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An accurate determination of the Hubble constant from baryon acoustic oscillation datasets

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Even though the Hubble constant cannot be significantly determined just by the low-redshift Baryon Acoustic Oscillation (BAO) data, it can be tightly constrained once the high-redshift BAO data are combined. We combined BAO data from 6dFGS, BOSS DR11 clustering of galaxies, WiggleZ and $z = 2.34$ from BOSS DR11 quasar Lyman-α forest lines to get $H_0 = 68.17^{+1.55}_{-1.56}$ km s^{-1} Mpc^{-1}. In addition, we adopted the simultaneous measurements of $H(z)$ and $D_A(z)$ from the two-dimensional two-point correlation function from BOSS DR9 CMASS sample and two-dimensional matter power spectrum from SDSS DR7 sample to obtain $H_0 = (68.11 \pm 1.69)$ km s^{-1} Mpc^{-1}. Finally, combining all of the BAO datasets, we conclude that $H_0 = (68.11 \pm 0.86)$ km s^{-1} Mpc^{-1}, a 1.3% determination.

Hubble constant, baryon acoustic oscillation, large-scale structure

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1 Introduction

Since Hubble [1] firstly published the linear correlation between the apparent distances to galaxies and their recessional redshift in 1929, the measurement of Hubble constant H_0 became a central goal in cosmology. H_0 measures the present expansion rate of the universe and is closely related to the components of the universe. Moreover, the inverse of H_0 roughly sets the size and age of the universe. Its value was estimated between 50 and 100 km s^{-1} Mpc^{-1} for decades, until Hubble Space Telescope (HST) and its Key project released their results in ref. [2], which was the first time that H_0 was measured accurately, namely $H_0 = (72 \pm 8)$ km s^{-1} Mpc^{-1}, a roughly 11% determination. This result was significantly improved by Riess et al. [3] in 2011 where H_0 was equal to (73.8 ± 2.4) km s^{-1} Mpc^{-1}, a 3% determination. On the other hand, the Hubble constant can be determined by the Cosmic Microwave Background (CMB) data indirectly. Assuming a flat universe, the nine-year Wilkinson Microwave Anisotropy Probe (WMAP9) data alone [4] gave a 3% determination, i.e. $H_0 = (70.0 \pm 2.2)$ km s^{-1} Mpc^{-1}, in the ΛCDM model in the end of 2012. In the early of 2013, Planck [5] released its first result and found the derived Hubble constant of (67.3 ± 1.2) km s^{-1} Mpc^{-1}, which is roughly 2.5σ tension with the Riess et al. [3] cosmic distance ladder measurement at low redshift. In order to clarify such a tension, Efstathiou [6] reanalyzed the Riess et al. [3] Cepheid data. Based on the revised geometric maser distance to NGC 4258, he found $H_0 = (70.6 \pm 3.3)$ km s^{-1} Mpc^{-1}, which is consistent with both HST [3] and Planck [5]. Recently, combining Baryon Acoustic Oscillation (BAO) results of 6dF Galaxy Surver (6dFGS) [7], Baryon Oscillation Spectroscopic Survey (BOSS) Data Release 11 (DR11) [8,9], distance ladder H_0 determination [3], WMAP9 [4] and supplementary CMB data at small angular scales from two ground-based experiments (Atacama Cos-

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mology Telescope and South Pole Telescope), Bennett et al. [10] got a more accurate determination of $H_0 = (69.6 \pm 0.7)$ km s^{-1} Mpc^{-1}. All of these results are summarized in Figure 1. Even though the different measurements gave roughly the same value of H_0, there were still $1 \sim 2\sigma$ discrepancies. So determining the Hubble constant from other independent cosmological experiments is still worthy. In this paper we adopt the BAO data alone to constrain the Hubble constant, and find $H_0 = (68.11 \pm 0.86)$ km s^{-1} Mpc^{-1}. See the red point in Figure 1.

Measurement of BAO is a very important tool for probing cosmology. Before recombination and decoupling the universe consisted of a hot plasma of photons and baryons tightly coupled via Thomson scattering. The competition between radiation pressure and gravity sets up oscillations in the photon fluid. At recombination the universe became neutral and the pressure on the baryons disappeared, and this abrupt change imparted a slight over-density of baryons on the length scale given by the distance that the sound waves could have traveled since the big bang, i.e. the sound horizon $r_s(z_d)$. Since the baryons and dark matter interact though gravity, the dark matter also preferentially clumps on this scale. Therefore, BAO imparts a characteristic signal in the matter power spectrum on the scale of the sound horizon at recombination. This signal in the matter power spectrum can be used as a "standard ruler" to map out the evolution of the Hubble parameter $H(z)$ and the angular diameter distance $D_A(z)$ at redshift z. Usually the Hubble parameter and the angular diameter distance cannot be extracted simultaneously from the BAO data. In ref. [11] an effective distance $D_V \propto (D_A(z)^2 H^{-1}(z))^{1/3}$ was introduced according to the different dilation scales for $H(z)$ and $D_A(z)$. Unfortunately the low-redshift BAO data, for example $D_V(z)/r_s(z_d)$, are insensitive to the Hubble constant, and hence the low-redshift BAO data can tightly constrain the matter density parameter Ω_m, but not the Hubble constant, by themselves. But this degeneracy of the Hubble constant can be significantly broken once the high-redshift BAO data are taken into account.

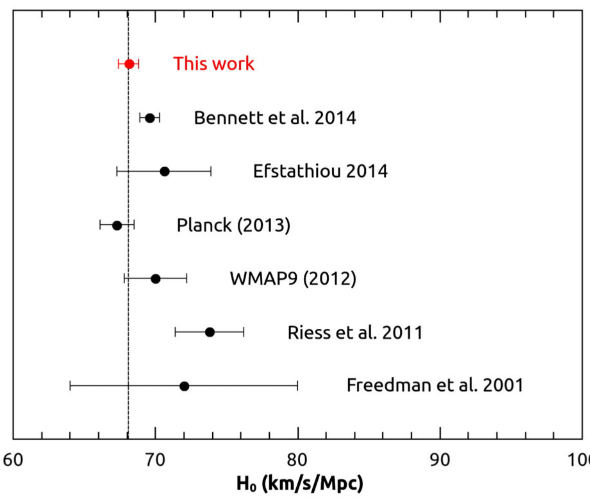

Figure 1 (Color online) Comparison of different H_0 measurements.

In principle, the Hubble parameter $H(z)$ and the angular diameter distance $D_A(z)$ can be extracted simultaneously from the data through the measurement of the BAO scale in the radial and transverse directions. In refs. [12–14], Chuang and Wang made significant improvements in modeling for the two-dimensional two-point correlation function (2d2pCF) of galaxies, and succeeded in simultaneously measuring $H(z)$ and $D_A(z)$ from data without assuming a dark energy or a flat universe. Recently a similar method and model has been applied to measure $H(z)$, $D_A(z)$ and the physical matter density $\Omega_m h^2$ from the anisotropic galaxy clustering of DR9 CMASS sample of the SDSS-III BOSS at the effective redshift $z = 0.57$ in ref. [15]. In addition, a method to measure $H(z)$ and $D_A(z)$ simultaneously from the two-dimensional matter power spectrum (2dMPS) was proposed by Hemantha et al. in ref. [16]. Applying this method to Sloan Digital Sky Survey (SDSS) DR7, Hemantha et al. simultaneously constrained $H(z)$, $D_A(z)$, and $\Omega_m h^2$ as well. These two measurements can provide a significant constraint on the cosmological parameters, e.g. the Hubble constant, themselves.

In this paper we assume a spatially flat universe containing a cosmological constant and cold dark matter, namely a concordance ΛCDM cosmological model. We will introduce the BAO data and explain our methodology in sect. 2. Our main results will be presented in sect. 3. Summary and discussion will be given in sect. 4.

2 BAO data and methodology

BAO provides an independent way to determine cosmological parameters. The BAO signal is a standard ruler such that the length of the sound horizon can be measured as a function of redshift. This measures two cosmological distances: $D_A(z)/r_s(z_d)$ (the correlations of two spatial dimensions orthogonal to the direction of sight) and $H(z)r_s(z_d)$ (the fluctuation of one dimension along the direction of sight).

In a spatially flat universe the angular diameter distance is given by

$$D_A(z) = \frac{1}{1+z}\int_0^z \frac{\mathrm{d}z'}{H(z')}, \tag{1}$$

where $H(z)$ is related to the Hubble constant H_0 by

$$\frac{H(z)}{H_0} = [\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + (1-\Omega_r-\Omega_m)f(z)]^{\frac{1}{2}}, \tag{2}$$

here $f(z) \equiv \rho_{\rm de}(z)/\rho_{\rm de}(0)$ depends on dark energy model, i.e.

$$f(z) = (1+z)^{3(1+w_0+w_a)}\exp\left[-\frac{3w_a z}{1+z}\right], \tag{3}$$

in the w_0w_aCDM model [17] where $w = p_{\rm de}/\rho_{\rm de}$ is the equation of state parameter of dark energy, which is parameterized by $w(z) = w_0 + (w_a z)/(1+z)$. For the ΛCDM model, $w_0 = -1$ and $w_a = 0$. In this paper we adopt Eisenstein and Hu [18] form to calculate the sound horizon at redshift z_d, which is the time when baryons decoupled from the Compton drag of photons, namely

$$r_s(z_d) = \frac{1}{\sqrt{3}} \int_0^{\frac{1}{1+z_d}} \frac{\mathrm{d}a}{a^2 H(a)\sqrt{1+\frac{3\Omega_b}{4\Omega_\gamma}a}}, \tag{4}$$

where

$$z_d = \frac{1291(\Omega_m h^2)^{0.251}}{1+0.659(\Omega_m h^2)^{0.828}}[1+b_1(\Omega_b h^2)^{b_2}] \tag{5}$$

and

$$b_1 = 0.313(\Omega_m h^2)^{-0.419}[1+0.607(\Omega_m h^2)^{0.674}], \tag{6}$$
$$b_2 = 0.238(\Omega_m h^2)^{0.223}. \tag{7}$$

Since the Hubble parameter changes differently from the angular diameter distance, the dilation scale is usually treated as the cube root of the product of the radial dilation times the square of the transverse dilation [11], namely

$$D_V(z) \equiv \left[(1+z)^2 D_A^2(z)\frac{z}{H(z)}\right]^{\frac{1}{3}}, \tag{8}$$

which is the so-called volume-averaged effective distance.

In this paper, $\Omega_b h^2$ and $\Omega_\gamma h^2$ are fixed as their best fit values of Planck, namely

$$\Omega_b h^2 = 0.02203, \tag{9}$$
$$\Omega_\gamma h^2 = 2.46\times 10^{-5}. \tag{10}$$

The present energy density of radiations is related to Ω_γ by

$$\Omega_r = \Omega_\gamma(1+0.2271N_{\rm eff}) = 4.16\times 10^{-5}h^{-2}, \tag{11}$$

where $N_{\rm eff} = 3.046$ is the effective number of neutrinos in the standard model. The changes of $\Omega_b h^2$ within its error bars do not substantially shift our results.

2.1 BAO-I

In ref. [7] the distance-redshift relation at the effective redshift $z_{\rm eff} = 0.106$ is $r_s(z_d)/D_V = 0.336\pm0.015$ from the large-scale correlation function of the 6dF Galaxy Survey (6dFGS) BAO.

Fitting for the position of the acoustic features in the correlation function and matter power spectrum of BAO in the clustering of galaxies from BOSS DR11, Anderson et al. [8] got $D_V(z=0.32)(r_s(z_d)_{\rm fid}/r_s(z_d)) = (1264\pm25)$ Mpc and $D_V(z=0.57)(r_s(z_d)_{\rm fid}/r_s(z_d)) = (2056\pm20)$ Mpc. Here $r_s(z_d)_{\rm fid} = 153.19$ Mpc[1)] in their fiducial cosmology. When fitting cosmological models, we adopted $D_A(z=0.57)(r_s(z_d)_{\rm fid}/r_s(z_d)) = (1421\pm20)$ Mpc and $H(z=0.57)(r_s(z_d)/r_s(z_d)_{\rm fid}) = (96.8\pm3.4)$ km s^{-1} Mpc^{-1}, with a correlation coefficient between D_A and H of 0.539, which is recommended by Anderson et al. in ref. [8].

Reconstructing the baryonic acoustic feature from the WiggleZ Dark Energy Survey, the model independent distances $D_V(r_s(z_d)_{\rm fid}/r_s(z_d))$ given by Kazin et al. in ref. [19] are (1716 ± 83) Mpc, (2221 ± 101) Mpc, and (2516 ± 86) Mpc at effective redshifts $z = 0.44, 0.6$, and 0.73, respectively. The fiducial cosmology adopted in ref. [19] implies $r_s(z_d)_{\rm fid} = 148.6$ Mpc.

From BOSS DR11 latest released sample, Delubac et al. [9] figured out the BAO feature in the flux-correlation function of the Lyman-α forest of high-redshift quasars, and found $\alpha_\parallel = 1.054^{+0.032}_{-0.031}$ and $\alpha_\perp = 0.973^{+0.056}_{-0.051}$ at the effective redshift $z = 2.34$, where

$$\alpha_\parallel = \frac{c/(H(z)r_s(z_d))}{c/(H(z)r_s(z_d))_{\rm fid}}, \tag{12}$$
$$\alpha_\perp = \frac{D_A(z)/r_s(z_d)}{(D_A(z)/r_s(z_d))_{\rm fid}}. \tag{13}$$

In ref. [9] Delubac et al. recommended the use of $\alpha_\parallel^{0.7}\alpha_\perp^{0.3} = 1.025\pm0.021$, which is the most precisely determined combination, to fit the cosmological models. According to their fiducial cosmology, $c/(H(z=2.34)r_s(z_d))_{\rm fid} = 8.708$ and $(D_A(z=2.34)/r_s(z_d))_{\rm fid} = 11.59$.

The distance ratio $D_V(z)/r_s(z_d)$ for the BAO-I data are accumulated in Table 1 and Figure 2. Keeping $\Omega_m = 0.27$ fixed, we plot $D_V(z)/r_s(z_d)$ versus redshift z in Figure 2 where the solid, dashed, and dotted lines represent $H_0 = 68, 75, 60$ km s^{-1} Mpc^{-1}, respectively. It shows that these three curves trend to converge at low redshift. That is why the low-redshift BAO data alone can not be used to constrain the Hubble constant. But these three curves diverge at high redshift. So the combination of the low and high-redshift BAO data can be used to precisely determine the Hubble constant H_0.

2.2 BAO-II

In ref. [15], Chuang et al. analyzed the broad range shape of the monopole and quadrupole 2d2pCF from the BOSS DR9 CMASS sample, and obtained the constraints at the effective redshift $z = 0.57$: $\{H(0.57), D_A(0.57), \Omega_m h^2\} = \{87.6^{+6.7}_{-6.8}$ km s^{-1} Mpc^{-1}, (1396 ± 73) Mpc, $0.126^{+0.008}_{-0.010}\}$ and their covariance matrix

Table 1 The distance ratio $D_V(z)/r_s(z_d)$ for the BAO-I datasets

z	$D_V(z)/r_s(z_d)$	Experiment	Reference
0.106	2.976 ± 0.133	6dFGS	[7]
0.32	8.251 ± 0.163	BOSS DR11	[8]
0.57	13.421 ± 0.131	BOSS DR11	[8]
0.44	11.548 ± 0.559	WiggleZ	[19]
0.6	14.946 ± 0.680	WiggleZ	[19]
0.73	16.931 ± 0.579	WiggleZ	[19]
2.34	31.233 ± 0.663	BOSS DR11	[9]

1) In this paper, we use Eisenstein & Hu form. So we adopt $r_s(z_d)_{\rm fid} = 153.19$ Mpc

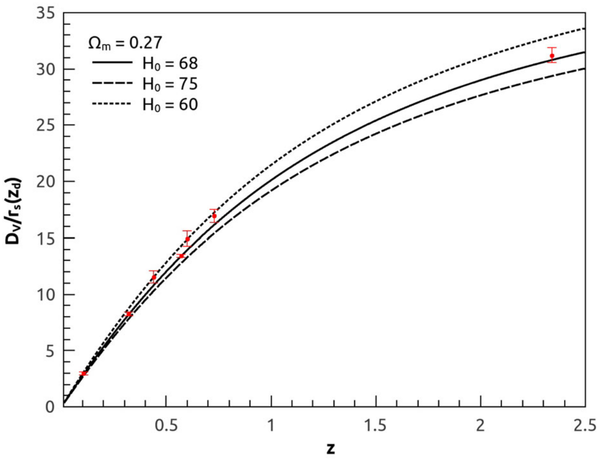

Figure 2 (Color online) $D_V(z)/r_s(z_d)$ varies with z. Here Ω_m is fixed as 0.27. The solid, dashed and dotted lines correspond to $H_0 = 68, 75, 60$ km s^{-1} Mpc^{-1}, respectively. It implies that the low-redshift BAO alone cannot determine H_0 precisely, but H_0 can be tightly constrained once the high-redshift BAO data are combined.

$$\begin{pmatrix} 0.0385 & -0.001141 & -13.53 \\ -0.001141 & 0.0008662 & 3.354 \\ -13.53 & 3.354 & 19370 \end{pmatrix}. \tag{14}$$

In ref. [16], Hemantha et al. presented a method to measure $H(z)$ and $D_A(z)$ simultaneously from the 2dMPS from galaxy surveys with broad sky coverage. Adopting the SDSS DR7 sample, they obtained the measurements of $\{H(0.35), D_A(0.35), \Omega_m h^2\} = \{(81.3 \pm 3.8)$ km s^{-1} Mpc^{-1}, (1037 ± 44) Mpc, $(0.1268 \pm 0.0085)\}$ with covariance matrix

$$\begin{pmatrix} 0.00007225 & -0.169609 & 0.01594328 \\ -0.169609 & 1936 & 67.03048 \\ 0.01594328 & 67.03048 & 14.44 \end{pmatrix}. \tag{15}$$

3 Analysis

3.1 Consistency of BAO data

BAO datasets cannot be used to determine the Hubble constant in a model-independent way. Here we assume a spatially flat universe containing a cosmological constant and cold dark matter, namely a concordance ΛCDM cosmological model. Before combining the BAO datasets to constrain the cosmological parameters, we need to check whether these datasets are consistent in the concordance ΛCDM cosmological model. Since the BAO data mostly constrain the expansion history of the universe, which is determined by the two parameters (Ω_m and H_0) in concordance ΛCDM cosmology, we explore the constraints on these two parameters explicitly. In order to check the consistency of different BAO data, the representative BAO measurements at different redshifts from both BAO-I and BAO-II datasets are plotted in Figure 3 individually.

From Figure 3, one can clearly see that even though different BAO measurements at different redshifts have different degeneracy directions, there is no significant tension among them.

3.2 Constraints on the Hubble constant from different BAO datasets

The constraints on H_0 from different BAO datasets are illustrated in Figure 4.

According to the previous arguments, the value of H_0 cannot be significantly constrained just by the low-redshift BAO-I data. Adopting the BAO-I dataset without $z = 2.34$, $H_0 = 74.32^{+5.87}_{-5.73}$ km s^{-1} Mpc^{-1}. See the black dashed curve

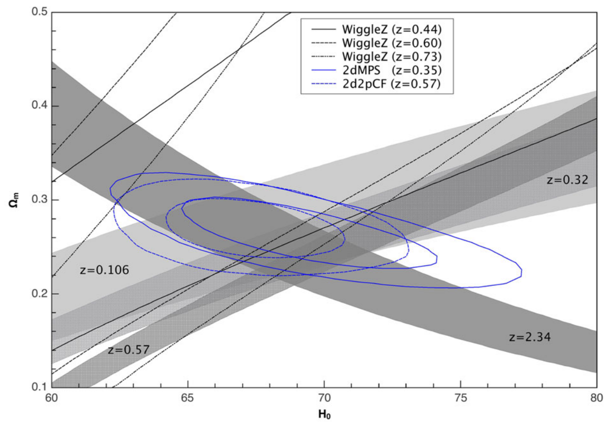

Figure 3 (Color online) BAO 1σ constraints for redshifts 0.106 from 6dFGS [7], 0.32 and 0.57 from BOSS DR11 clustering of galaxies [8], WiggleZ ($z = 0.44$, 0.60, 0.73) [19], and $z = 2.34$ ($\alpha_{\parallel}^{0.7}\alpha_{\perp}^{0.3}$) from BOSS DR11 quasar Lyman-α forest lines [9]. The solid and dashed blue contours correspond to the constraints from SDSS DR7 2dMPS at the effective redshift $z = 0.35$ [16] and BOSS DR9 2d2pCF at $z = 0.57$ [15], respectively.

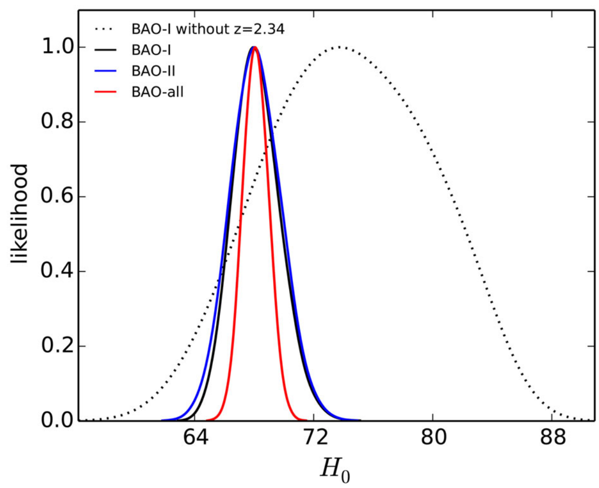

Figure 4 (Color online) The likelihoods of H_0 from different BAO datasets. The black dotted and solid curves correspond to the constraints from BAO-I without $z = 2.34$ and all BAO-I data respectively. The blue one is the constraint from BAO-II. The likelihood of H_0 from all of BAO data is illustrated by the red curve.

in Figure 4. But it can be tightly constrained once one high-redshift BAO (z=2.34) is added. See the black solid curve in Figure 4. From all of the BAO-I data, the constraint on the Hubble constant is $H_0 = 68.17^{+1.55}_{-1.56}$ km s^{-1} Mpc^{-1}, a 2.3% determination.

Since the Hubble parameter $H(z)$ and the angular diameter distance D_A can be measured simultaneously from the two-dimensional two-point correlation function and two-point matter power spectrum, the Hubble constant is precisely determined by the two BAO-II datasets alone, namely $H_0 = (68.11 \pm 1.69)$ km s^{-1} Mpc^{-1}, a 2.5% determination, which is roughly the same as that from BAO-I.

Since BAO-I and BAO-II are consistent with each other, combining both of them, we reach a 1.3% determination of the Hubble constant, namely $H_0 = (68.11 \pm 0.86)$ km s^{-1} Mpc^{-1}.

The contour plots of H_0 vs. Ω_m from BAO-I, BAO-II, and BAO-all show up in Figure 5.

It is interesting that the contour plots from BAO-I and BAO-II are roughly orthogonal to one another. Therefore it is quite effective to constrain the cosmological parameters, e.g. H_0 and Ω_m, once both BAO-I and BAO-II are combined. The numerical results are summarized in Table 2.

4 Discussion and summary

We accumulated all of the BAO data, including 6dFGS, WiggleZ, and BOSS DR11 clustering of galaxies and quasar Lyman-α forest lines, SDSS DR7 2dMPS and BOSS DR9 2d2pCF, and found that the Hubble constant can be precisely determined by the BAO data alone: $H_0 = (68.11 \pm 0.86)$ km s^{-1} Mpc^{-1}, a 1.3% determination. Our result is consistent with that from Planck in ref. [5] and Efstathiou in ref. [6] where the revised NGC 4258 maser distance was used. Our result is also not so different from that obtained by Bennett et al. in ref. [10]. But there is around 2.4σ tension compared to the Hubble constant given by Riess et al. in ref. [3].

The present matter energy density is also tightly constrained by the BAO datasets alone: $\Omega_m = 0.268^{+0.009}_{-0.010}$. This result is consistent with the combination of supernova Union2.1 compilation of 580 SNe (Union 2.1) [20] ($\Omega_m = 0.277^{+0.022}_{-0.021}$), but has around 2.6$\sigma$ tension with Planck [5] ($\Omega_m = 0.315^{+0.016}_{-0.018}$).

Finally, we want to stress that the high-redshift BAO and the simultaneous measurements of $H(z)$ and $D_A(z)$ from the two-dimensional 2-point correlation function and two-dimensional matter power spectrum are very powerful tools for probing cosmology. We hope that more data about them can be provided in the near future. If we go beyond the Λ CDM model [21–24], a slightly different result is expected.

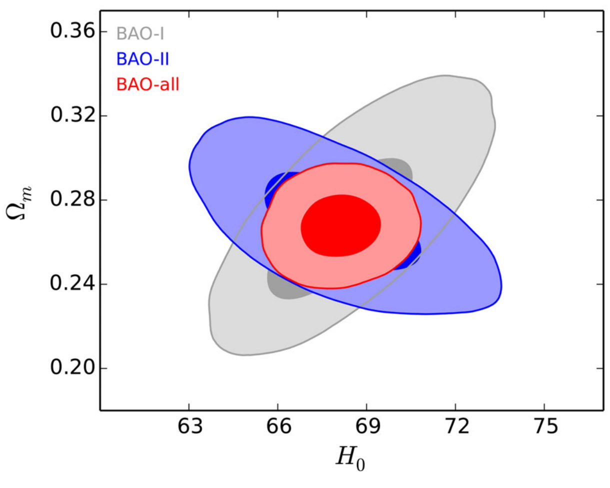

Figure 5 (Color online) The contour plot of H_0 vs. Ω_m from BAO-I, BAO-II, and BAO-all, respectively.

Table 2 Constraint on H_0 and Ω_m from different BAO datasets

BAO data sets	H_0 (km s^{-1} Mpc^{-1})	Ω_m
BAO-I without z = 2.34	$74.32^{+5.87}_{-5.73}$	$0.351^{+0.081}_{-0.077}$
BAO-I	$68.17^{+1.55}_{-1.56}$	$0.268^{+0.022}_{-0.021}$
BAO-II	68.11 ± 1.69	$0.269^{+0.015}_{-0.014}$
BAO-all	68.11 ± 0.86	$0.268^{+0.009}_{-0.010}$

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1 Hubble E. A relation between distance and radial velocity among extra-galactic nebulae. Proc Natl Acad Sci USA, 1929, 15: 168–173
2 Freedman W L, Madore B F, Gibson B K, et al. Final results from the Hubble space telescope key project to measure the Hubble constant. Astrophys J, 2001, 553: 47–72
3 Riess A G, Macri L, Casertano S, et al. A 3% solution: Determination of the Hubble constant with the Hubble space telescope and wide field camera 3. Astrophys J, 2011, 730: 119
4 Hinshaw G F. Nine-year Wilkinson microwave anisotropy probe (WMAP) observations: Cosmology results. Astrophys J Suppl S, 2013, 208: 19
5 Planck C, Aghanim N, Armitage-Caplan C, et al. Planck 2013 results. XVI. cosmological parameters. Astron Astrophys, 2014, 571: A16
6 Efstathiou G. H_0 revisited. Mon Not R Astron Soc, 2014, 440: 1138–1152
7 Beutler F, Blake C, Colless M, et al. The 6dF galaxy survey: Baryon acoustic oscillations and the local Hubble constant. Mon Not R Astron Soc, 2011, 416: 3017–3032
8 Anderson L, Aubourg É, Bailey S, et al. The clustering of galaxies in the SDSS-III baryon oscillation spectroscopic survey: Baryon acoustic oscillations in the data releases 10 and 11 galaxy samples. Mon Not R Astron Soc, 2014, 441: 24–62
9 Delubac T, Bautista J E, Busca N G, et al. Baryon acoustic oscillations in the Lyα forest of BOSS DR11 quasars. arXiv: 1404.1801
10 Bennett C L, Larson D, Weiland J L, et al. The 1% concordance Hubble constant. Astrophys J, 2014, 794: 135
11 Eisenstein D J, Zehavi I, Hogg D W, et al. Detection of the baryon acoustic peak in the large-scale correlation function of SDSS luminous red galaxies. Astrophys J, 2005, 633: 560–574
12 Chuang C H, Wang Y. Measurements of $H(z)$ and DA(z) from the two-

dimensional two-point correlation function of Sloan digital sky survey luminous red galaxies. Mon Not R Astron Soc, 2012, 426: 226–236

13 Chuang C H, Wang Y. Using multipoles of the correlation function to measure $H(z)$, DA(z) and $\beta(z)$ from Sloan digital sky survey luminous red galaxies. Mon Not R Astron Soc, 2013, 431: 2634–2644

14 Chuang C H, Wang Y. Modeling the anisotropic two-point galaxy correlation function on small scales and improved measurements of $H(z)$, DA(z), and $\beta(z)$ from the Sloan digital sky survey DR7 luminous red galaxies. Mon Not R Astron Soc, 2013, 435: 255–262

15 Chuang C H, Prada F, Cuesta A J, et al. The clustering of galaxies in the SDSS-III baryon oscillation spectroscopic survey: Single-probe measurements and the strong power of normalized growth rate on constraining dark energy. arXiv: 1312.4889 [astro-ph.CO]

16 Hemantha M D P, Wang Y, Chuang C H. Measurement of $H(z)$ and DA(z) from the two-dimensional power spectrum of Sloan digital sky survey luminous red galaxies. Mon Not R Astron Soc, 2014, 445: 3737–3744

17 Chevallier M, Polarski D. Accelerating universes with scaling dark matter. Int J Mod Phys D, 2001, 10: 213; Linder E V. Exploring the expansion history of the universe. Phys Rev Lett, 2003, 90: 091301

18 Eisenstein D J, Hu W. Baryonic features in the matter transfer function. Astrophys J, 1998, 496: 605–614

19 Kazin E A, Koda J, Blake C, et al. Improved WiggleZ dark energy survey distance measurements to z=1 with reconstruction of the baryonic acoustic feature. arXiv: 1401.0358

20 Suzuki N, Rubin D, Lidman C, et al. The Hubble space telescope cluster supernova survey: V. improving the dark energy constraints above $z > 1$ and building an early-type-hosted supernova sample. Astrophys J, 2012, 746: 85

21 Wu J, Li Z X, Wu P X, et al. Constrains on $f(T)$ gravity with the strong gravitational lensing data. Sci China-Phys Mech Astron, 2014, 57: 988–993

22 Zhang M, Sun C Y, Yang Z Y, et al. Cosmological evolution of quintessence with a sign-changing interaction in dark sector. Sci China-Phys Mech Astron, 2014, 57: 1805–1808

23 Hu Y Z, Li M, Li X D, et al. Investigating the possibility of a turning point in the dark energy equation of state. Sci China-Phys Mech Astron, 2014, 57: 1607–1612

24 Li Z X, Wu P X, Yu H W, et al. A possible resolution of tension between Planck and Type Ia supernova observations. Sci China-Phys Mech Astron, 2014, 57: 381–386