

Testing dark energy beyond the cosmological constant barrier

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Although well motivated from theoretical arguments, the cosmological constant barrier, i.e., the imposition that the equation-of-state parameter of dark energy ($\omega_x \equiv p_x/\rho_x$) is ≥ -1 , seems to introduce bias in the parameter determination from statistical analyses of observational data. In this regard, phantom dark energy or superquintessence has been proposed in which the usual imposition $\omega \geq -1$ is relaxed. Here, we study possible observational limits to the phantom behavior of the dark energy from recent distance estimates of galaxy clusters obtained from interferometric measurements of the Sunyaev-Zel'dovich effect and x-ray observations, type Ia supernova data, and cosmic microwave background measurements. We find that there is much acceptable parameter space beyond the Λ barrier, which opens, from a purely observational point of view, the possibility of the existence of more exotic forms of energy in the Universe.

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I. INTRODUCTION

Dark energy or quintessence is the invisible fuel that seems to drive the current acceleration of the Universe. Phenomenologically, this energy component is usually described by an equation-of-state parameter ω_x which represents the ratio of the dark energy pressure to its energy density, $\omega_x \equiv p_x/\rho_x$. In order to achieve cosmic acceleration, Einstein field equations (EFEs) require ω_x to be less than $-1/3$ for a universe described by a single component whereas for a dark matter and dark energy dominated universe the required value, $\omega_x < -(\Omega_m/3\Omega_x + 1/3)$, depends on the ratio between the baryonic or dark matter (Ω_m) and dark energy density parameters (Ω_x). In other words, what the EFEs mean with these upper limits is that any physical field with a positive energy density and negative pressure, which violates the strong energy condition ($\rho + 3p > 0$), may cause antigravity regimes (see [1] for a review on classical energy conditions).

Since cosmic acceleration from EFEs provides only an upper limit to ω_x , a point of fundamental importance associated with this parametrization for the dark energy equation of state (ES) is related to the physical and/or observational lower limits that may be imposed on the parameter ω_x . Physically, if one wants dark energy to be stable, then it must obey the null energy condition which, in the Friedmann-Robertson-Walker metric, is equivalent to $\rho + p > 0$. This energy condition implies $\omega_x \geq -1$ when applied to a dark energy component described by $\omega_x \equiv p_x/\rho_x$ or, equivalently, that the vacuum energy density or the cosmological constant (Λ), which is characterized by $\omega_x = -1$, would constitute the natural lower limiting case. Following this reasoning, first made explicit in [2], a number of theoretical and observational analyses in which the restriction $-1 \leq \omega_x < 0$ is imposed have appeared in the recent literature [3]. However, by focusing our attention only on the observational side, what would current observations have to tell us about that? As well observed by Caldwell [4], it is curious that most of the

observational constraints on ω_x are consistent with models that go right up to the $\omega_x = -1$ border. Thus, paraphrasing him, one might ask what lies on the other side of the cosmological constant barrier.

The answer to this question has been given by several authors who have also pointed out some strange properties of phantom dark energy ($\omega_x < -1$); such as, for instance, the fact that its energy density increases with the expansion of the Universe in contrast with the usual quintessence ($\omega_x \geq -1$); the possibility of a rip-off of the large and small scale structure of matter; the possible occurrence of future curvature singularity, etc. [5]. Although having these unusual characteristics, a phantom behavior is predicted by several scenarios, e.g., kinetically driven models [6] and some versions of brane world cosmologies [7] (see also [1] and references therein). Moreover, from the observational point of view, phantom energy is found to be compatible with most of the classical cosmological tests and seems to provide a better fit to type Ia supernovae (SNe Ia) observations than do cold dark matter models with a cosmological constant (Λ CDM) or generic quintessence scenarios ($\omega_x \geq -1$) [8]. Therefore, given our state of complete ignorance about the nature of dark energy, it is worth asking whether current observations are able to shed some light on the other side of the Λ barrier.

Our aim, in this article, is to seek possible observational limits to the phantom behavior of the dark energy ES, as well as to detect the bias in the ES parameter determination due to the imposition $\omega_x \geq -1$, from recent distance estimates of galaxy clusters obtained from interferometric measurements of the Sunyaev-Zel'dovich effect (SZE) and x-ray observations. We use, for that, the largest homogeneously analyzed sample of the SZE/x-ray clusters with angular diameter distance (ADD) determinations thus far, as provided by Reese *et al.* [9]. In order to constrain more precisely regions of the parameter space, we also combine SZE/x-ray ADD data with the newest SNe Ia sample of the Supernova Cosmology Project [10], recent determinations of the matter density parameter, Wilkinson Microwave Anisotropy Probe (WMAP) distance estimates [11] and the latest measurements of the Hubble parameter as given by the HST key project [12]. In agreement with other independent analyses, it is shown that

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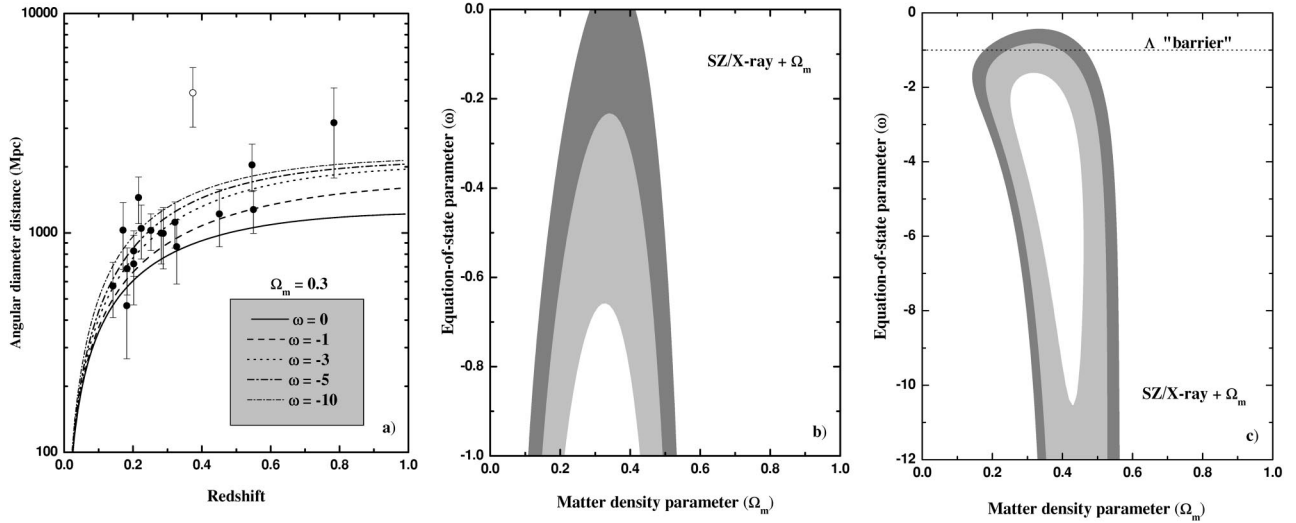


FIG. 1. (a) SZE/x-ray determined distances for 18 clusters as a function of redshift for a fixed value of $\Omega_m = 0.3$ and selected values of the ES parameter. The open circle corresponds to the Abell 370 cluster which has been excluded from the statistical analyses. (b) Confidence regions (68%, 95% and 99%) in the Ω_m - ω plane provided by the SZE/x-ray ADD data from Reese *et al.* [9] by assuming a Gaussian prior on the matter density parameter $\Omega_m = 0.35 \pm 0.07$. (c) The same as in (b) with the Λ barrier removed.

with or without such a combination, these observational data do prefer the supernegative behavior of the dark energy equation of state.

II. SZE, X-RAY EMISSION, AND DISTANCE ESTIMATES

Among the sources of temperature fluctuations in the cosmic microwave background radiation (CMBR), a small distortion due to inverse Compton scattering of CMBR photons passing through an intracluster medium is of particular importance to estimating distances to galaxy clusters. This is so because for a given temperature this effect, known as the Sunyaev-Zel'dovich effect [13], is proportional to the line integral of the electron number density through the cluster, $\Delta T \propto \int n_e T_e d\ell$, while the x-ray bremsstrahlung surface brightness scales as $S_X \propto \int n_e^2 d\ell$. Thus, by using x-ray spectroscopy to find the temperature of the gas and by making some assumptions on the cluster geometry, the distance to the cluster may be estimated (see [14] for recent summaries).

By applying this technique, suggested long ago [15], Reese *et al.* [9] determined the distance to 18 galaxy clusters with redshifts ranging from 0.14 to 0.78, which constitutes the largest homogeneously analyzed sample of the SZE/x-ray clusters with distance determinations thus far. From these intermediary and high- z measurements, the authors estimated the Hubble parameter for three different cosmologies, with the uncertainties agreeing with the HST key project results [12], which probes the expansion rate in the nearby universe. Since the redshift range of the galaxy cluster sample is comparable to the intermediary and high- z SNe Ia data compiled by the Supernova Cosmology Project [10,16] and the High- z Supernova Team [17], we understand that it may also provide an independent cross-check of the cosmic acceleration mechanism. Thus, in what follows, we use these data as well as a combination of them with SNe Ia measurements to place

observational limits on the ES parameter of the phantom dark energy.

III. ANALYSIS

With the usual assumption that the effective equation of state, $\omega \sim \int \omega_x(z) \Omega_x(z) dz / \int \Omega_x(z) dz$, is a good approximation for a wide class of dark energy scenarios [18], the angular diameter distance as a function of the redshift can be written as

$$D_A(z; \Omega_m, \omega) = \frac{3000h^{-1}}{(1+z)} \int_0^z \frac{dz'}{\mathcal{E}(z'; \Omega_m, \omega)} \text{ Mpc}, \quad (1)$$

where the dimensionless function $\mathcal{E}(z'; \Omega_m, \omega)$ is given by

$$\mathcal{E} = [\Omega_m(1+z')^3 + (1-\Omega_m)(1+z')^{3(1+\omega)}]^{1/2}. \quad (2)$$

Figure 1(a) shows the SZE/x-ray determined distances for 18 clusters as a function of redshift for a fixed value of $\Omega_m = 0.3$ and selected values of the ES parameter. Note that Abell 370 cluster (the open circle) is clearly an outlier in the sample so that, following [9,19], we exclude it from the statistical analyses that follow. In Fig. 1(b) we show the confidence regions (68%, 95%, and 99%) in the plane Ω_m - ω from SZE/x-ray ADD data. Since we have nowadays good estimates of the dark matter density [20], we have assumed a Gaussian prior on the matter density parameter, i.e., $\Omega_m = 0.35 \pm 0.07$. Such a value, which is in good agreement with dynamical estimates on scales up to about $2h^{-1}$ Mpc [20], is derived by combining the ratio of baryons to the total mass in clusters determined from SZE/x-ray measurements with the latest estimates of the baryon density $\Omega_b = (0.020 \pm 0.002)h^{-2}$ [21] and the final value of the Hubble parameter obtained by the HST Key Project $H_0 = 72$

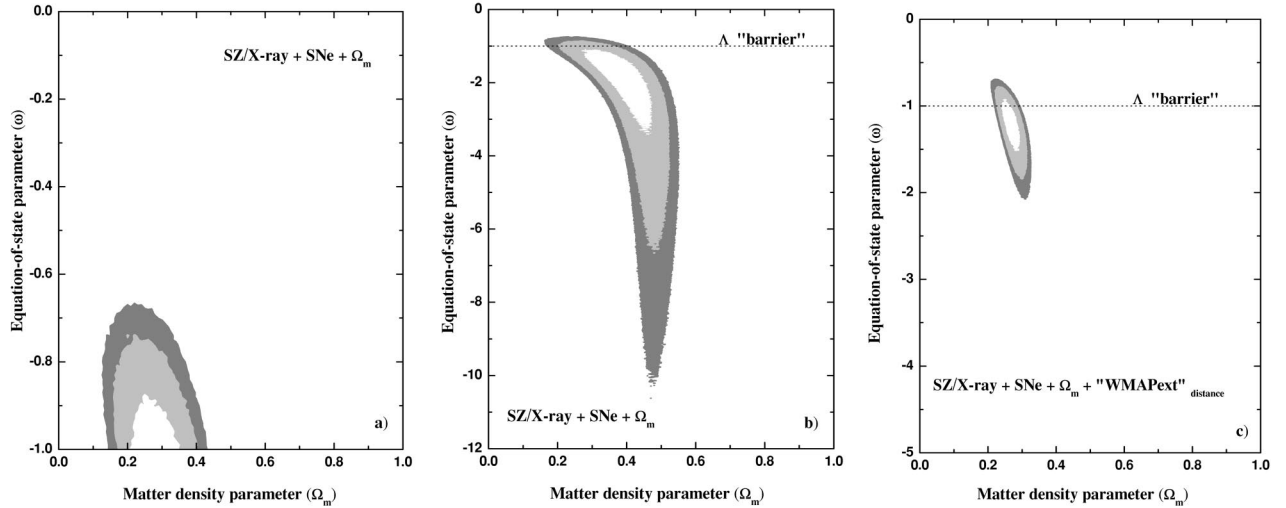


FIG. 2. (a) The likelihood contours in the Ω_m - ω plane for the joint SZE/x-ray ADD + Ω_m + SNe Ia analysis described in the text. The contours correspond to 68%, 95%, and 99% confidence levels. (b) The same as in (a) with the Λ barrier removed. For this analysis the best fit values are located at $\omega = -1.7$ and $\Omega_m = 0.38$. (c) The same as in (b) with the “WMAPext” constraint on the angular size distance to the decoupling surface at $z = 1089$. The best-fit model converges to $\omega = -1.2$ (and $\Omega_m = 0.27$), with a 68% confidence bound of $-1.38 \leq \omega \leq -1.09$.

$\pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [12]. As the figure shows, given the Λ barrier, the best-fit converges to $\omega = -1$ (and $\Omega_m = 0.32$), with a 68% confidence bound of $\omega \leq -0.84$.

A generalization of this analysis to a parameter space that extends ω to values smaller than -1 is presented in Fig. 1(c) (in all extended analyses, we have used a χ^2 minimization for the range of Ω_m and ω spanning the interval $[0,1]$ and $[-15,0]$, respectively). There, it is shown that there is much observationally acceptable parameter space beyond the Λ barrier, in full agreement with other similar analyses [22–24]. In actual fact, the best-fit model for these data sets occurs for $\Omega_m = 0.36$ and $\omega = -3.5$ ($\chi_{min}^2 = 10.8$) with a 68% confidence bound of $-5.5 \leq \omega \leq -2.2$ ($0.30 \leq \Omega_m \leq 0.41$). In particular, this best-fit model corresponds to an accelerating universe with deceleration parameter $q_o \approx -2.8$ and total expanding age of $9.7h^{-1}$ Gyr. It is also worth noticing that extreme values of ω are allowed because for intermediary and high redshifts angular diameter distances become quite insensitive to large variations of the ES parameter [see Fig. 1(a)]. For example, at $z = 0.78$ (the redshift of MS1137, the farthest galaxy cluster), the angular diameter distance for $\Omega_m = 0.3$ and $\omega = -3$ ($\mathcal{D}_A \approx 1840$ Mpc) is only $\sim 10\%$ smaller than in a model with the same amount of dark matter and $\omega = -10$ ($\mathcal{D}_A \approx 2045$ Mpc). This particular behavior is quite similar to what happens in analyses involving age estimates. There, as here, the function of the cosmological parameters (Ω_m and ω) quickly asymptotes for large values of ω [25].

In our search for possible lower limits to the ES of the phantom component, we now perform a joint analysis of SZE/x-ray ADD and SNe Ia data. For that, we use the newest SNe Ia sample of the Supernova Cosmology Project [10] (with stretch and extinction correction applied) and follow the analytical marginalization method for the “zero point magnitude” \mathcal{M} as given in Ref. [26]. The results of the

present analysis are shown in Figs. 2(a) and 2(b). In Fig. 2(a) we show the 68%, 95%, and 99% C.L.s in the Ω_m - ω plane by imposing the Λ barrier ($\omega \geq -1$). From this combination of observational data sets we find that the best-fit model occurs exactly on the $\omega = -1$ border with $\Omega_m = 0.29$ and $\chi_{min}^2/\nu \approx 1.26$. At 95% C.L., we obtain $\omega \leq -0.83$ and $0.19 \leq \Omega_m \leq 0.37$. Figure 2(b) generalizes the previous analysis to include more negative values of the dark energy ES. Again, we find that there is much acceptable parameter space beyond the line $\omega = -1$ and that the confidence regions are modified by its presence, which clearly indicates the existence of bias in the parameter determination due to the Λ barrier. This particular analysis provides a 68% confidence bound of $-1.98 \leq \omega \leq -1.42$ and $0.30 \leq \Omega_m \leq 0.45$, with the best-fit model happening at $\omega = -1.7$ and $\Omega_m = 0.38$ ($\chi_{min}^2/\nu \approx 1.2$), which corresponds to an accelerating universe with deceleration parameter $q_o \approx -1.0$ and total expanding age of $9.3h^{-1}$ Gyr. If one combines this 68% confidence bound on ω with the upper limit from the EFEs, one would have $-1.9 \leq \omega < -1/3$ instead of the usual $-1 \leq \omega < -1/3$.

At this point, it is important to observe that the very-low- ω region of the above analyses can be considerably reduced by combining them with high- z data such as, for instance, the current CMB measurements (see, e.g., [27]). To better visualize that, Fig. 2(c) shows the results of a combined test involving SZE/x-ray ADD + SNe Ia data and the “WMAPext” constraint (which includes other CMB experiments in addition to WMAP) on the angular size distance to the decoupling surface at $z = 1089$, i.e., $d = 14.0_{-0.3}^{+0.2}$ Gpc [11]. This analysis shows that the best-fit model moves up to converge at $\omega = -1.2$ (and $\Omega_m = 0.27$), with a 68% confidence bound of $-1.38 \leq \omega \leq -1.09$. These results, along with the gradual decrease of the low- ω region seen from

Figs. 1(a)–2(c), clearly show that SNe Ia and CMB measurements dominate the analyses over SZE/x-ray ADD data, which can be directly associated with the current systematics uncertainties on these latter measurements. As commented in Ref. [9], such systematics are observationally approachable and will be addressed in the coming years through the current generation of x-ray satellites (Chandra and XMM-Newton) and radio observatories (OVRO, BIMA, and VLA). Surely, these improvements will be very welcome once the SZE/x-ray determined distances are measurements independent of the extragalactic distance ladder that may provide the distance to high- z galaxy clusters. With such a future sample of high- z objects, it is expected that SZE/x-ray ADD data will be able to provide a valuable independent check of SNe Ia and primary CMB power spectrum results.

We now compare our results with other recent limits on the ES parameter of the phantom energy derived by independent methods. For example, in Ref. [22] data from CMBR, large scale structure (LSS), and SNe Ia were combined to find a 95% confidence bound of $-2.68 < \omega < -0.78$. Such results agree with the constraints obtained from a combination of Chandra observations of the x-ray luminosity of galaxy clusters with independent measurements of the baryonic matter density and the latest measurements of the Hubble parameter. This last analysis gave $-2.0 \leq \omega \leq -0.6$ at 68% C.L. [28] while a combination of these x-ray data with measurements of the angular size of milliarcsecond radio sources provides $-2.22 \leq \omega \leq -0.62$ at 95% C.L. [29]. Recently, constraints from several CMBR experiments (including the latest WMAP results) along with LSS data, Hubble parameter measurements from the HST Key Project, and SNe Ia data were obtained, with the ES parameter ranging from -1.38 to -0.82 at 95% C.L. [27]. More recently, the authors of Ref. [23] used a sample of 57 SNe Ia to find a 95% confidence bound of $-2.4 < \omega < -1$ whereas estimates of the age of the Universe as given by WMAP ($t_o = 13.7 \pm 0.2$ Gyr) provide $-1.18 < \omega < -0.93$, which corresponds to an accelerating scenario with the deceleration parameter q_o lying in the range $-0.8 < q_o < -0.52$ [24]. All these results agree at some level with the ones found in this work.

IV. CONCLUSION

This paper, like many of its predecessors, is mainly motivated by our present state of ignorance concerning the na-

ture of the so-called dark energy (or dark pressure). Initially the vacuum energy density or a cosmological constant were thought of (also motivated by the old age of the Universe problem) as the most viable explanation for the evidence of cosmic acceleration as given by SNe Ia observations. Observationally, Λ remains as a good candidate for dark energy although, from a theoretical viewpoint, one has to face a fine-tuning of 120 orders of magnitude in order to make its “observed” value compatible with quantum field theory expectations [30]. Later on, a first generalization of this former description, in which an “X matter” component with ES parameter ranging from a cosmological constant ($\omega = -1$) to pressureless matter ($\omega = 0$) was proposed as a possible description for current observations [3]. More recently, a new generalization, the so-called phantom energy, in which the Λ barrier ($\omega = -1$) is removed, has received increasing attention among theorists. Naturally, all these theoretical attempts to describe dark energy would not be valid without observational support. But that is not the case since several observational analyses support these parametrizations for dark energy. Here, we have explored the prospects for constraining the phantom behavior of the dark energy from SZE/x-ray distance estimates of galaxy clusters, SNe Ia data, and CMB-based distance estimates. We have shown that these data allow much acceptable parameter space beyond the line $\omega = -1$, which indicates not only the possibility of bias in the parameter determination when the Λ barrier is imposed but also the possibility of existence of more exotic forms of energy in the Universe. Naturally, we do not expect such results to be completely free of observational and/or theoretical uncertainties, mainly because there still exist considerable systematic uncertainties associated with SZE/x-ray distance determinations. What we do expect is that in the near future new sets of observations along with more theoretical effort will be able to decide on which side of the Λ barrier lies the so far mysterious dark energy.

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