4E: The Quantum Universe

Lecture 33, June 1

Brian Wecht

Towards a Unified Theory

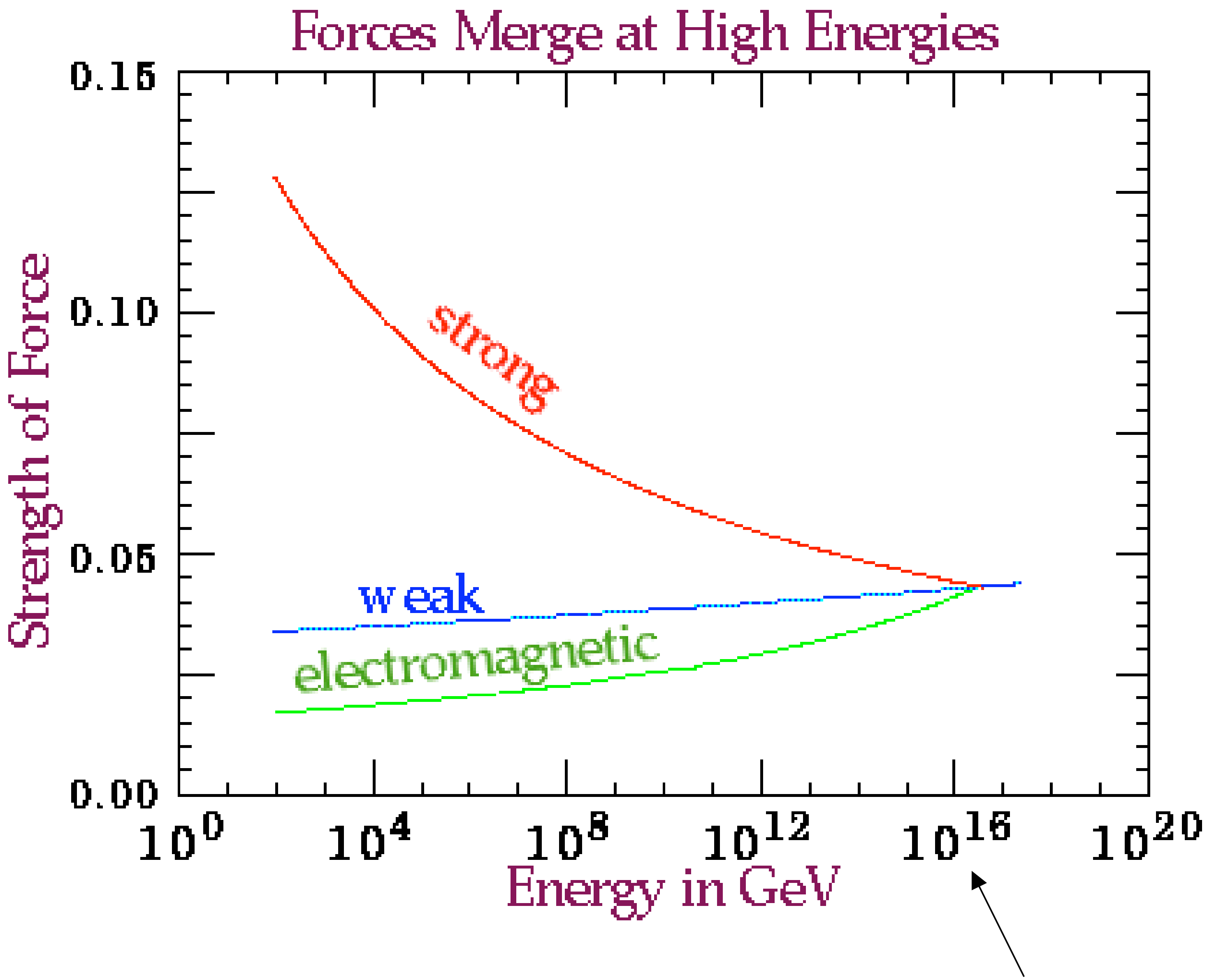
Table 15.1 Particle Interactions

Interaction (Force)	Particles Acted on by Force	Relative Strength[a]	Typical Lifetimes for Decays via a Given Interaction	Range of Force	Force-Carrying Particle Exchanged
Strong	Quarks, hadrons	1	$\leq 10^{-20}$ s	Short ($\approx$1 fm)	Gluon
Electromagnetic	Charged particles	$\approx 10^{-2}$	$\approx 10^{-16}$ s	Long (∞)	Photon
Weak	Quarks, leptons	$\approx 10^{-6}$	$\geq 10^{-10}$ s	Short ($\approx 10^{-3}$ fm)	$W^{\pm}$, Z^0 bosons
Gravitational	All particles	$\approx 10^{-43}$	?	Long (∞)	Graviton[b]

[a] For two *u* quarks at 3×10^{-17} m.

[b] Not experimentally detected.

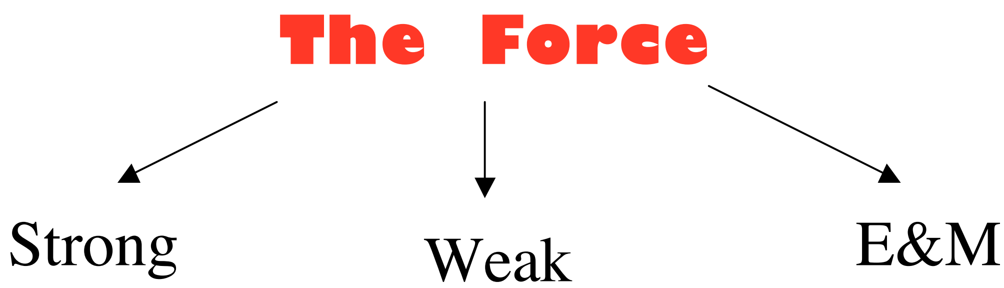
Can we find **one** theory that describes them all?



We know that at high energies, the forces **unify**!

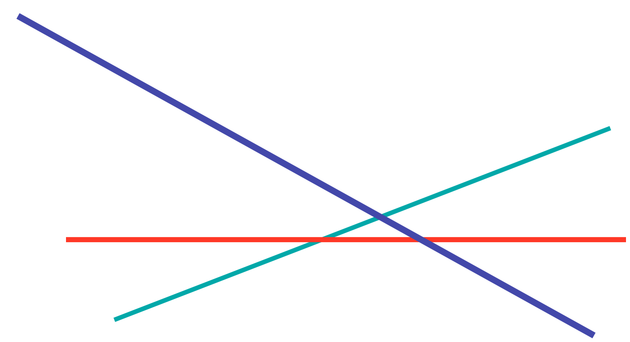
We say that 10^{16} GeV is the **unification scale**, where all the forces are equally strong. This is a very high energy scale, not present in nature except during the very early universe.

At low energies, this symmetry gets **broken**:



Actually, though, the forces **don't** quite unify…

The picture looks more like



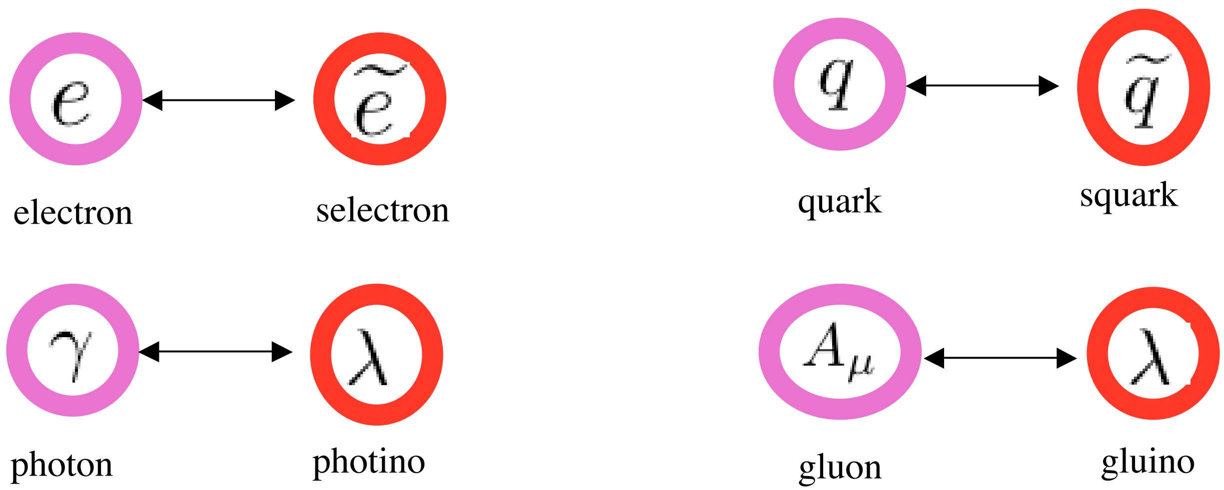
How can we fix this?

SUPERSYMMETRY!

Supersymmetry (SUSY) says that there is a symmetry

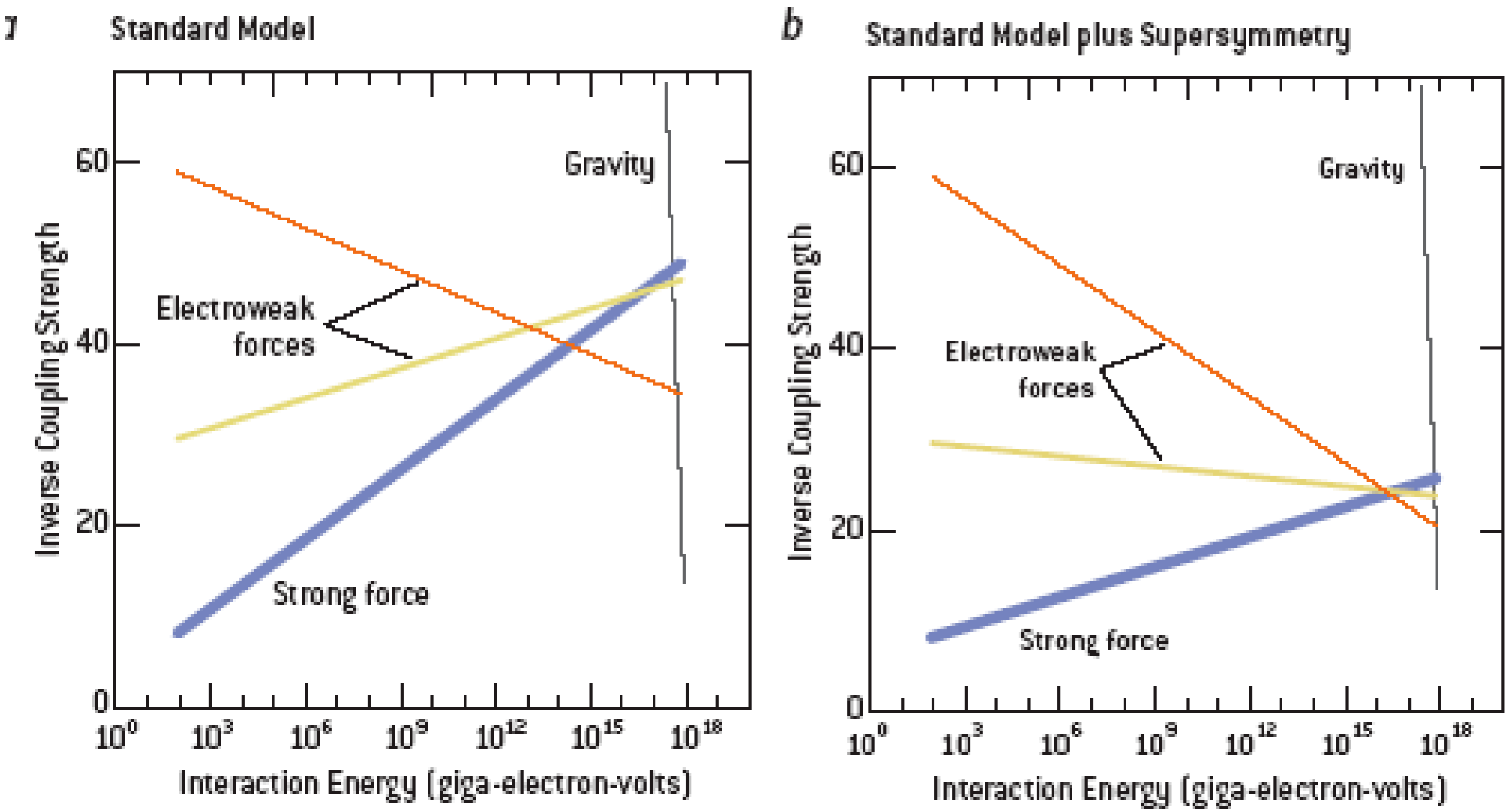
Bosons ⟷ Fermions

The supersymmetric pairs are called "superpartners," and have the same mass, charge, etc.



This is deep! Particles with different spins behave very differently.

It turns out that adding superpartners to the Standard Model makes the gauge couplings **unify**!



From a theoretical standpoint, this is a compelling argument for SUSY.

In the late ‘60s, Glashow, Weinberg, and Salaam showed that one can think of the electromagnetic and weak forces as different manifestations of the same force – the **electroweak** force.

$$SU(2) \times U(1) \rightarrow U(1)$$

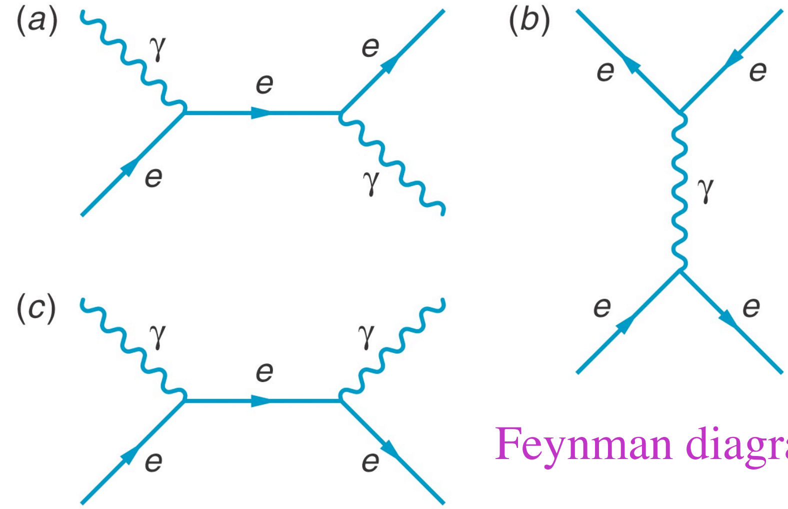
So maybe it’s not so surprising that those couplings unify.

However, it is **EXTREMELY** surprising that the strong force also unifies. This gives us hope that maybe we can include **gravity** too!

Strong and Electroweak	Gravity (GR)
mediated by	mediated by
Photon, Gluon, $W^{\pm}$, Z^0	Graviton
Spin 1	Spin 2 ← **BIG DIFFERENCE**

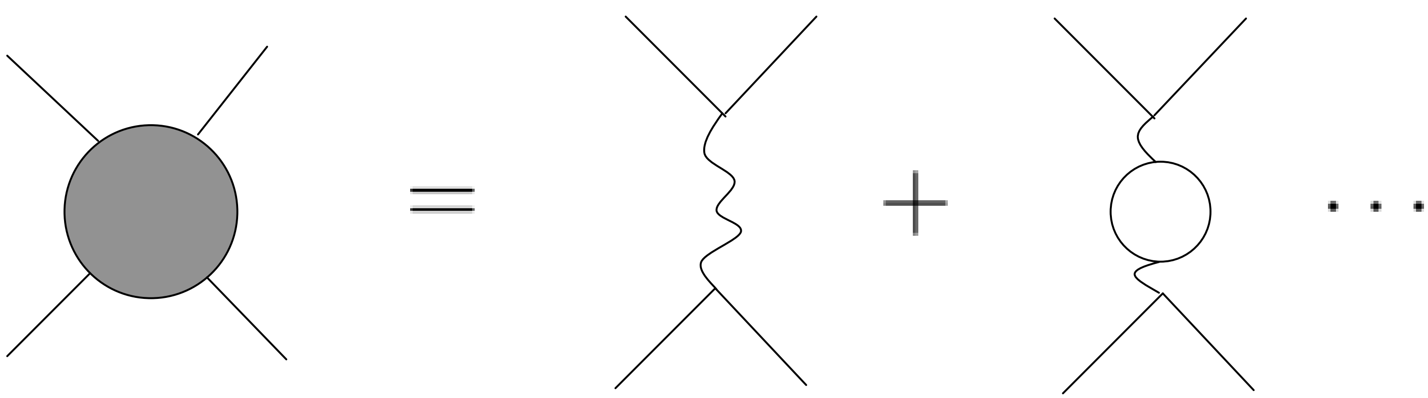
The Problem With Gravity

In QFT, must compute amplitudes:



Feynman diagrams

But you need to sum over all the different ways this can happen!



Sometimes, these diagrams give infinite amplitudes!!

Can fix it = **Renormalizable**

Can't fix it = **Non-renormalizable**

Gravity, because it works by exchanging spin 2 particles, is **NON-RENORMALIZABLE**.

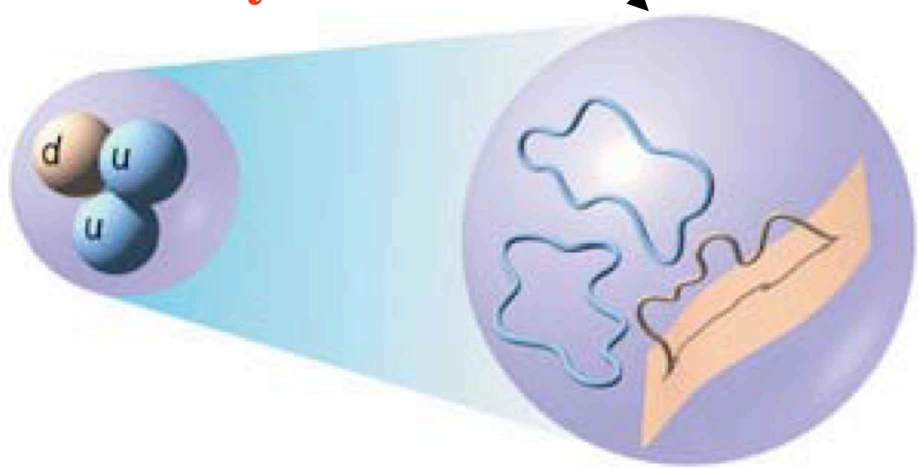
There is no way within the confines of field theory to allow gravitational interactions.

Quantum Gravity

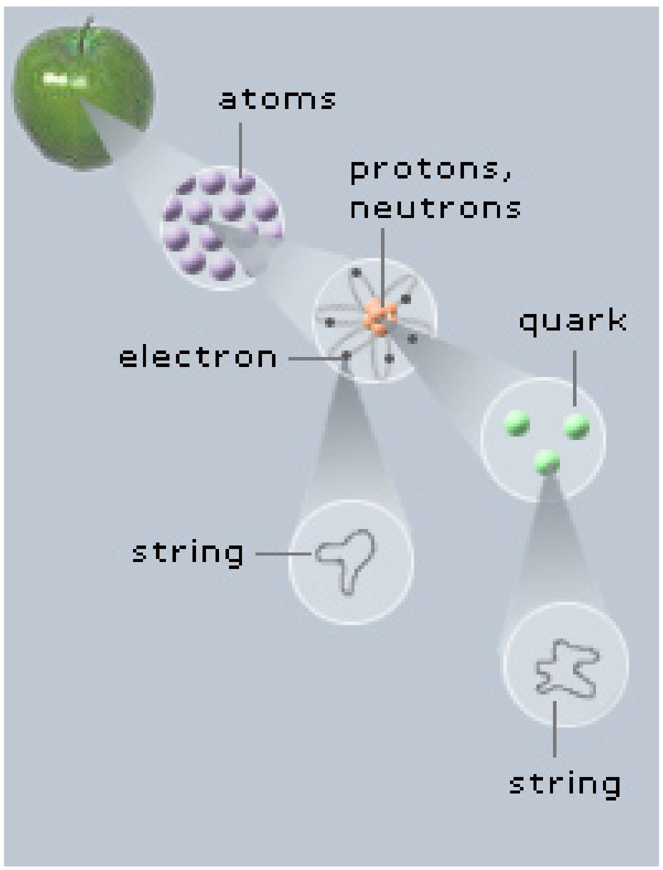
The problems with gravity all come from QM effects, where stuff blows up. Can we find a consistent quantum theory?

It's difficult!

Options:
1) String Theory
2) Loop Quantum Gravity
3) ????
4) Miller time!



String Theory: The Best Theory EVER



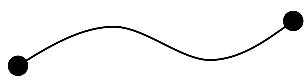
The idea behind **String Theory** is simple: The fundamental constituents of nature are not point particle, but strings!

Roughly speaking, to see stringy structure, you need to be at distance scales of 10^{-34} m!

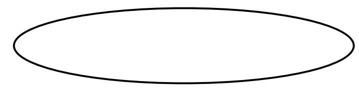
So no direct tests are possible, yet.

Basic String Lingo

There are two kinds of strings:



Open



Closed

Just like on a normal string, you can have waves!

On closed strings, they can go clockwise or counterclockwise.
These are referred to as **left-** and **right-**movers, respectively.

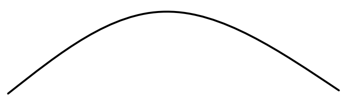
On open strings, BC’s mean that there’s only one kind of wave.

But if all particles are actually strings, what's the difference?

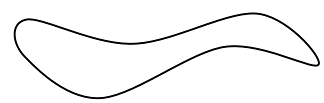
The vibrational modes of the string correspond to different particles.

This makes sense:

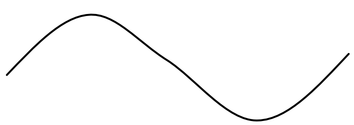
More **vibrating** means more **energy**, so more **mass**!



Photon



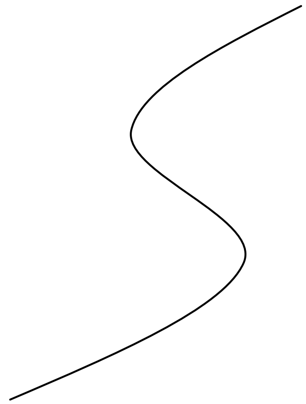
Graviton



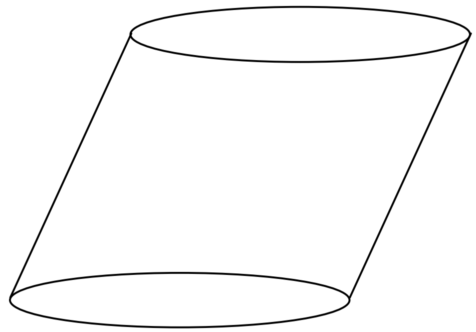
electron

And an infinite number of other states! Their masses are so big, though, that we don't see them.

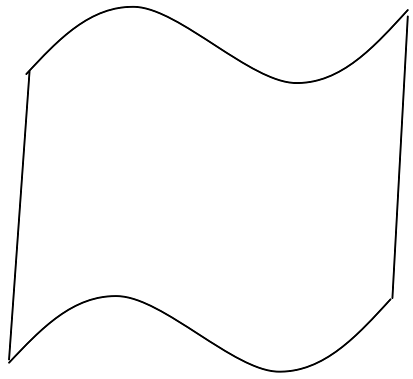
Just like point particles trace out **worldlines**:



Strings trace out **worldsheets:**

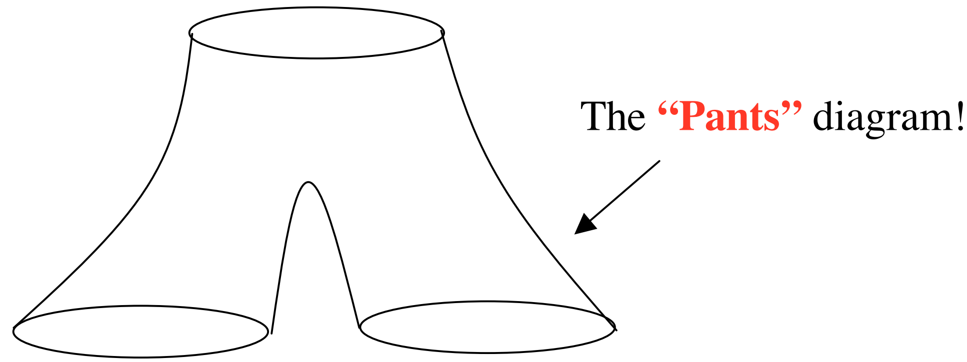


Closed



Open

Strings can interact, too:



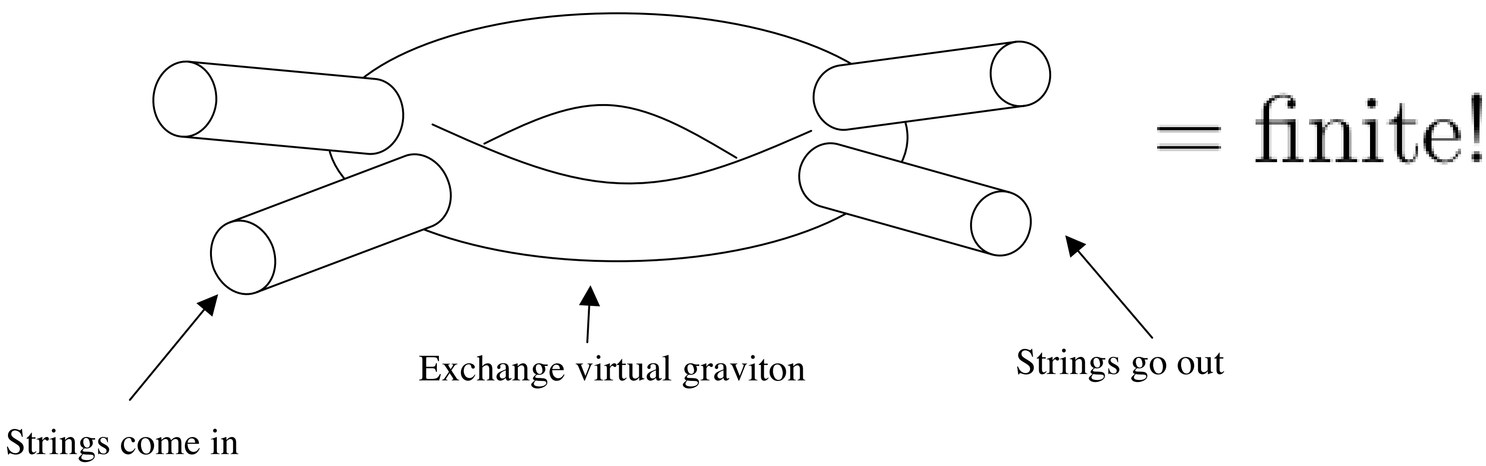
Notice that this is just a Feynman diagram done with strings.

Let's do more!

How does string theory help solve our **gravity problem?**

Remember, **infinities** in gravity come from very high energy (short distance) processes. String theory basically gets rid of these processes by saying that below some length scale, you should do **string Feynman diagrams** instead!

These string Feynman diagrams do NOT diverge.



❤❤❤ String Theory is Awesome!!! ❤❤❤

So what's the big problem? Why doesn't EVERYONE ♥ 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.

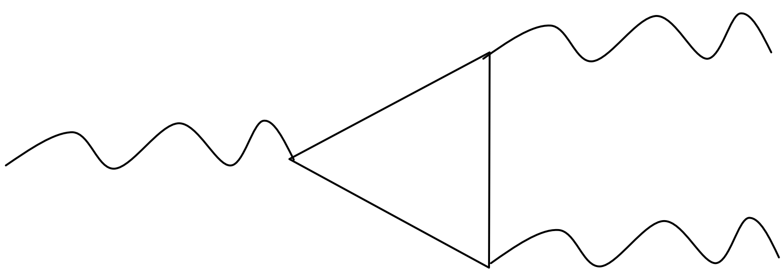
Why Ten Dimensions?

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

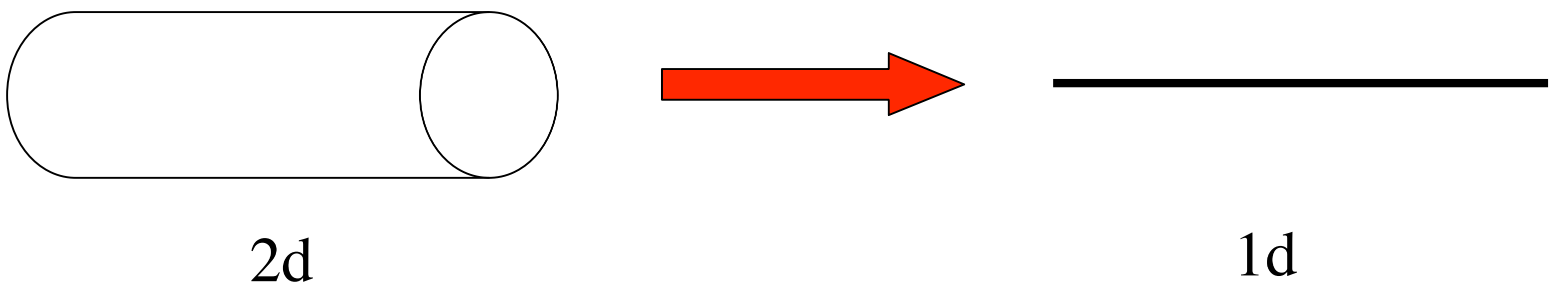
$$\text{Anomaly} \sim D - 10 + \cdots$$

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!

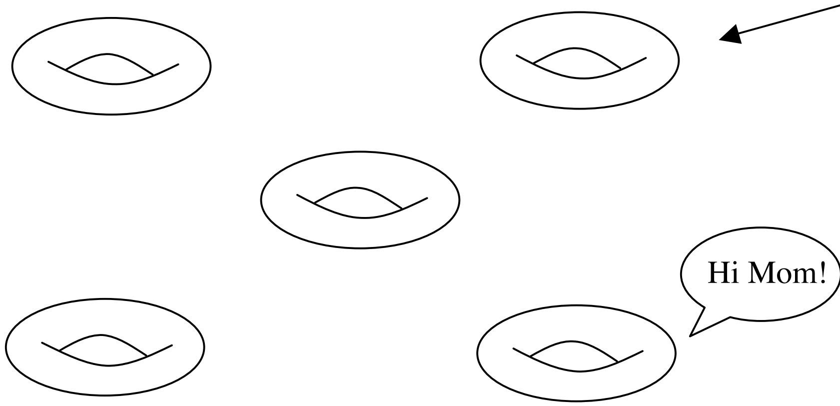
An important example of a space which does is a
Calabi-Yau manifold,

Some Calabi-Yau manifolds:

2d T^2

4d $T^4, \; K3$

6d Lots and lots!



These are **very special** spaces, and have lots of nice properties!

Next time:

Getting the SM out of String Theory!

Where SUSY Comes From!

How can we test it?

and

The Equation of the Universe