The Supernova Legacy Survey: Dark Energy and SNe Ia

Mark Sullivan
University of Oxford

http://legacy.astro.utoronto.ca/
http://cfht.hawaii.edu/SNLS/
Full list of collaborators at: http://cfht.hawaii.edu/SNLS/
SNLS: Vital Statistics

- 2003-2008 SN survey with “MegaCam” on CFHT
- griz every 4 nights in queue mode, densely sampled SN light curves
- 400 high-z confirmed SNe Ia to measure “w”
- 2000 SN detections in total
Cosmology with SNe Ia

\[ m_{B}^{\text{obs}} = m_{B} - M_{B} \]

\[ m_{B}^{\text{obs}} = m_{B} - M_{B} + a (s - 1) - bc \]

\[ m_{B}^{\text{mod}} = 4 D_{L}(z, w, W_{M}, W_{DE}) \]

\[ c^2 = 4 \left( \frac{(m_{B}^{\text{obs}} - m_{B}^{\text{mod}})^2}{s_{\text{stat}}^2 + s_{\text{int}}^2} \right) \]

\[ \chi^2/DOF \text{ is } >>1 \text{ unless "intrinsic dispersion" } s_{\text{int}} \text{ is added – parameterises our lack of knowledge about SNe Ia} \]
$\Omega_M = 0.263 \pm 0.042 \text{ (stat)} \pm 0.032 \text{ (sys)}$

$\langle w \rangle = -1.02 \pm 0.09 \text{ (stat)} \pm 0.054 \text{ (sys)} \text{ (with BAO + Flat Universe)}$
SNLS3 versus SNLS1: Highlights

- **More SNe! 71 to 250: sub-samples & “astrophysical systematics”**
  - Represents about 60-70% of final SNLS5 sample

- **Optimised survey calibration and understanding of selection**
  - 3-year monitoring of fields; better calibration of MegaCam
  - Malmquist corrections understood and applied to data

- **Improved understanding of SN Ia properties**
  - New “k-correction” templates; UV spectra,
  - New techniques exploit SN data at $\lambda<4000\text{A}$

- **Independent analyses (“French” and “Canadian”)**
  - All aspects of analysis cross-checked independently

- **Systematics included directly in cosmological fits**
SNLS3 Hubble Diagram (preliminary)

~250 distant SNLS SNe Ia

311 SNe total

SNLS+flatness+w=-1:

$\Omega_M \ 0.25 \ 9.9\% \ \text{error}$

error is 15.7\% for SNLS1 sample

Improvement just a little worse than SQRT(N)

(comparison uses new light curve fits and calibration improvements)
Cosmological Constraints (Preliminary)

SNLS + BAO + WMAP5 “shifts” + Flat

5.9% statistical measure of $<w>$
How fast are SN constraints improving?

SN contour area decrease since Astier et al. 2006 again just worse than SQRT(N)
SNe Ia: Systematics

“Experimental Systematics”
- Calibration; photometric system; Malmquist effects

Non-SN systematics
- Peculiar velocities; Weak lensing

SN model and K-corrections
- SED uncertainties; colour relations; light curve fitters

Extinction/Colour
- Effective $R_V$; Mix of intrinsic colour and dust

Redshift evolution in the mix of SNe
- “Population drift” – environment?

Evolution in SN properties
- Light-curves/Colours/Luminosities
Identified systematics in SNLS3 (preliminary)

<table>
<thead>
<tr>
<th>Systematic</th>
<th>% &lt;w&gt; error</th>
<th>Extra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical only</td>
<td>0.060</td>
<td>...</td>
</tr>
<tr>
<td>SNLS zero points</td>
<td>0.069</td>
<td>0.031</td>
</tr>
<tr>
<td>SNLS filters</td>
<td>0.065</td>
<td>0.023</td>
</tr>
<tr>
<td>External zero points</td>
<td>0.064</td>
<td>0.021</td>
</tr>
<tr>
<td>External filters</td>
<td>0.061</td>
<td>0.010</td>
</tr>
<tr>
<td>SN colour relation</td>
<td>0.067</td>
<td>0.027</td>
</tr>
<tr>
<td>Vega colours</td>
<td>0.068</td>
<td>0.030</td>
</tr>
<tr>
<td>Vega SED</td>
<td>0.061</td>
<td>0.009</td>
</tr>
<tr>
<td>Peculiar velocities</td>
<td>0.061</td>
<td>0.006</td>
</tr>
<tr>
<td>Malmquist bias</td>
<td>0.061</td>
<td>0.005</td>
</tr>
<tr>
<td>Nicmos non-linearity</td>
<td>0.060</td>
<td>0.004</td>
</tr>
<tr>
<td><strong>All systematics</strong></td>
<td>≈0.09</td>
<td>0.068</td>
</tr>
</tbody>
</table>

Conley et al., in prep
Systematic errors included in the error contours. Filled are statistical only.
Identified systematics in SNLS3 (preliminary)

<table>
<thead>
<tr>
<th>Systematic</th>
<th>% &lt;w&gt; error</th>
<th>Extra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical only</td>
<td>0.060</td>
<td>…</td>
</tr>
<tr>
<td>SNLS zero points</td>
<td>0.069</td>
<td>0.031</td>
</tr>
<tr>
<td>SNLS filters</td>
<td>0.065</td>
<td>0.023</td>
</tr>
<tr>
<td>External zero points</td>
<td>0.064</td>
<td>0.021</td>
</tr>
<tr>
<td>External filters</td>
<td>0.061</td>
<td>0.010</td>
</tr>
<tr>
<td>SN colour relation</td>
<td>0.067</td>
<td>0.027</td>
</tr>
<tr>
<td>Vega colours</td>
<td>0.068</td>
<td>0.030</td>
</tr>
<tr>
<td>Vega SED</td>
<td>0.061</td>
<td>0.009</td>
</tr>
<tr>
<td>Peculiar velocities</td>
<td>0.061</td>
<td>0.006</td>
</tr>
<tr>
<td>Malmquist bias</td>
<td>0.061</td>
<td>0.005</td>
</tr>
<tr>
<td>Nicmos non-linearity</td>
<td>0.060</td>
<td>0.004</td>
</tr>
<tr>
<td><strong>All systematics</strong></td>
<td>(\approx 0.09)</td>
<td>0.068</td>
</tr>
</tbody>
</table>

Most uncertainties arise from combining different SN samples.
Calibration

The single greatest challenge in SNLS3
(and probably every current SN Ia survey!)

All SNe must be placed on the same photometric system

Different SN samples are calibrated to different systems:
- Historical low-redshift samples: Observed in U,B,V,R (Landolt)
- High-z: Observed in g,r,i,z - calibrate to SDSS or Landolt?

Challenges:
- Zeropoints (colour terms)
- “Landolt” filter responses

Goal: Replace low-z sample & remove dependence on Landolt system
Identified systematics in SNLS3 (preliminary)

<table>
<thead>
<tr>
<th>Systematic</th>
<th>% &lt;w&gt; error</th>
<th>Extra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical only</td>
<td>0.059</td>
<td>...</td>
</tr>
<tr>
<td>SNLS zero points</td>
<td>0.069</td>
<td>0.031</td>
</tr>
<tr>
<td>SNLS filters</td>
<td>0.065</td>
<td>0.023</td>
</tr>
<tr>
<td>External zero points</td>
<td>0.064</td>
<td>0.021</td>
</tr>
<tr>
<td>External filters</td>
<td>0.061</td>
<td>0.010</td>
</tr>
<tr>
<td>SN color relation</td>
<td>0.067</td>
<td>0.027</td>
</tr>
<tr>
<td>Vega colours</td>
<td>0.068</td>
<td>0.030</td>
</tr>
<tr>
<td>Vega SED</td>
<td>0.061</td>
<td>0.009</td>
</tr>
<tr>
<td>Peculiar velocities</td>
<td>0.061</td>
<td>0.006</td>
</tr>
<tr>
<td>Malmquist bias</td>
<td>0.061</td>
<td>0.005</td>
</tr>
<tr>
<td>Nicmos non-linearity</td>
<td>0.060</td>
<td>0.004</td>
</tr>
<tr>
<td><strong>All systematics</strong></td>
<td>≈0.09</td>
<td>0.068</td>
</tr>
<tr>
<td><strong>All systematics</strong></td>
<td>≈0.07</td>
<td>0.042</td>
</tr>
</tbody>
</table>

When low-redshift sample is replaced, systematics should drop to 4-5%.

Need for a “rolling” low-z survey (e.g. CSP, Skymapper/PTF, SDSS?)
SNe Ia: Systematics

“Experimental Systematics”
- Calibration; photometric system; Malmquist effects

Non-SN systematics
- Peculiar velocities; Weak lensing

SN model and K-corrections
- SED uncertainties; colour relations; light curve fitters

Extinction/Colour
- Effective $R_V$; Mix of intrinsic colour and dust

Redshift evolution in the mix of SNe
- “Population drift” – environment?

Evolution in SN properties
- Light-curves/Colours/Luminosities

How “Standard” is the standard candle?

Increasing knowledge of SN physics
“Population Evolution”

Tractable, can be modelled
Concern: Colour/dust systematics?

Colour—luminosity relationship inconsistent with MW-type dust

Best-fit: $\beta \sim 3$

MW-dust: $\beta R_B = 4.1$

\[ m_B = m_B - M_B + a (s - 1) - bc \]
Concern: SN evolution?

Evidence for multiple SN Ia components, or just a wide-range of delay-times with one channel?

Sullivan et al. (2006)
Averagely, the recent enhancement intrinsic brightness of SNe Ia evolves with redshift. If stretch “works”, this will not affect cosmology—but it must work equally well at all scales:

e.g. Sarkar et al. 2008

This is a demographic change, not evolution in SN properties.

Nearby

\begin{align*}
z &< 0.75 \\
z &> 0.75
\end{align*}

Howell et al. (2007)
Demographic shifts in SN spectra

SN Ia spectra stretch dependence

SN light curves powered entirely by decay of $^{56}\text{Ni}$

Higher stretch implies:

- Higher luminosity
- More $^{56}\text{Ni}$ synthesised
- Less intermediate mass elements (and hotter ejecta)

High-s SNe show weaker:

- Mg 4400Å
- Si 4000Å
- as well as a bluer UV continuum

See also Ryan Foley's talk

Ellis et al. (2008)
Demographic shifts in SN spectra

Spectra matched in phase

Highest-z spectrum has highest mean stretch

As expected, less Si and Ca in this spectrum

But, note the redder continuum

Sullivan et al. (2008); spectra from Ellis et al. (2008), Matheson et al. (2008), Riess et al. (2007)

See also Ryan Foley’s talk
Demographic shifts and cosmology

- Are $\alpha$ and $\beta$ “universal” coefficients? An age or metallicity (environmental) dependence might imply “drifts” with redshift.

- Test with SNLS sample where host information is available; hosts span full range of stellar mass and SFR.

- Each SN host has stellar mass / mean age / SFR estimates.

- Split into young/old, passive/star-forming, metal-rich/metal-poor samples.
Stretch (□) correction by age/environment

Plot cosmological residual without (s-1) correction

Hosts split by age

Hosts split by SFR

\[ m_B^{\text{obs}} = m_B - M_B + a(s - 1) - bc \]

SNLS z<0.8
Colour (□) correction by age/environment

Plot cosmological residual without □colour correction

Hosts split by age

Hosts split by SFR

\[ m_B^{\text{obs}} = m_B - M_B + a(s - 1) - b c \]

Cosmology fixed -- fit for and only SNLS z<0.8
rms is smaller in passive galaxies

is smaller in passive galaxies

H is consistent

Approaching limit of current method? But no better alternative!

SNLS z<0.8
All CNO catalysts pile up into $^{14}\text{N}$ when H-burning is completed.

During He-burning all $^{14}\text{N}$ is converted into $^{22}\text{Ne}$, neutron-rich

→ Higher metallicity progenitor means more neutron-rich SN Ia

→ More neutrons during SN, more stable $^{58}\text{Ni}$ instead of $^{56}\text{Ni}$

→ Fainter SN

See Timmes, Brown & Truran (2003) for full story, including role of $^{56}\text{Fe}$
The decay powers of $^{56}\text{Ni}$ light curve can be estimated from SN luminosity and rise-time. Galaxies with higher stellar mass and therefore inferred gas phase metallicity tend to host SNe with smaller $^{56}\text{Ni}$ fraction. This is consistent with theoretical predictions.

(Howell et al. 2008)
Uses SNLS1 (Astier et al.) residuals

No trend between HD residual and inferred metallicity

(Note intriguing inconsistency with Gallagher et al. relation)

SN Samples? Light curve fitters? Metallicity diagnostics?
Summary

Current constraints on $\langle w \rangle$: $\langle w \rangle = -1$ to $<6\% \text{ (stat)}$
(inc. flat Universe, BAO+WMAP-5)

Systematics ~7%; dominated by $z<0.1$ sample

SNLS5 survey statistical uncertainty will be 4-5%:
- 400 SNLS + 200? SDSS + larger $z<0.1$ samples, BAO, WL

Current issues:

Photometric calibration limiting factor; will improve dramatically

Mean SN Ia properties evolve with redshift - so far no bias in cosmology detected

Colour corrections need to be understood; some evidence for environmental dependence

Urgent need for $z<0.1$ samples with wide wavelength coverage
- Replace existing sample & disentangle SN Ia colours
Assuming $\beta=4.1$ leads to systematic errors – Hubble Bubble

Latest MLCS2k2 Paper (Jha 2007)
- MLCS2k2 attempts to separate intrinsic colour-luminosity and reddening
- The latter part assumes $\beta \equiv R_B = 4.1$

$3\sigma$ decrease in Hubble constant at $\approx 7400$ km/sec – local value of $H_0$

No Bubble with other light-curve fitters
- Local void in mass density?

Would have significant effects on $w$ measurement

Conley et al. (2007)
SiFTO versus SALT2

![Graph comparing SiFTO and SALT2](image-url)
SNLS3 Highlights: Sifto & lightcurve fitters

Normalized, combined data

2700A

Normalized, combined data

3200A

Normalized, combined data

3600A

Normalized, combined data

Normalized, combined data

Normalized, combined data

Normalized, combined data
Weighting of different colours
Cosmological Constraints (Preliminary)

SNLS + BAO