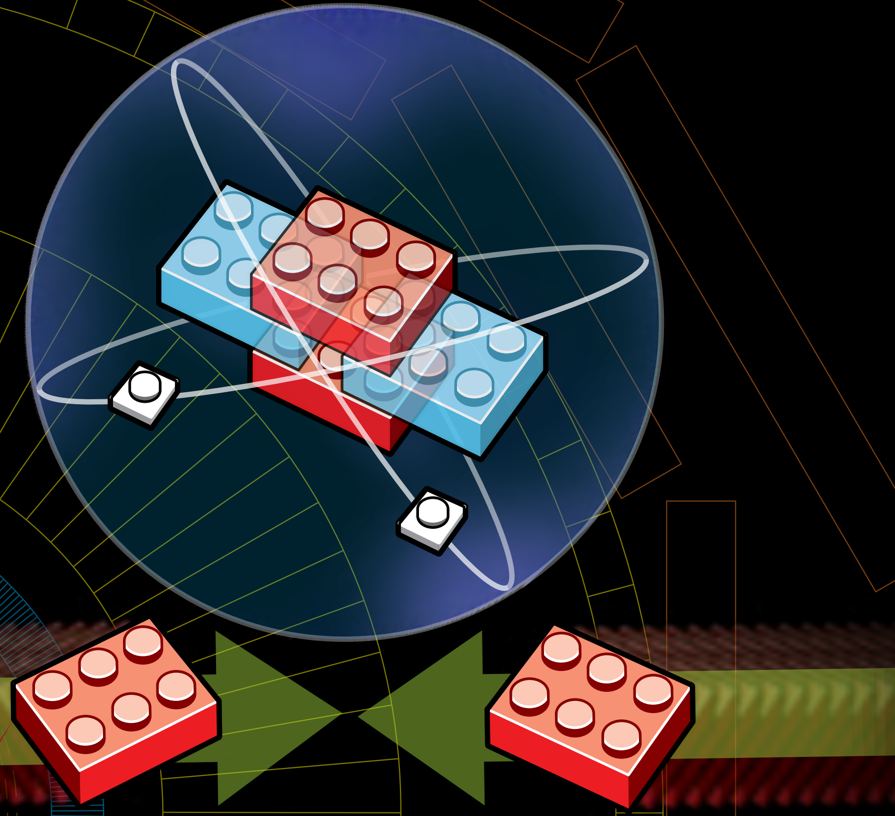
THE LITTLE BOOK OF LITTLE BIG BANGS



THIS BOOK BELONGS TO:

UKRI Science and Technology Facilities Council

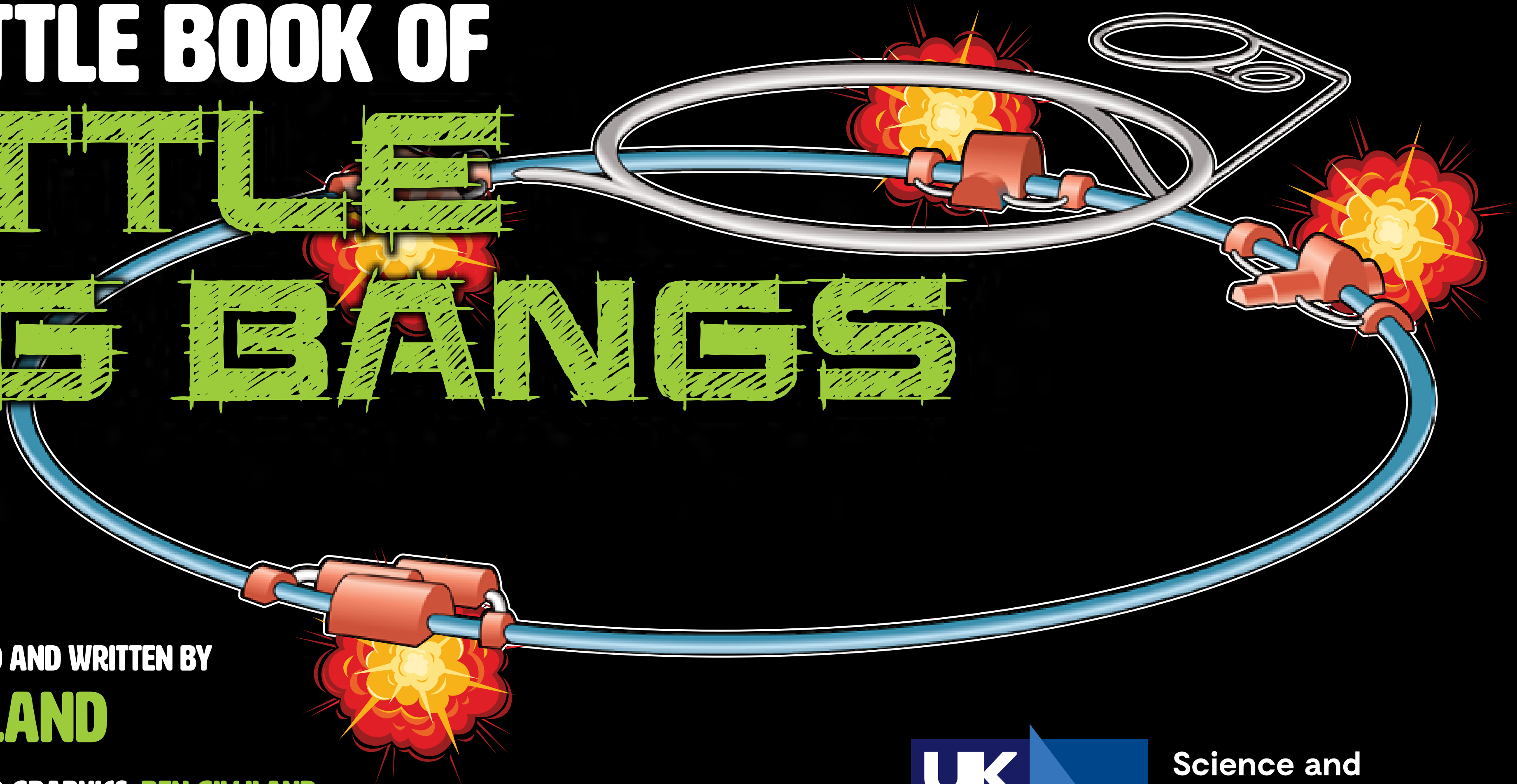
What are the types of particle accelerator and how do they work?

What are particles? How do they fit together?

What can smashing particles together tell us about the Universe?

You'll find all this out (and lots more) in...

THE LITTLE BOOK OF LITTLE BIG BANGS



CONTENT DEVELOPED AND WRITTEN BY

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OTHER IMAGES: CERN

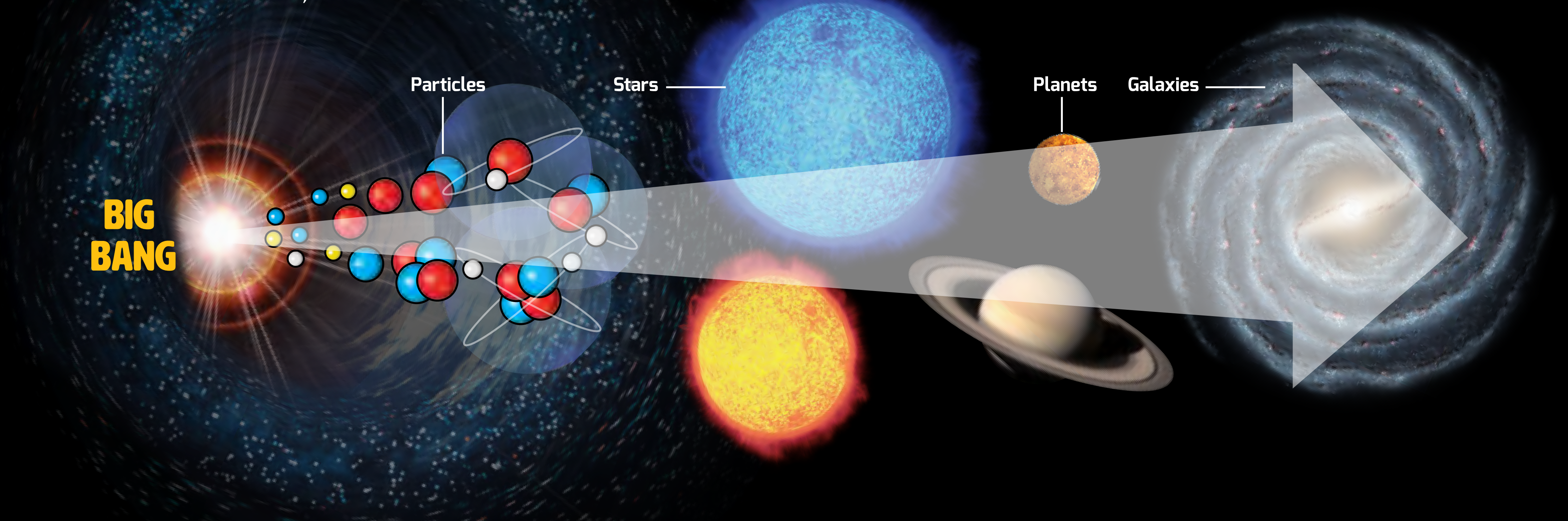
UKRI Science and Technology Facilities Council

LITTLE BOOK OF LITTLE BIG BANGS

WHAT WAS THE BIG BANG?

Long before there was a you and me or a planet called Earth, there was nothing at all – no stars, planets, galaxies or even a thing called a universe. The Universe began life as a tiny speck of energy that, 13.8 billion years ago, suddenly expanded in the '**Big Bang**' and stretched to become the Universe we know today.

At first the Universe was just a tiny ball of super-hot energy but, as it expanded and cooled, atoms and particles formed and these became clouds of gas that became the stars and planets and galaxies that make up the Universe.



SO WHAT'S A 'LITTLE' BIG BANG?

Because we can't travel back in time to watch it happen, the best way to understand the Big Bang is to recreate it in the laboratory. Obvious creating an actual Big Bang would be too dangerous, but we can create 'little' Big Bang by smashing together atoms in giant machines called particle accelerators.

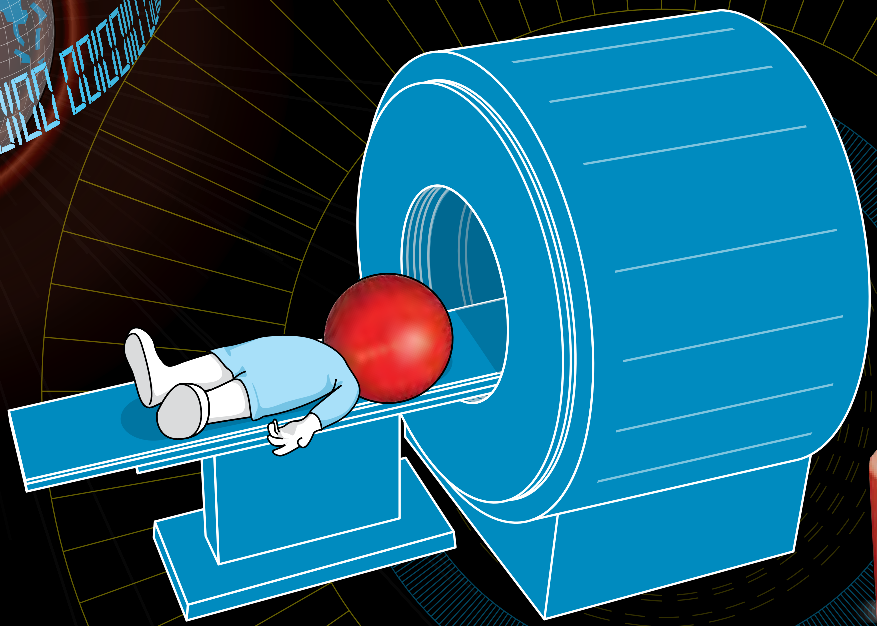
As well as teaching us about the Big Bang, little Big Bangs can teach us about what atoms are made of, help us find new particles and even help us understand how the universe works.

LITTLE BOOK OF LITTLE BIG BANGS

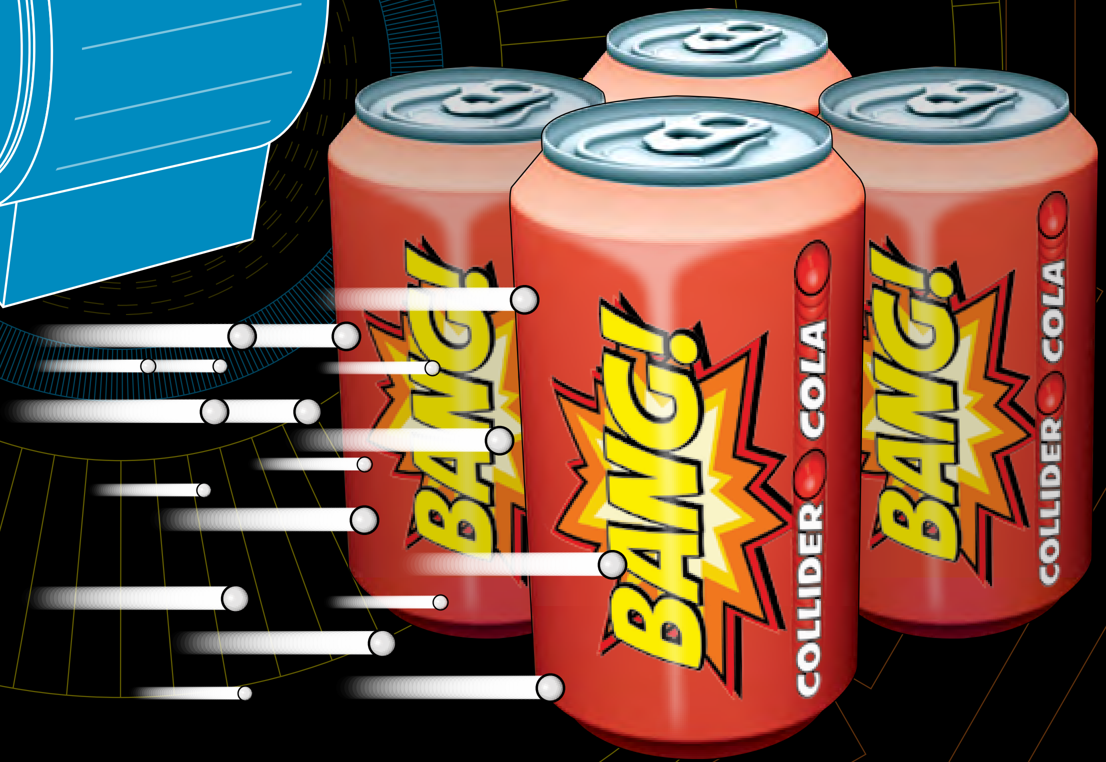
DID YOU KNOW?

The **World Wide Web** was invented by physicists at CERN.

Detector technology developed for particle accelerators is used in **medical imaging** for diagnosing illnesses and accelerators are used for **treating illnesses** such as cancer.



Particle accelerators can be used as super-powerful **X-ray microscopes** and they can also used for drying the ink on **soft drinks cans**.



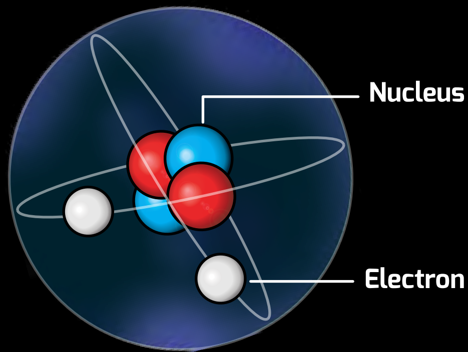
LITTLE BOOK OF LITTLE BIG BANGS

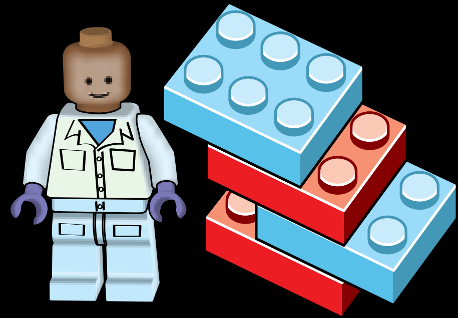
1 WHAT ARE PARTICLES?

Everything in the universe that is made of matter (stuff like you, me and a table) is made up of atoms and particles (we'll come to things that aren't made of matter later). These building blocks of matter are called the 'elementary particles'.

THE ATOM

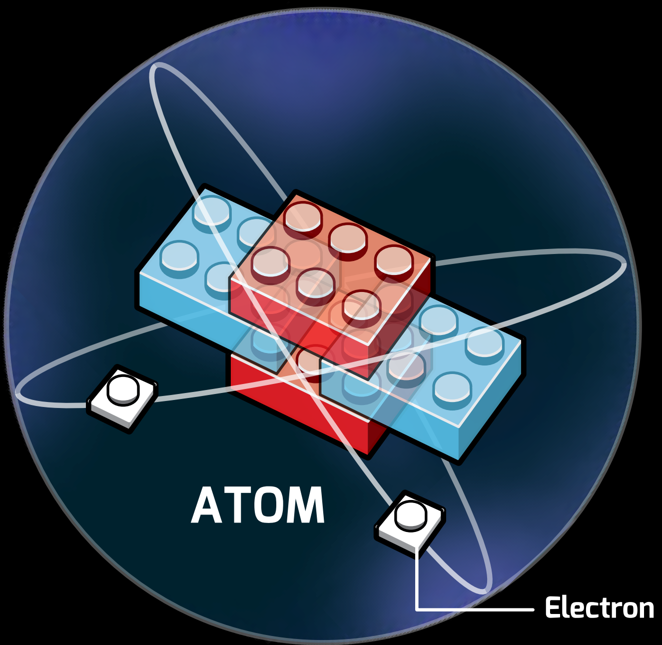
Atoms are made up of a nucleus surrounded by negatively-charged electrons. The nucleus is made up of positively-charged particles called protons and neutral particles called neutrons.





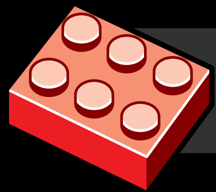
The set of rules that helps explain how the fundamental particles work is called the 'Standard Model' of particles physics.

It can seem quite complicated so let's turn these particles into building blocks we are little more familiar with...

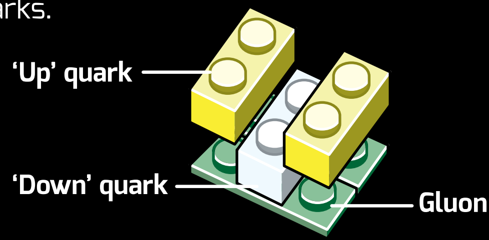


Electrons are elementary particles (the teeniest, tiniest anything can be) and so aren't made of anything smaller, but protons and neutrons are made of elementary particles called quarks.

Proton

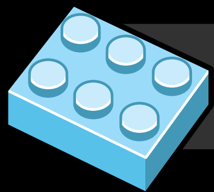


Protons are made of two **'up' quarks** and one **'down' quark**

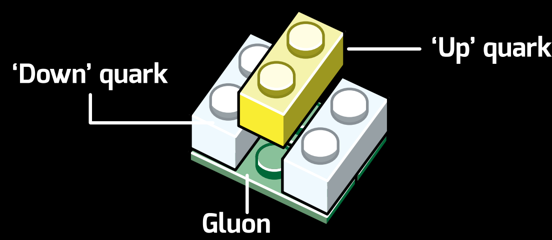


The quarks are held together by gluons, which are force-carrier particles (bosons).

Neutron



Neutrons are made of two **'down' quarks** and one **'up' quark**

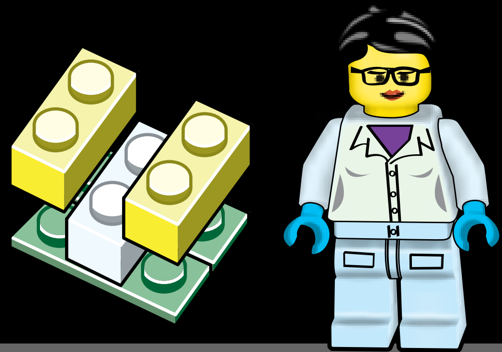


1.1 MEET THE PARTICLE BUILDING BLOCKS

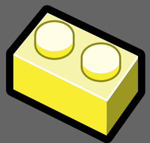
The Standard Model of particle physics is currently our best understanding of how our Universe is built. It describes how the elementary particles (which are also known as the fundamental particles) and the fundamental forces interact.

THE ELEMENTARY PARTICLES

Elementary particles come in two families – quarks and leptons. All matter is made up of a combination of two quarks ('up' and 'down') and the lepton called the electron.

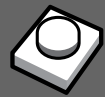


Quarks



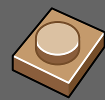
- All of the matter in the universe is made of a combination of 'up' and 'down' quarks.
- All particles composed of quarks are called hadrons (Greek for heavy)
- Protons and neutrons are also known as baryons.
- Quarks come in six 'flavours", which have different properties and masses.

Leptons



Electron

The most familiar lepton is the **electron.** There are also two 'heavy' leptons called the **muon** and **tau.**

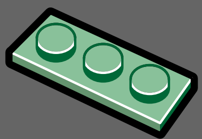


Neutrino

Another lepton is the **neutrino** – a ghostly, almost massless particle that hardly interacts with matter

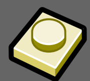
Bosons (force carriers)

Bosons tell other particles how to interact with the fundamental forces (the 'strong' force. 'weak' force, electromagnetism, and gravity).



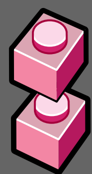
Gluon

This carries the 'strong' force and is responsible for holding quarks together to form protons and neutrons.



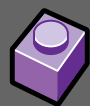
Photon

This tiny package of energy carries the electromagnetic force, which affects any fundamental particle that carries a charge.



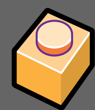
W & Z bosons

These mediate the 'weak' nuclear force, which is responsible for radioactive decay.



Higgs boson

The particle representative of the Higgs Field, which gives mass to quarks and leptons.



Graviton

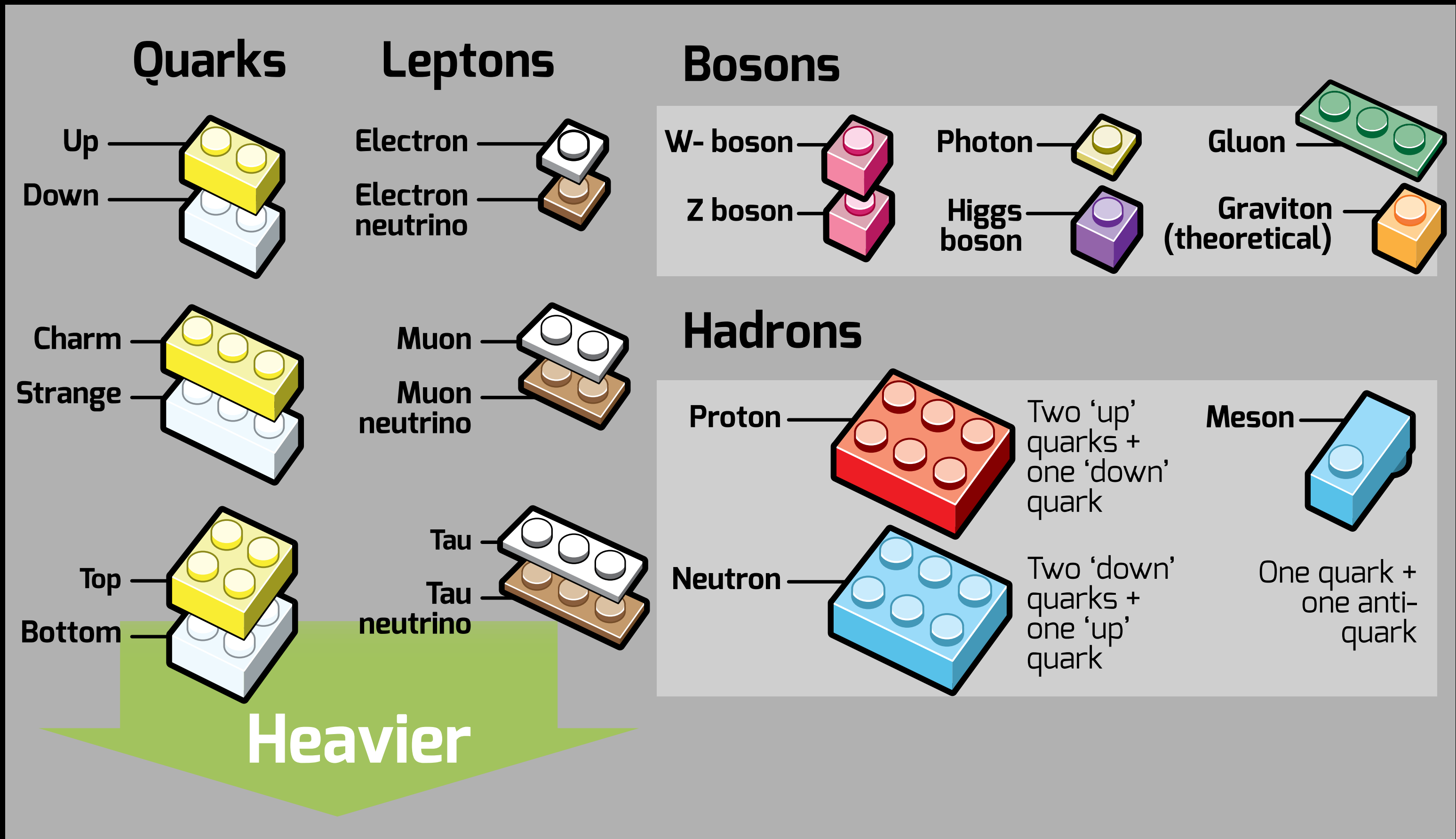
A theoretical particle that (if it exists) is responsible for carrying the gravitational force.

1.2 MEET THE PARTICLE BUILDING BLOCKS

Most of the Universe you can see and touch is made up of matter. These particles of matter made up of quarks, which we saw on the previous page, are called **hadrons**. Then there are the force carriers, which are called **bosons**. And there are the **leptons**, which we have already met as an electron.

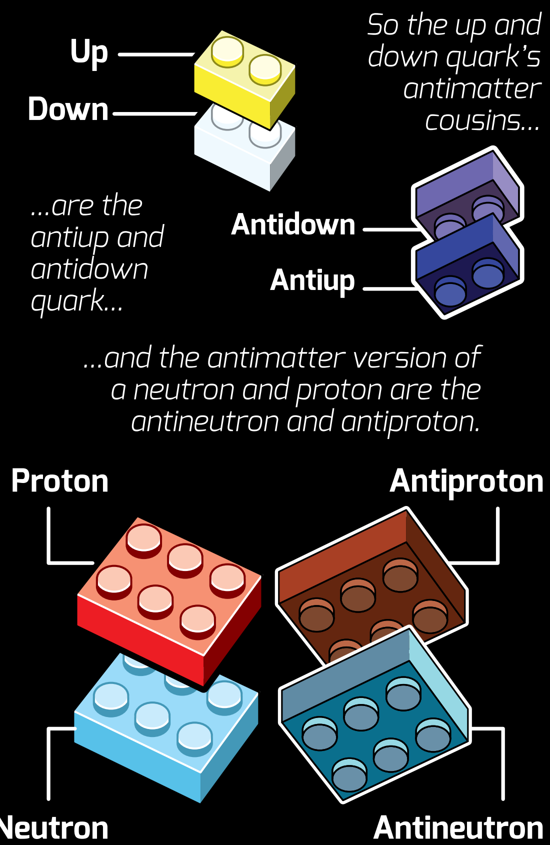
MATTER

Quarks and leptons also have heavier relatives with strange names like muon, charm, bottom, tau and... well, strange! These heavy relatives are more unstable than their everyday cousins and they quickly decay and become normal quarks.



ANTIMATTER

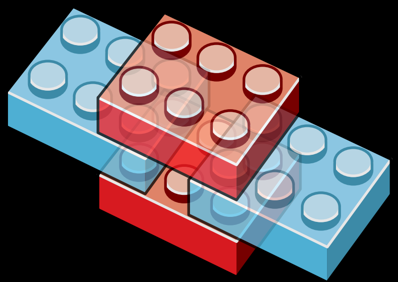
Each Standard Model particle has an antimatter equivalent in which the particle's properties are reversed (charge and spin)– a positive charge becomes negative; a negative becomes positive; a neutral particle remains neutral but other properties are reversed.



1.3 THE FUNDAMENTAL FORCES

The fundamental forces are the set of rules that tells the matter in the Universe how to behave and interact. Each force has a 'force carrier' particle – these are like tiny packets of energy that particles how to play by the fundamental force's rules.

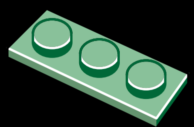
STRONG NUCLEAR FORCE



This binds matter together. It can't reach very far but is strong enough to bind together protons within an atom (and other particle building blocks) even though their mutual positive charge wants to force them apart.

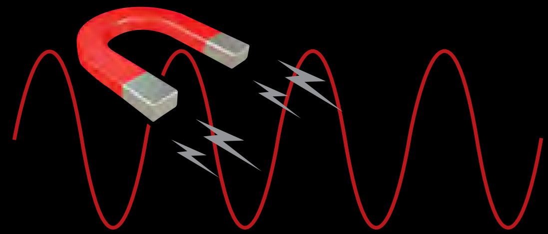
Force carrier:

Gluon



The strong nuclear force has the gluon, which has no mass and no charge.

ELECTROMAGNETIC FORCE



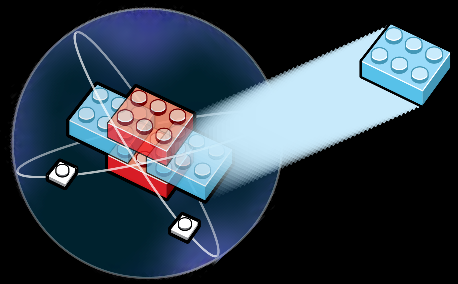
This affects any fundamental particle that carries a charge. Electromagnetism is perhaps the most familiar force as it rules everything from magnetism to the light we see and the radio waves we communicate with.

Force carrier:

Photon

The electromagnetic force has the photon – a massless, chargeless particle also known as a particle of 'light'.

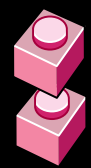
WEAK NUCLEAR FORCE



This is the force responsible for radioactive decay. It allows an atom to change by taking on or losing particles.

Force carrier:

W & Z bosons



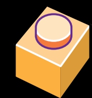
The weak nuclear force has two force carriers called the 'w' boson, which is positively charged *(there is also a 'w-' boson, which is negatively charged)* and the 'z' boson, which has no charge.

GRAVITY

Gravity is the force that allows the planets to orbit the Sun and that makes a stone fall when you drop it. It has a powerful effect on matter on the largest scales (planets, stars etc) but has almost no influence on matter as small as particles.

Force carrier:

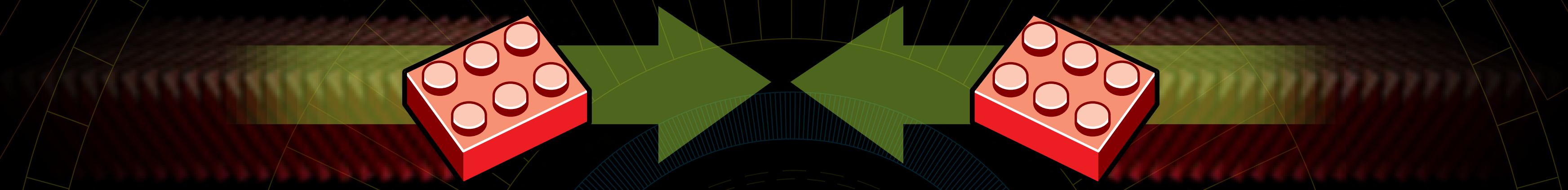
Graviton?



Gravity's force carrier is thought to be a massless and chargeless particle called a graviton, but we haven't found it yet.

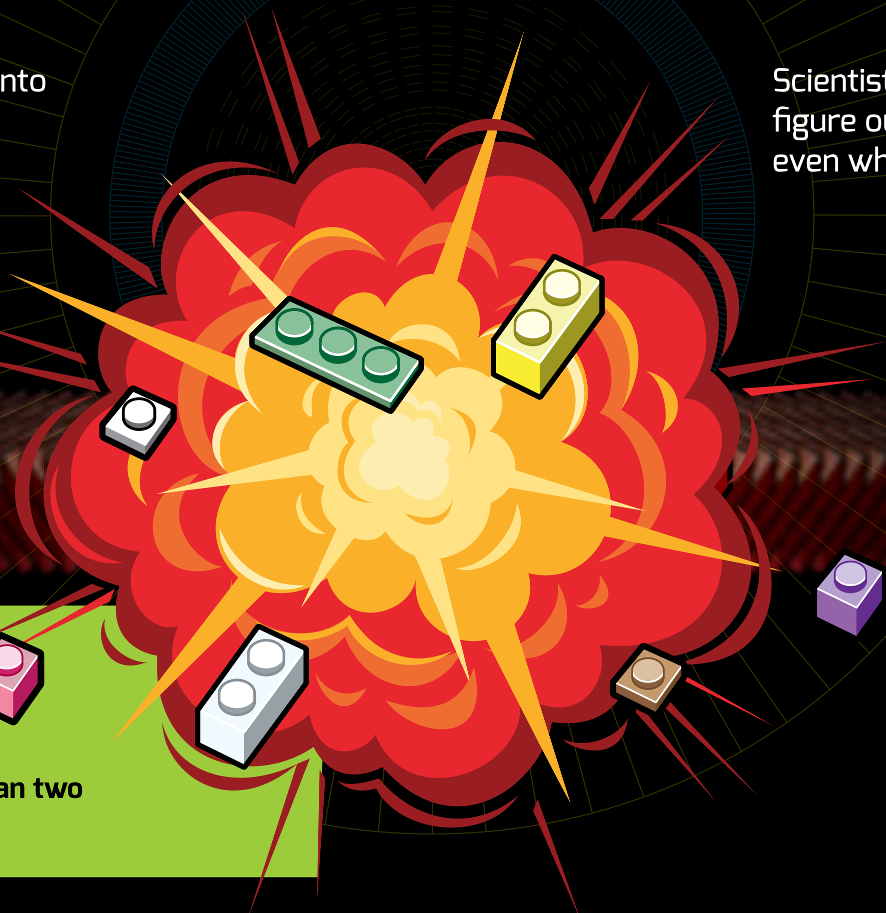
1.4 WHY DO WE SMASH ATOMS?

Image you have a model made of plastic building bricks and you want to build another one, but you don't have the instructions. The only way to find out what sort of pieces the model is made of is to take it apart and see what's inside. This is what particle accelerators like the Large Hadron Collider are made to do.



They take particles of matter and fire them into each other at such huge speeds that the particles are smashed to pieces.

Scientists can then look at what comes out to figure out what particles are made from and even what particles were made in the Big Bang!

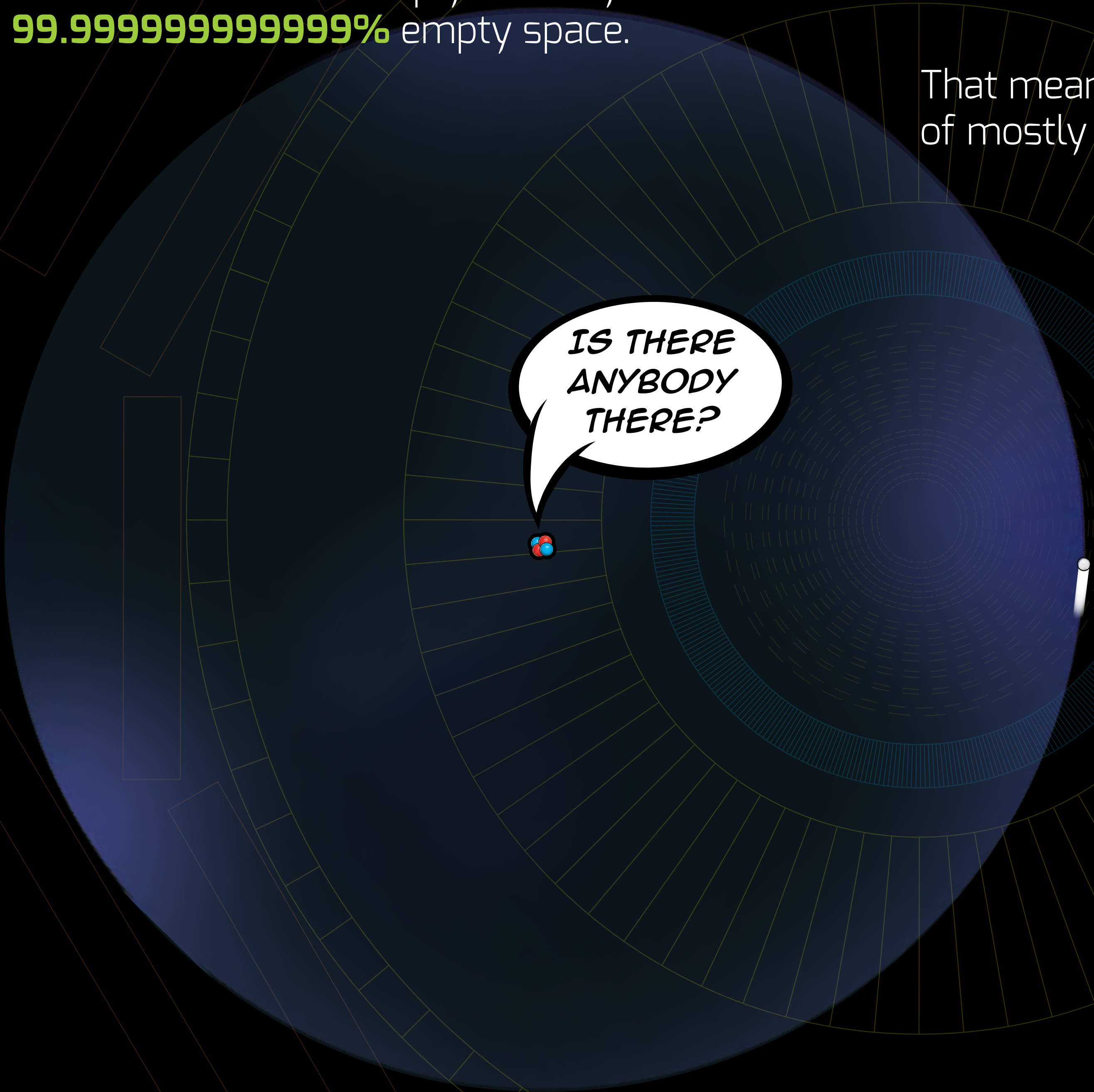


DID YOU KNOW?

If you smash two models together, all you get are the pieces those models are made from. In a particle accelerator, energy from the collision can become new particles – sometimes with more mass than two particles you smashed together!

DID YOU KNOW?

The atoms that make up your body are **99.9999999999999%** empty space.



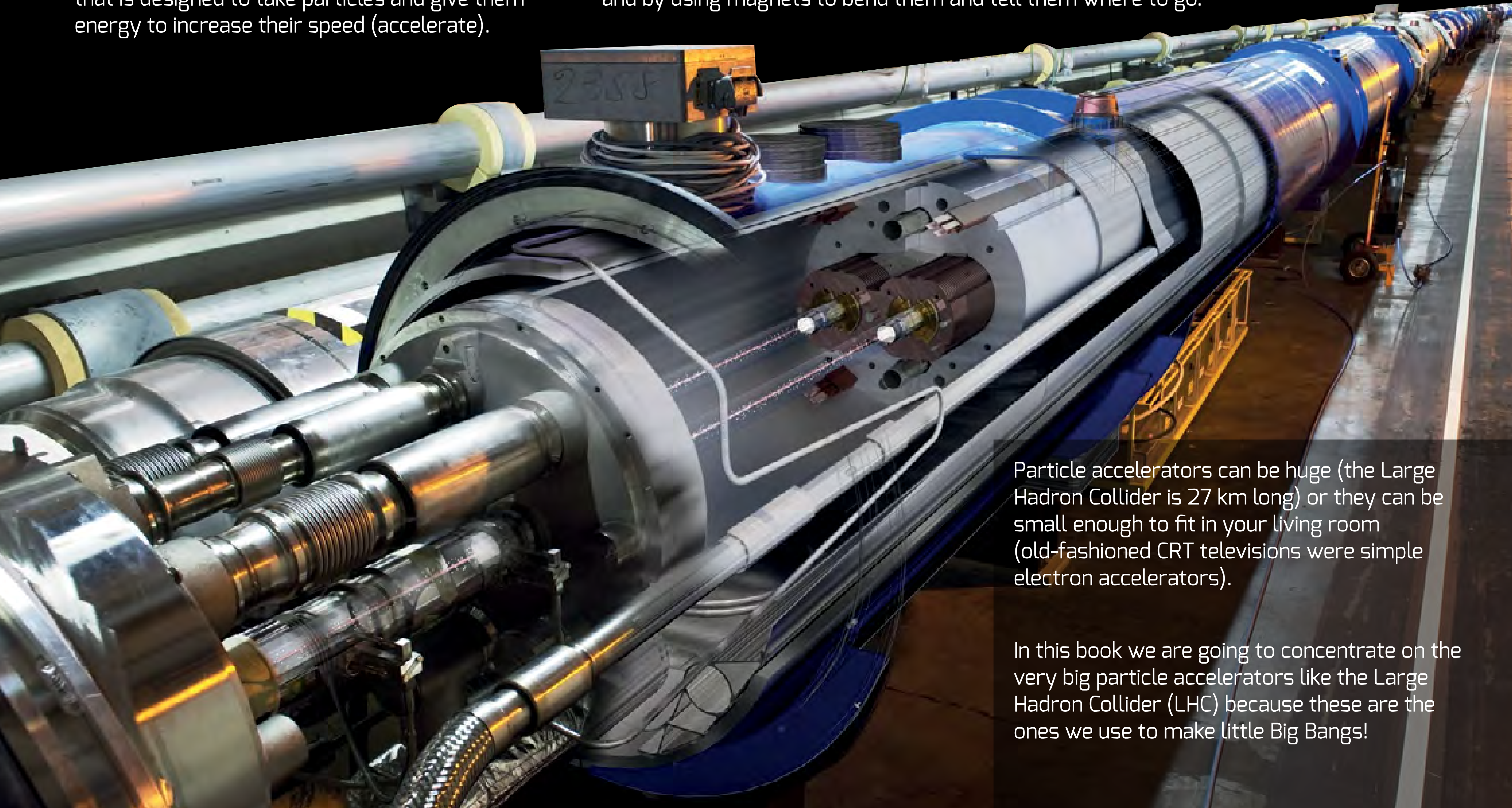
That means you are made up of mostly **nothing** at all!

If you could **squash** all the empty space out of **every human on Earth**, you'd be left with a lump of quarks and electrons about the size of a **sugar cube**!

2 WHAT IS A PARTICLE ACCELERATOR?

Most simply, a particle accelerator is a machine that is designed to take particles and give them energy to increase their speed (accelerate).

This is usually done by using electric fields to accelerate the particles and by using magnets to bend them and tell them where to go.



Particle accelerators can be huge (the Large Hadron Collider is 27 km long) or they can be small enough to fit in your living room (old-fashioned CRT televisions were simple electron accelerators).

In this book we are going to concentrate on the very big particle accelerators like the Large Hadron Collider (LHC) because these are the ones we use to make little Big Bangs!

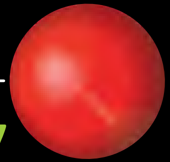
2.1 HOW TO BUILD A PARTICLE ACCELERATOR

Every particle accelerator has five basic things it needs:

1. CHARGED PARTICLES

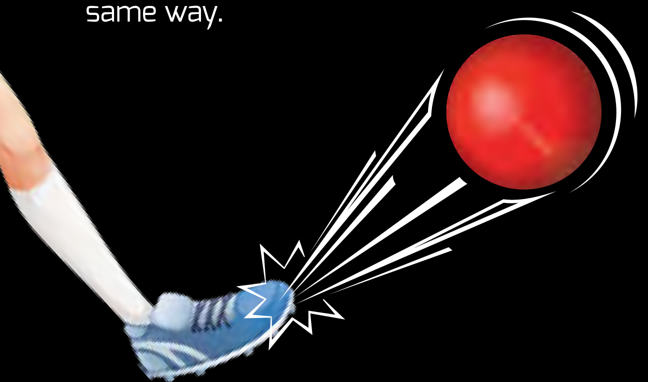
Because we use electric and magnetic fields, you have to use particles that have an electric charge – either negatively charged (like an electron) or positively charged (like a proton).

Proton



2. GIVE THEM ENERGY

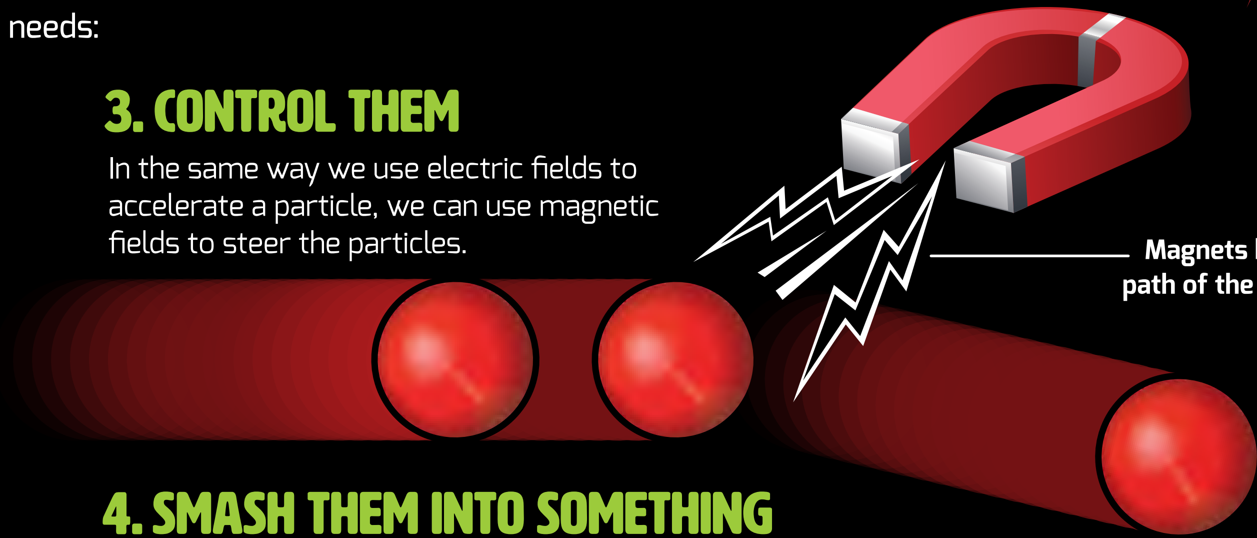
If you take a two magnets and try to put the same poles together you will feel them push each other apart. We use charged particles because they react to electric fields in the same way.



A positive electric charge will kick away a positively-charged particle. A negative charge will kick away a negatively-charged particle. Each kick gives the particle a little more energy and makes it go faster and faster.

3. CONTROL THEM

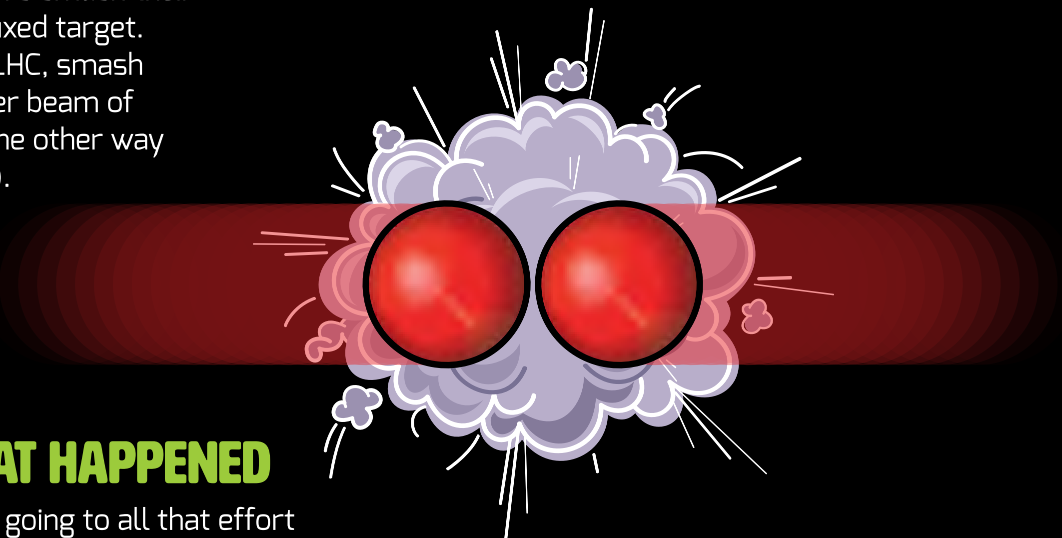
In the same way we use electric fields to accelerate a particle, we can use magnetic fields to steer the particles.



Magnets bend the path of the particles

4. SMASH THEM INTO SOMETHING

Some accelerators smash their particles into a fixed target. Others, like the LHC, smash them into another beam of particles going the other way (twice the bang!).



5. SEE WHAT HAPPENED

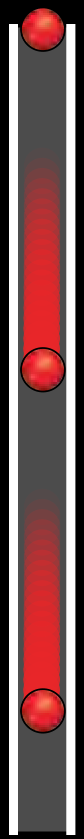
There's no point going to all that effort unless you can see what happened. To do this, accelerators have special detectors that act a bit like super-sensitive cameras.

2.2 TYPES OF PARTICLE ACCELERATOR

There are three basic types of particle accelerator:

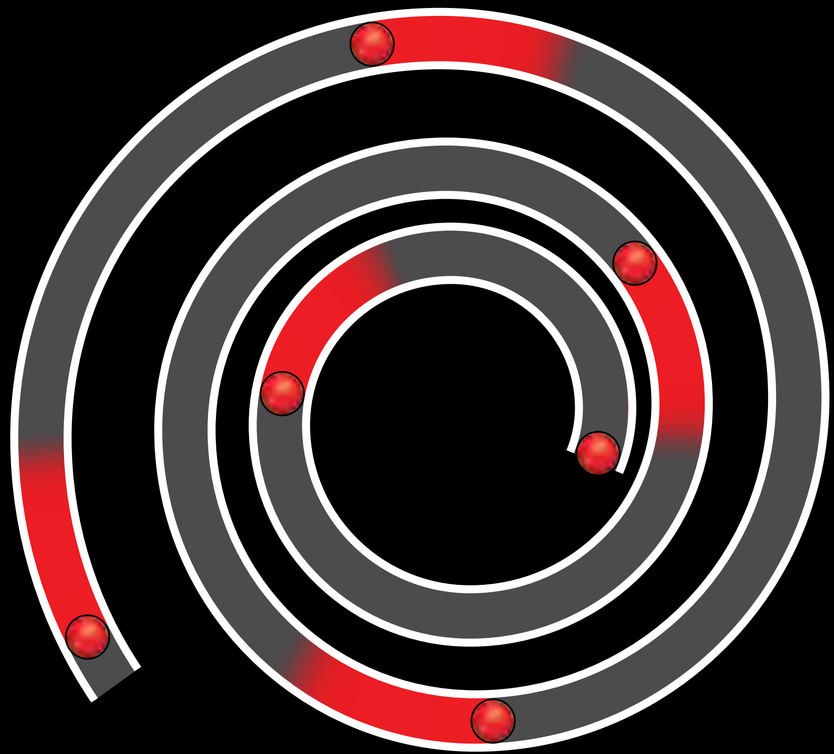
1. LINEAR

Linear accelerators, as their name suggests, accelerate particles in a straight line – rather like a bullet in the barrel of a gun. Accelerators like this are used in radiotherapy in hospitals to accelerate electrons to create X-rays, which are used for cancer treatment.



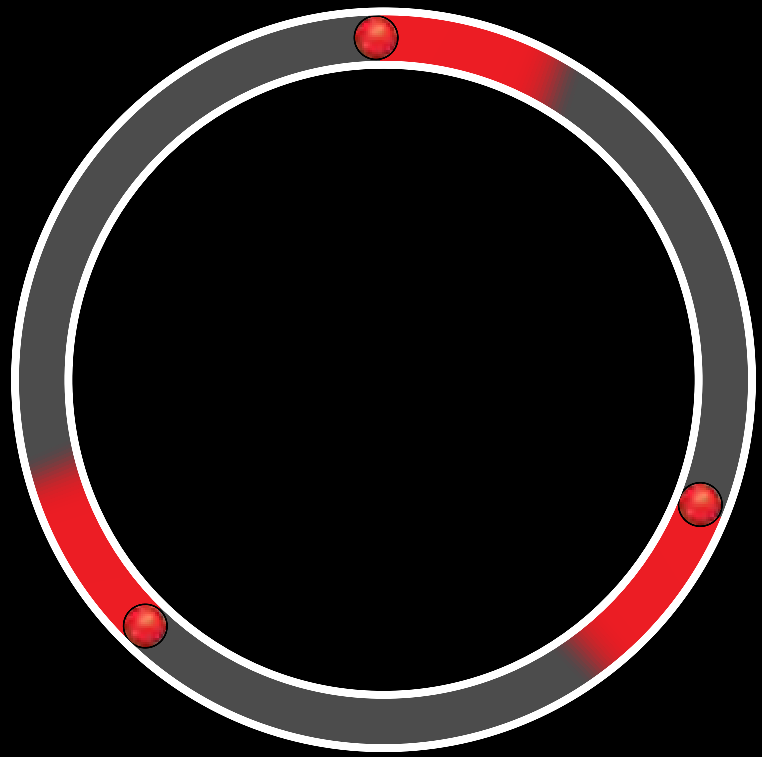
2. CYCLOTRON

Cyclotrons are like linear accelerators that have been coiled up like snail shells. They accelerate particles from the centre outwards. The coil means you have a much longer accelerator that takes up less space.



3. SYNCHROTRON

These accelerators are big rings. They accelerate particles round and round in circles thousands of times until the particles are moving as fast as they can go. They are called synchrotrons because the electric and magnetic fields used to accelerate the bend the particles have to be perfectly synchronised. The LHC is a synchrotron.



DID YOU KNOW?

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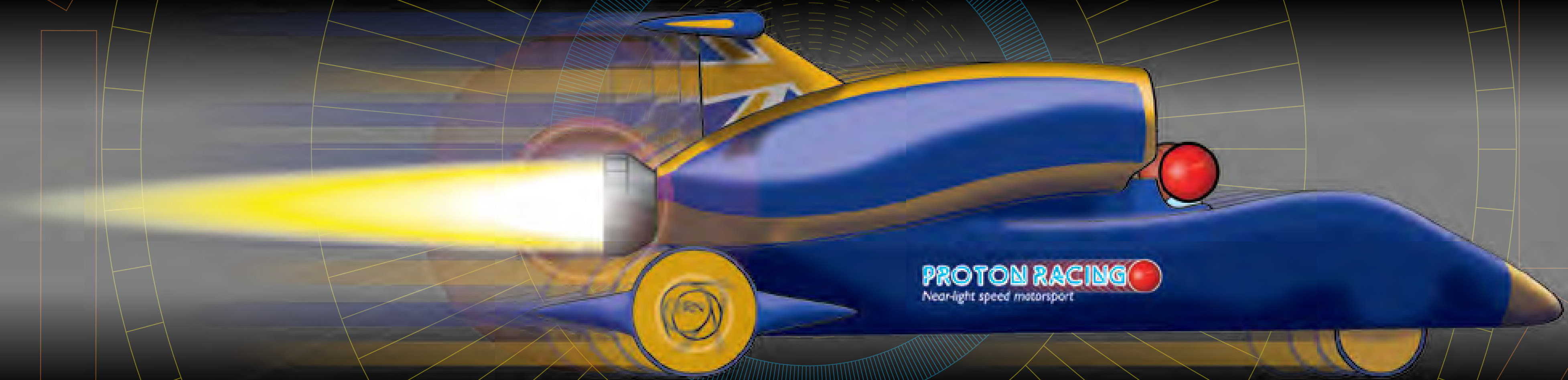
Particle accelerators like the LHC accelerate protons to close to **speed of light**. That's more than **290,000 kilometers per second!**

It takes a lot of energy to make even something as small as proton move that fast. This is why the Large Hadron Collider is so big! In fact, the Large Hadron Collider's synchrotron is **27 km long**.

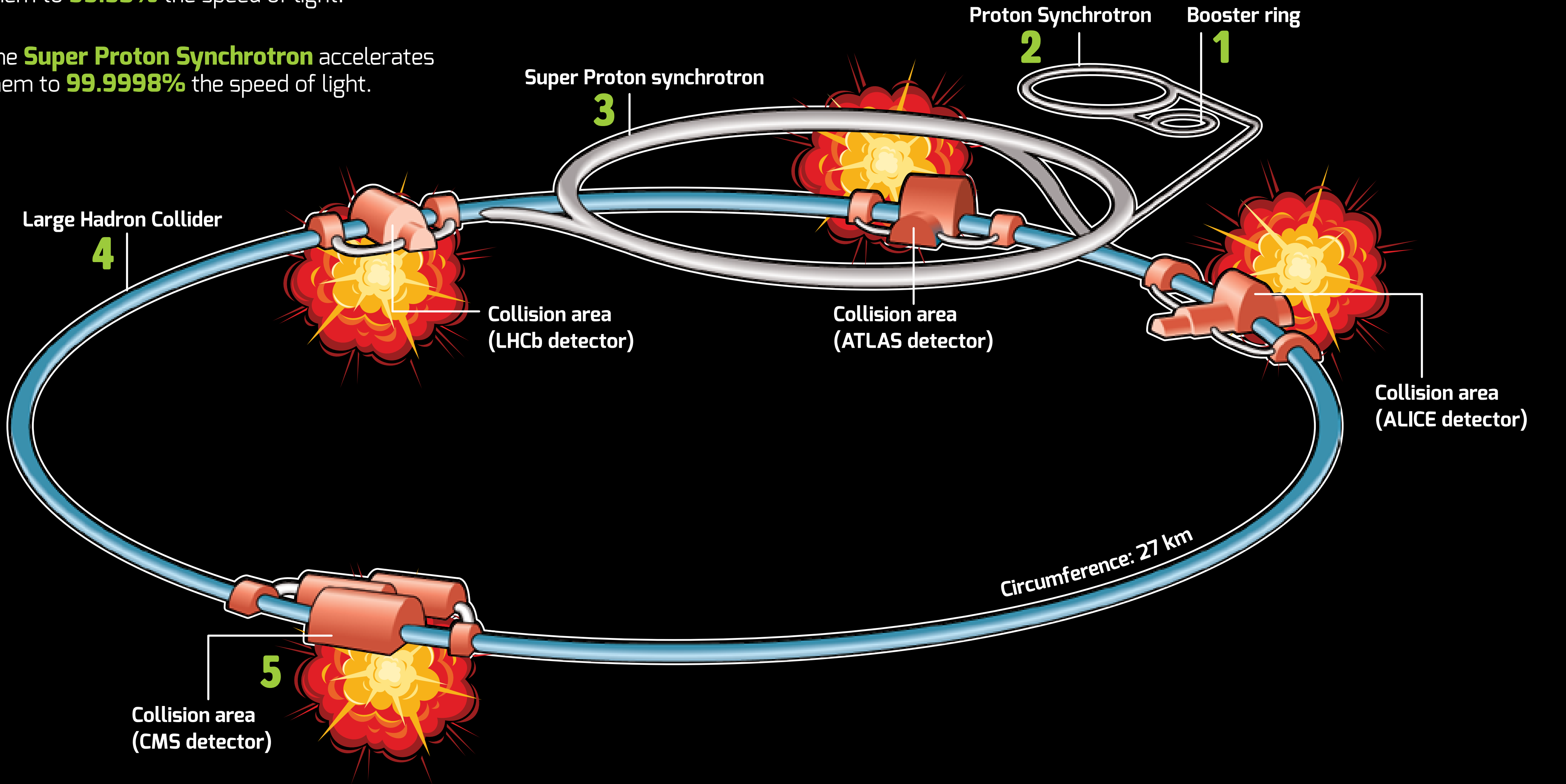


At close to the speed of light even something as small as proton can carry as much energy as car travelling at **1,600 km per hour!**

2.2 MEET THE LARGE HADRON COLLIDER

The faster you can make a particle go, the more energy it has and the better the little big bang you will get. The Large Hadron Collider is actually made up of lots of synchrotron accelerators - each one adds more energy to the particles to make them go faster and faster and faster...

1. The **booster ring** accelerates protons to **91.6%** of the speed of light.
2. The **Proton Synchrotron** accelerates them to **99.93%** the speed of light.
3. The **Super Proton Synchrotron** accelerates them to **99.9998%** the speed of light.
4. To get that last tiny bit closer to the speed of the light, the protons are accelerated around the **27 km-long Large Hadron Collider**.
5. When they reach **99.9998%** the speed of light, two beams of protons travelling in opposite directions are smashed together in one of four collision areas.



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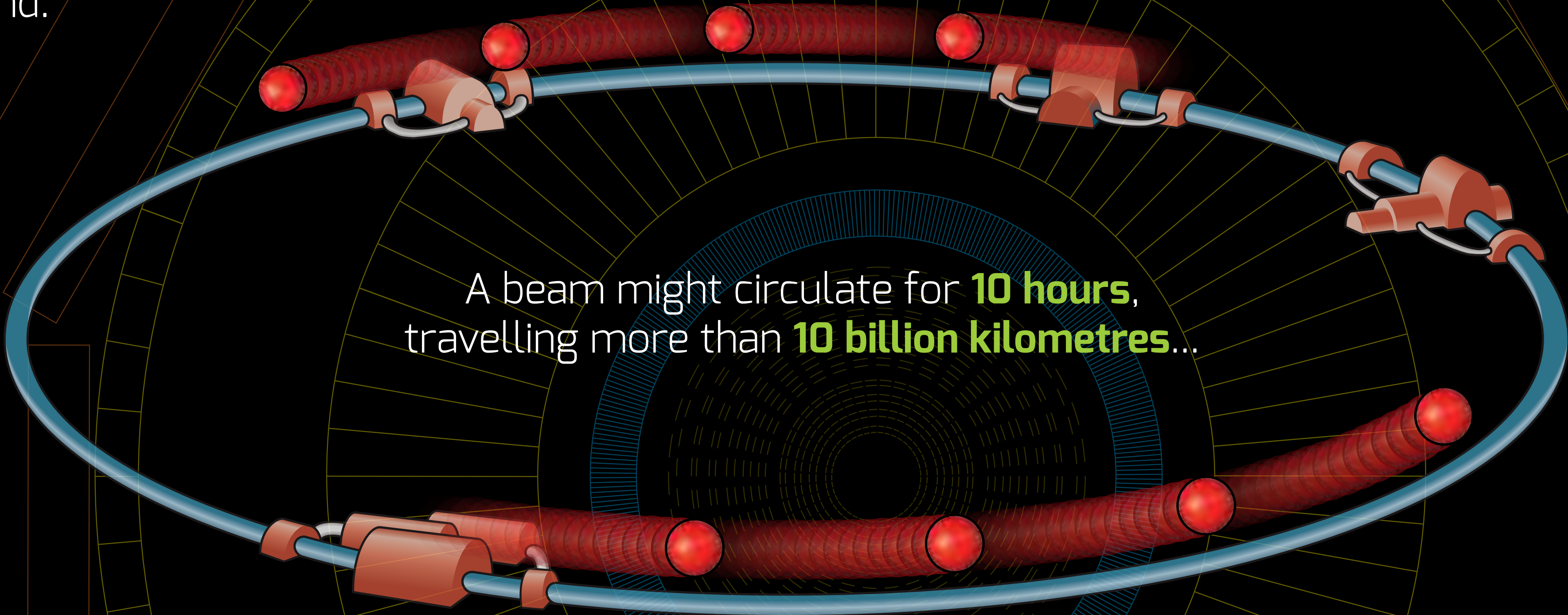
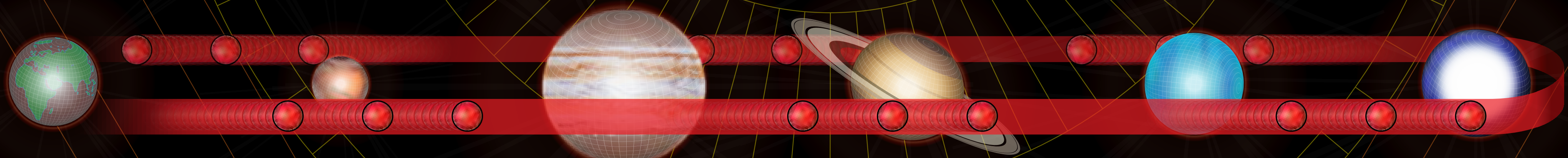
DID YOU KNOW?

At **near-light speed**, a proton in the LHC will complete more than **11,000** laps every second.



A beam might circulate for **10 hours**, travelling more than **10 billion kilometres**...

...that's far enough to get to **Neptune and back** again!



2.3 LET'S PLAY LHC TOP DETECTORS

As you saw on the previous page there are four collision areas at the LHC where particles smash together and detectors analyse the collisions. Although there are many experiments at the LHC, the four main one: CMS, ALICE, ATLAS, and LHCb.

Why not play our Top Detectors game and see which one comes out on top?

TOP DETECTORS — CMS

Weight (tonnes)	14000
Dimensions (metres)	21x15x15
Scientists involved	4000
Institutions involved	200
Countries involved	40

CMS (Compact Muon Solenoid) is a general purpose detector. Together with ATLAS, this was one of the detectors responsible for the groundbreaking discovery of the Higgs Boson.

TOP DETECTORS — ALICE

Weight (tonnes)	10000
Dimensions (metres)	26x16x16
Scientists involved	2000
Institutions involved	174
Countries involved	40

ALICE (A Large Ion Collider Experiment) creates mini Big Bangs to investigate the soup of particles that existed at the birth of the Universe. It also explores properties of quark–gluon plasma (a fifth state of matter).

TOP DETECTORS — ATLAS

Weight (tonnes)	7000
Dimensions (metres)	46x25x25
Scientists involved	5500
Institutions involved	245
Countries involved	42

ATLAS (A Toroidal LHC ApparatuS) is the world's largest general purpose detector. It helped to discover the Higgs Boson and is also designed to search for evidence of physics beyond the Standard Model.

TOP DETECTORS — LHCb

Weight (tonnes)	5600
Dimensions (metres)	21x10x13
Scientists involved	1565
Institutions involved	86
Countries involved	20

LHCb (Large Hadron Collider beauty) is designed to investigate the subtle differences between matter and antimatter. It also studies the decay of particles containing beauty quarks.

DID YOU KNOW?

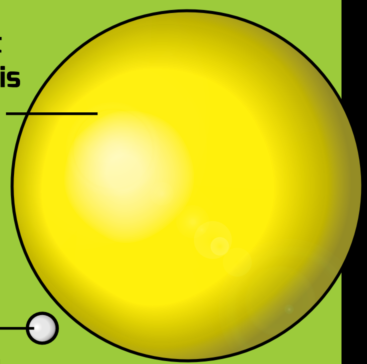
The ATLAS detector is so heavy it is about the same weight as the Eiffel Tower in Paris!

2.4 FINDING THE HIGGS BOSON

Although the Standard Model is very good at explaining how lots of things work, there are some things it can't explain. One of those things it can't explain is where particles like quarks get their mass... or why does anything weigh what it does?

A MASSIVE PROBLEM

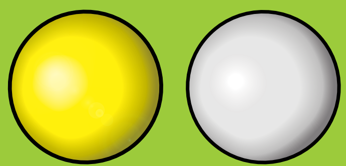
The heaviest particle is the top quark.



The lightest is the electron.

The top quark is 350,000 times more massive than the electron.

This is about the difference between the Sun and the Earth...



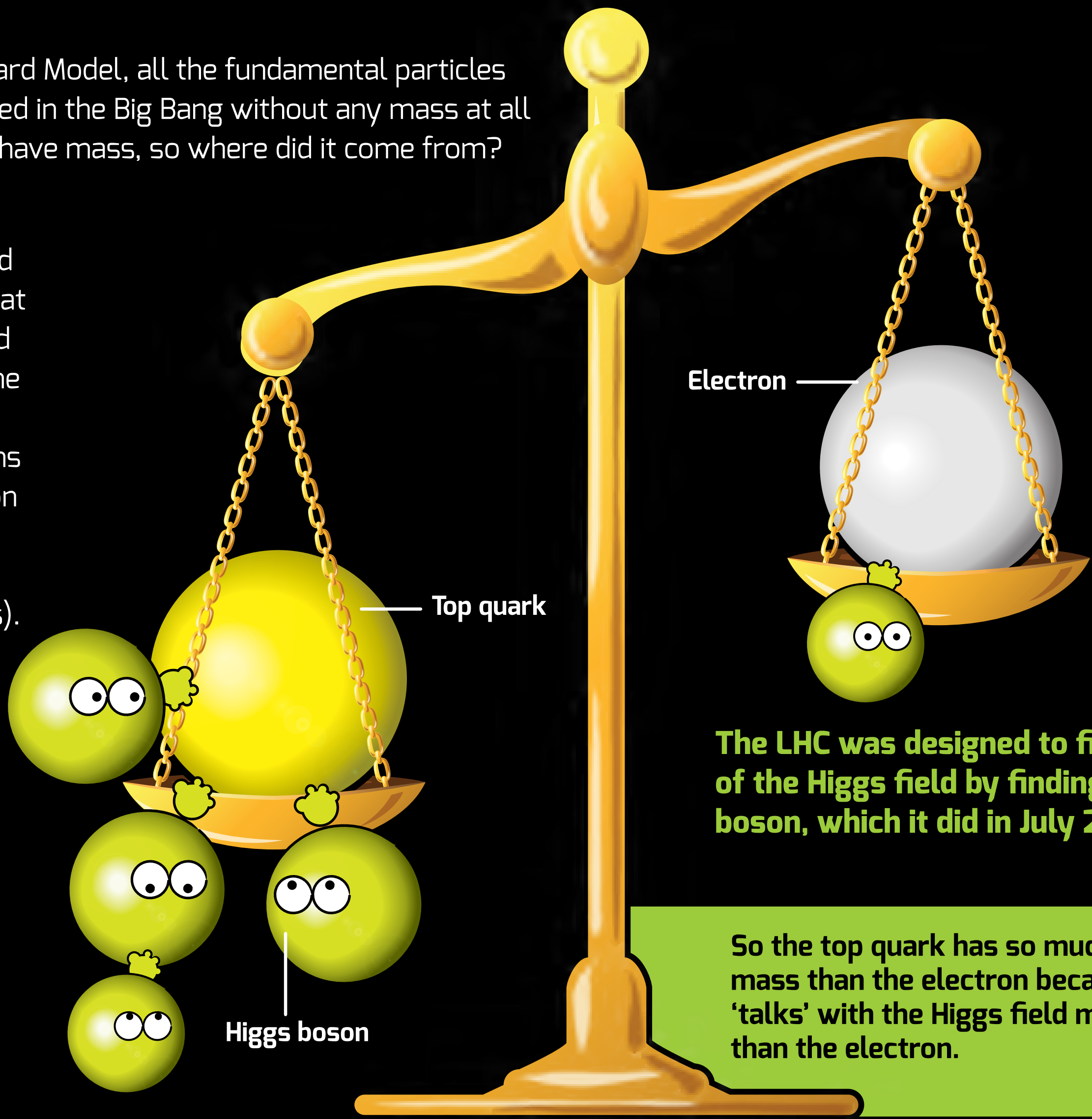
...yet the top quark and the electron are about the same size!

How?

1. According to the Standard Model, all the fundamental particles should have been created in the Big Bang without any mass at all – but we know they do have mass, so where did it come from?

2. A British physicist called **Peter Higgs** imaged that there was a special field that is everywhere in the Universe that particles like quarks and electrons 'talk' to through a boson (in the same way they use bosons to 'talk' to the fundamental forces).

3. The more they 'talk' to this field, the more mass a particle will have. The field was called the **Higgs field** and the boson was called the **Higgs boson**.



The LHC was designed to find proof of the Higgs field by finding the Higgs boson, which it did in July 2012.

So the top quark has so much more mass than the electron because it 'talks' with the Higgs field more than the electron.

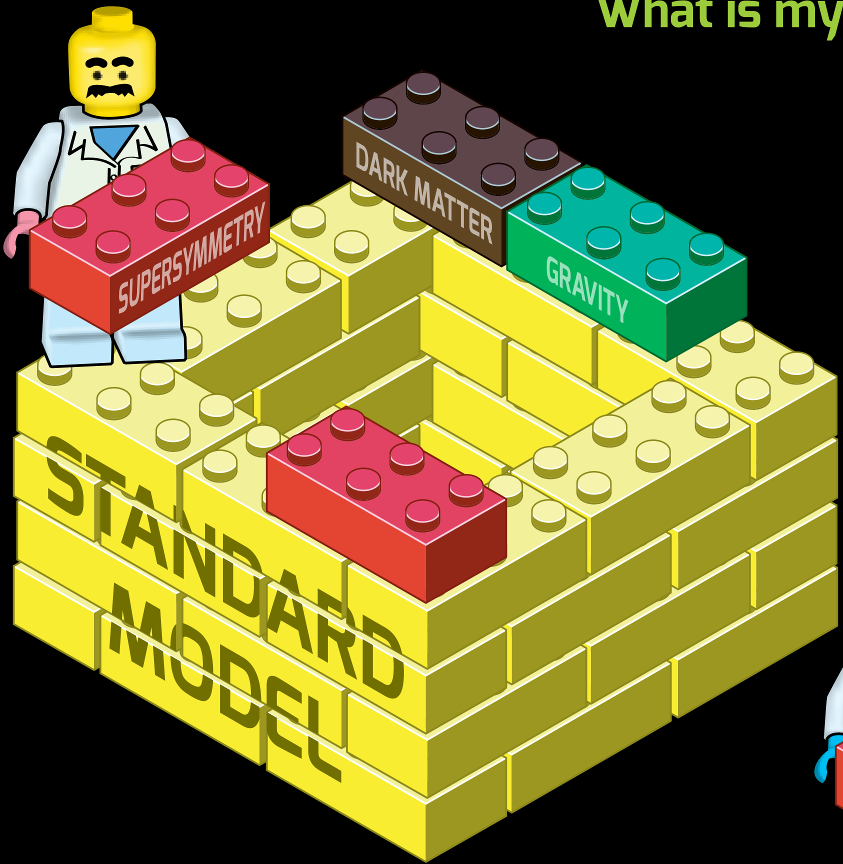
3 WHAT IS THERE LEFT TO FIND?

LITTLE BOOK OF LITTLE BIG BANGS

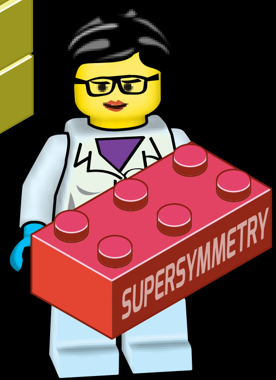
The Standard Model of particle physics is a very successful theory, but it there are still lots of things it can't explain and it has many missing pieces.

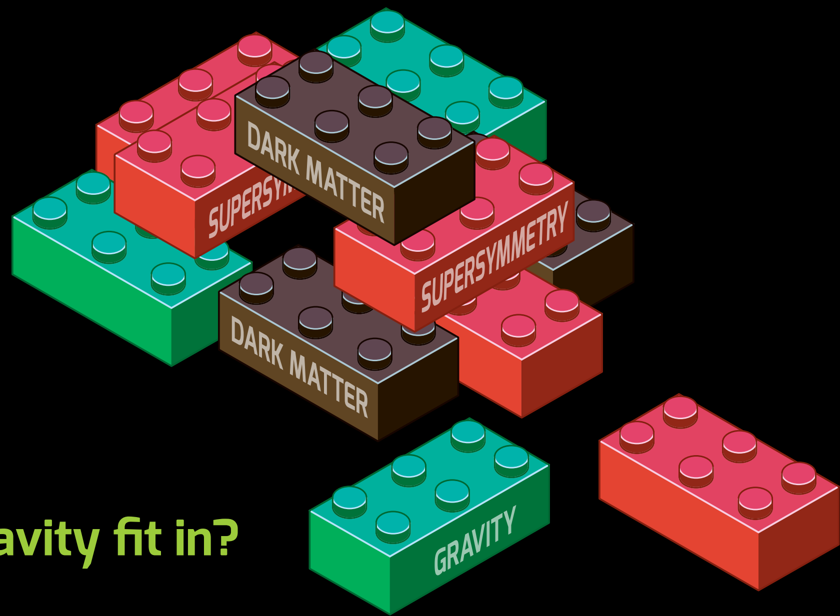
Now that they've found the Higgs boson, particle accelerators like the LHC will be searching for answers to questions like:

What is mysterious dark matter?



Higgs only explain some of matter's mass, where does the rest come from?





How does gravity fit in?

3.1 SHED LIGHT ON DARK MATTER

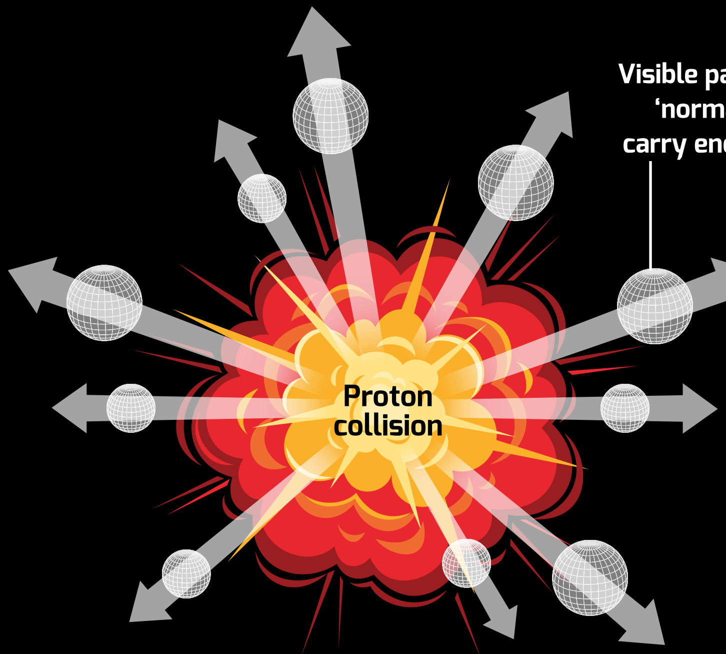
LITTLE BOOK OF LITTLE BIG BANGS

All of the stars, planets, galaxies and life forms in the Universe make up less that 20% of all the matter in the Universe. More than 80% is made up of a form of matter we can't see, called **dark matter**.

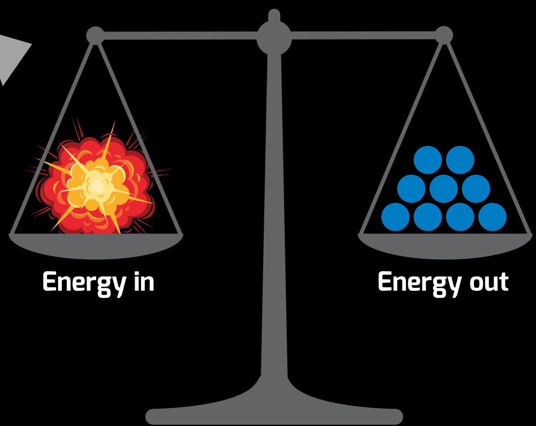
We know dark matter exists because we can see the effects that it's gravity has on the things we can see, but what is it made of? Is it made from a new sort of particle that is invisible to us?

HOW TO FIND SOMETHING WE CAN'T SEE

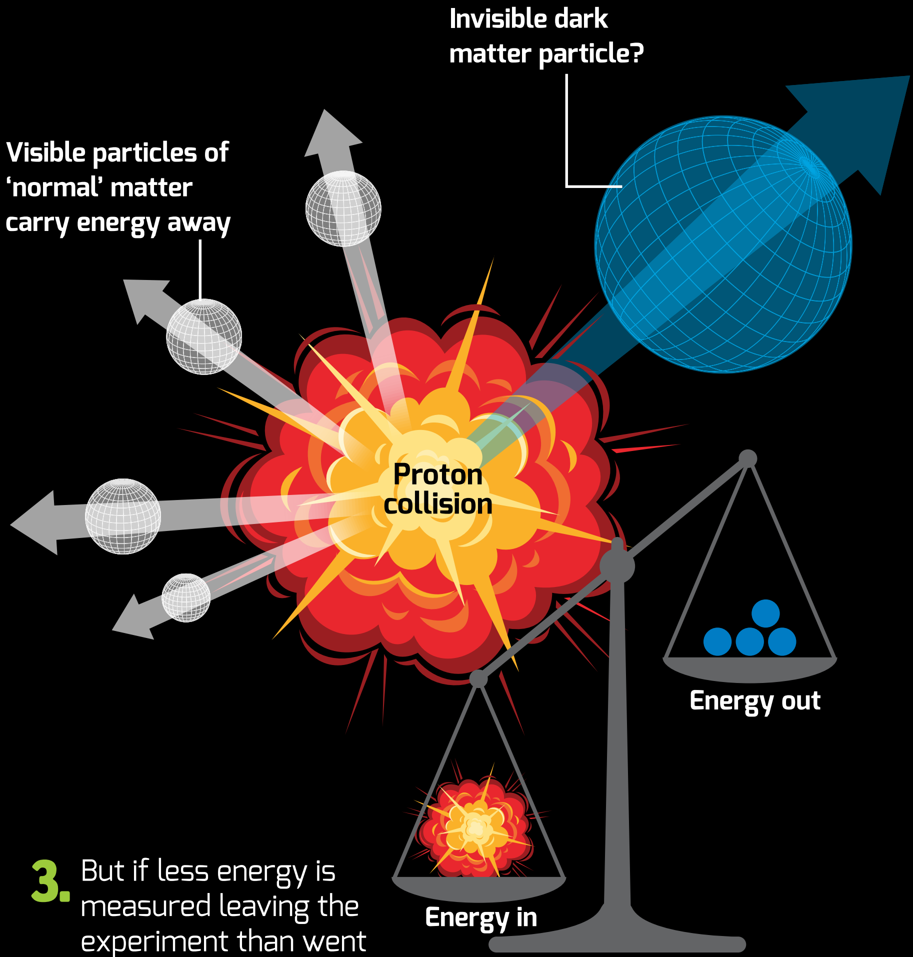
The LHC will search for evidence of dark matter particles by trying to spot if there is something missing after a collision.



1. When protons collide in the LHC the energy released is converted into new particles.



2. When the energy out is measured and compared to the energy put in, they should both balance out.



3. But if less energy is measured leaving the experiment than went in, it might be a sign that the energy has been carried away by something the detectors can't see – such as dark matter.

DID YOU KNOW?

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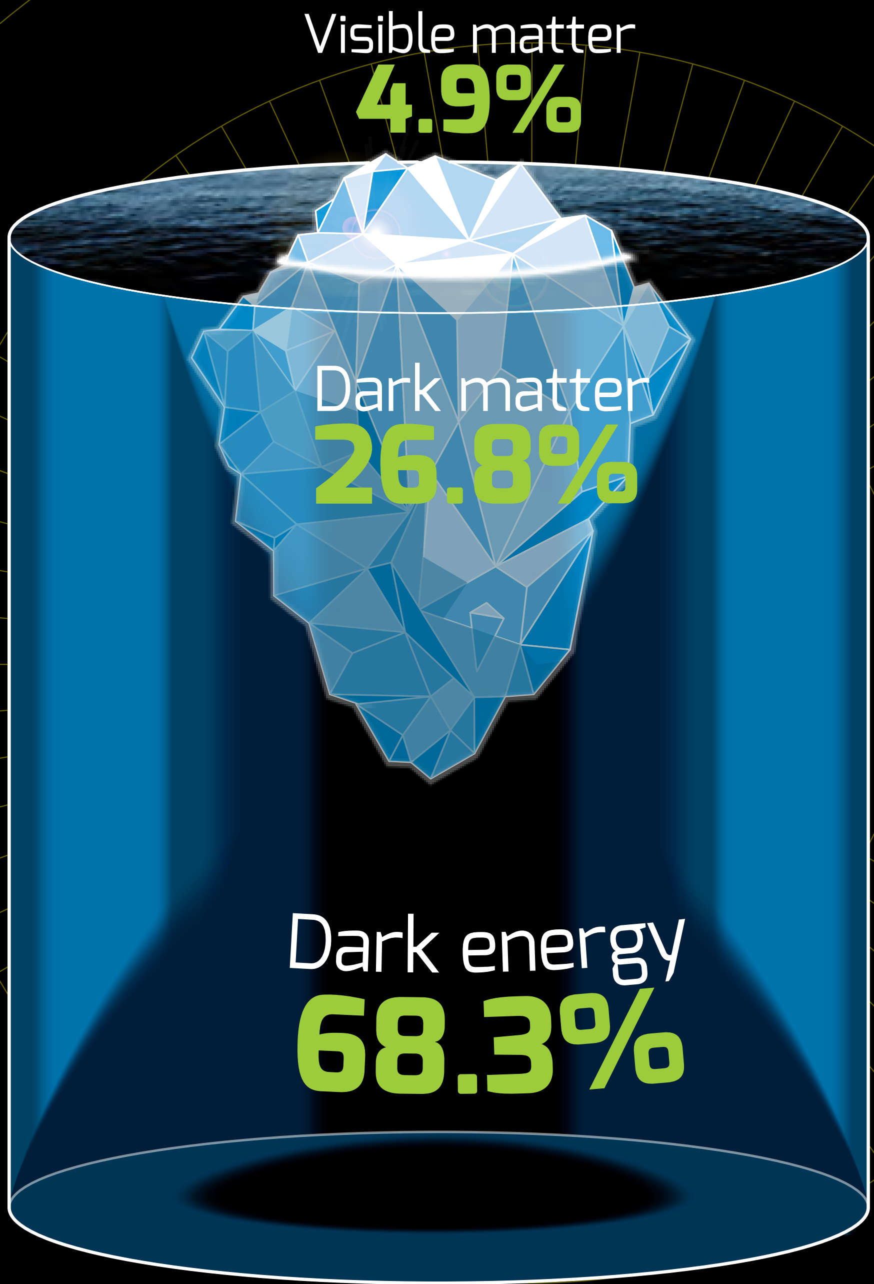
Visible matter makes up **less than 5%** of all the energy in the Universe. The stuff that makes up all the dust, comets, planets and stars is just the tiny visible tip of a huge hidden iceberg!



Dark matter helps to hold galaxies and clusters of galaxies together.

Dark energy is thought to be speeding up the expansion of the Universe. The more the Universe expands, the more dark energy there is and the faster it expands.

3.2 A HIDDEN WORLD OF SUPER PARTICLES?

Along with dark matter, another sort of particle scientists are hoping will 'pop' out of collisions in the LHC is something called a SUSY particle.

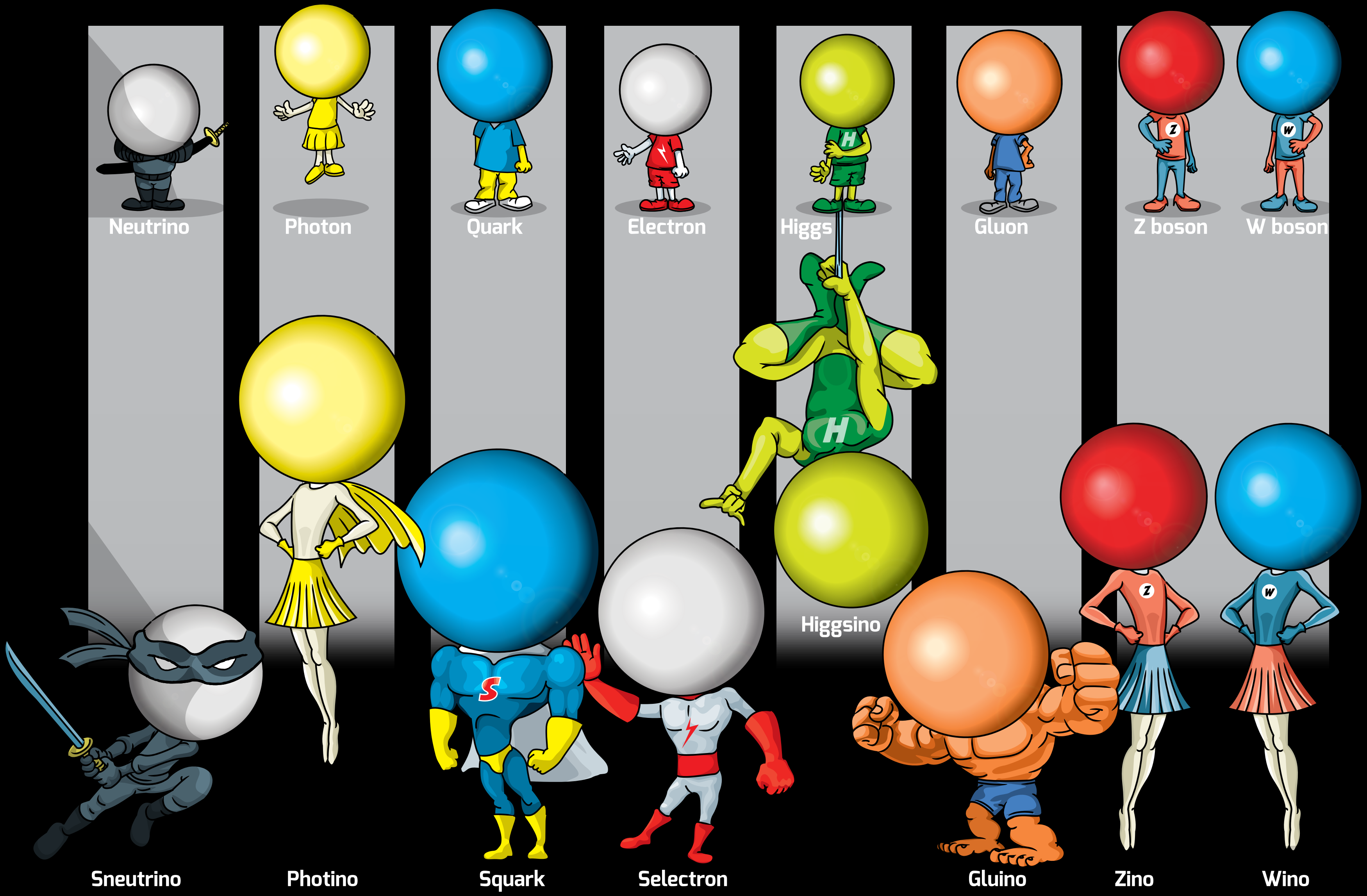
One of the theories that attempts to explain why the Standard Model can't account for things like missing mass and dark matter is called **supersymmetry**.

SUPERSYMMETRY

Supersymmetry (also known as **SUSY**) is a theory that predicts that for every elementary particle we can see, there is a hidden super particle version that we haven't seen yet.

The super particles will have similar properties to their 'normal ' cousins, but will have much more mass. So, for every **quark**, there will be a heavier 'super quark', called a **squark**, hidden from view

The massive SUSY particles could provide some of the missing **dark matter** that scientists are searching for.



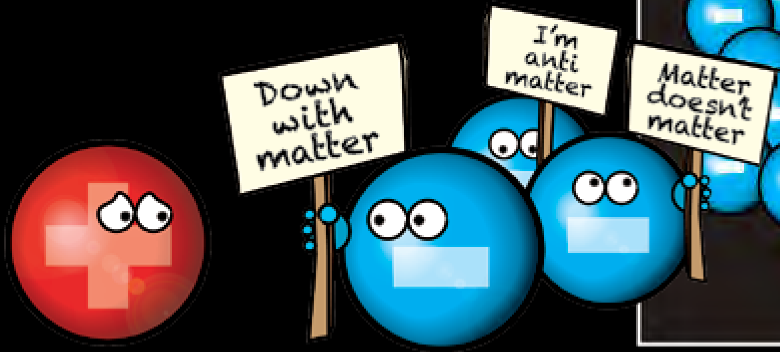
3.3 WHY IS THE UNIVERSE MADE OF MATTER?

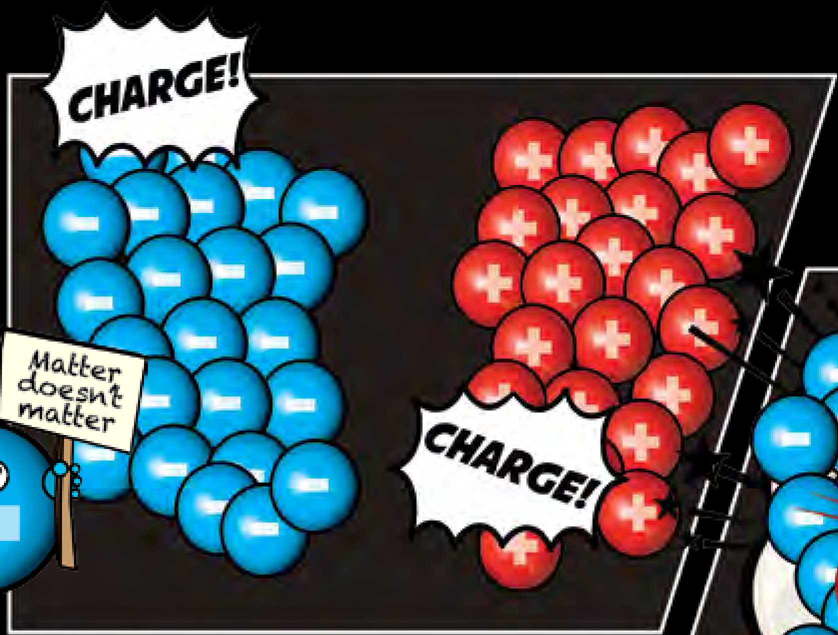
According to the Standard Model, in the Big Bang, matter and **antimatter** should have been made in equal measure.

Antimatter is like the mirror version of matter. The antimatter version of the negatively-charged electron, for example is the positively-charged positron.

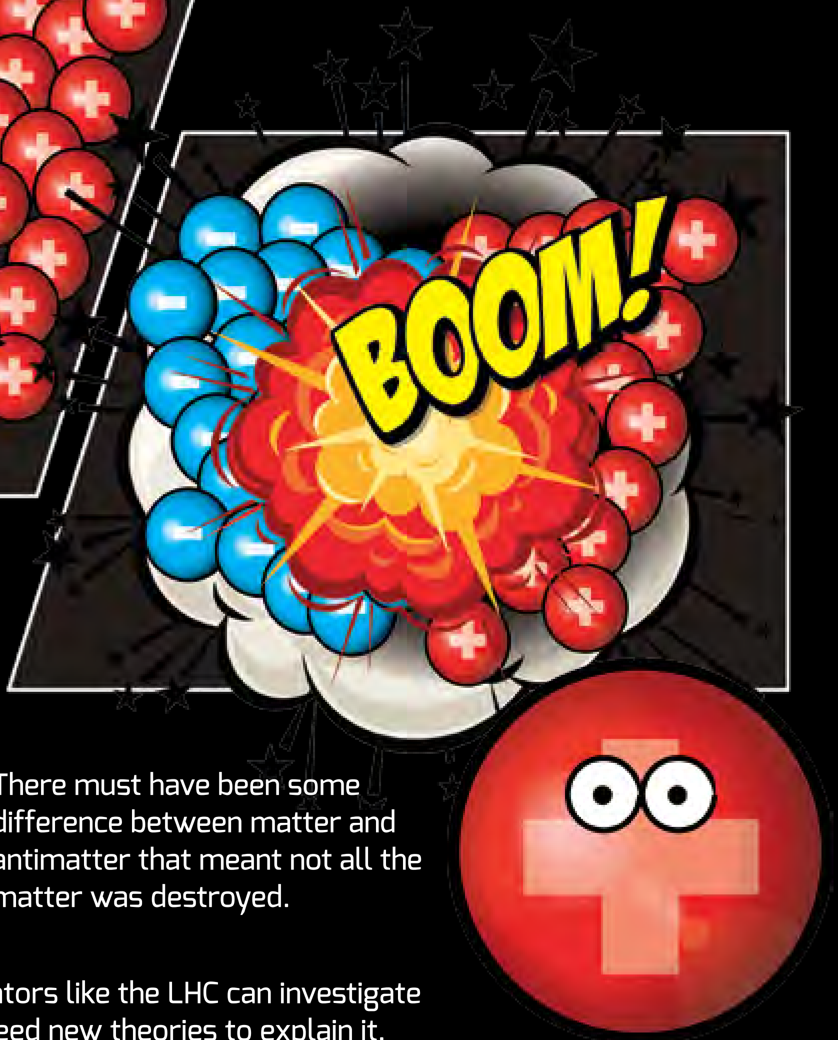
WHY DID MATTER WIN?

Matter and antimatter really don't like each other and they destroy each other if they make contact.





They should have totally destroyed each other within the first few moments of the Big Bang.



We know this didn't happen not because we live a Universe made of matter, but because if it had happened, nothing would exist at all!

There must have been some difference between matter and antimatter that meant not all the matter was destroyed.

By creating **little big bangs**, particle accelerators like the LHC can investigate what might have happened and whether we need new theories to explain it.

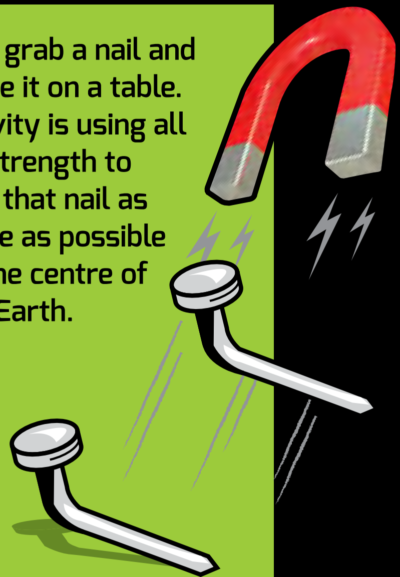
3.3 WHAT'S WRONG WITH GRAVITY?

Compared to the other fundamental forces, gravity very very weak. Every time you pick an object off the floor, or lift a foot you are overpowering the force of gravity. But there's no way you could overpower the strong nuclear force and pull apart an atom.

Basically, gravity doesn't fit into the Standard Model of physics and no one knows why. Einstein spent the last years of his life trying to come up with a theory that made gravity and particles work together, but even he couldn't figure it out.

IS IT WEAK?

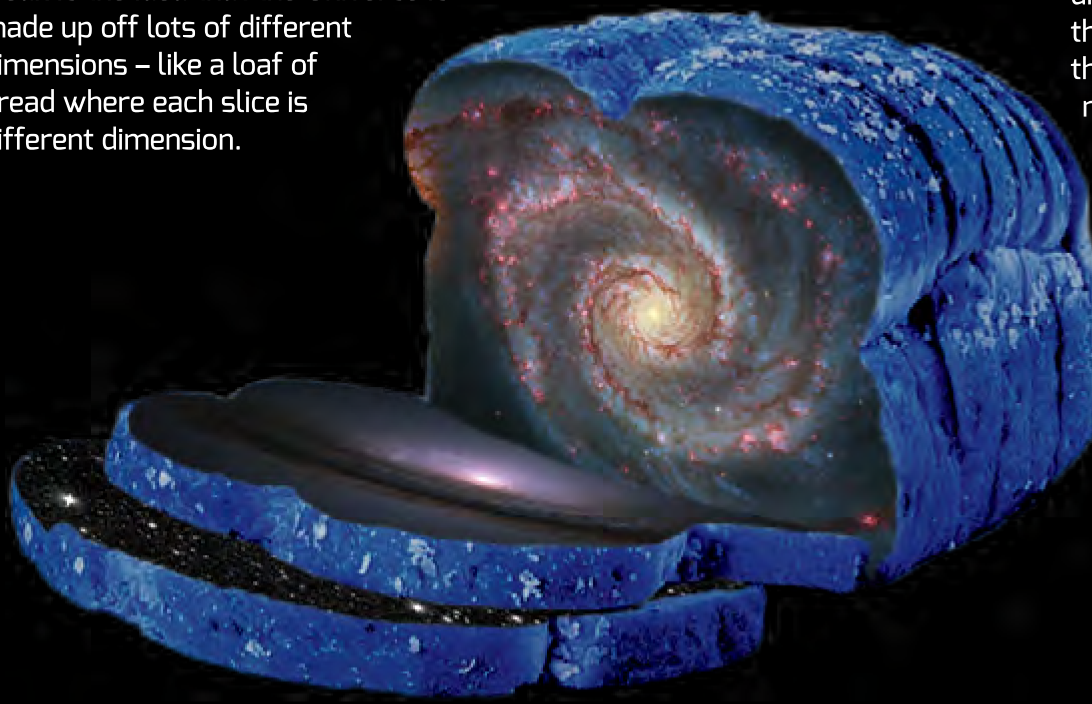
Just grab a nail and place it on a table. Gravity is using all its strength to pull that nail as close as possible to the centre of the Earth.



Now take a small magnet and watch in awe as its electromagnetic force easily dismisses the gravitational force of an entire planet and lifts the nail.

COULD THERE BE HIDDEN DIMENSIONS?

One theory to explain why gravity is so weak is the idea that the Universe is made up off lots of different dimensions – like a loaf of bread where each slice is different dimension.



Gravity might work across the dimensions and so is spread really thin (like a bit of butter spread through a whole loaf of bread) – making it appear as if gravity is very weak in our dimension.

The other fundamental forces only work in our dimension so are not spread too thin – which is why they seem stronger.

The LHC could test this by smashing together particles and seeing if a **graviton** (the particle that is thought to be gravity's force carrier) is produced.

If they can see the graviton be produced but then suddenly disappear, it might mean that it vanished into another dimension that we can't see.

NOTES

Need to make some notes or doodle some ideas?
This is the place to do it!

THE LITTLE BOOK OF

LITTLE BIG BANGS

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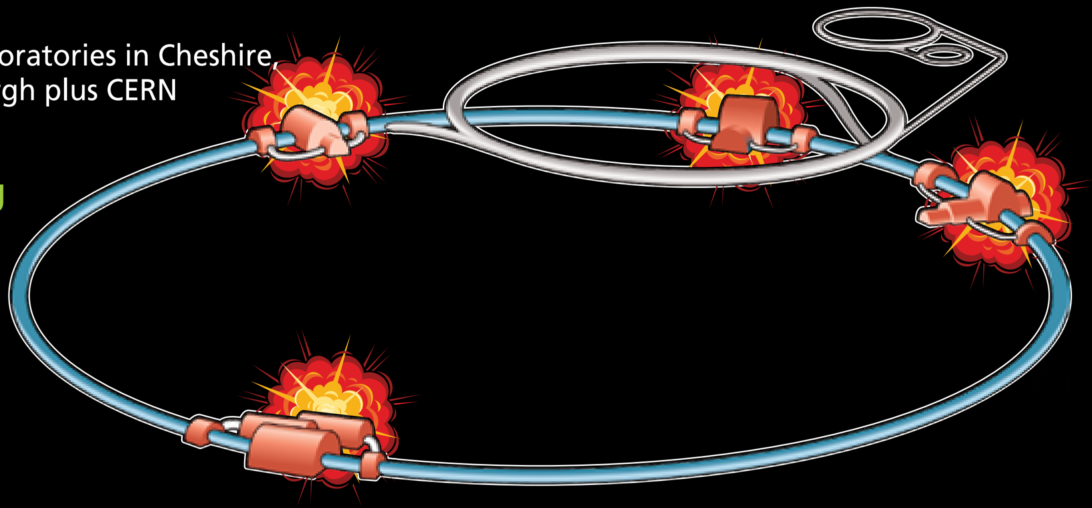

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