UNIVERSITY OF SCIENCE AND TECHNOLOGY OF HANOI
DEPARTMENT OF SPACE AND APPLICATIONS

FINAL REPORT
BACHELOR GRADUATION

By:
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Project:

USING LOCALIZED FAST RADIO BURSTS TO CONSTRAIN DARK ENERGY PARAMETER WITH BETTER HOST GALAXY DISPERSION MEASURES ESTIMATION

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LIST OF ABBREVIATIONS

FRB	Fast Radio Burst
DM	Dispersion Measure
CHIME	Canadian Hydrogen Intensity Mapping Experiment
ΛCDM	Lambda Cold Dark Matter
IGM	Intergalactic Medium
MW	Milky Way
PDF	Probability Density Function

LIST OF FIGURES

Figure 1.1 Time vs. Frequency plot (dynamic spectrum) of the first FRB detection by Parkes Observatory's multibeam receiver. This image was enhanced and in the resolution added in the color by the authors of this research [1], the original of this image was in another research in 2007 by Lorimer et al. [2]. The frequency-dependent delay in arrival time of the signal due to the column density of free electrons in the propagatin path, called Dispersion Measure (DM) is shown by the quadratic sweep. The saturation of the receiver for this beam is evident by the flat-topped signal across the band. The flux density of this burst was ~ 30 Jy. with a DM of $375\,\mathrm{pc\,cm^{-3}}$. Only one eighth of this DM is accounted for, in this direction, by the Milky Way, suggesting an extragalactic origin. **Credit:** M. Caleb, E. Keane[1] 2

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Figure 1.3 All-sky distribution of FRBs detected by various telescopes across the world at the time this figure was made (2021[1]). The galactic electron density[3] is shown in the background. The FRBs are denoted by red circles and follow the same color scale as the background Any given FRB is observed to have a DM in excess of the galactic contribution. The distribution of FRBs is almost isotropic. Any biases in the spatial distribution are likely due to differences in various survey depths and sky coverage.[1] **Credit:** Laura Driessen 4

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ABSTRACT

Fast Radio Burts (FRBs) are brief, intense bursts of radio wave emissions that originate from the distant Universe, typically lasting only a few miliseconds. FRBs have enormously large Dispersion Measures (DMs).

Recently, a new research[4] suggested that the preference for evolving dark energy over a cosmological constant is over 4σ with the inclusion of Type Ia supernova data, hence, the confirmation of the presence of dark energy inside our Universe is stronger than ever before. Nevertheless, the nature of this mysterious energy is still one of the most significant unsolved question in Astronomy. For that reason, I propose a new method for constraining the dark energy parameter W_a in the well-known ΛCDM model using a mock data generated based on the CHIME/FRB catalogue 1[5]. I will also utilize the scattering time to provide a better measurement of the DM from the host galaxy. This research is based on an earlier work of Yang et al. 2025[6].

Please note that since this is an ongoing scientific research, a final result will not be included in this thesis as the research is still going on. If there are any updates on the result, I will present it on the graduation defense day.

Keywords. Cosmology - Extragalactic Transients - Scattering Time - Dark Energy - Inferring Parameters - Data Analysis

1 CHAPTER 1. INTRODUCTION

FRBs are one of the most intriguing phenomena in the astrophysics. In 2007, the first FRB was discovered by Lorimer et al.[2], since then our many more FRBs have been detected by many telescopes on the world. Our understanding about FRBs has also been built upon rapidly. One of the characteristics of FRBs is their extremely high dispersion measure, and they often "flash" for only a few milliseconds which posting quiet a challenge for astronomers to observe them as they can be mistaken as noise especially in the realm of radio frequency. FRBs primarily emit radio waves, however, their frequency spectrum can vary. They are mostly detected in the frequency range of 400 MHz to 8 GHz, but they can have frequency below or higher. CHIME telescope, for example, primarily observes the lower end of this range focusing on 400 MHz and 800 MHz. Meanwhile, other telescopes like Parkes and Arecibo have observed FRBs in higher frequency range, up to 3 GHz and 10 GHz. The frequency spectrum of FRBs can be used to derive their DM, which is the delay between the arrival times of different frequencies. This delay is caused by the ionized gas in the host galaxy of the FRB, the intergalactic medium (IGM) and the Milky Way, and it allows scientists to estimate the distance of the source and the amount of ionized material along the line of sight.

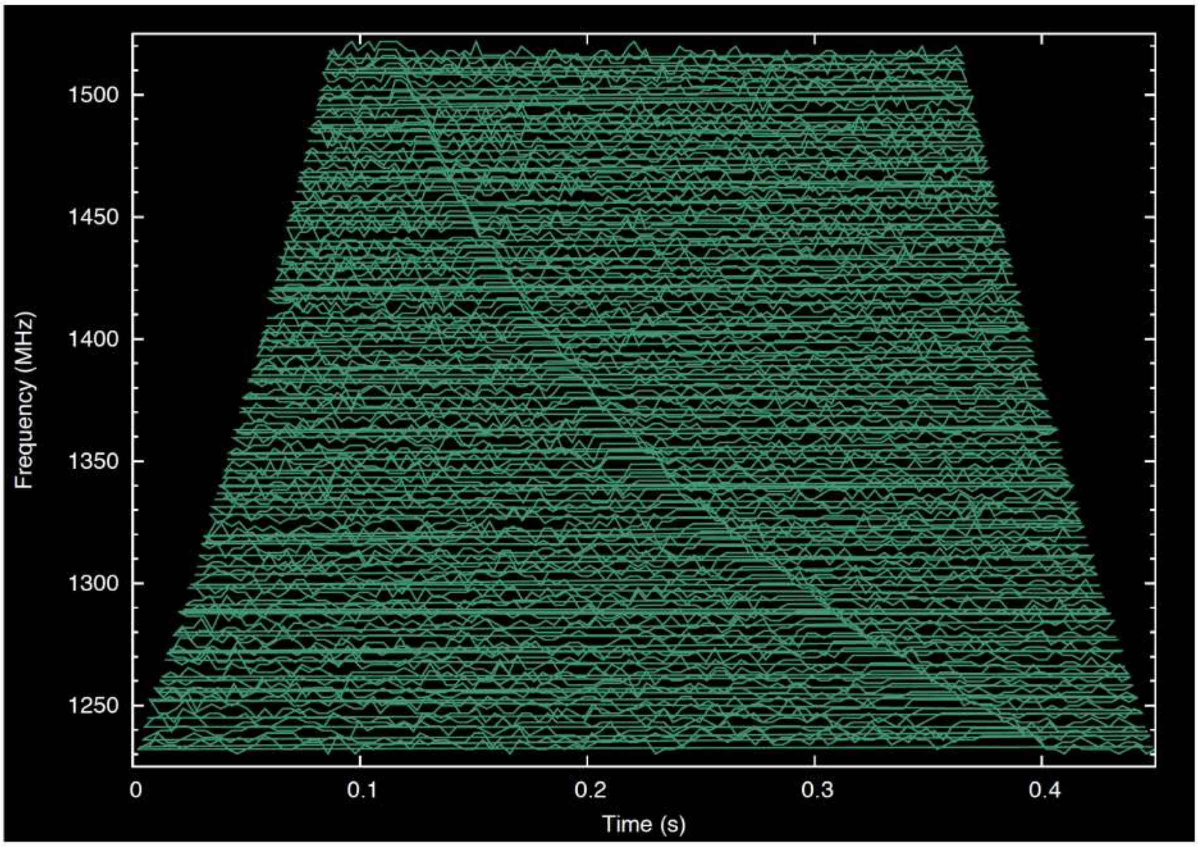

FIGURE 1.1: Time vs. Frequency plot (dynamic spectrum) of the first FRB detection by Parkes Observatory's multibeam receiver. This image was enhanced and in the resolution added in the color by the authors of this research [1], the original of this image was in another research in 2007 by Lorimer et al. [2]. The frequency-dependent delay in arrival time of the signal due to the column density of free electrons in the propagatin path, called Dispersion Measure (DM) is shown by the quadratic sweep. The saturation of the receiver for this beam is evident by the flat-topped signal across the band. The flux density of this burst was ~ 30 Jy. with a DM of $375\,\mathrm{pc\,cm}^{-3}$. Only one eighth of this DM is accounted for, in this direction, by the Milky Way, suggesting an extragalactic origin. **Credit:** M. Caleb, E. Keane[1]

The DMs of FRB are distributed by three factors. The DM_{IGM} is the dispersion measure contributed by the intergalactic medium. The DM_{MW} is the dispersion measure come from the Milky Way galaxy, NE2001[7] and YMW16[3] are two models which are heavily well-known for its description of the galactic electron density distribution. Finally, the DM_{host} is not only the most mysterious but also the hardest one to analyze as it is extremely hard for us to observe as well as recognize the distant progenitors of FRBs. Contrary to its mystery, localizing FRB means to pinpointing the progenitor of that FRB is very important as knowing the contribution of DM_{host} in the dispersion measure function of a FRB.

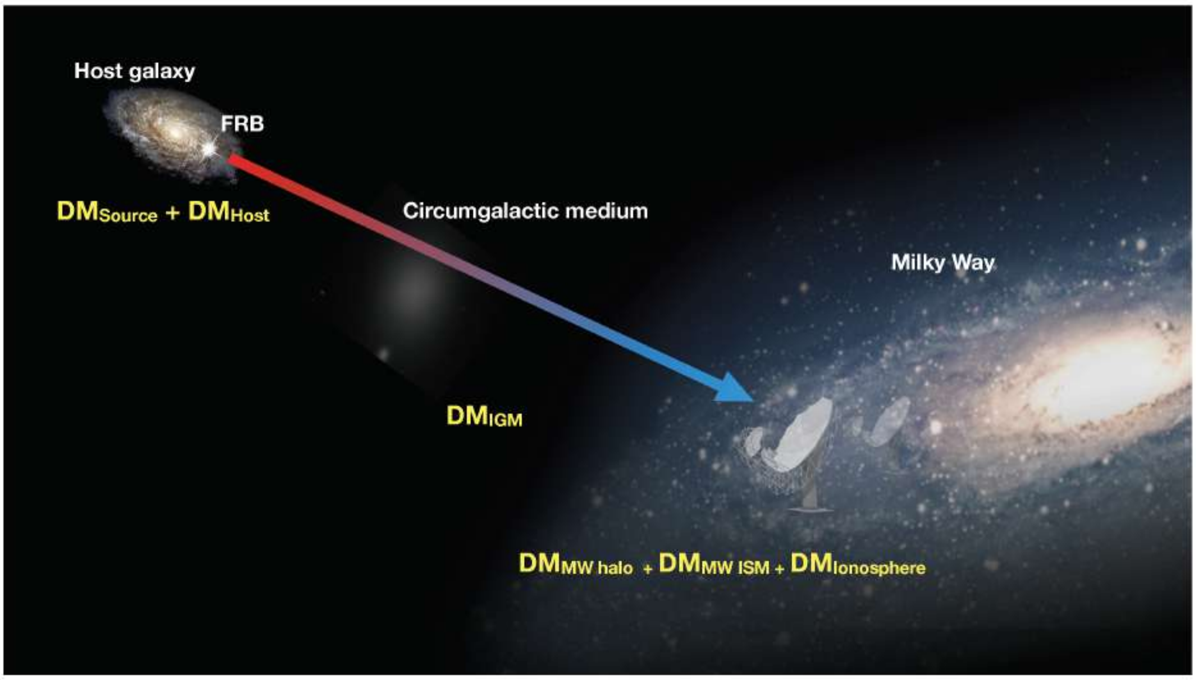

FIGURE 1.2: This image depicts the DM contribution of FRB. We can see that there are 6 factors contribute to the DM of FRB. However, normally astrophysicists will combine that factors into only 3 factors which is $\mathrm{DM}_{host}, \mathrm{DM}_{IGM}, \mathrm{DM}_{MW}$ **Credit:** M. Caleb, E. Keane[1]

The scattering time τ refers to the timescale over which the radio signal is temporarily broadened due to propagation through plasma. The scattering time becomes longer as the radio pulse propagates through larger amount of plasma making the tail of the signal easier to be recognized. The scattering time from the IGM and MW is minimal[8]. Therefore, Yang et al. 2025 assumed that scattering only occurs within host galaxies[6]. In fact, the scattering time contains valuable information on the DM_{host} and it is proportional to the square of DM_{host}.This is a novel discovery as it could propose an aspect of measuring the dark energy parameter.

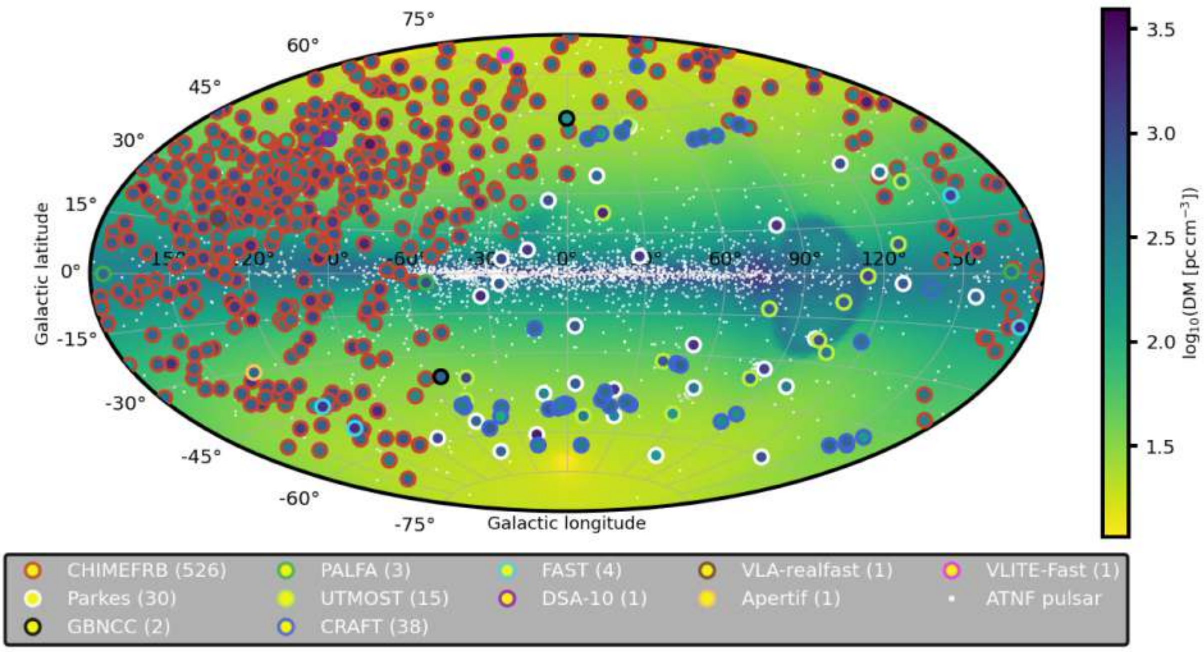

FIGURE 1.3: All-sky distribution of FRBs detected by various telescopes across the world at the time this figure was made (2021[1]). The galactic electron density[3] is shown in the background. The FRBs are denoted by red circles and follow the same color scale as the background Any given FRB is observed to have a DM in excess of the galactic contribution. The distribution of FRBs is almost isotropic. Any biases in the spatial distribution are likely due to differences in various survey depths and sky coverage.[1] **Credit:** Laura Driessen

This is the order of this thesis: chapter 2 is for the method and data, where I will introduce the method and the data I adopted for this research; chapter 3 will be for the results; chapter 4 will be the discussion and future work for this project.

2 CHAPTER 2: METHOD AND DATA

I will provide the method that I adopted from Yang et al. 2025[6] to constrain the w_a using both DM and scattering time. The scattering τ was used to measure the PDF of DM$_{host}$. The PDF of DM$_{host}$ is described as a function of DM$_{host}$ and $A_\tau \tilde{F} G$ where $A_\tau \tilde{F} G$ is a parameter that I will explain later in this paper. The integration of the PDF over all possible ranges of two parameters was computed as a function of redshift, hence adopted the PDF of redshift. By deriving the 50th percentile of the PDF of redshift, I derived the redshift (z_{model}) from two parameters DM$_{host}$ and τ. Finally, z_{model} can be optimized with the observed redshift by changing w_a. The most optimal z_{model} provides the w_a.

2.1 Method

2.1.1 Measuring DM$_{host}$

We adopted this equation for calculating the τ at rest frame using DM$_{host}$

$$\tau_{\rm rest}(DM_h, \nu_{\rm rest}) = C_\tau \nu_{\rm rest}^{-4} A_\tau \tilde{F} G \left(\frac{DM_h}{100} \right)^2 \tag{2.1}$$

$\nu_{\rm rest}$ is rest frame frequency in GHz. $C_\tau = 0.48$ is a numerical constant according to Cordes et al. 2022[8]. The $A_\tau \tilde{F} G$ term is a combination of three different parameters. $A_\tau \tilde{F}$ characterizes the density fluctuation while the G is a dimensionless geometry factor. Although three parameters are different, they usually join together as a formalization. Typically, $A_\tau \tilde{F} G$ ranges from 0.001 to 10 $(kpc^2 km)^{-1/3}$[8].

DM$_{host}$ $(pc \cdot cm^{-3})$ and $A_\tau \tilde{F} G$ $(kpc^2 km)^{-1/3}$ are used to desribed the PDF of DM$_{host}$[8]

$$f_{DM_h,\phi}(DM_h, \phi | DM_{\rm obs}, z_{\rm spec}, T_{\rm obs}) \propto f_{DM_h}(DM_h | DM_{\rm obs}, z_{\rm spec}) \times f_\tau(T_{\rm obs} - \hat{\tau}) \tag{2.2}$$

For more convenience, DM_{host} will now be changed to DM_h and the $A_\tau \tilde{F} G$ term will now be called ϕ . On the right side of the equation, there are two terms, the first one is DM and the second is τ. The first term, $f_{DM_{host}}$ is expressed as

$$f_{DM_h}(DM_h|DM_{obs},DM_W,z_{spec}) = \frac{f_{DM_{IGM}}(DM_{IGM}|DM_{obs},DM_W,z_{spec})}{1+z_{spec}} \quad (2.3)$$

The PDF of DM_h is described by the PDF of DM_{IGM} where the $DM_{IGM} = DM_{obs} - DM_{MW,disk} - DM_{MW,halo} - \frac{DM_h}{1+z_{spec}}$, z_{spec} is basically the observed redshift. The PDF of DM_{IGM} will follow a log-normal distribution with the following parameters:

$$\mu = \ln(\overline{DM_{IGM}}) - \frac{\sigma^2}{2} \quad (2.4)$$

$$\sigma = \sqrt{\ln\left(1+\left(\frac{\sigma_{DM_{IGM}}}{DM_{IGM}}\right)^2\right)} \quad (2.5)$$

with $\sigma_{DM_{IGM}}$ is the cosmic variance of DM_{IGM}

$$\sigma_{DM_{IGM}(z_{spec})} = \sqrt{DM_{IGM}(z_{spec})DM_c} \quad (2.6)$$

DM_c is a constant, that is $DM_c = 50\ pc\,cm^{-3}$ [9]. And $\overline{DM_{IGM}}$ is the average of DM_{IGM}. The $\overline{DM_{IGM}}$ is defined as below

$$(DM_{IGM}(z) = \Omega_b \frac{3H_0c}{8\pi Gm_p}\int_0^z \frac{(1+z')f_{IGM}(z')Y_HX_{e,H}(z') + \frac{1}{2}Y_pX_{e,He}(z')}{(\Omega_M(1+z')^3 + \Omega_{DE}(1+z')^{3(1+w(z'))})^{1/2}}dz' \quad (2.7)$$

This equation was adopted from Zhou et al. 2014[10]. Where $w(z') = w_0 + \frac{w_a z}{1+z}$ is the equation of state of the dark energy, in the equation w_a is what I am constraining here. $X_{e,H}$ and $X_{e,He}$ are the ionization fractions of the intergalactic hydrogen and helium. $Y_H = 0.75$ and $Y_P = 0.25$ are the mass fractions of H and He. Current observations suggest that for $z \leq 6\,(\leq 3)$ the intergalactic hydrogens (helium) are fully ionized[11, 12]. So for $z \leq 3$ it is reasonable to take both $X_{e,H} = 1$ and $X_{e,He} = 1$. Hence, in this research, I will take $X_{e,H} = 1$ and $X_{e,He} = 1$ as my considered range for the redshift z is from 1 to 3.

There is a challenge that I faced when dealing with equation 2.7 is the evolving of f_{IGM}, which is the ionization fraction of the intergalactic medium. At

$z1.5$, about 90% of the baryons produced in the Big Bang are in the IGM (i.e., $f_{IGM} \approx 90\%$) [10]. While at $z \leq 4$, $f_{IGM} \approx 82\%$ [10]. For that reason, in this research I will take $f_{IGM} = 0.9$ at $z \geq 1.5$, and make it linearly increase from 0.82 at $z = 0$ to 0.9 at $z = 1.5$.

Returning back to the main points, in the second term of equation 2.2, f_τ is the PDF of $\tau_{obs} - \hat{\tau}$. This is actually the PDF of the difference between the observed scattering time (τ_{obs}) and the theoretical scattering time ($\hat{\tau}$). Where $\hat{\tau}$ is defined below

$$\hat{\tau} = C_\tau \nu_{\rm obs} \phi \left(\frac{\rm DM_h}{100}\right)^2 (1+z_{\rm spec})^{-3}, \tag{2.8}$$

A Gaussian function was assumed to express $f_\tau(T_{\rm obs} - \hat{\tau})$ with mean value is 0 and taking the observed tau error σ_τ as the standard deviation.

2.1.2 PDF of redshift

The PDF of redshift will be a function of DM_{obs} and τ_{obs}

$$f_z(z|{\rm DM_{obs}}, \tau_{\rm obs}) \propto \iint (d{\rm DM}_h d\phi)\, f_{\rm DM_{h,\phi}}({\rm DM}_h, \phi) \times f_\tau(\tau_{\rm obs} - \hat{\tau}), \tag{2.9}$$

where the integration range of DM_h is from 20 to 1600[8], and the integration range for ϕ is from 0.001 to 10. After integrating all possible range of both DM_h and ϕ, I will get the PDF of redshift ($f_{z_{model}}$).

2.1.3 Optimize w_a

Taking the 50th percentile of the model redshift. Letting w_a be a parameter of z, I can find what z_{model} value provide the best fitted by comparing it with $z_{observe}$.

2.2 Process of making FRB mock samples

Because of the fact that I am trying to constrain dark energy, using a real data would be very challenging or rather impossible. Current data only provides very limited localised FRBs at high z, hence, I will make a set of mock data for this research.

My aim was to see if this method is feasible within a near future. That said, within a near future, 100 FRBs with know host galaxy is definitly achievable with the advancement of future FRBs telescopes.

I selected the 100 FRBs as follows. Firstly, I randomly selected 100 redshift values for mock FRBs from the CHIME/FRB catalogue 1 [5] based on the DM-derived redshift of Hashimoto et al. 2022 [13]. The range for the redshift of these mock FRBs should be from 1 to 3, creating the mock redshift data, z_{mock}. Then I randomly sampled 100 NE2001 values for 100 FRBs from the same catalogue to create the mock $DM_{MW,disk}$ ($DM_{disk,mock}$). I adopted a specific value for $DM_{halo,mock} = 52.5\,(pc\,cm^{-3})$. Here the values for both $DM_{MW,disk}$ and $DM_{MW,halo}$ were adopted as specific values for the data selection process only, the PDF of $DM_{MW,disk}$ and $DM_{MW,halo}$ were still taken into account when applying the method mentioned above. Using z_{mock} generated above, I can calculated the cosmic average of DM_{IGM} based on equation 2.7 assuming $H_0 = 70\,km\,s^{-1}\,Mpc^{-1}$ and $w_a = -0.8$, $w_0 = -0.7$. The line-of-sight fluctuation of DM_{IGM} was taken into account based on equation 2.6 to create mock DM_{IGM} data $DM_{IGM,mock}$.

In general, the uncertainty of the DM_h is significant [6]. This limitation is come from the truth that the observed dispersion measure is an integrated quantity along a trail (line-of-sight) of a FRB, hence, it is very challenging to separate between DM_{IGM} and DM_h without using scattering [6]. A research in 2020 [14] took $DM_h = 50\,\mathrm{pc\ cm^{-3}}$ in their work. However, in later year 2021, another research[15] statistically concluded that $DM_h \approx 400\,\mathrm{pc\ cm^{-3}}$ by conducting a cross-correlation analysis between CHIME/FRB data and galaxy catalogs. A suggestion was made that even higher DM_h might be reached as the model contains more data [16].

The above highlights the significant uncertainty of DM_h, currently ranging from $\sim 50\,\mathrm{pc\ cm^{-3}}$ to $\sim 400\,\mathrm{pc\ cm^{-3}}$. For that reason, Yang et al. 2025 [6] chose to generate mock DM_h data by assuming it follows a normal distribution with a mean of $200\,\mathrm{pc\ cm^{3}}$ and a standard deviation of $50\,\mathrm{pc\ cm^{-3}}$, making it the data for $DM_{h,mock}$.

The mock scattering time ($\tau_{rest,mock}$) at the host frame (rest-frame) with the frequency of 1 GHz for the mock data were determined using previous $DM_{h,mock}$, assuming on $A_\tau \tilde{F} G = 1\,\mathrm{pc^2 km^{-1/3}}$ and $\nu = 1$ GHz as mentioned before for equation 2.1. The scattering time at the frame of the observer ($\tau_{obs,mock}$) was calculate by dividing the $\tau_{rest,mock}$ by a factor of $(1+z_{mock})^3$, assuming ν_{obs}^{-4} is dependent of τ and $(1+z)$ is the time dilation factor. The mock error for the scattering time

($\sigma_{\tau,mock}$) was generated based on the median value of the fractional errors of Table 1 from Yang et al. 2025 [6]

In conclusion, I have generated 100 FRBs mock data with each FRB contains these mock parameters:

- z_{mock}
- $DM_{IGM,mock}$
- $DM_{MW,mock}$
- $DM_{h,mock}$
- $DM_{obs,mock}$
- $\tau_{obs,mock}$
- $\sigma_{\tau,mock}$

3 CHAPTER 3: RESULTS

Like I mentioned above, the research is still ongoing and a final result is not yet yielded. However, I can give some of the figures and data that I have achieved so far.

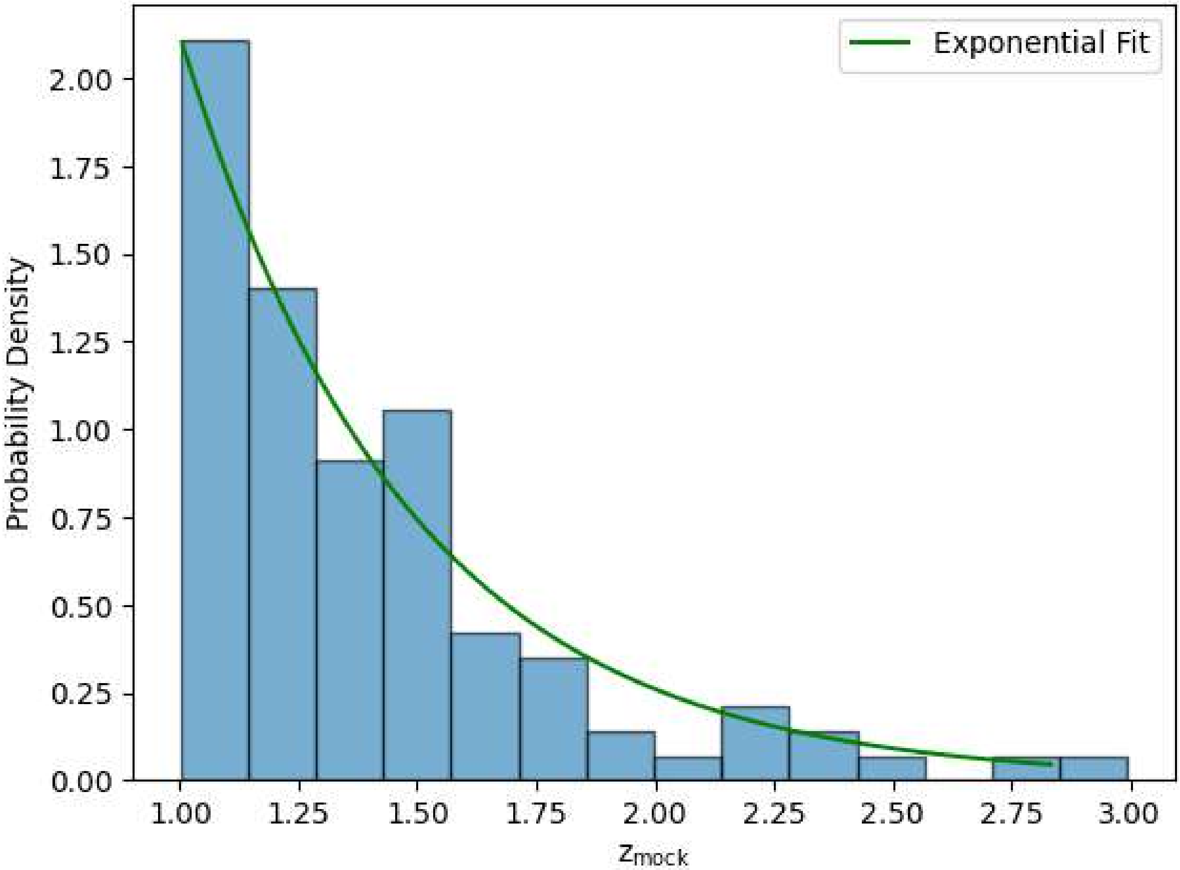

FIGURE 3.4: Probability density function of mock redshift data

The scatter plot depicts the probability density of the z_{mock}. I chose range of the redshift from 1 to 3 following the original distribution from the CHIME/FRB catalogue 1. However, the catalogue did not have enough values for redshift so I had to find the PDF of redshift from 1 to 3 in the catalogue and randomly generated the data values based on that PDF. The green curve demonstrates the PDF of redshift as an exponential PDF.

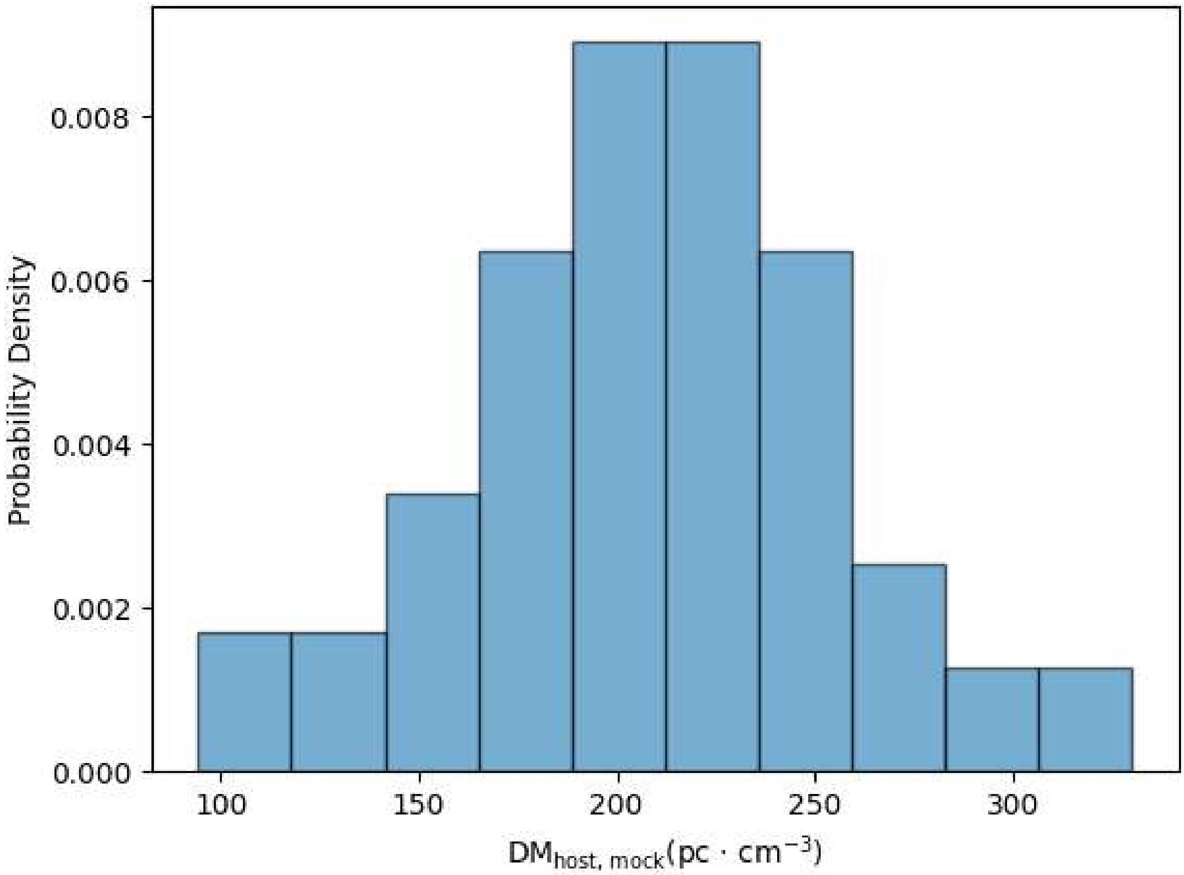

FIGURE 3.5: Probability density of $DM_{h,mock}$

As suggested in Chapter 2, the $DM_{h,mock}$ will be generated based on a normal distribution with the mean is $200\,\text{pc cm}^{-3}$ and a standard deviation of $50\,\text{pc cm}^{-3}$. Another earliest result that I have gotten so far is the figure of the relationship between redshift and the average of DM_{IGM}

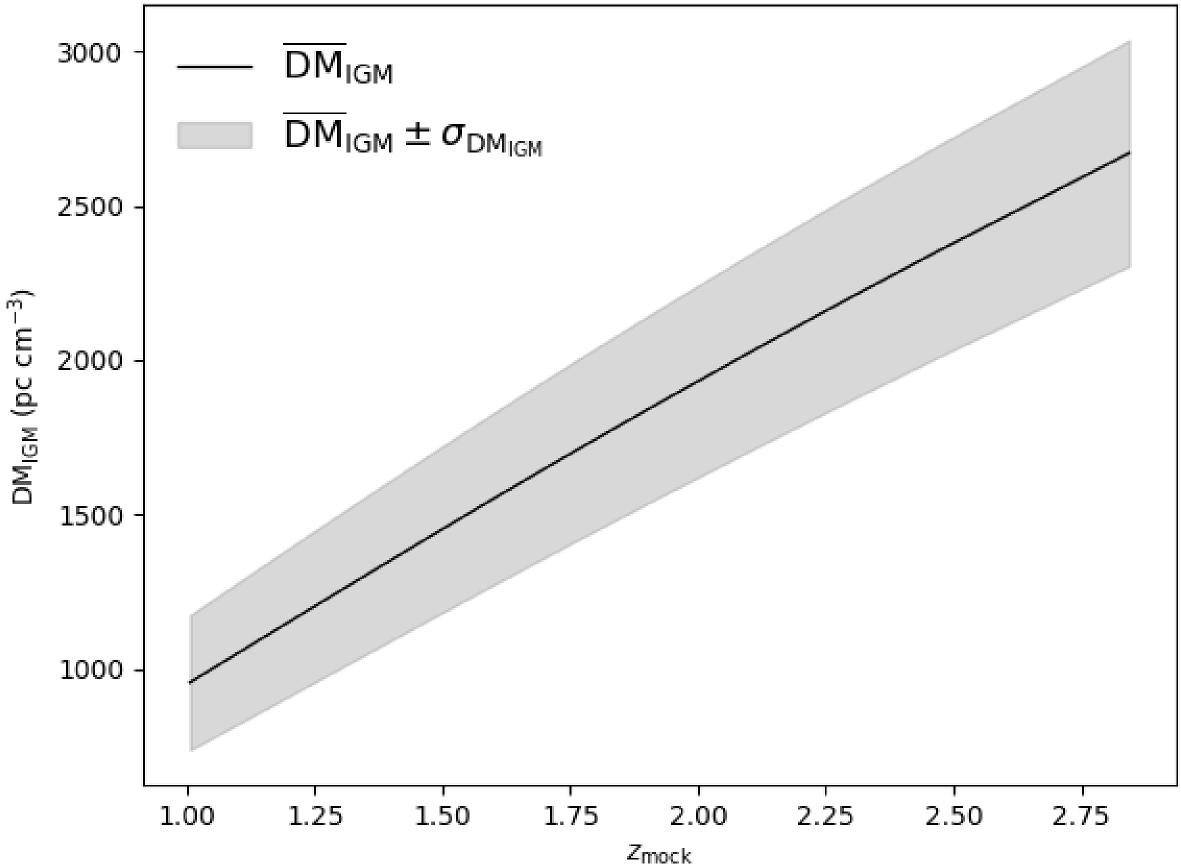

FIGURE 3.6: Relationship between the redshift z and the cosmic average of DM_{IGM}

In figure 3.6, we can see the relationship between redshift, here is the z_{mock} of the mock data is following a straight line. Nevertheless, the relation between these two parameters actually follows a curve, meaning these two parameters are not linearly correlated. The reason for this mistake is because the considered range of the redshift, which is from 1 to 3, the trend of the figure can be seen more easily at redshift range from 0 to 3. However, in this figure, we can still see the little change in the trend as $\overline{DM_{IGM}}$ tends to increase more gradually when z increases.

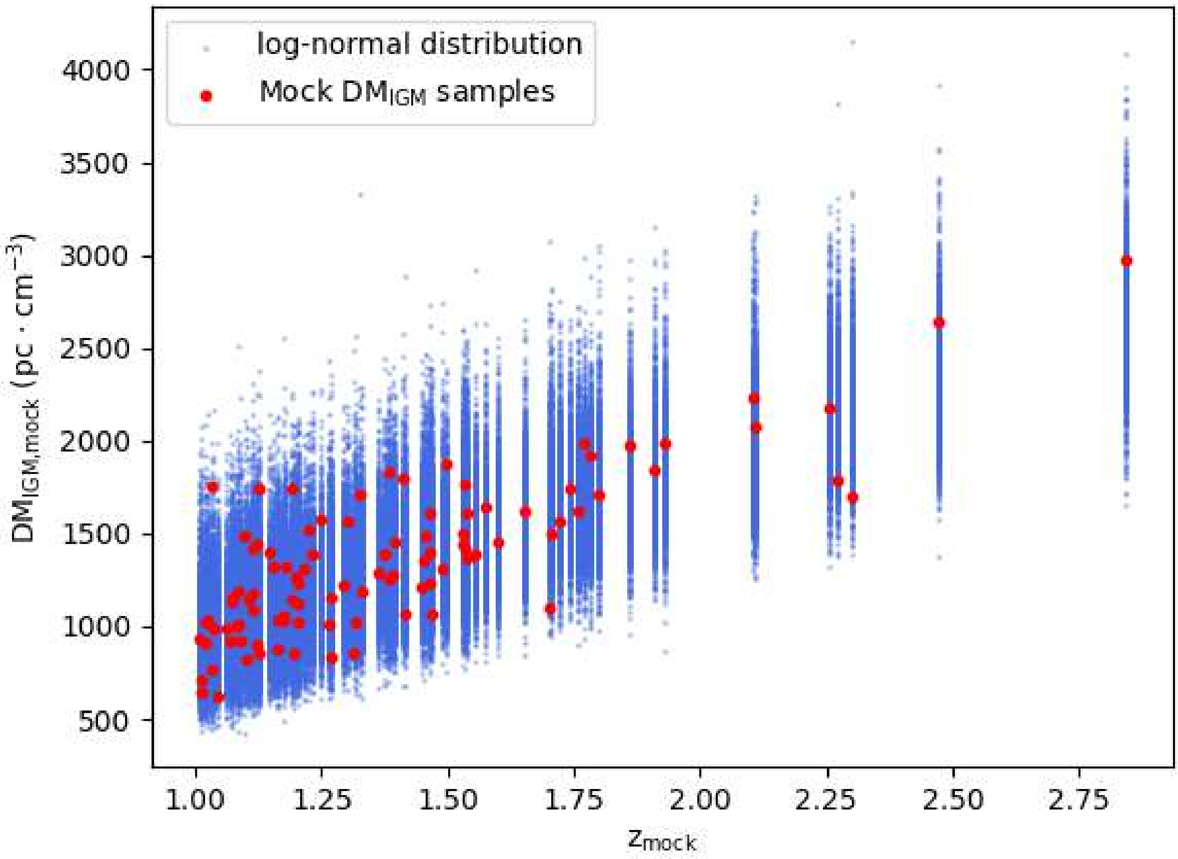

FIGURE 3.7: $DM_{IGM,mock}$ generated by the method above

The figure shows how the $DM_{IGM,mock}$ was generated. The blue dots represent the average of $DM_{IGM,mock}$ generated by the equation 2.6 at each mock redshift value, taking the line-of-sight fluctuation of DM_{IGM} into account. Hence, we got the vertical line of blue dots as the possible $DM_{IGM,mock}$ values possible at that specific redshift following a log-normal distribution mentioned above at Chapter 2. For each vertical line of blue dots, I randomly choose a value and represent it as a red dot. By repeating the process 100 times corresponding to 100 mock FRBs, I can generate the mock DM_{IGM} values for 100 mock FRBs.

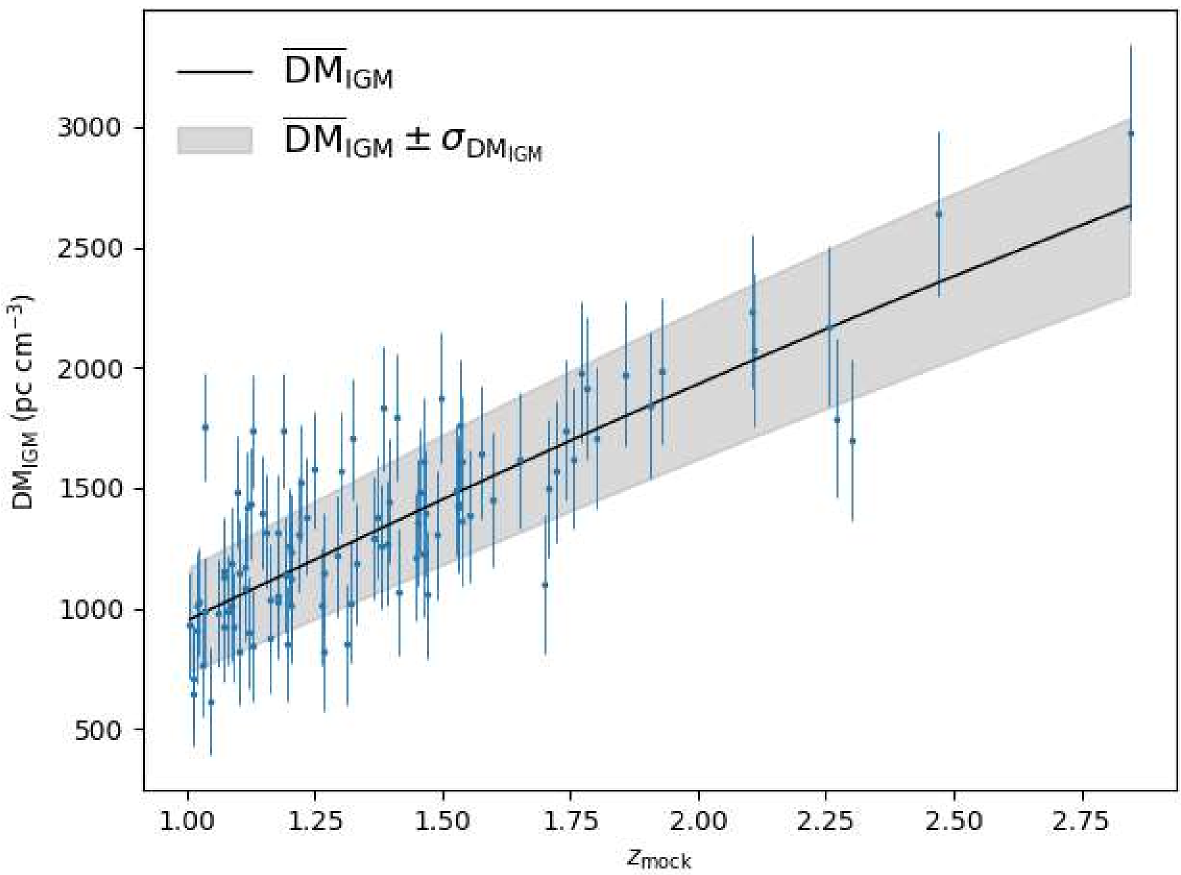

FIGURE 3.8: $DM_{IGM,mock}$ of the mock data

The red dots in the figure 3.7 was plotted along with z_{mock} including the line-of-sight fluctuation. The black curve represents the cosmic average along with the shaded region is the line-of-sight fluctuation.

As I said in the Chapter 1, this project is not yet finished and it is still on going. At the moment, I have written the code for calculating the PDF of redshift based on previous mentioned method. And then I can deduce the model redshift by taking the 50th percentile of the redshift PDF. By optimizing it with the z_{mock} (z_{spec}) with Chi-square test, I can find the optimal value for the w_a. However, there were error arose from process and my Chi-square is calculated wrong.

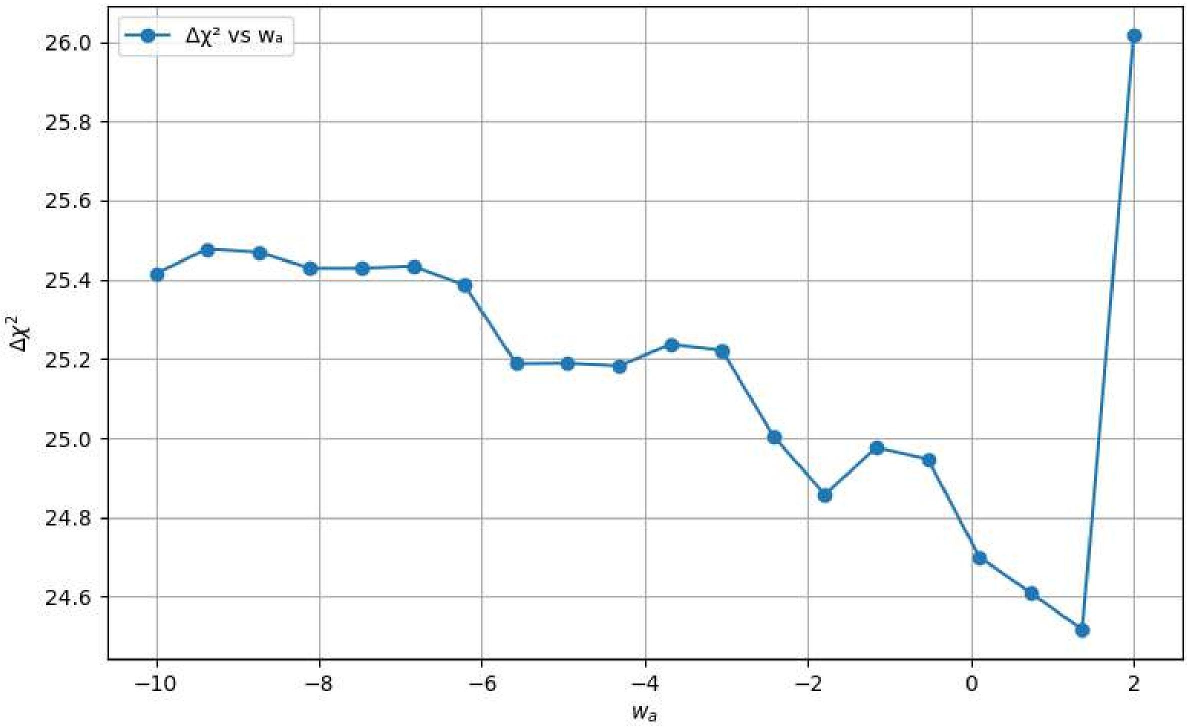

FIGURE 3.9: Chi-square test with w_a

The fist thing wrong here is the range of w_a is so large ranging from -10 to 2. That is unreasonably large for a parameter which has a statistically calculated possible range between -3 to 1 [4]. Moreover, the values of the Chi-square are extremely large. After all, the shape of the Chi-square function is the easiest to be recognized as the shape is strange. All these combined makes the Chi-square is wrong and need to be reconsidered.

After revisited the calculations and codes, I found out the problem could come from multiple reasons such as the code calculating the PDF of redshift, or the bins of the parameters, or it is the mock data itself. Huge amount of work is needed in order to tackle the problem.

4 CHAPTER 4: DISCUSSION AND FUTURE WORK

The primary goal of this project was to develop a method for constraining the dark energy w_a parameter by utilizing the scattering time of FRBs in their host galaxies. The method [6] promises to reduce the systematic errors associated with the assumptions about the dispersion measure in FRB host galaxy. However, as noted throughout the report. The calculations encountered significant errors that to be further investigated before the results can be included in this report.

During the calculations, an issue with either the code or the data arose. For that reason, the yielded results is not as expectation and there is uncertainty about the reason for this occurrence. The root of the errors could be from either a flaw in the code or issues with data used, or can be calculations involving PDF of redshift, 50th percentile, integration. So the next will be revisiting both code and data in order to identify the problem.

Despite these challenges, the potential of this research remains clear. After fully functional, this method could provide an outstanding method for estimating the nature of dark energy. Also future refinements on the approach could also tackle this issue. Here are some of the possible explanations for the problem.

The first priority should be an overall debugging of the code model. A thorough inspection is required, focusing on data handling aspects and also data calculations. Debugging tools should be applied to ensure the calculations align with theoretical expectations. After all, comparison with theoretical model would be necessary.

The quality of the data used in the model needs to be reassessed. This included the values of the mock parameters follow the model. It is essential to ensure that the alignment of mock and observed data is done correctly. Cleaning outliers is also essential.

In conclusion, while the project encountered significant challenges, the work so far demonstrates the potential for a new method to measure the dark energy with FRBs. Resolving the existing issues will be key to refining the approach to the natural of dark energy.

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