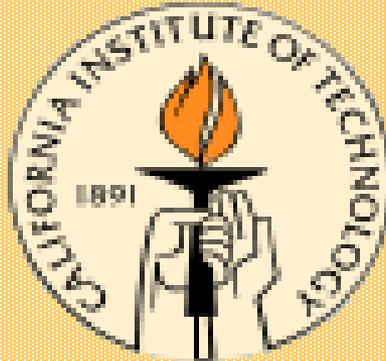


UNIFYING GR WITH QUANTUM THEORY

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GR100

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OUTLINE

- I) What does unifying GR and quantum theory mean? Why should we do it?
- II) String theory: history and concepts
- III) Surprising discoveries
- IV) Conclusion

Fundamental physics

The ultimate goal of particle physics is to achieve a unified understanding of fundamental forces and particles in terms of beautiful and compelling mathematical principles. A related goal, which I will not discuss, is to understand the origin and evolution of the Universe.

These themes were pioneered by Einstein. It seems appropriate to reflect on them in this centennial year of his general theory of relativity.

Fundamental constants

Special Relativity: The speed of light, denoted **c** , is the same for all observers. It appears in the famous equation $E = mc^2$.

Quantum theory: Planck's constant, denoted **h** , appears in the famous Heisenberg uncertainty principle and in the equation $E = hf$, where f denotes frequency.

Gravity: Newton's constant, denoted **G** , appears in the famous force equation $F = GmM / r^2$.

I) Unification

We need to unify:

The Standard Model (SM) -- a relativistic quantum theory that describes the strong nuclear, weak nuclear, and electromagnetic forces. This theory involves c and h but not G .

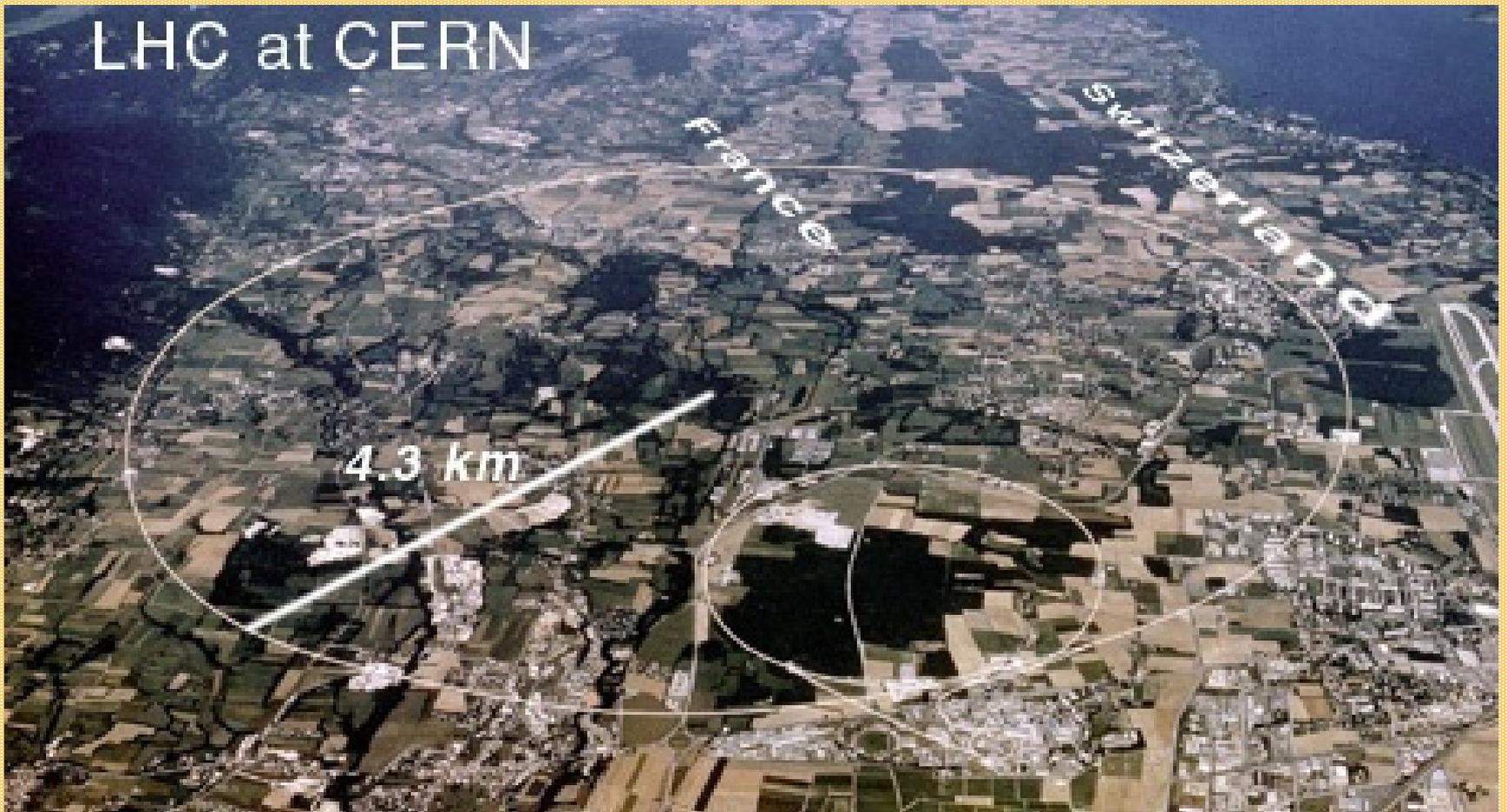
and

General Relativity (GR) -- Einstein's theory of gravity, unlike Newton's, is relativistic. However, it is still classical (i.e., not quantum). This means that it involves c and G but not h .

The Standard Model

- The SM is an extremely successful theory of matter particles (**quarks** and **leptons**), force particles (**photon**, **gluons**, etc.), as well as a **Higgs particle**, discovered at the LHC in 2012.
- The SM does not contain gravity, and it has many arbitrary features for which we would like to find a deeper explanation. So far, the LHC has found no evidence for physics beyond the SM, but the search continues.

LHC at CERN



7 + 7 TeV proton – proton collider

General Relativity

- GR is a very beautiful theory that describes gravity in terms of the geometry of spacetime.
- GR has successfully predicted gravitational lensing, black holes, gravitational waves, and much more. No discrepancies have been found.
- Some solutions (e.g. black holes) contain singularities that suggest a breakdown of GR.

Massless particles

- Massless particles travel with the speed of light, c .
- The electromagnetic force is mediated by a **massless spin-one particle**, called the **photon**. The force can be attractive or repulsive (depending on the charges).
- The gravitational force is mediated by a **massless spin-two particle**, called the **graviton**. The force is always attractive.

The Planck length

There is a unique way to combine c , h , G that gives a length. This length must play a fundamental role in a unified theory.

The Planck length, first computed by Max Planck in 1899, is

$$L_P = [\hbar G/c^3]^{1/2} = 1.6 \times 10^{-35} \text{ m}$$

which is an extremely short distance – far beyond what can be accessed with any foreseeable technology.

Summary of Part I

- The SM is a very successful relativistic quantum theory of electromagnetic and nuclear forces. GR is a very successful classical theory of gravity.
- Consistency requires the existence of a unified theory containing the SM and GR. This theory is expected to predict qualitatively new phenomena at the Planck scale. They may not be accessible experimentally.

II) String Theory

String theory originated around 1970 in an attempt to understand the **strong nuclear force**. This force holds protons and neutrons together inside the nucleus of an atom. It also holds **quarks** and **gluons** together inside the neutron and proton.

A correct theory of this force should incorporate the well-established principles of **special relativity** and **quantum mechanics**. String theory does that.

Strings are physical objects that make curved lines (like rubber bands) in space. They have **tension** and **energy density**, just as point particles have **mass**.

String theory had some success in describing the spectrum of strongly interacting particles (called **hadrons**) and their interactions at high energy. To give realistic masses the size of the strings needed to be about the same as a proton, which is roughly $10^{-15} m$.

The basic idea

Different modes of oscillation, rotation, etc. of the string behave as different particles.

In this sense, there is a **unique object** (namely, the string). The dream was that this could give a unified understanding of the multitude of hadrons and their interactions that were discovered in experiments of the 1960s.

There were problems

- Quantum consistency of the original string theory requires **26 dimensions** (25 are space and 1 is time). This was completely unexpected – and certainly not what we wanted (3+1).
- Quantum theories have two classes of particles, called **bosons** and **fermions**. The original string theory only contains bosons, but realistic quantum theories always involve fermions as well. (e.g. electrons and quarks.)

Superstrings

A second string theory, containing fermions as well as bosons, was constructed in 1971 by Pierre Ramond, André Neveu, and me. It requires 10 dimensions (9 space and 1 time).

The development of this string theory led to the discovery of supersymmetry, a previously unknown type of symmetry that relates bosons and fermions. Strings in supersymmetric theories are called superstrings.

Both string theories – the 26d bosonic string theory and the 10d superstring theory -- have modes that correspond to **massless particles**.

This was another disturbing fact, since it was known that **every hadron has a positive mass**. (The photon and graviton are not hadrons.) We tried hard to modify the string theories to describe only massive particles and 4d spacetime, but all such attempts led to inconsistencies.

The death of string theory

In 1973 a theory of the strong nuclear force, called **QCD** (or **quantum chromodynamics**), was developed. It is a relativistic quantum theory based on point particles (**quarks** and **gluons**). QCD is part of the SM.

It was clear that QCD is correct, so string theory was abandoned by almost all of its practitioners. A community of several hundred was reduced to a handful of diehards (including me).

Gravity in string theory

One of the massless particles in string theory has the right properties (zero mass and spin two) to be the **graviton**, the particle responsible for gravity.

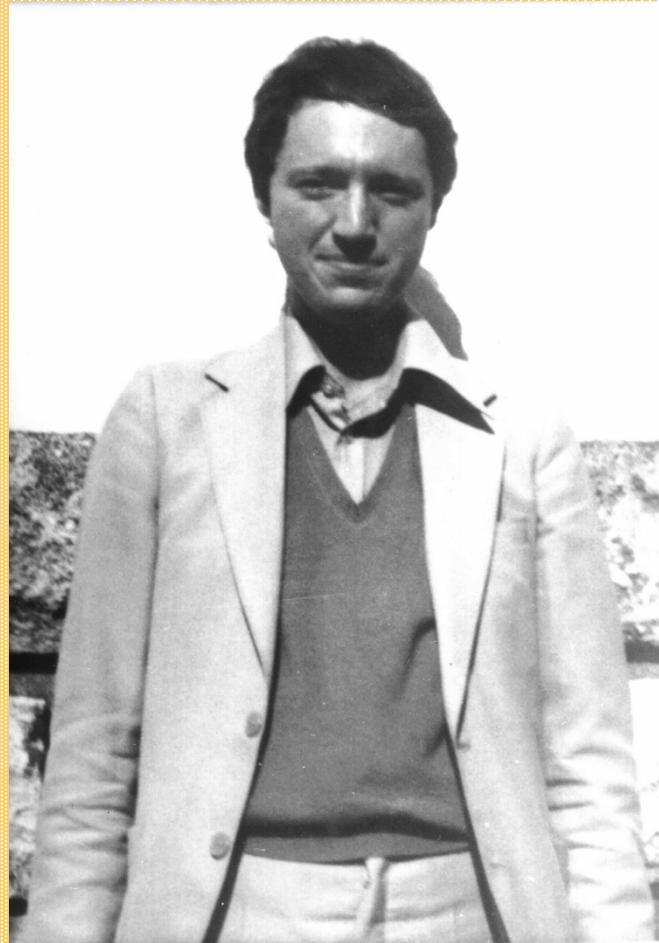
At accessible energies, the interactions of the string theory graviton agree with the graviton in General Relativity. Thus, **“String theory requires the existence of gravity.”**

Unification

Massless string modes also include spin one particles that behave like the particles that are responsible for the forces described by the SM (nuclear and electromagnetic).

These facts led **Joël Scherk and me** in 1974 to propose using string theory as a **unified theory of all forces** (including gravity). This required that the typical size of a string L_S is close to the Planck length L_P , 20 orders of magnitude smaller than hadronic strings!

Joel Scherk (1946-1980)



The physics world was different in 1974

Relativists (people who work on GR) had little use for particle physics and **particle physicists** felt they had no need for considering gravity. Nowadays, the two communities interact a lot.

As a result, in 1974 there was little interest in our proposal. It wasn't criticized; it was ignored (with a few exceptions). Nevertheless, we were excited. I knew what I would be doing for the rest of my career.

Advantages of string unification

Prior attempts to construct a quantum version of GR had assumed point-like particles (quantum field theory). This gave rise to nonsensical infinite results (“nonrenormalizable ultraviolet divergences”).

By contrast, as we already knew from our previous studies, **string theory gives finite results** (no ultraviolet divergences).

In a relativistic theory of gravity, such as GR or superstring theory, **the geometry of space-time is determined by the dynamics, *i.e.*, by solving the equations.**

When string theory is used to describe gravity, extra dimensions are an advantage. It makes sense to consider solutions in which **the six extra dimensions form a tiny compact space.** They can form a sphere or a torus or, as seems likely, a much more complicated geometry.

Implications of extra dimensions

It seems likely that the compact space is extremely small, perhaps approaching the Planck length. If so, it is not observable with current technology. So **space appears to be three-dimensional.**

Experiments at the LHC are looking for extra dimensions, improving the experimental limits. I could be wrong about their size, so it is important that they keep looking.

Anomaly cancellation

An important property of Nature (and the SM) is **parity violation** -- asymmetry under mirror reflection. Parity violation is difficult to incorporate into a quantum theory, since mathematical inconsistencies, called **anomalies**, often arise.

For a long time it was unclear whether parity violation is possible in string theory. In 1984 **Michael Green and I** discovered an **anomaly cancellation mechanism** that makes parity violation possible in superstring theory.

Superstring resurrection

After more than a decade in the doldrums, string theory became a hot subject again in the mid-1980s. The anomaly cancellation result and other developments convinced many theorists that superstring theory could provide a unified quantum theory of all forces.

Interest in reconciling GR with quantum theory had increased over the preceding decade, so by 1985 there was a substantial community of physicists ready and eager to contribute.

The invisible geometry is important

The geometry of the six extra dimensions of space determines the types of particles and forces that occur in ordinary 4d space-time!

So determining this geometry is essential for understanding the detailed properties of the known elementary particles as well as ones yet to be discovered. This has been a very active area of research ever since 1985.

Supersymmetry

Supersymmetry is the prediction that has the best chance of being confirmed experimentally, though it hasn't shown up yet.

- The spin $\frac{1}{2}$ quarks and leptons have spin 0 superpartners called **squarks** and **sleptons**.
- The spin 1 gauge particles and spin 0 Higgs particles have spin $\frac{1}{2}$ superpartners called **gluinos**, **neutralinos**, and **charginos**.

Superpartners could still be discovered at the LHC. The collider, detectors, data collection, and data analysis continue to be improved.

Summary of Part II

- String theory was developed to describe the strong nuclear force. This was unsuccessful because of unrealistic **extra dimensions** and **massless particles**. The correct theory (QCD) was discovered, so string theory was abandoned for more than a decade by all but a few diehards.
- The goal of string theory was changed to constructing a **unified theory of particles and forces** containing the SM and GR.

- The strings shrank by 20 orders of magnitude, and the previous “shortcomings” of string theory became important advantages.
- Superstring theory became a mainstream field of theoretical physics in the mid-1980s, and it has remained one ever since.
- Superpartner particles might be discovered at the LHC if they are not too heavy.

III) Surprising Discoveries

Superstring theory is forcing us to revise many long-held principles, as was the case previously for GR and quantum theory.

One class of surprises concerns equivalences, called **dualities**. They relate seemingly different solutions of superstring theory, implying that they are actually different descriptions of the same solution!

Geometric dualities

A circular dimension of radius R can be equivalent to one of radius L_s^2/R . This is called **T duality**. This happens because strings probe space-time differently from point particles. For instance, they can wrap around the circle.

There are analogous equivalences that relate geometries of **different topology**. This is one of the many results that has had a very big impact on mathematics.

Electric–magnetic symmetry

The equations of electromagnetism (Maxwell's equations) are symmetric under interchange of electric and magnetic charges and fields.

This symmetry has a dramatic generalization in string theory called **S duality**. In certain cases it relates a solution with **interaction strength g** to one with **interaction strength $g' = 1/g$** . Thus, a large g solution is equivalent to a small g one.

p -branes and black holes

Superstring theory contains objects with p spatial dimensions, called p -branes with $p = 0, 1, 2, \dots, 9$. Strings, which are 1-branes, are special. The other branes become infinitely heavy as g approaches 0.

In certain cases it has been shown that microstates account for the entropy of black holes. These microstates can be constructed by wrapping p -branes around extra dimensions.

AdS/CFT duality

In 1997 **Juan Maldacena** discovered a class of dualities that relate superstring theory solutions with certain space-time geometries (**AdS**) to certain quantum field theories (**CFT**) that are defined on the boundary of the AdS space.

The AdS theory is represented **holographically** by the CFT, which has one less dimension. This is an enormous and fascinating subject, which has applications to other areas of physics that allow previously intractable problems to be solved.

More superstring surprises

- The distinction between “**fundamental**” objects and “**composite**” ones is not sharp except in special limits.
- The distinction between what is “**quantum**” and “**classical**” is not sharp except in special limits.
- **Space and time are emergent.** Their existence is a property of certain classes of solutions, but it is not an intrinsic feature of the theory itself.

Status of superstring theory

Superstring theory is not yet formulated. We only understand certain limits and dualities. However, it is clear that the theory is **completely unique** without any adjustable dimensionless parameters. All such numbers are determined dynamically.

Because of the surprising properties listed on the previous slide, the final formulation of superstring theory must be radically different from all previous theories. This requires another Einstein.

IV) Conclusion

Superstring theorists are trying to understand Nature at the most fundamental level. After 30 years of intense effort by many very clever people, we have learned a great deal, but much more remains to be understood.

A good historical analog is the early days of quantum theory. There were successes before quantum mechanics was properly understood.

String theory has evolved remarkably over the past 45+ years. It is now unifying many areas of mathematics and physics as well as forces and particles.

It will probably take many decades, or even centuries, to answer all of our questions. As answers are found, new questions arise. The string theory community is (mostly) young, hard-working, talented, and enthusiastic, and it is making good progress.

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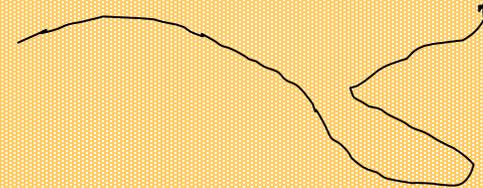
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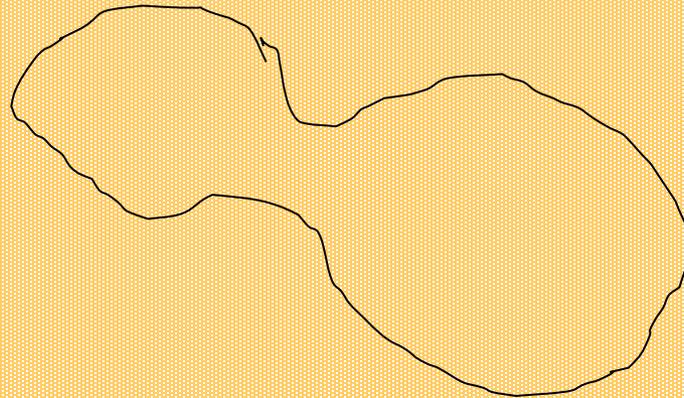
Extra Slides

Two possible topologies for strings

Open strings have two ends:



Closed strings are loops without any ends:



Five Superstring Theories

Type I, Type IIA, Type IIB

$SO(32)$ Heterotic and $E8 \times E8$ Heterotic

Each of these theories requires supersymmetry and ten dimensions and has no adjustable parameters.

Calabi-Yau Compactification

In 1985 a group of four authors considered attaching a **tiny 6d Calabi-Yau space** to every point in 4d space-time. This solves the equations and gives a parity-violating supersymmetric theory in 4d space-time.

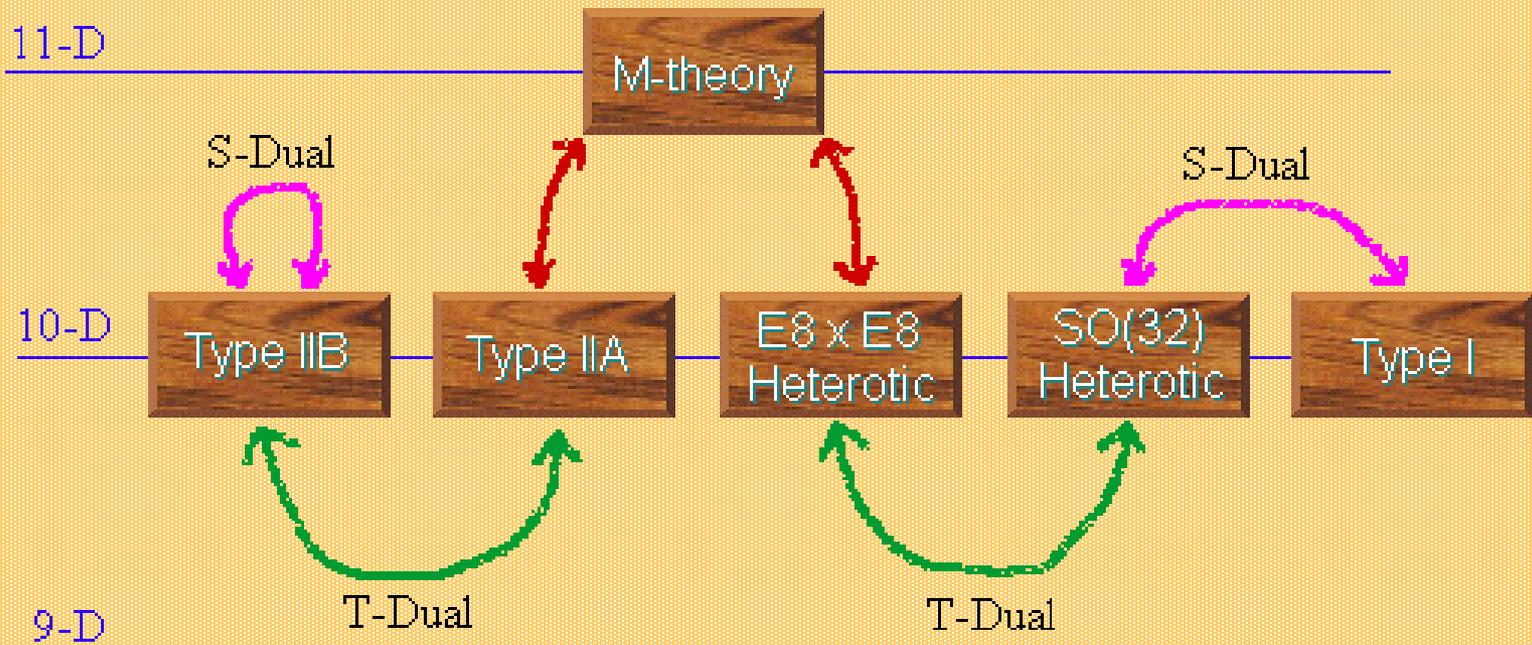
Starting with the $E8 \times E8$ Heterotic theory, and choosing the right CY space, one can obtain a supersymmetric extension of the SM with many realistic features.

M-theory and F-theory

In certain cases (IIA and $E8 \times E8$) a solution with coupling strength g is equivalent to one with an **eleventh dimension of size gL_S** . This dimension is a circle in the IIA case and a line interval in the $E8 \times E8$ one. 11d solutions of superstring theory are referred to as **M-theory**.

There are also quasi-12d solutions of Type IIB referred to as **F-theory**. There was a conference on F-theory at Caltech in Feb. 2016.

There's just one theory!



Many Challenges Remain

1. Develop the required mathematical techniques and concepts
2. Find a complete and compelling formulation of superstring theory
3. Understand dark energy
4. Explain elementary particle physics

5. Understand space-time and quantum mechanics
6. Understand the origin and evolution of the Universe
7. Understand the quantum properties of black holes
8. Apply string theory methods to other branches of physics. (This is an active area of research.)

MBG and JHS – Aspen 1984

