# Black Holes

Chapter 24

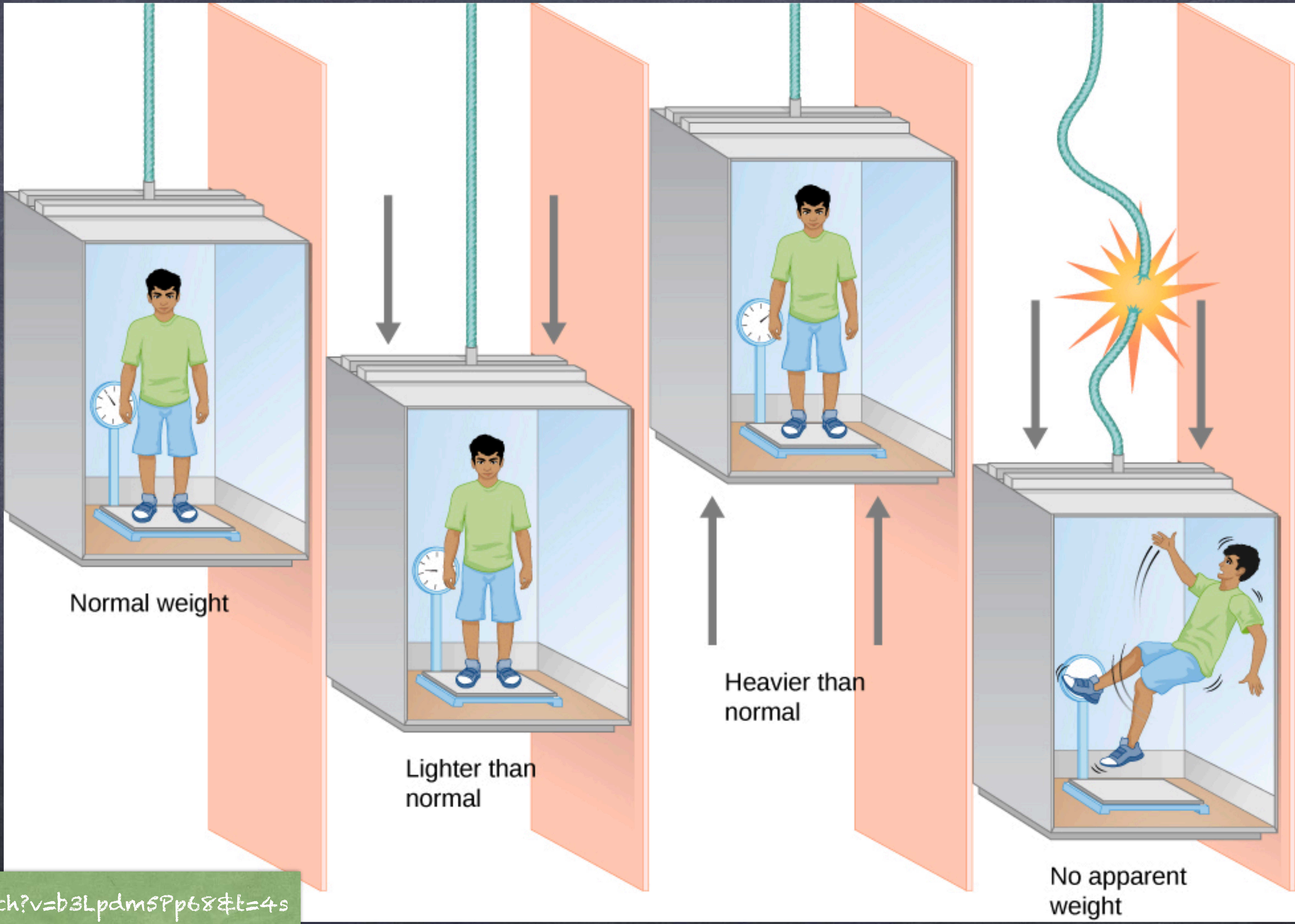

Detecting black holes requires a lot of deduction.
We may have the picture on the right in our head,
but what we actually see is the one on the right.

# General Relativity

- To understand black holes we first have to learn more about gravity. While Newton's law of universal gravity works to describe the vast majority of cases, there are some conditions where it fails.
- In those cases we must use Einstein's theory of General Relativity which is a more advanced theory of gravity.
- General Relativity starts with the observation that gravity and acceleration 'feel' the same.

Inside an elevator you cant tell if gravity is getter weaker or strong or gone. Gravity and acceleration seem to have the same effect.

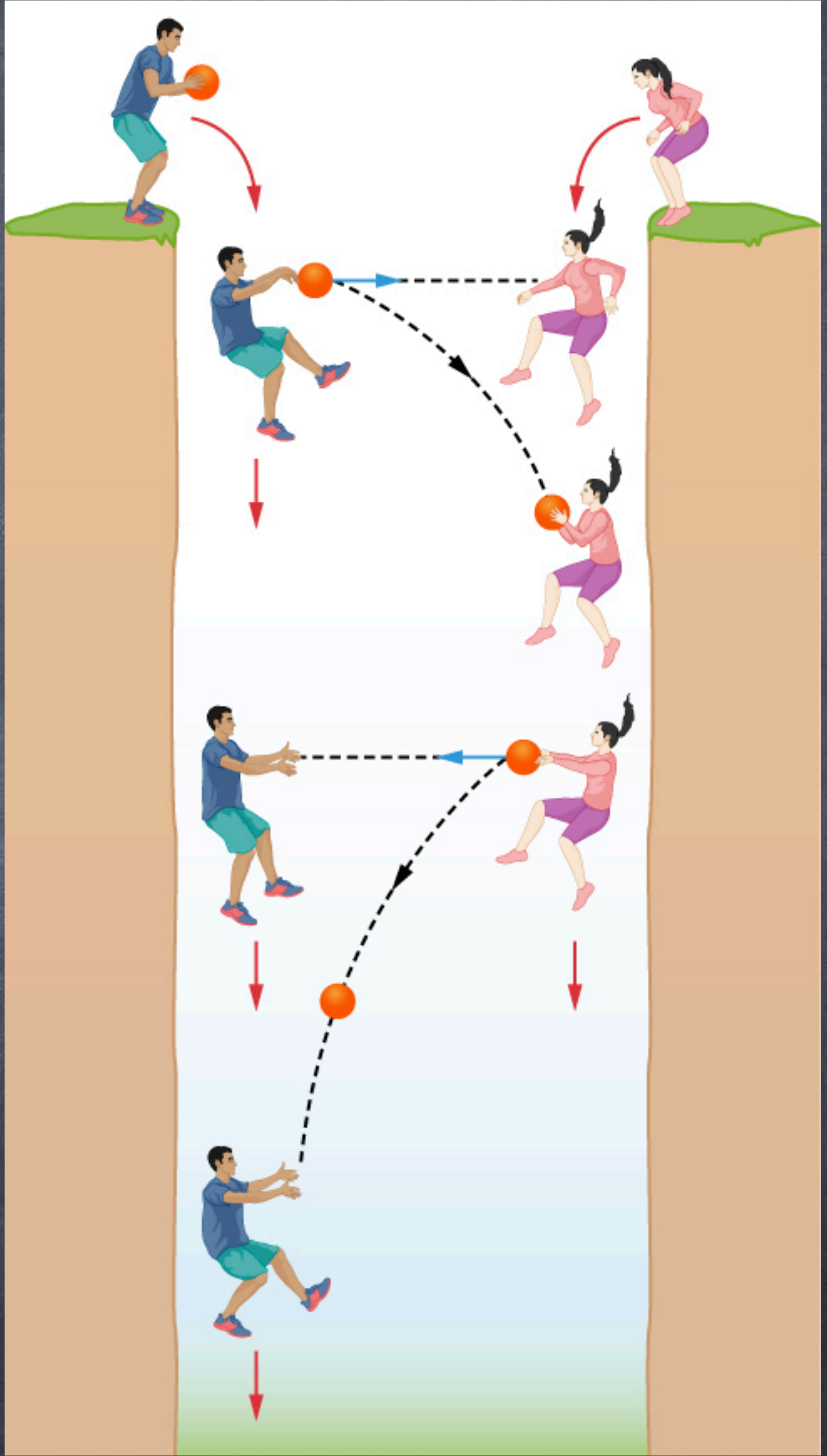
General Relativity says this equivalence must hold and we can use it to better understand gravity.




https://www.youtube.com/watch?v=b3Lpdm5Pp68&t=4s

Einstein's approach to general relativity was to suggest that since you can't tell if you are accelerating or effected by gravity they must be equivalent. For example consider the people to the right playing ball and falling. While they are doing this, they can throw the ball directly at each other. Since they and the ball are all falling at the same rate, the falling itself doesn't change anything. So even though they are falling this should be equivalent to two people who feel no gravity.

https://www.youtube.com/watch?v=WMK36dpHIkg



We think of light traveling in a straight line. If you turned on a laser point at the back of a ship, you would expect it to hit the front. But what if the ship was falling like our ball players, then to hit the front the light would actually have to bend like the ball's path.

So general relativity predicts that gravity bends light.

# Curved Spacetime

- How can we understand gravity bending light? Let's instead think about a curved surface like a ball. If you draw a straight line on the ball the line will be curved, because the surface is curved.
- Einstein concluded that space and time are curved like on a ball and that light is going in as straight a direction as it can.
- Why spacetime? because the curvature can be in space and in time, the two are linked. Light can't move only in space, it takes time to get to another place, so the curvature is from one point in space and time to another point in space and time.

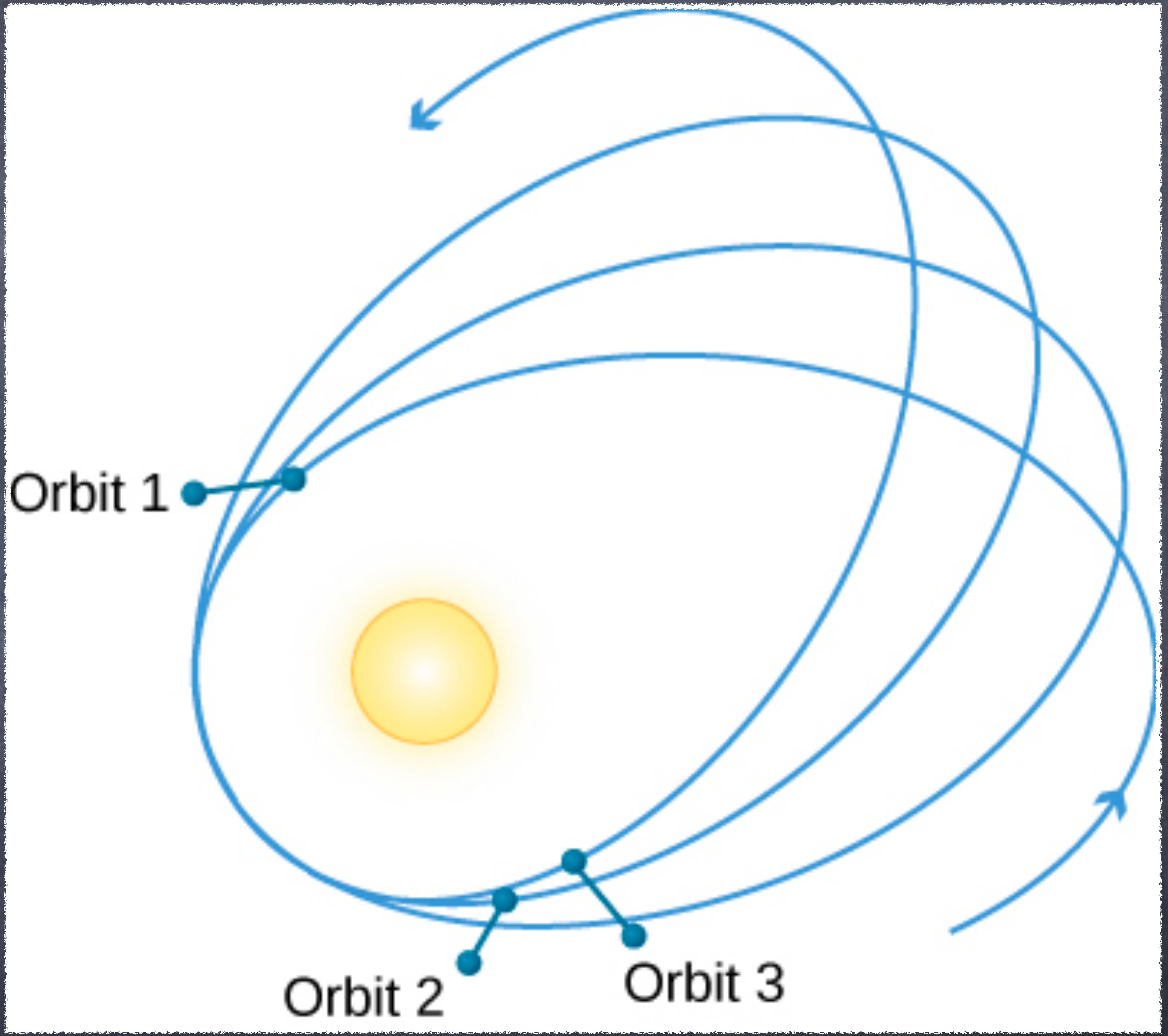
Moving on curved surfaces is actually rather common. For example, consider the ant on the rubber sheet below. The main different in general relativity is that we can't see the curvature of the surface and it is 4 dimensional instead of 2, but otherwise it is the same idea.

# Tests of GR

- Einstein's Theory suggested a radical change to the way we think about space and time, this is what made him famous. But is it really true? How can we test it?
- Tests of General Relativity are rather hard, they involve either incredible precision or incredible strong gravity like that found near neutron stars and black holes. Most tests have happened in the last two decades, but two were done a hundred years ago.

# Mercury's Precession

- Mercury has an elongated orbit, which precesses over time because of the effect of the other planets.
- However the predicted effect is less than observed, making astronomers in the 1800s think there was another planet closer to the sun which they names Vulcan.
- Vulcan was never found, but GR correctly predicts Mercury's precession.



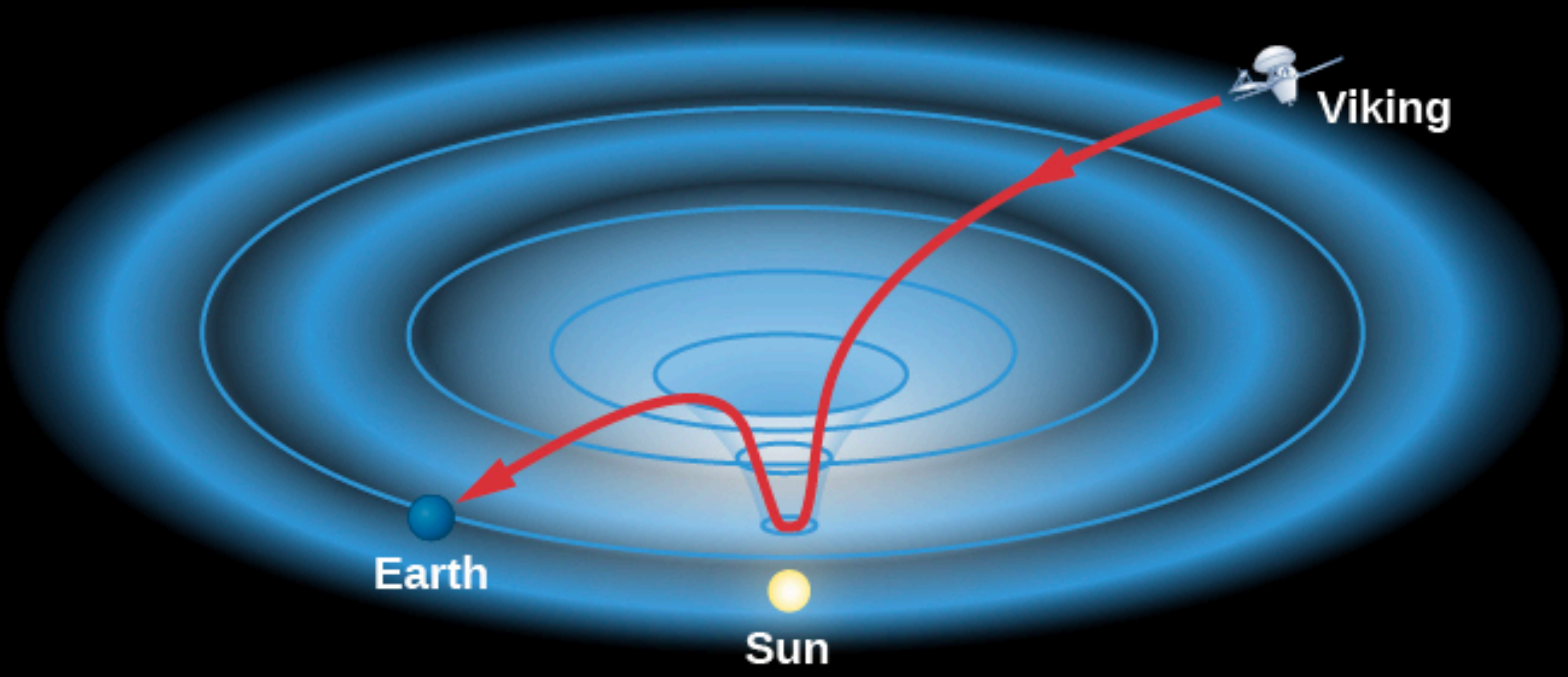
A true testable prediction of GR was how much light is bent by the sun. The bending of light by astrophysical bodies is called gravitational lensing. We normally can't see the stars near the sun, because the sun is bright. But during a total eclipse, the sun is blocked out and the positions of stars around it can be measured. These can then be compared to the position of those stars when the sun is not between them and us.

This was done in 1919 and GR was shown to be correct.

# Tests of Time

- GR predicts that time should run slower the stronger the gravity.
- This was tested in 1959 using the most accurate clocks of the time in the physics building at Harvard. The clock on the top floor ran faster than the clock on the bottom floor.
- Subsequently this has been tested on aircraft and space flights.
- This effect has to be taken into account when using GPS which is based on very accurate clocks. Since the satellites are high above the Earth's surface their clocks run just a little bit faster.

In 1976 a spacecraft on mars sent a radio wave back to Earth just passing the Sun. The wave was slightly delayed by the Sun's gravity matching GR predictions.

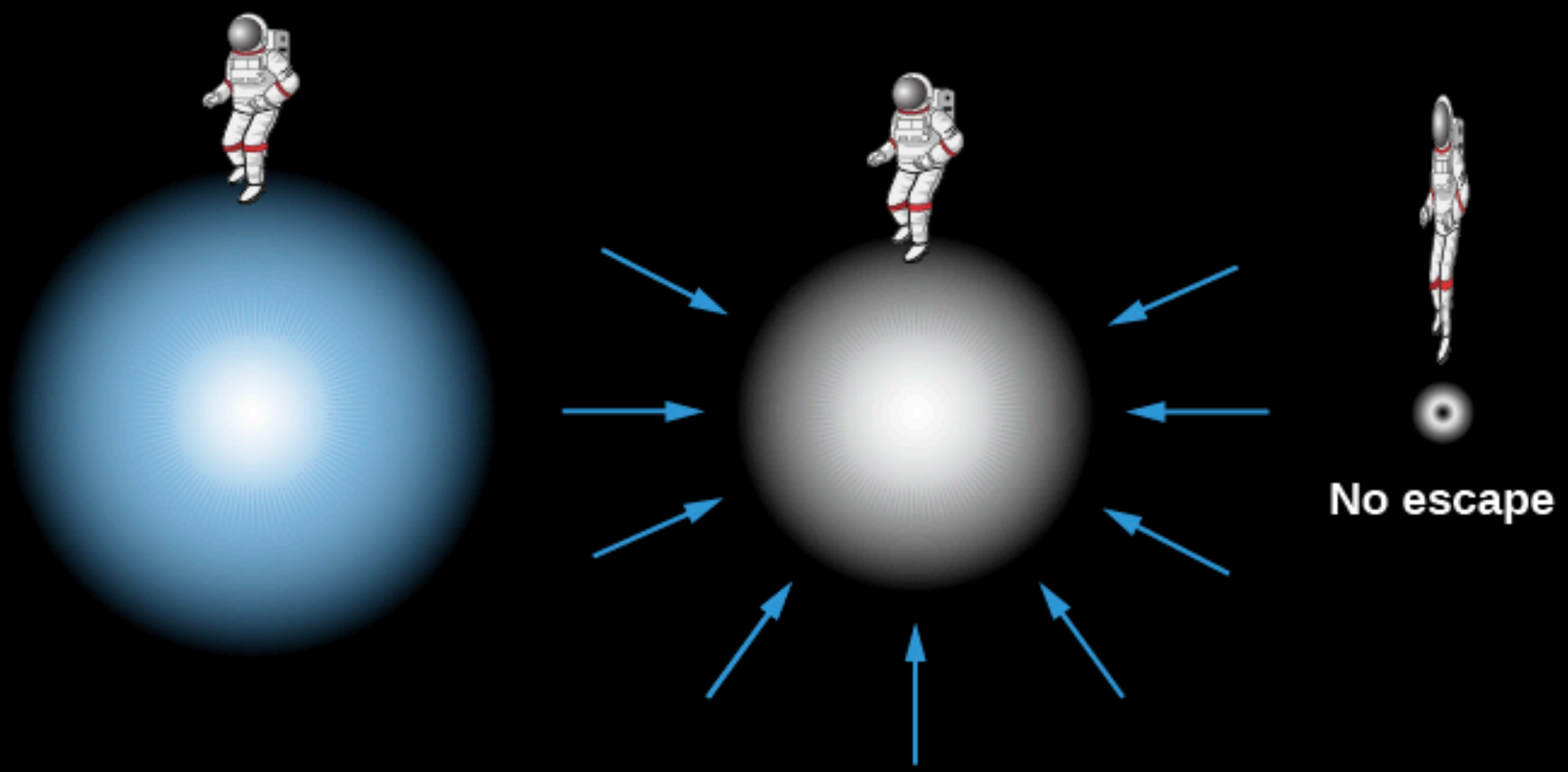


# Gravitational Redshift

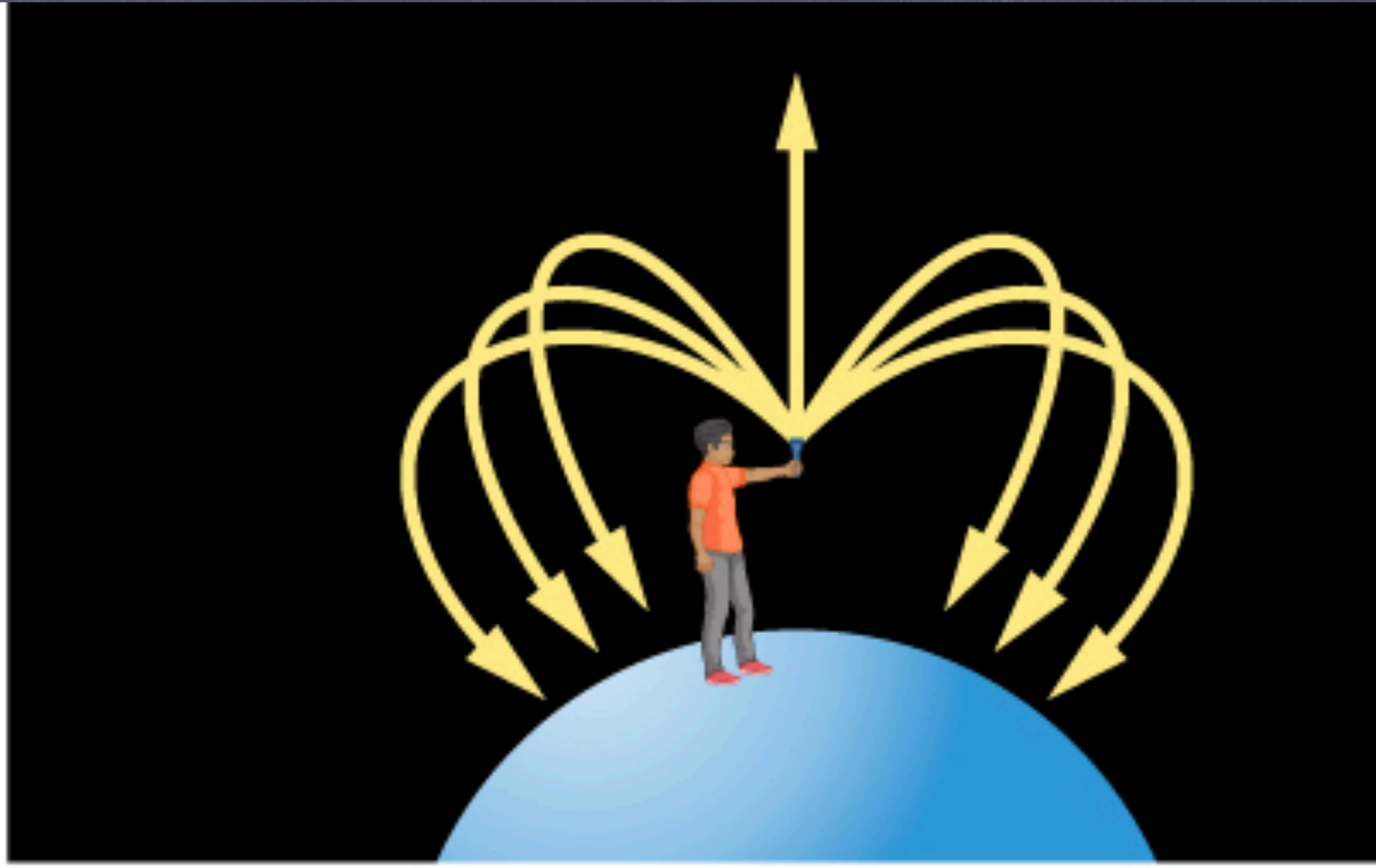
- What happens to electromagnetic radiation as it leaves a place of strong gravity? Radiation is a wave so how long it takes the wave to go up and down is like a clock.
- But now since time is slower the frequency as measured by someone far away from the gravity is slower too. Thus the wave seems to have longer frequencies or to be redshifted like a doppler shift.
- This is called a gravitational redshift because it is caused by gravity and it has been measured in the 70s comparing radio waves emitted from a rocket and from Earth's surface. Another validation of GR.

# Black Holes

- Let us now return to our collapsing star. Remember we learned that the speed one needs to escape the gravitational pull of an object depends on its mass and radius.
- As the core shrinks the mass stays the same but the radius decreases, so the escape speed increases. From the surface of a neutron star the escape speed is about 100,000 - 150,000 km/s. Or 1/3 to 1/2 the speed of light.
- If one shrinks to smaller than a neutron star the escape speed will eventually be greater than the speed of light, but nothing can go faster than the speed of light, so nothing can escape. We have a black hole.


No escape

Thinking of this in terms of GR as the core collapses the spacetime around it becomes more curved. Light bends back towards the object until only light emitted directly away from the object is able to escape. Eventually all paths from the black hole are cut off, light that leaves it always circles back. The black hole is cutoff from the rest of the universe. The boundary, the last point where light can escape is called the event horizon.



# A Trip to a Black Hole

- The creation of a black hole erases all the information about its formation. A black hole only has 3 properties; mass, spin and charge. So in fact black holes pretty simple.
- Let's imagine an astronaut falls into a black hole, what is his trip like? If she sends out a radio signal to us far away every second, we will receive the signals farther and farther apart as she gets closer to the event horizon. The wavelength of the radio signals will be redshifted to longer and longer wavelengths.
- As she just touches the event horizon the next signal will take infinitely long to reach us and be redshifted to an infinitely long wave. We will see her stop as she takes an infinite time to cross the black hole.

# A Trip to a Black Hole

- For the astronaut her experience is totally different. Time runs totally different. Her radio pulses go off every second and as she crosses the event horizon nothing happens. There is no physical boundary or event that happens.
- This is a key part of relativity, that different observers see very different things. Unless the astronaut is infinitesimally small, she will feel the tidal forces from the black hole which are catastrophic .

https://www.youtube.com/watch?v=h1iJX0UMJpg&t=4s

# Stellar Mass Black Holes

- So theory tells us we should get black holes, but that same theory says we can't see them. So how can we test it.
- They first way we identify black holes is from their gravity in a small region and having too much mass to be a neutron star.
- If a black hole has a stellar companion then we can detect it like a binary star, but there will be no light where one of the stars is supposed to be. The other object may emit high energy radiation like x-rays if it accretes material from the companion.
- Many such x-ray binaries that are too massive to be neutron stars have been found.

# Gravitational Waves

- Another source of evidence for black holes comes from detection of gravitational waves. Gravitational waves are a prediction of GR.

- Just like electromagnetic waves, if a mass is accelerated it should cause gravitational waves. However, the effect is very small and took four decades to develop the technology to detect.

- We actually knew there were gravitational waves from a pulsar in orbit around another neutron star at 1/10 the speed of light. According to theory this should emit so much energy in gravitational waves that the neutron stars spiral closer together. This has been observed in the pulsar, showing that GR is right.

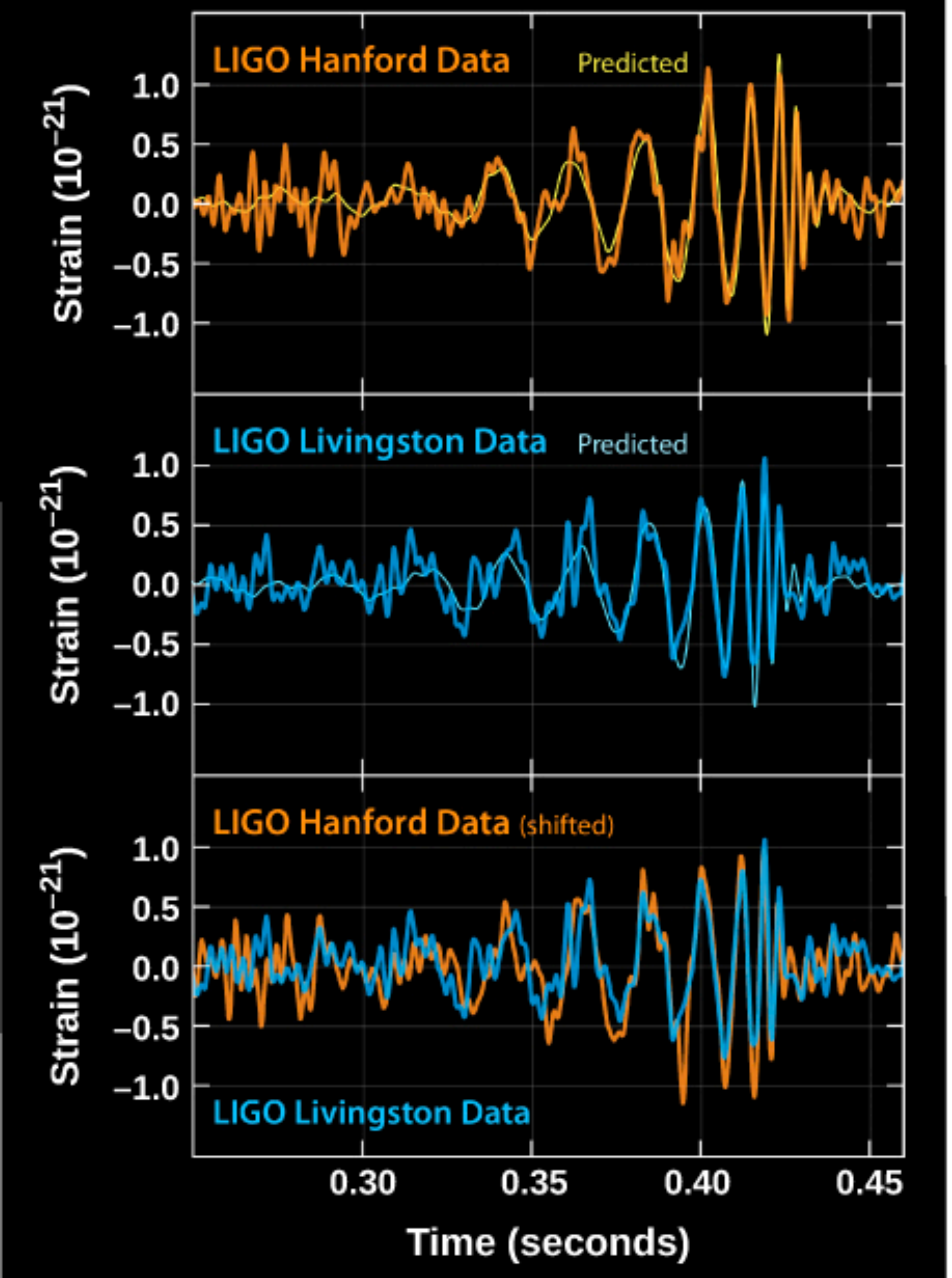
# LIGO

- To detect gravitational waves LIGO consists of two 4km long, 1.2m vacuum tubes that are 90 degrees from one another. A test mass with a mirror is suspended at the end of each tube. Ultra-stable laser light is reflected on the mirrors and travels back and forth in the tubes.

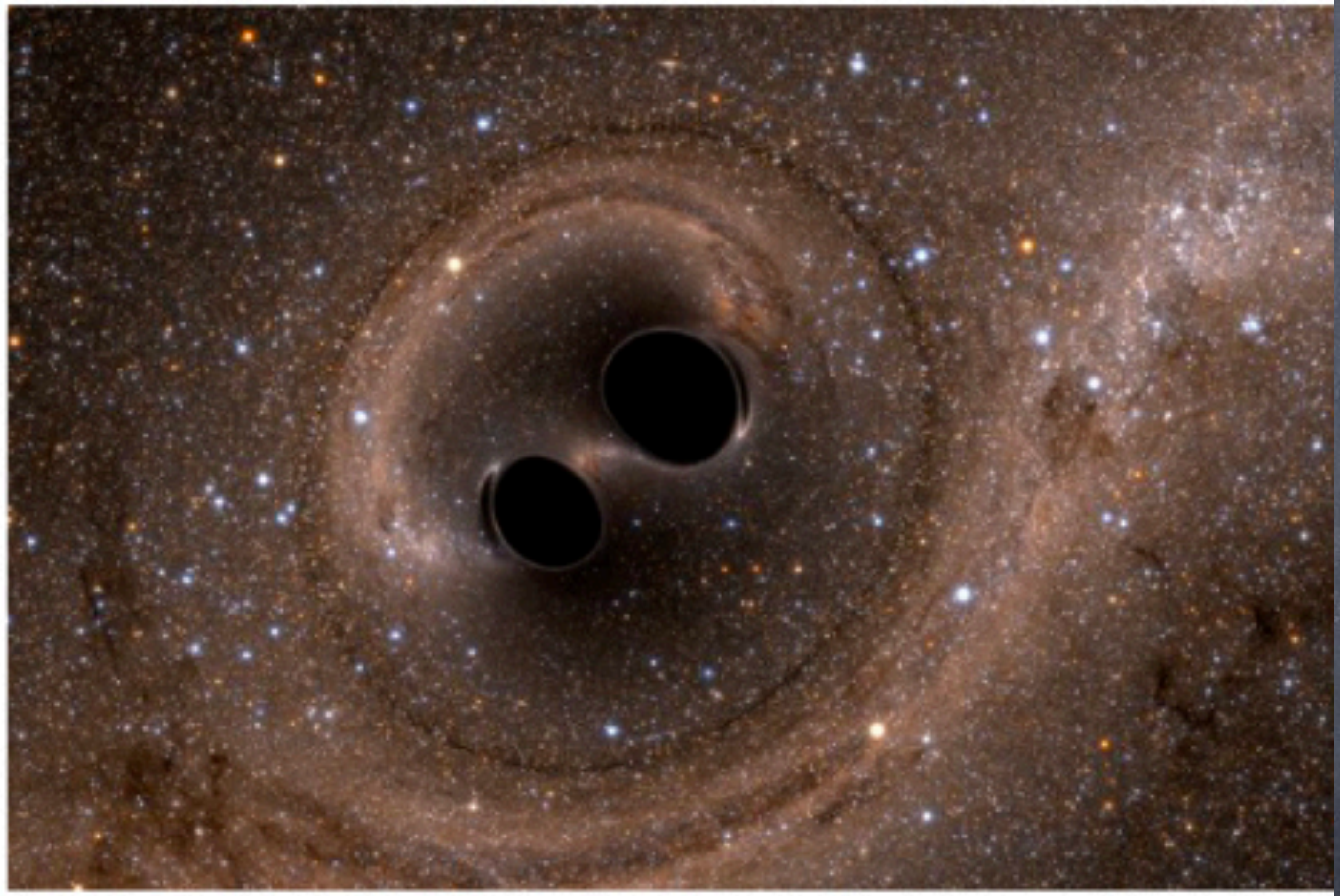
- A gravitational wave will shrink and expand the space changing the distance the light travels by a little in one arm of the experiment and be detectable. But the change is the length of 1/10,000th the size of a proton so very hard to detect.

- However, starting in 2015 with an upgraded LIGO, the mergers of many black holes and some neutron stars have been detected.


LIGO in Livingston, Louisiana. The detectors are 4km long in each direction.




The signal from LIGO seen in different locations



LIGO has detected many black hole mergers and a few neutron star mergers