Dark Energy

Daniel Gruen, NASA Einstein Fellow at SLAC/KIPAC

APS DPF Meeting, Fermilab, Aug 3 2017
Dark Energy Survey Year 1 Results: Cosmological Constraints

Daniel Gruen, NASA Einstein Fellow at SLAC/KIPAC
on behalf of the DES Collaboration

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Structure of this talk

• Dark Energy
  – Introduction
    • How to observe Dark Energy
    • How to explain Dark Energy
  – Recent results
    • geometry of expanding universe vs. growth of structure
    • early universe vs. late-time universe
• Cosmological Constraints from DES
What goes up must come down?

- on large scales, Universe described as homogenous fluid in expanding space

\[
\left( \frac{\dot{a}}{a} \right)^2 = \Omega_{m,0} a^{-3} + \text{radiation} + \text{relativistic species} + \text{curvature}
\]

scale factor of Universe
mean matter density
What goes up keeps getting faster!

- on large scales, Universe described as homogenous fluid in expanding space

\[ \left( \frac{\dot{a}}{a} \right)^2 = \Omega_m,0 a^{-3} + \Omega_\Lambda \]

- constant vacuum energy density
What goes up keeps getting faster!

• on large scales, Universe described as homogenous fluid in expanding space

\[
\left( \frac{\dot{a}}{a} \right)^2 = \Omega_{m,0} a^{-3} + \Omega_{\Lambda}
\]

4 additional parameters:

- \( \sigma_8 / S_8 \): amplitude of density fluctuations
- \( m_\nu / \Omega_\nu \): mass/density of neutrinos
- \( h / H / \left( \frac{\dot{a}}{a} \right) \): rate of expansion today
- \( n_s \): scale dependence of early density fluctuations

\( \Omega_m = 0.3, \sigma_8 = 0.8 \) “fiducial \( \Lambda \)CDM”
This is a remarkably odd model

- 70% of energy content of Universe is an unknown substance that appears like vacuum energy, but 120 orders of magnitude smaller than QFT prediction
- 80% of matter is an unknown matter-like substance that does only interacts via gravitation
- We have a wide range of independent observations that cannot be explained without these assumptions
This is a remarkably odd model, but alternatives are even odder

**Lovelock (1969) theorem:**

GR + Λ are the only *local, second-order* gravitational field equations that can be derived from a *four-dimensional action* that is constructed *solely from the metric tensor*, and admitting Bianchi identities.

**Theory zoo of:**

- non-local field equations
- higher order field equations f(R)
- higher dimensions: e.g. strings & branes
- new degrees of freedom = substances

Credit: Elisabeth Krause, Tessa Baker
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Need phenomenological tests of the most simple model:

Are data from early Universe and late Universe fit by the same parameters?
Do measurements of cosmic distances and growth of structure agree?
Does the dark energy density change as space expands?
“Equation of state” parameter $w=\frac{\text{pressure}}{\text{density}}$
How to survey Dark Energy

Q: Do all these measurements agree with predictions in the same, fiducial ΛCDM model?
Measurements of expansion history

- Comparison of distance and redshift

  - **Standard ruler:** angle subtended by known scale
    - **CMB:** sound horizon in early Universe (380,000 years)
    - **BAO:** same scale, but expanded at later times (billions of years)

- **Standard candle:** brightness of source with known luminosity
  - **SNe:** luminosity can be determined from duration/color

- These are consistent and very tightly constrain $w=-1$, $\Omega_m$, $\Omega_{DE}$, flatness
Measurement of late-time structure

- redshift space distortions (RSD):
  growth rate consistent with fiducial $\Lambda$CDM
Measurement of late-time structure

✓ RSD

• Galaxy clusters:
  count of clusters as a function of mass and redshift consistent with fiducial $\Lambda$CDM

see also: talks by Antonella Palmese & Huan Lin, Yuanyuan Zhang, Mathew Madhavacheril
Planck CMB temperature
$z=1100$
$\delta$ of $O(10^{-5})$
Dark sky simulation (Skillman, ..., Wechsler+2014)
Visualization: Ralf Koehler (KIPAC)

Dark matter simulation
$z=0$
$\delta >> 1$
Measurement of late-time structure

- RSD
- Galaxy clusters

- cosmic shear:
  recent studies have claimed 2-3σ offset from Planck CMB in $\Omega_m - \sigma_8$

  A non-issue?
  A crack in $\Lambda$CDM?
  A systematic error?
The Dark Energy Survey

- 5000 sq. deg. survey in grizY from Blanco @ CTIO, 10 exposures, 5 years, >400 scientists
- Primary goal: dark energy equation of state
- Probes: Large scale structure, Supernovae, Cluster counts, Gravitational lensing

- Status:
  - SV (150 sq. deg, full depth): most science done, catalogs at http://des.ncsa.illinois.edu
  - Y1 (1500 sq. deg, 40% depth): data processed, results on cosmology today
  - Y3 (5000 sq. deg, 50% depth): data processed, vetting catalogs
  - Y4: data taking finished (70% depth)
Collaborating institutions:
Gravitational lensing

- When light passes massive structures, it feels gravity and its path gets bent.
- This causes shifting, and magnification, and shearing of the galaxy image.

\[
\gamma_t(\theta) = \langle \kappa(\theta') \rangle_{\theta' < \theta} - \kappa(\theta) \\
\kappa = \sum / \left[ \frac{c^2}{4 \pi G} \frac{D_s}{D_d D_{ds}} \right]
\]
RXC J2248.7-4431, z=0.35; DG+2014
DES SV ... to Y1

Weak lensing map of projected matter density, made with 26 million sheared galaxies

$\kappa_E; 0.2 < z < 1.3$

Chang et al. (released today)
With great statistical power comes great systematic responsibility

Unprecedented size and depth of photometric data

Two independent shape & photo-z catalogs and calibrations

Full, validated treatment of covariance and nuisance parameters (including $\nu$)

Theory and simulation tested, blind, analysis with two independent codes, CosmoLike and CosmoSIS

Drlica-Wagner, Rykoff, Sevilla+ released today

Zuntz, Sheldon+; Samuroff+; Hoyle, Gruen+ released today; Davis+, Gatti, Vielzeuf+, Cawthon+ in prep.

Krause, Eifler+2017; MacCrann, DeRose+ in prep
Measurements: cosmic shear

Troxel+ released today

• Light from **distant galaxies** passes the same foreground structure

Credit: S. Colombi / IAP
Measurements: cosmic shear

**Troxel+ released today**

- Light from distant galaxies passes the same foreground structure
- We measure their shapes

35 million shapes in primary catalog with metacalibration (Sheldon+2017; Huff+2017) with multiplicative bias $|m|$ below 1.3% (68% C.L.)

Independent im3shape (Zuntz+2013) catalog, calibrated with image simulations (Samuroff+ released today)

Suite of detailed tests: Zuntz, Sheldon+ released today
Measurements: cosmic shear

Troxel+ released today

- Light from distant galaxies passes the same foreground structure
- We measure their shapes
- We measure the correlation of shapes of galaxy pairs
Measurements: cosmic shear

Troxel+ released today

- Light from distant galaxies passes the same foreground structure
- We measure their shapes
- We measure the correlation of shapes of galaxy pairs
- Using photometric redshifts, we do this tomographically

Redshift distributions $n(z)$ measured with independent methods
[BPZ, Benitez+2000; DNF, de Vicente+2016; COSMOS, Laigle+2016]

Bias in redshifts independently calibrated with COSMOS photometry and cross-correlations with LRGs (WZ).
Hoyle, Gruen+ released today; Cawthon+, Davis+, Gatti, Vielzeuf+ in preparation
Measurements: cosmic shear

Troxel+ released today

- Light from distant galaxies passes the same foreground structure
- We measure their shapes
- We measure the correlation of shapes of galaxy pairs
- Using photometric redshifts, we do this tomographically
- We constrain cosmological parameters – blindly first, before we pass all tests

most precise cosmic shear experiment to date!
combination of these three two-point functions maximizes use of information and jointly and robustly constrains nuisance parameters


largest individual data sets and joint constraints from these three probes for the first time: DES Collaboration+ released today
Measurements: galaxy clustering and galaxy-galaxy lensing
Elvin-Poole+; Prat, Sanchez+ released today

- Lens galaxies: redMaGiC LRGs with high-quality photometric redshift estimates (Rozo, Rykoff+2016)
Consistency of the individual constraints in $\Lambda$CDM

- Cosmic shear and redMaGiC clustering + lensing yield consistent cosmological constraints
- Criterion: Bayes Factor
  \[
  R = \frac{P(D_1, D_2|M)}{P(D_1|M)P(D_2|M)} = 2.8 > 0.1
  \]
- passing 11 other null tests, we unblind
Key result: Consistency of late Universe with Planck in $\Lambda$CDM

- DES and Planck constrain matter density and $S_8$ with equal strength
- Difference in central values 1-2$\sigma$ in the same direction as earlier lensing results
- Bayes Factor 4.2 – no evidence for inconsistency
Key result: Consistency of late Universe with Planck in ΛCDM

- DES and Planck constrain matter density and $S_8$ with equal strength.
- Difference in central values 1-2σ in the same direction as earlier lensing results.
- Bayes Factor 4.2 – no evidence for inconsistency.
- Still consistent (R=9.0) for joint low-z results + Planck, which is why we combine...
Planck No Lensing

DES Y1

DES Y1+Planck No Lensing

DES Y1+Planck+BAO+JLA

\[ \Omega_m = 0.301^{+0.006}_{-0.008} \]

\[ S_8 = 0.799^{+0.014}_{-0.009} \]

\[ w = -1.00^{+0.04}_{-0.05} \]
Key result: DES + geometry + CMB yields consistent, tightest constraints

- consistent constraints from geometric probes + DES (R=244)
- most precise measurements in $\Lambda$CDM:
  \[
  \Omega_m = 0.301^{+0.006}_{-0.008} \\
  S_8 = 0.799^{+0.014}_{-0.009}
  \]
- no evidence for $w \neq -1$ in any combination
  \[
  w = -1.00^{+0.04}_{-0.05}
  \]
Steps forward: more precise tests of broader range of models

- This is a precise test of $\Lambda$CDM, and it shows any potential discrepancies are smaller than its uncertainty.
- It does not explain $\Lambda$CDM.
- It is not very sensitive to models with time-varying Dark Energy equation of state (among others).
- Future joint analyses will be!

Credit: T. Eifler, E. Krause, J. Frieman
Summary

- Wide range of probes from early & late Universe, geometry & structure, agree on fiducial ΛCDM cosmology
- DES has added the most precise measurement of structure in the evolved Universe
  - Competetiveness and consistency with Planck CMB in ΛCDM, insignificant offset in the direction of other lensing studies
  - Precise joint measurements close to $\Omega_m=0.30$, $\sigma_8=0.80$, $w=-1.0$
  - Papers released now on http://www.darkenergysurvey.org/
  - DES Collaborators in the audience happy to discuss later!
- Need even more precise & different model tests to understand Dark Energy – work in progress!