Dark Energy Survey
Year 1 Results

Josh Frieman
DES Project Director
Fermilab, U. Chicago

HEPAP Meeting
Sept. 26, 2017
Cosmology 2017: ΛCDM

• A well-tested (6-parameter) cosmological model:
  – Universe is expanding from hot, dense early phase (Big Bang) 13.8 Gyr ago.
  – Early epoch of accelerated expansion (inflation) produced nearly flat & smooth spatial geometry and generated large-scale density perturbations from quantum fluctuations
  – From these, structure formed from gravitational instability of cold dark matter (CDM, 25%) in currently Λ-dominated (70%) universe, which is again accelerating.

• Consistent with all data from the CMB, large-scale structure, lensing, supernovae, clusters, light element abundances (BBN), …
Planck CMB Temperature Map

Fluctuations ~1 part in $10^5$ at 380,000 years
Planck 2015 Results

6-parameter $\Lambda$CDM fit:

$\Omega_\Lambda = 0.692 \pm 0.012$

$\Omega_m = 0.301 \pm 0.012$

$n_s = 0.968 \pm 0.006$

$H_0 = 67.8 \pm 0.9$ km/sec/Mpc

$\sigma_8 = 0.815 \pm 0.009$

$\Omega_b h^2 = 0.02226 \pm 0.00023$

(TT+lowP+lensing)
First Year of Data: ~1800 sq. deg. out of 5000 for full survey

- Weak lensing mass map based on shapes of 26 million source galaxies (Chang, et al)

- 660,000 red galaxies with precise photometric redshifts (Elvin-Poole, et al)
DES Year 1 Cosmic Shear Results

Best-fit ΛCDM model shown

Fluctuations ~1 at 10 Gyr
Probing the Cosmological Paradigm

• \( \Lambda \)CDM rests on physics beyond the Standard Model:
  – Inflation, dark energy, dark matter

• Understanding this physics constitutes 2 of the P5 science drivers (they bundled two of them).

• Are these 6 parameters all we need?
  – spatial curvature, \( m_v \), \( w \) [\( w_0 \), \( w_a \)], modified gravity,…
  – Tensions? Planck vs local \( H_0 \), Planck vs WL \( \sigma_8 \)
What is the physics of cosmic acceleration?

• Dark Energy or modification of General Relativity?
  • If Dark Energy, is it \( \Lambda \) (the vacuum) or something else?
    – What is the DE equation of state parameter \( w \) and (how) does it evolve? (For \( \Lambda \), \( w=-1 \).)

![Pie chart showing percentages of dark energy, dark matter, and normal matter.]

- Dark Energy: 70%
- Dark Matter: 26%
- Normal Matter: 4%
What can we probe?

Expansion History

\[ r(z) = \int dz' \left( \frac{a}{\dot{a}} \right) \]

Geography: Distances, Expansion rate vs. Redshift

Growth of Structure

Require both to distinguish Dark Energy from Modified Gravity. Aiming toward %-level measurements of geometry & structure.

JF, Turner, Huterer
Supernova Ia Hubble Diagram

Joint Lightcurve Analysis (JLA)
Betoule, et al. 2014
740 supernovae

Percent-level distance determination
The Dark Energy Survey

- Probe origin of Cosmic Acceleration:
  - Clusters, Weak Lensing, Galaxy clustering, Supernovae

- Two multicolor surveys:
  - 300 M galaxies over 5000 sq deg, grizY to 24th mag
  - 3000 supernovae (27 sq deg)

- New camera for CTIO Blanco 4m telescope
  - DECam Facility instrument

- Survey started Aug. 2013
  - Now in 5th of 5 seasons, 105 nights per season (Aug-Feb)

International collaboration led by FNAL; DOE+NSF support
DES Year 1 Cosmology Analysis: 3x2

- Compare & consistently combine three 2-point correlation function measurements:
  - **Angular clustering**: autocorrelation of 660,000 luminous red galaxies in 5 redshift bins
  - **Cosmic shear weak lensing**: shear correlation of 26 million galaxy shapes in 4 redshift bins
  - **Galaxy-galaxy lensing**: correlate red galaxy positions (foreground lenses) with source galaxy shear
- Fully blind analysis, 10 papers released Aug. 3
Multi-Probe Constraints: $\Lambda$CDM

DES Year 1 results:

- Weak Lensing Cosmic Shear
- Galaxy-galaxy lensing+galaxy clustering
- Detailed modeling of covariance between probes

DES Collaboration 2017

\[ S_8 = \sigma_8 (\Omega_m / 0.3)^{0.5} \]
Comparison of DES Y1 with Planck: low-z vs high-z in $\Lambda$CDM

- DES and Planck constrain $S_8$ and $\Omega_m$ with comparable strength!
- Differ in central values by $>1\sigma$, but consistent according to Bayesian evidence
- DES final analysis will include 4x Y1 data and additional probes (clusters, supernovae)

$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$

DES Collaboration 2017
Comparison of DES Y1 with Planck: low-z vs high-z in $\Lambda$CDM

- DES and Planck constrain $S_8$ and $\Omega_m$ with comparable strength!
- Differ in central values by $>1\sigma$, but consistent according to Bayesian evidence
- DES final analysis will include 4x Y1 data and additional probes (clusters, supernovae)

$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$

DES Collaboration 2017
Combine multiple data sets: $\Lambda$CDM

Combined constraints:

\[
\begin{align*}
\Omega_m &= 0.301^{+0.006}_{-0.008}, \\
\sigma_8 &= 0.801 \pm 0.014, \\
h &= 0.682^{+0.006}_{-0.006}, \\
S_8 &= 0.799^{+0.014}_{-0.009}.
\end{align*}
\]
Combine multiple data sets: $w_{\text{CDM}}$

- Combine to achieve very stringent parameter constraints:

$$w = -1.00^{+0.04}_{-0.05}.$$  

- Haven’t yet tested model with time-varying $w$
Where do we go from here? Y3-Y5 analyses

5000 sq. deg. with increasing depth

- **Galaxy Clusters**
  - Tens of thousands of clusters to $z \sim 1$

- **Weak Lensing**
  - Shape measurements of $\sim 200$ million galaxies

- **Galaxy Clustering**
  - $\sim 300$ 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, WL x CMB lensing

\[ w(a) = w_0 + w_a (1 - a(t)) \]

DES forecast
T. Eifler, E. Krause
DES Galaxies X CMB Lensing

- DES galaxies associated with projected mass partly responsible for CMB lensing
- Additional cosmological information in this cross-correlation

Giannantonio, Fosalba, Cawthon et al (earlier DES SV data)
Constraining Growth Function of Perturbations

Powerful test of $\Lambda$CDM and GR (complements Redshift Space Distortions)
What new techniques, technology, or data enabled this?

- **Technology:** DECam on the Blanco: highly efficient, red-sensitive CCDs (LBNL), wide-field imager (3 sq. deg., 570 megapixels) w/ excellent optical design on 4m telescope: unprecedented survey power (depth x area)/time. 525 nights awarded in exchange for facility instrument.
- **Techniques:** control systematics of photo-z’s; new weak lensing shape methodologies; model complex covariance matrices, test with realistic N-body simulations.
- **Data:** DES Y1, extensively vetted for systematics; NCSA-led production system for data management, augmented by collaboration-produced value-added catalogs for analysis.
Meaning & Impact

- Measurements from galaxy surveys now rival precision of CMB for certain cosmological parameters (and exceed it for some others): compare low- and high-z Universe to obtain complementary constraints (break parameter degeneracies).
- DES Y1 consistent with Planck CMB in context of $\Lambda$CDM. Quite remarkable for simple 6-parameter model.
- DES Y1 in combination with Planck, BAO, JLA SN provide most stringent constraints on $\Lambda$CDM parameters to date.
- Precision will increase with larger data sets ($Y1 \rightarrow Y3 \rightarrow Y5$) and by using more probes (clusters, SNe, CMB cross-correlations), enabling tests of more complex models ($w_0w_a$CDM, modified gravity), and eventually will be even better with LSST, DESI, Euclid, WFIRST.
Extra Slides
$H_0$: CMB vs. Local Measurements

CMB results assume ΛCDM model

3.4σ discrepancy
What about $H_0$?

- DES 3x2 doesn’t constrain $H_0$ on its own
- DES $\Lambda$CDM constraint on $\Omega_m$ combined with Planck shifts $h$ up by $>1\sigma$ from Planck central value, toward but not reaching local $H_0$ values

DES Collaboration 2017
What if we fix neutrino mass?

• Hold neutrino mass at 0.06 eV (lower limit from oscillation experiments)

• DES 3x2 still consistent with Planck in $\Lambda$CDM

$S_8 = 0.797 \pm 0.022$ DES Y1

$= 0.801 \pm 0.032$ KiDS+GAMA [62]

$= 0.742 \pm 0.035$ KiDS+2dFLenS+BOSS

DES Collaboration 2017
DES Y1 Galaxy Clustering

Elvin-Poole, et al
Galaxy-Galaxy Lensing

- Measurement of the tangential shear of background (source) galaxies around foreground (lens) galaxies.

\[
\gamma_{ij}^t(\theta) = b^i \frac{3}{2} \Omega_m \left( \frac{H_0}{c} \right)^2 \int \frac{d\ell}{2\pi} \ell J_2(\theta\ell) \times \\
\times \int dz \left[ \frac{g^j(z)}{a(z) \chi(z)} n_i^i(z) P_{\delta\delta} \left( k = \frac{\ell}{\chi(z)} , \chi(z) \right) \right],
\]
Prat, et al.
Covariance Matrix

Mocksv

Theory

Krause, et al