IMPLICATIONS OF SN LUMINOSITY EVOLUTION ON Λ & H_0 MEASUREMENTS

Project Report

submitted in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE

IN

PHYSICS

by

Ananthu Krishnan A

Reg No:186PH003

DEPARTMENT OF PHYSICS
NATIONAL INSTITUTE OF TECHNOLOGY
KARNATAKA, SURATHKAL, MANGALORE-575025

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DECLARATION

I hereby declare that the report of the P.G. Project Work entitled "Implications of SN luminosity evolution on Λ & H_0 measurements" which is submitted to National Institute of Technology Karnataka, Surathkal, in partial fulfillment of the requirements for the award of the Degree of Master of Science in the Department of Physics, is a bonafide report of the work carried out by me. The material contained in this report has not been submitted to any University or Institution for the award of any degree. In keeping with the general practice in reporting scientific observations, due acknowledgement has been made whenever the work described is based on the findings of other investigators.

Place:Surathkal
Date:08-07-2020

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CERTIFICATE

This is to certify that the project entitled "Implications of SN luminosity evolution on Λ & H_0 measurements" is an authenticated record of work carried out by Ananthu Krishnan A, Reg.No:186PH003 in partial fulfillment of the requirement for the award of the Degree of Master of Science in Physics which is submitted to Department of Physics, National Institute of Technology, Karnataka, during the period 2020-2021.

Dr.DEEPAK VAID
Project Advisor

Chairman-DPGC

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Abstract

The discovery of dark energy from Supernova cosmology was one of the biggest triumphs of observational cosmology. But recently a team [Kang et al., 2020] claimed that this observation might not be as conclusive as was previously thought. The Nobel prize winning discoveries made by Supernova Cosmology Project [Perlmutter et al., 1999] and High-Z Supernova Search Team [Schmidt et al., 1998] led to the reintroduction of the long forgotten cosmological constant, Λ, which sparked a revolution in the field of cosmology. In this project the methodologies of experiment and the results of SCP and High-Z SN team are explained. The observations made by [Perlmutter et al., 1999] and [Schmidt et al., 1998] are compared with the recent claims made by [Kang et al., 2020] that the Supernova luminosity evolution can mimic the dark energy model. The discrepancy in the value of Hubble constant, H_0, calculated from the Cosmic Microwave Background and from Supernova data is one of the biggest puzzles in modern cosmology. An examination as to whether this luminosity evolution of Supernova as proposed by [Kang et al., 2020] impact the Hubble tension is also done.

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1 Introduction

1.1 Hubble's law

The basic priciple on which the whole of modern cosmology is built is that the universe is homogeneous and isotropic. This is often referred to as the cosmological principle. The cosmological principle is only valid on scales bigger than a few hundred of parsecs. The beginning of physics cosmology is often attributed to the observational findings made by Edwin Hubble to prove that stellar objects are moving away from earth with a velocity proportional to the distance of the object from earth. This simple linear equation relating the distance of an object from earth(d) and the velocity of the object with which it is moving away(v) is called Hubble's law.

$$v = Hd \tag{1}$$

The Hubble constant(H) is a constant that varies over time, but remains constant over space. It is normally calculated in $km\ sec^{-1}\ Mpc^{-1}$ and a subscript is used to denote the epoch on which it is calculated. The current value of Hubble constant(H_0) is calculated to nearly 70 $km\ sec^{-1}\ Mpc^{-1}$. But the value of this constant calculated from two independent experiments does not match. This is on of the most puzzling questions to be solved in modern cosmology.

1.2 FRW metric

While trying to study the universe as a system using general relativity, arguably the most important step is to define a metric for the system. The Minkowski metric would have been enough for this purpose if only the universe was static. But since it is not the case and it has been proven beyond reasonable doubt that the universe is expanding, FRW metric was introduced. This metric is a slightly modified version of Minkowski metric which incorporates the expanding nature of the universe by the introduction of comoving coordinates and scale factor(a). Comoving coordinate system assigns fixed comoving coordinates to a point on space which does not change over time. But the coordinate system itself expands with the expansion of the universe so as to preserve the comoving coordinates. The scale factor is a function of time which multiplies the comoving distances to obtain the physical distance from the comoving coordinate system. The FRW metric is defined as follows:

$$ds^2 = dt^2 - a(t)^2(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)) \tag{2}$$

The geometry of the universe depends on the value of k which can be zero for a flat model, positive for a three-sphere and negative for a saddle like geometry. By using the FRW metric to calculate the Einstein tensor and thereby writing the Einstein equations, an equation that can explain the dynamics of the universe can be obtained.

1.3 Dynamics of the universe

In 1915 Albert Einstein proposed general relativity which was a geometric theory of gravitation(3). Efforts to model the universe with this new idea sparked almost immediately. Among that the most notable work was done by Alexander Friedmann who developed a relativistic equation explaining the dynamics of the universe which was latter called as Friedmann equation(4).

$$G_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} - \frac{\Lambda}{c^2}g_{\mu\nu} \tag{3}$$

Einstein equations without the cosmological constant predicted a dynamic universe. But this was in contrast with the popular belief at that time which was a static universe. This dynamic universe was

able to be modelled without even the help of general relativity and only using Newtonian gravitation. So Einstein included the cosmological constant(Λ) in the equation to model a static universe.
Equation 4 and 5 can be derived from equation 3 using the FRW metric. Equation 4 describes the kinematics and dynamics of the universe and are called Friedman equation and acceleration equation respectively. ρ is the density due to the dust and radiation, H is the Hubble constant and k is a constant that specifies the geometry of the universe. From equation 5 it is evident that for a vanishing cosmological constant, a stable condition cannot be achieved.

$$\frac{\dot{a}^2}{a^2} = H^2 = -\frac{kc^2}{a^2} + \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} \tag{4}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + \frac{3P}{c^2}) + \frac{\Lambda}{3} \tag{5}$$

But the condition for stable universe was finely tuned and even a small deviation from the theoretically predicted value could be destabilise the model. So when Edwin Hubble found that the universe is expanding in the mid 1920's, Einstein had to immediately retract his idea of Cosmological constant. Although cosmological constant did not appear in most of the literature for a few decades, it was known that the vacuum energy was non-zero and the idea of cosmological constant cannot be completely written off that easily.[Weinberg, 1989].

1.4 Energy density of vacuum

The contents of the universe can be classified on the fundamental level as radiation and matter. The evolution of energy density of the respective component has a particular dependency on the scale factor. The relation between pressure P and ρ is $P = w\rho c^2$, where w is a unitless number.

Considering a sphere of radius a which increases as a function of time. A volume of mass density ρa^3 has an energy density $\rho a^3 c^2$. Using the first law of thermodynamics and considering the expansion to be adiabatic, it can be found that:

$$\rho \propto a^{-3(1+w)} \tag{6}$$

The value of w is different for different components of the universe and thus the dependency of ρ on scale factor varies according to the component under consideration.

From equation 4, when Λ and k vanishes, it is possible to find a density which will halt the expansion after a while and this density is known as *critical density*(ρ_c). Density parameter, Ω, is an important parameter used in cosmology as it has theoretical as well as experimental advantages. The density of matterρ_m and density of radiation ρ_r divided by critical density gives the Ω of the corresponding component. The density of vacuum ρ_v, can be defined by,

$$\rho_v = \frac{\Lambda}{4\pi G} \tag{7}$$

The density at any arbitrary time can be expressed in terms of initial density $\rho_{m,0}$ and $\rho r, 0$ and initial scale factor a_0. Using equation 7, Friedman equation can be rewritten as in case of negligible pressure as,

$$H^2 + \frac{kc^2}{a^2} = \frac{8\pi G}{3}(\rho_{m,0}\frac{a_0^3}{a^3} + \rho_{r,0}\frac{a_0^4}{a^4} + \rho_v) \tag{8}$$

It can be inferred from equation 8 that the density of vacuum does not have a dependency on the scale factor and so $w = -1$ for ρ_v. Since $P = w\rho c^2$, cosmological constant acts like a fluid with constant density and negative pressure. This negative pressure can be thought of as the driving force behind the accelerated expansion the universe undergoes.

1.5 Luminosity-redshift relation

One of the major challenges of cosmology is the measurement of distances. While nearby astronomical objects can be measured using relatively straight forward techniques like parallax, distances of objects of higher redshift from earth cannot be measured so easily. The distance becomes increasingly dependant on the global geometry as well as the energy densities when the scale increases. Presently the standard candle technique is used to measure distances of objects at higher redshifts. A standard candle is an astronomical object of near constant known intrinsic brightness(L). Then the flux(F) measured at a distance D from the standard candle can be calculated as:

$$F = \frac{L}{4\pi D^2} \tag{9}$$

For higher redshift distance between the objects(standard candle and observer) at the time the photon was emitted gets multiplied by the scale factor at the the time of detection(a_0) due to the expansion of the universe. When the photon emitted by the standard candle of wavelength λ_{em} gets stretched by a factor of $(1+z)$, thus the energy gets reduced by a factor of $(1+z)$ and thereby flux. Also the time interval in which emission happens gets dilated by a factor of $(1+z)$ which also need to be taken care of. Thus equation 9 gets modified as:

$$F = \frac{L}{4\pi a_0^2(1+z)^2 r^2} = \frac{L}{4\pi d_l^2} \tag{10}$$

A new quantity called luminosity distance d_l can be introduced which can be calculated from observations, since F is a known quantity and apparent luminosity F can be measured. For convenience the luminosity is measured in astronomy using a unit less number, magnitude which is defined as 2.5 times the negative logarithm(of base 10) of the luminosity. Thus the intrinsic brightness magnitude and the apparent brightness magnitude can be related as:

$$m - M = 5log_{10}d_l(in\,pc) + 25 \tag{11}$$

Luminosity distance depends on the energy densities as well as the geometry of the universe. It is possible to derive an expression that represents luminosity distance in terms of the measurable quantities(z) and the matter densities, which is:

$$d_l = \frac{(1+z)c}{H_0\sqrt{\Omega_\kappa}}\chi(\sqrt{\Omega_\kappa}\int_0^z \frac{1}{\sqrt{\Omega_M(1+z')^3 + \Omega_\Lambda + \Omega_\kappa(1+z')^2)}}dz') \tag{12}$$

The function $\chi(x)$ takes the form $sinh(x)$ for universe with negative curvature and $sin(x)$ for positive curvature. The value of Ω_κ is constrained by vacuum and matter densities as $\Omega_\kappa + \Omega_M + \Omega_\Lambda = 1$, for both positive and negative curvature models. The radiation density can be neglected as it has a considerably lesser influence on the luminosity distance compared to other components. For a universe with flat geometry, $\chi(x) = x$ and $\sqrt{\Omega_\kappa}$ is removed from the equation.
For lower redshift($z < 0.3$) equation 12 can be approximated by Taylor expansion and assuming that the value of $\ddot{a}$ vanishes. This leads to a very simple expression where luminosity distance is a linear function of the observed redshift.

$$d_l = \frac{cz}{H_0} \tag{13}$$

The apparent luminosity m is a function of redshift of the emitter and thus equation 11 gets modified for lower redshift as as:

$$m(z) - M = 5log(cz) - 5log(H_0) + 25 \tag{14}$$

2 Supernova cosmology

2.1 Type Ia supernova

Supernovae type Ia is formed by accretion of material from a neighbour donor or merger which leads to a thermonuclear explosion as it reaches Chandrasekhar limit [Fowler and Hoyle, 1960, Colgate and McKee, 1969, Arnett, 1979]. The progenitor of SN Ia can be a binary system of main sequence stars of which one becomes a white dwarf and the other a red giant. This is what is called a single degenerate progenitor model. In a doubly degenerate progenitor model both the mergers are white dwarfs. A technique to distinguish if a SN is created by a double degenerate progenitor or a single degenerate is yet to be developed. Luckily the progenitor model of a SN has little to no effect on the luminosity properties of a SN. The distinctive feature of SN Ia is the strong Silicon absorption spectra at 6355 angstroms and a near constant intrinsic brightness of about -19 magnitude. The peak brightness dispersion of these objects range from 0.1 to 0.6 magnitude after standardisation[Perlmutter et al., 1997]. This property of near constant intrinsic brightness is what makes SN-Ia an invaluable standard candle to astronomers.

It was proposed in 1979 by S.A Colgate that using SN Ia as a standard candle it is possible to find the deceleration parameter(q) [Colgate, 1979] and thereby the expansion history of the universe by observing SN Ia at various redshifts. The deceleration parameter can be expressed as a function of energy densities as:

$$q = \frac{1}{2}\sum_i (1+3w_i)\Omega_i \tag{15}$$

The current deceleration parameter(q_0) can be found from equation 15 as:

$$q_0 = \frac{\Omega_m}{2} - \Omega_\Lambda \tag{16}$$

Thus by evaluating the matter densities of the universe, it is possible to find the deceleration parameter which indicates if the universe is accelerating or decelerating. From the lower redshift SN it is possible to find the value of Hubble constant using equation 14.

2.2 Standardisation

The light curve(luminosity vs time plot) of every SN Ia follows the same template but the peak brightness is not constant. Although not constant the peak brightness dispersion is considerably less than other known standard candles(less than 1 mag). This can affect the distance measurement made using SN Ia as a standard candle. In 1993, a relationship between the peak brightness and the luminosity evolution of the supernovae was found by M.M Phillips [Phillips, 1993]. It was found that the luminosity decline of the supernovae in the 15 days after the peak brightness is achieved(Δm_{15}) will decide the peak brightness of that supernova. Many methods to correct this deviation were proposed[Phillips, 1993, Nugent et al., 1995, Branch et al., 1997] so that the SN Ia can be used as a better standard candle. In the discovery of dark energy by the SCP 'timescale stretch factor method' was used[Perlmutter et al., 1997]. The factor by which the light curve of a supernova need to be stretched in order to be fit a template curve is called stretch factor. A linear change in the peak luminosity of the supernova will be made by a monotonic function Δ of stretch factor(s) and thus the peak brightness can be standardised[Goobar, 2000].

$$m_{corrected} = m + \Delta(s) \tag{17}$$

Another aspect to be taken care of while using SN Ia as a standard candle to measure distance at higher redshift is K-correction. While making observation of an astronomical object we observe a particular part of the spectrum depending on various factors. The light reaching us from higher

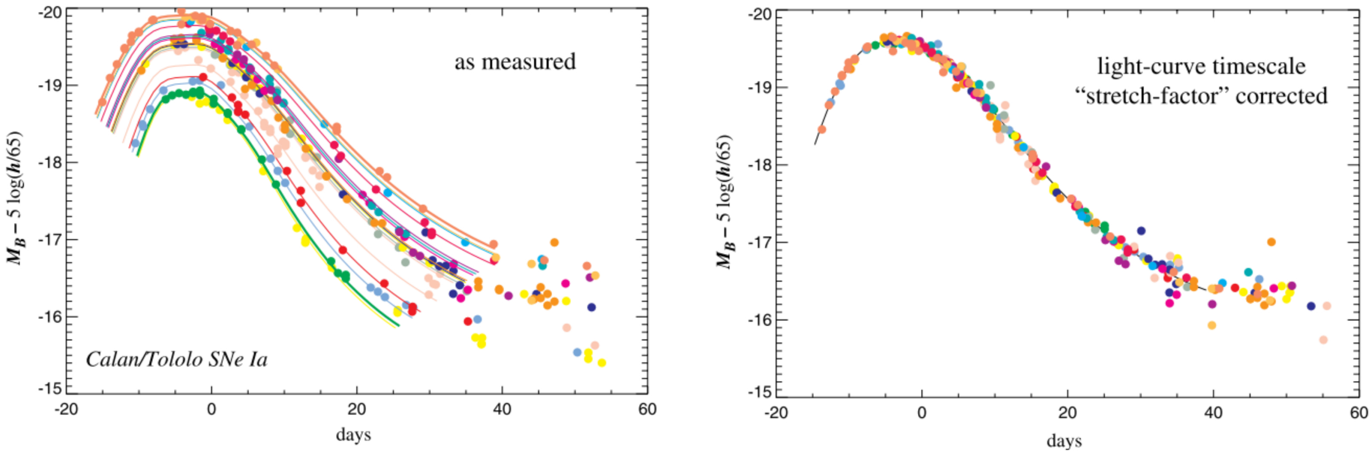

Figure 1: Measured light curves on the left and the light curves after stretch factor correction is applied on right.**Source:***[Kim, 2004]*

redshift can redshifted to an extent where the observation sometimes need to be made in a different band so as to maintain uniformity. This correction that needed to be done so as to standardise the observation is called K-correction. A SN Ia observation on which timescale stretch factor method is applied and K-corrected can be considered standardised.

3 Dark energy detection

3.1 SCP and High-Z SN Search Team

In 1999 two teams, Supernova Cosmology Project(SCP)[Perlmutter et al., 1999] and High-Z Supernova Search Team[Riess et al., 1998] independently found evidence for an accelerated expansion of the universe by observing high redshift SN. The high redshift SN was used as a standard candle and deceleration parameter was calculated using the methods proposed by Colgate[Colgate, 1979]. The calculated value of deceleration parameter was a negative number indicating accelerated expansion, contrary to the popular belief at the time that the expansion of the universe was slowing down. This acceleration of the expansion could be explained by the existence of dark energy, which can be thought of as a driving force for the expansion.

The techniques used by SCP and High-Z team were devised decades before the actual experiment took place, but the technology needed for the experiment did not exist until then. The development of charge-coupled device(CCD) and Hubble space telescope made this experiment possible. Another hurdle was the unpredictability of SN occurrence. A SN is a glorified explosion in space and because of the lack of information on the event, it is impossible to predict it's occurrence. The best observation of a SN until SCP and High-Z, was of a SN at redshift 0.31 by a search team in Chile[Nørgaard-Nielsen et al., 1989], several days after it's peak passed.

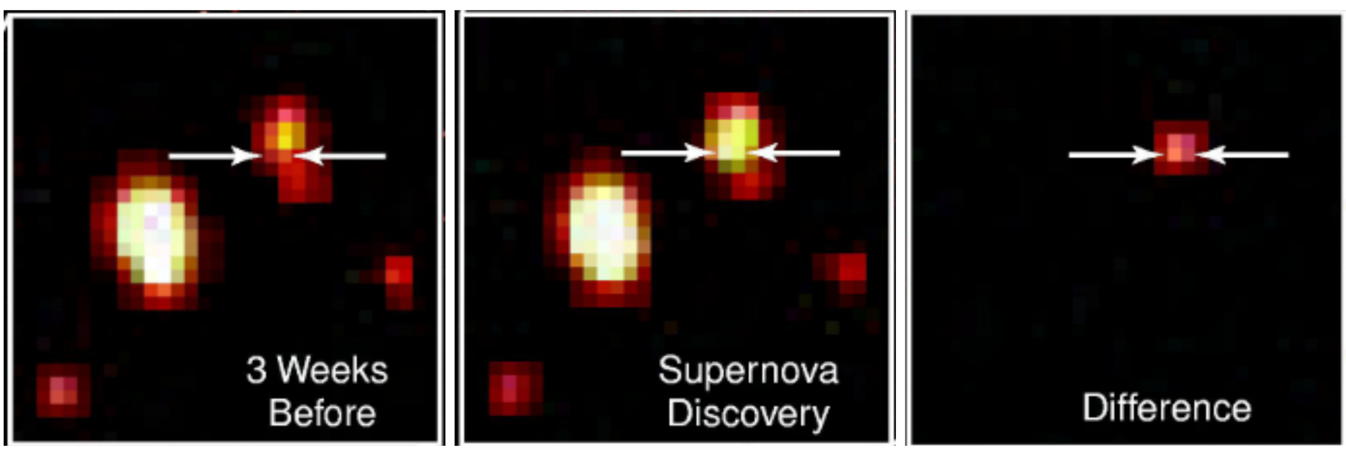

Figure 2: Detection of SN-Ia using batch analysis. Source: [International Journal of Modern Physics, 2000]

To tackle this problem Supernova Cosmology Project team came up with a batch analysis approach[Perlmutter et al., 1997]. A large patch of sky containing thousands of galaxies(more galaxies imply more probability of finding a SN) were observed in a period of three weeks. A SN created during this time period will not reach the peak brightness, but will be bright enough to be observed. So by comparing the two slides of the same patch of the sky at different times the exact location of SN, which is moving towards the peak brightness, can be found. Then by observing the SN directly using HST the brightness is measured. Figure(2) shows a small patch of sky where a SN was formed over the period of three weeks.

Measurement of the mass-energy budget of the universe

The primary aim of SCP and High-Z team was to measure two quantities, Hubble constant(H_0)and deceleration parameter(q_0). A rough image of the evolution of the universe can be obtained from these quantities. The expansion rate of the universe can be given by H_0, which can be measured using equation(14). The intrinsic magnitude and redshift are observable quantities and the rest are constants in 14 and so by observing lower redshift SN, H_0 can be calculated.

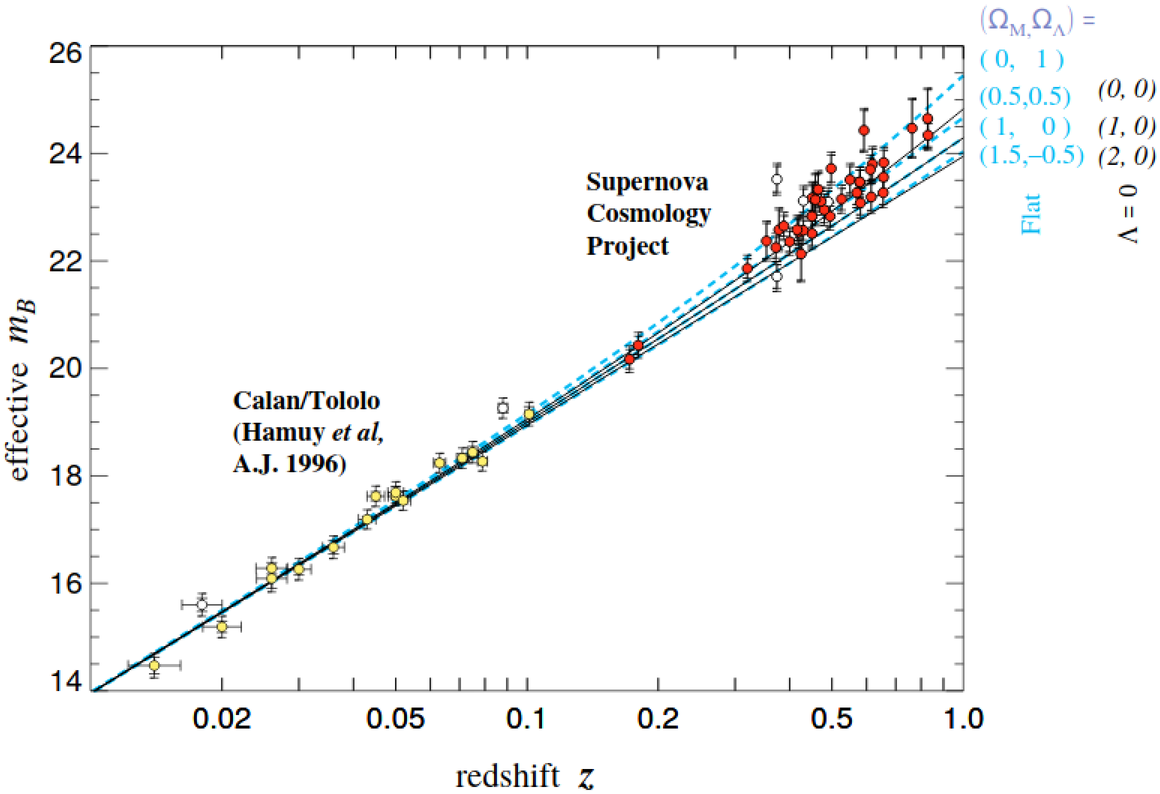

Figure 3: The observed data fits with the cosmological model with $\Omega_M \sim 0.7$ and $\Omega_\Lambda \sim 0.3$.**Source:***[**Perlmutter et al., 1999**]]*

The reason for observing higher redshift SN was to measure the deceleration parameter(q_0). The value of deceleration parameter is given by equation(15) and can be seen that it depends directly on the energy densities. The present value of deceleration parameter(q_0) will be positive if the universe was composed only of baryonic matter and radiation. From equation(16), it can be seen that the presence of dark energy can result in the value of q_0 being negative. Thus an informed knowledge of the energy-matter budget is essential in understanding the dynamics of the universe.

Using HST, SCP and High-Z team was able to measure the redshift and intrinsic brightness of SN. But the approximation 13 cannot be used for higher redshift and so 12 needs to be used to calculate the luminosity distance. To eliminate the Hubble constant dependence, equation(9) is rewritten using $\mathcal{D} = H_0 d_l$.

$$\begin{aligned} m(z) &= M + 5log\mathcal{D}(z; \Omega_M, \Omega_\Lambda) - 5logH_0 + 25 \\ &= \mathcal{M} + 5log\mathcal{D}(z; \Omega_M, \Omega_\Lambda) \end{aligned} \tag{18}$$

$\mathcal{M} = M - 5logH_0 + 35$, is a parameter independent measurable quantity which can be obtained from the observation of low redshift SN. The standard candle equation18 is parameterised by Ω_M and Ω_{Lambda}. By measuring the redshift(z) and apparent brightness(m) and using curve fitting techniques, an estimate of Ω_M and Ω_Λ can be made. From 12, it is clear that the geometry of the universe has a huge impact on the luminosity distance as χ takes different forms in different geometries. Since the cosmic microwave background observations point towards a flat geometry, the SN experiment too take flat geometry into account.

4 Hubble constant

The SCP and High-Z team have measured the Hubble constant using SN of lower redshift. Instead of using the approximate equation 14, by using the exact equation 11(radiation pressure neglected) and curve fitting techniques a better estimate of Hubble constant can be obtained. Since a fairly good idea of the geometry of the universe is available from cosmic microwave background measurements form PLANCK[Planck et al., 2018], this fitting is possible now. The project SHOES was launched with this purpose of measurement of Hubble constant using SN of higher and lower redshift. The SHOES project is led by Adam Riess who also led the High-Z team to the detection of dark energy.

4.1 CMB

The cosmic microwave background is the remnant radiation of the big bang. It is highly isotropic in temperature and has the spectrum of a perfect black body. But the radiation contains anisotropy of the order or $10^{-3}K$. By analysing this anisotropy, the cosmological parameters can be extracted. Consider a temperature variation ΔT in the direction Φ, then the angular correlation with a direction $\Phi + \theta$ is given as:

$$C(\theta) = \left\langle \frac{\Delta T}{t}(\Phi) . \frac{\Delta T}{T}(\Phi + \theta) \right\rangle \tag{19}$$

The function is averaged for all possible Φ and for all possible θ around Φ[Choudhuri, 2010]. The correlation function can then be expanded using Legendre polynomials as:

$$C(\theta) = \sum_l \frac{2l+1}{4\pi} C_l P_l(cos\ \theta) \tag{20}$$

The Legendre coefficient C_l versus l plot gives us the power spectrum of the cmb. The nature of the power spectrum varies with the cosmological principles. WMAP and Planck are space probes launched to collect more data from the CMB. The initial parameter estimations made from the WMAP(launched in 2001) data was heavily improved by the data collected by Planck(2009). The current best estimate of Hubble constant made from CMB is $67.36 \pm 0.54 km\ sec^{-1}\ Mpc^{-1}$[Planck et al., 2018].

4.2 Hubble tension

A universe filled with cold dark matter and having a non-vanishing cosmological constant is the widely accepted cosmological model today. The global geometry of the universe is believed to be flat from the CMB experiments. This will cause the curvature density to vanish and the constraining equation of the components becomes:

$$\Omega_\Lambda + \Omega_M = 1 \tag{21}$$

The dark energy density becomes a derivative in the ΛCDM model and the free parameters left in the equation 12 will be H_0 and Ω_M. So a precise estimation of Hubble constant is not just a necessity to understand the expansion of the universe, but also the density of the components.

The value of Hubble constant can be measured independently from the CMB experiments as well as from SN. The value measured from CMB has been improving it's precision with time, but it always seems to be around $67 km\ sec^{-1}\ Mpc^{-1}$. This is in disagreement with the value of H_0 measured from the SN experiments. The best fit value obtained by SHOES in 2016 is $73.24 \pm 1.74\ km\ sec^{-1}\ Mpc^{-1}$[Riess et al., 2016]. This is about 3σ higher that the value calculated from the CMB experiment. This may seem like an insignificant dicrepancy, but the slight variation in H_0 can cause variation in the matter densities, which can cause huge difference in the evolutionary fate of the universe.

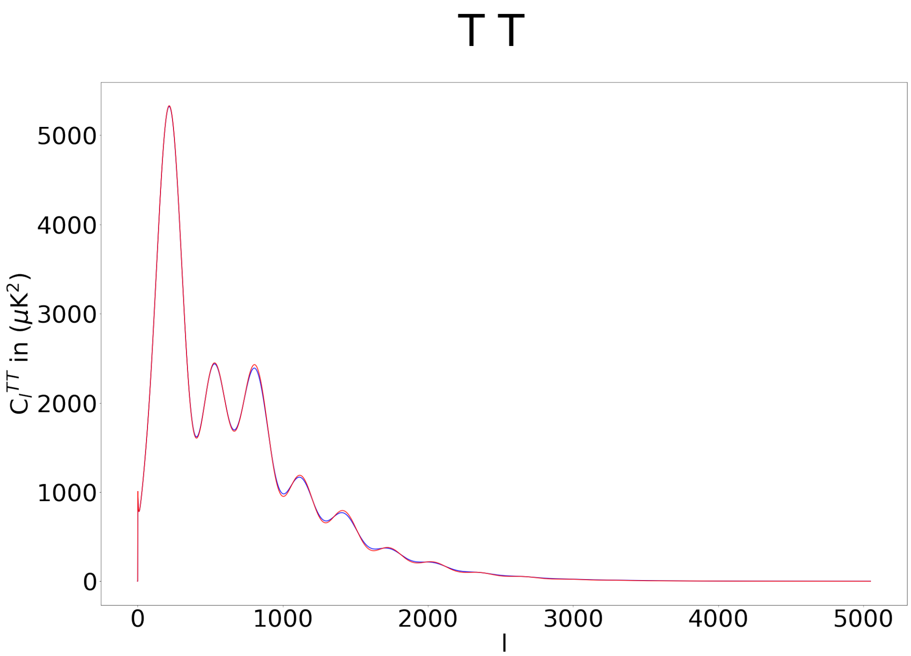

Figure 4: CMB Power spectra plotted using CLASS[Blas et al., 2011]

The value of Hubble constant measured is highly model dependant, as the constraint equation 21 varies with the cosmological model. Thus a reason for the Hubble tension could be a systematic error in the experiment or a flaw in the cosmological model.

5 Luminosity evolution[Kang et al., 2020]

The search for a true "standard" candle has been one of the major the challenges in the field of observational cosmology. The assumption that the intrinsic brightness of the standard candle will remain constant is very often questioned. It was Beatrice Tinsley who first pointed out this luminosity evolution standard candles[Tinsley, 1968] used by Allan Sandage, who first calculated a reasonably accurate value of Hubble constant, need to be taken care of. She proved conclusively that higher redshift galaxies will not have the same intrinsic brightness as lower redshift galaxies, and so the standard candles need to be further calibrated to accommodate this luminosity evolution. The evidence of accelerated expansion was given by SCP and High-Z team by measuring the luminosity distance to high redshift SN. But, if this measurement is affected by the host properties of the SN, that is if the standardised luminosity of all SN-Ia is not constant, then the experiment needs to be further caliberated.

A correlation of Supernova-Ia luminosity with host mass[Sullivan et al., 2010, Kelly et al., 2010], host morphology[Hicken et al., 2009] and star formation rate(SFR) [Rigault et al., 2018] were established in the last two decades. Recently [Kang et al., 2020] found a correlation of population age with the SN standardised brightness. By establishing correlations between the population age and the other host properties(mass, morphology and SFR), [Kang et al., 2020] was able to claim that mass-luminosity correlation, morphology-luminosity correlation and SFR-luminosity correlation are likely caused due to the age-luminosity correlation.

5.1 Population age and metallicity

To verify if the standardised brightness of SN-Ia is correlated to population age project YONSEI(YOnsei Near Supenova Evolution Investigation) was launched. To verify the correlation between population age and SN luminosity early type galaxies of lower redshift($0.01 < z < 0.08$) were chosen from the YONSEI catalog[Kim et al., 2015]. The target galaxies were of early type (E-S0) because reliable age dating techniques has been developed for them and have a very low dust extinction[Gallagher et al., 2008]. Since the target galaxies are of lower redshift, the geometry of the universe is irrelevant, to this particular experiment. Since the properties of the central region of a galaxy is more studied and accounted for than the edges, the target galaxies were chosen such that the SN is located at the central region. This is important in an experiment to check the environmental effects on a SN. A total of 32 galaxies satisfying these criteria were studied by [Kang et al., 2020] to study the population age-luminosity correlation of SN-Ia.

An older galaxy will have very different photometric properties than that of an older one. This is because as galaxies get older the stars in the galaxy too will get older and this result in the galaxy having a very different composition to that of a younger galaxy. A younger galaxy will have more region of star formation, which is visible in the spectrum of the galaxy. So by studying the spectrum of a galaxy, an approximate age of the galaxy can be obtained. [Kang et al., 2020] has used absorption lines for age calculation, since they are very strong in early type galaxies. Early type galaxies with recent episodes of star formation can have strong emission lines in the spectra which can lead to ambiguity in the age determination. Such galaxies were omitted from the experiment by YONSEI team in the experiment. The major drawback of spectrophotometric technique for age determination is the age-metallicity degeneracy[Worthey, 1994]. The ageing of population will have a similar spectra with a similar galaxy of higher metallicity. Worthey's 3/2 rule states that the increase in the population age by a factor of three will have similar effect on the spectrum of the galaxy to that of an increase in the metallicity of the galaxy by a factor of two. To study the population age dependence of SN luminosity, this degeneracy has to be broken.

The age-metallicity degeneracy can be broken by carefully analysing the H-R diagram. An H-R diagram is a luminosity versus temperature scatter plot of a population. The luminosity and temperature of a normal star is linear and will fall in the "main sequence" in the H-R diagram. But the older stars of the population will be either a red super giant or a white dwarf in the H-R diagram. The red giants will have a very high luminosity but a lower temperature whereas the white dwarf will have very low luminosity but high temperature. As the population gets older more and more stars from the main sequence will move towards the red giant region in the H-R diagram. Thus the main sequence will have a point where it slowly deviates into the red giant branch, which is called "turnoff point". A older population age will have a redder H-R diagram and so will a population with higher metallicity. But the turnoff point of the H-R diagram is only sensitive to the age of the population. A younger population will have a longer main sequence and the turn off will be near the high temperature region. A high metallicity will redden the whole sequence but the turnoff point will remain unaffected. So by observing a spectra that is highly sensitive to the turnoff point stars, the degeneracy can be broken.

It has already been established that the non-standardised peak brightness of SN-Ia depends on the stretch factor[Phillips, 1993]. A strong correlation between the stretch factor and population age has already been found[Johansson et al., 2013, Sullivan et al., 2010, Sullivan et al., 2010, Suzuki et al., 2012]. But standardised luminosity of SN-Ia is taken into account in the standard candle tests and so a reliable correlation between standardised luminosity and age needs to be established to consider this luminosity evolution to have an effect on the standard candle tests. In the study done by YONSEI, a correlation between the standardised peak luminosity and population age is established with 99.5% confidence. This correlation is made using the sample that has been carefully chosen fulfilling all the previously mentioned criteria. Including early type galaxies with emission lines due to the star formation can bring the confidence level lower. A dependency of standardised brightness on metallicity of the host was written off since no meaningful correlation between them was found by[Kang et al., 2020].

The correlation between population age and standardised luminosity found by the luminosity is that a younger host will have a fainter SN-Ia. The difference in standardised luminosity of a Supernova-Ia caused by an age difference of 1Gyr of the host is 0.051mag[Kang et al., 2020].

5.2 Morphology

A classification scheme for galaxies based on morphology was first proposed by Hubble. This scheme is considered too vague nowadays but the basic idea remains the same. The galaxies were classified mainly into two: elliptical and spiral galaxies, where the spiral galaxies were further classified into barred and unbarred. Because the classification scheme is often represented in the shape of tuning fork, it is known as Hubble tuning fork diagram5.2. The original assumption made by Hubble in proposing this model was that the evolution of galaxies took place from left to right in the tuning fork5.2. So the elliptical galaxies were known as early type galaxies and the arms of the tuning fork was known as late type galaxies.

A correlation between the host galaxy morphology and the SN luminosity was ruled out by SCP. They tested the dependence of SN luminosity on host morphology and concluded that there was no significant correlation. But a test with a much bigger sample done by [Hicken et al., 2009] proves that a SN-Ia in Scd/Sd/Irr(late type) galaxies are intrinsically fainter(after standardisation) than SN-Ia with E/S0(early type) hosts. The SN in late type galaxies were found to be 0.14 magnitude fainter than the ones in late type galaxies. A similar result was also reported by [Suzuki et al., 2012] where a dimming of SN in early type galaxies was found. Recent observations made by [Scott et al., 2017] found that the stellar population in an early type galaxy is 4Gyr older than the population in late type galaxies. If the morphology-luminosity correlation is converted into age-luminosity correlation, a 0.14mag difference per 4Gyr is calculated. This matches very well with the observation made by [Kang et al., 2020].

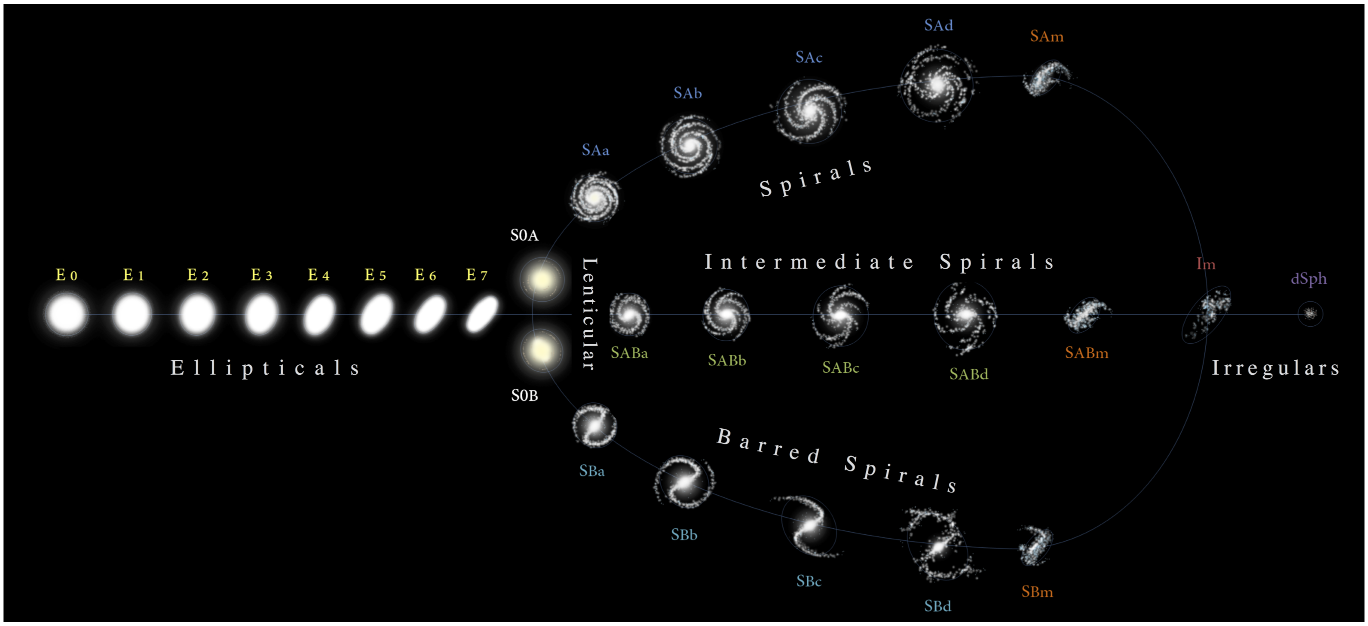

Figure 5: Hubble tuning fork classification scheme. **Source**:*[Ciccolella and Leo, 2020]*

5.3 Mass

To check whether a correlation between host mass and SN-Ia luminosity exists, the mass of the host need to be measured. But technique to directly measure the mass of galaxy is not yet developed. So velocity dispersion is used as a proxy for the mass measurement in astronomy. The velocity dispersion(σ) of a galaxy is a statistical measure of the deviation of velocity of individual particles(stars) from the mean velocity of the galaxy. This velocity dispersion can be related to the mass of the galaxy(M) and radius(R) using Virial theorem.

$$\frac{GM}{R} \approx \sigma^2 \tag{22}$$

A correlation between the host mass and SN-Ia standardised brightness was found by [Sullivan et al., 2010, Kelly et al., 2010]. They found that a less massive host will cause the SN to be fainter. A SN in a host that is about ten times massive will have the luminosity 0.08mag brighter. The mass of progenitor will have a direct impact on the properties of the SN, but the host galaxy mass will not. A result published by YONSEI team in 2016, has proved that the mass and age of a galaxy are correlated[Kang et al., 2016]. Younger galaxies were found to be less massive than older ones. By mean a galaxy that is ten times massive will be 2Gyr older[Kang et al., 2016]. This correlation was found for non-host galaxies. But there is no reason that this will not hold for host galaxies too and so a correlation between host galaxy mass and age can be established. So by converting the luminosity difference in terms of mass to luminosity difference in terms of age, a host which is 2Gyr younger will cause the SN-Ia to be 0.08mag fainter[Kang et al., 2020].

5.4 Star formation rate

Star formation rate(SFR) is the total mass of star formed over unit time over an area. The SFR of a galaxy is usually measured in solar masses per year. The SFR of a galaxy plays a major role in deciding the evolution and fate of the galaxy. Observing the galactic spectrum in the region where the newborn stars are prominent is how the SFR is usually measured. This region of observation is not the same for all types of galaxies. So by carefully choosing the region of spectrum to be observed according to the type of galaxy, SFR can be measured within a reasonable confidence interval.

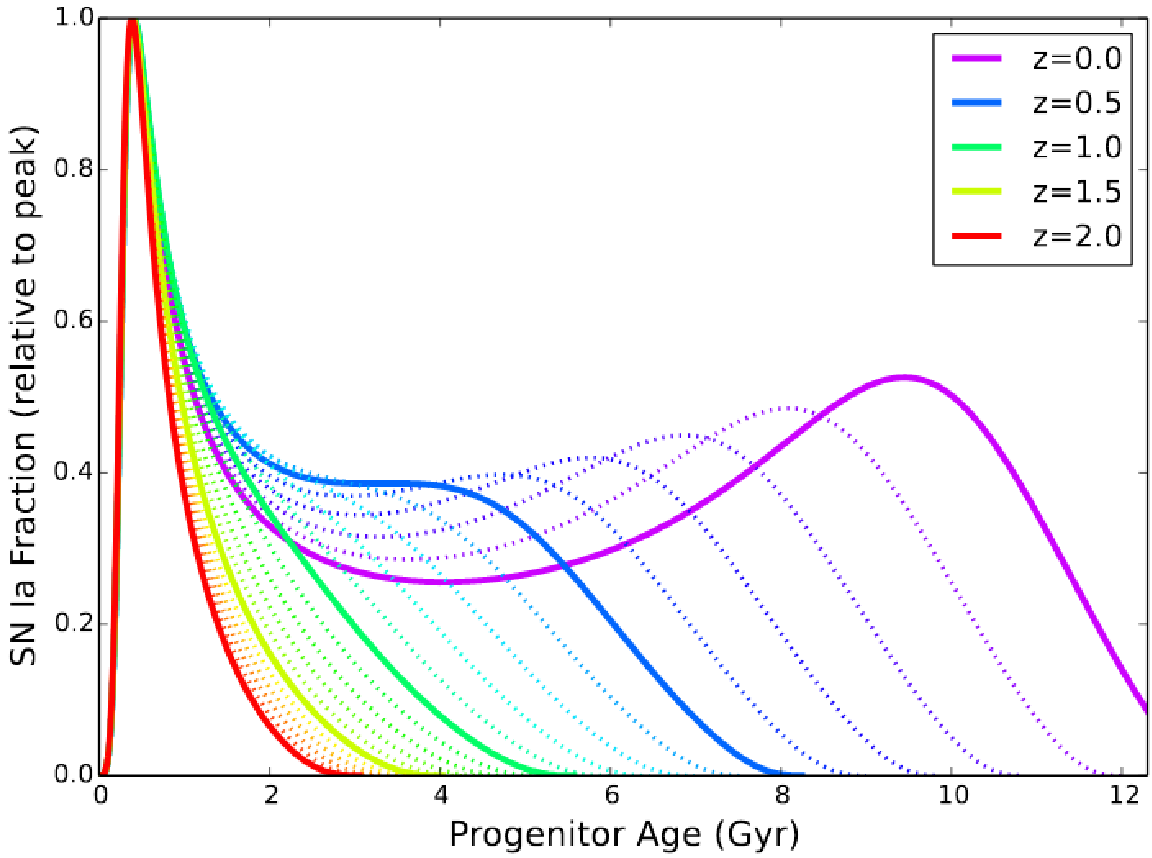

Figure 6: SN progenitor age distribution over varying redshifts. **Source**:*[Childress et al., 2014]*

A correlation between local SFR and SN-Ia standardised luminosity was found by [Rigault et al., 2018]. The SFR of a region of radius 1kpc from the SN-Ia was measured. The SN in a region with higher local SFR was found to be 0.16mag fainter than an SN in a region with higher local SFR[Rigault et al., 2018]. By studying the population age of galaxies with different SFR[Galbany et al., 2014], it was found that the mean age of low SFR galaxy is 0.6Gyr and high SFR galaxy is 3.1Gyr. An age difference of 2.5Gyr exists between the region of high SFR and low SFR. [Rigault et al., 2018] suggested that the variation of luminosity due to local SFR is likely caused by the proportion of younger and older stars in the region. [Kang et al., 2020] calculated that the luminosity SFR correlation can be converted into SN-Ia standardised luminosity-age correlation as a difference of 0.16mag corresponding to a 2.5Gyr age difference.

5.5 Population age variation with redshift

The variation of SN-Ia progenitor age over redshift has been extensively studied by [Childress et al., 2014]. The distribution of progenitor age over varying redshifts as modelled by [Childress et al., 2014] is shown in figure(5.4). It is well established that the early universe consisted only of younger population while the current universe consists of both of younger and older population. The progenitor age distribution derived by [Childress et al., 2014] agrees with this observation and it can be seen that at lower redshift there are two peaks corresponding to young and old population, whereas at higher higher redshift there is only one peak. The median age of the progenitor as calculated by [Kang et al., 2020] using the model described by[Childress et al., 2014] is 6.54Gyr at z=0 and 1.25Gyr at z=1. So a difference in the median age of 5.3Gyr can be found between SN progenitor at z=0 and z=1.

6 Conclusion

6.1 Dark energy

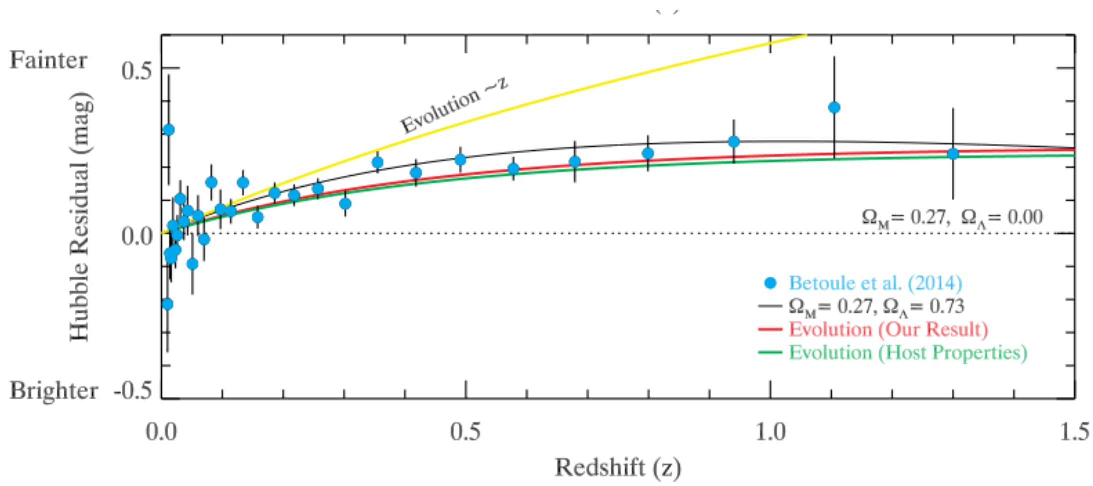

Figure 7: The black solid line is the model used in discovery of dark energy and the red and green curves are the luminosity evolution plots. **Source:*[Kang et al., 2020]***

The standardised intrinsic brightness of SN-Ia is assumed to be constant over the cosmic time in dark energy detection experiment conducted by SCP and High-Z SN Search team. Even though luminosity evolution of SN due to varying host mass, SFR and morphology was observed, none of this variation could be related to the redshift. But the population age-luminosity correlation of SN-Ia found by [Kang et al., 2020] has an impact on the dark energy detection experiment as the luminosity evolution can be associated with redshift. By being able to associate the luminosity correlations with other properties(mass,morphology and SFR) to the luminosity-age correlation, [Kang et al., 2020] is able to build a strong case to check into the calibration of SN-Ia as standard candles. The previous observations made by [Rigault et al., 2018],[Sullivan et al., 2010] and [Hicken et al., 2009] converted into population age correlation is listed below.

Property	Reference	Change in luminosity/5.3Gyr
Host mass	[Sullivan et al., 2010]	0.21mag
Host morphology	[Hicken et al., 2009]	0.19mag
Local SFR	[Rigault et al., 2018]	0.34mag
Population age	[Kang et al., 2020]	0.27mag

Source:[Kang et al., 2020]

The change in luminosity detected by the four observations when converted into the age correlation has a standard deviation of σ=0.05. This is remarkable since the luminosity evolution was detected in four different experiments with different samples. The luminosity evolution over redshift found by [Kang et al., 2020] can mimic the effect of dark energy found from the SN-Ia observations. This can observed from 6.1, as the dark energy model(black) is very similar to the luminosity evolution calibrated plots(red and green).

6.2 Hubble constant

The Hubble constant measurement too will be affected by the SN luminosity evolution. A parameter estimate made by applying improved photometric calibration has estimated Hubble constant to

70 $km\ sec^{-1}\ Mpc^{-1}$[Betoule et al., 2014]. Thus the systematic error in the SN measurements can affect the estimates considerably. The luminosity evolution proposed by [Kang et al., 2020] needs to be considered in the estimation of Hubble constant from SN and this could possibly be the systematic error that cause the Hubble tension.

In a non accelerated universe modelled by [Tutusaus et al., 2019] where the SN luminosity evolves with redshift, the Hubble constant was found to be 62 $km\ sec^{-1}\ Mpc^{-1}$. The luminosity evolution model used by [Tutusaus et al., 2019] was, $\Delta m = \varepsilon z^{\delta}, \delta \in [0.2, 2]$. A linear evolution of intrinsic brightness as proposed by [Kang et al., 2020] will not solve the Hubble tension, as this possibility is already explored by [Tutusaus et al., 2019]. But the linear evolution was proposed using a sample of only 32 SN. Using a much bigger sample and by finding out the exact luminosity evolution nature of the Sn intrinsic brightness an improved Hubble constant estimate can be made. It is possible to model a non-accelerated universe with all the parameters being fitted properly except for Hubble constant. But anomaly arises due to the evolution model adopted, which was theoretical. By being able to model a better evolution model for SN luminosity which also agrees with the observational results, this anomaly can be resolved. So, with further investigation of the SN luminosity evolution the Hubble tension could be possibly solved.

The supernova luminosity evolution results made by [Kang et al., 2020] demands need for further understanding of the SN cosmology and improvement in the calibration methods.

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