

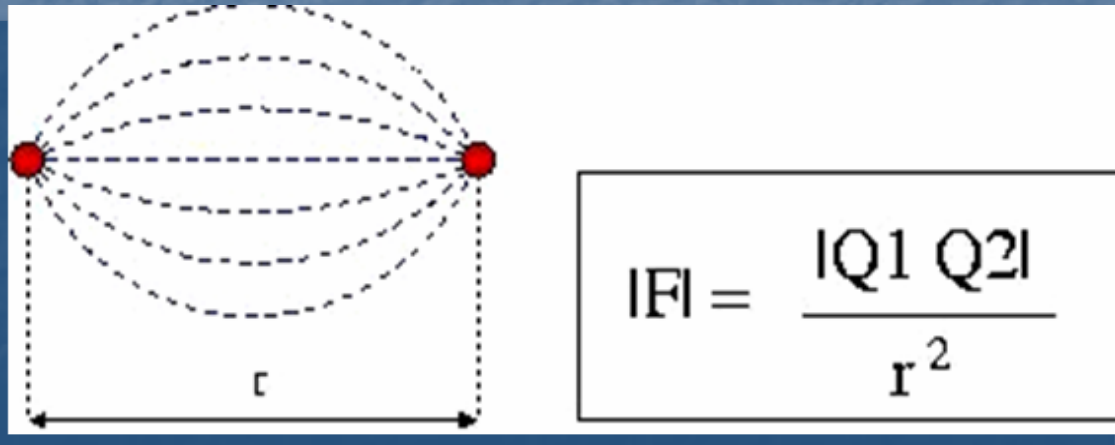
# *Strings, Gravity and Particle Physics*

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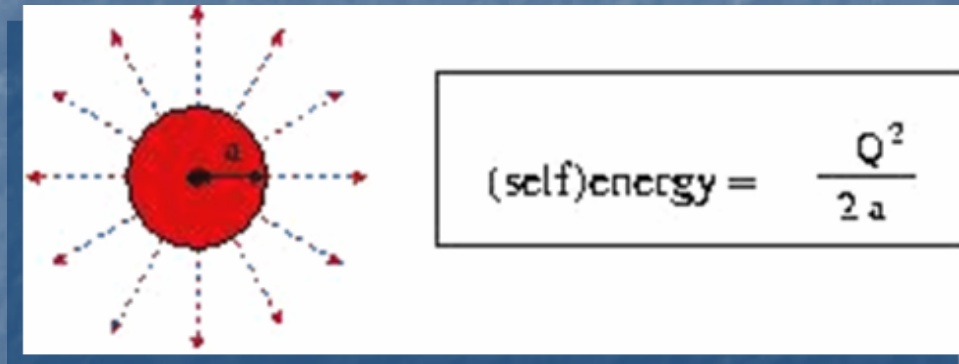
# Particles and Forces

- ◇ All matter is (apparently) made of “elementary particles”
- ◇ Particles exert *mutual forces*
  - ◇ *Example* : Coulomb force



# Particles and Field Theory

- ◇ A charged particle creates an *electric field*  $\mathbf{F} = q\mathbf{E}$



- ◇ *Elegant dynamics*: Maxwell equations and waves

**Problem:** self-interaction and self-energy



# Quantum Mechanics and Special Relativity

- ◇ *Particles are waves (and waves are particles)*

$$\Delta x \Delta p \geq \hbar$$

- ◇ *Identical particles: bosons and fermions*
- ◇ *Special Relativity:  $\Delta E > mc^2$  can destroy a particle and transform it into others*

Thus ( $m > 0$ ):

$$\Delta x > \lambda_C \approx \frac{\hbar}{mc}$$

*A theory of all types of (anti) particles !*

# Quantum Field Theory

- ◇ *Quantum Field Theory*: quanta of wave fields
  - ◇ Example: photons and the e.m. field

- ◇ *Quantize* (photon) oscillators: 
$$H = \frac{\hbar\omega}{2} (a^\dagger a + a a^\dagger) = \hbar\omega \left( a^\dagger a + \frac{1}{2} \right)$$

- ◇ *Bosons*: *positive* zero-point energy

- ◇ *Fermions*: Pauli principle, *negative* zero-point energy

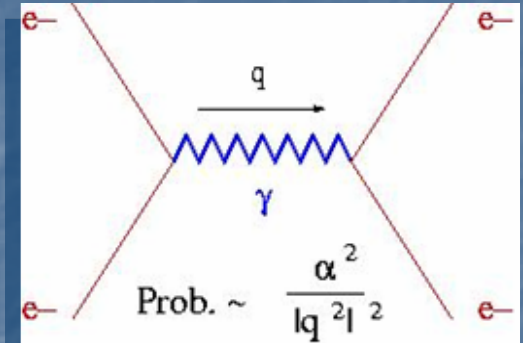
$$H = \frac{\hbar\omega}{2} (a^\dagger a - a a^\dagger) = \hbar\omega \left( a^\dagger a - \frac{1}{2} \right)$$

*Supersymmetry (SUSY)*: zero point energies cancel for bosons and fermions of same mass

# Particle Interactions

◇ *Interactions: “(sub) nuclear chemistry”*

◇ *e.m. (Q.E.D.), strength :*  $\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}$

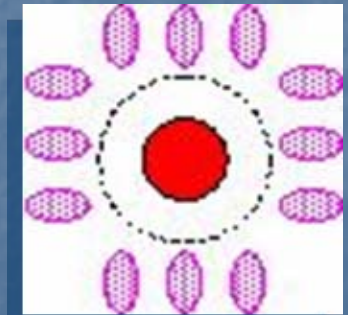


◇ *(Almost) free particles, interact via :*

$$\nabla \rightarrow \nabla - \frac{ie}{\hbar c} A$$

◇ *QED vacuum: “quantum aether” (zero-point fluctuations)*

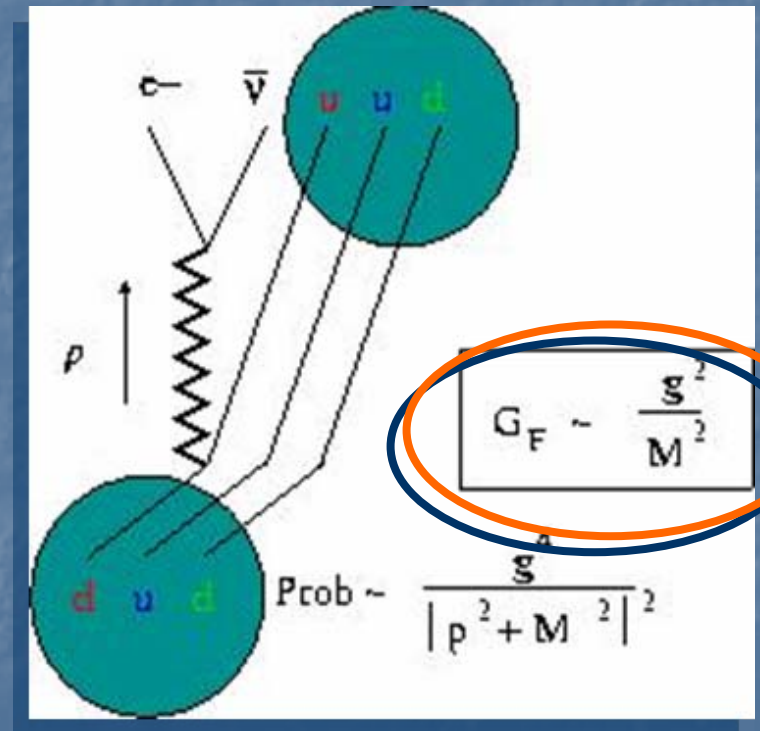
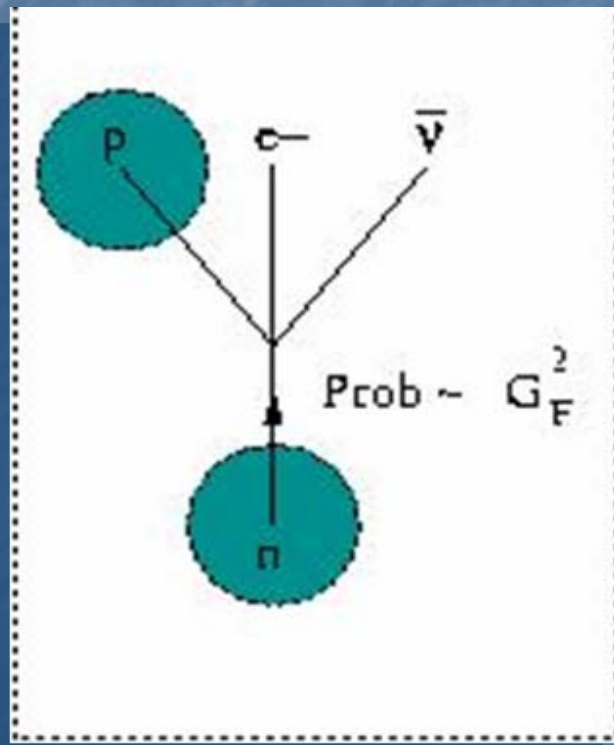
*“Screening”: e<sup>+</sup> - e<sup>-</sup> plasma, α increases slowly with increasing (decreasing) energy (distance)*





# Fundamental Interactions

- ◇ *Particles and interactions: can also manifest themselves indirectly*
- ◇ *themselves indirectly*



# Standard Model

- a. Electromagnetic (Q.E.D.)
  - b. Weak
  - c. Strong (Q.C.D.) : quarks
- } *Electro-weak : quarks and leptons*

- ◇ (matrix) vector potentials  $W, B, G$  (Yang-Mills fields)
- ◇  $W, B \rightarrow A$  (long-range);  $W^+, W^-, Z$  (short-range)
- ◇ *Short range* : Higgs, or BEH mechanism?

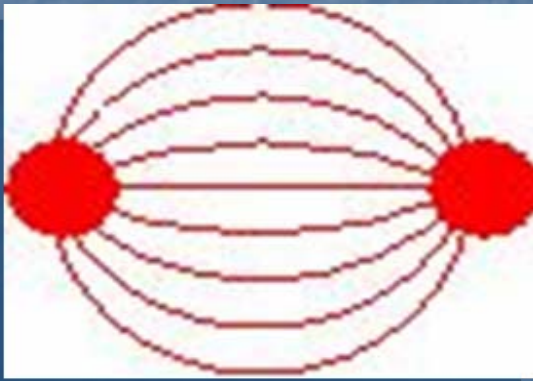
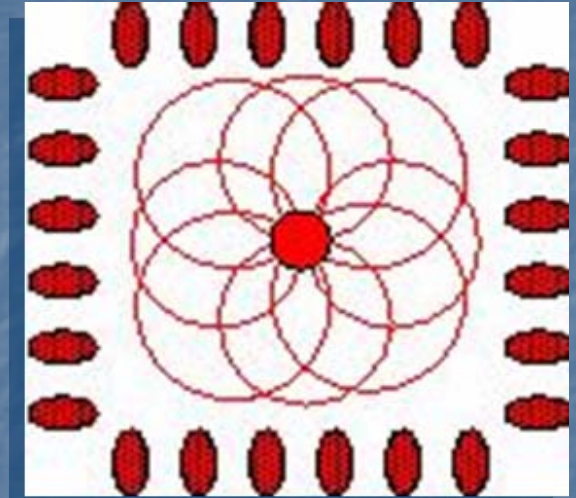
*New degrees of freedom from the e-w scale ( $\sim 100$  GeV or "proton masses")*



# Q.C.D.

*Anti-screening*: "colored" plasma hampers "Faraday" lines, gauge bosons "spread" the charge

- $\alpha_s$ : decreases slowly with increasing energy (*asymptotic freedom*)
- ◇ Strong interactions dynamically generate a scale



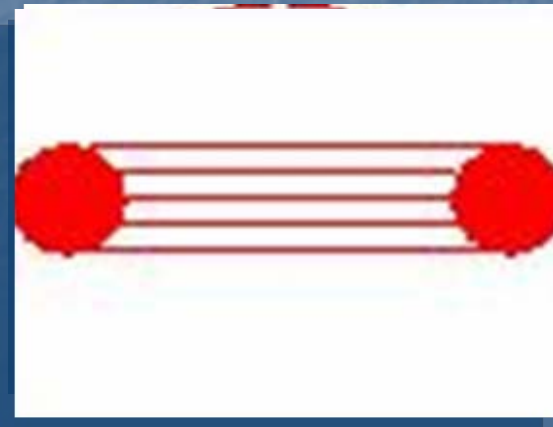
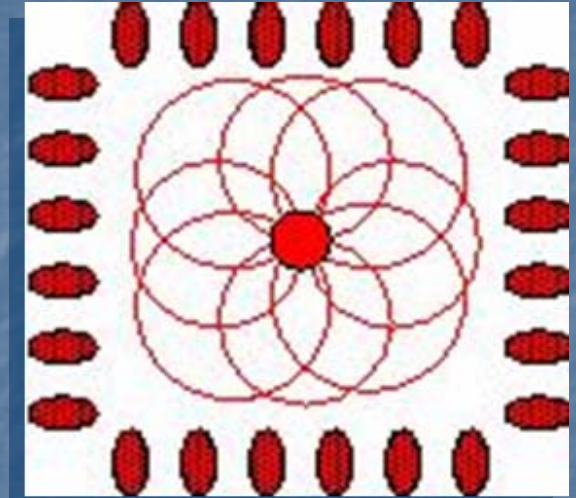
*"thick" strings!*

$$V \approx V_0 \frac{r}{l_s}$$

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# Classical Gravity

◇ *Newton :*

$$F = \frac{G_N m_1 m_2}{r^2}$$

◇ *Newton vs Coulomb:*

$$\frac{e^2}{\hbar c} \rightarrow \frac{G_N m^2}{\hbar c} \rightarrow \frac{G_N E^2}{\hbar c^5}$$

◇ *Einstein: dynamics vs space-time geometry  $\rightarrow g_{mn}$*

◇ *Mass (energy) induces space-time curvature*

$$[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} ]$$

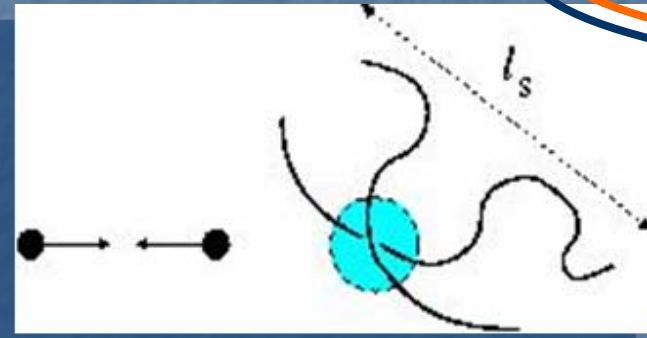
◇ *Violent fluctuations at high energies !*

[ *Vacuum energy: cosmological constant* ]



# Strings, Gravity and Particles

- ◊ Diluting energy  $\rightarrow$  **new degrees of freedom at "string scale"**

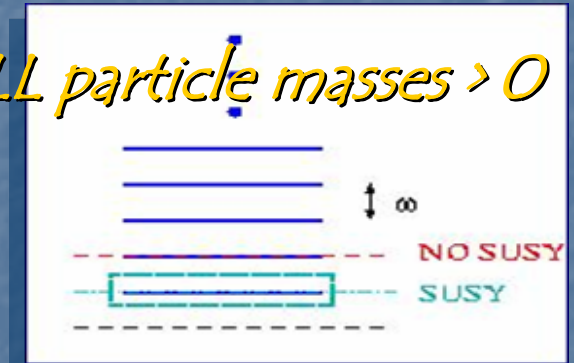


$$\frac{G_N E^2}{\hbar c^5} \rightarrow \frac{G_N E^2}{\hbar c^5} \times \left[ \frac{(\hbar c/E)}{l_s} \right]^2$$

- ◊ **Elementary particles as string modes : ALL particle masses  $> 0$  ?**



**NO!**

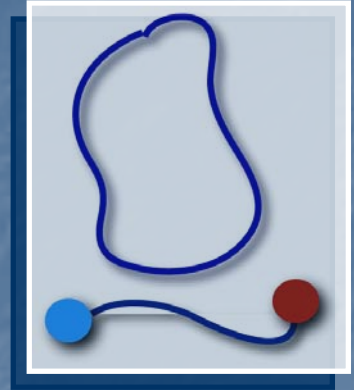


- ◊ **Zero-point**  $\rightarrow$  massless modes & long-range forces
- ◊ **gravity!** (+ e.m. & YM)
- ◊  **$| + \infty$  massive Higher-Spin fields |**

# Superstrings

- ◇ *5 different types: Open and Closed, Bose and Fermi*
- ◇ *SUSY: NO VACUUM ENERGY*

*BUT: 10 space-time dimensions !*



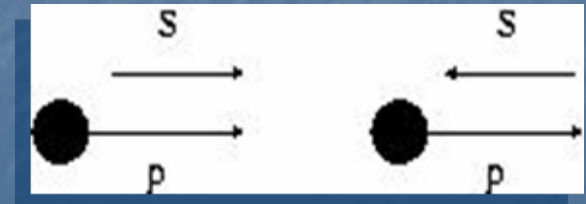
*10D superstrings (w. CHIRAL ASYMMETRY):*

- Closed only:*  
*HO (SO(32)), HE (E8 x E8), Type IIA, IIB;*
- Open and closed: Type I*

**CHIRAL ASYMMETRY** → Anomalies

(Standard Model: Quarks  $\leftarrow \rightarrow$  Leptons)

**HERE:** Green-Schwarz mechanism



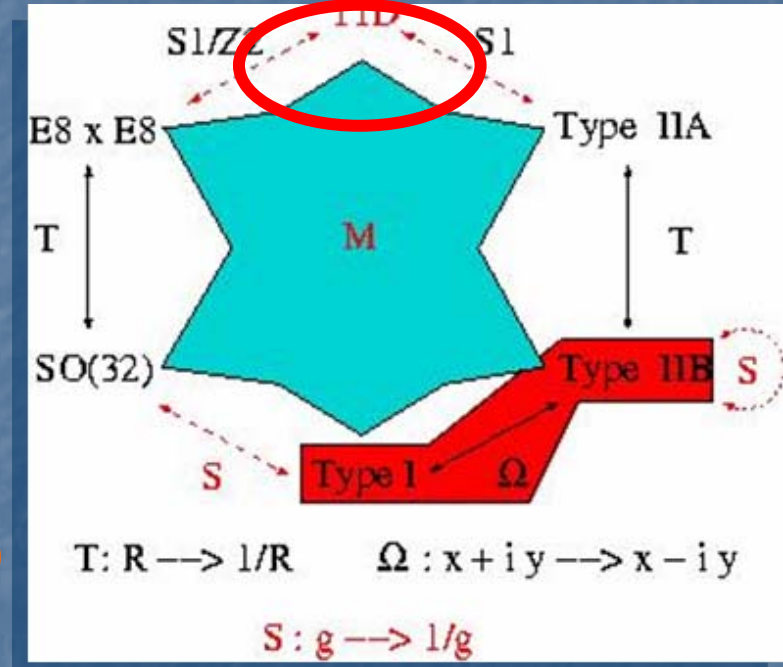
# String Dualities

a. *T-duality*



$$X = x + (2\alpha') \frac{m}{R} \tau + 2nR\sigma$$

All (+11D) equivalent mysterious "M-theory"



b.  $\Omega$ : world-sheet parity

$$(\sigma, \tau) \rightarrow (-\sigma, \tau)$$

c.  $S$ : (e.m.-like) strong-weak duality

$$g \rightarrow \frac{1}{g}$$

d.  $S1$  &  $S1/Z2$ : growth of ONE EXTRA DIMENSION!



# Forms, branes and String Dualities

◇ With a  $(p+1)$ -form  $B$  in  $D$  dimensions:

- ◇ "Electric" sources :  $p$ -branes
- ◇ "Magnetic" sources:  $(D-4-p)$ -branes

◇ *E.m.*: electric  $0$ -branes (particles)  
magnetic  $(D-4)$  branes (monopoles only in  $D=4$ )!

$$H_{p+2} = d B_{p+1}$$

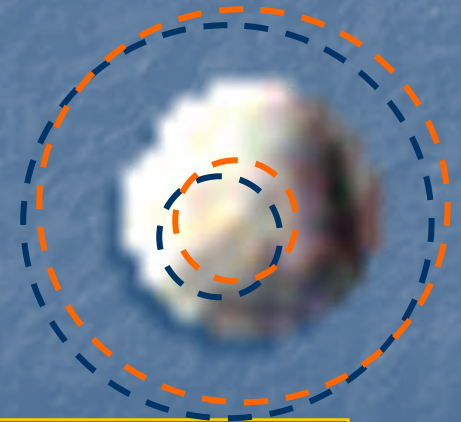
$$d \star H_{p+2} = \star J_{p+1}$$

$$d H_{p+2} = \star \tilde{J}_{D-p-3}$$

◇ How can different strings be equivalent?

◇ Solitons : energy "blobs"

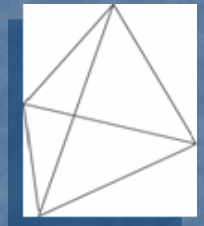
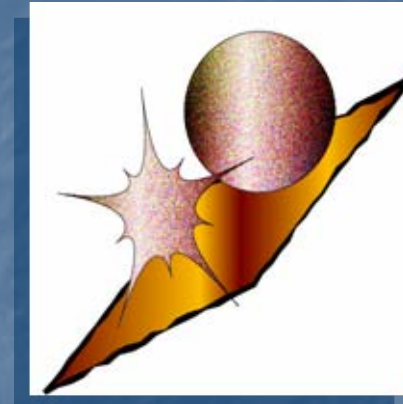
◇ Size:  $\Delta \approx \frac{1}{\Lambda}$       ◇ Compton:  $\lambda_C \approx \frac{g}{\Lambda}$



For  $g$  small "classical", for  $g$  large like "quanta"

# Compactification

- ◇ *Standard Kaluza-Klein scenario :*
  - ◇ *small "symmetric" extra dimensions*
- ◇ *Calabi-Yau : small "non symmetric" dimensions*
  - ◇ *D=4 flat space, N=2 or N=1 SUSY*
  - ◇ *10D  $\rightarrow$  4D chirality*
  - ◇ *internal "shape"  $\rightarrow$  low-energy D=4 Physics*
  - ◇ *moduli (can be fixed with extra fluxes)*
  - ◇ *String realization via orbifolds*



- ◇ *Symmetry-breaking-like, but NO minimum principle*
  - ◇ *NO WAY to select a priori the internal manifold*

*WHY, then, a unique D=10,11 theory ?*



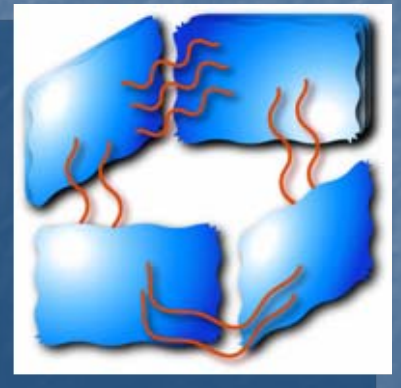
# D-Branes & Orientifolds

- Low-energy excitations: spin-1/2, spin-0 AND **spin-1**

Particle Physics on D-branes?



- (Green-Schwarz) Anomaly cancellations:
  - Branes "exchange" anomalies
- New types of phase transitions:
  - Branes can become "tensionless"





# "Large" Extra Dimensions?

- ◇ What string length ?
- ◇ What size (and shape) for extra dimensions ?



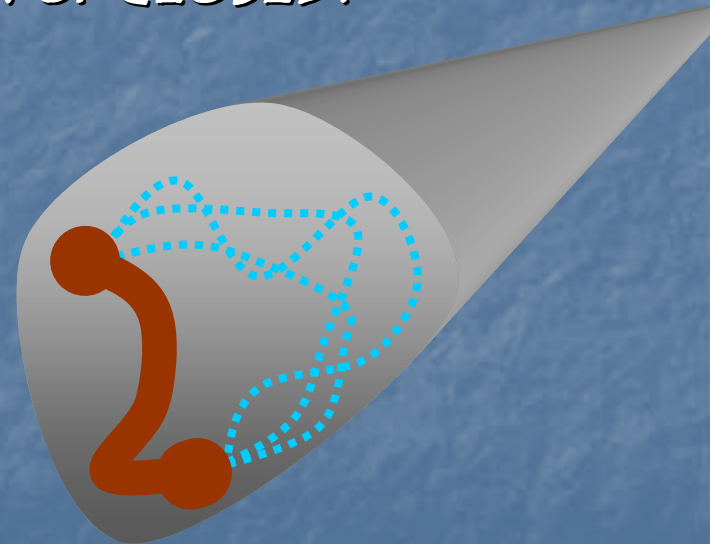
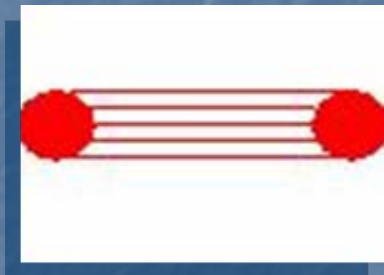
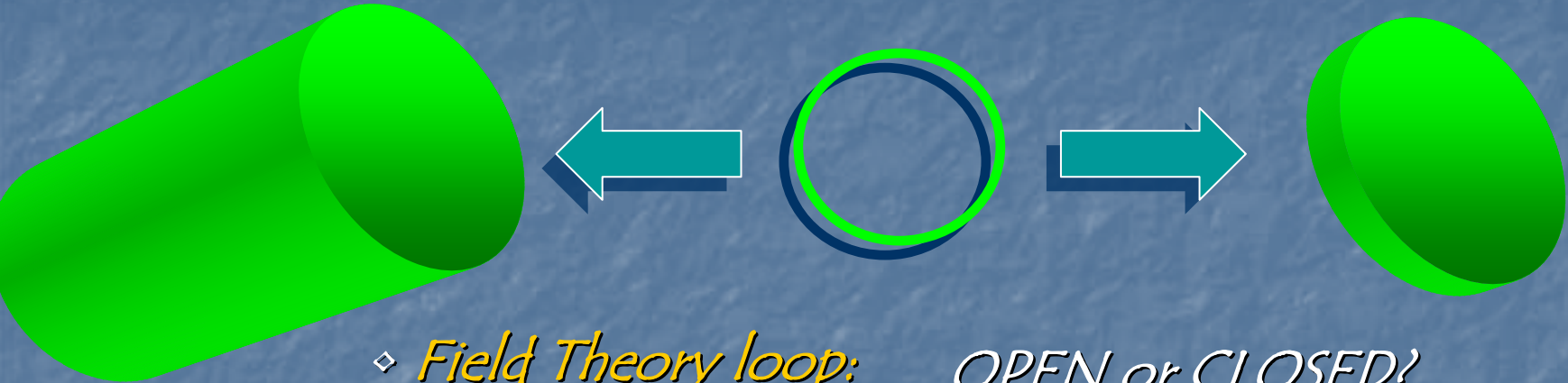
◇ *Closed strings only:*  $G_N \approx l_s^2 \approx R^2$

◇ *Open and closed:*

$$G_N \approx l_s^2 \left( \frac{l_s}{R} \right)^n$$

*Newton force modified below 1mm ??*

# AdS/CFT Correspondence



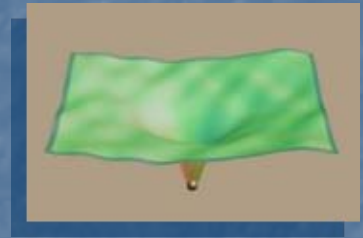
*Effective "thick" QCD string!*

*QFT on AdS boundary  
(strong coupling)*

*String Theory in AdS bulk  
(weak coupling)*

# Black holes

- ◇ *BH Thermodynamics: what, microscopically?*
- ◇ *For some (SUSY) BH two computations:*
  - ◇ *strong-coupling: Supergravity*
    - ◇ *entropy vs. macroscopic charges*
  - ◇ *weak-coupling: String Theory*
    - ◇ *D-brane excitations*
    - ◇ *[count (BPS) states at weak coupling]*
    - ◇ *THEY persist at strong coupling*



*What microscopic degrees of freedom?*



# Outlook

- ◇ Remarkably rich (apparently *UNIQUE*)  $D=10,11$  framework
  - ◇ Why a given "shape" of extra dimensions ?
  - ◇ Can realistic vacua be stable (without *SUSY*) ?
- ◇ We *DO NOT* know the complete field equations
  - ◇ They seem background dependent (vs Einstein gravity)
  - ◇ [*NO control* over  $\infty$  massive Higher-Spin modes]

*All this has the flavor of the Bohr-Sommerfeld rules for Q.M. !  
(for its logical incompleteness)*

*What is really String Theory ?*