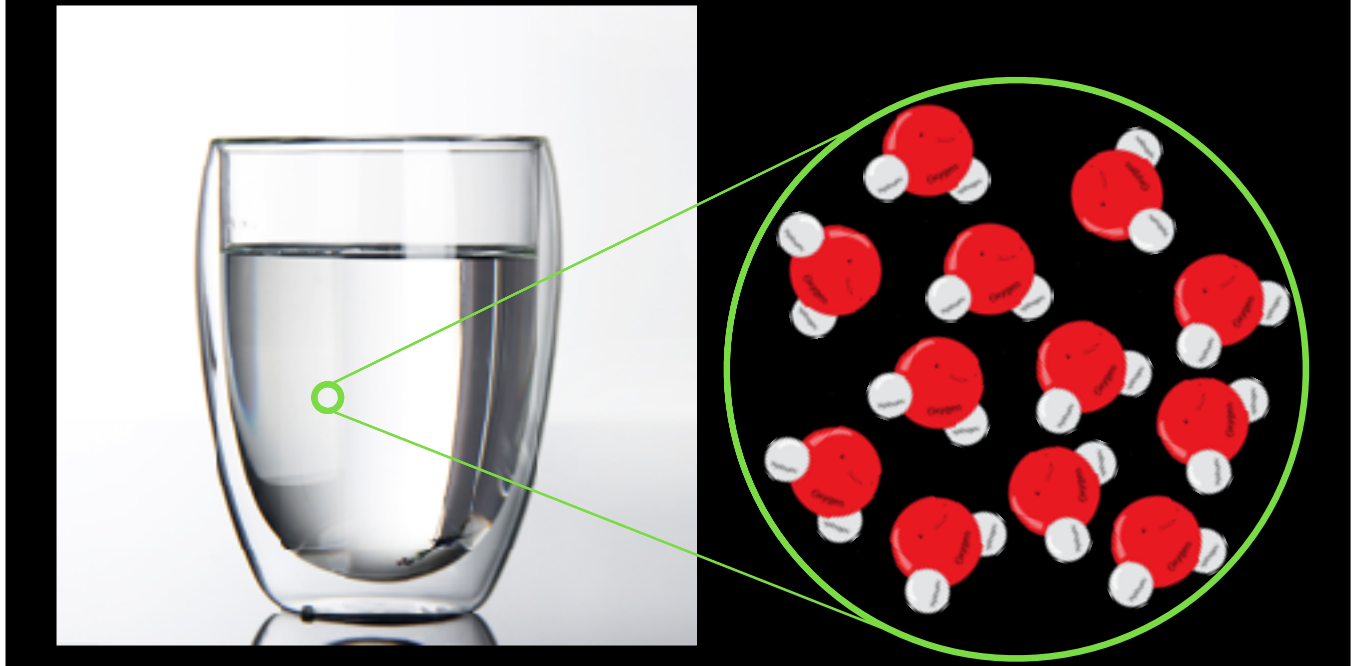
Particle Physics 101

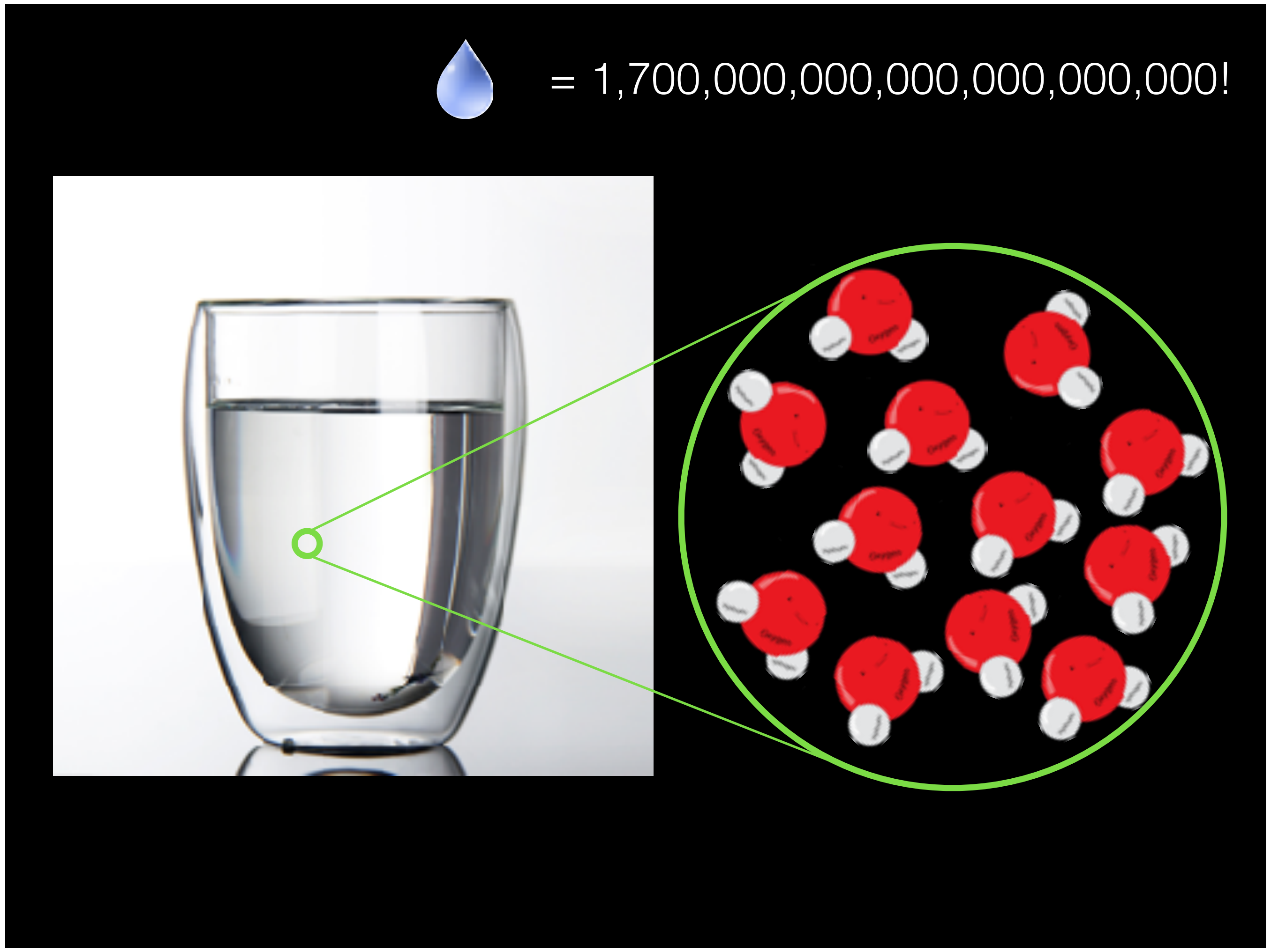
Note: Must bring cup

Before we talk about particle physics, lets look at something a little bit random: a cup of water.

What would we see if we zoomed in on this cup of water?



We’d see that it’s made out of tons of little teeny tiny particles - and like TONS! Each of these little particles is a molecule and its the smallest you can split up the water and still call it water.

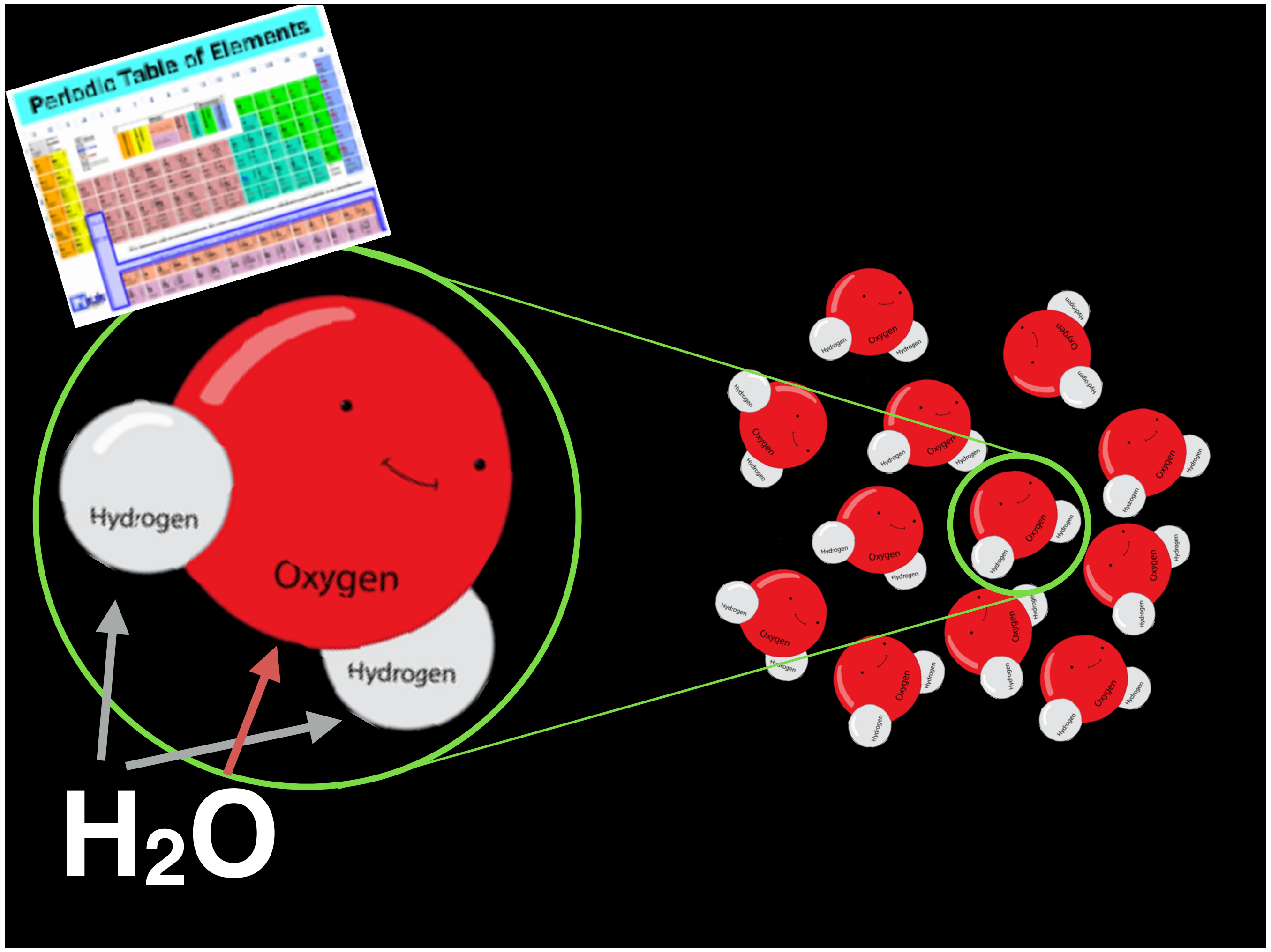


= 1,700,000,000,000,000,000,000!

Remember how I said there’s a lot of these in a glass of water? I meant it. Each drop of that water has 1.7 sextillion of these molecules in it (thats 1.7 trillion billion of them - I want to trade water molecules for dollar bills. Or pennies. Your pick.)

These molecules jiggle around and bounce off each other. We call that motion temperature. If one of them jiggles fast enough (aka gets hot enough) it’ll fly right out of the glass as a particle of water vapor, now as a gas.

So now we have a single water particle. Nice.



H_2O

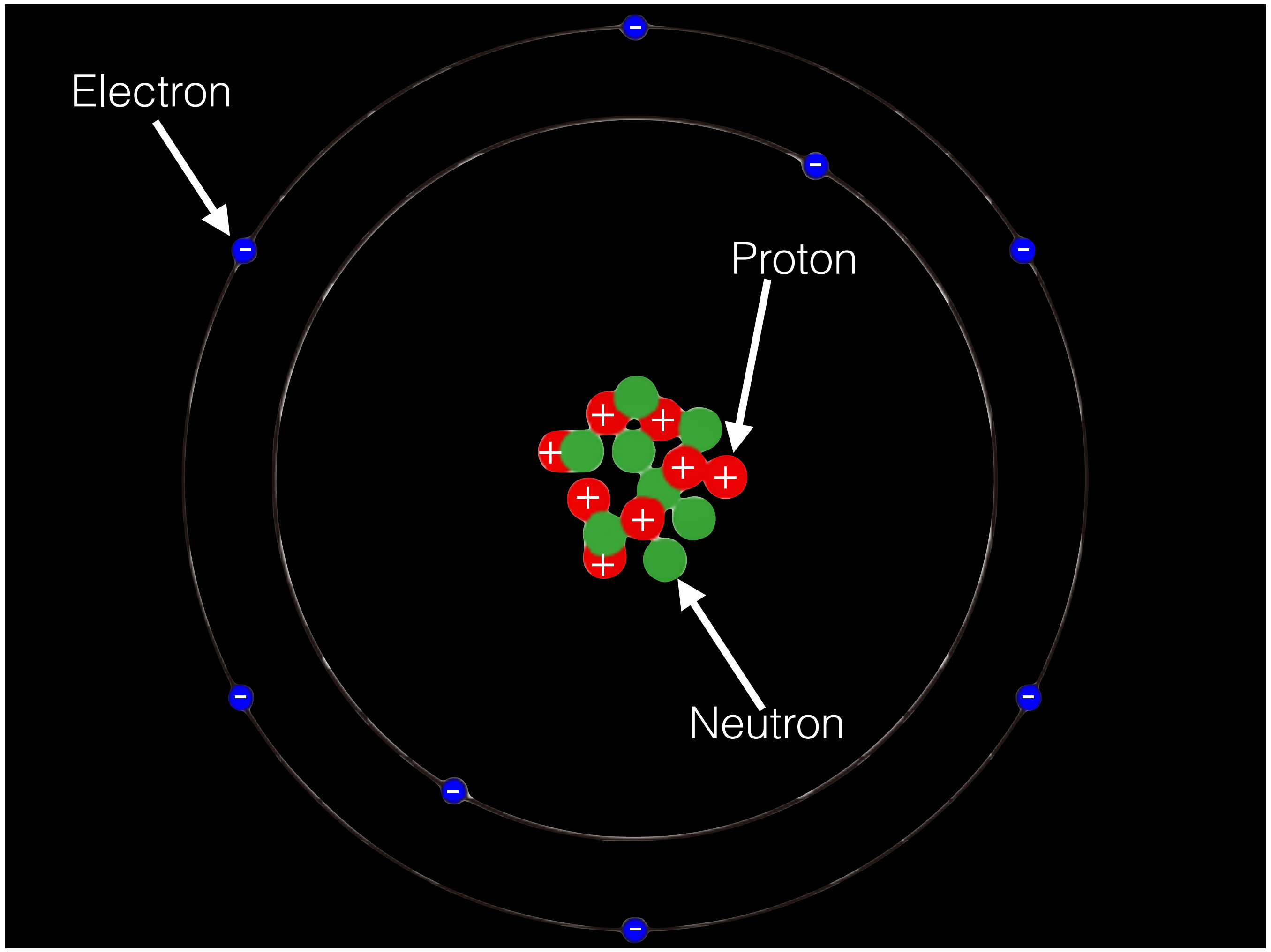
We can keep going and ask what would we see if we zoomed in on one of these water molecules?

We'd see that they're made of even smaller things, called atoms.

Atoms are the fundamental building blocks of everyday matter (Most of the time stuff exists as these molecules, or groups of atoms instead of just single lone atoms. However, there are exceptions and we can certainly get them alone in the lab.) The study of their interactions is called chemistry (you might have heard of the periodic table?).

In the water molecule's case, you can see its made out of one oxygen atom (oxygen makes the stuff we breathe) and two hydrogen atoms. This is why we call it H_2O

Remember how we zoomed in on the molecule to get these atoms? Lets zoom in on the oxygen atom and see what it's made out of.



Bring balloon, magnet & paperclips, hopefully vdg.

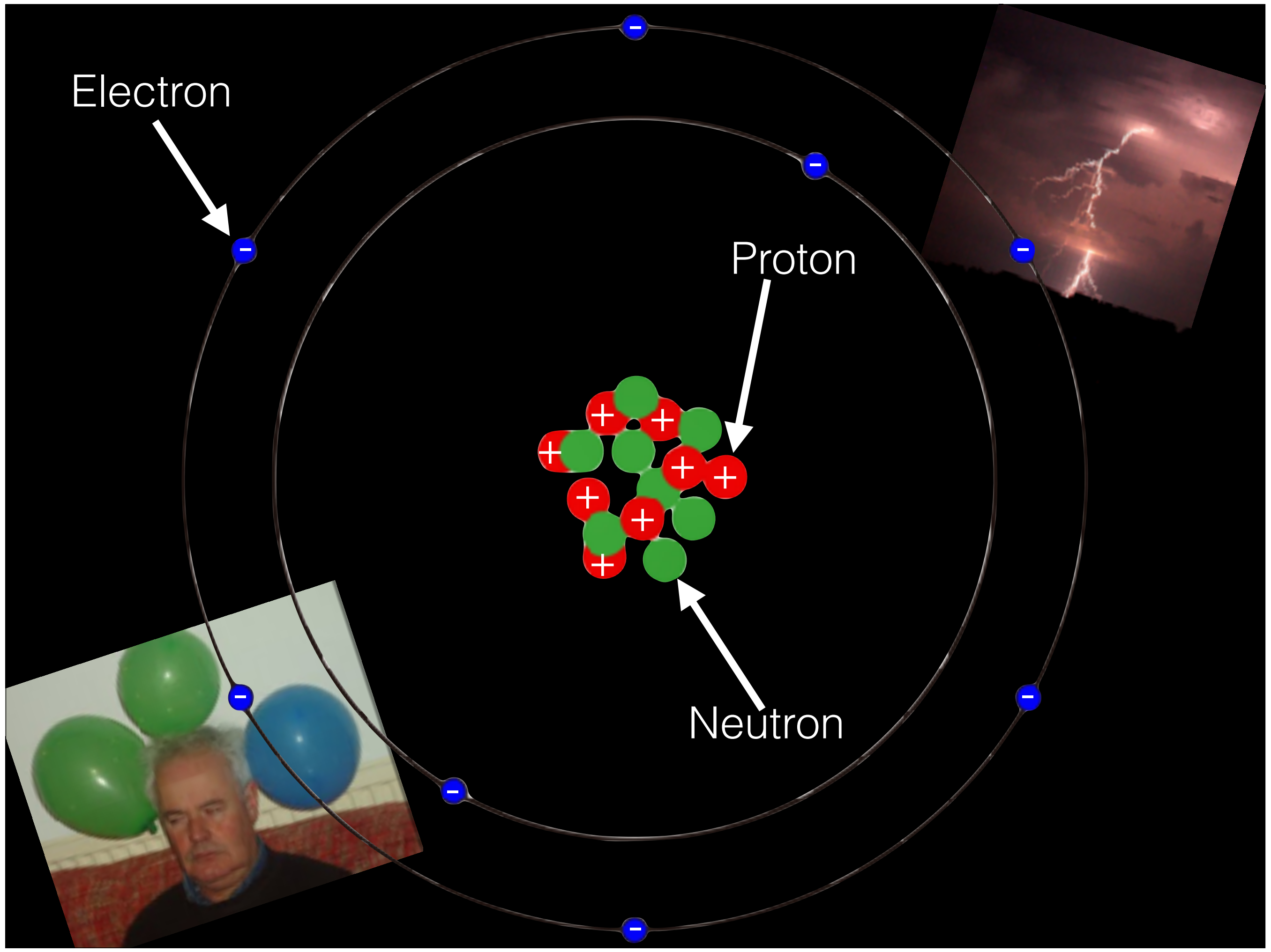
note: email mats for van de graaff generator

Need better oxygen atom graphic. This one has some residual strong force lol. We should bring a van de graaff to demonstrate static electricity. Would help with explaining of EM and therefore forces.

If you go ahead and zoom in, no matter what type of atom you picked to zoom in on, you'd see its made out of three particles - protons (the red particles), neutrons (the green particles) & electrons (the blue particles).

The protons are all in the middle, and each carry a charge of +1. The positively charged protons each attract a negatively charged electron, which carries a charge of -1. These electrons whiz around the nucleus kind of like planets orbiting the sun, but really really quickly.

The neutrons are weird. They don't carry any charge. Think of them as buffers to keep the positively charged protons from repelling each other.



Note: need more visible electrons.

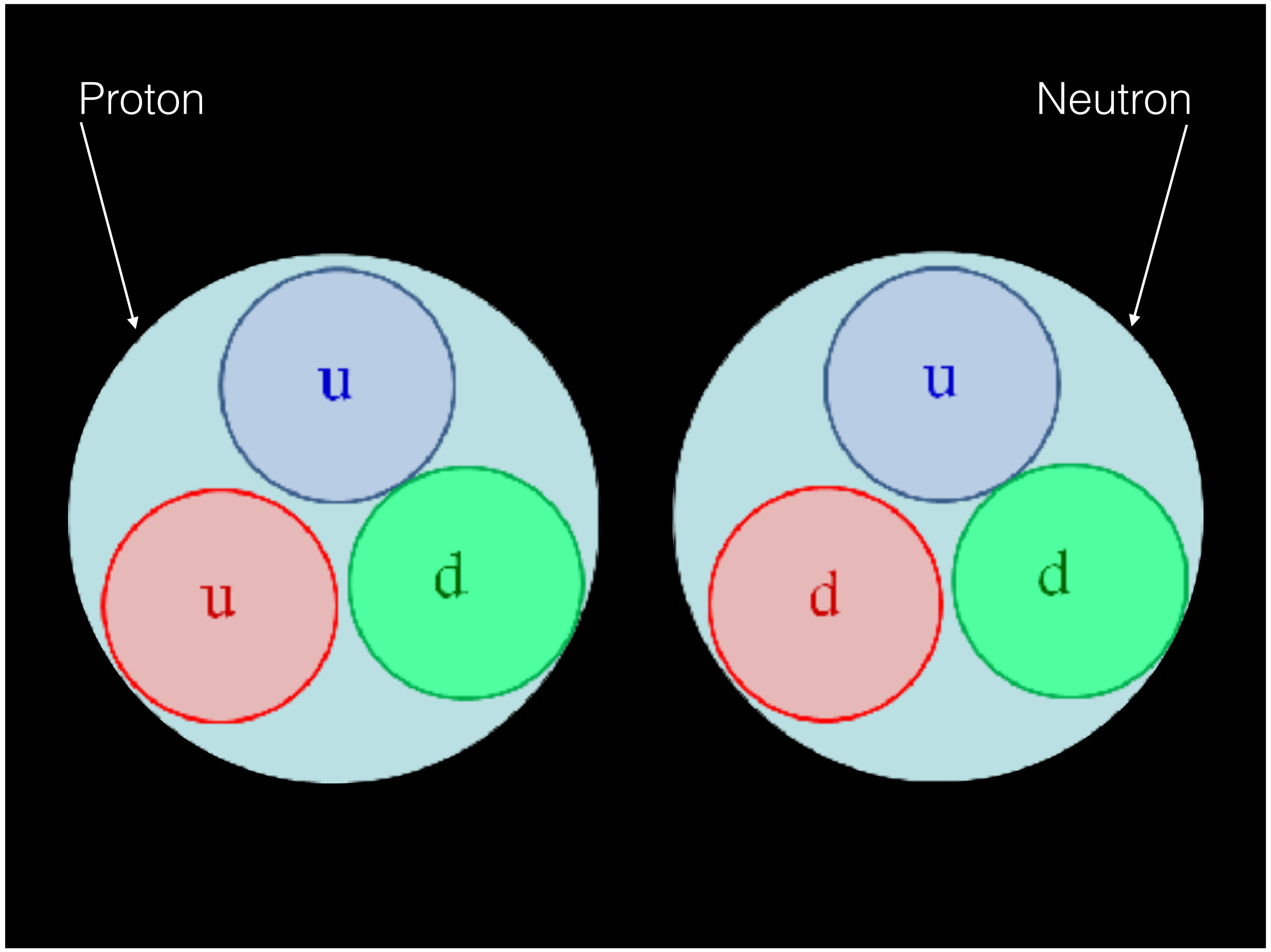
The force that attracts the electrons to the protons is called electromagnetism. If you guessed that thats how electricity and magnets work, you were right. In this case, it is electric charge that attracts the electrons to the protons because opposites attract.

This electric force is responsible for static electricity. If you rub a balloon on your shirt, and then gently place it on the spot you rubbed it it will stay there. The balloon took a few electrons from my shirt, giving the balloon a negative charge and my shirt a positive one. Opposites attract, and the balloon sticks.

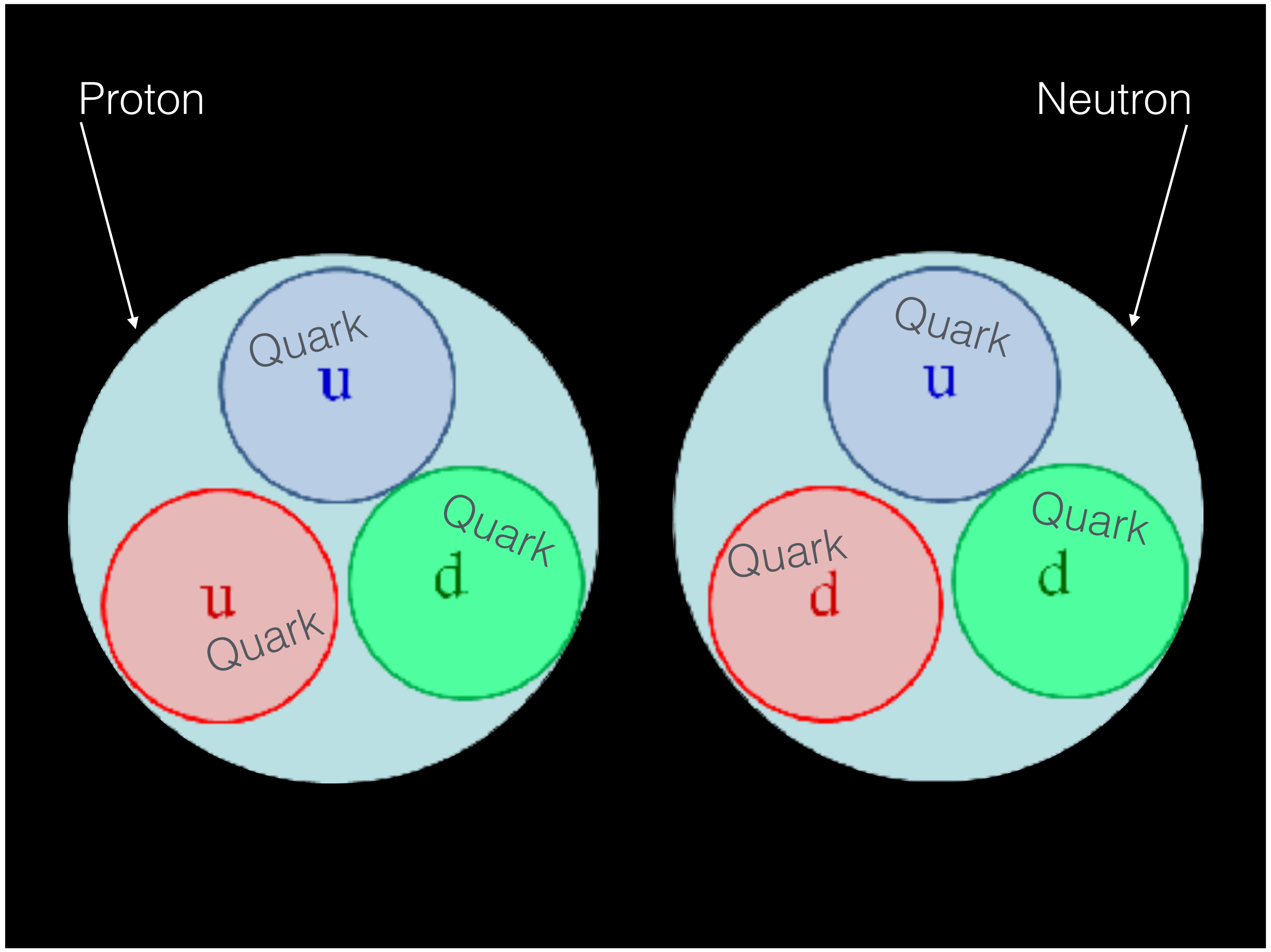
We have a machine that is like a continuous balloon-rubbing-on shirt device. It can collect so many electrons it'll make your hair stand up!

Going back to zooming in on things, as far as we know, there's nothing else to see if you zoom in on an electron. This means that the electron is something we call a *fundamental particle*. These are important in particle physics.

The protons and neutrons, on the other hand, are not fundamental particles. There's more inside if we zoom in on them.



Once you zoom in on the proton and neutron…



Notes: should color charge be included?

…you see that they're made out of the same two types of particles - called Up (labeled with a U) and Down (labeled with a D) quarks. These particles have +2/3 and -1/3 charge (sure is a weird amount of charge…) respectively, which is why the neutron and proton have the charge they do. As far as we know, quarks are like electrons in that they too are fundamental particles.

Remember how the negative charge of the electrons caused them to be attracted to the positive charge of the protons in the middle of the atom by electricity? Something similar holds these quarks together, and its called color charge and the strong force (good name for a band).

This strong force is like electricity, except it's so strong that it's able to keep the protons from repelling each other despite their positive charge.

The strong force works in terms of something called "color charge" like you see in this picture. The red, green, and blue quarks cancel out to make white, allowing a proton and neutron to form.

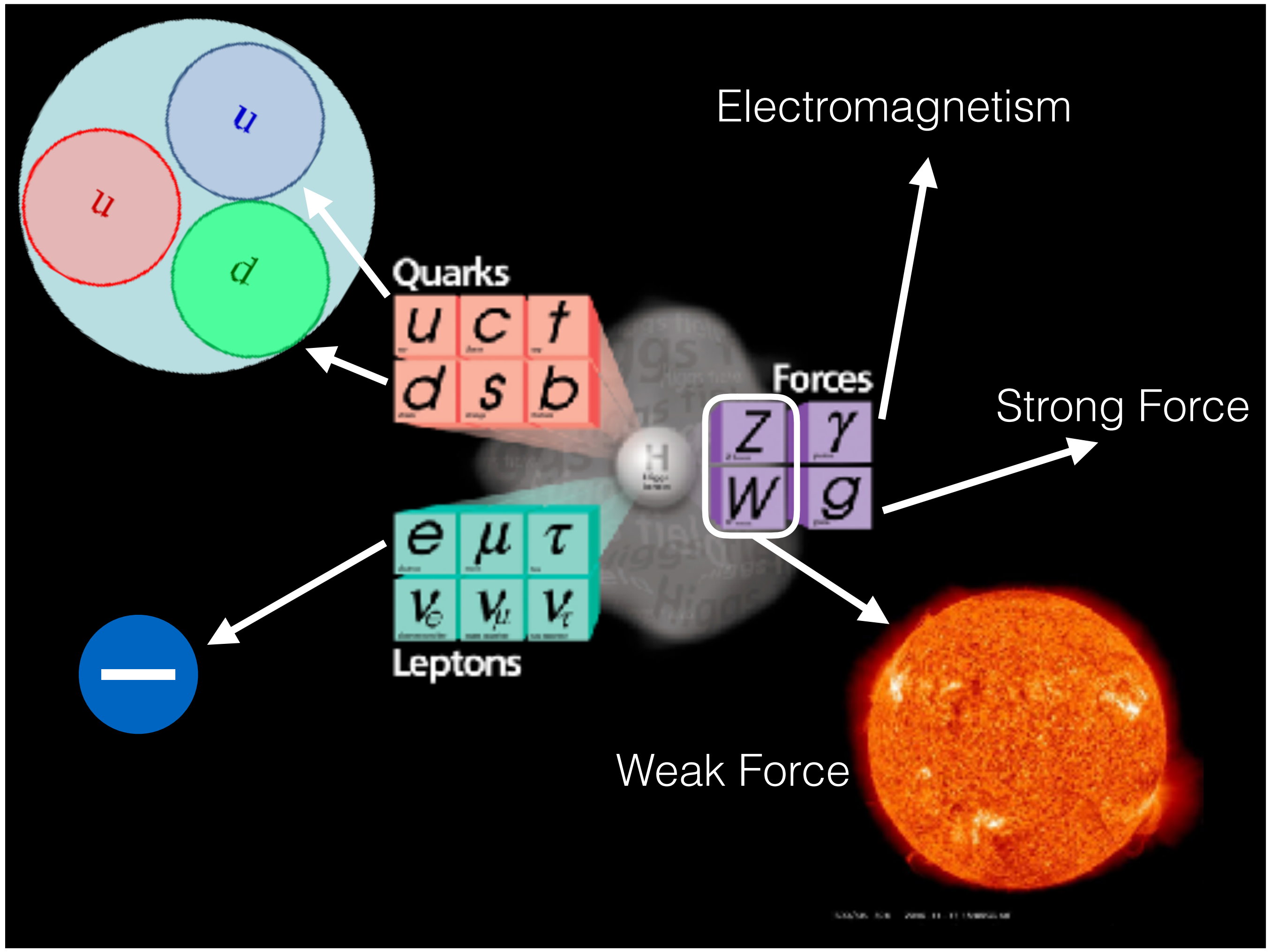
The electrons we talked about before don't have any color charge. They actually don't use the strong force at all.

We're starting to see a pattern, with these fundamental particles (up, down quarks & electron) and interactions (electr(omagnetism), the strong force).

Fundamental particles and interactions. Simple. I like it.

Particle physics is the study
of fundamental particles
and their interactions

We’ve zoomed in enough that now we can stop talking about a cup of water and start talking about particle physics. Particle physics is the study of these fundamental particles, and how they can interact with each other.



Right now, our best way to explain all of this is something called the standard model. The equations that define this model explain everything from how lightning works to what keeps the sun burning to why we're made of atoms.

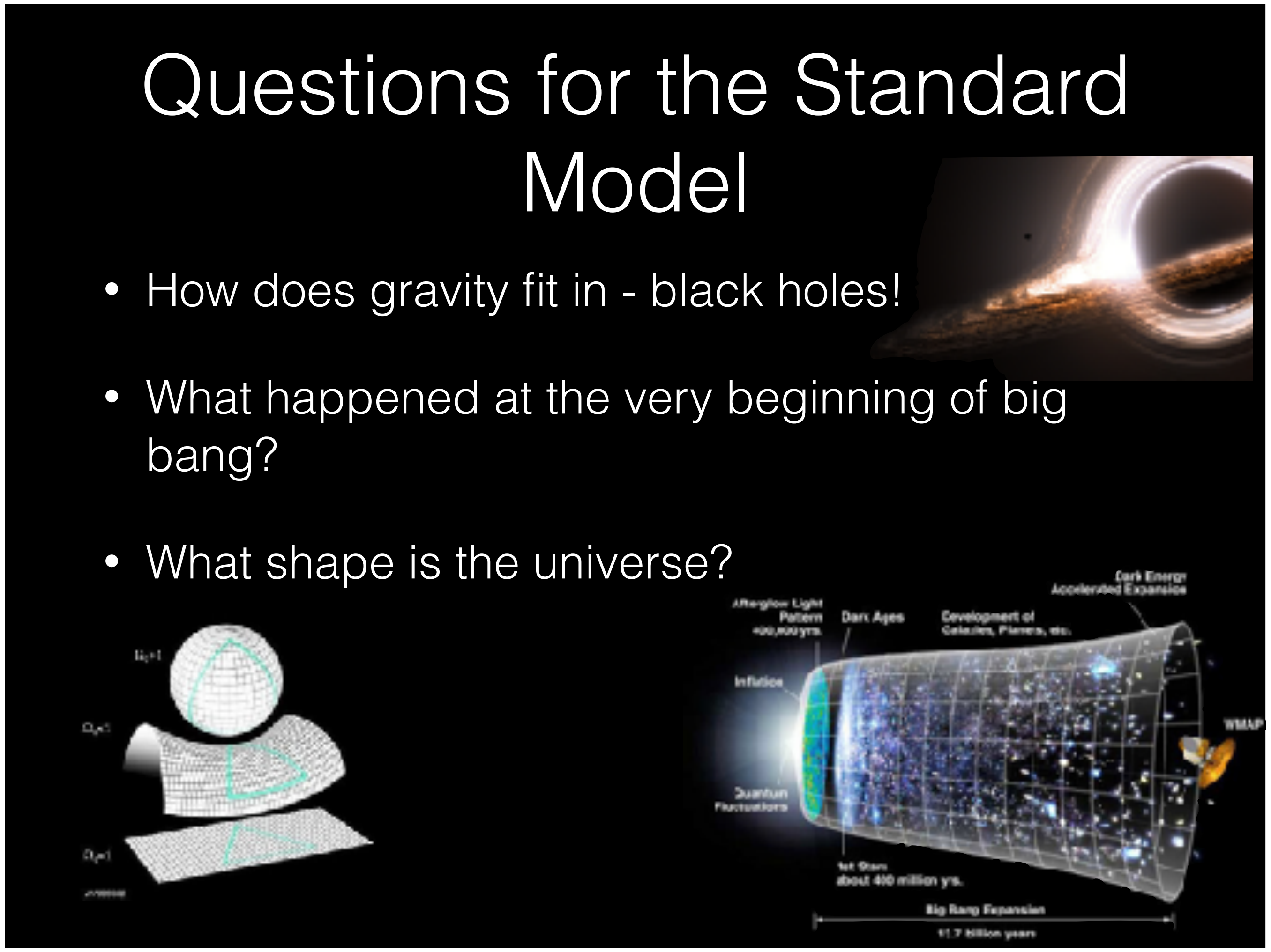
The standard model predicts two groups of six matter particles. These consist of quarks (the up and down quarks are members of this), and leptons. You can think of leptons as heavy electrons.

We only see the electrons and up and down quarks in everyday life because the other particles are too heavy to exist for long periods of time. They rapidly break up into combinations of up and down quarks, electrons, and things called neutrinos, a type of lepton.

Along with the matter particles, it predicts 3 forces. These are the strong and electromagnetic forces we already talked about, along with a third called the weak force. The weak force explains how the sun gets its energy - its not just burning up there!

These forces get particles to carry around the information about the force. For electromagnetism, this particle is called the photon. In the strong force it is the gluon. The weak force is weird and gets two. They're called the W and Z bosons.

While the standard model is a pretty good explanation of the world around us, its still not perfect and we have a few things we're trying to figure out.



Questions for the Standard Model

- How does gravity fit in - black holes!
- What happened at the very beginning of big bang?
- What shape is the universe?

Why does everything have weight?

What is the universe made out of?

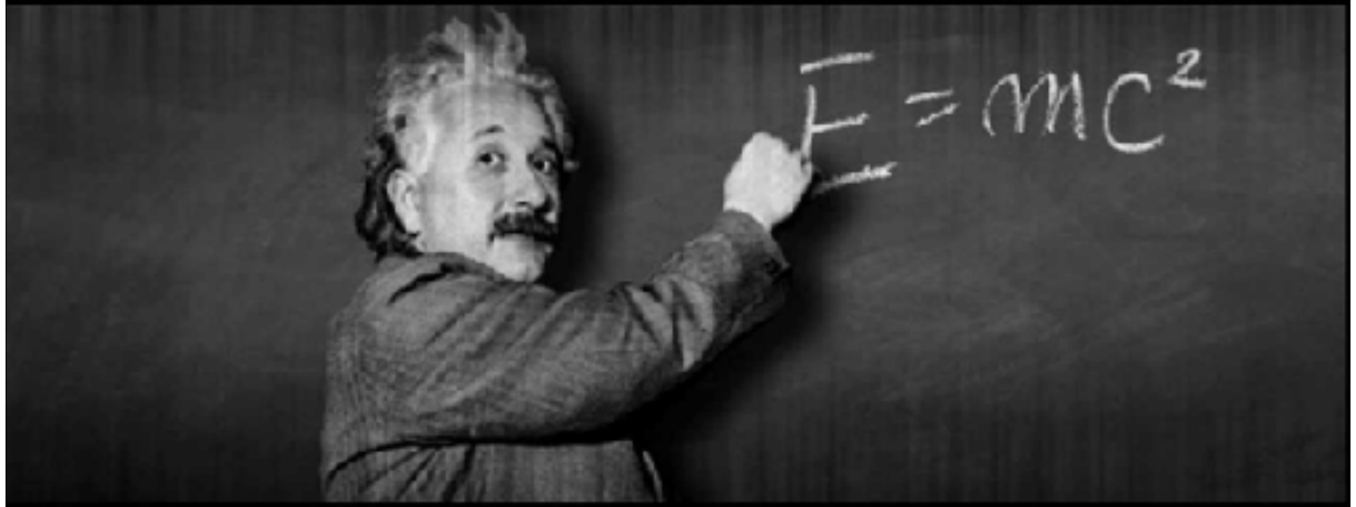
These are some of the things we haven't explained yet with the standard model.

First of all, you might have noticed I haven’t mentioned gravity (probably the most familiar force) ONCE today. That’s because gravity doesn't fit into the standard model as it exists today. We’d like to find a way to get that fixed.

Another big question we’d like to ask is what happened at the very beginning of the big bang? This can tell us a lot about why the universe is the way it is today.

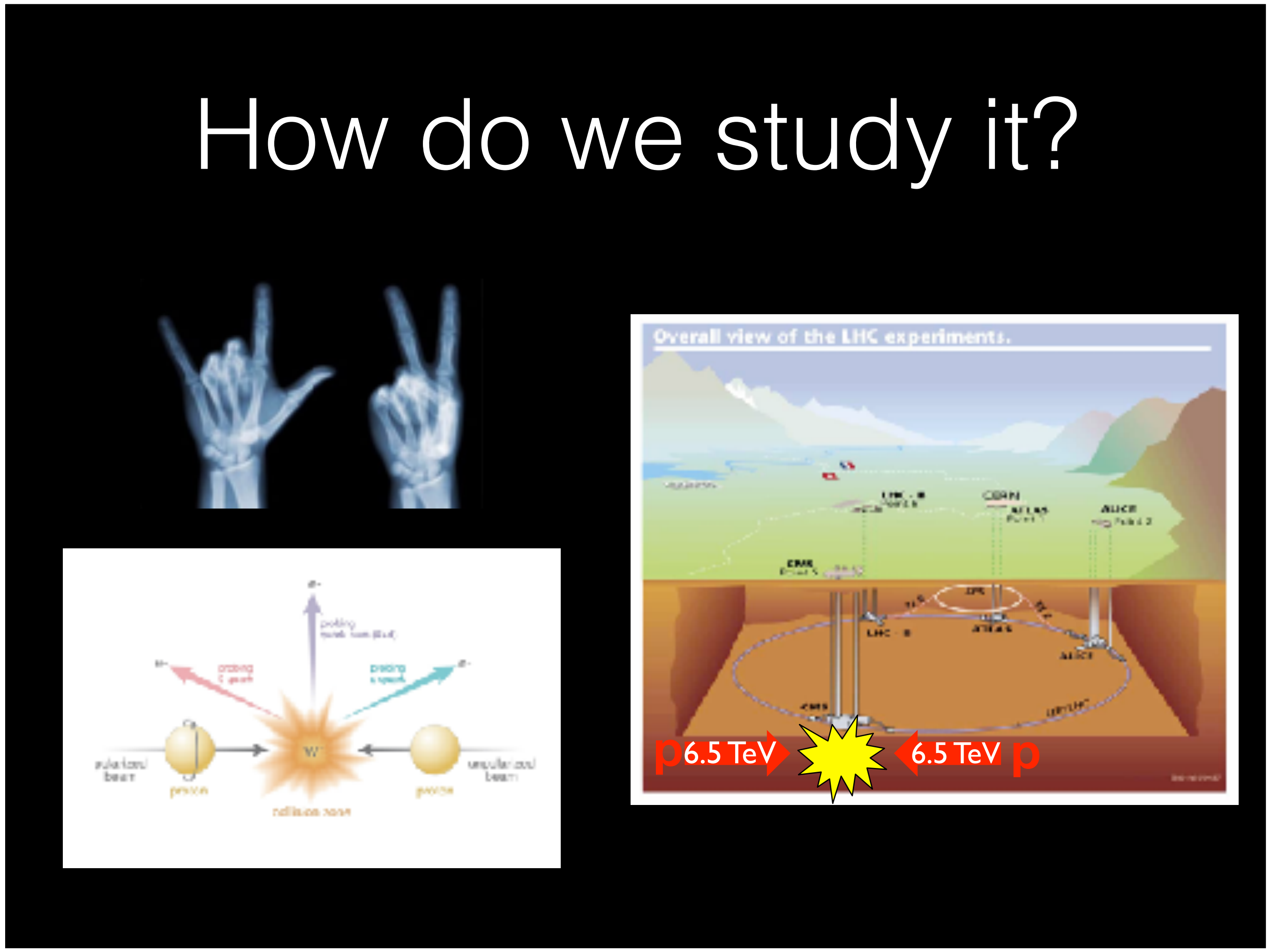
Finally, we’d also like to know the shape of the universe. We want to know if it is sort of closed up on itself like a ball, open like a saddle, or flat.

How do we study it?



Now that we know what we’re looking for, we need to find a way to actually go ahead and make experiments in the lab. It turns out that the most convenient way to do this is an equation you guys have all heard of - E = mc^2. What this equation is saying is that matter (stuff with a mass/weight m) and energy (in our case, kinetic energy) are completely exchangeable, with an exchange rate of the speed of light squared.

This is really handy for us because it means if we can get a lot of energy in the right place we can make some matter pop out and see what it does!



How do we study it?

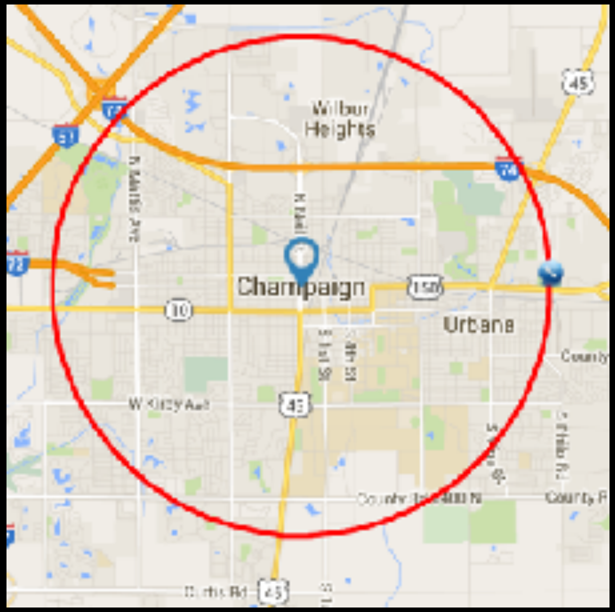
When I said we need a lot of energy, I mean that we need a LOT of energy. The speed of light squared is a really big number, so in order to get even a teeny tiny amount of mass out (like the weight of a fundamental particle) we need a beam with about the energy a 747 needs to take off.

The easiest way of doing this (this is just the easiest way for us. There are actually a number of ways of going about this) is by taking two protons, and putting them on a merry-go-round of death. The proton then gets a “push” every time it goes around until it’s going 99.999…% the speed of light.

The Large Hadron Collider, which is the machine we use to accelerate the protons, is a type of particle accelerator. Particle accelerators are actually pretty common in daily life. They’re used in a lot of medical applications, like X-ray machines.

Those particle accelerators, though, can’t reach anywhere near the energy of the LHC. That’s because of….

How do we study it?



….just how massive the ring for the LHC is.

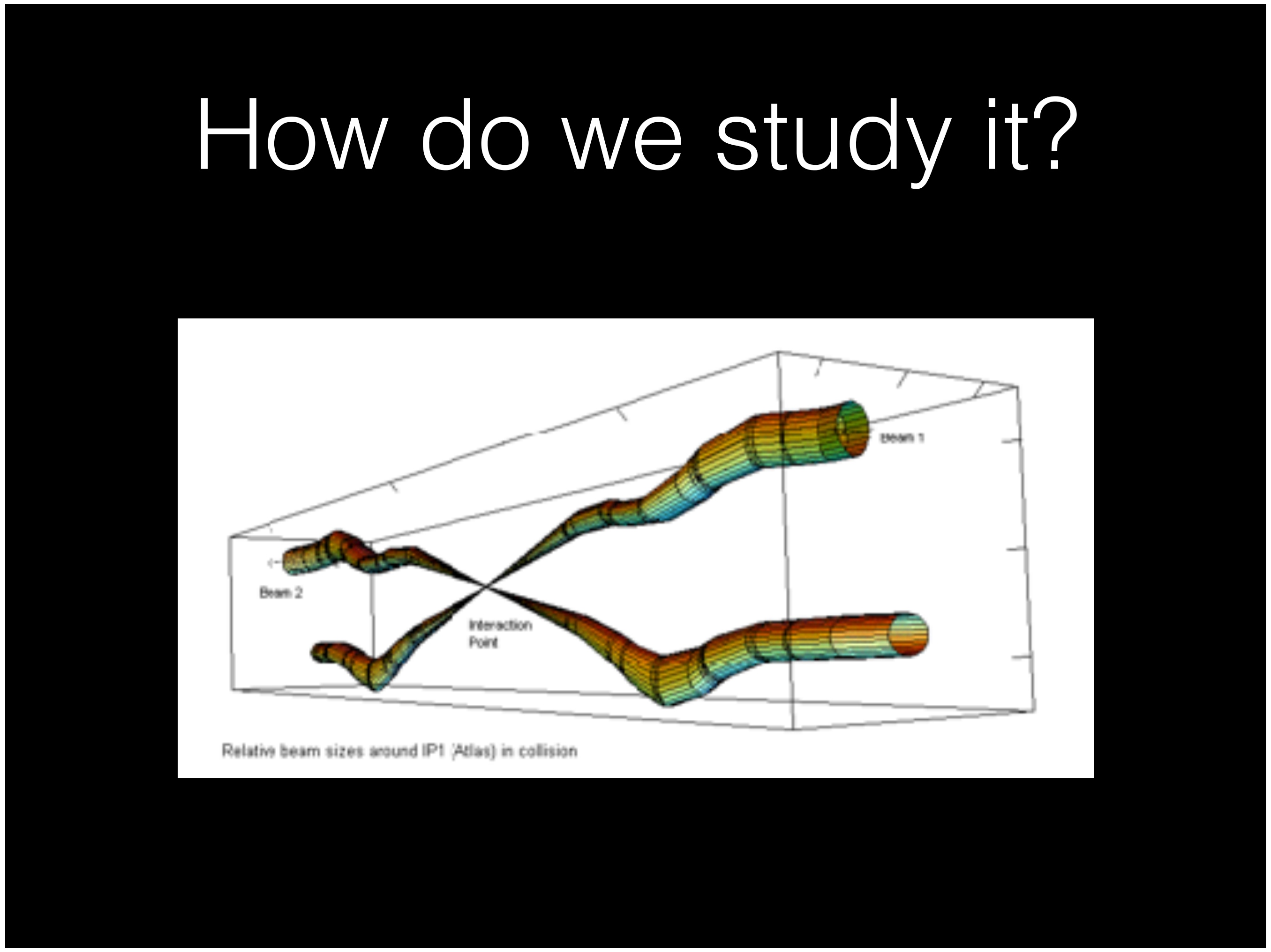
The ring that we call the LHC is in Europe straddling the border between Switzerland and France. It's so big that if it were centered in Champaign, it would easily stretch from the east side of Urbana (~philo rd) to nearly I-57

A bigger ring makes it easier to get the particles going faster. Its kind of like going around a turn on a bike. If a turn is very sharp, you need to slow down before you navigate it. If the turn is smooth and long, you can go around it much more quickly.

It's made out of a small tube ~3 inches across that is put about 300 ft below the surface of the earth. It has powerful magnets that switch on and off millions of times each second to give the protons a kick every lap around the ring. This is probably easier to watch in a video.

How do we study it?

This ring takes two groups of protons and sends them whizzing opposite directions around its 17 mile long ring at 99.999….% the speed of light. At a very specific point on the ring, magnets push the groups of particles so they hit each other. Einstein’s famous E=mc^2 applies here, and the weight of the protons turns into a massive amount of energy. This sends particles flying out that we can detect, and use to figure out what happened in the beginning of the collision.



How do we study it?

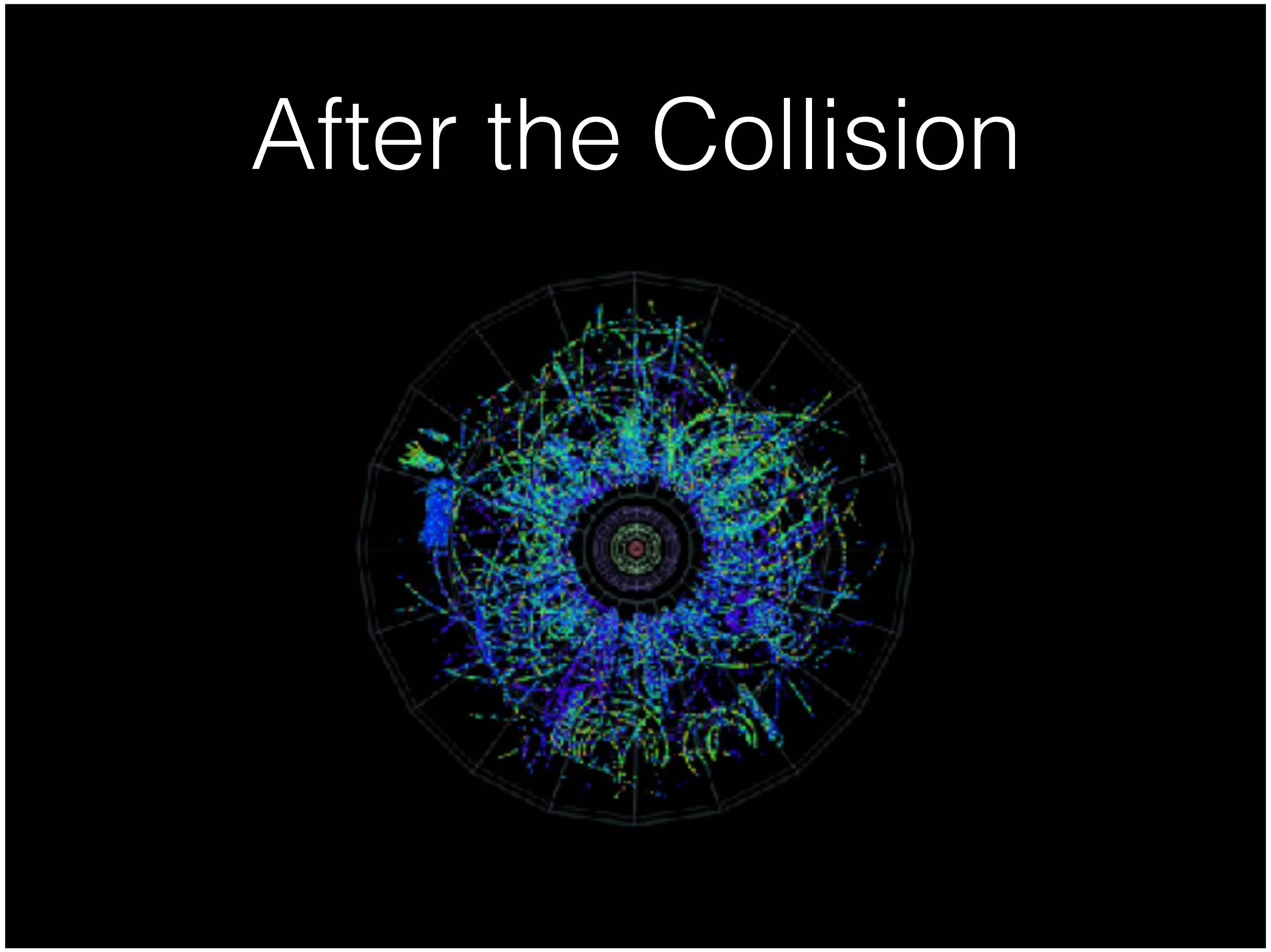
Relative beam sizes around IP1 (Atlas) in collision

Something a lot of people don’t realize or know about the ring is just how many protons are in the beam line at a time and just how fast they’re going.

We don’t just release two protons into the ring at a time because protons are REALLY small and we would almost never get a collision. Instead, we make these things called “bunches” which each have ~100 billion protons. There’s about 2800 (2808 to be exact) bunches in the ring at any given time.

Each bunch is also moving really quickly. It goes around the ring ~11,000 times a second.

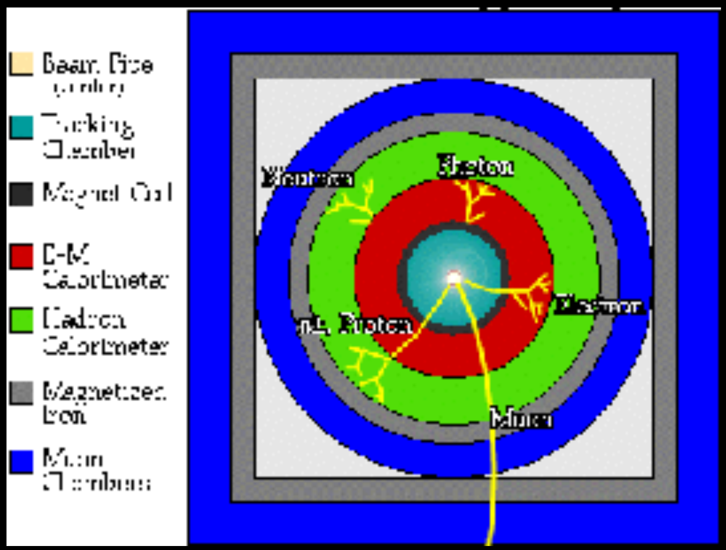
This means each second we can get upward of 600 MILLION collisions - thats a LOT of data to process.



After the Collision

Thankfully, though, the vast majority of the collisions are not interesting to us and we can throw them out.

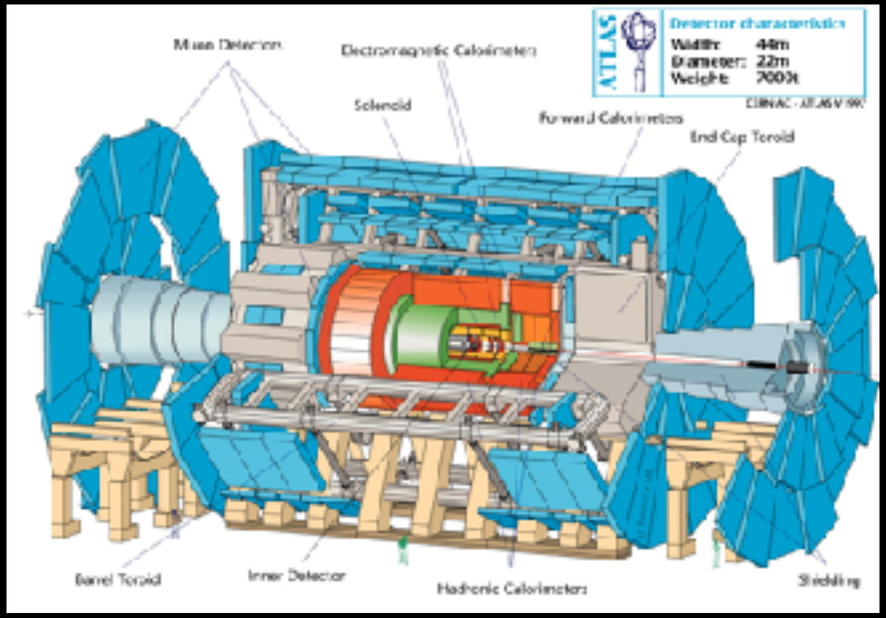
After the Collision



Once we've gone and looked at the collisions and figured out which ones might be interesting and which ones are not based on what came out, it becomes a matter of determining what exactly happened in the collision. To do this, we use a detector (this picture is an example of a generic one) made up of a bunch of layers rolled up like a burrito.

The innermost layer can actually track the locations of particles, and the outer layers tell us how much energy different particles were carrying.

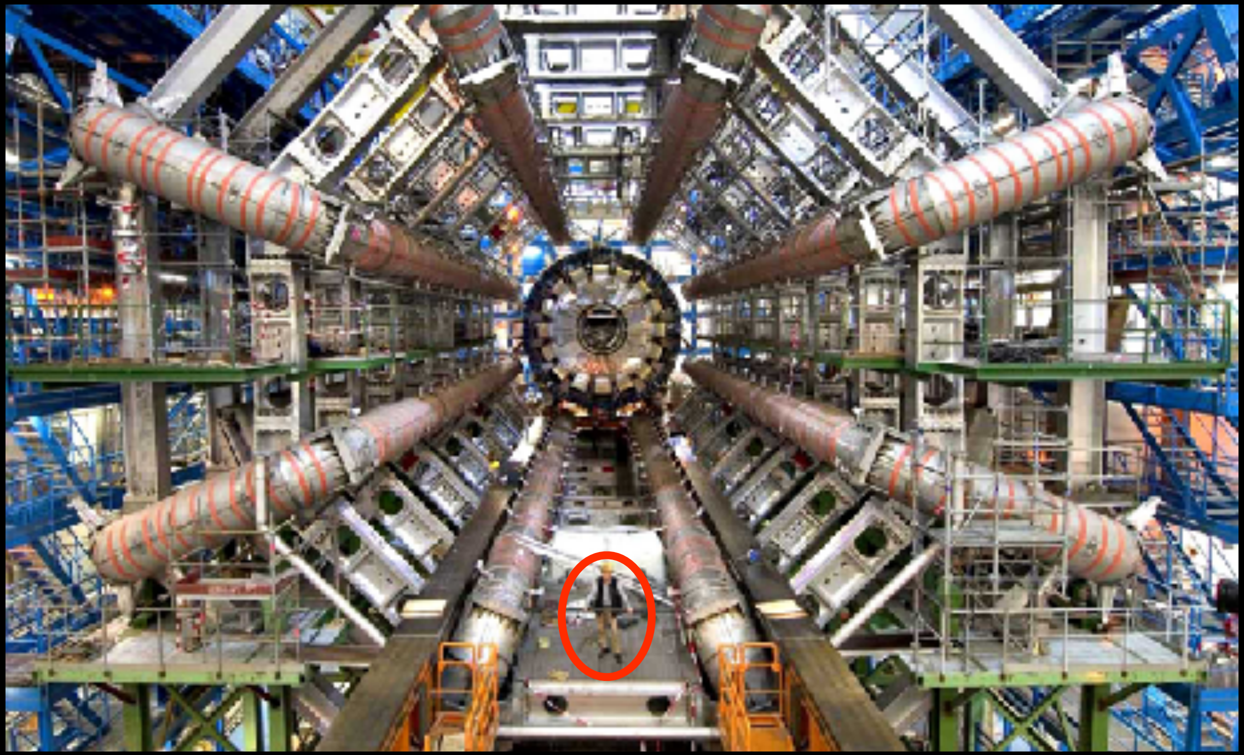
The whole detector is also inside of a really big magnet. Magnets have a weird effect on charged particles where it makes them curve. This helps us figure out what happened.



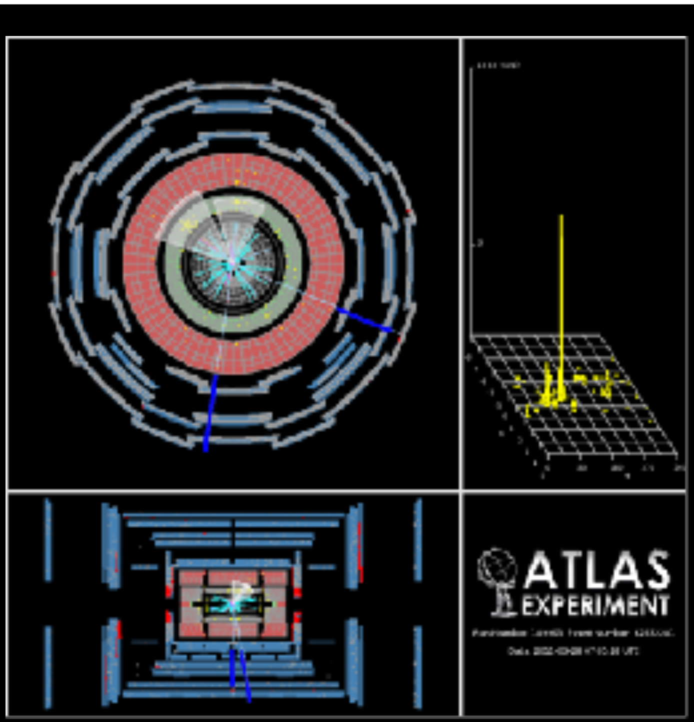
The detector

This is a diagram of the actual detector used at the LHC. You can see it still has that “rolled up burrito” structure.

Something a lot of people don't notice is just how big this thing is.



When I said it was big, I meant REALLY big. Take this picture for scale. That’s a guy.



The data

The detector tells us a lot, and when we think an event is interesting it ends up getting plotted like this.

Each part of this picture is a different view of the collider. The top left is straight on (from the beams perspective) and the bottom one is a top down view. The third image that looks like a grid is what you'd get if you took the green layer and "unrolled" it and laid it out flat. That plot is arguably the best way to tell which way the energy "went" after the collision.

Using these directions, and the fact that momentum is conserved in a collision, is what allows us to see if we've created something new.