Constraints on Dark Energy and Distance Duality from Sunyaev Zel’dovich Effect and Chandra X-ray measurements

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Abstract

We demonstrate that the recent measurements of the angular diameter distance of 38 cluster of galaxies using Chandra X-ray data and radio observations from the OVRO and BIMA interferometric arrays place new and independent constraints on the dark energy component. In particular we found that the equation of state is bound to be $-1.18 < w < -0.35$ at 68% c.l.. We also search for deviations in the duality relation between angular and luminosity distances. Using only cluster data, we found that the ratio between the two distances defined as $\eta = D_L/D_A(1+z)^2$. is bound to be $\eta = 0.97 \pm 0.03$ at 68% c.l. with no evidence for distance duality violation in the framework of the $\Lambda$-CDM model. Comparing the cluster angular diameter distance data with luminosity distance data from type Ia Supernovae, we obtain the model independent constraint $\eta = 1.01 \pm 0.07$ at 68% c.l.. Those results provide an useful check for the cosmological concordance model and for the presence of systematics in SN-Ia and cluster data.

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I. INTRODUCTION

One of the most important questions in modern cosmology is to understand the nature of the Dark Energy component of our Universe. Recent cosmological data coming from measurements of the Cosmic Microwave Background (CMB) anisotropies (see e.g. [1]), on galaxy clustering (see e.g. [2]) and, more recently, on Lyman-alpha Forest clouds (see e.g. [3]) are indeed in spectacular agreement with the expectations of a cosmological model where about 70% of its energy density is in the form of a dark, unclustered, component ([3],[4]). When further combined with measurements of luminosity distance $D_L(z)$ of high redshift type Ia supernovae (SN-Ia, see [11]) the data provide compelling evidence that the universe is currently undergoing an acceleration phase, i.e. the equation of state of the dark energy component must be $P/\rho = w < -1/2$. Several theoretical models have been proposed to explain dark energy but none of them seems to provide a simple and natural solution to the cosmological constant problem (why is the dark energy density so small?) and to the “Why now?” problem (why the dark energy dominates today?) (see e.g. [12] and references therein). Moreover since systematics may be present in SN-Ia data, is crucial to test the apparent late time acceleration using the largest amount of independent and complementary information.

One possible way to test the results from high redshift SN-Ia is to measure the angular diameter distance $D_A(z)$ of high redshift objects and verify the distance duality relation:

$$D_L(z) = (1 + z)^2 D_A(z)$$  \hspace{1cm} (1)

Any systematic (both experimental and theoretical) in the determination of the luminosity distance and in its interpretation will indeed break this relation (see e.g. [3]). Unfortunately a measurement of $D_A$ is a very difficult task. One possible way is to use FRIIb radio galaxies or compact radio sources but these methods may be plagued by several systematics. The most promising way to measure the angular distance is using the Sunyaev-Zel’dovich (SZ) effect togheter with X-ray emission of galaxy clusters. Briefly, by combining the Cosmic Microwave Background temperature decrement due to the SZ effect with measurements of the X-ray surface brightness, one can in principle determine the typical size of the line of sight inside the cluster and measure its angular diameter distance. In this respect, it is particular timely to analyze the latest results on the cosmic distance scale from X-ray data and SZ effect measurements of high redshift clusters presented by Bonamente et al. 2006 ([9]). In [9] the angular diameter distance of 39 clusters in the redshift range $0.14 < z < 0.89$ has been determined using Chandra X-ray data and radio observations from the Owens Valley Radio Observatory (OVRO) and Berkeley-Illinois-Maryland Association (BIMA) interferometric arrays. The goal of our paper is therefore to make use of this new high-quality data in order to constrain properties of dark energy and violations of the distance duality relation. We do this following 3 steps: first of all, we compare the new angular distance data with a database of theoretical models, providing new constraint on the dark energy equation of state parameter $w$. Secondly, we investigate how the new data is compatible with the current “concordance” cosmological model constraining the $\eta$ parameter mentioned above. Finally we compare the angular distance data with the latest luminosity distance observations of SN-Ia further constraining possible systematics in both datasets and investigating signatures of new physics. In the next section we describe our method analysis and our results. In the final section we derive our conclusions.
II. DATA ANALYSIS AND RESULTS

The data we use in this paper comes from the results presented in [9]. We consider the angular diameter distance data of 38 clusters presented in Table 2 of [9] and we associate to each measurement an error \( \sigma_{\text{Clusters}} \) which is obtained by combining the uncertainties in the cluster modelling plus the statistical and systematic errors. The contribution to the statistical errors comes primarily from the cluster asphericity, SZ point sources and the kinetic SZ effect. Statistical errors affect the measurement of \( D_A \) at the level of about \( \sim 20\% \). The systematic contributions come from the X-ray absolute flux calibration, the X-ray temperature calibration and the SZ calibration. The overall effect from systematics is about \( \sim 15\% \) of the measured signal. The data is then compared with the prediction of the angular diameter distance in a flat universe given by (in units of \( c = 1 \)):

\[
D_A(z) = \frac{H_0^{-1}}{(1 + z)} \int_0^z \frac{dz'}{E(z')}
\]

where \( H_0 \) is the Hubble constant and

\[
E(z) = ((1 - \Omega_w)(1 + z)^3 + \Omega_w(1 + z)^{3(1+w)})^{1/2}
\]

where \( \Omega_w \) is the dark energy density component in units of the critical density \( \rho_c = 3H_0^2/8\pi G \).

For each theoretical model we then evaluate the likelihood function \( \exp(-\chi^2/2) \) where

\[
\chi^2 = \sum_i \frac{(D_A^{\text{Cluster}}(z_i) - D_A(z_i))^2}{\sigma^2_{\text{Clusters},i}}
\]

with \( z_i \) as the redshift of the \( i \)-th cluster and \( D_A^{\text{Cluster}} \) is its measured angular diameter distance. Fixing \( \Omega_m = 0.27 \) and \( w = -1 \) we constrain the Hubble parameter as \( H_0 = 76.8^{+3.7+10}_{-2.9-8} \) (first error statistical, second systematic) in extremely good agreement with the results presented in [9].

In Figure 1 we report the constraints obtained on the \( H_0 - w \) plane using the cluster data. Since the cluster data alone is not powerful enough in determining the dark energy component we combine the cluster data with the HST result on the Hubble parameter \( h = 0.72 \pm 0.07 \) at 68\% c.l. (see [6]) and we also include a gaussian prior on the lower value of the age of the universe as \( t_0 = 12 \pm 1 \) Gyr/s when the age of the theoretical model is \( t < t_0 \). We also restrict the analysis to \( \Omega_m = 0.3 \). As we can see, this analysis bounds \( w \) to be \( -1.18 < w < -0.35 \) at 68\% c.l.. This constrain is less stringent than the one obtained from recent combined analysis of cosmic microwave background anisotropies, SN-Ia and large scale structure data (see e.g. [4]). It is however completely independent, constrains in a stronger way phantom \( w < -1 \) models and provides an useful cross-check of the current cosmological concordance model.

As next step we check the consistency of the angular diameter distance cluster data with the current theoretical concordance model by computing a database of \( \Lambda \)-CDM models with \( \Omega_m = 0.30 \pm 0.10, h = 0.73 \pm 0.04, \Omega_\Lambda = 0.7 \pm 0.01 \). As pointed out by [7], measuring the X-ray surface brightness involves a measurement of the luminosity distance as well. Therefore if the distance duality relation is violated:

\[
\eta(z) = \frac{D_L(z)}{D_A(1 + z)^2} \neq 1
\]

then the angular diameter distance measured by the cluster will be (see [2]):
FIG. 1: Constraints on the $H_0 - w$ plane from current angular distance measurements of high redshift clusters. The dotted, slash and solid lines correspond to 68%, 95%, 99% confidence levels respectively. Flatness and priors on the Hubble constant and on the age of the Universe are assumed (see text).

\[ D_{A_{Clusters}}(z) = D_A(z)\eta^2(z) \]  

Before a comparison with luminosity distance data we have therefore to compare the clusters angular distance with the theoretical expectations of the standard $\Lambda - CDM$ model in order to see if the data is consistent with no violation of the distance duality relation (see \[7\]).

We then estimate the values of the parameter:
FIG. 2: Values of \( \eta = \sqrt{D_{A,\text{Cluster}}/D_{A,\text{Theory}}} \) derived from each cluster angular diameter distance and the expected angular distance in the concordance model. The error bars include the statistical errors on each cluster plus the uncertainty in the cosmological concordance model. The data is in agreement with a constant-with-redshift \( \eta = 1 \) with \( \eta = 0.97 \pm 0.03 \) at 68% c.l.
FIG. 3: Comparison of luminosity distance data from SN-Ia (Riess et al. 2004, Astier et al. 2005) and angular distance data from SZ/X-Ray cluster observations (rescaled by \((1 + z)^2\)). The datasets are compatible providing no indication for systematics and/or modification of the duality distance relation.

\[
\eta(z) = \sqrt{\frac{D_{\text{Cluster}}}{D_{\text{Theory}}}}
\]  

(7)

where the error bars on this quantity are estimated by combining the experimental error bars and the uncertainties on the concordance model as in [1].

In Fig.2 we plot the results of this analysis. As we can see, the data is in good agreement with a constant value of \(\eta = 1.0\), i.e. yielding no indication for a violation of the distance-duality relation. Considering \(\eta\) as a constant but varying its amplitude we obtain \(\eta = 0.97 \pm 0.03\) at 68\% c.l. with a best-fit of \(\chi^2 = 32.1\) with 38 clusters. This result should be compared with the previous result of \(\eta = 0.91 \pm 0.04\) by [7] based on 17 clusters from the catalog of [10]. Our analysis of the new data therefore improves previous constraints and is more consistent with no violation of the distance duality relation.

As final step, we compare the cluster data with the luminosity distance of high redshift type Ia supernovae from [11] and [13]. Since no violation of the distance duality is observed in the cluster data we assume that the cluster data provide a faithful estimation of the angular distance.
If systematics are present in the SN-Ia, like non conservation of the photon number by absorption from an unknown dust component, we can parametrize their effect as:

\[ D_{SN-Ia}^L(z) = \eta(z)D_L(z) \] (8)

yielding:

\[ D_{SN-Ia}^L = \eta(z)D_A(1+z)^2 \] (9)

In Figure 3 we plot the recent luminosity distance SN-Ia data with the angular diameter distance data multiplied by \((1+z)^2\). As we can see, already from a first qualitative analysis, the datasets are consistent yielding no strong indication for a violation of the distance duality relation. In order to compare the datasets in a quantitative way we consider the weighted average of the data in 7 bins spanning the range \(z = 0.15, ..., 0.8\). For each bin \(i\) we then consider a possible variation of the distance duality relation by a term \(\eta_i\) assumed as constant. For each value of \(\eta_i\) we can therefore construct a likelihood distribution function \(e^{-\chi^2/2}\) where:

\[ \chi^2 = (d_i^L - \eta_i(1+z_i)^2d_A^i)^2/(\sigma_i^L + \eta_i^2(1+z_i)^4\sigma_A^i)^2 \] (10)

where \(d_i^L\) and \(d_A^i\) are the weighted averages of the angular and luminosity distances inside the bin (with error bars \(\sigma_i^{L,A}\)).

We plot in Figure 4 (Top Panel) the normalized likelihood distribution functions for each \(\eta_i\). As we can see a value of \(\eta_i = 1\) is consistent at 68% c.l. with the data in each bin, yielding no evidence for a variation of redshift for \(\eta\). Assuming \(\eta\) as constant over all the redshift range and combining all the datasets we obtain:

\[ \eta = 1.01 \pm 0.07 \] (11)

at 68% c.l., i.e. yielding no evidence for variations in the duality distance relation. The likelihood distribution function for \(\eta\) is plotted in Figure 4 (bottom panel).

### III. CONCLUSIONS

In this paper we demonstrated that the recent measurements of the angular diameter distance of 38 cluster of galaxies using Chandra X-ray data and radio observations from the OVRO and BIMA interferometric arrays place new and independent constraints on the dark energy component. In particular we found that the equation of state is bound to be \(-1.18 < w < -0.35\) at 68% c.l.. We have also constrained possible deviations from the duality relation between luminosity and angular diameter distance. Those deviations may hint for systematics like photon absorption by an unknown dust component or even be a signature of new physics like photon-axion oscillation in an external magnetic field (see e.g. [8]). We found that the ratio between the 2 distances defined as \(\eta = D_L/D_A(1+z)^2\) is bound to be \(\eta = 0.97 \pm 0.03\) at 68% c.l. with no evidence for distance duality violation in the framework of the Λ-CDM model.

We finally compare the cluster angular diameter distance data with luminosity distance data from SN-Ia obtaining the model independent constraint \(\eta = 1.01 \pm 0.07\) at 68% c.l.. Those results provide an useful check for the cosmological concordance model and for the presence of systematics in SN-Ia and cluster data. Future cluster data will reduce the effect of systematics, provide a much better angular distance estimates and, togheter with SN-Ia data, a stronger test of the duality distance relation.
FIG. 4: Likelihood distribution functions for the values of $\eta_i$ in each bin (Top Panel) and for $\eta$ considered as constant over all the redshift range spanned by the data (Bottom Panel). The data is consistent with no violation of the distance duality relation ($\eta_i = 1$) and $\eta = 1.01 \pm 0.07$ at 68% c.l.
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