CosmoVerse Adventures

The Big Bang History

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

The classroom

Introduction: The Universe and Entropy

Teacher :

Good morning, class! Welcome to the CosmoVerse Adventures class. Before we start our conversation, I have a video for you.
[The teacher plays **a video** of a scrambled egg being unscrambled]

Video 1: This snippet is taken from a Ted talk by David Christian about the Big History Project

Student A :

Why did we just watch a video of unscrambling eggs?

Teacher :

That's an excellent question, Student A. Does anyone have any ideas about how this video might connect to our topic for today?

Student B :

Is it something to do with how things are formed or made?

Teacher :

Brilliant, Student B! We are going to explore the biggest formation event ever – the formation of the universe, known as **the Big Bang.** However, have you noticed something a bit strange about our video?

Student C :

Yes, Eggs don't unscramble themselves!

Teacher :

Exactly, Student C! In fact, this process of 'unscrambling' contradicts one of the most fundamental laws of physics, the second law of thermodynamics, or **the law of entropy**. This law states that the universe tends to move from order and structure to lack of order, lack of structure — in essence to mush. That is why, we never see eggs unscrambling themselves in the real world. (See figure 1)

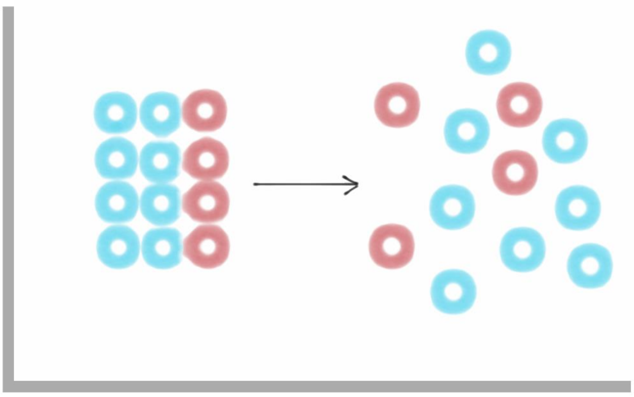

Figure 1: This shows the arrow of entropy from Structure to lack of structure

Student D :

"Wait, so you're saying the universe is getting more disordered over time? But how come we see all these complex things like stars, galaxies, and even us?"

Teacher :

That's a fantastic observation, Student D! Despite the overall trend toward disorder, the universe can indeed create complexity, but it's a difficult and delicate process. There are specific pockets in the universe where 'Goldilocks conditions' occur - conditions that are just right, not too hot, not too cold, for complexity to arise. Over billions of years, complexity has built up stage by stage, crossing different thresholds. Each of these thresholds represents a significant step up in the level of complexity in the universe. (See figure 2)

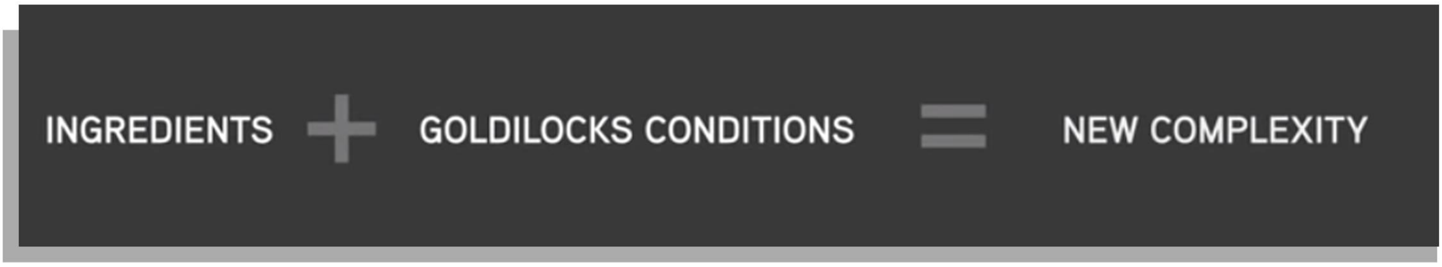

Figure 2: Adopted from the story of Goldilocks and the Three Bears, Goldilocks Conditions are when conditions are "just right" for something new and more complex to emerge.

Student D :

"That's mind-boggling! But why do we need to learn this? Why is the history of our universe so important?"

Teacher :

Well, Student D, we, as extremely complex creatures, live in an incredibly complex universe. Understanding how this complexity came to be and how it evolves is crucial to understanding our own place in the universe, our origins, and perhaps our future. This knowledge can help us make sense of how we fit into the grand cosmic story. Our Cosmic Buddy, Quark the Quantum Quokka, will guide us on this fantastic journey through the universe. We'll traverse space and time, explore the creation and evolution of the universe, the formation of stars and galaxies, and even discover how elements that make up our bodies were cooked up in the stars. Are you ready for this adventure?

Students (In Unison) :

"Yes!"

Teacher :

Excellent! Let's climb aboard Quark's spaceship of imagination as today, we're winding the timeline back **13.7 billion years,** to the beginning of everything, the Big Bang.

Spaceship of Imagination

A brief history of the big bang

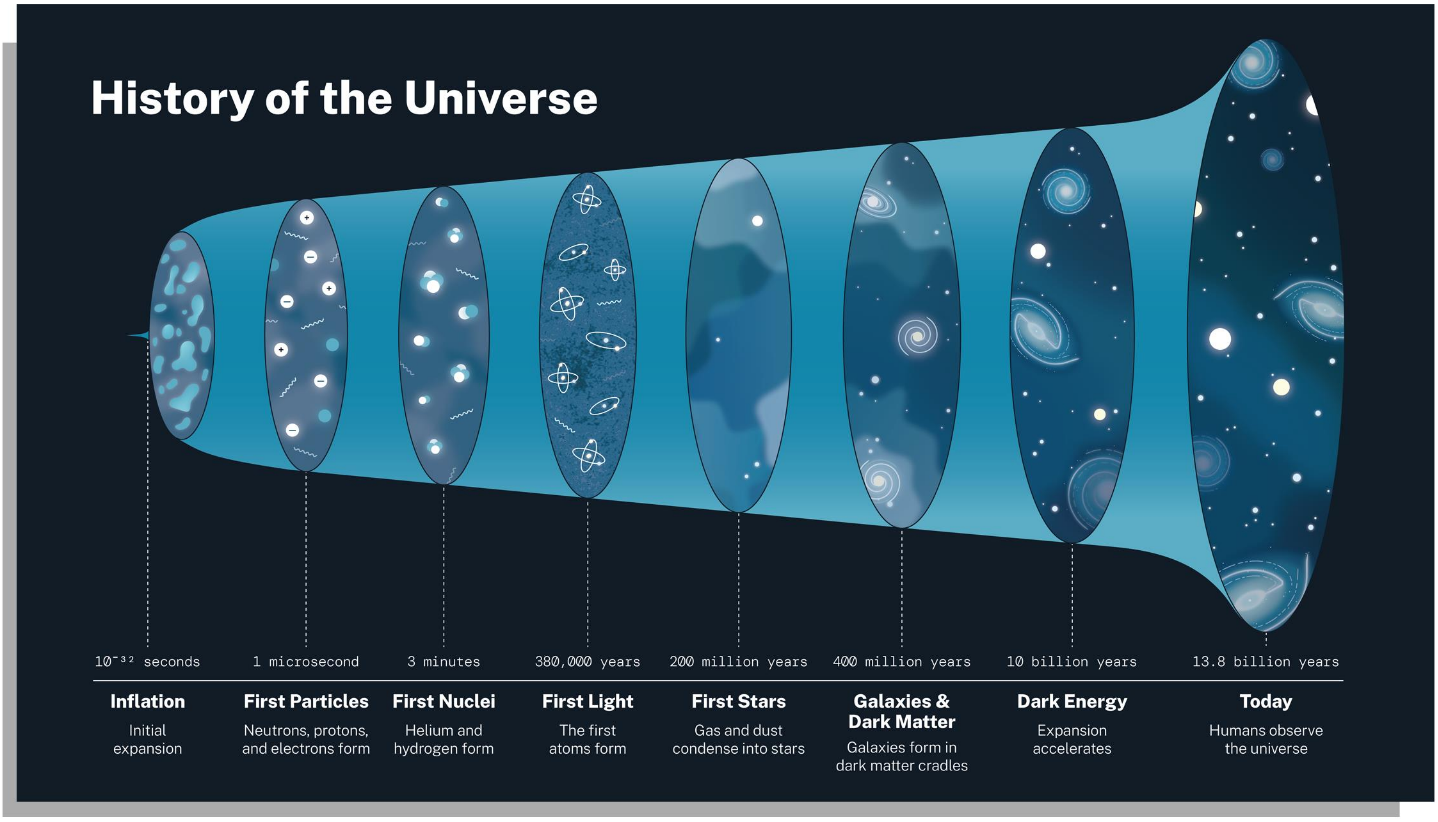

Figure 3: The history of the universe is outlined in this infographic. Credit: NASA

Quark :

Students, gather around this window. We're about to witness the birth of the universe, a story more astonishing than anything we've known.

Student 1 :

All I see is darkness. What's happening?

Quark :

Ah, that's the enigma. The Big Bang, the universe's grand entrance, happened in absolute darkness. Light, as we understand it, didn't even exist yet.

Student 1 :

Well, our spaceship of imagination is equipped with a cosmic night vision that will help us to see the unseen. And remember, at this very moment, there's no "outside" to the universe. The only existence was the "inside."

(Student gasps as a sudden surge of radiation fills the viewport)

Quark :

And there it is, the birth of the universe, the Big Bang. As you can see, it was not a bang, it was not an explosion, but a stretching of space everywhere at once. The universe expanded from smaller than an atom to about the size of an orange in less than a trillionth of a second, almost no time at all, the universe simply inflated into existence, unfolding, unfurling, getting bigger and cooler with every passing moment. Remember, the universe didn't expand into something, but rather, space was expanding into itself. Because the universe is all there is. No "outside" exists by definition.

Student 3 :

And what was there in this rapidly expanding universe?

Quark :

This hot, dense environment was teeming with energy forming trillions of subatomic particles. Half of these were **matter** called **Quarks** – the stuff we're made of. The - other half was **antimatter**, its exact opposite. When they met, they would annihilate and destroy each other in bursts of energy.

Student 2 :

But now, we have more matter than antimatter, right Quark?

Quark :

Absolutely, Student 2. Fortunately, there was just a bit more matter than antimatter. Just one in a billion particles of stuff survived, which was lucky for us because that residue is what our present-day universe is made of. You could say we are made of the smoke of the big bang.

Student 3 :

So, what happened to the quarks then?

Quark :

The quarks started to form new particles, **hadrons,** like **protons** and **neutrons.** There are many possible combinations, but only few are stable. And by this time, only one second has passed since the beginning of everything.

Student 4 :

So, the first atom was formed?

Quark :

Correct, Student 4! As the universe continued to cool, most neutrons decayed into protons to form the first nuclei of an atom, **hydrogen.** The universe, now a hundred billion kilometres across, was an extremely hot soup of particles and energy.

Student 3 :

But there were no stars or light at this point, right?

Quark :

Right, Student 1. No stars, no visible light to move around. But in order to see the first light we need to fast-forwarding to 380,000 years after the origin as the universe cooled to about 3000 Kelvin, or about 2700 degrees Celsius. Now you can see the first light of the universe as yellowish-white. Notice the enormous clouds of hydrogen atoms, cosmic mush with barely any structure. Yet, it's the tiny differences that changed the universe from a cloud of gas into a place filled with perhaps more than a trillion galaxies, Swirling in a vast chaotic dance. (See figure 3)

Student 3 :

What were these tiny differences?

Quark :

in order to understand what happened then, let's meet Robert Wilson and Aron Penzias, two radio astronomers who discovered the Cosmic Background Radiation, the cooled remnant of the first light that could ever travel freely throughout the Universe.

Meet a scientist

Cosmic Microwave Background

Robert Wilson :

Hey there, young explorers! So now around 380,000 years after the big bang, the universe was like a hot, dense soup. Electrons and protons danced around in it, making the universe a glowing, red-hot place. Light couldn't travel far without being scattered, much like how light bounces inside a hall of mirrors. As the-universe expanded, it cooled. Electrons and protons, previously too energetic to bond, fell into an embrace, creating neutral hydrogen atoms. With fewer free-roaming electrons, the universe became clearer. The light that had been bouncing around now began its journey through the vast cosmos.

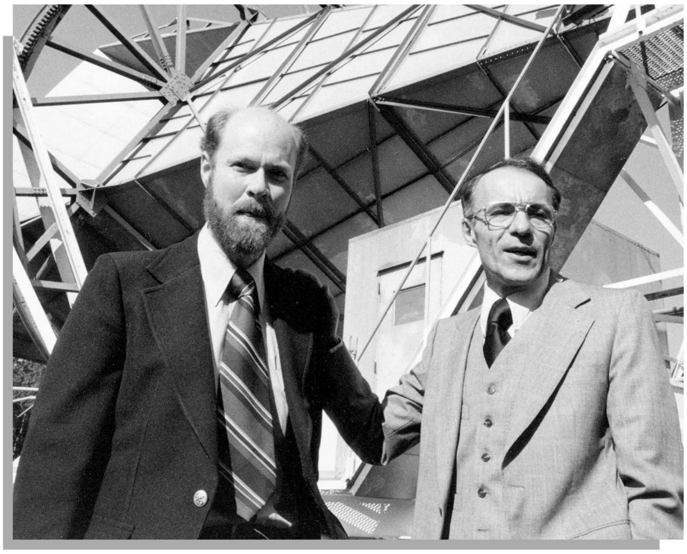

Figure 4: Robert W. Wilson (left) and Arno Penzias pose next to their antenna after winning the Nobel Prize in 1978 for discovering the Big Bang's afterglow. (AP)

Student 2 :

Is it similar on a cloudy day, we can see the sky and clouds clearly, but we can't see through the thick clouds?

Aron Penzias :

Exactly, In the same way, scientists can 'look' back through the universe's history, but they hit a 'wall' when trying to see beyond 380,000 years after the Big Bang. This 'wall' is the 'Surface of Last Scattering.' It's the point where cosmic light last scattered or 'bounced off' matter before traveling freely. (See figure 5).
This picture that you see in (figure 6) is the picture of the universe when it was only 380,000 years after the Big Bang. See those red and blue areas?

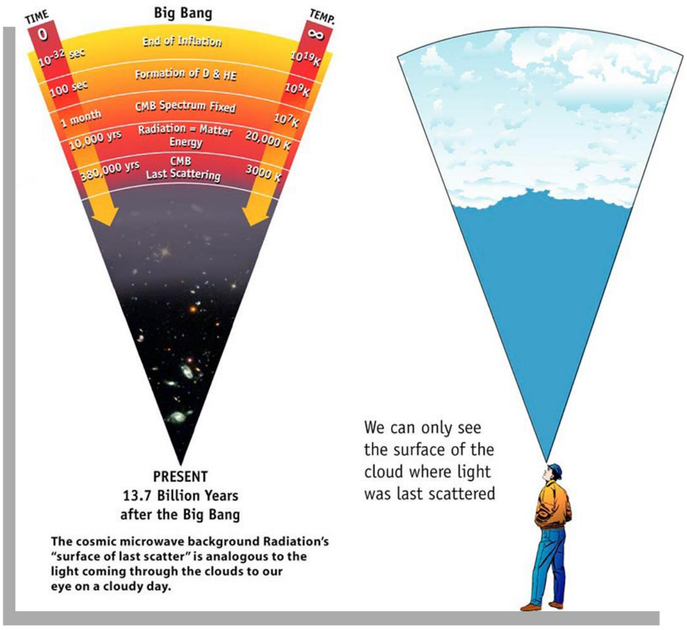

Figure 5: Surface of Last Scattering. Image credit: NASA / WMAP science team

Student 2 :

Yes, they're beautiful. What do they signify?

Robert Wilson :

Picture a vast sea that's calm and even. The Cosmic Microwave Background, or CMB, is like seeing ripples on that sea. And while our universe, at 380,000 years old, seemed calm and simple, there were these tiny ripples, or differences. So, with the help of Satellites like COBE, WMAP, and Planck, we found out that the blue areas on the map were about a thousandth of a degree cooler than the red areas. These minute variations, as tiny as a bacteria's influence on a beach ball, eventually led to the grand cosmic structures we see today – galaxies, stars, and much more. They are the seeds from which the universe bloomed.

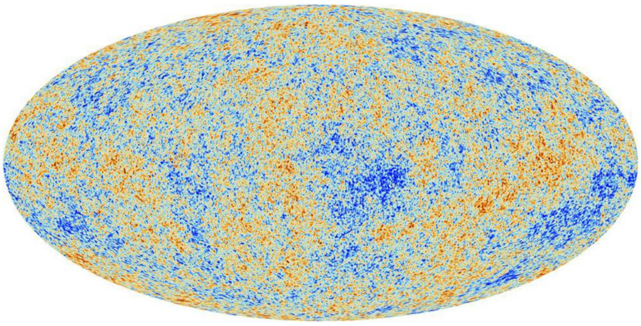

Figure 6: This image unveiled March 21, 2013, shows the cosmic microwave background (CMB) as observed by the European Space Agency's Planck space observatory. Image credit: ESA and the Planck Collaboration

Student 1 :

But how do tiny temperature changes end up creating...well, everything?

Aron Penzias :

Think of these spots as seeds in soil. Where the seeds are denser, they grow bigger and faster. Gravity, our universe's gardener, pulled these seeds or gas clouds together. As they got squeezed tighter and tighter, it's like they heated up, just as your hands get hot when you rub them together. Once they got hot enough about 10 million degrees, protons began to fuse, leading to a vast energy release. And voilà! Our first stars emerged, roughly 200 million years after the Big Bang.

Student 4 :

So, stars are like...flowers sprouting from these seeds?

Robert Wilson :

Exactly! And the biggest, most beautiful flowers—our massive stars—had an even more magical touch. When they 'died', they create temperatures so high that they fuse protons in various combinations, sprinkle the universe with all sorts of elements in the periodic table, like gold. We call these events, **Supernova**. Imagine a grand firework finale, where each explosion leaves behind special stardust. This stardust swirled, danced, and eventually clumped together to form planets and moons around new stars.

Student 1 :

So that's how our solar system was formed?

Robert Wilson :

Correct, Student 1. Now, look at the Earth, perfect with its oceans of liquid water. Deep beneath those oceans, fantastic chemistry began to happen. Atoms combined in all sorts of exotic combinations. That's where life began.

Student 2 :

So, that's where we, as humans, came in?

Aron Penzias :

Yes, Student 2. Humans appeared about 200,000 years ago. What sets us apart is our language. Our ability to communicate and share knowledge precisely means that it can outlast individuals who learned that information.

Student 2 :

But Dr. Smoot, what about the very beginning? What happened at and before the Big Bang?

Aron Penzias :

Ah, Student 2, the biggest question of all! We're still not entirely sure. To understand this, we need a theory that unifies Einstein's relativity and quantum mechanics, something scientists are actively working on. We don't know what triggered the Big Bang, or if there were universes before ours. We have more questions than answers at this point

Student 3 :

So, we are part of this cosmic journey?

Robert Wilson :

Indeed, Student 3. Remember, we're all made of stardust. We're not separate from the universe; we are part of it. You could even say that we are the universe's way of experiencing itself. Do you have any other questions?

Student 1 :

Yes, I would like to know why it is called ''Cosmic Microwave Background?''

Aron Penzias :

Great question, Student 1. Imagine the universe as a vast, evolving canvas. At the - start, this canvas was filled with fiery, brilliant light, like the bright colours you see on a fresh painting. As the universe expanded over billions of years, this light stretched and cooled, just like how colours fade and stretch on an old, weathered painting.

Robert Wilson :

The light's original fiery brilliance, akin to bright visible colours, stretched into longer wavelengths. So instead of seeing the light as the original yellowish-white, it now appears in the microwave part of the spectrum, which is beyond the red, or infrared, region that our eyes can perceive. Hence, we term it the "Cosmic Microwave Background" because it's the afterglow of the universe's creation, now detectable in the microwave frequency.

Quark :

Thank you Prof. Penzias and Prof. Wilson, as a matter of fact, we are transitioning back to the school to the ‘’ Action Lab ’’ where the teacher has prepared an experiment set up that will allow the students to visualize this concept of stretching and its effect on light. This will give them a clearer perspective on why the once fiery light of the universe now appears to us as microwaves.

Action Lab

Activity: Elastic band model–a one-dimensional model

Objective :

To provide students with a tangible representation of how the expansion of the universe stretches light waves, resulting in the cosmic microwave background.

Preparation Time : 5 minutes

Activity Time : 10 minutes

Materials Needed :

- Strips of elastic (about 30 cm long)
- Felt pen or marker
- Ruler or measuring tape
- Reference chart of the electromagnetic spectrum

Procedures :

1. Wave Drawing :

- Distribute the strips of elastic to each student or group.
- Using a felt pen and ruler, students should draw evenly spaced dots on the elastic. These dots will represent the crest of a visible light wave.
- To add depth to the exercise, inform the students that for this activity, every 1 millimetre on the elastic signifies 100 nm. Therefore, they should place their dots approximately 5 or 6 mm apart.
- Using the electromagnetic spectrum chart, students should determine and record the colour that corresponds to the wavelength they've represented with their dots.

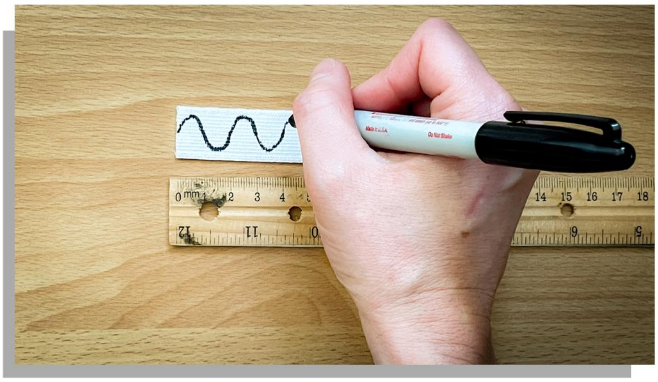

Figure 7: draw wave segments connecting the dots. Image credit: NASA/JPL-Caltech

2. Stretching the Universe :

- Once the dots are drawn, students should draw the remaining wave pattern, connecting the dots, to help visualize the wave.

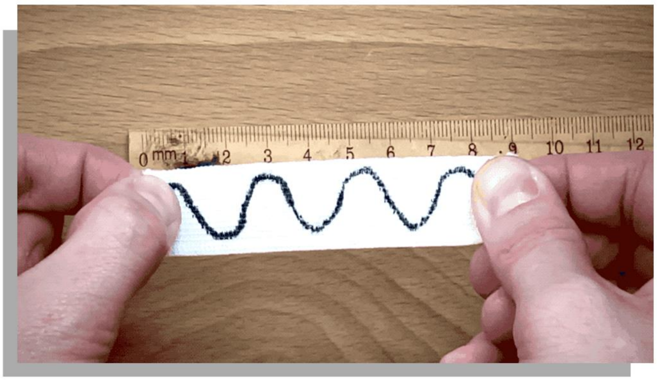

Figure 8: The wavelength drawn on the piece of elastic gets longer as the elastic is stretched. Image credit: NASA/JPL-Caltech

- One student should hold one end of the elastic while another student slowly stretches the elastic. Depending on preference, students can either stretch the elastic to its limit or only a partial amount.
- While the elastic is being held stretched, the distance between the dots (representing the wave crests) should be measured and noted.

Observations :

- The groups should note that as the elastic is stretched, the distance between the dots (or wave crests) increases.
- If students have used the scaled measurements from step 1, they should now convert their new stretched measurements back into the nanometre scale. Using the electromagnetic spectrum chart again, they should identify where their new stretched wave fits.

Discussion and Conclusion :

Teacher :

Alright, everyone! Now that we've conducted our experiment, what observations did you make when you stretched the elastic?

Student 1 :

The distance between the dots increased as we stretched it.

Teacher :

Precisely. And how might this relate to the universe and the light waves within it?

Student 2 :

Just like the dots on our elastic, as the universe expands, the light waves get stretched too!

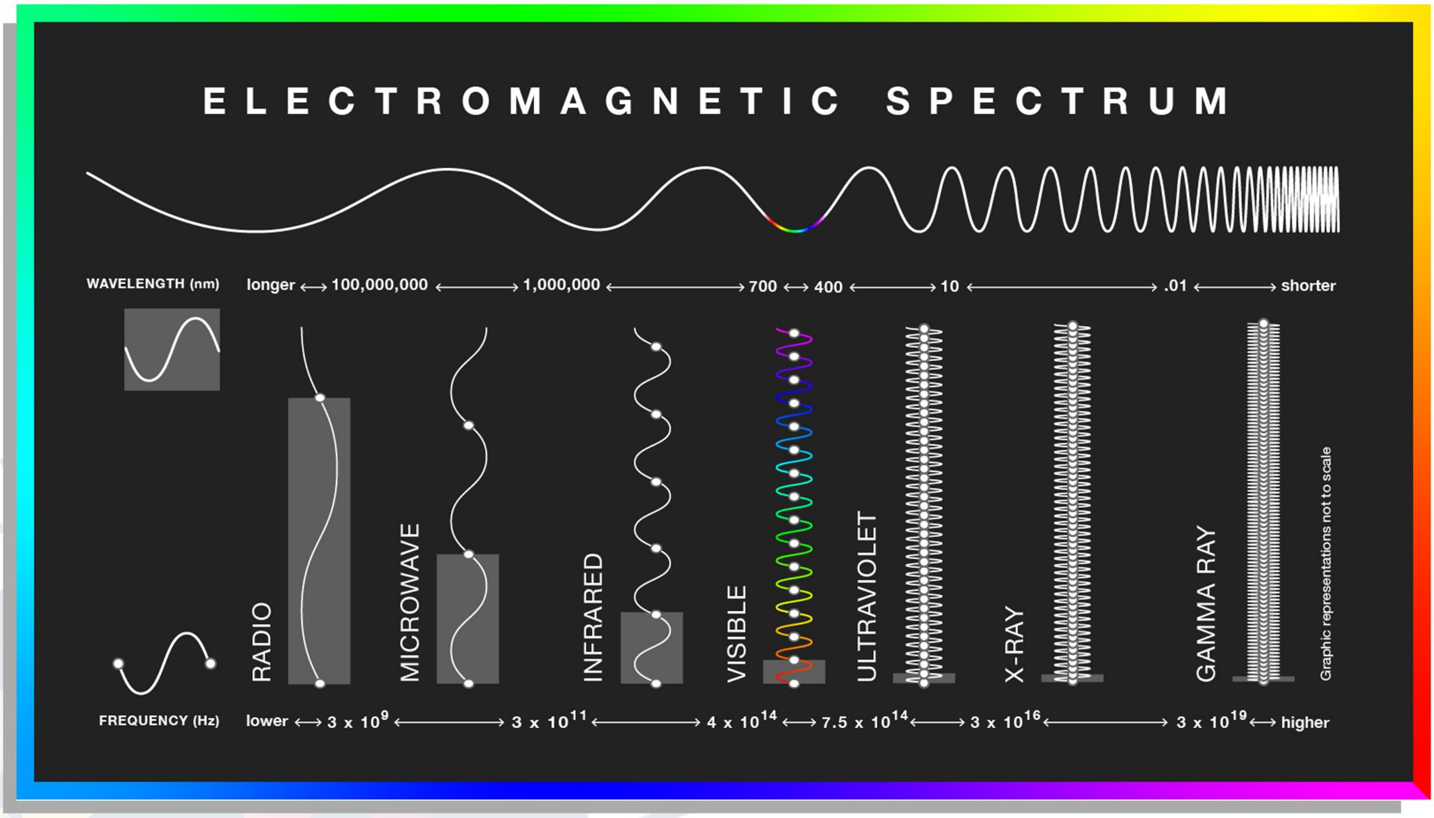

Figure 9: Visible light, the type of light humans can perceive with their eyes, is just one tiny piece of the electromagnetic spectrum. This chart compares the wavelength and frequency range of each kind of wave on the electromagnetic spectrum. Note: The graphic representations are not to scale. Image credit: NASA/JPL-Caltech |
+ Expand image | › Download low-ink version for printing

Teacher :

Spot on, Student 2. Now, referring back to the electromagnetic spectrum chart, where did your initial wave (dots) fit before stretching?

Student 3 :

Ours was in the visible light section, representing a certain colour.

Teacher :

Great. And post-stretching, where did your stretched wave fit on the spectrum?

Student 4 :

After stretching, it moved towards the infrared and if we stretched more it shifts toward the microwave section of the spectrum. So, it's like the light changed its form?

Teacher :

Exactly. Just as the dots moved further apart on your elastic, representing longer wavelengths, the light from the early universe stretched due to its expansion. Does anyone remember what we call this phenomenon when we observe it now?

Student 1 :

The Cosmic Microwave Background!

Teacher :

Brilliant, Student 1. And why is it called "microwave"?

Student 2 :

Because the stretched light waves from the early universe now appear to us in the microwave part of the electromagnetic spectrum!

Teacher :

Well-done. So, just like the light waves on your elastic bands were stretched and changed, the light from the universe's beginning was stretched over billions of years. Today, we detect this stretched light as the Cosmic Microwave Background, a relic from the early days of our universe.

Today, we've journeyed from the very birth of the universe to its current state, understanding the fundamental processes that have shaped it. We've seen how light itself has evolved, giving us insights into the universe's past. It's a reminder that while the universe is vast and ever-changing, we, through our curiosity and intelligence, can connect with its grand narrative. Always keep that spark of wonder alive, for it's our bridge to the cosmos. Until our next cosmic journey, keep looking up and never stop questioning. 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 :

UNDERSTANDING THRESHOLDS OF INCREASING COMPLEXITY
What is the Cosmic Microwave Background?
The Beginning of Everything -- The Big Bang
The Big Bang Theory
The beginning of the universe, for beginners - Tom Whyntie
The Big Bang: Crash Course Big History #1
The Big Bang, Cosmology Part 1: Crash Course
The Evolution of The Universe Explained by Brian Cox
Evidence for the Big Bang Theory
Where Was the Big Bang?
Picture of the Big Bang (a.k.a. Oldest Light in the Universe)
Misconceptions About the Universe
Big Bang: The Theory and the Origin of the Universe
What Emerged from the Big Bang?
Brain Cox explains Entropy in a short video
What is entropy?
Entropy: The Most Misunderstood Concept in Physics

Website :

The Big History Project
NASA's summary of the latest discoveries made around the Big Bang
Big Bang Theory Teacher Resources

Documentaries :

Into The Universe with Stephen Hawking the Story of Everything
Origins of the universe, explained

Books :

A Brief History of time – Stephen Hawking
The First Three Minutes – Steven Weinberg

Articles :

What is the Big Bang Theory?
Cosmic timeline: What's happened since the Big Bang
The history of the universe: Big Bang to now in 10 easy steps
The Big Bang - NASA
The Big Bang - History of the Universe
Top 10 Facts About The Big Bang Theory

Quiz :

Threshold 1: The Big Bang
The Big Bang

Games :

Escape the Cosmic Microwave Background Maze Activity
Tour of the Map of the Big Bang

Glossary

Entropy: A measure of the amount of disorder or randomness in a system. The second law of thermodynamics states that the entropy of an isolated system will tend to increase over time, meaning systems will become more disordered.

Big Bang: The theoretical event marking the beginning of the universe. It is believed that the universe originated as an extremely hot and dense point roughly 13.7 billion years ago and has been expanding ever since.

Goldilocks Conditions: Refers to conditions that are " just right " for a specific phenomenon to occur. It's derived from the story of Goldilocks and the Three Bears where Goldilocks prefers things that are neither too extreme one way nor the other.

Galaxy: A massive system that consists of stars, star clusters, planetary systems, interstellar clouds, and dark matter, all bound together by gravity.

Cosmic: related to space or the universe.

Radiation: Energy that travels in the form of waves or particles. In this context, it refers to the energy released during the initial stages of the universe's formation.

Inflation: The rapid expansion of the universe from its origin, growing from smaller than an atom to a much larger size almost instantly.

Subatomic Particles: Tiny particles that are smaller than atoms, like quarks, electrons, and neutrinos.

Quarks: Fundamental particles that combine in various ways to make up larger particles, like protons and neutrons.

Antimatter: The "opposite" of normal matter. When antimatter and matter meet, they destroy each other.

Hadrons: Particles made up of quarks. Protons and neutrons are examples of hadrons.

Protons: Positively charged particles found in the nucleus of an atom.

Neutrons: Particles with no charge, also found in the nucleus of an atom.

Nuclei: The central part of an atom, containing protons and neutrons.

Hydrogen: The simplest and lightest element in the universe. Its atom consists of one proton and one electron.

Kelvin: A unit of temperature. 0 Kelvin (absolute zero) is the lowest possible temperature, where all molecular motion stops.

Cosmic Microwave Background (CMB): A kind of "afterglow" from the Big Bang. It's like a snapshot of the universe when it was very young, showing tiny temperature differences in the early cosmos.

Surface of Last Scattering: The point in the universe's history where light last scattered or bounced off matter before it could travel freely.

Supernova: A stellar explosion that occurs when a massive star reaches the end of its life cycle, leading to the scattering of elements.

Protons Fusion: A process where protons combine to form a heavier nucleus, releasing energy in the process.

Periodic Table: A table of chemical elements arranged in order of atomic number.

Relativity: A theory by Einstein that describes the relationship between space and time.

Quantum Mechanics: A branch of physics that studies the behaviour of the smallest particles and waves on the atomic and subatomic scale.

Stardust: The remnants or dust left behind by dying stars, which can form new stars, planets, and other celestial objects.

Electromagnetic Spectrum: The range of all types of electromagnetic radiation, from radio waves to gamma rays.

Wave Crests: The points on a wave that have the maximum value or upward displacement within a cycle.

Wavelength: The distance between successive wave crests.

Frequency: The number of waves that pass a fixed point in a given amount of time.

Nanometre (nm): A unit of length in the metric system, equal to one billionth of a meter.

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)

COST (European Cooperation in Science and Technology) is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, career and innovation.

www.cost.eu

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

ANOMALIES & TENSIONS IN COSMOLOGY

COSMOVERSE