<u>SFB-lectures</u>

Phenomenological Aspects of String Theory

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<u>Outline of the lectures:</u>

1. overview (today)
2. more details (January 26)
3. more details (Feburary 2)

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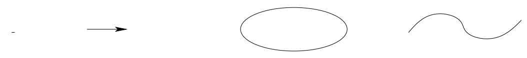
(Perturbative) String Theory

[Veneziano, Nambu, Goto, Susskind, . . .]

Idea: point-like objects $\longrightarrow$ strings



fundamental length scale l_s: extension of the string

$\Rightarrow$ locality is given up (modified) in controlled way

Strings move in D-dimensional Minkowskian background.

(perturbative) string theory is quantum theory of extended objects (strings).

Quantum excitations:

- finitely many massless excitations L:

s = 2	$\longrightarrow$	graviton	$\Rightarrow$ general relativity
s = 3/2	$\longrightarrow$	gravitino	$\Rightarrow$ supersymmetry
s = 1	$\longrightarrow$	gauge bosons	$\Rightarrow$ gauge theories
s = 1/2	$\longrightarrow$	fermions	$\Rightarrow$ quarks & leptons
s = 0	$\longrightarrow$	scalars	$\Rightarrow$ Higgs, ...

- infinitely many massive excitations H

$$M \sim n \cdot M_S$$

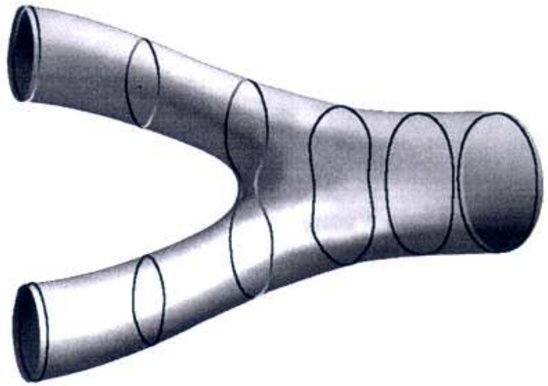
M_{S} = characteristic scale of string theory (tension of the string)

$\Rightarrow$ soft UV behavior

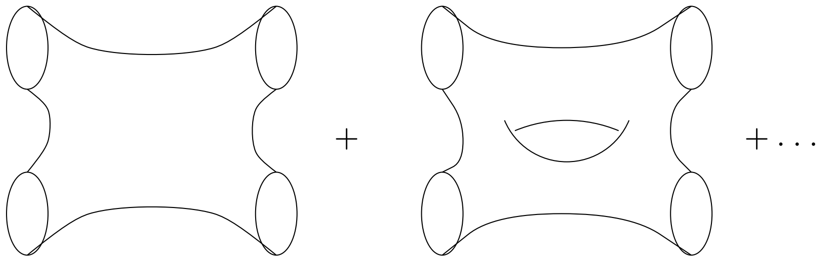
- Identification of $s = 2$ excitation with Einsteins graviton leads to

$$M_S \sim M_{PL} \sim 10^{19} GeV \Rightarrow l_s \sim l_{Pl} \sim 10^{-35} m$$

Interactions:



$g_s = e^{-\langle\phi\rangle}$ is coupling constant, ϕ is scalar field (dilaton) scattering amplitudes:



quantization via "Feynman-diagrams" — sum over all topologies:

$$\text{scattering amplitude:} \qquad A = \sum_{n=0}^{\infty} A^{(n)} g_s^{2+2n} + \mathcal{O}(e^{-g_s^{-2}}) \ .$$

$g_s < 1$: perturbative region

$g_s \geq 1$: non-perturbative region

Until 1995 only perturbative region accessible !

Still today no analog of action functional/path integral $\Rightarrow$ how is the theory defined?

Properties of string theory:

- ➪ spectrum contains non-Abelian gauge theory
  with families of chiral fermions coupled to gravity
- ➪ for scattering processes with $p \ll M_S$ (low energy limit):

$$\text{string theory} \stackrel{p \ll M_S}{\longrightarrow} \text{QFT \& GR}$$

$$A_{string} \longrightarrow A_{QFT,GR}$$

$$(\text{with } M_S \sim M_{Pl})$$

$\Rightarrow$ QFT & GR are low energy limit of string theory.

- ➪ g_s is free parameter and one can choose $g_s \ll 1$
  $\Rightarrow$ perturbative evaluation of A possible
- ➪ amplitudes $A^{(n)}$ are UV-finite ?

$\Rightarrow$ string theory is candidate for perturbative quantum gravity
coupled to non-Abelian gauge theory

Intermezzo: Supersymmetry and Supergravity

- ➪ symmetry among fermions and bosons;
- ➪ generalization of Poincaré-algebra

$$\{Q^I, Q^{\dagger J}\} = \gamma^\mu P_\mu \delta^{IJ} + Z^{IJ} , \quad I, J = 1, \ldots, N ,$$

Q is generator of supersymmetry transformation, Z are central charges

- ➪ Properties:
  - fermions & bosons sit in the same multiplet $n_B = n_F$
    $\Rightarrow$ enlargement of particle spectrum;
  - spin $s \leq 2 \Rightarrow N \leq 8$
  - N large: quantum corrections more constrained
    $\Rightarrow$ strongly coupled QFT can be better controlled
  - $M \geq Z$, $M = Z$ reduction of degrees of freedom (BPS bound)
  - phenomenological attractions:
    light Higgs boson is 'natural' and predicted; consistent with electro-weak precision data; dark matter candidate; gauge coupling unification

Supergravity

Supergravity $\equiv$ gauged (local) supersymmetry

- necessary to introduce fermionic gauge field, the gravitino $(s = 3/2)$
  forms together with graviton a supermultiplet
  $\Rightarrow$ local supersymmetry only exists when gravity is turned on

- If gravitino (& Higgs) exist all spins $0 \leq s \leq 2$ occur

- supersymmetric SM with soft supersymmetry breaking
  can be embedded into spontaneously broken supergravity

- UV-finiteness of $N = 8$ supergravity not settled
  (recent progress: [Bern,Dixon,Roiban; Green,Russo,Vanhove])

Back to string theory

➪ spectrum is supersymmetric $\Rightarrow$ necessary for consistency ?

➪ positivity of Hilbert space $\Rightarrow$ $\boxed{D \leq 10}$

- $D = 10$: 5 different string theories:
  IIA, IIB, I, Het. $E_8 \times E_8$, Het. $SO(32)$
  with different spectra and different interactions

- $D < 10$: families of theories/backgrounds
  geometrical compactification: string moves in space-time background

$$\mathcal{M}^{(10)} = \mathcal{M}^{(D)} \times K^{(10-D)}$$

$\mathcal{M}^{(D)} = D$-dimensional Minkowski space-time
$K^{(10-D)} =$ compact manifold with volume $V \sim l_S^{(10-D)}$

– consistency demands $K =$ (generalized) Calabi-Yau manifold
– geometrical & topological properties of K are related to spectrum and interactions of excitations

Problems

1. which string theory do we choose ?

   what chooses D ?

   what chooses K ?

   $\Rightarrow$ Is there a (dynamical) selection principle?

   $\Rightarrow$ Or are there many consistent backgrounds with very different properties?

   ($\Rightarrow$ is there a landscape of vacua?)

2. supersymmetry unbroken !

3. quarks, leptons and Higgs massless, $SU(2) \times U(1)$ unbroken

   $\Rightarrow$ what generates small masses ?

   $\Rightarrow$ what generates the hierarchy $\frac{m_Z}{m_{Pl}} \approx 10^{-17}$

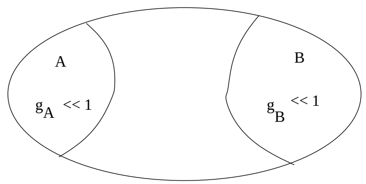
hope: cured by non-perturbative effects.

Non-perturbative Aspects of String Theory

[Hull,Townsend, Witten, . . .]

conjecture:

different string theories are dual description of one quantum theory:



perturbative spectrum A ⇔ non-perturbative spectrum B

perturbative spectrum B ⇔ non-perturbative spectrum A

$$g_A \sim g_B^{-1}$$

difficult to prove but successful checks on 'protected' couplings:

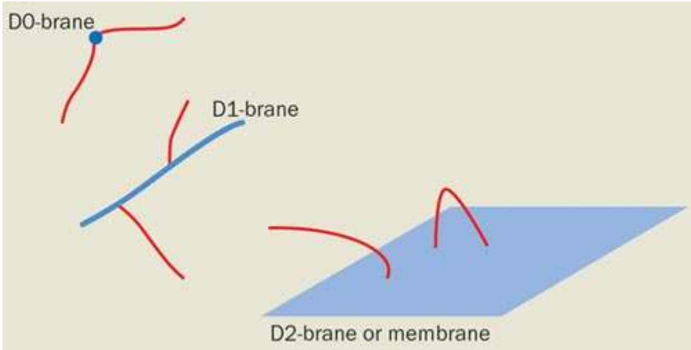
BPS-multiplets, holomorphic couplings

Non-perturbative states of string theory: D-branes

D-Branes

[Polchinski]

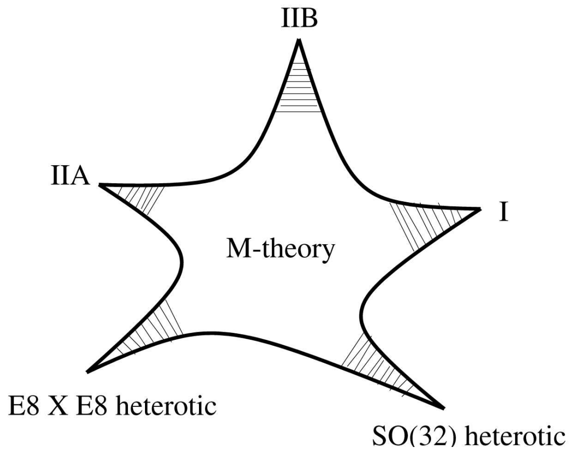
open string with Dirichlet boundary condition define hyper-plane



- ➪ D-Branes are dynamical objects of string theory
  - light modes: supersymmetric vector multiplet
  - stack of N D-branes: non-Abelian $U(N)$ vector multiplet
  - gauge theory is localized on the D-brane
- ➪ D-Branes are non-perturbative states of string theory (tension $\sim g_s^{-1}$)
- ➪ string theory is not a theory of only strings but also describes higher-dimensional objects – Branes

M-Theory

Generalization: All string theories are perturbative limits of one quantum theory



What is M-theory ?

Suggestion: theory of D-particles [Banks, Fischler, Shenker, Susskind].

$\Rightarrow$ space-time becomes non-commutative

Contact with Particle Physics and Cosmology

➪ Proposition:

- String theory replaces quantum field theory at short distances
- Both Standard Models arise from one specific string background (vacuum)

➪ Question:

- Is there a (dynamical) selection principle?
- Or are there many consistent backgrounds with very different properties

  ($\Rightarrow$ is there a landscape of vacua)?

➪ Consequences

- study space of all string vacua and its properties
- study 'realistic' string vacua by imposing phenomenological constraints

  for example: (vacuum cleaning)

  - $D = 4$
  - $G \supset SU(3) \times SU(2) \times U(1)$ + representations of SM + $n_g \geq 3$
  - spontaneously broken $N = 1$ supergravity
  - sector for successfull inflation
  - compatibility with dark energy constraint

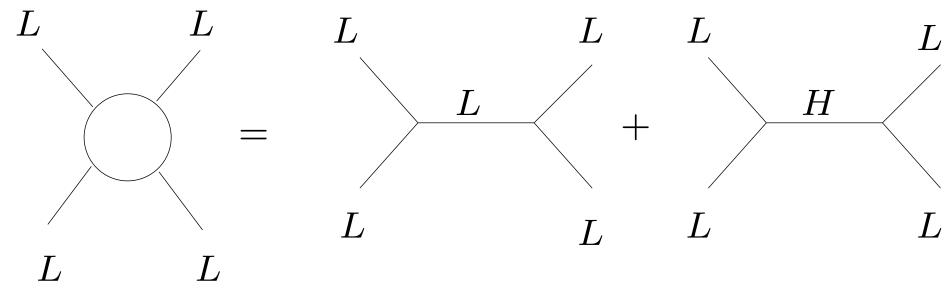
Contact with Particle Physics and Cosmology

Steps:

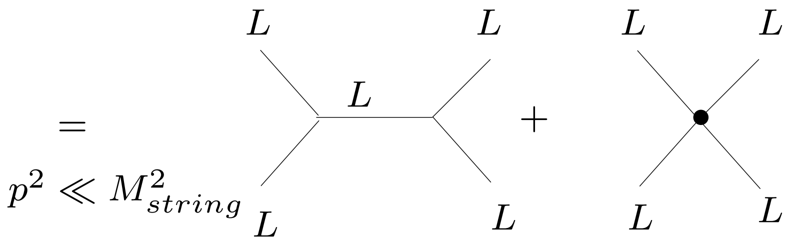
1. compute light spectrum and low energy effective action perturbatively
   (can be done seriously in string theory)
2. employ non-perturbative effects
   to spontaneously break supersymmetry and lift continuous vacuum degeneracy
   (needs to use string dualities and/or field theory intuition)
3. compute soft supersymmetry breaking terms
   (will be measured at LHC)
4. compute inflaton potential and value of cosmological constant.

The low effective action

Integrating out the heavy modes H results in the low energy effective action $\mathcal{L}_{\text{eff}}(L)$ of the light modes L



$+$ t and u channels



$+$ t and u channels

for $p^2 \ll M^2_{string}$: amplitudes of an effective field theory

$D = 4, N = 1$ effective Lagrangian

[Wess,Bagger]

- spectrum:

multiplet	B	F
gravity multiplet	$g_{\mu\nu}$	Ψ_μ
vector multiplets	V_μ	λ
chiral multiplets	M	χ

- effective Lagrangian

$$\begin{aligned} L &= -\big(\tfrac{1}{2}R + G_{I\bar{J}} D_\mu M^I D^\mu \bar{M}^{\bar{J}} + \tfrac{1}{4}\mathrm{Re} f_{\kappa\lambda}\ F^\kappa_{\mu\nu} F^{\lambda\mu\nu} + \tfrac{1}{4}\mathrm{Im} f_{\kappa\lambda}\ F^\kappa \tilde{F}^\lambda + V\big)\ , \\ &\quad + \text{fermions} \\ V &= e^K\big(G^{I\bar{J}} D_I W D_{\bar{J}} \bar{W} - 3|W|^2\big) + \frac{1}{2}\,(\mathrm{Re}\ f)^{-1\ \kappa\lambda} D_\kappa D_\lambda\ . \end{aligned}$$

L is completely determined in terms of K, W, f:

- Kähler metric: $G_{I\bar{J}} = \partial_I \bar{\partial}_J K(M, \bar{M})$
- holomorphic superpotential: $W(M), \quad D_I W = \partial_I W + (\partial_I K) W$
- holomorphic gauge kinetic function: $f(M) = g^{-2} + i\,\frac{\Theta}{8\pi^2}$

Next: compute K, W, f for your favorite string background.

Generic features perturbatively:

- effective potential V has flat directions (moduli T)
  $\Rightarrow$ continuous vacuum degeneracy parameterized by $\langle T \rangle$

- $$W(T, \phi) = Y_{ijk}(T)\phi^i\phi^j\phi^k \ ,$$

  $\phi =$ charged matter field.

  $\Rightarrow$ Yukawa coupling Y dynamically determined!

- similarly, gauge couplings $g = g(\langle T \rangle)$
  $\Rightarrow$ g is dynamically determined
  If moduli are undetermined couplings are still free parameters.

- need to stabilize moduli and break supersymmetry
  known mechanism:
  1) gaugino condensation
  2) Fluxes

Gaugino Condensation

gaugino condensiation is non-perturbative effect of supersymmetric field theories

asymptotically free gauge theory becomes strong at

$$\Lambda = M_{\rm Pl}\, e^{-\frac{8\pi^2}{bg^2}}$$

such effects can

- generate a hierarchy $\frac{\Lambda}{M_{\rm Pl}} \ll 1$ if g and/or b are small

$$M_{3/2} \approx \frac{\Lambda^3}{M_{\rm Pl}^2} \quad \Rightarrow \quad \Lambda \sim 10^{13} - 10^{14} GeV \rightarrow M_{3/2} \sim 10^1 - 10^3 GeV$$

- break supersymmetry (hierarchically) and stabelize moduli

$$V \cong \frac{|\Lambda\,(g(T))|^6}{M_{\rm Pl}^2}$$

drawbacks:

– usually unstable directions (run-away)

– usually large cosmological constant

Summary

- string theory unifies all interactions and provides perturbative quantum gravity.

- qualitative agreement with generalizations of the Standard Model but no quantitative agreement yet.

- biggest problems:
  - hierarchical supersymmetry breaking,
  - determination of the ground state,
  - cosmological constant.

- non-perturbative properties at least partially under control.