Cosmological Constraints using the newest VLT-KMOS HII Galaxies and the full *Planck* CMB spectrum.

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ABSTRACT

We present novel cosmological constraints based on a joint analysis of our HII galaxies (HIIG) Hubble relation with the full *Planck* Cosmic Microwave Background anisotropy spectrum and the Baryon Acoustic Oscillations (BAO) probes. The HII galaxies span a large redshift range (0.088 $\leq z \leq 2.5$), reaching significantly higher redshifts than available SNIa and hence they probe the cosmic expansion at earlier times. Our independent constraints compare well with those based on the "Pantheon" compilation of SNIa data, which we also analyse. We find our results to be in agreement with the conformal Λ CDM model within 1σ . We also use our HIIG data to examine the behaviour of the dark energy equation of state parameter under the CPL parameterisation, $w = w_0 + w_a z/(1 + z)$, and find consistent results with those based on SNIa, although the degeneracy in the parameter space as well as the individual parameter uncertainties, when marginalizing one over the other, are quite large.

Key words: galaxies: high-redshift - dark energy - cosmological parameters

1 INTRODUCTION

Since 1998 the scientific community of cosmology has been at a consensus over the expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999); type Ia Supernovae (SNIa) observations have proven beyond doubt that we live in an expanding Universe, whose rate of expansion is accelerating. Over the last two decades the combined analysis of Cosmic Microwave Background (CMB) anisotropies (eg. Jaffe et al. 2001; Pryke et al. 2002; Spergel et al. 2007; Planck Collaboration et al. 2014; Ade et al. 2016; Aghanim et al. 2020) with Baryon Acoustic Oscillations (BAOs) (eg. Eisenstein et al. 2005; Blake et al. 2012) and Hubble parameter measurements (eg. Chávez et al. 2012; Freedman et al. 2012; Riess et al. 2016; Riess et al. 2018; Fernández Arenas et al. 2018) have shown that the cosmic fluid appears to be dominated by an unknown component which is usually referred to as dark energy (hereafter DE). From the phenomenological viewpoint, the unknown nature of dark energy is reflected in the equation of state parameter (hereafter EoS), namely $w = p_D/\rho_D$, where the quantities ρ_D and p_D are the density and pressure of the DE fluid respectively. It is well known that one of the main targets of observational cosmology is to constrain *w* as well as to test its evolution.

In this context, the basic cosmological parameters (including the EoS) are constrained by a combination of (a) relatively low redshift ($z \le 2$) cosmological probes (SNIa and BAOs: Riess et al. 1998; Perlmutter et al. 1999; Hicken et al. 2009; Amanullah et al. 2010; Riess et al. 2011; Suzuki et al. 2012; Betoule et al. 2014; Scolnic et al. 2018) and (b) high redshift probes ($z \sim 1000$ *Planck* CMB fluctuations; eg., Planck Collaboration et al. 2014; Ade et al. 2016; Aghanim et al. 2020). Such a combination is essential in order to minimize degeneracies among the cosmological parameters; however, if we assume that w is a function of redshift then strong degeneracies persist. It is important to note that probing intermediate redshifts ($2 \le z \le 10$), where the maximum difference in cosmological models take place (cf. Plionis et al. 2011), is a prerequisite for effectively constraining w(z).

HII galaxies are alternative and effective tracers of the Hubble relation for two reasons: (a) they can be observed up to high redshifts $z \sim 3.5$ (Terlevich et al. 2015; Chávez et al. 2016), where the distance modulus is more sensitive to the cosmological parameters, and (b) there is a tight relation between the $H\beta$ luminosity and the emission line velocity dispersion, which pro-

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vides an effective HIIG distance indicator. Indeed it has been proven (cf. Melnick et al. 2000; Siegel et al. 2005; Plionis et al. 2011; Chávez et al. 2012; Chávez et al. 2014, 2016; Terlevich et al. 2015; González-Morán et al. 2019; González-Morán et al. 2021) that this relation can be used as an alternative cosmological tracer. Despite the fact that the scatter of the HIIG distance modulus is larger (by a factor of 2) than that of high-*z* SNIa, this demerit is fully compensated by the fact that HIIG are observed to larger redshifts than SNIa, where, as discussed above, the degeneracies for different DE models are reduced (Plionis et al. 2011). It is important to remark that over the last ten years our team has published a series of papers on this subject.

In the current article, we use our new set of high spectral resolution observations of high-z HIIG obtained with VLT-KMOS (González-Morán et al. 2021) along with published HIIG data (González-Morán et al. 2019; Terlevich et al. 2015), and combine them with the full *Planck* spectrum (Aghanim et al. 2020), Type 1a Supernovae data from the Pantheon dataset (Scolnic et al. 2018), Baryon Acoustic Oscillations data points (Beutler et al. 2011; Kazin et al. 2014; Ross et al. 2015; Alam et al. 2017), and the value for the H_0 parameter reported in Riess et al. (2018) in order to place constraints on the main cosmological parameters, as well as to check for dynamical DE. In this work we consider the ACDM model as the fiducial model, and also explore the popular Chevallier-Polarski-Linder (Chevallier & Polarski 2001; Linder 2003) parameterisation (hereafter CPL).

This paper is organised as follows: in section 2 we provide the basic cosmological equations, in section 3 we briefly describe the data samples used in the current analysis. In section 4 we present our analysis along with comments on our results, while in section 5 we draw our conclusions and discuss future research prospects.

2 BASIC COSMOLOGICAL EQUATIONS

In the context of general relativity we consider that the universe is a self-gravitating fluid, endowed with a spatially flat homogeneous and isotropic geometry. Furthermore, we also assume that the cosmic fluid is dominated by non-relativistic matter plus a dark energy component with an equation of state given by $p_D = w(a)\rho_D$ which is responsible for the accelerated expansion of the universe. Within this framework, the Hubble parameter takes the form:

$$E^{2}(a) = \frac{H^{2}(a)}{H_{0}^{2}} = \Omega_{m,0}a^{-3} + \Omega_{D,0}X(a),$$
(1)

where

$$X(a) = \exp\left(3\int_{a}^{1} d\ln y [1+w(y)]\right).$$
(2)

with E(a) denoting the normalized Hubble flow, H_0 the Hubble constant, a(t) the scale factor and w(a) the equation of state parameter. Notice, that $\Omega_{m,0}$ and $\Omega_{D,0} (\equiv 1 - \Omega_{m,0})$ are the fractional matter and dark energy density parameters at the present time, respectively.

For the concordance Λ CDM model we have $w(a) \equiv -1$ and thus X(a) = 1. On the other hand we can parameterise the unknown form of the EoS parameter by using the CPL parameterisation. This approach has been largely discussed in the literature, namely the equation of state parameter is expressed as a first order Taylor expansion around the present time, $a(t_0) = 1$:

$$w(a) = w_0 + w_a(1-a),$$
(3)

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hence

$$X(a) = a^{-3(1+w_0+w_a)} \exp\left[3w_a(a-1)\right],$$
(4)

where w_0 and w_a are constants. Notice that for $a \to 0$ we have $w \simeq w_0 + w_a$, while prior to the present time (a = 1) the EoS parameter tends to w_0 .

Finally, the luminosity distance corresponding to the spatially flat Friedmann-Lemaître-Robertson-Walker metric reads:

$$d_L(z) = c(1+z) \int_0^z \frac{du}{H(u)},$$
(5)

and the distance modulus is given by

$$m - M = 5\log d_L + 25,\tag{6}$$

where the distance d_L is given in units of Mpc, z is the redshift and $1 + z = a(z)^{-1}$.

3 COSMOLOGICAL DATA

In the current work we use the publicly available *Planck* CMB spectrum in combination with HII galaxies data and other cosmological probes, described below, in order to constrain the standard set of cosmological parameters of the Λ CDM and CPL models, respectively. Notice that for the former case the parameter space is

$$(\Omega_b h^2, \Omega_c h^2, 100\theta_{MC}, \ln(10^{10}A_s), n_s, \tau_{\rm reio})$$

while for the latter we have

$$(\Omega_b h^2, \Omega_c h^2, 100\theta_{MC}, \ln(10^{10}A_s), n_s, \tau_{\text{reio}}, w_0, w_a),$$

where Ω_b and Ω_c are the fractional baryonic and dark matter density parameters at the present time, respectively, θ_{MC} is the angular size of the sound horizon at recombination, A_s is the amplitude of the primordial power spectrum, n_s is the spectral index and τ_{reio} is the optical depth at reionisation.

In the following we briefly present the type of cosmological data used in our current statistical analysis.

• *HII galaxies data*: In a series of papers (González-Morán et al. 2021; González-Morán et al. 2019; Fernández Arenas et al. 2018; Chávez et al. 2016; Terlevich et al. 2015; Chávez 2014; Plionis et al. 2010, 2011; Melnick et al. 2000; Plionis et al. 2009) HII galaxies have been used as alternative tracers of the Hubble relation, hence extending Hubble relation on redshifts beyond the range of available SNIa data. Here we utilize the HII galaxies dataset discussed in González-Morán et al. (2021). The current HIIG sample contains 181 objects, which can be separated in the local sample (107 HIIG with z < 0.16) and a high-z sample based on 29 KMOS, 15 MOSFIRE, 6 XShooter and 24 literature objects (for details see González-Morán et al. 2021). The luminosity of the HIIG in the sample is attributed mostly to a recent single starburst (< 5*Myr*).

• *Supernovae (SNIa)*: We also use the binned data from the Pantheon Supernova type Ia (SNIa) dataset (Scolnic et al. 2018), which combines the confirmed SNIa sources discovered by the Pan-STARRS1 (PS1) Medium Deep Survey with a large number of other surveys, to compare the two distinct and independent tracers of the Hubble function.

• *CMB*: We use the full CMB spectrum from the Planck 2018 data release (Aghanim et al. 2020). Specifically, we focus on the full (TT+TE+BB+lowE) spectrum, and compare results with those based on the CMB shift parameter likelihood, considered in Terlevich et al. (2015) and González-Morán et al. (2021). To this end we use the publicly available CLASS software (Blas et al. 2011) within the



Figure 1. 1 σ and 2 σ contour plots for the Λ CDM model using CMB+HIIG data (red), CMB+HIIG+BAO data (blue), and CMB+HIIG+H0 data (green).

Monte Python MCMC code (Brinckmann & Lesgourgues 2019; Audren et al. 2013).

• *Baryon Acoustic Oscillations*: We use the BAO probe with measurements from various sources: the WiggleZ Dark Energy Survey (Kazin et al. 2014), the BOSS DR12 survey (Alam et al. 2017), one single 6DFGS point (Beutler et al. 2011) and the Main Galaxy Sample of Data Release 7 of Sloan Digital SkySurvey (SDSS-MGS) (Ross et al. 2015).

• *Hubble constant*: Lastly, we utilize the value $H_0 = 73.48 \pm 1.66$ km s⁻¹Mpc⁻¹ as reported in Riess et al. (2018).

4 OBSERVATIONAL CONSTRAINTS

We perform a joint analysis of the HII galaxies Hubble relation with the full *Planck* CMB spectrum and the BAO probes in order to place constraints on the cosmological parameters of the concordance ACDM and the popular CPL models. We shall consider that the above datasets can be treated as statistically independent probes of the models, which is a reasonable assumption since the individual probes are based on different cosmic objects which trace mostly different redshift ranges and are based on different physical mechanisms. Only in one case, where we make combined use of both the HIIGs and the SNIa as tracers of the Hubble expansion, does the latter assumption come under question, given the fact that there is some spatial overlap



Figure 2. Similar to 1, with SNIa data instead of HIIG.

Table 1. The results from the Λ CDM analysis using the HIIG data. The 1- σ error bars are quoted. The parameter H_0 is displayed in km s⁻¹Mpc⁻¹ units.

Parameters	CMB+HIIG	CMB+HIIG+BAOs	Planck+HIIG+BAOs+H0
$ \frac{\Omega_c h^2}{\Omega_b h^2} \\ \tau_{\text{reio}} \\ n_s \\ h_s (10^{10} h^2) $	$\begin{array}{c} 0.1206 \pm 0.0014 \\ 0.02234 \pm 0.00015 \\ 0.0543 {}^{+0.0038}_{-0.0042} \\ 0.965 \pm 0.004 \\ 2.046 \pm 0.016 \end{array}$	$\begin{array}{c} 0.1196 \pm 0.0011 \\ 0.02241 \pm 0.00014 \\ 0.00556^{+0.0037} \\ -0.0041 \\ 0.967 \pm 0.004 \\ 2.046 \pm 0.016 \end{array}$	$\begin{array}{c} 0.1188 \pm 0.0011 \\ 0.02249 \pm 0.00014 \\ 0.0571 \substack{+0.0038 \\ -0.0042 \\ 0.969 \pm 0.004 \\ 2.047 \pm 0.0014 \end{array}$
$\frac{\ln(10^{10}A_s)}{100\theta_{MC}}$	3.046 ± 0.016 1.0419 ± 0.0003	3.046 ± 0.016 1.0420 ± 0.0003	3.047 ± 0.007 1.0420 ± 0.0003
$\sigma_8 \ \Omega_m \ H_0$	$\begin{array}{c} 0.812 \pm 0.008 \\ 0.317 \pm 0.008 \\ 67.19 \pm 0.61 \end{array}$	$\begin{array}{c} 0.810 \pm 0.007 \\ 0.311 \pm 0.006 \\ 67.58 \pm 0.47 \end{array}$	$\begin{array}{c} 0.808 \pm 0.007 \\ 0.306 \pm 0.006 \\ 68.11 \pm 0.45 \end{array}$

between the two probes, which in turn could introduce correlations in the statistical analysis.

While this could be important, unfortunately at the moment there is no standard way to account for it, given the lack of the full correlation matrix between the samples. Therefore, following the standard χ^2 procedure, we have assumed in all cases that the different datasets are uncorrelated, which is equivalent to simply summing over their corresponding χ^2 functions.

Within this context, for the case of the concordance Λ CDM model, we constrain the standard parameter space, namely $(\Omega_b h^2, \Omega_c h^2, 100\theta_{MC}, ln(10^{10}A_s), n_s, \tau_{reio})$. In Table 1 we provide an overall presentation of the observational constraints imposed by the joint analysis of HIIG, CMB spectrum and BAO probes, while in Table 2 we present the corresponding results based on using SNIa instead of HIIG. Obviously, this is a comparison of the performance of the two independent tracers, HIIG and SNIa, in probing the cosmic expansion within this particular model. Moreover in figures 1 and 2 we show the 1σ and 2σ contours in various parameter planes.

Inspecting the aforementioned constraints, we verify that the results based on HII galaxies are in excellent agreement with those based on SNIa. It is noteworthy that this agreement extends also to the relative errors associated with the quoted values. This, however, is because the majority of the sampled parameters are mostly constrained by the CMB spectrum. Note that both joint analyses (based on either HIIG or SNIa) provide results which are consistent (within 1σ) with those provided by the Planck collaboration (see Ade et al. 2016; Aghanim et al. 2020).

Regarding the well known Hubble constant tension problem, ie., the fact that local measurements (ie. $H_0 = 73.48 \pm 1.66$ km s⁻¹Mpc⁻¹ as measured by SNIa Riess et al. 2018) and HIIG (Chávez et al. 2012; Fernández Arenas et al. 2018) are in ~ 4 σ tension with the $z \sim 1100$ value provided by *Planck*, ie., $H_0 = 67.36 \pm 0.54$ km/s/Mpc (Aghanim et al. 2020), our results are consistent with the latter measurements, as expected from the fact that the CMB spectrum probe dominates the H_0 -constraints imposed by the joint analysis. We also note that such results are in agreement with those of Shanks et al. (2019), who found $H_0 = 67.6 \pm 1.52$ km/s/Mpc utilizing the GAIA parallax distances of Milky Way Cepheids. We need to emphasize however all local Universe studies support larger values of H_0 (cf. Lima & Cunha 2014; Beaton et al. 2016; Fernández Arenas et al. 2018; Di Valentino et al. 2021).

We now focus on the CPL parameterisation, which allows a dynamic evolution of the equation of state (EoS) parameter, $w = w_0 + w_a(1 - a)$, and hence it introduces two more parameters in the original parameter space.

We repeat our statistical analysis but now for the parameter space $(\Omega_b h^2, \Omega_c h^2, 100\theta_{MC}, \ln(10^{10}A_s), n_s, \tau_{reio}, w_0, w_a)$. Due to the large number of free parameters we restrict our analysis to the maximum data combinations of: CMB+HIIG+BAOs+ H_0 and CMB+SNIa+BAOs+ H_0 . However, we also allow the combined use of both Hubble expansion tracers, with the caveats discussed previously, providing results based on the joint analysis CMB+HIIG+SNIa+BAOs+ H_0 .

Our results are listed in table 3, while in figure 3 we present the 1 and 2σ contours in the $w_0 - w_a$ plane when using the combination of HIIG data and SNIa data. It is worth noting that Λ CDM model lies within the 1- σ region.

Furthermore, we compare the aforementioned best fit values with those of González-Morán et al. (2021). This work is in alignment with the aforementioned, with the exception that the full Planck spectrum has been utilised in the analysis, in place of the CMB shift parameter, in an effort to include other important cosmological



Figure 3. 2D contours for the pair w_0 - w_a from the dataset CMB+HIIG+BAOs+H0 (blue), CMB+SNIa+BAOs+H0 (green), CMB+HIIG+SNIa+BAOs+H0 (red).

parameters overlooked by the shift parameter such as σ_8 , τ_{reio} etc, as well as to have a more complete check of the tested models.

In all cases, González-Morán et al. (2021) have found for the combination HIIG+CMB_{shift}+BAOs $\Omega_{m,0} = 0.298^{+0.018}_{-0.021}$, $H_0 = 69.8\pm2.3$ km/s/Mpc, $w_0 = -1.07^{+0.23}_{-0.32}$ and $w_a = 0.16^{+0.96}_{-0.55}$, while for SNIa+CMB_{shift}+BAOs they found $\Omega_{m,0} = 0.3011 \pm 0.0085$, $H_0 = 68.85 \pm 0.99$ km/s/Mpc, $w_0 = -1.062 \pm 0.040$ and $w_a = 0.25^{+0.22}_{-0.19}$. Evidently, our constraints are compatible within 1σ with those of González-Morán et al. (2021); González-Morán et al. (2019) and Terlevich et al. (2015, see figures 4 and 5). Finally, our results are also consistent with those of Scolnic et al. (2018), who found $\Omega_{m,0} = 0.300 \pm 0.008$, $H_0 = 69.057 \pm 0.796$ km/s/Mpc, $w_0 = -1.007 \pm 0.089$ and $w_a = -0.222 \pm 0.407$ for SNIa+CMB+BAOs.

Evidently, we can place constraints on both CPL parameters, marginalizing one over the other, but their corresponding uncertainties remain quite large. However, what is important to highlight is that the parameter degeneracy in the $w_0 - w_a$ plane is large, significantly larger than that of the corresponding SNIa analysis. Future HII galaxies data are expected to improve the relevant constraints dramatically, since, based on Monte-Carlo simulations, our team has shown (Chávez et al. 2016) that a significant improvement is expected when increasing the number of high-z HII galaxies to ~ 500, a goal that can be achieved in reasonable observing time with the existing large telescopes, as we have discussed in a number of our previous works.

5 CONCLUSIONS

We used HII galaxies as tracers of the Hubble expansion in a joint analysis, and combined them for the first time with the Planck CMB power spectrum (using CLASS) in order to constrain the parameters for the most popular cosmological models, namely Λ CDM and CPL. We also compared the performance of HII galaxies with that of the widely used Type Ia Supernovae data and found that the best fit parameters of the explored cosmological models are mutually in good agreement. Then we combined HIIG+CMB in a joint statistics with other cosmological probes (SNIa, BAOs, H_0) to place constraints on the CPL cosmological parameters. We find that the degeneracy of the parameters w_0 and w_a is quite large, which improves however (especially with the reduction of the w_0 uncertainty)

Parameters	CMB+SNIa	CMB+SNIa+BAOs	Planck+SNIa+BAOs+H ₀
$\Omega_c h^2$	0.1198 ± 0.0013	0.1192 ± 0.0010	0.1184 ± 0.0010
τ_{reio}	$0.02238 \pm 0.00013 \\ 0.0547^{+0.0038}_{-0.0041}$	$0.02243 \pm 0.00014 \\ 0.0558^{+0.0036}_{-0.0041}$	$0.02231 \pm 0.00014 \\ 0.0571^{+0.0038}_{-0.0042}$
n_s	0.966 ± 0.004	0.967 ± 0.004	0.970 ± 0.004
$\ln(10^{10}A_s)$	3.045 ± 0.016	3.046 ± 0.016	3.047 ± 0.017
$100 \theta_{MC}$	1.0419 ± 0.0003	1.0420 ± 0.0003	1.0421 ± 0.0003
σ_8	0.810 ± 0.008	0.810 ± 0.007	0.807 ± 0.007
Ω_m	0.314 ± 0.008	0.310 ± 0.006	0.305 ± 0.006
H_0	67.47 ± 0.60	67.76 ± 0.44	68.14 ± 0.44

Table 2. The results from the Λ CDM analysis using the Pantheon data. The 1- σ error bars are quoted. The parameter H_0 is displayed in km s⁻¹Mpc⁻¹ units.

Table 3. The results from the CPL analysis using the HIIG data (second column), Pantheon data (third column), and both datasets (fourth column). The 1- σ error bars are quoted. The parameter H_0 is displayed in km s⁻¹Mpc⁻¹units.

Parameters	CMB+HIIG+BAOs+ H_0	CMB+SNIa+BAOs+ H_0	CMB+HIIG+SNIa+BAOs+ H_0
$\Omega_c h^2$	0.1203 ± 0.0013	0.1201 ± 0.0013	0.1202 ± 0.0012
$\Omega_b h^2$	0.02237 ± 0.0015	0.02236 ± 0.00035	0.02238 ± 0.00015
$ au_{ m reio}$	0.0545 ± 0.0078	0.0545 ± 0.0076	0.0544 ± 0.0075
n_s	0.965 ± 0.005	0.965 ± 0.004	0.965 ± 0.004
$\ln(10^{10}A_s)$	3.046 ± 0.020	3.046 ± 0.019	3.046 ± 0.017
$100 \theta_{MC}$	1.0420 ± 0.00031	$1.0419 \pm 0,00030$	1.0419 ± 0.00031
w_0	-1.06 ± 0.26	-1.02 ± 0.08	-1.012 ± 0.07
Wa	-0.092 ± 0.45	-0.19 ± 0.32	-0.29 ± 0.31
σ_8	0.829 ± 0.022	0.830 ± 0.020	0.829 ± 0.019
Ω_m	0.293 ± 0.021	0.299 ± 0.015	0.301 ± 0.014
H_0	69.92 ± 0.89	69.27 ± 0.71	69.20 ± 0.70

when confronted with the full set of standard candles (SNIa+HIIG). This attests to the necessity of further HIIG observations. Indeed, according to Plionis et al. (2011) and Chávez et al. (2016), a deviation from Λ CDM could in principle be detected when using a few hundreds of high redshift HIIG galaxies ($1.5 \le z \le 4$). The current HIIG sample contains in total 181 objects, out of which 74 are high redshift galaxies (0.6 < z < 2.6), which are already yielding very promising results. Our team, however, is designing the appropriate future KMOS-VLT observations of high-z objects to which we will add ~ 100 additional HIIG, with intermediate redshifts, $z \sim 0.7$, to be observed with MEGARA-GTC as part of the INAOE guaranteed time, as well as to explore the Hubble diagram to redshift $z \sim 3.5$ using MOSFIRE data (González Morán et al. in preparation). Hence, we argue that future HIIG data are expected to substantially improve the relevant constraints (especially on w_a) and thus the validity of dynamical dark energy on extragalactic scales will be effectively tested. We are also planning to utilize the HII galaxies Hubble expansion probe to constrain modified gravity models in a future work.

DATA AVAILABILITY

The main analysis of the present work is based on HII galaxy data, which have been made available in González-Morán et al. (2021), at https://doi.org/10.1093/mnras/stab1385, González-Morán et al. (2019) at https://doi.org/10.1093/mnras/stz1577, Fernández Arenas et al. (2018) at https://doi.org/10.1093/mnras/stx2710, Terlevich et al. (2015) at https://doi.org/10.1093/mnras/stv1128Chávez et al. (2014) at https://doi.org/10.1093/mnras/stu987.

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REFERENCES

- Ade P. A. R., et al., 2016, Astron. Astrophys., 594, A13
- Aghanim N., et al., 2020, Astron. Astrophys., 641, A6
- Alam S., et al., 2017, Mon. Not. Roy. Astron. Soc., 470, 2617
- Amanullah R., et al., 2010, ApJ, 716, 712
- Audren B., Lesgourgues J., Benabed K., Prunet S., 2013, JCAP, 1302, 001
- Beaton R. L., et al., 2016, The Astrophysical Journal, 832, 210
- Betoule M., et al., 2014, Astron. Astrophys., 568, A22
- Beutler F., et al., 2011, MNRAS, 416, 3017
- Blake C., et al., 2012, MNRAS, 425, 405
- Blas D., Lesgourgues J., Tram T., 2011, Journal of Cosmology and Astroparticle Physics, 2011, 034–034
- Brinckmann T., Lesgourgues J., 2019, Phys. Dark Univ., 24, 100260
- Chávez R., 2014, PhD thesis, INAOE, Puebla (arXiv:1410.7843)
- Chávez R., Terlevich E., Terlevich R., Plionis M., Bresolin F., Basilakos S., Melnick J., 2012, MNRAS, 425, L56
- Chávez R., Terlevich R., Terlevich E., Bresolin F., Melnick J., Plionis M., Basilakos S., 2014, Mon. Not. Roy. Astron. Soc., 442, 3565
- Chávez R., Plionis M., Basilakos S., Terlevich R., Terlevich E., Melnick J., Bresolin F., González-Morán A. L., 2016, Mon. Not. Roy. Astron. Soc., 462, 2431
- Chevallier M., Polarski D., 2001, Int. J. Mod. Phys., D10, 213
- Di Valentino E., et al., 2021, arXiv:2103.01183[astro-ph.CO]
- Eisenstein D. J., et al., 2005, Astrophys. J., 633, 560
- Fernández Arenas D., et al., 2018, Mon. Not. Roy. Astron. Soc., 474, 1250

- Freedman W. L., Madore B. F., Scowcroft V., Burns C., Monson A., Persson S. E., Seibert M., Rigby J., 2012, The Astrophysical Journal, 758, 24
- González-Morán A. L., et al., 2019, Mon. Not. Roy. Astron. Soc., 487, 4669
- González-Morán A. L., et al., 2021, Monthly Notices of the Royal Astronomical Society (accepted)
- Hicken M., Wood-Vasey W. M., Blondin S., Challis P., Jha S., Kelly P. L., Rest A., Kirshner R. P., 2009, ApJ, 700, 1097
- Jaffe A. H., et al., 2001, Phys. Rev. Lett., 86, 3475
- Kazin E. A., et al., 2014, Mon. Not. Roy. Astron. Soc., 441, 3524
- Lima J. A. S., Cunha J. V., 2014, Astrophys. J., 781, L38
- Linder E. V., 2003, Phys. Rev. Lett., 90, 091301
- Melnick J., Terlevich R., Terlevich E., 2000, Mon. Not. Roy. Astron. Soc., 311, 629
- Perlmutter S., et al., 1999, Astrophys. J., 517, 565
- Planck Collaboration et al., 2014, A&A, 571, A16
- Plionis M., Terlevich R., Basilakos S., Bresolin F., Terlevich E., Melnick J., Georgantopoulos I., 2009, Journal of Physics: Conference Series, 189, 012032
- Plionis M., Terlevich R., Basilakos S., Bresolin F., Terlevich E., Melnick J., Chávez R., 2010, AIP Conf. Proc., 1241, 267
- Plionis M., Terlevich R., Basilakos S., Bresolin F., Terlevich E., Melnick J., Chávez R., 2011, Monthly Notices of the Royal Astronomical Society, 416, 2981
- Pryke C., Halverson N. W., Leitch E. M., Kovac J., Carlstrom J. E., Holzapfel W. L., Dragovan M., 2002, ApJ, 568, 46
- Riess A. G., et al., 1998, Astron. J., 116, 1009
- Riess A. G., et al., 2011, The Astrophysical Journal, 730, 119
- Riess A. G., et al., 2016, Astrophys. J., 826, 56
- Riess A. G., et al., 2018, ApJ, 855, 136
- Ross A. J., Samushia L., Howlett C., Percival W. J., Burden A., Manera M., 2015, Mon. Not. Roy. Astron. Soc., 449, 835
- Scolnic D. M., et al., 2018, Astrophys. J., 859, 101
- Shanks T., Hogarth L., Metcalfe N., 2019, Mon. Not. Roy. Astron. Soc., 484, L64
- Siegel E. R., Guzman R., Gallego J. P., Orduna Lopez M., Rodriguez Hidalgo P., 2005, Mon. Not. Roy. Astron. Soc., 356, 1117
- Spergel D. N., et al., 2007, Astrophys. J. Suppl., 170, 377
- Suzuki N., et al., 2012, ApJ, 746, 85
- Terlevich R., Terlevich E., Melnick J., Chávez R., Plionis M., Bresolin F., Basilakos S., 2015, Mon. Not. Roy. Astron. Soc., 451, 3001

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