Robustness of $H_0$ determination at intermediate redshifts

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ABSTRACT

The most recent Hubble constant ($H_0$) estimates from local methods ($z < 1$), $H_0 = 73.8 ± 2.4$ km s$^{-1}$ Mpc$^{-1}$, and the one from high redshifts $H_0 = 67.3 ± 1.2$ km s$^{-1}$ Mpc$^{-1}$, are discrepant at 2.4σ confidence level. Within this context, Lima & Cunha (LC) derived a new determination of $H_0$ using four cosmic probes at intermediate redshifts ($0.1 < z < 1.8$) based on the so-called flat ΛCDM model. They obtained $H_0 = 74.1 ± 2.2$ km s$^{-1}$ Mpc$^{-1}$, in full agreement with local measurements. In this Letter, we explore the robustness of the LC result searching for systematic errors and its dependence from the cosmological model used. We find that the $H_0$ value from this joint analysis is very weakly dependent on the underlying cosmological model, but the morphology adopted to infer the distance to galaxy clusters changes the result sizeably, being the main source of systematic errors. Therefore, a better understanding of the cluster morphology is paramount to transform this method into a powerful cross-check for $H_0$.

Key words: cosmological parameters – cosmology: observations – cosmology: theory – dark energy – distance scale – large-scale structure of Universe.

1 INTRODUCTION

The new controversy in the value of the Hubble constant $H_0$ determined from local and global measurements raised a lot of activity to pin down evidence of new physics or unaccounted systematic errors. While a local measurement with Cepheids and Type Ia supernovae (SNe Ia) derived $H_0 = 73.8 ± 2.4$ km s$^{-1}$ Mpc$^{-1}$ (Riess et al. 2011), the Planck Collaboration (2013) determined $H_0 = 67.3 ± 1.2$ km s$^{-1}$ Mpc$^{-1}$ within a flat Λ cold dark matter (ΛCDM) model from temperature anisotropies in the cosmic microwave background (CMB).

Many systematic errors may be responsible for the difference. Concerning local measurements, the first rung in the distance ladder is crucial for $H_0$ measurements. Depending on what method is used to calibrate SNe Ia distances, a variety of values is derived for $H_0$. For example, Riess et al. (2011) used three distance indicators to calibrate the SNe Ia: a geometric distance to NGC 4258 based on a megamaser measurement; parallax measurements to Milky Way Cepheids (MWC) and Cepheids observations and a revised distance to the Large Magellanic Cloud (LMC). Revising the distance to NGC 4258 from Humphreys et al. (2013), with only this indicator Efstathiou (2014) used Riess et al. (2011) data to get $H_0 = 70.6 ± 3.3$ km s$^{-1}$ Mpc$^{-1}$, while combining the three indicators the value is $H_0 = 72.5 ± 2.5$ km s$^{-1}$ Mpc$^{-1}$, alleviating the tension. On the other hand, calibrating the SNe with the tip of the red giant branch (TGRB) Tammann & Reindl (2013) obtained $H_0 = 63.7 ± 2.7$ km s$^{-1}$ Mpc$^{-1}$. This is very intriguing since many local determinations obtained higher values for $H_0$ (see Table 1).

The systematic errors may also come from the CMB analysis. For example, Spergel et al. (2013) claim that the 217 × 217 GHz detector can be responsible for some part of the tension, where its removal provides $H_0 = 68.0 ± 1.1$ km s$^{-1}$ Mpc$^{-1}$. Moreover, an inconsistency of the Planck data with a flat ΛCDM model was claimed by Hazra & Shafieloo (2014), where a lack of power for high and low multipoles may indicate new physics or systematic errors.

On the new physics side, it could be just cosmic variance (Marra et al. 2013; Woitak et al. 2014); if we live in a ‘Hubble bubble’ we would infer a higher local value for $H_0$ compared to the global one. This possibility requires a very unlikely size for the void, although it is compatible with observations (Keenan et al. 2013). Other possibilities include extensions of the cosmic concordance model (Salvatelli et al. 2013).
By considering the Universe described by a homogeneous and isotropic Friedmann–Lemaître–Robertson–Walker (FLRW) geometry, the angular distance $D_A$ is given by

$$D_A = \frac{h^{-1}}{1+z} \sqrt{\Omega_k} \left[ \sqrt{\Omega_m} \int_0^z \frac{dz'}{E(z')} \right] \text{Mpc},$$

(1)

with $h = H_0/100$ km s$^{-1}$ Mpc$^{-1}$, the function $E(z) = H(z)/H_0$ is the dimensionless Hubble parameter defined by the specific cosmology adopted, $\Omega_k$ is the density curvature parameter and $S_k(x) = \sin x, x, \sinh x$ for $k = +1, 0, -1$, respectively.

On the other hand, the age-redshift relation, $t(z)$, is given by $t(z) = \int_0^z \frac{dz'}{H(z')}$. For the cosmological models adopted in this Letter, $E(z)$ reads $E^2(z) = \frac{H^2(z)}{H_0^2} = \Omega_M(1+z)^2 + \Omega_k(1+z)^{2(1+w)} + \Omega_b(1+z)^2$, where $\Omega_k = 1 - \Omega_m - \Omega_M$. We consider two cases: a $\Lambda$CDM model with $\omega = 0$ and a flat XCDM model with $\Omega_k = 0$.

3 SAMPLES

In order to have a reliable comparative study with the LC results, the only difference between their and our cosmological probes it is the addition of the De Filippis et al. sample (2005). Summarizing, in this Letter we use the following.

(a) Three samples of ADD from galaxy clusters obtained from their Sunyaev–Zel’dovich and X-ray observations (the so-called ESZ/X-ray technique). The first one, used in LC, composed of 38 ADD in redshift range $0.1 < z < 0.89$ compiled by Bonamente et al. (2006) where the cluster plasma and dark matter distributions were analysed assuming a non-isothermal spherical double $\beta$ model. This model generalises the single $\beta$ model proposed by Cavaliere & Fusco-Ferramino (1978). Summarizing, the cluster plasma and dark matter distributions were analysed assuming a hydrostatic equilibrium model and spherical symmetry, accounting for radial variations in density, temperature and including the possible presence of cooling flow. The new samples used here are formed by 18 galaxy clusters from De Filippis et al. (2005) in the redshift range $0.142 < z < 0.79$. These authors re-analysed archival X-ray data of the XMM-Newton and Chandra satellites of two samples (Mason et al. 2001; Reese et al. 2002) for which combined X-ray and SZE analysis have already been reported. In the reanalysis were used two models to describe exactly the same clusters: the isothermal elliptical and spherical $\beta$ models, providing two ADD samples, named from now on, samples i and ii, respectively.

It is important to comment that, in general, different cluster gas profiles do not affect the inferred central surface brightness ($S_{\alpha 0}$) or central Sunyaev–Zel’dovich decrement ($\Delta T_0$), but give different $\theta_{\text{tot}}$ (the core radius). De Filippis et al. (2005) found, for instance, $\theta_{\text{ell}} = \frac{\theta_{\text{circ}}}{1 + e_{\text{proj}}\theta_{\text{circ}}}$ (in first approximation), where $\theta_{\text{ell}}$ and $\theta_{\text{circ}}$ are the core radius obtained by using an isothermal elliptical $\beta$ model and an isothermal spherical $\beta$ model, respectively, and $e_{\text{proj}}$ is the axial ratio of the major to the minor axes of the projected isophotes. Since $D_A(z) \propto 1/\theta_{\text{tot}}$, different core radius affect the ESZ/X-ray distances and, consequently, the $H_0$ estimates (see fig. 1 in De Filippis et al. 2005). Thus, for
these single $\beta$ models, $D_\Lambda$ obtained by the spherical model is overestimated compared with the elliptical one.

(b) 18 Hubble parameter versus redshift data points, $H(z)$, from cosmic chronometers and BAOs in redshift range $0.1 < z < 1.70$. These 18 data points are subsamples from Ferreras et al. (2009) and Longhetti et al. (2007) catalogues. As argued by LC, the selected data set provides accurate and restrictive galaxy ages (see fig. 1 in their paper).

(d) The BAOs peak at $z = 0.35$. As it is largely known, the relevant distance measure is the dilation scale that can be modelled as the cube root of the radial dilation times the square of the transverse dilation, at the typical redshift of the galaxy sample, $z = 0.35$ (Eisenstein et al. 2005):

$$D_V(z) = [D_\Lambda(z)^2/H(z)]^{1/3}.$$  

However, the BAO quantity that we use is the $H_0$ independent BAO datum given by

$$A(0.35) = D_V(0.35) \frac{\Omega_m H_0^2}{0.35} = 0.469 \pm 0.017.$$  

4 ANALYSES AND RESULTS

We perform the $\chi^2$ statistics combining the four tests discussed above such as (LC)

$$\chi^2(z|p) = \sum_i \frac{(D_\Lambda(z_i,p)-D_{\text{obs},i})^2}{\sigma_{D_{\text{obs},i}}^2} + \sum_j \frac{(H(z_j,p)-H_{\text{obs},j})^2}{\sigma_{H_{\text{obs},j}}^2 + \sigma_{H_{\text{inc}}}^2} + \frac{(\Delta(p)-\Delta_{\text{obs},k})^2}{\sigma_{\Delta_{\text{obs},k}}^2}.$$  

The quantities with subscript 'obs' are the observational quantities, $\sigma_{D_{\text{obs},i}}$ is the uncertainty in the individual distance, $\sigma_{H_{\text{inc}}}$ is the incubation time error. For the galaxy cluster samples, the common statistical contributions are SZE point sources $\pm8\%$, X-ray background $\pm2\%$, galactic NH $<\pm1\%$, $\pm15\%$ for cluster asphericity, $\pm8\%$ kinetic SZ and for CMB anisotropy $<\pm2\%$. The term $t_{\text{inc}}$ is the incubation time, defined by the amount of time interval from the beginning of structure formation process in the Universe until the formation time of the object itself. The complete set of parameters is given by $p$. Following LC, we have considered initially $t_{\text{inc}} = 0.8 \pm 0.4$ Gyr.

4.1 $\Lambda$CDM

In Figs 1(a)-(c) we display the $(h, \Omega_k)$ plane. Here and in the flat XCDM analyses, the red-dashed and black dash-dotted lines correspond to 1$\sigma$ and 2$\sigma$ limits obtained by using OHRG+BAO and $H(z)$, respectively. The blue solid lines correspond to limits from galaxy clusters samples: Bonamente et al. and De Filippis et al. samples i and ii, respectively. For $\Lambda$CDM model, there is a degeneracy between $\Omega_k$ and $h$ for all cosmological probes, and, therefore, the possible values for $h$ are weakly constrained by data separately. The filled central regions correspond to the joint analysis. The open circle with its error bar is that one from LC analysis.

From the joint analysis by using the galaxy clusters (Bonamente et al. sample)+OHRG+BAO+$H(z)$ we obtain in figure (1a) for two free parameters: $h = 0.74^{+0.04}_{-0.04}$, $\Omega_k = -0.044^{+0.14}_{-0.15}$ and $\chi^2_{red} = 0.98$ at 68.3% (c.l.) . This $h$ estimate is in full agreement with the LC value, being the constraints on $h$ independent of a flat universe assumption. However, by using the other galaxy cluster samples
4.2 Flat XCDM

In Figs (a)-(c) we display the ($h$, $\omega$) plane. There is a strong dependence between $h$ and $\omega$ for all cosmological probes. The filled central regions correspond to the joint analyses. Again, the open circle with its error bar is that one from LC analysis.

From the joint analysis by using the galaxy clusters+OHRG+BAO+$H(z)$ we obtain in Fig. 2(a) for two free parameters $h = 0.73^{+0.06}_{-0.06}$, $\omega = -1.1^{+0.50}_{-0.45}$ and $\chi^2_{red} = 0.97$ at 68.3% (c.l.). This $h$ estimate is in agreement with the LC value, being, therefore, the constraints on $h$ independent of $\omega = -1$ assumption. However, again, from the joint analyses in the figures 2(b) and (c), we obtain $h = 0.68^{+0.07}_{-0.05}$, $\omega = -0.73^{+0.45}_{-0.5}$ and $\chi^2_{red} = 0.95$ and $h = 0.64^{+0.06}_{-0.04}$, $\omega = -0.73^{+0.45}_{-0.5}$ and $\chi^2_{red} = 0.94$, respectively. As one may see, it is strongly dependent on the model used to describe the galaxy clusters.

In Fig. 3(b) we display the likelihood function of the $h$ parameter. To obtain this graph we have marginalized over $\Omega_M$ and $\omega$ parameters. The horizontal lines are cuts in the probability regions of 68.3 and 95.4 per cent. For this case we obtain, at 1$\sigma$, $h = 0.74^{+0.030}_{-0.037}$ and 0.65$^{+0.042}_{-0.044}$ for Bonamente et al. and De Filippis et al. samples i and ii, respectively. The shaded region corresponds to 1$\sigma$ interval derived by LC. We also performed the analysis by using the De Filippis et al. samples in a flat $\Lambda$CDM, obtaining $h = 0.705^{+0.028}_{-0.021}$ for samples i and ii, respectively, incompatible at least in 1$\sigma$ with the one obtained by LC ($0.719 < h < 0.763$).

4.3 Systematic errors

Besides the cluster morphology, there are other sources of systematic errors which can affect the constraints. Therefore, we redid all analyses including the systematic errors in quadrature (see Figs a and b) used in LC analysis, they are 8 per cent on $H(z)$ and 15 per cent on OHRG ages, moreover,

Figure 3. Likelihood of the $h$ parameter. (a) and (b): correspond to $\Lambda$CDM and flat XCDM models, respectively, including only statistical errors. The black solid, blue dotted and red dash-dotted lines are from analyses by using Bonamente et al. and De Filippis et al. samples i and ii, respectively. The shaded region is the 1$\sigma$ interval of the LC analysis.

Figure 4. Likelihood of the $h$ parameter. (a) and (b): correspond to $\Lambda$CDM and flat XCDM models, respectively, by adding statistical and systematic errors in quadrature. The correspondent lines are the same as in Fig.3.
from SZE/X-ray technique we have SZ calibration ±5 per cent, X-ray flux calibration ±5 per cent, radio haloes +3 per cent and X-ray temperature calibration ±7.5 per cent. As a matter of fact, one may show that typical systematic errors amount for nearly 13 per cent (details can be found in Bonamente et al. 2006). We obtain at 1σ for Bonamente et al. and De Filippis et al. samples i and ii, respectively: (1) $\Lambda$CDM: $h = 0.74_{-0.03}^{+0.04}$, $0.70_{-0.03}^{+0.04}$ and $0.64_{-0.02}^{+0.03}$, (2) flat XCMD: $h = 0.74_{-0.03}^{+0.04}$, $0.69_{-0.03}^{+0.04}$ and $0.63_{-0.02}^{+0.03}$. We also performed the analysis by using the De Filippis et al. samples in a flat ACDM, obtaining $h = 0.70_{-0.03}^{+0.04}$ and $0.65_{-0.03}^{+0.04}$ for samples i and ii, respectively. Thus, for all cases, the tension between LC analysis and the De Filippis et al. sample ii is still at least 1σ, with the last one preferring low $H_0$ value in agreement with Busti et al. 2014. On the other hand, the results by using De Filippis et al. samples i are in full agreement with that one from 9-year Wilkinson Microwave Anisotropy Probe (WMAP9; see Table 1). It is important to comment that numerical simulations (Sulkanan 1999) showed that a spherical model fit to triaxial X-ray and SZE clusters should provide an unbiased estimate of $H_0$ when a large ensemble of clusters are used (since elongated clusters give $H_0$ underestimated), which is not the case at the moment. Moreover, we also explored a possible dependence on $h$ estimates arising from the chosen incubation time. Thus, we changed the incubation time to $1.2 \pm 0.6$ and $0.4 \pm 0.2$ Gyr and redid our analyses. The influence found was negligible.

## 5 CONCLUSIONS

In this work we have discussed the robustness of determination of the Hubble constant by using the following cosmic probes at intermediate redshifts: (i) angular diameter distances for galaxy clusters, (ii) the inferred ages of OHRG, (iii) measurements of the Hubble parameter and (iv) the BAO signature. In the angular diameter distances we consider three samples of galaxy clusters from Bonamente et al. (2006) and De Filippis et al. (2005), which use different assumptions on the galaxy clusters properties. As emphasized by LC, the combination of these four independent phenomen-ena at intermediate redshifts is independent of any calibrator usually adopted in the determinations of the distance scale.

From our results, we conclude that the $H_0$ estimates present a negligible dependence on dark energy models and the incubation time of the OHRG analysis. However, even taking into account statistical and systematic errors, the galaxy clusters data proved to be an important source of systematic errors (see Table 1), making this technique at the moment unable to discriminate between the local value obtained by Riess et al. (2011) and the global value determined by Planck as claimed by LC.

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## Table 1. Constraints on $h$ for different methods (statistical plus systematic errors).

| Reference                  | Method             | $h$ (1σ)       |
|----------------------------|--------------------|----------------|
| Chen & Ratra 2011          | Median Statistics  | $0.680 \pm 0.028$ |
| Hinshaw et al. 2013        | WMAP9              | $0.700 \pm 0.022$ |
| Freedman et al. 2012       | SNe Ia/Cepheid     | $0.743 \pm 0.026$ |
| Ade et al. (2013)          | Planck             | $0.673 \pm 0.012$ |
| Busti et al. 2014          | $H(z)$             | $0.649 \pm 0.042$ |
| LC (flat ACDM)             | Comb1              | $0.741 \pm 0.022$ |
| This Letter (flat ACDM)    | Comb2              | $0.70 \pm 0.03$ |
| This Letter (flat ACDM)    | Comb3              | $0.65 \pm 0.03$ |
| This Letter (ACDM)         | Comb1              | $0.74_{-0.03}^{+0.04}$ |
| This Letter (ACDM)         | Comb2              | $0.70_{-0.03}^{+0.04}$ |
| This Letter (XCDM)         | Comb1              | $0.64_{-0.070}^{+0.051}$ |
| This Letter (XCDM)         | Comb2              | $0.74_{-0.038}^{+0.048}$ |
| This Letter (XCDM)         | Comb3              | $0.70_{-0.028}^{+0.031}$ |
| This Letter (XCDM)         | Comb3              | $0.65_{-0.03}^{+0.04}$ |
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