

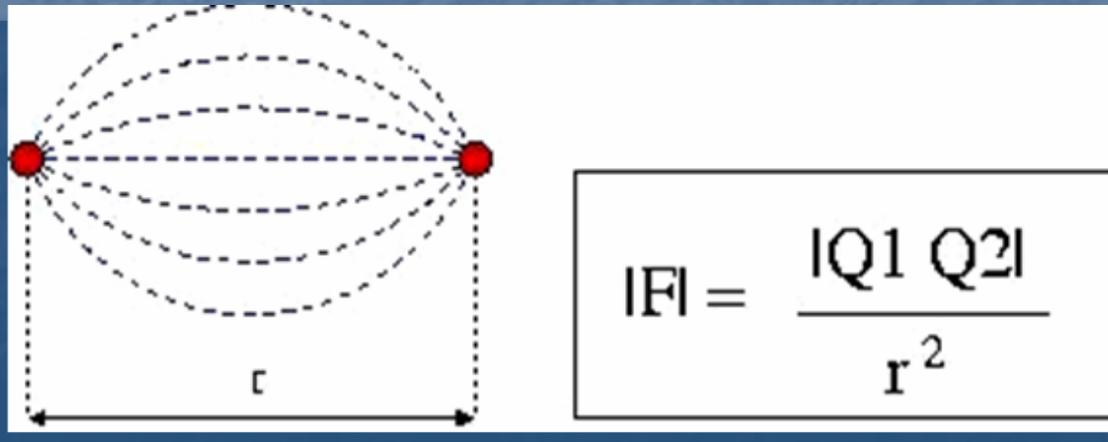
Strings, Gravity and Particle Physics

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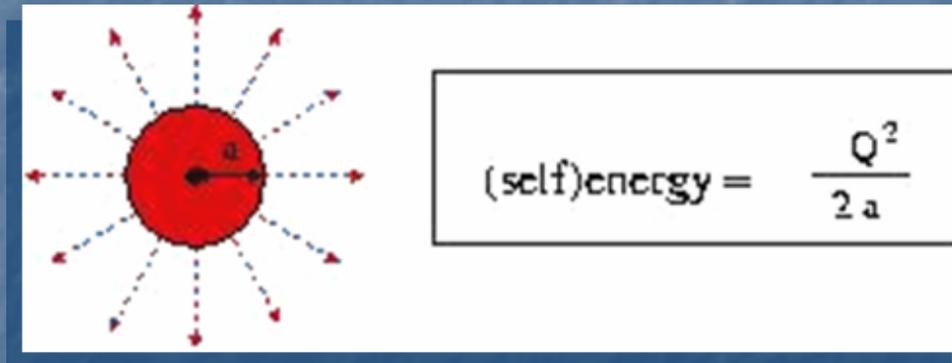
Particles and Forces

- ◇ 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

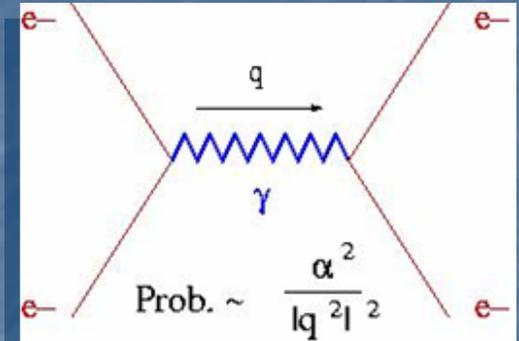
$$H = \frac{\hbar\omega}{2} (a^\dagger a - a a^\dagger) = \hbar\omega \left(a^\dagger a - \frac{1}{2} \right)$$

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 :* $\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}$

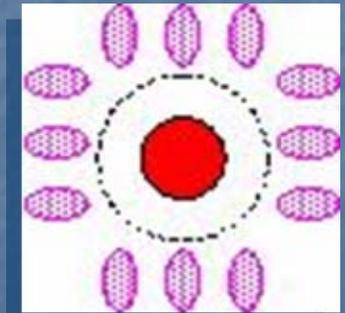


◇ *(Almost) free particles, interact via :*

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

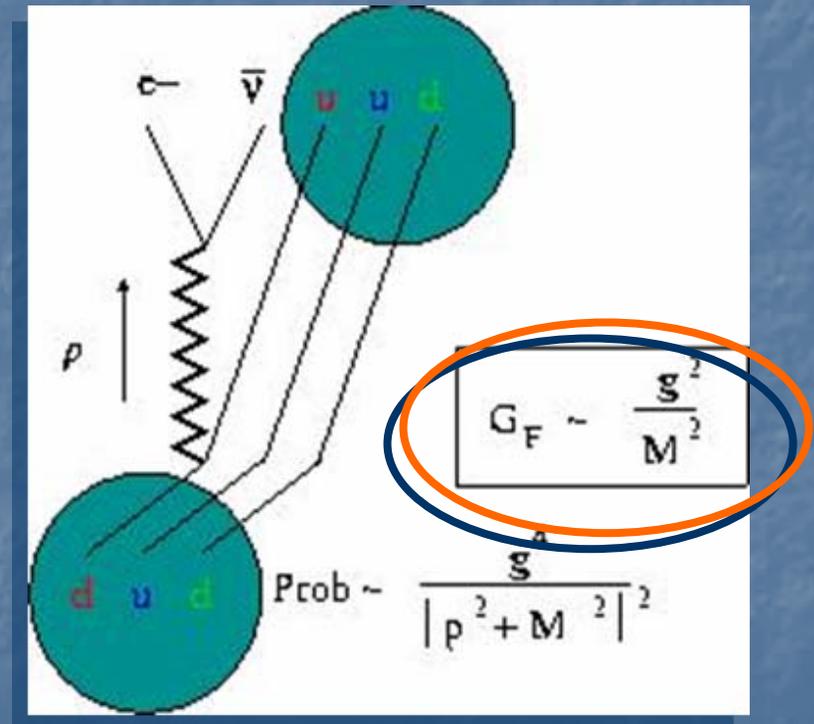
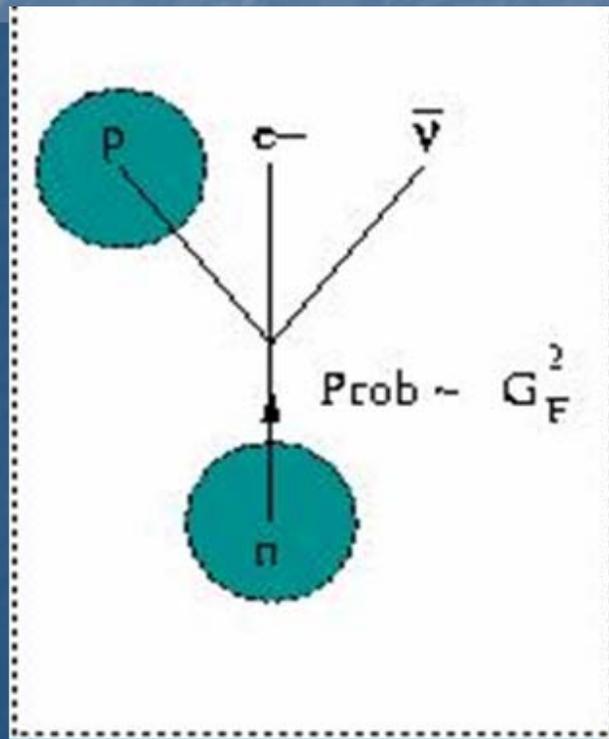
◇ *QED vacuum: “quantum aether” (zero-point fluctuations)*

“Screening”: e^+ – e^- 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

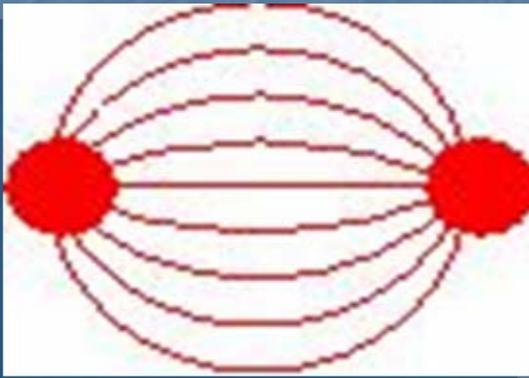
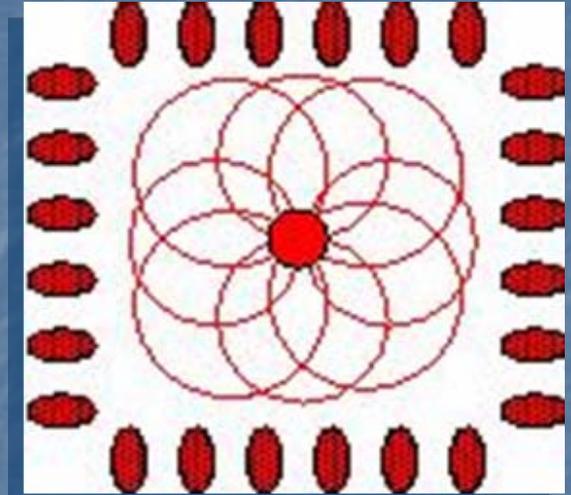
- ◇ (matrix) vector potentials W, B, G (Yang-Mills fields)
- ◇ $W, B \rightarrow A$ (long-range); W^+, W^-, Z (short-range)
- ◇ *Short range* : Higgs, or BEH mechanism?

New degrees of freedom from the e-w scale (~ 100 GeV or "proton masses")

Q.C.D.

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

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



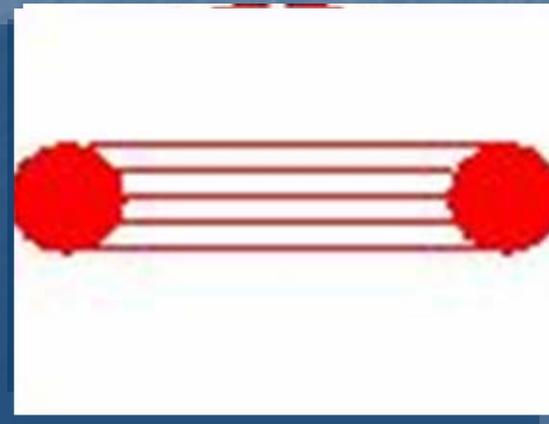
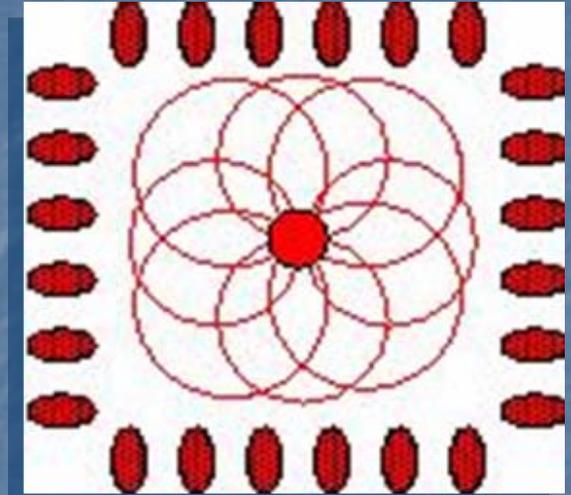
"thick" strings!

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

Q.C.D.

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"thick" strings!

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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*

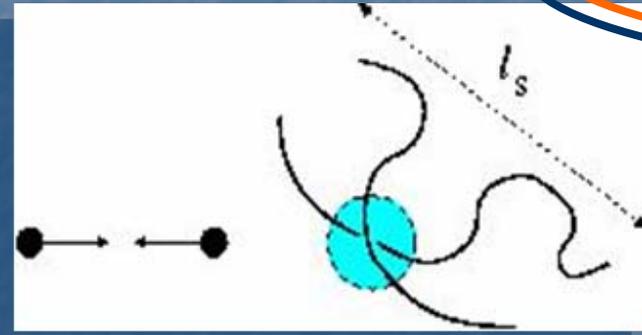
$$[g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}]$$

◇ *Violent fluctuations at high energies !*

[*Vacuum energy: cosmological constant*]

Strings, Gravity and Particles

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

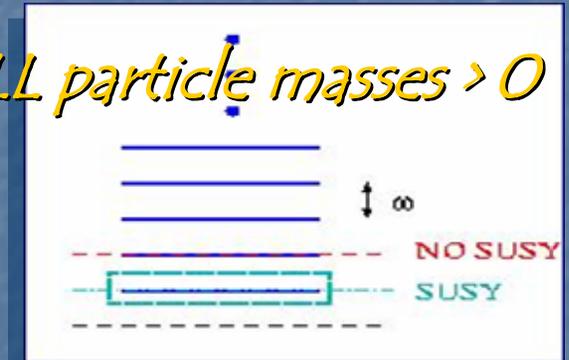


$$\frac{G_N E^2}{\hbar c^5} \rightarrow \frac{G_N E^2}{\hbar c^5} \times \left[\frac{(\hbar c/E)}{l_s} \right]^2$$

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



NO!

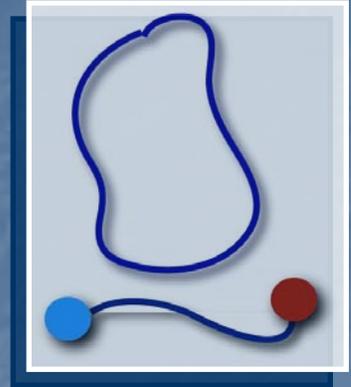


- ◇ **Zero-point \rightarrow massless modes & long-range forces**
- ◇ **gravity! (+ e.m. & YM)**
- ◇ **[+ ∞ massive Higher-Spin fields]**

Superstrings

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

BUT: 10 space-time dimensions !



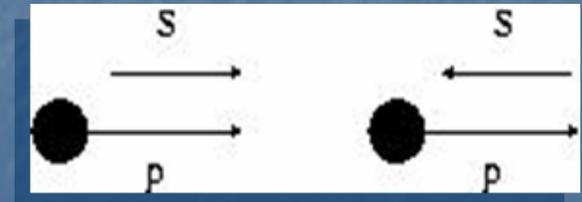
10D superstrings (w. CHIRAL ASYMMETRY):

- 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



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 $D=4$)!

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

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

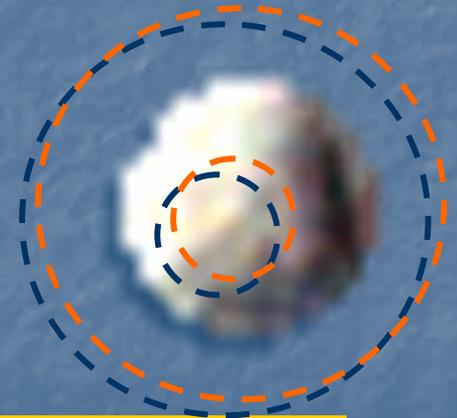
$$d H_{p+2} = \star \tilde{J}_{D-p-3}$$

◇ How can different strings be equivalent?

◇ Solitons : energy "blobs"

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

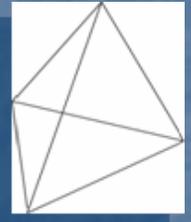
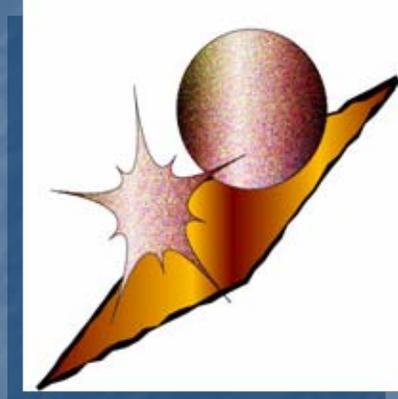
◇ Compton: $\lambda_C \approx \frac{g}{\Lambda}$



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 ?

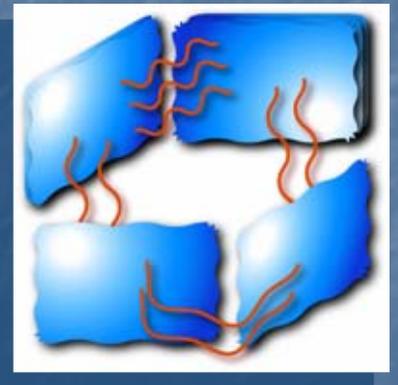
D-Branes & Orientifolds

- 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 ?

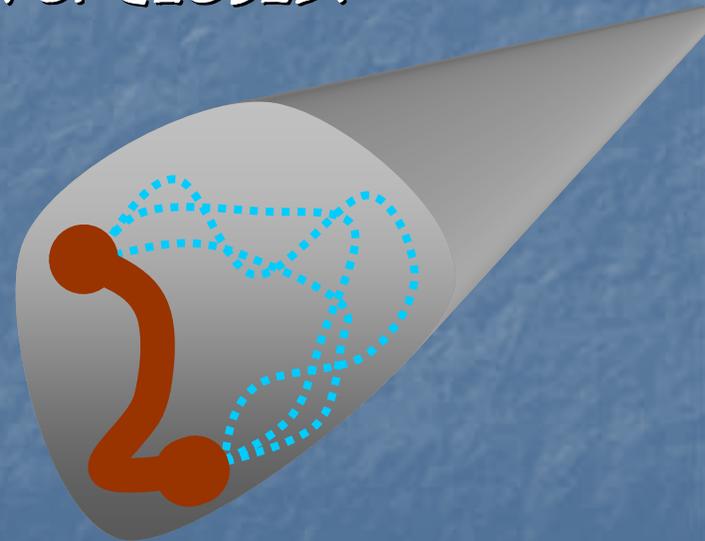
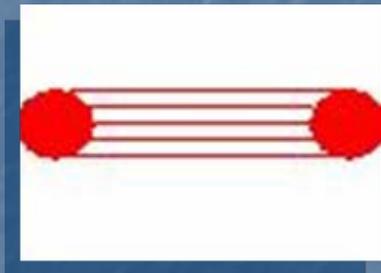
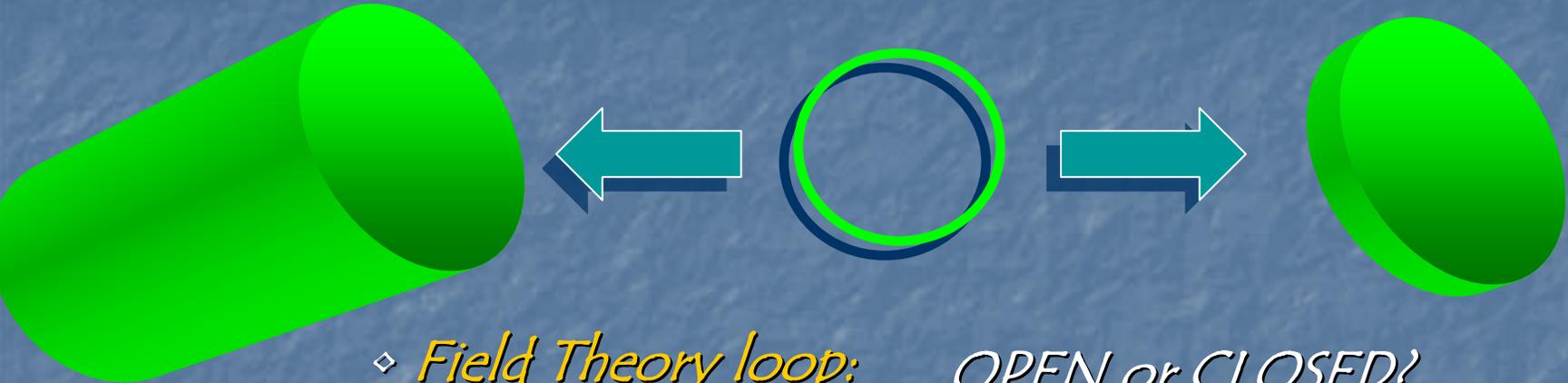


◇ *Closed strings only:* $G_N \approx l_s^2 \approx R^2$

◇ *Open and closed:* $G_N \approx l_s^2 \left(\frac{l_s}{R} \right)^n$

Newton force modified below 1mm ??

AdS/CFT Correspondence



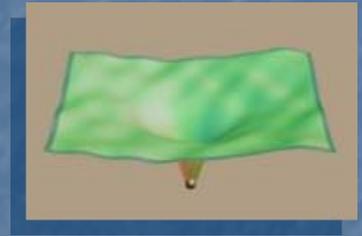
Effective "thick" QCD string!

*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 ∞ 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 ?