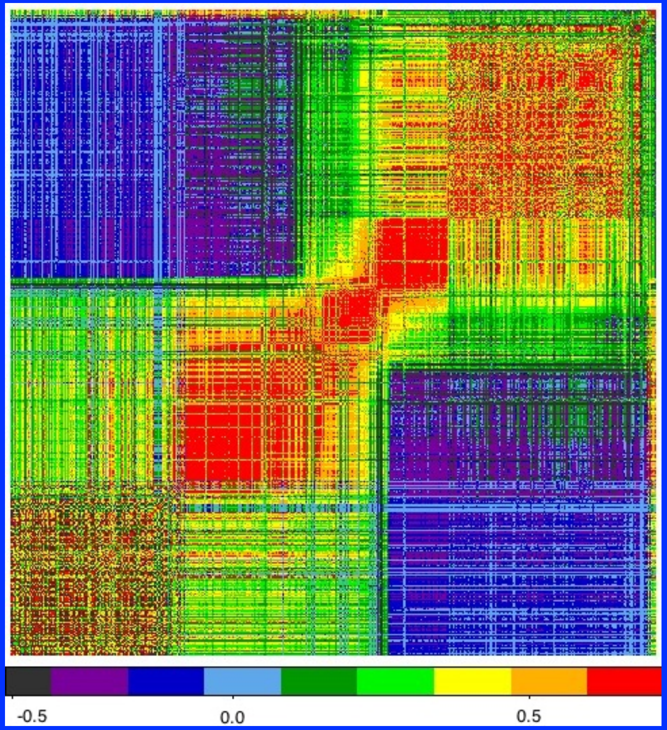
Supernovae Ia and Dark Energy

tracking systematic uncertainties



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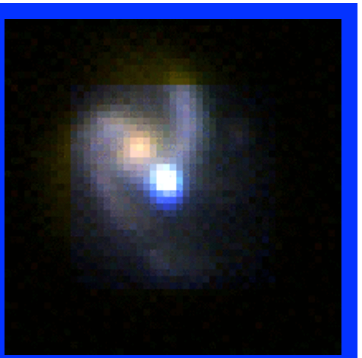
SNe Ia and Dark Energy



- Measuring the Energy Content of the Universe
- Data reduction : tracking systematic uncertainties
- Latest SN cosmological constraints
- What's coming next ?

I - SN Cosmology in a few slides

Experimental Principle

2 observables :
flux: f
Redshift: **z**

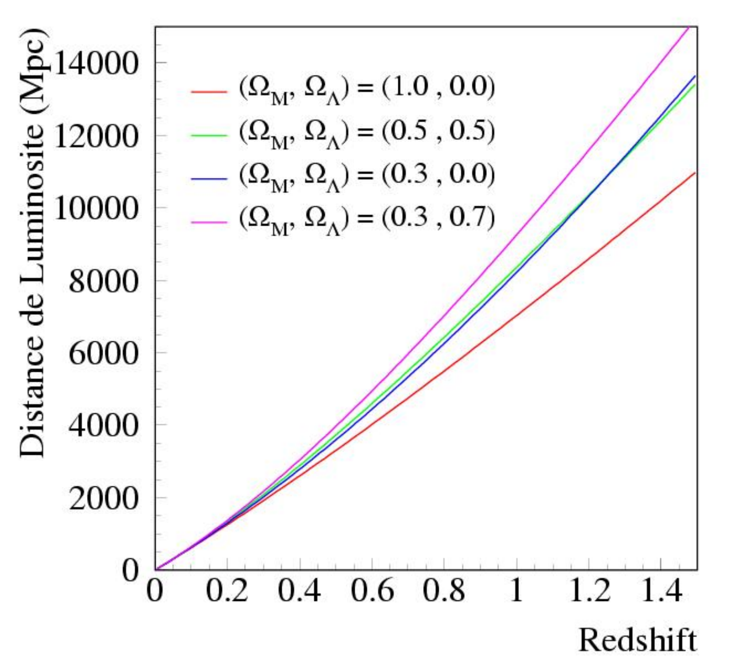
$d_L^2 = \mathcal{L}/4\pi f$

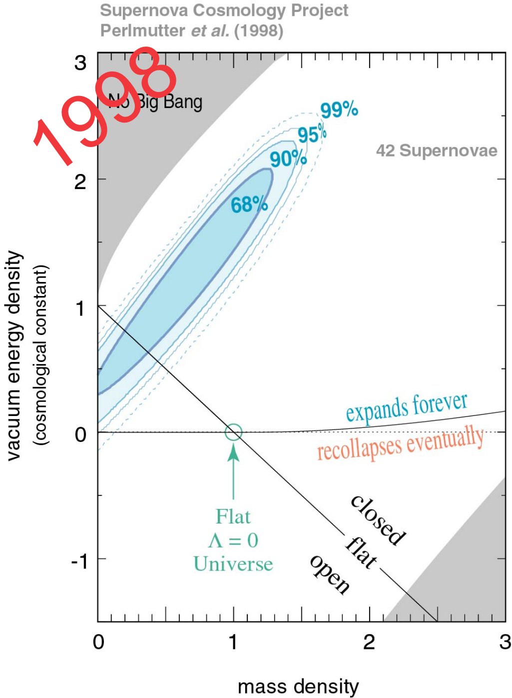
- Use SN Ia as distance indicators to measure the Luminosity distance d_L
- d_L is sensitive to the expansion rate and to the Energy content of the Universe

The Luminosity Distance

Assume the Universe is made of 2 « fluids » : Masse and X of density ρ_X

$$d_L(z) = (1+z)\frac{c}{H_0}\int dz' \left(\Omega_M(1+z')^{-3} + (1-\Omega_M)\frac{\rho_X(z')}{\rho_X(0)}\right)^{-1/2}$$



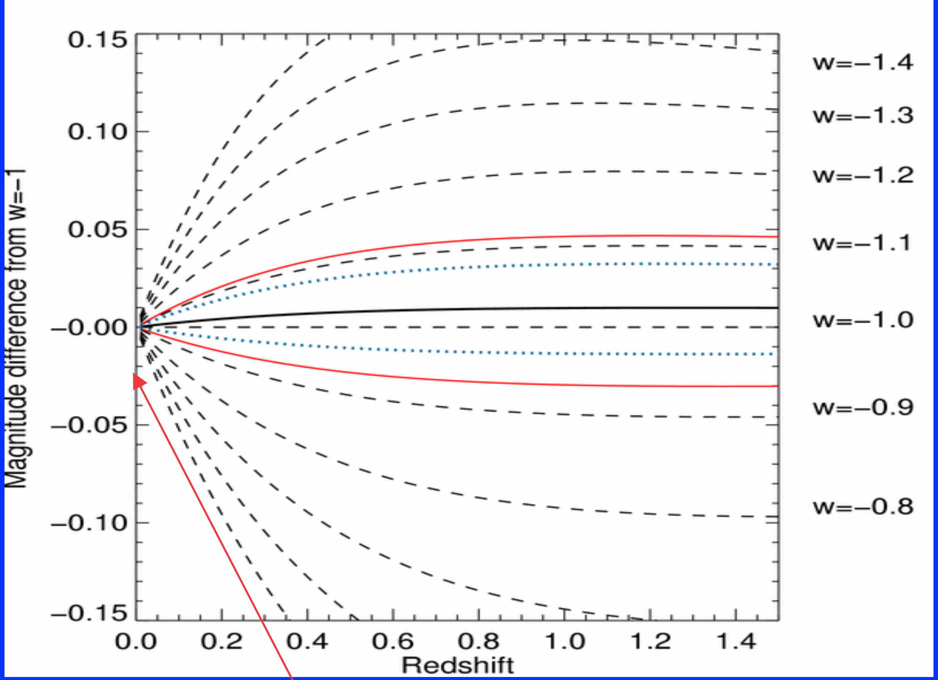


Favor a non zero Λ

What is X (dark energy) ?

$$\rho(z) = \rho_0 \exp\left(\int 3\frac{w(z)+1}{1+z}dz\right)$$

Equ. of State $$w = \frac{p}{\rho}$$



δw (w=-1) ~ 2.5 δm

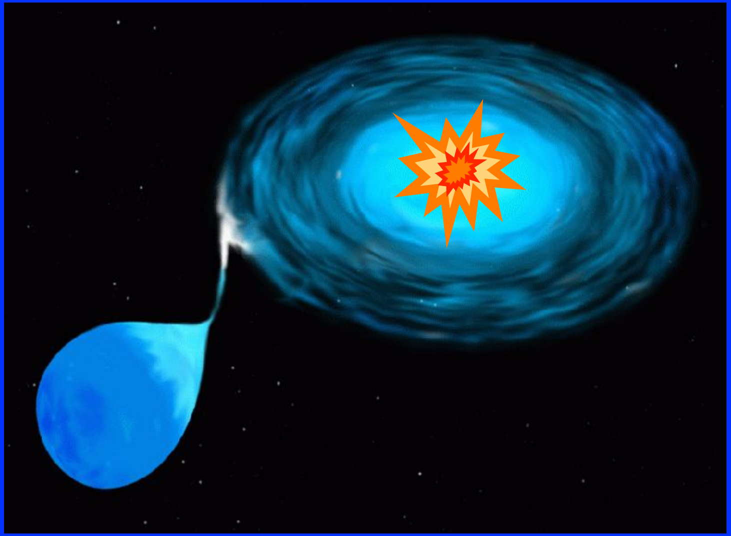
Experiment ingredients:

- Low-z and High-z SNe Ia
- Ω_M prior or constraint -> increase precision

SNe Ia are good cosmological tools

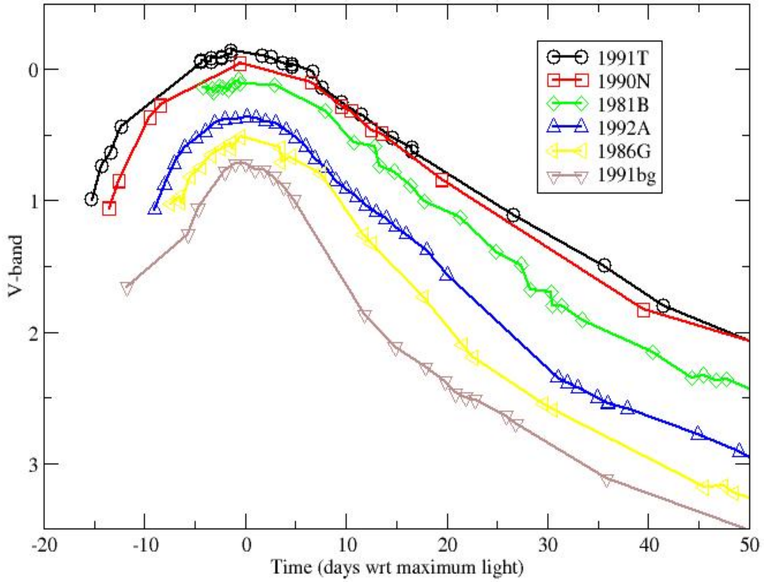
Very Luminous events

⇒ visible at cosmological distances



Show little luminosity dispersion

But they are NOT standard candles

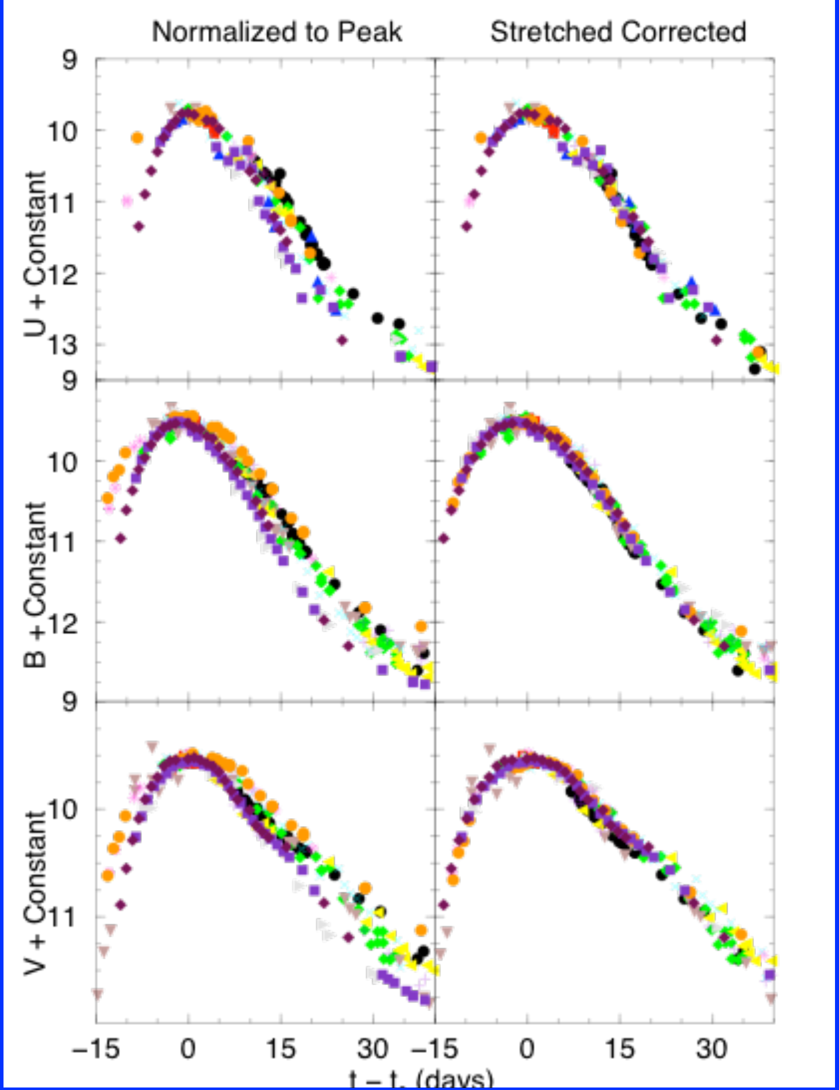


Calibrating Supernovae Ia

SNe Ia show Light Curve shape-luminosity relationships (similar to Cepheids P-L relation)

They also exhibit color luminosity relation (brighter-bluer)

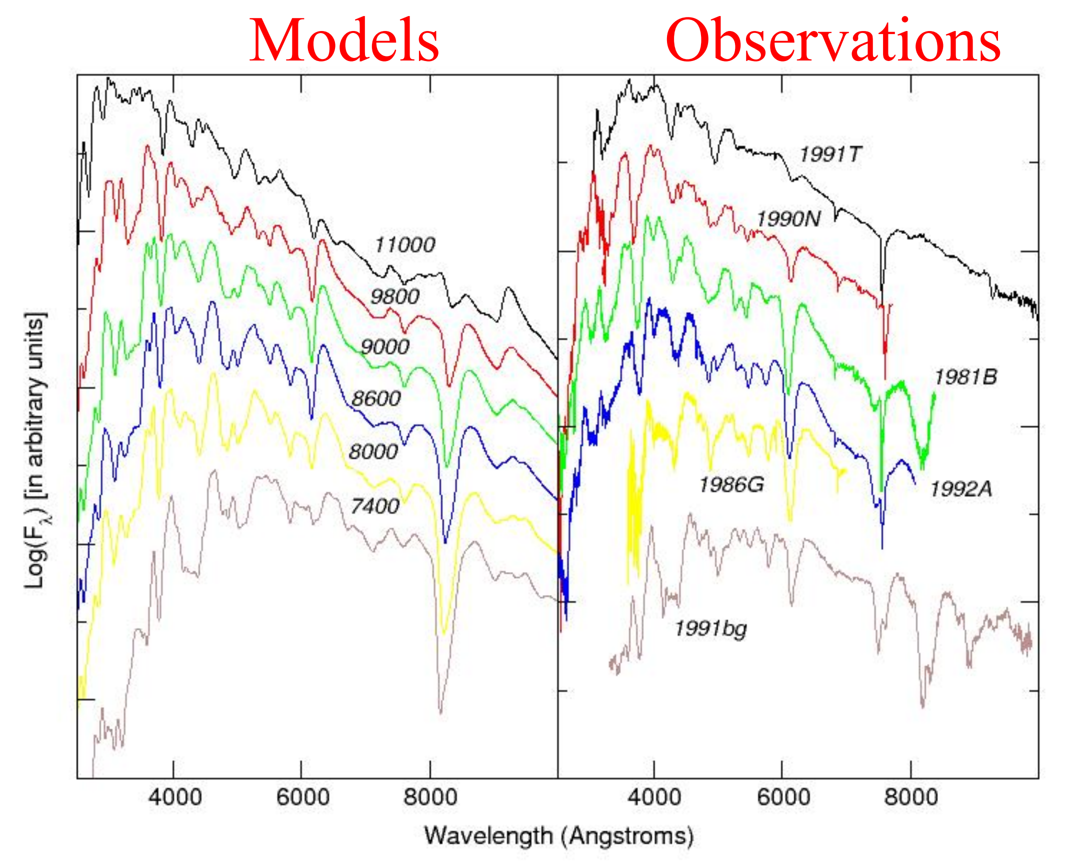
⇒Allows us to measure - after empirical corrections - distances to 5% precision



SNe 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.



Cosmology with SNe Ia

An empirical approach

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

Absolute magnitude at maximum

Light curve shape correction

Resframe apparent magnitude at maximum

Color correction. Accounts for
- extinction by dust
- intrinsic color variations

II – Data reduction : tracking systematic uncertainties

Why worrying about systematics?

SN cosmology is conceptually simple,
and (mostly) a relative measurement ($\Omega_{i,}$ w)

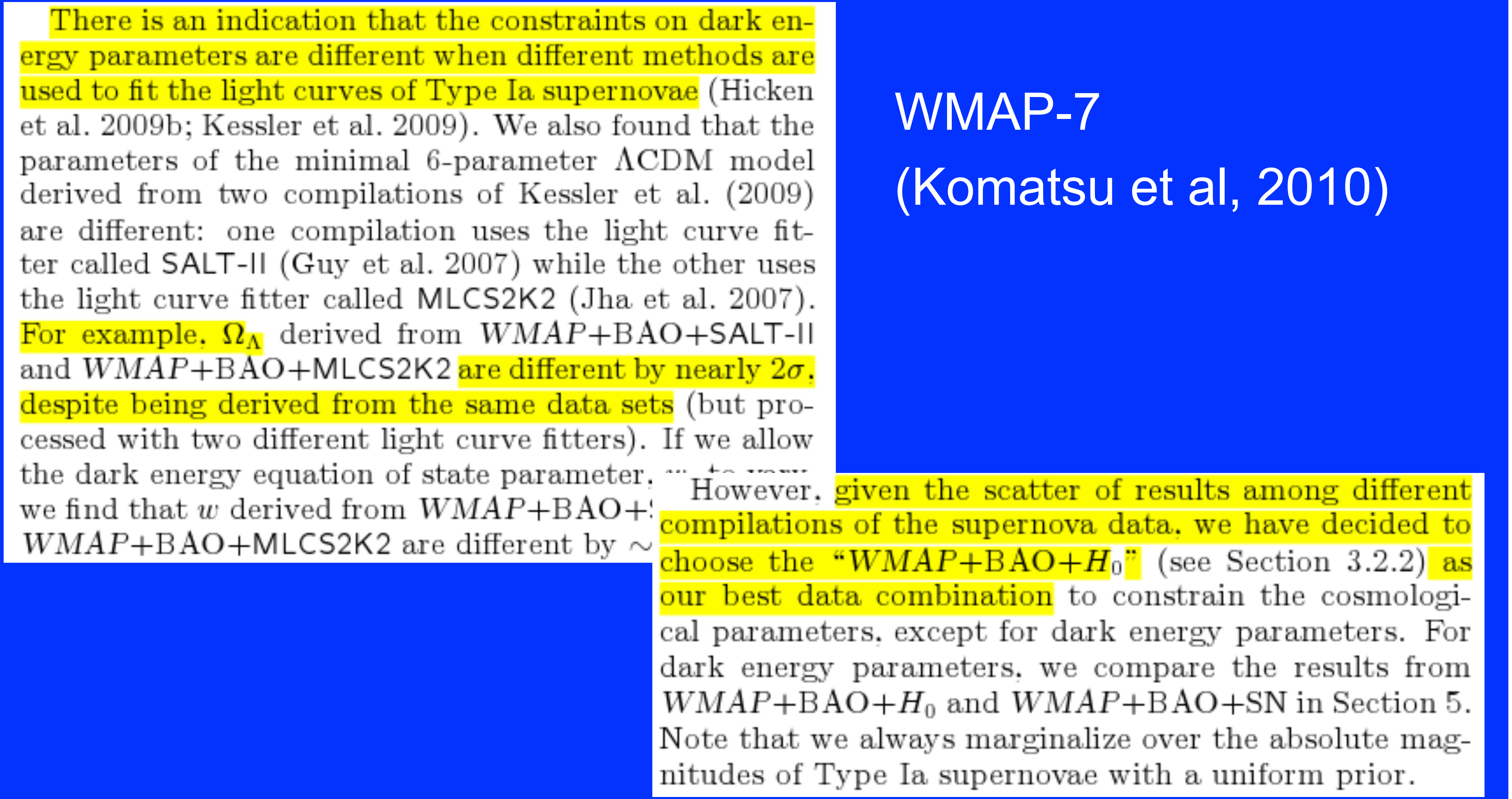
But it is (mostly) empirical : no precise theoretical understanding of SN Ia explosion mechanism and therefore of their physical properties

And subject to z dependent (known) systematic uncertainties

- affecting measurements : e.g selection effects (malquist), PSF photometry on galaxy, …

- of astrophysical nature : e.g dust, lensing along the ligne-of-sight

Can SN still be used to constrain cosmological parameters?



There is an indication that the constraints on dark energy parameters are different when different methods are used to fit the light curves of Type Ia supernovae (Hicken et al. 2009b; Kessler et al. 2009). We also found that the parameters of the minimal 6-parameter ΛCDM model derived from two compilations of Kessler et al. (2009) are different: one compilation uses the light curve fitter called SALT-II (Guy et al. 2007) while the other uses the light curve fitter called MLCS2K2 (Jha et al. 2007). For example, Ω_Λ derived from *WMAP*+BAO+SALT-II and *WMAP*+BAO+MLCS2K2 are different by nearly 2σ, despite being derived from the same data sets (but processed with two different light curve fitters). If we allow the dark energy equation of state parameter,

we find that w derived from *WMAP*+BAO+

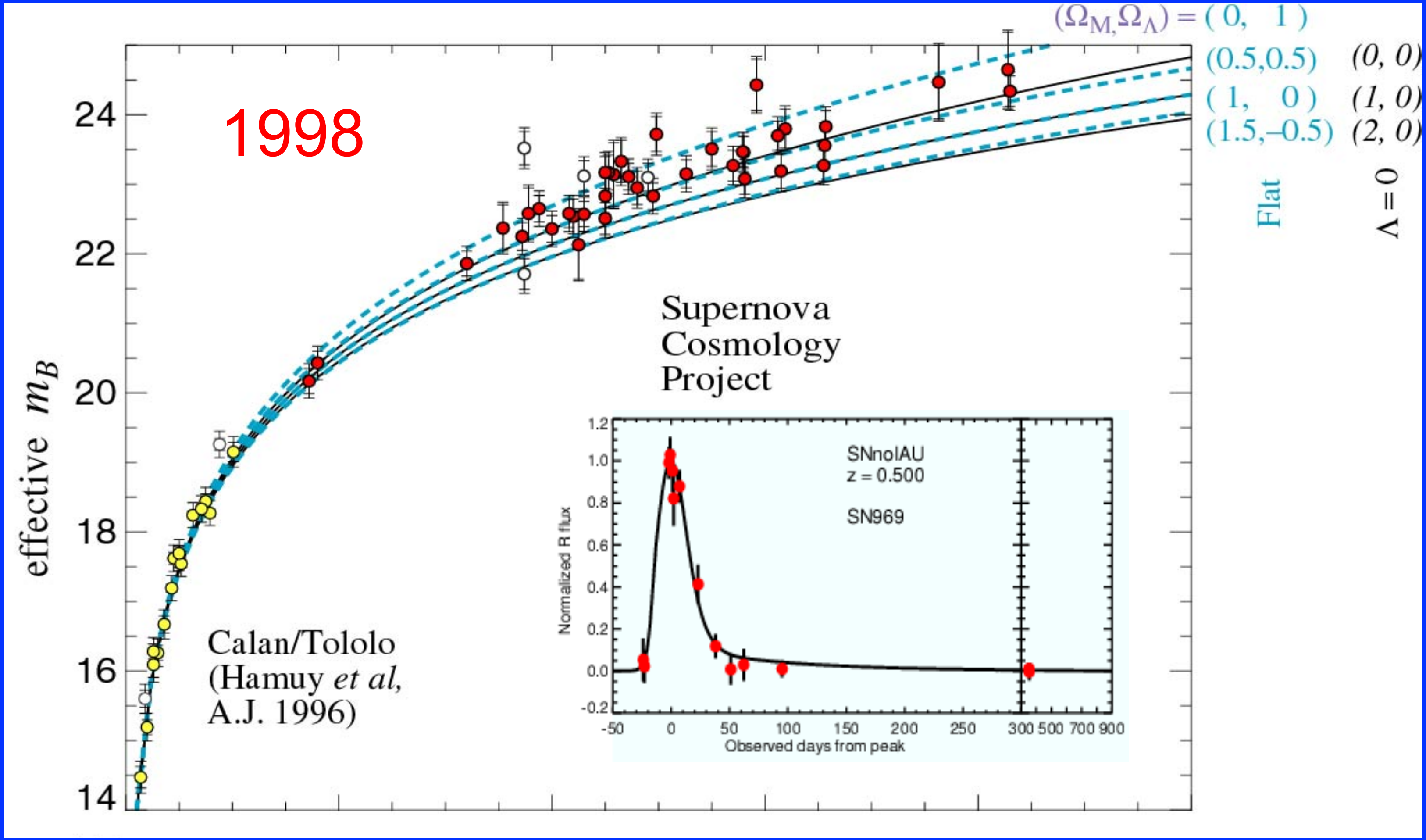
WMAP+BAO+MLCS2K2 are different by ~

However, given the scatter of results among different compilations of the supernova data, we have decided to choose the "*WMAP*+BAO+H_0" (see Section 3.2.2) as our best data combination to constrain the cosmological parameters, except for dark energy parameters. For dark energy parameters, we compare the results from *WMAP*+BAO+H_0 and *WMAP*+BAO+SN in Section 5. Note that we always marginalize over the absolute magnitudes of Type Ia supernovae with a uniform prior.

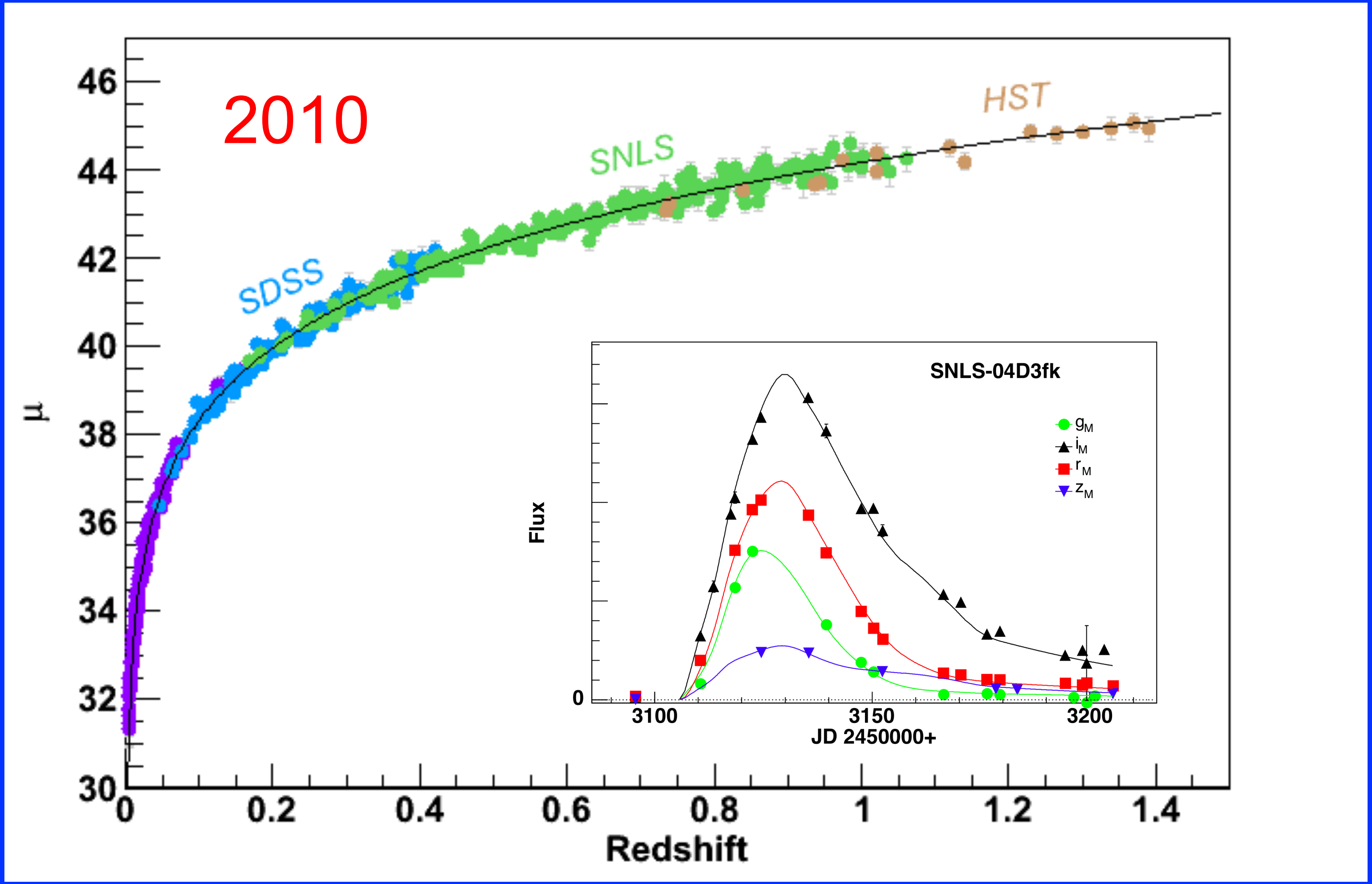
WMAP-7

(Komatsu et al, 2010)

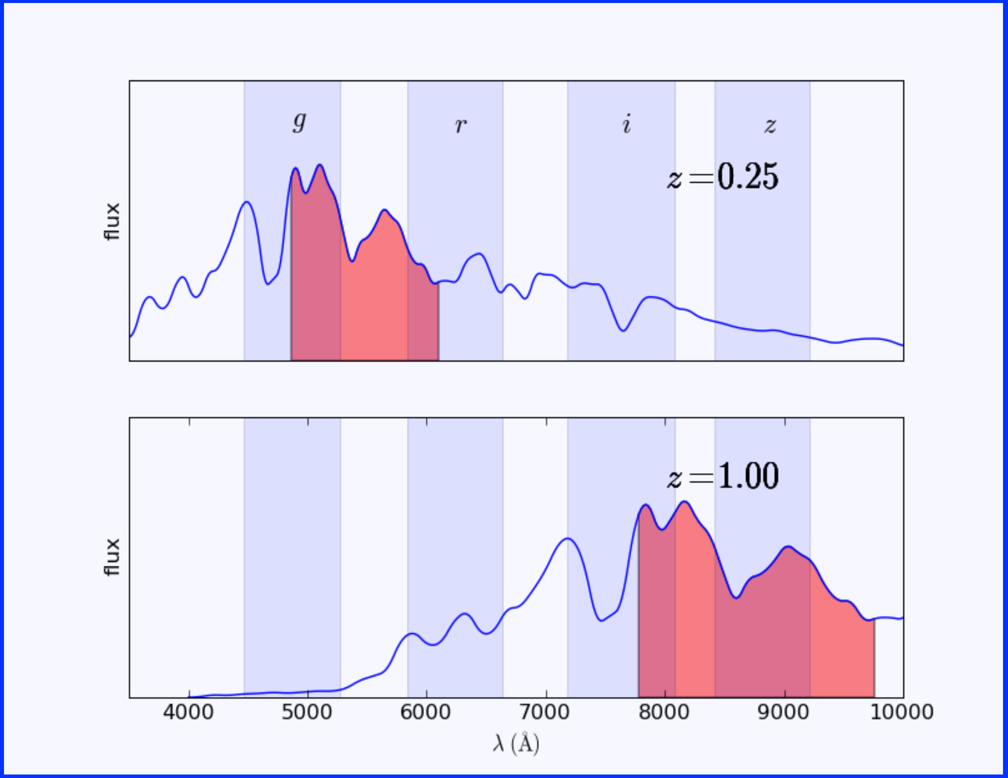
Systematic floor reached ?



Systematic floor reached ?



Extracting mb, s and c from observations



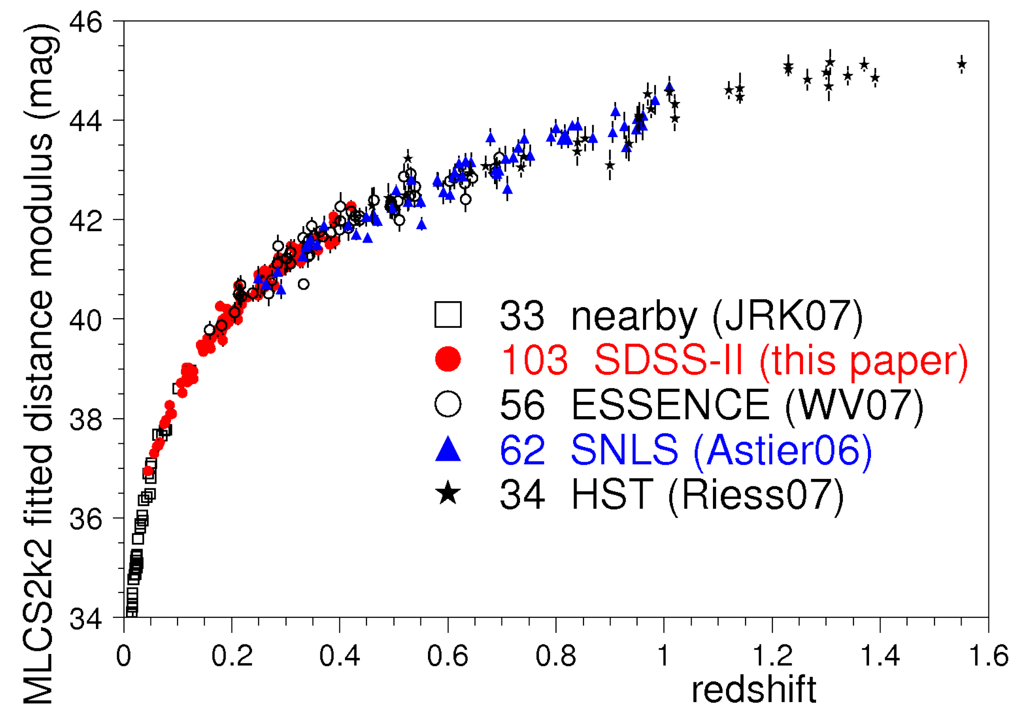
SN restframe fluxes at different redshifts

→ empirical model to interpolate between photometric measurements

→ Trained on sets of nearby & distant SNe

Several LC fitters : SALT2 (Guy et al, 2007), SIfTO (Conley et al, 2007), MLCS2k2 (Jha et al, 2007), CMAGIC (Wang et al, 2003), ...

SDSS-II First Year Results



(Kessler et al, 2009)

Large combined data sample

→ Measurement of w

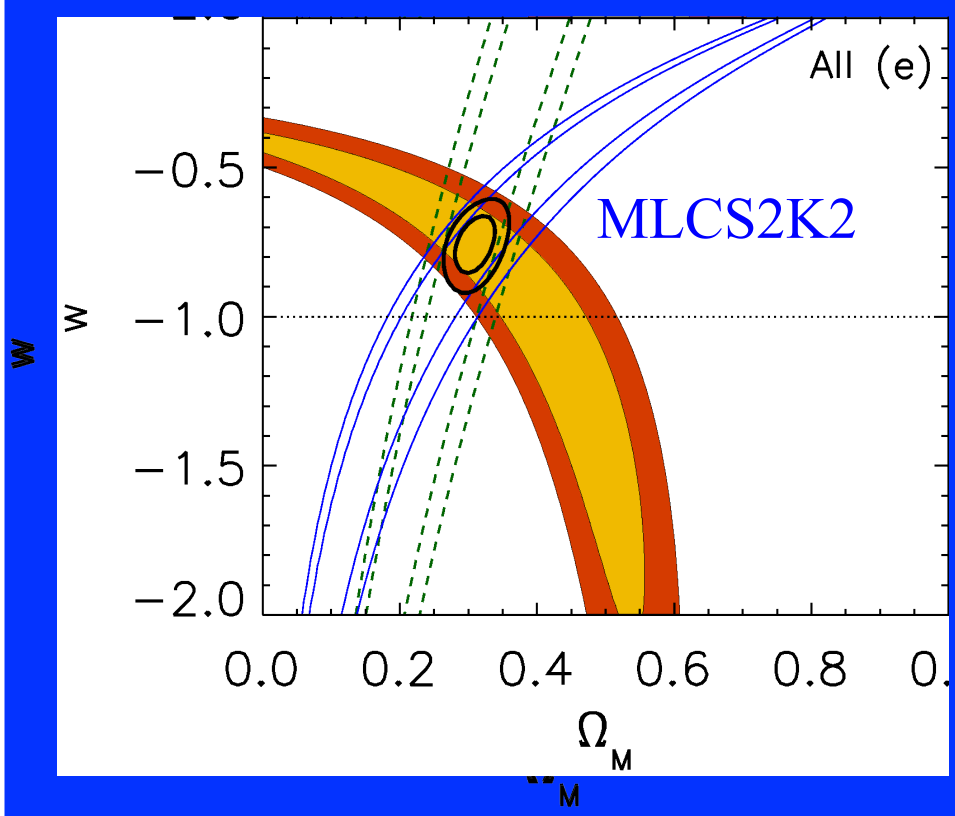
Analysis performed with two LC fitters:

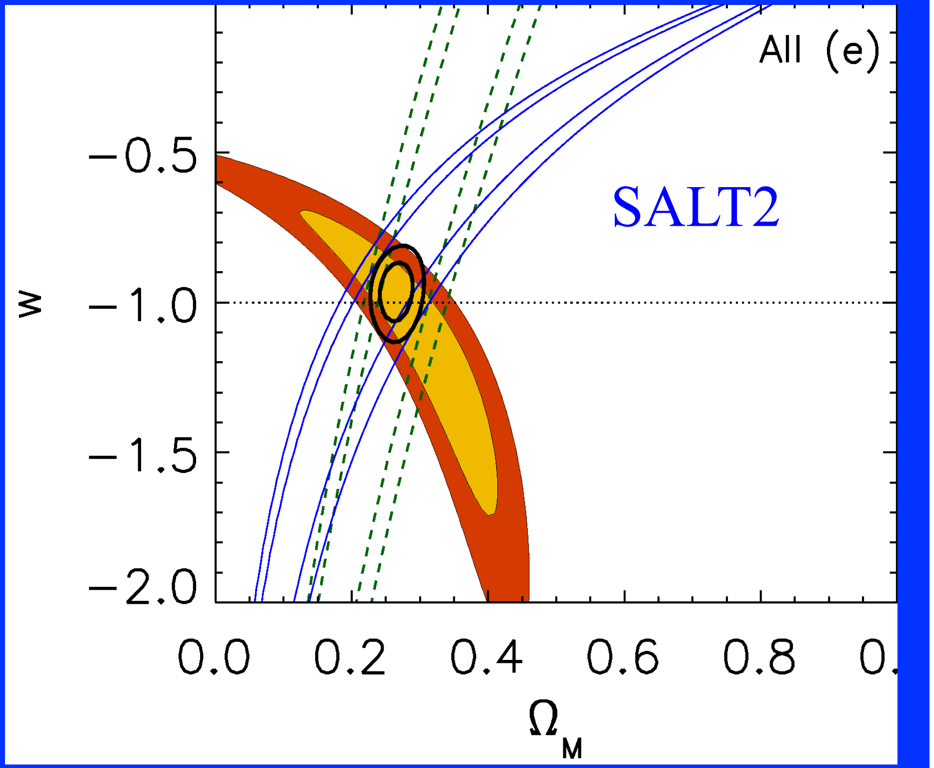
MLCS2k2 (Jha et al, 07)

SALT2 (Guy et al, 07)

→ thorough comparison of two lightcurve fitters / distance estimators.

Discrepancies between methods ?





w = -0.76 ± 0.07 (stat)

± 0.11 (sys)

w = -0.96 ± 0.06 (stat)

± 0.12 (sys)

Differences in LC fitters is not a systematic uncertainty

Origins of the “discrepancy” now well identified

(1) Model rest-frame UV calibration

→ disappears with improved photometric calibration

(2) Treatment of the color variability of the SNe Ia.

→ disappears when assumptions (and priors) are dropped (empirical approach)

The SN Ia color “problem”

- SN Color variability : dust + intrinsic variability ?
- 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

$$A_\lambda = R_\lambda \times E(B-V)$$

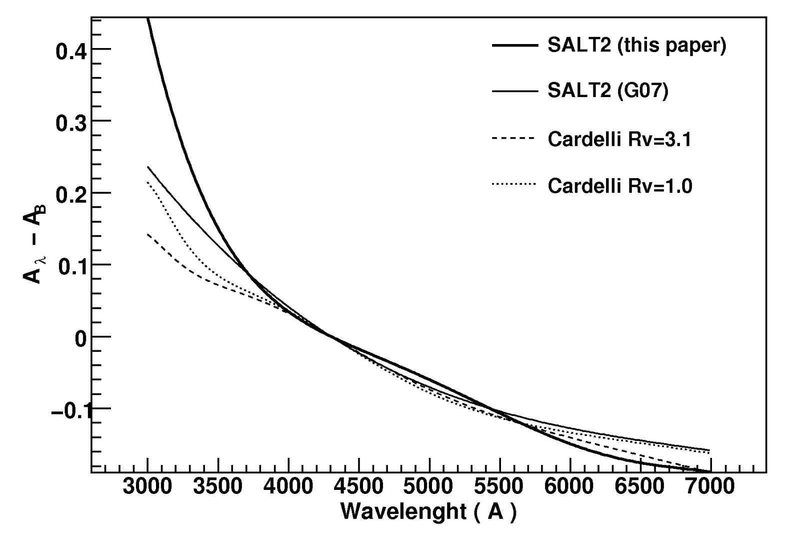
R_B ~4.1 for MW dust

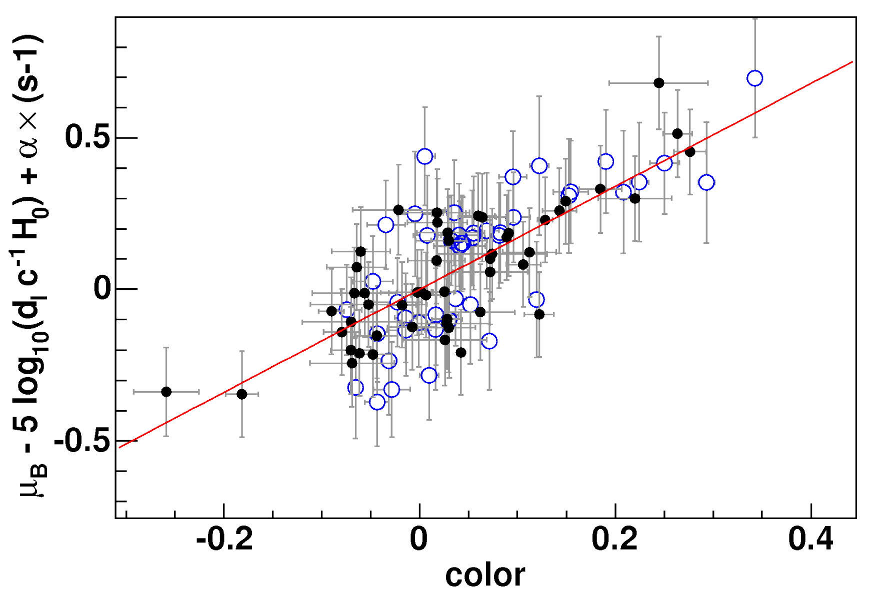
→ no a-priori knowledge of the properties of (2), (3) & (4)

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

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

SN Ia colors





- The “effective” reddening law for SNe does not follow the CCM law.

- For SNe Ia the total to selective extinction ratio

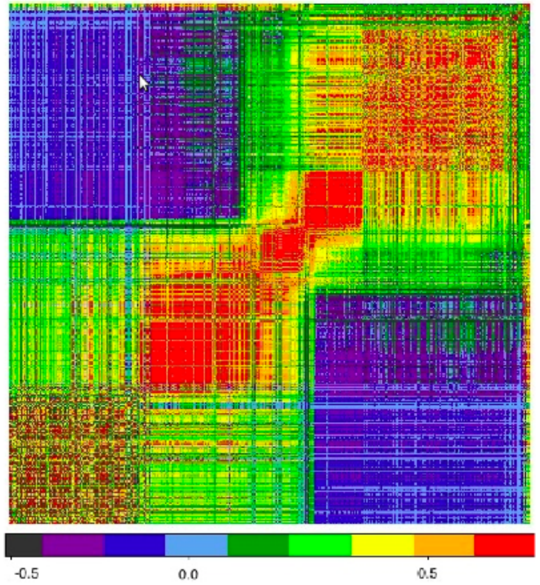
  $R_B \sim 2.5\text{-}3 < 4.1$

Other possible systematic uncertainties

- Peculiar velocities for low-z SNe
- Contamination by Core collapse SNe for high-z SNe
- **Evolution of color-luminosity relation with redshift**
- **Evolution of SNe with z : age of stellar population or metallicity**
- Gravitational magnification

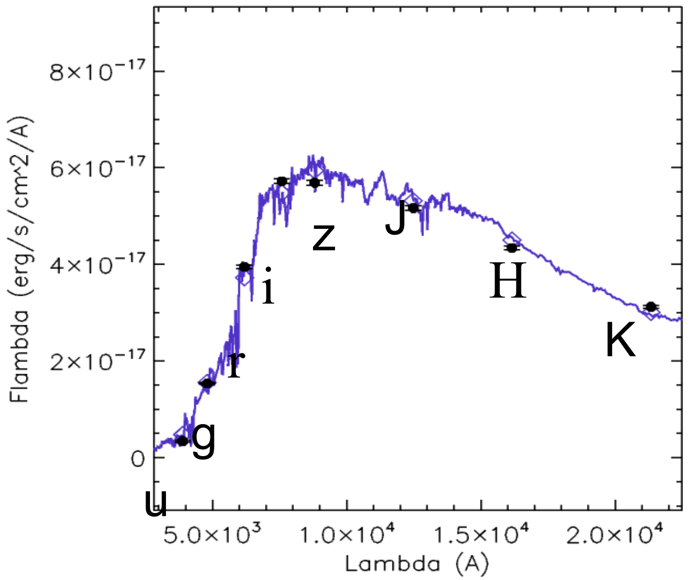
- about 200 different systematics (S_k) identified.

- Conversion of those systematics into a covariance matrix of SNe distance moduli (μ_i) $C_{sys,ij} = \sum_k \frac{\partial \mu_i}{\partial S_k} \frac{\partial \mu_j}{\partial S_k} (\Delta S_k)^2$

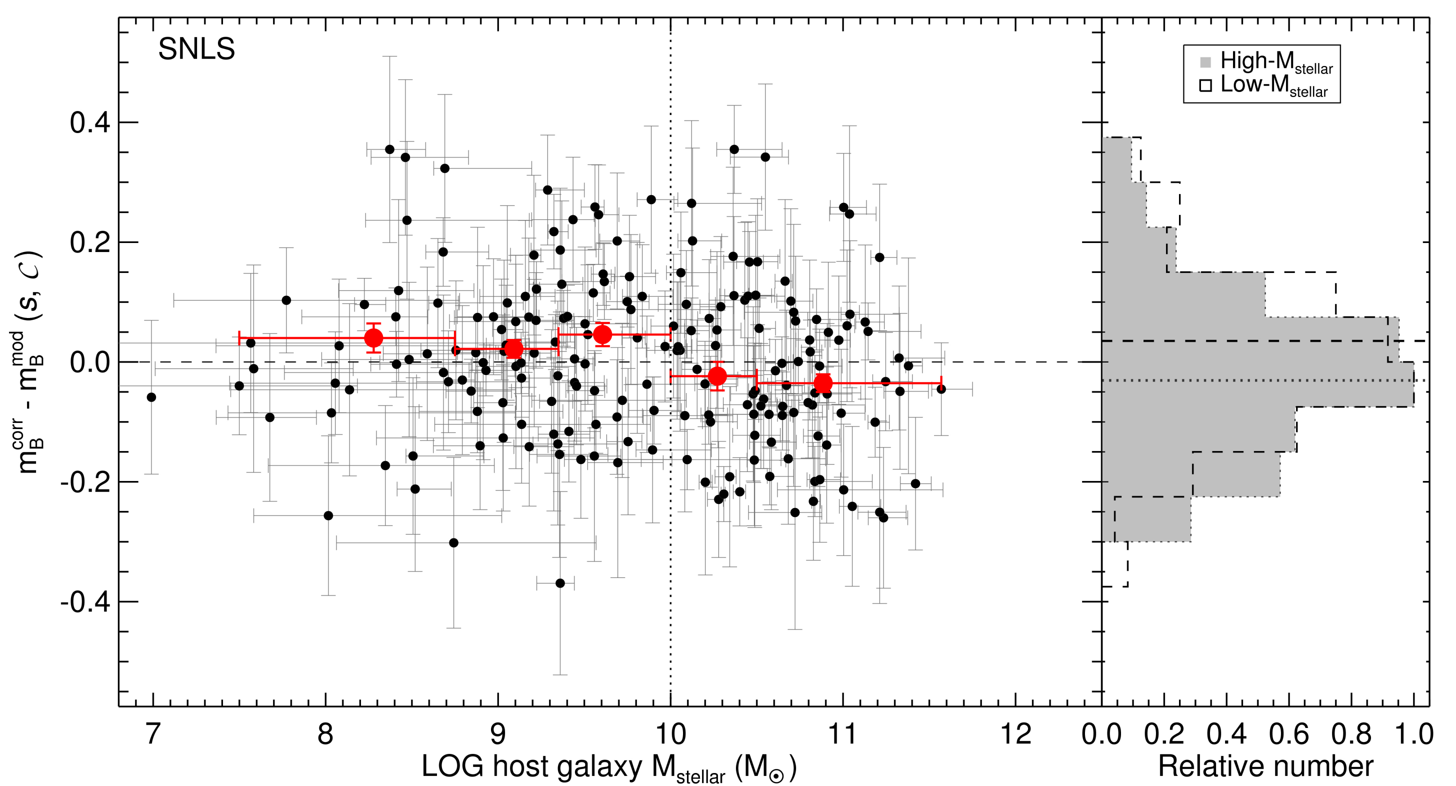


SN Ia host galaxies

- No detailed understanding of SN Ia progenitors
- Are M_B, α and β “universal” parameters? Any age or metallicity (environmental) dependence?
- ugrizJHK host data allows estimations of:
  - Host star formation rate
  - Host stellar mass content



Hubble residuals versus host mass



SNe Ia are brighter (4σ) in massive galaxies after lightcurve shape and colour correction

Subtle effect – 0.08mag – smaller than stretch and colour corrections

Independent of light curve shape

Improved Cosmological analysis

Two ways to proceed:

1) Add a further linear host term, H, to the analysis:

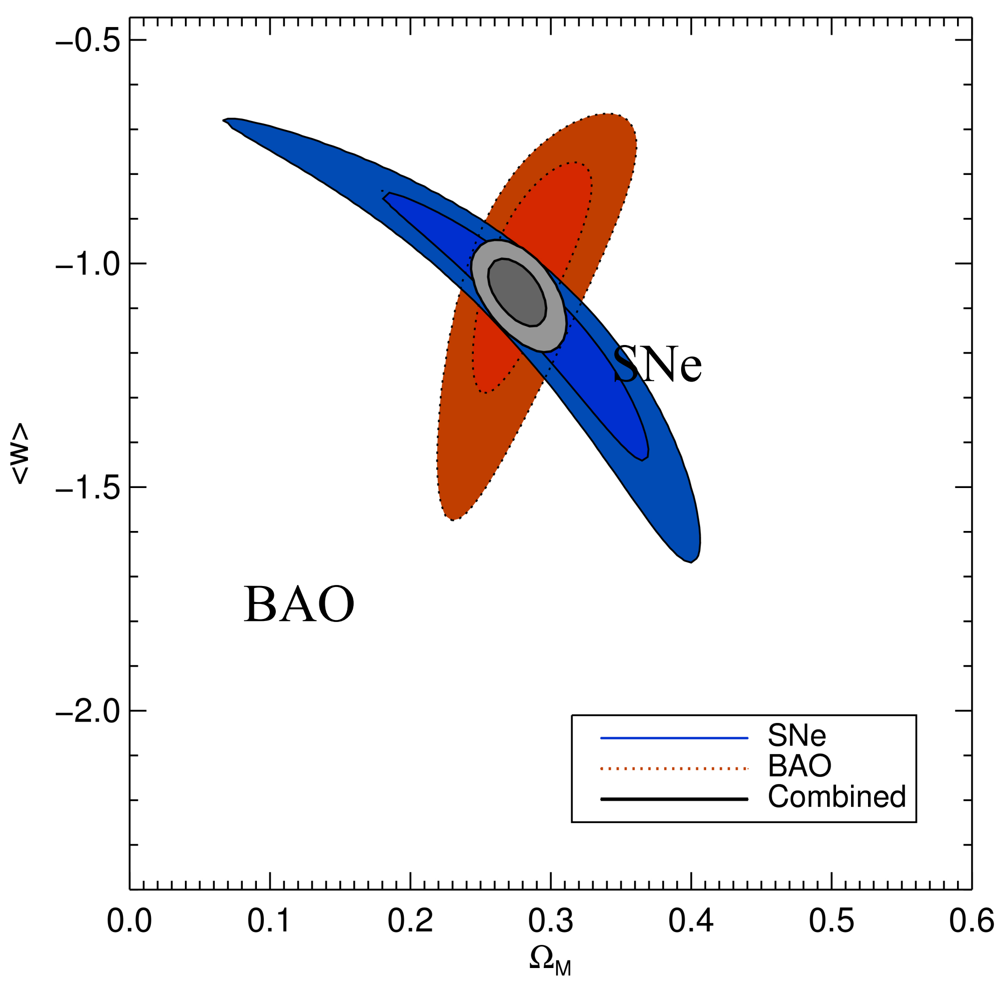
$$\boxed{\mu_B = m_B - M_B + \alpha(s-1) - \beta c + \gamma H}$$

- *Requires very precise measure of H, and robust errors*

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

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

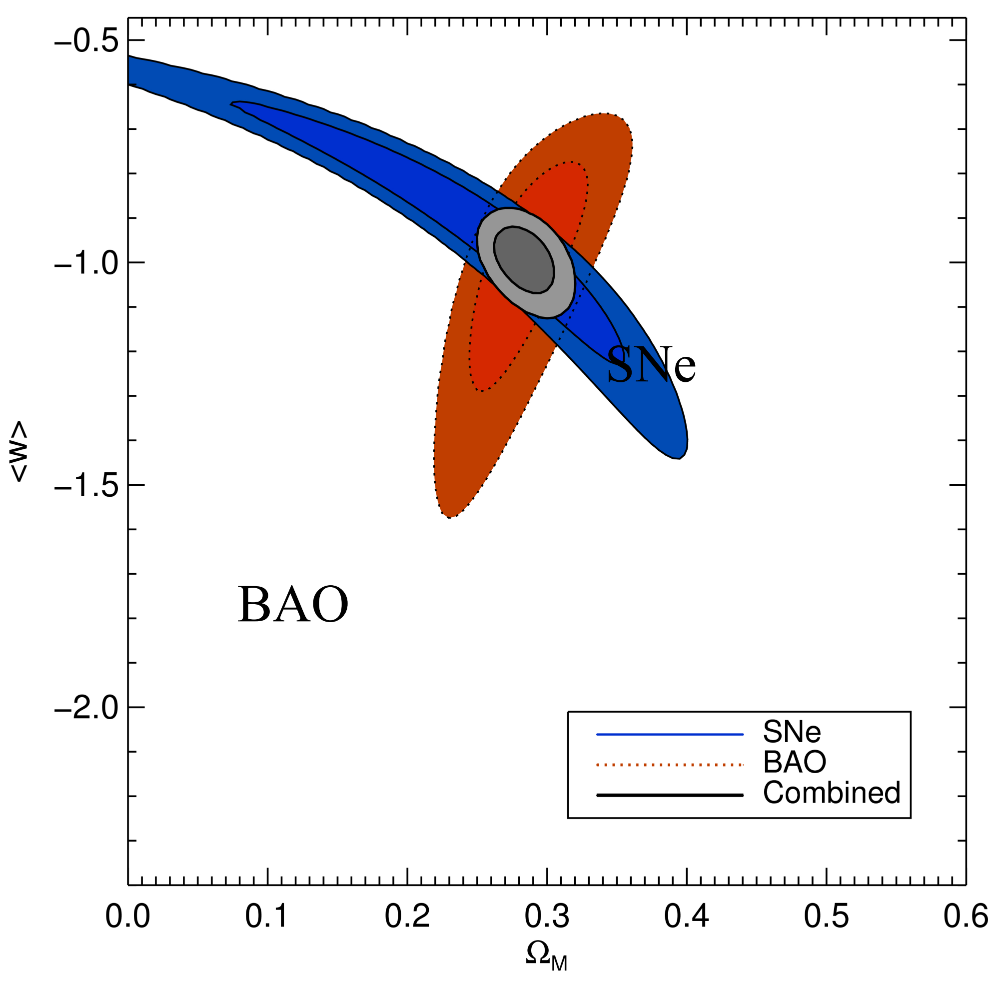
SNLS3 Cosmological Constraints



SNLS3 + BAO + WMAP7 + **Flat**

Without host galaxy term

SNLS3 Cosmological Constraints

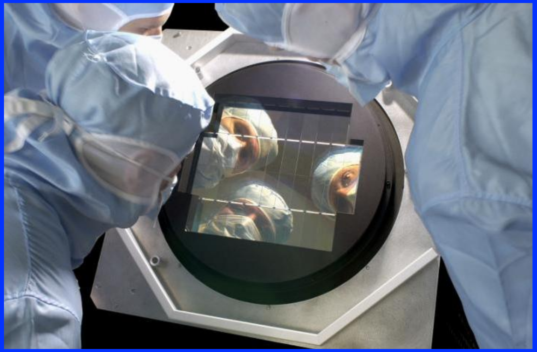


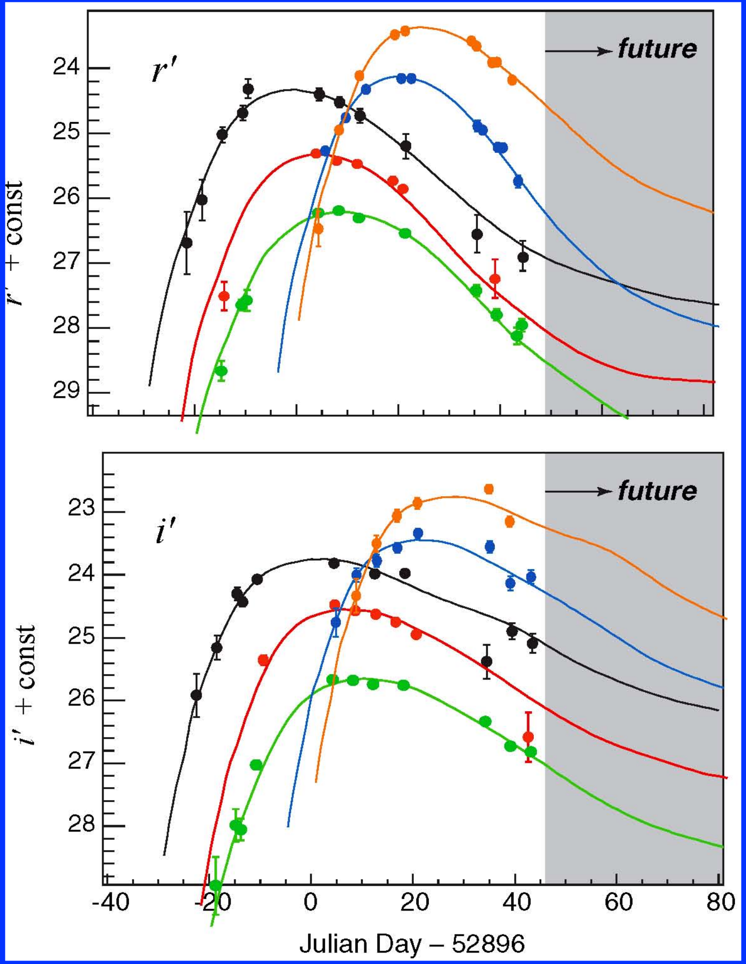
SNLS3 + BAO + WMAP7 + **Flat**

With mass host galaxy term

III - SNLS 3yr data and combined SN constraints

SNLS : a “Rolling Search” survey





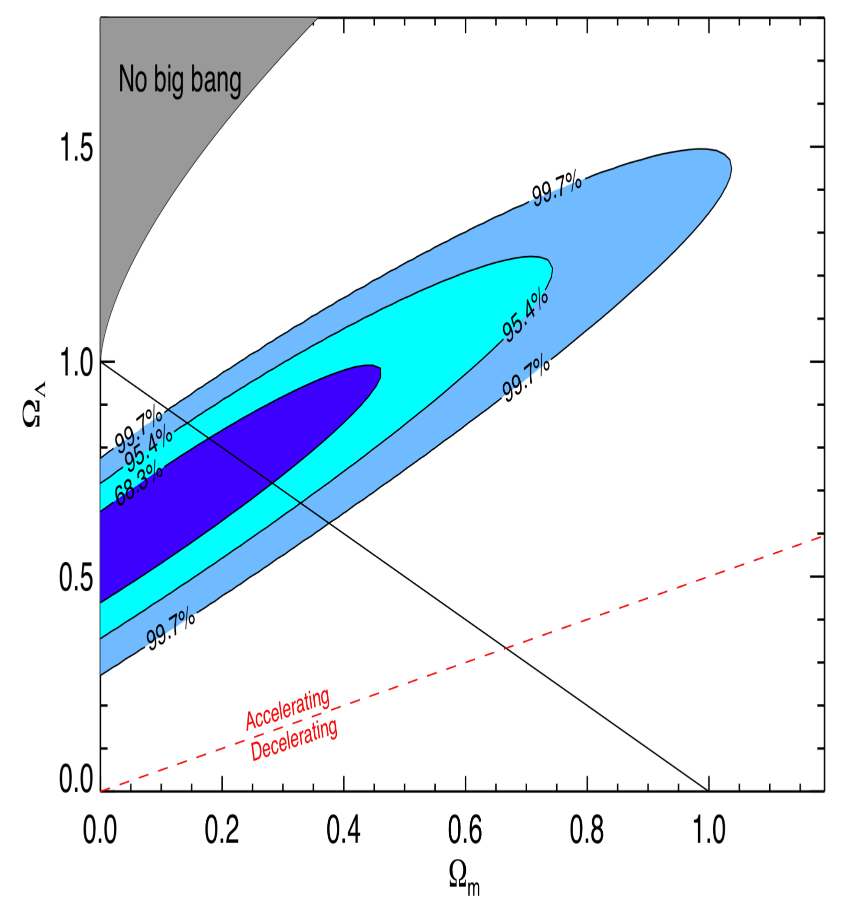
Each lunation (~18 nights) :
repeated observations
(every 3-4 night) of
2 fields in four bands (griz)+u
for as long as the fields stay
visible (~6 months)

for 5 years: ~500 SN Ia identified

SNLS 3yr Analysis

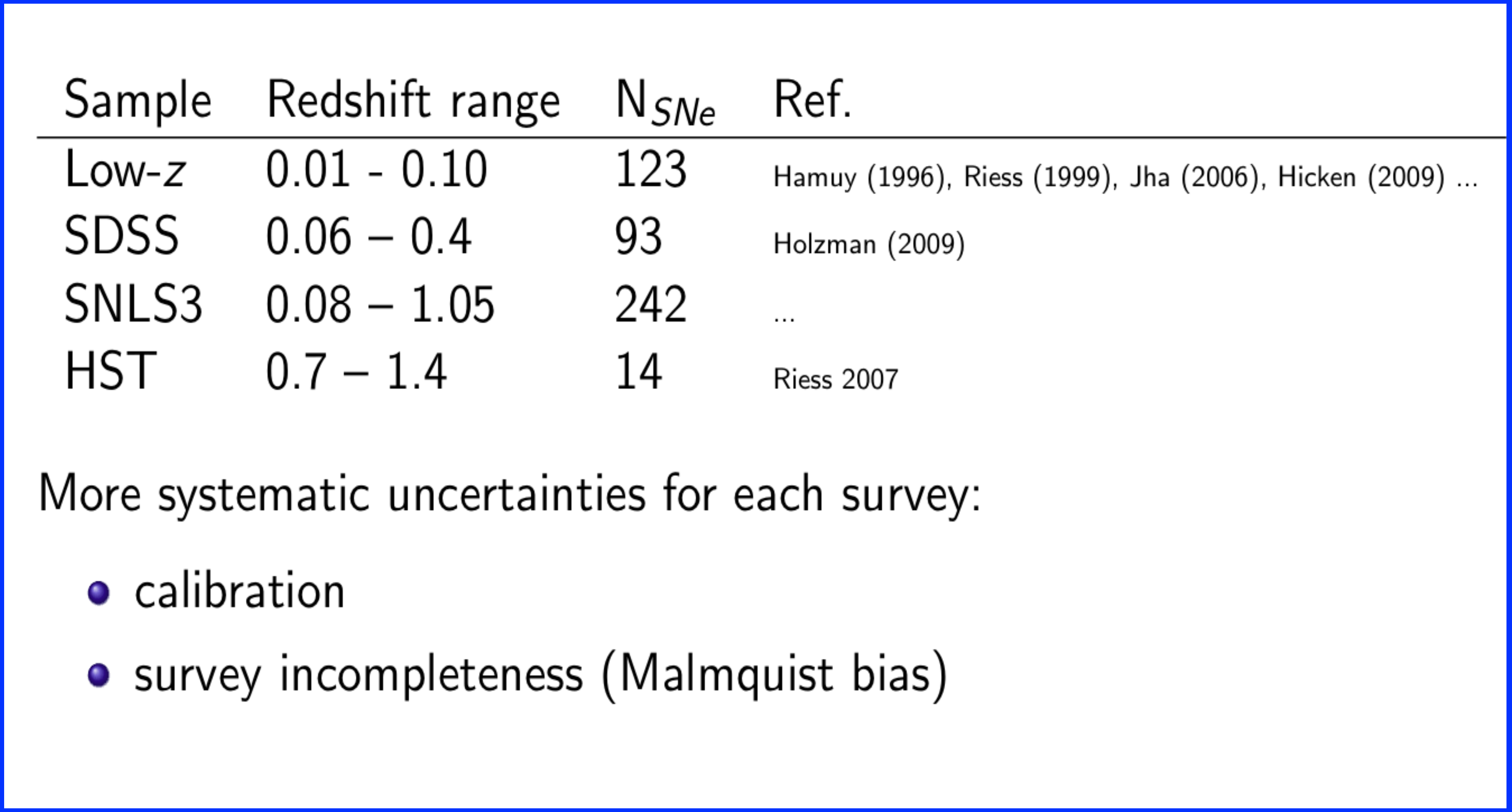
- Statistics x 3.5 71 → ~ 280
- Two independent analyses (control of systematics)
  - → SN photometry
  - → photometric calibration
  - → light curve fitters SALT2 + SiFTO
- Improved photometric calibration
- Improved supernova modeling (models trained on the SNLS data → bluer part of the restframe spectrum constrained without using observer frame U)
- Detailed studies of the SN host properties
- Systematics included in the cosmology fit

LCDM SNLS only constraints [stat+syst]



Acceleration detected at >99.999% confidence – including systematic effects

Combined SN sample

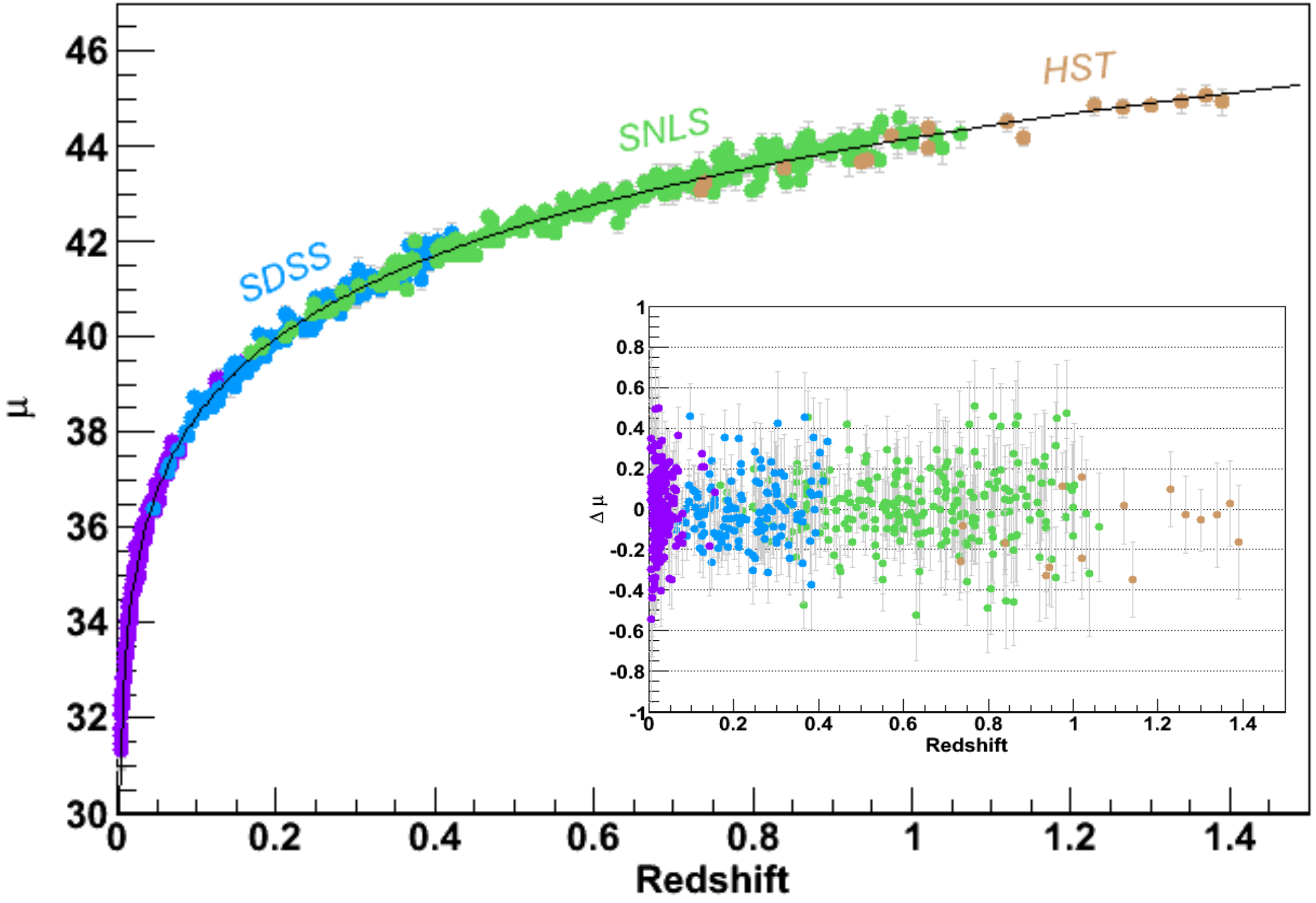


Sample	Redshift range	N_{SNe}	Ref.
Low-z	0.01 - 0.10	123	Hamuy (1996), Riess (1999), Jha (2006), Hicken (2009) ...
SDSS	0.06 – 0.4	93	Holzman (2009)
SNLS3	0.08 – 1.05	242	...
HST	0.7 – 1.4	14	Riess 2007

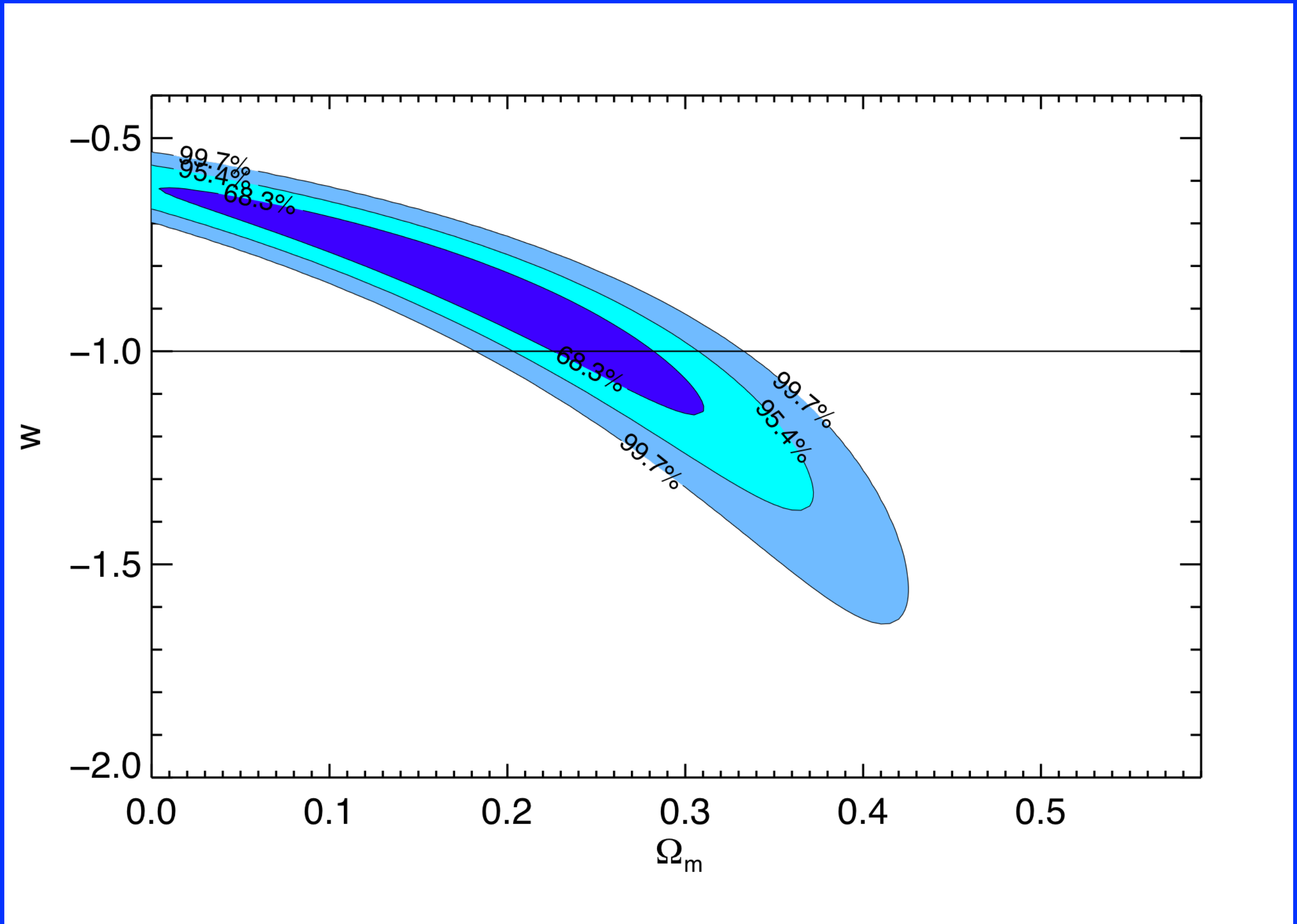
More systematic uncertainties for each survey:

- calibration
- survey incompleteness (Malmquist bias)

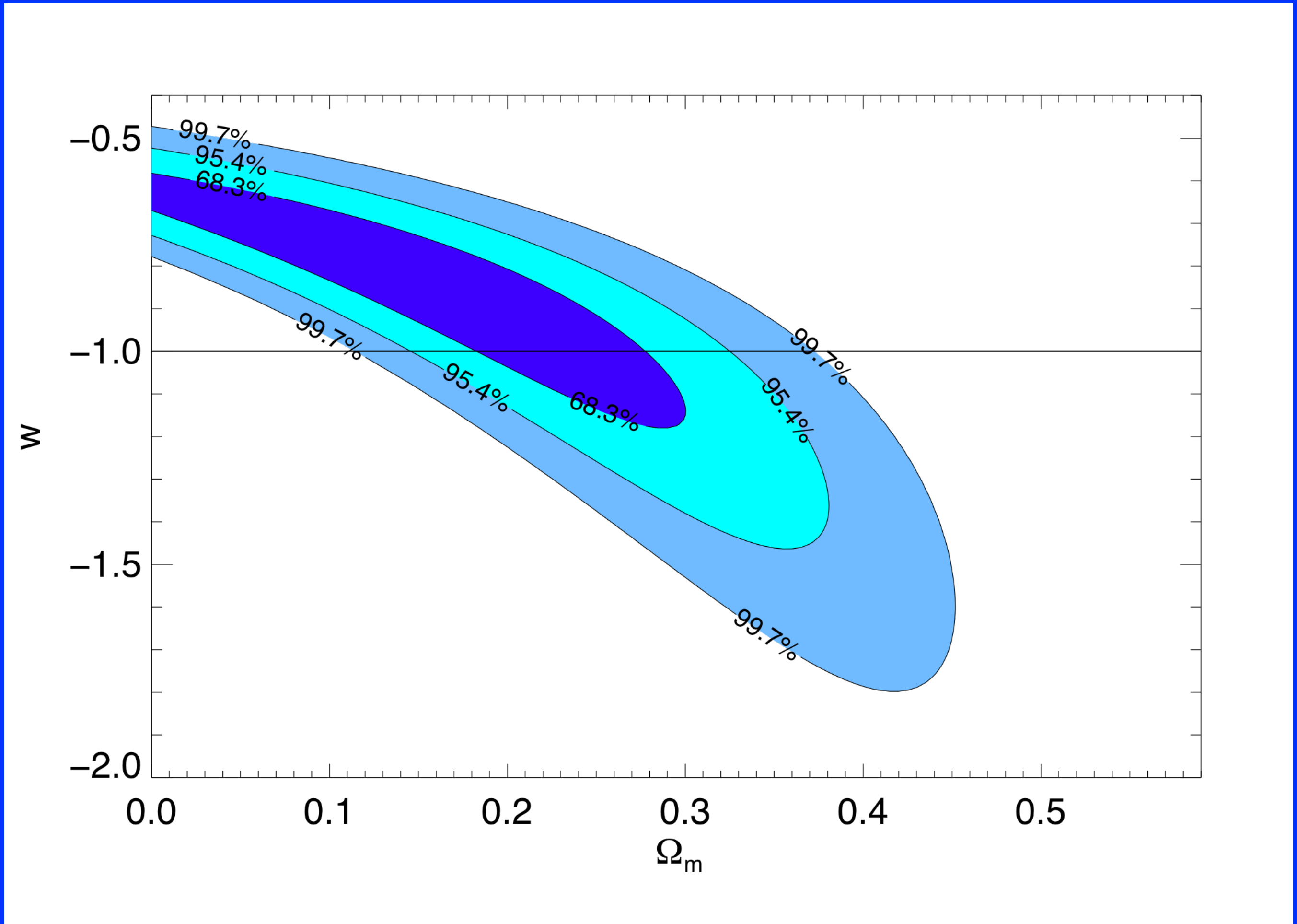
Combined Hubble diagram



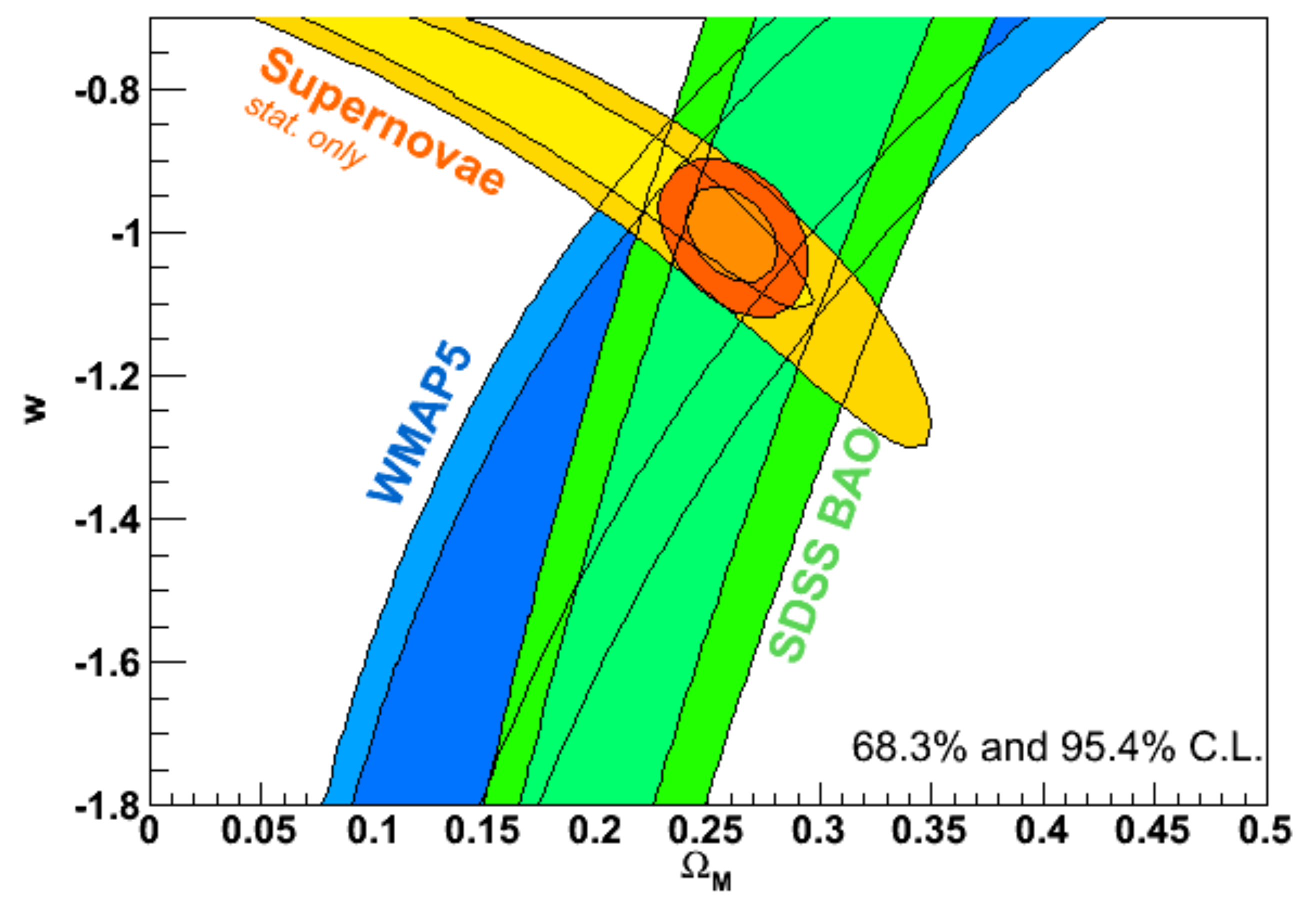
SN only constraints on w



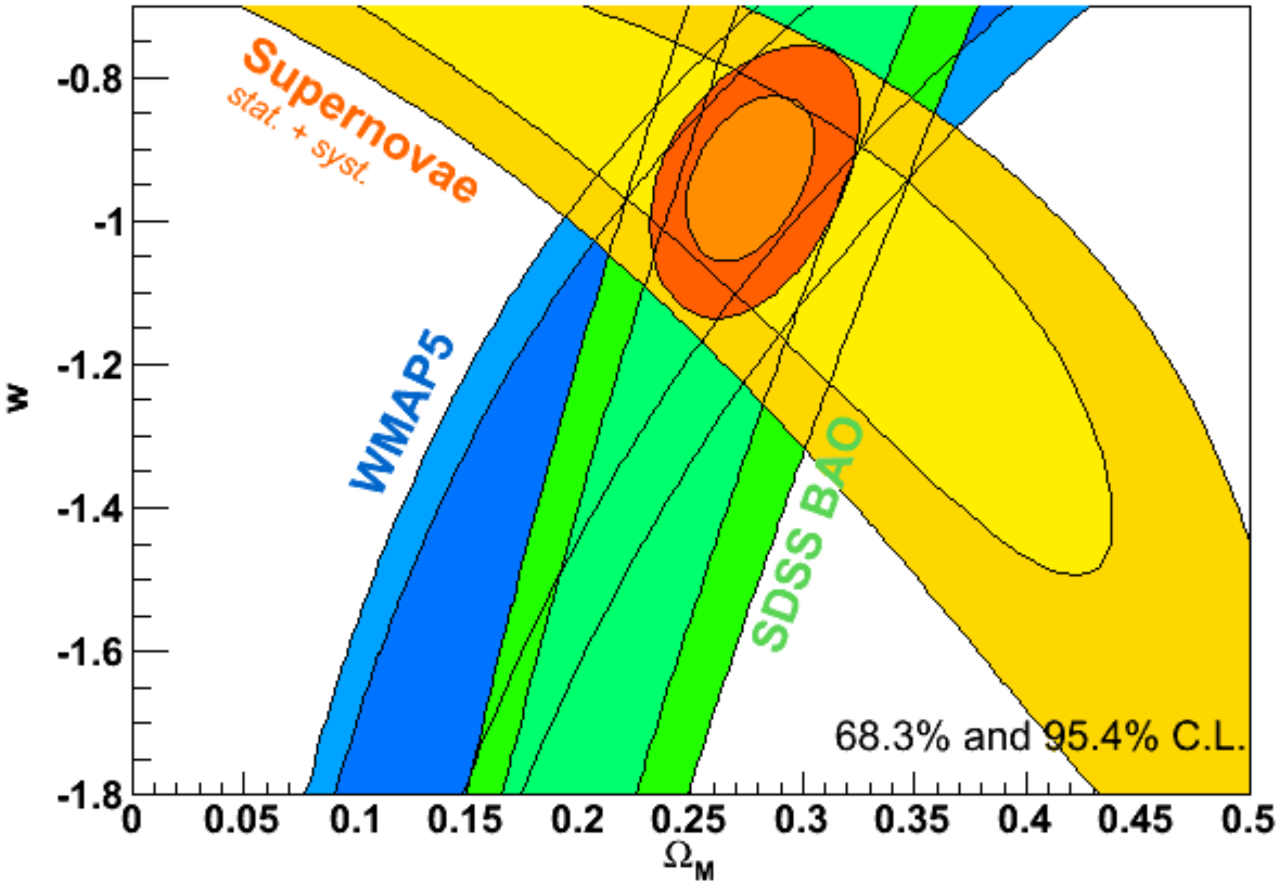
SN only constraints on w



$$w = -0.91^{+0.15}_{-0.21}\,(\text{stat})\,^{+0.07}_{-0.14}\,(\text{syst})$$



(see SNLS-3 papers (Sullivan et al, in prep)



w = -1.0x +/- 0.07 (stat+syst) (in prep)

IV - What’s coming next ?

Currently active SN programs

Low-z :

SNF (200 $0.03<z<0.08$ SN with multi-epoch spectrophotometry

PTF1a : similar z : rolling trigger search + extensive photometric follow-up

CSP : NIR follow-up

higher-z :

SDSS : + 400 SN $0.1<z<0.4$ to analyze

SNLS : + 200 SN $0.3<z<0.9$ to analyze

Joint SDSS/SNLS analysis (calibration + LC analysis)

$z>1$:

HST measurement of o(10) SN to study specific issues (cluster selected SN, …)

Aim : robust combined statistic+systematic uncertainty on constant w of better than 0.07 and attempt at measuring wa

« 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 (z~0.1) - yield ~100 SN Ia /yr
2011-2014

Will address some of possible systematics.
Very difficult to significantly improve on precision

Stage IV ground based SN projects

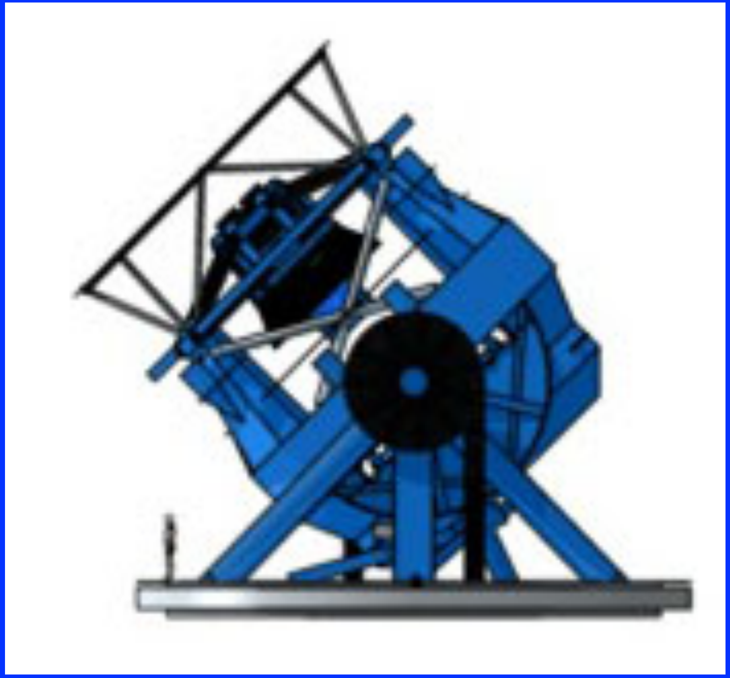
- Pan Starrs 4 :

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

- LSST :

One 8m telescope with
9 deg2 fov

=> 250000 SN/yr !

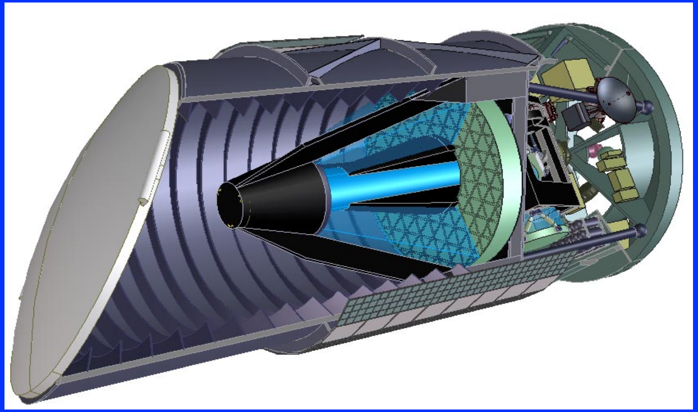


by 2020?

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

Space based cosmology with SN Ia

Detect/follow distant SN Ia from Space



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

+ Several incarnation : DESTINY, JEDI, JDEM, DUNE, EUCLID,
… now WFIRST,

New study (Astier et al. submitted)
based on a modified EUCLID concept (+filter wheel)
All space SNe, no onboard spectroscopy
13000 SN up to z~1.5 with rest-frame NIR for a subsample
$\sigma(w_p) = 0.03$ incl. Systematics

by 2025 ?

Summary

SNe Ia are excellent distance indicators

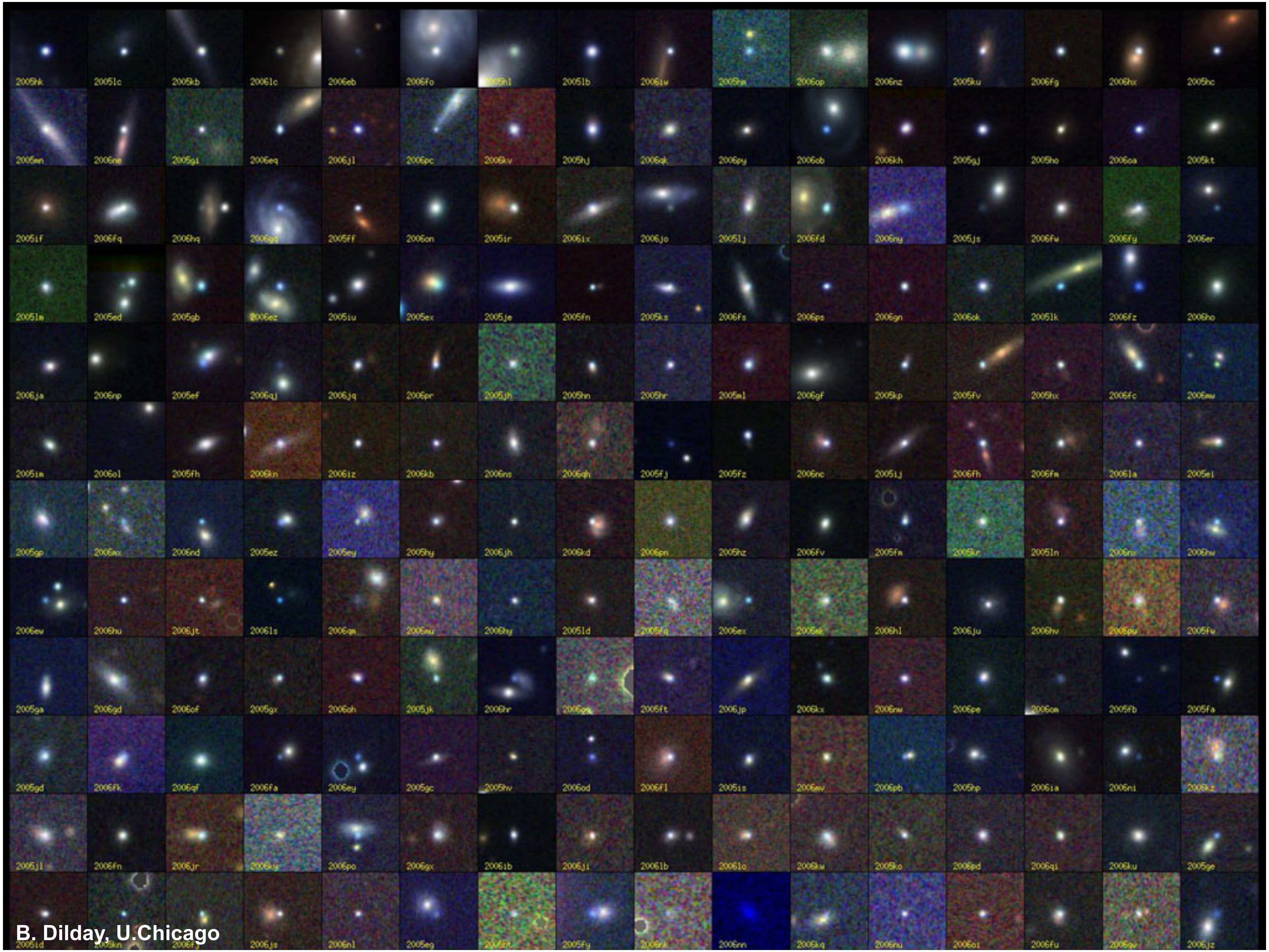
- Current projects are getting more and higher quality data toward building a systematic limited Hubble diagram with ~1000 SN Ia with an expected precision on w (flat Univ., constant) of

+/- 0.04-5 (stat) +/-0.04-5 (syst)

To overcome the current (systematic) limitations:

- More and better quality nearby SN (badly) needed
- More and better quality distant (z>0.7) SN needed
- Improve theoretical understanding of SNIa physics and environment

Percent precision on w and significant precision on w' (wa) with SN is achievable. It will require exquisite control of systematics



B. Dilday, U.Chicago