Cosmology with the Dark Energy Survey

Proposal:
- Perform a 5000 sq deg imaging survey of the Southern Galactic Cap
- Obtain 2% global photometry in griz via multiple tilings of the survey area
- Constrain the Dark Energy parameter w to ~5% with 4 complementary techniques.
- Begin to constrain dw/dz

New Equipment:
- Replace the PF cage on the CTIO Blanco with a 2.2 deg FOV optical CCD camera
- Construct instrument 2005-2009

Survey:
- 30% of the telescope time (525 nights) from 2009-2014
The DES Instrument

- 5-element optical corrector
- 4 filters: $g,r,i,z$
- 2k x 4k LBNL CCDs
- 0.27"/pixel
- 62 CCD, 520 Megapixel mosaic camera
- 3 deg$^2$ field of view

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Four Probes of Dark Energy

- **Galaxy Cluster counting**
  - 20,000 clusters to z=1 with $M > 2 \times 10^{14} M_{\text{sun}}$

- **Weak lensing**
  - 300 million galaxies with shape measurements over 5000 sq deg

- **Spatial clustering of galaxies**
  - 300 million galaxies to z = 1 and beyond

- **Standard Candles**
  - 2000 SNe Ia, z = 0.3-0.8

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**DES: Vital Statistics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanco Effective Aperture/ f number @ prime focus</td>
<td>4 m/ 2.7</td>
</tr>
<tr>
<td>Blanco Primary Mirror - 80% encircled energy</td>
<td>0.25 arcsec</td>
</tr>
<tr>
<td>Optical Corrector Field of View</td>
<td>2.2 deg</td>
</tr>
<tr>
<td>Wavelength Sensitivity</td>
<td>400-1100 nm</td>
</tr>
<tr>
<td>Filters</td>
<td>SDSS g, r, i, z</td>
</tr>
<tr>
<td>Effective Area of CCD Focal Plane</td>
<td>3.0 sq. deg.</td>
</tr>
<tr>
<td>Image CCD pixel format/ total # pixels</td>
<td>2k X 4k/ 519 Mpix</td>
</tr>
<tr>
<td>Guide, Focus &amp; Wavefront Sensor CCD pixel format</td>
<td>2k X 2k</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>0.27 arcsec/ 15 μm</td>
</tr>
<tr>
<td>Readout Speed/Noise goal</td>
<td>250 kpix/sec/ 5 e</td>
</tr>
<tr>
<td>DECam Corrector (Reference Design)</td>
<td></td>
</tr>
<tr>
<td>80% encircled energy (center/edge)</td>
<td></td>
</tr>
<tr>
<td>g (0.32/0.59 arcsec)</td>
<td></td>
</tr>
<tr>
<td>r (0.11/0.37 arcsec)</td>
<td></td>
</tr>
<tr>
<td>i (0.17/0.41 arcsec)</td>
<td></td>
</tr>
<tr>
<td>z (0.31/0.47 arcsec)</td>
<td></td>
</tr>
<tr>
<td>Survey Area</td>
<td>5,000 sq. deg.</td>
</tr>
<tr>
<td>Survey Time/Duration</td>
<td>525/5 (nights/years)</td>
</tr>
<tr>
<td>Median Site Seeing Sept. – Feb.</td>
<td>0.65 arcsec</td>
</tr>
<tr>
<td>Median Delivered Seeing with Mosaic II on the Blanco</td>
<td>0.9-1.0 arcsec (V band)</td>
</tr>
<tr>
<td>Limiting Magnitude: 10σ in 1.5” aperture assuming 0.9” seeing, AB system</td>
<td>g=24.6, r=24.1, i=24.3, z=23.9</td>
</tr>
<tr>
<td>Limiting Magnitude: 5σ for point sources assuming 0.9” seeing , AB system</td>
<td>g=26.1, r=25.6, i=25.8, z=25.4</td>
</tr>
</tbody>
</table>

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Cluster Abundances

\[
\frac{d^2 N}{dzd\Omega}(z) = \frac{d^2 V}{dzd\Omega}(z)n_{\text{com}}(z) = \frac{c}{H(z)} D_A^2 (1+z)^2 \int_0^\infty dM f(M, z) \frac{dn}{dM}(z)
\]

Volume  Selection  Abundance

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Cluster Masses

The cluster redshift distribution and selection function depends on the cluster masses

- Independent estimators of cluster mass:
  - Count Galaxies (or luminosity) in a cluster
  - Velocity dispersions
  - Weak Lensing
  - Strong Lensing
  - The ICM:
    - X-ray Temperature of the gas
    - Sunyaev-Zeldovich (SZ) luminosity
Synergy with the South Pole Telescope

The South Pole Telescope
- John Carlstrom (PI)
- 8m submm telescope
- 150 & ~250 GHz
- 1000 element bolometer array
- 4000 sq. deg. survey Southern Galactic cap
- measures cluster masses using SZ effect
- funded and in construction – expect first data in 2006

Credit: L. Van Speybroek
Sunyaev & Zeldovich (1980)
Finding Clusters with the SZE

Pros:
- can identify galaxy clusters nearly independent of redshift

Credit: Carlstrom et al. (2002)

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Finding Clusters with the SZE

Pros:
- can identify galaxy clusters nearly independent of redshift

Cons:
- can identify galaxy clusters nearly independent of redshift

Credit: Carlstrom et al. (2002)
DES: Galaxy Cluster Redshifts

- four filters (griz) track 4000 Å break
- need z band filter to get out to redshift > ~1
- DES data will enable cluster photometric redshifts with dz~0.02 for >10,000 clusters out to z~1
  (e.g., Red-Sequence--Gladders and Yee)

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Issues and Statistical Challenges: Clusters

- Cluster Selection
  - Great effort has recently gone into carefully analyzing optical cluster selection functions (Miller et al. 2005; Kim et al. 2002, Annis et al. 2001).
  - SZE Selection less well-understood (AGN, bright star-bursts, etc (White et al. 2004). SZA pre-cursor data will help.

- Cluster Redshifts
  - Photo-z techniques for clusters utilize the red-sequence, a stable and reasonably well understood galaxy population to z~1.

- Cluster Masses
  - SZE Integrated Flux Decrement provides a clean mass estimate (10%). SZA pre-cursor helps.
  - Optical Observable-to-Mass Scaling Relations are good not as good (20-40% uncertainties compared to 10-20% in SZE).
  - Weak Lensing (see J. Frieman’s talk)
Galaxy Angular Power Spectrum

- DES main survey will yield photo-z’s on approximately 300 million galaxies extending beyond a redshift z~1
- We can study the angular clustering within redshift bins to z~1
- Theory predicts how the shape of the angular power depends on redshift
- Peak of the angular power spectrum represents a standard rod
- Location of the peak is a measure of the angular diameter distance to each redshift shell (i.e. Cooray et al 2001).

\[
C^{i}_{gal}(l) = \int_{0}^{\infty} k^2 dk \frac{2}{\pi} f^2_i(l,k) P_{gal}(k).
\]
Galaxy Photometric Redshifts

Spectroscopic Training Sets: SDSS (70,000 Southern Stripe to r=20); 2dF (90,000 to b_j=19.45); VMOS VLT Deep Survey (60,000 to I_AB=24); DEEP2 (30,000 to R_AB=24.1)
Galaxy Photo-z Simulations

DES + VISTA
griz+YJHKs filters
Photo-zs and their effect on $w$

![Graph showing the effect of photo-z biases on $\sigma_w$.](image)
Issues and Statistical Challenges: Galaxies

• Availability of Precursor data
• Calibration Issues
  – Survey strategy
  – sub-samples
• Biasing (Scale dependent bias >100Mpc scales?)
  – Separate by types
  – Bi-spectrum
• Photo-z biases
  – A bias in the redshift-distance relation
  – Test vs. type, color, magnitude, redshift, and so on
• Photo-z uncertainties
  – Statistical techniques (polynomial fitting (Connolly et al.); neural networks (Collister and Lahav et al.); templates (Bozonella et al.)

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Weak Lensing

Measure shapes for ~300 million source galaxies with \( \langle z \rangle = 0.7 \)

Direct measure of the distribution of mass in the universe, as opposed to the distribution of light, as in other methods (e.g. Galaxy surveys)

Independently calibrates SZ cluster masses
Issues and Statistical Challenges: Lensing

• **Shape-measurement errors**
  – Multiplicative errors (calibration)
    • Know your system
    • Bernstein and Jarvis (2004)
  – Additive errors in the shear are minimal (anistotropies in the PSF)
    • Jarvis et al. (2005) 75 sq deg Weak Lensing Survey on the CTIO 4m
    • Jarvis and Jain (2004)

• **Small-scale power spectrum**
  – hi-res simulations w/baryons
  – Null the small-scale power (Huterer et al. 2005)
DES Supernovae

- Repeat observations of 40 deg$^2$, 10% of survey time
- ~1900 well-measured riz SN Ia lightcurves, 0.25 < z < 0.75
- Larger sample, improved z-band response compared to ESSENCE, CFHTLS;
- Combination of spectroscopic (~25%) and photometric redshifts
- Develop & test color typing and SN photo-z’s (needed for LSST)
- In-situ photometric response measurements (Stubbs laser system)

SN constraints ‘orthogonal’ to the other methods

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Issues and Statistical Challenges: SNe

- Evolution
- Extinction
- Photometric Calibration
  - New calibration system for the 4m (Essence project--Stubbs et al.)
- Redshifts or Photo-z’s
  - Overlap area with VLT deep spectroscopic surveys (20%)
  - host photo-zs (80%)
  - Light-curve photo-zs
Conclusions

Currently: $\sigma(w) \sim 0.15$, $w < -0.76$ (95%) (CMB+LSS+SNe; ~0.3 alone)


<table>
<thead>
<tr>
<th>Method/Prior</th>
<th>Uniform</th>
<th>WMAP</th>
<th>Planck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clusters:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>abundance</td>
<td>0.13</td>
<td>0.10</td>
<td>0.04</td>
</tr>
<tr>
<td>w/ WL mass calibration</td>
<td>0.09</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>Weak Lensing:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear-shear (S-S)</td>
<td>0.15</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Galaxy-shear(G-S)+G-G</td>
<td>0.08</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>S-S+G-S+G-G</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>S-S+bispectrum</td>
<td>0.07</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Galaxy angular clustering</td>
<td>0.36</td>
<td>0.20</td>
<td>0.11</td>
</tr>
<tr>
<td>Supernovae Ia</td>
<td>0.34</td>
<td>0.15</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Epilogue

Mentioned only Dark Energy...

... but the DES is very similar to the SDSS imaging survey (
\textit{griz} vs. \textit{ugriz})...

... but deeper! \((r \text{ to } 24 \text{ instead of } r \text{ to } 22)\)

Like with SDSS, can do:

— Quasars
— Galaxy environments
— Superclusters
— Stellar streams associated with Milky Way
— ...

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Improvements to the Instruments

- Fix the small but detectable coma produced by movement of the prime wrt to the cage
- Primary mirror ring supports
- Study and control cage/primary relative motions and implement wavefront sensing
- Reduce thermal sources
- Replace TCS
- New prime-focus corrector
- Add focus chips
Probing Dark Energy

- Expansion rate of the universe:
  \[ H^2(z) = H_0^2 \left[ \Omega_M (1+z)^3 + \Omega_{DE} (1+z)^{3(1+w)} \right] \]
  (flat Universe, const. \( w \),
  dark matter        dark energy
  \( w = -1: \) cosm. const.)

- rate of growth of structure
  - mass, number and spatial distribution of galaxies as a function of \( z \)

- The EOS parameter,  \( w = p/\rho \), describes the evolution
  of the density of dark energy with redshift.

- Current Status: \( \sigma(w) \sim 0.15^* \),  \( w < -0.76 \) (95%)

* CMB+LSS+SNe; no
  single dataset constrains
  \( w \) better than \( \sim 30\% \)
CCDs

- LBNL
- 2x4k, 15 micron pixels
- Molybdenum foot; Aluminum Nitride board;
**SPT Survey Predictions**

**Constraints:** In our calculations of the constraints on dark energy from SPT+DES, we assume the SPT survey has a $\theta_{\text{FWHM}} = 1'$ beam, one channel at 150 GHz, and a 1.9 mJy (5σ) detection threshold over 4000 deg$^2$. We include the effects of clusters larger than 1' by degrading the beam size, up to a maximum of 5' (Battye and Weller 2003). Using a standard $\beta=2/3$ gas density profile with a central overdensity factor of 10 and a maximum redshift $z_{\text{max}} = 1.5$ results in ~12,000 SPT clusters. The predicted SZE cluster mass limit and cluster abundance as a function of redshift is shown in Figure 2.1 for the fiducial cosmology.

![Graph](image)

Figure 2.1. The predicted SZE 5σ cluster mass limit and abundance above that limit as a function of redshift for the SPT+DES survey for the fiducial cosmology used in the White Paper.

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