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The role of ESO observations in the Dark Energy Survey.

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Abstract

The Dark Energy Survey is a large scale program to study the properties of dark energy through photometric observations of a large volume of the southern sky, in the optical and near-infrared, from the CTIO Blanco telescope in Chile. It ended its observations in 2019 and is currently preparing its final results, which include more than 500 nights of observations. It has already provided independent constraints on several cosmological parameters and models for half of the data, and in particular, its results have been combined with the Planck observatory measurements creating the most precise set of values to date. ESO instruments, both spectroscopic and photometric, have provided a fundamental input to many of these results, especially for redshift calibration and infrared complementary data. We briefly review these various contributions.

1 Introduction: the Dark Energy Survey

The Dark Energy Survey (DES) is a photometric survey of the Southern sky that took place during 570 nights from the Blanco 4 meter telescope in Cerro Pachón, Chile. Its goal is to pin down the nature of dark energy starting from the recommendations of the Dark Energy task force [14], using several probes: measurement of the redshift-distance relationship through supernovae Ia and the baryon acoustic oscillation peak (BAO); the combination of large scale structure distribution of galaxies and the weak lensing effect of these on the images of background galaxies and the number of clusters as a function of mass and redshift. In addition, other cosmological parameters and fundamental physics parameters can be explored by detecting strong lensing systems and measuring H_0, finding counterparts to gravitational wave events, and with the exploration of the Galactic neighborhood, ascertain the nature of dark matter. The instrument used to carry out DES is the Dark Energy Camera (DECam [7]) which uses for this survey the $grizY$ bands (Figure 1). In reality, two types of surveys are combined in DES, one covers 5000 square degrees in a homogeneous fashion in the five bands, plus a time domain survey returning to the same areas every few days to detect transient phenomena which are potential supernova of type Ia of potential cosmological interest (Figure 2).

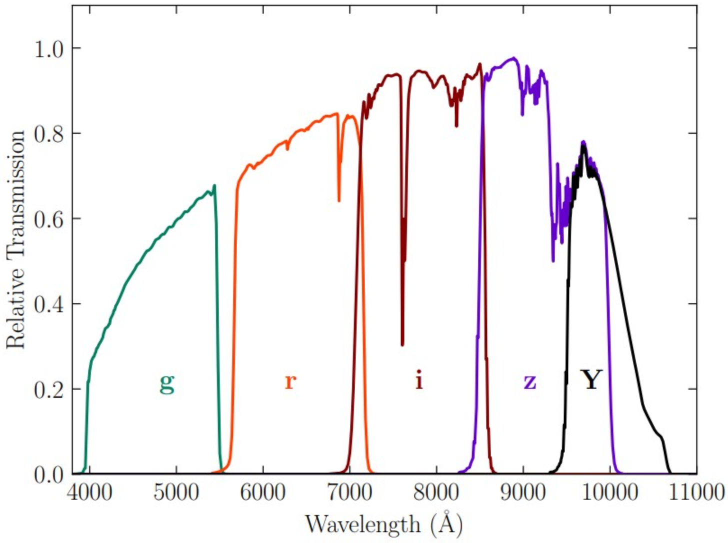

Figure 1: Standard bandpasses for DECam, valid for both data releases from DES. The need for ESO observations comes from a higher spectral resolution and blue and infrared (beyond Y) coverage.

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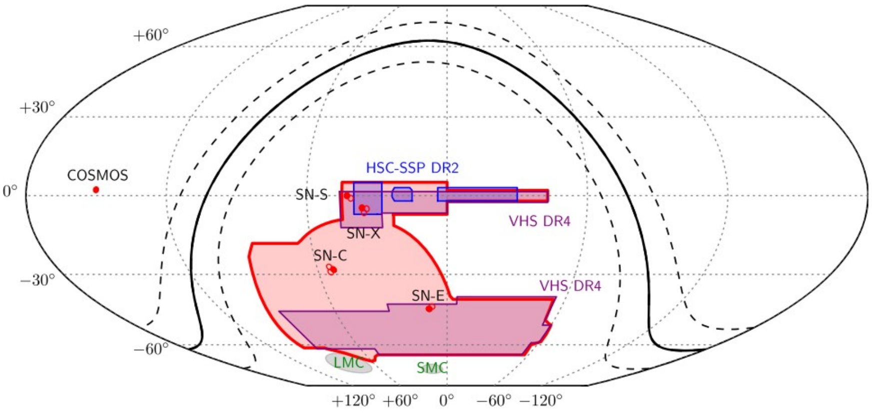

Figure 2: Layout of the wide field and supernova surveys of DES. From [11].

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It ended on January 2019 and the participants of the international collaboration managing it are currently analyzing the complete data set (Year 6 or Y6). The main findings for the first half of the data set (Y3) are summarized in [18, 16, 19], and point to the ΛCDM cosmological model as being compatible with the data, with cosmological parameters in line with those found by the Planck satellite [20] measuring the cosmic microwave background at a vastly different redshift (see Figure 3, left).

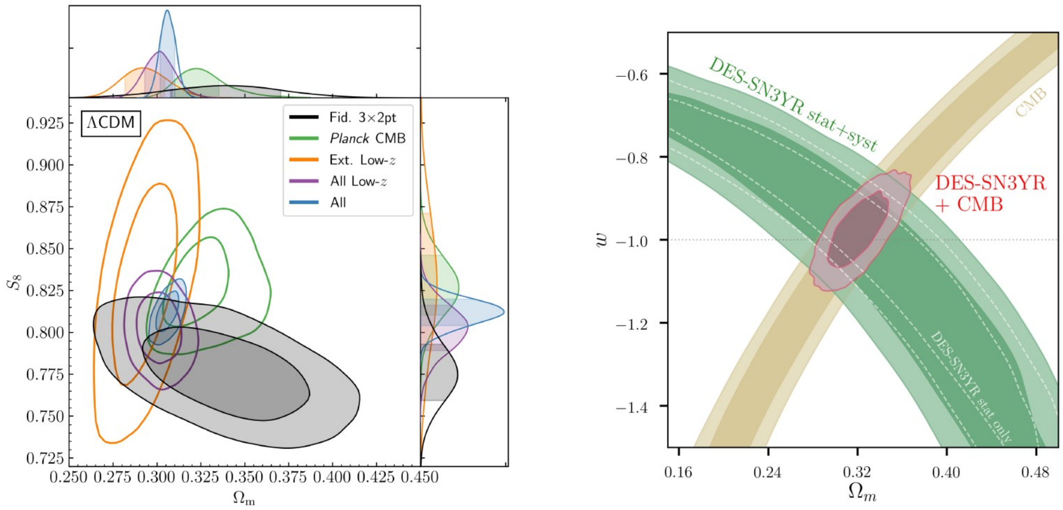

Figure 3: Left: The Y3 key project results on the $S8 - \Omega_M$ parameter plane. The gray contour corresponds exclusively to the combination of DES large scale structure and weak lensing data (the 3x2pt probe). In green, the prediction, assuming the ΛCDM model, from the Planck analysis. Right: Parameter constraints for a constant equation of state value in the $w - \Omega_M$ space using three years worth of supernovae Ia detections. Contours are 68% confidence intervals.

The data used in these results have been made public through successive data releases in 2017 (DR1, [15], for Y3 data) and 2021 (DR2, [17], covering the complete data set of Y6), and the latest cosmology-tuned catalogs as well for Y3 at [11, 8].

2 The Dark Energy Survey and ESO collaborations

Despite DECam being such a powerful instrument, it is restricted to the visible and near infrared wavelengths, and the need for imaging for measuring the shapes of the objects for instance, limits the spectral resolution to broad band photometry. This restricts the information one is able to get out from individual sources, which would be accessible through dedicated spectroscopic observations. In order to alleviate this, observations from other state of the art instruments are necessary, and in particular, ESO instruments have been able to close this gap either by direct observation proposals on competitive time allocation calls or by usage of the vast archival information in the form of spectral and photometric catalogs.

In the following sections, we go through a few examples that demonstrate the pivotal role that ESO has played in obtaining these cosmological constraints.

2.1 X-SHOOTER spectra for supernovae

One of the core results from DES is the measurement of cosmological constraints from supernovae Ia data, effectively extending the original dark energy detections from the late 1990s. In [16], the first results from a combination of spectroscopically confirmed supernovae from the DES sample plus a low redshift subsample from the literature, are discussed, finding $\Omega_M = 0.331 \pm 0.038$ for a ΛCDM model, and an equation of state for dark energy compatible with the cosmological constant both for the wCDM and $w_0 w_a$CDM models.

A fundamental element in the compilation of these supernova data sets is to have spectroscopic redshifts for the largest amount of these transients as possible, in order to construct the Hubble diagram. As detailed in [13], a devoted follow-up program partnered up with DES (OzDES, [5]) mainly focused on low to intermediate redshift transients. However, in order to cover the faintest objects to avoid any selection bias due to OzDES not being able to access these, a large spectroscopic follow-up campaign complemented de OzDES observations. In particular, a $\sim$ 14-night program was awarded at the VLT with the X-SHOOTER instrument. Thanks to this, 89 candidates on faint host galaxies (Figure 4, left) were followed up and those identified as Ia, added to the Hubble diagram of [16]. As can be seen in Figure 4 (right) the VLT spectra represent a significant fraction of the supernovae used at redshifts $z > 0.4$.

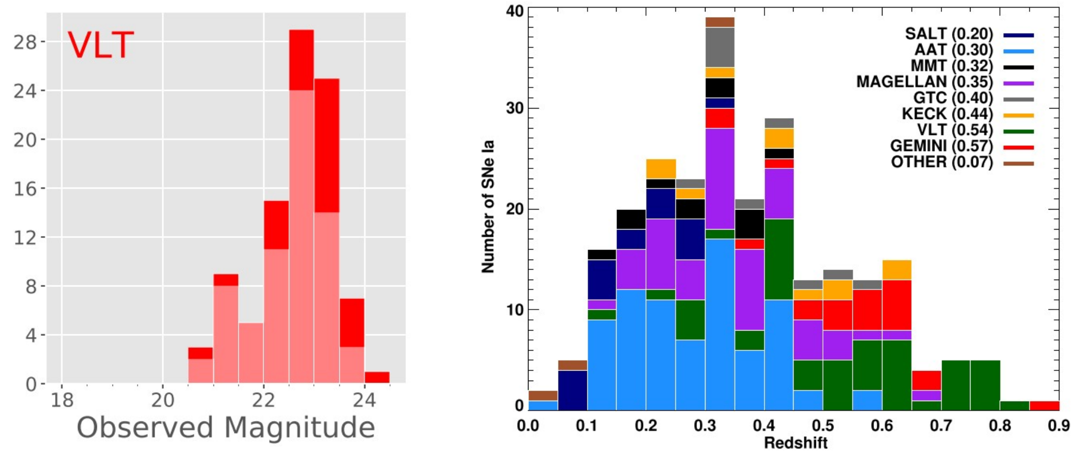

Figure 4: (left) The i-band magnitude distributions of the spectroscopically observed transients using VLT for the work in [13]. The lighter shaded histogram corresponds to confirmed supernovae of type Ia (right) Redshift histogram of all 251 spectroscopically confirmed SNe Ia in the first three seasons of DES (from [13]). The VLT data is an important contributor in the high redshift range.

2.2 MUSE data cubes for time delay cosmography

Time delay cosmography is a technique that allows the measurement of the Hubble parameter from the measurement of the time varying luminosity from objects whose light is being deflected by an intervening strong lensing system ([21]). An external collaboration of DES, the STRIDES project [23], has exploited the strong lens systems found in DES data, and obtained very relevant results to the current Hubble parameter tension research. A single system in DES data with these rare characteristics has already found 4% constraints to the Hubble parameter [12]. In order to make these complex measurements, external complementary spectra have to be obtained: the velocity dispersions of the lensing system, which can give an accurate estimate of the mass model, and the redshift distribution of objects in the line of sight of the time varying object that we are using to measure its delay.

In [3], these spectroscopic campaigns are detailed for two strong lensing systems, including DES 0408-5354, which was used in [12]. Observations using the MUSE instrument [1] at the VLT as part of an ESO program were used during two nights. The DES image for this system is shown in Figure 5 (left), whereas the redshifts for the ensemble of objects measured by MUSE's IFU is shown on the right. This distribution of objects along the line of sight, plus the measurement of the width of the spectral lines for the G1 lensing object, provides key information for the model parameters to be fitted in the extraction of cosmological information.

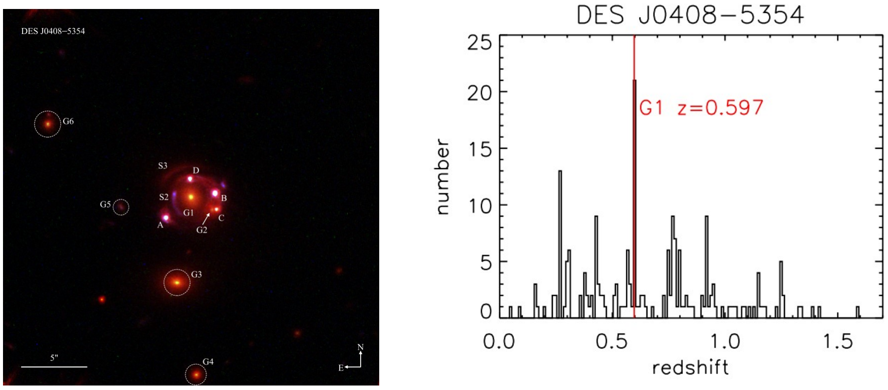

Figure 5: (left) The image of the DESJ0408-5354 system, from [12] (right) Redshift histogram 101 objects in the vicinity of this system, taken by MUSE. G1 corresponds to the central lensing system, from [3]

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2.3 VIPERS data for accurate redshift distributions

Galaxy samples used for cosmological inference in photometric surveys need a well characterized N(z), or redshift distribution. In the DES BAO analysis, the project leads used the archival ESO VIPERS data [22] as a reference. This catalog was built with the intention of providing a complete set of galaxies with spectroscopic information for the range of redshifts in $0.5 < z < 1.2$, which is precisely the range of interest for DES BAO studies at the depth that the survey operated. Out of the $\sim$ 90000 galaxies over 23.5 square degrees of the catalog, a subselection of them are a subsample over that area of the complete DES BAO sample. We can then use the redshift distribution of said sample as a representation of how the true N(z) looks like for that sample, within statistical errors, given the characteristics of VIPERS (Figure 6).

In addition, we can also use VIPERS to validate our photometric redshift estimates from the DNF code [24].

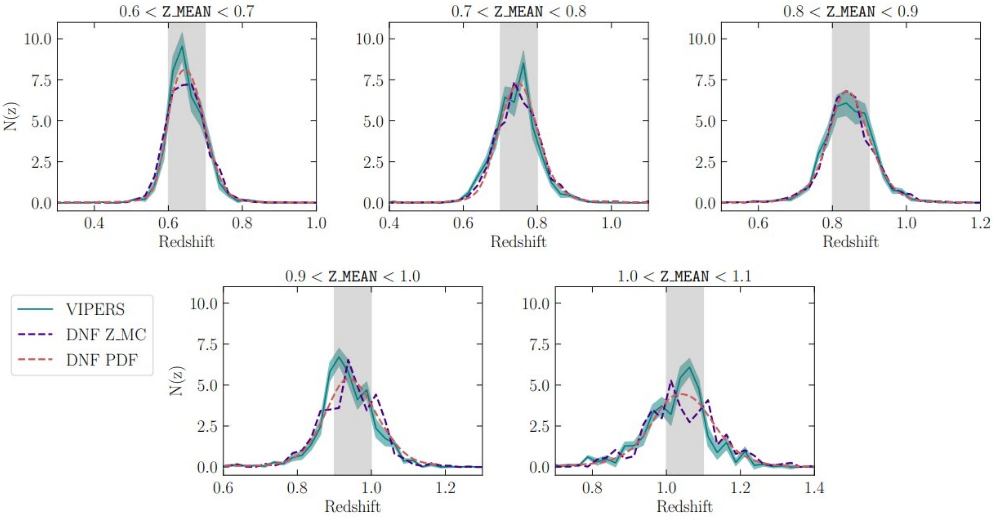

Figure 6: N(z) sample comparison for the different DES BAO redshift bins, using the DNF estimates and the spectroscopic dataset. From [4].

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2.4 Infrared photometry from VISTA

Besides spectroscopic observations, DES can be complemented with imaging in other wavelengths towards bluer or redder parts of the spectrum. The blue and ultraviolet are useful, in broad terms, for understanding the physics of the nearby Universe, as well as for instrumental purposes (to fine tune calibration). In the case of dark energy studies, we can use infrared data to understand better the estimation of photoz at higher redshifts.

In particular, DES has benefitted from a close collaboration with the VHS survey [2], using the VISTA telescope and camera, with whom it has had a close cooperation since the start, with early access to data releases and members belonging to both collaborations. This survey spans a very large area which, despite not covering completely the DES footprint, does provide complementary infrared information that helps with object classification and selection of stars for PSF extraction [8][11], especially through the use of the Ks band, at least for the brighter sources at $i < 21$. VISTA adds the J, H and Ks infrared bands spanning wavelengths from 1 micron to beyond 2 microns.

In addition, in the supernova fields, DES has produced very deep coadd images [9] to serve a multitude of purposes but, in particular, to provide very accurate redshifts for objects in those regions using u band from DECam, and deep VISTA data (Figure 7). These practically noise 'free' objects in these deep fields, can be stored as reference objects for synthetic simulations to be injected in other parts of the wide footprint [6]. The estimated redshifts using the main survey's optical filters for those same injected objects can be used to make a mapping between the main survey less accurate redshifts and their true counterparts in the deep fields, so that a probability that a given wide survey galaxy belongs to one type of galaxy or another can be created [10]. In this way a complete N(z) distribution can be built profiting from the deep field information, using this link to the wide field observations.

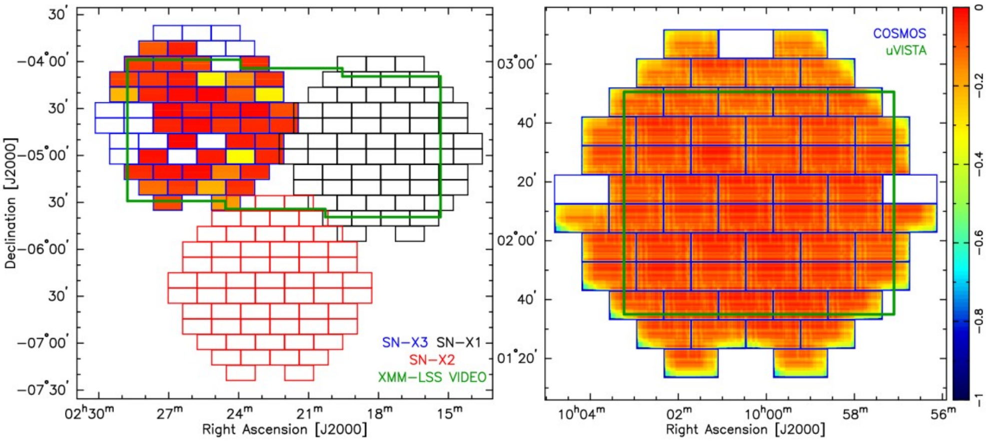

Figure 7: Location and layout of a few supernova fields of DES, with an overlay of pointings from ESO VISTA surveys. From [9].

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3 Summary

The Dark Energy Survey has been able to profit from the state of the art astronomical facilities, complementing its observations with spectroscopic data and imaging in infrared wavelengths. This has been approached from three different angles:

- Through participation in competitive calls for observation time.
- Through the use of archival data.

- Through direct agreeements or close collaborations with ESO-linked surveys. For instance, since their early data releases, a close collaboration with the KiDS survey has been established to understand the root cause for the slight differences seen in the measurement of the $S8 - \Omega_M$ parameters.

The examples shown in this contribution show some cases from different areas of cosmology where ESO data has been a core contribution to obtaining some of the most constraining results on cosmological parameters to date.

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