Supernovae & Cosmology

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(SNLS Collaboration)
A lot has been going on...

- Growing photometric samples ($\sim 10^3$ SNe @ 0.05 < z < 1)
  - “Union sample” (Kowalski et al, 2008)
  - “Constitution sample” (CfA3) (Hicken et al, 2009)
  - SDSS-II (Kessler et al 2009)
  - ... and also ESSENCE (Wood-Vasey et al, 2007), HST (Riess et al, 2007), SNLS-1 (Astier et al, 2006), SNLS-3 (in prep)
A lot has been going on ...

- Growing spectroscopic samples
  - SNLS-3 (Balland et al, 2009; Bronder et al, 2008; Howell et al, 2005)
  - ESSENCE-4 years (Foley et al, 2009)
  - CfA low-z sample (Matheson et al, 2009)
  - SNfactory (see E. Gangler’s talk)
- Evolution studies (Foley et al, 2008; Ellis et al, 2008 + SNLS papers)
- Spectroscopic standardization (Bailey et al, 2009)
- + many other papers on individual supernovae.
A lot has been going on ...

- **Photometric redshifts of SNe**
    (see N. Palanque-Delabrouille’s Talk)

- **Correlations of SN distance luminosity with**
  - **Line of sight properties**
    - Gravitational lensing (Kronborg et al, 2010) (see T.K.'s Talk)

- **Host environment**
  - Host stellar mass & metallicity (Sullivan et al, 2008),
    (Sullivan et al, submitted)
  - Host galaxy metallicity (Howell et al, 2009)
  - Host galaxy stellar mass (Kelly et al, 2009)
However...
Outline

• Introduction
  – Standard candles in cosmology
  – Cosmology with SNe Ia
• Recent measurements of $\Omega_m$, $\Omega_x$, $w_x$
  – SDSS-II (Kessler et al, 2009)
  – SNLS3
• SN Ia Host Galaxies
Standard Candles in Cosmology

- **Observables:**
  - Redshift $z = \delta \lambda / \lambda$
  - Apparent flux
  - Apparent angle

- **Standard candles**

$$\Phi_{obs} = \frac{L(\lambda_{obs}/(1 + z))}{4\pi(1 + z)d_L^2}$$

- **Quasi-degeneracies $\rightarrow 1$**
  - parameter well measured

$$d_L(z) = (1 + z) \frac{c}{H_0} \int d'z' \left( \Omega_m (1 + z)^2 + \Omega_k (1 + z)^2 + \Omega_X \exp \left( \int_0^z \frac{1 + w(z')} {1 + z'} d'z' \right) \right)^{-1/2}$$

\[\Omega_m = 0.0, \Omega_\Lambda = 0.0 \quad (\Lambda CDM)\]
\[\Omega_m = 0.3, \Omega_\Lambda = 0.7 \quad (\Lambda CDM)\]
\[\Omega_m = 1.0, \Omega_\Lambda = 0.0 \quad (\Lambda CDM)\]
\[\Omega_m = 0.3, w = -0.9 \quad (FwCDM)\]
Type Ia Supernovae

- Thermoneuclear explosion of WD
  - Rare events (~1 / Gal / 1000 yr)
  - Very bright (~$10^{10}$ solar luminosities)
  - Transients (~ 1 month)
  - $\sigma(L_{\text{max}}) \sim 40\%$

Standardizable $\rightarrow \sigma(L_{\text{max}}) \sim 15\%$

Spectroscopy

- Identification (broad features)
- Chemical composition & velocities
Cosmology with SNe Ia

- Standardizeable Candles

\[ \mu_B = m_B - M_B + \alpha(s - 1) - \beta c \]

- Resframe apparent magnitude @ maximum
- Absolute magnitude @ maximum
- Light curve shape correction
- Color correction. Accounts for:
  - extinction by dust
  - intrinsic color variations
SN Ia luminosity distances

- SN restframe fluxes @ different redshifts
  → empirical model to interpolate between photometric measurements
  → Trained on sets of nearby & distant SNe

SALT2 (Guy et al, 2007), SIfTO (Conley et al, 2007), MLCS2k2 (Jha et al, 2007), CMAGIC (Wang et al, 2003)...
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• SN Ia Host Galaxies
SDSS-II

- Intermediate SN search
  \[0.05 < z < 0.4\]
- SDSS 2.5-m telescope
- Rolling search: repeated scans of a 2.5 x 120 deg\(^2\) equatorial stripe.
- ugriz lightcurves
- \(~500\) spectroscopically confirmed SNe Ia (\(~100\) during the first year)

Fills the “redshift desert”
SNLS-3

- High-z supernova search
  \[0.3 < z < 1.0\]
- MegaCam @ CFHT 3.6-m
  (1 deg\(^2\), 36 4kx2k CCD, griz)
- Rolling search: repeated scans of 4 1 deg\(^2\) fields.
- griz lightcurves.
- \(~450\) spectroscopically confirmed SNe Ia (\(~257\) after 3 years of survey).
SDSS-II First Year Results

- (Kessler et al, 2009)
- Large combined data sample → Measurement of $w$
- Analysis performed with two LC fitters:
  - MLCS2k2 (Jha et al, 07)
  - SALT2 (Guy et al, 07)
→ thorough comparison of the two lightcurve fitters / distance estimators.

(Kessler et al, 2009)
Discrepancies between methods?

$w = -0.76 \pm 0.07$ (stat) $\pm 0.11$ (sys)

$w = -0.96 \pm 0.06$ (stat) $\pm 0.12$ (sys)
Tracking syst. differences

As noted earlier, there is strong evidence of systematic discrepancies in rest-frame $U$-band between the nearby and higher-redshift samples. These discrepancies are reflected in the differences between the MLCS2K2 and SALT–II $U$-band models, differences that account for part of the cosmological parameter disagreement between the two models. The other major contributor to the cosmological disagreement is the differing treatment of SN color variation in the two models. There is a trend toward negative apparent SALT–II color at high-redshift within the SNLS sample. SALT–II and MLCS2K2 with a flat-$A_V$ prior assign these blue events large intrinsic luminosities and therefore large distance moduli. By contrast, MLCS2K2 with the nominal $A_V$ prior identifies these events as having $A_V \sim 0$ and assigns them lower luminosities and distances. As illustrated in Fig. 19, the nominal MLCS2K2 interpretation of these events is consistent with the observed color distributions, so it is not obvious which model is correct.
# SALT2 versus MLCS2K2

<table>
<thead>
<tr>
<th></th>
<th>SALT2</th>
<th>MLCS2K2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance Estimate</td>
<td>Fitted along with the cosmology <em>(no distance information in the model)</em></td>
<td>Directly from the model <em>(trained on SNe with known distances)</em></td>
</tr>
<tr>
<td>Training sample</td>
<td>➔ Nearby SNe</td>
<td>Well measured nearby SNe, with known distances.</td>
</tr>
<tr>
<td></td>
<td>➔ Distant SNe <em>(SNLS)</em></td>
<td></td>
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<tr>
<td></td>
<td>(∨ u-band constraints)</td>
<td></td>
</tr>
<tr>
<td>K-corrections</td>
<td>Built in the model</td>
<td>External K-corrections applied to the data.</td>
</tr>
<tr>
<td>Color vs. luminosity</td>
<td>No assumption on the nature of the color-luminosity relation.</td>
<td>Assumes all the color-luminosity relation captured in the model. <em>Additional color variation → reddening by dust</em></td>
</tr>
</tbody>
</table>
The “U-band anomaly”

- Restframe U-band information has a strong impact on distance estimates.
- Can be tested by comparing distances including or not restframe UV information.

Calibration offsets

SNLS ↔ SDSS ↔ Nearby SNe

- Photometric calibration of the nearby SNe Ia in the UV not reliable.

(Kessler et al, 2009)

(Guy et al, in prep)
The “U-band anomaly”

- **SNLS-3**: new calibration + new SALT-2 training.
  - Better agreement between SNLS – SDSS data.
  - Larger dispersion (0.1 mag RMS) in the U band when fitting nearby data.

- **Large uncertainties** on ground-based U-band obs

  - Variable Atmosph cutoff @ 350 nm → effective passbands not well known

  - Resframe color(with UV) - (no UV)
    - → no visible effect as a function of z
SN Ia colors

- **SN Color variability**: dust + intrinsic variability?

- At least 4 (obvious) sources of dust
  - (1) MW dust (Cardelli et al., 1989; Schlegel et al., 1998)
  - (2) Intergalactic dust
  - (3) Host galaxy dust
  - (4) Dust shell around the supernova

→ no a-priori knowledge of the properties of (2), (3) & (4)

→ may be different, may evolve with the environment (and z)

→ no a-priori knowledge of the SN **intrinsic colors** (variability)

\[ A_\lambda = R_\lambda \times E(B - V) \]

\[ R_B \sim 4.1 \text{ for MW dust} \]
SN Ia colors

- The “effective” reddening law for SNe does not follow the CCM law.

- For SNe Ia the total to selective extinction ratio

\[ R_B \sim 2.5 < 4.1 \]

Different dust properties? (see e.g. Goobar et al, 2009) Intrinsinc variability?
SN Ia colors

- SALT2 makes no assumption on the SN colors
- MLCS2K2 assumes that
  - The intrinsic color variations are captured in the LC model (variability fully described with 1 parameter)
  - Residual color variations due to extinction by dust (> 0)
  → Prior on the extinction (to ensure extinction > 0)
  - Redshift-dependant (to account for selection biases)
  - Determined using a simulation and a subsample of the SDSS-II dataset
Effect of Prior on SN Ia colors

- **MLCS2K2** interpret the color variability as extinction by dust → prior to ensure $A_{\lambda} > 0$

- Redshift dependent bias

- Strong effect on the cosmological parameter determination

- Explains ~ half of the discrepancies

(Kessler et al, 2009)
Conclusion

- Origins of the “discrepancy” well identified

  (1) Model restframe UV calibration
    - disappears with improved photometric calibration
    - future imagers with better near-IR sensitivity (DarkCam) will be less sensitive to the model UV calibration.

  (2) assumptions on the nature of the color variability of the SNe Ia.
    - not a systematic uncertainty.
SNLS-3 Analysis

- **Statistics x 3.5**  \( 71 \rightarrow \sim 280 \)
- **Two independent analyses** (control of systematics) performed in Canada & France
  - SN photometry
  - photometric calibration
  - light curve fitters SALT2 + SiFTO (Conley et al, 2008)
- **Improved photometric calibration**
- **Improved supernova modeling** (models trained on the SNLS data → bluer part of the restframe spectrum constrained without using observer frame U)
- **Detailed studies of the SN host properties**
- **Systematics included in the cosmology fit**
Two LC Fitters

- **SALT2** (Guy et al, 2007): empirical model of the SN spectral sequence

\[
S(\lambda, t) = x_0 \times [M_0(\lambda, t) + x_1 M_1(\lambda, t)] \times \exp(c \ C'L(\lambda))
\]

- **SiFTO** (Conley et al, 2008): SN spectral sequence (Hsiao, 2007), pure stretch (wavelength dependent), restframe color relations.

Both models trained on nearby and distant (SNLS) lightcurves (lightcurve fit ≠ distance estimator)
SALT2 vs. SiFTO

- $m, c, s_{SALT2} = f(m, c, s_{SiFTO})$
- $\delta m(z)$ significantly $\neq 0$ at some $z$
  $\rightarrow$ due to differences in SALT2 / SiFTO spectral sequences.
  $\rightarrow$ syst. uncertainty.

Guy et al, SNLS-3, subm
Photometric Calibration

- **Magnitude systems** do **not** define their physical flux scale → rely on a fundamental standard with known magnitudes and spectrum to convert magnitudes into physical fluxes

\[ \Phi = 10^{-0.4(m-m_{\text{ref}})} \times \int S_{\text{ref}}(\lambda)T(\lambda)d\lambda \]

- The HST has selected 5 primary standards (pure hydrogen WD). **Models** of these stars' spectra are used to calibrate the HST instruments.

- Calibration then propagated to a larger network of secondary standards. SNLS uses one of them, BD +17 4708, as a fundamental flux standard.

- **Uncertainties** on flux calibration: \( \sim 0.005 \) (gri), \( \sim 0.02 \) (z)

(Regnault et al, 2009)
Syst. uncertainties on $\langle \mu \rangle$ [*]

- Photometric calibration
- Residual scatter
- SALT2 vs. SiFTO

Model statistical uncertainties (Training)

$\delta z$ bins of 0.2

See SNLS-3 papers (Guy et al, in prep)
SNLS-3 Hubble diagram
SNLS-3 Hubble diagram

SNLS-3 Hubble diagram residuals

Graph showing the relationship between redshift and Δμ.
Constraints on $w_x$

(see SNLS-3 papers (Sullivan et al., in prep))
Constraints on $w_x$

(see SNLS-3 papers (Sullivan et al, in prep))
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SN Ia Host Galaxies

- Influence of the environment on the SN Ia luminosity
  - Dust
  - Metallicity
  - Progenitor / age of the stellar population
- Photometric & spectroscopic comparisons low-z ↔ high-z
  → (Foley et al, 2008; Ellis et al, 2008; SNLS-3 papers)
  → no clear signal of evolution
- Comparison of SN properties w/ host galaxy properties
Two populations?

SNe Ia are ~ 10 times more common in star forming galaxies than in passive galaxies (Mannucci et al, 2005; Sullivan et al, 2006)

Bi-modal delay-time distribution required to accommodate observed SN rate vs. galaxy SFR (Mannucci et al, 2006)

- prompt component
- "tardy" component

multiple astrophysical channels → SN Ia?

→ Demographic shift?

→ Impact on the cosmology?
Stretch & luminosity vs. host type

- SNe in star forming galaxies → larger stretch → brighter
- SNe in passive galaxies → smaller stretch → fainter

(Sullivan, LeBorgne et al, 2006)
SN properties vs. Host Galaxies

- SNe Ia in passive elliptical galaxies are **fainter**, with lower **stretch** than SNe in star forming galaxies.

- Effect of demographic shift visible in the stretch distribution.

- Effect on SN luminosity distances well accounted for by the standardization relations (SNLS 1 year sample, Howell et al, 2007).

(Howell et al, 2007)
SN Ia Host Galaxies

- **On larger (recent) samples**: no clear correlation
  - (Kelly et al, 2008): correlation of Hubble residuals with host galaxy mass (2.5 $\sigma$ effect)
  - No clear correlations between SN luminosities and galaxy metallicity (see Howell et al, and ref therein)
  - (Sullivan et al, SNLS-3, 2010) show dependence of standardized SN luminosity distances with host galaxy stellar mass ($\sim$4 $\sigma$ significance) and with specific star formation rate ($\sim$ 2.5 $\sigma$ significance).
SN Ia Host Galaxies

- **SNLS-3**: dependence of
  standardized SN luminosity distances with:
  
  i. host galaxy stellar mass (~ 4 σ significance)
  ii. specific star formation rate (~ 2.5 σ significance).

→ Accounted for by adding a host specific term in the cosmological fit.

SNLS-3 (Sullivan et al, subm)
Conclusion

- Growing low-z and high-z SN Ia samples
  → compatible measurements of $\Omega_{\Lambda}$, $\Omega_{\cdots}$, $w_X$
  → $\sigma(w)$: $\sim 0.05$ (stat) $\sim 0.1$ (sys)
  → SDSS-II: apparent discrepancy from LC fitters well understood: photometric calibration + color prior

- Future surveys (e.g. Dark Energy Survey) more efficient in the red will be less affected by photometric calibration uncertainties.

- First evidence for SN demographic shifts can be corrected with host dependant parameters.