CosmoVerse Adventures

Dark Matter

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

The classroom

Introduction: The elusive Dark Matter

Figure 1: The world at night. The image has been generated using the NASA VIIRS DNB algorithm.
Click to See full 3km resolution global image.

Teacher :

(Switches off the classroom lights, turning on a projector displaying a map of the world at night) Let's start today with a simple observation exercise. What do you see on this map?

Student 1 :

It's the Earth at night. You can see some cities lit up.

Teacher :

Precisely, and what about the areas with no lights? What do they tell us?

Student 2 :

These could be oceans, forests, deserts... places without people?

Teacher :

Exactly! This map, much like our understanding of the universe. You get some clues from where the light is, but there's a lot that you can't see, everything from people to mountain ranges. You have to infer what is there from these limited clues.

Student 3 :

You mean there's more to the universe than what we can see?

Teacher :

Significantly more. Cosmology is a humbling field. We find ourselves as a tiny part of an enormous cosmos. Our planet orbits a star among hundreds of billions in a galaxy that is one of hundreds of billions more. And yet, all of this—everything that makes up the stars, the planets, and even us—is just about 5% of the universe's total mass and energy. This is what we refer to as Baryonic matter or ordinary matter. (See figure 2).

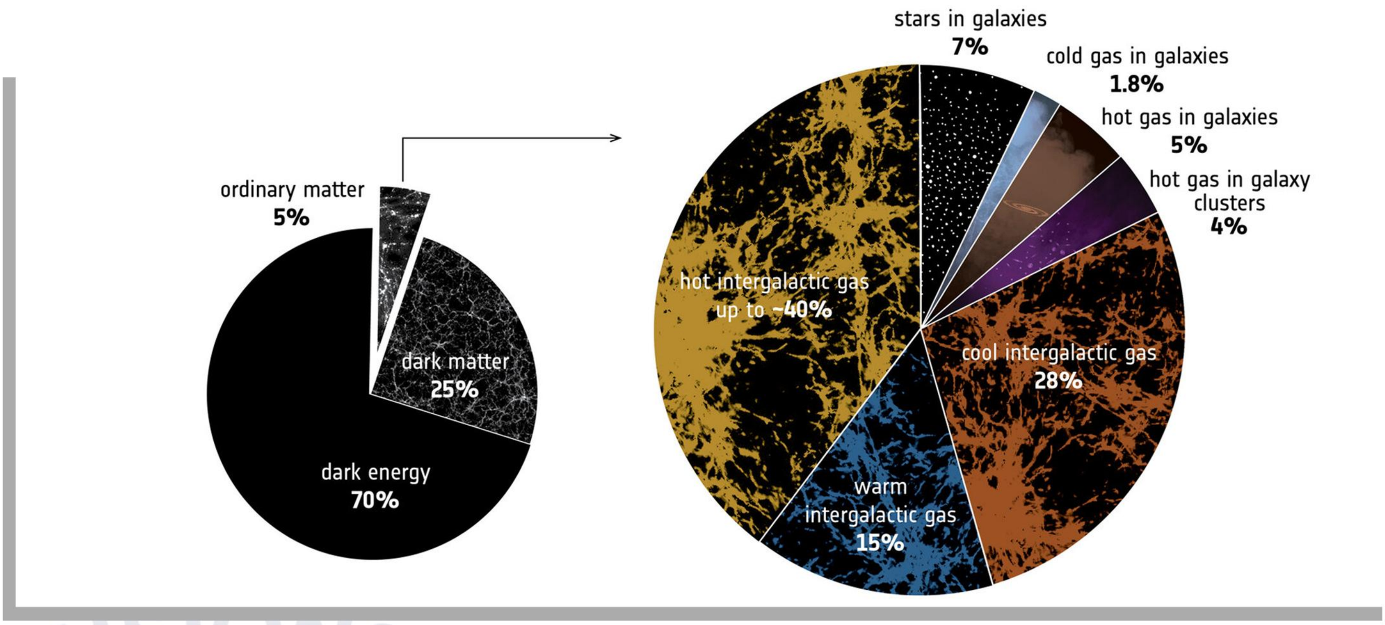

Figure 2: Dark matter and dark energy make up 95 percent of our universe; the remaining 5 percent is made up of ordinary matter called baryons, most of which has remained hidden until recently. Scientists have now discovered much of the intergalactic material that they'd never previously seen. Credit: ESA.

Student 4 :

Only 5%? What's the rest made of?

Teacher :

That's where our journey into the unseen begins. The rest, a staggering 25%, is made of something that doesn't emit or absorb light. We call this 'dark matter.' While it may seem abstract or distant, it's closer than you think. In fact, dark matter particles could be passing through us right now, as we speak! The other 70% is made of something called 'dark energy,' which we will explore in another CosmoVerse adventure!

Student 1 :

Dark matter goes through us? How come we don't feel it?

Teacher :

Dark matter is elusive. It doesn't interact with light or any form of electromagnetic radiation including radio waves and microwaves. It's invisible and completely intangible to us. We're all like ships sailing through a sea of dark matter, oblivious to its nature.

Student 2 :

If it's invisible and doesn't interact with light, how do we even know it exists?

Teacher :

That's the fascinating part. We infer its existence from the gravitational effects it has on the things we can see. Dark matter's gravity pulls on stars and galaxies, affecting their motion in ways we can measure.

Student 3 :

So, it's like feeling the wind on your face even though you can't see it?

Teacher :

An excellent analogy! And just as we use the wind to sail, galaxies use dark matter to hold themselves together as they rotate. Without dark matter, the universe as we know it wouldn't exist.

Student 4 :

Could dark matter have been a part of the universe since the big bang?

Teacher :

Possibly, it is one of the prevailing scenarios. Now, let's prepare for a celestial quest with our cosmic friend Quark to witness some very dark matters right from the aftermath of the big bang.

Spaceship of Imagination

Dark Matter in the early universe

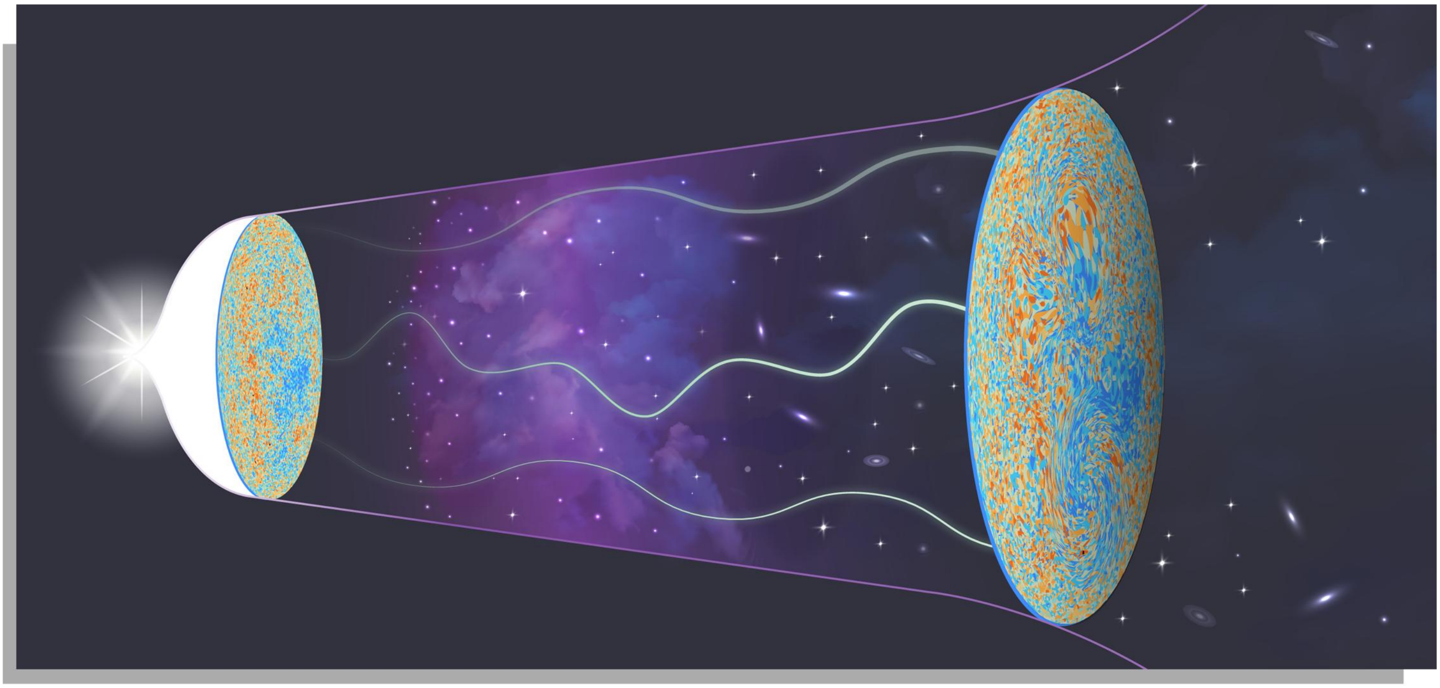

Figure 3: Cosmic Microwave Background (CMB) radiation. Image credit to Image: Lucy Reading-Ikkanda/Simons Foundation.

Quark :

Alright students, let's zoom back in time to just after the big bang. Remember what we saw on our last trip?

Student 1 :

The universe started really small and then it got expanded really, really quickly!

Quark :

Exactly! The universe was tiny and then-whoosh-it expanded faster than anything you can imagine. What was it filled with; can anyone recall?

Student 2 :

It was filled with energy and these tiny particles, some of them were quarks!

Quark :

Spot on! Now, I've got something new to add. Quantum Mechanics tells us that matter is being created and destroyed all the time, in every moment. At this time, the universe was expanding so fast that the matter that got created couldn't get destroyed.

Student 3 :

So, all the stuff we're made of, and the dark matter too, it all got made back then?

Quark :

Yes, you've got it! Fast forward a bit, after the matter was created, after protons, neutrons and hydrogen atom formed, about 400,000 years after the big bang.

Student 4 :

Oh! That's when space finally got cool enough for light to shine through, and we could see the Cosmic Microwave Background (CMB)!

Quark :

That's right. The universe was like a thick soup, smooth yet with tiny lumps. Those tiny lumps are super important because...

Student 3 :

They were the places with a bit more heat and stuff, and that's where gravity started to work its magic, pulling in more and creating the first stars, right?

Quark :

Precisely! And those first stars came together to form tiny galaxies. Over billions of years, these tiny galaxies bumped and combined to make bigger galaxies, like our Milky Way.

Student 1 :

But what's this dark matter doing all this time?

Quark :

Ah, that's the secret ingredient! The lumps we see in the CMB are too small to have had enough gravitational force and attract the matter to form large structures like galaxies but if this normal matter were accompanied by dark matter, however, these early lumps would have had enough gravitational attraction to create the universe we see today.

Student 2 :

It is like when we make rock candy, the sugar needs something to cling to (the string) in order to grow into crystals.

Quark :

Great analogy! Dark matter is like invisible glue. Look at these two universes, side by side. What can you see in the universe that has dark matter? (See figure 4)

Student 2 :

You can see that things get clumpy quickly!

Quark :

Exactly, in a universe with dark matter, clumps of matter can grow to become galaxies. Now, if we peek at a universe with little dark matter...

Figure 4: On the left is a universe model filled with dark matter, and on the right is a universe model lacking dark matter. Image credit to Mao, Wechsler & Kaehler / Stanford & SLAC.

Student 4 :

It looks like nothing much happens. The clumps are too small and don't grow up.

Quark :

Spot on again! Without dark matter, the universe would be very boring—no Milky Way, no Sun, no us. Dark matter is the unsung hero that makes our universe interesting and our existence possible. Let's keep that in mind as we venture deeper into the cosmos!

Student 3 :

That's interesting!! So, the Cosmic Microwave Background is one of the evidences that supports the existence of dark matter, are there any others?

Quark :

Absolutely! There are other clues that hinted at the presence of dark matter long before we could see the big picture. And you know what? We have the chance to learn from someone who was pivotal in discovering this. Let’s get ready to meet the legendary astronomer Vera Rubin, who uncovered the cosmic dance that hinted at dark matter's existence.

Meet a scientist

Dark Matter's effect

Quark :

Welcome, students! Today, we have the - honor of meeting someone truly special in our cosmic journey. Let's extend a warm welcome to astronomer Vera Rubin

Vera Rubin :

Hello, young explorers! It's a pleasure to join you on your adventure to understand the universe.

Student 1 :

Ms. Rubin, we've heard you found something surprising about galaxies. Could you tell us more?

Vera Rubin :

Certainly! Back in the '60s and '70s, I spent a lot of time studying spiral galaxies, just like our Milky Way. I was particularly interested in how they rotate because that tells us a lot about their mass.

Student 2 :

How does that work? Is it like how we learned planets closer to the Sun move faster?

Vera Rubin :

You're thinking in the right direction. Kepler and Newton taught us that the farther a planet is from the Sun, the slower it orbits. I expected to find something similar in galaxies—the outer parts moving slower than the inner parts.

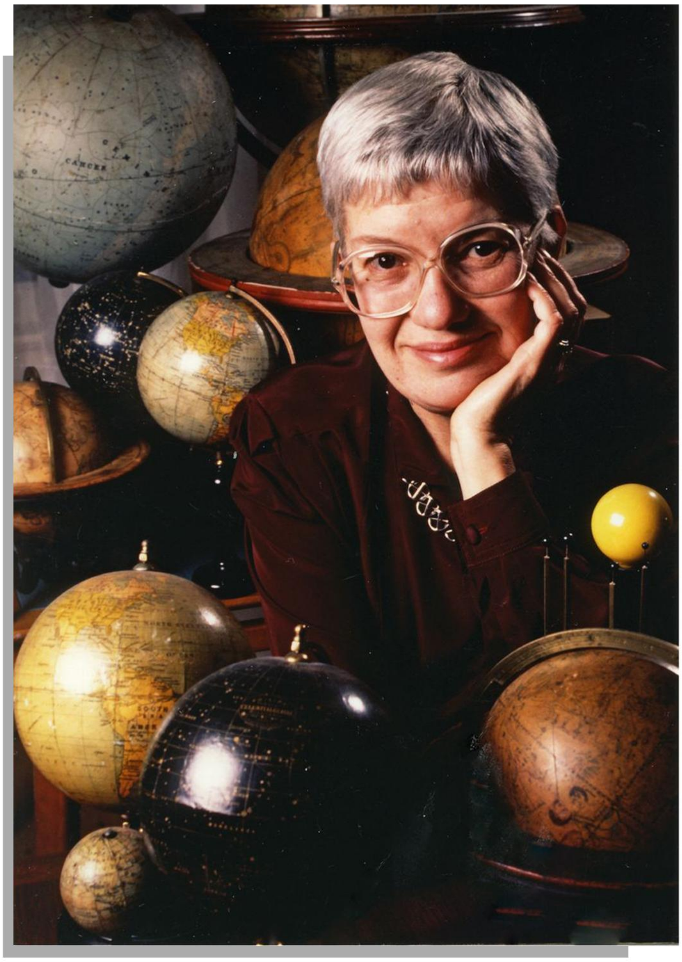

Figure 5: Vera C. Rubin. Image courtesy of Mark Godfrey (photographer).

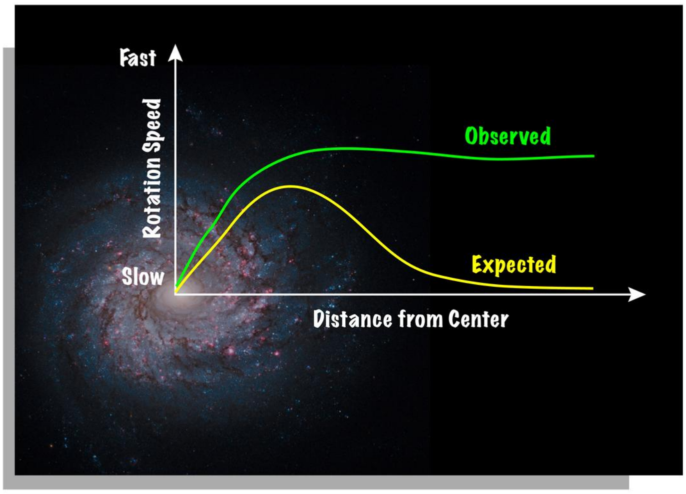

Figure 6: Predicted and observed galaxy rotation curve of a spiral galaxy. Dark matter is needed to explain the 'flat' rotation velocity curve even for stars located at very large distances from the galactic centre. Credit: www.resonance.is

Student 3 :

But that's not what you found, right?

Vera Rubin :

Exactly, it was quite the opposite. look at the graph of how fast parts of a galaxy rotate against their distance from the center, you'd expect the rotation speeds to drop off—the farther out you go, the slower the rotation should be. But instead, what we observe is that the rotation speeds flatten out.

Student 3 :

What does that mean?

Vera Rubin :

It means that the gas clouds at the edges of galaxies were moving just as fast, sometimes even faster, than parts closer to the center, implying that the gravitational pull is the same throughout the galaxy. This was puzzling because there seemed to be fewer stars and less mass there.

Student 4 :

So, how did you explain what you were seeing?

Vera Rubin :

Well, if we only considered the visible matter-stars, gas, and dust-my observations didn't make sense. But, if there was some unseen matter, it could explain the strong gravity that was pulling the gas clouds.

Quark :

And that's where dark matter comes into play, right?

Vera Rubin :

Precisely. The idea is that galaxies are surrounded by a halo of dark matter, invisible to us but with enough gravitational force to affect the rotation of galaxies. In fact, my observations suggested that there might be five times as much dark matter as visible matter in galaxies.

Student 1 :

Why do we call it 'dark matter'?

Vera Rubin :

The term 'dark matter' was actually coined by another astronomer, Fritz Zwicky, back in the 1930s (see figure 7). He was studying the Coma cluster, a massive cluster of galaxies, and he noticed something peculiar.

Student 2 :

What did he notice?

Vera Rubin :

Zwicky examined the speeds of individual galaxies within the Coma Cluster of galaxies (see figure 8) and found that they were so high they exceeded the cluster's escape velocity. This meant that the cluster should have been unstable and falling apart, when clearly it was not.

Student 4 :

So, he thought there was invisible matter in there?

Vera Rubin :

Precisely. He concluded that there must be a vast amount of unseen mass within the cluster holding it together via gravity. This invisible matter is what he called 'dunkle Materie,' German for 'dark matter.' However, Zwicky's data contained large uncertainties and other physicists were sceptical.

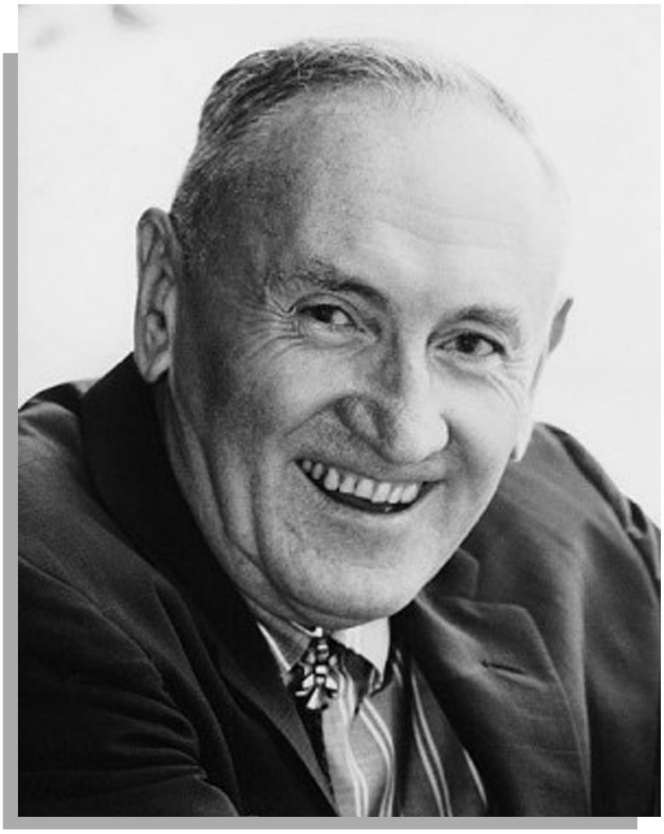

Figure 7: Fritz Zwicky. Image credit: totallyhistory.

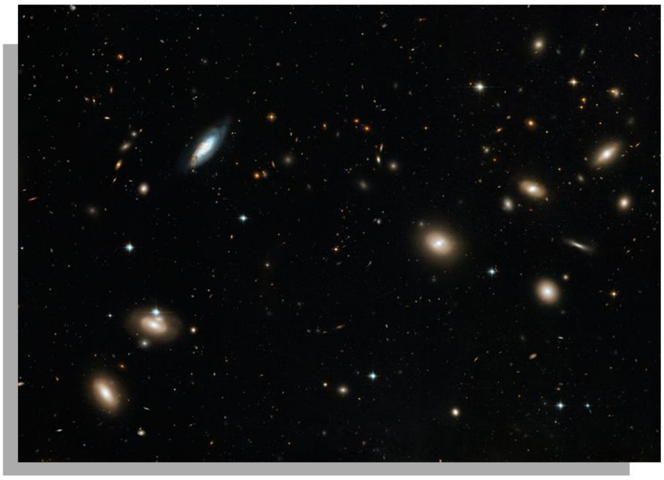

Figure 8: Coma Cluster, stretching across several million light-years across. The entire spherical cluster is more than 20 million light-years in diameter and contains thousands of galaxies. Image credit to NASA, ESA, and the Hubble Heritage Team (STScI/AURA).
Extended image

Quark :

We're grateful for your insights, Ms. Rubin. Now, students, let's transition from theory to practice. It's time to return to the Action Lab, where we'll conduct experiments to explore the gravitational effects of dark matter. Get ready to see some of this invisible force at work!

Action Lab

Demo : Gravitational lensing

Objective :

To understand and observe the effects of gravitational lensing as evidence of dark matter.

Preparation Time : 5 minutes

Activity Time : 10 minutes

Materials Needed :

- Lens or the base of a wine glass (Figure 9).
- Canvas print of the Hubble Ultra Deep Field image (Figure 10).
- Graph paper

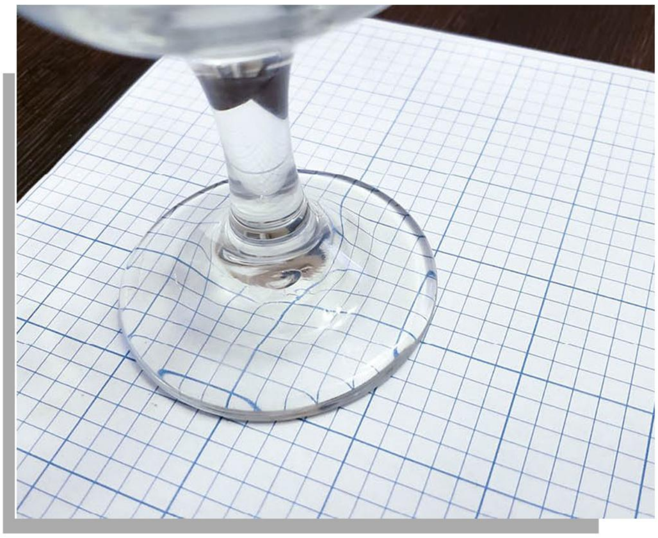

Figure 9: base of a wine glass on a graph paper

Observations :

- Make a large dot on the graph paper. Have students put the wine glass over the graph paper and observe how it distorts both the grid of the graph paper, and the dot.

- If the dot is centered below the wine glass, they should view a ring. If it is not centered, they should see arcs.

- Place the lens or the base of the wine glass upright on top of the canvas print. Observe the distortions of the images beneath the glass.

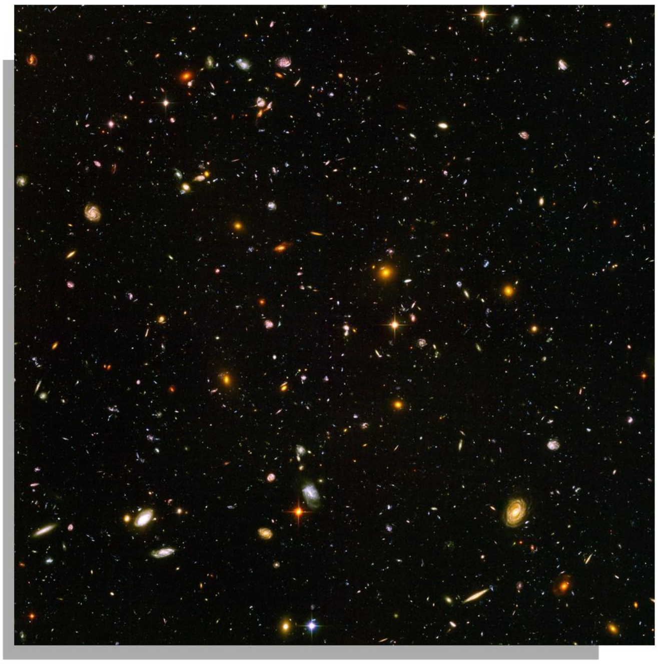

Figure 10: Canvas print of the Hubble Ultra Deep

Demonstration and Discussion :

Teacher :

Today, we have a fascinating experiment to understand how dark matter influences light. Here, we have a lens and a canvas print of the Hubble Ultra Deep Field. What happens when we place the lens over it?

Student 1 :

The image looks distorted, kind of stretched and bent.

Teacher :

Exactly! This is similar to gravitational lensing in space. Imagine light traveling across the universe from a distant galaxy. If there's nothing in the way, the light comes straight to us. But what if there's a cluster of galaxies-and dark matter-between us?

Student 2 :

You mean the dark matter would bend the light?

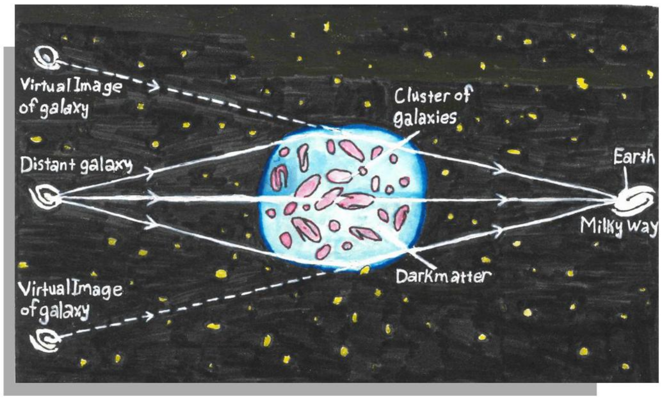

Figure 11: Gravitational lensing of a distant galaxy due to a nearby galactic cluster. Art by Mikayla Kauinana.

Teacher :

That's right! Einstein's theory of general relativity as you learned before tells us that massive objects bend the fabric of space-time, and this includes light. So, when light from a distant galaxy passes by a massive object, like a galaxy cluster filled with dark matter, it bends.

Student 3 :

So, we see the galaxy in a different place than where it actually is?

Teacher :

Precisely. If the galaxy, the cluster, and us are perfectly aligned, we see what's called an Einstein ring—a perfect circle of light similar to what you have seen when the dot is cantered below the base of the wine glass. But when you moved the lens or the glass base off to the side, the ring split up into arcs.

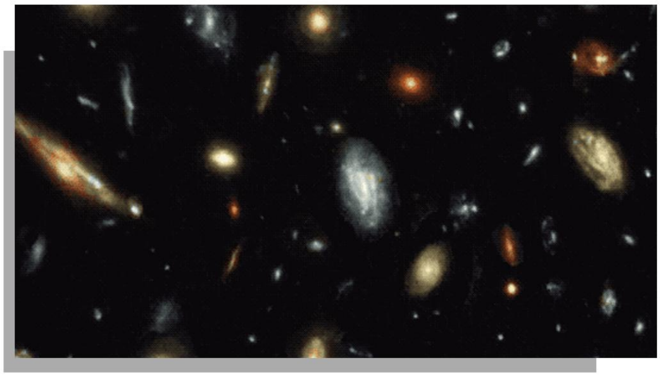

*Figure 12: Gravitational lensing effect. Credit to NASA. See the gif through this **link.***

Student 4 :

And these arcs tell us where the dark matter is?

Teacher :

Correct. By analyzing the arcs, we can map the dark matter in the cluster, even though we can't see it directly. This is what astronomers do with actual galaxies and clusters in space. They use the distortions to "see" the dark matter.

Student 1 :

That's like being a cosmic detective, finding clues in light!

Teacher :

It is! Astronomers studied something incredible called the Bullet Cluster. It's about 3.5 billion light-years away and consists of two galaxy clusters colliding. When galaxies collide, they tend to pass through each other like ghosts. But in clusters, between the galaxies, there are vast amounts of gas so that the gas in the two clusters does indeed smack into each other, and gets incredibly hot. So hot in fact, the gas will emit X-rays.

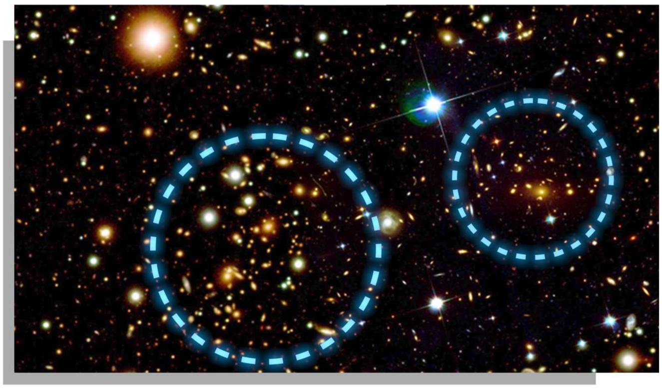

Figure 13: the bullet cluster, a site where two clusters of galaxies collided. Image credit to Veritasium.

Student 4 :

So, if they emit x-rays. It means we can actually see them?

Teacher :

Exactly and they use observatories like Chandra, which detects X-rays, to see the hot gas. In the Bullet Cluster, they found the gas exactly where you'd expect—between the colliding galaxies.

Student 3 :

What does that tell us about dark matter?

Teacher :

Using gravitational lensing, astronomers can pinpoint where the mass really is. It turned out that it's not in the middle with the gas; rather it's spread out on the sides.

Student 2 :

So, the dark matter isn't slowed down like the gas because it doesn't interact with it, right?

Teacher :

Correct! The dark matter doesn't interact with the gas or itself, so it just keeps moving which means there's more gravity where there's less visible stuff. And that implies that most of the mass, the stuff causing the lensing, is dark matter.

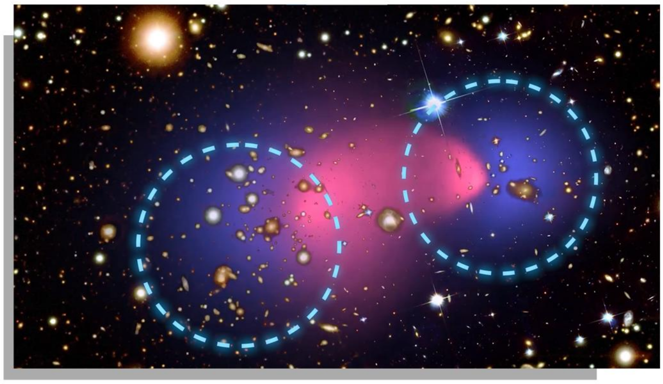

Figure 14: When the clusters collided, all that gas got stuck in the middle, but the dark matter passed right through, creating the most gravitational lensing. Image credit to Veritasium

Student 1 :

That's incredible! So, we can 'see' dark matter by how gravity affects light around it?

Teacher :

Precisely! It's like dark matter's shadow in space, invisible yet detectable through its gravitational pull on light. This observation from the Bullet Cluster is one of the best pieces of evidence we have for dark matter's existence.

Student 4 :

While we've seen the effects of dark matter through gravitational lensing, I am still wondering what could it be made of?

Teacher :

Theories about the nature of dark matter range from the microscopic to the massive. It could be tiny particles smaller than any we know, or it could be large objects with the mass of a hundred suns.

Student 2 :

How do scientists look for something so elusive?

Teacher :

They get creative. One method involves deep underground detectors in mines, where they hope to catch a dark matter particle leaving a trace as it collides with a dense material. These particles are called Weakly Interacting Massive Particles (WIMPs).

Student 3 :

What about looking in space?

Teacher :

Good point. Astronomers also search the skies for signs of dark matter particles colliding and releasing high-energy light, which special gamma-ray telescopes can detect. Another candidate for dark matter could be massive astrophysical compact halo objects (MACHO) such as black holes and neutron stars which emit little or no radiation.

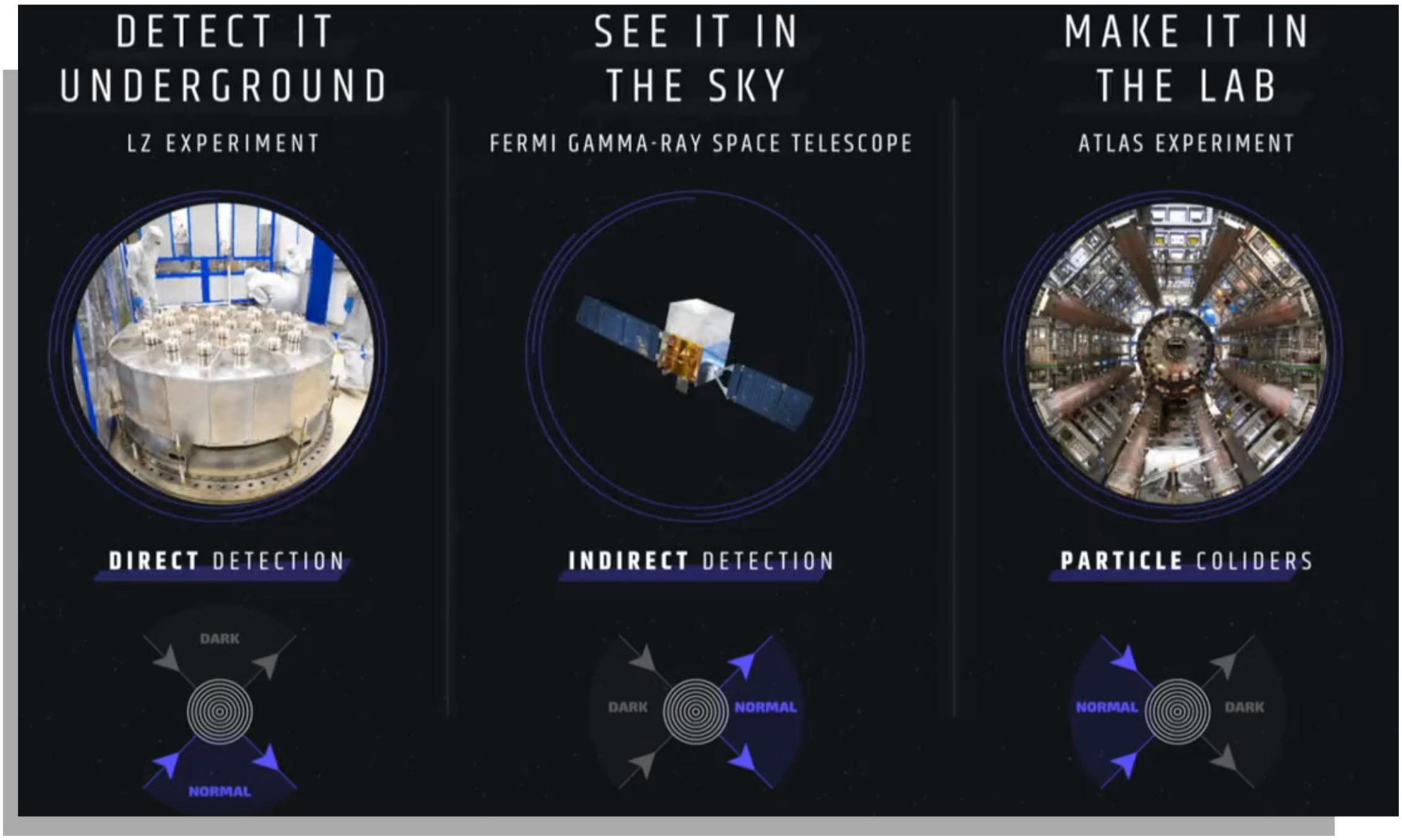

Figure 15: The search for Dark Matter. Image credit to Risa Wechsler.

Student 4 :

Could we make dark matter here on Earth?

Teacher :

That's another frontier. Using particle accelerators like the Large Hadron Collider, scientists try to create dark matter by smashing particles together and observing the aftermath.

Student 1 :

Have they found it yet?

Teacher :

Not quite. So far, these experiments have told us a lot about what dark matter isn't. But the mystery of what it is remains unsolved. The search for dark matter is more than just a hunt for another cosmic component; it's a journey that could redefine our understanding of physics and our place in the universe. It's a thrilling, open-ended quest that continues to captivate scientists and stargazers alike. For those eager to dive deeper into this vast expanse, the Cosmic Library section offers a treasure trove of knowledge, waiting to be explored.

Cosmic Library

Videos :

Shedding light on dark matter
The Absurd Search For Dark Matter
What Is Dark Matter? An Astrophysicist Explains
Dark Matter: Crash Course Astronomy
A Beginner's Guide to Dark Matter
Dark matter: The matter we can't see - James Gillies
Is Dark Matter Made of Particles?
The search for dark matter -- and what we've found so far
Neil deGrasse Tyson: What is Dark Matter?
The Dark Side Of The Universe – Brian Green

Interactive & Infographics :

Gravitational Lensing by a Point Mass
How Do We See Dark Matter?
Dark matter infographic
PhD comic about dark matter
Jelly Bean Universe (Dark Matter)

Websites & Articles :

Dark Matter: Exploring the Origin of the Universe
Science Made Simple: What Is Dark Matter?
Dark Matter: NASA
What is dark matter?: Space.com
Dark matter - CERN
Annenberg Learner's Physics for the 21st Century: Dark Matter
How Gravity Warps Light

Documentaries :

Mysteries of Dark Matter | Space Documentary
THE DARK SIDE - Black Holes And Invisible Matter | SPACETIME - SCIENCE SHOW

Where Did Dark Matter And Dark Energy Come From?
BBC - Horizon - 2006 - Most of our universe is missing (Dark matter)
Dark side of the Universe – Discovery Channel

Quiz :

The Age of the Universe
Hubble- Lemaître law
Hubble's Law & Hubble's Constant

Glossary

Baryonic Matter: Ordinary matter that makes up stars, planets, and all visible objects in the universe, constituting about 5% of the universe's total mass and energy.

Big Bang: The theory that describes the beginning of the universe as a singular, extremely hot and dense point, which has since expanded to form the cosmos as we know it.

Bullet Cluster: A pair of galaxy clusters whose collision and resulting gravitational effects provide significant evidence for the existence of dark matter.

Coma Cluster: A large cluster of galaxies, whose study by Fritz Zwicky led to the early hypothesis of dark matter due to the high velocities of the galaxies within it.

Cosmic Microwave Background (CMB): Radiation left over from the early stages of the universe, providing evidence for its origin and composition.

Dark Energy: A mysterious form of energy that makes up about 70% of the universe and is responsible for its accelerated expansion.

Dark Matter: A form of matter that does not emit or absorb light, making up about 25% of the universe and exerting gravitational effects on visible matter.

Einstein Ring: A phenomenon of gravitational lensing that produces a circular ring of light from a distant object, caused by the bending of light due to a massive object's gravity.

Galactic Rotation Curve: The plot of the orbital speeds of stars in a galaxy against their radial distance from the galaxy's center, which led to the discovery of dark matter due to unexpected flat rotation curves.

Gravitational Lensing: The bending of light from distant objects by the gravity of massive objects like galaxy clusters, used to detect and map dark matter.

Kepler's Laws: Laws describing the motion of planets around the Sun, influencing the study of galactic rotation and the discovery of dark matter.

MACHO (Massive Astrophysical Compact Halo Object): A proposed form of dark matter, consisting of massive objects like black holes or neutron stars that emit little or no radiation.

Quantum Mechanics: A fundamental theory in physics describing the behavior of matter and energy at the atomic and subatomic levels.

Quarks: Fundamental particles that are constituents of protons and neutrons, playing a role in the early universe's formation.

Space-Time: The four-dimensional continuum of space and time in which all objects in the universe exist, as described in Einstein's theory of relativity.

Spectral Lines: Specific wavelengths of electromagnetic radiation emitted or absorbed by an atom or molecule, used in astrophysical observations.

WMP (Weakly Interacting Massive Particle): A hypothetical particle that is a candidate for dark matter, which interacts only through gravity and weak nuclear force.

This article/publication is based upon work from COST Action CA21136 – "Addressing observational tensions in cosmology with systematics and fundamental physics (CosmoVerse)", supported by COST (European Cooperation in Science and Technology)

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