Cosmic distance duality and cosmic transparency

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Abstract. We compare distance measurements obtained from two distance indicators, Supernovae observations (standard candles) and Baryon acoustic oscillation data (standard rulers). The Union2 sample of supernovae with BAO data from SDSS, 6dFGS and the latest BOSS and WiggleZ surveys is used in search for deviations from the distance duality relation. We find that the supernovae are brighter than expected from BAO measurements. The luminosity distances tend to be smaller then expected from angular diameter distance estimates as also found in earlier works on distance duality, but the trend is not statistically significant. This further constrains the cosmic transparency.

Keywords: distance duality, cosmic acceleration, supernovae, baryon acoustic oscillations, cosmic opacity
1 Introduction

The last few decades have been truly exciting in the field of Cosmology. With the success of many cosmological surveys and many more lined up in near future, we are in an era of data driven Cosmology [1]. Most of these observations hint at a Universe going through a phase of late time accelerated expansion [2]. There have been many attempts to understand the physical interpretations of these measurements [3, 4], within and beyond the framework of general relativity (GR). In the framework of GR the component that drives the cosmic expansion is termed as Dark Energy. The simplest and most successful candidate for dark energy is the cosmological constant (Λ), whose energy density remains constant with the expanding Universe. However, Λ suffers from serious problems like fine tuning and the coincidence problem [5]. Alternatively, a evolving dark energy scenario can be explained by using scalar field models (See [6] for a review). Alongside there have been attempts to explain the observed accelerated expansion by modifying gravity at large scales (see [7] for a recent review and references therein).

Cosmological studies are based on some fundamental assumptions like the Copernican principle, conservation of photons etc. There is no evidence of structure formation at scales larger than 100 Megaparsec and hence large scale homogeneity of the Universe is a common assumption in Cosmology. The almost uniform Cosmic Microwave Background (CMB) hints at a Universe that is isotropic as well. Building a robust cosmological model requires us to validate these assumptions. There have been many attempts to constrain the inhomogeneity of the Universe. Using observations from Sunyaev-Zeldovich effect in clusters of galaxies, excitation of low-energy atomic transitions, and the thermal spectrum of the CMB, Goodman [8] examined the radial homogeneity of the Universe. Caldwell et al., [9] used the blackbody nature of the CMB spectrum to test the Copernican principle and placed a limit on the possibility that we occupy a privileged location. Clarkson et al., [10] proposed an observational test for the Copernican assumption based on a consistency relation of the Friedmann-Lemaître-Robertson-Walker (FLRW) model between cosmic distances and the Hubble expansion rate. Further, there have been attempts to constrain the transparency of the Universe at visible and cm wavelengths [11, 12]. More et al. [13], used the Supernovae data and the Baryon acoustic feature to constrain the optical depth of the universe, and
Avgoustidis et al. [14], constrained the cosmic transparency by combining Supernovae with Hubble rate data.

The dynamical properties of the Universe can be deduced by analysing multiple cosmological observations. Moreover, various independent measurements can be combined to find better constraints on our estimates of the Cosmological parameters. It is important to device consistency probes using these measurements to verify the underlying model and its assumptions. In this work we analyse a consistency relation between distances: the Distance Duality relation (DD). It relates the angular diameter distance (ADD) to the Luminosity distance (LD). DD is a model independent probe that can be used to compare and chose between competing cosmological models. Bassett and Kunz [15] used it to rule out the replenishing grey-dust model which causes redshift-dependent dimming of the Supernovae (no cosmic acceleration). Additionally, deviation from DD, if observed, would hint at a breakdown of one or more of its underlying assumptions. One of the assumptions is photon number conservation. There could be both clustered and un-clustered sources of photon attenuation in the Universe. Clustered sources like gas and plasma in the galaxies are correlated with large scale structures. More exotic sources causing change in photon number are axions or axion like particles, motivated from string theory models. Photon-axion coupling can give rise to Supernovae dimming, but such scenario are strongly constrained by cosmological data [16]. Unclustered sources of attenuation effect all the lines of sight equally and can be detected by comparing radiation sources of known properties at different redshifts. We build here on the method proposed by More et.al [13] to put constraints on the cosmic transparency using the current Baryon Acoustic Oscillations (BAO) and the SNeIa data.

The plan of the paper is as follows. In section 2 we give a quick overview of DD. This is followed by section 3 on cosmic transparency. Section 4 summarises data sets used, with subsections on constraints on distance duality and cosmic transparency. We conclude with a section discussing main results.

2 The distance duality relation

In 1933 Etherington showed that a relation exists for area distances between a source and an observer in relative motion with each other. He proved a reciprocity relation valid for any curved spacetime, i.e., it does not assume even the basic symmetry assumptions like homogeneity and isotropy [17]. The relation holds as long as gravity is described by a metric theory, photons travel on null geodesics and the geodesic deviation equation is valid [15, 18]. Further, if photon number is conserved one can relate the angular diameter distance (ADD) and the Luminosity distance (LD) using the reciprocity relation [19],

\[ d_L = d_A (1 + z)^2. \]  

This is termed as the Distance-Duality (DD) relation and plays an important role in galaxy cluster observations and lensing studies [20]. A consequence of DD is the optical theorem which states that the surface brightness of an object depends on its redshift and not on its distance from the observer. This allows us to derive a temperature shift relation for CMB photons relating their observed and emitted temperature via \( T_o = T_e / (1 + z) \).

Evidently DD is crucial to Cosmological studies and plays a key role in how galaxy observations are analysed. Hence, it is important to check its validity. This is possible in
principle since both the distances in the duality relation are observable. Defining
\[ \eta(z) \equiv \frac{d_L}{d_A(1 + z)^2}, \]
the DD holds if \( \eta(z) = 1 \) at all redshifts. As stated earlier the violations in DD could arise due to change in photon number, if there are deviations from metric theory of gravity, or if photons do not travel on unique null geodesics. For our analysis here we look for violations in DD due to a less extreme possibility: violation of photon number conservation.

There are various ways of measuring cosmic distances. One has to look for sources that can be used as standard candles for deriving LD, and as standard rulers for deriving ADD. Type Ia Supernovae (SNeIa) have a peak luminosity that is tightly correlated with the shape of their light curves and they can be calibrated to be treated as standard candles. Combined measurements of the Sunyaev-Zeldovich effect and X-Ray analysis (SZE/X-ray) provides a measure of the ADD to a cluster. Other sources that can be used for ADD estimates are FRIIb radio galaxies, compact radio sources etc. The Baryon acoustic feature in the matter clustering is another independent distance indicator and can be used as a standard ruler.

Bassett & Kunz [15] were the first to propose DD as a powerful tool for testing exotic physics. They used SNeIa data for LD, and FRIIb radio galaxies, compact radio sources and X-ray clusters for ADD to verify the duality relation. Uzan et al., [18] showed that the X-Ray/SZ combined analysis of galaxy clusters offers a validity test of DD. More importantly they proved that the analysis does not give a measurement of the ADD if DD is violated. Since then there have been many attempts to constrain violations in DD. De Bernardis et al. [21] used Chandra cluster data and found no evidence for DD violation within the framework of ΛCDM. Corasaniti [22] modeled the intergalactic dust in terms of the star formation history of the universe and forecasted a deviation in the DD relation due to the presence of the cosmic dust extinction. Lazkoz et al., [23] used SNeIa and CMB + BAO as standard candles and standard rulers respectively to test the validity of this relation and found \( \eta = 0.95 \pm 0.025 \) in the redshift range \( 0 < z < 2 \), which is consistent with distance duality at the 2\( \sigma \) level. Holanda et al.[24] checked the validity of DD relation using two different galaxy cluster samples and SNeIa data and constrained violation in DD by parameterizing \( \eta(z) \). They concluded that the best fit values of the parameters of the \( \eta(z) \) parametrization obtained through the data set based on spherical \( \beta \) model of cluster are not consistent with the DD relation. We found similar results in our earlier work on DD using different distance measures for the ADD [25]. There have been many other attempts to verify/constrain DD or use it to put constraints on different cosmological parameters [26].

The standard practice to check the consistency of DD is to use the LD estimate from the SNeIa data, and get corresponding ADD estimate from one of the aforementioned sources. There are two main sources of error in such a analysis. Firstly, it is not possible to find SNeIa and galaxy clusters at exactly the same redshift and some kind of selection criteria (eg. \( \Delta z = |z_{\text{cluster}} - z_{\text{SNeIa}}| < 0.005 \)) is applied. The redshift mismatch between the cluster and the SNeIa may introduce some errors in the analysis. Secondly, the measurement of ADD from clusters, as described above, is effected by the assumption on cluster geometry. It has been shown earlier that different assumptions regarding cluster geometry gives significantly different constraints on the deviation from DD (see for example [24, 25]). Thus if DD holds it can act as probe of cluster geometry.
To study deviation from DD in a model independent way we parameterize $\eta$ as follows:

$$\eta(z) = 1 + \eta_0 z,$$

$$\eta(z) = 1 + \eta_0 \frac{z}{1 + z},$$

(2.3)

(2.4)

The first one is a simple Taylor series expansion near low $z$ but is ill behaved at higher $z$ values. The second is well behaved even at really high redshifts and is slowly varying as compared to the first one. For both the parameterizations DD is recovered if $\eta_0 = 0$. Note here that though such parameterizations are a useful model independent tool yet a particular form for $\eta(z)$ puts a strong prior. As we do not expect large variation in the value of $\eta$ over a small redshift range a piecewise constant parametrization can be particularly useful here. Since we have a small data set of seven BAO observations we divide the redshift range in three bins with boundaries: $0 < z < 0.35$, $0.35 < z < 0.7$ and $0.7 < z < 1$.

We will analyse one more parameterization (see next section for details) to account for deviations in DD due to violation in photon number conservation.

3 Cosmic transparency

The measurement of the CMBR intensity spectrum is one of the most precise measurements in Cosmology today [27, 28]. The temperature redshift relation mentioned earlier, relating the observed and emitted temperature of the CMB photons, assumes photon conservation. The relation will be modified if this assumption was violated. Many mechanisms have been proposed which may give rise to such a violation, for example decaying vacuum cosmology, photon axion coupling etc. (see [29] and references therein). There have been attempts to measure the CMB temperature at different redshifts, using, for example, quasar absorption line spectra [11]. This can be used to check the validity of the temperature shift relation and hence the validity of the assumption of photon conservation. But the uncertainties are large and more data is required to put robust constraints. Here we look at an alternate method to find evidence for violation of photon conservation and consequently a violation in DD.

In this section we build on a method proposed by More et al., [13], to constrain the opacity of the Universe. As mentioned before if there is some kind of photon-absorption in the Universe then DD will be violated. If one assumes that there are some unclustered sources of photon attenuation in the Universe, and $\tau(z)$ is the opacity between the source (for example a Supernovae) at some redshift $z$ and the observer, then the flux observed at $z = 0$ is reduced by a factor of $e^{-\tau(z)}$ or equivalently

$$d^2 L_{\text{obs}} = d^2 L_{\text{true}} e^{-\tau(z)}.$$  

(3.1)

More et al., used the BAO data at redshifts 0.2 and 0.35 along with Supernovae data to constrain the opacity between these redshifts. Defining $\Delta \tau$ as the difference in optical depth between the two redshifts, assuming DD, in a flat-$\Lambda$CDM Universe and with a prior $0 < \Delta \tau < 0.5$, they found that $\Delta \tau < 0.13$ at 95% confidence. But the best fit value was negative indicating that there was slight disagreement between BAO and SNeIa measurements and that the Supernovae are brighter than expected if estimated using BAO data (assuming DD).

Avgoustidis et al., [14] proposed a parameterization of $\eta(z)$ to account for photon attenuation

$$\eta(z) = (1 + z)^{\epsilon}.$$  

(3.2)
Here $\epsilon$ is a parameter that characterizes departure from DD. They found results similar to More et al., using SNeIa and Hubble data. Since $\epsilon$ can be related to the optical depth parameter $\Delta \tau$ as $\tau = 2cz$ for low $z$, they gave an upper bound on the opacity $\Delta \tau < 0.02$. We also analyse this parametrization to put constraints on $\epsilon$. Further, we follow the strategy used in [13] and constrain the cosmic opacity between various redshifts using the BAO and Supernovae data.

If distance duality holds then $\eta$ is a constant in time (redshift), i.e. $\eta(z_1) = \eta(z_2)$, implying

$$\frac{d_L(z_1)}{d_A(z_1)(1+z_1)^2} = \frac{d_L(z_2)}{d_A(z_2)(1+z_2)^2}.$$  \hfill (3.3)

The distance modulus and luminosity distance are related $(d_L(parsec) = 10^{0.2\mu+1})$, and most galaxy cluster surveys provide measurements of an angle-averaged distance $D_V$

$$D_V = \left(\frac{cz(1+z)^2d_A}{H(z)}\right)^{\frac{1}{2}},$$  \hfill (3.4)

or the distilled parameter $d_z = r_s/D_V$ [30, 31]. Using (3.1) and (3.4) in (3.3) we can derive the difference in opacity between two redshifts $z_1$ & $z_2$ as given in ([13]),

$$\Delta \tau = \frac{\ln(10)}{2.5} \left[ \Delta \mu_{obs} + 2.5 \log \left( \frac{z_2(1+z_1)^2H(z_1)}{z_1(1+z_2)^2H(z_2)} \right) \left( \frac{d_A(z_2)}{d_A(z_1)} \right)^{\frac{1}{3}} \right].$$  \hfill (3.5)

which is written in terms of the distilled parameter $d_z$. Here $\mu(z)$ is the distance modulus corresponding to redshift $z$ as obtained from the Supernovae data and $\Delta \mu_{obs} = \mu(z_2) - \mu(z_1)$.

4 Constraints from current data

In this work we use the BAO measurements as a standard ruler for inferring ADD [32, 33]. This data is more reliable since the BAO physics is well understood and is not effected by the systematics mentioned earlier. To obtain $\eta(z)$ we require the observed values of LD and ADD at the same redshift. This can be achieved by redshift-matching, as mentioned earlier. Further, a solution to the redshift-mismatch problem can be found using local regression technique by inferring the distance modulus of the SNeIa at the same redshift as the effective redshift of the BAO measurement [34].

4.1 Data

For estimating LD we use the Union2 sample of type Ia Supernovae [35], and BAO data from different galaxy cluster surveys - SDSS ($z=0.2, 0.35$), 6dFGS($z=0.106$), WiggleZ($z=0.44, 0.6, 0.73$) and BOSS($z=0.57$) for estimating ADD [30, 36–38]. BAO in the observed galaxy power spectrum has a characteristic scale ($r_s(z)$) determined by the comoving sound horizon at an epoch ($z_*$) slightly after decoupling. This epoch is measured by CMB anisotropy data [27]. The strength of BAO over other probes lies in the fact that it can be measured in both radial (giving $r_sH(z)$) and transverse directions (giving $d_A/r_s$). Here $H(z)$ is the Hubble expansion rate, $d_A$ is the ADD. Since $r_s$ is well constrained by the CMB data, it is possible to get a direct estimates of $d_A$ and $H(z)$ from transverse and radial BAO measurements.

We analyse three data sets. The estimate of distance modulus in all three data sets comes from the Union2 sample. The estimate of the angular diameter distance in data set
I and II come from SDSS, 6dFGS WiggleZ and BOSS and the difference in the two data sets arises due to the different methods used to find the LD estimate corresponding to the ADD estimate. Data set III uses \( d_A \) estimates from some recent papers. Our main analysis will be based on data set II but we show some results obtained from data set I and III for comparison. Now we briefly discuss the three data sets:

- **Data set I (Redshift matching)**: If a Supernova is not available at a particular BAO redshift, a nearby Supernova satisfying \( \Delta z = |z_{BAO} - z_{SNeIa}| < 0.005 \) is chosen. Here \( z_{BAO} \) and \( z_{SNeIa} \) are the BAO redshift and redshift of the Supernova, respectively.
  
  The estimate on \( d_A \) can be derived from \( d_z \) within the framework of ΛCDM assuming \( r_s = 153.3 \pm 2.0 \) Mpc, \( \Omega_m = 0.283 \pm 0.017 \) and \( H_0 = 69.3 \pm 1.5 \) Km/s/Mpc [39]. We have 7 data points in this set.

- **Data set II (Local regression)**: The distance modulus can be obtained at the BAO redshift by using a local regression method. Following Cardone et al.,[34] we form subsamples of the Union2 data by choosing 14 Supernovae which are nearest to the BAO redshift. We then fit a first order polynomial to this subsample weighing each Supernova with its corresponding weight where the weighing function is
  
  \[
  W(Z) = \begin{cases} 
  (1 - |Z|^3) & |Z| \leq 1 \\
  0 & |Z| > 1 
  \end{cases} 
  \]  

  Here \( Z = |z_d - z_i|/\Delta \) and \( \Delta \) is the maximum value of the \( |z_{BAO} - z_i| \) in the subsample. The zeroth order term is chosen as the estimate of the distance modulus at the redshift \( z_{BAO} \). The error on the distance modulus is estimated as the r.m.s value of the residuals (weighted) with respect to the best fit. The \( d_A \) estimates are the same as in data set I. This data set also contains 7 data points.

- **Data set III**: In this data set \( d_L \) is estimated using local regression as discussed above. For \( d_A(z) \) estimates we use the values given in [39–41]. Reid et al. [39] give an estimate of \( d_A \) for \( z = 0.57 \), Xu et al. [40] use the anisotropy of the BAO signal measured in the galaxy clustering distribution of the Sloan Digital Sky Survey (SDSS) Data Release 7 (DR7) Luminous Red Galaxies (LRG) sample and apply density-field reconstruction to an anisotropic analysis of the acoustic peak to give estimate of \( d_A \) at \( z = 0.35 \). Blake et al. [41] give estimates of \( d_A \) at redshifts \( z = 0.44, 0.6 \) and 0.73 by combining measurements of the acoustic parameter \( A \propto (D_A^2/H)^{1/3} \) and Alcock-Paczynski distortion parameter \( F \propto D_AH \) from galaxy clustering in the WiggleZ Dark Energy Survey. This data set has 5 data points.

### 4.2 Constraints: Cosmic distance duality

We obtain \( \eta_{obs} = d_L/d_A(1 + z)^2 \) using estimates of \( d_L \) and \( d_A \) as discussed above for the three data sets. The error on \( \eta_{obs} \) is obtained by combining errors from SNeIa measurement and BAO measurements (data set I and II have additional errors from the Cosmological parameters \( r_s, \Omega_m \) and \( H_0 \)). We assume that the errors have a gaussian distribution and find the best fits to the parameters by minimizing the chi-squared function:

\[
\chi^2(p) = (\eta_{obs} - \eta^{th}(p))^T C^{-1}(\eta_{obs} - \eta^{th}(p)),
\]

with \( \eta^{th}(p) \) being the theoretical value of \( \eta \) for a given set of parameters \( p \).
where \((\eta^{\text{obs}} - \eta^{\text{th}}(p))\) is the vector of the differences between the observed and theoretical \(\eta\). The model parameters \((\eta_0 \text{ or } \epsilon)\) are denoted by \(p\). \(C\) is the covariance matrix evaluated using the correlation coefficients between different redshift slices in the BAO data. We present our best fits with \(1\sigma\) error bars in the table 1 below. Figure 1 summarises the results of this section.

Figure 1: Figure (a) and (b) show the variation of \(\eta\) with \(z\) for the two parameterizations with \(1\sigma\) error bars. (c) shows piecewise constant parametrization with \(1\sigma\) error bars. (d) shows the likelihood plots for the three binned parameters along with the constant \(\eta\). All the results are for data set II.

If we don’t model \(\eta\) and calculate the value of \(\eta = d_L/d_A(1 + z)^2\) from the data we see that a value slightly less than one is favoured. We find \(\eta\) equal to 0.965 ± 0.040, 0.971 ± 0.037 and 0.966 ± 0.070 for the first, second and third data set respectively. This is in agreement with earlier works in this direction. Uzan et al. [18], found a best fit value slightly less than one and related this trend to the systematics in the SZ/X-ray analysis of galaxy clusters.
Table 1: Best fit values of $\eta_0$ with 1σ error bars

\begin{tabular}{|c|c|c|c|}
\hline
$\eta(z)$ & Data set I & Data set II & Data set III \\
\hline
$1 + \eta_0 z$ & $-0.105 \pm 0.085$ & $-0.098 \pm 0.084$ & $-0.066 \pm 0.070$ \\
$1 + \eta_0 \frac{z}{1+z}$ & $-0.161 \pm 0.134$ & $-0.151 \pm 0.155$ & $-0.103 \pm 0.106$ \\
\hline
\end{tabular}

Bassett and Kunz [15], also found that the Supernovae are brighter relative to the $d_A$ data. They suggested the gravitational lensing of high-$z$ supernovae as a possible explanation. The constraints on the three piecewise constant $\eta_i$ for the data set II are $\eta_1 = 0.967 \pm 0.040$ for $0 < z < 0.35$, $\eta_2 = 0.940 \pm 0.054$ for $0.35 < z < 0.7$ and $\eta_3 = 0.944 \pm 0.101$ for $0.7 < z < 1$. We see a decrease and then a marginal rise in $\eta$ from redshift bin one to three (figure 1c).

Here we note that the errors on the parameters $\eta_0$ are slightly improved in comparison to earlier analysis which used SZ/X-ray measurement of galaxy cluster for $d_A$ [24]. The distance duality is not accommodated within 1σ in all three parameterizations with the present data but the errors on the parameters quantifying deviation from DD are still large. This is mainly due to a few BAO data points. The constraints on the parameters should improve with more BAO data in future observations.

4.3 Constraints: Cosmic transparency

The value of $\Delta \tau$ is obtained for 6 pairs of measurements using data set II. As mentioned earlier we work within the framework of ΛCDM Cosmology assuming $\Omega_m = 0.283 \pm 0.017$ and $H_0 = 69.3 \pm 1.5$ Km/s/Mpc. The results are given in table 2. One can further relate the difference in opacity to the parameter $\epsilon$ in the third parameterization considered in the previous section as $\tau(z) = 2\epsilon \log(1 + z)$. And if $z << 1$ then we can approximate $\tau(z) = 2\epsilon z$.

Table 2: $\Delta \tau$ for different redshift pairs with 1σ error bars

\begin{tabular}{|c|c|c|}
\hline
Redshift & Pairing redshift & $\Delta \tau$ \\
\hline
0.106 & 0.2 & $-0.110 \pm 0.193$ \\
0.2 & 0.35 & $-0.095 \pm 0.175$ \\
0.35 & 0.44 & $0.180 \pm 0.260$ \\
0.44 & 0.57 & $-0.185 \pm 0.266$ \\
0.57 & 0.6 & $0.030 \pm 0.371$ \\
0.6 & 0.73 & $-0.015 \pm 0.447$ \\
\hline
\end{tabular}

The best fit value of $\epsilon$ estimated from the third parameterization is $\epsilon = -0.159 \pm 0.097$. We see from our results that although the errors are very large, the best fit value of $\Delta \tau$ is negative for a majority of redshift pairs. Further a negative value of $\epsilon$ is preferred by the data when the third parameterization is used. Since $\epsilon$ characterizes a departure from transparency its negative value indicates that SNeIa are brighter than expected when estimated from BAO data. Similar trends were reported in some of the earlier works [13, 14]. Figure 2 summarises the results of this section. The constraints on $\Delta \tau$ are consistent with zero but we see that the error bars are large and there is scope for improvement from future data.
5 Discussion

To look for deviations from the underlying assumptions of the Cosmology, one can device consistency checks that compare different cosmological measurements. The distance duality relation that derives from Etherington’s relation is one such model independent probe. In this work we have used the distance duality as a probe to find consistency between distance measurements obtained from two different distance indicators: SNeIa and BAO. Performing such consistency checks can also shed light on possible systematics present in the data. Earlier works in this direction used ADD estimates from astrophysical sources such as galaxy clusters, FRIIb galaxies, radio galaxies etc. Using BAO for the ADD estimate has an advantage that it is unaffected by the astrophysical assumptions and modeling that goes into the other probes mentioned before. Note that the distance estimates derived from BAO here are not completely model independent since we have assumed $\Lambda$CDM Cosmology to calculate $d_A$ from the $dz$ measurement. We summarise our results below:

- To perform the DD test one often applies a selection criteria to chose the Supernovae nearest to the ADD redshift. To avoid introducing errors due to this redshift mismatch we used the local regression method as advocated by Cardone et al., [34]. We constrained the parameter $\eta = d_L/(d_A(1+z)^2)$ which should be equal to 1 if DD holds and the distance measurements agree, and found that the present data prefers a value slightly less than 1. DD is not accommodated within 1σ, and the systematic trend of $\eta$ being less than 1 has been reported before and needs to be accounted for.

- Nesseris and Garcia-Bellido recently used Genetic Algorithm aproach to extract model independent and bias-free reconstruction information from SNeIa, BAO and the growth

\[ \eta(z) = (1+z)^2 \]

\[ \Delta \tau \]
rate of matter perturbations. They found a $3\sigma$ deviation of $\eta$ from one at redshifts $z \sim 0.5$ [42]. We too observe a marginal dip in $\eta$ in the redshift bin $0.35 < z < 0.7$. But we require more data to derive a statistically significant conclusion.

- The analysis present here is limited due to small data set. But the qualitative trend of $\eta < 1$ agrees with earlier works in this direction. From future measurements of BAO and SNeIa we will be able to better constrain the parameters describing deviations from DD and hence look for violations in the assumptions that lead to DD. We also looked for an evidence for photon absorption by analysing the cosmic transparency of the Universe. Assuming that there is some photon absorption in the Universe we used the present data to constrain its transparency. We found that the best fit to the parameter characterizing absorption $\epsilon$, is negative indicating that the Supernovae are brighter than expected from BAO measurements. Various mechanism are available in the literature that could provide a physical explanation to this: axion-photon mixing, Chameleon-photon mixing, gravitational lensing etc. [43]. But a probable answer could lie in some systematic biases present in these measurements.

Tension between the SNeIa and BAO measurements have been reported before [15, 23, 44]. We can’t constrain violation in DD or the transparency of the Universe with much confidence with the present data. But within the framework of ΛCDM a slight disagreement between the two different distance indicators used, is evident. We look forward to future BAO and Supernovae data which will greatly improve our constraints on these parameters.

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