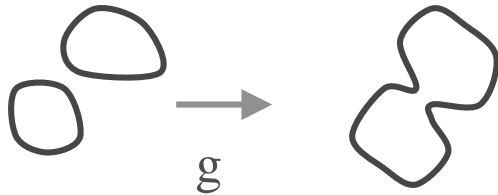
Mass of the object = total energy

$M=0$  states include a graviton (a spin 2 particle)

First massive state has  $M^2 \sim T$

## String Interactions

Splitting and joining



String theory Feynman diagram

Simplest case: Flat 10 dimensions and supersymmetric

Precise rules for computing the amplitudes that yield finite results

At low energies, energies smaller than the mass of the first massive string state



Gravity theory

Very constrained mathematical structure

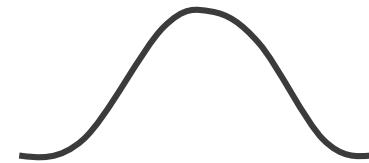
## Non-perturbative aspects

In field theories we can have solitons

e.g. magnetic monopoles (monopoles of GUT theories)

Collective excitations that are stable (topologically)

$$M = \frac{1}{g^2} \quad g = \text{coupling constant}$$



In string theory

we have D-p-branes



Can have different dimensionalities

p=0    ●    D-0-brane    D-particle

p=1    —    D-1-brane    D-string

p=2    ▮    D-2-brane    membrane

etc.

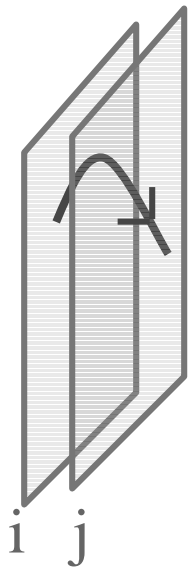


D-branes have a very precise description in string theory.

Their excitations are described by open strings ending on the brane.

At low energies these lead to fields living on the brane. These include gauge fields.

$N$  coincident branes give rise to  $U(N)$  gauge symmetry.



$$A_{ij}$$

## Going down to four dimensions

Compactification: 4 dimensions are large and 6 dimensions are small



$$M_{KK} \approx \frac{1}{R} = \text{mass of the excitations with momentum in the extra dimensions}$$

- 2 possibilities:
- 1) They are very small, all of Planck size.
  - 2) Some dimensions could be as big as 1mm

In this case the Standard Model matter would live in a brane localized in the extra large dimensions and extended in 4 dimensions

In both cases the Standard Model parameters would depend on the details of the internal manifold or brane configuration.

This compactification process is well understood in cases with 8, 4 and 2 supersymmetries in four dimensions. Less is understood about the case with one supersymmetry. It is not clear how supersymmetry is broken, specially why the cosmological constant is so small.

# Dualities

## In field theory

Electric - Magnetic duality

$$E \longleftrightarrow B$$

$$\text{Particles} \longleftrightarrow \text{Solitons}$$

$$g \longleftrightarrow 1/g$$

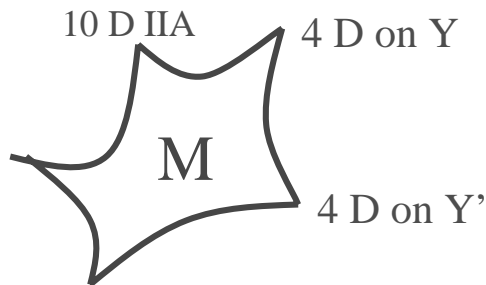
$$\text{weak} \longleftrightarrow \text{strong}$$

Example: N=4 supersymmetric  
Yang Mills theory

As we change the parameters the theory becomes strongly coupled in the original variables but weakly coupled in the new variables.

## In string theory

Dualities connect different string theories.



M-theory = Full non-perturbative theory.

We do not know exactly what it is, we only know some limits. So we do not know what the M stands for.

In 4-d theories compactified on manifolds with different topologies, which have different matter content or different number of generations are connected.

Dualities in field theories  $\longleftrightarrow$  Brane configurations

### Checks of dualities

Supersymmetry plays a crucial role in *testing* proposed dualities.

Supersymmetry implies that some calculations do not depend on the coupling. Then we can compute at small coupling and extrapolate to strong coupling and compare with the answer we obtain in the dual theory.

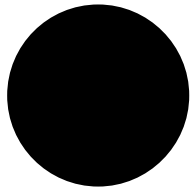
- 1) Low energy effective action
- 2) Degeneracies of various “protected” states, these states are typically some charged particles. These states could be elementary on one side and solitons on the other side.

### Summary

All string theories seem connected (at least supersymmetric ones).

# Black hole entropy

Gravitational collapse leads to black holes



Classically nothing can escape once it crosses the event horizon

Quantum mechanics implies that black holes emit thermal radiation.

(Hawking)

$$T \approx \frac{1}{r_s} \approx \frac{1}{G_N M}$$

$$T \approx 10^{-8} K \left( \frac{M_{sun}}{M} \right)$$

Black holes evaporate

Evaporation time

$$\tau = \tau_{\text{universe}} \left( \frac{M}{10^{12} \text{ Kg}} \right)^3$$

Temperature is related to entropy

$$dM = T dS \quad S = \frac{\text{Area of the horizon}}{4 L_{\text{Planck}}^2}$$

What is the statistical interpretation of this entropy?



(Hawking-Bekenstein)

## Charged black holes

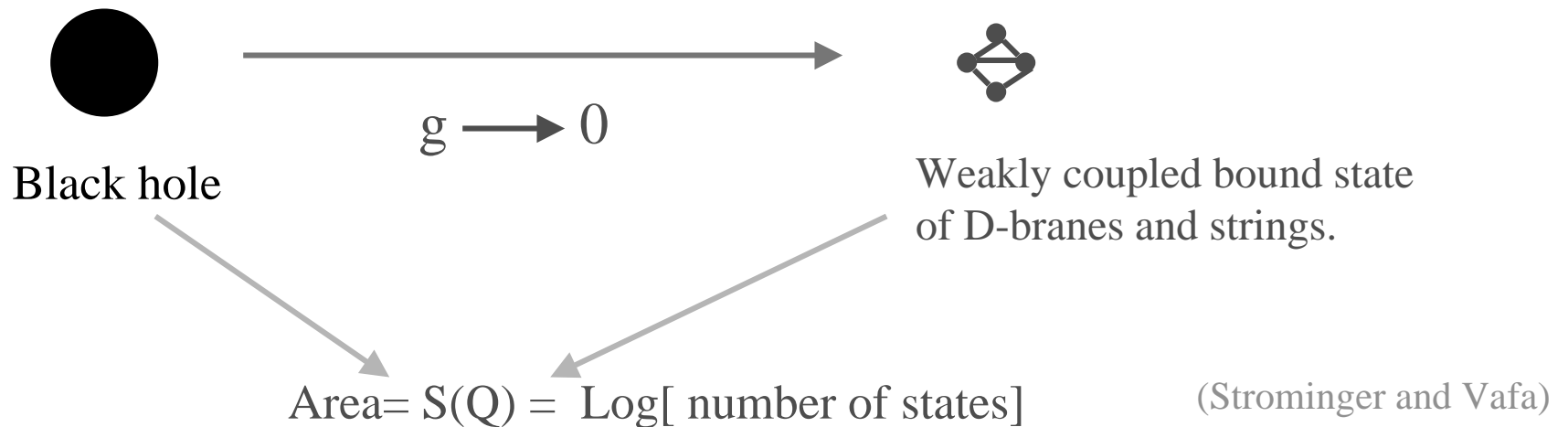
$$M \geq Q$$

In order to have a non-singular solution

$$M = Q$$

Is called extremal, for these the temperature vanishes.

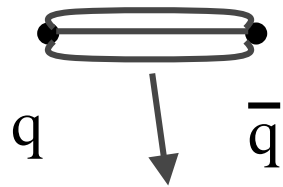
In supersymmetric theories these extremal black holes are stable, in fact they are “protected”. So the number of states with a given charge is independent of the coupling.



## Why Strings?

Relativistic strings can appear in other contexts.

For example in low energy QCD. In fact this is where strings first appeared



Flux tubes of color field = glue

At low energies QCD is strongly coupled. It could be that it can be best described as a theory of strings. These would be effective strings, strings made with gluons.

Mesons = open strings

Glueballs = closed strings

Baryons = solitons = D-branes.

# The Large $N$ limit

(t' Hooft)

$$SU(3) \longrightarrow SU(N)$$

$$N \longrightarrow \infty, \quad g^2 N = \text{fixed}$$

The field theory Feynman diagrams start to look like string theory Feynman diagrams in this limit. All planar Feynman diagrams contribute at the same order in  $N$ .  $1/N$  plays the role of the string coupling constant.

This argument applies to any large  $N$  gauge theory.

What kind of string theory?

Strings are not consistent in four flat dimensions.

Anomalies generate at least one more “dimension”. This means that one needs one more variable to specify the string configuration than the two transverse positions. We can crudely think of this new variable as the “thickness” of the string.

(Polyakov)

At least 5 dimensions. But all strings include gravity...?



Simplest case: Most supersymmetric,  $N=4$   $SU(N)$  Yang Mills theory

This theory contains gauge fields and their supersymmetric partners.  
The theory is scale invariant. The coupling does not run.

Conformal symmetry group =  $SO(2,4)$

$g^2N$  is small  $\longrightarrow$  perturbation theory is OK

$g^2N$  is large  $\longrightarrow$  Dual description?

t' Hooft argument suggest a string theory. What is the 5-d geometry?

Since we have lots of supersymmetry it is natural to suspect that  
the corresponding string theory is a 10-d superstring.

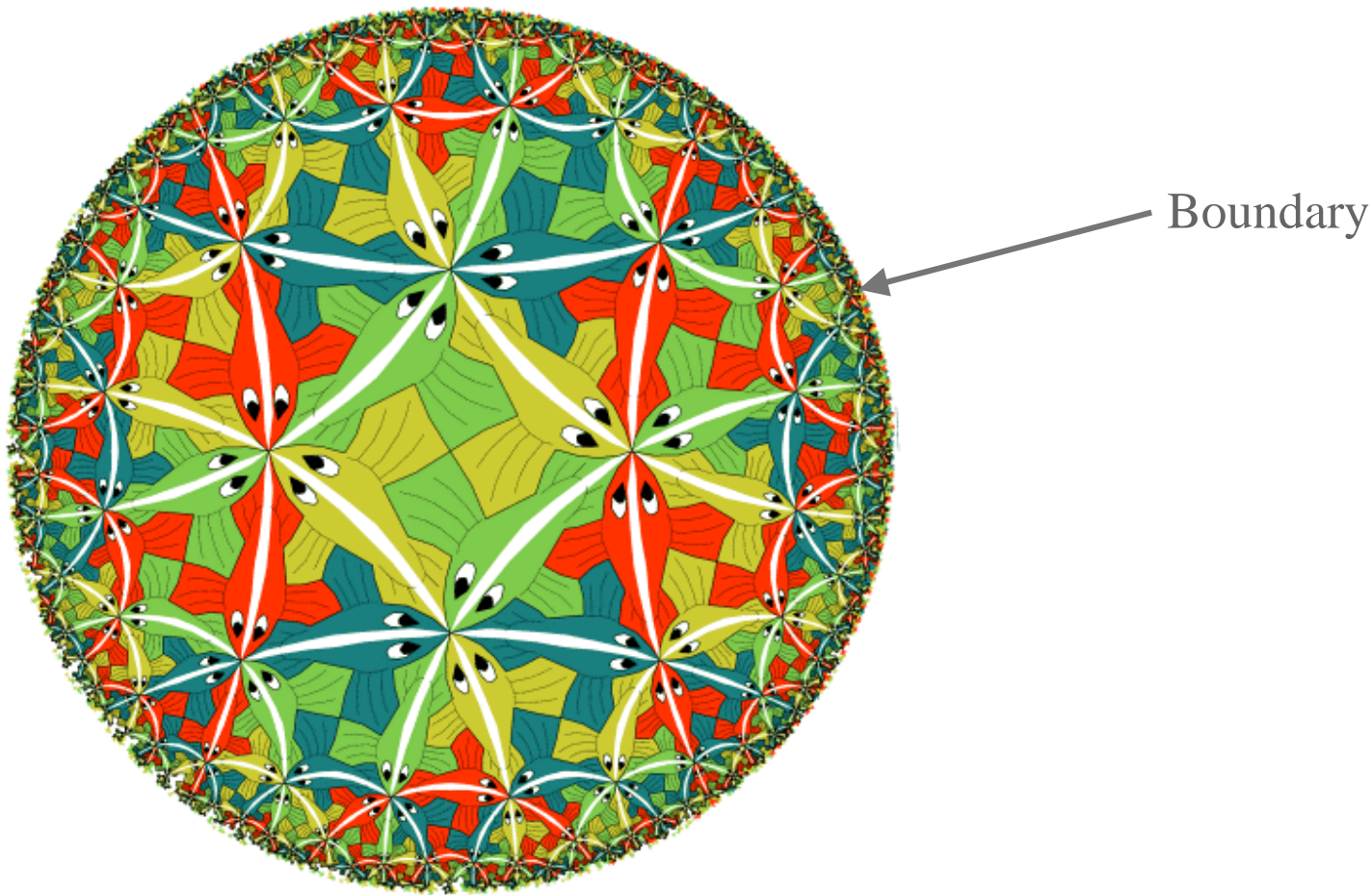
It is string theory on

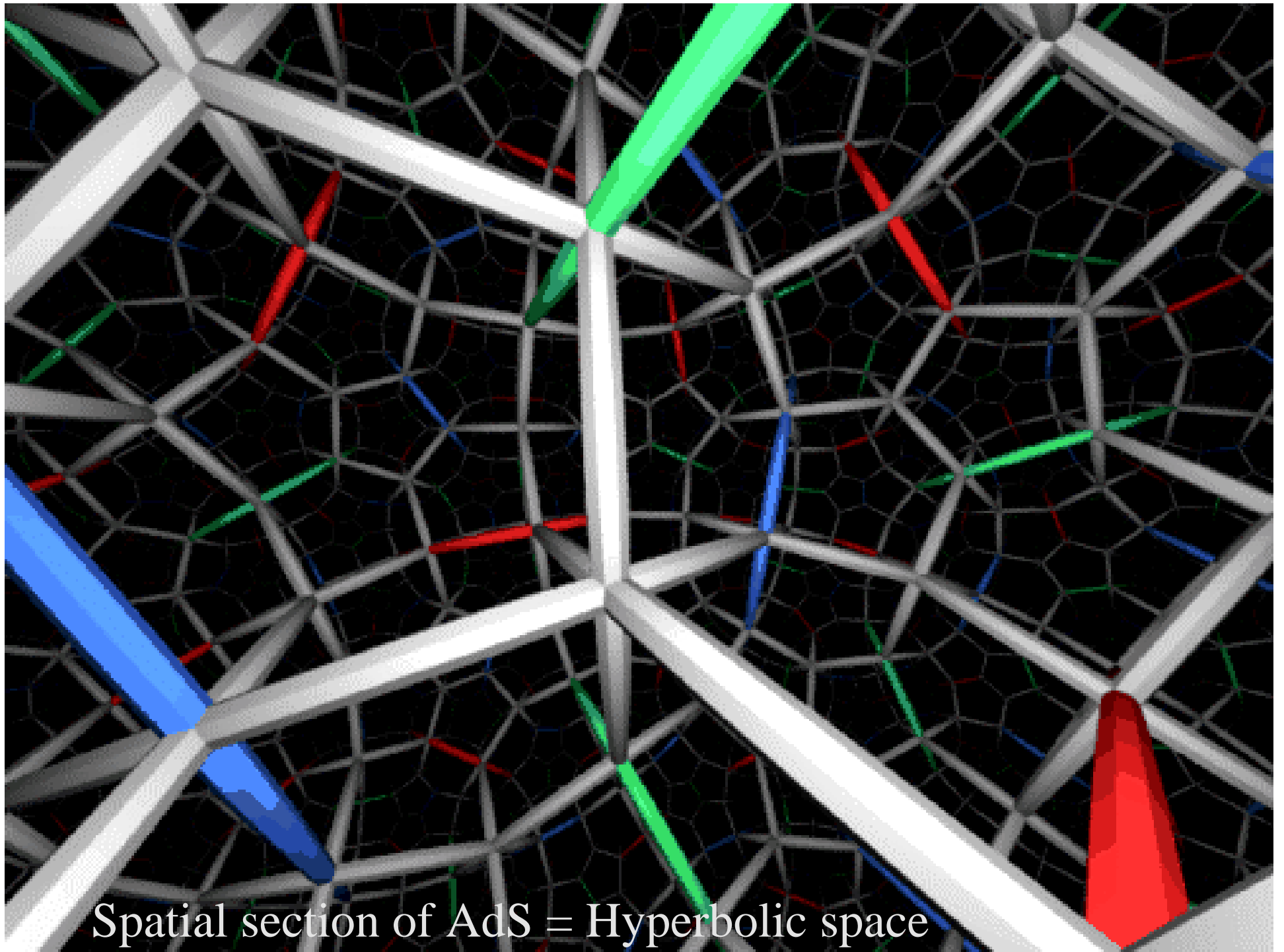
$$AdS_5 \times S^5$$

# Anti-de-Sitter spacetimes

Simplest negatively curved spacetime. It is completely uniform.  
Its isometry group is  $SO(2,4)$ .


It has a boundary. Light can go to the boundary and come back in finite time, but the boundary is at infinite spatial distance.





Spatial section of AdS = Hyperbolic space

$$\boxed{\begin{array}{c} N = 4 \text{ SU}(N) \text{ Yang-Mills} \\ \text{theory on } S^3 \times (\text{Time}) \end{array}} = \boxed{\begin{array}{c} \text{String theory on} \\ \text{AdS}_5 \times S^5 \end{array}} \quad (\text{J.M.})$$


  
 Boundary of AdS

Radius of curvature

$$R_{S^5} = R_{\text{AdS}_5} = \left( g_{YM}^2 N \right)^{1/4} l_s$$

Duality:

$g^2 N$  is small  $\longrightarrow$  perturbation theory is OK

$g^2 N$  is large  $\longrightarrow$  Gravity is a good description of the system.

Strings made with gluons become fundamental strings.

# Correlation Functions

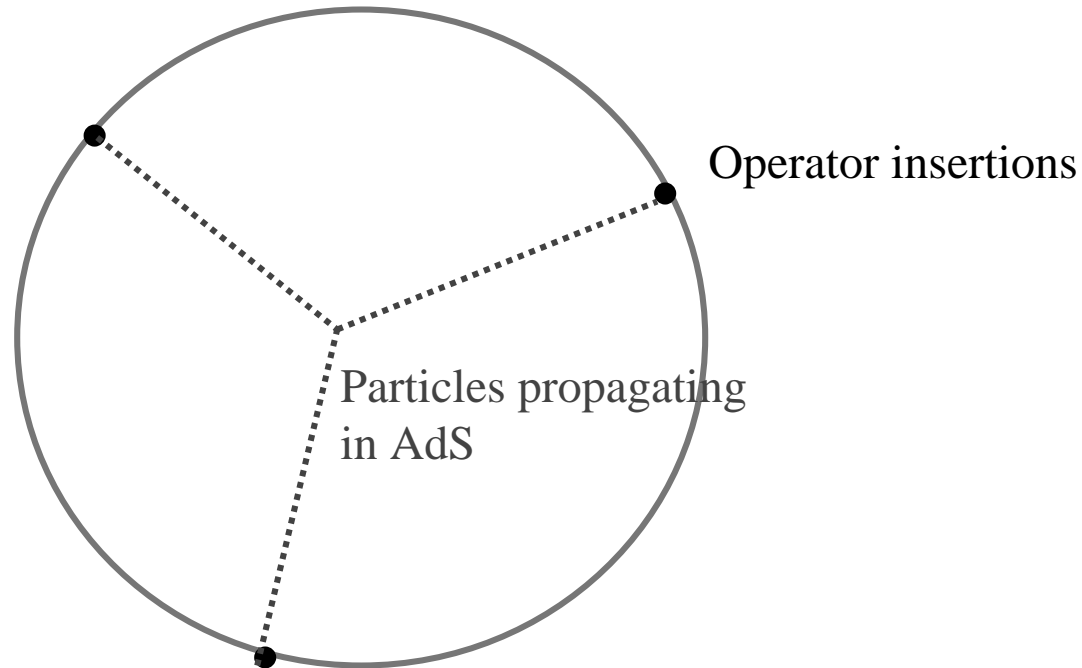
(Gubser, Klebanov,  
Polyakov, Witten)

Operators live in the field theory.

Each operator corresponds to a particle (a field, or more precisely a string state) in the gravity description.

The correlation function is equal to the amplitude for the propagation of the particles between prescribed points at the boundary.

$\langle O \dots O \rangle_{\text{FT}} =$  Amplitude for propagation in AdS



# Holography

(t' Hooft Susskind)

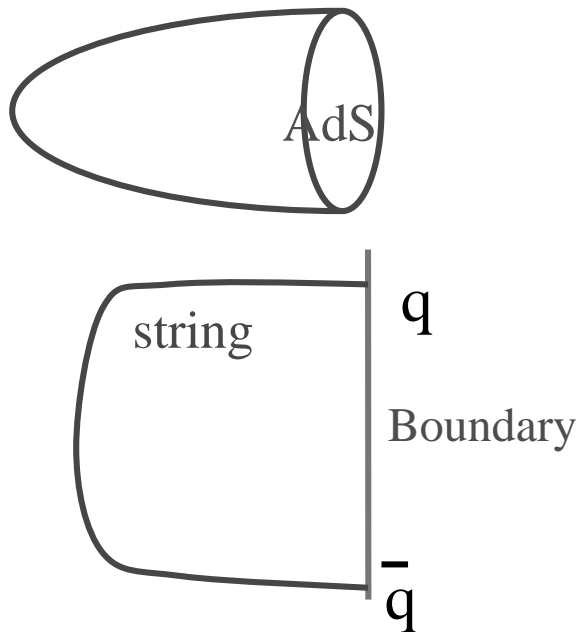
Physics inside some region of space can be described by a theory that lives on the boundary with less than one degree of freedom per Planck area.

This is a precise realization of this. Physics inside AdS is described by a theory living at its boundary.

**Black Holes** → Correspond to thermal states in the Yang-Mills theory. Their entropy can be calculated also for non-extremal black holes, and one can describe the Hawking radiation process. Most precise for AdS<sub>3</sub>

## QCD-like-theories

It is possible to deform the field theory and the gravity solution so as to break supersymmetry, giving mass to fermions and scalars. This leads to a new geometry.



Now there is a mass gap

Quark-antiquark potential is calculated as the length of a fundamental string going between two points on the boundary. It gives a confining potential in this case.

Baryons are D-branes.

It is not exactly the same as QCD because the coupling is not small in the UV

## Achievements

- Consistent theory of quantum gravity
- Very constrained mathematical structure which passes many tests
- Black hole entropy is reproduced
- Field theory dualities can be “derived” from string theory dualities
- Has all the ingredients to be able to produce the Standard Model.

## Main open problems

- Why 4 dimensions?
- Why is the cosmological constant so small? Hierarchy.
- Understand string theory in time dependent backgrounds
- Understand cosmological situations.
- Understand what selects the Standard Model
- Effective strings  $\longrightarrow$  QCD string theory.