4E: The Quantum Universe

Lecture 34, June 2

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A Few Quick Announcements

1. Quiz 5 on Friday! Covers Ch. 7 of Tipler and Ch. 8 of Serway

2. You may bring one sheet of paper (front and back) of notes for the Final Exam. We will provide 5 pages of equations as well, which will be attached to the exam.

3. Please frequently check the announcements page on the course website. Important info may appear there sometime within the next week.

4. Ch. 7 of Tipler and Ch. 8 of Serway will be on the final. However, the particle physics and string theory stuff will not be.

Yesterday, we stopped by listing some problems with
String Theory:

1) **String theories must be 10 dimensional**
2) **It is very difficult to get the Standard Model**
3) **Not really testable (yet?)**
4) **Too many particles (including SUSY)!**
5) **They're just jealous ("fundamental envy")**

Let's explain where these problems come from, and deal with them one by one.

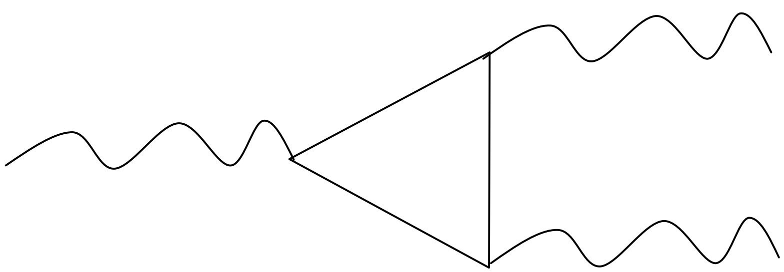
Why Ten Dimensions?

Both quantum field theories AND string theory are delicate.

Sometimes you have classical symmetries that do not exist quantum mechanically!

These lead to **ANOMALIES** which are **scary** and **bad**.

The theory is inconsistent!



Anomaly diagram

In String Theory, the classical worldsheet theory is **scale invariant!**

If you compute the anomaly, you get

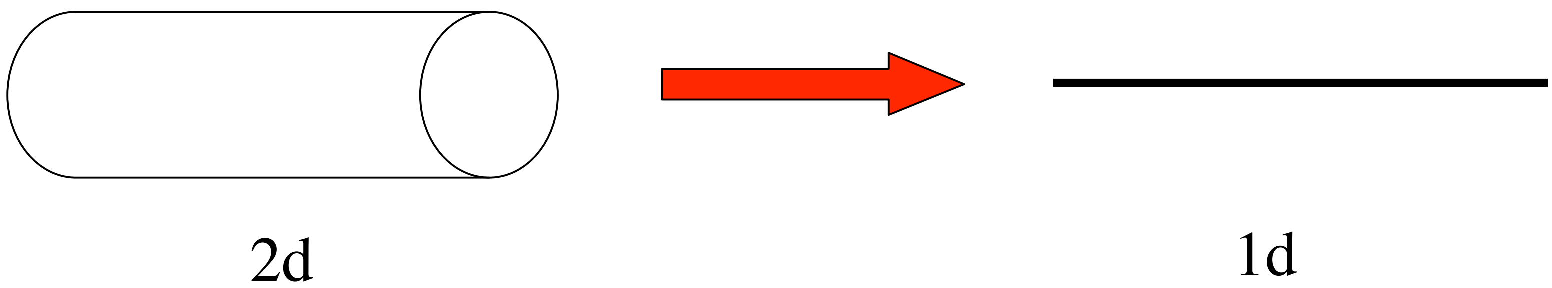
$$\text{Anomaly} \sim D - 10 + \cdots$$

So to preserve this symmetry, you must have D=10!

The fact that String Theory is 10 dimensional comes from the necessity of preserving scale invariance on the worldsheet.

How do we deal with this?

It is possible to get four-dimensional theories from ten-dimensional ones via **compactification.**



The **spectrum** in the lower-dimensional theory depends on the **geometry** of the compact space!

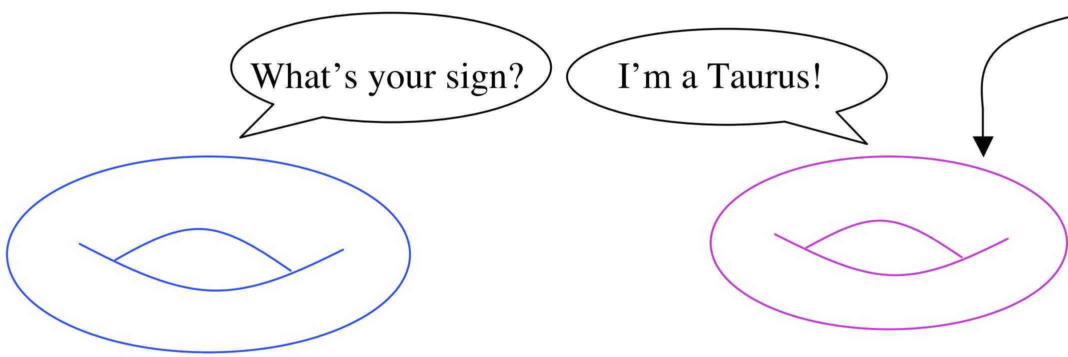
In a real string theory computation, we would need to have a **six-dimensional** compact space.

Generic compact spaces will not preserve any SUSY!

An important example of a space which does is a
Calabi-Yau manifold.

Some Calabi-Yau manifolds:

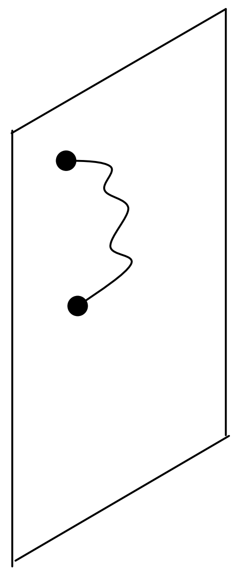
2d	T^2
4d	$T^4, \ K3$
6d	Lots and lots!



Calabi-Yau manifolds are essentially the **only** manifolds that give supersymmetric theories, so they're worth studying.

There are other ways to get 4d theories, though…

String theory isn't just a theory of strings! There are extended objects called **D-branes** in the theory, too.

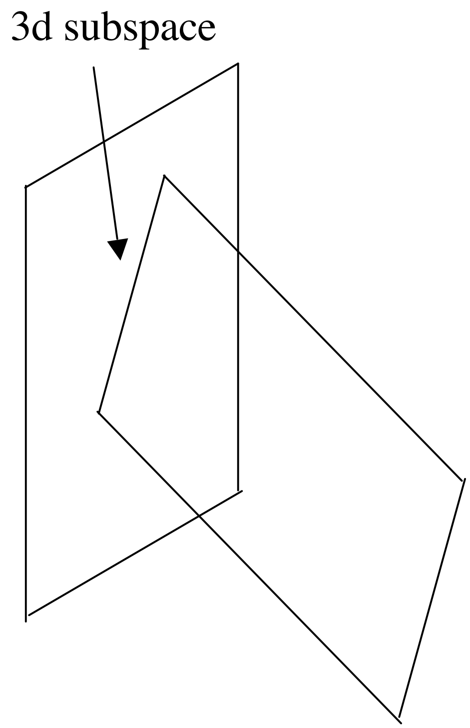


A D-brane is a multidimensional hyperplane where open strings can end.

Usual notation: **Dp-branes** have **p** spatial dimensions.

So we can get a **4d theory** by looking at the theory induced on the worldvolume of a D3-brane!

We can get all sorts of interesting theories by **intersecting D-branes.**



Like 2 D5's intersecting along 3 of their common directions, for example.

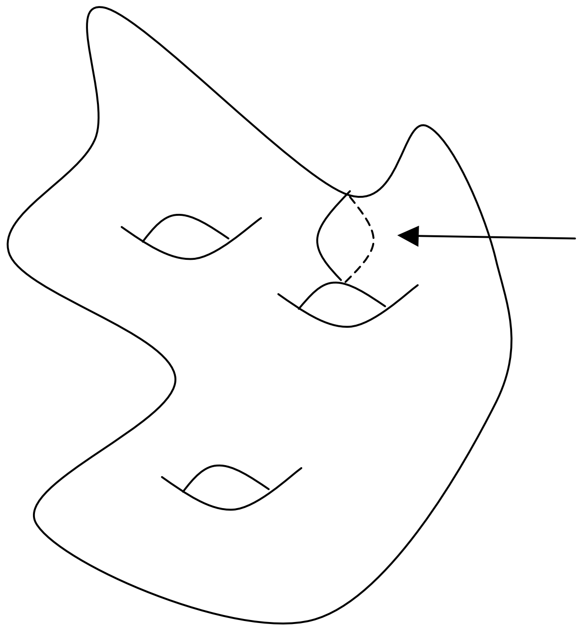
In general, we can have all sorts of cool brane configurations that give interesting physics. It's all a part of string theory!

Could we be living on a D3-brane in a higher dimensional universe?

Maybe, but **gravity** would have to propagate in the other directions. We can test this! So far, no dice – but **who knows**?

Getting the Standard Model

Compactifying on a Calabi-Yau yields many fields in the lower-dimensional theory:



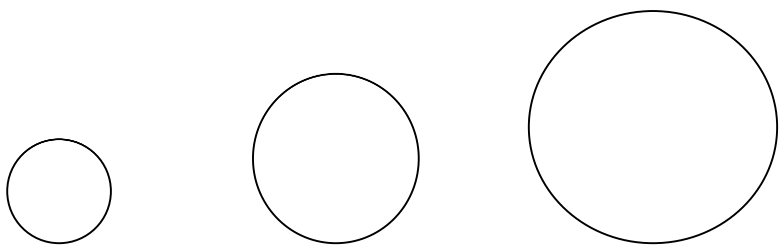
The number of different nontrivial **loops** in the CY determine the different ways we can wrap strings around it. Each different wrapping becomes a different particle in 4d.

So maybe getting the Standard Model is just a matter of picking the right Calabi-Yau!

But there are actually a **lot** of problems with this! In particular, it's mostly a matter of trial and error.

All known CY's yield not just the Standard Model, but a lot of **other stuff** as well. Getting the Standard Model is then equivalent to getting rid of the extra particles.

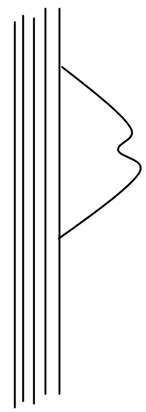
Another problem: It's difficult to fix the size of the CY!



There's no obvious way of choosing which one.

People have been searching for a potential for the size of the CY for **years**, but nothing has come up so far.

We can also get Standard Model-type stuff with **D-branes**!



N D3's

The ends of the string show up as **quarks**, **electrons**, etc. Depending on the branes, we can get different numbers of quarks.

We can also do stuff with intersecting branes, just like before. But there are still problems with this – still hard to get the SM!

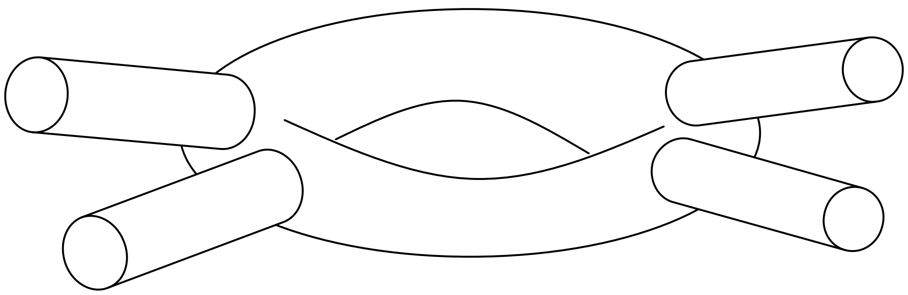
There's lots of work to be done before we figure out how String Theory yields the observable universe!

Evidence for String Theory

At present, there is no direct experimental evidence for String Theory. But there are still lots of reasons to take it seriously!

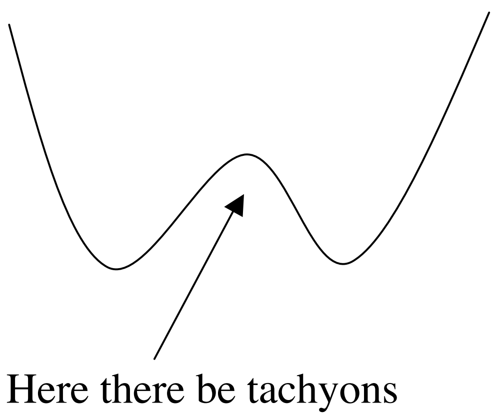
1. It is a theory of quantum gravity.

Stringy Feynman diagrams are finite. This is major! We should take any quantum theory of gravity very seriously, since it is so difficult to engineer one.



2. String Theory predicts supersymmetry.

Nonsupersymmetric string theories have tachyons, indicating that the theory is unstable.

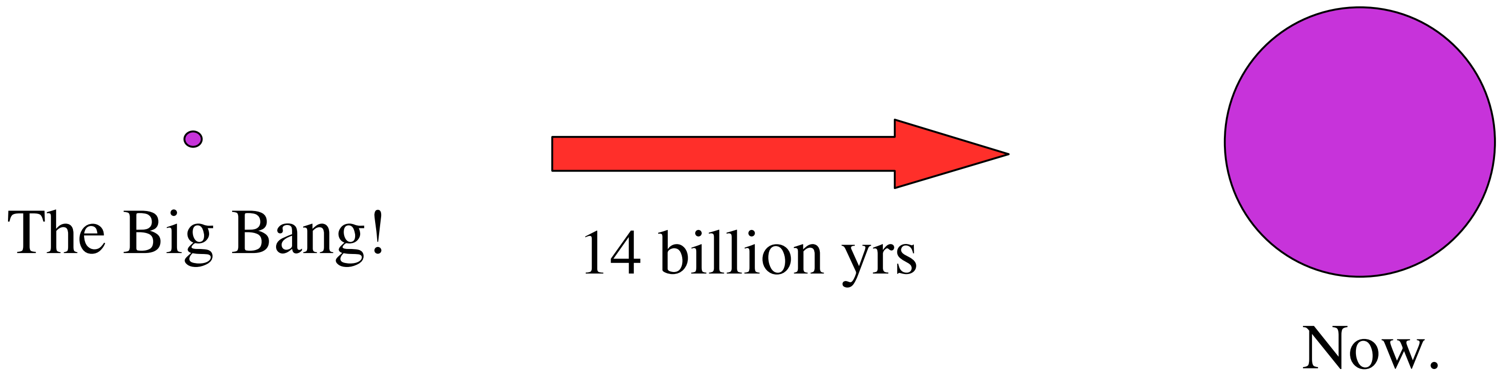


All known non-SUSY string theories have vacuum instabilities, so we can say that string theory predicts the existence of SUSY.

This is good! **SUSY** means **unification**, which we want.

LHC (2007) will explore energies at which we **may** see SUSY, so perhaps (indirect) evidence for string theory isn't so far off!

3. It may be possible to test string theory on cosmological scales.



String theory effects would be present in the very early universe. But due to the expansion of the universe, these effects will exist on very large distance scales now! Perhaps we can measure them (i.e. CMB spectrum) and see if they match up with String Theory.

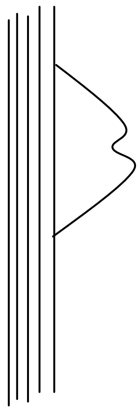
Dualities between String and Field Theories

String Theory was originally proposed as the solution to an entirely different problem than finding a quantum theory of gravity – originally, it was thought to describe the strong interaction!

This wasn't right – eventually QCD emerged as the answer.

However, according to the AdS/CFT correspondence, we can still get info about **field theory** from **string theory**!

String Theory in 10d	**Field Theory in 4d**
Weakly coupled	Strongly coupled
Strongly coupled	Weakly coupled
Symmetry in geometry	Symmetry in field theory



N D3's

We can think of the string theory as living in the **full** 10d, but the field theory as living on the large stack of D3-branes!

What if it's Wrong?

Even if String Theory turns out to not be a valid physical theory, it has still yielded a lot of cool stuff:

New Math Theorems

AdS/CFT

New Techniques

Interesting Physics

Alternative to QFT

Quantum Gravity

So even if String Theory ends up getting discarded, it's still been a fun ride!

References

Brian Greene, “The Elegant Universe”

Brian Greene, “Some Other Book That Just Came Out”

Stephen Hawking, “The Universe in a Nutshell”

Gordon Kane, “Supersymmetry”

Stephen Hawking, “A Brief History of Time”

Also check out the NOVA special on string theory, which you can watch online! (Google “Nova string theory”)

Finally, to see the current research, visit www.arxiv.org and check out the High Energy Physics-Theory section!