DES Supernova
Cosmology with Gemini

Ryan Foley, Yen-Chen Pan (UCSC)
on behalf of DES-SN
SNe Ia Are Exploding White Dwarfs

White Dwarf in Binary System

Accretes Matter Until ~1.4 times the Mass of the Sun

Explodes and is Very, Very Luminous
Obs: \[ D = \left( \frac{L}{4\pi F} \right)^{1/2} \]
Theory: \[ D = f(z, \Omega, w(z), \text{etc}) \]
SNe Ia are NOT Standard Candles!
Luminous supernovae have slower light curves.

Standard Candle

$\sigma = 0.44$ mag

MLCS

$\sigma = 0.18$ mag!
Accelerating Universe!

Riess et al. 1998

Perlmutter et al. 1999
What is Dark Energy?

Look at Equation of State: \( w = \frac{P}{\rho c^2} \)

Need \( w \leq -1/3 \) for acceleration

\( w = -1 \) for cosmological constant

Several Problems with Cosmological Constant:

1. Simple theory suggests \( \Lambda \) should be much larger

2. Why is \( \Omega_\Lambda \approx \Omega_m \)?

3. Already another period of accelerated expansion without cosmological constant (inflation)
$$w = -1.040 \pm 0.046 \mid w_0 = -0.97 \pm 0.10; w_a = -0.38 \pm 0.45$$
DES is a 5-year survey to probe the dark energy using galaxy clusters, weak lensing, large-scale structure, and type Ia supernovae.
<table>
<thead>
<tr>
<th>wErr (stat+sys)</th>
<th>#SNe</th>
<th>SURVEY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.054</td>
<td>740</td>
<td>JLA-Spec (2014)</td>
</tr>
<tr>
<td>0.040</td>
<td>1049</td>
<td>PANTHEON-Spec (2018)</td>
</tr>
<tr>
<td>0.058</td>
<td>~1000</td>
<td>PS1-Phot (2017)</td>
</tr>
<tr>
<td>?</td>
<td>334</td>
<td>DES3YR-Spec (2018)</td>
</tr>
</tbody>
</table>

**How Does DESSN Stack Up?**

<table>
<thead>
<tr>
<th>Days From Peak Brightness</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20</td>
<td></td>
</tr>
<tr>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
</tr>
</tbody>
</table>

**DESSN**

z = 0.769
DES15C3kue

**Pan-STARRS1 (Scolnic et al. 2018)**

PS1-380040
z = 0.68
The Ingredients for Supernova Cosmology

- **Difference Imaging** → SNe Candidates
- **Spectra** → Type & redshift
- **Photometry** → Light Curves → Distances
- **Calibration** → Relative Distance between all SNe
- **Simulations** → Distance Bias Corrections
- **Systematics** → Covariance Matrix
- **CosmoMC** → wCDM fit with SNeIa + Planck 2015
The Ingredients for Supernova Cosmology

- Difference Imaging → SNe Candidates
- Spectra → Type & redshift
- Photometry → Light Curves → Distances
- Calibration → Rel. Dist. b/w All
- Simulations → Distance Bias Corrections
- Systematics → Covariance Matrix
- Cosmology → wCDM fit w/ binned + Planck 2015

(unblinded December 22nd, 2017)
**Preliminary RESULTS!** (flat wCDM)

<table>
<thead>
<tr>
<th>wErr (stat+sys)</th>
<th>#SNe</th>
<th>SURVEY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.054</td>
<td>740</td>
<td>JLA-Spec (2014)</td>
</tr>
<tr>
<td>0.040</td>
<td>1049</td>
<td>PANTHEON-Spec (2018)</td>
</tr>
<tr>
<td>0.058</td>
<td>~1000</td>
<td>PS1-Phot (2017)</td>
</tr>
<tr>
<td><strong>0.057</strong>*</td>
<td>334</td>
<td>DES3YR-Spec (2018)</td>
</tr>
</tbody>
</table>

*equally STAT and SYS dominated*
Preliminary RESULTS!

$$w = -1.002 \pm 0.057$$

$$\Omega_M = 0.314 \pm 0.017$$
### Where do we go from here?

<table>
<thead>
<tr>
<th>wErr (stat+sys)</th>
<th>#SNe</th>
<th>SURVEY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.054</td>
<td>740</td>
<td>JLA-Spec (2014)</td>
</tr>
<tr>
<td>0.040</td>
<td>1049</td>
<td>PANTHEON-Spec (2018)</td>
</tr>
<tr>
<td>0.058</td>
<td>~1000</td>
<td>PS1-Phot (2017)</td>
</tr>
<tr>
<td>0.057</td>
<td>334</td>
<td>DES3YR-Spec (2018)</td>
</tr>
<tr>
<td>?</td>
<td>~500</td>
<td>DES5YR-Spec (future)</td>
</tr>
<tr>
<td>?</td>
<td>~2000</td>
<td>DES5YR-Phot (future)</td>
</tr>
</tbody>
</table>
**Systematics Dominate**

<table>
<thead>
<tr>
<th>Source</th>
<th>( dw )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Uncertainty</td>
<td>0.072</td>
</tr>
<tr>
<td>Statistical Uncertainty</td>
<td>0.050</td>
</tr>
<tr>
<td>Systematic Uncertainty</td>
<td>0.052</td>
</tr>
<tr>
<td>Photometric calibration</td>
<td>0.045</td>
</tr>
<tr>
<td>SN color model</td>
<td>0.023</td>
</tr>
<tr>
<td>Host galaxy dependence</td>
<td>0.015</td>
</tr>
<tr>
<td>MW extinction</td>
<td>0.013</td>
</tr>
<tr>
<td>Selection Bias</td>
<td>0.012</td>
</tr>
<tr>
<td>Coherent Flows</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Statistical and systematic sources of uncertainty for SN (+CMB+BAO+\(H_0\)) measurements of \(w\) (Scolnic et al., 2014a). The statistical and systematic uncertainties are currently similar in size. We also list the individual major sources of systematic uncertainty (which combine to make the total systematic uncertainty). The largest, by far, individual systematic uncertainty is photometric calibration. The Foundation survey will reduce the calibration uncertainty to the point where it is no longer dominant in the overall error budget.
Dust Makes Things Fainter/Redder

Dust
Dust Makes Things Fainter/Redder

\[ R_V = \frac{A_V}{E(B-V)} \]

\[ \mu = m - M - A_V \]

\[ = m - M - E(B-V) R_V \]
Dust Makes Things Fainter/Redder

\[ A_V = E(B-V) \, R_V \]
Samples of SNe Ia have Low $R_V$

$R_V = \frac{A_V}{E(B-V)}$

Foley & Kasen 2011
Dust Makes Things Fainter/Redder

Dust
Dust Makes Things Fainter/Redder

Different Intrinsic Colors
Optical Spectrum to Measure Velocity

High Velocity

Low Velocity

Silicon
Measuring Silicon Velocity

High Velocity:
~ -13,000 km s^{-1}

Low Velocity:
~ -10,000 km s^{-1}

Wider Lines With Higher Velocity
Samples of SNe Ia have Low $R_V$

$R_V = \frac{A_V}{E(B-V)}$

Foley & Kasen 2011
Intrinsic Color Depends on SN Velocity

\[ R_V = \frac{A_V}{E(B-V)} \]

Foley & Kasen 2011
also Foley 2012; Foley, Sanders, & Kirshner 2011; Mandel, Foley, & Kirshner 2014
Ejecta Velocity is the “Next Parameter”

Velocity Improves Precision by 2.4x and Reduces Bias
Intrinsic Color Depends on SN Velocity

![Graph showing the relationship between Si II velocity and the change in modal A_V estimate. The top panel is a scatter plot with black dots representing individual SN Ia measurements. The bottom panel is a histogram showing the distribution of SN Ia measurements for different change in modal A_V estimates.](image)

Mandel, Foley, & Kirshner 2014
No Velocity Bias in Gemini Sample

Si II Velocity at Maximum (10^3 km s^{-1})

Cumulative Fraction

High z (DES)  Low z
Supernova SED

Flux vs Wavelength

10,000 K Blackbody

Line Blanketing

Absorption Lines
Opacity Depends on Velocity

Ellis et al. 2008
Supernova SED

- Flux
- Wavelength

10,000 K Blackbody
Line Blanketing
Absorption Lines
Supernova SED

- 10,000 K Blackbody
- Line Blanketing
- Absorption Lines