6ª Escola de Astrofísica e Gravitação
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A brief introduction to the AdS/CFT conjecture

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AdS/CFT: what is it about?

AdS = anti-de Sitter spacetime

(maximally symmetric solution of the Einstein equations with a negative cosmological constant)

CFT = conformal field theory

(relativistic quantum field theory invariant under scaling transformations)

AdS/CFT: what is it about?

- It is a conjectured mapping between two (apparently) completely different theories:

- Holographic in nature ('CFT lives at the boundary of AdS')
- It is a powerful correspondence (strong-weak duality).
- Can extend to situations ≠ CFTs ('gauge/gravity correspondence').

Vast literature

- Polchinski's books "String Theory" (1998)
- Johnson's book "D-branes" (2003)
- Aharony, Gubser, Maldacena, Ooguri & Oz (AGMOO's) review "Large N field theories, string theory and gravity", hep-th/9905111
- D'Hoker & Freedman's TASI lectures "Supersymmetric gauge theories and the AdS/CFT correspondence", hep-th/0201253
- Mateos' review "String Theory and Quantum Chromodynamics" , arXiv:0709.1523 [hep-th]
- Nastase's review "Introduction to AdS-CFT", arXiv:0712.0689 [hep-th]
- Gubser & Karch's review, "From gauge-string duality to strong interactions: A Pedestrian's Guide", arXiv:0901.0935 [hep-th]
- McGreevy's review, "Holographic duality with a view toward many-body physics", arxiv: 0909.0518 [hep-th]
- Argyres' lecture, "Introduction to the AdS/CFT correspondence" in "From gravity to thermal gauge theories: the AdS/CFT correspondence", ed. Papanthonopoulos (2011)

Impact of AdS/CFT on High Energy Physics

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AdS/CFT: not so crazy...

- A quantum theory of gravity should contain a spin-2 massless particle ('graviton'). The Weinberg-Witten theorem forbids such particles in QFTs with usual stress tensors.

  ➡ The graviton and the CFT should live on different spaces.

- The Holographic Principle implies that the quantum theory of gravity must have a number of degrees of freedom which scales like the area, not the volume.

  ➡ The quantum gravity theory should live in one more dimension than the CFT.

- It is convenient to slice up QFTs according to energy scale u.
  The Renormalization Group Equations tell us how coupling constants depend on u.

  ➡ The extra dimension should be identified with energy scale.

AdS = anti-de Sitter spacetime

- In vacuum: $$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T_{\mu\nu} = 0$$

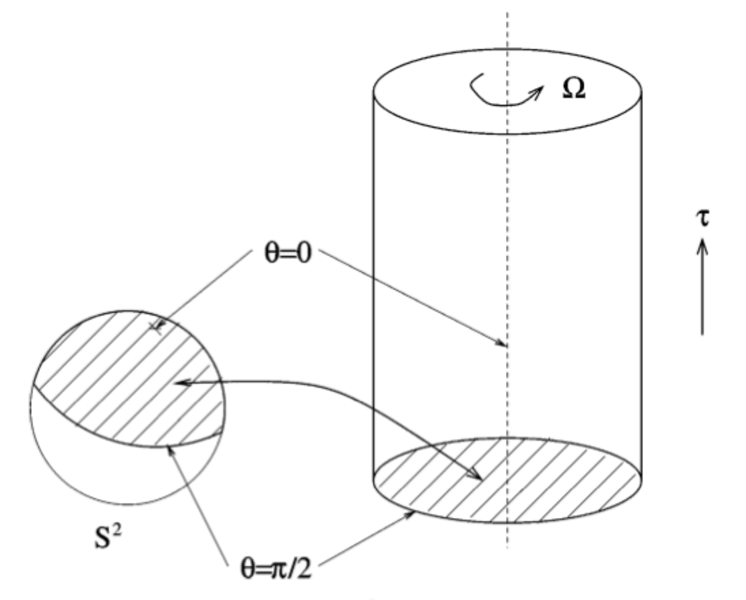
- Maximally symmetric ➡ constant curvature: $$R = \frac{2d}{d-2}\Lambda$$

- Global parametrization: $$ds^2 = -R^2 \cosh^2\left(\frac{\rho}{R}\right) dt^2 + d\rho^2 + R^2 \sinh^2\left(\frac{\rho}{R}\right) d\Omega_{d-2}^2$$

- Boundary at $\rho = \infty$ with topology $R \times S^{d-2}$.

- Another parametrization (not global):

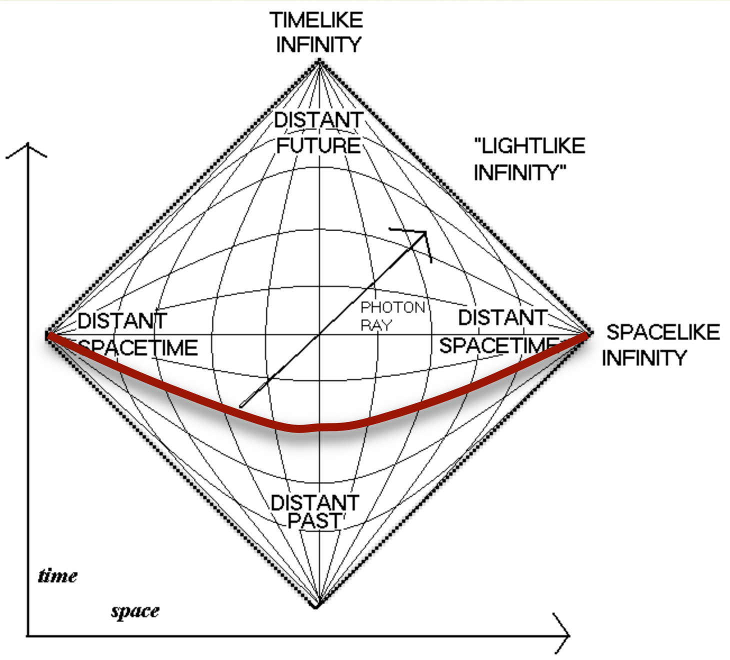
$$ds^2 = \frac{R^2}{r^2} dr^2 + \frac{r^2}{R^2}(-dt^2 + d\vec{x}^2)$$

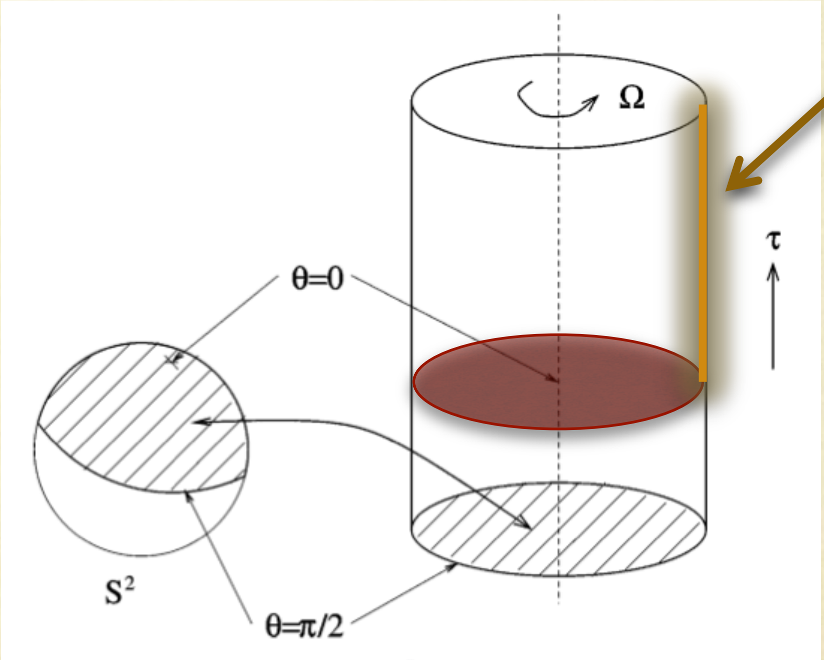


AdS vs Minkowski

- Minkowski is the maximally symmetric solution of Einstein eqs with Λ=0:

$$ds^2 = -dt^2 + d\vec{x}^2 = -dt^2 + dr^2 + r^2 d\Omega_{d-2}^2$$





- Minkowski is globally hyperbolic but AdS is not.
  Data must be specified on the boundary of AdS.

CFT = conformal field theory

- Quantum field theory (QFT) is the framework for constructing quantum mechanical models of systems classically represented by an infinite number of degrees of freedom (fields).
- Example: the standard model of particle physics.
- Unitary scale invariant QFTs are also conformally invariant.

conformal group:

- $M_{\mu\nu}$ Lorentz rotations
- P_{μ} Translations
- D Dilatations
- K_{μ} Special conformal transformations

CFT local operators and correlators

conformal group
- $M_{\mu\nu}$ Lorentz rotations
- P_μ Translations
- D Dilatations
- K_μ Special conformal transformations

- Generators satisfy an algebra which is SO(d,2) $\supset$ SO(d) × SO(2).

spin (SO(d)) — conformal dimension Δ (SO(2))

Classify local operators by their transformation properties under SO(d) × SO(2).

$$O_\Delta(\lambda x^\mu) = \lambda^{-\Delta} O_\Delta(x^\mu)$$

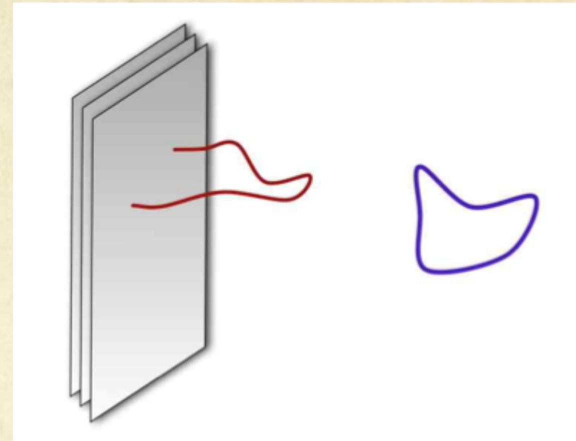
- Correlation functions are highly constrained by conformal symmetry:

$$\langle O_{\Delta_1}(x_1) O_{\Delta_2}(x_2) \rangle = \frac{\delta_{\Delta_1,\Delta_2}}{|x_1 - x_2|^{2\Delta_1}}$$

Recap: string theory basics

- ST is a theory of strings, but not only!

It is inhabited by other creatures and among the most important are D-branes.



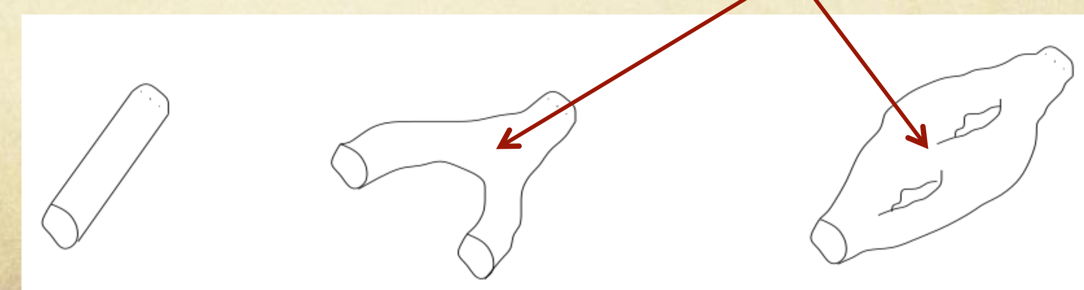
- What parameters do we have in ST?

➡ α' controls stringy effects. String tension is $T = \dfrac{1}{2\pi\alpha'}$

➡ g_s controls quantum effects. ('string coupling constant')

➡ Splitting/joining of closed (open) introduces a factor of g_c (g_o)

$$g_o^2 \sim g_c = g_s\, \alpha'^2$$



Recap: D-branes

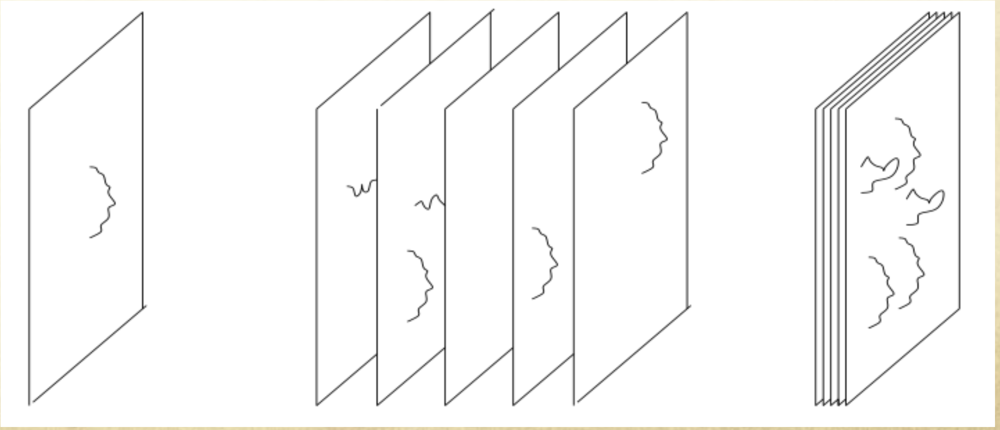
- D-branes are very special objects. They preserve half of the SUSYs

  BPS states → no force between parallel branes

- Dp-branes couple to (p+1)-form potentials.
- Tension of Dp-brane: $\tau_p^2 \propto g_s^{-2} \alpha'^{-(1-p)}$
- World-volume effective action of a single Dp-brane is (p+1)-dimensional Super Yang-Mills with gauge group U(1).

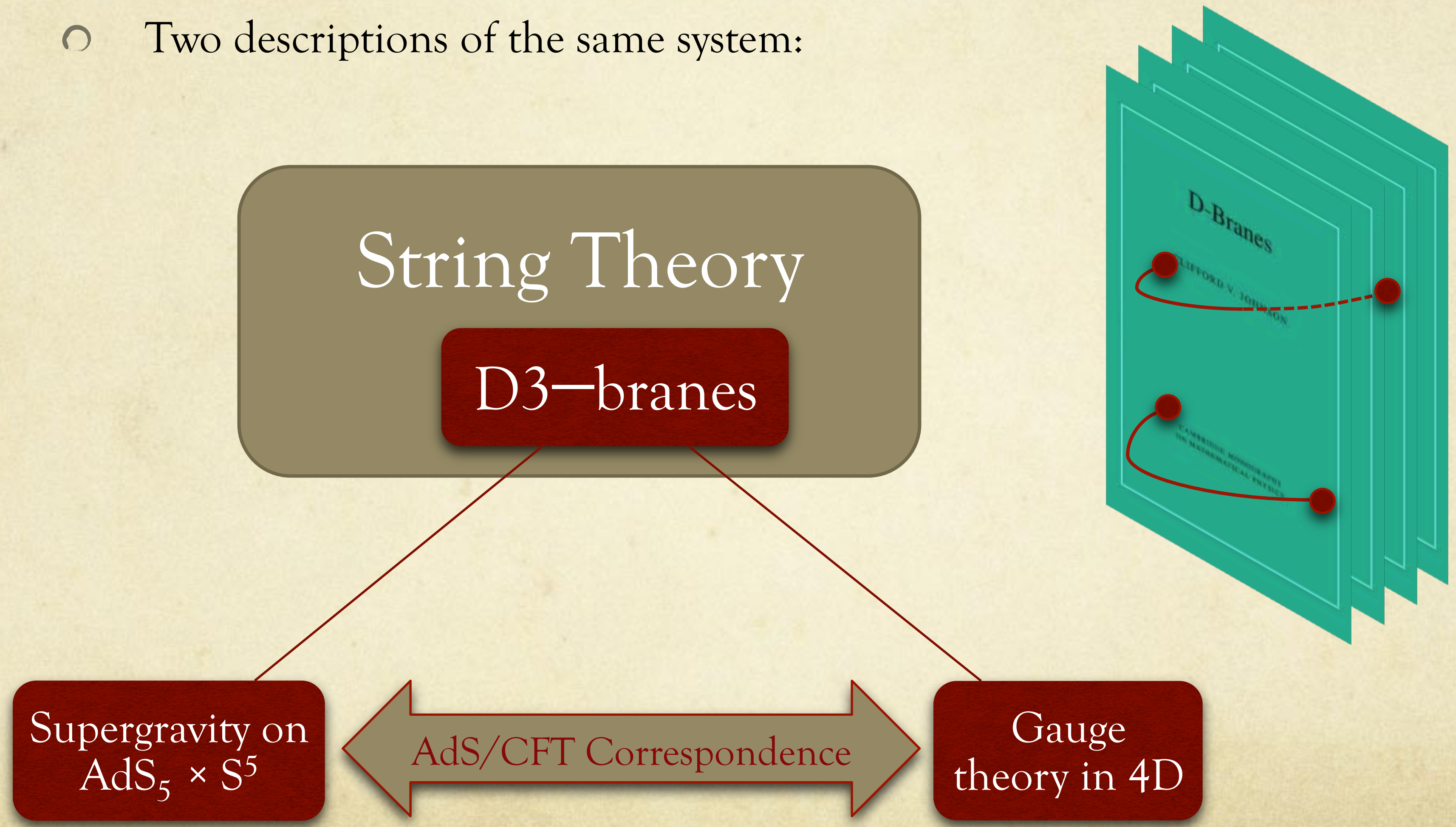
For N coincident branes there is symmetry enhancement:

$$U(1)^N \longrightarrow U(N)$$



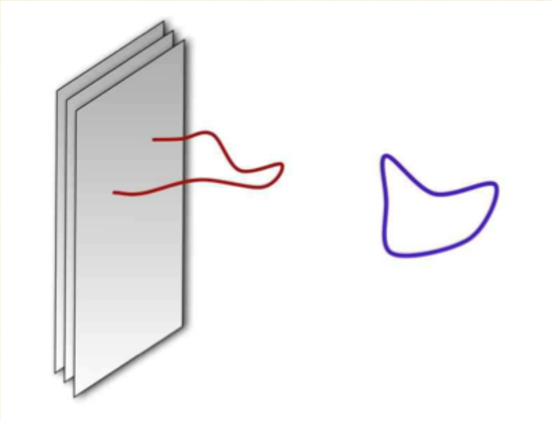
‘Deriving’ the correspondence

- Consider type IIB superstring theory with a stack of N D3-branes.
- Two descriptions of the same system:



Taking limits (cleverly)

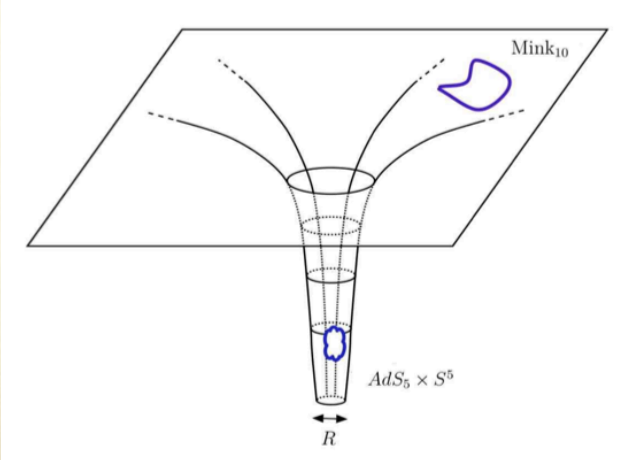
- Can use N as a parameter, in addition to g_s and α'.
- Weak coupling limit: $g_s \longrightarrow 0$, N fixed .



Back-reaction can be ignored and we just get

4d SYM with gauge group SU(N) 'living on the branes'

- 't Hooft limit: $g_s \longrightarrow 0$, $N \longrightarrow \infty$, $\lambda = g_s N$ fixed .



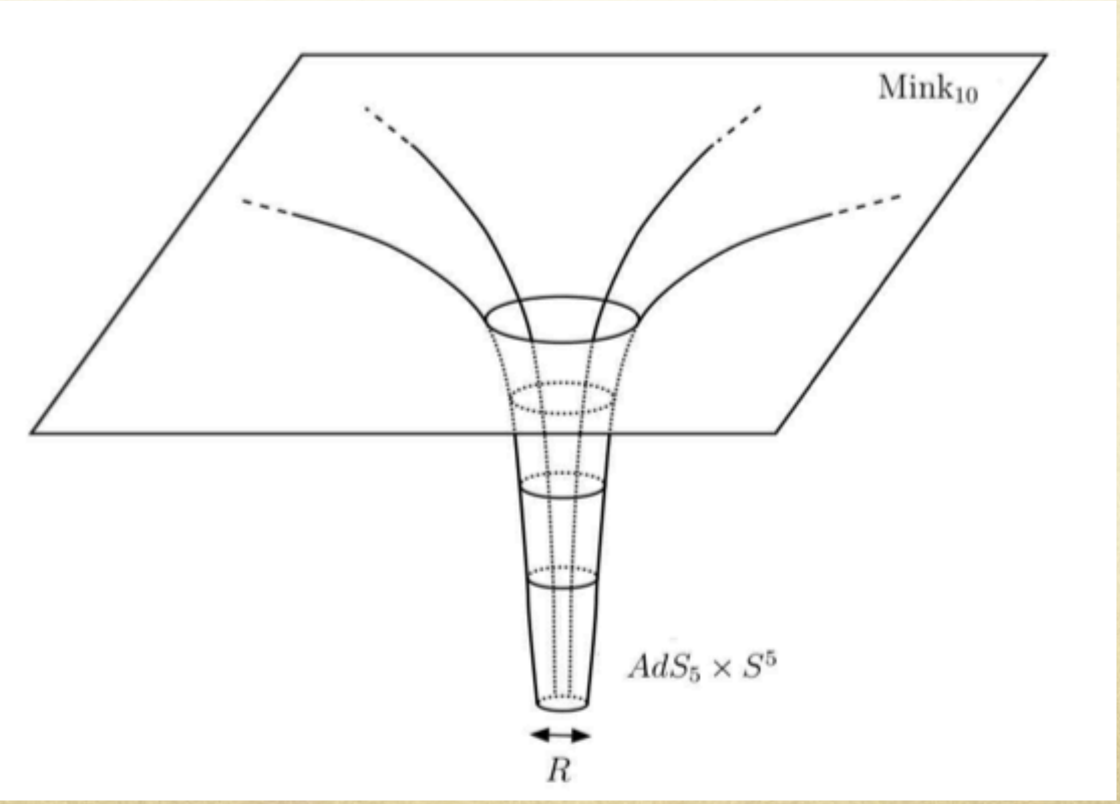
Back-reaction ($\propto g_s N$) cannot be neglected.

D-branes source a classical supergravity solution.

Throat geometry

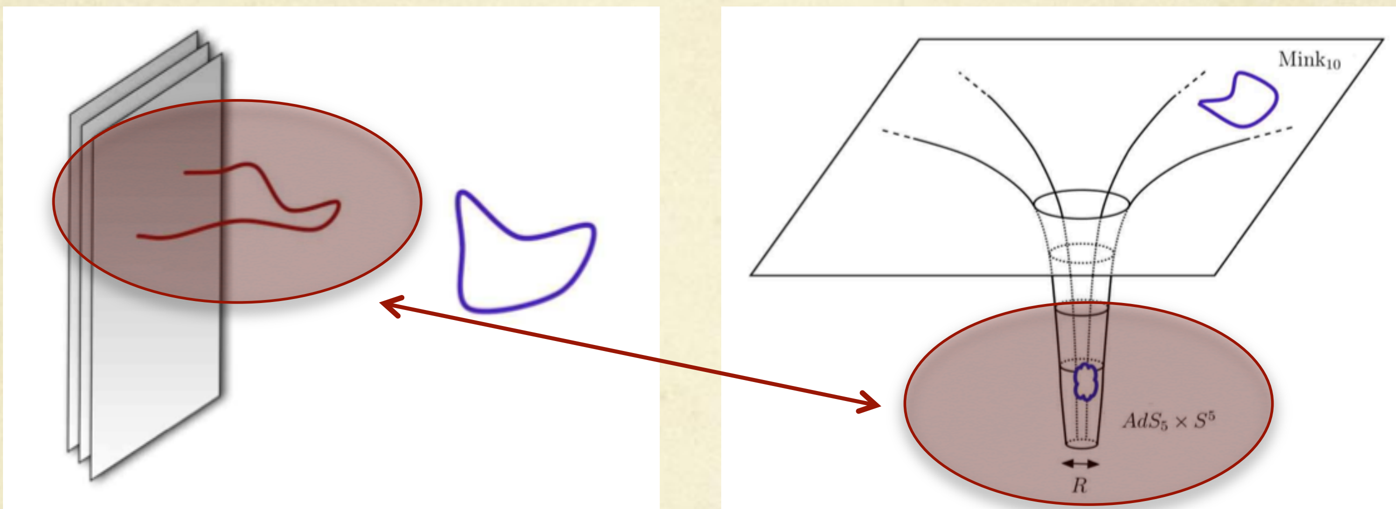
$$ds^2 = f^{-1/2}(-dt^2 + d\vec{x}^2) + f^{1/2}(dr^2 + r^2 d\Omega_5^2), \qquad f = 1 + \frac{R^4}{r^4}, \qquad R^4 = 4\pi g_s N \alpha'^2$$

- For $r >> R$ we get flat spacetime.
- For $r << R$ we get $AdS_5 \times S^5$ geometry: $$ds^2 \approx \frac{R^2}{r^2} dr^2 + \frac{r^2}{R^2}(-dt^2 + d\vec{x}^2) + R^2 d\Omega_5^2$$



The decoupling limit

- For low energies, $E << \alpha'$, only massless modes can be excited.
- 10d supergravity describing the massless modes in the bulk and in the asymptotically flat region both decouple.



4d SU(N) SYM

with $g_{YM}^2 = 2\pi g_s$

dual

IIB string theory on $AdS_5 \times S^5$

with $R^4 = 4\pi \lambda \alpha'^2$

Strong/weak duality

$$\frac{R^4}{\alpha'^2} = 4\pi\lambda \qquad \textit{and} \qquad g_s = \frac{\lambda}{2\pi N}$$

- O(α') corrections ⟷ O($\lambda^{-1/2}$) corrections
- O(g_s) corrections ⟷ O(N^{-1}) corrections (at fixed λ)

This is both a blessing and a curse!

Matching of symmetries

- The AdS_d metric can be obtained from the embedding of a hyperboloid in (d+1)-dimensional flat spacetime ('with two time coordinates').

➡ the isometry group of AdS_d is $SO(2,d-1)$

- The isometry group of S^5 is $SO(6)$, the rotation group.

- The isometry group of $AdS_5 \times S^5$ is $SO(2,4) \times SO(6)$.

- This precisely matches the conformal symmetry and R-symmetry of SYM ☑

(rotations of the six scalar fields)

AdS/CFT in practice

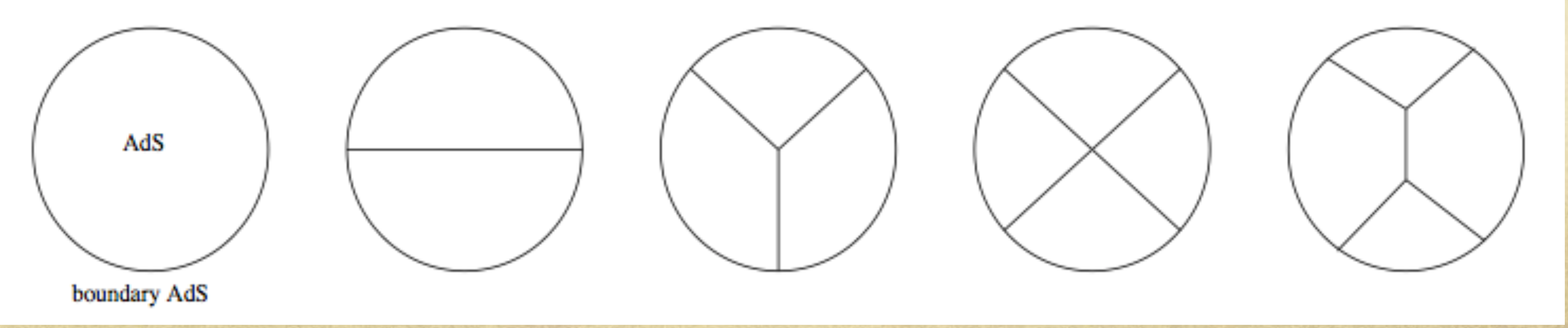
- The precise statement of the correspondence is the equality of the partition functions of the two theories:

$$\int_{\phi|_\partial=\bar{\phi}} D\phi(z,\vec{x})\,e^{-S[\phi(z,\vec{x})]} \equiv Z_{AdS}[\bar{\phi}(\vec{x})] = Z_{CFT}[\bar{\phi}(\vec{x})] \equiv \left\langle e^{\int d^d x \bar{\phi}(\vec{x}) O(\vec{x})} \right\rangle$$

- Boundary conditions in AdS are associated with sources for the field operators.

- Computing correlators is straightforward:

$$\left\langle O_{\Delta_1}(x_1) O_{\Delta_2}(x_2) \ldots \right\rangle = \left. \frac{\partial^n Z[\phi_{\Delta_i}]}{\partial \bar{\phi}_{\Delta_1}(x_1)\, \partial \bar{\phi}_{\Delta_2}(x_2) \ldots} \right|_{\bar{\phi}_{\Delta_i}=0}$$



Applications: modeling QCD

- 4d SYM is conformal but QCD is not. Actually they are very different theories:

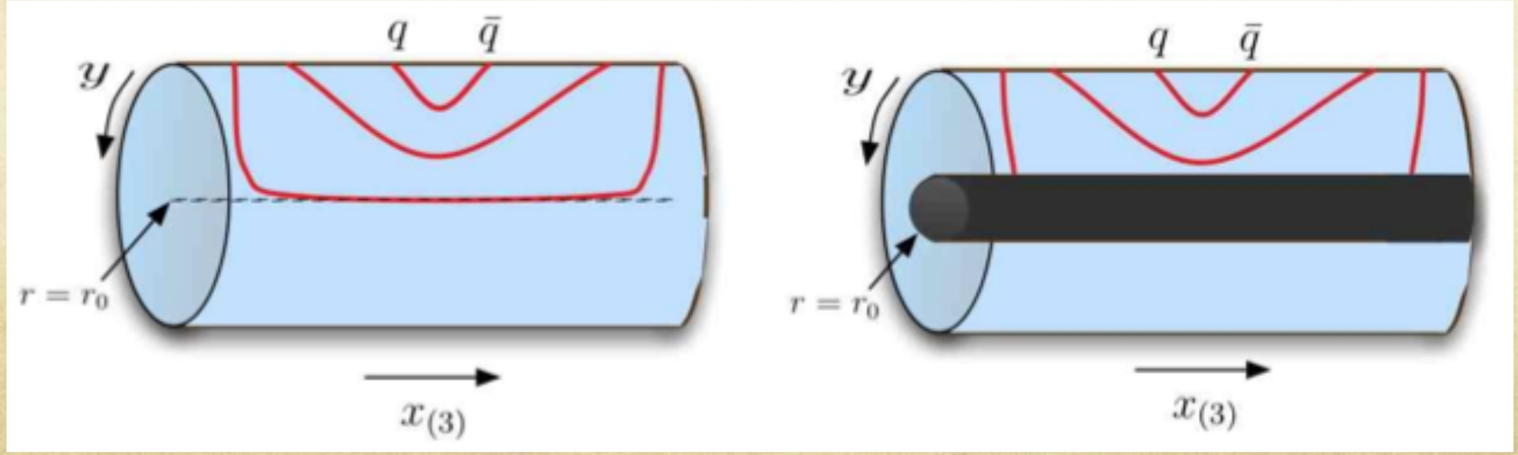
  QCD is asymptotically free, exhibits confinement and is not SUSY.

- It is known how to construct gravitational duals for confining theories.

  Confinement/deconfinement phase transition

  ⇕

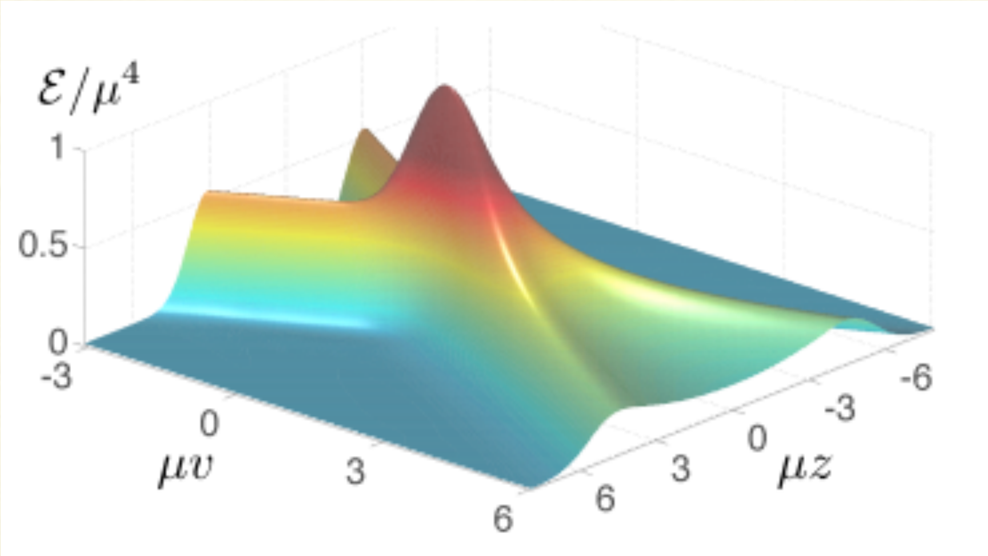
  Hawking-Page phase transition



Applications: Heavy ion collisions

- Transport coefficients (e.g. viscosity) can be computed from correlation functions.

AdS/CFT is a great tool to study quark-gluon plasmas (strongly coupled systems) that are observed at particle accelerators.



Applications: Holographic superconductors

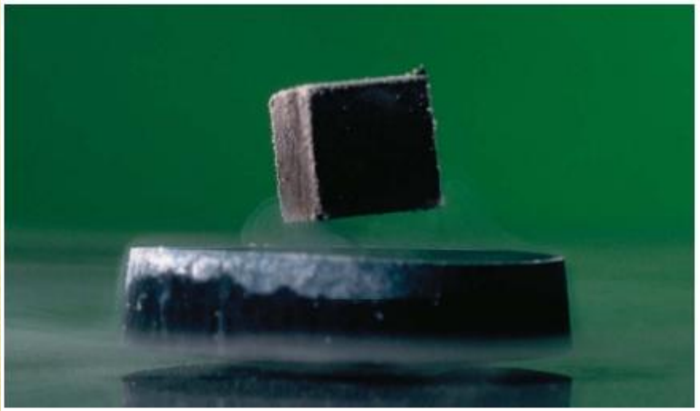
- We have a theory (BCS, 1957) that correctly describes low T_c superconductors.

Weakly coupled Cooper pairs of electrons form and condense below temperature T_c.

- But in 1986 a new class of high T_c superconductors was discovered!

These are not well understood: the electron pairing mechanism is strong coupling.

- AdS/CFT is appropriate to address this problem and holographic superconductors have been theoretically constructed with very similar qualitative properties as real world high T_c superconductors.



Applications: Hydrodynamics and turbulence

- The fluid-gravity correspondence shows that the Navier-Stokes equations can be obtained from the Einstein equations (in the regime of long wavelength perturbations of AdS black holes).

- Can we understand turbulence?

Conclusions

- Is String Theory the correct theory of quantum gravity?
  It is certainly an excellent candidate (arguably the best).

- We are perhaps still far from confirming the ‘reality’ of String Theory but it has already produced an extremely important legacy:

the AdS/CFT correspondence.