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CONSTRAINTS ON THE DVALI-GABADADZE-PORRATI MODEL FROM RECENT SUPERNOVA OBSERVATIONS AND BARYON ACOUSTIC OSCILLATIONS

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ABSTRACT

Although there is mounting observational evidence that the expansion of our universe is undergoing a late-time acceleration, the mechanism for this acceleration is yet unknown. In the so-called Dvali-Gabadadze-Porrati (DGP) model this phenomenon is attributed to gravitational "leakage" into extra dimensions. In this work, we mainly focus our attention on the constraints on the model from the "gold sample" of Type Ia supernovae (SNe Ia), the first-year data from the Supernova Legacy Survey (SNLS), and the baryon acoustic oscillation (BAO) peak found in the Sloan Digital Sky Survey (SDSS). At 99.73% confidence level, the combination of the three databases provides $\Omega_m = 0.270^{+0.018}_{-0.017}$ and $\Omega_{r_c} = 0.216^{+0.012}_{-0.013}$ (hence, a spatially closed universe with $\Omega_k = -0.350^{+0.080}_{-0.083}$), which seems to be in contradiction with the most recent *WMAP* results indicating a flat universe. Based on this result, we also estimated the transition redshift (at which the universe switches from deceleration to acceleration) to be $0.70 < z_{q=0} < 1.01$, at $2\,\sigma$ confidence level.

Subject headings: cosmological parameters — cosmology: theory — distance scale — galaxies: general — supernovae: general

Online material: color figures

1. INTRODUCTION

Recent observations of Type Ia supernovae (SNe Ia) suggest that the expansion of the universe is accelerating (Riess et al. 1998, 2004; Perlmutter et al. 1999; Tonry et al. 2003; Barris et al. 2004; Knop et al. 2003). As is well known, all usual types of matter with positive pressure generate attractive forces, which decelerate the expansion of the universe. Given this, a dark energy component with negative pressure was suggested to account for the invisible fuel that drives the current acceleration of the universe. There are a huge number of candidates for the dark energy component in the literature (see, e.g., Sahni & Starobinsky 2000; Peebles & Ratra 2003; Padmanabhan 2003; Lima 2004; Copeland et al. 2006 for recent reviews), such as a cosmological constant, Λ (Carroll et al. 1992), an evolving scalar field (referred to by some as quintessence; Ratra & Peebles 1988; Caldwell et al. 1998; Weller & Albrech 2002; Guo et al. 2005a), the phantom energy, in which the sum of the pressure and energy density is negative (Caldwell 2002; Dabrowski et al. 2003; Wu & Yu 2005a), the quintom model (Feng et al. 2005; Zhao et al. 2005, 2006; Guo et al. 2005b; Wu & Yu 2005b), the holographic dark energy (Li 2004; Gong 2004; Wang et al. 2005; Myung 2005; Zhang & Wu 2005; Pavon & Zimdahl 2005; Chang et al. 2006), the Chaplygin gas (Kamenshchik et al. 2001; Bento et al. 2002; Dev et al. 2003; Silva & Bertolami 2003; Makler et al. 2003; Zhu 2004; Gong 2005; Zhang & Zhu 2006), and the Cardassion model (Freese & Lewis 2002; Zhu & Fujimoto 2002, 2003; Godlowski et al. 2004; Amarzguioui et al. 2005; Koivisto et al. 2005; Lazkoz & León 2005; Szydlowski & Godlowski 2006).

Another possible explanation for the accelerating expansion of the universe could be the infrared modification of gravity expected from extradimensional physics, which would lead to a modification of the effective Friedmann equation at late times. An interesting model incorporating modification of gravitational laws at large distances was proposed by Dvali et al. (2000), the so-called DGP model. It describes our four-dimensional world as a brane embedded into flat five-dimensional bulk. While ordinary matter fields are supposed to be localized on the brane, gravity can propagate into the bulk. Unlike popular braneworld theories at the time, the extra dimension featured in this theory is astrophysically large and flat (for a recent review of the DGP phenomenology, see Lue 2006). A crucial ingredient of the model is the induced Einstein-Hilbert action on the brane. In this model, gravitational leakage into the bulk leads to the observed late-time accelerated expansion of the universe. Such a possible mechanism for cosmic acceleration has been tested in many of its observational predictions, ranging from local gravity (Lue 2003; Lue & Starkman 2003; Lue et al. 2004) to cosmological observations, such as SNe Ia (Deffayet et al. 2002a, 2002b; Avelino & Martins 2002; Alam & Sahni 2006; Maartens & Majerotto 2006; Dabrowski et al. 2004), angular size of compact ratio sources (Alcaniz 2002), the age measurements of high-redshift objects (Alcaniz et al. 2002), the optical gravitational lensing surveys (Jain et al. 2002), the large-scale structures (Multamäki et al. 2003), and the X-ray gas mass

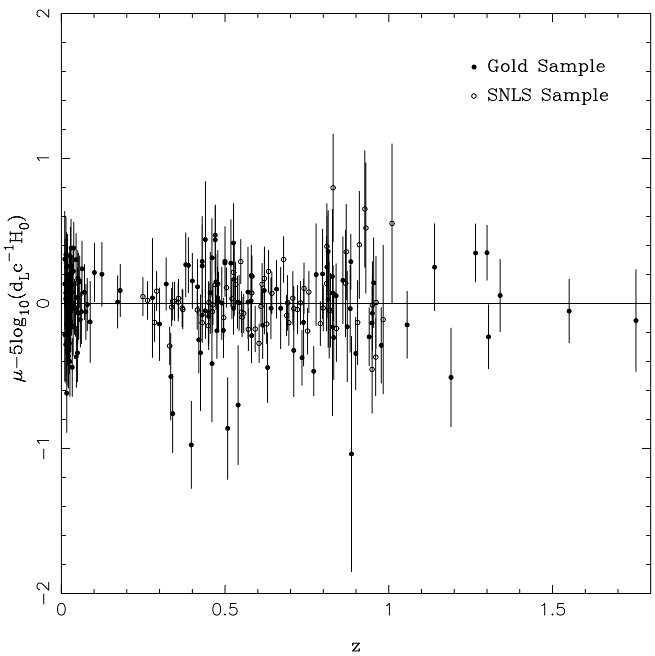

FIG. 1.—Gold sample and SNLS sample shown in a residual Hubble diagram with respect to the DGP model with the best-fit parameters, $(\Omega_m, \Omega_{r_c}) = (0.270, 0.216)$. [*See the electronic edition of the Journal for a color version of this figure.*]

fraction in galaxy clusters (Zhu & Alcaniz 2005; Alcaniz & Zhu 2005).

This paper aims at placing new observational constraints on the DGP model by using the gold sample of 157 SNe Ia compiled by Riess et al. (2004), the 71 new SNe Ia released recently by the Supernova Legacy Survey (SNLS; Astier et al. 2006), and the baryon acoustic oscillations detected in the large-scale correlation function of Sloan Digital Sky Survey (SDSS) luminous red galaxies (Eisenstein et al. 2005). It is shown that if only the SNe Ia databases are used, Ω_{r_c} and Ω_m are highly degenerated. However, when we combine the baryon acoustic oscillations found by Eisenstein et al. (2005) from the SDSS data for analyzing, the degeneracy between Ω_{r_c} and Ω_m is broken and the two parameters are accurately determined.

We structured this paper as follows. Section 2 discusses the basic expressions of the DGP model. In § 3, we present our analysis of the model using the updated SNe Ia data and the baryon acoustic oscillations found in the SDSS data. We end the paper by discussing its main results in § 4.

2. BASIC EXPRESSIONS OF THE DGP MODEL

In the DGP model the modified Friedmann equation due to the presence of an infinite-volume extra dimension reads (Deffayet et al. 2002a, 2002b)

$$H^2 = H_0^2\left\{\Omega_k(1+z)^2 + \left[\sqrt{\Omega_{r_c}} + \sqrt{\Omega_{r_c} + \Omega_m(1+z)^3}\right]^2\right\}, \quad (1)$$

where H is the Hubble parameter (H_0 is its current value), Ω_k and Ω_m represent the fractional contribution of curvature and of the matter (both baryonic and nonbaryonic), respectively, and Ω_{r_c}, the bulk-induced term, is defined as

$$\Omega_{r_c} \equiv \frac{1}{4r_c^2 H_0^2}. \quad (2)$$

In the above equations, r_c is the crossover scale beyond which the gravitational force follows the five-dimensional $1/r^3$ behavior. Note that on short length scales $r \ll r_c$ (at early times) the gravitational force follows the usual four-dimensional $1/r^2$ behavior; i.e., the standard cosmological models are recovered. It has been shown that by setting the crossover scale r_c close to the horizon size, this extra contribution to the Friedmann equation leads to acceleration that can in principle explain the supernova data (Deffayet et al. 2002a, 2002b). From equation (1) we find that the normalization condition is given by $\Omega_k + [(\Omega_{r_c})^{1/2} + (\Omega_{r_c} + \Omega_m)^{1/2}]^2 = 1$, while for a spatially flat scenario it reduces to $\Omega_{r_c} = (1 - \Omega_m)^2/4$.

The current value of the deceleration parameter, defined as $q \equiv -\ddot{a}a/\dot{a}^2$, takes the form (Zhu & Fujimoto 2003, 2004)

$$q_0 = \frac{3}{2}\Omega_m\left(1 + \frac{\sqrt{\Omega_{r_c}}}{\sqrt{\Omega_{r_c} + \Omega_m}}\right) - \left(\sqrt{\Omega_{r_c}} + \sqrt{\Omega_{r_c} + \Omega_m}\right)^2. \quad (3)$$

The transition redshift $z_{q=0}$, at which the universe switches from deceleration to acceleration, can be expressed in the following analytic form (Zhu & Alcaniz 2005):

$$z_{q=0} = -1 + 2\left(\frac{\Omega_{r_c}}{\Omega_m}\right)^{1/3}. \quad (4)$$

Note that from a phenomenological standpoint, the DGP model is a testable scenario with the same number of parameters as the ΛCDM scenario, contrasting with models of quintessence that have additional free parameters to be determined (Deffayet et al. 2002b).

3. CONSTRAINTS FROM SNe Ia AND SDSS DATA

In this section we analyze the DGP model by using two recently released supernova data sets, the gold supernova data set (Riess et al. 2004) and the SNLS data set (Astier et al. 2006). We also use these data sets in conjunction with the recent discovery of the baryon acoustic oscillation peak in the SDSS (Eisenstein et al. 2005) to place constraints on the cosmological parameters.

Recently, Riess et al. (2004) compiled a large database of 170 previously reported SNe Ia and 16 new high-redshift SNe Ia observed by the *Hubble Space Telescope* (*HST*). The total sample spans a wide range of redshift ($0.01 < z < 1.7$). To reflect the difference in the quality of the spectroscopic and photometric record for individual supernovae, they divided the total sample into "high-confidence" (gold) and "likely but not certain" (silver) subsets. Here we consider only the gold sample of 157 SNe Ia (for recent usages of the sample, see, e.g., Padmanabhan & Choudhury 2003; Nesseris & Perivolaropoulos 2004; Alcaniz 2004; Choudhury & Padmanabhan 2005; Gong 2005; Feng et al. 2005; Zhang & Wu 2005; Guo & Zhang 2005a, 2005b; Ichikawa & Takahashi 2006; Cai et al. 2006).

More recently, the SNLS collaboration released the first-year data of its planned five-year Supernova Legacy Survey (Astier et al. 2006). An important aspect to be emphasized on the SNLS data is that they seem to be in a better agreement with the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) results than the gold sample (see, e.g., Jassal et al. 2006). The two samples are illustrated on a residual Hubble diagram with respect to our best -fit universe ($\Omega_m = 0.270$, $\Omega_{r_c} = 0.216$) in Figure 1.

It is well known that the acoustic peaks in the cosmic microwave background (CMB) anisotropy power spectrum can be used

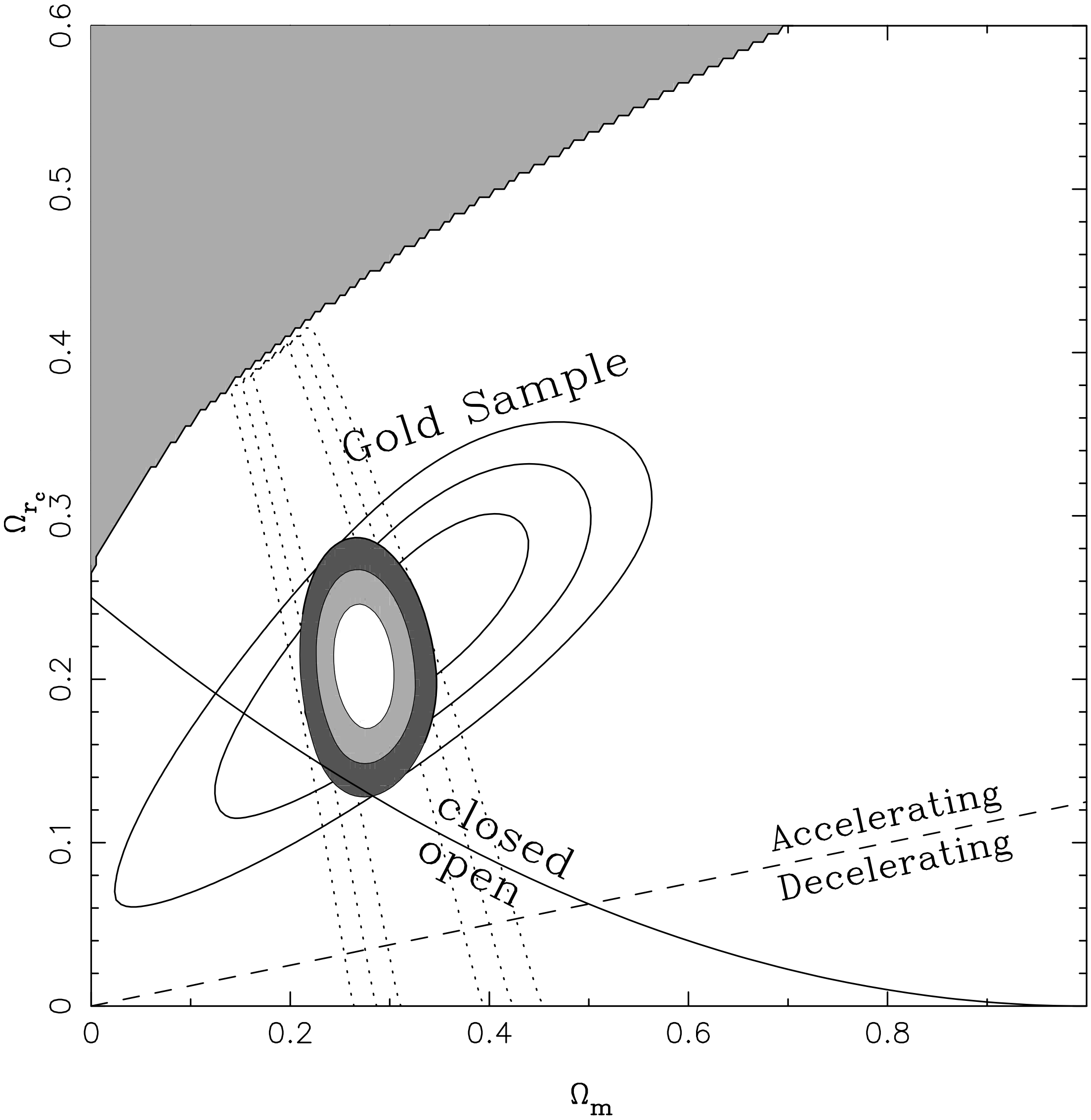

FIG. 2.— Probability contours at 68.3%, 95.4%, and 99.7% confidence levels for Ω_m vs. Ω_{r_c} in the DGP model from the gold sample of SNe Ia data (*solid contours*), from the baryon acoustic oscillations found in the SDSS data (*dotted lines*), and from the combination of the two databases (*shaded contours*); see the text for a detailed description of the method. The upper left shaded region represents the "no-big-bang" region, the thick solid line represents the flat universe, and accelerated models of the universe are above the dashed line. The best fit happens at $\Omega_m = 0.272$ and $\Omega_{r_c} = 0.211$. [*See the electronic edition of the Journal for a color version of this figure*.]

to determine the properties of the cosmic perturbations and to measure the contents and curvature of the universe, as well as many other cosmological parameters (see, e.g., Spergel et al. 2003). Because the acoustic oscillations in the relativistic plasma of the early universe will also be imprinted on to the late-time power spectrum of the nonrelativistic matter (Peebles & Yu 1970; Eisenstein & Hu 1998), the acoustic signatures in the large-scale clustering of galaxies yield additional tests for cosmology. In particular, the characteristic and reasonably sharp length scale measured at a wide range of redshifts provides the distance-redshift relation, which is a geometric complement to the usual luminosity-distance relation from Type Ia supernovae (Eisenstein et al. 2005). Although the acoustic features in the matter correlations are weak and on large scales, Eisenstein et al. (2005) have successfully found the peaks using a large spectroscopic sample of luminous, red galaxies (LRGs) from the SDSS (York et al. 2000). This sample contains 46,748 galaxies covering 3816 $\deg^2$ out to a redshift of $z = 0.47$. They found a parameter, A, that is independent of dark energy models (Eisenstein et al. 2005). From their equations (2) and (4), we write it as follows:

$$A = \frac{\sqrt{\Omega_m}}{z_1}\left\{\frac{z_1}{E(z_1)}\frac{1}{|\Omega_k|}\,\mathrm{sinn}^2\left[\sqrt{|\Omega_k|}\int_0^{z_1}\frac{dz}{E(z)}\right]\right\}^{1/3}, \quad (5)$$

where $E(z) \equiv H(z)/H_0$, $z_1 = 0.35$, A is measured to be $A = 0.469 \pm 0.017$, and the function $\mathrm{sinn}(x)$ is defined as $\mathrm{sinn}(x) = \sin(x)$ for a closed universe, $\mathrm{sinn}(x) = \sinh(x)$ for an open universe, and $\mathrm{sinn}(x) = x$ for a flat universe. In our analysis, we combine these measurements.

In order to place limits on our equation (1), we perform χ^2 statistics for the model parameters (Ω_m, Ω_{r_c}) and the Hubble constant H_0. Since we want to concentrate solely on the density parameters, we need to marginalize over the Hubble parameter H_0.

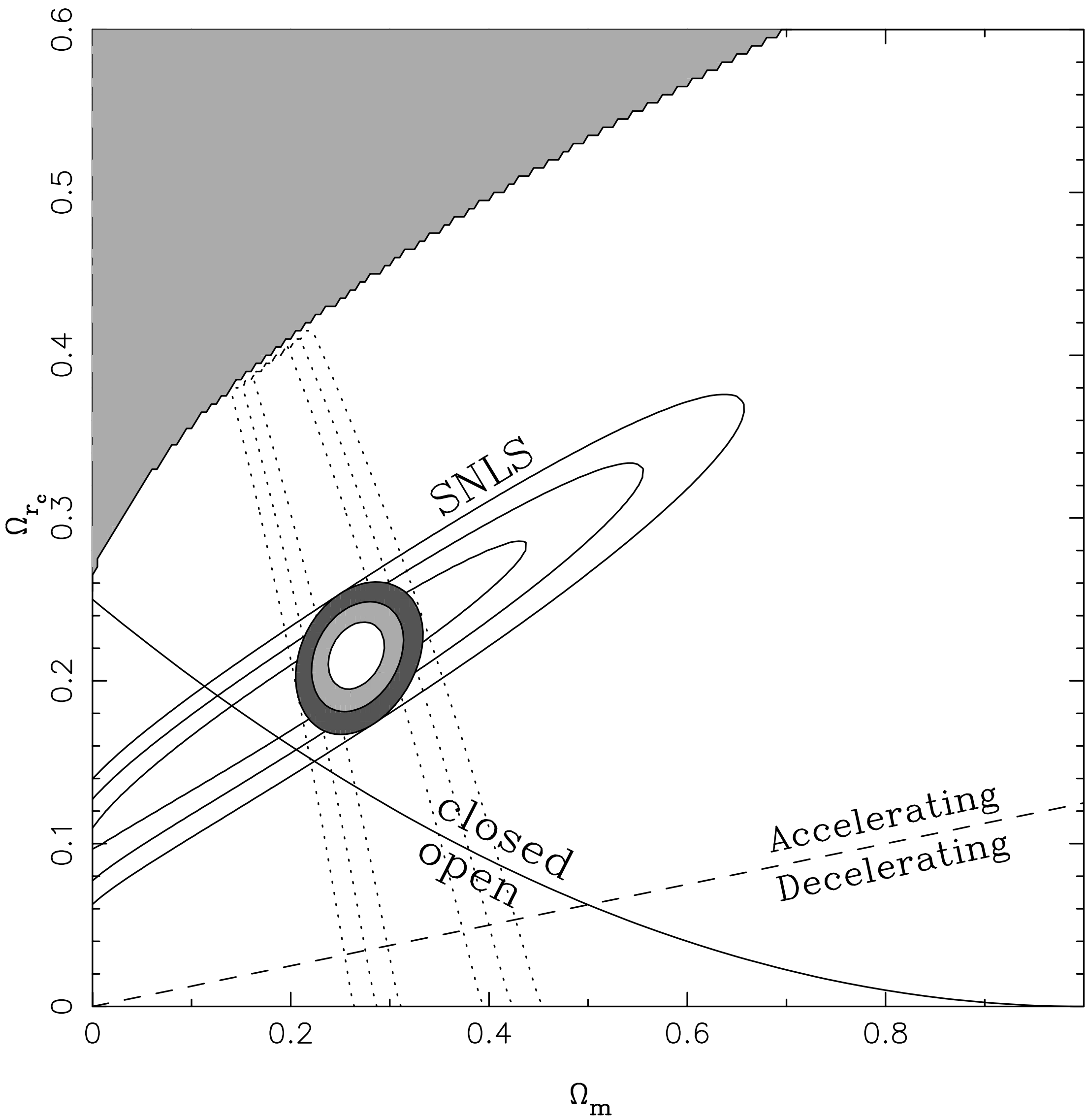

FIG. 3.— Same as Fig. 1, but from the first-year SNLS data (*solid contours*), from the baryon acoustic oscillations found in the SDSS data (*dotted lines*), and from the combination of the two databases (*shaded contours*). The best fit happens at $\Omega_m = 0.265$ and $\Omega_{r_c} = 0.216$. [*See the electronic edition of the Journal for a color version of this figure*.]

However, H_0 appears as a quadratic term in χ^2 or, equivalently, appears as a separable Gaussian factor in the probability to be marginalized over. Thus, marginalizing over H_0 is equivalent to evaluating χ^2 at its minimum with respect to H_0 (Barris et al. 2004). Here we marginalize over the Hubble parameter by using the analytical method of Wang et al. (2004). Figure 2 shows the joint confidence contour at 68.3%, 95.4%, and 99.7% confidence levels in the parametric space Ω_m-Ω_{r_c} arising from the gold sample of SN Ia data and the SDSS baryon acoustic oscillations. The best-fit parameters for this analysis are $\Omega_m = 0.272$ and $\Omega_{r_c} = 0.211$. Note that the best-fit value for Ω_{r_c} leads to an estimate of the crossover scale r_c in terms of the Hubble radius H_0^{-1}, i.e., $r_c = 1.089H_0^{-1}$. Compared to Figure 2 of Alcaniz & Pires (2004), the model parameters are more tightly constrained by using the prior from the baryon oscillation results than by assuming a Gaussian prior on the matter density parameter, $\Omega_m = 0.27 \pm 0.04$, as provided by the *WMAP* team (Spergel et al. 2003).

Figure 3 illustrates the allowed regions in the Ω_m-Ω_{r_c} plane by using the first-year SNLS data in conjunction with the SDSS baryon acoustic oscillations (see also Fairbairn & Goobar 2005 for a similar analysis[1]). Our best fit for this joint SNLS plus BAO analysis happens at $\Omega_m = 0.265$ and $\Omega_{r_c} = 0.216$. The parameter space is considerably reduced relative to Figure 2, since the SNLS data set is more sensitive to the value of Ω_{r_c} than the gold sample.

In Figure 4 we show the joint confidence contours from the gold sample of SN Ia data and the first-year SNLS data. In this case, the best-fit model happens for $\Omega_m = 0.31$ and $\Omega_{r_c} = 0.23$. We find that the degeneracies between these parameters are broken by combining these two data sets in the joint statistical analysis. With the prior from the SDSS baryon acoustic oscillations, our fits provide $\Omega_m = 0.270$ and $\Omega_{r_c} = 0.216$. Compared to Figure 4, the allowed confidence regions are slightly reduced.

Note that a closed universe is obtained at 3 σ confidence level in the above analyses, which confirms the previous results obtained

[1] During the writing of this work we became aware of the results of Fairbairn & Goobar (2005). In their analysis, however, they paid particularly more attention to a generalized version of the DGP model.

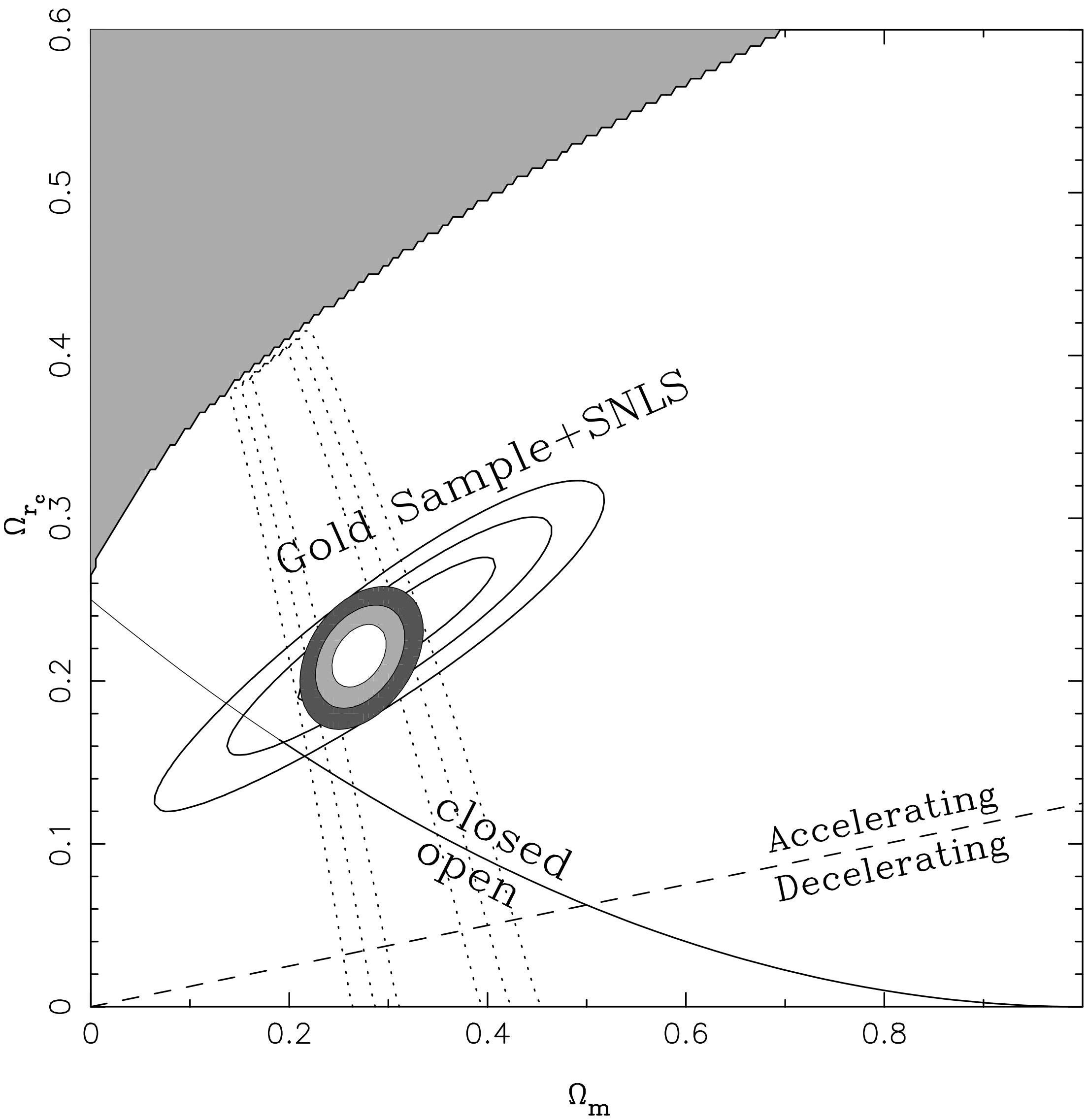

FIG. 4.—Same as Fig. 1, but from the combination of both the gold sample of SN Ia data and the first-year SNLS data (*solid contours*), from the baryon acoustic oscillations found in the SDSS data (*dotted lines*), and from the conjunction of the three databases (*shaded contours*). The best fit happens at $\Omega_m = 0.270$ and $\Omega_{r_c} = 0.216$. [*See the electronic edition of the Journal for a color version of this figure*.]

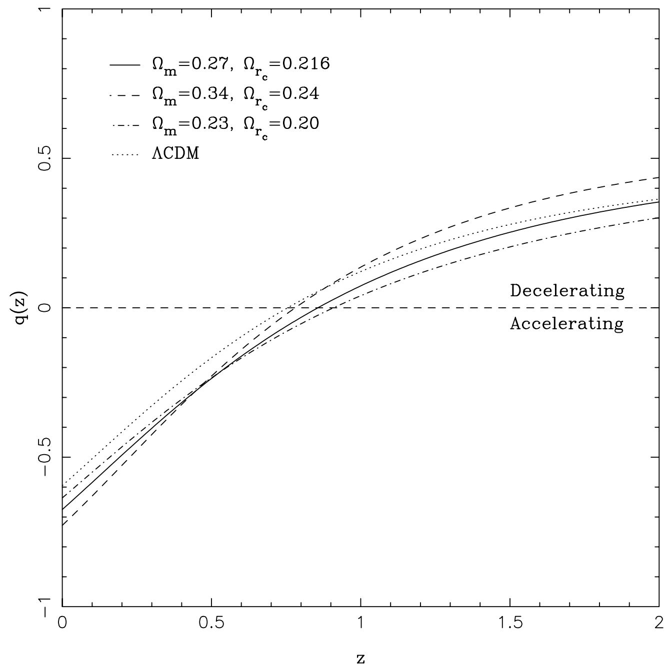

Fig. 5.—Deceleration parameter as a function of redshift z for some best-fit values in DGP model and the standard ΛCDM.

using the SNe Ia and the X-ray mass fraction data of galaxy clusters (Zhu & Alcaniz 2005; Alcaniz & Zhu 2005). Although there is a range on the parameter plane that is consistent with both the SNe Ia and the SDSS data, and the resulting matter density Ω_m is reasonable, a closed universe is obtained at a 99% confidence level, which seems to be inconsistent with the result, $\Omega_k = -0.02 \pm 0.02$, found by the *WMAP* team (Bennett et al. 2003; Spergel et al. 2003) and $\Omega_k = 0$ predicted by the simplest inflationary scenarios. Avelino & Martins (2002) analyzed the same model with the 92 SNe Ia from Riess et al. (1998) and Perlmutter et al. (1999). Assuming a flat universe, the authors obtained a low matter density and claimed the model was unfavorable. *In addition to including new SN Ia data and combining the SDSS data, we relax the flat universe constraint in our analysis.* We obtained a reasonable matter density but a closed universe. This means that in light of *WMAP* results—a nearly flat universe with $\Omega_k = -0.02 \pm 0.02$—the accelerating universe from gravitational leakage into an extra dimension seems not to be favored by the current observational data. Note also that the best-fit values of Ω_m and Ω_{r_c} lead to an estimate of the transition redshift $z_{q=0} = 0.86^{+0.07}_{-0.08}$, which is larger than that estimated from the gold sample, i.e., $z_{q=0} = 0.46 \pm 0.13$ (Riess et al. 2004). It means that acceleration in the DGP model happens earlier. Figure 5 shows the deceleration parameter as a function of redshift z for our best-fit values in DGP model. For comparison, we also plot the curve for the standard ΛCDM model. In Table 1 we summarize the main results of the paper.

4. CONCLUSION AND DISCUSSION

Observations of SNe Ia indicate that the expansion of the universe is accelerating. What drives the acceleration, however, is still a completely open question. From the observational viewpoint, it is of fundamental importance to differentiate between the two major possibilities, namely, the existence of new fields in high-energy physics (dark energy) or modifications of gravitation theory on large scales. In this paper, we have focused our attention on one of the leading contenders in the modified-gravity explanation of acceleration, the so-called DGP model. We have analyzed the DGP model by using the gold SN Ia sample, the recent SNLS data, and the SDSS baryon acoustic oscillations. Since SN Ia data are sensitive to the value of Ω_{r_c}, while the baryon acoustic oscillations are sensitive to the value of Ω_m, the combination of these data sets breaks the degeneracies between the model parameters and leads to strong constraints on them, as shown in Figures 2–4. The joint analysis strongly indicates a spatially closed universe, which was already obtained by fitting the combination of SN Ia data and the X-ray gas mass fraction in galaxy clusters (Zhu & Alcaniz 2005; Alcaniz & Zhu 2005). We also estimate the transition redshift $z_{q=0} \geq 0.70$ at 2 σ confidence level.

In summary, we have discussed the gravitational leakage into extra dimensions as an alternative mechanism for the late-time acceleration of the universe (and an alternative route to the dark energy problem). In agreement with other recent analyses, we have shown that a spatially closed DGP scenario with a crossover scale $r_c \sim H_0^{-1}$ is largely favored by most of the current observational data.

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TABLE 1

Constraints on Ω_m, Ω_{r_c}, r_c, and $z_{q=0}$

Test	Ω_m	Ω_{r_c}	r_c (H_0^{-1})	$z_{q=0}$
Gold sample	$0.34^{+0.07}_{-0.08}$	0.24 ± 0.04	1.02 ± 0.09	$0.78^{+0.24}_{-0.22}$
Gold + SDSS	$0.272^{+0.021}_{-0.019}$	$0.211^{+0.023}_{-0.027}$	$1.089^{+0.070}_{-0.059}$	$0.84^{+0.11}_{-0.13}$
SNLS	$0.23^{+0.14}_{-0.17}$	$0.20^{+0.06}_{-0.07}$	$1.12^{+0.20}_{-0.17}$	$0.91^{+0.66}_{-0.61}$
SNLS + SDSS	$0.265^{+0.019}_{-0.018}$	$0.216^{+0.013}_{-0.014}$	$1.076^{+0.035}_{-0.032}$	$0.87^{+0.08}_{-0.09}$
Gold + SNLS	$0.31^{+0.07}_{-0.06}$	0.23 ± 0.03	1.04 ± 0.07	$0.81^{+0.20}_{-0.22}$
Gold + SNLS + SDSS	$0.270^{+0.018}_{-0.017}$	$0.216^{+0.012}_{-0.013}$	$1.076^{+0.032}_{-0.030}$	$0.86^{+0.07}_{-0.08}$

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