Final Report

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Lay Summary

To the average person gravity is not something you need to know about, it is there though, with an infinite reach, even across the universe. However, it truly is a fundamental force of nature. We see gravity in everyday activities; throwing a ball up results in the ball falling towards the Earth. It is this attractive force that has formed the galaxies and stars within the universe, as well as our planet and mankind.

Though, this attraction due to gravity seems to have been thwarted by some unknown presence in the universe. Instead of the universe falling back in on itself just like a ball is pulled toward the Earth, as you would expect, it seems that everything is being pushed away from everything else. In short, the universe is expanding, and it shows no signs of slowing down. Quite the opposite in fact, the speed of this expansion is increasing, suggesting that there is a force acting opposite of gravity on a large scale. The best explanation in existence for this phenomenon is called "Dark Energy".

This all falls under the area of Cosmology, a field of astronomy that deals with the very large scales of the observable universe and how it has changed since the Big Bang. The main aim here is to extend what we know of the universe and answer questions about our origins.

Through the report I will introduce some of the concepts that are and have been applied to the universe, as well as models and theories that try and explain some of the things we have observed in the night sky. Mainly how the distance to a star can be found, how Einstein first developed the concept of a Cosmological Constant describing Dark Energy in his theory of general relativity, then leading onto what we know about the universe to date in regards to Dark Energy.

Along the way, I hope that you will begin to sympathise with cosmologists and gain an insight into why we look at the universe.
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Introduction

The term ‘Dark Energy’ was coined by the Theoretical Cosmologist Michael Turner in 1998, where he used it to describe how the rate at the universe is expanding was accelerating.\(^1\)

Dark Energy is an enigma, an aspect of the universe that cosmologists and astronomers are hunting down in their quest to obtain an understanding of the physical interpretation of the universe that we inhabit. Along the journey, small steps have been taken, slowly leading to the theory of dark energy becoming more established throughout the scientific community.

The theory behind Dark Energy serves to enlighten us on many of the greatest scientific questions of our time. Among the most profound and truly defining questions we can ask are: ‘How was the universe formed? How has it evolved from the beginning of time and space, and into our current epoch?’ Venturing from there to wonder what will be the end of it all; will there be a large collapse in cosmological structure under the infinitely reaching and dominant force of gravity? Or will the universe tear itself apart after continued expansion? Questions like these have been pondered by the likes of Einstein, Hubble and many other cosmologists and physicists alike, each with their own spin and contribution.

The search of answers to such questions has revealed a wealth of knowledge about the history of our universe and the circumstances that lead to how it has evolved over the past 13.82 billion years, as inferred by the Planck satellite in 2013\(^2\).

This investigation will primarily be a review of what collectively has been documented and reported over the last 90 years in regards to space observations and predictions. There will also be strong emphasis on areas dedicated and linked to the search for the explanation behind the accelerated expansion, i.e. Dark Energy. Although widely argued for and against, we have on multiple occasions made attempts to observe the effect that Dark Energy incurs on the universe through different methods and geometry shifts.

This paper is a literature study, and will consist of two major parts. The first is a historical review of how research into Dark Energy began and has evolved over time as well as an in depth look into distance measurement.

The second part will focus on the future prospects of this research, both in terms of which new experiments and theories are being worked on, but also the possible consequences of this research and how current theory predicts the future of the universe as a whole.
1. The Theory behind Dark Energy

1.1 Introduction of $\Lambda$

The universe was not always believed to have been expanding. Einstein’s equations of General Relativity did originally predict an expansion and an eventual collapse. This makes sense though; if the universe is filled with matter and radiation only as was believed at the time, then surely just like how a ball will fall to the ground under the Earth’s own gravitational field, then all the galaxies and structures in the universe should feel attracted to each other ending with a collapse of all matter into a condensed ‘blob’.

![Figure 1: Dependent on the matter density of the universe, in respect of the critical matter density, the universe is predicted to take different paths over time.](Taken from <www.nat.vu.nl/~wimu/FundConst-Notes.html>, accessed 20 Feb 2015)

Einstein dismissed the “Big Crunch” eventuality as seen in Figure 1, due to observations of stars and galaxies and their respective motions. The discovery of ‘random movement’ led to the conclusion that the universe’s overall motion should be static. If it were to have initially expanded to then collapse under gravity, there would have to be some suggestion in the movement of galaxies that they were moving in a uniform direction. That wasn’t the case, therefore a static model is most appealing for the state of the universe.

The problem was that when applying General Relativity to these circumstances, Einstein needed to counteract gravity in the long run, stopping the universe from ever collapsing. The universe therefore needed an antigavity term, something to act as a buffer to the universe’s tendency to act under gravity as mathematically predicted, a factor that would repel matter instead of attract it. This antigavity term is what became known as the ‘Cosmological Constant’ $\Lambda$.

This constant was later labelled as Einstein’s biggest blunder. To this date it has been introduced, scrapped and re-introduced a number of times, and it now stands firmly as a great contender aimed at the explanation for the accelerating expansion of the known universe. Today it is referred to in part as a ‘Vacuum energy’, an unchanging background energy contained within space-time.
1.2 Hubble’s Law and Redshift

Not long after the addition of this constant to Einstein’s field equations, came the revelation that the universe was in fact expanding, as proved by Edwin Hubble and his famous Hubble law:

\[ v = H_0d \] (1.21)

Where \( v \) is velocity in km\(^{-1} \), \( H_0 \) is the current Hubble Constant in km\(^{-1} \) Mpc\(^{-1} \) and \( d \) is distance in Mpc.

Hubble discovered this correlation when observing the velocities of different galaxies and their respective distances from Earth. Determining these two properties was already a developed science; distance can be calculated from the estimation of magnitudes of stars, or from parallax. Hubble was working on Cepheid variables at the time and so used these stars, as well as supernovae within galaxies to estimate distances to galaxies. Velocity was a harder value to calculate, and for this you need to use the line spectra observed from stars.

Astronomers have used light from distant stars and galaxies for centuries, from comparing their apparent brightness, to determining the abundant elements in stellar atmospheres. So the physics behind how light waves behave is a well-developed area, it is then no surprise that for the majority of the discoveries are from the observations of objects in the night sky.

A galaxy spectrum is obtained by the photons detected by a telescope. The light is then split up into its fundamental constituents by passing the incoming light though a diffraction grating. This disperses the light at specific angles to the normal, depending upon the energy of the photons.

Figure 2: Absorption line spectra graph depicting both redshift and blue shift of incoming light. Redshifted spectral lines shift to the right (red end of the spectrum), while blue-shifted spectral lines shift to the left (blue end of the spectrum).

The use of line spectra from galaxies and stars, when compared with line spectra obtained from laboratory experiments, meant that you could detect any anomalous occurrences. It was redshift that was observed by Hubble when he was looking at galaxy spectral graphs, and it was known how redshift arises and what it means in physical terms, due to the Doppler Effect.

> The Doppler Effect is when the wavelength emitted from a source, be it sound or light waves, is stretched or compressed due to a motion of the source with respect to a rest frame, i.e. the observer. Figure 3 is a representation of how the wave either stretches out behind the moving source or is compressed in front.

Figure 3


Redshift is the term given to light that has a longer wavelength due to the source moving in the opposite direction, away from the observer and hence the observer reads a wavelength longer than that at the time of emission. This is known from the Doppler Effect.\(^3\)

Redshift is assigned \(z\), and defined mathematically as:

\[
Z = \frac{\lambda_o - \lambda_e}{\lambda_e}
\]  

(1.22)

Where \(\lambda_o\) and \(\lambda_e\) are the observed and emitted wavelengths respectively. The connection to Hubble’s law from here is to apply the Doppler Effect to the relative velocity of the light, since a reduction in wavelength can be seen as a drop in energy, and hence velocity. The equation then becomes that of this new velocity \(v\) as compared to the universal speed of light \(c\) (-3×10\(^8\) ms\(^{-1}\)).

\[
Z = \frac{v}{c}
\]  

(1.23)

And now the ground works have been established for comparing velocity \(v\) against distance \(d\) as described in Hubble’s law. His work went onto then cement the understanding of an expanding universe over Einstein’s static universe, rendering the Cosmological constant redundant.

Through the use of the Hubble law and its relation with motion at a constant velocity, Hubble was able to calculate an average age for the universe. For the case of a continuously expanding universe (no acceleration) this was a time when all the galaxies would have been clumped together, but not at the same point. Equation 1.24 shows the relation made to retrieve the Hubble time from the Hubble law:

\[
t = \frac{d}{v} \rightarrow and \rightarrow \frac{1}{H_0} = \frac{d}{v} \rightarrow equate the two \rightarrow \frac{1}{H_0} = t
\]  

(1.24)

Where \(t\) is time in seconds, and the rest are the same as in equation 1.21.

A key aspect that is worth bearing in mind about Hubble’s constant is, by its very nature, not a complete constant and must evolve as the universe ages. Therefore, we use the subscript \(0\) to signify the Hubble constant of ‘now’.

The current Hubble Constant’s value; \(H_0\) is still being investigated and refined. Initially there were two values that physicists took sides on: 50 kms\(^{-1}\) Mpc\(^{-1}\) or 100 kms\(^{-1}\) Mpc\(^{-1}\). It is this dividing of opinion that introduced the parametrizing factor of \(h\) into certain equations, where the Hubble constant would be written as:

\[
H = 100 h \text{ kms}^{-1} \text{ Mpc}^{-1}
\]  

(1.25)

Where \(h\) is somewhere within the range of 0.5<\(h\)<1.0 and unit less, meaning later on as the value was changed to reflect newer, more reliable and less error clouded measurements, \(h\) could be altered at will to accommodate the new findings.

The next stepping stone is the measuring of a scale distance in the universe, different standard lengths by which to track the current expansion. The development of one such ‘standard candle’ resulted in the knowledge that there is also an acceleration to this expansion, although that was not discovered until 1998.

Before determining the Hubble law / relation and the Hubble Constant though, Hubble played a key role in the observation of Cepheid Variable stars and supernovae, most notably those classified as ‘type 1a’. The observations carried out at Mt. Wilson observatory were the first steps towards finding a standard ‘candle’ for measuring distances to objects and setting up for further investigations into how the universe was expanding.
1.3 Steady State Theory

Since before the concept of a Big Bang and the Cosmic Microwave background radiation, cosmologists have been trying to predict how the universe came into being; was it as Hubble suggests from a small clump that expanded out? Or is it that the universe is infinitely old and therefore never had a beginning? One theory of the universe is the Steady State Theory, it is based on the infinitely old concept, but to understand why such a notion has been dismissed by a large portion of the scientific community, there needs to be a basic understanding of its pit falls due to now known theories.

The idea that the universe is governed by the same laws of physics and physically appears the same at large scales, i.e. distances of 200Mpc or more is known as the Cosmological principle: stating that the universe is both isotropic and homogeneous no matter where you look. The Steady State theory makes use of these assumptions and forms a ‘perfect’ cosmological principal.

Whereas the original Cosmological Principle, first described by Einstein, was to simplify the universe at scales larger than 200 Mpc out ($10^6$ parsecs, 1 parsec=$3.0857 \times 10^{16}$ meters). The universe is then said to be homogenous: “the same in every place” and also isotropic: “looking the same in every direction”. So to look out on the universe would be to see the same features everywhere. This ‘perfect’ Cosmological principle went one step further in saying that the universe is infinitely old, that no matter where you view the universe from, or what time, it will always appear homogeneous and isotropic. Another point it makes is that it is just an ever expanding volume of space with a constant matter density value.

There are however some consequences that arise from such an assumption: the continuous need for new matter to be created, making sure that the matter density inside the expanding universe is kept constant. The other is that from what has been covered about Hubble’s law so far, is that it predicts the universe began all at the same time, expanding outwards, and hence has a certain age.

The rate at which matter would need to be introduced to the universe can be calculated using the following series of equations.

From equation (1.4), we can re-write velocity $v$ in terms of distance $r$:

$$ v = \frac{d(r)}{dt} = H_0 r $$

(1.31)

From here, integrating this expression reveals a relation between how $r$ varies with $t$:

$$ r(t) \propto e^{H_0 t} $$

(1.32)

This relation shows that when $r$ tends to zero, $t$ will tend to infinity, ultimately stating that the universe never had a beginning; no central point in space where all matter came into existence (i.e. a singularity – a point of infinite density). If matter had started at a point, then the whole structure for the ‘perfect’ cosmological principle would fall to ruin, as there can never be a special moment or place in the whole of existence.

The next step is setup the mass influx rate into the expanding volume of space. With a constant energy density $\rho_0$ (Kgm$^{-3}$), there would need to be this influx to balance out the decrease in density that occurs over the time of expansion, just as you pump in more air to increase the volume of a balloon.

First set up the volume of the universe and then describe how it expands with time:

$$ V_{universe} = \frac{4\pi}{3} r^3 $$

(1.33)
We can see that equation 1.32 will hold true for 1.33, and therefore the volume will increase exponentially with time:

\[
\frac{4\pi}{3} r^3 \propto e^{3H_0 t} \rightarrow V_{\text{universe}} = e^{3H_0 t} \quad (1.34)
\]

To then account for the mass input rate, we introduce the time derivative of mass, \( \dot{M} \) (Kg s\(^{-1}\)), and this function will reveal just how much mass needs to be generated in order to keep the matter density constant:

\[
\dot{M} = \rho_0 \dot{V}_{\text{universe}} \quad (1.35)
\]

Where the change in volume equals:

\[
\dot{V} = \frac{dV}{dt} = 3H_0 e^{3H_0 t} = 3H_0 V_{\text{universe}} \quad (1.36)
\]

\[
\dot{M} = 3\rho_0 H_0 V_{\text{universe}} \quad (1.37)
\]

If we apply this to our current universe, with a \( \rho_0 \sim 3 \times 10^{-24} \text{Kg m}^{-3} \), we would then have a mass inflow rate of:

\[
\frac{\dot{M}}{V_{\text{universe}}} = 3\rho_0 H_0 \sim 6 \times 10^{-28} \text{Kg m}^{-3} \text{Gyr}^{-1} \quad (1.38)
\]

This value is comparable with creating about one hydrogen atom per cubic km per year.\(^5\)

The concept of continuous creation is very hard to accept, especially knowing that matter and energy cannot be destroyed or created. Though we have not been able to recreate this matter creation system, it is such a small addition to the overall mass of the universe that trying to directly observe such a phenomenon would be almost impossible due to the scale and frequency of creation.

This notion of ‘creating matter’ still stands as the main argument against Steady State Theory, and physicists have been split on which model they believe, either the Big Bang or Steady State. Another topic that doesn’t aid the belief in Steady State is the ‘perfect cosmological principle’, as the universe does alter with time, especially when you model it with equation 1.33 (if you set \( r = 0 \) then you have no universe). It was the discovery of the CMB in 1965 by Penzias and Wilson that crippled the Steady State model and pushed forward the notion that the universe had started from a single point with a Big Bang.

1.4 The Smoking Gun

To date the Cosmic Microwave Background stands as one of the most obvious signs of a Hot Big Bang model, the proverbial ‘Smoking Gun’ as it is the most conclusive evidence yet. The theory behind the CMB and its origins are backed up by observations and research, both through the use of ground and space based telescopes and satellites, WMAP and COBE to name two.

Over the years more and more data has been retrieved on the CMB, initially the fact that it was a perfect blackbody source, subsequently emitting and absorbing radiation entirely, was a key understanding and establishment that proved the work of Peeble and Dicke to be correct; that the CMB is the last remnants of the hot dense state of the universe.\(^6\)

More recently, with the aid of the PLANCK satellite, we have improved our mapping of the power spectrum associated with the CMB. This spectrum contains a large amount of information on the properties of the universe as well as the key to understanding what was occurring at the different epochs after the Big Bang, mainly those of Decoupling and Last Scattering.
The CMB has helped topple theories like the Steady State argument by providing strong evidence for a starting point for the universe, as well as to show how the universe is indeed expanding. If it had not been expanding, then the photons would never have cooled enough to decouple and form the blackbody source we see today throughout the universe.

Baryonic Acoustic Oscillations can also be measured from the CMB, this being the separation of matter due to pressure waves setup within the dense plasma in the epoch of Recombination.

Another property of the universe that has been calculated is the constituent parts and their contribution to the whole picture, via data taken by both WMAP and the PLANCK satellites. This provided insight into certain phenomena and how they are shaped by the ‘Dark sector’ of the universe. The components that we know of and assume to be there today are: Baryonic Matter, Radiation, Dark Matter and most importantly of all Dark Energy, which sits with the largest slice of the universal pie, and therefore is said be the dominant presence in the universe.

Figure 4: The contribution from the density content of Dark Matter, Dark Energy and Ordinary matter, corrected by PLANCK satellite in 2013 by ESA. From the scale of Dark Energy’s presence, it is easy to see how it has had such an impact on our known visible matter structures.

The CMB helped to solidify the theory of the expanding universe and therefore having a measureable age. The transition from Einstein’s aesthetically pleasing static universe to Hubble’s expanding one was quite the shock, as it meant quite a few predictions needed reviewing. It did nevertheless open up more questions to ask on the subject of the universe; “why is the universe expanding?”, “will the expansion continue on forever or will the universe slow under the effect of gravity as Einstein once thought?”

Quite a few of these queries have been answered, with still a few to go. What the scientific community didn’t expect was for this expansion to be accelerating. Hubble’s law states that the further away a galaxy is the greater it’s relative velocity, but what if those velocities were also changing over time and distance? This is where the Cosmological Constant, or better now known as Dark Energy, enters the discussion.

1.5 Distance Measurement
The universe is the largest known structure so far observed by mankind, so trying to measure cosmological distances within it just isn’t viable in conventional terms used here on Earth. To combat this limitation there have been studies and continued developments in the estimation of distances using light. The underpinning physics behind this choice of radiation is that the intensity of light adheres to the Inverse Square law:

\[ \text{Intensity} \propto \frac{1}{r^2} \]  

(1.51)

Equation (1.51) states that as you increase the distance between you and a source, the intensity will drop proportionally to the square of the distance.
There is also an abundance of light, we can see many celestial bodies emitting light and can
gather a multitude of data from it, from UV to radio waves. With today’s measurements for
the speed of light in a vacuum at precisely 299,792,458 metres per second, or for ease of use
~3×10⁸ m s⁻¹. Such methods include the observation of a Cepheid Variable star and their
periodic changes in magnitude, another is to record the light curve of supernovae allowing
you to work out the type 1a supernovae among all the recorded events, this is because all
SN1a have very similar light curves. Today’s efforts though are focused on another, more
reliable means of measuring distances in space: Baryonic Acoustic Oscillations (BAOs).

At this point, the magnitude scale system needs to be explained so as to help with the
understanding of how astronomers can measure galactic distances with only light.

The use of magnitudes and flux density is the backbone of distance calculus. Both observable
properties have been used to classify how bright a star is as compared first to another star
and then later on to a reference star, that reference star should be the brightest compared
to its local counterparts. Something to note here is that there is a known factor in brightness
that correlates to a difference in magnitude: a difference of 5 in stellar magnitudes is a
change by a factor of 100 in their apparent brightness. Therefore it can be said that an
alteration of 1 magnitude scale equals a brightness difference of 100¹/⁵.

Before defining the modern use of stellar magnitudes and the different types, I will go from
the beginning steps and lead towards a comprehensive and required knowledge to
understand the next chapter.

Let us consider two stars, each with a different magnitude and brightness (flux), m and n, fₘ
and fₙ respectively. The difference in their magnitudes can be related to the ratio of their
apparent brightness: (using the above relation in brightness to magnitudes)

\[ \frac{f_n}{f_m} = 100^{(m-n)/5} \]  

(1.52)

Taking the log₁₀() of equation 1.52 and with some re-arrangement of the subsequent form,
the result is an expression for the apparent magnitude relating to their respective flux
densities:

\[ m - n = -2.5 \log \left( \frac{f_n}{f_m} \right) \]  

(1.53)

Now for the current magnitude system, there are two key definitions for a star’s magnitude:

- Apparent Magnitude, m – the magnitude as observed from earth and compared to a
reference star. Vega was originally set at 0, but has since been re-evaluated to 0.3.⁸
- Absolute Magnitude, M – defined as the magnitude of the source if it were placed at
a standard distance of 10pc from Earth.⁹ (Rowan-Robinson, 1996)

Since we know that light follows the inverse square law, it is then possible to say that the
brightness is also governed by this law, note that we measure distance d in parsecs. For
absolute magnitude we use a capitalized term, here F and D will signify the absolute terms,
allowing us to make the substitution of D=10pc:

\[ \frac{F}{f} = \left( \frac{d}{D} \right)^2 = \left( \frac{d}{10} \right)^2 \]  

(1.54)

With such a distance relation it is then possible to use the magnitude system to calculate a
distance. This is the starting point on the path to finding the distance to star:

\[ m - n = -2.5 \log \left( \left( \frac{d}{10} \right)^2 \right) \]  

(1.55)
Through the manipulation of logarithms, mainly that \( \log(a/b) = \log(a) - \log(b) \) and \( \log(a^2) = 2\log(a) \):

\[
m - M = 5 \log_{10}(d) - 5
\]

(1.56)

Which re-arranged yields an equation for finding the distance \( d \) in parsecs (where 1pc = 3.0857\times10^{16}m):

\[
d = 10^{\frac{(m-M)+5}{5}}
\]

(1.57)

These equations can be used on a multitude of objects in the universe. The use of the magnitude and flux density system has one drawback though; the inverse square law, meaning that as you observe further into the cosmos, the fainter the source will become.

It is also impossible to individually read out a star sitting within other galaxies and as such the use of Cepheid Variable stars and supernovae are used. These phenomena are described in the next chapter, explaining how they arise and how they have become synonymous with the subject area of both astronomy and cosmology.
2. Standard Measurements - Baryon Acoustic Oscillations and Standard Candles

2.1 Cepheid Variable Stars

The first attempt at measuring distances was accomplished by Edwin Hubble in 1924\(^1\), who observed a Cepheid variable star within the Andromeda galaxy consequently leading to the finding that Andromeda is not actually contained within our own galaxy. Instead it is a galaxy in its own right and at a fair distance from us.

Cepheid variable stars are stellar objects that have an oscillating magnitude, i.e. brightness, over time, it is this periodic behavior that allows us to measure the distance between us and itself. The oscillation in radius and temperature is due to changes in the star’s parameters, some fluctuate in mass and luminosity, some Cepheid variables are part of a binary system, with a smaller companion star that will occasionally orbit in front of the star, causing it to dim for a time and then return to its characteristic magnitude.

Within the classification of Cepheid variables, there are 2 groups: Intrinsic and Extrinsic, where the first is due to physical changes from pulsations in the stars structure or from events like eruptions or deforming momentarily, the second arises from an external factor, i.e. eclipsing or as previously mentioned, affected by a binary companion’s orbit path.\(^1\)

Figure 5: A plot type 1 Cepheid Variables Stars, comparing their calculated luminosity, from magnitude equations, against their respective periods of oscillation in brightness.

Available from <http://hyperphysics.phy-astr.gsu.edu/hbase/astro/cepheid.html>

Figure 6: A plot of the measured period of Cepheids and how their apparent magnitude varies over that period. It is this property of this star type that allows for ease of detection within a galaxy. The typical range in periods is from 1 to 70 days.

Available from <http://hyperphysics.phy-astr.gsu.edu/hbase/astro/cepheid.html>
2.2 Supernova Type 1a – Standard Candles
Cepheid Variable stars are a good distance measurement system, but only within the local neighborhood of galaxies, also known as the local group which is about 3.066Mpc (10 million light years) in size and a surmised mass of 1.29x10^{18} solar masses. If you want to measure a distance to galaxies outside our cluster, then a new method is required. The use of Type 1a supernova was the next step in cosmological and astronomical observations. These supernovae have the same luminosity profiles, and thus they can be used to measure distances using the relation between apparent magnitude and luminosity; if the absolute magnitude, M and apparent magnitude, m are known, where d is in parsecs:

\[ m - M = 5 \log(d) - 5 \]  

(2.21)

This characteristic of the luminosity peak can be used to identify a detected supernova, while taking observations and images of the night sky you may well detect such an event. The next step is to track that patch of sky over the following nights so as to capture the luminosity profile. Fortunately, supernovae are hard to miss, as they will on occasion outshine their host galaxy, but are an extremely rare occurrence.

Type 1a supernovae have since been labeled as ‘standard candles’ of measurement. They arise from the thermonuclear explosion of a white dwarf that reaches the Chandrasekhar mass limit of 1.4 solar masses. This limit is reached when a white dwarf that is in a binary system accrete mass from its partner star, due to their inherent strong gravitational forces.

A white dwarf is a star that has evolved from a low to medium mass main sequence star, with a varying lifespan which is dependent on mass to be roughly 10 billion years or more, with a hydrogen burning core. Eventually the hydrogen core is mostly used up and hydrostatic equilibrium begins to shift, the core becomes mostly filled with helium that has not been ignited. The dying star then starts to contract resulting in an increase in core pressure while driving temperature up. When T_{core} \sim 10^{8} \text{Kelvin} and M_{core} \sim 0.48 M_{\odot} (\text{solar masses}) is achieved helium ignites.

The next stage, after the Red Giant Branch (RGB), which can last 1 billion years for a 1 solar mass star, after the majority of the helium in the core is burnt up, the star’s physical parameters change again. The radius decreases due to gravity and is no longer in hydrostatic equilibrium, the temperature increases due to this higher pressure from more material taking up less space and finally density increases, as more and more of the RGB star collapses down. Finally, the collapse is abated, the core is now electron degenerate and mainly made out of a carbon / oxygen mix, with respective hydrogen and helium burning shells surrounding this very dense core. The shells though are very thin.

You are finally at the white dwarf era of your star. Now if this WD is in the vicinity of another star due to being in a binary system, the WD’s high density core will cause the gravitational forces exerted upon itself to increase, meaning that there will be a pull on the neighboring star. Slowly these high gravitational forces will effect it and eventually lead to matter being drawn towards the WD, known as matter accretion. The overall effect is that the white dwarf strips this other star of its outer mass and adds it to its own, building up to what is known as the Chandrasekhar limit of 1.4 M_{\odot}.15
Figure 7: The relation between the radius and mass for a white dwarf star, showing that as more mass is accreted onto the White Dwarf, the radius decreases until a point is reached, this is the Chandrasekhar limit.

Once this mass limit is surpassed, the WD begins to collapse under its own gravitational pull. Pressure is building within the core due to electron degeneracy: electrons are trying to occupy the lowest possible energy level, but due to the Pauli Exclusion Principle, there is only a set amount of space that can be occupied at each level. This collapse of the star leads to the next evolutionary stage; a neutron star, as well as the infamous supernovae classified as ‘type 1a’, with a stupendous amount of energy released in the order of $10^{44}$ Joules. This supernova is commonly found within both elliptical and spiral galaxies. The absolute magnitude of such an event can reach levels as bright as $-16$ to $-20$.16

Figure 8: The magnitude of a type 1a supernova over a certain period, a characteristic peak is observed, which is how astronomers know that the event is an SN 1a. Note the initial peak in luminosity, and then the gradual decline.

Even today scientists are using new techniques to measure the distances of SN1a for the benefit of mapping the acceleration and expansion of the universe. NASA recently posted a segment on how astronomers are now focusing on a certain type of SN1a event; those that occur near “youthful stars”, the group behind this discovery went on to mention that the “light output depends very precisely on how quickly they fade, making it possible to measure very exact distances to them.”18

The detection of supernovae is mainly down to ground based and space based surveys, as later described in chapter 5. But due to their infrequency and rarity, those types of surveys need to be conducted over large timescales to even detect a reasonable number of events and measure their apparent brightness.
2.3 Baryonic Acoustic Oscillations

Just as SN1a was used as a standard candle for measuring distances in the universe, the distribution of large scale structure and the elements within, i.e. galaxies and galaxy clusters, can reveal another means of measuring stellar distances, even extending to become the next standard measurement for distances within the universe.

This new model is based on the Baryonic Acoustic Oscillations, pressure waves setup during the epoch of Recombination, and frozen in the CMB angular power spectrum, which points at the current distribution of matter in the universe. Such waves had a short lifespan, freezing in place once the universe cooled below the ionization energy of hydrogen. This distance is called the Sound Horizon, simply put, the speed of the wave \( c_s \), times the age of the universe that they froze.

To understand the formation of such a new standard for measuring distance, we need to look at an epoch occurring approximately 370,000 years after the Big Bang, the epoch of Recombination.\(^{19}\)

Leading up to the epoch, the universe mainly consisted of a relativistic plasma, consisting of photons, electrons and baryonic matter, protons and neutrons. The photons were the cause behind the radiation pressure preventing matter from forming, and any hydrogen that did form was short lived. The gravitational force which acted against the radiation pressure was due to the baryonic matter and Dark Matter, but here I will discuss the effects and occurrences of normal, baryonic matter.

The photons were essentially trapped within the plasma, travelling at the speed of light, but due to the high number density of both photons and electrons it was difficult to travel far before colliding with an electron via Thompson scattering, transferring energy and momentum between the two. It is this continuous interaction that caused hydrogen to be re-ionized soon after forming, and can be shown as:

\[
p + e^- \rightleftharpoons H + \gamma \tag{2.31}
\]

At this time, the universe was about 300,000K in temperature and equated to an energy per photon of about:

\[
hv = 2.7KT = 60 \text{ eV} \tag{2.32}
\]

\( h \) – Planck constant  
\( v \) – Frequency  
\( K \) – Boltzmann constant  
\( T \) – Temperature of the universe

The dual arrow symbol in (2.31) is applied to signify that this reaction occurs in both directions: a proton attracts an electron and forms a hydrogen atom, releasing some energy in the form of a photon. Unfortunately for the other hydrogen atoms around this reaction, the photon emitted is at a high enough energy to re-ionize and hence split a hydrogen back down to its baryonic matter component and an electron.

\[
\gamma + e^- \rightarrow \gamma + e^- \tag{2.33}
\]

This is the interaction for Thompson Scattering, a photon (\( \gamma \)) bumping into an electron, exchanging energy and momentum, with the magnitude of each value dependent on the angle of impact and recoil.
From the formation of the hydrogen atoms within the plasma, pressure waves appeared due to the imbalances in radiation pressure and gravitational forces. These waves propagated through the universe, much like how sound waves travel through air, and hence are treated as sound waves today. Another similarity that can be drawn is that at the peaks of these sound waves, the air would be found to be clumped together, and hence be of a higher pressure. This mechanism can also be applied to the pressure waves permeating the plasma; these sound waves are the Baryonic Acoustic Oscillations.

Each oscillation could only travel so far though, at a period of $z \approx 1000$, the recombination phase of the matter caused a rapid decrease in the wave’s speed, leading to an end in the propagation of the BAOs, and were hence frozen with matter spread out in each peak. Now as with any wave, different waves managed to reach different distances before such an occurrence, and therefore it is possible to translate the time of propagation into a length scale, from one peak to the next, i.e. the sound horizon.\textsuperscript{20}

Now that a basic grasp of the formation of BAOs is understood, the next part is measuring the distance connected to the sound horizon and how that can help us with the issue of distance measurement in the universe.

A paper by Eisenstein et al. posted in the Astrophysical journal in 2005 presented the “large-scale correlation function” as quantified by the Sloan Digital Sky Survey (SDSS), a cosmological survey that took a spectrographic sample of 46,748 red galaxies over a sky region encompassing “0.72 h$^3$ Gpc$^3$ over 3816 deg$^2$ and 0.16<z<0.47, making it the best sample yet for the study of large-scale structure.”\textsuperscript{21}

In the paper, Eisenstein et al. discusses the results obtained, mainly the detection of a ‘well defined peak’ in the correlation at 105 h$^{-1}$ Mpc separation, where currently $h=0.7$: 105Mpc/0.7=150Mpc. Described as a great match for current measurements on the “predicted shape and location of the imprint of the recombination-epoch acoustic oscillations on the low-redshift clustering of matter.” This peak can be seen in figure 9.

*Figure 9*: Plot of the commoving separation against the correlation function $\xi(s)$. The correlation function measures the excess probability of finding a pair of galaxies separated by some distance ($s^2$). Each line of the main graph indicating different models, from top to bottom: $\Omega_{\text{matter}} h^2=0.2$, 0.13, 0.14, 0.105, all the while $\Omega_{\text{baryon}} h^2= 0.024$. Something to note is that the bottom line is the case for a Cold Dark Matter universe (i.e. small structures could form after epoch of last scattering) and lacks an acoustic peak.\textsuperscript{23}

By today’s measurements, the BAO standard distance is set at 150 Mpc, taken from the correlation of galaxies formed which are imposed upon the CMB. As previously noted, there was a greater probability in finding a higher matter density at the peak of the BAOs after Recombination, it is then this separation of the greater matter content ‘red’ spots in the CMB that relate to the peaks of the BAO. I go into more depth in chapter 3 on how the CMB was found as well as the physics behind the power spectrum and the separation factor.\textsuperscript{24}

\textsuperscript{*} Figure 9 taken from same paper as referred to in the text; Eisenstein, D. et al (2005) page 562
3. History / Background

3.1 Einstein’s Biggest Blunder

1917\textsuperscript{25}, 2 years after Albert Einstein first published his paper on General Relativity, a theory which in short describes gravity and its effect on the geometry of space time, Einstein introduced the Cosmological Constant. Naturally Einstein wanted to apply these new field equations to the cosmos, at the time though, not much was known pertaining to the contents of the universe. Only from observations was it understood that there was mass which made up planets, stars and gas, and also radiation was present; since the CMB hadn’t been discovered yet, the majority of radiation must have been the result of emission by stars.

The main equation introduced by Einstein is his relation between Gravity or space curvature and both Mass and Energy:

\[ G_{\mu\nu} = 8\pi T_{\mu\nu} \]  

(3.11)

Where \( G_{\mu\nu} \) is the term for gravity or space time and \( T_{\mu\nu} \) is the term for mass and energy.\textsuperscript{26} This short and somewhat complex looking equation ties together how gravity influences both mass and energy within the universe, but also establishing that space time is conducted by the properties of mass and energy. In other terms, a planet will cause space time to curve around itself, and then that curvature of space time will dictate the movement of matter and energy within that area of curved space time.

Observations by Einstein, in the levels of radiation emitted from local stars as compared to their expected rest mass emissions, lead to the conclusion that the majority of the energy density spectrum was dominated by matter. This outcome meant that Einstein could safely parameterize the universe to not contain any pressure from this radiation, i.e. a negligible amount. This is where Einstein heads on the wrong track of reasoning for our universe’s condition; at the time it was argued whether or not we were the only galaxy in the universe, or if there were a multitude of them occupying space.

The now believed expansion of the universe was not observed until Hubble later proposed a paper on the subject in 1929\textsuperscript{27}. Einstein had pondered the case of an expanding and /or contracting universe. He looked towards the stars within our own galaxy and their motions, finding them to be moving away and towards us. There wasn’t much evidence to point to a definitive answer, no clear expansion or contraction of the universe. It was this notion of objects moving to and fro, that the situation that must be prevalent is a static universe, with no collapse or expansion imminent, but a plateau.

“Can a universe filled with non-relativistic matter, and nothing else, be static?”\textsuperscript{28} (Ryden, 2003, p. 72)

The answer is clearly not. The universe cannot be both static and filled with non-relativistic matter, which would go against the main reasoning behind General Relativity and the fundamentals behind gravity: matter attracts other matter towards itself. If the universe was only dominated by such conditions then either expansion or contraction would be inevitable, only an empty universe could be static. This is shown when looking at the acceleration equation:

\[
\ddot{a} = \frac{-4\pi G}{3c^4} (\epsilon + 3P)
\]  

(3.12)

Note: \( a \) is the scale factor of the universe, \( \ddot{a} \) is the expansion of the scale factor, \( \epsilon \) is the energy density (Jm\textsuperscript{-3}) and \( P \) is pressure (Pa).
A static universe requires there to be no mass with which gravity can act upon, a totally empty universe, devoid of matter. When you introduce matter into that empty universe you would assume under the laws of gravity that it would follow one of a set few outcomes: (U is potential energy in joules)

- Initial expansion but leading to contraction under gravity
  (Newtonian terms: U is initially >0, but tends to U<0).

- Continued expansion under the effects of some factor
  (Newtonian terms: U ≥ 0).

For a universe containing non-relativistic matter; \( \ddot{a} \neq 0 \) and therefore will have a positive or negative value, it is this term that must be accounted for when considering the motion of the universe you wish to have in your calculations. Einstein was pushing for a static model and therefore needed to introduce a constant to force \( \ddot{a} = 0 \), meaning that the energy density and pressure terms would be balanced out. This constant is termed The Cosmological Constant \( \Lambda \): (as seen applied to the acceleration equation from before)

\[
\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2} (\epsilon + 3P) + \frac{\Lambda}{3}
\]

(3.13)

Then applied to equations 3.11:

\[
G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}
\]

(3.14)

Just as with equation 3.11, \( G_{\mu\nu} \) and \( T_{\mu\nu} \) are the same, and \( \Lambda g_{\mu\nu} \) is the Cosmological constant. Further insight into the current state of the Cosmological constant is provided in chapter 4.

### 3.2 Hubble’s Law

After Einstein’s introduction of General Relativity, the model of a static universe was present in many physicist’s minds and predictions, it didn’t seem likely that that view would change, or at least for a while. Introduce Edwin Hubble into the mix and suddenly the picture of an expanding universe can really be argued for. This argument started with the Doppler Effect, a property of waves emanating from a source. The propagating waves will bunch up in front of the source (\( \lambda \) decreases), and spread out behind (\( \lambda \) increases), effectively altering the wavelength that the observer will detect if the observer is in front or behind the object. The root of this phenomena is the motion of the source, and it is this key fact that has led to the detection of redshift and blueshift.

Here though we will be concentrating on the redshift of the light emitted from galaxies, the reason being that when observing galaxies, mainly the constituent stars that are emitting the light, the majority of them have been found to be moving away from us, and very few towards us even directly. While some of the key physics has been discussed in the introduction part of this report, here I will go into more detail as to how some of the mentioned concepts, such as the Hubble time and the estimated age of the universe, were derived.

Vesto Slipher was the first to observe redshift in galaxies through his observations of spiral galaxies and mapping their apparent radial velocities.\(^{29}\) At the time though he did not truly understand the occurring events, just that all galaxies were moving with some velocity. Hubble then looked at Slipher’s findings, believing that due to the redshift apparent in the line spectra taken of these galaxies, the galaxies were moving away from us, verified by the concept of the Doppler shift, which Hubble applied to the system and was able to calculate their velocity away from us.
The Doppler Shift can be applied due to observations and experiments carried out here on Earth of spectra from different elements which can be controlled within a laboratory. Finding the emitted wavelength and then comparing that to the observed wavelengths (i.e. the inhabiting stars) we can spot anomalies.

To equate distance with redshift and apparent radial velocity, Hubble used the apparent magnitude of galaxies, mainly Cepheid variable stars within as they were easier to identify, a distance can be found, as discussed in the chapter on standard measurements. Plotting these two data sets against one another: Distance in Mpc and the galaxies Radial Velocity, Hubble was surprised to find a correlation:

![Figure 10](image1.png)

*Figure 10*: The original plot by Edwin Hubble, showing the linear relation between distance in Mpc (along vertical axis) and Velocity in Km/s (along horizontal axis). The gradient of the ‘line of best fit’ is the Hubble constant, it is this gradient that has changed over the years as distance and velocity measurements have increased.

![Figure 11](image2.png)

*Figure 11*: After more observations on galactic recession velocities and their respective distances, the Hubble constant has been altered to reflect this new data. As a more up-to-date counterpart, inclusive of error bars. Something to note here is the size of the error bars, overall they seem greater for velocity measures than for the distance, and this makes sense since distance measurement has evolved considerably since, whereas velocity is still calculated by means of redshift.

Once Hubble discovered this linear correlation between velocity and distance, the next step was to find a way to display this gradient / constant in a formula. Starting from equation 1.22 for redshift, if you consider the change in wavelength as a change in the velocity due to a Doppler shift, we can express that as:\[32\]

\[
z = \frac{\lambda_0 - \lambda_e}{\lambda_e} = \frac{v}{c}
\]  

(3.21)

This can be considered due to fact that as there is a change in wavelength, the energy of the photon has decreased, and hence the velocity can be said to have been affected by this change in energy, reduced from the speed of light to a velocity \(v\).

Using the correlation from Figures 10 and 11, we can express \(v\) and \(d\) with the inclusion of the gradient, i.e. the Hubble Constant:

\[
v = Hd
\]  

(3.22)
Or in terms of redshift, this is another great use for knowing the redshift of a galaxy:

\[ z = \frac{Hz}{c} \]  

(3.23)

A quick note to make on the use of this form is that it is only appropriate if \( v < c \) or \( z < 1 \), these were the limitations imposed back then, and even now a galaxy appearing to travel faster than the speed of light seems outlandish and impossible, although redshifts of \( z > 1 \) have been found, even measuring out to \( z = 8.2 \).\(^{33}\)

This Hubble law is fundamental. It holds many properties of galaxies within such a simple formula; we can find the distance at certain redshifts, calculate redshifts for galaxies at a distance calculated by other methods, however the most renowned discovery that this law revealed was a prediction for the age of the universe. Hubble’s work on stellar object observations yielded many fundamental answers and revelations about our universe.

Without first detecting an expansion of the universe, there would not be such a large study in cosmology today. There are other observations made by other scientists on stellar objects in the universe and their relative motions, as well as continuing the work of Hubble into the modern era, working down the errors in the Hubble constant and extending the search for supernovae to help with the age of the universe predictions.

### 3.3 Cosmic Microwave Background radiation

Referred to as the ‘smoking gun’, the Cosmic Microwave Background radiation, CMB, is considered to be the final nail in the coffin for the prediction of a big bang. First accidently observed by Penzias and Wilson in 1965, while trying to study the radio emissions of the Milky Way, their results were plagued by a very uniform, excess of radiation. The radio telescope they were using was set to a wavelength of 7.35 cm, where the predicted noise from the galaxy would be low. But there it was, a background radiation, one that would not vary with the time of observation in the day, the position in the sky that you were observing or season.\(^{34}\)

When measured, the intensity of this background noise had a curve that resembled that of a perfect blackbody at \(~3\) Kelvin, a perfect blackbody spectrum indicates that the source is a perfect absorber of radiation as well as emitting it.

![Figure 12](image-url)  

*Figure 12*: The spectrum reading of the CMB taken by the FIRAS instrument aboard COBE.
While down the road another group of astrophysicists were working on a prediction for a remnant of the Big Bang. Stating that if the universe had expanded out from a hot dense clump, then any photons from that era would be at very high redshifts by now and be apparent everywhere in the universe.\textsuperscript{36}

The CMB is the remaining photons from epoch of last scattering, the time when the typical photon endured its last scattering off of the thinning number of electrons. So when you observe outwards, you see what can be called the inside of a sphere made entirely of photons ejected from the plasma present at the epoch of photon decoupling, i.e. when the universe went from being opaque to translucent in radiation.

The understanding of the CMB as the most visible remnant of the Hot Big Bang model has grown and developed over the years, standing as the most agreed upon evidence for such a beginning. We know more due to satellite observations such as COBE, WMAP and the most recent PLANCK mission, each identifying a new level of resolution to the CMB. Along with the new images from the satellites, we also measure the power spectrum of the CMB, which in itself holds quite a few different properties of both the current universe as well the state of matter and radiation not long after the Big Bang.

![Figure 13: The power spectrum of the CMB, showing how the temperature of the CMB varies with the angular scale. Note the peak at an angular scale of 1 degree, this is due to the imprint of the BAOs on the CMB.](image)

Figure 13 is the power spectrum of the CMB, one of the most useful plots formed from the data taken via observations on the CMB. The waves that are present after about 6 degrees in Angular Scale arise from the Baryonic Acoustic Oscillations that froze within the early hot dense plasma that the CMB was born from. There are a few things that can be deduced from this plot, the main aspect is the greatest temperature fluctuation occurs at the angular scale of 1 degree on the sky, this is one of the ways of detecting the presence of BAO’s within the CMB.

To conclude then on the topic of 1° separation, when looking at the CMB images from PLANCK, you would see a large distribution of orange-red ‘blobs’ set on a dark blue background. The darker red the spot is the higher the temperature there, it is then safe to say that that is where you would find matter in some form, be it a galaxy or cluster, depending on the red spot’s area. The average separation then of the red segments is about 1 degree, showing that there is a higher probability of finding another orange-red region if you look 1 degree in another direction, it is this spacing of matter imprints on the CMB that leads to the BAO detection and measurement.
3.4 First evidence of an Accelerating Expansion

There were two teams that set about the task of extending and adding to our current understanding of the universe, by mapping the cosmic expansion using standard candles as distance measurements. The two teams concentrated on observing as many Type 1a supernovae as possible; Saul Perlmutter headed one team and the other was by Adam Riess, they found about 50 distant supernovae whose light was weaker than first expected, Riess and Perlmutter concluded that their results showed that the observed supernovae were further away than they should be, this was the first indication that the universe’s expansion was not uniform.  

The detection of Sn1a is a slow process, with no prediction available for when or where one might occur, the best method for observing the night sky in search of them was to continuously sweep the sky, taking images, comparing images of the same patch of sky over several weeks. Then when a potential case was spotted, it had to be verified, found and then have the light curve over its duration plotted.

In the paper published by Riess, A. et al. (1998), a search program is mentioned which would set the search parameters; the redshift range was to be 0.3<z<0.6. Then when measuring the distances to each of the supernovae, the measurement was to be taken just before maximum brightness and within a redshift range of 0.35<z<0.55 where they could measure the light in the B and V filter bands. With such a small chance of finding the supernovae, a large survey was planned with the aim of achieving a limiting magnitude of $m_{\text{red}} \approx 23$ magnitude, this would mean that the survey would yield a high number of SN1a at the desired redshift.

The results were published in 1998, with Reiss stating that from the observed supernovas, on average their distances were 10%-15% greater than expected for a universe of low matter density, $\Omega_M = 0.2$ and without a cosmological constant.

The calculation used for the distance of the supernovae 1a was the luminosity distance relation:

$$R_L = \left( \frac{L}{4\pi F} \right)^{1/2}$$  \hspace{1cm} (3.41)

Where $L$ is the luminosity, measured in Watts or J s$^{-1}$, and $F$ is the observed flux, measured in W m$^{-2}$.

With the accelerating expansion of the universe now widely believed, more and more teams have taken observations of different areas of the night sky to map out the furthest reaches of the universe. In 2011 Saul Perlmutter, Brian P. Schmidt and Adam G. Riess, won the Nobel Prize in Physics “for the discovery of the accelerating expansion of the Universe through observations of distant supernovae”.

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Figure 14: (Top) A Hubble diagram of high redshift SN1a. The full line is that of Dark Energy dominance $\Omega_{\Lambda}$ indicating an acceleration in the expansion. The dashed line and dotted line are both for a universe only containing normal matter $\Omega_m$.

(Bottom) Another view of the above depiction, the lines indicate the same properties as the above graph does. The sample of data is from two teams and shows an agreement between their two data sets.

And finally, Adam Riess et al. (1998) concluded with the following statements:

> “The distances to the spectroscopic sample of SNe 1a measure by two methods are consistent with a currently accelerating expansion...” with stated confidence levels of “99.5% (2.8\(\sigma\)) to more than 99.9% (3.9\(\sigma\))...”

> The data recorded pointed to an ever expanding universe.

> A new estimate for the age of the universe: $14.2 \pm 1.7$ Gyrs.
4. Models for Dark Energy

Since the discovery of the acceleration factor in the expansion of our universe in 1998, there has been quite a few theories, predictions and models proposed to try and explain the phenomena known as Dark Energy. The models discussed here are those that are currently being investigated the most, other models do exist for the explanation but lack fundamental grounding via the known physics, or lack data to provide an arguable case for it and therefore are not deemed sufficiently plausible for funding further experiments solely for that prediction.

Therefore, I present the models of the universe as examined through the Friedmann equations, the re-instated Cosmological Constant (or Vacuum energy) and finally the concept of Quintessence; the evolution of Dark Energy and it’s equation of state over the age of the universe.

4.1 Friedmann model

Most of the models I am about to discuss are rooted to the Cosmological Principal, here is a reminder:

> The notion that, within the universe, the matter distribution is Homogeneous and Isotropic when viewed on a large enough scale, at a distance of ~200 Mpc.

This is the point that all points of sight are treated the same, not irregularities or unknown phenomena, of course this rings alarm bells almost instantly, but from what we know of the observable universe this assumption seems to hold so far. These two assumptions were made by Einstein to simplify the universe for his models.

After the publication of Einstein’s paper on General Relativity, many scientists and astronomers turned these new rules to the realms of cosmology, Alexander Friedmann, a Russian Physicist was the first to mathematically model the expanding universe, publishing a paper on the subject in 1922. Even today his workings are used to model varying universes with different contents; empty, matter dominated, radiation dominated etc.

A powerful tool used to compare the size of the universe at varying ages and times is the scale factor \(a\), where comparing two different known values of the scale factor can tell you if the universe has expanded or contracted in size. The scale factor of now \(t_0\) is \(a_0\) and is equal to 1, thereby if we compare it with another age of the universe we will either see a reduction in size; \(a(t)<1\) or an expansion; \(a(t)>1\). The equation that related scale factor with redshift is shown here, this relation is very powerful, and from it you can see the size of the universe at certain redshifts.

\[
a(t) \equiv \frac{1}{1+z(t)}
\]  

(4.11)

There are two forms of the Friedmann equation that I will discuss here, both are in the Newtonian form and fully relativistic. These equations explain a test volume of the universe which is undergoing expansion, and how it behaves under self-gravity from the matter enclosed within that volume. In some occasions it is written as equal to \(H(t)\) to help understand the state of the universe via the Hubble parameter at time \(t\).

\[
H(t)^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2} \epsilon(t) - \frac{k c^2}{R_0^2} \frac{1}{a(t)^2}
\]  

(4.12)

With equation (4.12) there are a few new terms:

- \(H(t)\) is the Hubble parameter at time \(t\), where \(H_0\) and \(t_0\) are the current Hubble constant and time at the present time.
• Scale factor $a$, is used to compare the relative size of the universe at different points in time: $a(t_0)=1$ at $t_0=0$ (i.e. now).

• Energy density, $\rho(t)$ is the energy density at time $t$ in the universe. A useful relation between energy and matter density is $\varepsilon = \rho c^2$

• $K$ is the curvature index with three distinct values: +1, 0, and -1, this is defined more in the Robertson-Walker Metric.
  > +1 is an open universe.
  > 0 is a flat universe.
  > -1 is a closed universe.

• $R_0$ is the present value of the curvature radius for the universe.

Introducing $\Lambda$ (Cosmological constant) into the Friedmann equation allows the already explored models of the universe to take into account an acceleration term, much like our current one.

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3c^2} \epsilon - \frac{\kappa \epsilon^2}{R_0^2 a(t)^2} + \frac{\Lambda}{3}$$

(4.13)

Using equation 4.12 you can determine the state of that scenario, evaluating the outcomes of different universes with different proportions of content; matter and radiation etc. Some interesting examples are the Hubble constant, the Hubble time or the age of the universe at different epochs and then also the distance to objects; the distance at light emission and then the time of detection. This distance is known as the proper distance $d_p(t)$.

$$d_p(t_0) = \frac{c}{H_0} \ln(1 + z)$$

(4.14)

With proper distance, we see yet another use of the redshift measured from a galaxy. The Friedmann equations act more as a tool to help understand what could happen under certain parameters set for the universe, such as matter dominated (also known as an ‘Einstein – de Sitter’ universe), radiation dominated universes, how does curvature effect the system and finally how each universe will evolve due to these parameters.

Figure 15: Scale factor $a$ plotted against time, showcasing the different paths the universe can take with either matter, radiation, cosmological constant being the main constituent, or even an empty universe. Note how with the empty universe expands linearly, a static case, whereas with matter or radiation, the expansion is a lot slower, and potentially won’t last for ever. with the cosmological constant only universe, the expansion increases exponentially with time.

We know though that the universe is not made up of just one constituent, but a bundle of many different states. Instead the universe went through different epochs, each with their own dominating constituent. Though the dominating presence changed over time, the question some have asked is wether the Cosmological constant has either been constant or has it also varied over the cosmic timescale and only recently become dominant? That view is the Quintessence model and is described, along with the Cosmological constant / Vacuum energy in the rest of the this chapter.
4.2 Cosmological Constant \( \Lambda \)

The model of \( \Lambda \) has already been discussed in chapters 1 and 3, though those accounts are a review of the first implementations of the constant, and its swift withdrawal. Discussed here is how the constant has been adapted and reintroduced into cosmology, accounting for the theorized negative pressure behind the accelerating expansion of the universe.

At this point we know that the universe is not static and is in-fact expanding, though the source of this has been labelled Dark Energy due to its uncanny nature of not directly interacting with visible matter, beyond that we have only been able to list and characterize what this Dark Energy is doing to our universe.

The way in which Dark Energy is characterized today is through the equation of state:

\[
P = w \epsilon
\]  
\[\text{(4.21)}\]

Where \( P \) is pressure, \( w \) is used to symbolize the amount of Dark Energy and finally \( \epsilon \) is energy density.

Using equation 4.13 we are able to describe some different scenarios depending upon the value of \( w \), equation 3.13 in chapter 3 shows what would occur if \( w = -1 \); the allowance for the scale factor to accelerate. We therefore say that for \( w = -1 \) it is the case for the Cosmological Constant.

One thing to note about \( \Lambda \) is that it is constant throughout time, not like Hubble’s constant, more like the gravitational constant \( G \). The value is set throughout space and time and has been around since the Big Bang, another way that physicists are describing this parameter of the universe is as Vacuum energy, an underlying energy contained within the vacuum of space. This energy is also believed to be the leftovers from inflation in the extremely early universe.

There are also investigations into other values for \( w \), where \( w < 1 \) as only then will we see a negative pressure acting in the universe, another value of some interest is \(-1/3\). No matter the actual value, all we are sure of is that it is negative, and hence causing expansion.

The effects of \( \Lambda \) are not observable at local scales, we do not see any ‘anti-gravity’ effect upon our solar system, nor within our own galaxy. Therefore the energy value associated with \( \Lambda \) must be very small, so small but yet so abundant that it really has a noticeable effect on structures such as galaxy clusters or larger, and hence the term ‘Cosmological’ constant.

The idea behind Vacuum energy is that it arises from the Uncertainty Principle; this principle does not allow for energy states to exist that are equal to exactly zero energy. This applies even to the vacuum of space, as there are virtual particles come in being and destroy themselves almost instantly.

Due to Einstein’s equation relating gravity to both mass and energy (equation 4.14), we can see that this ‘ground state vacuum energy’ will have a gravitational impact over the universe. Now as there is a lot more vacuum than there is matter, this would then affect the expansion of the universe via an overall gravitational influence.\(^{45}\)

\[
G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}
\]  
\[\text{(4.5)}\]
4.3 Quintessence

Another view for Dark Energy has been termed as Quintessence, dating back from the ancient Greeks, with the original intent for describing the fifth fundamental element alongside Earth, Water, Wind, Fire. The Quintessence model uses the idea of a scalar field to deal with how Dark Energy and its energy density affects normal space and matter, it is this field that is said to allow its energy density profile to mimic that of other present background materials profiles, i.e. matter or radiation.\(^{46}\)

A fundamental difference to make note of is that when compared to the Cosmological Constant or vacuum energy, Quintessence may have the same negative equation of state value at the end and contain a negative pressure value, but unlike \(\Lambda\), quintessence is modelled to evolve over time and hence by definition cannot be constant.

One of the ways that the quintessence model is described as delves into the quantum properties, such that the quantum field wave is extremely long, approximated to the be the size of the observable universe. The wave is considered to carry with it two energy forms: kinetic and potential, the kinetic energy is due to the rate of oscillations in the field and then the potential energy depends on the interaction between the field, both with itself and matter. It is the difference between these two variables that gives rise to the scale of the pressure.

Due to the size of the wave, the oscillations that it undergoes act over a large timescale, roughly the age of the universe, being such a small value then would lead to a small value in kinetic energy, leaving only potential energy to dominate the pressure profile, and seeing as how it interacts with itself quite readily, that value is much higher than for kinetic. And hence the conclusion you arrive at means that a negative pressure is exerted, although only at large scales.\(^{47}\)

![Figure 16: Redshift / Time evolution of matter, radiation and q (Dark Energy) energy density. Clearly shown is the deviation with time that q tends to have as compared the linear descent of both matter and radiation as redshift increases.](http://physicsworld.com/cws/article/print/2000/nov/01/quintessence)

Depicted in Figure 16, both radiation and matter decrease linearly, though at different rates, with redshift, along-side dark Energy which is mimicking the energy density profile of each dominant material, then ultimately becoming the dominant presence itself. During the inflation period, Dark Energy and radiation’s tracks are quite similar, but as with the green dotted lines, there may have been several paths of evolution Dark Energy could have taken. Then there is a phase change in the universe and Dark Energy ceases a behavior akin to radiation and starts to flatten out, this leads to the eventual overtaking of matter and dominance of the universe.

Seeing as matter domination ended roughly 10Gyrs ago, the assumption is that Dark Energy, or the presence it is associated with, prevails over all other forms of matter density and or
energy density today, this belief was put forward by Steinhardt; Dark Energy could have switched on due of the transition between radiation and matter.\textsuperscript{48}

To understand why Dark Energy would have ‘activated’ at this time, when gas cooled to such a temperature to allow star formation etc., we need to consider how Dark Energy seems to interact with the visible baryonic matter that we are surrounded by.

So far we have not observed its effects on a local scale, and therefore it can safely be predicted to only have a resultant effect upon scales much larger than we have both measured or uncounted. This makes it harder to observe the effects Dark Energy has on ordinary matter at say galactic scales, leading to the need for deep sky surveys as well as large scale, close field surveys that can observe such massive structures.

It is safe to say though that Dark Energy to-date seems to be the driving force, with a negative pressure produced from either a constant background energy (vacuum energy) or from a steadily evolving factor such as what quintessence describes.
5. Projects for the Discovery of Dark Energy

The main aim of the following projects is to map out the acceleration of the expanding universe. Several techniques can be implemented to aid with this observational research, mainly the detection and mapping of type 1a supernovae (SN1a) as well as Baryonic Acoustic Oscillations (BAO). The main aim of the majority of today’s projects is the acquisition of a large sky survey database.

There is even a Dark Energy Task Force (DEFT), established with the intent of setting out goals and areas of key research, all for the purpose of extending our knowledge and understanding of the acceleration of the universe and consequently what is causing it, i.e. the effects of Dark Energy. The four areas of research that it has laid out for different organizations to look into are: the mapping of supernovae type 1a (SN1a) occurrences, the Baryonic Acoustic Oscillations (BAOs) and their scale imprint on the universe, galaxy clustering and finally Weak Gravitational Lensing (WGL).

5.1 Dark Energy Survey – DES

The search for the elusive and very mysterious Dark Energy has recently been the interest of many an observational project. One such project is the Dark Energy Survey (DES), made up from 120 scientists from 23 different organizations with the main aim of mapping a large portion of the night sky. With the use of a 4 meter telescope at the Cerro Tololo Inter-American Observatory which is situated high up in the Chilean Andes, the team behind DES has attached a new, aptly names camera to the telescope: the Dark Energy Camera (DECam).

Installed in 2012, the DECam is a 500 Megapixel camera equipped with a data retrieval system that “reads out images in 17 seconds.” Additionally, the camera has 5 different optical filters enabling the capture of different wavelengths. DECam is set to catalog an area of 5000 square degrees of the night sky over 525 nights.

The choice in location is key when deciding to undertake a ground based survey of such magnitude; one major requirement is that you reduce as much atmospheric noise from your observations as possible, this is combated through placing a telescope high up in the atmosphere in an isolated environment. An additional reason for choosing this specific location is that the team want to look directly out of the spiral arm of the galaxy, looking along the spiral arm would result in too many close objects obscuring your intended field of targets.

The drive behind this project is to fulfil scientific requirements of such a large, deep sky survey, taking information on over 300 million galaxies, reaching redshifts within the range 0.2<z<1.3, a reasonable distance to measure the effects of Dark Energy over. Such a large survey requires a tradeoff between how high a redshift you observe to and the area that you cover, this is done to keep the time taken to conduct such research down to an acceptable timescale.

The requirements laid out by DETF for this survey are all based on the prospect of collecting a large database of cosmological information in regards to mapping out the effects of Dark Energy on different objects. The following are the main areas of study with set parameters:

- **Type 1a Supernovae** – measuring appropriate light curves, about 3000 predicted supernovae at a maximum distance of z=1.2.
- **Baryonic Acoustic Oscillations** – Using the 300 million galaxies, archiving the photometric redshift.
- **Galaxy Cluster Counts** – measuring redshift and mass at a maximum range of z~1.5
- **Weak Gravitational Lensing** – again using the 300 million galaxies to detect lensing effects.
Weak Gravitational Lensing is the effect that gravity has upon light, as stated within Einstein’s GE equations, shown as equation 3.11. We have seen the effect of gravitational lensing due to normal matter in the form of galaxies and galaxy clusters, as well as from dark matter. If Dark Energy and Dark Matter have such a gravitational effect on space-time, then it makes sense that such a curving of light can be mapped from the ‘arclets’ produced or from slight distortions in galaxy shapes. Arclets are the projected deformations of the original light source, these arclets will tend to form a ring around the lensing object, and this is known as an Einstein Ring. The radius out from the lensing object to the ring, as measured in radians can be shown as:

$$\theta_E = \sqrt{\frac{4GM}{c^2 d d}}$$

(5.11)

Where $d$ is the distance to the lensed object, $xd$ is the distance to the lensing object (where $0<x<1$).52

A strength of such a project is that it can detect all 4 cosmological phenomena and do so over a reasonable timescale of a few observations made every few nights. Not only looking at the inherent expansion of the universe through BAO’s and SN1a but also how Dark Energy and the acceleration it commands effects structures on a large scale, as it is predicted to have negligible effects on structures as small as galaxies. Galaxy cluster’s and super clusters are the prime targets for observing such effects.53

5.2 Baryon Oscillation Spectroscopic Survey – BOSS

Measuring and observing multiple parameters and events in the universe is beneficial when accomplished by a single survey, although it is also necessary to provide further observations into specific key areas. For the case of the Baryonic Acoustic Oscillations embedded upon the distribution of galaxies and the Cosmic Microwave Background, there is the Baryon Oscillation Spectroscopic Survey (BOSS).

BOSS is a survey that is a part of the Sloan Digital Sky Survey, a ground based observatory with a telescope measuring 2.5m in diameter. SDSS-III is the third generation of surveys, which includes BOSS, and was launched in 2008 and continuing up until 2014.

As described by Dawson, K. S. et al. (2013) the BOSS survey is designed to observe the distribution of $\sim$1.5 million galaxies at redshifts of $z<0.7$, over an area of 10,000 deg$^2$. The main aim was to measure the BAO distance imprinted upon the CMB and reduce the error to 1% in the readings.

Another task of the survey is to take spectroscopic readings of “neutral hydrogen in the Ly$\alpha$ forest in more than 150,000 quasar spectra”, this will help look at the state of the BAO in further reaches of the universe, a range quoted to be “2.15<z<3.5”. Additionally BOSS also looked at contributing to the current Hubble Constant value $H_0(z)$ at redshifts “$z=0.3$ and $z=0.57$” while helping to reduce the error in the value to an accuracy of 1.8% to 1.7%.54

The Ly$\alpha$ forest appears due to quasars producing a continuous spectrum of light, it is then when that light interacts with a dust / gas cloud that we see the absorption of Hydrogen in the Lyman alpha series wavelengths, and become dark lines on the continuous spectrum.

With the past success of the SDSS-I and SDSS-II projects, having a third stage of measurements means that the results can be directly compared and improved upon compared to previous observations made via the same array. It is crucial at this current time
that we know as much as possible, with the lowest errors achievable, about BAO’s as they are referred to observable aspects of the geometry of the universe.

Measuring that geometry leads to an understanding of how the universe evolves due to constraints, as well as providing a system so as to accurately measure distances within space.

The selection process though for such a sky survey needs to be refined, chosen mainly from previous observations and the probability of actually finding relevant targets at certain redshift. That selection process is apparent in all present and future observations, as we take more and more sky surveys, you begin to weed out the objects that will not benefit the conclusion.

Figure 17: A plot from two different surveys undertaken with the SDSS program. There is a distinct difference in the number density of galaxies within a range of $0.1<z<0.4$, but beyond that limit there is a large ‘pool’ of targets to select from. The limits then for the BOSS (SDSS-III) will then be determined by previous readings.\(^5\)

Figure 18: Power spectrum distribution $P(k)$ as a function of wavenumber $k$. The solid line is a best fit for the data; (Top) data taken from Luminous Red Galaxies (elliptical), the data is that from lower redshift galaxies, as seen in Figure 18. (Bottom): Data set from a different detection technique at higher redshifts, the data has a more coherent pattern to it when compared to the SDSS-II LRG survey.

Wavenumber, $k=2\pi/\lambda$ (wavelength).

It’s somewhat clear to see that the peaks of the best fit lines’ maxima and minima contain the majority of signals, as expected due to the nature of the BAO setup in the early universe.
5.3 EUCLID – ESA and NASA

Named after the famous Greek mathematician and ‘father of geometry’, the Euclid probe will be a space based, 1.2m wide telescope. The launch date is set for 2020, the project is headed by the European Space Agency (ESA) with the recent addition of NASA and some of their state of the art hardware; Infra-Red detectors (IR) as well as hardware to connect to the detectors as well as interpret that data.56

When deployed, Euclid will be in position at the L2 Lagrange point for an optimum large and deep sky survey. The Lagrange points are a calculated set of positions or orbits that take into account the orbital mechanics of the Earth and Sun, as well as their gravitational effects.

For instance, the L1 point is an orbit that is shorter than the Earth’s by fraction of 100, of course being closer to the Sun normally requires a faster orbital velocity, whereas with L1 being so close to Earth, the gravitational effect from Earth will pull the satellite along, speeding it up and helping to maintain its position.

Whereas the L2 point is at a point further out than the Earth, at a distance on 1.5 million km, Euclid will sit in the Earth’s shadow, allowing for an extremely cold working environment. This factor of low temperatures is key to the operation of the satellite, even though it will on encounter light from the Sun, which it needs to power the system via solar panels, Euclid itself is encased in a large heat-shield. As with any electronic equipment, as it uses energy it will inevitably warm up by a few kelvins which would have quite a substantial effect on the satellite, distorting the images it produces through the expansion of certain materials within the telescope and camera.

The benefits of such a location as L2 are as follows:

> No direct sunlight to interfere with incoming light, i.e. white out of image on long exposure.
> A colder region of space as compared to the Earth’s orbit, due to being shielded by the Earth but not 100% covered.
> Best location to observe IR sources in any direction is required, though as mentioned before, observations made perpendicular to the spiral arm of the galaxy are the primary areas for observations.
> Ecliptic polar views are key as can be compared with previous data to account for any discrepancies, as well as be used for filtering out targets.

That potential distortion is on the scale of what is needing to be observed through Weak Gravitational Lensing, one of Euclid’s objectives. As well as the lensing effect, ESA are also setting their sights on capturing the largest sky survey carried out to date, covering ~15,000 square degrees of sky in a timescale of 30 minutes, something the Hubble Space Telescope could not achieve within a nearly as practical timescale. Euclid aims to observe as far out as roughly z>2, where it has been predicted in a number of papers to contain the highest number of observable candidates.

Alongside the low redshift sky survey, two “Euclid Deep Fields” will cover 20 square degree patches of the universe to help understand high redshift galaxies, “6<z<8”. Euclid aims to observe “about 10 billion sources”57, from which ~1 billion galaxies will be used to observe and measure the effects of WGL. 60,000 of those sources will be used to map and measure clustering of galaxies, through these sources it is possible to find higher densities in matter and hence determine the effects of the baryonic oscillations at varying scales, with such a large number of viable sources, measuring the BAOs will be of great importance as different redshift ranges can be examined.58
On the subject of BAOs, it is relevant to discuss the ‘angular diameter distance’ $D_A(z)$, where this physical distance is the ratio of the object's actual size to the angular diameter the object takes up when viewing from Earth. As we know the physical size of the BAO to be $s \approx 150$ Mpc, then it becomes possible to find the value for the angular diameter distance from measuring the angular size of the sky: $s / D_A(z)$. This is an important point as it can then be used to directly measure the expansion of the universe.

The same exercise can be applied to the Hubble parameter at redshift $z$, where you would measure across the entire sky and get a value for $s*H(z)$, both the Hubble factor and the angular diameter distance are extremely powerful values to know, they are essentially the radial and transverse distance measurements across the observed cosmos, leading on from there the curvature at varying redshift can be determined. Evaluating that data will mean a clearer picture can be presented on how the ‘geometry’ of the universe has evolved over time, a crucial goal indeed to aid with the understanding of what could be causing our current expansion and subsequent acceleration.

At this point though it is essential to have already set out parameters, limits and test points for what it is you actually intend to observe. A few candidates are clear: SN1a events, BAO’s and galaxy dispersion. While Euclid is mapping out a very large portion of the sky, it’s primary objective is not SN1a, if though it happens upon one then it will be logged and interpreted by a team back on Earth, obviously covering more space will lead to more SN1a being detected but so far it is forecast at potentially 1 a week, still too low for such an expensive and all round telescope to focus upon.

As for the galaxy parameters, you need to make sure that there is a defined redshift limit you will be exposing the camera to, as well as potential targets that have already been observed and tagged as being beneficial to the spectrum you wish to observe in.

Hydrogen-alpha (Hα) galaxies are one such filter to be applied to the Euclid mission, these galaxies are targeted for their emission lines which can be cataloged at a fair rate, aiding in the timescale that Euclid can achieve when taking readings. A study by Geach, J. E. et al (2010) on the predicted count of these Hα emitters lays out the reasons why future Dark Energy surveys would use such targets, going into how dense and populated the universe is with these star forming galaxies as you observe greater redshifts, but with the main focus of keeping the limits of distance to around “$z \sim 0.5$ to 2”.

6. The future of Dark energy, where will we be in 10-20 years, what will it mean for us?

We have a while to wait till even Euclid gets off the ground, and even then it has a scheduled 6 years of observations to help reduce the errors. The question is then: How little do we need these errors to be before we accept some model? Whether or not we need more observations after Euclid is beyond question right now, though I am sure that more specific projects will run in conjunction with ESA and NASA for the search of the elusive Dark Energy, as well as Dark Matter.

As the years roll by though newer means of distance measure could become prominent, though the BAO seems to be set as the standard for the time being. Methods in measuring the expansion may change though and a few ideas are pegged for future missions, mainly the mapping of Gravitational lensing from the presence of Dark Matter, if that can be observed over a range of redshift then, just like we are mapping the effects Dark Energy has on ordinary, visible matter, it should be possible to map out how it has impacted the evolution of Dark matter distribution over time.⁶¹

Depending on whether the near future missions reveal what we are looking for, it could be a while yet before a definitive model for either Dark Matter or Dark Energy is established. It would then be viable to figure out how these two components have shaped the universe to a finer degree than just observing and inferring. The next landmark in this field of research would be the actual definition of a model being tried and tested, standing up to scientific scrutiny and found to be still standing at the end. Otherwise it will be back to the drawing board for quite a few cosmologists.

In terms of what a discovery in the Dark Sector would lead to, there is not much use, with present knowledge, for such knowledge outside the study of cosmology and understanding the universe. Dark Energy for instance has no observable impact on the scales in the universe that we deal in in day to day life. Again, much like many other scientific programs that search for scientific answers about the world we inhabit, spin off technology is the benefit that will be seen in modern society. That is unless Dark energy turns out to be a viable energy source that we can tap into, it will only be useful in the context of describing how the universe evolves and has evolved, maybe even helping to explain the very beginning.
Conclusion – Final thoughts

The scope of this investigation was to introduce the concept behind Dark Energy to the reader, embedding a knowledge of the key aspects that has led to the present day and our current cosmological outlook. Starting from the great Albert Einstein and his infamous Cosmological constant, to the works of Hubble and his discovery of an expansion of the beautifully depicted static universe of Einstein.

The distance scale is a powerful tool, for example the Baryonic Acoustic Oscillations found imprinted upon the CMB allow us to measure the probable distance between galaxies. Another example is supernovae type 1a; we measure their light curves and use the magnitude of their brightness to calculate how far the light has travelled in order to reach us. These scales are the geometry of the universe, they are not man-made and as such are natural. There is quite a bit of wonder behind such a system, but it pales in comparison to the potential uses we have for such scales.

To name a few uses that have already been covered is the ability to map how matter and dark matter has been affected by the gravitational influence of dark energy, and how normal matter is affected by dark matter for the case of galaxy formation and gravitational lensing.

Knowing how far away an object is from Earth allows for the conceptualization of what scale some of these processes act upon.

Whether or not Euclid answers some of our enquiries, it will not mean the end of searching. If DE is discarded, then new predictions and ways of thinking will open up new models and theories for us to test. One example would be the revision of Einstein’s General Relativity, but applied to large scale structures, modified in an attempt to explain what is happening to space-time in our universe.

To conclude the subject of missions, each mission sets out with aims set by the DETF, with the end result of furthering our overall knowledge of how our universe has evolved, how it has expanded and what has caused the current acceleration of our universe, observed from SN1a and BAOs via geometry shifts. Beyond that, we use these experiments and research opportunities to determine what model the universe best fits: Is it our current concordance model that still rules over all? Is Dark Energy constant throughout time as \( \Lambda \) dictates or is it a quintessence case? Or is it that the formulae provided to us by Einstein are in need of modification, also referred to as the Modified Gravity theory, where on cosmic scales the equations of General Relativity need some revision to account for certain phenomena?

To date though we know that Dark energy is the most prevailing theory behind the acceleration of the Universe, that currently it dominates our known universe and that it makes up 68.3% of the observable universe. Dark matter follows behind at 26.8% and the final 4.9% is ordinary matter, i.e. Baryons etc. via the Planck satellite in 2013.\(^{52}\)

Our current cosmological model is the Concordance model, also known as the \( \Lambda \)CDM (Lambda Cold Dark Matter Universe) which is a universe that originally started with cold Dark Matter, a situation that allowed structure to form in the early universe, and has the cosmological constant present, i.e. Dark Energy. The age of the universe is predicted at 13.7Gyrs with the Hubble constant currently calculated at 67.7 kms\(^{-1}\) Mpc\(^{-1}\). Concordance is the accumulation of what has been observed and theorized so far, including the expansion and subsequent acceleration of the universe, while also agreeing with the Big Bang model the CMB.
While the model for our universe has altered over the years due to new observations, new physics and different predictions, some of the theory that has been developed on the way has become standard in either scale or time, for instance the Baryonic Acoustic Oscillations being at a measured scale of 150 Mpc. Measuring such constant distances and phenomena is crucial to the measuring of our universe, allowing for the mapping of large scale structures and the understanding of how our universe has evolved since the Big Bang occurred.

The search for Dark Energy is one that we do not know the end of, we can only halt the observations once a certain certainty is reached with the results. But after that it will be much like how physicists changed their view from Steady State to Hot Big Bang, it won’t affect their daily lives, but only bolster our knowledge of the universe.

We do not know what the eventual case for the universe is. If as predicted Dark Energy is dominant now and continues to be the driving force behind the acceleration then our universe will become a very lonely, very cold place indeed.

In its simplest form, the search for Dark Energy is to satiate scientific enquiry.
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