Discussion session: string phenomenology progress, challenges and prospects

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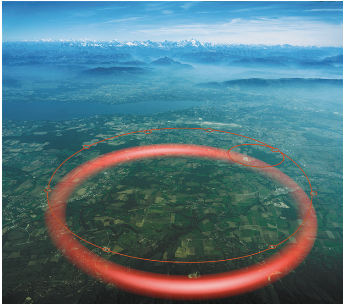
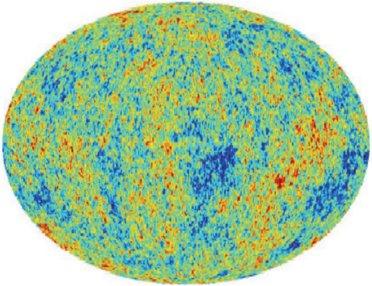
Strings: Geometry and Symmetries for Phenomenology

Connect string theory to the real world

- Is it a tool for strong coupling dynamics or a theory of fundamental forces?
- Can string theory describe both particle physics and cosmology?





Approach, problems to solve

- Compactification of extra dimensions

  geometric from 10/11 dim EFT or internal (S)CFT

- Moduli stabilisation

  avoid experimental conflict from long range forces etc

  compute low-energy couplings

- Supersymmetry breaking

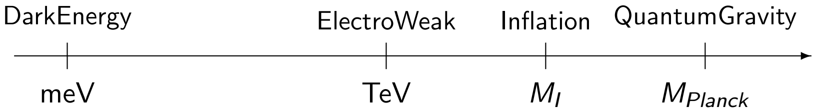
  at what scale and how (spontaneous vs. non-linear and explicit)

- Model building for particle physics and cosmology

Problem of scales

- describe high energy (SUSY?) extension of the Standard Model
  unification of all fundamental interactions
- incorporate Dark Energy
  simplest case: infinitesimal (tuneable) +ve cosmological constant
- describe possible accelerated expanding phase of our universe
  models of inflation (approximate de Sitter)

$\Rightarrow$ 3 very different scales besides M_{Planck} :



At what energies strings may be observed?

Very different answers depending mainly on the value of the string scale M_s

Before 1994: $M_s \simeq M_{\rm Planck} \sim 10^{18}$ GeV $l_s \simeq 10^{-32}$ cm After 1998:

- arbitrary parameter : Planck mass $M_P \longrightarrow$ TeV
- physical motivations $\Rightarrow$ favored energy regions:

- High : $\begin{cases} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\rm GUT} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{cases}$
- Intermediate : around 10^{11} GeV ($M_s^2/M_P \sim$ TeV)

  SUSY breaking, strong CP axion, see-saw scale
- Low : (multi) TeV (hierarchy problem)

High string scale

perturbative heterotic string : the most natural for SUSY and unification

gravity and gauge interactions have same origin

massless excitations of the closed string

But mismatch between string and GUT scales:

$M_s = g\, M_P \simeq 50\, M_{\rm GUT}$ $\qquad g^2 \simeq \alpha_{\rm GUT} \simeq 1/25$ [11]

in GUTs only one prediction from 3 gauge couplings unification: $\sin^2\theta_W$

introduce large threshold corrections or strong coupling $\to$ $M_s \simeq M_{\rm GUT}$

but loose predictivity

Heterotic string: Spectrum

- maximum rank: 22
- (non-abelian) gauge coupling unification at M_H
- in SM $\sin^2\theta_W = 3/8 \Rightarrow$ fractional electric charges
- allowed reps: fundamentals & 2-index antisym of unitary groups,

  spinors of orthogonal groups

  simplest constructions: CY's, orbifolds, lattices, free fermions
- no adjoints to break GUT groups $\Rightarrow$

  - Orbifold GUTs

  gauge group breaking by discrete Wilson lines

  - GUT variations without adjoints

  flipped $SU(5) \times U(1)$, Pati-Salam $SU(4) \times SU(2)_L \times SU(2)_R$, SM

Open strings and D-branes

gravity and gauge interactions have different origin

- gravity: closed strings propagating in 10 dims
- gauge interactions: open strings with their ends attached on D-branes

D-branes = hypersurfaces where open strings can end

Dp-brane: parallel dimensions: $X^1, \dots, X^p$ (also time X^0)

$$\partial_\sigma X^\mu = 0 \text{ at } \sigma = 0 \qquad \text{normal derivative vanishes}$$

Newmann boundary conditions $\Rightarrow$ free propagation along the boundary

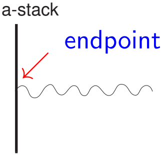
transverse dimensions: $X^{p+1}, \dots, X^9$

$$X^\mu = X_0^\mu \text{ at } \sigma = 0 \qquad (\partial_\tau X^\mu = 0 \text{ at } \sigma = 0)$$

Dirichlet conditions: endpoint fixed at the boundary

D-brane spectrum

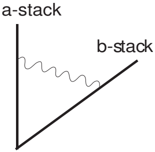
Generic spectrum: N coincident branes $\Rightarrow U(N)$



endpoint transformation: $\mathbf{N}_a$ or $\bar{\mathbf{N}}_a$ $U(1)_a$ charge: $+1$ or -1

$\Rightarrow$ gauged 'baryon' number

- open strings from the same stack $\Rightarrow$ adjoint gauge multiplets of $U(N_a)$
- stretched between two stacks $\Rightarrow$ bifundamentals of $U(N_a) \times U(N_b)$



non-oriented strings $\Rightarrow$ also:

- orthogonal and symplectic groups $SO(N), Sp(N)$

- matter in antisymmetric + symmetric reps

Intersecting branes: 'perfect' for SM embedding

product of unitary gauge groups (brane stacks) and bi-fundamental reps

but no unification: no prediction for M_s, independent gauge couplings

moreover GUTs are problematic:

- no perturbative $SO(10)$ spinors
- no top-quark Yukawa coupling in $SU(5)$: $10\,10\,5_H$

  $SU(5)$ is part of $U(5) \Rightarrow U(1)$ charges : 10 charge 2 ; 5_H charge ± 1

  $\Rightarrow$ cannot balance charges with $SU(5)$ singlets

  can be generated by D-brane instantons but ...

$\to$ Non-perturbative M/F-theory models:

combine good properties of heterotic and intersecting branes

but lack exact description for explicit computations

Type I string theory $\Rightarrow$ D-brane world

gravity and gauge interactions have different origin

- gravity: closed strings propagating in 10 dims
- gauge interactions: open strings with their ends attached on D-branes [6]

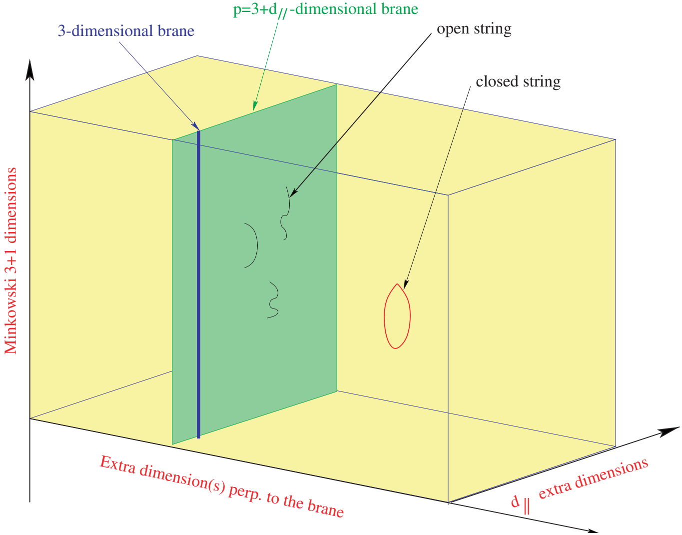
$$\Rightarrow \quad M_P^2 = \frac{V_\perp}{g_s^2} M_s^{2+n} \qquad g_s \simeq g^2$$

$V_\perp$ can become large lowering the string scale

Braneworld

2 types of compact extra dimensions:

- parallel ($d_\parallel$): $\lesssim 10^{-16}$ cm (TeV)
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)



Challenges

- Implement moduli stabilisation in explicit model building
- Combined models of particle physics and cosmology