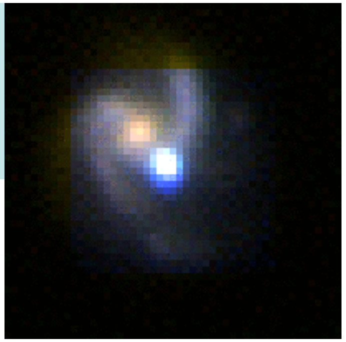
Supernovae Ia and Dark Energy

The Supernova Legacy Survey
3-year results

on behalf of SNLS
Delphine Hardin, LPNHE, Université Pierre et Marie Curie, Paris, France

HEP 2011, Genoble, France, July 22 2011

supernovae Ia and Dark Energy



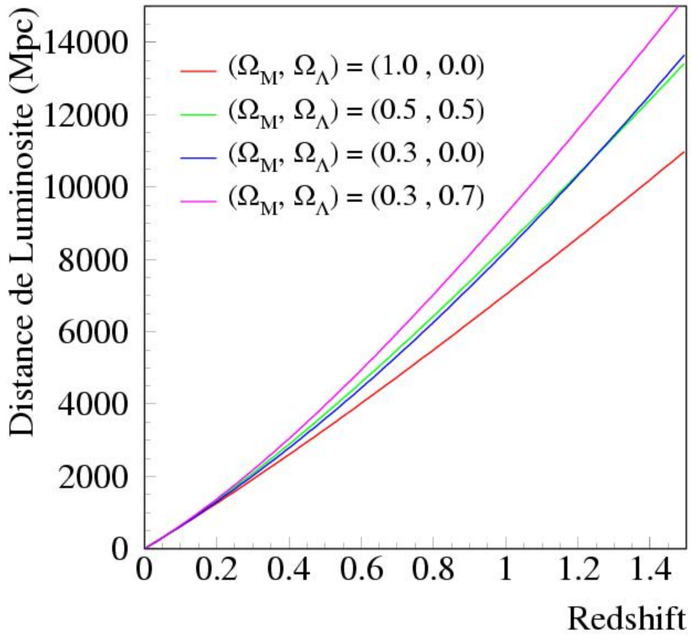
1. Measuring the Energy Content of the Universe

2. Cosmology with type Ia supernovae

3. SNLS 3-years analysis & results

4. What's next ?

Measuring the Energy Content of the Universe



Universe in expansion : d ∝ expansion factor **a(t)**

expansion history ⇔ energy content

when observing a luminous source, we measure :

- the redshift z : $1+z = \Delta\lambda/\lambda = a^{-1}(t)$
- the flux F : ➔ luminosity distance $\mathbf{d_L}$ (**L** : luminosity)

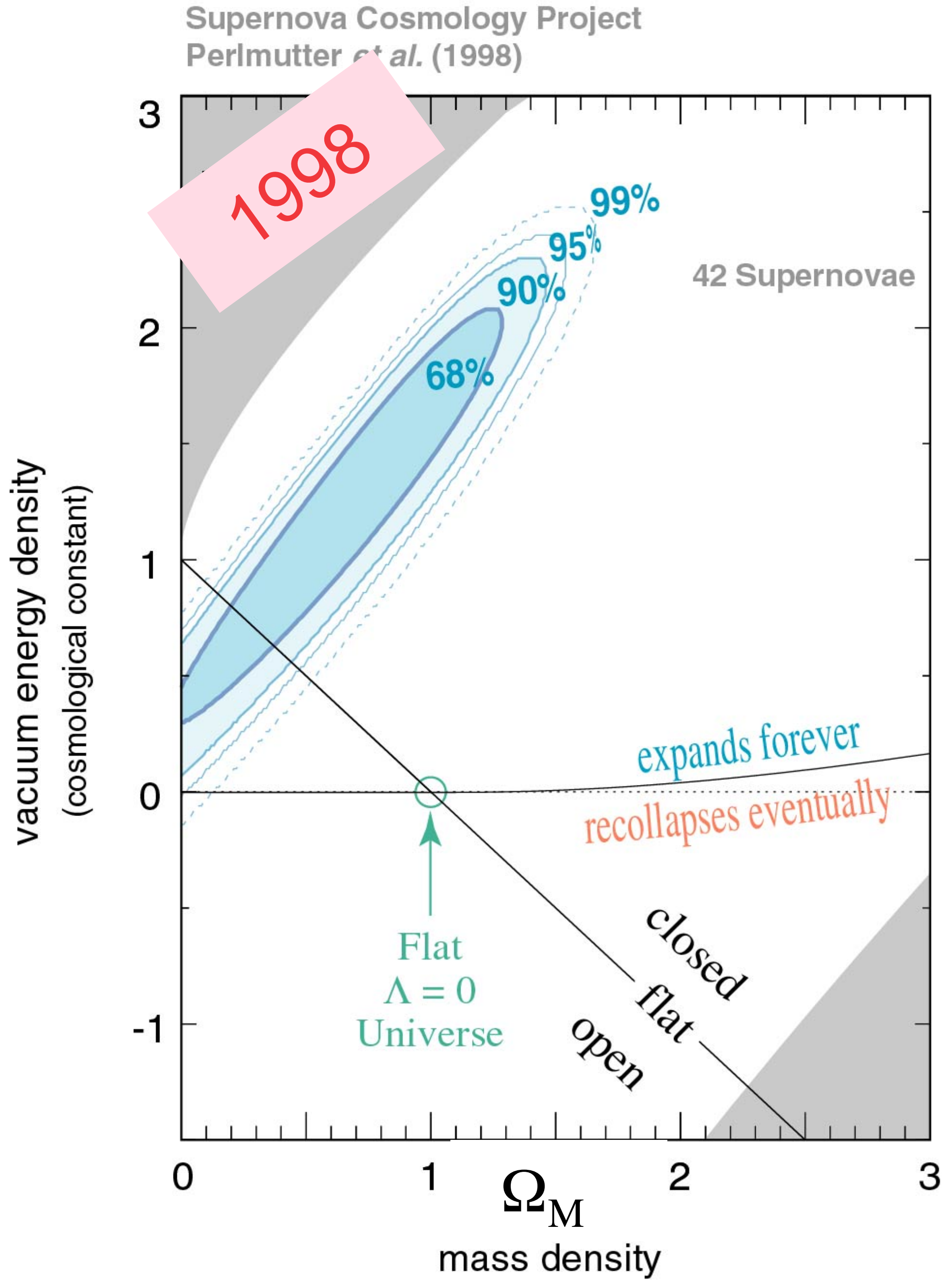
$$d_L = (L / 4\pi F)^{1/2}$$

•***Hubble Diagram :* $\mathbf{d_L(z)}$**

$$d_L(z) = \frac{cz}{H_0} \times \mathcal{D}(z; \Omega_M, \Omega_X, w_0, \ldots)$$

matter : $\rho_M(t_0)$ or : $\Omega_M = \rho_M(t_0)/\rho_{\rm crit}(t_0)$

Measuring the Energy Content of the Universe



expansion is accelerating :
X necessary !!

Flat universe: $\Omega_M + \Omega_\Lambda = 1$

➔ $\Omega_\Lambda \sim 0.7$

Measuring the Energy Content of the Universe

What is X (dark energy) ?

X: perfect fluid with equation of state $w = p/\rho$ & Ω_X

- Cosmological Constant Λ : formally equivalent to fluid with $\rho_\Lambda = \Lambda/(8\pi G)$ & $w_\Lambda = -1$
- Vacuum Energy : $\rho_V(t) = \text{cste} \rightarrow w_V = -1$
- X : $w = \text{cste}$, or $w = w(z) = w_0 + (1-a)\, w'$

To measure w precisely :

- low-z and high-z d_L
- high precision on d_L
- Ω_M prior or constraint increases precision

Measuring the Energy Content of the Universe

Standard Candles to Probe the Expansion History

$$d_L \equiv \left(\frac{L}{4\pi F}\right)^{1/2} = \frac{cz}{H_0} \times \mathcal{D}(z; \Omega_M, \Omega_X, w)$$

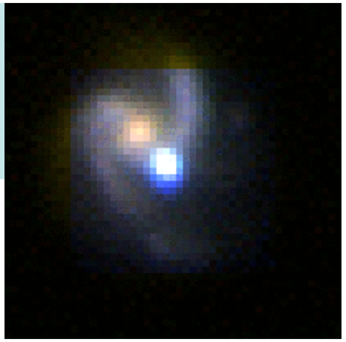
Problem : we measure the flux **F**, how do we know the luminosity **L** ????

STANDARD CANDLES : **L ≈ cste**

→ compare the fluxes of 2 standard candles at $\mathbf{z_1}$ and $\mathbf{z_2}$

$$\frac{d_L(z_1)}{d_L(z_2)} = \left(\frac{F_2}{F_1}\right)^{1/2} = \mathcal{F}(z_i; \Omega_M, \Omega_X, w)$$

supernovae Ia and Dark Energy



1. Measuring the Energy Content of the Universe

2. <u>Cosmology with type Ia supernovae</u>

3. SNLS 3-years analysis & results

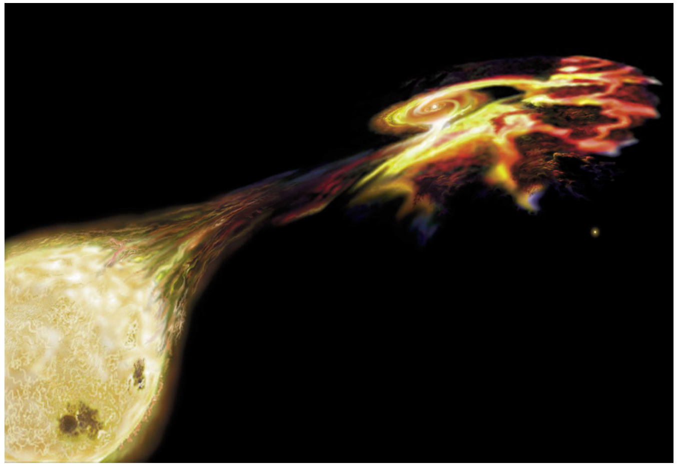
4. What's next ?

Type Ia Supernovae as cosmological tools

Type Ia Supernovae as Standard Candles

- thermonuclear explosion of a white dwarf :
  bright events (~10^{11} $L_\odot$)
- show little (40%) peak luminosity dispersion

…… they are standard candles

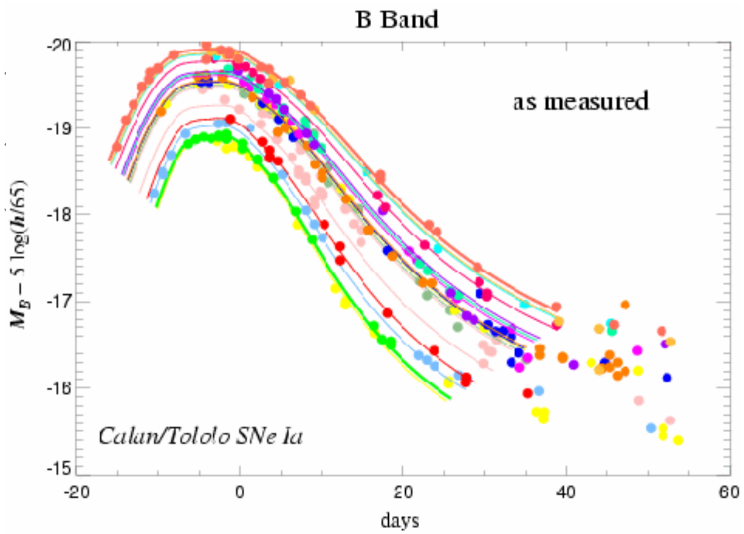


BUT :
- they show a light curve shape - luminosity relation :
  brighter - slower
- they also exhibit a color-luminosity relation :
  brighter-bluer

Standardisation : after empirical correction :

➙ 16% dispersion on L_{peak}

➙ 8% precision on distance d_L

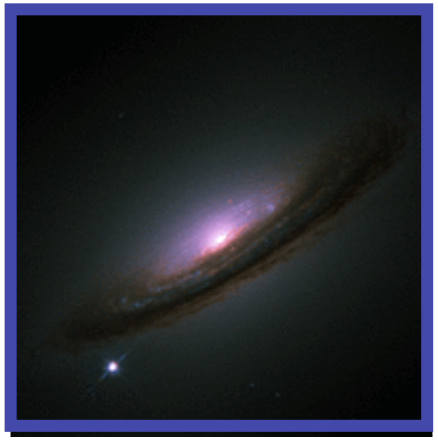


Type Ia Supernovae as cosmological tools

Type Ia Supernovae as Standard Candles

- thermonuclear explosion of a white dwarf :
  bright events (~10^{11} $L_{\odot}$)
- show little (40%) peak luminosity
  dispersion

…… they are standard candles

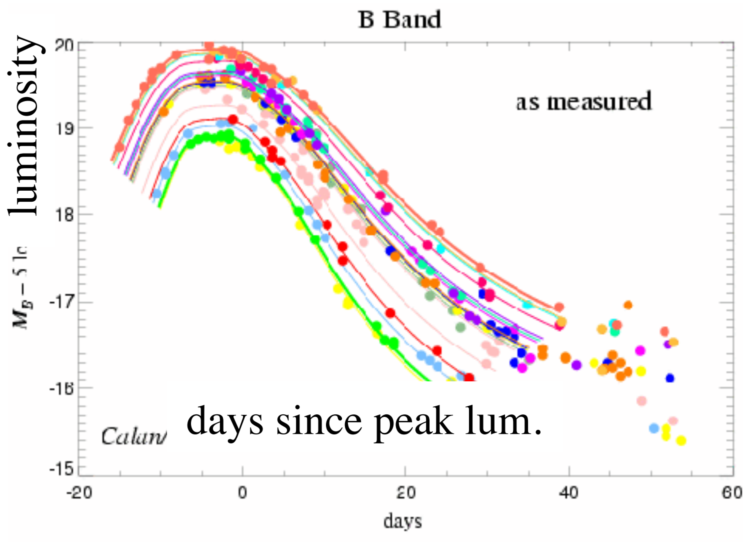


BUT :
- they show a light curve shape - luminosity relation :
  brighter - slower
- they also exhibit a color-luminosity relation :
  brighter-bluer

Standardisation : after empirical correction :

➡ 16% dispersion on $\mathbf{L_{peak}}$

➡ 8% precision on distance $\mathbf{d_L}$



Type Ia Supernovae as cosmological tools

Type Ia Supernovae as Standard Candles

- thermonuclear explosion of a white dwarf :
  bright events (~10^{11} $L_\odot$)
- show little (40%) peak luminosity dispersion

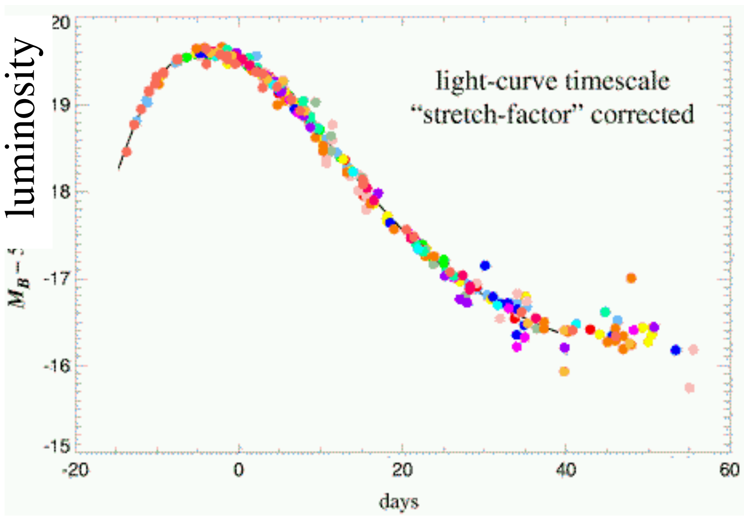
…… they are standard candles

BUT :
- they show a light curve shape - luminosity relation :
  brighter - slower
- they also exhibit a color-luminosity relation :
  brighter-bluer

Standardisation : after empirical correction :

➜ 16% dispersion on $\mathbf{L_{peak}}$

➜ 8% precision on distances $\mathbf{d_L}$



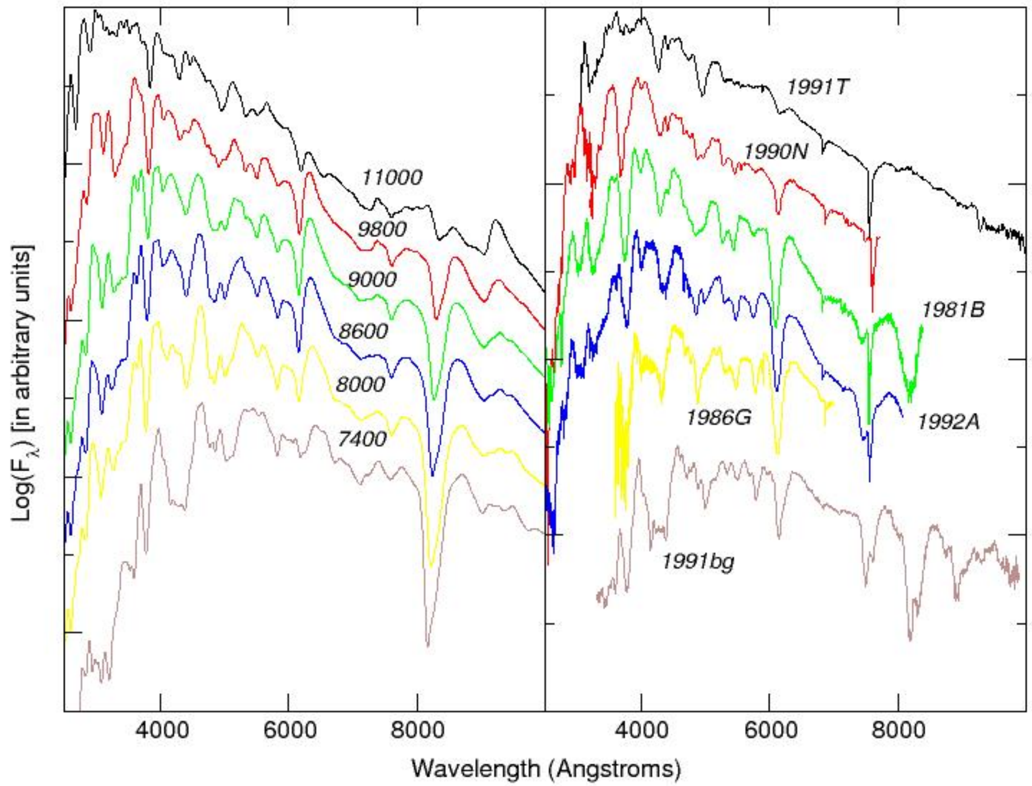
Type Ia Supernovae as cosmological tools

Supernovae Ia modelisation

Using radiative transfer codes, this relationship is reproduced simply by increasing the abundance of ^{56}Ni in the explosion.

Here this is characterized by increasing the effective temperature of the atmosphere.

Models Observations



Nugent et al., 1995

Type Ia Supernovae as cosmological tools

An empirical approach :

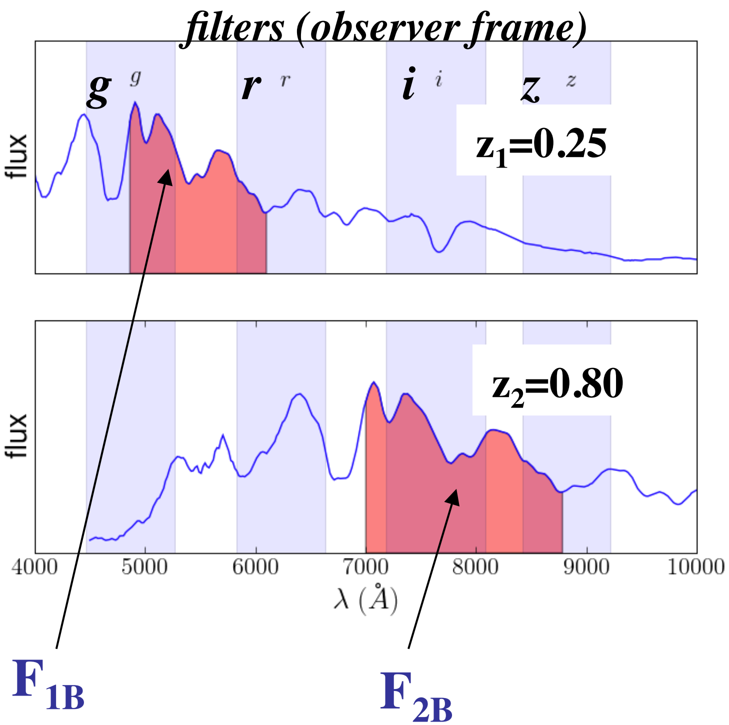
- comparing fluxes at different redshifts

- standardisation and distance estimator

Type Ia Supernovae as cosmological tools

comparing fluxes at different redshift

$$d_L \equiv \left(\frac{L}{4\pi F}\right)^{1/2} = \frac{cz}{H_0} \times \mathcal{D}(z; \Omega_M, \Omega_X, w)$$



F_B is the **restframe B band flux (m_B magnitude)** measured at ≠ redshifts
➞ in ≠ obs. frame filters
➞ flux inter-calibration of passbands

Calibration is crucial
(dominant systematics in survey)

to get **m_B at peak**, ***shape & color*** **:**
➞ empirical **spectro-photometric modeling** $\phi(\lambda, t)$ to interpolate between photometric measurements
➞ trained on a set of nearby & distant SNe

Type Ia Supernovae as cosmological tools

standardisation & distance estimator

distance — flux (magnitude) — luminosity (absolute magnitude)

$$\mu(z\,;\Omega_M,\Omega_X,w) = m_B - (M_B - \alpha\,\textit{shape} + \beta\,\textit{color})$$

m_B: measured peak magnitude in restframe B filter

M_B: absolute B (peak) magnitude for the « standard » SN (*shape*=0, *color*=0)

α *shape*: light-curve shape correction

β *color*: color correction

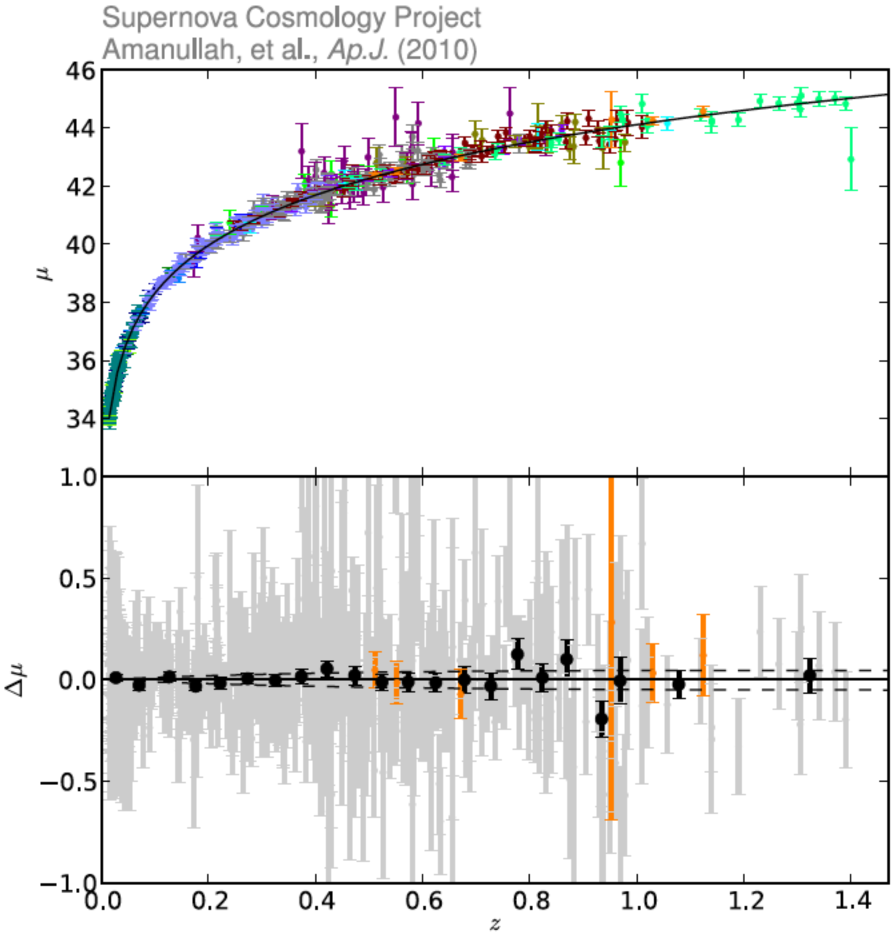
- m_B , ***shape*** , ***color*** measured on each SN
- M_B, α, β fitted on Hubble diagram along with cosmology

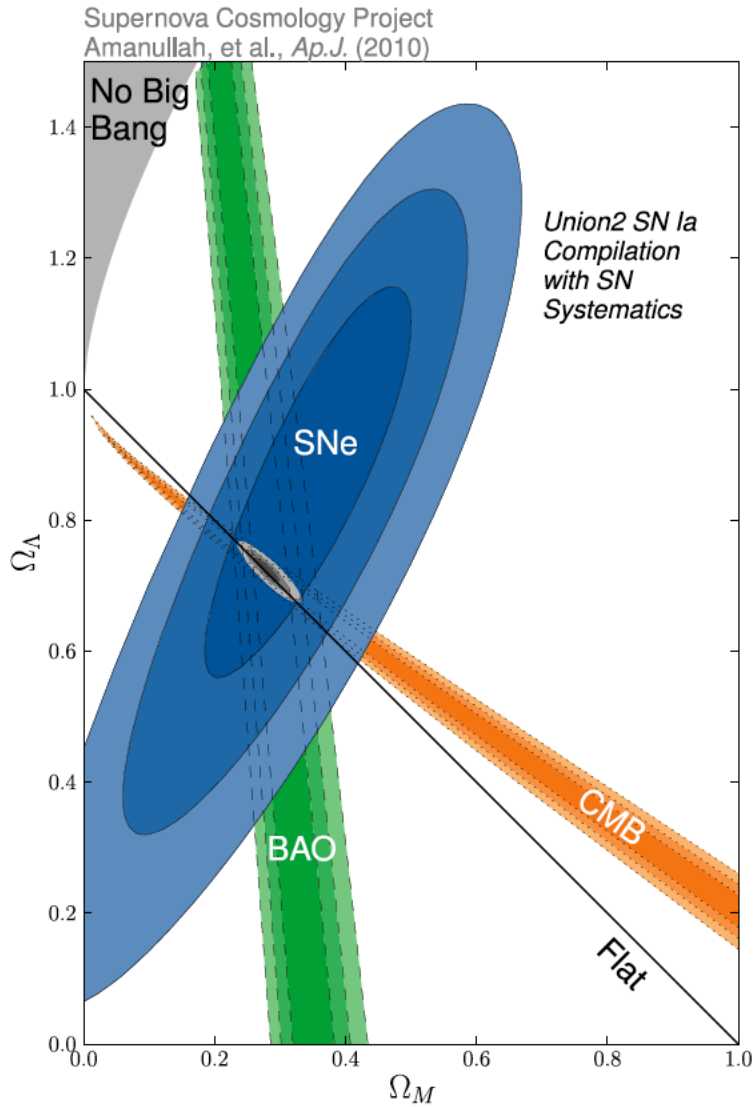
α : brighter-slower relation

β : brighter-bluer relation -- no assumption whether intrisic or due to extinction by dust

Type Ia Supernovae as cosmological tools

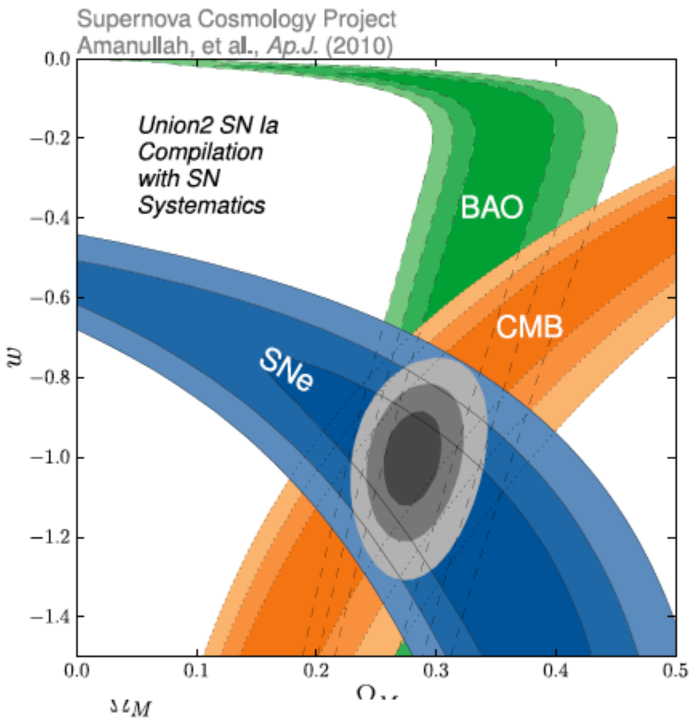
Hubble diagram and cosmological constraints





Type Ia Supernovae as cosmological tools

Dark Energy ?



SNe+BAO(+CMB) $\rightarrow w \simeq -1 \pm 0.1(sys.)$

Type Ia Supernovae as cosmological tools

Recent SN surveys and compilations

Recent photometric samples :

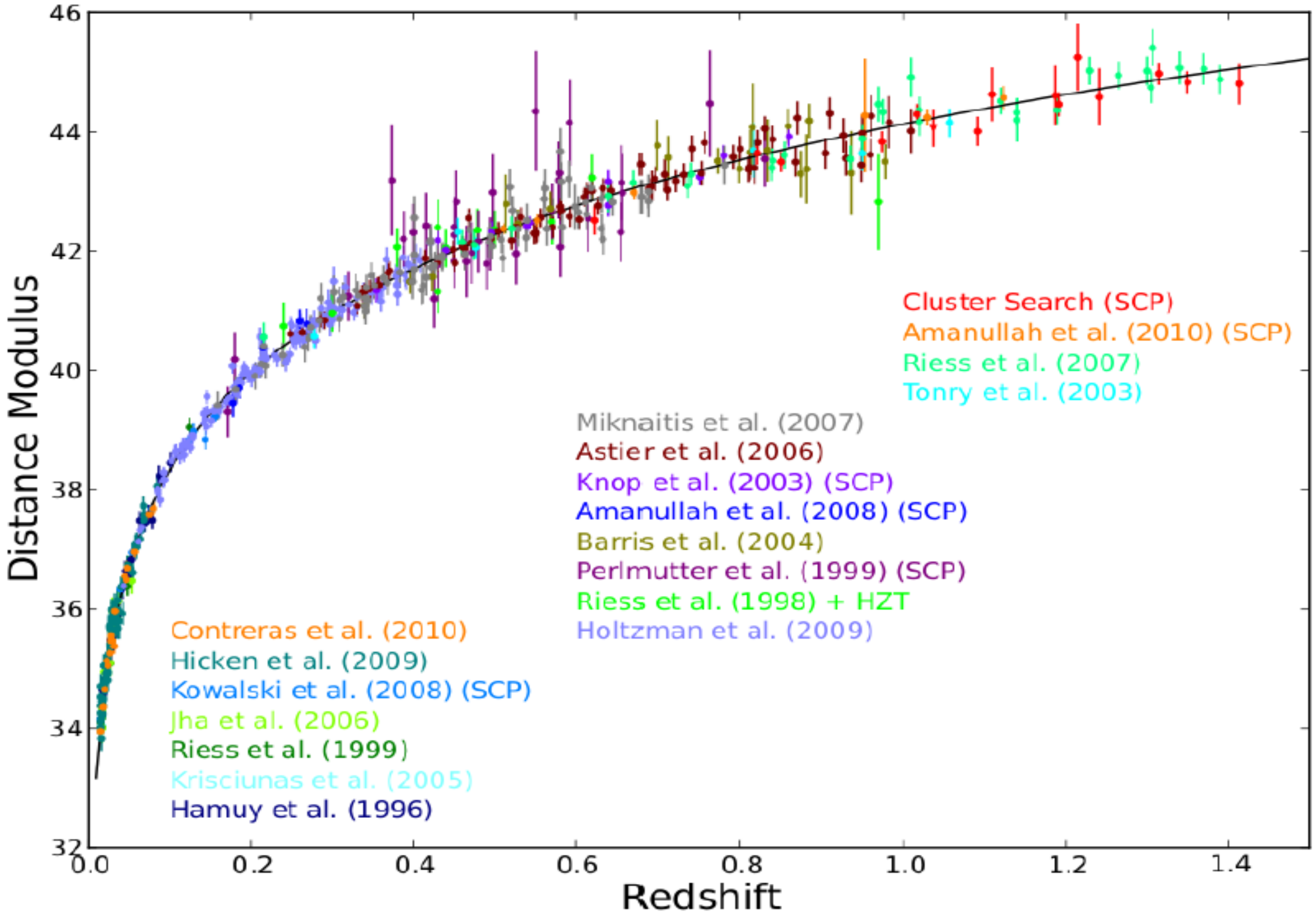
- Carnegie Sample (~ **20+30** , Freedman, 2009 (I-band HD), Folatelli 2010)
- SDSS-II (~**100**, Kessler 2009)
- ESSENCE (~ **60**, Wood-Vasey 2007)
- HST (~ **30**, Riess 2007, ~ **20** Suzuki 2011)
- SNLS, **SNLS-3** (~ **240**, Guy 2010), SNLS-1 (~ **70**, Astier 2006)

Recent compilations :

- Union sample (Kowalski 2008, Amanullah 2010, Suzuki 2011)
- Constitution sample (+CfA3) (Hicken, 2009)

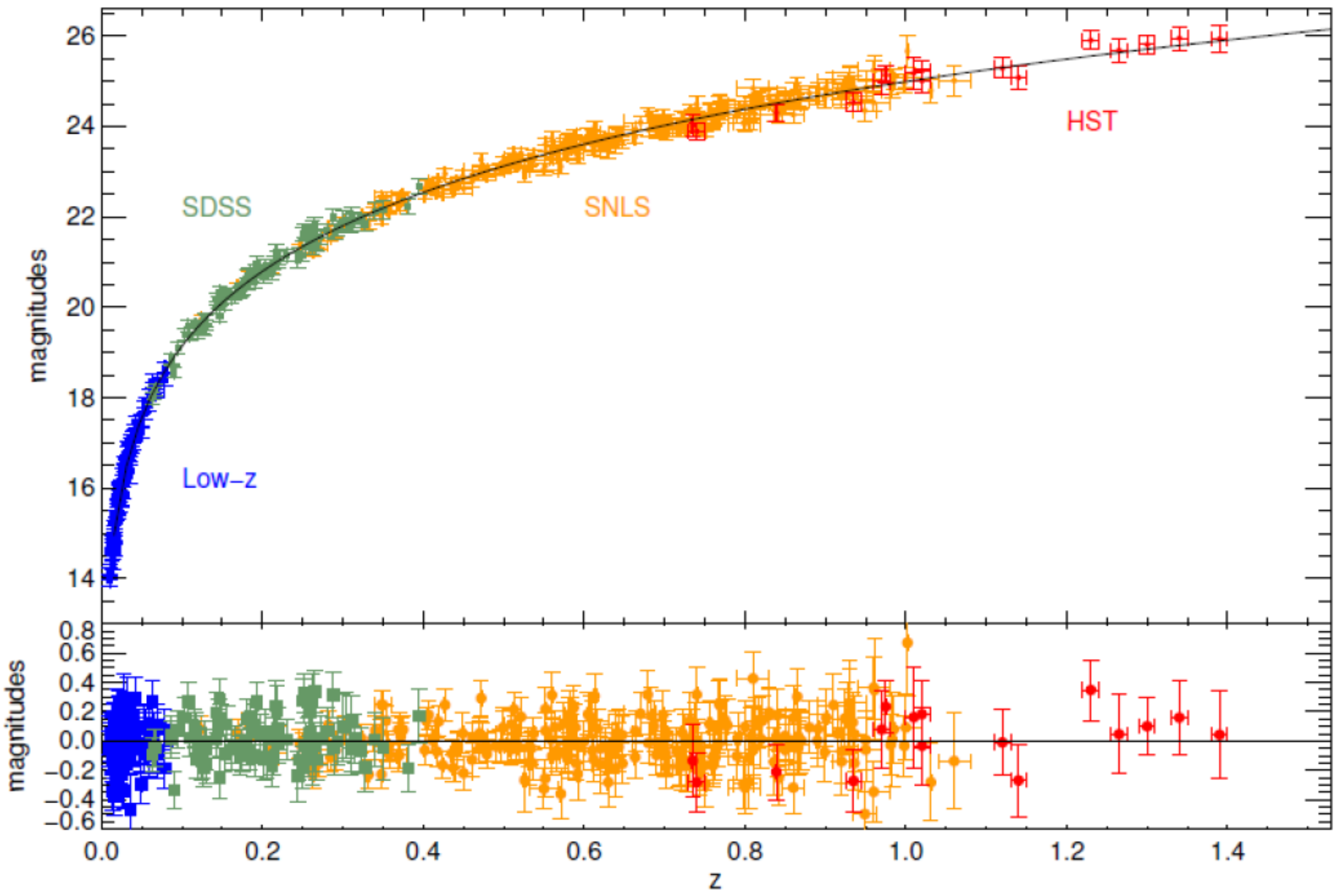
Type Ia Supernovae as cosmological tools

Union Hubble diagram (Suzuki 2011)

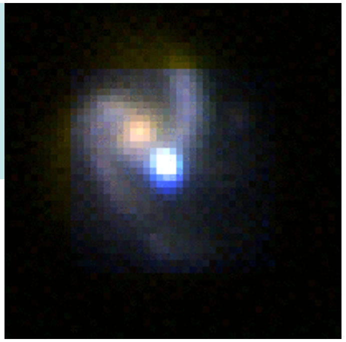


Type Ia Supernovae as cosmological tools

SNLS-3 Hubble diagram (Conley 2011)



supernovae Ia and Dark Energy



1. Measuring the Energy Content of the Universe

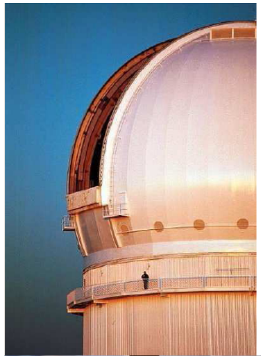
2. Cosmology with type Ia supernovae

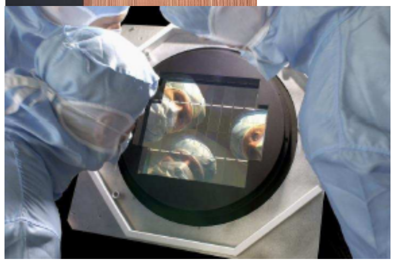
3. <u>SNLS 3-years analysis & results</u>

4. What's next ?

SNLS SuperNova Legacy Survey

Component of the Deep Canadian-France-Hawaii Telescope Legacy Survey





- **detection & follow-up with 1 instrument :**
  3.6-m telescope @ Hawaii (Mauna Kea, 4200m),
  Megacam (CEA/IRFU), 1 sq. degree

→ thorough understanding & **calibration** of instrument
→ deep survey (Malmquist bias)

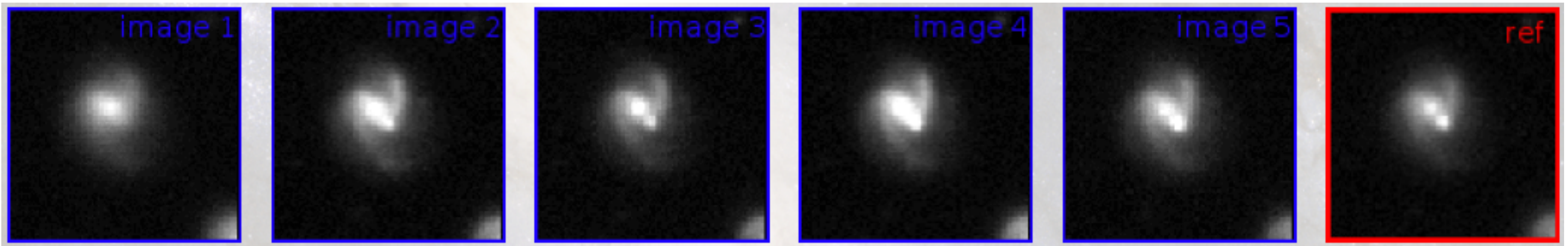
- **4 filters griz :** → $\mathbf{m_B}$ at ≠ z, B-V or U-B ***colors*** for all SNe

- ***rolling search*** **:** repeated observations of 4 fields
  detection & follow-up at the same time

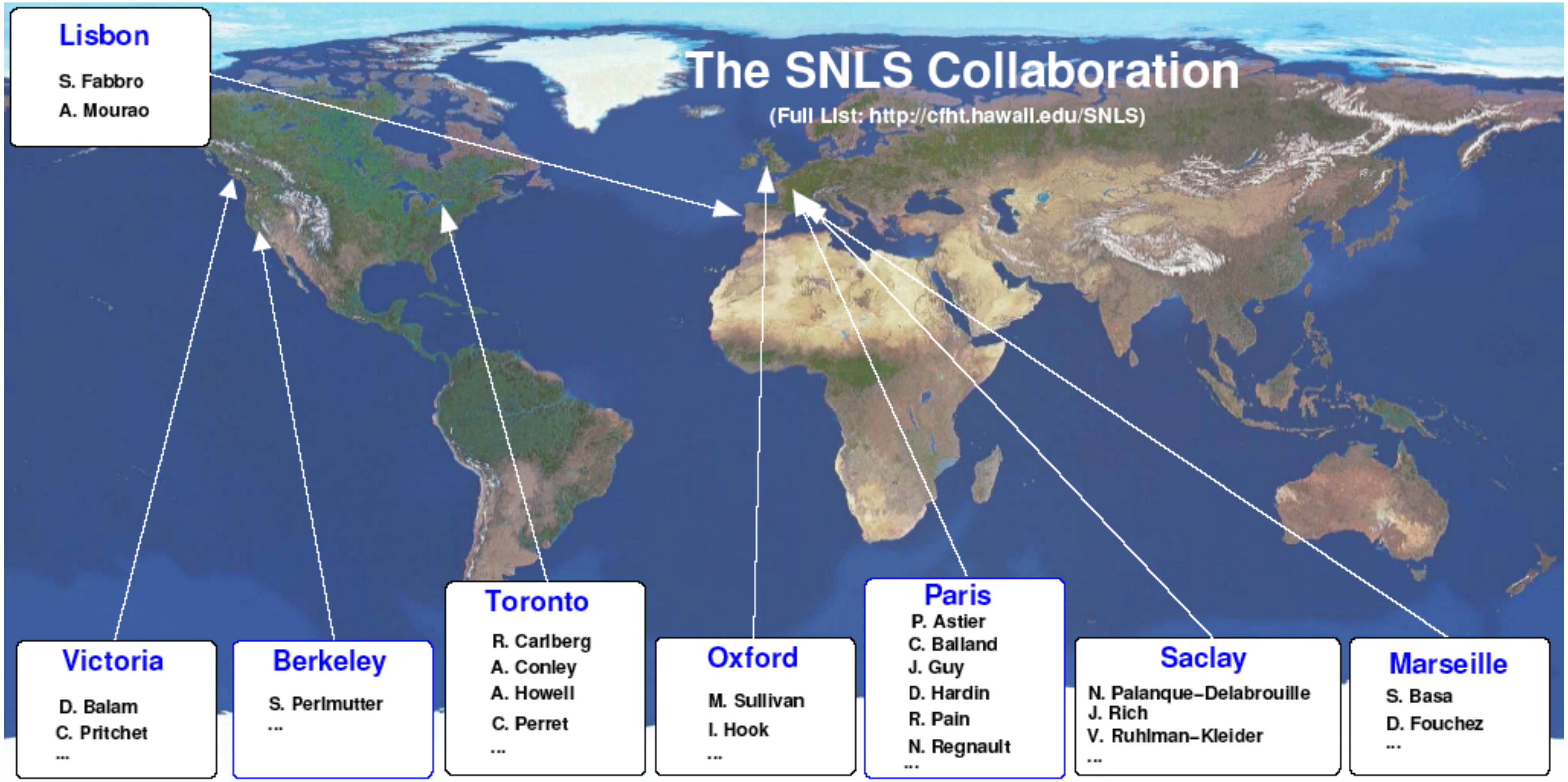
→ get early, pre-discovery SN photometry
→ well sampled & well measured lightcurve : **$\mathbf{m_B}$, lightcurve *shape***

40 nights /year during 5 years (end : 08/2009)

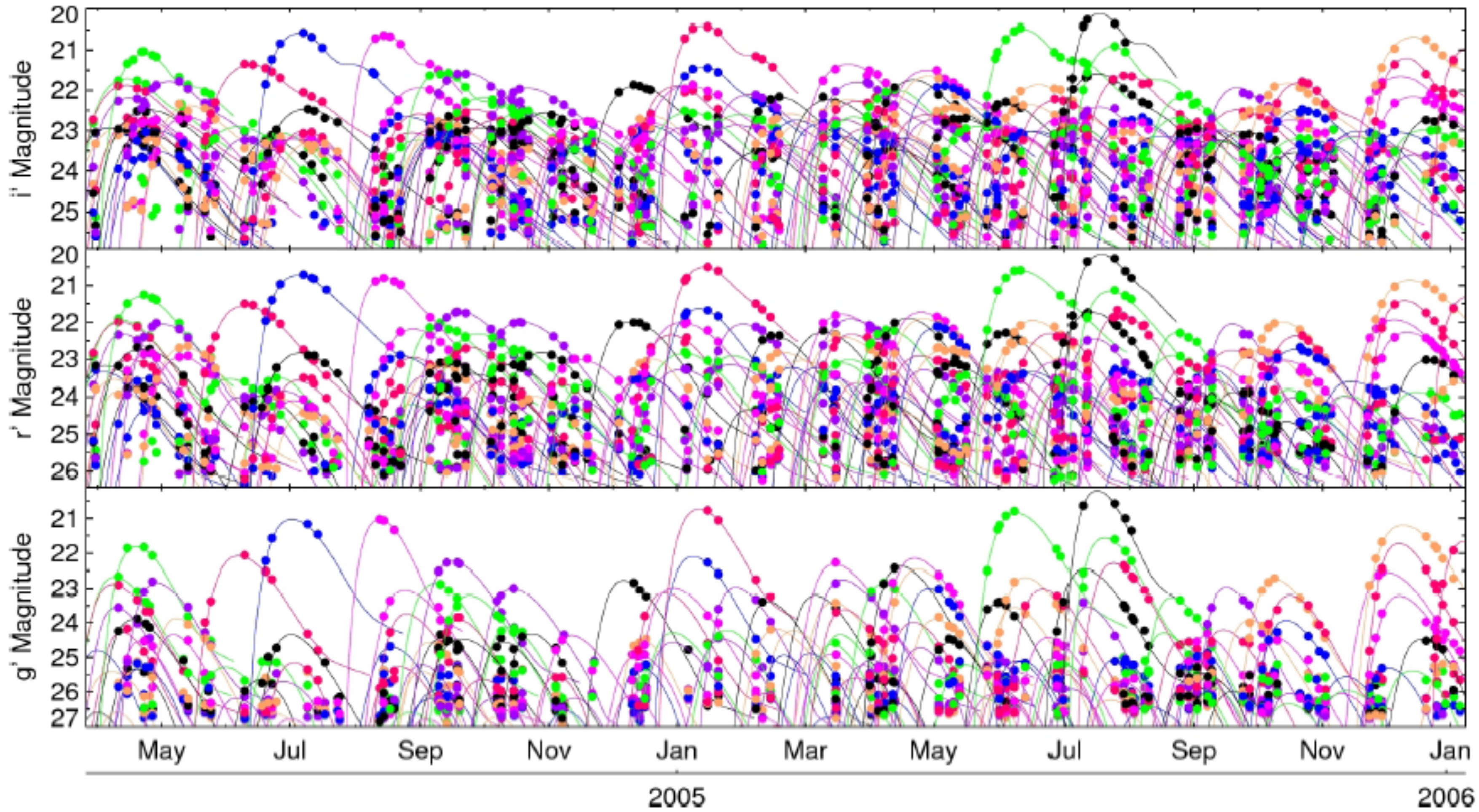
→ ~ 450 SNe Ia
→ deep SN-free images : **photometric study of SNe host galaxies**



SNLS SuperNova Legacy Survey



Rolling Search Mode



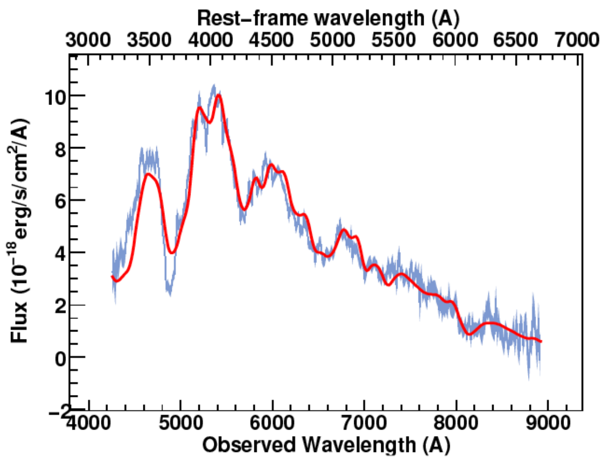
Spectroscopic Follow-up :

10-m class telescopes @ Hawaii, Chile

→ spectroscopic identification for all SNe Ia in SNLS-3 sample

→ redshift z measurement (host galaxy)

→ complementary program on spectral studies : pec. SN, UV …



Balland et al. 2009

Credit

Most plots shown here are borrowed from the following papers:

Regnault, et al., A&A, 2009

Guy et al., A&A 2010

Conley et al. , ApJS 2011

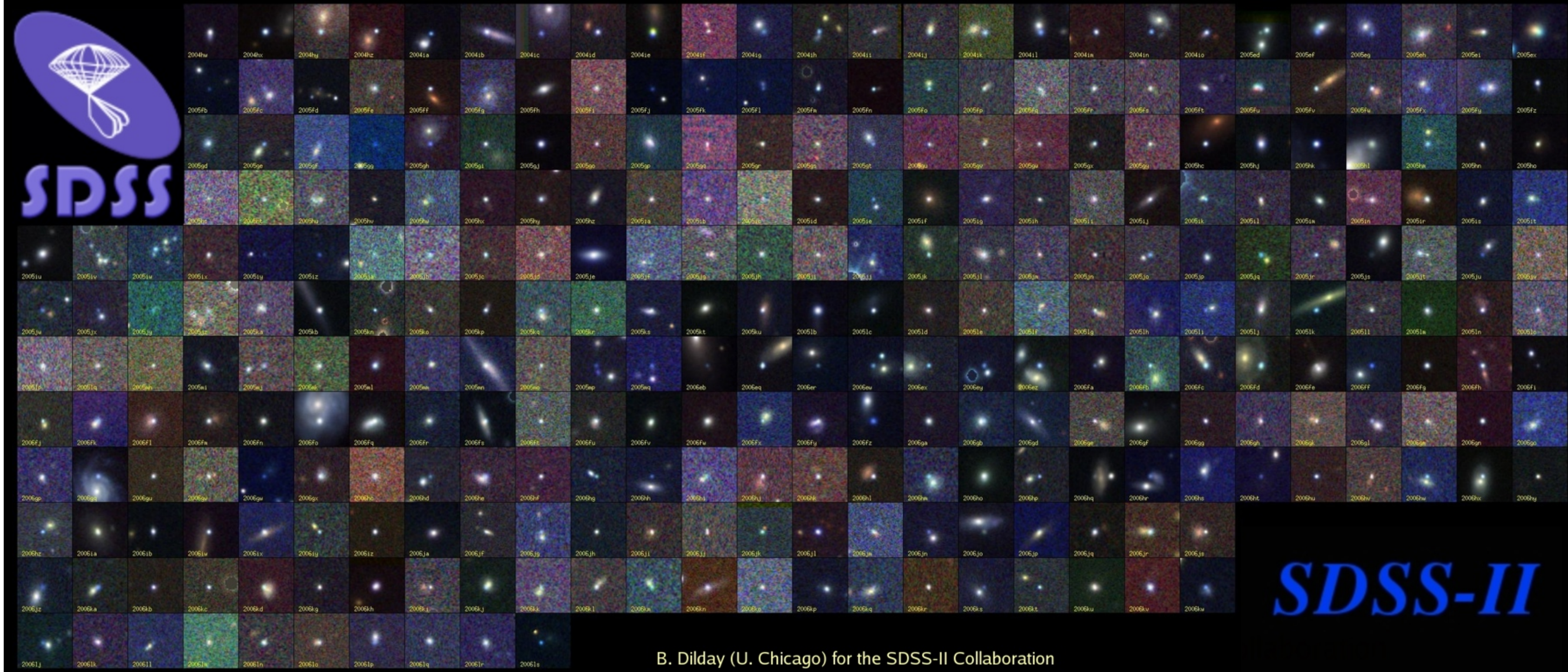
Sullivan et al., ApJ 2011, accepted

+ few others : Balland, et al. 2009, Perret et al. 2010, Sullivan et al 2010, ..

SNLS-3 years results :

- **Statistics : SNLS-1 : 71 ➔ 242 z ~ 0.2 - 1. spectro. SNe Ia**
- **extended with nearby + SDSS-II @ z<0.2 + HST : 472 SNe Ia**
- **2 independant analysis (France/Canada)**
- **improved calibration**
  → <1% precision
- **improved spectro-photometric supernova modeling SALT2& SIFTO**
  → trained on nearby & SNLS data
- **host galaxy nature influence**
  →« standard » SNe Ia brighter in massive galaxies
- **systematics included** in cosmology fit

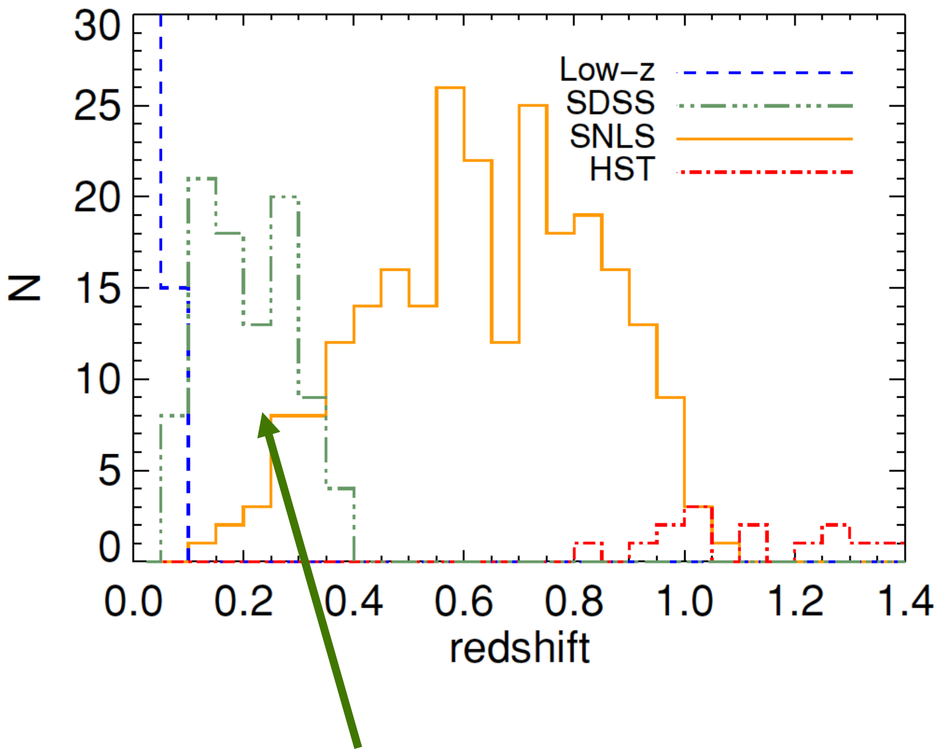
SDSS-II Supernovae Survey



B. Dilday (U. Chicago) for the SDSS-II Collaboration

SDSS-II Supernovae Survey

Holtzman et al., 2008



- intermediate-z SN search :
  0.05<z<0.4
- rolling search :
  2.5-m telescope
  repeated scans of a 2.5 × =120 deg^2
  equatotrial stripe
- ugriz light-curve
- ≈ 500 SNeIa (spectro. confirmed)

fills the « intermediate-redshift desert »

SNLS-3 years results :

➲ **Statistics : SNLS-1 : 71 ➔ 242   z ~ 0.2 - 1. SNe Ia**

➲ **extended with nearby + SDSS-II @ z<0.2**

➲ **2 independant analysis (France/Canada)**

➲ **improved calibration**
→ <1% precision

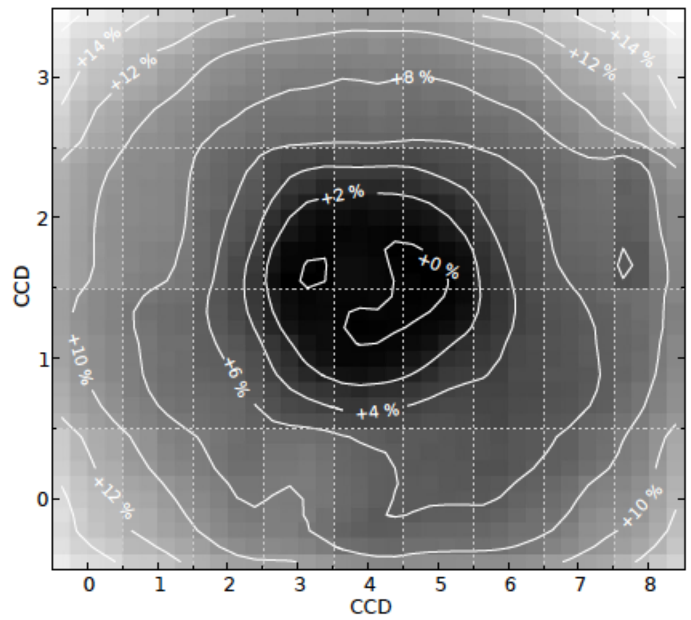
➲ **improved spectro-photometric supernova modeling SALT2& SIFTO**
→ trained on nearby & SNLS data

➲ **host galaxy nature influence**
→« standard » SNe Ia brighter in massive galaxies

➲ **systematics included** in cosmology fit

Calibration: < 1% precision

- a strict control of focal plane uniformities computed using dithered observation of dense stellar fields

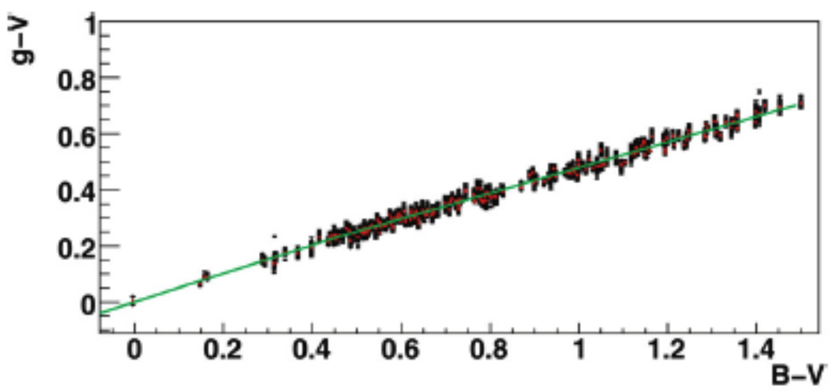


(b) $\delta zp_{r,r-i}(x)$

response variation up to 8%

- use BD+17 4708 for flux calibration instead of Vega (same color range as our observations)

- external low-z SNe sample : calibrated against Landolt UBVRI system
  --> anchor the Megacam griz system to Landolt reference stars
  --> main systematic source



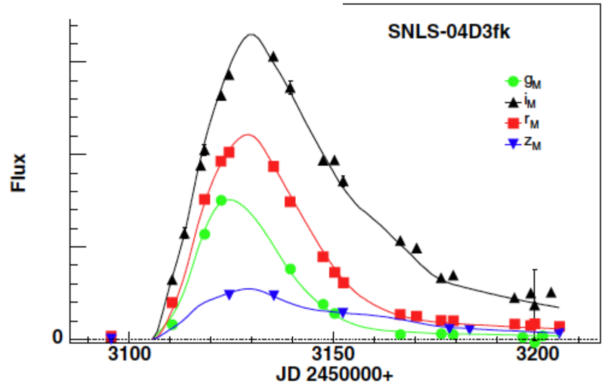
SNLS-3 years results :

- Statistics : SNLS-1 : 71 ➔ 242 z ~ 0.2 - 1. SNe Ia
- extended with nearby + SDSS-II @ z<0.2
- 2 independant analysis (France/Canada)
- improved calibration
  → <1% precision
- improved spectro-photometric supernova modeling SALT2& SIFTO
  → trained on nearby & SNLS data
  → perform equally well, differences provide systematics estimate
- host galaxy nature influence
  →« standard » SNe Ia brighter in massive galaxies
- **systematics included** in cosmology fit

SN spectro-photometric model : SALT2

$$\phi(\lambda_e, t) = X_0 [M_0(\lambda_e, t) + X_1 M_1(\lambda_e, t)] \exp(C\, CL(\lambda_e))$$

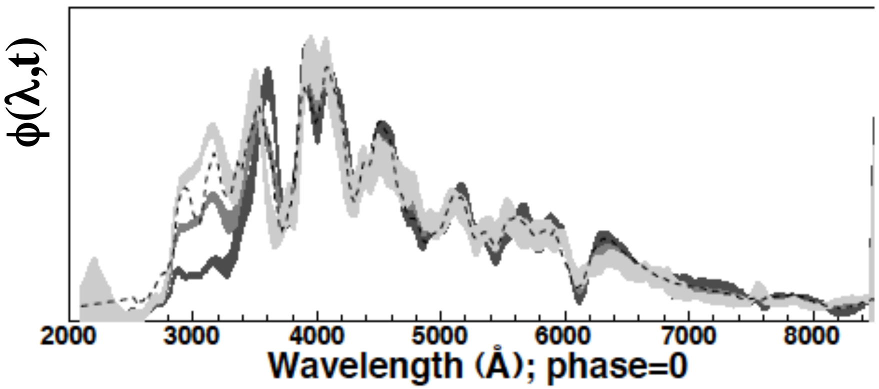
→ empirical model of the SN flux :
X_0 (flux normalisation), *X_1 (shape)* and *C (color)*



→ (M_0, M_1, CL) computed on training sample :
nearby (external sample) & distant (SNLS) SNe lightcurves & spectra

→ do not use SN distances

→ nearby U-band of little use,
using distant (z ~ 0.4) g (optical) data



Guy et al., 2007 & 2010

SN spectro-photometric model : SALT2

SN Colors :

→ **no assumption on CL(λ)** dependency nor causes : intrinsic SN variation, or reddening by dust

At least 4 (possible) 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

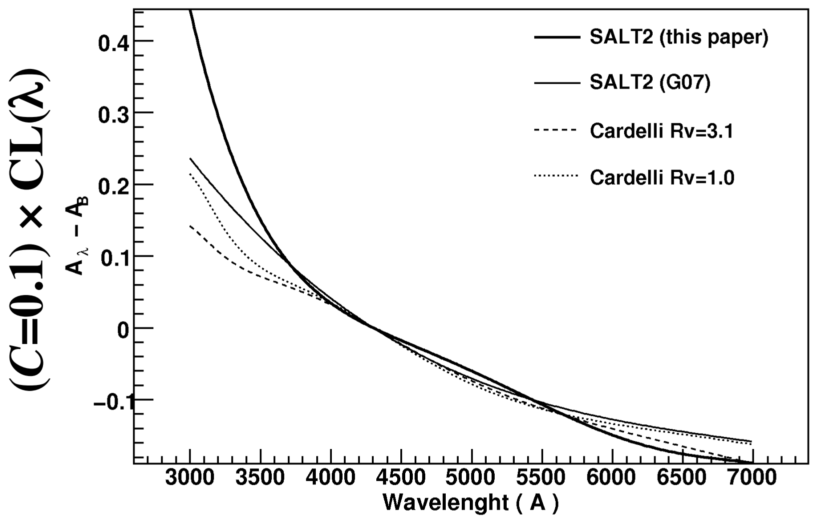
→ no a-priori knowledge of the properties of (2), (3) & (4)

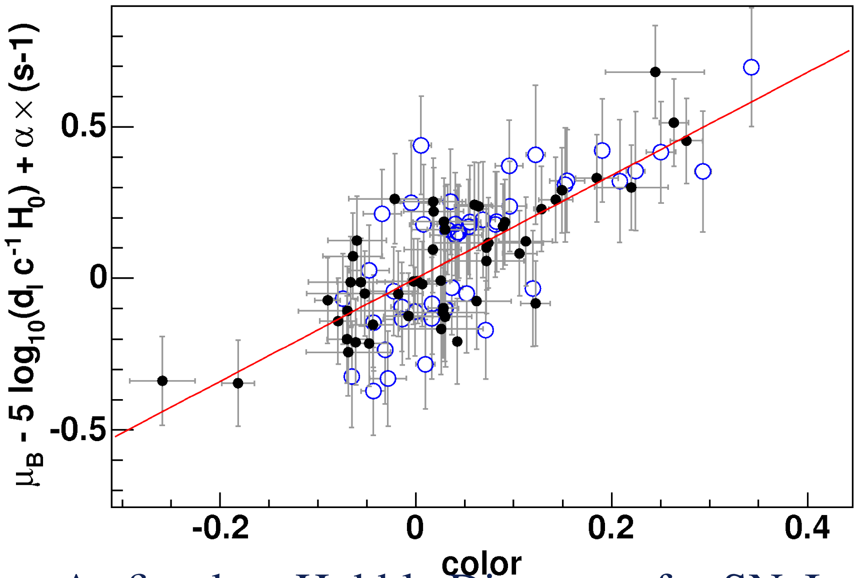
→ may be different, may evolve with the environment (and z)

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

→ **no prior on *C* (*color*)** distribution

SN spectro-photometric model : SALT2





- The "effective" reddening law for SNe does not follow the Cardelli et al. MW law.

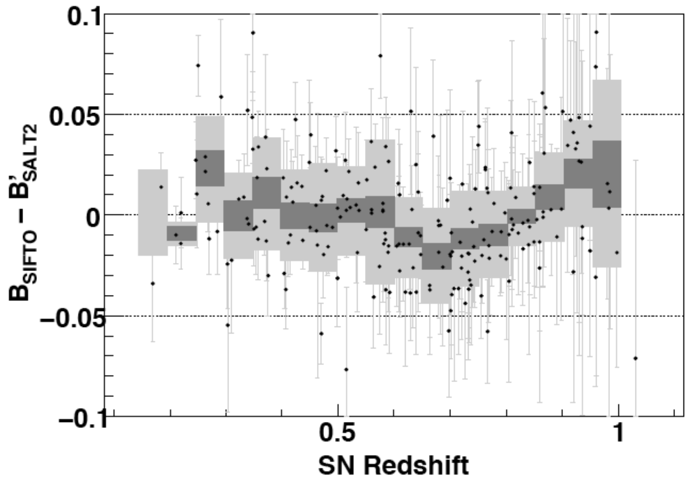
- As fitted on Hubble Diagram : for SNeIa the total to selective extinction ratio : $\beta = R_B \sim 2.5\text{-}3 < 4.$ (MW)

(link with « reddening » law : $R_\lambda = \beta(=R_B)$ -CL(λ))

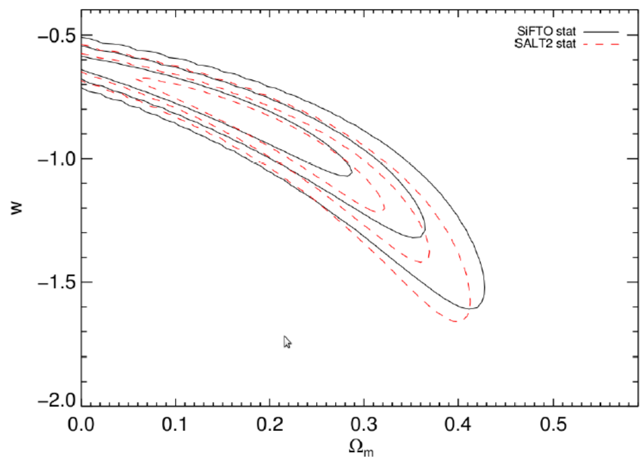
SN data decide - on their *C(color)* values
& - on both β & CL values !!

SNLS SuperNova Legacy Survey

The two methods that are used perform equally well.
The differences provide an estimate of the systematic uncertainties



Systematics on rest-frame magnitudes $\simeq 0.02$



SIFTO (Conley, 2008):

- SNIa spectral sequence from Hsiao, 2007
- pure stretching with time :
  $\phi(\lambda,t,s) = \phi_0(\lambda,t/s)$ with $s(\lambda)$
- color relations
- trained using nearby and SNLS data
  & SN distances not used

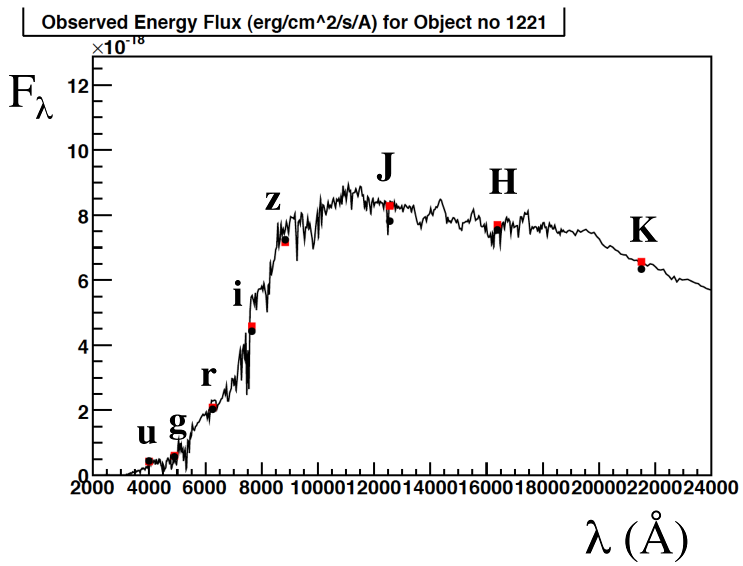
SNLS-3 years results :

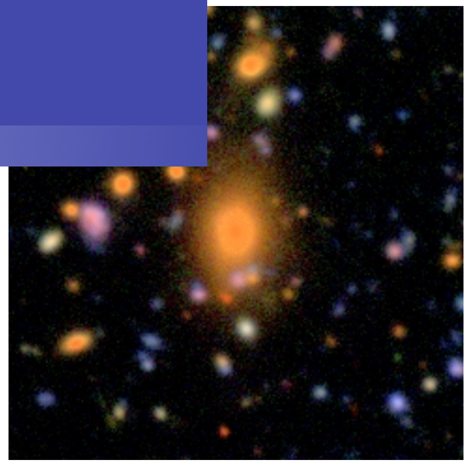
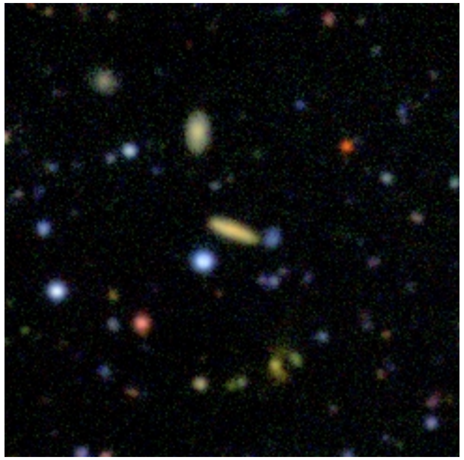
- ➲ **Statistics : SNLS-1 : 71 ➔ 242   z ~ 0.2 - 1. SNe Ia**
- ➲ **extended with nearby + SDSS-II @ z<0.2**
- ➲**2 independant analysis (France/Canada)**
- ➲ **improved calibration**
  → <1% precision
- ➲ **improved spectro-photometric supernova modeling SALT2& SIFTO**
  → trained on nearby & SNLS data
- ➲ **host galaxy nature influence**
  →« standard » SNe Ia brighter in massive galaxies
- ➲**systematics included** in cosmology fit

SNLS SuperNova Legacy Survey

SNIa host galaxies

- Are M_B, α and β "universal" parameters? Any host galaxy (environmental) dependence?
- ugrizJHK host data allows estimations of:
  - host colors & luminosity
  - fit using SED from galaxy synthesis model (PEGASE.2)
  - host star formation rate & stellar mass content

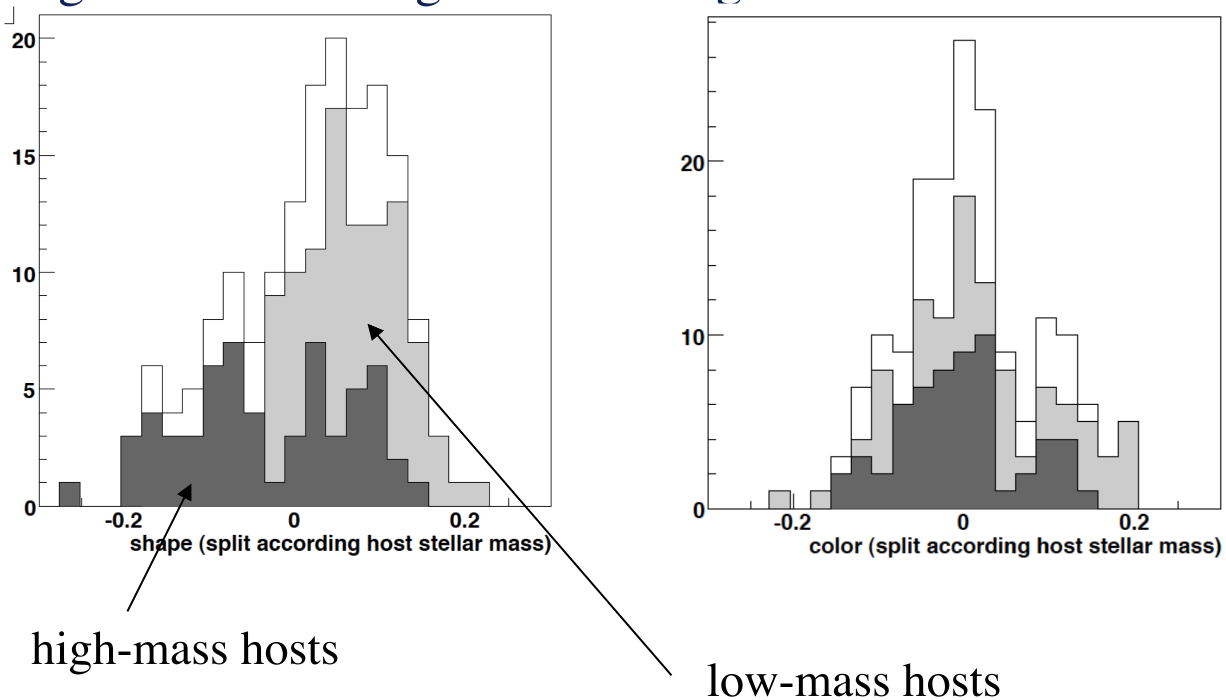


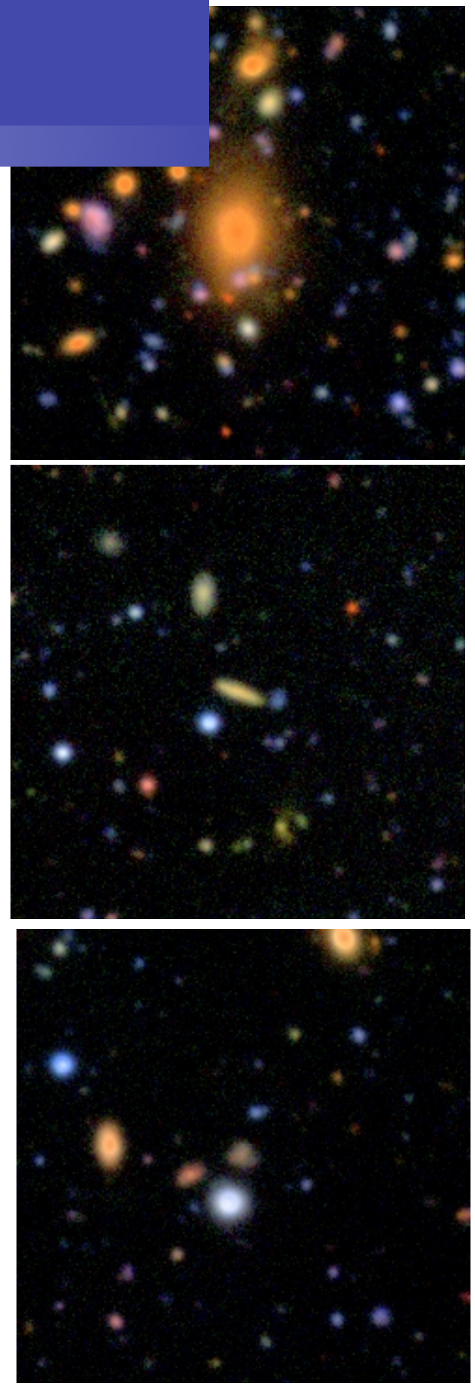




SNIa host galaxies

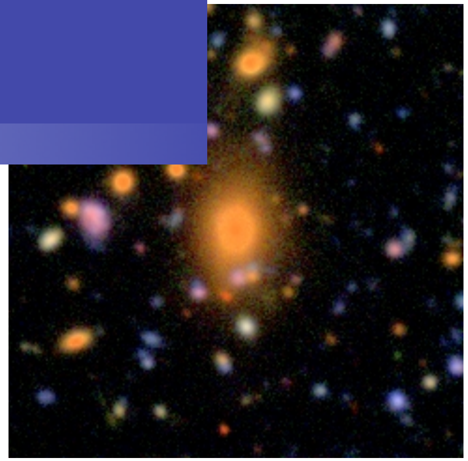
- when splitting SNe by their host galaxy color, SFR, luminosity, stellar mass …) : differences in shape, -- not in color (e.g. Sullivan et al., 2006)

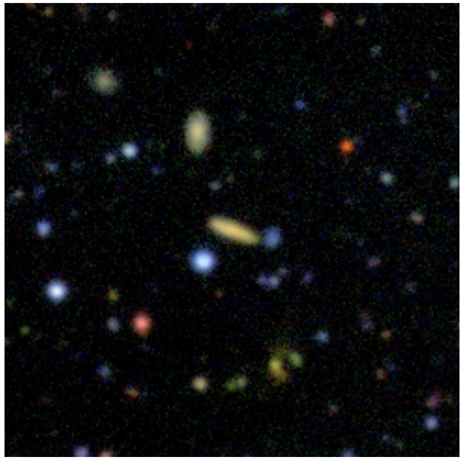
shape parameter > in blue/high SFR/less massive/fainter host galaxies : SN brighter in these galaxies





SNLS SuperNova Legacy Survey





Hubble residuals versus host mass

- the **mean** SNe Ia is brighter in low-mass galaxies (their mean *shape* is >) :

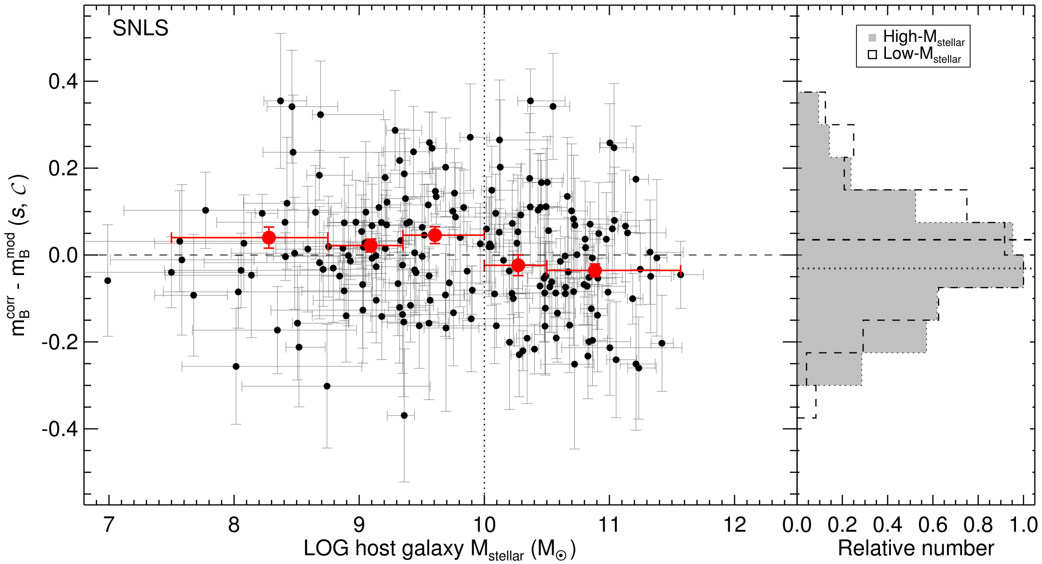
taken into account by the brighter-slower relation **…… but ……**

- **the “standard”(*) SNe Ia is brighter (4σ) in massive galaxies**

(*=after lightcurve shape and colour correction, i.e. *shape*=0, *color*=0)

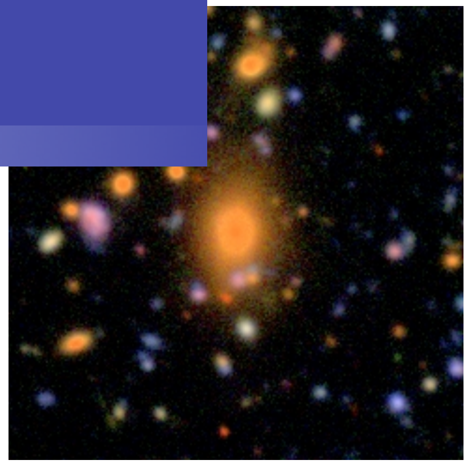
- **subtle effect – 0.08mag** – smaller than stretch and color corrections

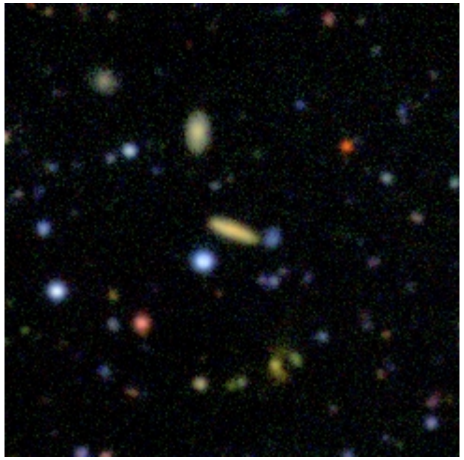
Sullivan et al., 2010, also see Lampeitl., et al 2010, Kelly, et al., 2010



SNIa host galaxies

Improved cosmological analysis





Add a further linear host term, H, to the analysis ?

$$\mu_B = m_B - M_B + \alpha(s-1) - \beta c + \gamma H$$

→ *requires very precise measure of H, and robust errors*

→ use two M_B – one for high-mass galaxies and one for low-mass host galaxies : $M_{split} = 10^{10}\ M_\odot$

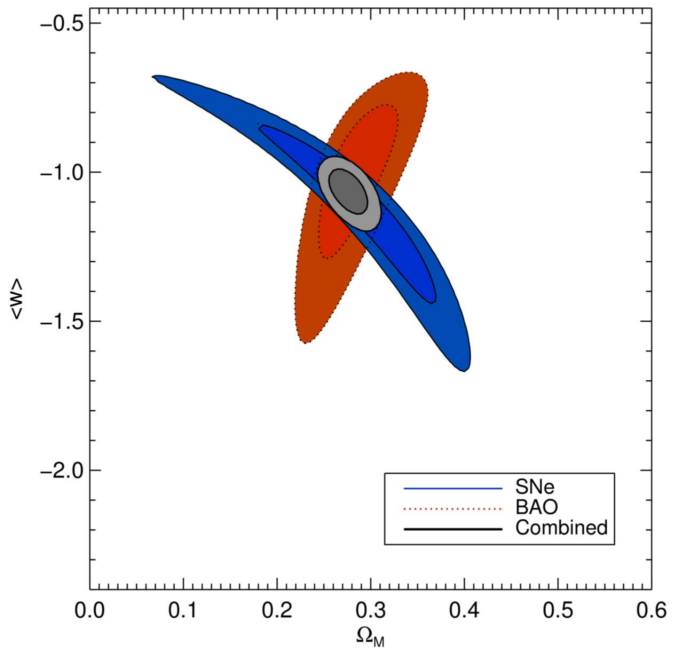
$$\mu_B = m_B - M_B^1 + \alpha\ \mathit{shape} - \beta\ \mathit{color} \quad \text{when } M_{host} < M_{split}$$

$$\mu_B = m_B - M_B^2 + \alpha\ \mathit{shape} - \beta\ \mathit{color} \quad \text{when } M_{host} > M_{split}$$

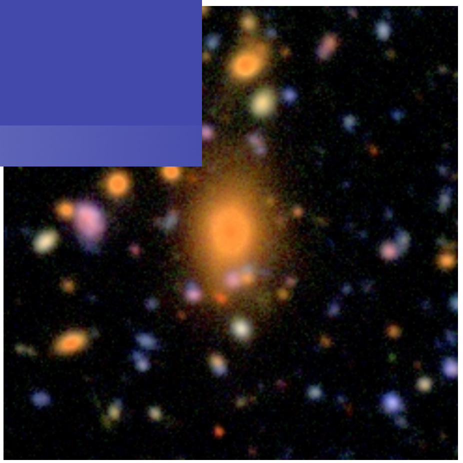
SNLS SuperNova Legacy Survey

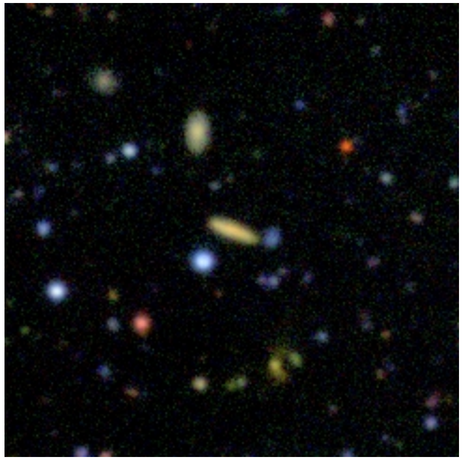
SNIa host galaxies

Improved cosmological analysis



without host galaxy mass term

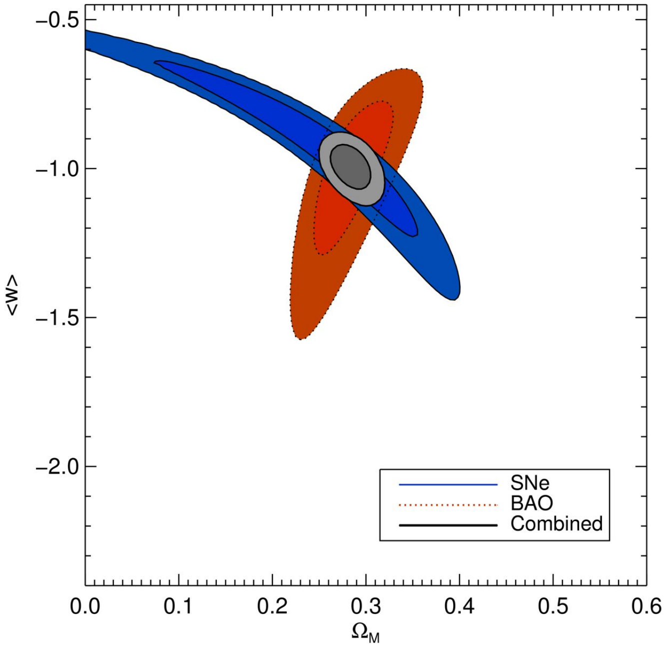




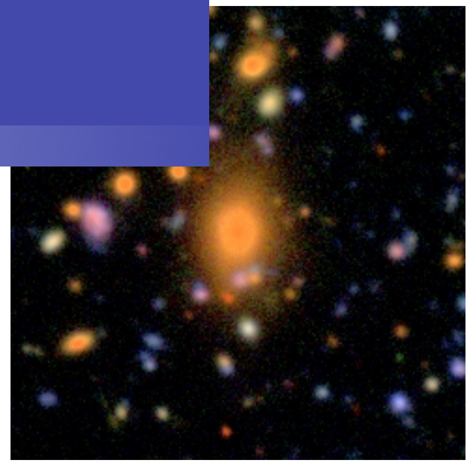
BAO+SNe+WMAP7+flat

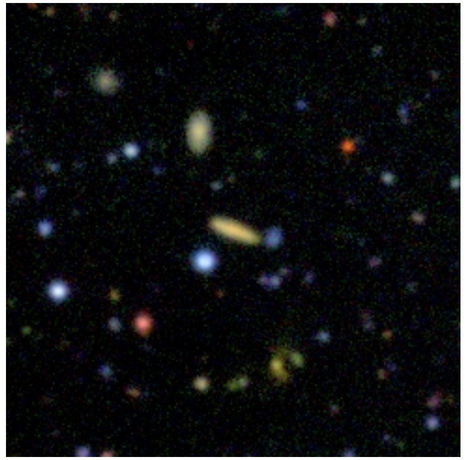
SNIa host galaxies

Improved cosmological analysis



with host galaxy mass term





SNLS SuperNova Legacy Survey

SNLS-3 years results :

➲ **Statistics : SNLS-1 : 71 ➔ 242   z ~ 0.2 - 1. SNe Ia**

➲ **extended with nearby + SDSS-II @ z<0.2**

➲**2 independant analysis (France/Canada)**

➲ **improved calibration**
→ <1% precision

➲ **improved spectro-photometric supernova modeling SALT2& SIFTO**
→ trained on nearby & SNLS data

➲ **host galaxy nature influence**
→« standard » SNe Ia brighter in massive galaxies

➲**systematics included** in cosmology fit

Including the systematics

For the ith SN :
distance modulus : $\mu_i = m_{Bi} - (M - \alpha s_i + \beta c_i)$
compared with : $\mu(z_i\ ; \mathrm{cosmo})$
residual : $r_i = \mu_i - \mu(z_i\ ; \mathrm{cosmo})$

$$\chi^2 = {}^t r \mathbf{C}^{-1} r.$$

with

$$\mathbf{C} = \mathbf{D}_{\mathrm{stat}} + \mathbf{C}_{\mathrm{stat}} + \mathbf{C}_{\mathrm{sys}}$$

D_{stat} / C_{stat} is the statistical uncertainty covariance matrix - depends on α and β

$$\mathbf{D}_{\mathrm{stat},\ ii} = \sigma^2_{m_B,i} + \alpha^2 \sigma^2_{s,i} + \beta^2 \sigma^2_{\mathcal{C},i} + \sigma^2_{\mathrm{int}} + \left(\frac{5\,(1+z_i)}{z_i\,(1+z_i/2)\log 10} \right)^2 \sigma^2_{z,i} + \sigma^2_{\mathrm{lensing}} + \sigma^2_{\mathrm{host\ correction}} + C_{m_B s \mathcal{C},i}$$

Including the systematics

$$\mathbf{C} = \mathbf{D}_{\text{stat}} + \mathbf{C}_{\text{stat}} + \mathbf{C}_{\text{sys}}$$

in C_{sys}: S_k is the kth systematic ; also depends on α and β

$$\mathbf{C}_{\text{sys},ij} = \sum_{k=1}^{K} \left(\frac{\partial \mu_i}{\partial S_k}\right)\left(\frac{\partial \mu_j}{\partial S_k}\right)(\Delta S_k)^2$$

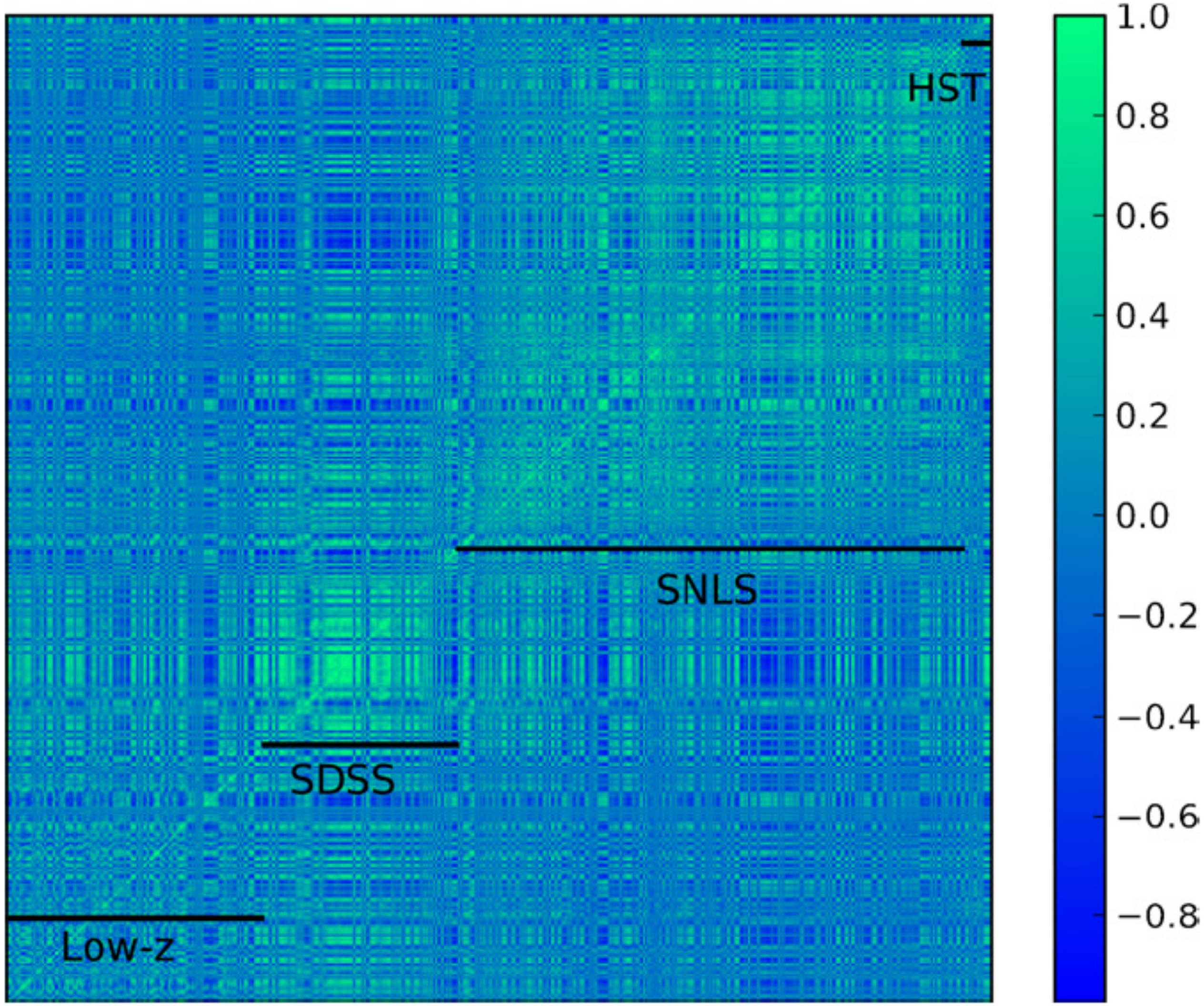
identified systematics :

- calibration
- comparison of different lightcurve fitters
- Malmquist bias
- contamination by core-collapse supernovae
- evolution

etc.

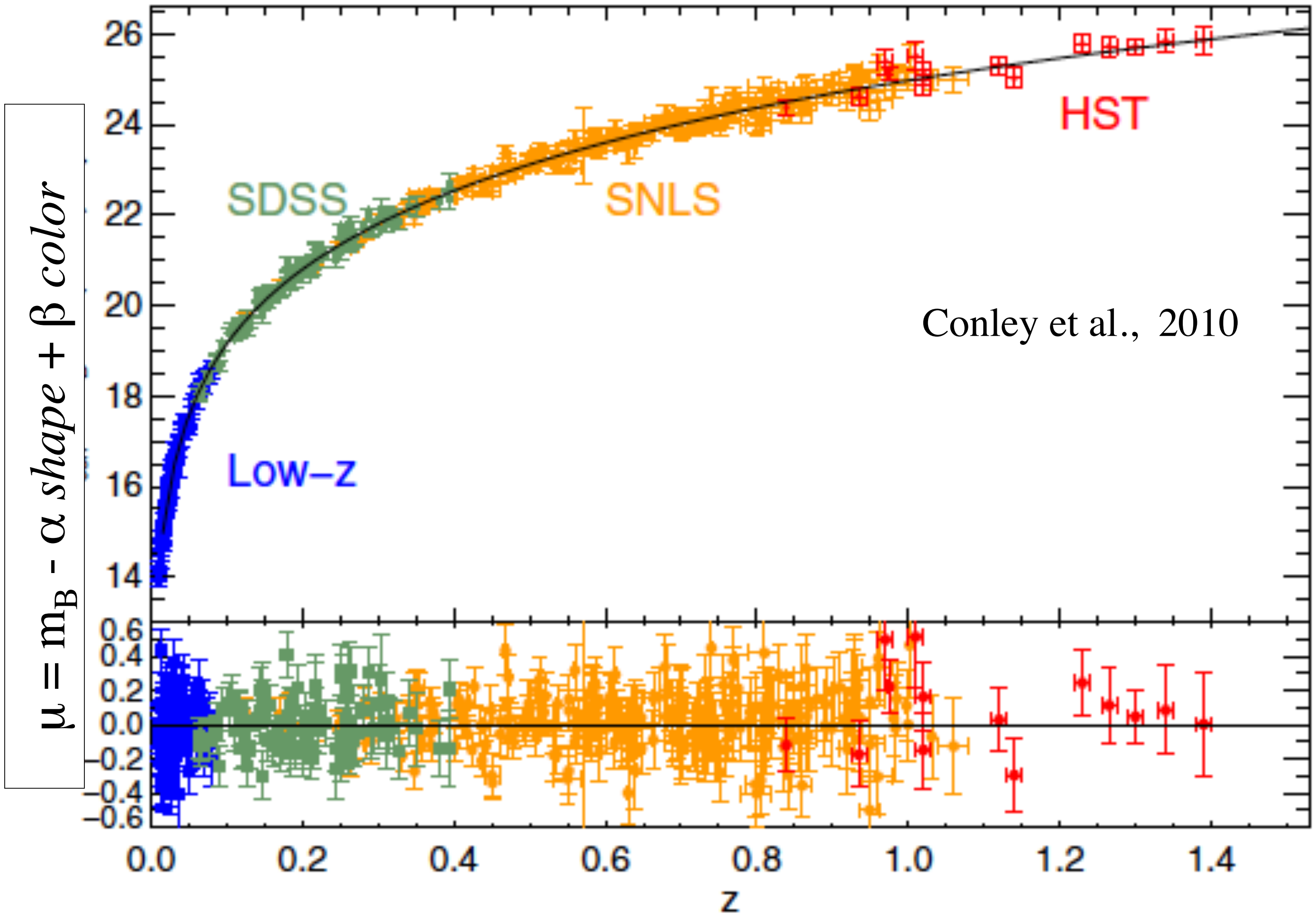
Including the systematics

- $C_{stat} + C_{sys}$

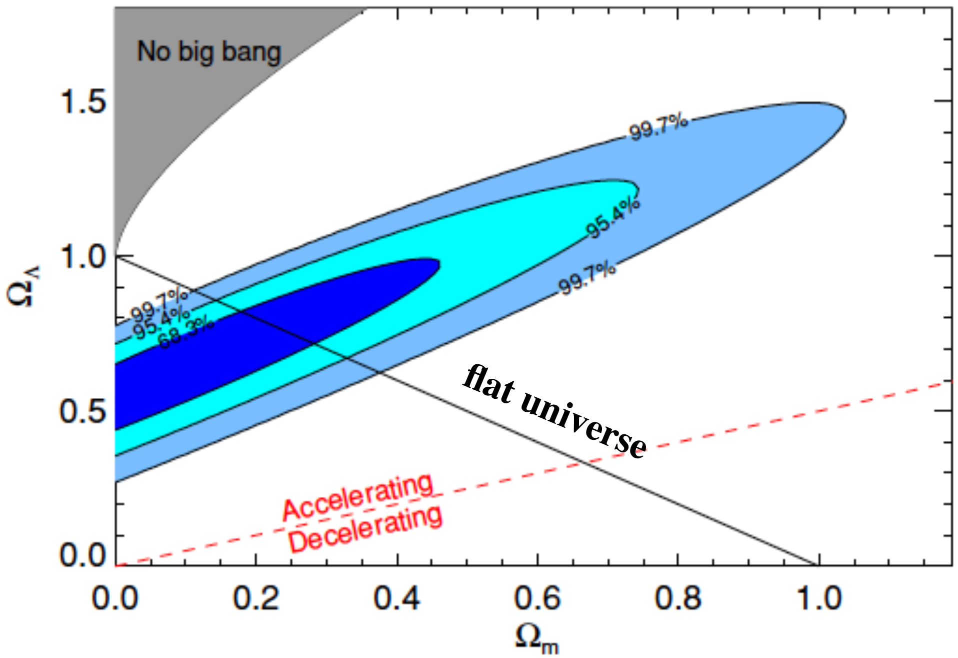


SNLS-3 extended Hubble Diagram

123 nearby (z ~ 0.05) & 93 SDSS-II (z~ 0.1-0.4)
& 242 SNLS (z ~ 0.2-1.) & 14 HST (z ~ 0.7-1.4) SNe Ia

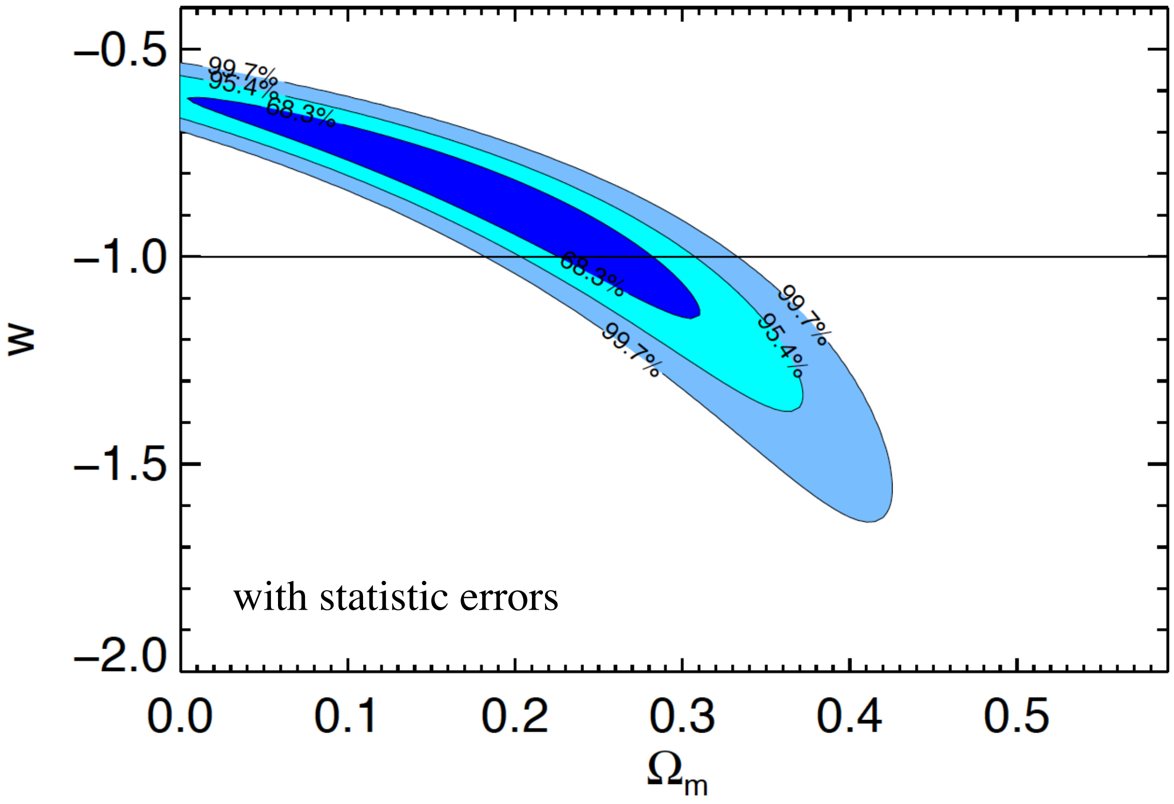


Universe still accelerating !



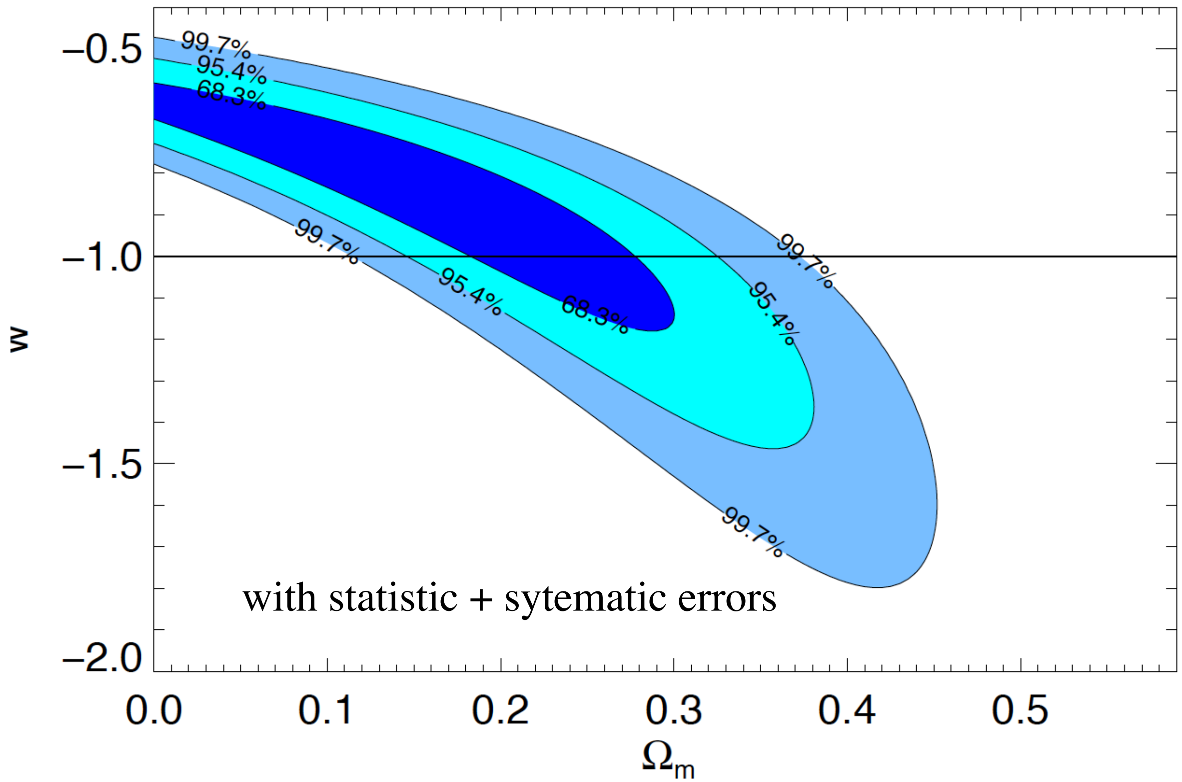
For a flat universe : require cosmic acceleration at > 99.999%

SNLS-3 + flat universe (SN only):



Conley et al., 2011

SNLS-3 + flat universe (SN only):



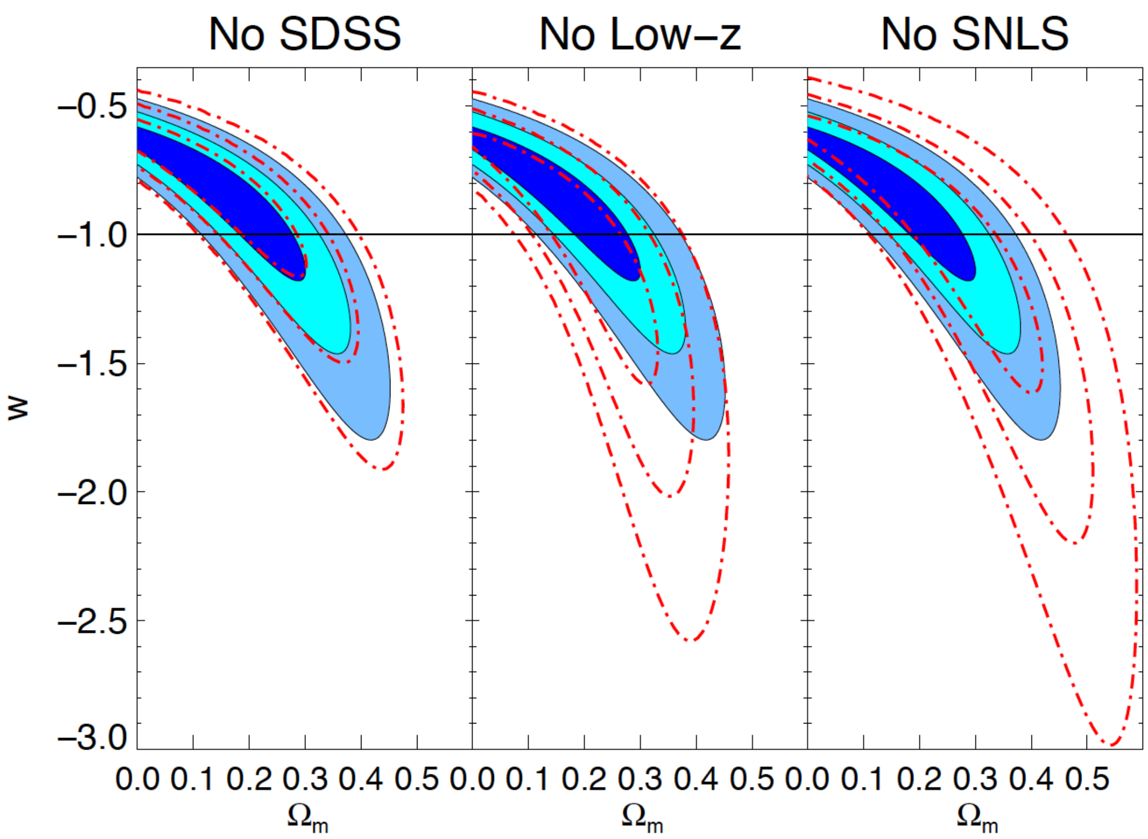
Conley et al., 2011

Sytematics in details :

Table 7
Identified Systematic Uncertainties

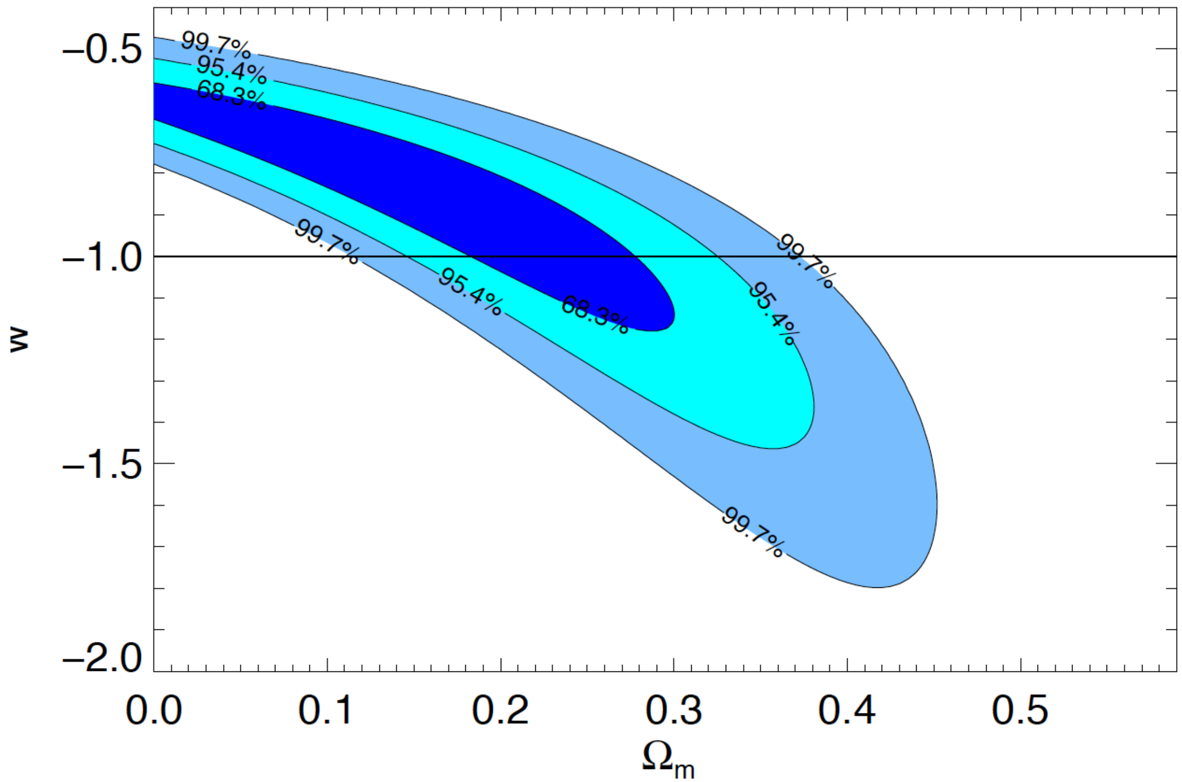
Description	Ω_m	w	Rel. Area [a]	w for $\Omega_m = 0.27$
Stat only	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1	-1.031 ± 0.058
All systematics	0.18 ± 0.10	$-0.91^{+0.17}_{-0.24}$	1.85	$-1.08^{+0.10}_{-0.11}$
Calibration	$0.191^{+0.095}_{-0.104}$	$-0.92^{+0.17}_{-0.23}$	1.79	-1.06 ± 0.10
SN model	$0.195^{+0.086}_{-0.101}$	$-0.90^{+0.16}_{-0.20}$	1.02	-1.027 ± 0.059
Peculiar velocities	$0.197^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.03	-1.034 ± 0.059
Malmquist bias	$0.198^{+0.084}_{-0.100}$	$-0.91^{+0.16}_{-0.20}$	1.07	-1.037 ± 0.060
Non-Ia contamination	$0.19^{+0.08}_{-0.10}$	$-0.90^{+0.16}_{-0.20}$	1	-1.031 ± 0.058
MW extinction correction	$0.196^{+0.084}_{-0.100}$	$-0.90^{+0.16}_{-0.20}$	1.05	-1.032 ± 0.060
SN evolution	$0.185^{+0.088}_{-0.099}$	$-0.88^{+0.15}_{-0.20}$	1.02	-1.028 ± 0.059
Host relation	$0.198^{+0.085}_{-0.102}$	$-0.91^{+0.16}_{-0.21}$	1.08	-1.034 ± 0.061

Sample importance:



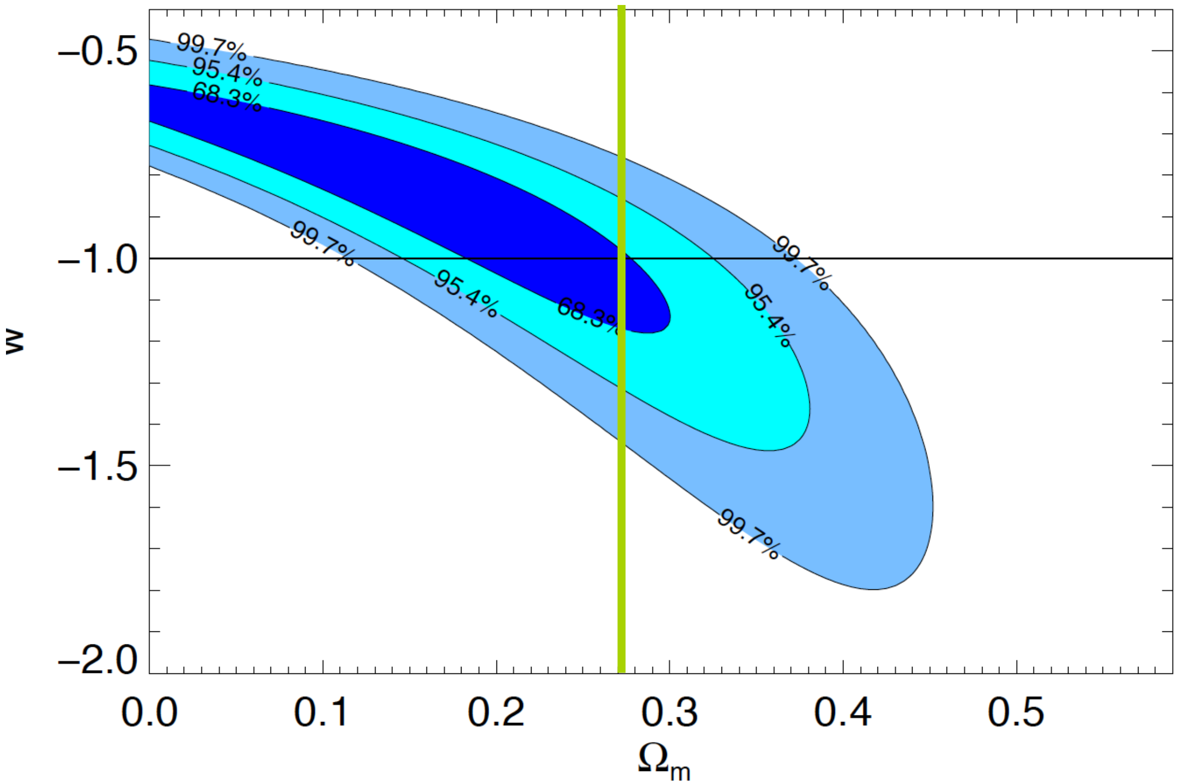
Conley et al., 2011

SNLS-3 + flat universe (SN only):



$$\Omega_M = 0.18 \pm 0.1, w = -0.91^{+0.17}_{-0.24} \text{ (syst. + stat.)}$$

SNLS-3 + flat universe (SN only):



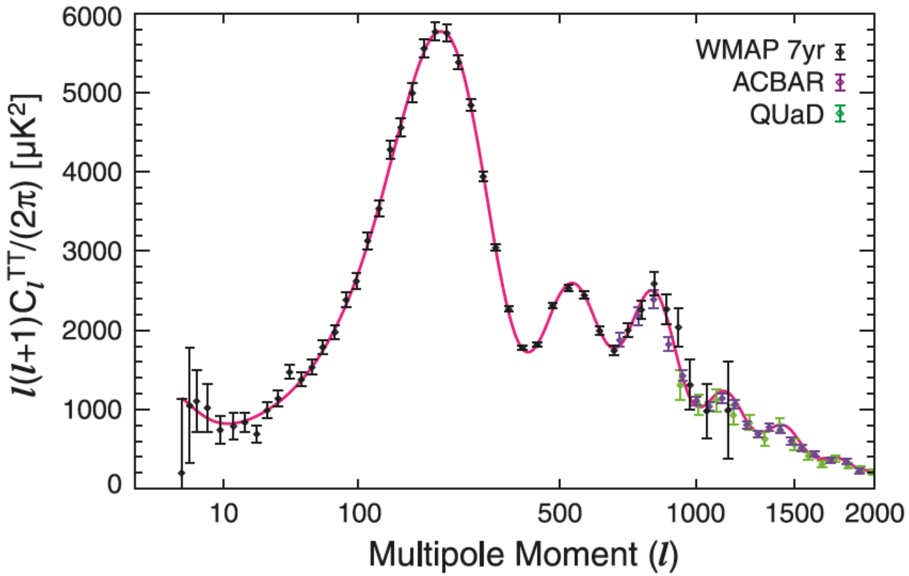
Assuming $\Omega_M = 0.27$: $w = -1.08 \pm 0.1$ (syst. + stat.)

Combining SNLS-3 with other cosmological probes :

❖ Cosmic Microwave Background temperature anistropies : WMAP7, Komatsu et al. 2011, Larson et al. 2011

imprint of processes in the photon-baryon fluid at recombination time when the photons escaped at z ~ 1100*

14 Komatsu et al.



$$l_A = \pi \frac{(1+z_*)D_A(z_*)}{r_s(z_*)}, \quad R \leftrightarrow \frac{cz_*/H(z_*)}{D_A(z)}, \quad z_*$$

TABLE 9
WMAP DISTANCE PRIORS OBTAINED FROM THE *WMAP* 7-YEAR FIT TO MODELS WITH SPATIAL CURVATURE AND DARK ENERGY. THE CORRELATION COEFFICIENTS ARE: $r_{l_A,R} = 0.1956$, $r_{l_A,z_*} = 0.4595$, AND $r_{R,z_*} = 0.7357$.

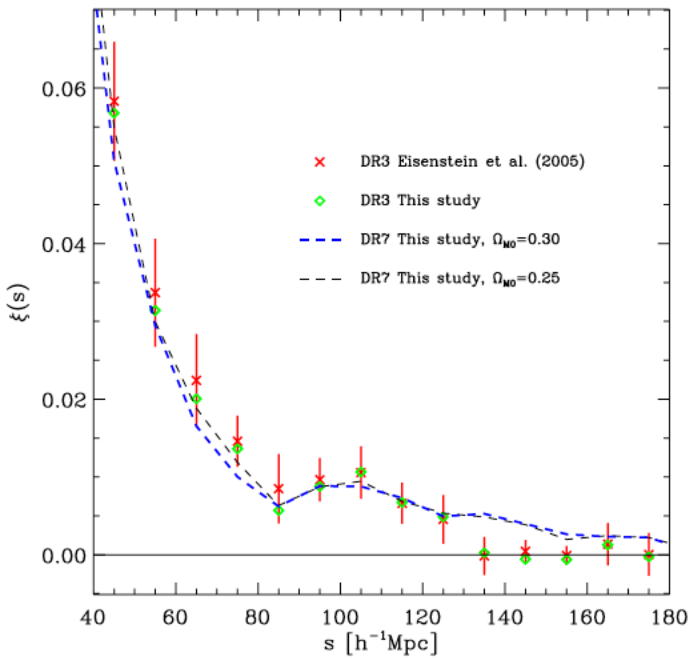
	7-year ML[a]	7-year Mean[b]	Error, σ
l_A	302.09	302.69	0.76
R	1.725	1.726	0.018
z_*	1091.3	1091.36	0.91

[a] Maximum likelihood values (recommended).
[b] Mean of the likelihood.

Combining SNLS-3 with other cosmological probes :

- Baryon Acoustic oscillations :
  SDSS Data Release 7, Percival et al., 2010

imprint of same process in the large scale distributions of galaxies observed at z = 0.2 & z = 0.35



- ratio of the spherical average of the angular-diameter distance D_V

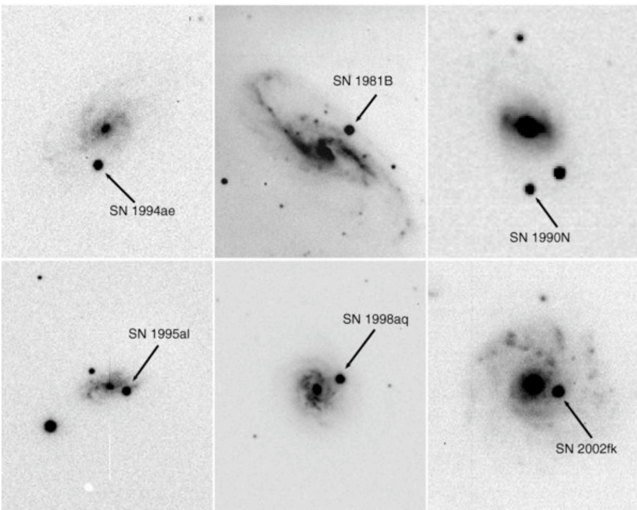
$$D_V(0.35)/D_V(0.2) = 1.736 \pm 0.065$$

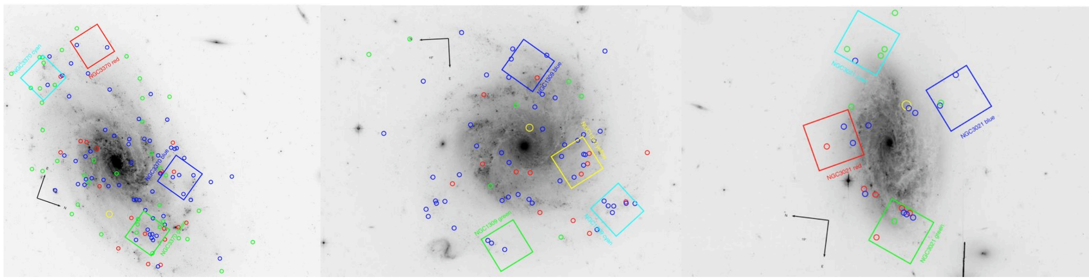
- power spectrum of the Luminous Red Galaxies, Reid et al., 2010

Combining SNLS-3 with other cosmological probes :

❖ H_0 SHOES (Supernovae and H_0 for the Equation of State) Riess et al., 2011

$$H_0 = 73.8 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

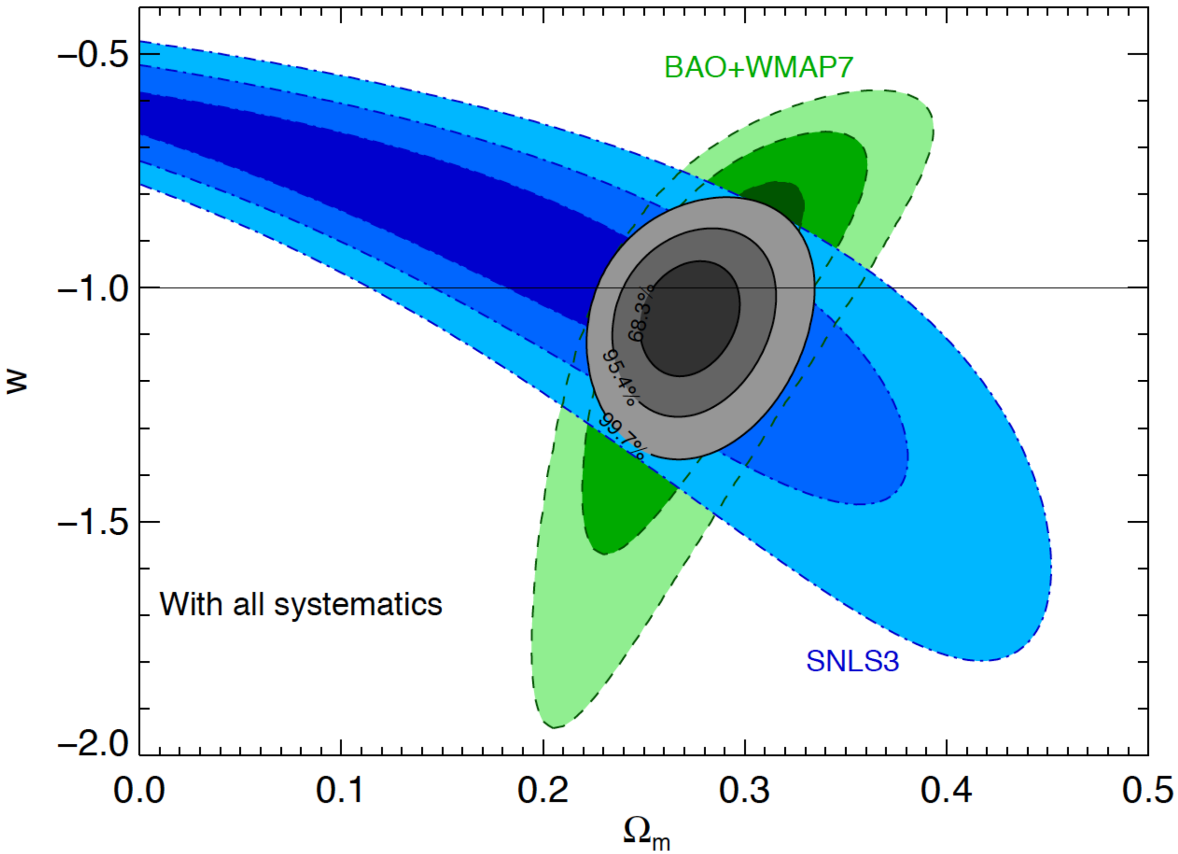




nearby supernovae distances calibrated with absolute cepheid distances (HST) ;
cepheids are themselves calibrated with parallaxes, eclipsing binaries distances …

SNLS SuperNova Legacy Survey

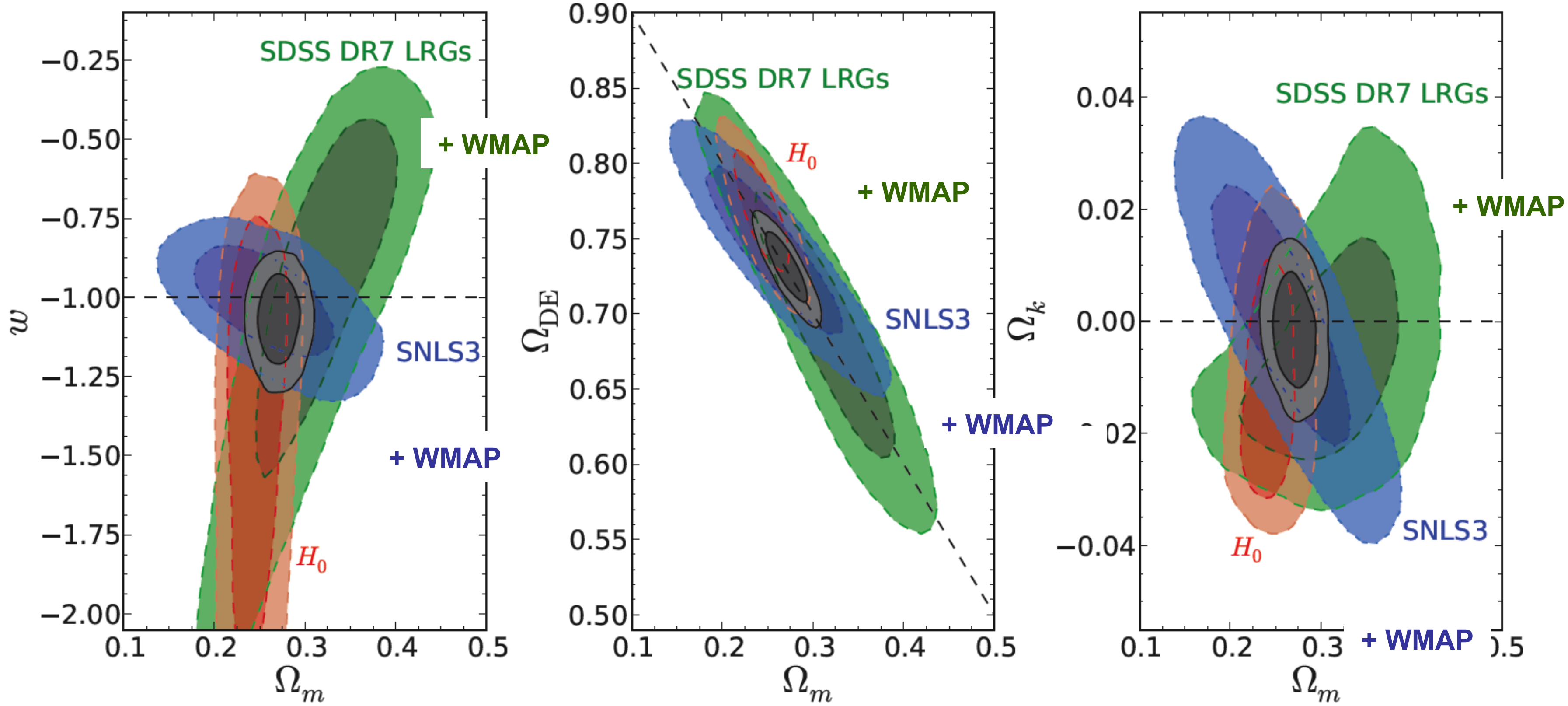
$$\Omega_M = 0.274^{+0.019}_{-0.015}, w = -1.068^{+0.08}_{-0.082} \text{ (syst. + stat.)}$$



Sullivan et al, 2011, accepted

Combining SNLS-3 with other cosmological probes :

SDSS + WMAP7 + H_0 + (no flat prior) :

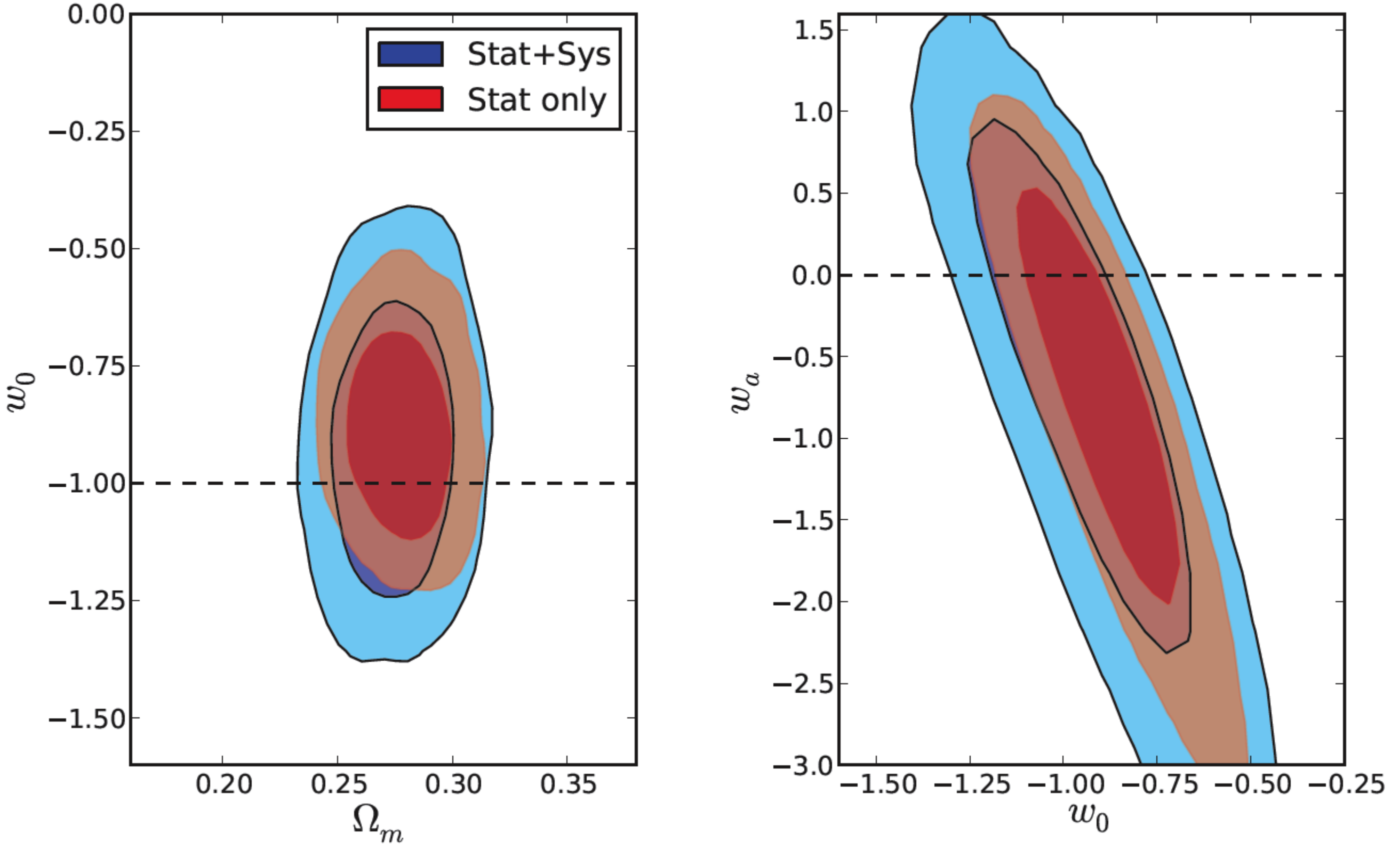


$$\Omega_M = 0.271 \pm 0.015,\ \ \Omega_k = -0.002 \pm 0.006,\ \ w = -1.069 \pm 0.092$$

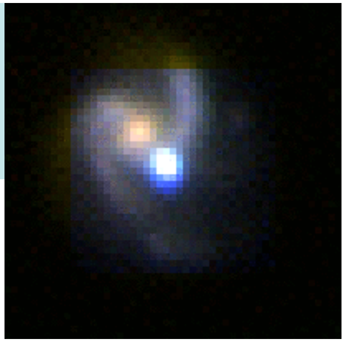
Combining SNLS-3 with other cosmological probes :

SDSS + WMAP7 + H_0 + Flat :

$w(z) = w_0 + w_a\,(1-a(z))$? we do not measure w_a ….



supernovae Ia and Dark Energy



1. Measuring the Energy Content of the Universe

2. Cosmology with type Ia supernovae

3. SNLS 3-years analysis & results

4. <u>What's next ?</u>

What's next ?

- SDSS & SNLS-5 joined analysis
- instrumental calibration
- Stage III & IV projects :
  SkyMapper, DES, LSST, WFIRST, EUCLID….

What's next ?

Joint SDSS-SNLS analysis

- SNLS data sample
  - 5 yr = 450 SNe Ia + ~ 400 "photometric" Ia for which we are acquiring host spectra

But syst. currently about equal to stat.

=> need to improve (photometric calibration)

- Ongoing joint SDSS-SNLS analysis : + 300 SDSS
  - Cross-calibrate (expected gain : ~2 in calib uncertainty)
  - Joint LC training

What's next ?

« STAGE III » SN programs

Pan-starrs PS1: 1.8m + 7 deg2

2010-2015? (primarily weak lensing)

goal : o(1000) up to z=1

DES : CTIO+new 3deg2 mosaic camera

2012-2016 (primarily weak lensing)

goal: 3000 SN up to z=1

Skymapper : 1.35m MSSO (Australia)

rolling nearby SNIa search (z~0.1) - yield ~100 SN Ia /yr

2011-2014

will address some of possible systematics.

very difficult to significantly improve on precision

SkyMapper

anchoring the Hubble Diagram with a SNLS- survey-like @ z ~ 0.05

- telescope 1.35-m @ Siding Spring Observatory (Australia)
- wide field imaging : 5.7 deg^2
- 6 filters uvgriz similar to Megacam griz
- Southern Sky Survey : 2 π
- Skydice

SkyMapper SuperNova Search :

- rolling search : 1200 deg^2 observed every 4 days in vgri
- ~150 SNe Ia discovered / year @ z~0.05

~ 450 SNe Ia @ z~0.05 : matching SDSS & SNLS quality

➞ dark energy study

- complementary spectro. identification on other telescopes
- starting **fall 2011**

What's next ?

Stage IV ground based SN projects

- Pan Starrs 4 :

Simultaneous observing with four 1.8m telescopes of 3 deg2 fov (0.3'' pixels)

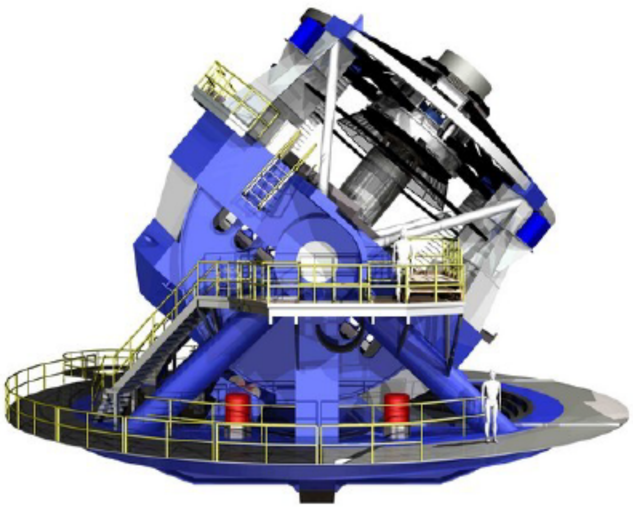
- LSST : => 250000 SN/yr !

- low AND high-z SNe from the same instrument
- repeat imaging (calibration <1%) + « sky calib. »

LSST : Large Synoptic Survey Telescope

a wide and deep field survey
-nature of dark energy
- solar - system
- optical transients
- galactic structure

complementary probe for DE with lensing/BAO:
~ O(10 000) SNe Ia z ~ 0.5-1.4
(photometry only)



Instrument :
- primary mirror 8.4-m @ Chile
- camera 3.2 10^9 pixels (189 CCDs)
- 9.6 deg^2

Survey:
- 10 years, 5 10^6 images
- 20 000 deg^2
- 6 filters UV - NIR
- > 3 10^9 galaxies with photo-z

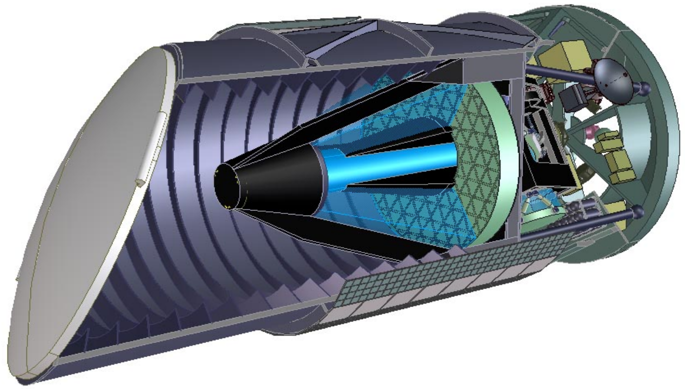
Schedule:
- 2010 : first priority by NAS
- funding NSF/DOE in 2013, first light 2018

What's next ?

Space based cosmology with SN Ia

➔ detect/follow distant SN Ia from space

➔ first proposed in 1999 (SNAP)
ϕ~2m telescope 0.6 sq. deg. -
Vis+NIR 0.4->1.7 m
2000 SNe 0.2<z<1.7 in 3 yrs



➔ several incarnations : DESTINY, JEDI, JDEM, DUNE, EUCLID, …
now WFIRST, mostly aiming at weak lensing and/or BAO

➔ recent study based on a modified EUCLID concept (+filter wheel)

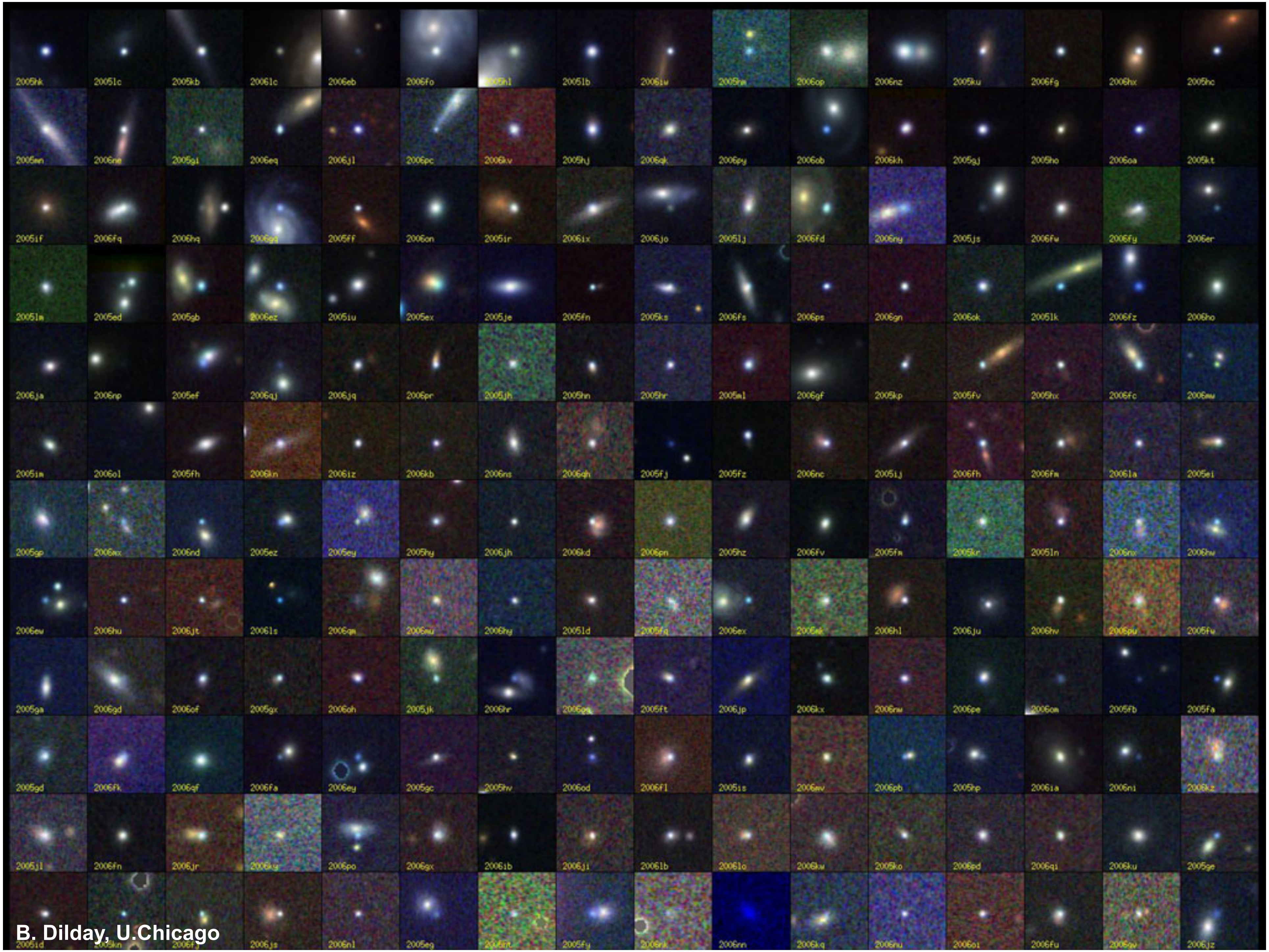
Conclusion

- SNe Ia remain excellent distance indicators. Today's precision:
(+BAO & CMB) : δw(stat+syst)~0.08

- full systematics included
(primary contributor : calibration
& inter-calibration on external photometric systems)
- taking into account host influence

Future :
- SDSS & SNLS-5 joined analysis
- improve nearby sample, understand environement, separate dust from intrinsic effects

- SkyMapper, DES, LSST, WFIRST, EUCLID….
will address some of possible systematics
very difficult to significantly improve on precision
w(z)


B. Dilday, U.Chicago