SNLS Results on Dark Energy

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

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(on behalf of the SNLS Collaboration)

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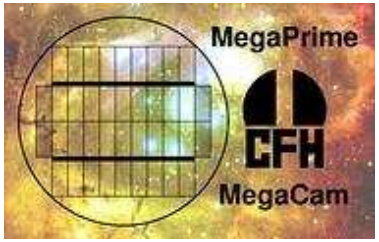
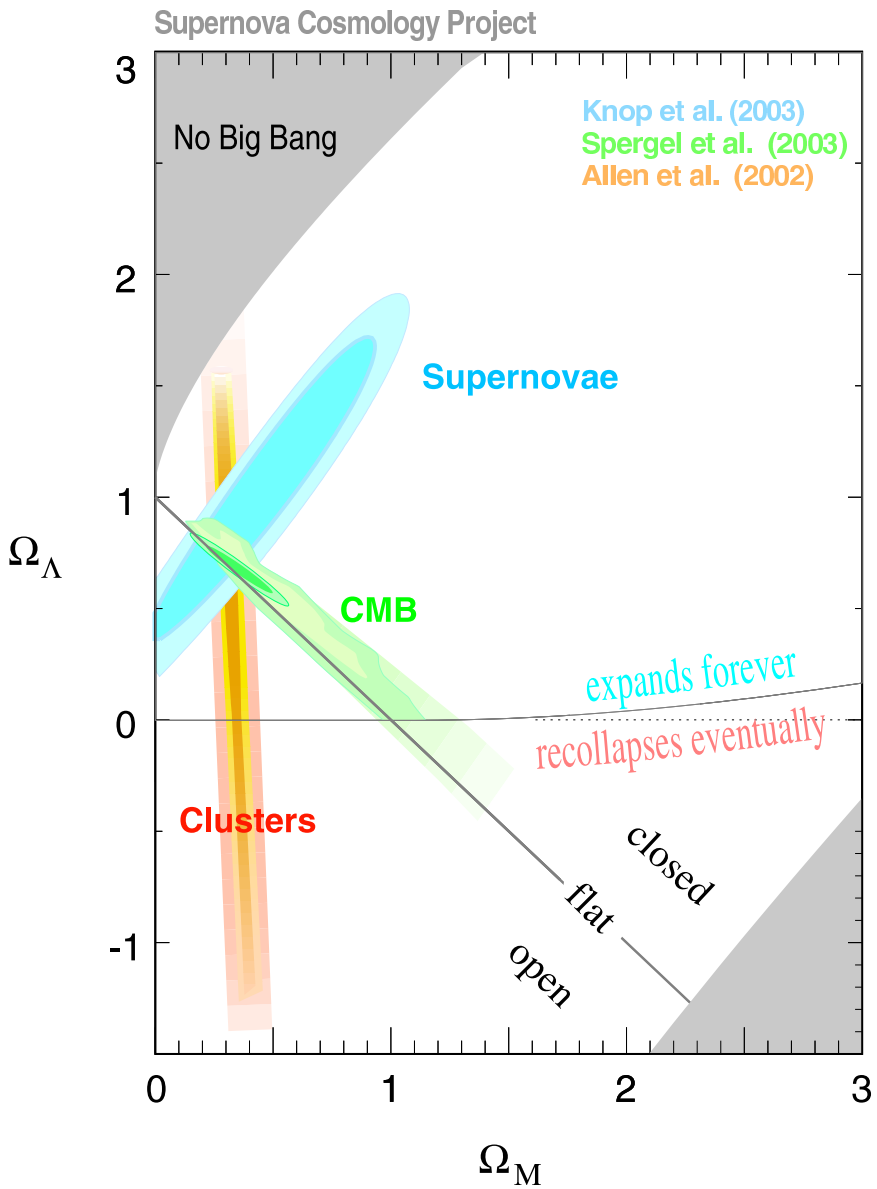


The Concordance Model



- Concordance model
  - The Universe is flat (CMB) with a low matter density (clusters) and its energy density is dominated by some repulsive dark energy (supernovae).
- Dark Matter $\sim 22\%$ of the universe energy density. Unknown nature. $p = 0 \Rightarrow \rho_m \propto R^{-3}$.
- Dark Energy $\sim 73\%$ of the universe energy density. Unknown nature. $p = w\rho \Rightarrow \rho_\Lambda \propto R^{3(1+w)}$.

Measurements of $w(z)$!

How can we study Dark Energy ?

Expansion history of the Universe: evolution of $H(z)$

$$H^2(z) = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left(\Omega_m (1+z)^3 + \Omega_{de} (1+z)^{3(1+w)}\right)$$

- Luminosity distance ..... $d_L(z) = (1+z) \int \times \frac{dz}{H(z)}$
  - Standard candles (SNe Ia) (SNLS, ESSENCE, DES, LSST, DUNE, SNAP)
- Angular distance ..... $d_A(z) = 1/(1+z) \times \int \frac{dz}{H(z)}$
  - Baryon Accoustic Peak (SDSS)
  - SZ-effect
- Volume factor ..... $\frac{dV}{dz d\Omega} = r^2(z) H(z)$
  - Galaxy number counts versus redshift (SDSS, CFHTLS, DES)

Growth rate of structures

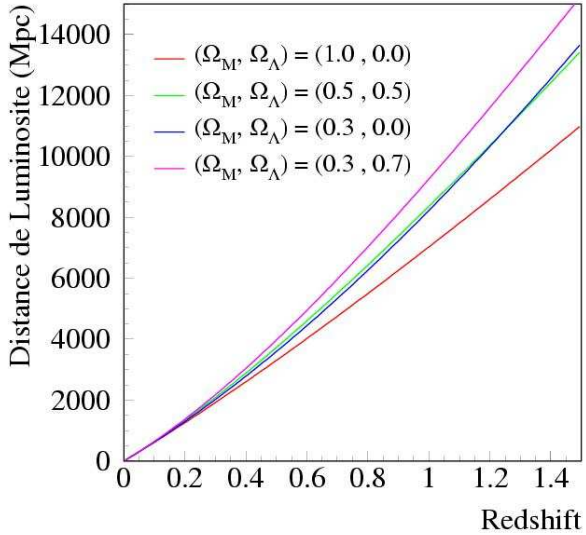
- Weak shear (CFHTLS, DES, LSST, SNAP, DUNE)
- 3D Weak shear (DarkCam)
- Cluster abundance as a function of z

SNe Ia as Standard Candles

- Very bright objects $\Rightarrow$ visible at cosmological distances.
- Dispersion of the absolute peak magnitude is small: $\sim$ 0.4 mag (20% in distance)
- This dispersion can be reduced to 0.15 mag using the empirical correlations between the SNe Ia peak absolute brightness and their light curve shapes.

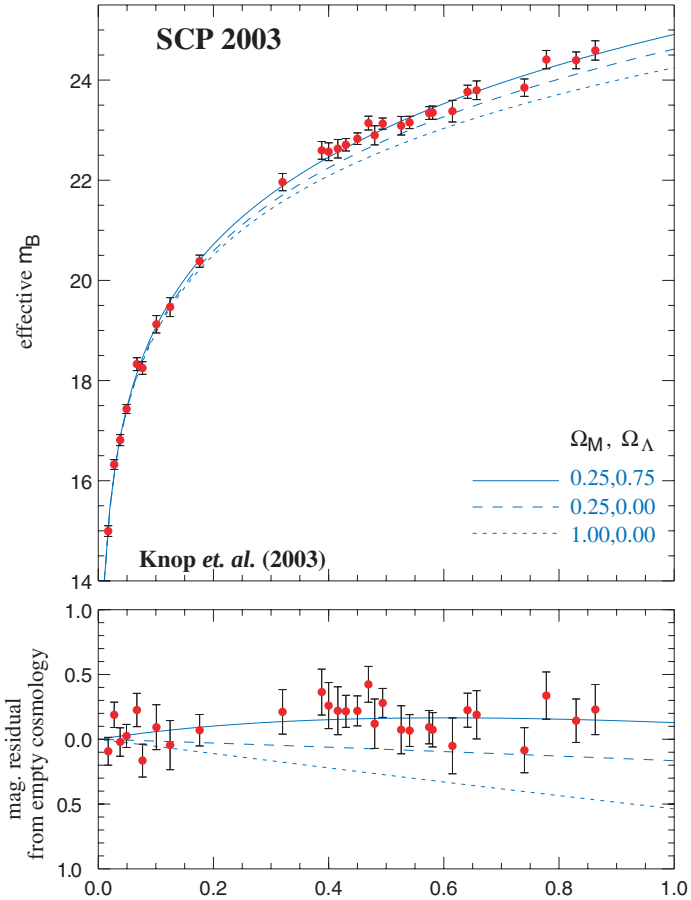
$$\phi_{obs} = \frac{L(\lambda_{obs}/(1+z))}{4\pi(1+z)d_L^2}$$

- Systematics
  - Dust ?
  - Evolution ?
  - $K-$corrections ?
  - Modeling of SN Ia Spectrum ?



First Measurements

- First measurements
  - (Riess et al, 1998) [10 SNe Ia]
  - (Perlmutter et al, 1999) [42 SNe Ia]
- HST
  - (Sullivan, 2002) [Host Galaxy Types]
  - (Tonry, 2003) [+10 high-z SNe]
  - (Barris, 2003) [+23 SNe Ia @ $z < 1$]
  - (Knop, 2003) [+11 SNe Ia, followed-up with HST]
  - (Riess, 2004) [+16 SNe Ia, discovered with HST ($z \rightarrow 1.6$)]
- New Generation Surveys
  - (SNLS Coll., 2005) [71 new SNe Ia, $0.3 < z < 0.9$, 700 by the end of the SNLS]



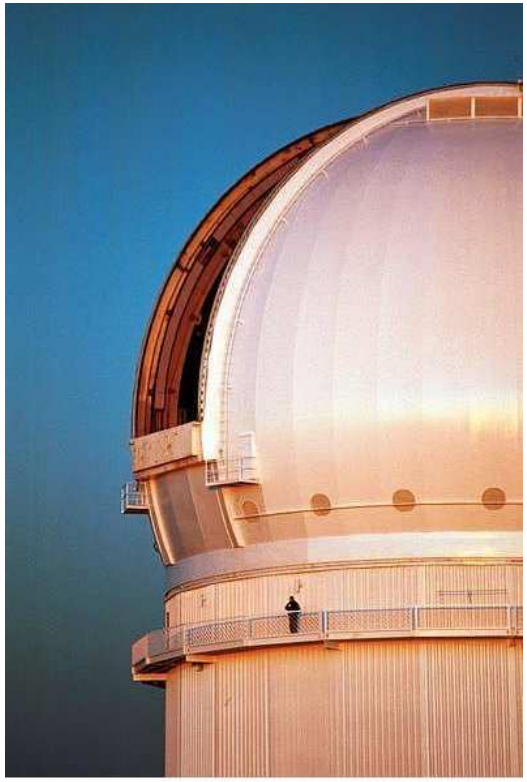
SuperNova Legacy Survey (SNLS)

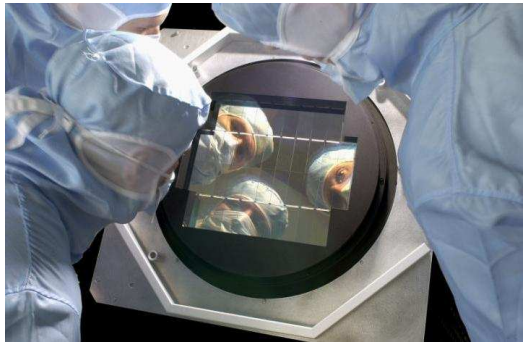
- $O(1000)$ SNe Ia ($10\times$ present statistics)
  - detected before maximum
  - followed-up in 4 passbands (g_M, r_M, i_M, z_M) ($\sim$ SDSS bands)
  - a good sampling of the lightcurves (1 point every 3 days)
  - spectroscopic identification of all the SNe Ia
- Large statistics $\longrightarrow$ better control of the systematics
- One single detector $\longrightarrow$ better control of calibration & selection bias
- Multiband observations $\longrightarrow$ to follow the same spectral region @ different z

BV @ $z \sim 0$	$\longrightarrow$	gr @ $z \sim 0.2$
	$\longrightarrow$	ri @ $z \sim 0.4$
	$\longrightarrow$	iz @ $z \sim 0.8$

The Photometric Survey

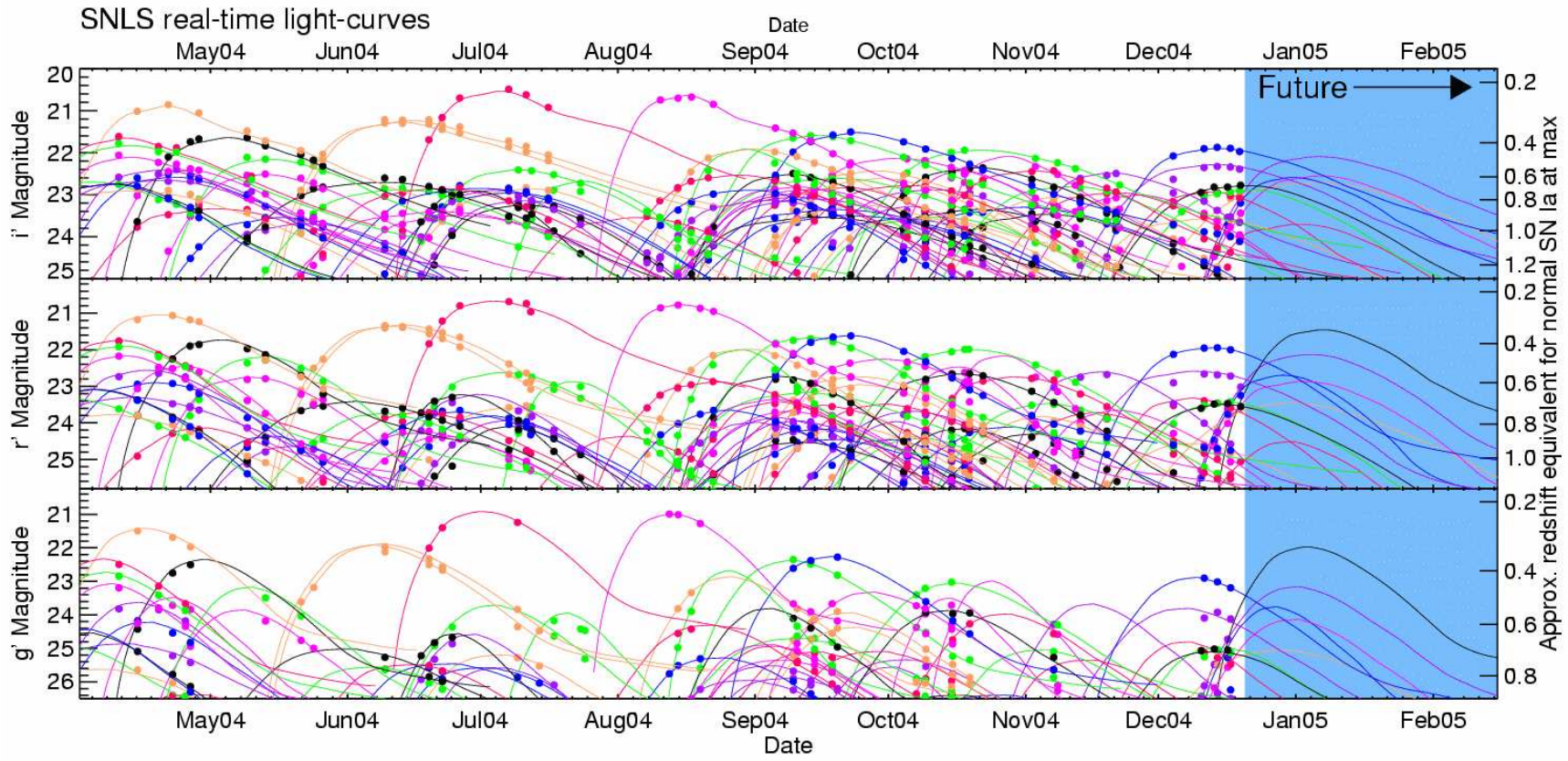
- $\sim$ 300h / year on a 3.6-m
  - CFHT @ Hawaii
- Wide Field Camera
  - Megacam (CEA/DAPNIA)
  - 1 deg^2, 36 2k$\times$4k CCDs
  - Good PSF sampling 1 pix = 0.2"
  - Excellent image quality 0.7" (FWHM)
- *Rolling search* mode
- Component of the CFHTLS survey
  - 40 nights / year during 5 years
  - Four 1-deg^2 fields
  - repeated observations (3-4 nights)
  - in 4 bands ($griz$)
  - queue observing (minimize impact of bad weather)





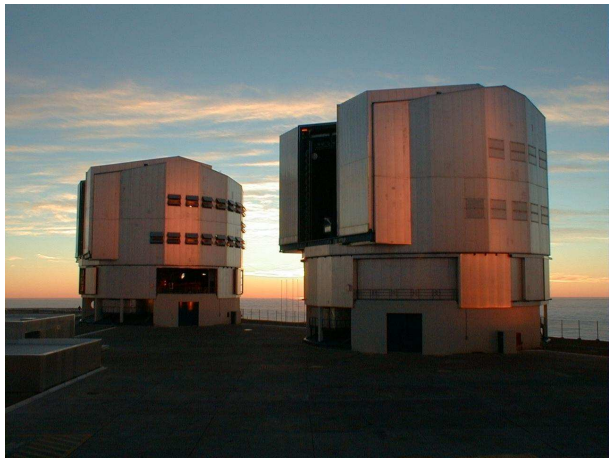
Rolling Search

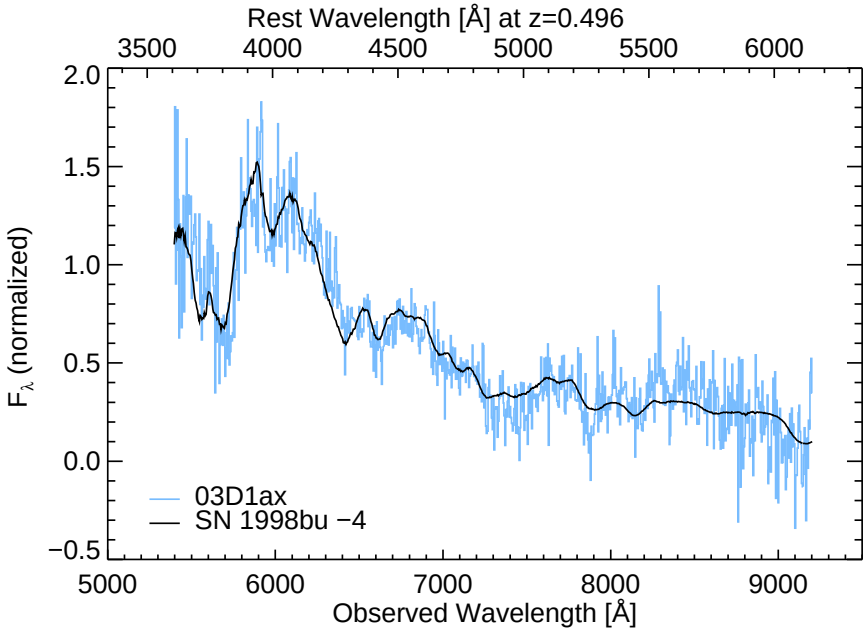
- Follow-up and detection performed on the same dataset
- 4 1 deg^2 fields (2 fields visible at a given time of the year)
- Observations every 2-3 nights, during new moon periods ($15 - 18$ days).
- $griz$ bands used for the detection
- 5 years $\rightarrow$ 2000 detections $\rightarrow$ 700 identified supernovae



The Spectroscopic Survey

- Goals
  - spectral identification of SNe Ia ($z < 1$)
  - redshift determination (host galaxy)
  - complementary programs
- $\sim$ 300h / year 8-m telescopes
  - VLT Large program (60h / semester)
  - Gemini (60h / semester)
  - Keck (30h / year, in one semester)



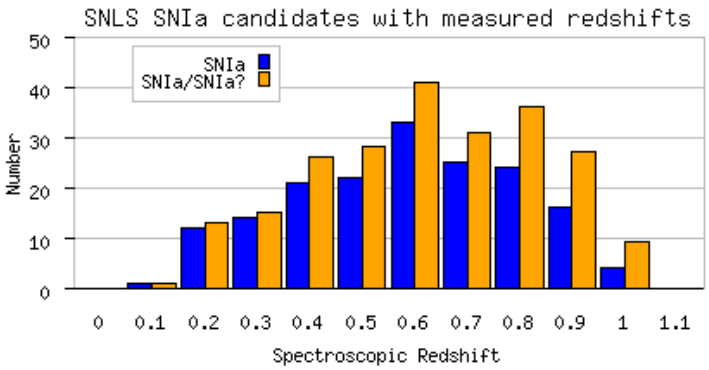


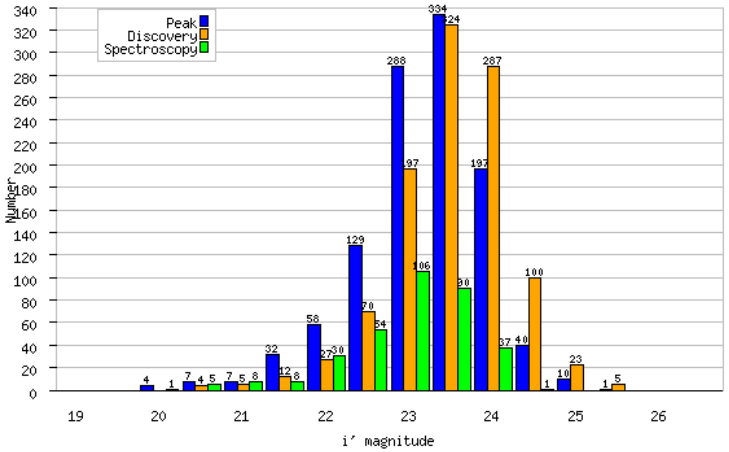
(from Howell et al, 2005 (ApJ 634 (1190)))

Progress

Candidate List is public:

http://legacy.astro.utoronto.ca





Telescope	SNIa/SNIa?	SNII/SNII?	Total SN/SN?	Other	Total
Gem	96	9	142	0	142
Keck	77	21	137	4	141
VLT	120	22	215	13	228

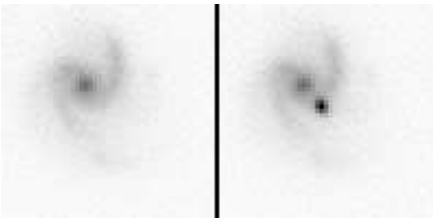
currently $>$ 300 identified SNe Ia/SNe Ia?

Analysis of the First Year Data

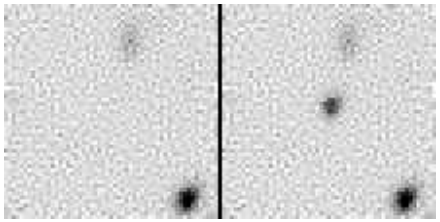
- Differential photometry
- PSF photometry of the field stars
- Calibration of the DEEP fields
- Fit of multicolor lightcurves
- Luminosity Distance Estimation
- Cosmological Results
- Systematics

Differential photometry

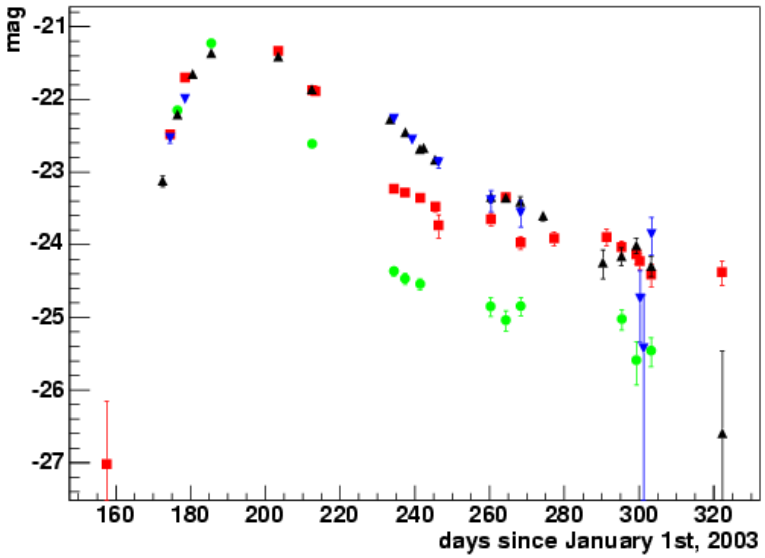
$$I(x,y) = \text{Flux} \times [\text{Kernel} \otimes \text{PSF}_{\text{best}}](x - x_{sn}, y - y_{sn}) + [\text{Kernel} \otimes \text{Galaxy}_{\text{best}}](x,y) + \text{Sky}$$

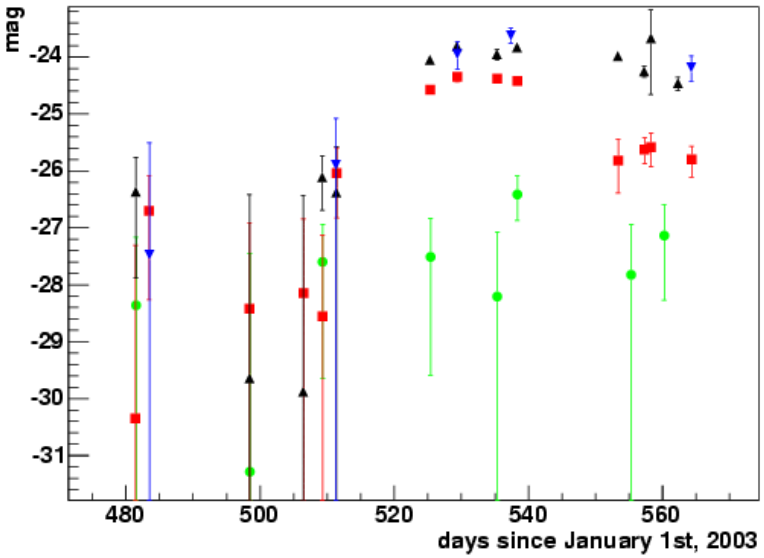


$(z = 0.28)$

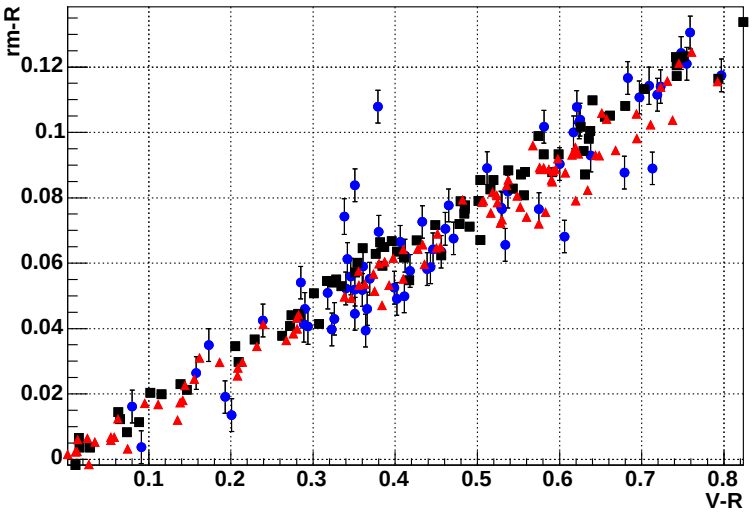


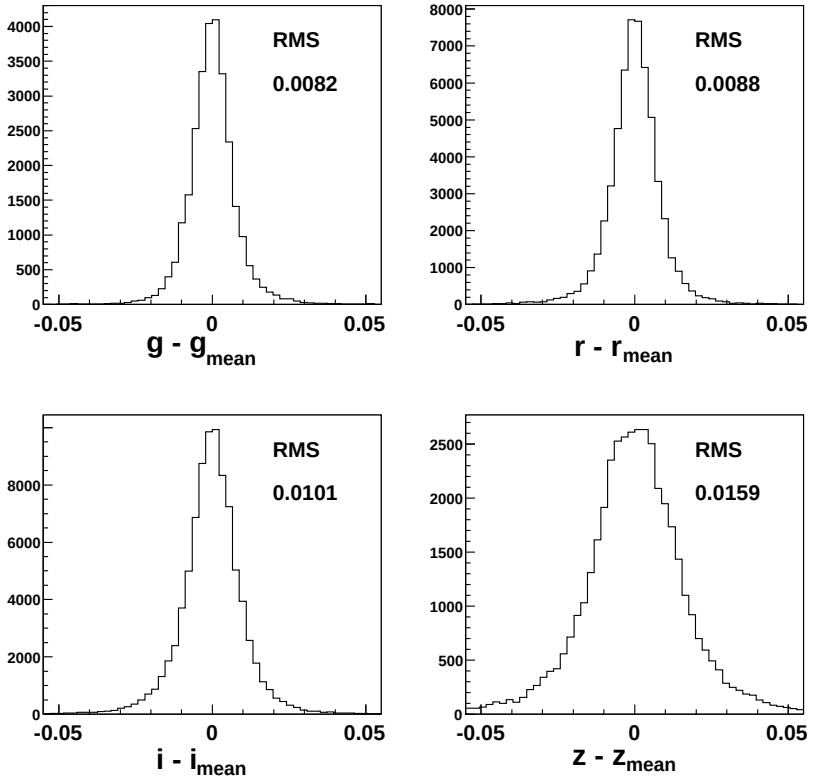
$(z = 0.95)$





Photometric Calibration





- align the SNLS flux scales on the nearby supernova flux scales
- using repeated (photometric) observations of Landolt stars
- then, we use well measured field stars to transport the calibration

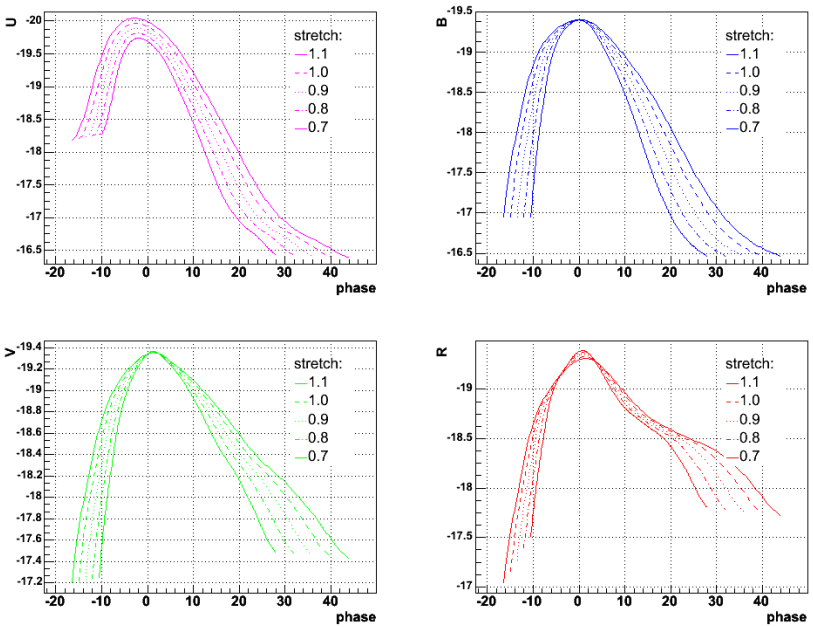
alignment precision on the Landolt catalog: $\sim 1 - 3\%$

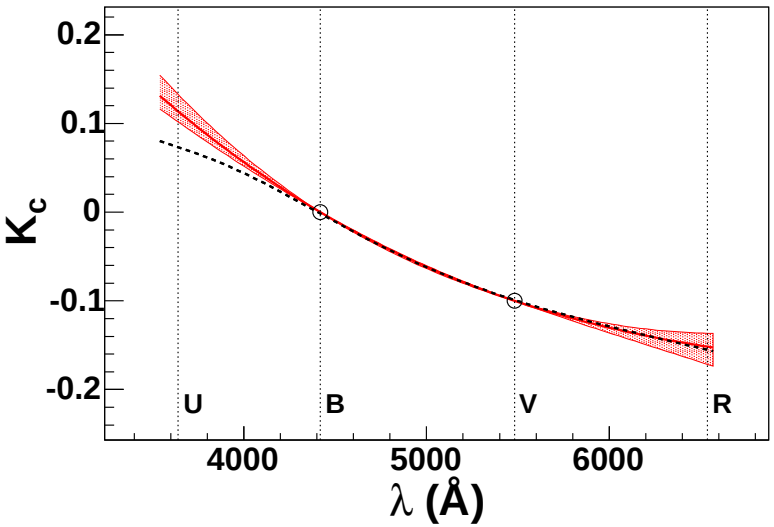
- monitor the stability of the camera
- assert the spatial uniformity of the camera (36 independant CCDs)

repeatability of the measurements: $< 1\%$ in gri, $\sim 1.5\%$ in z

Spectral Adaptive Lightcurve Templat

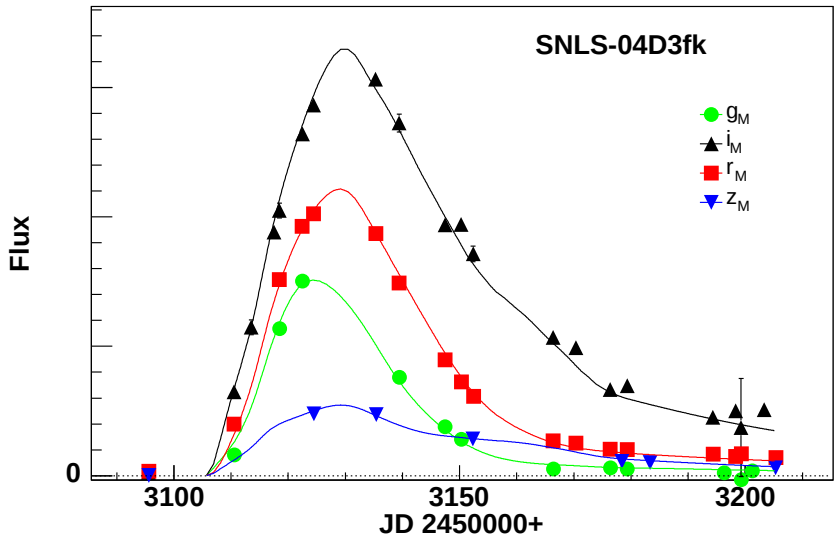
(Guy et al, 2005) – (A&A 443, 781) – (astro-ph/0506583)

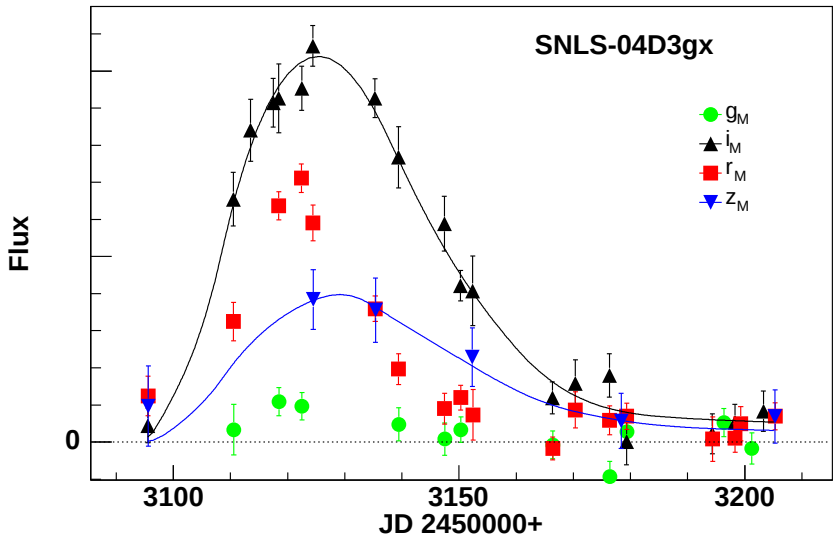




- Empirical model of SN Ia Spectral Energy Distribution (SED) as a function of
  - the date w.r.t. the date of B maximum
  - the rest-frame wavelength
  - dilatation of phase axis in the B-band (stretch)
  - a color parameter (@ B-band maximum)
- Trained on a sample of nearby SNe Ia in $UBVR$ (w/o using their distances)

Lightcurve fits



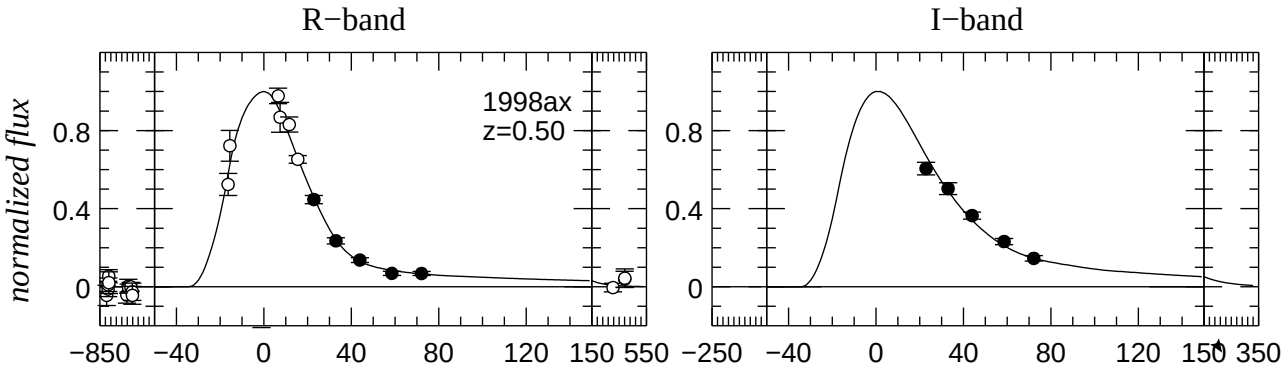


$z = 0.3578$

$z = 0.91$

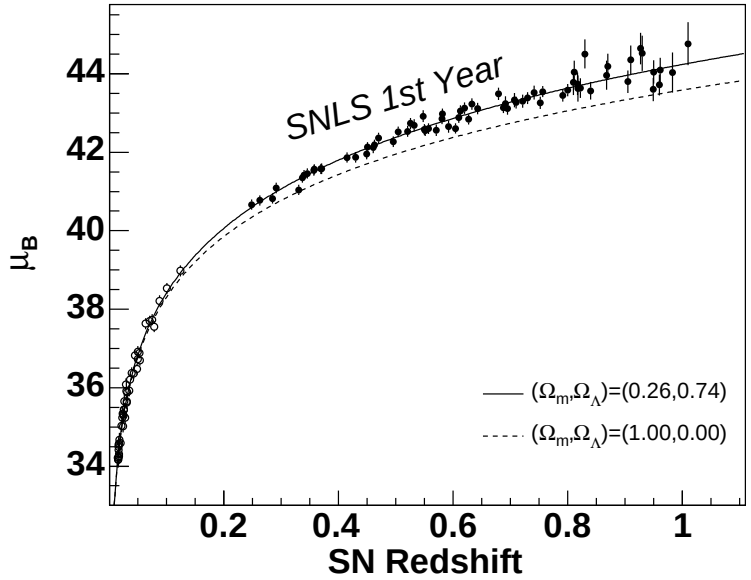
compare with LC from (Knop et al, 2003)

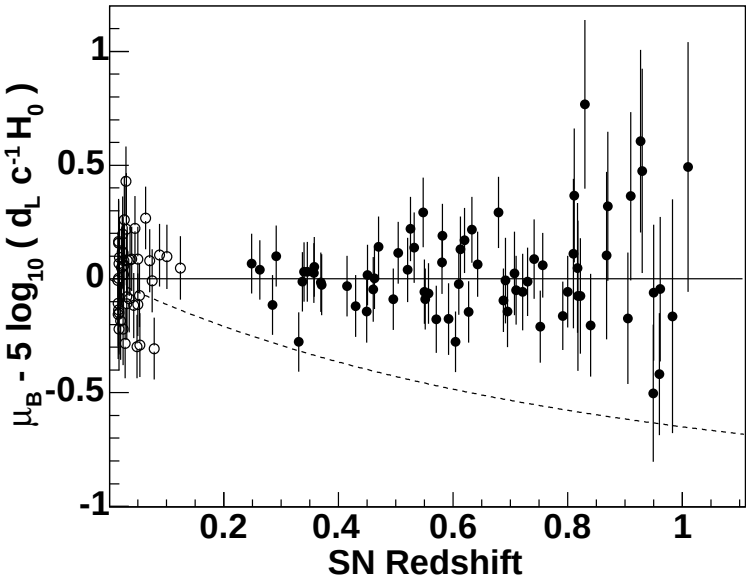
2 bands, HST + Ground base telescopes



SNLS First Year Hubble Diagram

(Astier et al (SNLS), 2005)





- Distance Estimate

$$m_B(z) - \mathcal{M}_B - \alpha\,(s-1) + \beta\,c = 5\,\log_{10}\left(\frac{d_L H_0}{c}\right.$$

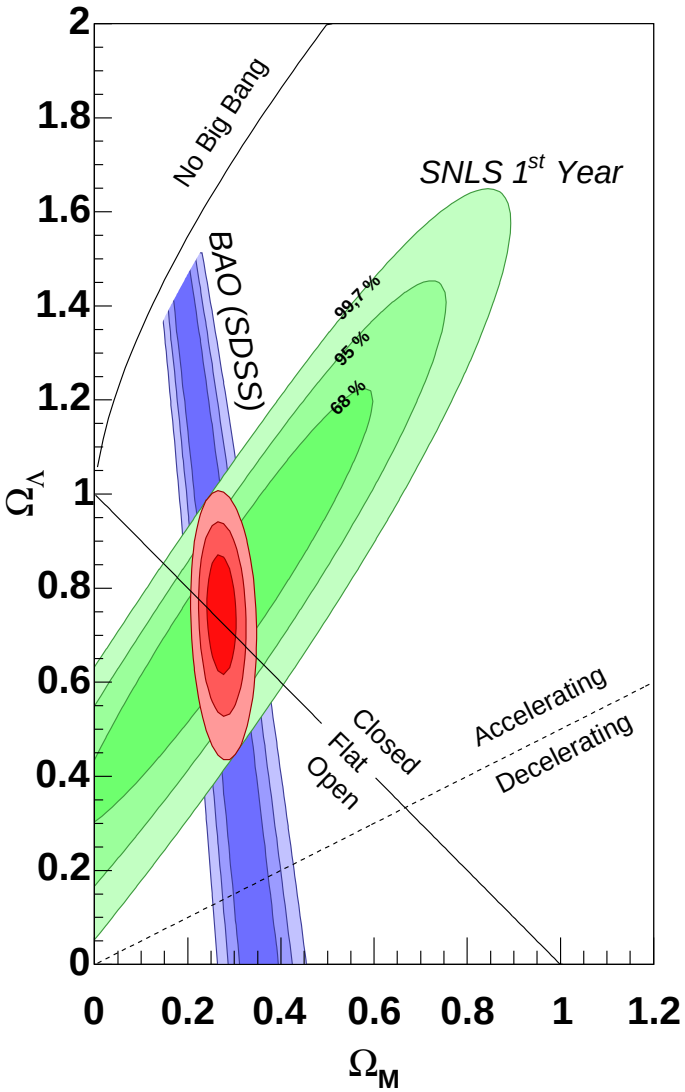
- Fitting simultaneously α, β, $\mathcal{M}$ and the cosmological parameters.

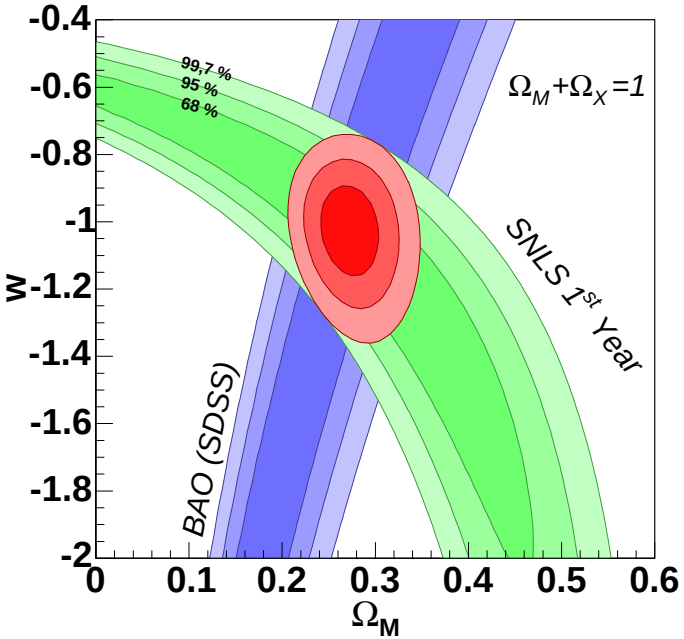
$$\chi^2 = \sum_{objects} \frac{\mu_B - 5\log_{10}(d_L(\theta,z)/10pc)}{\sigma^2_{\mu_B} + \sigma^2_{int}}$$

- Objects
  - 44 nearby SNe Ia (literature)
  - 71 SNLS SNe Ia
- $\chi^2/\mathrm{dof} = 1$ if we add an intrinsic dispersion $\sigma_{int} \sim 0.13$ mag

Cosmological Parameters

(Astier et al (SNLS), 2005)

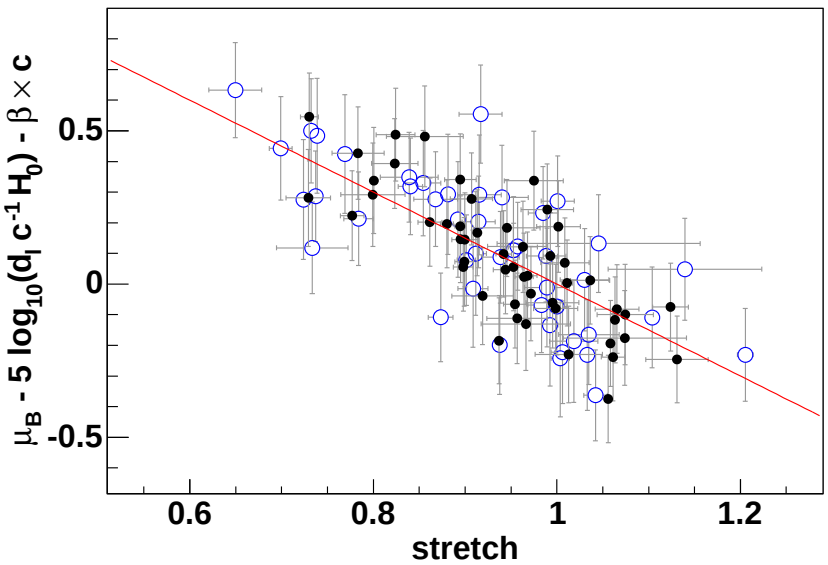




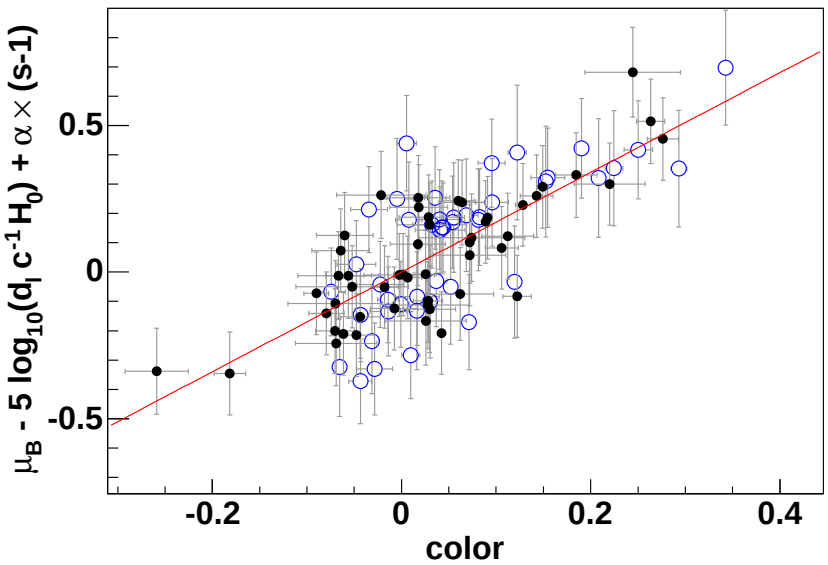
- BAO = Baryon Accoustic Peak (Eisenstein, 2005)
- 68.3, 95.5 and 99.7 CL

fit	parameters (stat only)
$(\Omega_m, \Omega_\Lambda)$	$(0.31 \pm 0.21, 0.80 \pm 0.31)$
$(\Omega_m - \Omega_\Lambda, \Omega_m + \Omega_\Lambda)$	$(-0.49 \pm 0.12, 1.11 \pm 0.52)$
$(\Omega_m, \Omega_\Lambda)$ flat	$\Omega_m = 0.263 \pm 0.037$
$(\Omega_m, \Omega_\Lambda)$ + BAO	$(0.271 \pm 0.020, 0.751 \pm 0.082)$
(Ω_m, w)+BAO	$(0.271 \pm 0.021, -1.023 \pm 0.087)$

Nearby versus Distant Samples



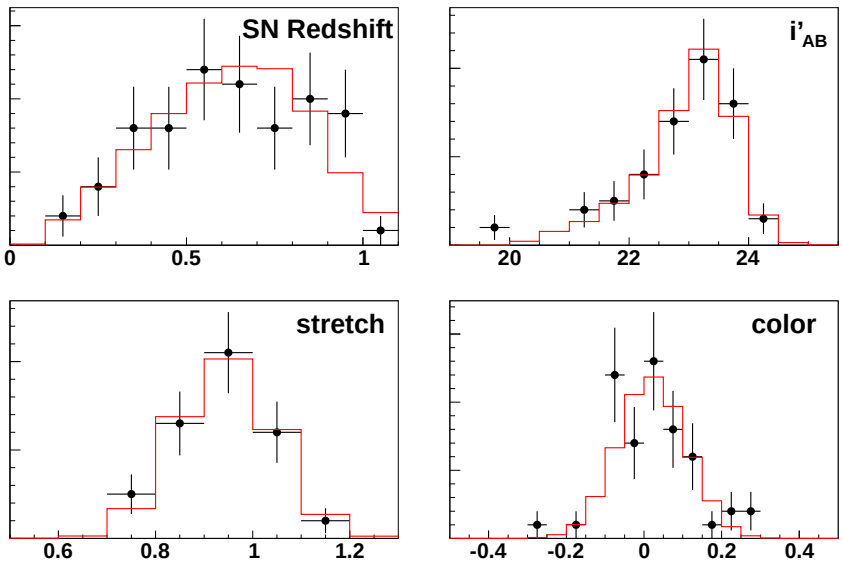
Hubble diagram residuals
(no stretch corrections applied)
as a function of stretch.

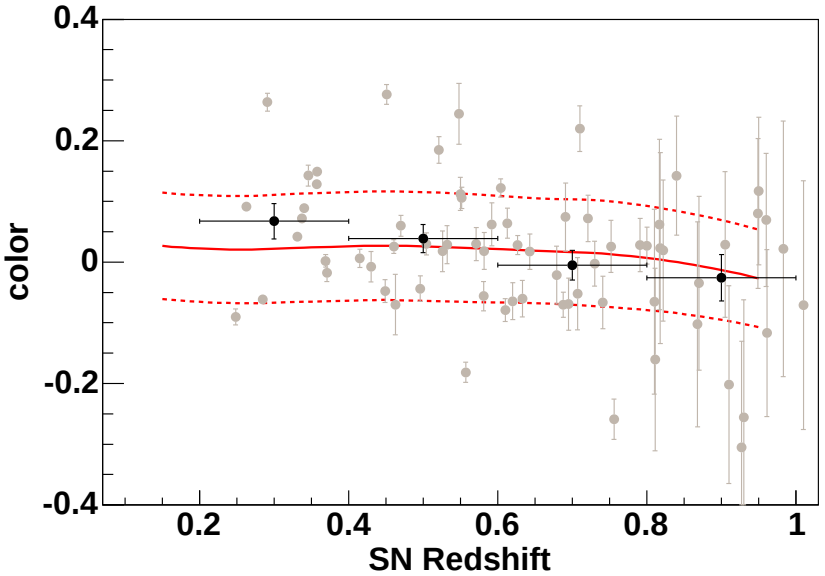


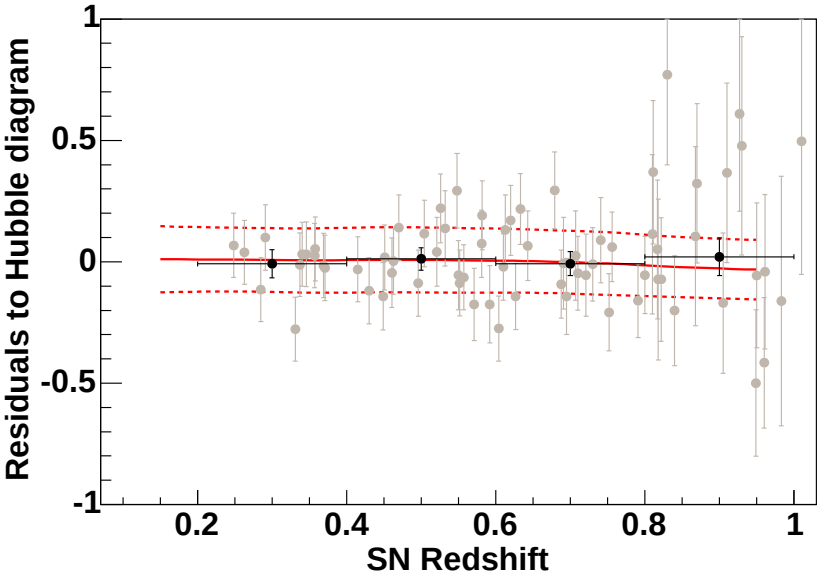
Hubble diagram residuals
(no color corrections applied)
as a function of color.

- brighter-bluer and brighter-slower relations at $z = 0$ (blue points) and $z \sim 0.6$ (black points) are compatible

Mamquist bias



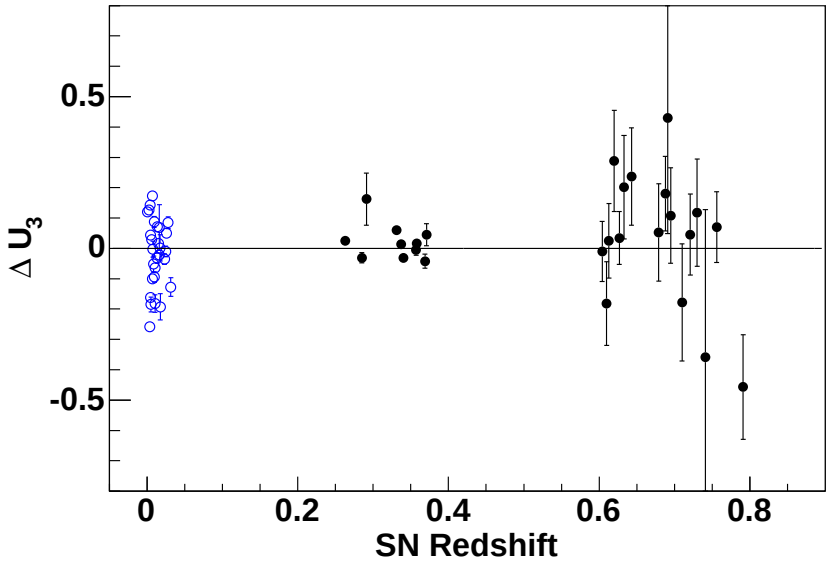




- As we get closer to the detection limit, we are more likely to detect brigther (bluer, slower) supernovae
- Impact on Ω_m (flat ΛCDM):
- affects nearby sample and SNLS sample
  - Nearby SNe: $+0.019 \pm 0.012$
  - SNLS SNe: -0.020 ± 0.010

SN Ia SED Modeling

- Compare
  - model predictions (U magnitude guessed from the B and V bands)
  - actual measurements (B measured U-band)



$$\Delta U3 = U(\mathrm{measured}) - U(\mathrm{guessedfrom}BV)$$

- SNLS data is redundant enough to allow one to check the SNe Ia modeling.

Summary of Identified Systematics

- Calibration
  - detector modeling (passbands, . . .)
  - photometric alignment on the low-z SN Ia sample
- Evolution
- Empirical SN Ia SED modeling
- Malmquist bias –we select only the brightest objects
- Contamination by SN Ib, SN Ic misidentified as SNe Ia.
- Grey dust
- Gravitational lensing at high-z

Source	$\sigma(\Omega_m)$ (flat)	$\sigma(\Omega_{tot})$	$\sigma(w)$	$\sigma(\Omega_m)$ (with BAO)	$\sigma(w)$ (with BAO)
Phot. Calibration	0.024	0.51	0.05	0.004	0.040
Vega spectrum	0.012	0.02	0.03	0.003	0.024
Filter bandpasses	0.007	0.01	0.02	0.002	0.013
Malmquist bias	0.016	0.22	0.03	0.004	0.025
Sum (sys)	0.032	0.55	0.07	0.007	0.054

Conclusion

- CFHTLS data taking is extremely efficient
  - observing queue efficiency improved
  - wide field corrector fixed $\Rightarrow$ excellent image quality
- More SNe Ia in one year than all previous ground based surveys.
- Hubble diagram with 71 SNLS supernovae and 45 nearby supernovae.
- For a flat ΛCDM model ($w = -1$)

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

- For a flat (Ω_m, w) cosmology (with BAO)

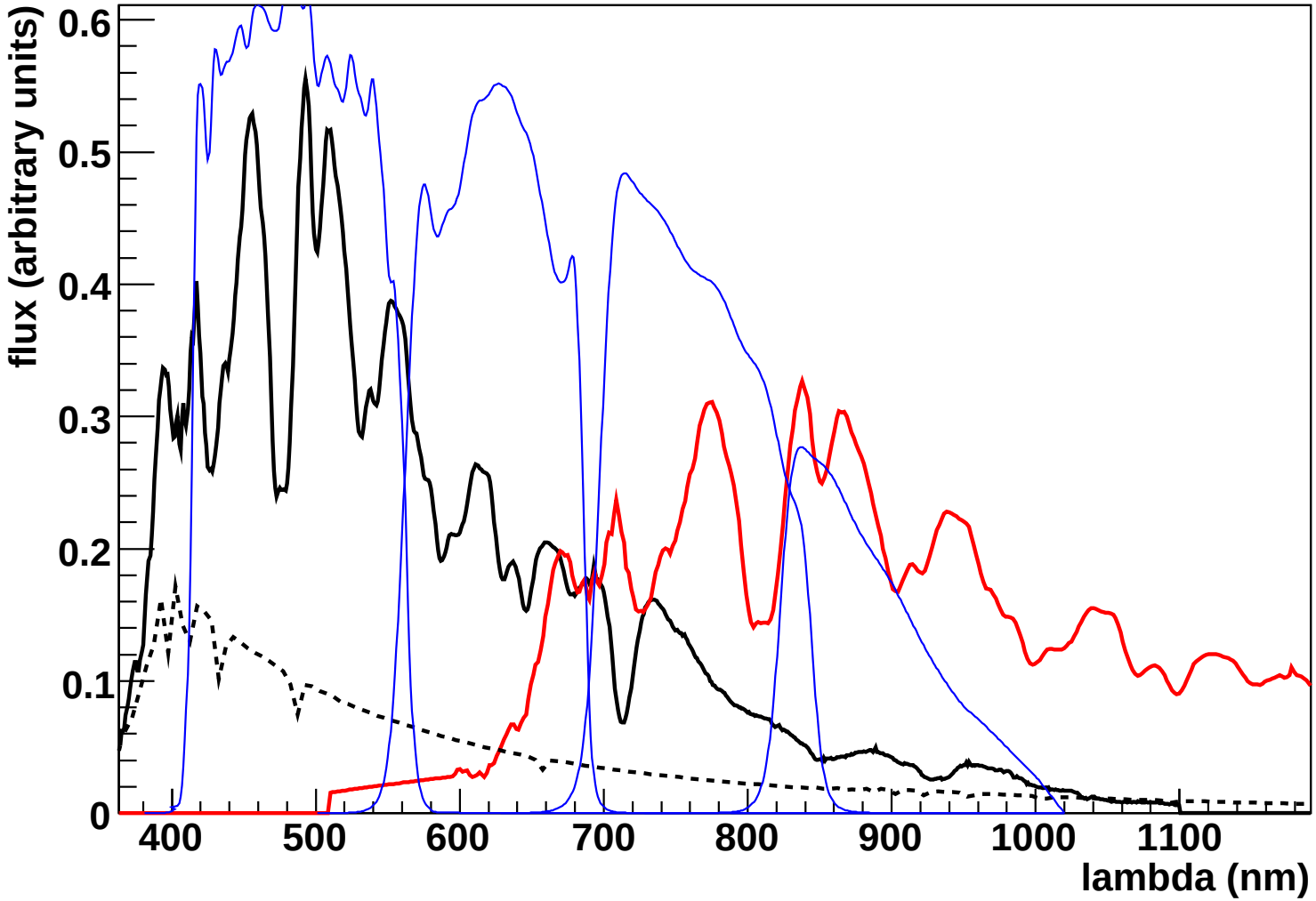
$$\begin{aligned} \Omega_m &= 0.271 \pm 0.021(stat) \pm 0.007(sys) \\ w &= -1.023 \pm 0.090(stat) \pm 0.054(sys) \end{aligned}$$

- More than 300 additional supernovae already on disk, and 700 supernovae by the end of the survey.
- Statistical errors improved by a factor ~ 2 by the end of the survey
- SNLS dataset large and redundant enough to test carefully the systematics (SN modeling, calibration).

Conclusion

- Ongoing work on improving the calibration
  - specific observation programs
  - instrumental calibration (using lab standards) under study
- Modeling the SNe Ia SED (in the blue and near-UV)
- SNIa properties w.r.t. their host galaxy types / ages
  - Sullivan et al, ApJ accepted, `astro-ph/0605455`
- Photometric identification
  - 30% more SNe Ia at $z > 0.8$
- SN detection efficiencies
  - better control of selection bias
  - better control of contamination by non SN Ia
- SN rates as a function of z
  - Neill et al, AJ accepted, `astro-ph/0605148`
- Not enough Nearby Supernovae !

Calibration (I)



Calibration (II)