Cosmology with the Dark Energy Survey

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   2. Galaxy Clustering and Weak Gravitational Lensing
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The DES Project
Optical/IR imaging survey with the Blanco 4m telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile with DECam (570 Mpx camera with 3 sq-deg FoV)

5000 sq-deg (1/8 of the sky) in grizY bands up to $i_{AB} \sim 24$th magnitude or $z \sim 1.5$ (2500 sq-deg overlapping with SPT survey) +

30 sq-deg time-domain griz (SNe)

4 probes of dark energy: Supernovae Ia, Galaxy clustering and BAO, weak gravitational lensing, Galaxy clusters counts
NGC 1365 (the Great Barred Spiral Galaxy) is a barred spiral galaxy about 56 million light-years away in the constellation Fornax. (Credit: DECam, DES Collaboration)
**USA:** Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of pennsylvania, Argonne National Laboratory, Ohio State University, Santa Cruz/SLAC Consortium, Texas A&M University, CTIO (in Chile)

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**UK Consortium:** UCL, Cambridge, Edinburgh, Portsmouth, Sussex, Nottingham

**Germany:** Munich

**Switzerland:** Zurich

**Spain Consortium:** CIEMAT, ICE, IFAE

**Brazil Consortium:** Observatorio nacional, CBPF, Universidade Federal do Rio de Janeiro, Universidade Federal do Rio Grande do Sul

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**DES Collaboration**

~500 scientists from 25 institutions in 7 countries
darkenergysurvey.org
Facebook.com/darkenergysurvey
Twitter: @theDESurvey
DES Survey Area
5000 square degrees, 1/8 of the sky

Footprint has been covered 900 seconds in each filter (g,r,i,z; 450 sec in Y) after 5.5 seasons.

Data taking is finished (09/01/2019)
Year 1: half of the footprint, half of the depth → Current Results
Year 3: whole footprint, half of the Depth → In a few months
Year 5: whole footprint, full Depth → For 2021
**Photometric Redshift**

Measure the Galaxy redshift using images in different colors (g, r, i, z, Y filters).

Not very precise for each Galaxy, but millions of galaxies

Measure relative flux in each filter and combine them to obtain the redshift

Several methods: Fit to template spectra, use known spectra to train a $P(z|g,r,i,z,Y)$ relation

Redshift relative precision $\sigma(z) < 0.1$

Selected subsamples can have much better resolution

Challenge: spectroscopic training sets and calibration data not complete to the depth of DES
Supernovae Ia

Hubble diagram with supernovae from the Y3 sample, that have spectroscopic redshift and identification. Supernovae Ia are standarizable candles

\[ \mu = m - M = 5 \log_{10}(d_L(z; \Omega_M, \Omega_\Lambda, w, ...)/10 \text{ pc}) \]

\[ d_L(z) = r(z)(1+z) \]

Distance modulus, \( \mu \)

Distance modulus Residual, \( \mu \) Residual

Redshift

\[ r(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_\Lambda + \Omega_k (1 + z')^2 + \Omega_M (1 + z')^3 + \Omega_r (1 + z')^4}} \]

\( \Omega_{DE} e^{-3 \frac{\omega a z}{1+z}(1+z)^{3(1+\omega_0+\omega a)}} \)
Supernovae Ia

Hubble diagram with supernovae from the Y3 sample, that have spectroscopic redshift and identification

Results are compatible with the dark energy being the cosmological constant

For these results, a total of 207 spectroscopically confirmed SNe have been used, combined with 122 at low redshift from previous experiments

This is a 10% of the total number of supernovae that have been discovered in DES

Results will significantly improve in the near future with the full sample
Galaxy Clustering and Weak Lensing

The measurements of positions and shapes of the galaxies can be combined to obtain the maximum information about cosmological parameters.

**SOURCES:**

Remove stars and images within 30 pixels of the edge of a CCD. High quality: S/N > 10 all exposures and all bands.

We need to measure the redshift and **MAINLY, THE SHAPE** of all these galaxies.

**LENSES:**

redMaGiC galaxy selection: Large, red and bright galaxies.

Easily identifiable, strongly clustered, having small photometric-redshift errors and massive.

6.6x10^5 galaxies with \( \sigma_z/(1 + z) = 0.017 \)

26 million galaxies.

**Main Points:**

- **2 samples of galaxies:** “lenses” and “sources”
- Combine the auto and cross-correlation of:
  1. **positions** of the lens galaxies
  2. **shapes** of the source galaxies

**Diagram Notes:**

- Galaxy clustering
- Galaxy-galaxy lensing
- Cosmic shear

1321 sq-deg
Galaxy Clustering and Weak Lensing

The distribution of galaxies in space contains a lot of information about cosmological parameters. Source sample.

Redshift distributions for lenses and sources in the cosmology analysis.

Validation of these distributions is done with spectroscopic Galaxy samples and galaxy cross-correlation functions between different redshift bins.
Galaxy Clustering and Weak Lensing

Galaxy Clustering data vectors

Angular correlation functions for 5 redshift bins

Scales in grey are not used for cosmology (non-linearities, scale dependent bias, baryonic effects...)

DES Y1 fiducial
best-fit model
scale cuts

θw (arcmin)

θ (arcmin)
Galaxy Clustering and Weak Lensing

Galaxy-Galaxy lensing data vectors

DES Y1 fiducial best-fit model scale cuts
Galaxy Clustering and Weak Lensing

Cosmic shear data vectors

[Diagram showing cosmic shear data vectors with annotations]

DES Y1 fiducial
best-fit model
scale cuts
Galaxy Clustering and Weak Lensing

Cosmic shear data vectors

DES Y1 fiducial
best-fit model
scale cuts
Galaxy Clustering and Weak Lensing

Huge effort to accurately determine the covariance matrix among different cosmological probes. Use theory, simulations and data.
Galaxy Clustering and Weak Lensing

Results of the combined analysis. First time ever that these combinations are done in a single galaxy survey.

$S_8 = \sigma_8 (\Omega_m / 0.3)^{\frac{1}{2}}$ describes the inhomogeneity of the matter distribution now: $\sigma_8$ is the standard deviation of the matter-density distribution in spheres of radius 8 Mpc/h.

- $\Omega_m$: fraction of matter in the total matter-energy of the universe now.

- First measurement in late universe with precisión comparable to CMB.
Combination of all the late universe experiments compared to CMB results from Planck satellite

Results are statistically compatible

DES contours will shrink by a factor of at least 2 in a few months, when the análisis of the Y3 sample is finished
Combining all results: clustering + weak lensing + supernovae

DES only results are of a precisión comparable to the combination of all the previous cosmology projects combined

And are still going to improve by a large factor

Results are compatible with the dark energy being the cosmological constant
Extended models: beyond ΛCDM

We have also explored some extensions of ΛCDM.

Time varying EoS for the dark energy

No evolution of the EoS parameters for the dark energy is observed with the 3x2pt analysis.

These measurements are completely independent of the supernovae results.
**Other results:**

**H₀ with clustering, BAO and D/H**

**Determination of the Hubble parameter from DES-3x2pt+BAO (no DES) + BBN (no DES)**

Independent of all the previous measurements

Result compatible with Planck measurement
Extrapolate backwards the distances measurements from supernovae

Including BAO measurements from other experiments

Results compatible with Planck measurement
Other results:

**H₀ with gravitational waves**

**Measure redshift for Neutron star collisions from DES and distance from LIGO-VIRGO**

**Accurate and independent determination of H₀**

**Best measurement with ~50 NS-NS collisions**

Measure redshifts for every galaxy that is candidate to host black hole collision and determine the statistical distribution of redshift for the distance determined with LIGO-Virgo

Can be a competitive measurement of H₀ with black hole collisions
Conclusions

DES has provided a wide set of results from its Y1 data set:

- Measurement of the anisotropies in the matter distribution now using WL and LSS, compatible with $\Lambda$CDM.
- Several measurements of the Hubble parameter that are independent of other probes.
- Y3 spectroscopic SNe results are competitive with previous surveys and in agreement with $\Lambda$CDM.
- DES Data Release 1, including Y1-Y3 catalogs, is publicly available at: https://des.ncsa.illinois.edu/releases/dr1

Much improved results to come in a few months for the Y3 data sample. Stay tuned!