Cosmology in the New Era
(Results from the Dark Energy Survey)

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on behalf of the Dark Energy Survey Collaboration
Dark Energy

What is the cause of the observed cosmic acceleration?

– Is it dark energy or a modification of general relativity?

• If it is dark energy, is it constant ($\Lambda$) or evolving; what is the DE equation of state?
What can we probe?

Geometry: Distances, Expansion rate vs. Redshift

Expansion History

Growth of Density Perturbations

Require both to disentangle Dark Energy from Modified Gravity

Frieman, Turner, Huterer 2008
Dark Energy Probes

Diagram:

- Redshift space distortions
- Cosmic shear
- Galaxy clustering
- Galaxy clusters
- "Late-time structure"
- CMB
- BAO
- Supernovae
- "Expansion history"
Dark Energy Probes

Probed by Dark Energy Survey
The Dark Energy Survey

- Two multicolor surveys:
  - 300 million galaxies over 5000 deg$^2$, grizY to 24th mag
  - 3000 supernovae (30 deg$^2$)

- DECam on CTIO Blanco 4-m
  - DECam facility instrument

- Survey started August 2013
  - 5 of 5.5 seasons completed
  - Y1 (1500 sq. deg, 40% depth)
  - Y3 (5000 sq. deg, 50% depth)
The Dark Energy Survey

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Results today + Y3 SNe

DECam:
- 570 Megapixel Camera
- 3 deg$^2$ FOV
DES Collaboration

~ 400 scientists
US support from DOE & NSF

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/Stanford, Texas A&M

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

ETH Zurich
Ludwig-Maximilians Universität

Spain Consortium:
CIEMAT, IEEC, IFAE

Brazil Consortium

OzDES Consortium

CTIO
Survey Footprint

5000 deg$^2$ footprint to be covered 900 seconds in griz and 450 sec in Y

10 SN fields, each observed every ~ 6 nights:
2 deep, 8 shallow
• **Galaxy Clusters**
  • Tens of thousands of clusters to $z \sim 1$

• **Weak Lensing**
  • Shapes of 200 million galaxies

• **Galaxy Clustering**
  • 300 million galaxies to $z \sim 1$

• **Supernovae**
  • 3000 well-sampled SNe Ia to $z \sim 1$

• **Strong Lensing**
  • $\sim$ 30 QSO lens time delays
  • Arcs with multiple source redshifts

• **Cross-correlations**
  • Galaxies, shear, CMB

\[ w(a) = w_0 + w_a (1 - a(t)) \]
DES Dark Energy Probes

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Galaxy Clustering

Galaxies form in dark matter overdensities.
Galaxy positions trace matter distribution

→ Construct power spectrum (or real-space correlation function) from positions

(Limited by an unknown galaxy bias relative to dark matter).

C.M. Baugh
Light from distant galaxies passes through the same structure → Change in ellipticities correlated

- Measure galaxy shapes
- Measure correlation of shapes of pairs on galaxies.
DES Year 1
~1500 deg$^2$

Galaxy distribution

Weak lensing map of projected mass from 26 million galaxies

Chang+ arXiv:1708.01535
Cross Correlations

Combination jointly constrains astrophysical and systematic parameters

Dark matter

Galaxy clustering

Cosmic shear

3x2pt

Galaxy-galaxy lensing

Elvin-Poole+ 1708.01536

Troxel+ 1708.01538

Prat, Sanchez+ 1708.01537
Double everything:
- Two shape measurement codes
- Two photo-z codes
- Two analysis pipelines

Similar constraining power to Planck on matter density and amplitude (1-2σ tension)

\[ \Omega_m = 0.301^{+0.006}_{-0.008}, \quad \sum m_\nu < 0.29 \text{ eV} \]
\[ S_8 = 0.799^{+0.014}_{-0.009}, \quad w = -1.00^{+0.04}_{-0.05} \]

wCDM, DES+Planck+BAO+SNe

DES collaboration 2017, arXiv:1708.01530
Cosmology with Clusters

Growth rate depends on balance between gravity and expansion rate

Clusters are rare overdensities
Cosmology with Clusters

What we can predict:
(# of massive halos)/volume at $z$

What we see:
Galaxies in survey solid angle at photometric $z$
Cosmology with Clusters

What we can predict:
(# of massive halos)/volume at z

What we see:
Galaxies in survey solid angle at photometric z

Richness (# of galaxies) $\rightarrow$ cluster mass
Solid angle $\rightarrow$ volume (cosmology dependent)
Counting Clusters

Measure number of clusters (bins of richness and redshift)
Counting Clusters

Measure number of clusters (bins of richness and redshift)

Step 1: Find clusters
Overdensity of galaxies with the same color
redMaPPer (Rykoff+ 2014)

Cluster red sequence
Gladders+ 1998
Counting Clusters

Step 2: Determine position, redshift, and richness
Counting Clusters

Step 2: Determine position, redshift, and richness

Color of red sequence $\rightarrow$ redshift (accurate to $\sim1\%$, McClintock+ 2018)
Counting Clusters

Step 2: Determine position, redshift, and richness

Color of red sequence $\rightarrow$ redshift (accurate to $\sim 1\%$, McClintock+ 2018)

Candidate central galaxy $\rightarrow$ position
Counting Clusters

Step 2: Determine position, redshift, and richness

Color of red sequence $\rightarrow$ redshift (accurate to $\sim$1%, McClintock+ 2018)

Candidate central galaxy $\rightarrow$ position

Assign galaxies a membership probability

$$\lambda_{RM} = \Sigma p_{\text{mem}} \rightarrow \text{richness}$$
Mean mass-richness relation – stacked weak lensing


<table>
<thead>
<tr>
<th>Source of systematic</th>
<th>SV Amplitude uncertainty</th>
<th>Y1 Amplitude Uncert</th>
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</thead>
<tbody>
<tr>
<td>Shear measurement</td>
<td>4%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Photometric redshifts</td>
<td>3%</td>
<td>2.6%</td>
</tr>
<tr>
<td>Modeling systematics</td>
<td>2%</td>
<td>0.73%</td>
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<tr>
<td>Cluster triaxiality</td>
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<td>2.0%</td>
</tr>
<tr>
<td>Line-of-sight projections</td>
<td>2%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Membership dilution + miscentering</td>
<td>≤ 1%</td>
<td>0.78%</td>
</tr>
<tr>
<td><strong>Total Systematics</strong></td>
<td>6.1%</td>
<td>4.3%</td>
</tr>
<tr>
<td><strong>Total Statistical</strong></td>
<td>9.4%</td>
<td>2.4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>11.2%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>
Mass Calibration – Scatter

Mass-richness scatter – X-ray and SZ observations

Hollowood+ in prep, Farahi+ in prep.

Scatter of $0.25 \pm 0.13$
Systematics

Miscentering: Zhang+ in prep.
• reduces lensing shear
• reduces observed richness
Calibrate with X-ray data

Projection: Costanzi+ 2018
• changes observed richness
Calibrate $p(\lambda_{\text{obs}}|\lambda_{\text{true}})$ with simulations

Cluster member contamination: Varga+ in prep.
• Reduces shear by adding unsheared galaxies
Calibrate boost using $p(z)$ distribution
**Y1 Cluster Cosmology - Blinded**

Coming soon: DES Key Paper on Year 1 cluster cosmology

Blinded results show constraining power equals combined 3x2pt

* blinded means position of contours unknown. Here they are artificially shifted to overlay 3x2pt.*
Supernovae

Type Ia Supernovae: Standardizable candles

DES supernova survey:

- 10 SNe fields visited every few days
- Spectroscopic follow-up by OzDES using AAT
Supernovae – DES Year 3

206 spectroscopically confirmed SNe Ia, $0.08 < z < 0.85$

+ 128 low-z external

DES collaboration, in prep.
Supernovae – DES Year 3

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Supernovae – DES Year 3

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DES collaboration, in prep.
Supernovae – DES Y3 Cosmology

\[ w = -1.002 \pm 0.057 \]

\[ \sigma_w = 0.041(STAT), 0.040(SYS) \]

\[ \Omega_M = 0.314 \pm 0.017 \]

(wCDM, DES Y3 SNe+CMB)

OmegaM: 0.314 +/- 0.017
w: -1.002 +/- 0.057

DES collaboration, in prep.

D. Brout, AAS talk
Coming Soon

CMB map from Planck or SPT
Structure associated to DES galaxies

5x2pt (+ DES clusters + DES SNe)

→ DES Year 3 triples area → more than double exposure by DES Year 5

DES forecast (T. Eifler, E. Krause)
Summary

- DES gives precise constraints on late-time structure, starting to rival CMB.

- Wide range of probes (early and late time, geometric and structure growth) agree on $\Lambda$CDM.

- The future is bright!
Thank you!
Looking for more than dark energy: Discovery* of GW170817 counterpart

25 deg²
LIGO/VIRGO positional constraint (90 % C.L.) >90% covered by DECam

Soares-Santos, ... DG+ ArXiv:1710.05459

10.5 hours post-merger among 1500 candidates


GW170817
DECam observation (0.5–1.5 days post merger)

GW170817
DECam observation (>14 days post merger)

Cosmology with Clusters

survey area covers less volume

Constant $\Omega_{DE}$ with increasing $w$

structure must form earlier to be in place before DE domination