Abstract. Considering a parametrization of the dark energy density, we explore signatures of evolution using data from gas mass fraction in clusters, type Ia supernova, BAO and CMB. We find, in agreement with previous studies, a preference for a evolution of $\rho_{de}(z)$ towards negative values, a surprising result in agreement with the recent BAO DR11 data.
1 Introduction

The ΛCDM model is the simplest model that fits a varied set of observational data. In this setup the cosmological constant Λ drives the current accelerated expansion of the universe, detected for the first time using type Ia supernovae [1, 2]. Although successful in fitting the data, the model is awkward in many ways: for example, we do not know what this constant is in the first place. We also do not expect to live in a special epoch where both the contribution of this constant be of the same order than the non relativistic matter contribution. This problem in particular is known as the “cosmic” coincidence problem.

From a theoretical point of view it is most natural to think that this contribution comes from an evolving source (with epoch) whose connection with the universe expansion is under study. Dark Energy (DE) is the name of this mysterious source [3].

Different DE models have been proposed to provide the mechanism that explains the observational data. There are models where a new field component is assumed to fill the universe, known as quintessence [4], and models where the mechanism is triggered by using a modified gravity theory [5].

In general, it appears practical to assume the existence of a dynamical source, or a theoretical model with a dynamical equation of state parameter \( w(z) = p/\rho \).

In 2009 the authors of [16], using the Constitution data set for SNIa [9], and the Chevalier-Polarski-Linder (CPL) parametrization for \( w(z) \) [18], [19]

\[
w(a) = w_0 + (1 - a)w_1, \tag{1.1}
\]

with \( w_0 \) and \( w_1 \) free parameters to be fixed by observations, found the SNIa data favor a scenario in which the acceleration of the expansion has past a maximum value and is now decelerating. However, once the BAO and CMB data were considered, the result changed completely, indicating that the universe increase their acceleration. Using the Union 2 data set [20] the authors in [21] found similar conclusions, under the assumption of a flat universe. In [12], we revisit this problem using the Union 2 data set extending the analysis to curved spacetimes. We found that using a small curvature parameter (\( \Omega_k \simeq -0.08 \)) all the three observational tests (SNIa, BAO and CMB) suggest the acceleration of the expansion has already reached its maximum, and is currently moving towards a decelerating phase.

In a recent paper [17], using gas mass fraction in galaxy clusters \( f_{\text{gas}} \), we found independent evidence for a low redshift transition of the deceleration parameter, the same behaviour found previously with SNIa. Because the \( f_{\text{gas}} \) data expand a similar redshift range as the SNIa, but depends on a completely different physics, this finding is of utmost importance.
We are also aware that this behavior - a low redshift transition of the deceleration parameter - does not depend on a particular parametrization \cite{13}. However, the analysis based on using \( w(z) \) increases the errors in the parameters we want to constraint. The problem of using \( w(z) \) as the focus of study was demonstrated in \cite{14},\cite{15}. The essential problem is that the observational quantity, as the luminosity distance or the angular diameter distance, depends on \( w(z) \) through a double integral smearing out the information about \( w(z) \) itself and its time variation.

If the key thing we want to demonstrate is a time variation of the cosmological “constant”, we do not need to work with \( w(z) \) or a particular parametrization of it, instead we just need to work directly with the dark energy density, whatever it be. This strategy was started in \cite{29}, \cite{30}, where the authors demonstrated the advantage of using the energy density instead of the EoS parameter as the main function to constraint.

In this paper we investigate the evolution of the dark energy density in light of recent data. We use gas mass fraction in clusters \cite{27} - 42 measurements of \( f_{\text{gas}} \) in clusters extracted from \cite{26} - and also type Ia supernovae (SNIa) from the Union 2 data set \cite{20}. We also consider the constraints obtained from baryon acoustic oscillations (BAO) and cosmic microwave background radiation (CMB).

The paper is organized as follows: in the next section we describe how to implement the interpolation method to constraint the DE density model using the observational data available. Then we present the results of our study, first using SNIa and \( f_{\text{gas}} \) data and then within a joint analysis. We end with a discussion of the results.

2 The Method

Observational cosmology is essentially based on quantities derived from the Hubble function. For example, using both type Ia supernova or galaxy cluster data, the key functions are written in terms of the comoving distance from the observer to redshift \( z \) given by

\[
r(z) = \frac{c}{H_0} \frac{1}{\sqrt{-\Omega_k}} \sin \sqrt{-\Omega_k} \int_0^z dz' \frac{E(z')}{E(z)},
\]

where \( E(z) = H(z)/H_0 \) contains the cosmology. For example, for the case of the \( \Lambda \)CDM model the function is,

\[
E^2(z) = \Omega_m (1 + z)^3 + \Omega_r (1 + z)^4 + \Omega_k (1 + z)^2 + \Omega_X.
\]

Here \( \Omega_m \) consider all the contribution for DM. We know the radiation component \( h^2 \Omega_r = 2.47 \times 10^{-5} \) is very small at low redshift, where DE is important. However, if we want to constraint our model using data from BAO and CMB, we have to use it, because these probes refers to both the last scattering redshift and the drag epoch.

In order to explore eventual redshift evolution of the DE density, we define the function \( X(z) = \rho_{\text{de}}(z)/\rho_{\text{de}}(0) \), and write the Hubble function as

\[
E^2(z) = \Omega_m (1 + z)^3 + \Omega_r (1 + z)^4 + \Omega_k (1 + z)^2 + \Omega_X X(z),
\]

where \( \Omega_m + \Omega_r + \Omega_k + \Omega_X = 1 \). In the special case of using the CPL parametrization for \( w(z) \) Eq.(1.1), we find that

\[
X(z) = e^{- \frac{3w_{01}z}{1+w_{01}} \left( 1 + z \right)^{3(1+w_0+w_1)}},
\]
that can be interpreted as a very special parametrization for $X(z)$.

In this work we want to use the method suggested in [29], [30], and extended in [31], [32] parameterizing the DE density through a quadratic interpolation with two free parameters. In this work we restrict ourselves to this number of free parameter, just to compare with previous ones [33] and maintain a meaningful statistical analysis. In this case we use

$$X(z) = 1 + \frac{z(4f_1 - f_2 - 3)}{z_m} - \frac{2z^2(2f_1 - f_2 - 1)}{z_m^2},$$

(2.5)

where $z_m$ is the maximum redshift value of the data, and where the free parameters are: $f_1 = X(z_m/2)$ and $f_2 = X(z_m)$.

3 Results

Using the data from the Union 2 set [20], consisting in 557 SNIa, and also from [26] which consist in 42 measurements of the X-ray gas mass fraction $f_{gas}$ in relaxed galaxy clusters (the details of data handling are explained in [17]), we obtain the best fit values of the model (2.5) using the Hubble function (2.3) in (2.1). The SNIa data give the luminosity distance $d_L(z) = (1+z)r(z)$. We fit the SNIa with the cosmological model by minimizing the $\chi^2$ value defined by

$$\chi^2_{SNIa} = \sum_{i=1}^{557} \frac{[\mu(z_i) - \mu_{obs}(z_i)]^2}{\sigma_{\mu i}^2},$$

(3.1)

where $\mu(z) \equiv 5 \log_{10}[d_L(z)/\text{Mpc}] + 25$ is the theoretical value of the distance modulus, and $\mu_{obs}$ is the corresponding observed one. The gas mass fraction data we use is from [26] which consist in 42 measurements of the X-ray gas mass fraction $f_{gas}$ in relaxed galaxy clusters spanning the redshift range $0.05 < z < 1.1$. The $f_{gas}$ data are quoted for a flat $\Lambda$CDM reference cosmology with $h = H_0/100 \text{ km s}^{-1}\text{Mpc}^{-1} = 0.7$ and $\Omega_M = 0.3$. To obtain the restrictions we use the model function [28]

$$f_{gas}^{\Lambda CDM}(z) = \frac{b\Omega_b}{(1 + 0.19\sqrt{h})\Omega_M} \left[\frac{d_A^{\Lambda CDM}(z)}{d_A(z)}\right]^{3/2},$$

(3.2)

where $b$ is a bias factor which accounts that the baryon fraction is slightly lower than for the universe as a whole (see details in [12]). Using these data we find $f_1 = 0.86 \pm 0.14$ and $f_2 = 0.24 \pm 0.77$. We plot the DE density as a function of redshift in Fig.(1), with error propagation at one sigma. Notice the intriguing trend of a decaying DE density with increasing redshift, although it is still marginally consistent with a cosmological constant at one sigma.

We also consider the constraints from BAO and CMB. The BAO measurements considered in our analysis are obtained from the WiggleZ experiment [22], the SDSS DR7 BAO distance measurements [23], and 6dFGS BAO data [24]. We also include CMB information by using the WMAP 9-yr data [25] to probe the expansion history up to the last scattering surface. Once we consider the data from BAO and CMB, together the SNIa and $f_{gas}$, the results are $f_1 = 0.98 \pm 0.14$ and $f_2 = 0.91 \pm 0.76$. We plot the DE density as a function of redshift in Fig.(2), with error propagation at one sigma. This results resemble the one obtained in [16] using the reconstructed deceleration parameter $q(z)$. In that work, and also in the subsequent ones [21], [12], the authors use the CPL
parametrization for $w(z)$. The striking result, which as far as we know nobody has mentioned before, is that once the deceleration parameter shows a rapid change at small redshift, this implies a decreasing energy density with increasing redshift.

In fact, using the CPL parametrization and performing the statistical analysis, we find the best fit values of the parameters which in turns give us the best Hubble function $E(z)$ in terms of redshift that agrees with the data. From it, we can compute the deceleration parameter as

$$q(z) = -(1+z) \left( \frac{1}{E(z)} \frac{dE(z)}{dz} \right) - 1,$$  \hspace{1cm} (3.3)
Figure 3. Using the Union 2 data set [20] we plot the deceleration parameter reconstructed using the best fit values for the SNIa case. We consider the error propagation at one sigma in the best fit parameters.

Figure 4. Using the Union 2 data set [20] we plot the DE density (2.4) reconstructed using the best fit values for the SNIa case. We consider the error propagation at one sigma in the best fit parameters.

and also – something that was not performed in the previous works mentioned – we can plot the associated $X(z)$ from (2.4). Using the result of fitting the SNIa data only, the best fit parameters are $w_0 = -0.86 \pm 0.38$ and $w_1 = -5.5 \pm 5.4$. The deceleration parameter with error propagation is shown in Fig.(3) and the DE density $X(z)$ in Fig.(4). It is very clear that these data rule out completely a cosmological constant at within one sigma.

As we demonstrated in [12], the same trend is obtained using the gas mass fraction data. This means that such a behavior is not a peculiar result of SNIa data, but it is confirmed by using data that respond to different physics, revealing something about our local universe.

It is also interesting to mention that such a behavior – a low redshift transition of the
deceleration parameter \( q(z) \) (3.3) – was previously found first (as far as we know) in [34], in the context of Lemaitre-Tolman-Bondi inhomogeneous models. In this work, and in recent ones [35], [36], the authors derived an effective deceleration parameter for void models, indicating that such a behavior of \( q(z) \) may be considered a signature for the existence of voids.

Furthermore, a decreasing DE density with increasing redshift is also found in a recent BAO data release [37], where a tension between BAO data and CMB is found. This tension reveals that, in order to accommodate these new data, is not sufficient to go into models with nonzero curvature or a constant \( w \neq -1 \) DE, essentially because the data requires a decreasing \( D_A(2.34) \) while increasing \( D_H(2.34) \). The striking result, assuming a flat universe with dark matter and DE is that

\[
\frac{\rho_{de}(z = 2.34)}{\rho_{de}(z = 0)} = -1.2 \pm 0.8, \tag{3.4}
\]

in agreement with what we have found in this work.

4 Discussion

In this paper we have presented a study of the evolution of the DE density in light of recent data. We use gas mass fraction in clusters - 42 measurements of \( f_{\text{gas}} \) in clusters extracted from [26] - and also data of type Ia supernovae from the Union 2 set [20]. We also consider the constraints obtained adding measurements from baryon acoustic oscillations (BAO) and cosmic microwave background radiation (CMB). We have found evidence that relates the previously found low redshift transition of the deceleration parameter – indicating that the acceleration has pass a maximum around \( z \approx 0.2 \) and now evolve towards a decelerating phase in the near future – with a decreasing DE density evolution with increasing redshift. This result confirms the tension between the data at low redshift and those from CMB. This results is also consistent with a recent BAO measurement of BOSS DR11 [37], which shows the data prefers a decreasing DE density with increasing redshift.

In general, the tension between low and high redshift data found in this paper, does not allow us to conclude anything about the DE density evolution. However, because we expect the DE component be dominant at recent (low redshift) epoch, and the fact that now data from SNIa, gas mass fraction and the recent BAO DR11 results, all seem to agree with this peculiar behavior at low redshift, we can only conclude that something in our near neighborhood is producing this result. This conclusion is also reinforced with the astonishing similarity between our finding and the result using LTB inhomogeneous model, where the effective deceleration parameter shows the same transition at low redshift assuming we live inside a void. So, it is clear that a careful study of low redshift behavior is needed to enlighten our understanding of DE.

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