Dark Energy: The Engine Of Cosmic Acceleration

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Abstract- *The universe is so vast, and the quest unravel the mysteries of the universe is one of the greatest challenges to modern physicists, for only 5% of the universe is known and the laws of physics are applicable to that part only, the rest 95% is the unknown universe comprising of dark energy responsible of giving it accelerated expansion and Dark matter responsible for formation of galaxies. Physicists are also searching for "The theory of Quantum gravity" which can explain the origins of Universe and the super force that existed at the birth of the universe.*

Keywords- Big Crunch, Big Rip, Dark Energy, Dark Matter, Einstein's General Relativity Equations, Friedmann's equations, Super Force, Theory of Quantum Gravity, Vacuum Paradox

I. INTRODUCTION

Dark energy is an enigma for modern physicists. It is widely believed to be the energy responsible for accelerating expansion of the Universe. Before we delve upon mysteries of dark energy,we would like to place certain findings about our universe.The universe is more than 13.8 billion years old and it is believed started very small,thesize of one billionth of proton as a singularity, a dimensionless, volume less point and how could we get something out of nothing without violating the laws of conservation the answer to this physicists are searching in a theory that can explain both the laws of physics obeyed at sub atomic level-(Quantum Theory) to the level of galaxies and their clusters (The General Theory of Relativity), whereas individually both these theories stand correct the search is for a comprehensive theory that can explain from subatomic scale to galactic scales all the laws of physics.These physicists call "The theory of Quantum Gravity".The theory if propounded can explain the conditions prevailing at the birth of Universe– smallsubatomic scale and having very high energies. There is another theory suggesting the birth of Universe from tunneling from nothing which also involves theory of Quantum Gravity. This suggests that the geometry of space can undergoQuantumfluctuations, so from initial state of absolute nothingness of space, time, matter, and energy Quantum fluctuations can transition to a small Universewhich can form initial conditions for an inflationary scenario of the universe. In short, we need the Quantum Gravity theory to explain the initial conditions of the universe at the beginning when the super force that had in it all the four forces combined namely (1) gravity (2) strong nuclear force (3) weak nuclear force (4) electromagnetic force.

From the initial conditions of the universe at extremely high energies where the physical behavior of these four forces merge or unify into a single super force at temperatures of10^{32}K (temperature in terms of energy) and time 10^{-43}sec the initial path of super forceexpanded exponentially doubling every10^{-37}sec. Since volume is proportional to cube of diameter during say 100 such doublings the volume increases by $(2^{100})^3$= 2 X10^{29}times. So, the universe during initial inflation from a size of billionth of a proton went up by10^{90} times in 10^{-37} sec. As the universe expanded the total amount of mass contained in the initial patch increase during inflation by a colossal factor without violating the principle of energy conservation as during this time increase in mass (positive energy) is balanced by increase in negative energy of repulsive gravitational field (the initial patch of matter had this peculiar repulsive gravitational material having antigravity properties). So, there is proper cancellation, whereas density of normal matter on expanding goes down, but the repulsive gravitational material behaves completely differently, as it expands its density remains constant which means that the total amount of mass has increased by a colossal factor. Inflation ends as the repulsive negative gravity material which is fundamentally unstable anddecays like radioactive material exponentially into normal attraction gravity material. In the process of its decay the repulsive gravitational material releases energy locked up within itself in the form of quarks and photons. The Universe is now a hot primordial soup of matter and energy.By passing further evolution of universe from the Big Bang we come to universe which is now 300,000 years old that is 13.7 billion years back from today.The typical constituents of universe today and universe some 13.7 billion years ago (i.e., when universe was 300,000 years old) is as follows:

Constituents of Today's Universe		Constituents ofUniverse: 13.7 Billion Years Ago	
Dark energy	72%	Dark matter	63%
Dark matter	23.4%	Photons	15%
Ordinary matter	4.6%	Atoms	12%
		Neutrinos	10%
Total	100%	Total	100%

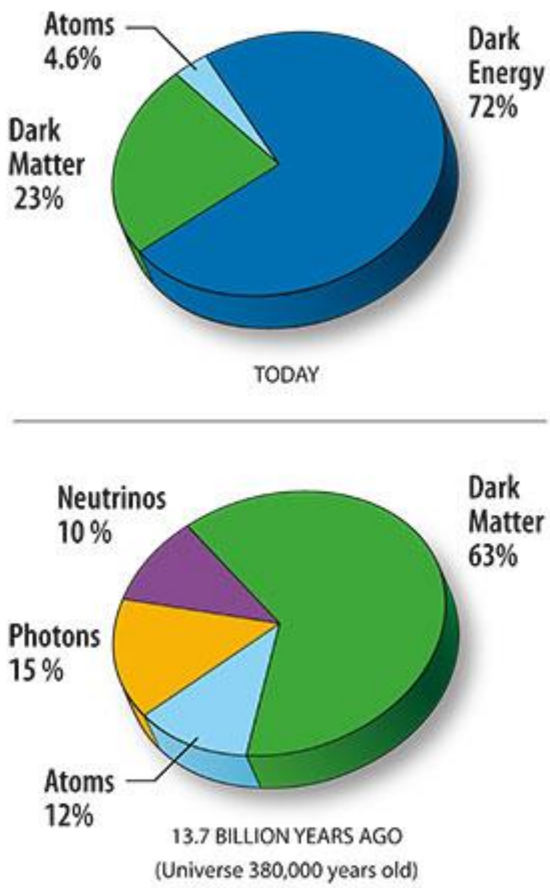

Figure 1

It is clear from Figure 1 that all the visible matter and energy that forms galaxy clusters, stars and planets comprise of 5% only, the rest 95 % of the constituents of the universe is completely unknown to us. It is amazing and surprising that our laws of physics holdtrue for only 5% of the Universe and the other 95% of the universe comprising about 72% dark energy and 23% dark matter, we do not know about them although we know that they exist. Since our topic being dark energy,we would stick to that but briefly we would like to state some characteristics of dark matter.

Swiss astronomer, Fritz Zwicky in 1933 while studying the motion of COMA cluster of galaxies (a few hundred light years away) found that motion of galaxies in the cluster was such that it could not be entirely due to the matter that could be seen by virtue of their light. The gravity of the matter in these galaxies was too small for their fast orbits and he estimated that clusters should have 400 times mass than visually observable mass. He concluded that there had to be additional stuff he called “Dark matter” that was responsible for the gravity that was pushing and pulling these galaxies around. This hidden dark matter mass was reason for additional gravity responsible for such fast orbits of galaxies in the COMA cluster.

From above it is clear that dark matter has decreased, and dark energy has increased since the Big Bang. So, what is dark energy?What is its significance in the universe and why are we interested in it and how was it discovered? We shall try to answer these questions through this paper. However, it would be pertinent to take up Einstein's General Relativity equations which have a relation with dark energy and Friedmann’s equations that describe the rate of expansion of our universe due to dark energy and the fate of the universebefore answering these questions.Einstein’s special theory of relativity related mass to energy i.e., E=mc2. In 1918, Einstein in his General theory of Relativity related mass and energy to gravity. These field equations replaced the Newton’s laws of gravitation $F=GMm/r^2$ which could not explain the precession in the orbit of mercury. Einstein’s General Relativity equations successfully predicted and explained the precession in the orbit of mercury and General Relativity predicted the bending of light by heavy masses like stars which was confirmed during total solar eclipse of 1919, a phenomenon we now call gravitational lensing. These equations also describe black holes and the expansion of universe besides the recent discovered phenomenon of gravitational waves.

II. EINSTEIN’S GENERAL RELATIVITY EQUATIONS –A PRECURSOR TO DARK ENERGY

Einstein’s General Relativity equations therefore remain the best bet to explain as to how gravity works. In Newton’s equations we have force on the left side created by mass on the right side. In Einstein’s General Relativity equations, we have analogue of force the curvature of space-time on the left side of the equation created by matter and energy on the right-hand side of the equation. In General Relativity gravity is not a force with the background of space-time like in Newton’s equations but it is the curvature of space-time background itself. Plainly stated gravity does not cause curvature of space-time rather it is the curvature of space-time. Coming back to General Relativity equations(GR) Einstein first obtained the field equations in vacuum in a rather geometric fashion and next, he obtained the field equations in the presence of matter from the field equations in vacuum. These equations relate the geometry of space-time to the distribution of matter within it.Einstein's space-time is in four dimensions (one time and three spatial). This is incorporated in μ and ν.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$R_{\mu\nu}$=R_{icci}tensor curvature
R = R_{icci} scalar curvature
$g_{\mu\nu}$=Metric tensor
$T_{\mu\nu}$= Stress-energy tensor
c= Speed of light in a vacuum
G= Universal gravitational constant
π= Famous constant from geometry

Subscripts zero (0) conventionally represents time and 1,2 and 3 subscripts represent the three spatial dimensions. μ and ν subscripts can have each values from 0-3 , for example if both μ and ν are (0,0) then left-hand side of equation would denote speeding or slowing down of time at appoint in space and right hand side tells us the energy at that point, and if μ and ν are 0 &1 then lefthand side of equation would denote stretching of space in one dimension in space and righthand side of the equation denotes momentum density, similarly if they are (1,1) or (2,2) then lefthand side of equation would denote stretching of space in one or two dimensions in space and righthand side of the equation denotes the pressure tensor at that point in space. Right hand side contains baryonic and dark matter radiation and other forms of energy like dark energy.

The left-hand side of the above equation describes the curvature of space-time and right-hand side of the equation represents mass and energy that cause the curvature of space-timefabric. As stated by John Wheeler, matter and energy cause space-time to curve and curvedspace-time tells matter how to move.Together $R_{\mu\nu}$and R tell us how distances are calculated given the curvature R at that point.It is the curvature of space-time fabric caused by mass which is perceived as gravity. Newton was unable to explain how gravity works, this was successfully thus explained by Einstein.In the above equations $R_{\mu\nu}$tells us how space-time is deviating from flat and tells us how curvature changes at a point. R is the scalar which tell us how to measure distance for a given curvature by telling us how much space has changed at any given point.$g_{\mu\nu}$tell us geometry and structure of space-time. Thus, the terms on left hand side ofthe equation tell us how to calculate distance in the curvature of space-time.$T_{\mu\nu}$on left hand side of the equation tell us mass energy content which is causing curvature and is called stress energy momentum tensor.So, in GR (General Relativity) equation left hand side is a geometric quantity and right-hand side is a physical quantity.

Einstein had assumed that the universe was static and unchanging. He thought this was true because that was what astronomers at the time thought they saw when they looked out into their telescopes. If gravity was only attractive, a static universe would be unstable. Every piece of matter would attract to every other and any slight imbalance in distribution would force the whole thing to eventually contract down into itself. Einstein added the cosmological constant lambda(Λ) to his equations (technically, he subtracted it from the scalar curvature) to hold back gravity so that his equations would have a solution that agreed with the static model. Maybe gravity is the curvature of space-time caused by the mass-energy of stuff within it plus the energy of space itself.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$

(space-time curvature) = (stress from stuff in space-time)–(stress from empty space-time itself)

Or maybe gravity is the curvature of space-time caused by mass- energy on top of the curvature of space time itself.

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

(curvature from stuff in space-time) +(curvature of space-time itself)=(mass-energy stress)

The cosmological constant was invented a way to hold back gravity so that static universe would not collapse.However, in 1923 Edwin Hubble discovery of the Andromeda galaxy confirmed the existence of other galaxies besides the Milky way and when Vesto Slipper first discovered the Doppler's shift in the spectrum of galaxies. Hubble used this along with his measured distance of Andromeda to prove that universe was not static but expanding.This caused Einstein to abandon the cosmological constant which he called his biggest blunder.

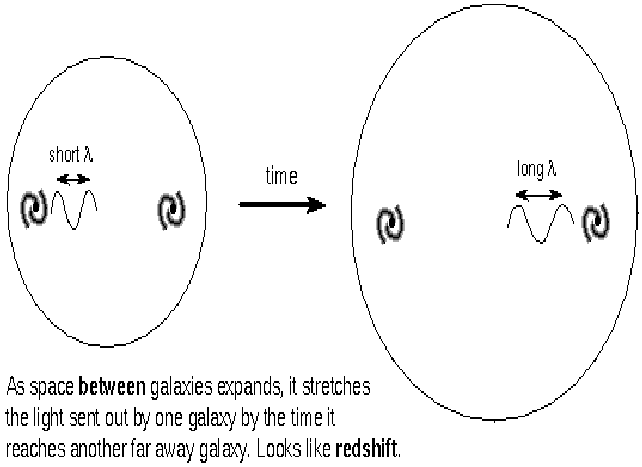

Figure 2

The light waves are stretched as they travel in space-time fabric due to stretching of space-time fabric caused by dark energy. The light from other stars and galaxies appearsredshifteddue tothe doppler effect and the galaxies appear as if they were moving through space away from us. However, the galaxies are simply being carried along with the expansion of the space between them. The expansion of the universe implies that galaxies were closer in the past. This implies that there is a finite age to the universe, it is not eternal.Thus, the universe as thought by Einstein could not be static but had to be dynamic.

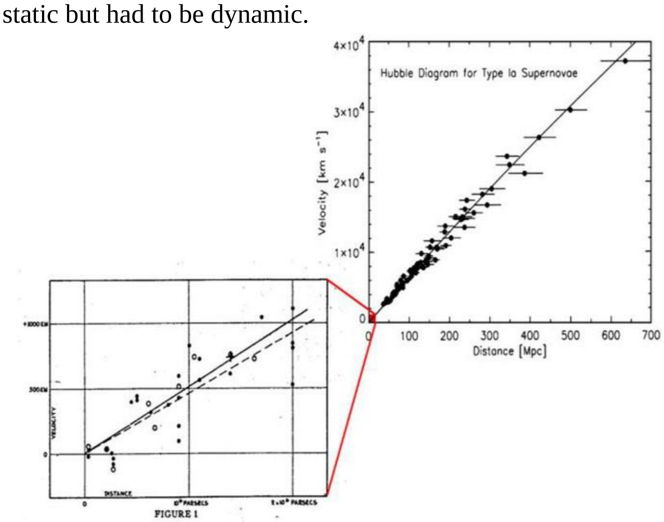

Figure 3

Hubble's graph clearly shows the redshift-distance relation with superior data to his predecessors and competitors; the modern equivalents go much farther.

However, late physicists believe that Einstein's blunder may be the best fit for dark energy as the cosmological constant matches up with observations, but scientists are still not certain just why it fits, as a result now cosmologists are reevaluating the importance of cosmological constant. Theuniverse is symmetric in its large-scale properties: homogenous(constantdensity) and isotropic (same in all directions). These also had been assumed by Einstein in his field equations and this simplicity had helped him in solving field equations.

It was Alexander Friedmann who in 1922 before Hubble discovered Andromeda and predicted mathematically an expanding universe. Friedman believed that Einstein's GR equations required a theory of Universe that was dynamic and not static as was believed by cosmologists at that time. He hypothesized a Big Bang followed by expansion, contraction and ultimately BigCrunch. Friedmann's equations govern the expansion in an isotropic, homogenous universe within the context of Einstein's GR equations and give us expansion of the universe which incidentally is due to dark energy as modern physicists believe. The Friedmann's equation tells us that space-time fabric changes i.e., contracts. Homogeneity and isotropy requirements reduce this set of 16 equationsto only one,$g\ (00) = T\ (00)$, which becomes the Friedman's Equation, these equations are thus special case of Einstein's equations, that describe motion of universe, an expanding universe, and is valid for ant space-time.

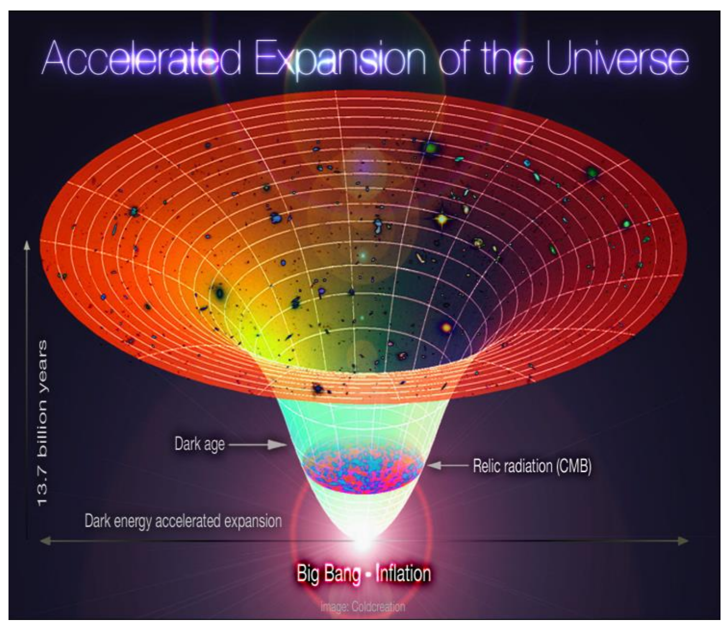

Figure 4: Diagram showing the Lambda-CBR universe from the Big Bang to the current era

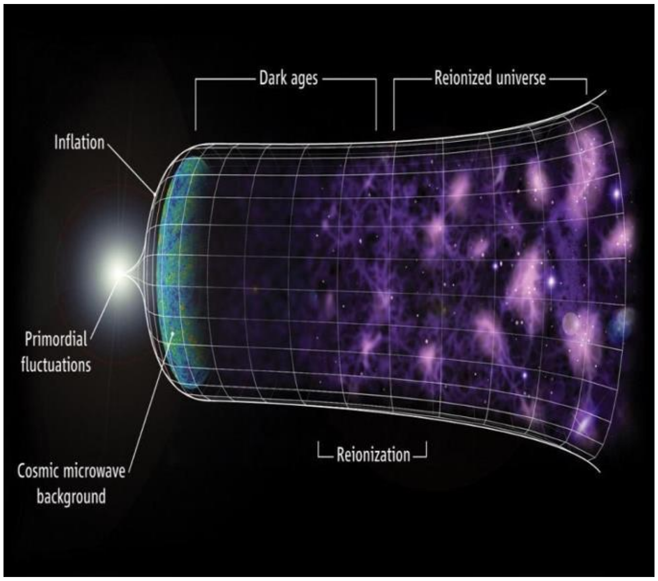

Figure 5: The expanding Universe, full of galaxies and the complex structure we observe today

There are two independent Friedmann equations for modelling a homogeneous, isotropic universe. The first is:

$$H^2 = \left(\frac{\mathring{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

which is derived from the 00 component of Einstein's field equations.

The Friedmann equation (1923) is a single ordinary differential equation that comes out of the ten coupled nonlinear partial differential equations of Einstein where "a" is the scale factor, ρ is the mass energy density of the universe, lambda(Λ) is the cosmological constant, energy density of space itself, empty space. K is the curvature of the universe (+1 closed,0 flat, -1 open)

We have three options for curvature:

K =1: positive curvature (like a ball)
K =0: zero curvature (flat like paper)
K = -1: negative curvature (saddle-like)

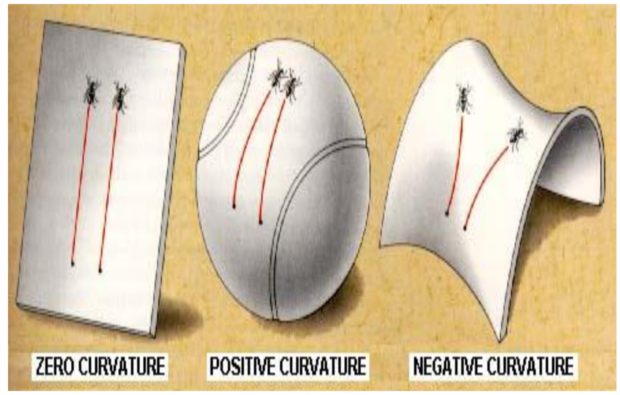

Figure 6

K, the curvature intrinsic to space is dependent on whether universe is open (negatively curved), if K<0 then energy density is positive and then right-hand side of Friedman's equation is always positive and an expanding universe will expand forever and end in "Big Rip".

If K>0 then matter dominates, universe is closed bound (positively curved) and right-hand side of Friedman's equation must eventually reach zero and universe will end in "Big Crunch".

If K=0 thenuniverse is flat.

In a flat universe light rays shall always remain parallel, in a negativelycurved universe light rays shall start parallel at a point and shall meet at infinity and for a positively curved or hyperbolic geometry of universe, rays of light shall diverge. This is as shown below:

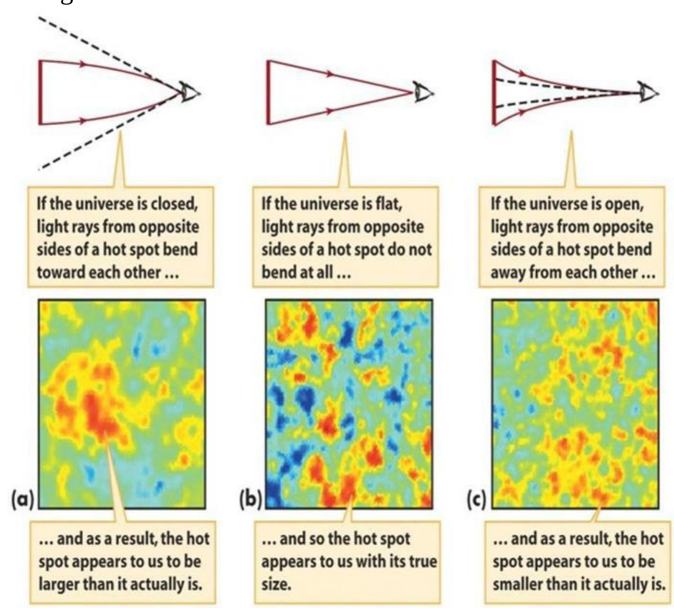

Figure 7

The equation also incorporates Einstein'scosmological constant which can either be a form of energy or can be an intrinsic property of space. Modern cosmologists connect this cosmological constant to the dark energy of the universe, or to intrinsic property of vacuum. However, if the vacuum of space has a constant energy density as it comes out from GR field equations and from Friedman's equation considering the flat observed universe there arises a problem.

III. ORIGINS AND EVIDENCE OF DARK ENERGY AND THE VACUUM PARADOX

But how does space acquire energy? Physicists explain this comes from Quantum fields. According to Quantum field theory empty space is defined by vacuum state, which is a collection of Quantum fields, all these Quantum fields exhibit fluctuations in their ground state (lowestenergy density) arising from zero-point energy present everywhere in space.The zero-point fluctuations should act as contributors to cosmological constant but when calculations are performed these give rise to enormous vacuum energy. Also,space is believed to be filled with virtual particles which continuously appear and disappear i.e., vacuum energy arises from Quantumfluctuations, butherein lies a problem,Quantum field theory predictsthat the energy from Quantum fluctuations is $\approx 10^{113}$J/cubic meter whereas experimentally we find this valueto be ≈1.5$\times 10^{-9}$J/cubic meter. This is one of the biggest mysteries of physics and is often called "The Vacuum Paradox". Physicists believe vacuum holds the key to fully understand dark energy.

The evidence of existence of dark energy comes from the Red shifts of type 1A Supernova. These are also called as standard candles as they are very regular, and they reach the same brightness at the peak of their burst and then they follow a distinct curve as they decrease in brightness. Type 1A Supernova happen when white dwarfs reach 1.4 times the solar mass (Chandrasekarlimit) then the pressure in the center becomes so great that a runaway fusion happens, and the star detonates in a thermonuclear Supernova. Since their brightness follows a distinct curve after Supernova, this allows physicists to calculate how much light their blasts emit as a function of time, farther the Supernova dimmer the light appears, so we can infer distance from its brightness. At the same time, we can know how much light coming from them is red shifted due to stretching of space-time fabric by expansion (due to dark energy). The red shifts tell us about the expansion of universe. So, if we measure type 1A Supernova (standardcandles) at different distances which really happened at separate times we can know how space has expanded or got stretched with time. These measurements and studies in type 1A Supernova were carried out bytwo teams of cosmologists: 1. Australian cosmologist, SaulPerlmutter and 2. Americanteam of Brian Schmidt and Adam Riess. They used the distance inferred from the brightness and the red shift of type 1A Supernova and found the only way to explain both type of measurements is that expansion of the universe is getting faster and this means that dark energy must exist. They were awarded Nobel prize for this in 2011.

Dark energy is thought to be energy of space itself and as it causes expansion of space and since its value is fixed in cosmological constant it will have same strength, and as more space is created more dark energy comes into the universe causing faster acceleration of expansion.As space gets created in the expanding universe,dark energy density remains constant. A positive vacuum energy resulting from cosmological constant implies a negative pressure, the associated negative pressure shall drive the accelerated expansion of the universe. Dark energy does not dilute but retains a constant value with expanding universe.

Why is dark energy important, is it getting stronger?Dark energy is 70% of the universe and shall determine the future of evolution of our universe and shall determine whether the universe shall end in "Big Crunch" or "Big Rip". If the dark energy causes the accelerated expansion of space, its repulsive force will become the dominant force as the baryonic matter and the dark matter density shall decrease as the space expands and as dark energy density remains constanteven human and subatomic level shall be overwhelmed besides all other forces and it will rip/ shear all atoms in space in Big Rip. So eventually as the universe expands all the other stuff present in the universe shall get diluted other than dark energy. If there is no dark energy, then the expansion of the universe shall halt and might even reverse in which case it will collapse into a singularity. Dark energy could be a property of vacuum, but wemust solve the "Vacuum Paradox".

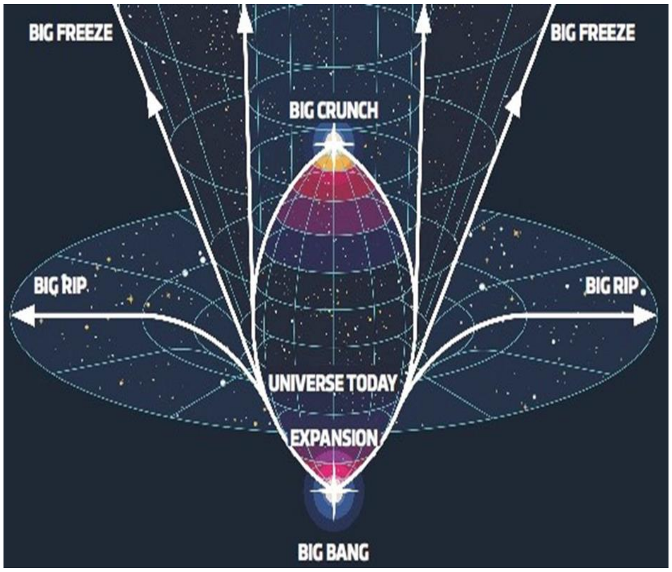

Figure 8

The accepted view is that accelerated expansion is due to constant energy density of the empty space so that more space created means more dark energy. Dark energy is constant in GR equations. It is a tiny constant,but it dominates the universe, gives it acceleration but there may be another constant in nature, may be in the unified theory of QuantumGravity yet to be propounded. The GR equations may not be correct, although the theory and equations have passed every test, they are incompatible with Quantum theory as they break down at the singularity.The problem is that the GR equations require energy and momentum to be described precisely at every space-time point which contradicts the Heisenberg's uncertainty principle forQuantum states at extremely high energies or at extremely short distances that exist for example at singularity. For example, General Relativity presumes that it is possible to pin down precisely where particles are and how they are moving, while quantum theory shows that is impossible.

IV. CONCLUSION

Dark energy was established to exist during type 1A Supernova studies.It comprises 70% of our universe. It was introduced as a small constant in Einstein's GR equations fixed as cosmological constant to counteract gravity i.e., as an antigravity force to justify a stationary static universe by Einstein whichwas later abandoned after Hubble discovered expansion of universe but today, we use cosmological constant or something like it to explain acceleration of the universe.Dark energy could be vacuum energy which does have the value required to produce cosmic acceleration but until we solve the "Vacuum Paradox" we cannot be sure. It is also possible that fundamental vacuum energy is zero and that acceleration of the universe is caused by some other negative pressure fluid or by breakdown of GR equations at cosmic scales (Prof Erik Verlinde of the University of Amsterdam). He believes it is the result of nothing less than a fundamental misconception about the most familiar force in the universe: Gravity.However, the gravitational effects of cosmological constant are identical to those of a form of energy with $P=-\epsilon$(P is pressure, ϵ is the density)which remains constant in space–time as the universe expands.Finally, GR equations itself may not be correct atlargee cosmic scales, of the level of cluster of galaxies (Prof Erik Verlinde of the University of Amsterdam) where gravity may behave differently than as described in GR equations and at singularity where GR equations cannot explain and where all laws of physics break down and finally where we need a Quantum theory of gravity. While this is a theoretical possibility, if the universe collapses into a "Big Crunch", observations suggest that he current cosmic expansion will continue indefinitely.It is amply clear that dark energy is a dominant form of energy of our universe and to know this form of energy is a quest for humankind for it shall unlock ultimate secrets of nature and may allow us to harness or manipulate it.

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