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Literature Survey on Dark Matter, Dark Energy and their effect on the overall geometry and fate of the Universe

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Abstract:- Dark Matter and Dark Energy make up 95% of our universe, the parts which are invisible to the eyes. In the currently popular 'concordance model' of the Universe, 68% of the cosmos is thought to be dark energy, 27% dark matter and 5% baryonic (visible, normal) matter (See Fig 1.1). Dark Matter and Dark Energy shape up our universe, deciding its future – whether it is torn apart in a Big Rip, i.e., the expansion accelerates so much that it tears itself apart into oblivion, or if it would simply go on in a series of Big Bangs and Big Crunches. In this research, we shall take a closer look at what are dark matter and dark energy, and how will they alter the growth of massive structures like galaxies, alter the shape of the universe, and help in predicting its destiny.

Keywords: - Dark Matter, Dark Energy, Expansion, Galaxies, Share of Universe

I. INTRODUCTION

The universe is an enormous, intricate network composed of galaxy clusters, superclusters, filamentary structures, and vast empty regions, all moulded by the combined forces of gravity and cosmic expansion over billions of years. Observational data from Euclid Telescope, launched by ESA in 2023, have added to our understanding of the cosmos. Most of this universe is made up of matter and energy which we cannot see, making it an enigma to us. The invisible matter is known as Dark Matter, while the energy is called Dark Energy. The part of the universe that we can see – the stars, planetary systems, nebulae, comets, and other visible features – make up a measly 5% of the universe.

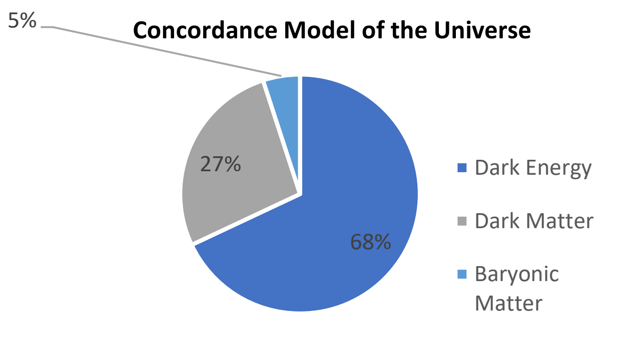

Fig. 1:

Dark Matter is invisible matter that makes up 27% of the universe and increases gravitational pull, which ultimately helps in slowing down expansion of the cosmos. It was first detected in the 1930s when Swiss-born astronomer Fritz Zwicky was examining the Coma Cluster of galaxies, and noticed an anomaly. The galaxies in the Coma Cluster were moving much faster than they should have if only the visible matter was holding the cluster together. Zwicky surveyed the galaxies in the Coma Cluster using a spectrograph that measured their Doppler shifts to determine their velocities. He applied the virial theorem—a classical mechanics principle linking orbital speeds to gravitational force—to calculate the cluster's total mass. Then, by measuring the total light from the cluster (about a trillion stars) and comparing its light-to-mass ratio with that of the nearby Kapteyn system, he discovered the cluster produced over 100 times less light per unit mass. From this, he inferred that most of the mass was made up of unseen matter, which he called "dark matter."

Another evidence of the existence of Dark Matter was found decades later by astronomers Vera Rubin and Kent Ford when they were studying the rotation rates of individual spiral galaxies. Scientists expected stars at the outer edge of a galaxy to orbit more slowly than stars near the centre due to the concentration of mass toward the central regions—much like how the planets in our solar system move, with those farther away orbiting slower. However, Vera Rubin's and Kent Ford's observations revealed that the stars at a galaxy's outskirts rotate at a faster speed than those closer to the galactic core. This phenomenon, evidenced by flat rotation curves, indicated that the visible matter is insufficient to produce the gravitational forces required for the observed orbital velocities, implying a significant presence of additional dark matter.

Dark energy, on the other hand, is the gravitationally repulsive force that helps speed up expansion of the universe. It is the dominant component of the universe, 68% of the universe is made up of dark energy. In 1927, Belgian astronomer Georges Lemaitre, published a paper factoring in Einstein's theory of general relativity. And, while Einstein stated in his theory that the universe was static, Lemaitre showed how the equations in Einstein's theory actually support the idea that the universe is not static but, in fact, is actually expanding. This was later confirmed by Edwin Hubble through his observations. Telescopes have shown that most galaxies are moving away from each other, which implies that the galaxies were closer together in the distant past. This led astronomers in the past to believe that if the universe had enough mass, it would contract and collapse in an event called the 'Big Crunch'. However, in the 1990s, scientists studying Type-1a supernova in extremely distant galaxies discovered that the supernovae were not as close as expected, meaning the galaxies they were in had travelled farther away from us faster than anticipated. These observations led scientists to ultimately conclude that the speed of expansion of the universe was increasing over time.

One simple theoretical explanation for dark energy is the cosmological constant (Λ). Albert Einstein introduced this concept as a modification to his general relativity equations, aiming to describe a static universe. Within this model, dark energy is envisioned as a uniform vacuum energy that permeates all of space.

Some scientists (E.g.: Paul Steinhardt) propose that dark energy might be interpreted as an energy fluid or field that exists throughout the space. Unlike normal matter, it behaves in an opposite manner and may vary in both its amount and its distribution over time and space. This theoretical interpretation of dark energy is often nicknamed quintessence, drawing inspiration from the ancient Greek concept of a fifth element.

Dark energy has also been thought of as a type of defect in the fabric of the universe itself; defects like cosmic strings, which are hypothetical one-dimensional "wrinkles" thought to have formed in the early universe.

Some astronomers think that dark energy isn't something physical that we can discover. Rather, they think there could be an issue with general relativity and Einstein's theory of gravity and how it works on the scale of the observable universe.

The difference between dark matter and dark energy has been stated in the table below:

Table 1:

	Dark Matter	Dark Energy
Nature	A form of matter that does not interact with electromagnetic radiation	A hypothetical form of energy that exists throughout space
Effect	Exerts attractive force; binds galaxies and galaxy clusters together	Exerts repulsive force; drives the accelerated expansion of the universe
Percentage	27%	68%
Detection	Gravitational Lensing, Cosmic Microwave Background (CMB), Dark Matter Detectors.	Type Ia Supernovae Observations, Galaxy Clustering, CMB, Baryon Acoustic Oscillations (BAO), Gravitational Lensing.
Missions	LUX-ZEPLIN (LZ), Fermi Gamma-ray Space Telescope (NASA), Large Hadron Collider (CERN), Euclid Mission (ESA), Planck Satellite (ESA).	Euclid Mission (ESA), Nancy Grace Roman Space Telescope (NASA), Dark Energy Spectroscopic Instrument (DESI), Planck Satellite (ESA).

II. THEORY

Both Dark Matter and Dark Energy are continuously playing a fundamental role in the shape and destiny of our universe.

Dark Matter is like cosmic glue, exerting enough gravitational force to allow expansion of the universe at a slow rate, while dark energy does the exact opposite – it accelerates expansion of the universe. Here are a few theories describing the end of the universe:

1) The Big Freeze (Heat Death):

In the Big Freeze scenario, the universe's expansion continues to accelerate indefinitely due to dark energy, characterized by an equation of state parameter w= -1, where w= p/ρ (p=pressure, ρ= energy density). As galaxies move further apart, stars burn out and the formation of new stars ceases. Over trillions of years, the universe will become increasingly cold, dark, and empty.

In the end, even black holes will evaporate via Hawking radiation, leaving behind only a sparse collection of particles and radiation at nearly absolute zero. This state is known as heat death (The Big Freeze), where the universe reaches maximum entropy and no usable energy remains to perform work.

This scenario is the most widely accepted if dark energy remains constant (w= -1), as described in the cosmological constant model.

2) The Big Rip:

The Big Rip is a hypothetical scenario for the ultimate fate of the universe, caused by phantom energy, a type of dark energy, with an equation of state parameter $w < -1$ (w defined in The Big Freeze). In this theory, the density of dark energy continues to rise over time, resulting in an ever-accelerating expansion of the universe that eventually becomes unrestrained. This will lead to the disintegration of galaxies due to the space between them expanding faster than gravitational forces holding them together. This will continue with the breaking apart of star systems, ripping apart even atoms as the very fabric of spacetime stretches infinitely.

The time when the Big Rip occurs depends on how far below -1 has w fallen. The farther below the value of w falls, the sooner with the catastrophic event take place, ending our universe.

3) The Big Crunch:
In contrast to the Big Rip, the Big Crunch is a proposed theory which portrays a universe where dark energy begins to reduce, with the equation of state parameter $w > -1$ (w defined in The Big Freeze), resulting in gravity taking over, halting and finally counteracting expansion. This would result in galaxies moving towards each other, colliding to form larger structures; until everything has collapsed to form an ultra-dense singularity. This would be the reverse of the Big Bang, potentially leading to a cyclic universe with a new Big Bang.

However, for the Big Crunch to happen, there should be sufficient matter density in our universe to allow gravitational forces to dominate, which would require an increase in the amount of dark and baryonic matter; or a significant reduction in dark energy, since dark energy is a factor that causes acceleration of expansion.

In the recent years, the readings from the Dark Energy Spectroscopic Instrument (DESI), which has been designed to map the universe in 3D and study the effects of dark energy on cosmic expansion, have suggested that dark energy is not constant, and has been evolving, if not possibly reducing, over time. These findings have indicated that the probable weaking of dark energy could allow gravitational force to take over, increasing the probability of the occurrence of a Big Crunch.

4) The Big Bounce:
The Big Bounce theory is an intriguing variation of the Big Crunch. It suggests that after the universe collapses due to gravity in a Big Crunch, quantum effects—particularly those described by loop quantum gravity—prevent the formation of a singularity. Instead, the universe rebounds, after reaching a certain density, initiating a new phase of expansion, a new Big Bang. This could give rise to a new universe, potentially with entirely different physical laws and properties. Some models even propose that this cycle of expansion and contraction might repeat infinitely, creating a cyclical universe. The idea of identical cycles, akin to a universal time loop, is another fascinating possibility.

Theoretical support for the Big Bounce comes from the loop quantum gravity, in which there are no singularities, rather the universe bounces back to its expanded state from an extremely dense one. DESI's findings, which shows the evolving, or weakening, of dark energy, heightens the possibility of such an occurrence.

However, just like the Big Crunch, the equation of the state parameter would need to be w> -1, to allow gravity to negate the expansion. The bounce would then be caused by quantum effects (based on the principles of loop quantum gravity).

5) The Vacuum Decay
Vacuum decay theorizes that the universe might transition from a false vacuum—a higher-energy, metastable state—to a true vacuum—its lowest energy state. If dark energy is tied to this false vacuum, a quantum tunnelling event could initiate the transition, creating a rapidly expanding bubble of true vacuum. Within this bubble, the fundamental laws of physics could change drastically—atoms might disintegrate, and the universe as we know it would cease to exist. This catastrophic event would propagate at the speed of light, leaving no time for detection or intervention.

Fortunately, such an occurrence is considered highly improbable on cosmic timescales. Observational projects like DESI have enhanced our understanding of dark energy but have found no evidence suggesting that the universe is currently in a false vacuum state or that vacuum decay is imminent. The concept, while unsettling, highlights the intricate relationship between quantum mechanics and cosmology, emphasizing how little we understand about the universe's ultimate fate.

The ability to detect dark matter and dark energy will help us understand it better, aiding us in our discoveries and theories about the future. Many space research organisations, like NASA and ESA, have made instruments and satellites to study these cosmic enigmas, with scientists countlessly working behind them.

Dark Matter can be detected through:
- Gravitational Lensing: Gravitational Lensing can be detected when light bends around a massive object due to gravity. This suggests presence of clustered dark matter and helps map its distribution.

- Cosmic Microwave Background (CMB): Tiny fluctuations in the CMB, the leftover radiation from the Big Bang, provide clues about dark matter's role in the early universe.

- Dark Matter Detectors: They are highly sophisticated devices that aim to capture interactions between dark matter and baryonic matter through indirect methods. These methods might include direct detection (like the LZ experiment) where underground experiments use liquid xenon or argon to detect collisions between dark and baryonic matter particles; indirect detection in which space-based or ground observatories look for particles like gamma rays or neutrinos that may result from dark matter annihilation or decay; or particle colliders (Large Hadron Collider (LHC)) which recreate high energy conditions to search for signs of dark matter.

Dark Energy can be identified using:
- Supernova Observations: Scientists observe Type Ia supernovae, known for their consistent brightness. By comparing their distances with their redshifts, they found that the universe's expansion is

accelerating—a discovery that led to the concept of dark energy. This technology has also been used by the Dark Energy Survey (DES) to observe the universe's expansion, by analysing thousands of Type Ia supernovae. It will also be used in the upcoming Nancy Grace Roman Space Telescope by NASA (scheduled to be launched in the end of 2026).

- Cosmic Microwave Background (CMB): A faint remnant glow and radiation of the Big Bang, it carries patterns that offer insights into how dark energy shapes the universe's geometry and drives its expansion. This has been used in many missions aiming to study dark energy, particularly, the Planck Mission, which belonged to ESA, and the Wilkinson Microwave Anisotropy Probe (WMAP) by NASA.

- Galaxy Clustering: The large-scale distribution of galaxies provides clues about how dark energy shapes cosmic structures. Used by Dark Energy Spectroscopic Instrument (DESI) and Euclid mission (led by ESA), it has helped measure dark energy's influence on our universe. This technology will also be used in the Nancy Grace Roman Space Telescope.

- Baryon Acoustic Oscillations (BAO): These are ripples in the early universe's matter distribution. BAO measurements help scientists understand dark energy's role in cosmic expansion. DESI is optimized to measure BAO, using it as a "cosmic ruler" to map the universe's expansion history and understand dark energy's evolution. The Euclid Mission has also used BAO to create a 3D map of our universe, further strengthening our understanding of this field.

- Gravitational Lensing: Gravitational lensing occurs when light bends around massive objects due to their gravitational pull. By studying how dark energy influences the universe's expansion and geometry, gravitational lensing can provide critical insights into its effects on the large-scale structure of the cosmos. This has been used by the Euclid Mission.

III. CONCLUSION

Dark Matter and Dark Energy are fundamental yet elusive components that govern the evolution and ultimate fate of the universe. Dark Matter serves as the gravitational scaffold that enables the formation and stability of galaxies and large-scale cosmic structures. In contrast, Dark Energy drives the universe's accelerated expansion. Together, they constitute more than 95% of the total energy density of the cosmos—yet their true nature remains one of the most profound unsolved questions in modern astrophysics.

The interplay between Dark Matter and Dark Energy is central to determining the universe's long-term trajectory. Current theoretical models predict several possible outcomes: the gradual cooling and isolation of celestial structures in the Big Freeze, the disintegration of matter under runaway expansion in the Big Rip, a collapse into a singularity in the Big Crunch, a repeating cycle of expansion and contraction in the Big Bounce, or a sudden transformation of space-time via Vacuum Decay. Each scenario depends on the properties and behaviour of these two components over cosmological timescales.

To investigate these possibilities, large-scale observational initiatives such as Euclid, the Dark Energy Spectroscopic Instrument (DESI), and the upcoming Nancy Grace Roman Space Telescope are conducting high-precision surveys of galaxy distributions, cosmic structures, and the universe's expansion history. These missions aim to constrain key cosmological parameters, test competing models, and illuminate the underlying physics of the dark sector.

As observational data becomes more precise and theoretical models grow increasingly sophisticated, researchers continue to make progress in decoding the true nature of Dark Matter and Dark Energy. This pursuit remains at the forefront of astrophysical research, with the potential to transform our understanding of the cosmos and redefine humanity's place within it.

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