ASTRONOMY PROJECT RESEARCH DOCUMENT

DARK ENERGY | AMIRALI BANANI | YOUTH STEM INITIATIVE

Before the Discovery of Dark Energy:

When we think of the universe, we often picture matter that is pulled and held together by the force of gravity – forming planets, planetary systems, galaxies, clusters of galaxies, and ultimately the "web" of the universe. When we think about the birth of our universe, we picture a rapidly expanding cosmos that began to slow down in its expansion as it cooled. But what if I told you that this hasn't always been the case?

At the end of the 20th century, observations done by NASA of supernovae millions to even billions of light years away using the Hubble Space Telescope showed that the universe's rate of expansion in its earlier days was actually slower than it is today. This was a revolutionary discovery in Astronomy because it contradicts the theories of many astronomers – showing that the universe's rate of expansion has not actually been slowing down due to gravity, but it has been accelerating. Scientists knew that there was an unknown, anti-gravity force causing this, yet to be discovered: Dark Energy.

What is Dark Energy?

Dark Energy is a perplexing form of matter or energy that is accelerating the universe's rate of expansion. Since it does not interact with any type of electromagnetic radiation, it is virtually invisible to us. However, rather astonishingly, 68% of all matter in the universe is composed of dark energy according to NASA. From the 32% that remains, 27% is composed of dark matter and only 5% is composed of visible matter (i.e., the matter that we can see and interact with). At this point in time, dark energy quite clearly dominates the universe, forcing the cosmos to expand at an ever-increasing rate.

How do we know about Dark Energy?

The effects of dark energy are evident primarily by their influence on the universe's rate of expansion; specifically, the rate at which distant galaxies are receding from planet Earth. Deep space observations by advanced telescopes and intense analysis of ancient supernovae have provided convincing evidence that the universe's rate of expansion is accelerating based on differences in the wavelengths of light reaching us from the supernovae overtime. Yes, you guessed it. I'm speaking of cosmological redshift - a phenomenon that will be explained more deeply later.

Dark Energy Vs. Dark Matter:

- As explained before, dark energy and dark matter are the two opposing forces governing the physics of the universe. As their names suggest, they are impossible to see even with the most sophisticated instruments that can detect other wavelengths of light. The only way to analyze them is by studying their interactions with other forms of matter in the universe.

- Now you may ask, what's the difference between the two? Dark energy is the force that's trying to accelerate the universe's rate of expansion, while on the contrary, dark matter tries to decelerate the universe's rate of expansion. Dark energy essentially tries to push objects in the universe apart from each other, while conversely, dark matter is the force that tries to pull objects together. In other words, dark matter interacts with gravity while dark energy repulsesit.

- In its early days, dark matter dominated the universe, forcing its rate of expansion to slow down following the Big Bang. However, figures show that between 5 and 7 billion years ago, the anti-gravity force of dark energy took over dark matter and began to dominate the universe, reversing its rate of expansion. To this day, it still remains a mystery to scientists as to why this occurred. However, for what we do know, we are fortunate that dark matter dominated the early universe otherwise there would be no planets, stars or galaxies and the universe would be a painfully uneventful void of pure oblivion.

- This cosmic tug of war has been going on since the birth of the universe, and from here on as the universe expands endlessly, dark energy's domination will only continue to increase.

Weakly Interacting Massive Particles:

Weakly Interacting Massive Particles (WIMPs) are abnormally heavy, electromagnetically neutral subatomic particles that are hypothesized to be the main constituents of both dark energy and dark matter and are therefore thought to make up 90-95% of all particles in the universe. What indicates that these particles are electromagnetically neutral is the absence of light that is absorbed or emitted by them, which is why they are invisible to us. This, again, is because WIMPs – like dark energy/matter as a whole – do not interact with electromagnetic radiation in any shape or form. These hypothetical particles are speculated to move slowly through space and time due to their abnormally large weight. Their presence can be detected only through gamma rays which are released when they annihilate each other. Scientists are now investing loads of money into research to measure the properties of WIMPs by observing the nature of their collisions and how they annihilate each other in particle accelerators and cyclotrons.

The Universe's Rate of Expansion:

It has only been for the last half of its life that the universe has been expanding at an accelerated rate. The rate of expansion is becoming faster by the second, even faster than the speed of light, therefore the laws of physics as we know it break down when we try to calculate the speed at which the universe is expanding. Using distance measurements between us and the **furthest astronomical objects we can observe** in relation to cosmological redshift calculations, we can provide convincing evidence that this phenomenon is true. This can be confirmed using Hubble's constant, which mathematically demonstrates that distant galaxies are moving away from Earth at speeds proportional to their distance.

Cosmological Redshift:

As described earlier, cosmological redshift is a key phenomenon used to measure the rate of the universe's expansion by analyzing the rate at which distant galaxies recede from Earth. Below is a summary of this phenomenon in point-form:

- Redshift is caused by the expansion of space which forces celestial objects to move apart from each other. The radiation emitted from one object relative to another gets stretched and shifted towards the red portion of the visible light spectrum, hence the name "red shift".

- As demonstrated by Hubble's constant which I explained earlier, recessional velocity increases with distance. This means that objects further away **move apart from us at a greater speed** and thus exhibit more red light than do objects that are closer to us.

- This phenomenon is arguably the most compelling piece of scientific evidence that confirms the existence of dark energy, and physicists have used it to calculate the effects of dark energy on the universe's rate of expansion with ever more precision.

VISUALIZATION: The Doppler Effect & Cosmological Redshift

The concept of Cosmological Redshift is very similar to that of the Doppler Effect. As you can see on the left, there is a source of the sound, the ambulance, moving towards the front observer and away from the back observer.

Due to this particular motion, the front observer will experience a higher pitched sound due to sound waves with shorter wavelengths and thus greater frequency, while the back observer will experience a lower pitched sound due to sound waves with longer wavelengths and thus lower frequency.

Similarly, when a galaxy moves towards an observer, as demonstrated on the right, blueshift occurs as the wavelength of the light waves decreases, but when the galaxy recedes from the observer, redshift occurs as the wavelength of the light waves increases.

These two concepts in Physics are based on the same underlying principle. The only difference is that redshift deals with light waves, while the doppler effect deals with sound waves.

Cosmological Constant:

The cosmological constant is an important constant in the field of astrophysics that arises from Einstein's field equations of General Relativity. It describes the energy density or vacuum energy of space, which ultimately explains the universe's accelerating rate of expansion. The cosmological constant is closely associated with the concepts of dark energy and quintessence (which is a hypothetical form of dark energy) and is depicted by the Greek letter Lambda. This incredible piece of work was thought to be the biggest blunder of Einstein's career, but is now regarded as one of the most spectacular equations in all of physics and astronomy.

Big Rip Vs. Big Crunch Theory:

- The universe could end in one of two main agreed-upon ways. One is a Big Rip, and the other is a Big Crunch.

- According to the Big Rip Theory, stars will literally be ripped apart from each other, and solar systems such as ours would lose the gravitational strength to remain together. Eventually, the immense force of dark energy will rip the last atoms apart, resulting in an empty void of elementary particles separated at great distances.

- Unless the expanding universe could not combat the collective inward pull of dark matter's gravity, it would die in a Big Crunch. In this theory, the universe's expansion would reverse and all the matter and energy in the universe would clump together into a space that's a tiny fraction of the size of a proton - comparable to the conditions of the Big Bang.

Consequences of the Universe's Expansion:

- As the universe continues to expand, space becomes colder and less dense. As distant astronomical objects move further away from us, we may eventually not be able to see them anymore as the light they emit becomes more and more stretched until it one day exits the range of the entire electromagnetic spectrum.

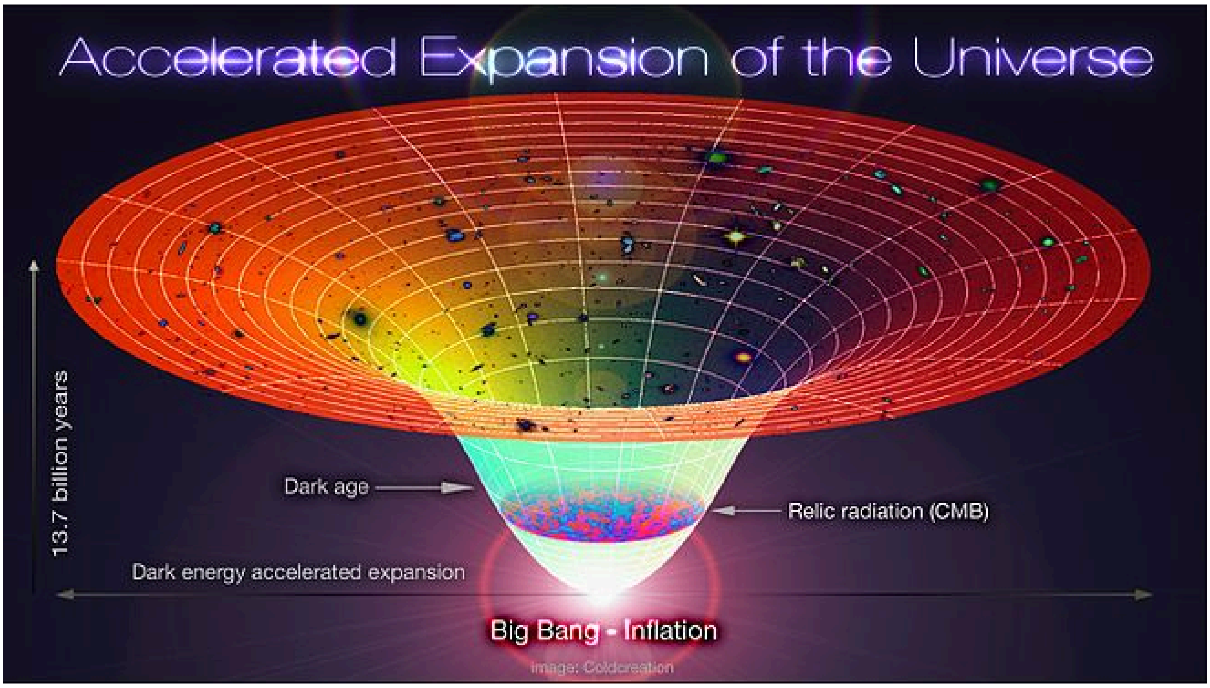
- Furthermore, space travel to distant galaxies may become physically impossible even at the speed of light as the galaxies would have travelled so far and would be travelling at such a fast speed away from us that we'd chase them forever without ever actually reaching the galaxies.

- As a result of the universe's current rate of expansion due to dark energy, we would forever be confined to our local cluster of galaxies: the virgo supercluster. Thus, the time to explore and learn as much as we can about the universe is now. We must take advantage of the technology we have to advance our understanding of the universe while we can, and while it's still feasible.

RESEARCH:

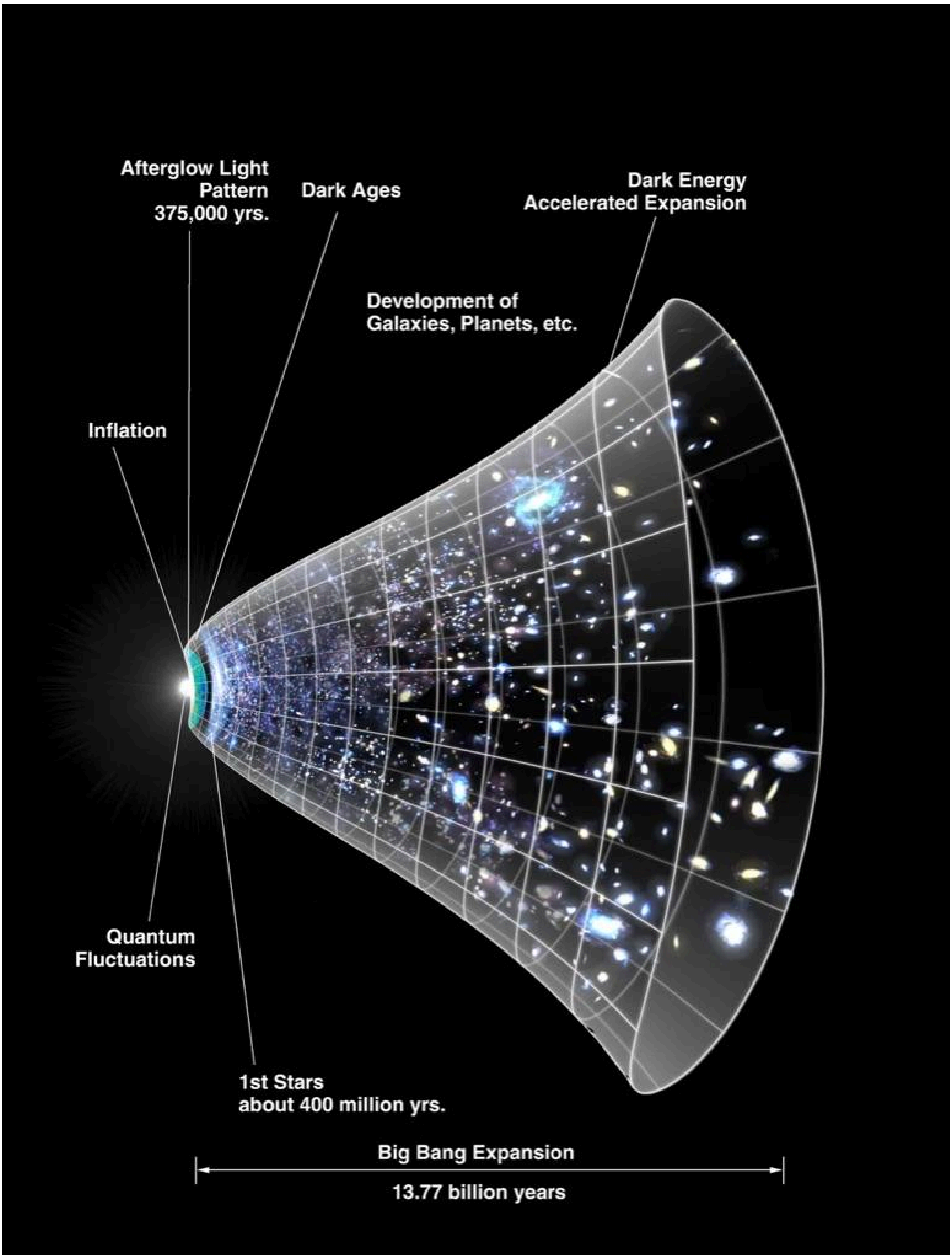
It was long that the universe's expansion might continue forever, or eventually – if the universe had enough mass and therefore enough gravity, reverse and cause a Big Crunch. Now, in early 21st-century cosmology, this idea has evolved. The universe is seen as expanding faster today than billions of years ago. Astronomers are researching the repulsive force of Dark Energy as a way to understand the universe's accelerating rate of expansion.

The astronomical community originally treated this discovery with skepticism, but the observations were soon replicated by other teams of scientists using other methods. By the end of the 20th century, it became evident that the expansion of the universe is not slowing down, but is accelerating.



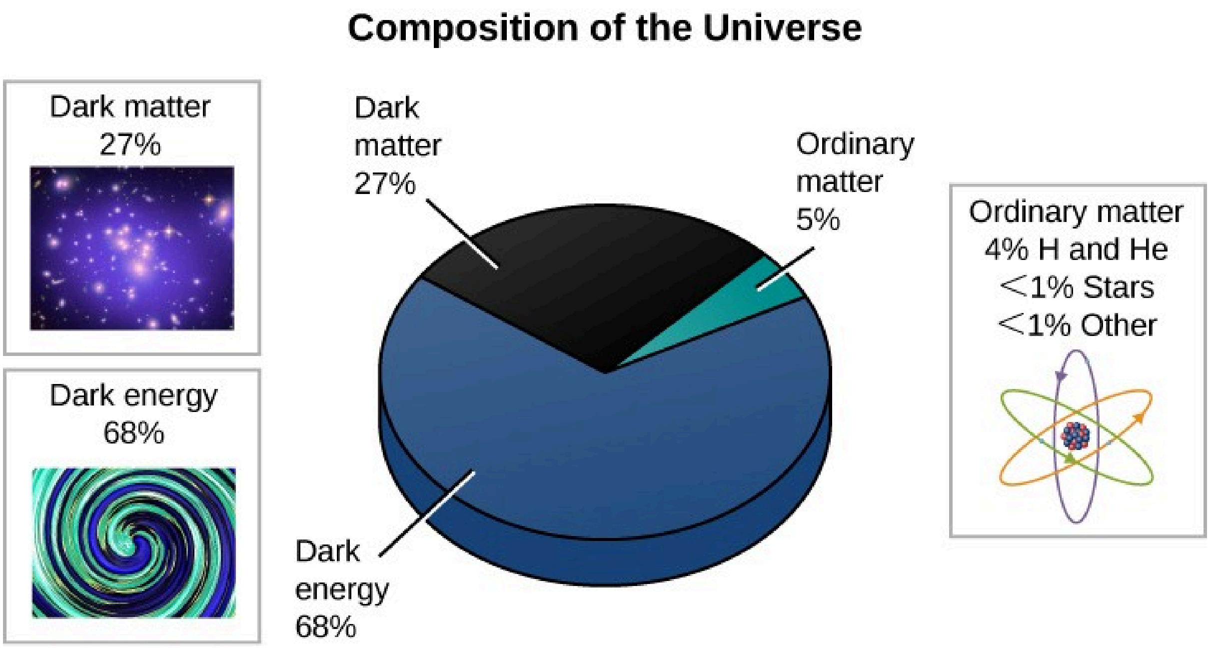
It has been confirmed now that the expansion had been decelerating until seven to eight billion years after the Big Bang. However, for unknown reasons, a mysterious anti-gravity force started to dominate the Universe, overcoming the “resistance” that gravity was placing on the expansion, which then reversed its deceleration and caused the universe to begin accelerating.

The mysterious force responsible for this acceleration was termed *dark energy* by scientists. In this context, *dark* means *unknown* rather than literally dark, as is the case with dark matter, a phenomenon that’s the exact opposite of dark energy.



Surprisingly, the properties of dark energy seem to match Albert Einstein's cosmological constant. The Cosmological constant mathematically demonstrates the accelerating expansion of the universe and is closely related to the concept of dark energy. Einstein however detested the idea of an expanding universe, preferring the static one postulated by steady-state cosmology, and later thought that the cosmological constant was the greatest blunder of his career.

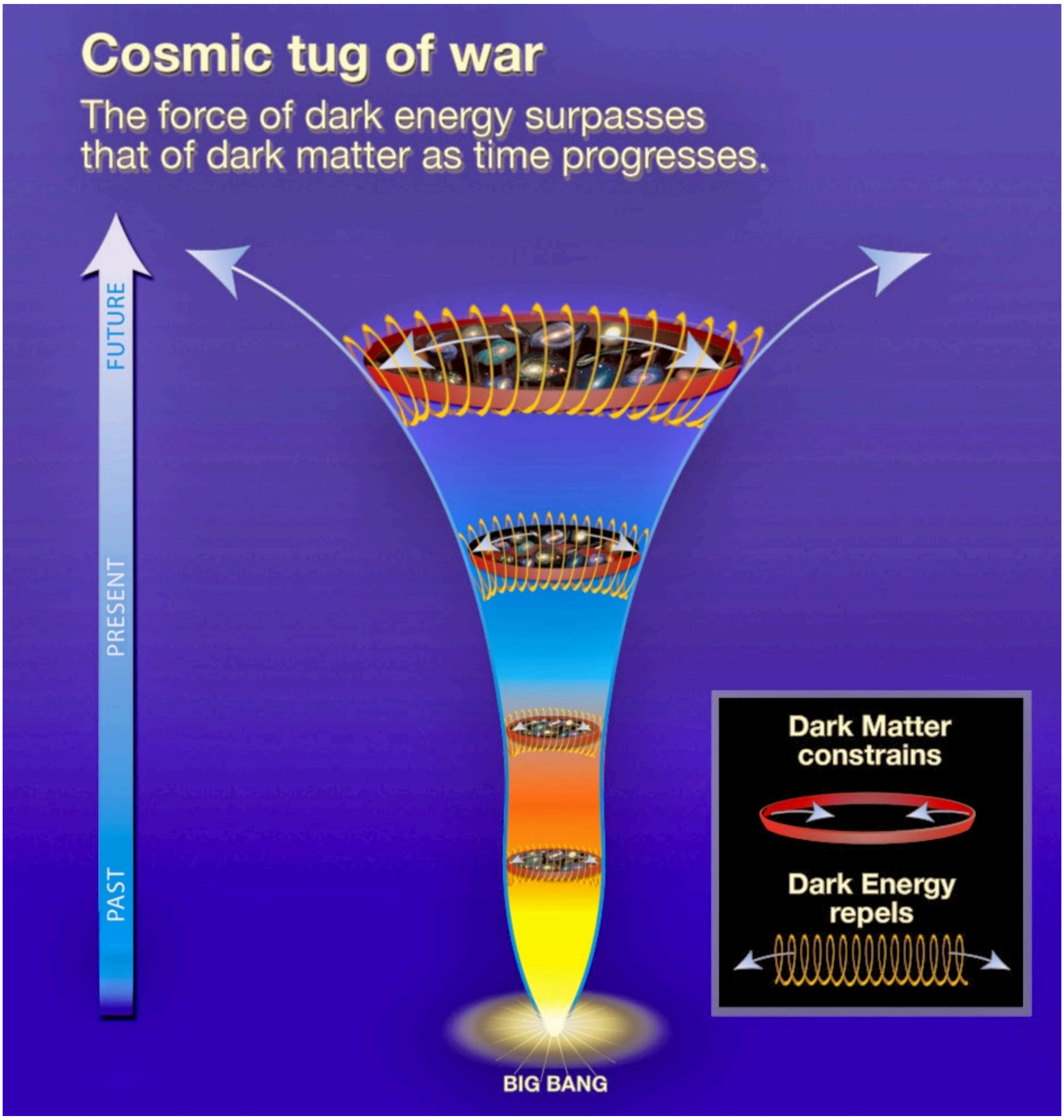
Dark energy still remains one of the great unsolved mysteries of cosmology. It is now thought to make up 68% of everything in the universe, with baryonic (normal) matter comprising only 5%. The other 27% is composed of dark matter, another huge astronomical mystery.



One of its greatest mysteries of modern cosmology is why dark energy began to dominate the rate of expansion of the universe at a particular point in time billions of years after the Big Bang. The physics behind dark energy are highly hypothetical. Cosmologists don’t have enough information to determine whether dark energy will continue to accelerate the universe’s expansion forever → leading to a scenario far in the future where the expansion of the Universe will overcome the forces (such as gravity) that hold it together and literally tear all the matter in the cosmos apart, resulting in a “Big Rip”.

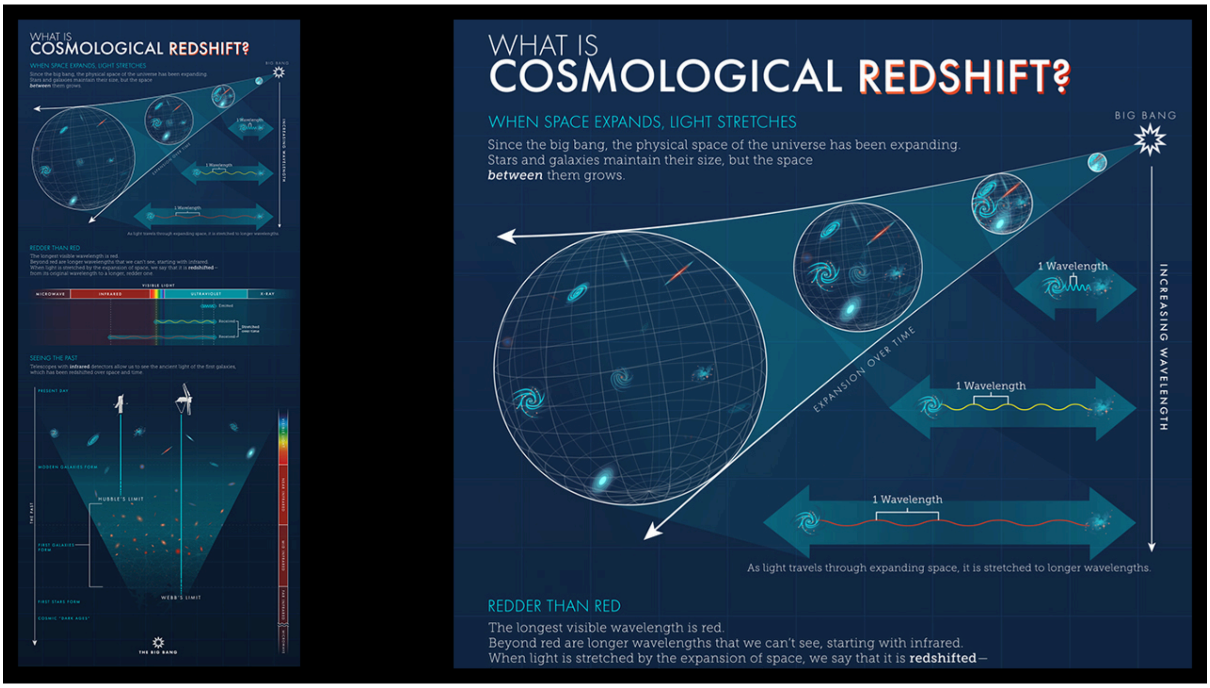
There are several space missions and ground-based surveys which will investigate the nature of dark energy, including NASA's WFIRST space telescope and the International Dark Energy Survey in Chile. With these scientific investigations, scientists are looking to develop a greater understanding of this mysterious force that's forcing the cosmos to expand, which will not only allow them to better hypothesize the fate of our universe but also to gain the understanding we need to sketch out a far more complete history of the universe.

THE COSMIC TUG OF WAR: DARK ENERGY VS DARK MATTER

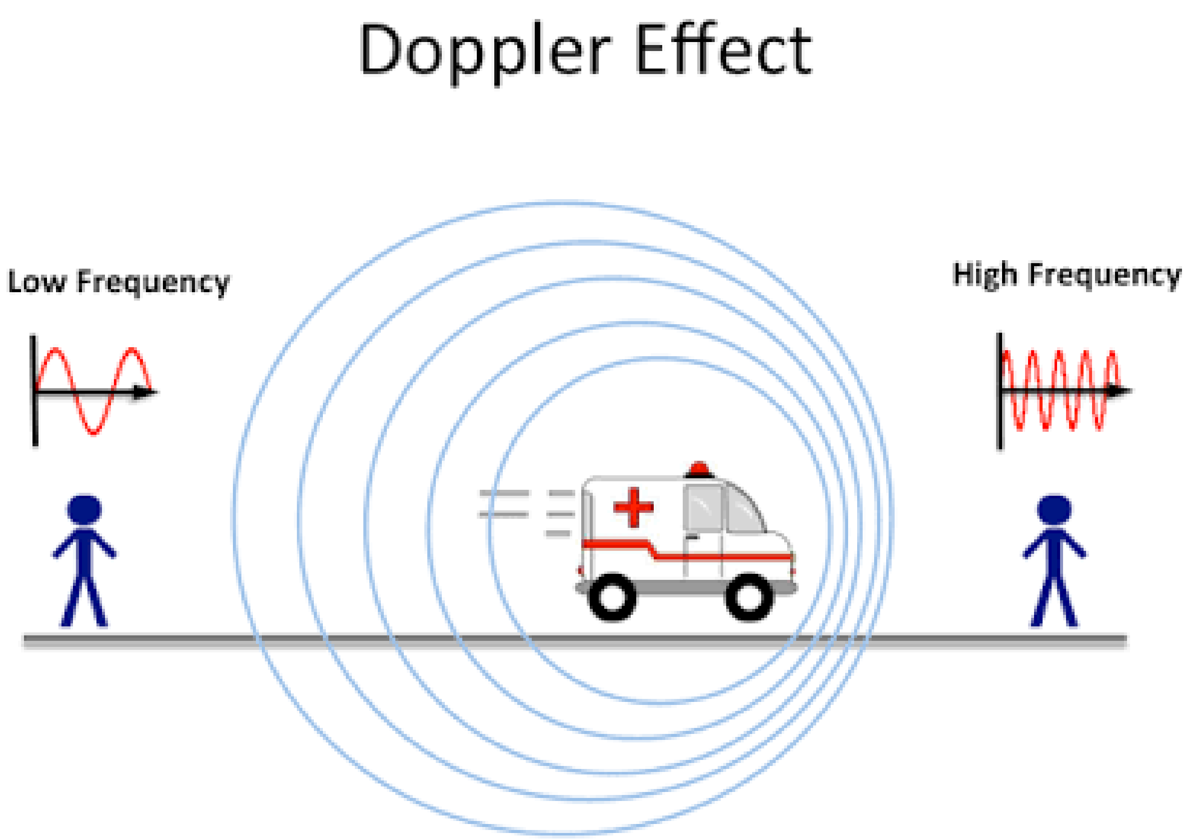


The Cosmic Tug of War is a “tug of war” between the two dark forces: Dark Energy and Dark Matter. Since dark matter interacts with gravity, it constrains the universe from expanding, while dark energy, since it repels gravity, forces the universe to expand at an ever increasing rate. After the Big Bang 13.8 billion years ago, dark matter was the dominant force → resulting in the formation of planets, stars and galaxies (due to gravitational forces pulling matter and energy together). From 5-7 billions years ago, however, dark energy began to dominate, causing the universe’s rate of expansion to accelerate and increase. As the universe continues to expand, dark energy’s domination increases. These two opposing forms of matter that account for a total of 95% of all matter in the universe will govern the fate of the universe → leading to either a Big Rip or a Big Crunch. This Cosmic Tug of War has been going on since the birth of the universe, and continues to “pull on each other” in opposite directions today.

COSMOLOGICAL REDSHIFT:



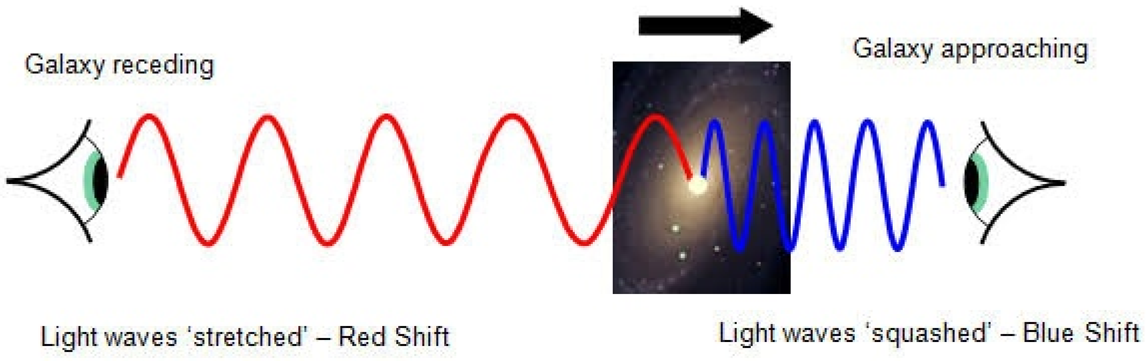
Astronomers use the phenomenon of cosmological redshift to measure the universe’s expansion rate, and thus to determine the distance to the most distant and ancient celestial objects from planet Earth. Redshift is often compared to the high-pitched sound of an ambulance siren approaching an observer, which then drops in pitch as the ambulance moves past the observer and away from it. The change in the frequency and wavelength and therefore the pitch of the sound from the siren of the ambulance is due to what’s called the Doppler Effect. This effect provides a good comparison to Redshift because both sound and light travel in waves and are affected by their movement through space.



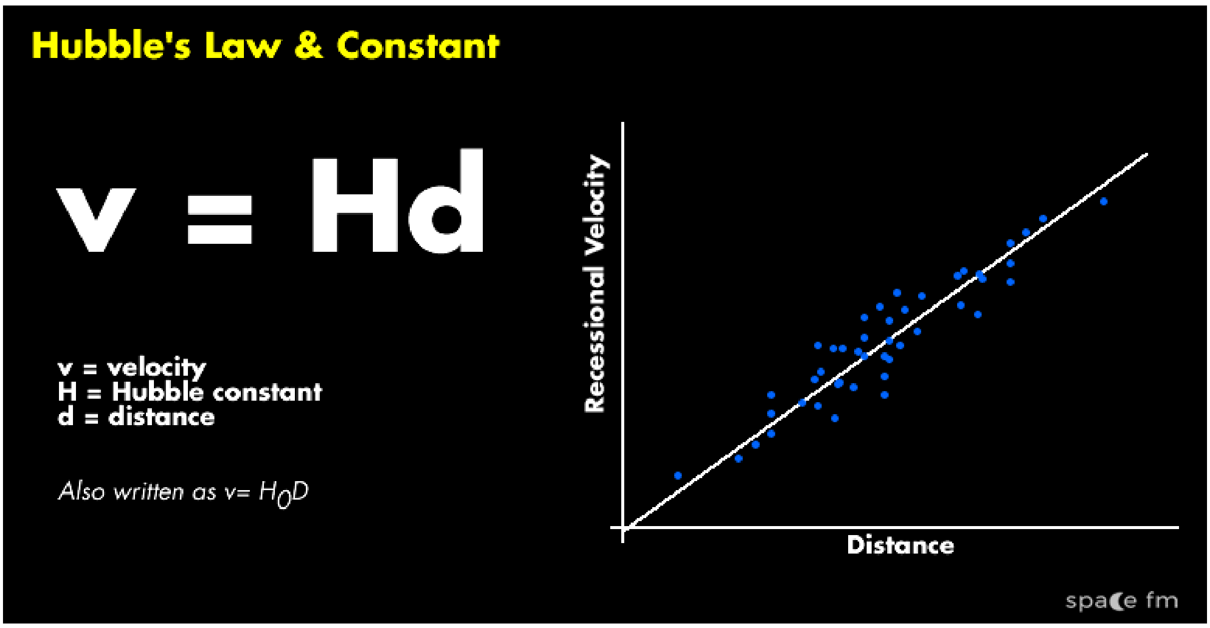
Sound travels at a constant speed of approximately 1,200km per hour. As an ambulance travels and blares its siren, the sound waves in front of the ambulance get compacted together, causing the wavelengths of the sound waves to decrease and their frequency to increase → producing a higher-pitched sound. Meanwhile, the sound waves behind the ambulance spread out, causing the wavelengths of the sound waves to increase and its frequency to decrease → producing a lower-pitched sound. Our brains interpret changes in the frequency of sound waves as changes in pitch.

Like sound, light is also a wave travelling at a constant speed (300,000km per second). Therefore, the light follows similar rules to sound, however, our retinas perceive changes in wave frequency of light as changes in colour, not as changes in pitch.

As a thought experiment to visualize cosmological redshift, imagine this: if a lightbulb were to move very rapidly through space, the light would appear blue as it approaches you and then become red after it passes. Measuring such slight changes in the frequency of light allows astronomers to measure the speed – and therefore the distance – of all observable celestial bodies in the universe.



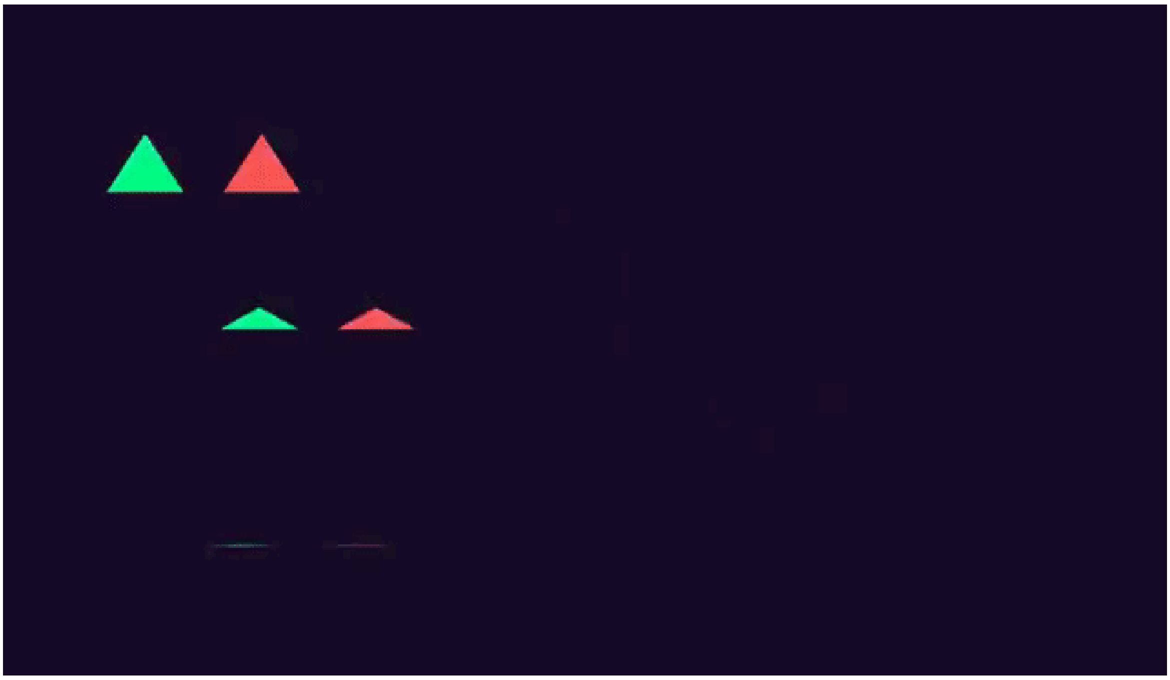
HUBBLE'S CONSTANT



Hubble's constant mathematically demonstrates the universe's accelerating rate of expansion as an approximately linear function. The law states that recessional velocity increases with distance, meaning that the further away a celestial body is from Earth, the faster it's moving away from us. Thus, in our expanding universe, a measurement of speed translates to a measurement of distance.

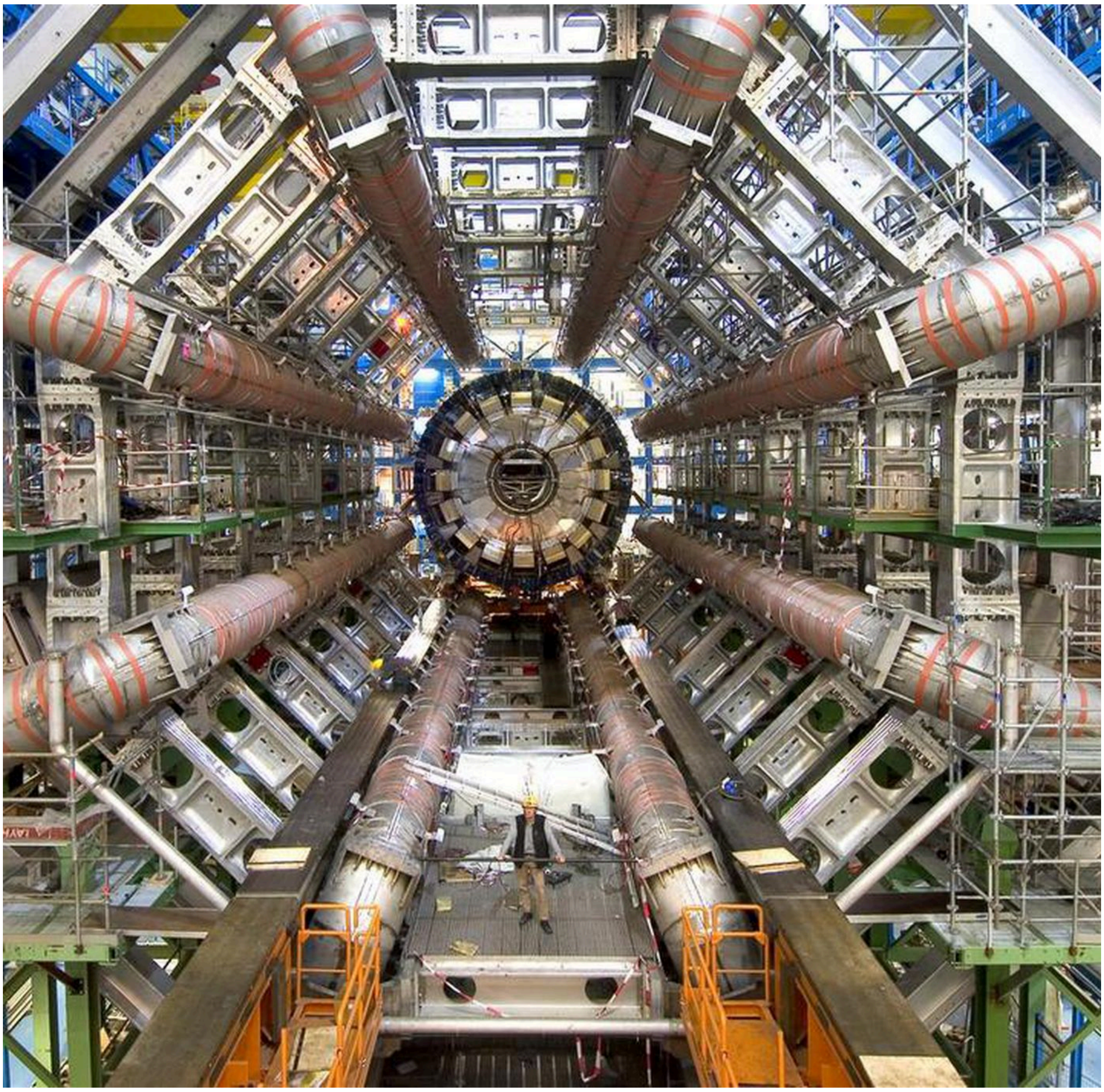
WEAKLY INTERACTING MASSIVE PARTICLES:

Dark Energy and Dark Matter are both hypothesized to be made up of Weakly Interacting Massive Particles (or WIMPS), which are heavy, electromagnetically neutral subatomic particles thought to make up about 90-95% of the particles in the universe. These hypothetical particles are speculated to be heavy and slow moving because if they were light and fast moving instead, the particles would not have clumped together in the density fluctuations from which galaxies and clusters of galaxies formed. When WIMPs annihilate each other, they tend to release radiation in the form of Gamma Rays. The absence of light and electromagnetic radiation from these particles of any form is what indicates that they are electromagnetically neutral. These properties essentially give rise to the common name of the particles, 'Weakly Interacting Massive Particles'.



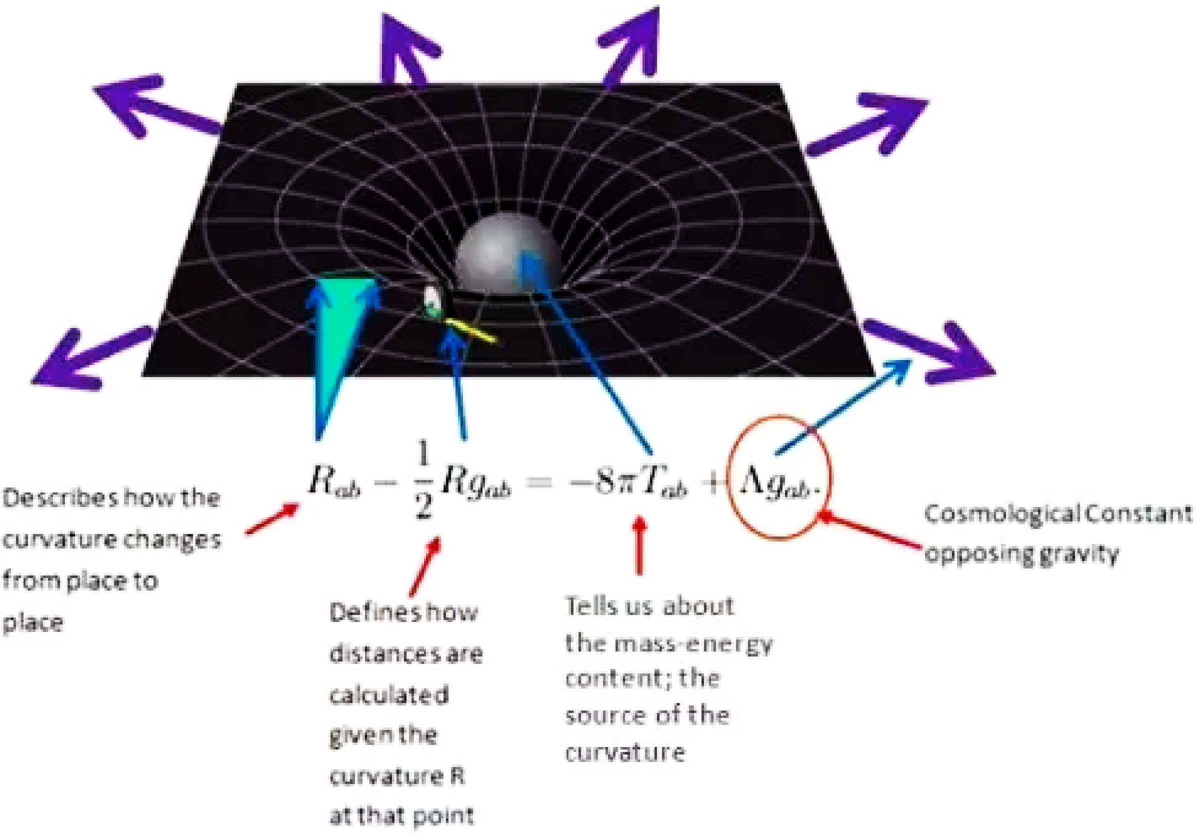
WIMPs are assumed to be **non baryonic**, meaning that they aren't **baryons** - massive subatomic particles such as the proton and neutron that are each made up of three quarks. This is because the quantity of baryons in the universe has already been mathematically determined by measuring the abundance of chemical elements heavier than Hydrogen that were created in the first few minutes after the Big Bang, 13.8 billion years ago. The precise nature of WIMPs is currently unknown to astrophysicists, and the particles are not predicted by the Standard Model of Particle Physics. A number of possible extensions to the Standard Model, however, such as the theory of supersymmetry, predict certain hypothetical elementary particles such as axions and neutralinos that may actually be the undetected Weakly Interacting Massive Particles.

Many extraordinary scientific efforts and initiatives are underway today to detect and measure the properties of these mysterious WIMPs, either by observing their impact in a laboratory detector or by observing their mutual annihilations when they collide with each other in a particle accelerator. Their presence and mass may also be inferred from experiments at particle accelerators such as the Large Hadron Collider in Geneva, Switzerland and TRIUMF at the University of British Columbia.



Above: Large Hadron Collider (LHC) in Geneva, Switzerland | CERN - European Organization for Nuclear Research

THE COSMOLOGICAL CONSTANT:



The cosmological constant, an ingenious constant that arises from Einstein's field equations of General Relativity, was thought to be the biggest blunder of Einstein's career, but is now regarded as one of the most spectacular equations in all of physics and astronomy. It describes the energy density or vacuum energy of space, which in turn explains the universe's accelerating rate of expansion. The cosmological constant is closely associated with the concepts of dark energy and quintessence (which is a hypothetical form of dark energy) and is depicted by the Greek letter Lambda. Below is a brief explanation of the different components of the equation:

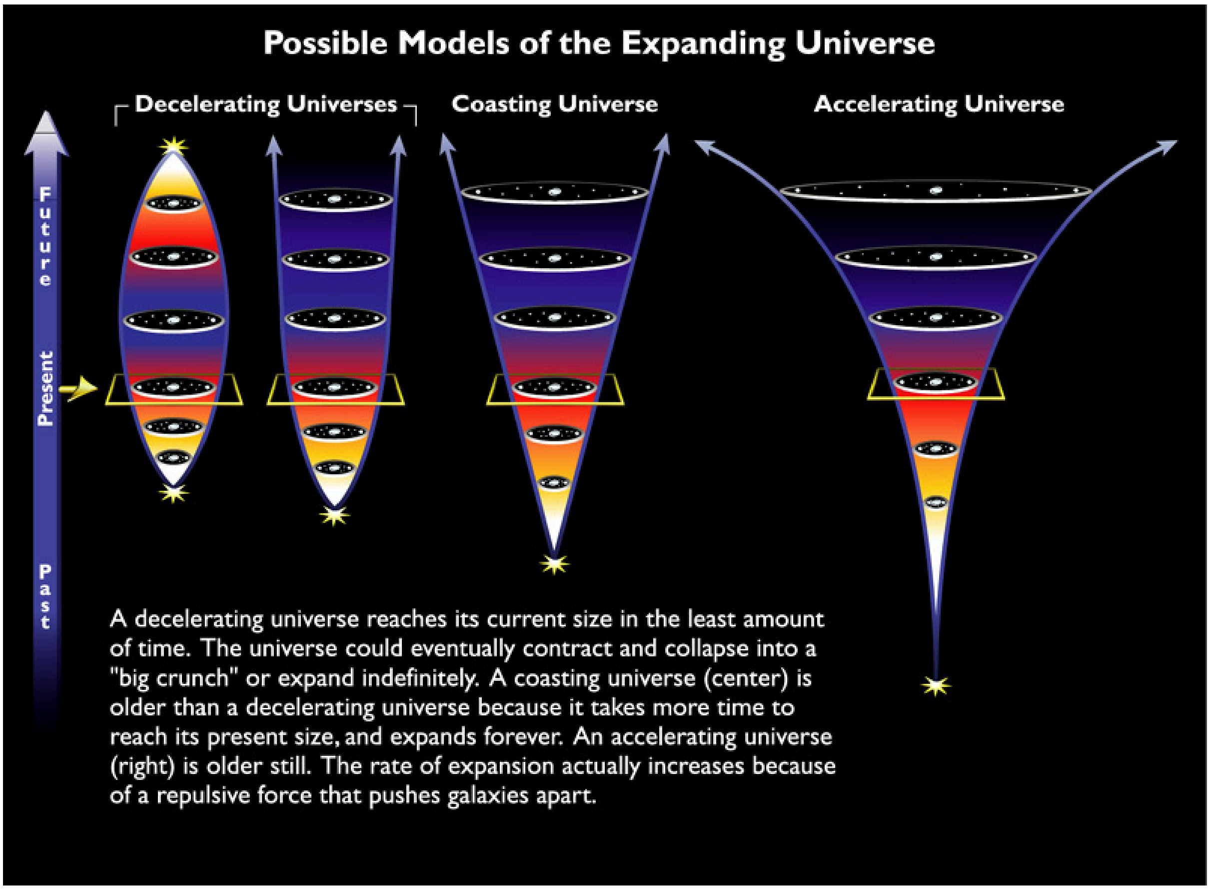
- The first variable describes how the curvature of the fabric of spacetime changes in different parts of the universe depending on the mass and gravitational influence of certain celestial bodies. The R represents the curvature, while a and b written as subscripts depict the curvature of spacetime between points a and b (for instance between the sun and the earth).

- The second variable which is subtracted from the first defines how distances are calculated between certain celestial bodies or points in space depending on the curvature of spacetime. As you can see, gravitational force (g) is also included in this second variable. Using the gravitational force and curvature of spacetime variables, astrophysicists can calculate distances between various points in space.

- The next variable on the other side of the equal sign represents the mass and energy content of the source that's causing the curvature. The more mass and energy a celestial body has, the greater it will curve spacetime and vice versa. This variable is demonstrated by the spherical object in the diagram that's forcing the fabric of spacetime to bend around it.

Finally, the cosmological constant is added at the end, which represents the force opposing gravity → accounting for the universe's accelerating rate of expansion as demonstrated by the outward-facing arrows in the diagram.

THE UNIVERSE'S FUTURE



There are 4 main speculated models of the universe's future based on its current rate of expansion.

1. The universe will continue to expand until at some point, dark matter will begin to dominate again as it did early in the universe's life and force all the mass and energy in the universe to condense → eventually resulting in a **Big Crunch**. **(Decelerating Universe)**

2. The universe will continue to expand indefinitely but at a slower rate of expansion. **(Decelerating Universe)**

3. The universe will continue to expand indefinitely at a constant rate; not at an accelerated or decelerated rate. **(Coasting Universe)**

4. The universe will continue to expand at an accelerated rate, meaning that its rate of expansion will become faster and faster by the second. Eventually, the force of expansion will become so strong that all matter will be stripped apart down to the last atom → resulting in a **Big Rip**.

The Discovery of Dark Energy

Dark Energy was first discovered in 1998 by 3 astronomers who measured light coming from exploding stars called Type 1A supernovae, known as "standard candles" for their consistent brightness. The fascinating result was that distant supernovae were dimmer, or in other words farther away, than they would be in a universe that was decelerating. This suggested that the expansion of the universe was accelerating. Following such an unexpected discovery, the astronomers proposed that something called dark energy could be driving this acceleration. The 3 astronomers were awarded the Nobel Prize in Physics for their discovery in 2011.

Photo: Lawrence Berkeley National Lab — **Saul Perlmutter**

Photo: Belinda Pratten, Australian National University — **Brian P. Schmidt**

Photo: Scanpix/AFP — **Adam G. Riess**

The Nobel Prize in Physics 2011 was awarded *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"* with one half to Saul Perlmutter and the other half jointly to Brian P. Schmidt and Adam G. Riess.

Quote by Neil deGrasse Tyson:

As world-renowned astrophysicist, Neil deGrasse Tyson states, “Dark matter and dark energy are two things we measure in the universe that are making things happen, and we have no idea what the cause is.” With extensive experimentation and the application of technology that we currently have, we can expand our understanding of these two significant constituents that make up 95% of the matter in the universe and ultimately learn more about our universe’s origins, the big bang, and how these two opposing forces account for the cosmic tug of war that has been going on for 13.7 billion years and counting.

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