String Theory: A Status Report

2004

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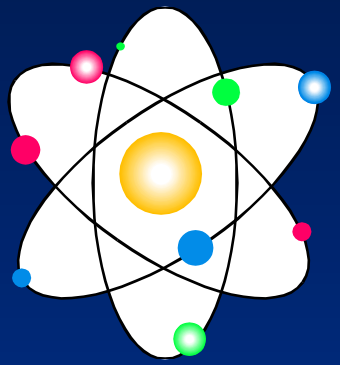
Foundations of Modern Physics

- Quantum Theory



- Special Relativity
- General Relativity

Quantum Mechanics + Special Relativity

=

Quantum Field Theory

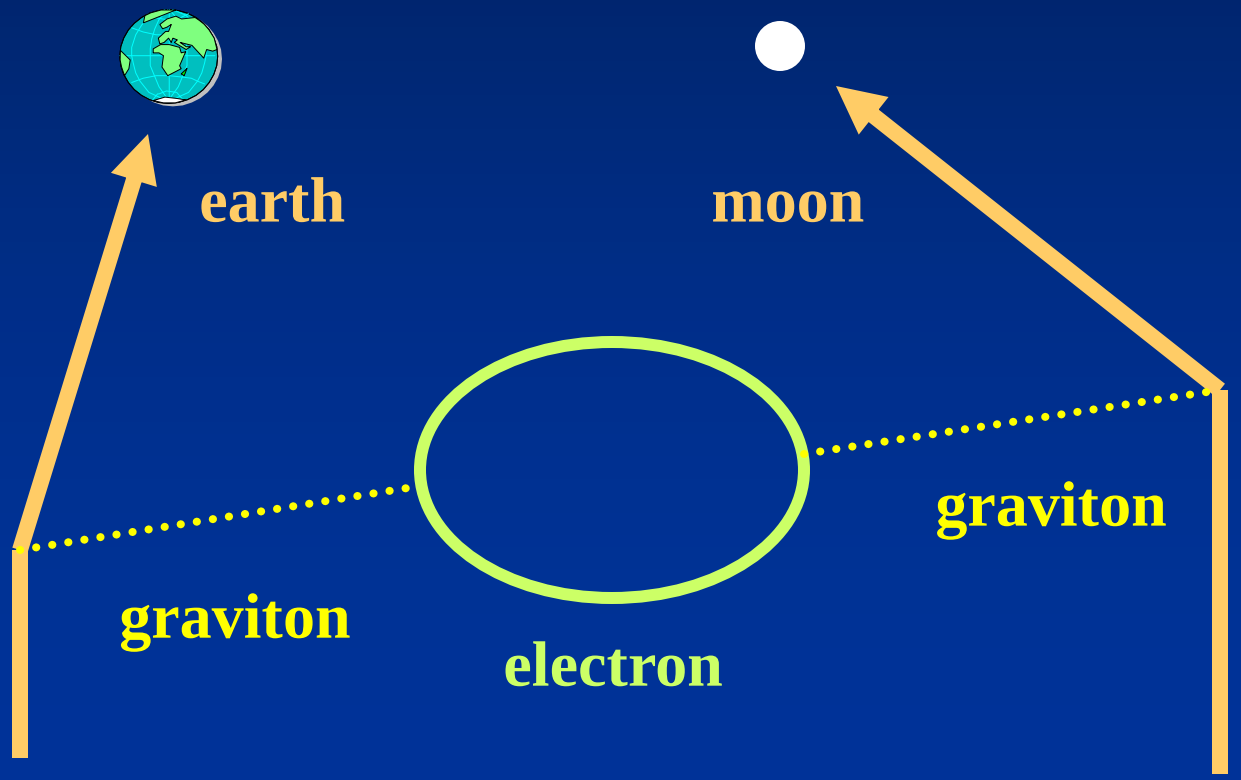
The standard model of particle physics

Unprecedented success!

Adding Gravity/General Relativity

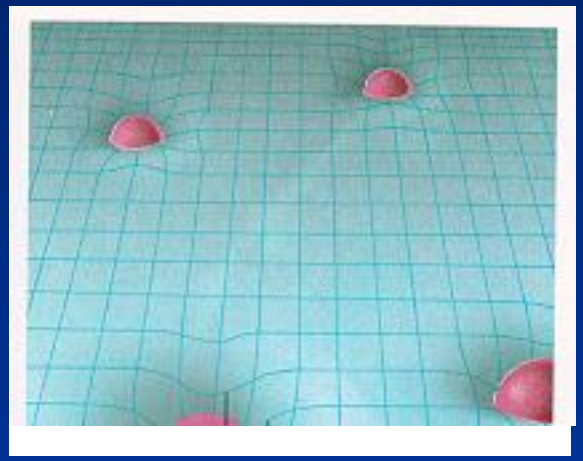
Many problems arise:

Quantum fluctuations are infinite!



This is not merely a technical problem but a conceptual problem.

Gravity = General Relativity
= Modification of space-time



We should not expect the quantization to be easy.

Conceptual problems:

- The light-cone undergoes quantum fluctuations
  - How to maintain causality?
- Information loss in black holes(?)
  - Is the theory unitary?
- The cosmological constant $\Lambda \cong 10^{-120} M^4_{\text{Planck}}$

  Why so small? Calculate it.
- Cosmology, early Universe, inflation
  - Wave function of the Universe
  - Initial conditions

Challenge:

Combine General Relativity with Quantum Mechanics

String Theory

Invented in the late 60's as a theory of the strong interactions.

Mid 70's: String theory is a theory of gravity!

Gravity is not an option in string theory. It is a logical consequence of it!

Main idea: the fundamental building blocks are not point-like particles but strings

Their small size (10^{-33}cm) makes them look point-like.

Different vibration modes of the string are different particles.

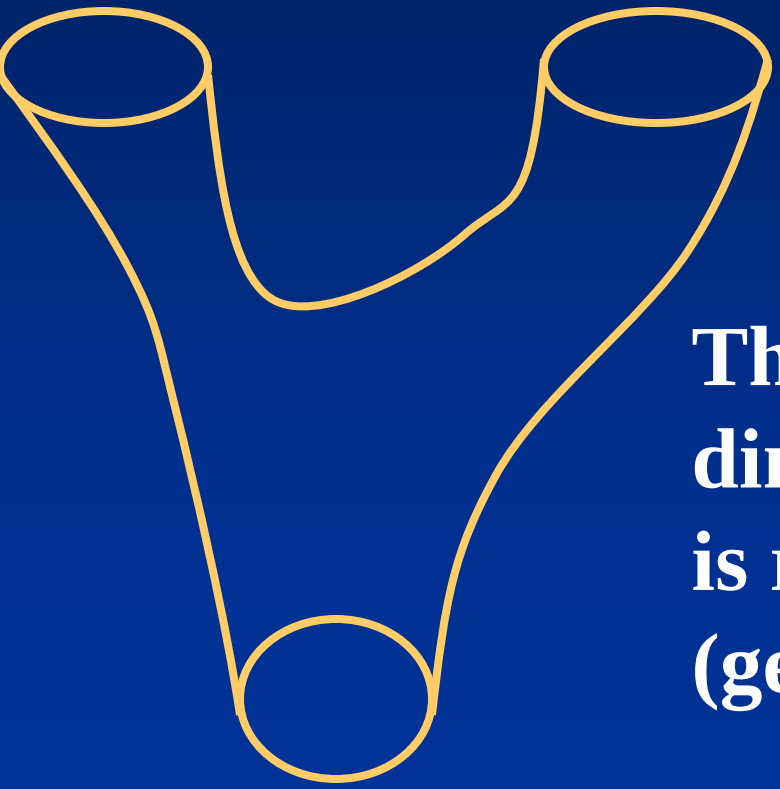
electron

quark

Very economical!

String Interaction

Joining and splitting

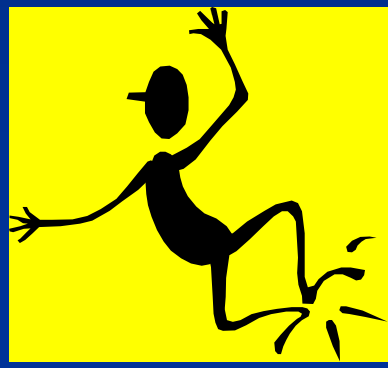


The theory on the two-dimensional string world-sheet is reparametrization invariant (geometrical).

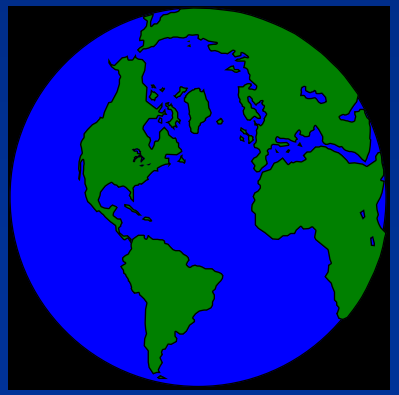
First String Revolution
The Perturbative era
(Mid 80's - Mid 90's)

- Consistent perturbation expansion
- Several consistent string theories (type I, type IIA, type IIB, heterotic SO(32), heterotic $E_8 x E_8$)
- String propagation in curved spaces

  Connection to conformal field theory

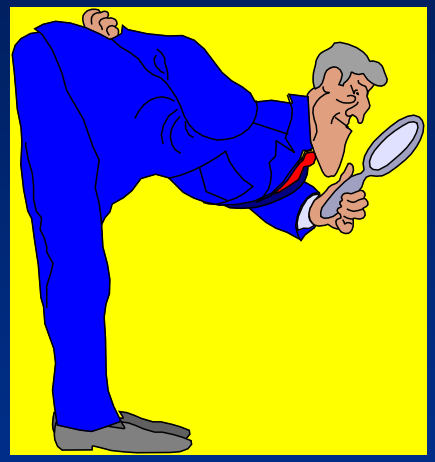


- The theory has many ground states characterized by the six dimensional compactification.
- Some of these ground states are similar to our world (4 dimensions, electrons, photons, etc.).



Experimental verification is not easy

In order to see stringy phenomena we need a microscope with a resolution of 10^{-33}cm.



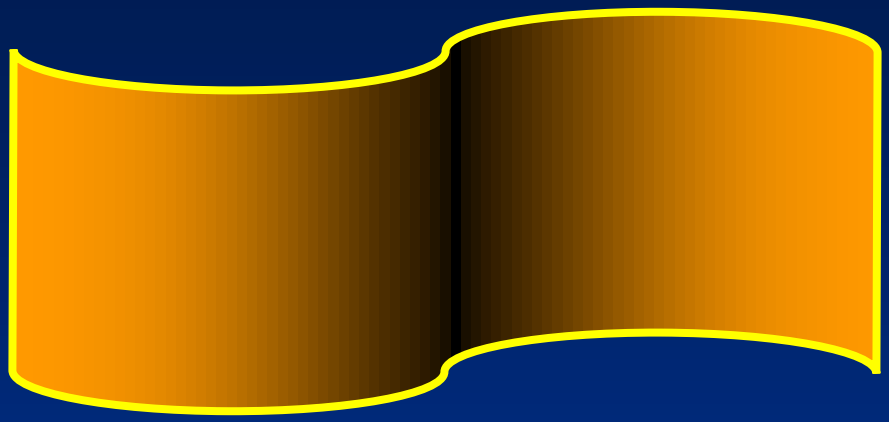
The resolution of the best available accelerators is only 10^{-16}cm.

Indirect experimental confirmation is needed!

Second String Revolution
The Non-perturbative era
(Mid 90's - ?)

- Exact results using the magic of supersymmetry
- Extended objects
- Large extra dimensions
- Non-commutative geometry
- String duality
- String theory is unique
- Black hole information puzzle
- Many "ground states"

The theory has extended objects like membranes



p-branes:

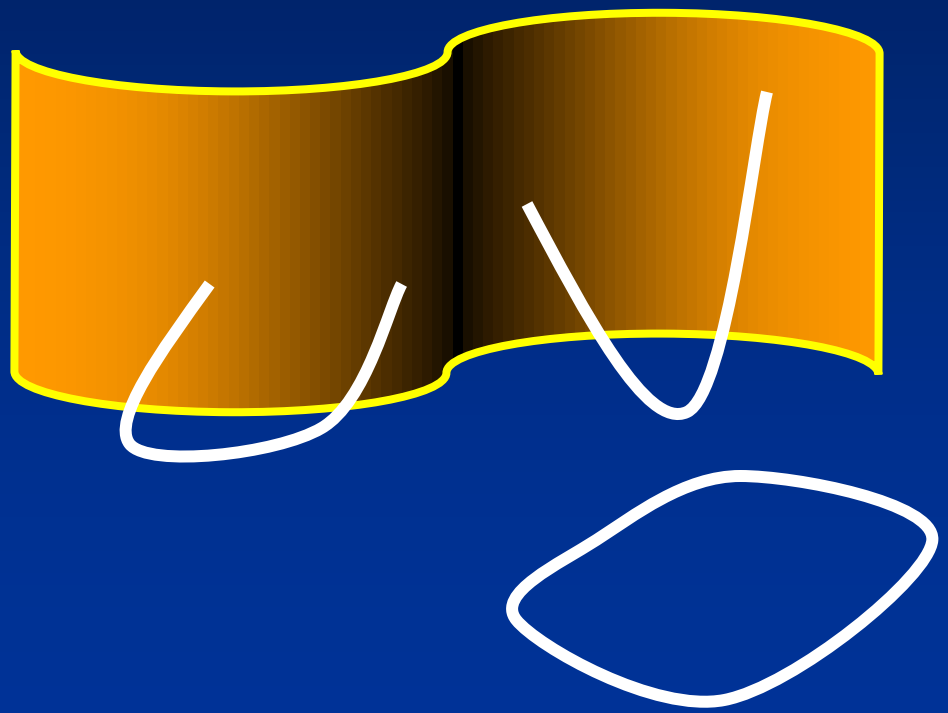
0-brane = particle

1-brane = string

2-brane = membrane

etc.

Some of them are regions where strings can end: D-branes (Dirichlet branes)



Non-Commutative Geometry

Sometimes the space-time coordinates on the D-brane do not commute

$$[\, x\, ,\, y\,] \neq 0$$

(Like electrons in the first Landau level.)
New connections to mathematics.

Extra Dimensions

In addition to the three space dimensions there can be more "invisible dimensions"

- **Small "invisible dimensions" (Kaluza Klein)**

- **Large "invisible dimensions" (brane world)**

Large “invisible dimensions” – brane world

We are trapped in a brane and cannot “see” the other dimensions.

Gravity is weak because the extra dimensions are large.

String Duality:

The underlying space-time on which the strings propagate is ambiguous

We cannot tell whether strings propagate on

or

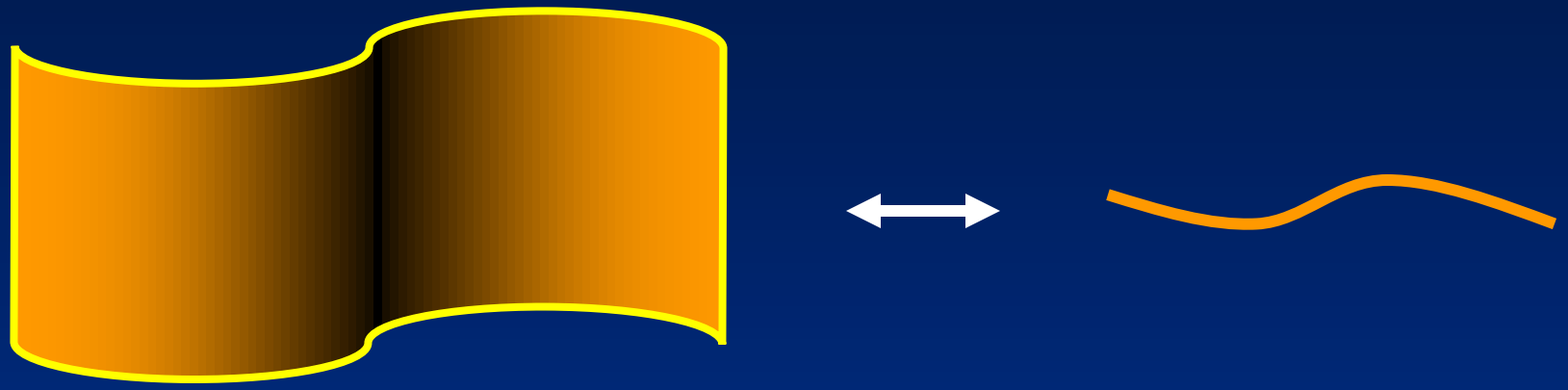
This duality generalizes:

- **E** ⟷ **B** **duality in electromagnetism**
- **P** ⟷ **Q** **“duality” in quantum mechanics**
- **Order** ⟷ **disorder** **duality in Ising model**

Duality exchanges
strong coupling ⟷ **weak coupling**

Telling the same story in different languages.

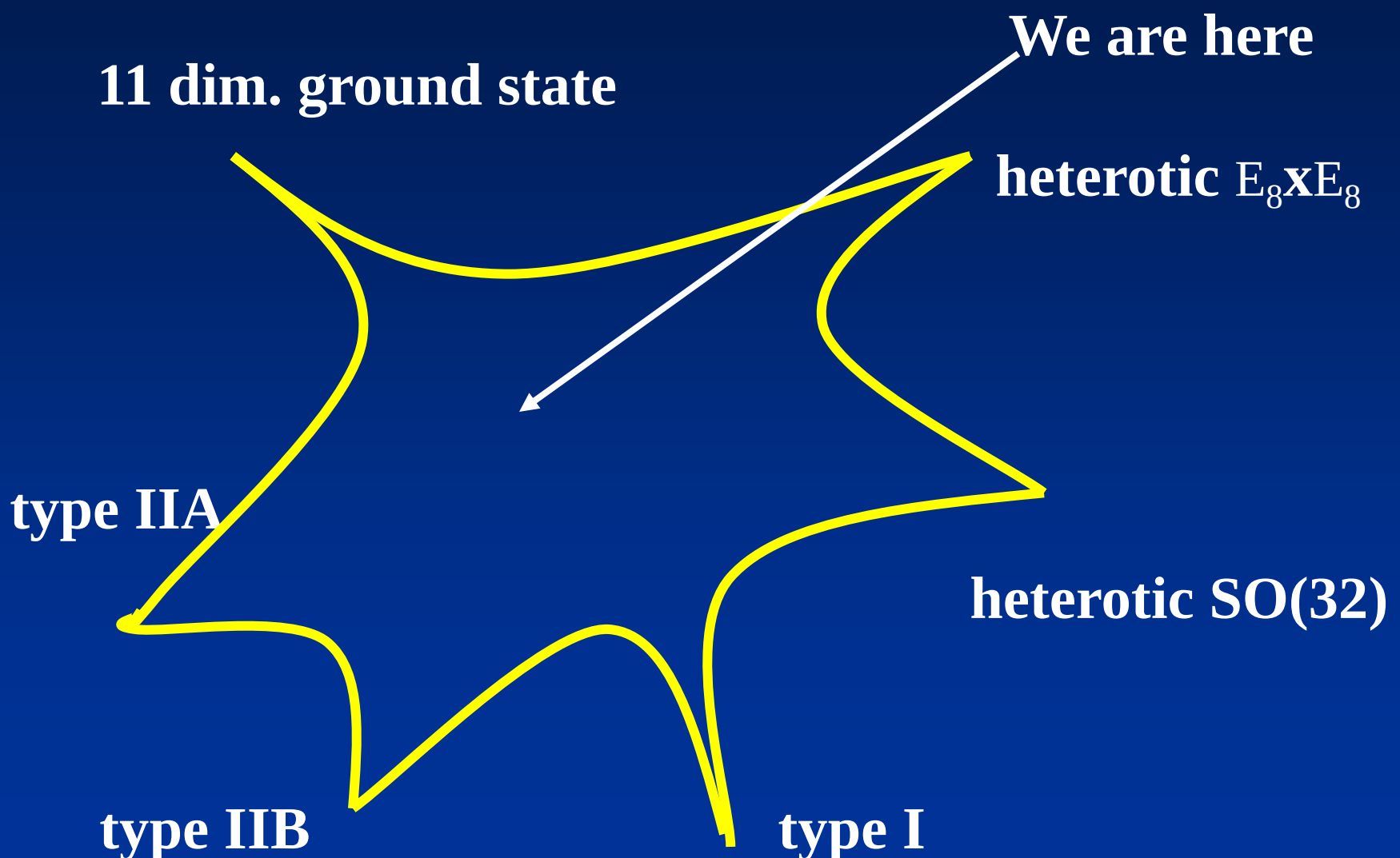
String duality exchanges the different branes



All p-branes are equally fundamental.

String theory is not a theory of strings!

Map of the ground states of string theory



All previously known theories are now understood as different descriptions of the same theory.

String duality exchanges them.

Telling the same story in different languages.

The theory is unique!

Some details

- “Fundamental objects” at one end are composites elsewhere
- Weak coupling at one end corresponds to strong coupling at another end
- The extrapolation from end to end uses the magic of supersymmetry
- The theory is inherently quantum mechanical

Black hole information puzzle

Suggestion: All the information about the interior of a black hole is summarized by the state of its surface, the horizon.

Recent developments - Holography - show that in string theory (at least in certain situations) the state of the system is completely characterized by the behavior of its boundary.

Strings in AdS = CFT on boundary

Entropy = Area

No information loss in black holes

The Ground State(s)

The recent advances have uncovered many new solutions of the equations of motion – ground states

- Is the ground state selected by initial conditions – connection to cosmology?
- If all these solutions are acceptable, do they exist elsewhere in the Universe – Anthropic solution?
- Our understanding lacks a crucial ingredient.

Summary

- String theory is the only candidate for a complete theory of Nature.
- Ultimate confirmation of the theory will require verification by experiment.
- Its fundamental principles are not yet understood, but the past few years have seen tremendous progress:
  - Nonperturbative understanding
  - The theory is unique
  - Black holes
  - Connections with other branches of physics and mathematics