Mapping the Universe with Dark Energy Survey

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Blanco telescope at Cerro Tololo, Chile
Michigan Stadium (115,000)

LCTP focuses on:
1. Particle theory
2. Particle pheno
3. Cosmology
Tl;dr for this talk:

• In a few weeks, DES will release Y3 results, more than tripling the area covered by any deep photometric survey

• Results will be interesting; and hopefully out in time that Michael Troxel’s (Dec 17) Joint Colloquium

• Here I will present background, as well as results of some of the accompanying (“essential”) Y3 papers
Evidence for Dark energy from type Ia Supernovae

Huterer & Shafer, Rep. Prog. Phys. 2018
\[ \Omega_m = 1 - \Omega_{DE} \]

\[ \Omega_{DE} \equiv \frac{\rho_{DE}}{\rho_{crit}} \]

\[ w \equiv \frac{p_{DE}}{\rho_{DE}} \]
Current evidence for dark energy is impressively strong

SN + BAO + CMB:
\( \Omega_\Lambda = 0.724 \pm 0.010 \)
\( \Omega_\Lambda = 0 \) is 72-\( \sigma \) away

Daniel Shafer, 2017
A difficulty:

DE theory target accuracy, in e.g. \( w = p/\rho \), not known \textit{a priori}

Contrast this situation with:

1. Neutrino masses:

\begin{align*}
(\Delta m^2)_{\text{sol}} &\approx 8 \times 10^{-5} \text{ eV}^2 \\
(\Delta m^2)_{\text{atm}} &\approx 3 \times 10^{-3} \text{ eV}^2
\end{align*}

\begin{equation}
\sum m_i = 0.06 \text{ eV}^* \quad \text{(normal)}
\end{equation}

vs.

\begin{equation}
\sum m_i = 0.11 \text{ eV}^* \quad \text{(inverted)}
\end{equation}

*(assuming \( m_3 = 0 \))

2. Higgs Boson mass (before LHC 2012):

\( m_H \lesssim O(200) \text{ GeV} \)

(assuming Standard Model Higgs)
Hubble tension

Type Ia supernovae + Cepheid distances give

\[ H_0 = 74.0 \pm 1.4 \text{ (km/s/Mpc)} \]

Cosmic Microwave Anisotropies give

\[ H_0 = 67.4 \pm 0.4 \text{ (km/s/Mpc)} \]

These two measurements are discrepant at about five sigma!*

* once strong-lensing constraints are added, which come out high \((H_0 \sim 73)\)
Hubble tension - a gift to cosmology!

- exciting, real tension in cosmology
- all major analysis very thorough
- no obvious systematics (as yet)
- theory models surprisingly hard to concoct (e.g. very finely tuned scalar field models that also don’t really work)
Major ongoing or upcoming DE expt’s:

• **Ground photometric:**
  - Kilo-Degree Survey (KiDS)
  - Dark Energy Survey (DES)
  - Hyper Supreme Cam (HSC)
  - Large Synoptic Survey Telescope (LSST)

• **Ground spectroscopic:**
  - Hobby Eberly Telescope DE Experiment (HETDEX)
  - Prime Focus Spectrograph (PFS)
  - Dark Energy Spectroscopic Instrument (DESI)

• **Space:**
  - Euclid
  - Wide Field InfraRed Space Telescope (WFIRST)
Dark Energy Survey

• 3 sq deg camera on the Blanco 4m telescope in Chile
• 5000 sqdeg (in Y5)
• 5 filters (grizY); 10 passes on sky
• 5.5 yrs of observation
• Major cosmological probes:
  1. Galaxy Clustering
  2. Weak lensing Shear
  3. Clusters of galaxies
  4. Type Ia Supernovae
• Intern. collaboration of ~700 scientists
• in Jan 2019 finished all 5.5 yrs of obs.; Y3 analysis in progress almost done
Dark Energy Survey (DES)

Cerro Tololo, Chile

Blanco Telescope
Dark Energy Survey Y1 highlights

• About 1300 sqdeg (~1/4 of final area)
• 35 million galaxies with shear measurements
• Redshift range roughly z<1; photometric redshifts for all objects (two independent methods agree well)
• “3x2” analysis includes galaxy shear, galaxy-galaxy lensing, galaxy clustering (papers out; discuss next)
• blinded analysis
• “double pipeline” for everything (next slides)
• Supernova analysis (papers out)
• BAO: 4% distance out to z=0.81
• cluster counts, strong lensing
• Over 250 papers already out
3x2 analysis in a picture

sheared image

$\alpha = 4GM/bc^2$

$g$

(positions of foreground galaxies; 5 redshift bins)

(image: LSST science book)

3x2 (point-function) clustering measurements:

\[
\begin{bmatrix}
gg & gs \\
gs & ss
\end{bmatrix}
\]

(shear of background galaxies; 5 redshift bins)
A. Halo Model Covariances

The covariance of two angular two-point functions $\xi, \Theta \in \{w, \gamma_t, \xi^+, \xi^-\}$ is related to the covariance of the angular power spectra by

$$\text{Cov}(\xi_{ij}(\theta), \Theta_{km}(\theta')) = \int dl l^2 \pi J_n(\xi_{ij}(l\theta)) \int dl' l'^2 \pi J_n(\Theta_{km}(l'\theta')) \left[ \text{Cov}_G(C_{ij}(\theta), C_{km}(\theta')) + \text{Cov}_{NG}(C_{ij}(\theta), C_{km}(\theta')) \right],$$

with $C_{\xi^+} \equiv C_{\xi^-} \equiv C_{\kappa\kappa}, C_{\gamma_t} \equiv C_{\delta g\kappa}$ and $C_w \equiv C_{\delta g\delta g}$ in the notation of Eqs. (5), and where the order of the Bessel function is given by $n = 0$ for $\xi^+, w$, $n = 2$ for $\gamma_t$, and $n = 4$ for $\xi^-$. We calculate the covariance of the angular power spectra $\text{Cov}(C_{ij}(\theta), C_{km}(\theta'))$ as the sum on Gaussian $\text{Cov}_G$ and non-Gaussian covariance $\text{Cov}_{NG}$, which includes super-sample variance [73], as detailed in Krause and Eifler [21], using the halo model to compute the higher-order matter correlation functions.

Equation 15 gives the covariance of two-point functions at angles $\theta$ and $\theta'$, and does not account for the finite width of angular bins. In practice, the covariance of two-point functions in angular bins is often evaluated at representative angles for each bin, assuming that the covariance varies only slowly across angular bins (called the narrow-bin approximation). The harmonic transform of the Gaussian contribution in Eq. (15) reduces to a single integral as different harmonic modes are uncorrelated in the Gaussian covariance approximation. In the evaluation of the Gaussian covariance we split off the pure white noise terms and transform these terms analytically [68].

B. Covariance Validation

Most analytic models for the covariance of two-point functions in configuration space are assume the narrow-bin approximation, and that the maximum angular scales are much smaller than the survey diameter [e.g. 67, 74, 75]. In the context of harmonic space correlation...
DES Y1 3x2 analysis highlights

A total of $\sim26$ parameters:
(6 cosmological, $\sim20$ astrophysical/systematic)

and a fanatical devotion to controlling the systematic errors:

Two independent pipelines for everything

1. Two shear measuring/calibration pipelines
2. Two redshift-distribution algorithms
3. Two data-vector (theory) codes
4. Two parameter sampling codes

and

All cosmology results are blinded
Systematic tests ("validation") are time-consuming but necessary.

"Prior-volume" effect!
DES Y1 Measurements:
shear clustering, galaxy-galaxy lensing, gal clustering

Shear clustering:

\[ \theta \xi_+ (10^{-4} \text{ arcmin}) \]

\[ \theta (\text{arcmin}) \]

DES Y1 fiducial
- best-fit model
- scale cuts
Shear-galaxy correlations
(“galaxy-galaxy lensing”)

DES Y1 fiducial
best-fit model
scale cuts

Galaxy clustering
DES Y1 3x2 results: $\Omega_m$-$S_8$ plane

Bayes factor (in 26D space):

$$R = \frac{P(\bar{D}_1, \bar{D}_2|M)}{P(\bar{D}_1|M) P(\bar{D}_2|M)} = 6.6$$

"substantial" agreement (DES,Planck)

\[
\begin{align*}
\Omega_m &= 0.267^{+0.030}_{-0.017} \\
S_8 &= 0.773^{+0.026}_{-0.020}
\end{align*}
\]

DES collaboration, arXiv:1708.01530
DES-only Y1 constraints on DE

“This is the first time a low-redshift survey has been capable of independently constraining these properties of dark energy to this level of precision”

DES collaboration,
arXiv:1811.02375
PRL 2019
DES Year1 results:
extensions to $\Lambda$CDM, incl. modified gravity

$1+\mu \sim \Psi$

$1+\Sigma \sim \Phi+\Psi$

CMB+BAO+SN+RSD

DES collaboration, arXiv:1810.02499;
PRD Editor’s suggestion
What if gravity deviates from GR?

For example:

\[ H^2 - F(H) = \frac{8\pi G}{3} \rho, \quad \text{or} \quad H^2 = \frac{8\pi G}{3} \left( \rho + \frac{3F(H)}{8\pi G} \right) \]

\[ \ddot{\delta} + 2H \dot{\delta} - 4\pi \rho M \delta = 0 \]

\[ \Rightarrow \text{measure geometry } [D(z), \text{Vol}(z)] \text{ and growth } [P_k(z)] \]

Modified gravity

Dark energy

Notice: there is no way to distinguish these two possibilities just by measuring expansion rate \( H(z) \)!

Growth of structure comes to the rescue: in standard GR, \( H(z) \) determines distances and growth of structure.
# Sensitivity to geometry and growth

<table>
<thead>
<tr>
<th>Cosmological Probe</th>
<th>Geometry</th>
<th>Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN Ia</td>
<td>$H_0 D_L(z)$</td>
<td>—</td>
</tr>
<tr>
<td>BAO</td>
<td>$\left(\frac{D_A^2(z)}{H(z)}\right)^{1/3}/r_s(z_d)$</td>
<td>—</td>
</tr>
<tr>
<td>CMB peak loc.</td>
<td>$R \propto \sqrt{\Omega_m H_0^2} D_A(z_*)$</td>
<td>—</td>
</tr>
<tr>
<td>Cluster counts</td>
<td>$\frac{dV}{dz}$</td>
<td>$\frac{dn}{dM}$</td>
</tr>
<tr>
<td>Weak lens 2pt</td>
<td>$\frac{r^2(z)}{H(z)} W_i(z) W_j(z)$</td>
<td>$P \left(k = \frac{\ell}{r(z)}\right)$</td>
</tr>
<tr>
<td>RSD</td>
<td>$F(z) \propto D_A(z) H(z)$</td>
<td>$f(z) \sigma_8(z)$</td>
</tr>
</tbody>
</table>

Ruiz & Huterer, 2015
Specifically: compare geometry and growth in order to stress-test the LCDM model and see if it “breaks”

Our approach:
Double the standard DE parameter space \((\Omega_M=1-\Omega_{DE} \text{ and } w)\):

\[ \Rightarrow \Omega_{M\text{geom}}, w_{\text{geom}} \Omega_{M\text{grow}}, w_{\text{grow}} \]

[In addition to other, usual parameters]

Geometry-growth tests with DES Y1

Split $\Omega_m$

- DES Y1 all
- Ext all
- DES + ext all
- $\Lambda$CDM

DES can break the growth-neutrino degeneracy...

...and get interesting constraints in geom-grow plane

Geometry-growth tests with DES Y1

\[ \Omega^\text{grow}_m - \Omega^\text{geo}_m \]

Split \( \Omega_m \)
- DES Y1 all
- DES + ext geo
- DES + ext all

Jessie Muir (Stanford)

Muir et al (DES collab.),
arXiv:2010.05935
How do you measure (N-dim) tensions?

In 1D it’s easy, but in ≥2D, ambiguous how to estimate

Lemos, Raveri et al (DES collab.), in prep (arXiv in ~2 weeks)
How do you measure (N-dim) tensions?

Principal result: tension metrics (roughly) agree

Lemos, Raveri et al (DES collab.), in prep (arXiv in ~2 weeks)
How do you measure (N-dim) tensions?

DES Y1 cosmic shear vs Planck 18
DES Y1 3x2 vs Planck 18
DES Y1 5x2 vs Planck 18

2-ish sigma tension

Lemos, Raveri et al (DES collab.), in prep (arXiv in ~2 weeks)
Harmonic vs real space analysis
- same information??

Doux et al (DES collab.),
arXiv.2011.06469
Systematics cleaning (of LSS maps)

- **Map contamination: a key systematic in LSS**
- due to variety of observ/astro/instrumental reasons
- visible “by eye” at large scales
- important for all galaxy-clustering, shear etc
- esp important for large-spatial-scale science ($f_{NL}$)
- multiplicative, so small scales affected too

![Systematics templates](image)

Leistedt & Peiris 2015
Systematics cleaning (of LSS maps)

Noah Weaverdyck
(U. Michigan)

Overfitting
Underfitting

Y1
EN
FS
MP
MP (add)
TS (add)

Uncleaned

\[
\text{Loss} = \frac{1}{2N_{\text{pix}}} \left| d_{\text{obs}} - \sum_{i} t_i \alpha_i \right|^2 + \lambda_1 \left( \sum_{i} |\alpha_i| \right) + \frac{\lambda_2}{2} \left( \sum_{i} |\alpha_i^\dagger \alpha_i| \right)^2,
\]

Least Squares Loss
Prefer fewer templates
Shrink imprecise estimates

\(\Delta \chi^2 = 1\)

Story so far:

- Cosmology definitely in the precision regime
- Impressive constraints on DM, DE and inflation...
- ...but some big questions unanswered
- Lots of potential from upcoming surveys

But are Planck++ constraints so good that they bias us?

Danger of declaring currently favored model to be the truth

⇒ blinding new data is key
Blinding the DES analysis

Our requirements:

- Preserve inter-consistency of cosmological probes
- Preserve ability to test for systematic errors

Our choice is specifically:

\[ \xi^{\text{blinded}}_{ij} = \xi_{ij}^{\text{measured}} + [\xi_{ij}^{\text{th model 1}} - \xi_{ij}^{\text{th model 2}}] \]

Applied to DES Y3!

Muir, Bernstein, Huterer, et al., arXiv:1911.05929
Blinding a multi-probe analysis
(synthetic test shown)
DES Y3 key paper: cosmological results

• Almost 5000 sqdeg
• ~100 million source galaxies for lensing
• Improved methodology across board
• Analysis was 3 years in the making
• Results unblinded, out in ~few weeks
Conclusions

• Dark Energy is a premier mystery in physics/cosmology; physical reason for accelerating universe still an open question

• Impressive variety of new data; new telescopes planned

• Like particle physicists, we would really like to see some “bumps” in the data (e.g. Hubble tension!).

• Forthcoming DES Y3 results will dramatically improve constraints from photometric LSS, may hold surprises
Extra slides
Prior-volume effect illustrated
**DES Y1 3x2 results: constraints on $w$**

- **Planck No Lensing**
- **DES-Y1**
- **DES-Y1+Planck**

**DES+Planck:**

$$w = -1.47^{+0.31}_{-0.22}$$

**DES+Planck+SN+BAO:**

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

**DES collaboration, arXiv:1708.01530**