Dark Energy Survey

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(thanks to Chris D’Andrea, Andreas Papadopoulos and DES collaboration)

Brazil Webinar March 2015
DISCOVERY OF COSMIC ACCELERATION

Type Ia supernovae that exploded when the Universe was 2/3 its present size are ~25% fainter than expected

(Ω_M, Ω_Λ)
(0.3, 0.7)
(0.3, 0.0)
(1.0, 0.0)

2011 Nobel Prize in Physics
Riess et al. (1998, AJ)

SUPERNova IA HubBLE Diagram

Riess et al. (1998)

Distance modulus $\mu$ (log distance)

Calán/Tololo

HZT

33 SNe

figures by A. Conley
SUPERNova IA Hubble Diagram

Perlmutter et al. (1999)

Distance modulus \( \mu \) (log distance)

Z

52 SNe

SCP

Calán/Tololo
JLA Collaboration

Distance modulus $\mu$ (log distance)

Betoule et al. (2014)

740 SNe

 Supernova Ia Hubble Diagram
Progress over the past 15 years

Supernovae

Cosmic Microwave Background (Planck, WMAP)

CMB+BAO

Here assuming $w = -1$

Betoule et al. 2014
**Cosmological Dynamics**

\[
\frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \sum_i \rho_i (1 + 3w_i)
\]

Friedmann Equation from GR

Equation of state parameter: \( w_i = \frac{p_i}{\rho_i c^2} \)

- Non-relativistic matter: \( p_m \sim \rho_m v^2 \), \( w \approx 0 \)
- Relativistic particles: \( p_r = \rho_r c^2 / 3 \), \( w = 1 / 3 \)

Acceleration (\( \ddot{a} > 0 \)) requires component with negative pressure:

- Dark Energy: \( w_{DE} < -1 / 3 \)
- Cosmological Constant: \( w_\Lambda = -1 \)

or Replace GR dynamics with another gravity theory
**Current Dark Energy Constraints**

Supernovae, CMB, and Large-Scale Structure

Assuming constant $w$

Assuming $w = w_0 + w_a (1-a)$

Consistent with vacuum energy ($\Lambda$): $w_0 = -1$, $w_a = 0$

Betoule et. al (2014)
Origins of the Dark Energy Survey

- Late 2003: NOAO Announcement of Opportunity for new facility instrument on the Blanco 4-meter telescope
  - Cerro Tololo Inter-American Observatory
  - Good seeing: ~0.75" median for site
  - High percentage of clear, photometric nights
- DES collaboration formed to build Dark Energy Camera and carry out Dark Energy Survey
THE DARK ENERGY SURVEY

• Probe Dark Energy and the origin of Cosmic Acceleration
  ✦ Distance vs. redshift
  ✦ Growth of Structure

• Two multicolor surveys:
  ✦ 300 M galaxies over 1/8 sky
  ✦ 3500 supernovae (30 deg²)

• Built new camera for CTIO Blanco telescope
  ✦ Facility instrument

• Five-year Survey
  ✦ 525 nights (Aug - Feb)
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

Spain Consortium: CIEMAT, IEEC, IFAE

Brazil Consortium

CTIO

~300 scientists
The Dark Energy Camera

570 Million Pixels
DECam CCDS

- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.264”) pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels
DECam CCDs

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DES filters

Asahi-Measured Transmission Curves for Delivered 100mm x 100mm DES grizy Filters

DECam / Mosaic II QE comparison

Transmission (%)

Wavelength (nm)

QE, LBNL (%)
QE, SITe (%)
Optical Corrector Lenses

- Field of view: 2.2 deg diameter
- Good image quality across FOV
- Optical elements aligned at UCL
Four Probes of Dark Energy:

- **Galaxy Clusters**
  - Tens of thousands of clusters to $z \sim 1$
  - Synergy with SPT, VHS

- **Weak Lensing**
  - Shape and magnification measurements of 200 million galaxies

- **Baryon Acoustic Oscillations**
  - 300 million galaxies to $z = 1$ and beyond

- **Supernovae**
  - 30 sq deg time-domain survey
  - 3500 well-sampled SNe Ia to $z \sim 1$

Forecast Constraints on DE Equation of State

$$w(a) = w_0 + w_a (1 - a(t))$$

Focus here on supernovae (expansion history)
Four Probes of Dark Energy:

- **Galaxy Clusters**
  - Tens of thousands of clusters to $z \sim 1$
  - Synergy with SPT, VHS
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- **Baryon Acoustic Oscillations**
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Focus here on supernovae (expansion history)
• **Wide Survey:** 5000 sq deg
  10x90s in griz; 10x45 s in Y
• Redder (bluer) bands in bright (dark) time
• Multiple overlapping exposures for photometric calibration ("ubercal")
• **Supernova Survey:** 10 fields
  ~5 day cadence
  (8) shallow: 175/150/200/400s
  (2) deep: 600/1200/1800/3600s
• Wide/SN trigger based on seeing and SN gaps
• Overlap with SPT, OzDES, VHS, SDSS, eBOSS, ACT, …
• Footprint overhead Aug – Feb
• DES members do all observing
Science Verification (SV): ~250 sq. deg. to ~full depth; 45 M objects
Year 1 (Y1): ~2000 sq. deg; overlap SPT, SDSS: 4/10 tilings; 140 M objects
DES Delivered Image Quality

PSF FWHM for r,i,z band wide field images

Median IQ = 0.91

DES Science Requirement

2013-14 Season through mid-Dec

Image Quality [arcsec]
DES Y1

~6 day average cadence
All DES results in this talk are (mostly) PRELIMINARY
Clusters in Science Verification

RXC J2248.7-4431 (z=0.35)

Eric Suchyta, Peter Melchior, + DES-WL
Clusters in Science Verification

RXC J2248.7-4431 (z=0.35)

Eric Suchyta, Peter Melchior, + DES-WL

30 x 20 arcmin
Clusters in Science Verification

RXC J2248.7-4431

(z=0.35)

preliminary mass
map contours:
significance
SN Ia at $z=0.2$ confirmed at AAO

Nov. 7, 2012

Dec. 15, 2012

SUPERNOVAE
Deep field search for SNe Ia
Deep field search for SNe Ia
Deep field search for SNe Ia
Deep field search for SNe Ia
Deep field search for SNe Ia
Deep field search for SNe Ia
Deep field search for SNe Ia
DES Supernova Survey

<table>
<thead>
<tr>
<th>Filter</th>
<th>Shallow Field Exposure Time (s)</th>
<th>Limiting Mag</th>
<th>Deep Field Exposure Time (s)</th>
<th>Limiting Mag</th>
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<td>$g$</td>
<td>175</td>
<td>24.9</td>
<td>600</td>
<td>25.6</td>
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<tr>
<td>$r$</td>
<td>150</td>
<td>24.3</td>
<td>1200</td>
<td>25.4</td>
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<td>$i$</td>
<td>200</td>
<td>23.9</td>
<td>1800</td>
<td>25.1</td>
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<td>$z$</td>
<td>400</td>
<td>23.8</td>
<td>3630</td>
<td>24.8</td>
</tr>
</tbody>
</table>

Pathway to Cosmology

FoM=120

- SN-like transients
- Classification
- Photometry (not today)

“Supernova Simulations and Strategies For the Dark Energy Survey”

Real or Artifact?

Consistently approximate a PSF

Dipoles, Streaks, Ripples, Holes...
Quantifying the Scanning Load

SNWG Scanning Decisions during SV (No ML)

Data rate: $\sim 1.5 \times 10^3$ new scannable candidates / night, after requiring two detections.

False positives: $\sim 85\%$ of scanned detections are artifacts.
Y2 with autoScan

8.2x fewer new candidates created / night with ML.

SNWG Scanning Decisions during Y2 (with ML, Anonymized)

Detection-level purity up by ~25x.

Number of scanners down by factor of 2 from SV in comparable period.
Photometric Classification

Sloan Digital Sky Survey - Supernova II

Photometric Classification
Too many, too faint for spectroscopic followup

Problems: Purity; loss of spectral information
Benefits: Numbers; selection biases

Campbell et al. (2013)
• AAOmega/2dF on AAT: perfect overlap with DECam FoV
• SN Host Galaxies targeted repeatedly to build depth
• Fibers placed on live SNe (r < 21)
• **100 nights over 5 years**

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**DES SV + Y1:** $fitprob_{ia} > 0.0001$, $p_{bayes_{ia}} > 0.9$
- AAOmega/2dF on AAT: perfect overlap with DECam FoV
- SN Host Galaxies targeted repeatedly to build depth
- Fibers placed on live SNe (r < 21)
- 100 nights over 5 years

**R=23.7 z=0.732**
AAOmega/2dF on AAT: perfect overlap with DECam FoV

SN Host Galaxies targeted repeatedly to build depth

Fibers placed on live SNe (r < 21)

100 nights over 5 years

23 nights so far with 15814 targets with 10212 redshifts
The goal is to select targets for spectroscopic follow-up observations such that the final spectroscopic sample provides the maximal improvement to our final cosmological measurements.

1. Spectroscopically complete sample to $z < 0.2$

We are complete to $r = -13.7/14.4$. This will get nearly every SN. But will result in ~140 SNe Ia and 210 CC SNe over the full survey... this is a lot of follow-up

2. Magnitude-limited sample for $r_{\text{peak}} < 21$

Will guarantee getting all low-$z$ SNe and will reduce bias. Overlaps with #1.

3. Representative “flat” sample for systematics

Randomly selected, weighted by Ia and z probability

Ryan Foley
Other telescopes for live transients (2014)

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Time (2014-15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLT (Sullivan)</td>
<td>7 nights</td>
</tr>
<tr>
<td>GTC (Castander)</td>
<td>13hrs (ToO)</td>
</tr>
<tr>
<td>MMT/Magellan (Kirshner)</td>
<td>9.5 nights</td>
</tr>
<tr>
<td>Keck (Nugent)</td>
<td>5.5 nights + 8hrs ToO</td>
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<tr>
<td>Magellan (Kessler)</td>
<td>0.5 nights</td>
</tr>
<tr>
<td>SALT (Smith)</td>
<td>10.5 hrs</td>
</tr>
</tbody>
</table>
LOW-z SALT FITS (SHALLOW)
LOW-z SALT (DEEP)
HIGH-Z SALT FITS (DEEP)
Inverse Hubble Diagram

\[ \frac{c \ln(1+z)}{D_m} \text{ [km s}^{-1}\text{ Mpc}^{-1}] \]

- BAO
- SN
- \( H_0 = 67.3 \pm 1.1 \)

Aubourg et al. 2015
Superluminous SNe (SLSNe)

Superluminous:
- $M_{\text{absolute}} < -21$
- ~50 times brighter

Light-curves:
- 100s of days
- long rise/fall timescales

Rare events:
- ~50 discovered up to date
- 0.01% of SNe Ia rates
  - local Universe
  - *15 increase @ $z>1$
  - SNLS, Cooke et al. 2012

High-z:
- SN 1000+0216 @ $z=3.9$, Cooke et al. 2012
DES13S2cmm - DES Y1

Peak Brightness:
• 28-September-2013

SLSNe type-I:
• VLT(ESO) spectrum
• $z = 0.663 \pm 0.003$
• $M_U = -21.0$
• ATeI #5603
DES13S2cmm Vs SNe type Ia

DES13S2cmm:
- VLT
  - $z = 0.663$
  - SLSN-I

DES13C3abht:
- Gemini-South
  - $z = 0.690$
  - type Ia

Observed phase (days)
Understanding SLSNe
DES14X2byo - confirmed

Detection:
- Auto-SNe: 22-Sep
- As SLSNe: 17-Oct

Spectra:
- 17-Oct - GTC - F.Gastander
- 22-Oct - MMT - R.Foley
- 23-Oct - Keck - P.Nugent
- 28-Oct - AAT - OzDES
- MgII 2800 absorption
- Fe II 2600 absorption
- O II 3727 emission
- SLSNe type-I @ z=0.869

Peak Brightness:
- ~29-Oct-2014
- Mr = -22.4 @ z=0.869

ATel#6635
- http://www.astronomerstelegram.org/?read=6635

Andreas.Papadopoulos@port.ac.uk
DES14C1fi

$M_{U,\text{peak}} \sim -22.5$
SURVEY USING DECam FOR SUPERLUMINOUS SUPERNOVAE

Increasing DES observing window helps significantly

24 deg² at ~14 day cadence for ~7 months to twice depth of DES shallow fields
DES + SUDSS will find ~100, improving the DES cosmology by at least 25%. LSST will find 20,000 of these events!
The VIDEO Survey

**VISTA Deep Extragalactic Observations**

(Jarvis et al. 2013)

- 12 deg^2
- (NIR): Z, Y, J, H, K_s
- Visible: ugriz (CFHTLS)
- z_phot < 4.0
- z_phot obtained from LePhare

Y = 24.5, J = 24.4, H = 24.1 and K_s = 23.8
DES & VIDEO Overlap

The VIDEO footprint overlaps with the DES X, C and E fields

Observations will coincide with DES SV, Y1 & Y2

Potential overlap in Y, J, H & K (invaluable for host galaxy prop)

Can we produce NIR light-curves of DES SNe....
• DES has started and is maturing
• First results are coming
• DES SN has found thousands of SNe; hundreds suitable for cosmology
• Control of systematics is vital but in-hand
• Serendipity!
  • DES+VIDEO
  • Superluminous SNe!
DES TIMELINE

- 2003: Project begins
- 2004 – 2008: R&D
- 2008 – 2011: DECam construction
- 2012: Installation
- Sept 2012: First light
- Sept – Oct 2012: Commissioning
- Nov 2012 – Feb 2013: Science verification (SV)
- 31 Aug 2013 – 9 Feb 2014: First season (Year 1)
- 15 Aug 2014: Year 2 begins
- Feb 2018: Nominal end of survey operations