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# Cosmology with the Dark Energy Survey

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The current standard model of cosmology, known as ΛCDM, has a solid observational basis, but requires the existence of two exotic entities, that sum a 95% of the matter-energy content of the Universe.These components are dark matter, of absolutely unknown physical nature, and dark energy, that is explained as the cosmological constant in ΛCDM. A full understanding of these dark entities is the main goal of the current cosmological activity. One of the leading projects in this task is the Dark Energy Survey (DES), an optical and near infrared galaxy survey that has imaged 5000 deg$^2$ of the southern celestial hemisphere in five broad bandpass filters. The survey observations started in 2013 and were completed in early 2019. DES studies the dark energy properties using four independent methods: number counts and spatial distribution of galaxy clusters, weak gravitational lensing, galaxy clustering including baryon acoustic oscillations and distances to supernovae Ia. The four measurements are performed using the same data set, with the idea of ensure a very strict control of the systematic uncertainties. Here, the first cosmological results, using data taken during the first season of the project, are presented. For the first time, the precision level from a galaxy survey is similar to that coming from the study of the CMB, opening a new era on cosmology.

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## 1. Introduction

The current theoretical description of the Universe, ΛCDM, is solidly stablished, since it is based on a very large set of independent observations that can explain with high accuracy. However, it has shocking consequences. Only a small fraction (around 5%) of the content of our Universe is ordinary matter. The other 95% is composed of exotic entities called dark matter and dark energy, that have never been produced in laboratories. The evidence of the existence of dark matter comes from its gravitational influence on the ordinary matter, that has been observed in a large range of scales. The dark energy shows its presence through the accelerated expansion of the Universe, that is a direct consequence of its exotic equation of state, with constant density and negative pressure. All the current cosmological observations agree with the dark energy being the vacuum energy, that translates into a non-zero value of the cosmological constant [1]. However, this value is not compatible with the Standard Model of particle physics. The current measurements of the dark energy properties are not very precise yet, and other explanations, like the uncompleteness of the General Relativity to describe gravity at cosmological scales or the existence of some mysterious fluid with negatibe pressure filling the whole Universe, are still possible. Whatever the physical nature of dark energy is, it most probably will require the existence of new physics. It is generally expected that the next advances in our understanding of the physical nature of the dark energy will come from new and better observations of the cosmos. Therefore, new cosmological projects are already taking data or will start in the near future, with the goal of improving the current measurements by at least one order of magnitude. One of the most important projects is the Dark Energy Survey (DES) [2].

## 2. The Dark Energy Survey

The main goal of DES[1] is to discover the physical nature of the dark energy. To reach this objective, two interleaved sky surveys have been carried out. First, an optical to near-infrared survey that has imaged 1/8 of the sky (5000 square degrees) in the southern hemisphere. This area of the celestial sphere has been covered with five wide bandpass filters, *grizY*, up to a magnitude of $i_{AB} < 24$. Second, a time domain *griz* survey over 30 square degrees has been performed to discover supernovae Ia and measure their light curves. The project took data from 2013 to 2019. The main instrument of the DES survey was the 520-Megapixel imager DECam [3], mounted at the prime focus of the Blanco 4m telescope at NOAO's Cerro Tololo Inter-American Observatory (Figure 1). The DES collaboration consists of more than 300 scientists from USA, UK, Spain, Brazil, Switzerland and Germany.

DES is studying the dark energy by measuring the parameter $w_0$ of its equation of state and how this parameter varies with time ($w_a$) to a precision level that will be five times better than the current errors. DES will use four independent methods to perform this measurement, what allows a reduction of the systematic errors. The four methods are: the counting of galaxy clusters and their spatial distribution at $0.1 < z < 1$, the measurement of weak lensing shear on several redshift shells up to $z \sim 1$, the determination of the scale of the baryon acoustic oscillations and the spatial

[1] http://www.darkenergysurvey.org

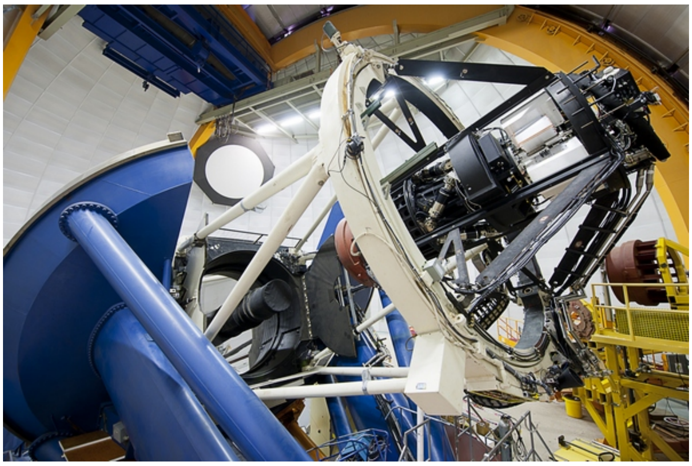

**Figure 1:** Image of DECam installed at the prime focus of the 4m Blanco telescope.

distribution of galaxies up to $z < 1.4$ and the Hubble diagram for several thousand supernovae Ia at $0.3 < z < 0.8$.

## 3. Recent Scientific Results

DES is producing many scientific results, and it is impossible to describe all of them here. We will highlight a few selected results.

### 3.1 First Cosmology Results using Supernovae at DES

The most mature probe of dark energy is the Hubble diagram for supernovae Ia. DES has recently produced the first cosmological parameter constraints using measurements of type Ia supernovae (SNe Ia) from the DES supernova survey, described above. This is an initial analysis that uses a subsample of 207 spectroscopically confirmed SNe Ia. The first three years of DES-SN data have been used and combined with a low-redshift sample of 122 SNe from the literature, for a total of 329 SNe Ia [4]. The fit of the Hubble diagram is shown in Figure 2. The final result, after combining with the results coming from the cosmic microwave background (CMB) data [5], gives the following cosmological parameters:

$$w_0 = -0.885 \pm 0.114$$
$$w_a = -0.387 \pm 0.430$$

for an equation of state parameter that changes with time as $w(a) = w_0 + w_a(1-a)$, where $a = 1/(1+z)$ is the scale factor of the universe. These results are in agreement with the dark energy being the cosmological constant and with previous constraints using SNe Ia.

The spectroscopically confirmed SN Ia sample that has been used in this analysis contains only $\sim 10\%$ of all the SNe Ia discovered by DES over the full survey. Many of the methods that have been developed for these data will be applied in upcoming analyses of the full sample, one order of magnitude larger, and that will allow an important improvement on the precision of the determination of the cosmological parameters.



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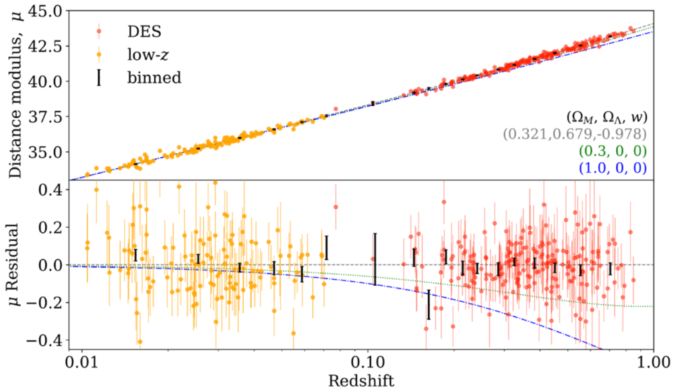


**Figure 2:** Hubble diagram for the DES-SN3YR sample. Top: distance modulus ($\mu$) as a function of redshift for each SN (red, orange circles) and binned (black dots). The dashed gray line shows the best fit, while the green and blue dotted lines show models with no dark energy and matter densities $\Omega_m = 0.3$ and 1.0 respectively. Bottom: residuals to the best fit model.

### 3.2 Combination of Galaxy Clustering and Weak Lensing for Cosmology

These results arise from from the analusis of DECam images taken between 2013 and 2014, known as DES-Y1, that cover 1321 square degrees. The cosmological results come from a combined analysis of galaxy clustering and weak gravitational lensing.

More specifically, three two-point correlation functions are fitted to the cosmological model at the same time:

- The cosmic shear correlation function of 26 million source galaxies in four redshift bins.
- The galaxy angular autocorrelation function of 650,000 luminous red galaxies in five redshift bins.
- The galaxy-shear cross-correlation of luminous red galaxy positions and source galaxy shears.

The analysis was carried out while blind to the true results. In addition, an extensive set of systematics checks have been performed during the blind phase, ensuring that the results are robust.

Once the systematic checks are passed, the data are modeled in flat ΛCDM and *w*CDM cosmologies, with 6 and 7 free parameters respectively. The full covariance matrix (of $457 \times 457$ elements), analitically obtained is taken into account. In addition, the consistency among the cosmological parameters obtained from each of the two-point correlation also verified. These two models are good descriptions of the data, what allows a precise determination of the cosmological parameters, as can be seen in Figure 3, green contours. The obtained results have a precision comparable to that from the Planck [5] CMB measurements (Figure 3, blue contours). This is the first time that a galaxy survey reaches these precision levels, what allows to compare the structure of the early and late universe on similar footings, a stringent test for cosmological models. Although the DES-Y1 best-fit values for $S_8$ and $\Omega_m$ are lower than the central values from Planck, the Bayes factor indicates that both data sets are still consistent with each other. In this situation, both data can be combined, as shown in Figure 3, red contours.

The statistical consistency allows us to combine DES-Y1 results with Planck, and, in addition, with baruon acoustic oscillation analyses from 6dF [7], SDSS DR7 [8] and BOSS [9] experiments and from JLA supernovae [10] data. This yields $S_8 = 0.802 \pm 0.012$ and $\Omega_m = 0.298 \pm 0.007$ for $\Lambda$CDM. These are the tightest constraints on cosmological parameters up to date.

In addition, when a free $w$ is allowed, the consistency of all these data sets remains. Therefore, we can combine all together, to strongly constrain the equation of state parameter to $w = 1.00^{+0.05}_{-0.04}$.

Upcoming DES analyses, including more data, will provide stonger tests.

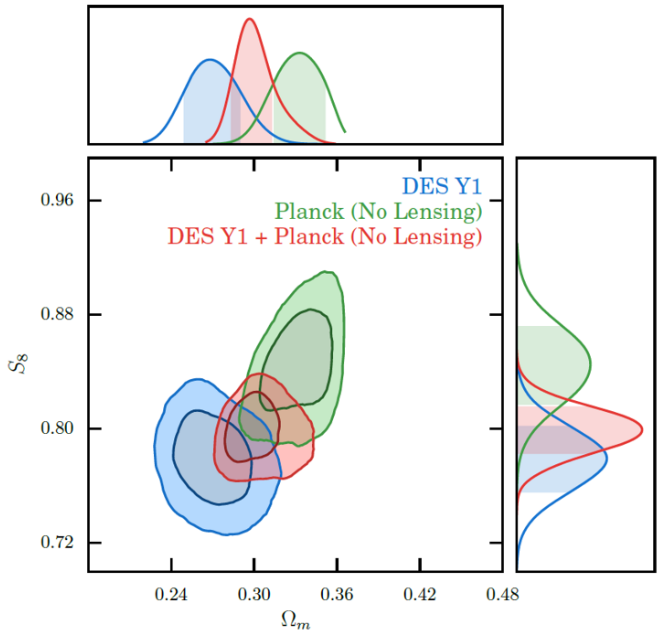


**Figure 3:** $\Lambda$CDM constraints from the three combined probes in DES-Y1 (blue), Planck with no lensing (green), and their combination (red). The agreement between DES and Planck can be quantified via the Bayes factor, which indicates that in the full, multi-dimensional parameter space, the two data sets are consistent.

Extended cosmological models have also been tested using the same set of two-point correlation functions. Several models were considered [11], and no evidence for any deviation wirh respect to $\Lambda$CDM is found. The results for a time varying equation of state parameter of the dark energy are depicted in Figure 4, for DES-Y1 alone in blue and combined with Planck, BAO and supernovae data as before, in red.

### 3.3 Combining All Results

There is no single observational probe of the dark energy that can improve the current constraints alone. In consequence, the combination of multiple observational probes is mandatory to reach better precision levels. DES has combined the results coming from weak gravitational lensing and galaxy clustering (the three types of two-point correlation functions described in subsection 3.2), with those coming from supernovae, described in subsection 3.1 and from DES-Y1 baryon acoustic oscillations [13].

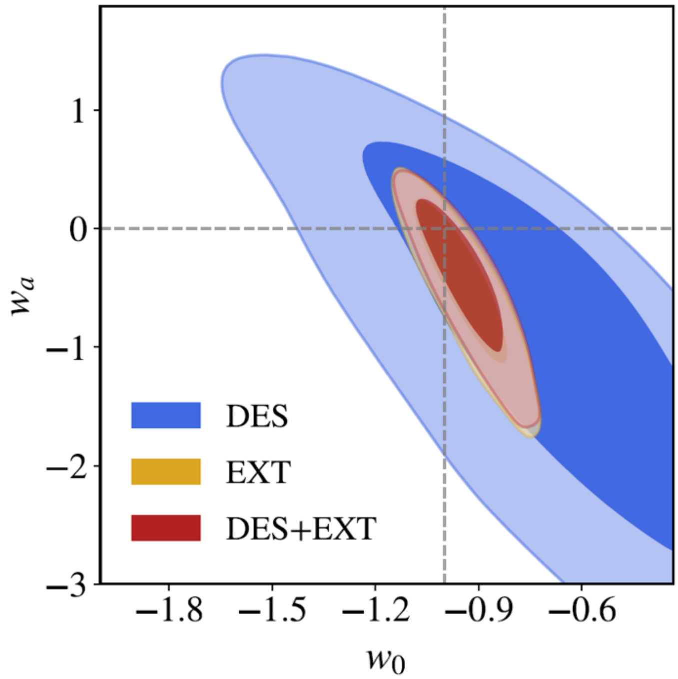


**Figure 4:** Constraints on dark energy parameters $(w_0, w_a)$. Blue contours show the 68% and 95% confidence regions from DES alone, yellow is external data alone, and red is the combination of the two. The intersection of the horizontal and vertical dashed lines shows the parameter values in the ΛCDM model.

From these combined results, constraints on the equation of state of the dark energy, $w$, and the matter density in the Universe, $\Omega_m$, are derived. The DES-Y1 only results, independently of any other experiment, rule out a Universe with no dark energy, and provide an independent measurement of $w$, as can be seen in Figure 5. These results demonstrate the potential power of large multi-probe photometric surveys and pave the way for order of magnitude advances in our constraints on properties of dark energy and cosmology over the next decade.

## 4. Conclusions

DES is a large galaxy survey that will improve the measurements of the dark energy properties using four independent probes: galaxy clusters, galaxy clustering (including baryon acoustic oscillations), weak gravitational lensing and supernovae Ia. Very robust and low systematics measurements are expected, since the multiprobe approach has been designed to improve the current precision by a large factor.

The most precise constraints on dark energy properties require combining cosmological probes, since there is no single probe that can reach enough improvement level by itself. DES has combined its measurements of SNe Ia, BAO, weak lensing and galaxy clustering to set strong constraints on the nature of the dark energy. These results share a common set of calibration frameworks and blinding policy across probes, what allows a strict control of the systematics uncertainties. The results are compatible with ΛCDM, and therefore, with the dark energy being the cosmological constant.

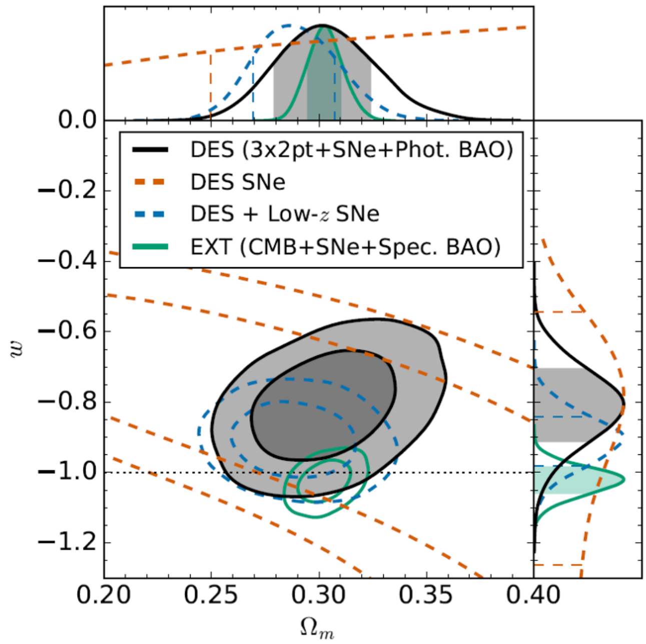


**Figure 5:** Constraints on the dark energy equation of state $w$ and $\Omega_m$ in a flat $w$CDM model. Constraints from the DES-Y1 data alone are the black contours, the best available external data are the green contours, the DES-Y1 data including low-redshift SNe Ia data set to anchor the DES SNe Ia are the blue.

We expect future DES results to provide a further factor of 2-4 improvement in these constraints due to increased area, depth, and number of SNe in the final analyses.

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## References

[1] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D98, 030001 (2018) and 2019 update

[2] B. L. Flaugher, Int.J.Mod.Phys. A20 3121–3123 (2005).

[3] B. Flaugher et al., Astron. Jour. 150 150 (2015).

[4] T. M. C. Abbott et al. (DES Collaboration), Astrop. Jour. 872 L30 (2019)

[5] P. A. R. Ade et al. (Planck Collaboration), Astron. & Astrophys. 594, A13 (2016)

[6] T. M. C. Abbott et al. (DES Collaboration), Phys. Rev. D98, 043526 (2018)

[7] F. Beutler at al., Mon. Not. R. Astron. Soc. 416, 3017 (2011)

[8] A. J. Ross et al., Mon. Not. R. Astron. Soc. 449, 835 (2015)

[9] S. Alam et al. (BOSS Collaboration), Mon. Not. R. Astron. Soc. 470, 2617 (2017)

[10] M. Betoule et al. (SDSS), Astron. & Astrophys. 568, A22 (2014)

[11] T. M. C. Abbott et al. (DES Collaboration), Phys. Rev. D99, 123505 (2019)

[12] T. M. C. Abbott et al. (DES Collaboration), Phys. Rev. Lett. 122, 171301 (2019)

[13] T. M. C. Abbott et al. (DES Collaboration), Mon. Not. R. Astron. Soc. 483, 4866 (2019)

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