The Supernova Legacy Survey
Measurement of $\Omega_M$, $\Omega_X$ and $w$ from the First Year Data Set

http://www.cfht.hawaii.edu/SNLS

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on behalf of the SNLS collaboration
Cosmology with Type Ia supernovae

Luminosity distance vs redshift $d_L(z)$

For $\Omega_T = 1$, $d_L(z) = c (1 + z) \int_{(1+z)^{-1}}^{1} \frac{da}{a} \phi(\lambda_{obs}) = \frac{L(\lambda_{obs}/(1+z))}{4\pi(1+z)d_{L}^2}$

Type Ia supernovae (SNe Ia):

- Very bright => visible at cosmological distances $M_B \sim -19.4 \ (10^{10} \text{ suns})$
  (can be brighter than host galaxy)

- Absolute peak magnitude with small dispersion ( $\sim 0.35$ mag, i.e. $\sim 35\%$)
  (~ same initial conditions, white dwarf @ Chandrasekar mass)

- Correlations between light curve shapes, colors and peak brightness =>
  decrease dispersion to $0.15$ mag
**History**

Type Ia Supernovae (SNe Ia):
- **Riess 1998** (10(+6) SNe Ia)
- **Perlmutter 1999** (42 SNe Ia)
=> Acceleration of expansion

- Allen 2002, X-ray clusters -> $\Omega_m$
- Spergel 2003, CMB (WMAP) -> $\Omega_T$

=> Concordance model:
Flat Universe with Dark Energy compatible with a cosmological constant, $\Omega_\Lambda \sim 0.7$

SNe:
- **Sullivan 2002** Hubble diagram vs Host galaxy type (test of evolution)
- **Tonry 2003** (+8)
- **Barris 2003** (+23 SNe Ia, z<1)
- **Knop 2003** (+11 SNe Ia, follow-up at HST)
- **Riess 2004**: (+16 SNe Ia discovery at HST) up to z~1.6

- **Astier 2005** (71 SNe), ~700 at the end of SNLS
SNLS

Goals:
- ~700 SNe Ia \( z < 1.1 \) (x10 previous statistics)
- observed in 4 bands \( (g,r,i,z) \) \( \sim \) SDSS
- good sampling of light curves
- spectroscopic identification (of all 700 SNe)

-> large statistics help controlling systematic uncertainties
-> photometry with a single telescope: better understanding of the detector
   - useful for calibration
   - better control of selection bias

-> multi-color observations:
  - required to follow the same spectral region at different \( z \):
    \[
    (B,V) \ z=0 \ <\Rightarrow \ (g,r) \ z=0.2
    \]
    \[
    <\Rightarrow \ (r,i) \ z=0.4
    \]
    \[
    <\Rightarrow \ (i,z) \ z=0.8
    \]
  - help for SNe modeling at \( z \sim 0.4 \)
Imaging survey with Megacam at CFHT (Hawaii)

CFHT: $\varnothing$ 3.6 m (1979)
Megacam (CEA/DAPNIA):
1 deg$^2$, 36 CCD 2k*4K
First light, fall 2002

Observation strategy: “Rolling Search”

- Part of CFHTLS/Deep survey
- 40 nights/yr during 5 years
- Repeated observations
  (every 3-4 nights) of 4 fields
  of 1 sq. deg. each in ugriz

- Good PSF sampling, 1pix = 0.2''
- High Quality images: 0.7'' (FWHM)
The Spectroscopic survey

Goals:
- spectral identification of SNe up to z~1
- redshift (host galaxy)
- detailed study of a subsample of SNe, Type IIs (complementary programs, ...)

Where?:
- **VLT** Large program (service)
  
  240h in 2003+2004, idem 2005+2006

- **Gemini** : 60h/semester

- **Keck** : 30h/an (in one semester)

Example of an identified Type Ia SN at z=0.496
(Howell 2005, astro-ph/0509195)
List of SNe candidates is public: http://legacy.astro.utoronto.ca/

=> 226 SNe Ia/Ia?
Analysis of the 1st year data set

Sketch:
- Calibration of Deep fields (anchored to Landolt system)
- Differential photometry of SNe (and PSF photom. of stars)
- Fit of multi-color light curves
- Final selection
- Fit of cosmology
- Study of systematics

91 spectroscopically identified Ia/Ia*
- 6 lost due to bad weather or instrument failure
- 10 missing data for reference (or software limitation)
=> 75 Ia/Ia* can be fitted
=> 71 in Hubble diagram
Differential Photometry of SNe light curves

- Several steps of image processing (flat-field, background subtraction, astrometric solution) + geometrical alignment + evaluation of convolution kernel from image of best quality

- Nearly optimal differential photometry:

\[ I(x, y) = \text{Flux} \times \left[ \text{Kernel} \otimes \text{PSF}_{\text{best}} \right](x - x_{\text{Sn}}, y - y_{\text{Sn}}) \]
\[ + \left[ \text{Kernel} \otimes \text{Galaxy}_{\text{best}} \right](x, y) + \text{Sky} \]

- Fit galaxy(i,j) on a stamp
- Can fit constant background
- SNe flux using PSF model
- Fit accurate SNe position (fit with about 3000 coefficients)

- Evaluate errors using dispersion of measurements per epoch.
  \[ \Rightarrow \text{errors are 12\% larger than expected from pure photon statistics.} \]
  \[ \text{i.e. little room for improvements} \]

- Save full covariance matrix of fluxes for subsequent analysis
Multi-color light curve fit with a Spectral Adaptive Light curve Template (SALT)

Model SNe Ia SED as a function of
- **phase** (date with respect to B-band maximum)
- **lambda** (rest-frame wavelength)
- **stretch s** (dilatation of phase axis in B-band)
- **color c=B-V+cst** at B-band maximum

Trained with a sample of nearby SNe Ia in UBVR
**Distance Estimate with SALT**

For each SN, the fit leads to 3 parameters: global intensity \((m_B)\), stretch \((s)\), color \((c)\)

**Distance estimate:**

\[
m_B(z) - M'_B - \alpha (s - 1) + \beta c = 5 \log_{10} \left( \frac{d_L H_0}{c} \right)
\]

On a test sample of nearby SNe, using either U+B or B+V bands

**Residuals to Hubble Diagram, dispersion of \(\sim 0.16\) mag:**

![Graphs showing residuals to Hubble Diagram](image)
Multi-color light curves

SNLS-04D3fk z=0.3578

SNLS-04D3gx z=0.91
Hubble diagram of SNLS 1st Year

Final sample:
44 nearby SNe from literature
+71 SNLS SNe

\[ \mu_B = m_B^* - \mathcal{M} + \alpha(s - 1) - \beta c \]

\[ \chi^2 = \sum_{\text{objects}} \frac{(\mu_B - 5 \log_{10}(d_L(\theta, z)/10pc))^2}{\sigma^2(\mu_B) + \sigma^2_{\text{int}}} \]

\( \chi^2/\text{d.o.f}=1 \) with an additional intrinsic dispersion \( \sigma_{\text{int}} = 0.13 \text{ mag} \)

(errors take into account covariance matrix of fitted parameters \( m_B, s, c \))

Next, cosmological fit ->
Cosmological parameters

$w = -1$

$\Omega_T = 1$

BAO: Baryon Acoustic Oscillations

Eisenstein 2005

68.3, 95.5 and 99.7% CL

<table>
<thead>
<tr>
<th>fit</th>
<th>parameters (stat only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\Omega_M, \Omega_\Lambda)$</td>
<td>$(0.31 \pm 0.21, 0.80 \pm 0.31)$</td>
</tr>
<tr>
<td>$(\Omega_M - \Omega_\Lambda, \Omega_M + \Omega_\Lambda)$</td>
<td>$(-0.49 \pm 0.12, 1.11 \pm 0.52)$</td>
</tr>
<tr>
<td>$(\Omega_M, \Omega_\Lambda)$ flat</td>
<td>$\Omega_M = 0.263 \pm 0.037$</td>
</tr>
<tr>
<td>$(\Omega_M, \Omega_\Lambda) + \text{BAO}$</td>
<td>$(0.271 \pm 0.020, 0.751 \pm 0.082)$</td>
</tr>
<tr>
<td>$(\Omega_M, w)$ + BAO</td>
<td>$(0.271 \pm 0.021, -1.023 \pm 0.087)$</td>
</tr>
</tbody>
</table>
Identified systematic uncertainties

- (photometry, calibration, modeling of the detector response)
- **Evolution:**
  Need for predictive SNe Ia theory
  -> SNe observables vs host galaxy type
  -> Nearby and distant SNe comparisons

- **Empirical modeling (k-corrections):**
  Observations vary in phase and wavelength sampling
  fit (B,V) -> (U,B) at high z
  -> tests based on SNe at z~0.4

- **Selection bias:**
  Only the brightest SNe are detected at high z
  (=> Blue color, large stretching of light curves)
  -> Controled with simulations of the detection pipeline

- **Contamination (interpolers):**
  SN II, SN Ib/c spectroscopic id. is not always conclusive

- **Grey Dust:**
  Intergalactic absorption mimic acceleration of expansion

- **Gravitational lensing at high z:**
  Asymmetric distribution of observed luminosities
Calibration

<table>
<thead>
<tr>
<th>Band</th>
<th>zero-point shift</th>
<th>$\delta\Omega_M$ (flat)</th>
<th>$\delta\Omega_{tot}$</th>
<th>$\delta w$ (fixed$\Omega_M$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_M$</td>
<td>0.01</td>
<td>0.000</td>
<td>-0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>$r_M$</td>
<td>0.01</td>
<td>0.009</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>$i_M$</td>
<td>0.01</td>
<td>-0.014</td>
<td>0.17</td>
<td>-0.04</td>
</tr>
<tr>
<td>$z_M$</td>
<td>0.03</td>
<td>0.018</td>
<td>-0.48</td>
<td>-0.03</td>
</tr>
<tr>
<td>sum</td>
<td>-</td>
<td>0.024</td>
<td>0.51</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Blue : Megacam observations of Landolt stars
Red/Back : synthetic magnitudes from spectrophotometric standards + models
Evolution

Same brighter-slower and brighter-bluer relations at $z \sim 0$ and $\langle z \rangle \sim 0.6$

( black: SNLS  blue: Nearby SNe )
Malmquist Bias

Impact on $\Omega_m$ (flat LCDM):
Nearby SNe $+0.019 \pm 0.012$
SNLS SNe $-0.02 \pm 0.01$

Black: SNLS SNe
Red: Simulations with SALT
Checks of SNe modeling with SALT

-> Measurement of m*B,s,c using rest-frame (U and B) or (B and V) light curves (référentiel de la SN)

-> SNLS LCs:

<table>
<thead>
<tr>
<th>z</th>
<th>0</th>
<th>0.3</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>g'</td>
<td>r'</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>r'</td>
<td>i'</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>i'</td>
<td>z'</td>
<td></td>
</tr>
</tbody>
</table>

\[ \Delta U_3 = U(B,V) - U(\text{meas}) \]

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>R</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBV</td>
<td>0+-0.02</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>g'r'i'</td>
<td>0+-0.008</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>i'r'z'</td>
<td>0.09+-0.04</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

-> good agreement UBV g'r'i'

-> 2 sigma i'r'z'

-> small dispersion en g'r'i'
Summary of systematics:

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta \Omega_M$ (flat)</th>
<th>$\delta \Omega_{tot}$ (fixed $\Omega_M$)</th>
<th>$\delta w$</th>
<th>$\delta \Omega_M$ (with BAO)</th>
<th>$\delta w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero points</td>
<td>0.024</td>
<td>0.51</td>
<td>0.05</td>
<td>0.004</td>
<td>0.040</td>
</tr>
<tr>
<td>($g_M r_M \lambda_M^2 \mu$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vega spectrum</td>
<td>0.012</td>
<td>0.02</td>
<td>0.03</td>
<td>0.003</td>
<td>0.024</td>
</tr>
<tr>
<td>Filter bandpasses</td>
<td>0.007</td>
<td>0.01</td>
<td>0.02</td>
<td>0.002</td>
<td>0.013</td>
</tr>
<tr>
<td>Malmquist bias</td>
<td>0.016</td>
<td>0.22</td>
<td>0.03</td>
<td>0.004</td>
<td>0.025</td>
</tr>
<tr>
<td>Sum (sys)</td>
<td>0.032</td>
<td>0.55</td>
<td>0.07</td>
<td>0.007</td>
<td>0.054</td>
</tr>
<tr>
<td>U-B color (stat)</td>
<td>0.020</td>
<td>0.12</td>
<td>0.05</td>
<td>0.004</td>
<td>0.024</td>
</tr>
</tbody>
</table>

**SNLS 1st year results on Cosmology**

**SNLS only, flat Universe with $w=-1$**

$\Omega_M = 0.263 \pm 0.042 \ (stat) \pm 0.032 \ (sys)$

**SNLS+BAO (Eisenstein 2005), flat Universe**

$\Omega_M = 0.271 \pm 0.021 \ (stat) \pm 0.007 \ (sys)$

$w = -1.02 \pm 0.09 \ (stat) \pm 0.054 \ (sys)$
Prospects

- Already ~ 200 new SNe Ia on disk
- Deeper reference images will improve photometry
- Statistical Errors x 1/2 at the end of the survey
- Survey is more efficient today:
  - Better image quality (wide field corrector fixed)
  - auto-focus: More science observations per night.
- Calibration is being improved
- Work on modeling to use rest-frame far UV observations
- Possibility to improve distance estimate
  => improvement of statistical errors
- Study of SNe properties vs Host Galaxy type
  => Strong test of evolution
- Measurement of the SNe Ia explosion rate:
  requires a good understanding of the detection efficiency
  => benefits to the selection bias control
- Photometric Identification (=> +30% de SNe at high z)