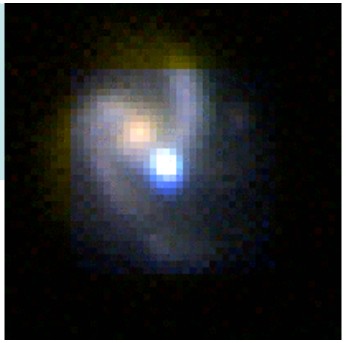
Supernovae Ia and Dark Energy

The Supernova Legacy Survey
3-year results

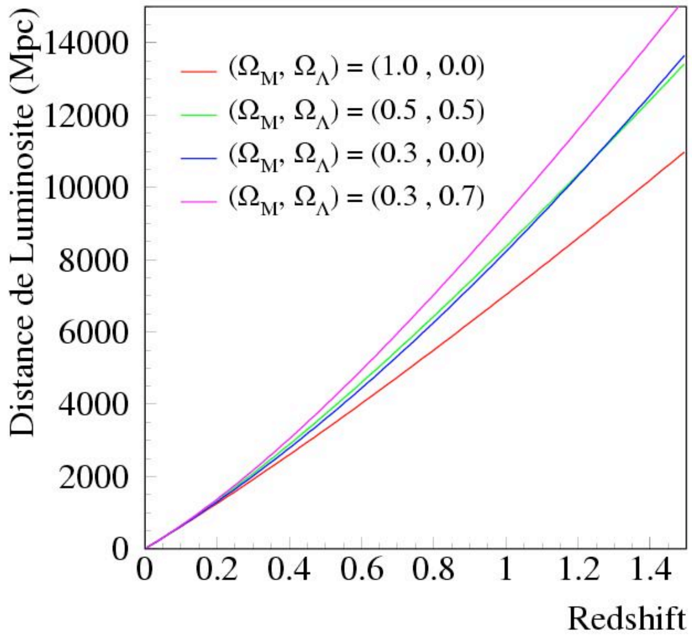
on behalf of SNLS
Delphine Hardin, LPNHE, Université Pierre et Marie Curie, Paris, France

SNe Ia and Dark Energy



1. Measuring the Energy Content of the Universe
2. Cosmology with type Ia supernovae
3. SNLS 3-years cosmological constraints
4. Conclusion & Future

Measuring the Universe Energy Content



Universe in expansion : d $\propto$ expansion factor **a(t)**

expansion history $\Leftrightarrow$ 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 :*** $\mathbf{d_L(z)}$

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

2 fluids : matter and X :
- matter : $\rho_M(t_0)$ or : $\boxed{\Omega_M} = \rho_M(t_0)/\rho_{\text{crit}}(t_0)$

expansion is accelerating ? ➔
- X : $\boxed{\Omega_X}$
  perfect fluid with equation of state $\boxed{w} = p/\rho$,

Standard Candles to Probe the Expansion History

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

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

<u>**STANDARD CANDLES :**</u> **L ≈ cste**

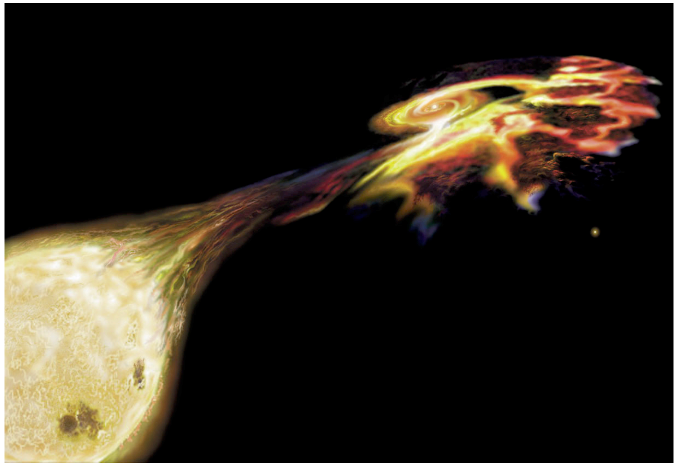
➜ compare the fluxes of 2 standard candles at $\mathbf{z_1}$ and $\mathbf{z_2}$

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

Type Ia Supernovae as Standard Candles

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

…… they are not standard candles



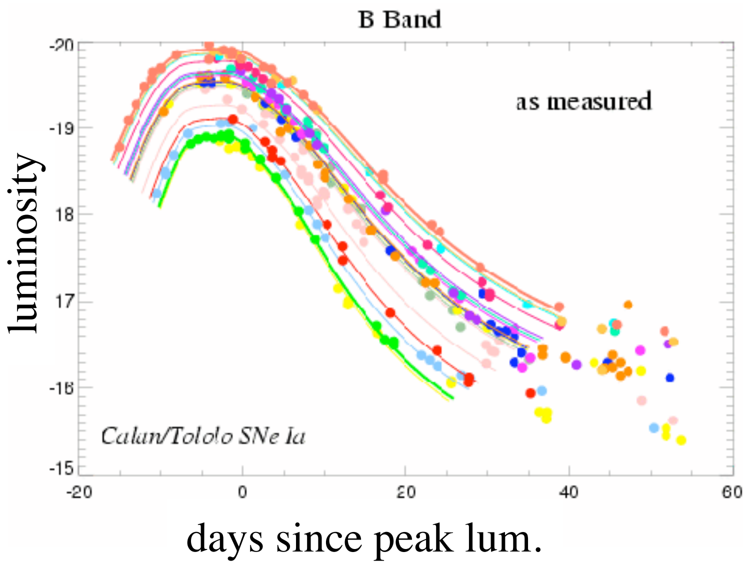
BUT :

- 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 $\mathbf{d_L}$



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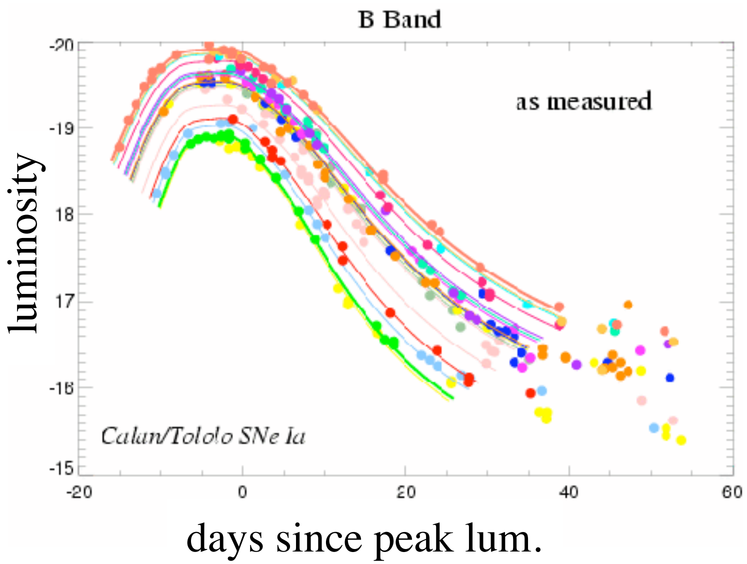

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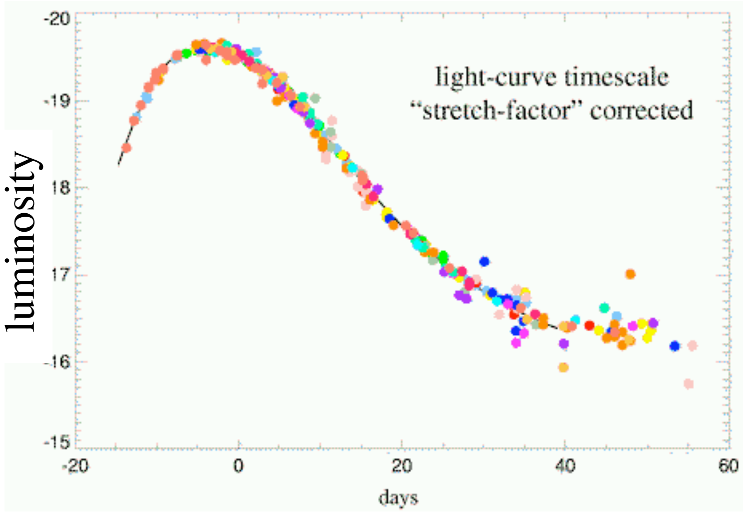
➞ **8%** precision on (relative) distances $\mathbf{d_L}$

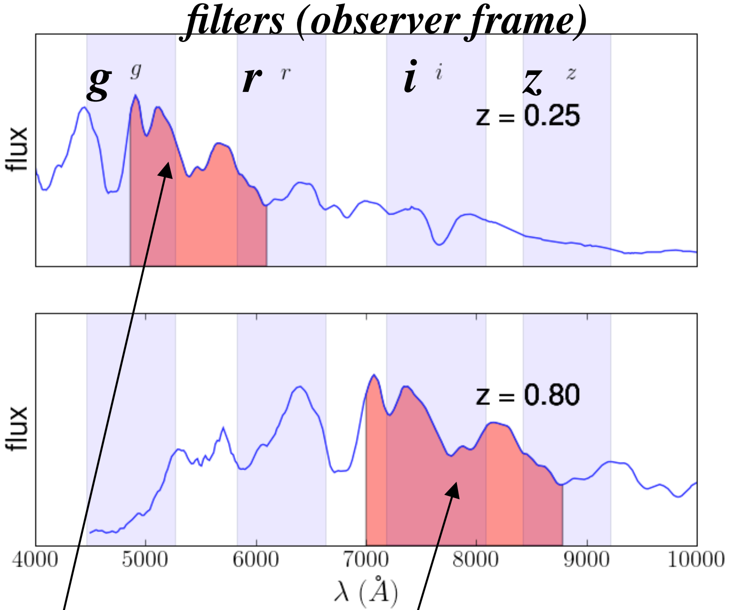


days since peak lum.

Type Ia Supernovae as cosmological tools

comparing fluxes at different redshift

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



F_{1B} F_{2B}

F is **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**
S(λ, 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)

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

measured peak magnitude
in restframe B filter

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

light-curve shape correction

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 due to

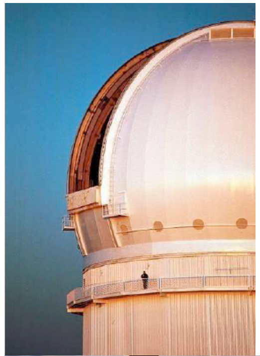
- intrisic SNe Ia color variation

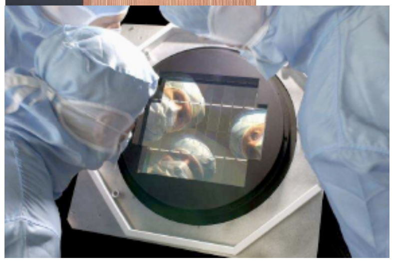
or

- due to extinction by dust at the SN location, in SN host galaxy or along line of sight

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

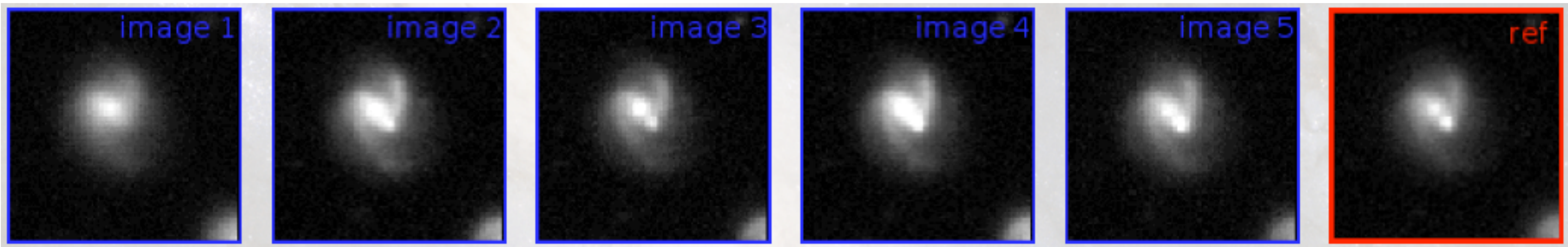
- ***rolling search*** **:** repeated observations of 4 fields

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**

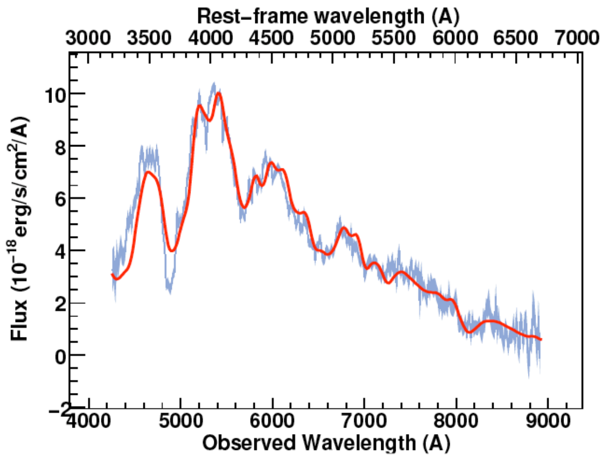


SNLS SuperNova Legacy Survey

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

SNLS-3 years results :

➲ **240 SNLS (z ~ 0.2 - 1.) SNe Ia, extended with nearby + SDSS-II @ z<0.2**
➲ **2 independant analysis (France/Canada)**

➲ **improved calibration** (Regnault et al., 2009)
→ <1% precision
→ main systematic source : tailing Megacam magnitude system to the magnitude system of the nearby SN (Landolt)

➲ **improved spectro-photometric supernova modeling SALT2** (Guy et al., 2010) :
model trained on nearby + SNLS SN (no distance info)
→ UV model : nearby SN U/u-band data less used, but highz (SNLS) optical (g) data

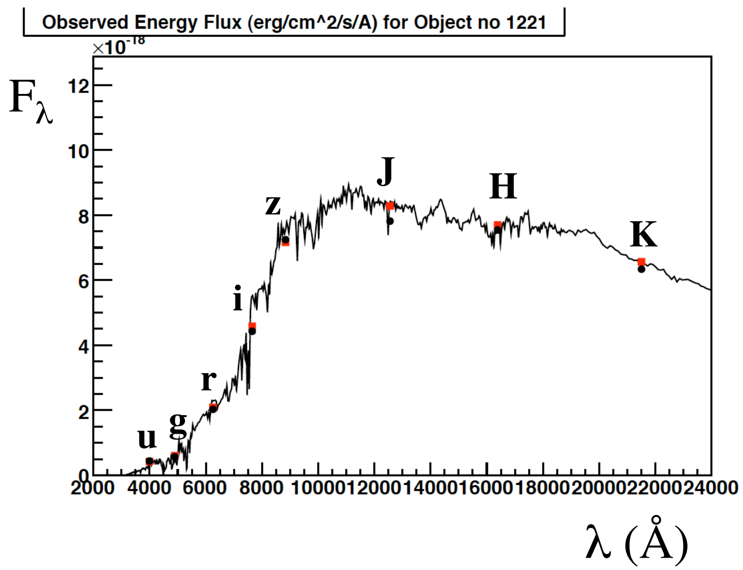
➲ **host galaxy nature influence** (Sullivan et al., 2010, Hardin et al. in prep)
« standard » SNe Ia brighter in massive galaxies
→ M_{B1} & M_{B2} whether SN host galaxy masss < 10^{10} $M_{\odot}$:

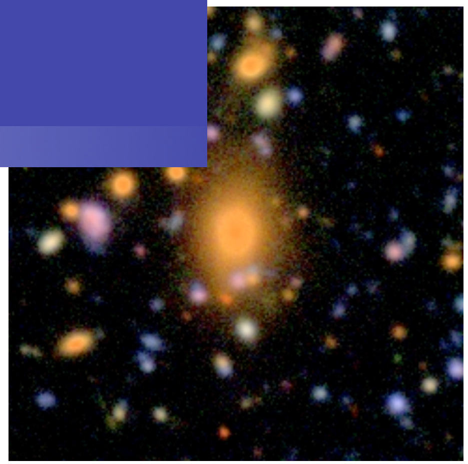
➲ **systematics included** in cosmology fit of an **extended nearby + SDSS** Hubble Diagram :
Conley et al. 2010

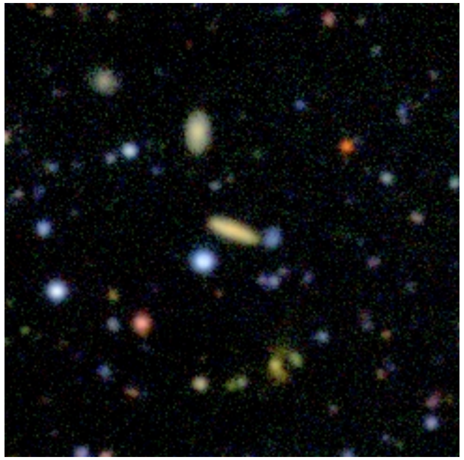
SNLS SuperNova Legacy Survey

SNIa host galaxies

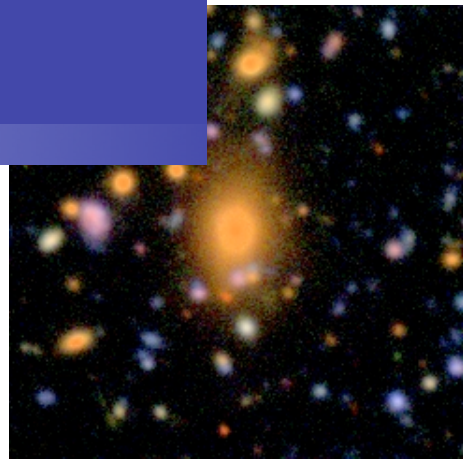
- Are M_B, α and β "universal" parameters? Any host galaxy (environmental) dependence?
- ugrizJHK host data allows estimations of:
  - host colors & luminosity
  - host star formation rate & stellar mass content

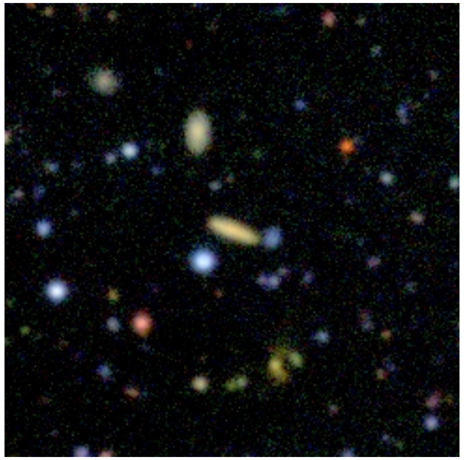






SNLS SuperNova Legacy Survey





SNIa host galaxies

Hubble residuals versus host mass

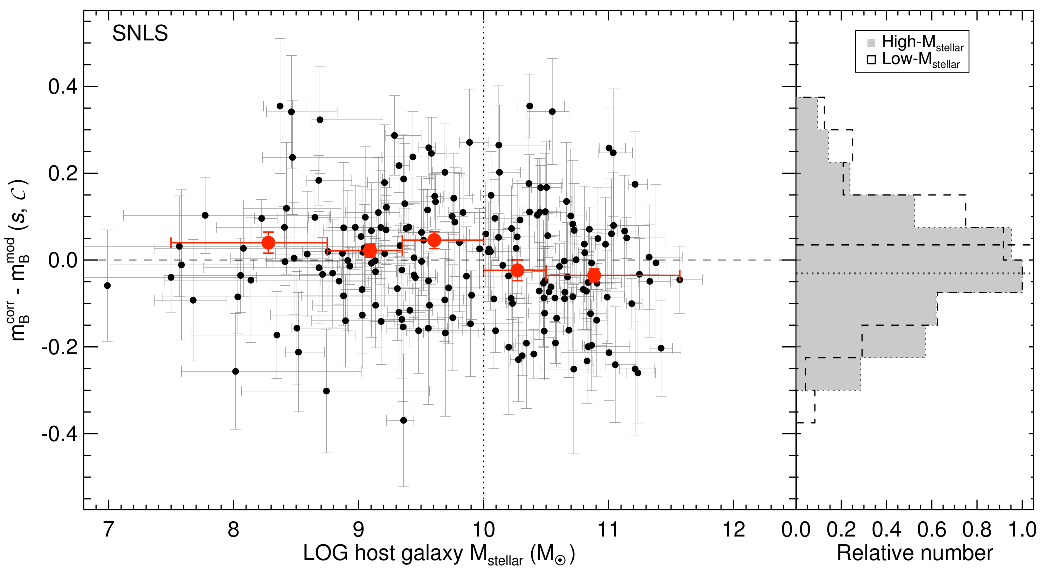
- the **mean** SNe Ia is brighter in low-mass galaxies (their mean *shape* is >) :

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

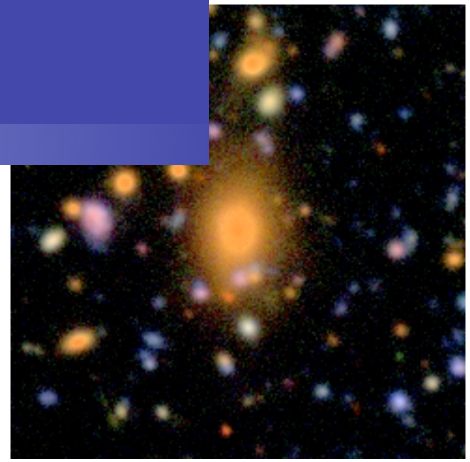
- **the "standard"(*) SNe Ia is brighter (4σ) in massive galaxies**

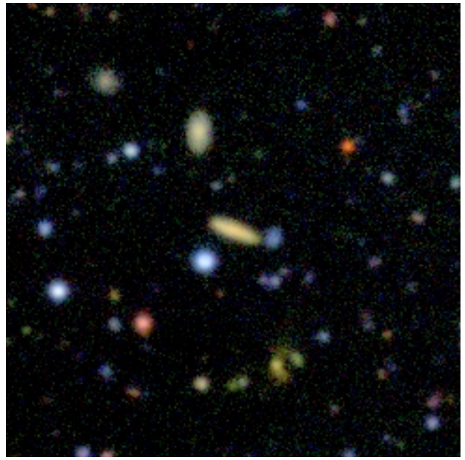
(*=after lightcurve shape and colour correction, i.e. *shape*=0, *color*=0)

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



SNIa host galaxies





Improved cosmological analysis

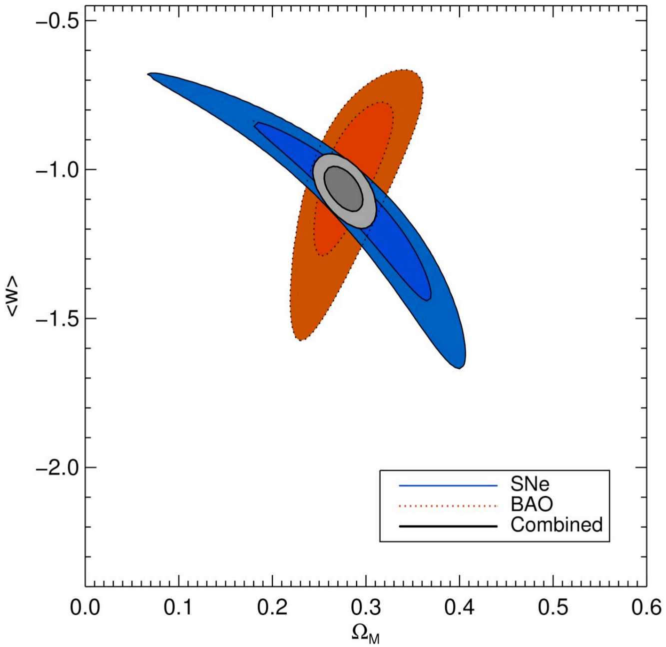
Use two M_B – one for high-mass galaxies and one for low-mass

$$\boxed{\begin{array}{l} \mu_B = m_B - M_B^1 + \alpha(s-1) - \beta c \quad \text{when } H < H_{\text{split}} \\ \mu_B = m_B - M_B^2 + \alpha(s-1) - \beta c \quad \text{when } H \geq H_{\text{split}} \end{array}}$$

SNLS SuperNova Legacy Survey

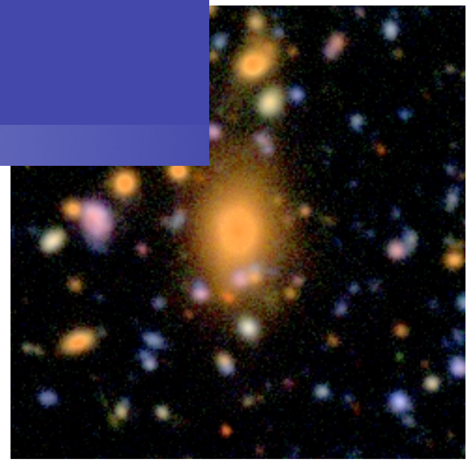
SNIa host galaxies

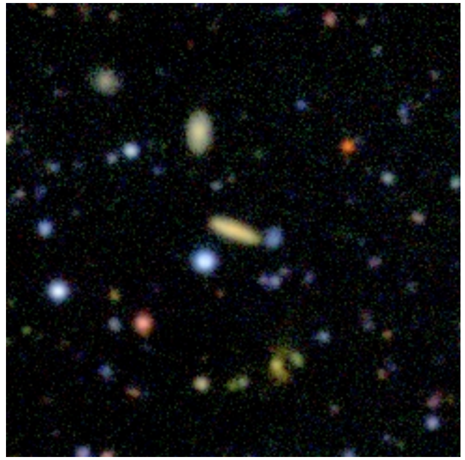
Improved cosmological analysis



without host galaxy mass term

BAO+SNe+WMAP7+flat





SNIa host galaxies

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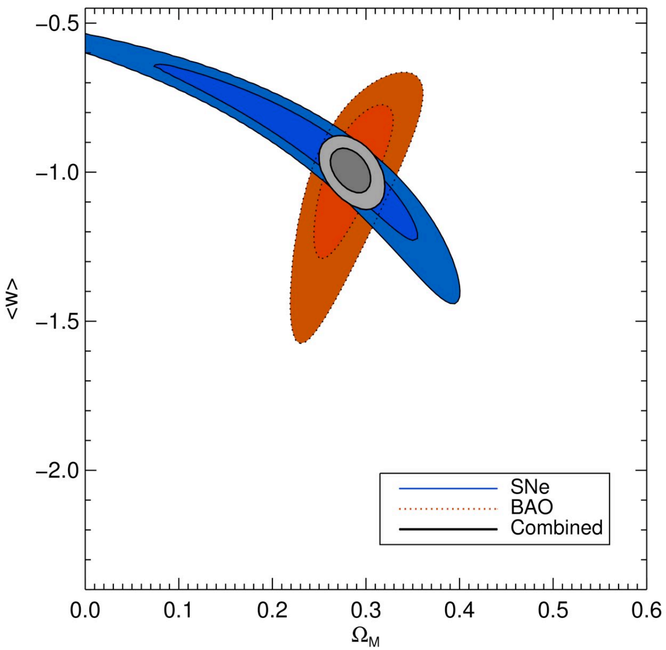
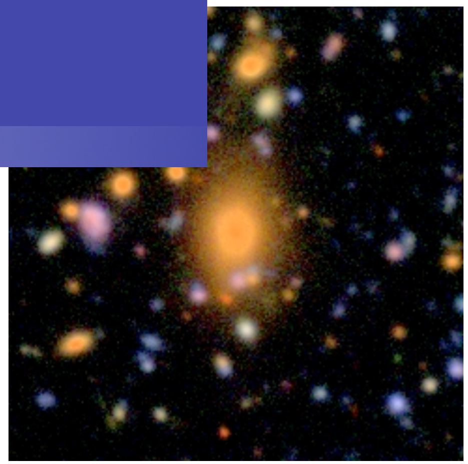
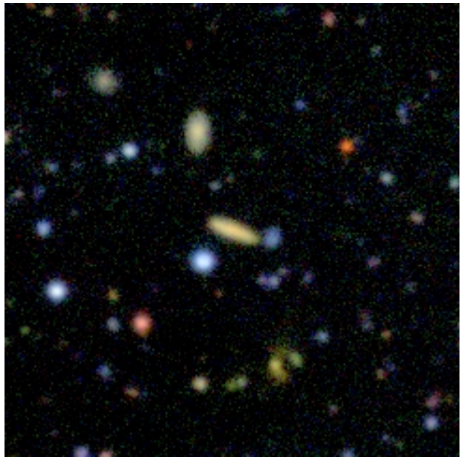


with host galaxy mass term

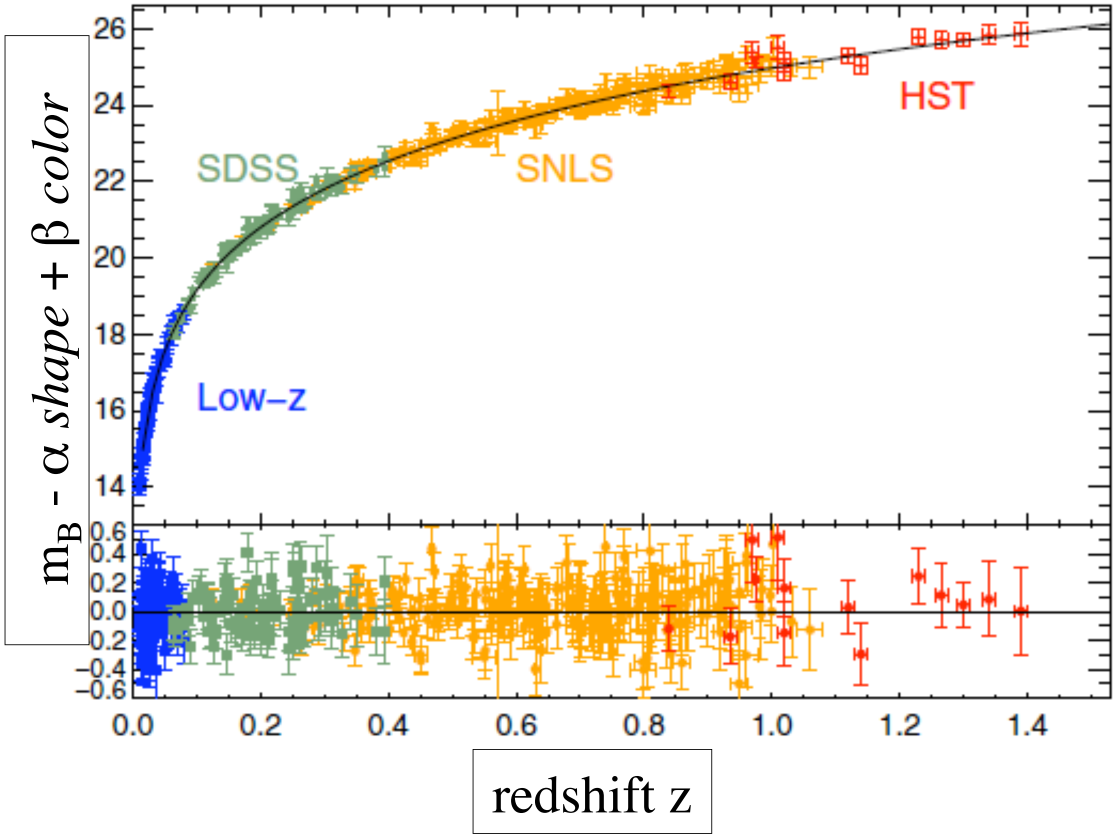




SNLS SuperNova Legacy Survey

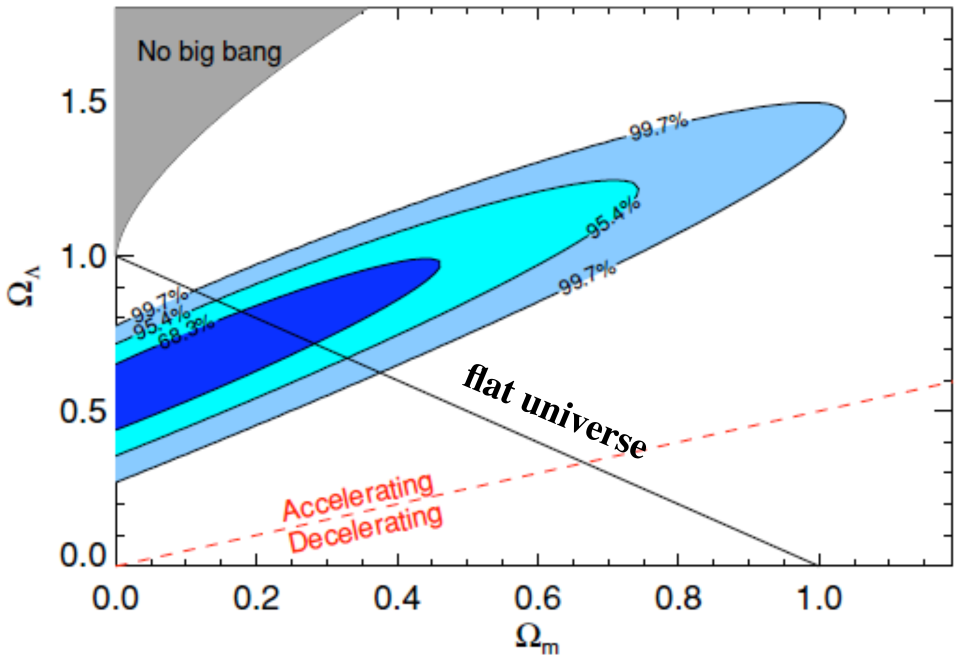
SNLS-3 extended Hubble Diagram

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**



Conley et al., 2010

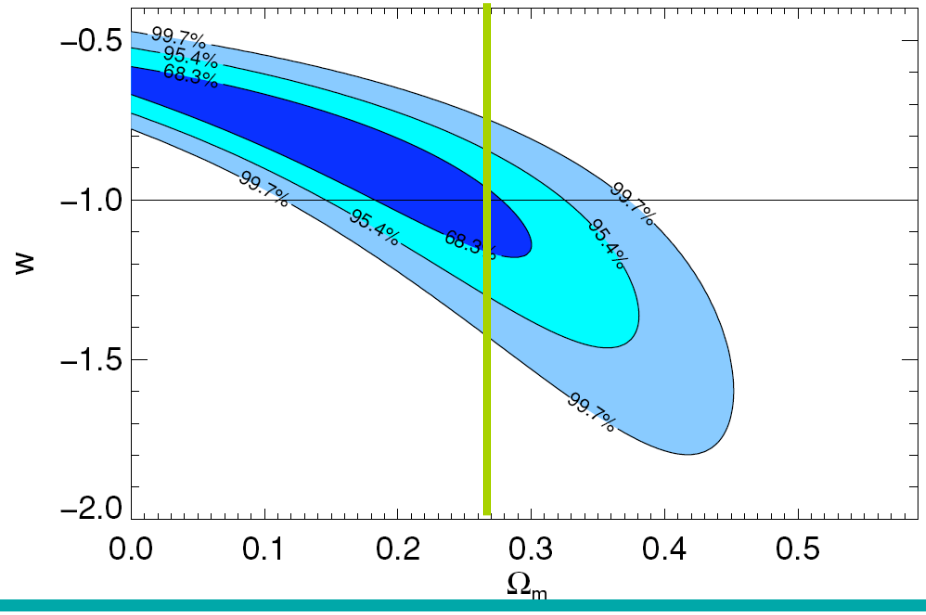
Universe still accelerating !



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

SNLS-3 + flat universe :

compatible with *w*=-1 (cosmological constant Λ, vacuum energy)



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

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

Conley et al., 2010

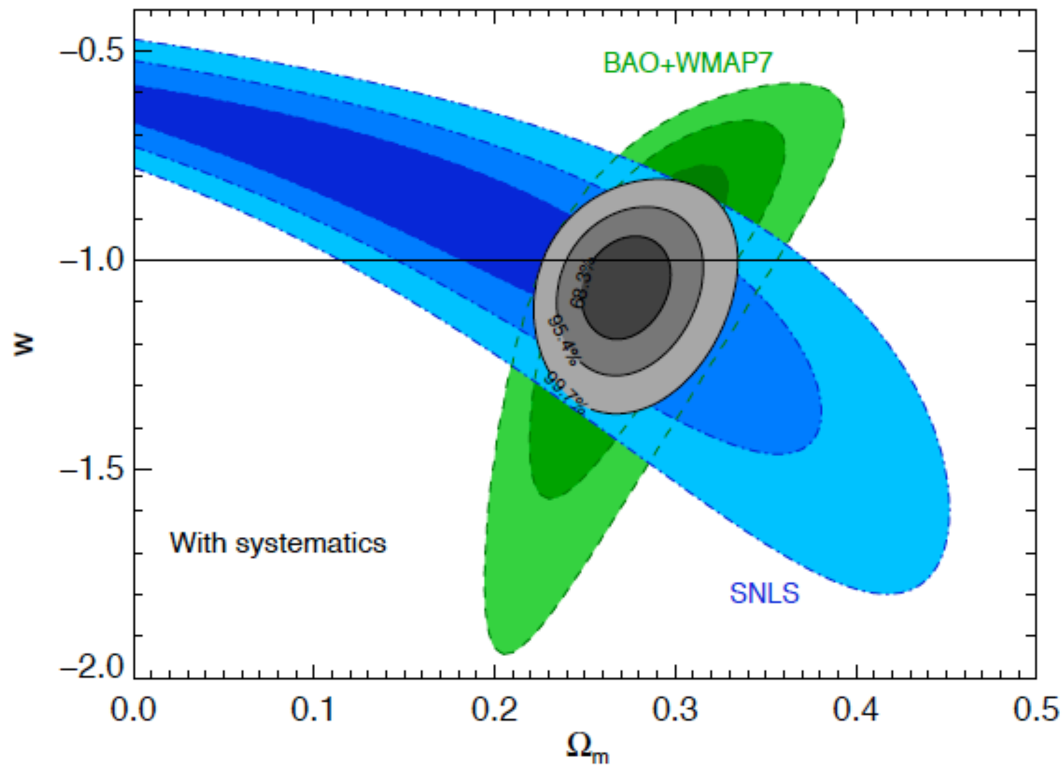
Sytematics in details :

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

Combining SNLS_3 with other cosmological probes :

BAO + WMAP7 + Flat



Sullivan et al, 2011, *in prep*

Conclusion

- SNLS3 SNe + external sample :

  w at aprecision of 0.1 for a flat universe, given Ω_M measurement
- full systematics included

  (primary contributor : calibration

  & inter-calibration on external photometric systems)
- taking into account host influence

Future :

- SDSS & SNLS-5 joined analysis :

  → 300 SDSS + 400 SNLS SNeIa

  → take full advantage of inter-calibration possibilities

  → full SN model re-training

- SkyMapper, DES, LSST, WFIRST, EUCLID….

will address some of possible systematics

very difficult to significantly improve on precision

w(z)