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# Exploring the expansion dynamics of the universe from galaxy cluster surveys

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ABSTRACT

To understand the expansion dynamics of the universe from galaxy cluster scales, using the angular diameter distance (ADD) data from two different galaxy cluster surveys, we constrain four cosmological models to explore the underlying value of $H_0$ and employ the model-independent Gaussian Processes to investigate the evolution of the equation of state of dark energy. The ADD data in the X-ray bands consists of two samples covering the redshift ranges [0.023, 0.784] and [0.14, 0.89], respectively. We find that: (i) For these two samples, the obtained values of $H_0$ are more consistent with the recent local observation by Riess et al. than the global measurement by the Planck Collaboration, and the $\Lambda$CDM model is still preferred utilizing the information criterions; (ii) For the first sample, there is no evidence of dynamical dark energy (DDE) at the $2\sigma$ confidence level (CL); (iii) For the second one, the reconstructed equation of state of dark energy exhibits a phantom-crossing behavior in the relatively low redshift range over the $2\sigma$ CL, which gives a hint that the late-time universe may be actually dominated by the DDE from galaxy cluster scales; (iv) By adding a combination of Type Ia Supernovae, cosmic chronometers and Planck-2015 shift parameter and HII galaxy measurements into both ADD samples, the DDE exists evidently over the $2\sigma$ CL.



## 1. Introduction

At the end of twentieth century, two cosmological groups discovered that the universe is undergoing a phase of accelerated expansion by using the Type Ia supernovae (SNe Ia) observations [1,2]. In the past about two decades, this mysterious phenomenon is well confirmed by the most recent SNe Ia data [3] and other astronomical observations such as cosmic microwave background (CMB) radiation [4], baryonic acoustic oscillations (BAO) [5], observational Hubble parameter [6], and so forth. To explain the accelerated mechanism, cosmologists have proposed an exotic and negative pressure fluid dubbed dark energy (DE). To date, the realistic nature of DE is still unknown, but its main properties are substantially explicit: (i) it must be homogeneously and isotropically distributed on large cosmological scales; (ii) the modulus of its effective pressure $p$ needs to be comparable to its energy density, namely $|p| \sim \rho$. In the literature, the simplest model to depict DE is the concordance model of cosmology, i.e., the so-called $\Lambda$-cold-dark-matter ($\Lambda$CDM) model, which is characterized by the equation of state (EoS) of DE $\omega = -1$. Although the $\Lambda$CDM model can explain successfully many aspects of the observational universe, it still faces two fatal problems, namely the fine-tuning and coincidence problems [7]. The former implies that the theoretical value for the vacuum energy density are far larger than its observational value, i.e., the well-known 120-orders-of-magnitude discrepancy that makes the vacuum explanation very puzzling; while the latter indicates why the energy densities of the dark matter (DM) and DE are of the same order at the present time, since their energy densities are so different from each other during the evolutional process of the universe. Recently, using new calibration techniques and indicators, Riess et al. reported the improved local measurement of the Hubble constant $H_0 = 73.24 \pm 1.74$ km s$^{-1}$ Mpc$^{-1}$ (hereafter R16) [8], which exhibits a stronger tension with the Planck 2015 release $H_0 = 66.93 \pm 0.62$ km s$^{-1}$ Mpc$^{-1}$ (hereafter P15) [9] at the $3.4\sigma$ CL. All these facts suggests that the true nature of DE may not be the cosmological constant $\Lambda$, and pose two great challenges to explore the expansion dynamics for cosmologists:

⋆ Is actually DE a time-dependent physical component ($\omega \neq -1$) or dominated by a cosmological $\Lambda$ term?

⋆ Theoretically, new physics is urgent to be mined to explain the current $H_0$ tension; Experimentally, how to determine more reasonably the value of $H_0$ with higher accuracy?

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To address these two issues, using the model-independent Gaussian Processes (GP), we have performed the improved constraints on the EoS of DE in light of recent cosmological data including 580 SNe Ia, 30 cosmic chronometers and Planck-2015 shift parameter [10], which indicates that the $\Lambda$CDM model is still supported by these data and the results of reconstructions support substantially R16's local measurement of $H_0$. Then, we also explore the values of $H_0$ and constrain the EoS of DE by only using the latest HII galaxy measurements [11], and find that the obtained values of $H_0$ are more consistent with the R16's local observation than P15's global measurement, and the $\Lambda$CDM model can fit the data well at the $2\sigma$ CL. Following this logical line, we are full of interest in exploring the underlying value of $H_0$ in a larger local scale than HII galaxies. As a consequence, we continue investigating the expansion dynamics of our universe from galaxy cluster scales. As is well known, galaxy clusters are the largest gravitationally collapsed structures in the universe, with a hot diffuse plasma ($T \sim 10^7$–$10^8$ K) that fills the intergalactic space, and they are also important cosmological probes to distinguish various cosmic evolutional models [12].

This paper is organized as follows: In Section 2, we describe the ADD data used in this analysis. In Section 3, we constrain four cosmological models by using the ADD data. In Section 4, we employ the GP method to constrain the EoS of DE. The discussions and conclusions are presented in the final section.

## 2. The ADD data

In this analysis, we adopt two galaxy cluster samples, which are based on different morphologies and dynamics, to explore the expansion dynamics of the universe. These two samples has been widely used to test the validity of the Einstein equivalence principle combining with other cosmological probes such as SNe Ia and strong gravitational lensing [13–15].

The first sample consists of 25 galaxy clusters lying in the redshift range $z \in [0.023, 0.784]$ from [12]. Motivated by images from the Chandra and XMM-Newton telescopes, which shows an elliptical surface brightness of galaxy clusters, the authors utilized an isothermal elliptical $\beta$ model to depict the galaxy clusters, and constrain the intrinsic shapes of galaxy clusters to obtain the ADD data by combining X-ray and Sunyaev–Zel'dovich (SZ) observations. The 25 ADD data points were obtained for two sub-samples: 18 galaxy clusters from [16] and 7 from [17], where a spherical $\beta$ model was assumed.

The second sample are formed by 38 galaxy clusters in the redshift range $z \in [0.14, 0.89]$ assuming the hydrostatic equilibrium model, which were obtained by using X-ray data from Chandra and SZ effect data from the Owens Valley Radio Observatory and the Berkeley–Illinois–Maryland Association interferometric arrays [18]. It is worth noting that, assuming generalized $\beta$ spherical models, the authors obtained the ADD data by analyzing the cluster plasma and dark matter distributions. As described in [18], all the data points are almost followed by asymmetric uncertainties. To deal with this, we adopt a simple dealing method to obtain the data with symmetric uncertainties. In [19], this method has been used to acquire data for comparing different morphological models of galaxy clusters (i.e., elliptical $\beta$ model and spherical $\beta$ model) through model-independent tests of cosmic distance duality relation (CDDR), and it can be concluded as

$$E(D_A) = D_A, \qquad \sigma_{D_A} = \max(\sigma_+, \sigma_-), \tag{1}$$

where $D_A$, $E(D_A)$, $\sigma_{D_A}$, $\sigma_+$ and $\sigma_-$ denote the ADD, expected value of ADD, $1\sigma$ standard deviation of ADD, the upper and lower limits of data error, respectively. More specifically, we use the reported value of ADD $D_A$ as the expected value $E(D_A)$ and the larger flank of each two-sided error as the $1\sigma$ standard deviation $\sigma_{D_A}$.

In history, Etherington verified the CDDR based on the following two assumptions for the first time in 1933 [20]:

⋆ The light travels always along the null geodesics in a Riemannian geometry;

⋆ The number of photons is conserved over during the evolutional process of the universe.

The CDDR is also called Etherington's reciprocity relation, and it connects two different scale distances via the identity

$$\frac{D_L}{D_A(1+z)^2} = \eta = 1, \tag{2}$$

which relates the luminosity distance (LD) $D_L$ and the ADD $D_A$ at the same redshift $z$. It is noteworthy that, using the current astronomical observations, one can test the correctness of the general metric theories of gravity including the Einstein's one, which correspond to the case of $\eta = 1$ (for details, see [21]). In a Friedmann–Robertson–Walker (FRW) universe, the expression of the LD $D_L(z)$ can be written as

$$D_L(z) = \frac{1+z}{H_0\sqrt{|\Omega_k|}} \mathrm{sinn}\left(\sqrt{|\Omega_k|}\int_0^z \frac{dz'}{E(z';\theta)}\right), \tag{3}$$

where $\theta$ denotes the model parameters, $H_0$ is the Hubble constant, the dimensionless Hubble parameter $E(z;\theta) = H(z;\theta)/H_0$, the present-day cosmic curvature $\Omega_k = -K/(a_0 H_0^2)$, and for $\mathrm{sinn}(x) = \sin(x), x, \sinh(x), K = 1, 0, -1$, which corresponds to a closed, flat and open universe, respectively.

In our analysis, we transform the ADD data to the available effective LD data at the same $z$ by assuming $\eta = 1$. Then, in order to constrain different cosmological models, we perform the so-called $\chi^2$ statistics using different expressions of the LD:

$$\chi^2 = \sum_{i=1}^{N}[\frac{D_{L_{obs}}(z_i) - D_{L_{th}}(z_i;\theta)}{\sigma_i}]^2, \tag{4}$$

where $\sigma_i$, $D_{L_{obs}}(z_i)$ and $D_{L_{th}}(z_i)$ denote the $1\sigma$ error, the effectively observed and theoretical value of the LD at a given redshift $z_i$ for every galaxy cluster, respectively, and $N$ denotes two different sample sizes (i.e., for the first and second samples, $N = 25$ and 38, respectively).

## 3. The constraints on DE models

In order to investigate the values of $H_0$, we constrain four different cosmological models by using the transformed LD data from galaxy clusters. These four models are, respectively, the spatially flat $\Lambda$CDM, non-flat $\Lambda$CDM, $\omega$CDM and decaying vacuum (DV) models.

The dimensionless Hubble parameter for the spatially flat $\Lambda$CDM model ($\omega = -1$) is

$$E(z) = \sqrt{1 - \Omega_m + \Omega_m(1+z)^3}, \tag{5}$$

and for the spatially non-flat $\Lambda$CDM model it is written as

$$E(z) = \sqrt{1 - \Omega_m + \Omega_k(1+z)^2 + \Omega_m(1+z)^3}, \tag{6}$$

where $\Omega_m$ is the dimensionless matter density ratio parameter at the present epoch.

In the spatially-flat $\omega$CDM parametrization we have

$$E(z) = \sqrt{(1-\Omega_m)(1+z)^{3(1+\omega)} + \Omega_m(1+z)^3}, \tag{7}$$

where $\omega$ is the constant, negative, EoS parameter connecting the DE fluid pressure with energy density through $p = \omega\rho$.

Another consideration is the so-called DV model, which is aimed at resolving the famous fine-tuning problem by assuming the cosmological constant to be dynamical. Generally, to obtain a definite DV model, one should specify a vacuum decay law.