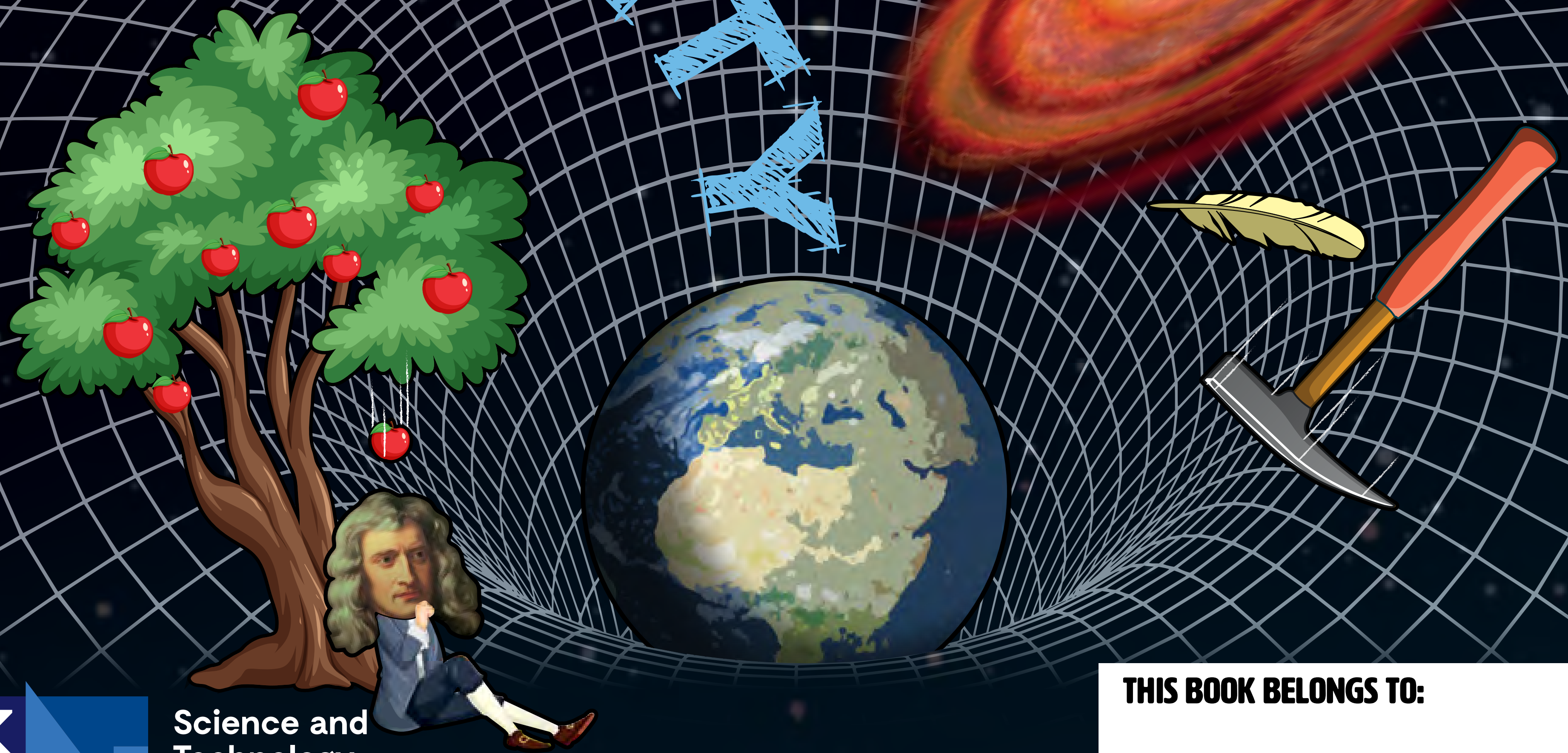
THE LITTLE BOOK OF GRAVITY



Science and
Technology
Facilities Council

THIS BOOK BELONGS TO:

Why do things fall down and not up?

What's the difference between weight and mass?

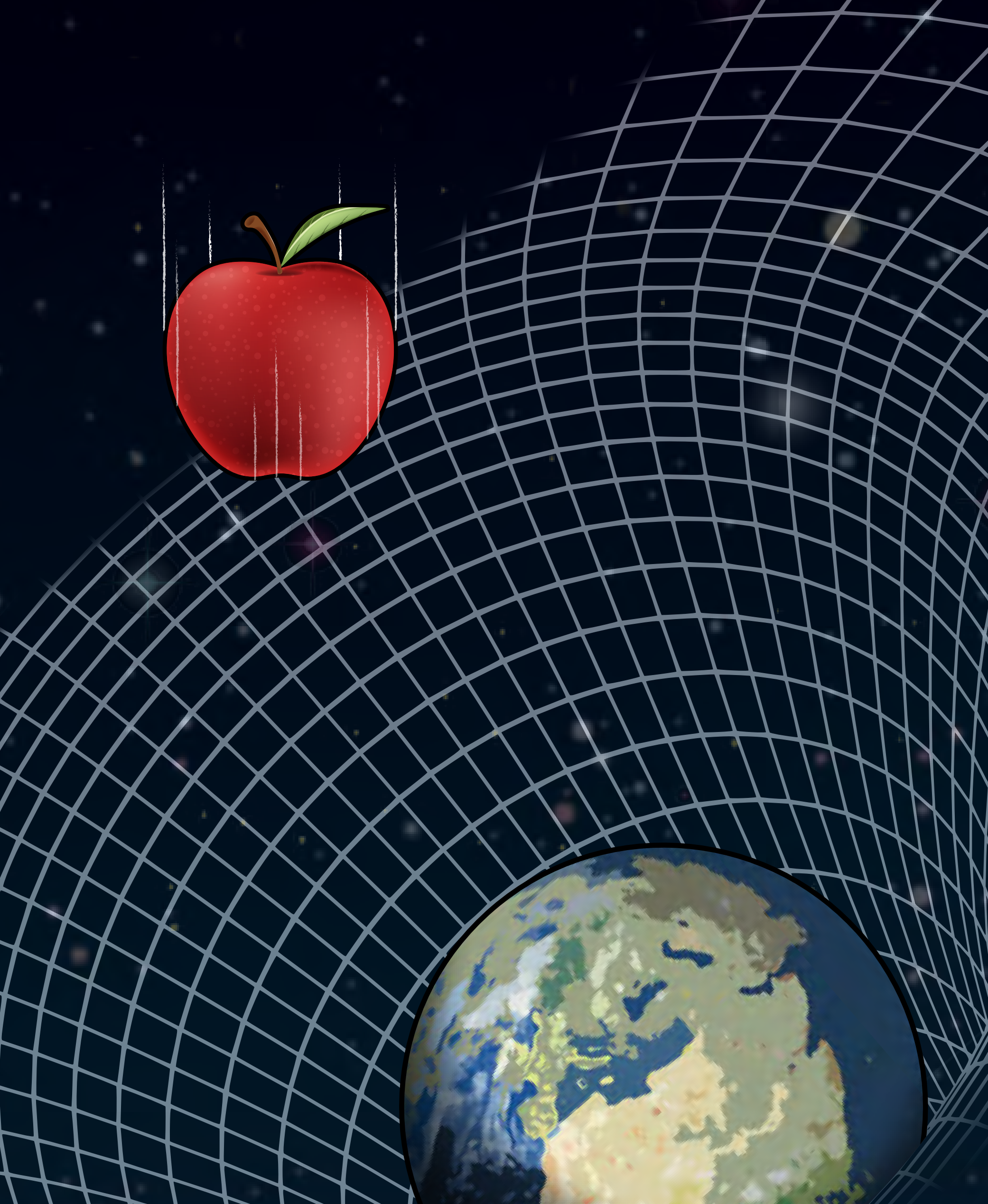
Why do astronauts weigh less on the Moon?

Is an orbiting object just 'falling with style'?

What do you mean black holes don't really suck?

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

THE LITTLE BOOK OF GRAVITY



CONTENT DEVELOPED AND WRITTEN BY

BEN GILLILAND

DESIGN, LAYOUT AND GRAPHICS: BEN GILLILAND

ADDITIONAL IMAGES: NASA

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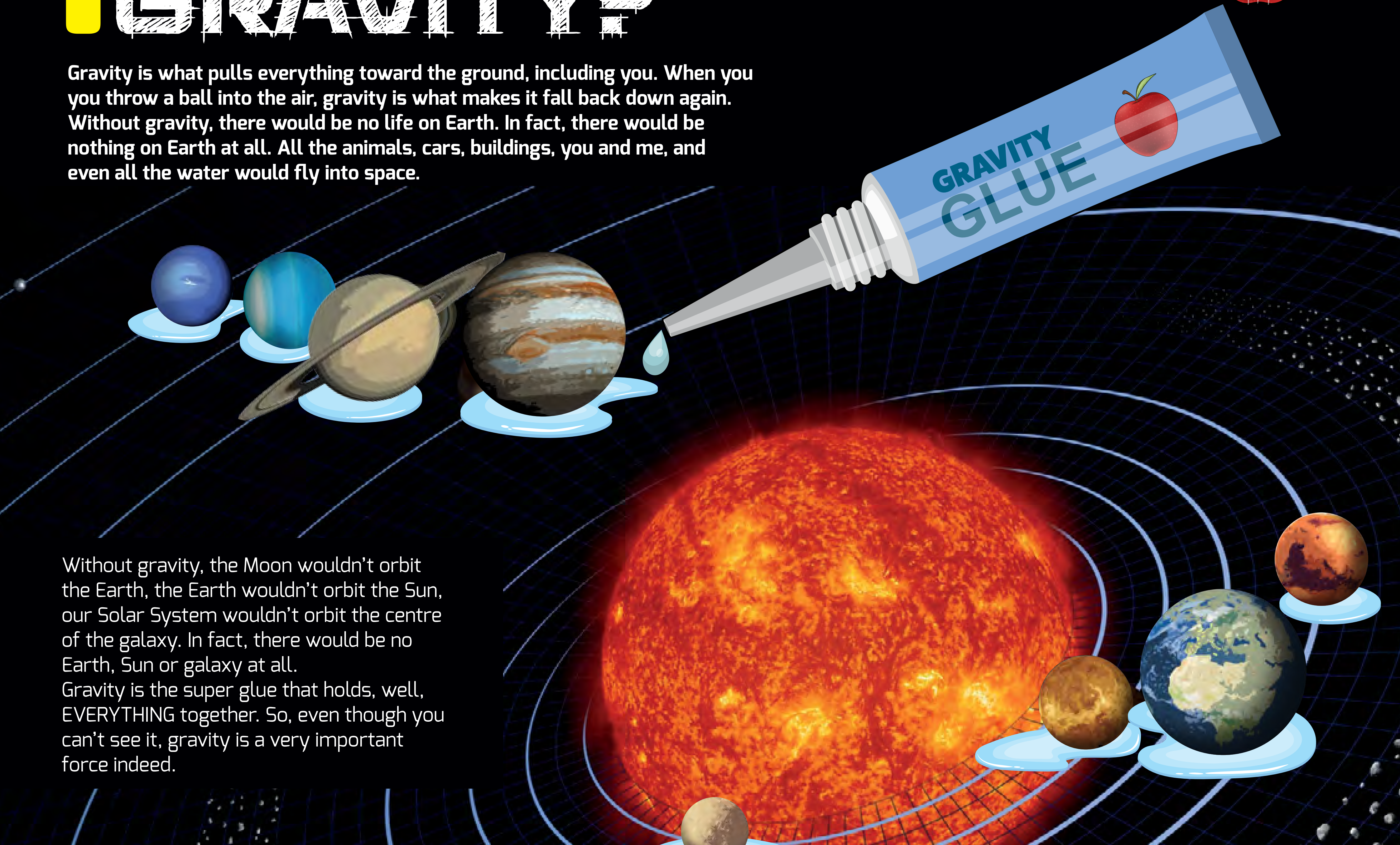
1 WHAT IS GRAVITY?

Gravity is what pulls everything toward the ground, including you. When you you throw a ball into the air, gravity is what makes it fall back down again. Without gravity, there would be no life on Earth. In fact, there would be nothing on Earth at all. All the animals, cars, buildings, you and me, and even all the water would fly into space.



Without gravity, the Moon wouldn't orbit the Earth, the Earth wouldn't orbit the Sun, our Solar System wouldn't orbit the centre of the galaxy. In fact, there would be no Earth, Sun or galaxy at all.
Gravity is the super glue that holds, well, EVERYTHING together. So, even though you can't see it, gravity is a very important force indeed.

1.1 GRAVITY ACCORDING TO ISAAC NEWTON

Humans spent a very long time taking gravity for granted. It was only about 300 years ago that an English scientist called Sir Isaac Newton decided to give it some serious thought and try to figure out what makes it work.

There is a famous story, which may or may not be true, about how Newton was prompted to think about gravity....

One day Newton was chilling out underneath an apple tree when an apple lost its fight against gravity and fell from the tree and landed on the famous scientist's head.

This made Newton wonder why the apple fell down instead of up or to the side. He realised that there must be a special kind of force that acts on all the objects on Earth and pulls them to the ground.

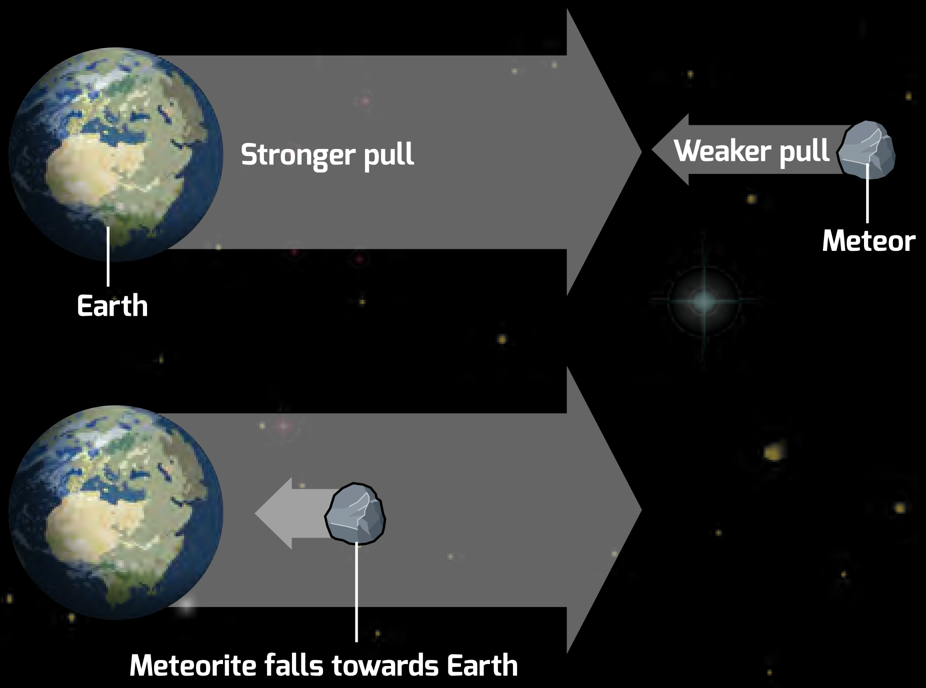
1.2 NEWTON'S GRAVITY FEELING THE PULL

Gravity isn't just something that happens on Earth. Throughout the Universe it is the force that draws two objects together. It is the force that helped to form moons, planets, stars and even the Universe itself.

Newton's theory of gravity showed us that gravity is a predictable force that acts on all matter in the Universe – every particle of matter is attracted to every other particle of matter – and that gravity's strength is affected by an object's mass and how far apart the objects are.

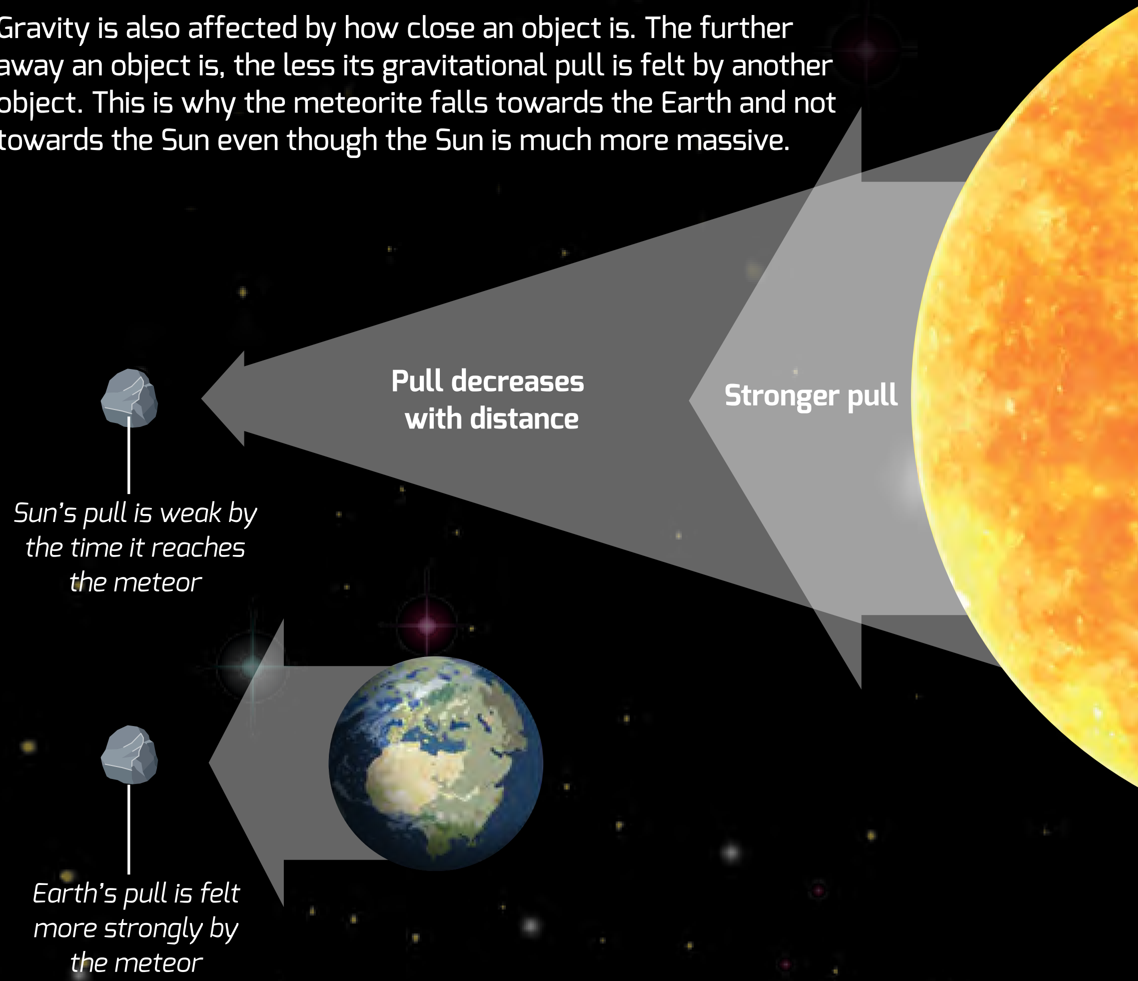
MASS MATTERS

The greater an object's mass, the more its gravitational pull is felt by another object. This is why a small object like a meteorite (or apple) falls towards a huge object like a planet.



CLOSE ENCOUNTERS

Gravity is also affected by how close an object is. The further away an object is, the less its gravitational pull is felt by another object. This is why the meteorite falls towards the Earth and not towards the Sun even though the Sun is much more massive.



1.3 WHAT IS MASS ANYWAY?

LITTLE BOOK OF GRAVITY

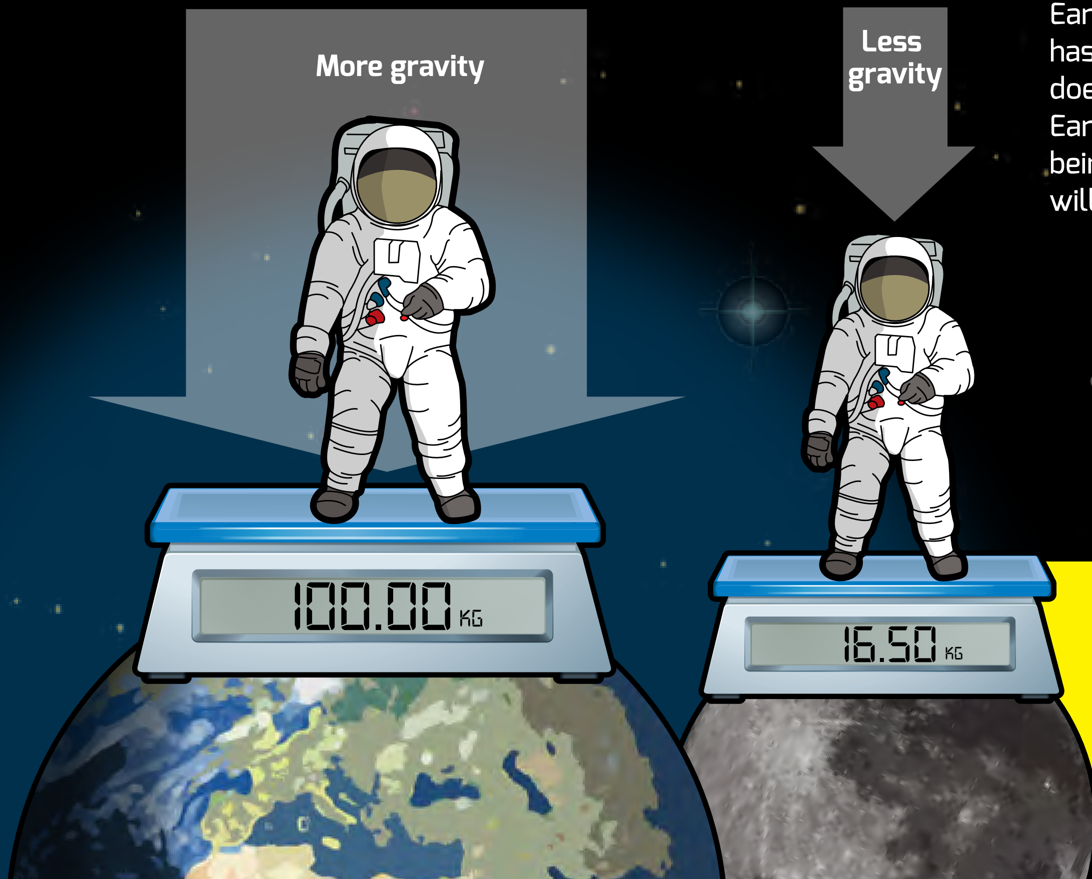
We'll talk about something called 'mass' a lot in this book. Now, it might seem that when we talk about something having lots mass, we could just say that it is heavy… but things are more complicated than that.

We will also confuse you by talking about objects being 'massive'. In this book, we don't mean that they are huge but that they are objects with lots of mass. In fact, the most massive objects in the Universe are not necessarily the largest.

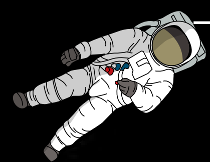
IS MASS THE SAME AS WEIGHT?

It is tempting to thing of mass as being the same as weight because a more massive object is likely to be the heaviest object, but that is not always the case.

An object only has weight when it is subjected to a gravitational force and the amount of that gravitational pull determines how much weight an object has.



Earth has more mass than the Moon and so has more gravitational pull than the Moon does. This means that a human being on Earth weighs more than the same human being would on the Moon – even though they will have the same amount of mass.



An astronaut floating in space can be described as being 'weightless' but he certainly isn't massless!

Your weight on the Moon is 16.5% what you would feel on Earth. If you weig 100 kg on Earth, you would only weigh 16.5 kg on the Moon. So, when you step on a set of scales, you are really measuring how much gravity is acting on your body. Pretty cool.

DID YOU KNOW?

MASSIVE DOESN'T MEAN HUGE

In day-to-day life and language, a massive object is one of enormous size but, in physics, something doesn't have to be huge to be massive.

A neutron star, for example, could be about the same size as a small city, but more massive than the Sun.

In a neutron star, the particles are packed together so tightly that all the empty space has been squeezed out.

If you could scoop out a teaspoon of neutron star material and take it to Earth, it would weigh about ten billion tonnes (that's the same as… a lot of elephants!).

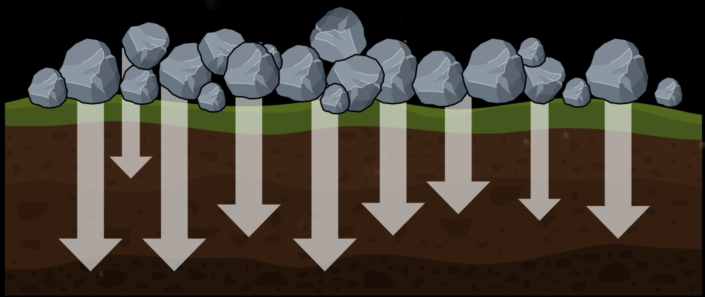
1.4 GRAVITY: THE GREAT PLANET SCULPTOR

LITTLE BOOK OF GRAVITY

If you look at images of the Earth, the Moon and the planet Jupiter. What do you notice about them? Yes, they are all round, or spherical to be precise.
All the planets, stars and moons are round for one very simple reason: **gravity**.

WHY DOES GRAVITY LOVE A SPHERE?

When you spill a pile of gravel on the ground, it spreads out flat because each piece of gravel wants to be as close to the Earth as possible.



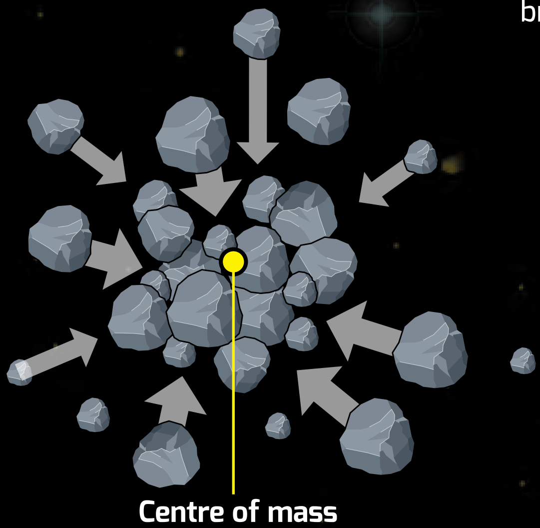
Objects are attracted to a more massive object's centre of mass.

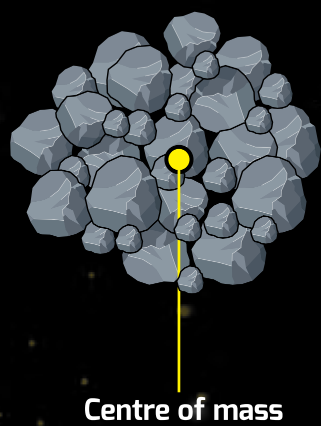
On the Earth, that is the centre of the planet, so the gravel spreads out on the surface.

In space, that's the centre of mass of the gravel itself – around which the gravel gathers.

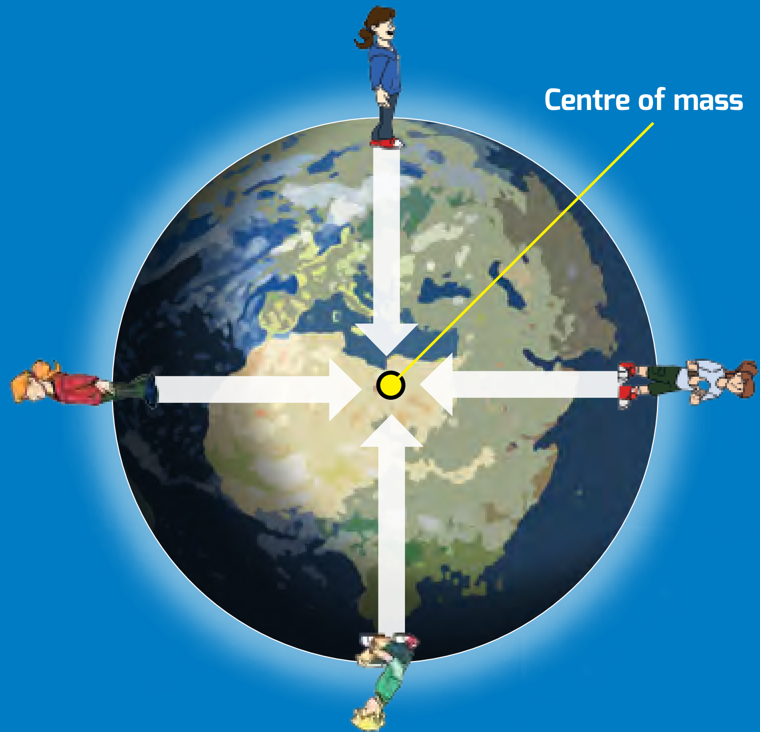
Eventually, if enough gravel were to gather together, you'd have a brand new spherical planet.

But if you were to throw a pile of gravel into space, instead of spreading out flat, it would all bunch together and form a ball, or sphere. This is because, without Earth's gravitational pull, the gravel is attracted to each other.





GRAVITY IS A REAL DOWNER



In this way, you are also attracted to the Earth's centre of gravity and this why you can stand on different sides of the planet and never fall off.

What we think of as 'down' is really just the direction things fall towards the centre of the Earth.

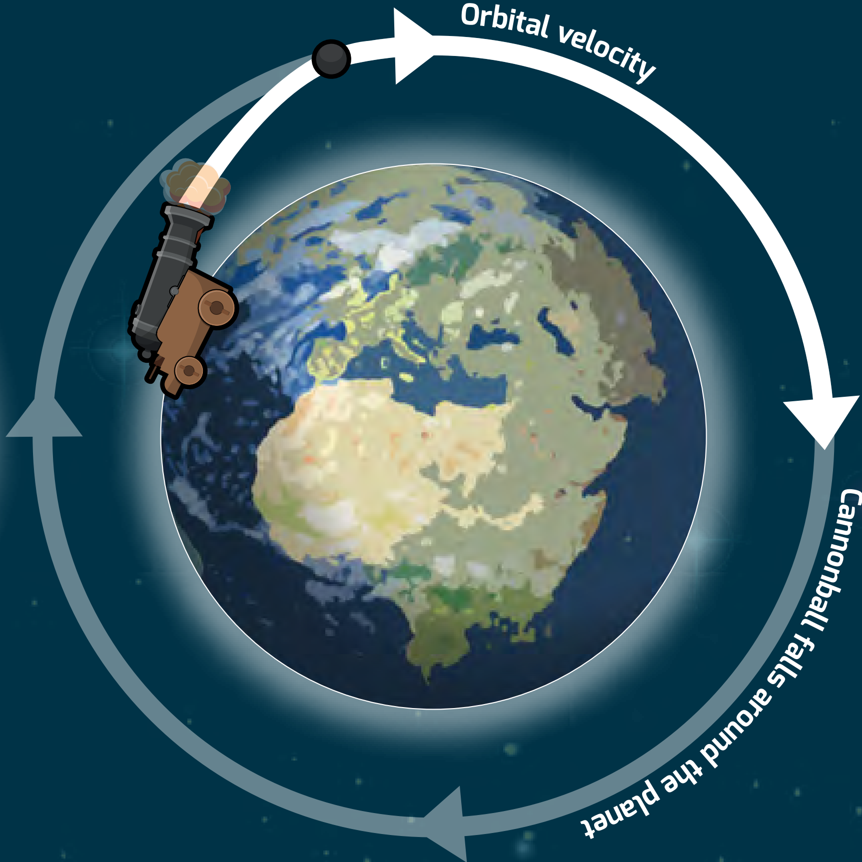
ORBITS: IT'S JUST FALLING WITH STYLE

If you fire a cannonball from a cannon you can see that as soon as it is fired, gravity takes effect and starts to pull the ball back towards the Earth, which is why it travels in an arc.

At less than 7,000 mph (11,300 kph) it falls back to Earth.

Newton came up with the idea that if you could fire a cannonball with enough speed, instead of falling back to Earth, it would fall around the Earth, never hitting the surface, in a circular orbit. It is this effect that keeps satellites in orbit around the Earth.

At 17,000 mph (27,000 kph) it will go into orbit.



He also suggested that a cannonball fired with enough speed would escape Earth's gravitational pull and travel into space.

At more than 25,000 mph (40,000 kph) it escape Earth's gravitational pull.

1.6 FALLING FOR GRAVITY (AGAIN)

EVERYTHING FALLS AT THE SAME SPEED

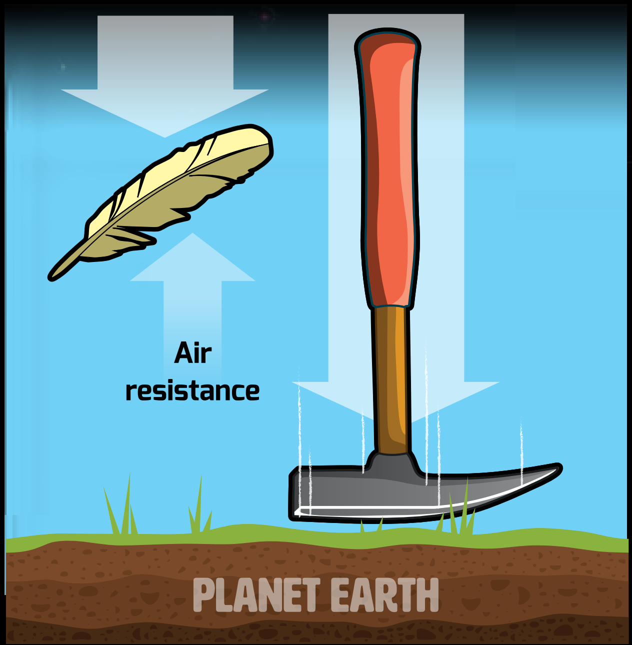
So, we've now learned that an object with lots of mass has more gravitational attraction than an object with less mass. That must mean that a more massive object would fall faster than a less massive object, right?

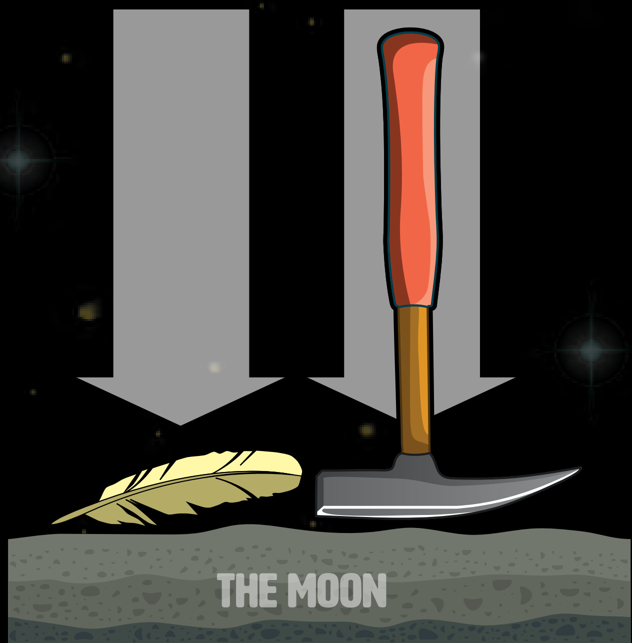
Something the size of a car must fall faster than something the size of a marble, it just makes sense! No, in fact, according Newton's laws, all objects within a gravitational field must fall at the same rate.

BUT A FEATHER DEFINITELY FALLS SLOWER THAN A HAMMER... DOESN'T IT?

Yes, and no. It is true, but only because the Earth is surrounded by a thick layer of air that pushes against the feather and slows it down.

In a vacuum (or on the surface of the Moon) the feather and hammer would fall at the same rate and hit the ground at the same time.





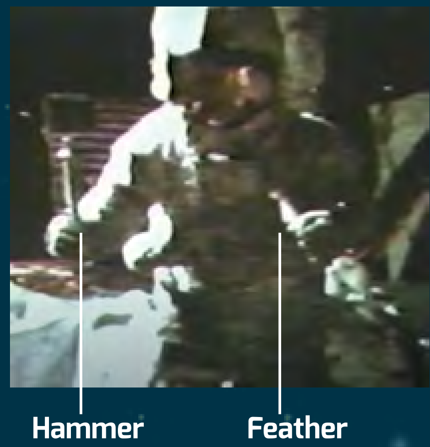
WEIGHT IS ACCELERATION

Everything has to fall at the same speed because an object's 'weight' can be described as being an object's mass being accelerated due to gravity. The rate of acceleration is always the same, regardless of mass.

The reason objects weigh less on the Moon is that the Moon's lower mass means that the rate of acceleration is lower, which means the weight is less.

So, on the Moon, objects don't fall more slowly becuase they weigh less, the actually weigh less because they fall more slowly!

MOON DROP



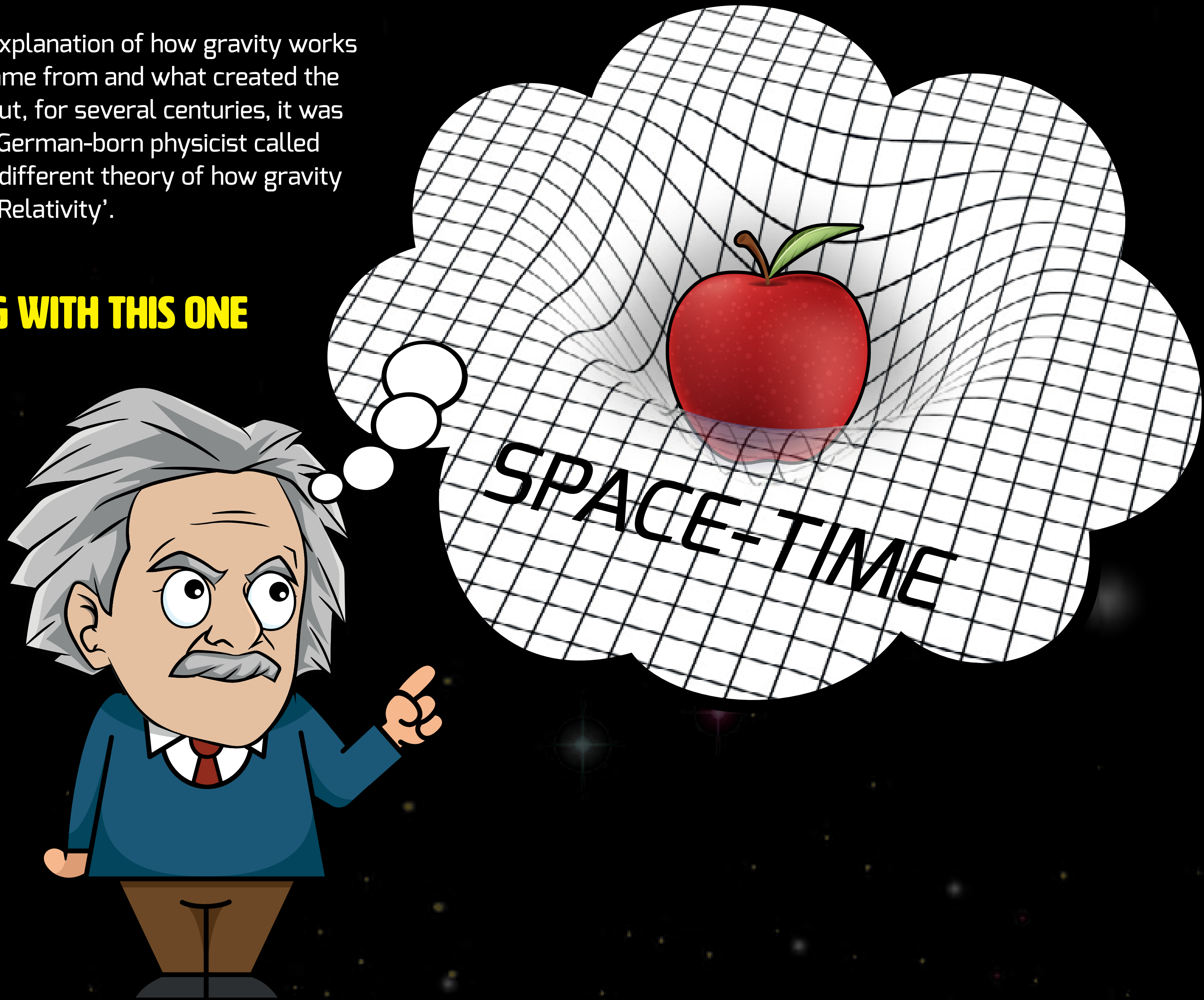
In 1971, while he was on the Moon, astronaut Dave Scott dropped a hammer and a feather from the same height at the same time. Because there was no atmosphere to slow the feather, they both landed at the same time.

2 GRAVITY ACCORDING TO ALBERT EINSTEIN

Newton's gravity was an excellent explanation of how gravity works but it didn't explain where gravity came from and what created the force that draws objects together. But, for several centuries, it was the best description we had. Then a German-born physicist called Albert Einstein came up with a very different theory of how gravity works called his 'General Theory of Relativity'.

THE FORCE IS NOT STRONG WITH THIS ONE

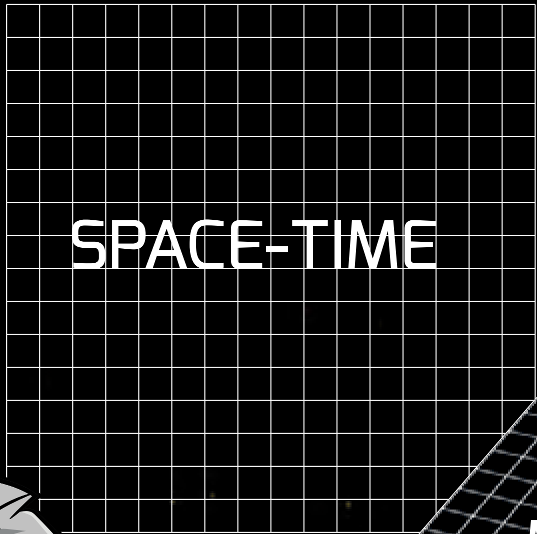
Einstein discovered that gravity was not a force at all. Instead, he discovered that gravity actually a side-effect of objects with mass making 'dents' in the fabric of the Universe itself – something known as space-time.



2.1 GRAVITY AND SPACE-TIME

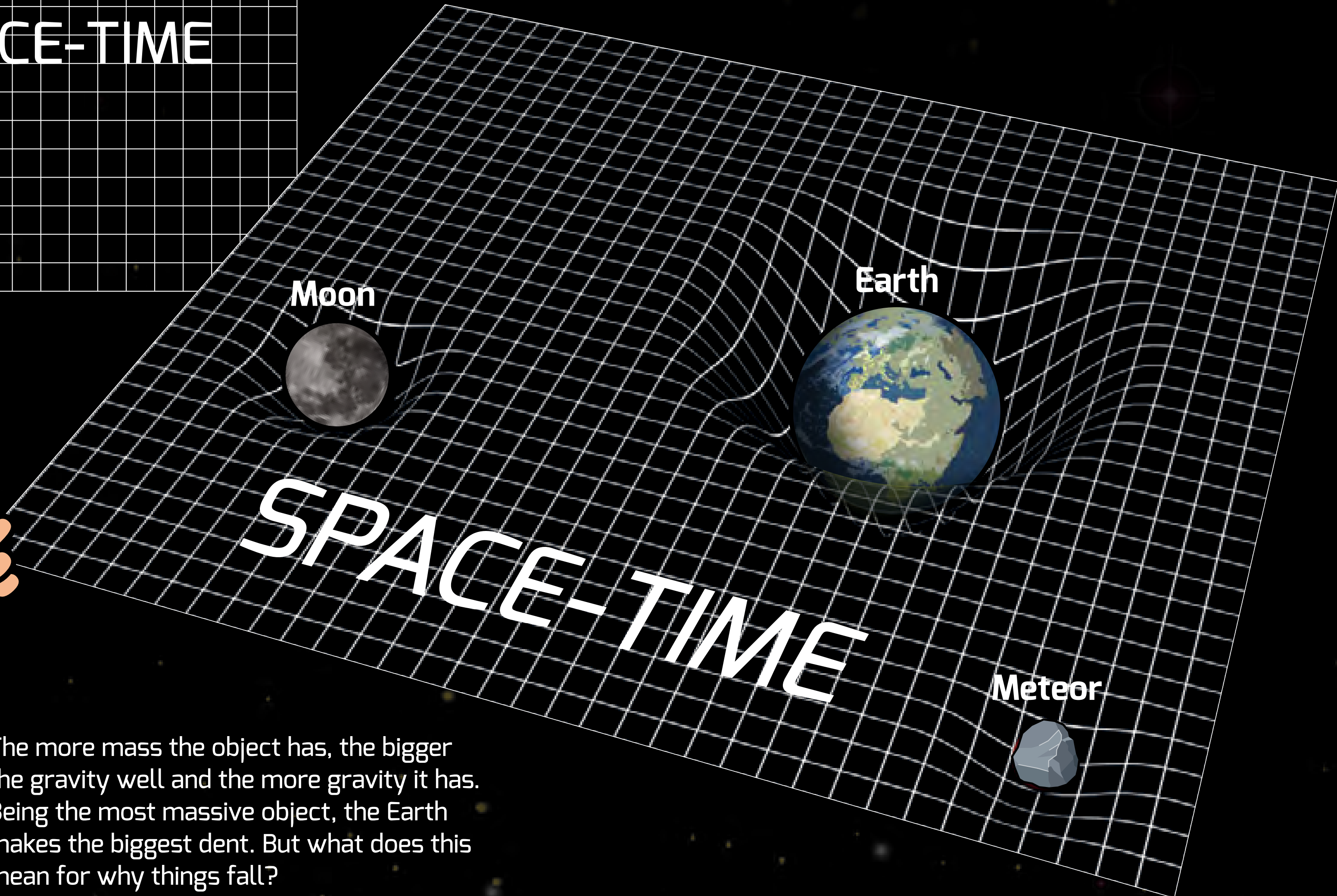
LITTLE BOOK OF GRAVITY

Einstein imagined that, instead of space being, well, empty space with the odd star and galaxy scattered through it, space was actually made up an invisible structure called space-time.



1 Space-time is often imaged as being like a giant rubber sheet that has been slowly stretching and expanding since the Big Bang.

2 Einstein figured out that if you were to place massive objects, such as a planet, moon or meteor, on this sheet, they would make a dent in space-time. This dent also known as a gravity well.



3 The more mass the object has, the bigger the gravity well and the more gravity it has. Being the most massive object, the Earth makes the biggest dent. But what does this mean for why things fall?

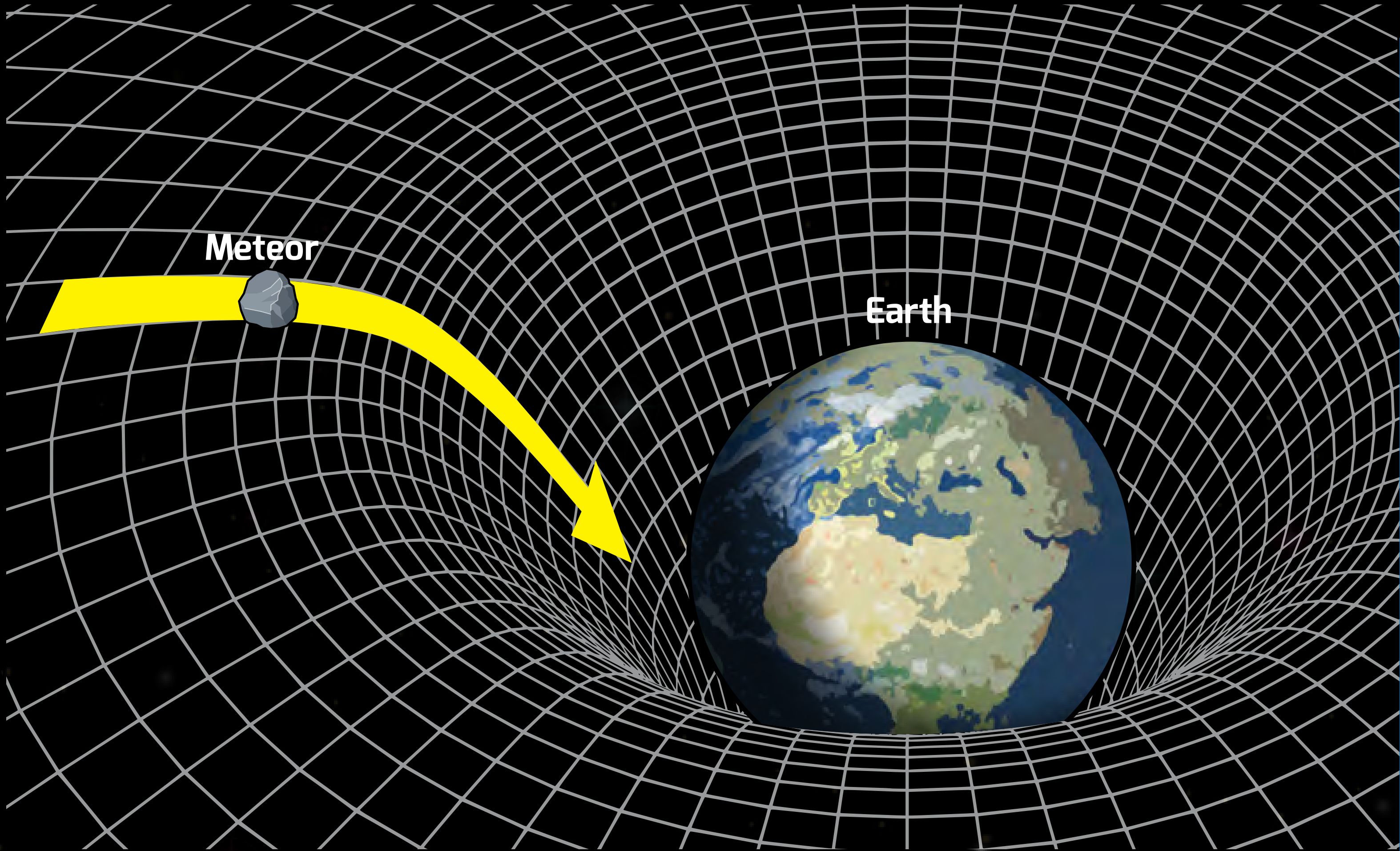
2.2 FALLING FOR EINSTEIN'S GRAVITY

WHY DO THINGS FALL?

Einstein showed us that things don't fall because they attracted to each other but because one object is making a bigger dent in space-time than another object.

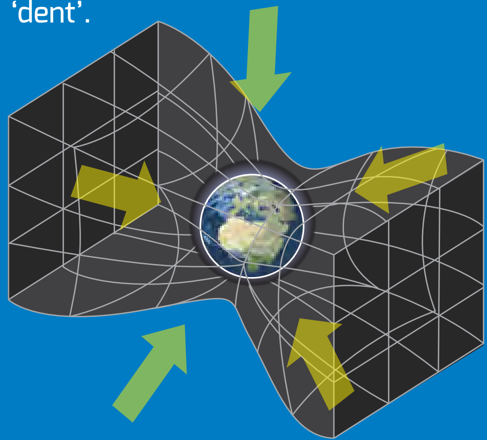
Take a look at the dent the Earth makes in space-time. It make a big dent because it has lots of mass.

Now, if a less massive object was to come along – such as a meteor – even though the meteor makes its own dent in space-time, the dent made by the Earth is much deeper and the asteroid will 'fall' into it (a bit like a golf ball rolling into a hole).



DID YOU KNOW?

Although the dent in a rubber sheet is a useful thing to imagine, space-time is not flat and one-dimensional. In reality, space-time has lots of dimensions – up/down, left/right, backwards/forwards etc – so it actually more like a 'pinch' in a three-dimensional cube, than a 'dent'.



But that's hard to imagine so we'll stick with the flat rubber sheet from now on.

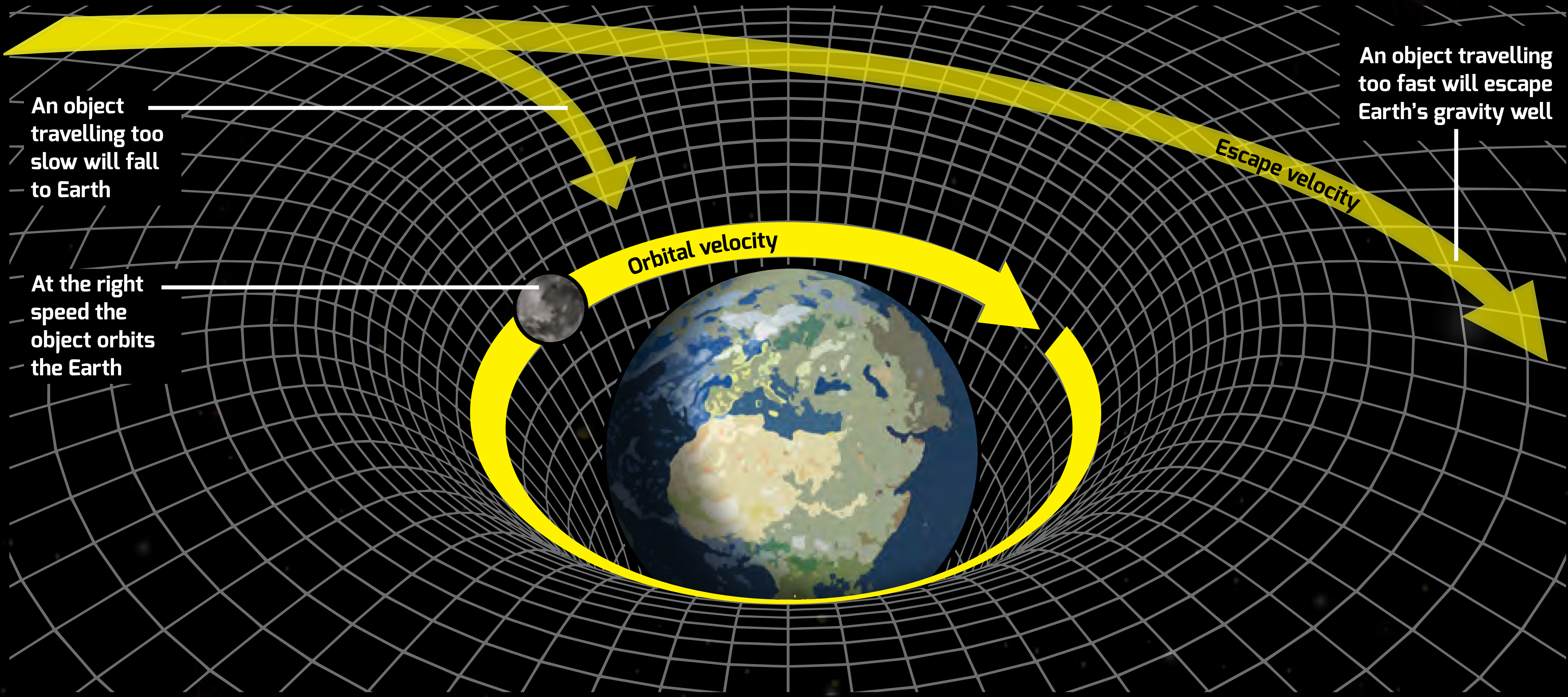
2.3 ORBITING WITH EINSTEIN'S GRAVITY

WHY DOESN'T THE MOON FALL TO EARTH TOO?

Newton wasn't wrong when he imagined that an object will orbit a planet because it is falling around the planet at the right speed. The Moon orbits the Earth because, although it is falling into the Earth's gravity well, it is moving fast enough to sort of 'roll' around the edge of the well.

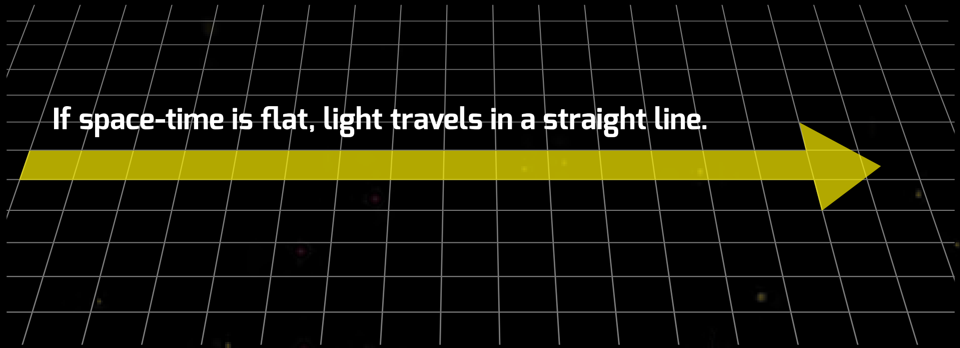
Imagine rolling a marble around the edge of a bowl – if you push it too fast, it'll fly out, but if you push it at the right speed, it'll roll around the edge as if orbiting. When it slows down, it'll fall to the bottom of the bowl.

Thanks to Einstein, we didn't need to imagine gravity as an invisible force that pulled objects together. Instead, gravity is just the effect objects have on the Universe around them.

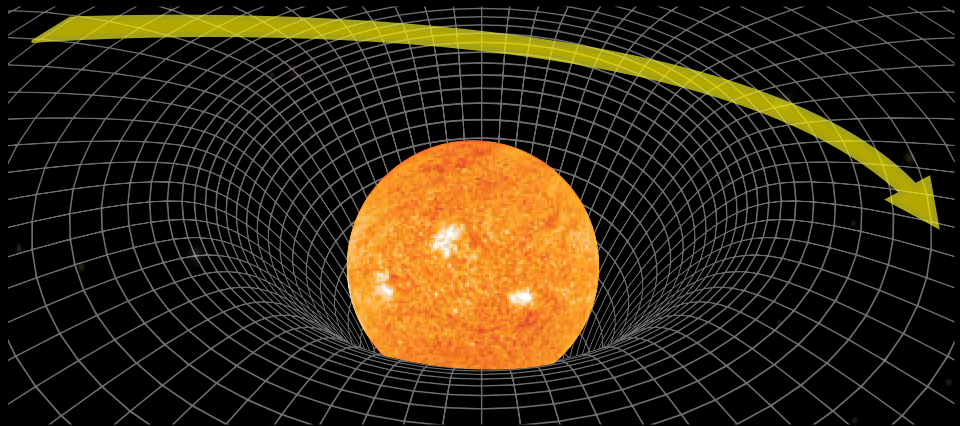


CAN GRAVITY BEND LIGHT?

Because light has no mass, Newton's theory of gravity would expect it to only follow a straight line. But Einstein predicted that, because light travels through space-time, the path of light must also follow the shape of space-time. If space-time is distorted by a massive object, the path that light travels through that space must also bend.

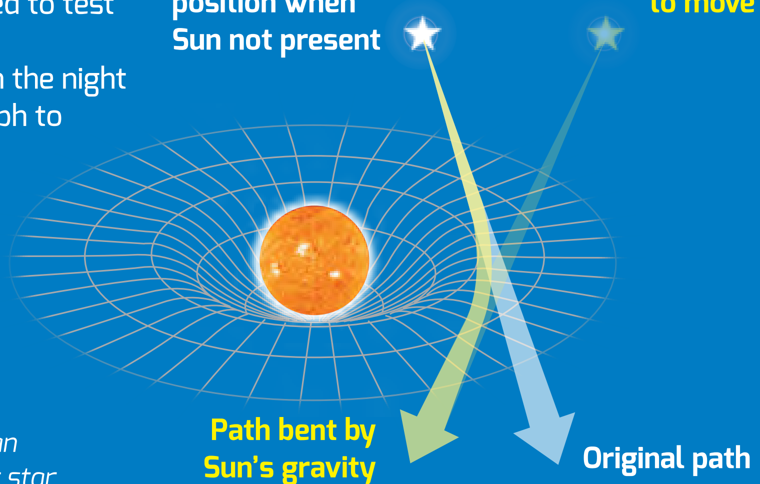


But a really massive object (like a star) bends space-time so much that the path of light is also bent.

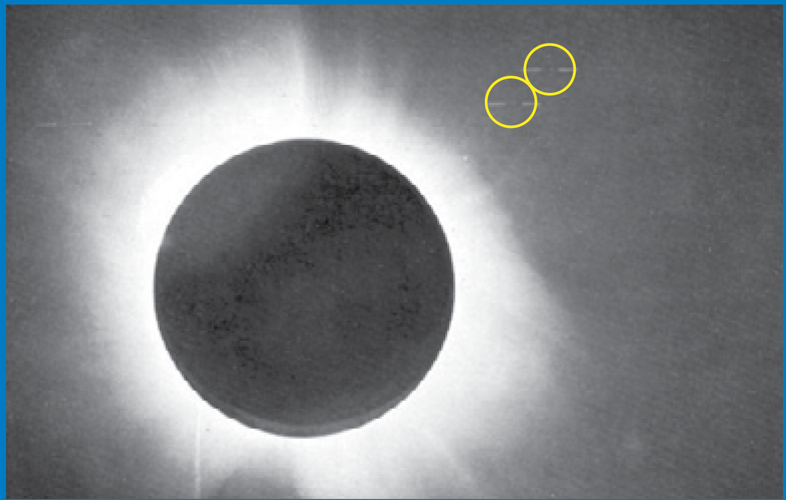


PROVING EINSTEIN RIGHT

In 1919 a British astronomer, Arthur Eddington, decided to test Einstein's idea.
He found a distant star in the night sky and took a photograph to note its position. Then he waited for a total solar eclipse and took another photograph of that part of the sky when the Sun appeared near to the distant star.



Eddington had to wait for an eclipse because the distant star would be too dim to see with the Sun blazing away in the sky.



If Einstein was correct and the light from the star was bent by the Sun, the star should appear to move position in the night sky.

Sure enough, the star seemed to move and Einstein was proven right.

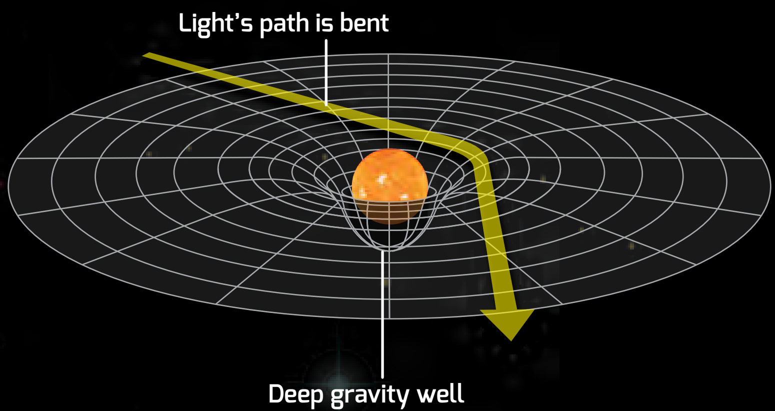
CAN GRAVITY SWALLOW LIGHT?

Another wacky side-effect of Einstein's theory was that an object with a really, really, really, really huge amount of mass (think several star's worth) would make a really, really, really, really deep dent in space-time. And that everything that got too close to that dent would fall into it and never escape.

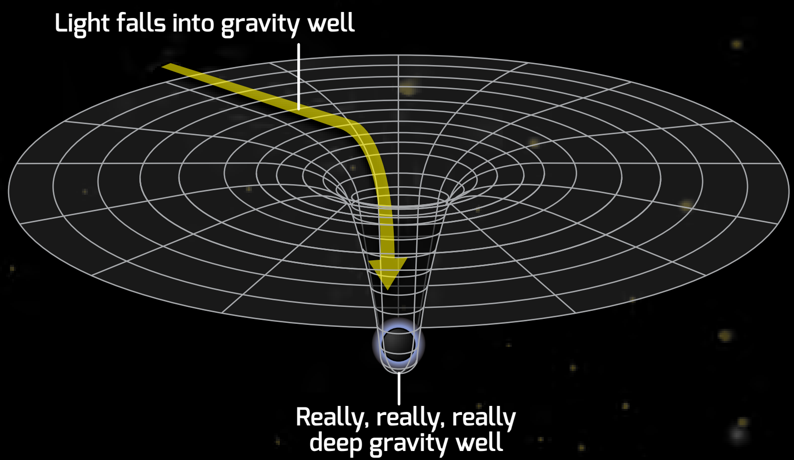
Not even light, which travels as fast as anything possibly can, would have enough speed to escape a black hole's gravity well. Even light would fall in and be trapped forever.
These have also been proven to exist and today we call them 'black holes'.

THE BLACK HOLE: WENT GRAVITY GETS EXTREME

1 We've already seen how objects with lots of mass make a deep dent in space-time. We've also seen that when light passes a massive gravitational object, its path can be bent.



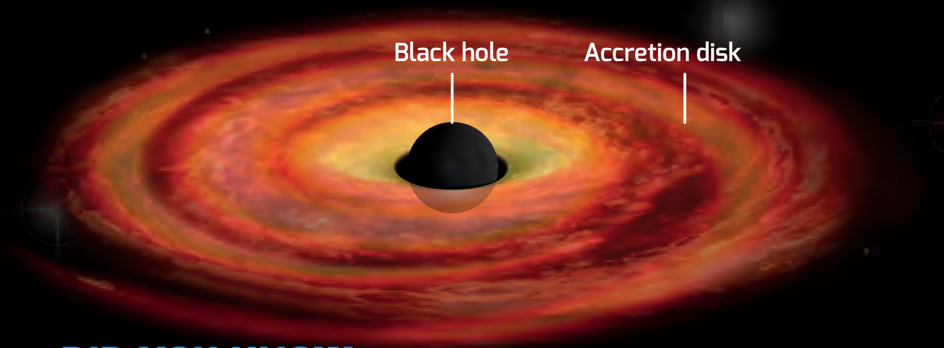
2 There are some objects out there that have so much mass that they make a really, really, really big dent in space-time. They create a gravity well so deep that even light can't escape.



3 These objects are known as black holes. They are often surrounded by a glowing disk of material that swirls around the black hole as it falls into the gravity well (a bit like water swirling around a plug hole in a sink).

The disk of swirling matter is known as an 'accretion disk'.

The point at which light tips over the edge of the black hole's gravity well is called the 'event horizon'.



DID YOU KNOW

When someone says that a black hole sucks, they are wrong. Stuff isn't 'sucked' in – it just gets too close and falls in!

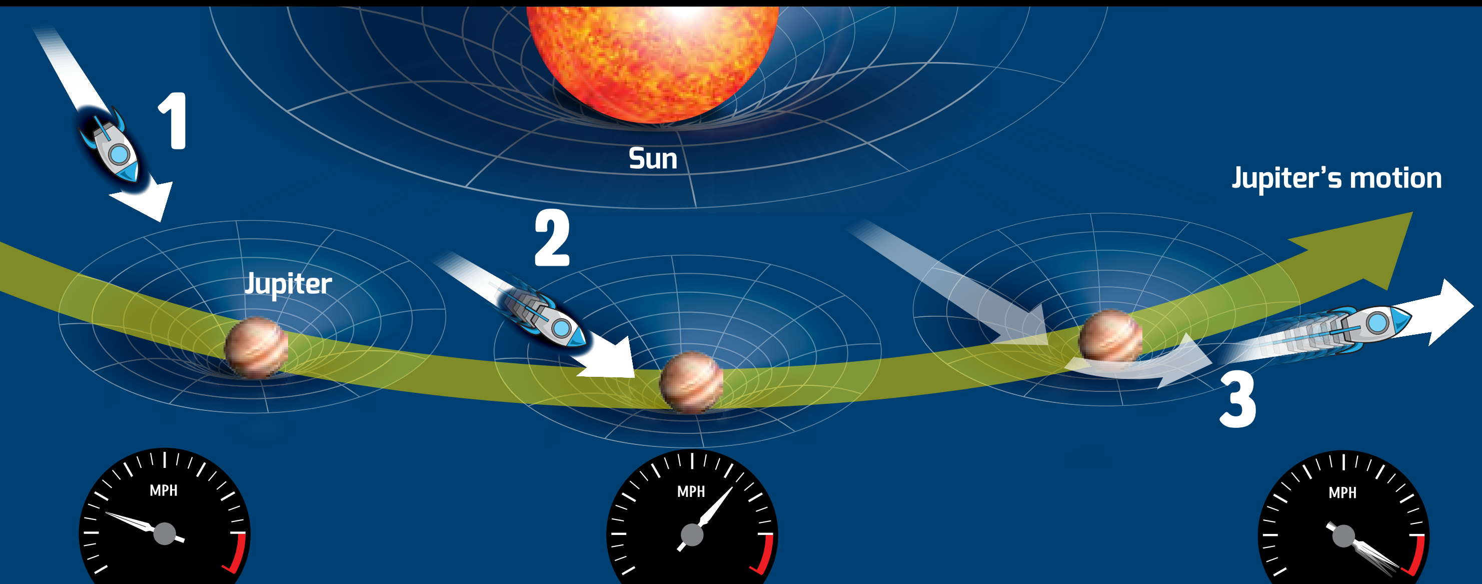
3 USING GRAVITY TO EXPLORE THE SOLAR SYSTEM

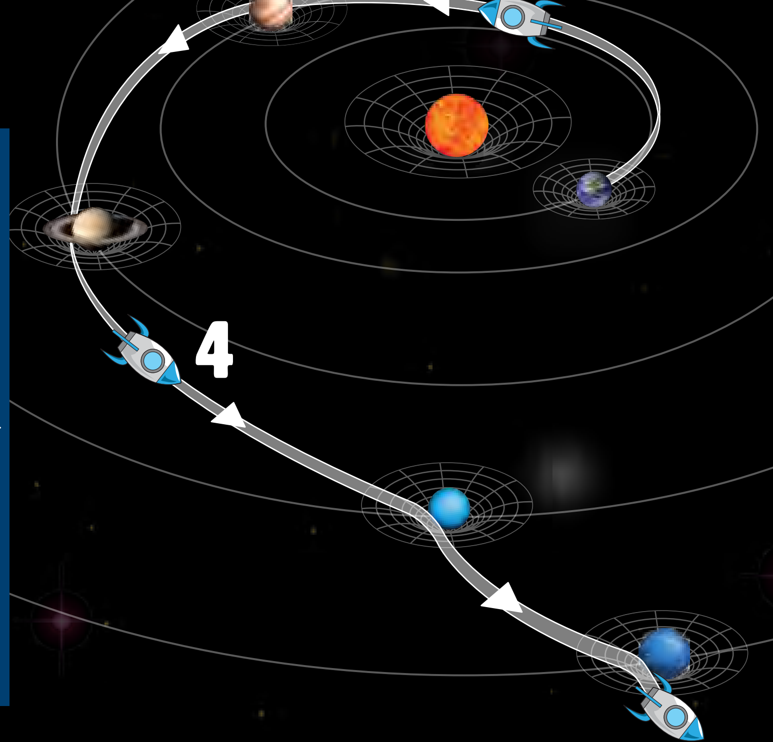
USING GRAVITY TO GET A SPEED BOOST

When a spacecraft leaves Earth in a rocket, it is launched with enough speed to escape the Earth's gravity but not much more. If it wants to travel into deep space, it has to find enough speed to escape the Sun's gravity too. Using rockets isn't a good plan because they'd need too much fuel – which makes the spacecraft heavier and harder to launch.

Luckily, scientists have a clever trick up their sleeves called a 'gravity assist'. Also known as a 'slingshot' manoeuvre, the technique works by using the gravity wells of other planets to gain the speed it needs to complete its journey.

HOW A GRAVITY ASSIST WORKS





1 Your spacecraft heads towards Jupiter as it whizzes around the Sun.

2 When you get close enough, you fall into Jupiter's gravity well and accelerate.

3 This gives you enough speed to climb out the other side of the gravity well. Because Jupiter is moving so fast through space, you have now added Jupiter's speed to your original speed!

It's like throwing a ball from a train moving 60 mph. You might be only able to throw at 10 mph but when it leaves the train, it will be travelling at the speed you threw it plus the speed of the train. Suddenly, your ball is travelling at 70 mph!

4 By 'slingshotting' from one planet to the next, your spacecraft can explore the entire Solar system.

3.1 USING GRAVITY TO EXPLORE THE UNIVERSE

USING GRAVITY AS A TELESCOPE

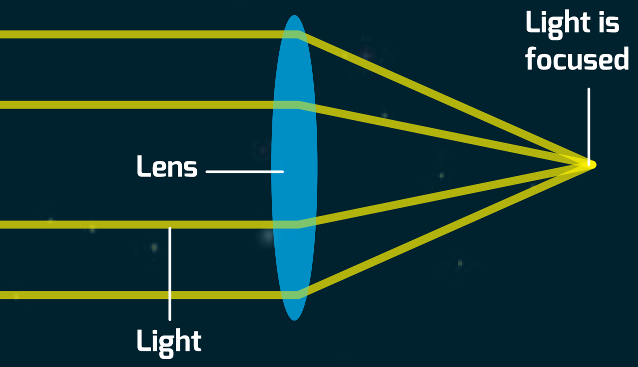
It might sound crazy, but the best way to see an object in the most distant recesses of the cosmos is to make sure that you have a nice big galaxy nearby that completely blocks your view.

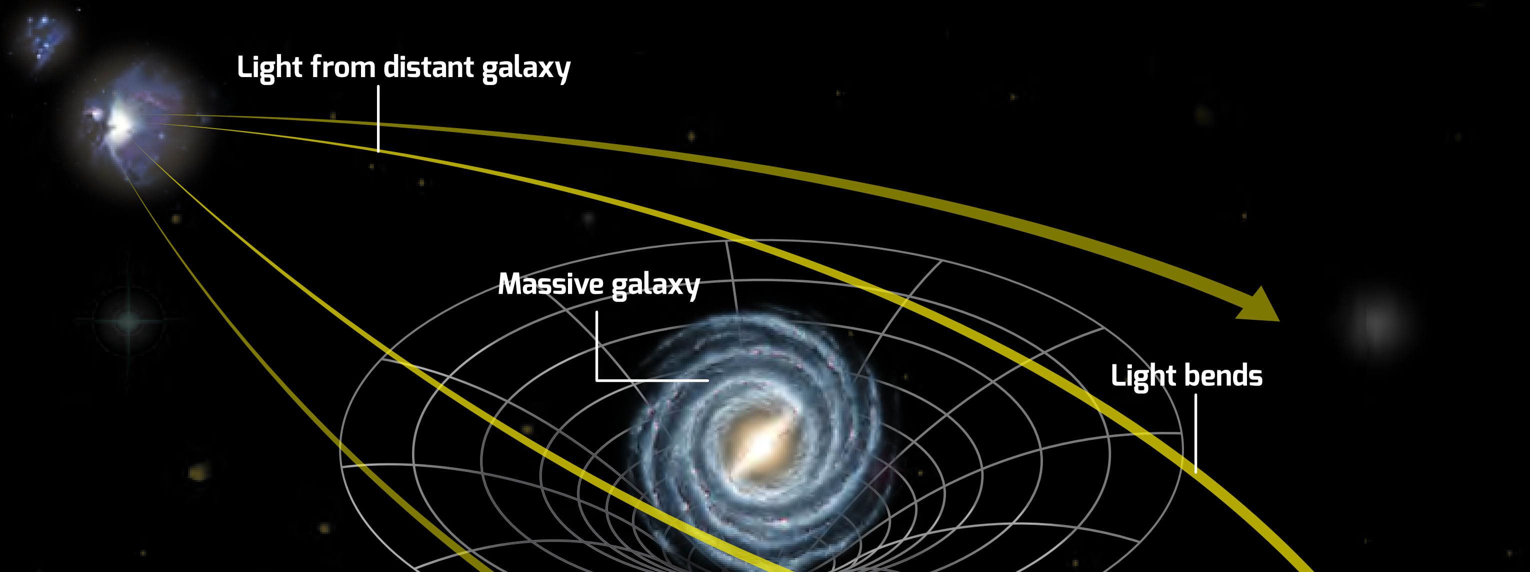
Confused? Well, in the weird world of astronomy, not only can you see a distant object hiding behind a massive galaxy, but you can see it bigger and brighter than you could by using even the very best of telescopes.

GRAVITATIONAL LENSING

We've already seen that objects with lots of gravity can bend light. Gravitational lensing uses this effect to bend light rays and focus them together – just like a lens in a telescope!

1 This is this sort of lens you might find in a telescope or magnifying glass. When light passes though the lens, it's path is bent and focused – making the image appear bigger.





2 A gravitational lens work in much the same way – except the light is bent by the gravity of a massive object (such as a galaxy). The light bends around the galaxy and is focused – making the image bigger.

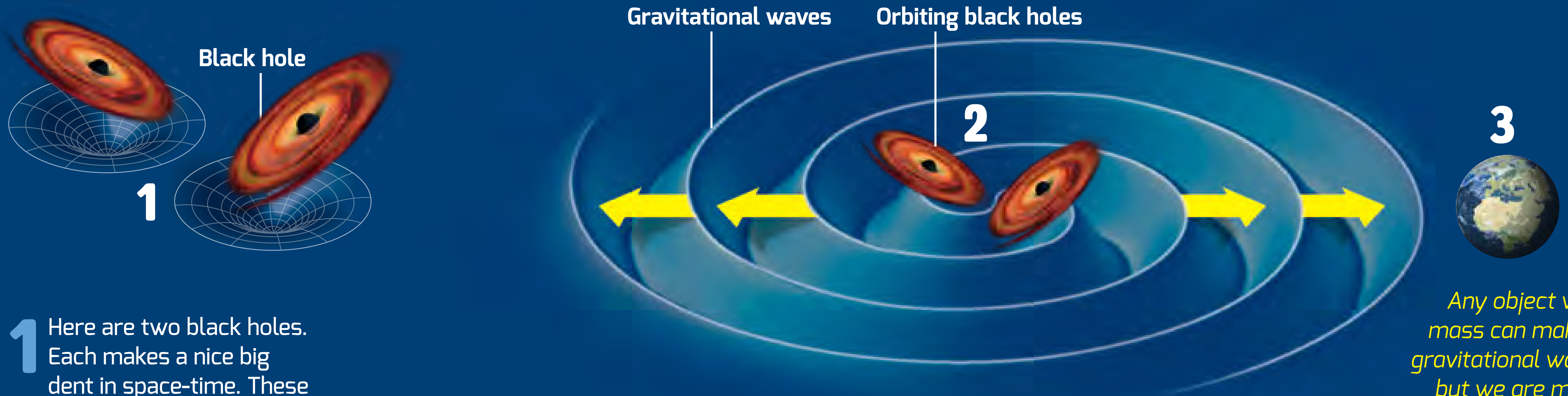
3.2 USING GRAVITY TO EXPLORE THE UNIVERSE

USING TELESCOPES TO 'SEE' GRAVITY

We've seen how gravity can be used as a telescope, but what if you could build a telescope that could 'see' gravity? If you could see the effects that a massive object have on the fabric of space-time, you could figure out what that object is – even if you can't see it.

Einstein had the idea that, if massive objects could make a dent in space-time, they should also be able to make waves that would travel out through the cosmos (like a stone thrown into a pond). If we could detect those waves, we could use them to figure out what made them.

GRAVITATIONAL WAVES



1 Here are two black holes. Each makes a nice big dent in space-time. These dents aren't moving – so what happens if they start to move and orbit each other?

2 Well, they start to make waves in space-time – just like if you were to stir a blow of gravy with your finger. These waves travel out through space.

3 Scientists on Earth have machines that can detect these gravitational waves. They can use the pattern the waves arrive to figure out what made them.

Any object with mass can make a gravitational wave, but we are more likely to detect really massive ones like orbiting black holes, or exploding stars.

Gravitational wave astronomy could revolutionise our view of the universe because, unlike light, gamma-rays, or radio waves, nothing can get in the way of gravitational waves.

In theory, there will be no part of the observable Universe that will be invisible to astronomers – including the very first moments of the Universe's existence after the Big Bang.

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- **Free Publications and resource guides** suitable for teaching ages 10-18.

- **Funding** schemes for projects and school visits.

- **A Moon rock and meteorite loan scheme.**

- **Visits** to STFC's UK laboratories in Cheshire, Oxfordshire and Edinburgh plus CERN in Geneva.

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