

# *Reflections on Strings* *(and Higher Spins)*

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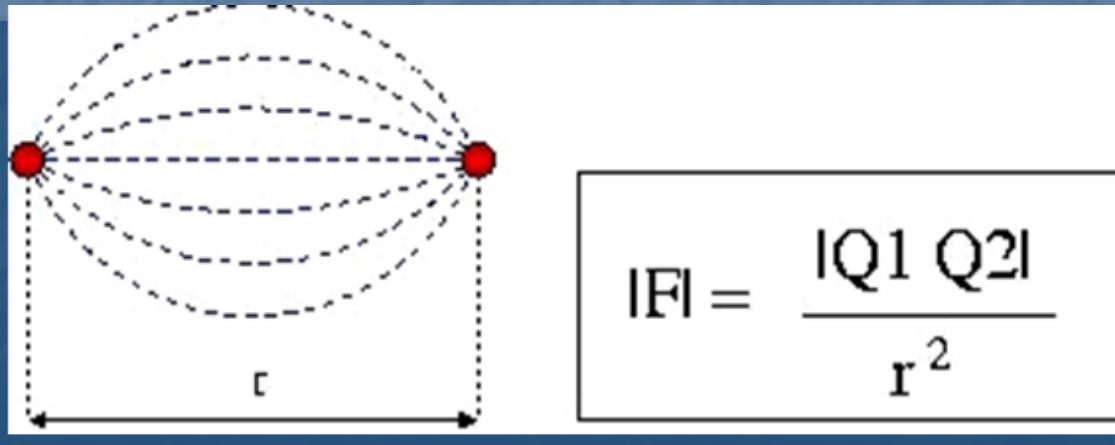
*U. Napoli, 29-3-2007*

# Plan

- ◇ *From particles to strings*
- ◇ *From strings to M theory*
- ◇ *And now ?*

# Particles and Forces

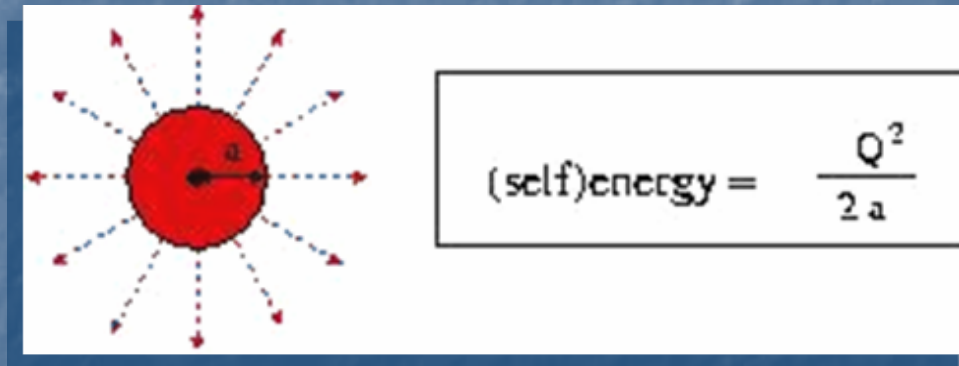
- ◇ All matter is (apparently) made of "elementary particles"
- ◇ Particles exert *mutual forces*
  - ◇ *Example* : Coulomb force





# 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 would cancel for bosons and fermions of same mass

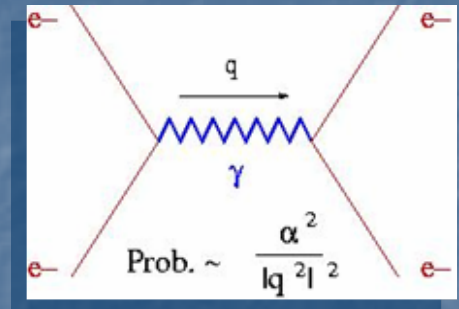


# Particle Interactions

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

◇ *e.m. (Q.E.D.), strength :*

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

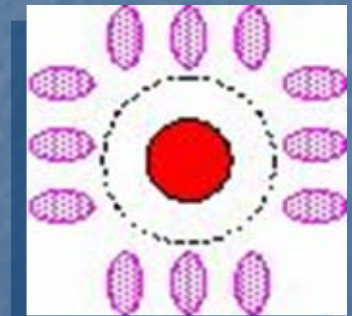


◇ *(Almost) free particles, interact via :*

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

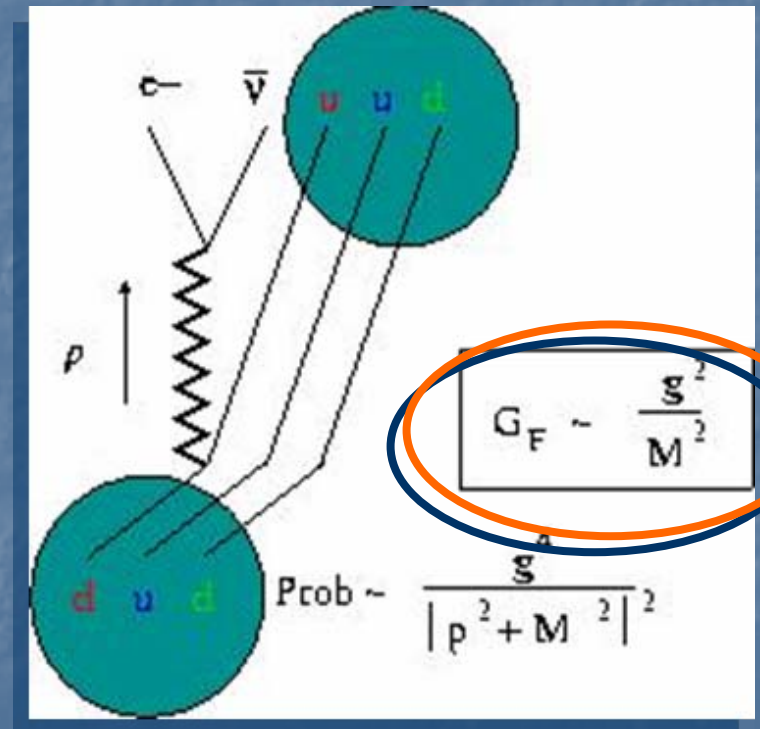
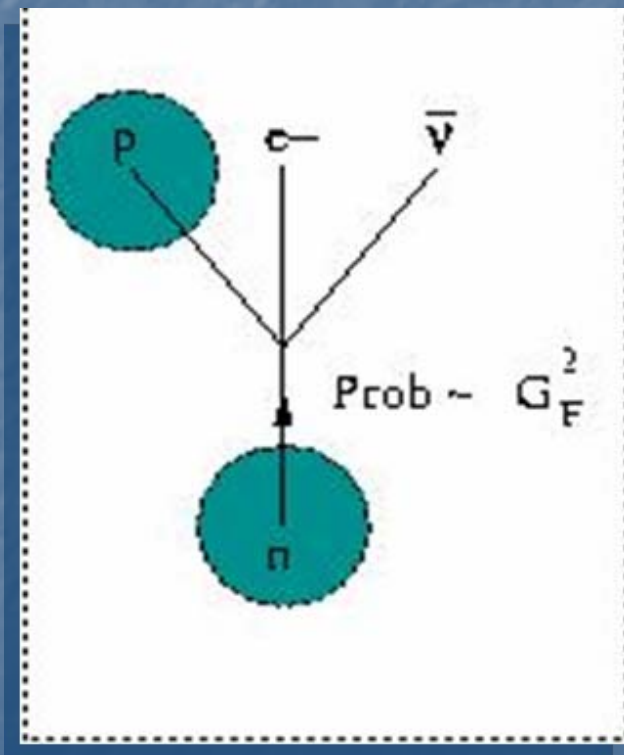
◇ *QED vacuum: “quantum aether” (zero-point fluctuations)*

*“Screening”:  $e^+ - e^-$  plasma,  $\alpha$  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

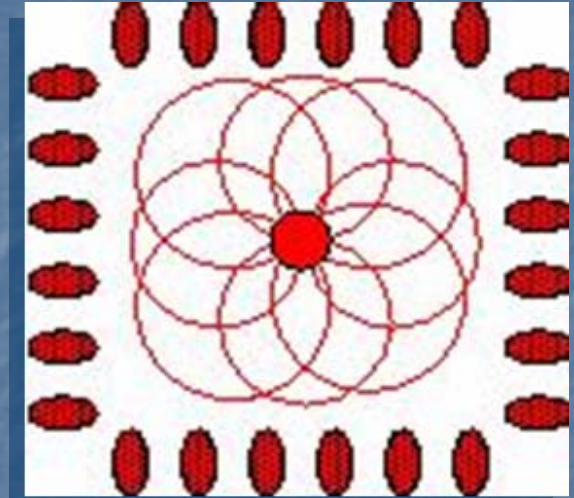
- ◇ (matrix) vector potentials  $W, B, G$  (Yang-Mills fields)
- ◇  $W, B \rightarrow A$  (long-range);  $W^+, W^-, Z$  (short-range)
- ◇ *Short range* : generalized "Meissner effect" (Higgs, or BEH)

*New degrees of freedom at 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

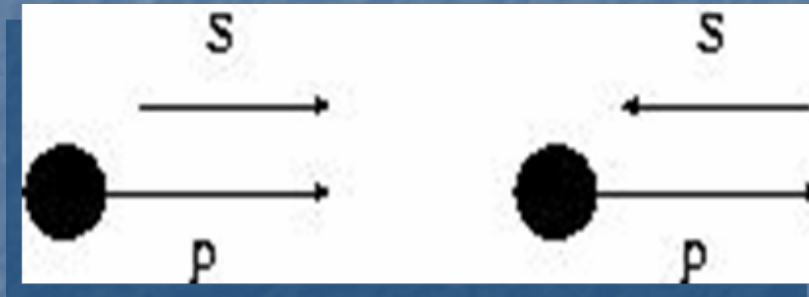


*"thick" strings!*

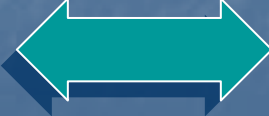
$$V \approx V_0 \frac{r}{l_s}$$

# Chiral Asymmetry

- ◊ *Weak interactions: violate P (actually also T): dependence on relative orientation of particle momenta and spins*



*Anomalies: classical conservation laws can be violated by quantum effects*

Quarks  Leptons



# 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*

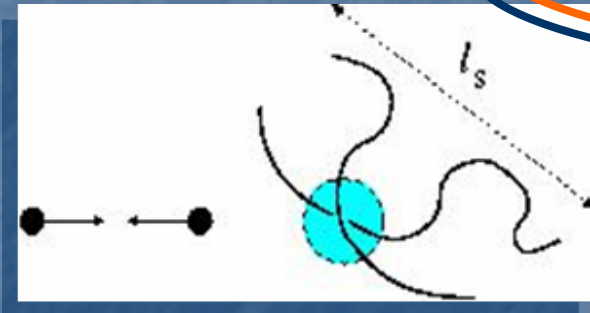
$$[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} ]$$

◇ *Violent fluctuations at high energies !*

[ *Vacuum energy: cosmological constant* ]

# Strings, Gravity and Particles

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

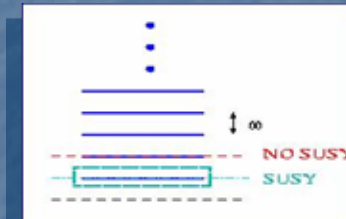


$$\frac{G_N E^2}{\hbar c^5} \rightarrow \frac{G_N E^2}{\hbar c^5} \times \left[ \frac{(\hbar c)}{E} \right]^2$$

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



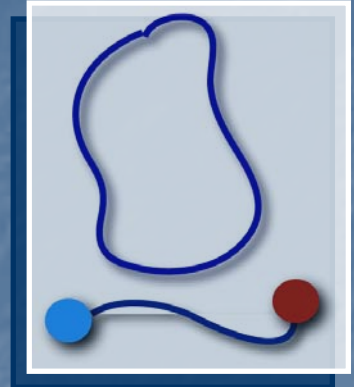
NO!



- ◊ **Zero-point**  $\rightarrow$  massless modes & long-range forces
- ◊ **gravity!** (+ e.m. & YM)
- ◊  **$1 + \infty$  massive Higher-Spin fields**

# Superstrings

- ◇ (Almost) unique: 5 different types
- ◇ Open and Closed strings
- ◇ Fermi and Bose particles
- ◇ SUSY. NO (target space) vacuum energy



**BUT: 10 space-time dimensions !**

Five types of 10D superstrings :

- Closed only:**
  - HO ( $SO(32)$ ), HE ( $E_8 \times E_8$ )
  - Type IIA, Type IIB;
- Open and closed:**
  - Type I



# Low-energy Field Theory

- ◇ *Einstein gravity at low energies?*      *NOT QUITE!*

$$\diamond g_s (=e^\varphi): \text{“string coupling”}, B_{\mu\nu} \rightarrow H_{\mu\nu\rho}$$

$$S_H = \int d^{10}x \left\{ e^{-2\varphi} \left[ R - 4(\partial_\mu\varphi)^2 + \frac{1}{12} (H_{\mu\nu\rho})^2 \right] - \frac{1}{4} e^{-2\varphi} (F_{\mu\nu})^2 + \dots \right\}$$

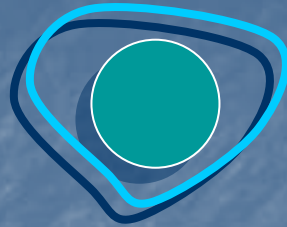
$$S_I = \int d^{10}x \left\{ e^{-2\varphi} \left[ R - 4(\partial_\mu\varphi)^2 + \frac{1}{12} (H_{\mu\nu\rho})^2 \right] - \frac{1}{4} e^{-\varphi} (F_{\mu\nu})^2 + \dots \right\}$$

- ◇ *Additional “long-range” forces:*

$$\left. \begin{array}{l} \diamond \text{Type IIA: } A_\mu, C_{\mu\nu\rho} \\ \diamond \text{Type IIB: } f', B'_{\mu\nu}, D_{(+)\mu\nu\rho\sigma} \end{array} \right\} \text{ (NO YM vectors)}$$

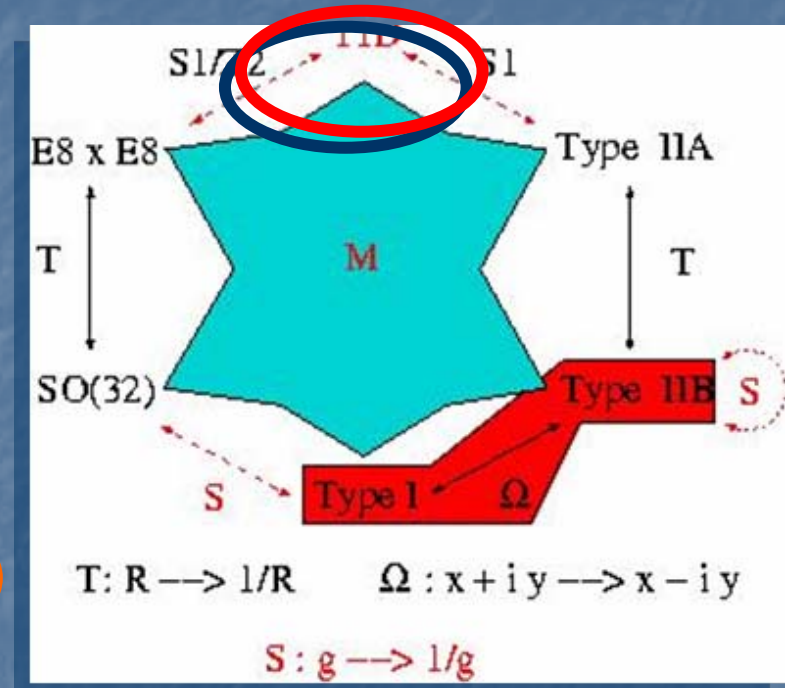
# String Dualities

a. *T-duality*



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

All equivalent to 11D  
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.  $S1/Z2$ : growth of an 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  $D=4$ )!

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

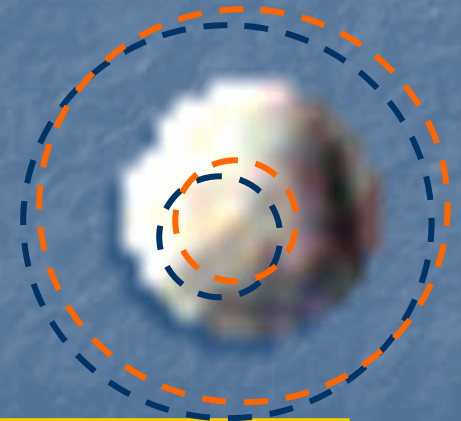
$$d \star H_{p+2} = \star J_{p+1}$$

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

◇ 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"



# From $D=10$ to $D=4$

◇ *Standard scenario :*

◇ *Kaluza-Klein: small extra dimensions*

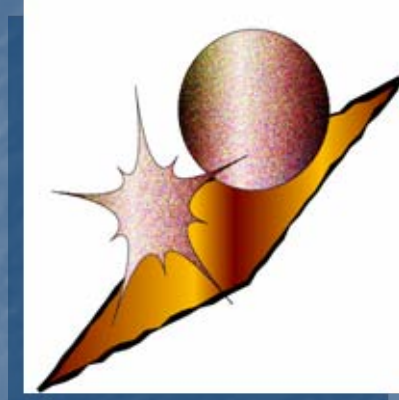
◇ *Calabi-Yau ( $D=4$  flat space,  $N=2(1)$  SUSY)*

◇  $g_{ij} B_{ij} (A_i)$  :  $10D \rightarrow 4D$  chirality

◇ *internal "shape" determines 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  $D=10$  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:*

$$G_N \approx l_s^2 \approx R^2$$

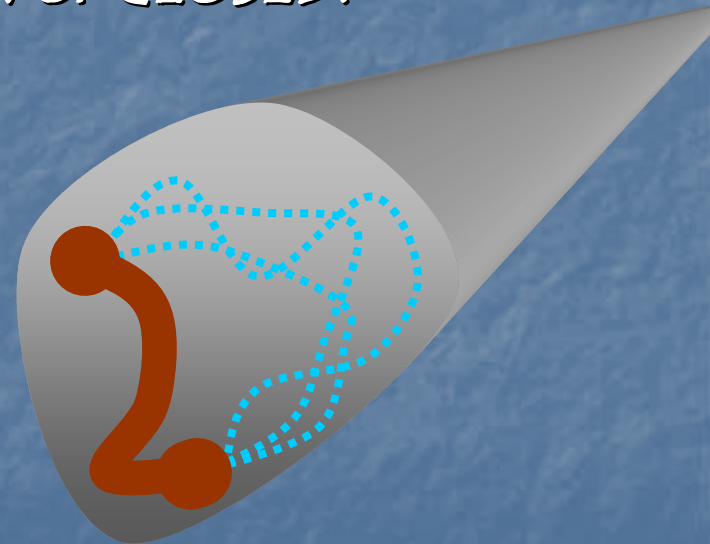
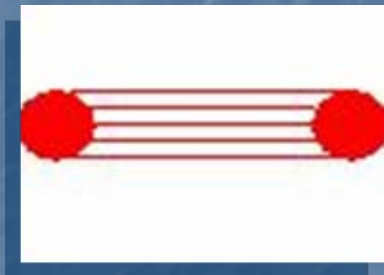
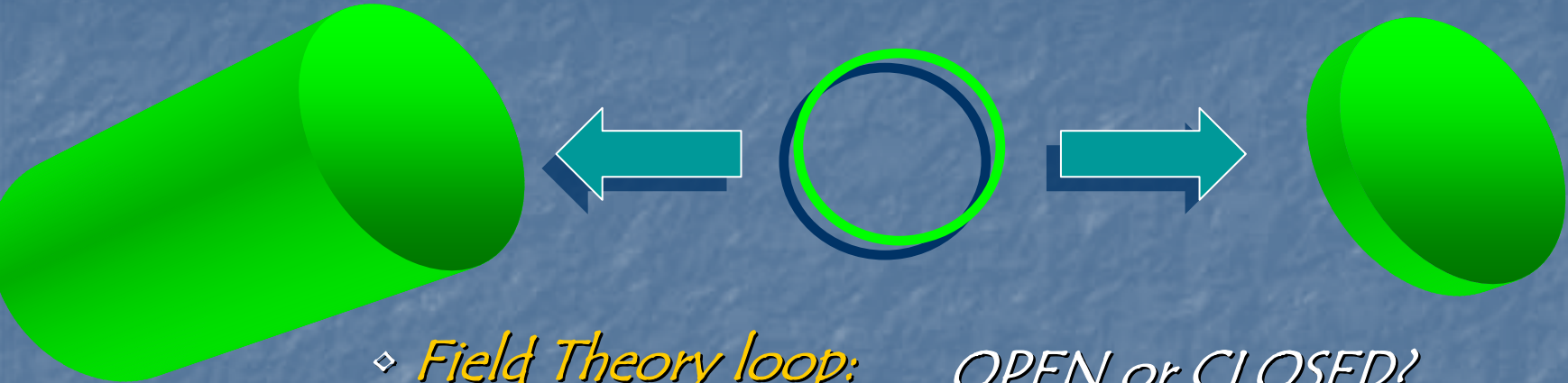
◇ *Open and closed:*

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

*Newton force modified below 1mm ??*

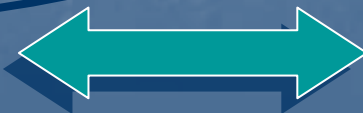


# AdS/CFT Correspondence



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*
    - ◇ *charges  $\sim$  D-brane excitations*
    - ◇ *count (BPS) states at weak coupling*
    - ◇ *THEY persist at strong coupling*



*What microscopic degrees of freedom?*

# Outlook

- ◇ Remarkably rich (apparently *UNIQUE*)  $D=10$  framework
  - ◇ Why a given "shape" of the 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

*What is String Theory?*