Dark Energy Experiments

Cosmic Surveys
• Dark Energy Survey: New analysis results
• Dark Energy Spectroscopic Instrument: Operations Update
• Legacy Survey of Space and Time (LSST): Construction

Tom Diehl
Fermilab User’s Meeting
August 3, 2021

All these are collaborative efforts of Dept. of Energy, NSF, International funding agencies, and US & International University Partners.
- Led by Fermilab
- **DECam**: The 570 Megapixel camera for the Blanco 4m telescope in Chile.
- **Wide field**: 5000 sq. deg. in 5 bands. ~23 magnitude depth.
- 27 sq. deg. 5-yr SNIa survey

N. Jeffrey; Dark Energy Survey Collaboration

Dark Matter map from DES observations
Through June 30, 2021, DES has 357 refereed science papers (not counting pre-data technical papers) with 15,700+ citations.

Some of the recent papers (up to May 25th):

**Instrumental:** “A Machine Learning Approach to the Detection of Ghosting and Scattered Light Artifacts in Dark Energy Survey Images”, “Reducing ground-based astrometric errors with Gaia and Gaussian processes” will both be useful to LSST

**Solar System:** “Testing the isotropy of the Dark Energy Survey's extreme trans-Neptunian objects”

**SN1ae:** “OzDES multiﬁbre spectroscopy for the Dark Energy Survey: Results and implications for future surveys”, “The Effect of Environment on Type Ia Supernovae in the Dark Energy Survey Three-Year Cosmological Sample”, “The Dark Energy Survey Supernova Program: Modelling selection efficiency and observed core collapse supernova contamination”, “Rates and delay times of type Ia supernovae in the Dark Energy Survey”

**Galaxy Clusters:** “Is diffuse intracluster light a good tracer of the galaxy cluster matter distribution?”, “$\mu$ Masses: Weak Lensing Calibration of the Dark Energy Survey Year 1 redMaPPer Clusters using Stellar Masses”, “The WaZP galaxy cluster sample of the Dark Energy Survey Year 1”

**Weak Lensing:** “Galaxy Clustering in Harmonic Space from the Dark Energy Survey Year 1 Data: Compatibility with Real Space Results”

**Galaxy Clusters + WL:** “Combination of cluster number counts and two-point correlations: Validation on Mock Dark Energy Survey”, “Dark Energy Survey Year 1 Results: Cosmological Constraints from Cluster Abundances, Weak Lensing, and Galaxy Correlations”

**Galaxy Clusters + External Data:** “Cosmological Constraints from DES Y1 Cluster Abundances and SPT Multi-wavelength data”, “Probing galaxy evolution in massive clusters using ACT and DES: splashback as a cosmic clock”, “The Atacama Cosmology Telescope: A Catalog of > 4000 Sunyaev-Zel'dovich Galaxy Clusters”

**Modified Gravity:** “Probing gravity with the DES-CMASS sample and BOSS spectroscopy”, “Galaxy-galaxy lensing with the DES-CMASS catalogue: measurement and constraints on the galaxy-matter cross-correlation”

**Optical + GW:** “Constraints on the Physical Properties of S190814bv through Simulations based on DECam Follow-up Observations by DES”

**Dark Matter:** “Milky Way Satellite Census. III. Constraints on Dark Matter Properties from Observations of Milky Way Satellite Galaxies”, “Constraints on Decaying Dark Matter with DES-Y1 and external data”.

**Galaxy Evolution:** “Galaxy Morphological Classification Catalogue of the Dark Energy Survey Year 3 data with Convolutional Neural Networks”
Flat Universe with Dark Energy in the form of a cosmological constant $\Lambda$ + Cold Dark Matter.

It assumes General Relativity.

$\Lambda \text{CDM}$ became the standard model following observations from Type Ia Supernovae and the Cosmic Microwave Background.
Testing ΛCDM: Is the late time clustering compatible with the ΛCDM prediction assuming initial conditions from the CMB?

$A_s$: Amplitude of primordial scalar density fluctuations.

$\sigma_8$: Amplitude of mass fluctuations today, at distance 8 Mpc/h.
DES: Cosmology

7 Ways

Growth rate of structure and Expansion History: Weak Gravitational Lensing, Galaxy Clustering, & Galaxy Cluster Abundance

Expansion History: BAO (standard rulers), SNIa (standard candles), Gravitational Wave Follow up (standard sirens), Strongly-Lensed Transients.

Time varying SL quasar
$H_0 = 74.2 \pm 2.7 - 3.0$ km/s/Mpc

Y1 Combo

To et al. arxiv:20100.01138

Y3 Spect. SNIa + Y1

3x2pt WL

DES, PRD 102, 023509 (2020)

Des Clusters
DES 3x2pt
Planck 18
SN Panth.
SPT-2500
WtG
BAO


Time varying SL quasar
$H_0 = 74.2 \pm 2.7 - 3.0$ km/s/Mpc

DES, PRL 122, 171301 (2019)

Shahib et al., MNRAS 494, 6072 (2020)

DES, PRD 102, 023509 (2020)
New Results from DES: “Y3 Weak Gravitational Lensing & Galaxy Clustering”: Sources and Lenses

Galaxies trace the underlying dark matter structure: they are observed to be spatially *clustered*.

Light from distant galaxies passes the foreground structures and acquires coherent distortions: they are observed to be *lensed (sheared)*.

We also measure the correlation of the shapes of source galaxy pairs as a function of angular radius and redshift *(shear-shear)*.

Summary:

- Galaxy Clustering: position-position
- Galaxy-Galaxy Lensing: position-shear
- Cosmic Shear: shape-shape (shear-shear)

Redshift (z)

100M sources

10M lenses
Y3 “3x2pt” Methodology: Pixels to Cosmology

Webinar from May 27, 2021 https://www.youtube.com/watch?v=8aHbLMUOwLc
30 Paper Compilation @ https://www.darkenergysurvey.org/des-year-3-cosmology-results-papers/
Y3 3x2pt Data + Model Fit
Largest area and Biggest samples so far for any WL analysis

**Galaxy-galaxy lensing** Prat+

**Cosmic shear** Amon+, Secco, Samuroff+

**Lens galaxy clustering** Rodriguez-Monroy+
**DES Y3 Weak Lensing Cosmology Results**

\[ S_8 = 0.776^{+0.017}_{-0.017} \quad (0.776) \]

\[ \Omega_m = 0.339^{+0.032}_{-0.031} \quad (0.372) \]

\[ \sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696) \]

\[ \Lambda CDM \]

\[ wCDM \]

\[ \Omega_m = 0.352^{+0.035}_{-0.041} \quad (0.339) \]

\[ w = -0.98^{+0.32}_{-0.20} \quad (-1.03) \]

- Lens samples MagLim and redMaGiC 3x2 in perfect agreement
- Evidence for potential systematics in the redMaGiC clustering data vector at all redshifts and above the fiducial lens redshift range for MagLim.  

Combinations

We find no significant evidence for inconsistency in $\Lambda$CDM between DES 3x2pt and Planck, and good agreement between DES + other complementary low-redshift probes and Planck.

“Low-redshift non-lensing data” is SNe Ia (but not DES), BAO, RSD

$S_8 = 0.812^{+0.008}_{-0.008}$ (0.815)

$\Omega_m = 0.306^{+0.004}_{-0.005}$ (0.306)

$\sigma_8 = 0.804^{+0.008}_{-0.008}$ (0.807)

$h = 0.680^{+0.004}_{-0.003}$ (0.681)

$\sum m_\nu < 0.13$ eV (95% CL)

$\Lambda$CDM

$\sigma_8 = 0.810^{+0.010}_{-0.009}$ (0.804)

$\Omega_m = 0.302^{+0.006}_{-0.006}$ (0.298)

$w = -1.03^{+0.03}_{-0.03}$ (−1.00)

wCDM
A long-time controversy: DM halo models predict hundreds of captured “satellite” galaxies for the Milky Way. DES data and selection function vs. magnitude (mass proxy) shows that there are! Distribution of MW satellite masses enables model-dependent constraints on Dark Matter properties. i.e. DM must be massive.

**Known MW satellites vs year**

**Distribution of MW satellite masses enables model-dependent constraints on Dark Matter properties. i.e. DM must be massive.**

**DECam**

**Mass v. Mixing angle**
Most Massive & Most Distant Comet
C/2014 UN271 “Bernardinelli-Bernstein”

- DES data is great for finding “Transient and Moving Objects”
- 245+ New Trans-Neptunian Objects @ 30 to 100 AU

- C/2014 UN271 was detected as it came in from the Oort cloud at 29 to 23 AU
- Massive (~200 km wide) comet discovered.
- Early studies of the coma show sub-mm sized grains at 7 m/s as well as sublimation of CO
- Perihelion at 11 AU in 2031, so we’ll watch this one “turn on” for a long time

https://www.syfy.com/syfywire/gigantic-comet-is-currently-inbound-toward-the-sun
DES Y6 Data is Amazing!

https://des.ncsa.illinois.edu/releases/dr2

- Y6 more homogenous than Y3 (typically 8 vs. 4)
- Y3 -> Y6 depth increase by completeness ~ 0.7 mag (partly attributed to detection threshold adjustments)
- 400M objects -> 700M objects
DECam Local Volume Exploration Survey

- DES covers only 1/6th of the sky accessible to DECam.
- DELVE leverages Fermilab infrastructure and expertise to cover 5x the sky area of DES.
- DELVE studies the nature of dark matter and dark energy through a combination of near-field cosmology, strong lensing, and weak lensing.
- First DELVE data release in January 2021

DES area outlined in blue

**DELVE** covers most of the high Galactic latitude sky.
DESI is a spectroscopic survey
- Led by LBNL
- Goal: Measure precise redshifts of targets that come from Imaging Surveys
- Survey from 2021 - 2025: ~30M galaxies and Quasars to measure Baryon Acoustic Oscillations and Redshift Space Distortions to redshift ~ 3.5.

Large instrument mounted at Prime Focus of the Mayall 4m telescope at Kitt Peak in Arizona
- 5,000 independently controllable optical fiber positioners
Dark Energy Spectroscopic Instrument

• Kitt Peak reopened for work in mid-Sept 2020 after a 6-month shutdown because of COVID
• Recommissioning was completed in December 2020
  • Many improvements/fixes to all systems (e.g., Instrument Control System, focal plane, spectrographs, fiber view camera)
  • The goal was to improve reliability and efficiency, reduce need for “experts”.
  • There was also work on the telescope and facilities
• Survey Validation (SV) December 2020 - March 2021
• 1% survey April-May 2021
  • Conduct 1 month of observations in survey mode
• **5-year survey started in mid-May 2021**
• Currently in summer shutdown: mid-July to mid-September
  • Remove all 10 petals and install new versions of some electronics boards then reinstall those petals
  • Remove two dozen of the failed positioners for in-lab forensics
Legacy Survey of Space and Time
Vera C. Rubin Observatory on Cerro Pachon in Chile

- Novel 3-mirror optical design @ F/1.2
- 8.4 m primary mirror (6.67 m “filled aperture”) and
- A 3.2B pixel Imaging Camera mounted at the top of the telescope will be the world’s largest digital camera
- 9.5 sq.deg. FOV will allow fast mapping of ½ the sky
- Science Stage IV DE

Led By SLAC

LSST DESC
Dark Energy Science Collaboration
### Legacy Survey of Space and Time

**Vera C. Rubin Observatory**

**Schedule as of April 2021**

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**Legend:***
- NSF MREFC
- DOE MIE
- Commissioning
- DOE Ops for Commissioning
- Operations
- Critical Path

**Key Steps:**
- Pre Commissioning Preparations
- Data Management
- Telescope & Site
- ComCam / Pathfinder on Tel
- Engineering First Light
- Early SIT-Comm
- Camera Refrigeration Test 2
- Camera ready at SLAC
- CD-4
- DOE Ops
- Camera Ready on Summit
- System First Light
- Operational Readiness Review
- EPO Readiness Review
- Full SIT-Comm
- Schedule Contingency

**Additional Notes:**
- Currently projecting a 15-month delay with CP in TMA to STF Comm.
- Camera has 6 wks float.
- Early Finish: Aug 2023
- Late Finish: Feb 2024

**Timeline:**
- 09 April 2021 – COVID Re-Plan
The Dark Energy Survey finished observations in 2019. It produced images and catalogs that is a gold mine for astrophysics and cosmology.

- For Weak Lensing & Galaxy Clustering “3x2pt” analysis, the unprecedented Y3 data sample required the development of novel methods at every stage.
- We find no significant evidence for inconsistency in $\Lambda$CDM between DES 3x2pt and Planck, and good agreement between DES + other complementary low-redshift probes and Planck. There are hints of a previously unknown systematic that doesn’t impact the Y3 results.
- DES Y6 data is fantastic, and we are initiating the Y6 cosmology analyses.

The Dark Energy Spectroscopic Instrument

- Start of observations was impacted by COVID
- Now in summer maintenance shutdown. Will continue 5-year observation program next month.

LSST

- System 1st light in Oct. 2023, start of regular observations about a year later.

After that? See Snowmass Process.
Credits

DES Y3 3x2pt analysis

List of participants
(Early Career Scientists in bold)

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Robert Morgan
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Paul Rogozinski
Elizabeth Krause
Joe DeRose
Richard Kron
H. Thomas Dehl
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Reese Wilkinson
Peter Mehlendorf
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Mitch McNanna
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Santiago Avila
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Mandi Barcetti
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Urban Zenteno
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Gary Bernstein
Sujeong Lee
Prudhvi Varma
Uli van Zeller
Simon Samroff
Richard Kesler
Huan Lin
Rutuparna Das
Lorna Whiteley
Annusa Shivaratanu
Tanja Davis
Jimena Gonzalez
Tim Eifler
Giorgia Pollina
Ashley Ross
Eleonora di Valenti
Lucas Sacco
Ji Won Park
Andrew Pace

Plus Slides from:
Elizabeth Buckley-Geer
Alex Drlica-Wagner
James Tiberius Annis
Pedro Bernardinelli
Gary Bernstein
Kevin Reil & the
Rubin Observatory Webpages
Two Lens Samples

- **redMagic**: LRG selection 2.9M galaxies in 5 redshift bins
- **MagLim**: Brightness selection 10.1M in 6 redshift bins
- Below: galaxy clustering (position-position)

Weights correct for effects of airmass, seeing, exposure time, depth, stellar density, dust, sky brightness, calibration residuals

Myles, Alarcon et al. (2021), Porredon et al. (2021), Gatti, Giannini et al. (2021), Sanchez, Prat et al. (2021), Cordero, Harrision et al. (2021), Cawthon et al. (2021), de Vicente et al (2015) Rodriguez-Monroy et al. (2021) Everett et al. (2020), ++
100.2 M source galaxy shapes for DES Y3

Many more source galaxy shapes than any previous analysis

Key improvements over DES Y1:
- More sky
- More accurate PSF models (Piff, Jarvis+2020) => better shear measurements
- Improved astrometry
- Expanded suite of null tests (Gatti, Sheldon+2021)
- Effects of deblending systematic (MacCrann+ 2021)
Position-Shear Measurements

Galaxy-Galaxy lensing around foreground galaxies

The two-point function between lens galaxy positions and source galaxy tangential shear.

Shown for MagLim

Prat et al. (2021)
The Correlation of Pairs of Galaxy Shapes

Detection significance $\sim 27$ (Y1) $\rightarrow$ 40 (Y3)

Final results from a Blinded Fit:
- Cosmology (7 params)
- Astrophysical Model (9 params)
- Calibration (16 params)

Amon et al. 2021
Secco, Samuroff et al. 2021
Equity, Diversity, and Inclusion Initiatives

- Currently engaged with the NOVA Collective ([HOME - The Nova Collective](HOME - The Nova Collective)),
  - We recently completed a climate survey. We’ll get the results soon.

- Mentorship Program
  - Volunteer Mentors. 25 Mentor/Mentee pairs. A dedicated Mentorship Coordinator.

- Adjustments to DES Collaboration written policies so that engagement with underrepresented people in STEM is encouraged

- Focus at recent Collaboration Meeting
  - Plenary Speaker from outside DES
  - EDI Parallel Sessions: Connecting with minority-serving institutions, Focusing EPO efforts on inclusion, Giving Credit in DES
  - EDI One-slides at the beginning of every Plenary session
Dark Energy Spectroscopic Instrument

Emission line galaxy redshift = 0.9

18M Emission Line Galaxies (ELGs)  
0.6 < z < 1.6

1.7M QSOs  
1.0 < z < 3.5

4M Luminous Red Galaxies (LRGs)  
0.4 < z < 1.0

0.7M Ly-α QSOs

Dark Time

Bright Time

Milky Way Survey: 10M stars

10M Bright Galaxies (BGS)  
r < 19.5, z < 0.4
Major Camera Elements

- Corner Raft Tower
- Science Raft Tower
- Utility Trunk
- Aux Electronics
- Cryostat
- L3 Lens Assembly
- Filters (6)
- Filter Exchange System
- L1-L2 Lens Assembly
- Shutter
- Sensors
All Camera hardware has been fabricated at the sub-system level except for some of the filters.