A&A 417, 833–837 (2004)
DOI: 10.1051/0004-6361:20034327

Astronomy & Astrophysics

Determining the equation of state of dark energy from angular size of compact radio sources and X-ray gas mass fraction of galaxy clusters

Zong-Hong Zhu[1,2], Masa-Katsu Fujimoto[2], and Xiang-Tao He[1]

[1] Department of Astronomy, Beijing Normal University, Beijing 100875, China
[2] National Astronomical Observatory, 2-21-1, Osawa, Mitaka, Tokyo 181-8588, Japan
e-mail: fujimoto.masa-katsu@nao.ac.jp

Received 15 September 2003 / Accepted 16 December 2003

Abstract. Using recent measurements of angular size of high-z milliarcsecond compact radio sources compiled by Gurvits et al. (1999) and X-ray gas mass fraction of galaxy clusters published by Allen et al. (2002, 2003), we explore their bounds on the equation of state, $\omega_x \equiv p_x/\rho_x$, of the dark energy, whose existence has been congruously suggested by various cosmological observations. We relax the usual constraint $\omega_x \geq -1$, and find that combining the two databases yields a nontrivial lower bound on ω_x. Under the assumption of a flat universe, we obtain a bound $-2.22 < \omega_x < -0.62$ at 95.4% confidence level. The 95.4% confidence bound goes to $-1 \leq \omega_x < -0.60$ when the constraint $\omega_x \geq -1$ is imposed.

Key words. cosmology: cosmological parameters – cosmology: theory – cosmology: distance scale – galaxies: active – radio continuum: galaxies – X-ray: galaxies: clusters

1. Introduction

One of the most remarkable cosmological findings of recent years is, in additional to the cold dark matter (CDM), the existence of a component of dark energy (DE) with negative pressure in our universe. It is motivated to explain the acceleration of the universe discovered by distant type Ia supernova (SNeIa) observations (Perlmutter et al. 1998, 1999a; Riess et al. 1998, 2001), and to offset the deficiency of a flat universe, favoured by the measurements of the anisotropy of CMB (de Bernardis et al. 2000; Balbi et al. 2000; Durrer et al. 2003; Bennett et al. 2003; Spergel et al. 2003), but with a subcritical matter density parameter $\Omega_{\rm m} \sim 0.3$, obtained from dynamical estimates or X-ray and gravitational lensing observations of clusters of galaxies (for a recent summary, see Turner 2002). While a cosmological constant with $p_\Lambda = -\rho_\Lambda$ is the simplest candidate for DE, it suffers from the difficulties in understanding of the observed value in the framework of modern quantum field theory (Weinberg 1989; Carroll et al. 1992) and the "coincidence problem", the issue of explaining the initial conditions necessary to yield the near-coincidence of the densities of matter and the cosmological constant component today. In this case, quintessence (a dynamical form of DE with generally negative pressure) has been invoked (Ratra & Peebles 1988; Wetterich 1988; Caldwell et al. 1998; Zlatev et al. 1998; Gong 2002; Sahni et al. 2002; Alam et al. 2003a). One of the important characteristics of quintessence models is that their equation of state, $\omega_x \equiv p_x/\rho_x$, varies with cosmic time whilst the cosmological constant remains a constant $\omega_\Lambda = -1$. Determination of values of ω_x and its possible cosmic evolution plays a central role to distinguish various DE models. Such a challenging has triggered a wave of interest aiming to constrain ω_x using various cosmological databases, such as SNeIa (Garnavich et al. 1998; Tonry et al. 2003; Barris et al. 2003; Knop et al. 2003; Zhu & Fujimoto 2003; Alam et al. 2003b; Gong 2004); old high redshift objects (Lima & Alcaniz 2000a); angular size of compact radio sources (Lima & Alcaniz 2002); gravitational lensing (Zhu 2000a,b; Chae et al. 2002; Sereno 2002; Dev et al. 2003; Huterer & Ma 2003); SNeIa plus Large Scale Structure (LSS) (Perlmutter et al. 1999b); SNeIa plus gravitational lensing (Waga & miceli 1999); SNeIa plus X-ray galaxy clusters (Schuecker et al. 2003); CMB plus SNeIa (Efstathiou 1999; Bean & Melchiorri 2002; Hannestad & Mörtsell 2002; Melchiorri et al. 2003); CMB plus stellar ages (Jimenez et al. 2003); and combinations of various databases (Kujat et al. 2002). Other potential methods for the determination of ω_x have also widely discussed in the literature, such as the proposed *SNAP* satellite[1] (Huterer & Turner 1999; Weller & Albrecht 2001; Weller & Albrecht 2002); advanced gravitational wave detectors (Zhu et al. 2001; Biesiada 2001); future

Send offprint requests to: Zong-Hong Zhu,
e-mail: zong-hong.zhu@nao.ac.jp

[1] *SNAP* home page, http://snap.lbl.gov

SZ galaxy cluster surveys (Haiman et al. 2001); and gamma ray bursts (Choubey & King 2003; Takahashi et al. 2003).

In this work, we shall consider the observational constraints on the DE equation of state parameterized by a redshift independent pressure-to-density ratio ω_x arising from the latest observations of angular size of high-z milliarcsecond compact radio sources compiled by Gurvits et al. (1999) and the X-ray gas mass fraction data of clusters of galaxies published by Allen et al. (2002, 2003). The basics of a constant ω_x assumption are twofold: on the one hand, the angular diameter distance $D^{\rm A}$ used in this work is not sensitive to variations of ω_x with redshift because it depends on ω_x through multiple integrals (Maor et al. 2001; Maor et al. 2002; Wasserman 2002); on the other hand, for a wide class of quintessence models (particularly, those with tracking solutions), both Ω_x and ω_x vary very slowly (Zlatev et al. 1999; Steinhardt et al. 1999; Efstathiou 1999), and an effective equation of state, $\omega_{\rm eff} \sim \int \omega_x(z)\Omega_x(z){\rm d}z / \int \Omega_x(z){\rm d}z$ is a good approximation for analysis (Wang et al. 2000). We relax the usual constraint $\omega_x \geq -1$, because in recent years there have been several models which predict a DE component with $\omega_x < -1$ (Parker & Raval 1999; Schulz & White 2001; Caldwell 2002; Maor et al. 2002; Frampton 2003) and also we hope to explore its effects on the ω_x determination. The confidence region on the $(\omega_x, \Omega_{\rm m})$ plane obtained through a combined analysis of the two databases suggests $-2.22 < \omega_x < 0.62$ at 95.4% confidence level, which goes to $-1 \leq \omega_x < 0.60$ when the constraint $\omega_x \geq -1$ is imposed.

The plan of the paper is as follows. In the next section, we provide the bounds on ω_x from the angular size-redshift data. Constraints from the X-ray gas mass fraction of galaxy clusters are discussed in Sect. 3. Finally, we present a combined analysis, our concluding remarks and discussion in Sect. 4. Throughout the paper, we assume a flat universe which is suggested by the measurements of the anisotropy of CMB and favoured by inflation scenario.

2. Constraints from the angular size-redshift data

We begin by evaluating the angular diameter distance $D^{\rm A}$ as a function of redshift z. The redshift-dependent Hubble parameter can be written as $H(z) = H_0 E(z)$, where $H_0 = 100\,h\,{\rm km\,s^{-1}\,Mpc^{-1}}$ is the Hubble constant at the present time. For a flat universe that contains (baryonic and cold dark) matter and dark energy with a constant ω_x (we ignore the radiation components in the universe that are not important for the cosmological tests considered in this work), we get (Turner & White 1997; Chiba et al. 1997; Zhu 1998)

$$D^{\rm A}(z;\Omega_{\rm m},\omega_x) = \frac{c}{H_0}\frac{1}{1+z}\int_0^z \frac{{\rm d}z'}{E(z';\Omega_{\rm m},\omega_x)},$$
$$E^2(z;\Omega_{\rm m},\omega_x) = \Omega_{\rm m}(1+z)^3 + (1-\Omega_{\rm m})(1+z)^{3(1+\omega_x)}. \quad (1)$$

We first analyze the angular size-redshit data for milliarcsecond radio sources recently compiled by Gurvits et al. (1999) to constrain ω_x. The basics of the angular size-redshit test in the context of dark energy was first discussed from a theoretical standpoint by Lima & Alcaniz (2000b) without using any database. They also provided an analytical closed form which determines how the redshift $z_{\rm m}$, at which the angular size takes its minimal value, depends on ω_x. Later on, using the same database compiled by Gurvits et al. (1999), Lima & Alcaniz (2002) obtained $\Omega_{\rm m} \sim 0.2$ and $\omega_x \sim -1$. A distinguishing characteristic of our analysis is that the usual constraint $\omega_x \geq -1$ is relaxed. This database shown in Fig. 1 contains 145 sources distributed in twelve redshift bins with about the same number of sources per bin. The lowest and highest redshift bins are centered at redshifts $z = 0.52$ and $z = 3.6$ respectively. We determine the model parameters ω_x and $\Omega_{\rm m}$ through a χ^2 minimization method. The range of ω_x spans the interval $[-3, 0]$ in steps of 0.01, while the range of $\Omega_{\rm m}$ spans the interval [0, 1] also in steps of 0.01.

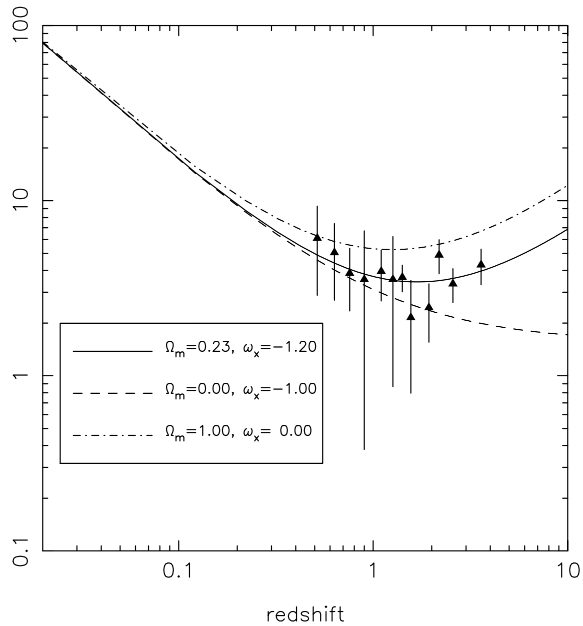

Fig. 1. Diagram of angular size vs redshift data for 145 compact radio sources (binned into 12 bins) of Gurvits et al. (1999). We assume the charateristic linear size $l = 22.64\ h^{-1}$ pc for theoretical curves. The solid curve corresponds to our best fit with $\omega_x = -1.19$ and $\Omega_{\rm m} = 0.23$, while the dashed and dot-dashed curves correspond to a Λ-dominated universe and the standard cold dark matter (SCDM) model respectively.

$$\chi^2(l;\Omega_{\rm m},\omega_x) = \sum_i \frac{[\theta(z_i;l;\Omega_{\rm m},\omega_x) - \theta_{{\rm o}i}]^2}{\sigma_i^2}, \quad (2)$$

where $\theta(z_i;\Omega_{\rm m},\omega_x) = l/D^{\rm A}$ is the angle subtended by an object of proper length l transverse to the line of sight and $\theta_{{\rm o}i}$ is the observed values of the angular size with errors σ_i of the ith bin in the sample. The summation is over all 12 observational data points.

As pointed out by the authors of previous analyses on databases of angular size-redshift (Jackson & Dodgson 1997; Gurvits et al. 1999; Vishwakarma 2001; Alcaniz 2002; Zhu & Fujimoto 2002; Jain et al. 2003; Chen & Ratra 2003; Jackson 2003), when one uses the angular size data to constrain the cosmological parameters, the results will be strongly dependent on the characteristic length l. Therefore, instead of assuming a specific value for l, we have worked on the interval

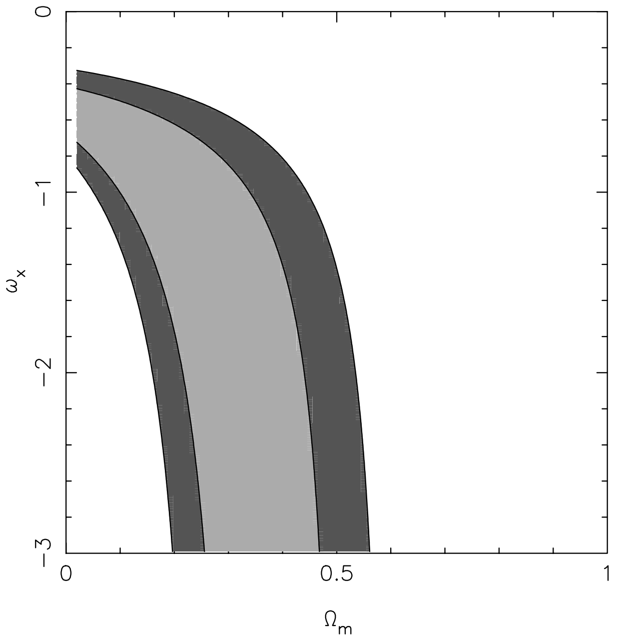

Fig. 2. Confidence region plot of the best fit to the database of the angular size-redshift data compiled by Gurvits et al. (1999) – see the text for a detailed description of the method. The 68% and 95% confidence levels in the ($\Omega_{\rm m}$, ω_x) plane are shown in lower shaded and lower + darker shaded areas respectively.

$l = 15\,h^{-1}$–$30\,h^{-1}$ pc. To make the analysis independent of the choice of the characteristic length l, we also minimize Eq. (2) for l, ω_x and $\Omega_{\rm m}$ simultaneously, which gives $l = 22.64\,h^{-1}$ pc, $\omega_x = -1.19$ and $\Omega_{\rm m} = 0.23$ as the best fit. Figure 2 displays the 68.3% and 95.4% confidence level contours in the ($\Omega_{\rm m}$, ω_x) plane using the lower shaded and the lower plus darker shaded areas respectively. It is clear from the figure that ω_x is poorly constrained from the angular size-redshift data alone, which only gives $\omega_x < -0.32$ at a 95.4% confidence level. However, as we shall see in Sect. 4, when we combine this test with the X-ray gas mass fraction test, we could get fairly stringent constraints on both ω_x and $\Omega_{\rm m}$.

3. Constraints from the galaxy cluster X-ray data

Clusters of galaxies are the largest virialized systems in the universe, and their masses can be estimated by X-ray and optical observations, as well as gravitational lensing measurements. A comparison of the gas mass fraction, $f_{\rm gas} = M_{\rm gas}/M_{\rm tot}$, as inferred from X-ray observations of clusters of galaxies with the cosmic baryon fraction can provide a direct constraint on the density parameter of the universe $\Omega_{\rm m}$ (White et al. 1993). Moreover, assuming the gas mass fraction is constant in cosmic time, Sasaki (1996) show that the $f_{\rm gas}$ data of clusters of galaxies at different redshifts also provide an efficient way to constrain other cosmological parameters decribing the geometry of the universe. This is based on the fact that the measured $f_{\rm gas}$ values for each cluster of galaxies depend on the assumed angular diameter distances to the sources as $f_{\rm gas} \propto [D^{\rm A}]^{3/2}$. The underlying cosmology should be the one which make these measured $f_{\rm gas}$ values invariant with redshift (Sasaki 1996; Allen et al. 2003).

Using the *Chandra* observational data, Allen et al. (2002, 2003) obtained the $f_{\rm gas}$ profiles for the 10 relaxed clusters. Except for Abell 963, the $f_{\rm gas}$ profiles of the other 9 clusters appear to have converged or be close to converging with a canonical radius r_{2500}, which is defined as the radius within which the mean mass density is 2500 times the critical density of the universe at the redshift of the cluster (Allen et al. 2002, 2003). The gas mass fraction values of these nine clusters at r_{2500} (or at the outermost radii studied for PKS0745-191 and Abell 478) were shown in Fig. 5 of Allen et al. (2003). We will use this database to constrain the equation of state of the dark energy component, ω_x. Our analysis of the present data is very similar to the one performed by Lima et al. (2003). However, in addition to including new data from Allen et al. (2003), we also take into account the bias between the baryon fractions in galaxy clusters and in the universe as a whole. Following Allen et al. (2002), we have the model function as

$$f_{\rm gas}^{\rm mod}(z_i;\omega_x,\Omega_{\rm m}) = \frac{b\Omega_b}{(1+0.19h^{1/2})\,\Omega_{\rm m}}\left[\frac{h}{0.5}\,\frac{D^{\rm A}_{\rm SCDM}(z_i)}{D^{\rm A}(z_i;\omega_x,\Omega_{\rm m})}\right]^{3/2} \quad (3)$$

where the bias factor $b \simeq 0.93$ (Bialek et al. 2001; Allen et al. 2003) is a parameter motivated by gas dynamical simulations, which suggests that the baryon fraction in clusters is slightly depressed with respect to the Universe as a whole (Cen & Ostriker 1994; Eke et al. 1998; Frenk et al. 1999; Bialek et al. 2001). The term $(h/0.5)^{3/2}$ represents the change in the Hubble parameter from the defaut value of $H_0 = 50$ km s^{-1} Mpc^{-1} and the ratio $D^{\rm A}_{\rm SCDM}(z_i)/D^{\rm A}(z_i;\omega_x,\Omega_{\rm m})$ accounts for the deviations of the model being considered from the default standard cold dark matter (SCDM) cosmology.

Again, we determine ω_x and $\Omega_{\rm m}$ through a χ^2 minimization method with the same parameter ranges and steps as in the last section. We constrain $\Omega_{\rm m}h^2 = 0.0205 \pm 0.0018$, the result from the primodial nucleosynthesis (O'Meara et al. 2001), and $h = 0.72 \pm 0.08$, the final result from the Hubble Key Project by Freedman et al. (2001). The χ^2 difference between the model function and SCDM data is then (Allen et al. 2003)

$$\chi^2(\omega_x,\Omega_{\rm m}) = \sum_{i=1}^{9}\frac{\left[f_{\rm gas}^{\rm mod}(z_i;\omega_x,\Omega_{\rm m}) - f_{{\rm gas},{\rm o}i}\right]^2}{\sigma^2_{f_{{\rm gas},i}}} + \left[\frac{\Omega_b h^2 - 0.0205}{0.0018}\right]^2 + \left[\frac{h-0.72}{0.08}\right]^2, \quad (4)$$

where $f_{\rm gas}^{\rm mod}(z_i;\omega_x,\Omega_{\rm m})$ refers to Eq. (3), $f_{{\rm gas},{\rm o}i}$ is the measured $f_{\rm gas}$ with the defaut SCDM cosmology, and $\sigma_{f_{{\rm gas},i}}$ is the symmetric root-mean-square errors (i refers to the ith data point, with totally 9 data). The summation is over all of the observational data points.

Figure 3 displays the 68.3% and 95.4% confidence level contours in the (ω_x, $\Omega_{\rm m}$) plane of our analysis using the lower shaded and the lower plus darker shaded areas respectively. The best fit happans at $\omega_x = -0.86$ and $\Omega_{\rm m} = 0.30$. As shown in the figure, although the X-ray gas mass fraction data constrains the density parameter $\Omega_{\rm m}$ very stringently, it still poorly limits

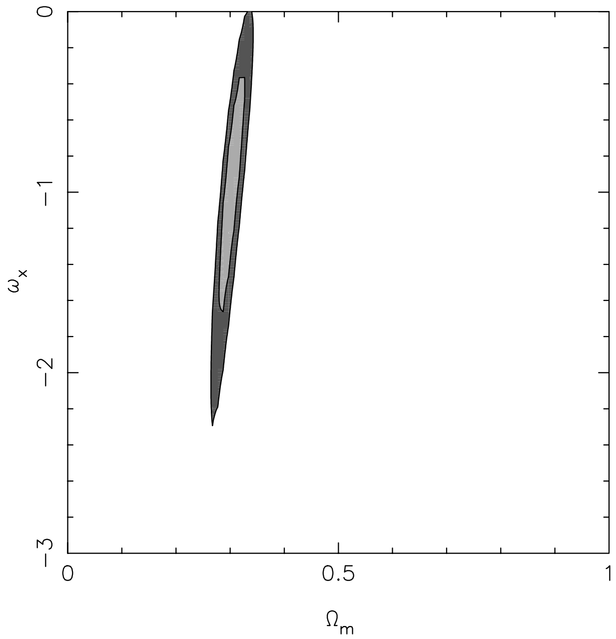

Fig. 3. Confidence region plot of the best fit to the $f_{\rm gas}$ of 9 clusters published by Allen et al. (2002, 2003) – see the text for a detailed description of the method. The 68% and 95% confidence levels in the ω_x–$\Omega_{\rm m}$ plane are shown in lower shaded and lower + darker shaded areas respectively.

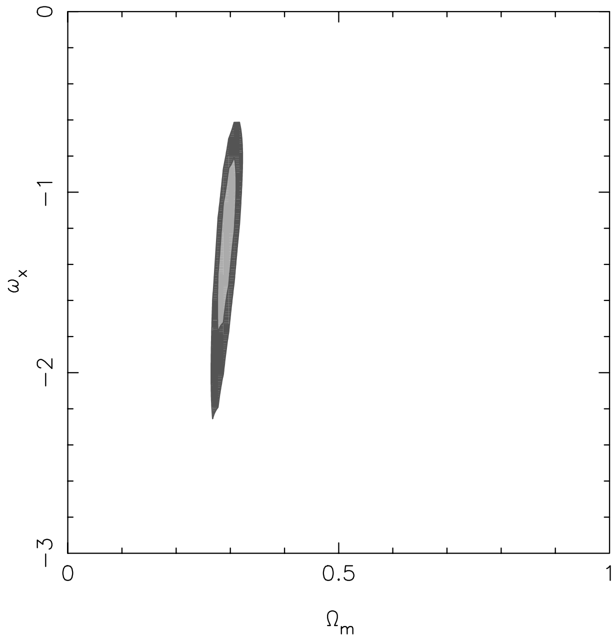

Fig. 4. Confidence region plot of the best fit from a combined analysis for the angular size-redshift data (Gurvits et al. 1999) and the X-ray gas mass fractions of 9 clusters (Allen et al. 2002, 2003). The 68% and 95.4% confidence levels in the ω_x–$\Omega_{\rm m}$ plane are shown in lower shaded and lower + darker shaded areas respectively. The best fit happans at $\omega_x = -1.16$ and $\Omega_{\rm m} = 0.29$.

the dark energy equation of state ω_x. The situation can be dramatically improved when the two databases are combined in analysis, in particular, a nontrivial lower bound on ω_x will be obtained (see below).

4. Combined analysis, discussion and conclusion

Now we present our combined analysis of the constraints from the angular size-redshift data and the X-ray gas mass fraction of galaxy clusters and summarize our results. In Fig. 4, we display the 68.3% and 95.4% confidence level contours in the (ω_x, $\Omega_{\rm m}$) plane using the lower shaded and the lower plus darker shaded areas respectively. The best fit happens at $\omega_x = -1.16$ and $\Omega_{\rm m} = 0.29$. As is shown, fairly stringent bounds on both ω_x and $\Omega_{\rm m}$ are obtained, with $-2.22 < \omega_x < -0.62$ and $0.28 < \Omega_{\rm m} < 0.32$ at the 95.4% confidence level. The bound on ω_x goes to $-1 \leq \omega_x < -0.60$ when the constraint $\omega_x \geq -1$ is imposed.

Although precise determinations of ω_x and its possible evolution with cosmic time are crucial for deciphering the mystery of DE, currently ω_x has not been determined well even with an assumption of ω_x being constant (Hannestad & Mörtsell 2002; Spergel et al. 2003; Takahashi et al. 2003). One should determine ω_x using a joint analysis. In this paper we have shown that stringent constraints on ω_x can be obtained from the combined analysis of the angular size-redshift data and the X-ray mass fraction data of clusters, which is complementary to other joint analyses. We compare our results with other recent determinations of ω_x from independent methods. For the usual quintessence model (i.e., the constraint $\omega_x \geq -1$ is imposed), Garnavich et al. (1998) found $\omega_x < -0.55$ using the SNeIa data from the High-z Supernova Search Team, while Lima & Alcaniz (2002) obtained $\omega_x < -0.50$ using the angular size-redshift data from Gurvits et al. (1999) (95% confidence level). Our result of $\omega_x < -0.60$ is slightly more stringent than theirs. However Bean & Melchiorri (2002) found an even better constraint, $\omega_x < -0.85$, by analyzing SNeIa data and measurements of LSS and the positions of the acoustic peaks in the CMB spectrum. For the more general dark energy model including either normal XCDM, as well as the extended or phantom energy (i.e., the constraint $\omega_x \geq -1$ is relaxed), Hannestad & Mörtsell (2002) combined CMB, LSS and SNeIa data and obtained $-2.68 < \omega_x < -0.78$ at a 95.4% confidence level, whose lower and upper bounds are slightly lower than ours ($-2.22 < \omega_x < -0.62$ at a 95.4% confidence level). Recently, Schuecker et al. (2003) combined REFLEX X-ray clusters and SNeIa data to obtain $-1.30 < \omega_x < -0.65$ with a 1σ statistical significance. From Fig. 4, it is found that our 1σ result is $-1.72 < \omega_x < -0.83$, which is comparable with the results of Schuecker et al. (2003). Using the X-ray gas mass fraction of 6 galaxy clusters, Lima et al. (2003) found $-2.08 < \omega_x < -0.60$ (1σ level), which is less stringent than the result presented in this work. This is because we used more X-ray gas mass fraction data of galaxy clusters and combined the angular size-redshift data of compact radio sources. The analysis presented here reinforces the interest in precise measurements of angular size of distant compact radio sources and statistical studies of the intrinsic length distribution of the sources. Our constraints will be improved when more acurate X-ray data from *Chandra* and *XMM-Newton* become available in the near future.

Acknowledgements. We would like to thank L. I. Gurvits for sending us the compilation of the angular size-redshift data and helpful explanation of the data, S. Allen for providing us the X-ray mass fraction data and his help with data analysis, J. S. Alcaniz and D. Tatsumi for their helpful discussions. Our thanks go to the anonymouse referee for valuable comments and useful suggestions, which improved this work very much. This work was supported by a Grant-in-Aid for Scientific Research on Priority Areas (No. 14047219) from the Ministry of Education, Culture, Sports, Science and Technology. Z.-H. Zhu acknowledges support from the National Natural Science Foundation of China and the National Major Basic Research Project of China (G2000077602), and he is also grateful to all TAMA300 & LCGT members and the staff of NAOJ for their hospitality and help during his stay. The support of X.-T. He is from the National Natural Science Foundation of China.

References

Alam, U., Sahni, V., Saini, T. D., & Starobinsky, A. A. 2003a, MNRAS, 334, 1057

Alam, U., Sahni, V., Saini, T. D., & Starobinsky, A. A. 2003b [astro-ph/0311364]

Alcaniz, J. S. 2002, Phys. Rev. D, 65, 123514

Allen, S. W., Schmidt, R. W., & Fabian, A. C. 2002, MNRAS, 334, L11

Allen, S. W., Schmidt, R. W., Fabian, A. C., & Ebeling, H. 2003, MNRAS, 342, 287

Balbi, A., Ade, P., Bock, J., et al. 2000, ApJ, 545, L1

Barris, B. J., et al. 2003, ApJ, accepted [astro-ph/0310843]

Bean, R., & Melchiorri, A. 2002, Phys. Rev. D, 65, 041302(R)

Bennett, C. L., Halpern, M., Hinshaw, G., et al. 2003, ApJS, 148, 1

Bialek, J. J., Evrard, A. E., & Mohr, J. J. 2001, ApJ, 555, 597

Biesiada, M. 2001, MNRAS, 325, 1075

Caldwell, R. R. 2002, Phys. Lett. B, 545, 23

Caldwell, R., Dave, R., & Steinhardt, P. J. 1998, Phys. Rev. Lett., 80, 1582

Carroll, S., Press, W. H., & Turner, E. L. 1992, ARA&A, 30, 499

Cen, R., & Ostriker, J. P. 1994, ApJ, 429, 4

Chae, K.-H., Biggs, A. D., Blandford, R. D., et al. 2002, Phys. Rev. Lett., 89, 151301

Chen, G., & Ratra, B. 2003, ApJ, 582, 586

Chiba, T., Sugiyama, N., & Nakamura, T. 1997, MNRAS, 289, L5

Choubey, S., & King, S. F. 2003, Phys. Rev. D, 67, 073005

de Bernardis, P., Ade, P. A. R., Bock, J. J., et al. 2000, Nature, 404, 955

Dev, A., Jain, D., & Mahajan, S. 2003 [astro-ph/0307441]

Durrer, R., Novosyadlyj, B., & Apunevych, S. 2003, ApJ, 583, 33

Efstathiou, G. 1999, MNRAS, 310, 842

Eke, V. R., Navarro, J. F., & Frenk, C. S. 1998, ApJ, 503, 569

Frampton, P. H. 2003, Phys. Lett. B, 555, 139

Freedman, W., Madore, B. F., Gibson, B. K., et al. 2001, ApJ, 553, 47

Frenk, C. S., White, S. D. M., Bode, P., et al. 1999, ApJ, 525, 554

Garnavich, P. M., Jha, S., Challis, P., et al. 1998, ApJ, 509, 74

Gong, Y. 2002, Class. Quan. Grav., 19, 4537

Gong, Y. 2004 [astro-ph/0401207]

Gurvits, L. I., Kellerman, K. I., & Frey, S. 1999, A&A, 342, 378

Haiman, Z., Mohr, J. J., & Holder, G. P. 2001, ApJ, 553, 545

Hannestad, S., & Mörtsell, E., Phys. Rev. D, 66, 063508

Huterer, D., & Ma, C.-P. 2004, ApJ, 600, L7

Huterer, D., & Turner, M. S. 1999, Phys. Rev. D, 60, 081301

Jackson, J. C. 2003 [astro-ph/0309390]

Jackson, J. C., & Dodgson, M. 1997, MNRAS, 285, 806

Jain, D., Dev, A., & Alcaniz, J. S. 2003, Class. Quan. Grav., 20, 4163

Jimenez, J., Verde, L., Treu, T., & Stern, D. 2003, ApJ, 593, 622

Knop, R. A., et al. 2003, ApJ, accepted [astro-ph/0309368]

Kujat, J., Linn, A. M., Scherrer, R. J., & Weinberg, D. H. 2002, ApJ, 572, 1

Lima, J. A. S., & Alcaniz, J. S. 2000a, MNRAS, 317, 893

Lima, J. A. S., & Alcaniz, J. S. 2000b, A&A, 357, 393

Lima, J. A. S., & Alcaniz, J. S. 2002, ApJ, 566, 15

Lima, J. A. S., Cunha, J. V., & Alcaniz, J. S. 2003, Phys. Rev. D, 68, 023510

Maor, I. Brustein, R., & Steinhardt, P. J. 2001, Phys. Rev. Lett., 86, 6

Maor, I., Brustein, R., McMahon, J., & Steinhardt, P. J. 2002, Phys. Rev. D, 65, 123003

Melchiorri, A., Mersini, L., Ödman, C. J., & Trodden, M. 2003, Phys. Rev. D, 68, 043509

O'Meara, J. M., Tytler, D., Kirkman, D., et al. 2001, ApJ, 552, 718

Parker, L., & Raval, A. 1999, Phys. Rev. D, 60, 063512

Perlmutter, S., Aldering, G., Della Valle, M., et al. 1998, Nature, 391, 51

Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999a, ApJ, 517, 565

Perlmutter, S., Turner, M. S., & White, M. 1999b, Phys. Rev. Lett., 83, 670

Ratra, B., & Peebles, P. J. E. 1988, Phys. Rev. D, 37, 3406

Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009

Riess, A. G., Nugent, P. E., Gilliland, R. L., et al. 2001, ApJ, 560, 49

Sahni, V., Saini, T. D., Starobinsky, A. A., & Alam, U. 2002, JETP Lett., 77, 201

Sasaki, S. 1996, PASJ, 48, L119

Schuecker, P., Caldwell, R. R., Böhringer, H., et al. 2003, A&A, 402, 53

Schulz, A. E., & White, M. J. 2002, Phys. Rev. D, 64, 043514

Sereno, M. 2002, A&A, 393, 757

Spergel, D. N., Verde, L., Peiris, H. V., et al. 2003, ApJS, 148, 175

Steinhardt, P. J., Wang, L., & Zlatev, I. 1999, Phys. Rev. D, 59, 123504

Takahashi, K., Oguri, M., Kotake, K., & Ohno, H. 2003 [astro-ph/0305260]

Tonry, J. L., Schmidt, B. P., Barris, B., et al. 2003, ApJ, 594, 1

Turner, M. S. 2002, ApJ, 576, L101

Turner, M. S., & White, M. 1997, Phys. Rev. D, 56, R4439

Vishwakarma, R. G. 2001, Class. Quan. Grav., 18, 1159

Waga, I., & Miceli, A. P. M. R. 1999, Phys. Rev. D, 59, 103507

Wang, L., Caldwell, R. R., Ostriker, J. P., & Steinhardt, P. J. 2000, ApJ, 530, 17

Wasserman, I. 2002, Phys. Rev. D, 66, 123511

Weinberg, S. 1989, Rev. Mod. Phys., 61, 1

Weller, J., & Albrecht, A. 2001, Phys. Rev. Lett., 86, 1939

Weller, J., & Albrecht, A. 2002, Phys. Rev. D, 65, 103512

Wetterich, C. 1988, Nucl. Phys. B, 302, 645

White, S. D. M., Navarro, J. F., Evrard, A. E., & Frenk, C. S. 1993, Nature, 366, 429

Zhu, Z.-H. 1998, A&A, 338, 777

Zhu, Z.-H. 2000a, Mod. Phys. Lett. A, 15, 1023

Zhu, Z.-H. 2000b, Int. J. Mod. Phys. D, 9, 591

Zhu, Z.-H., & Fujimoto, M.-K. 2002, ApJ, 581, 1

Zhu, Z.-H., & Fujimoto, M.-K. 2003, ApJ, 585, 52

Zhu, Z.-H., Fujimoto, M.-K., & Tatsumi, D. 2001, A&A, 372, 377

Zlatev, I., Wang, L., & Steinhardt, P. J. 1999, Phys. Rev. Lett., 82, 896