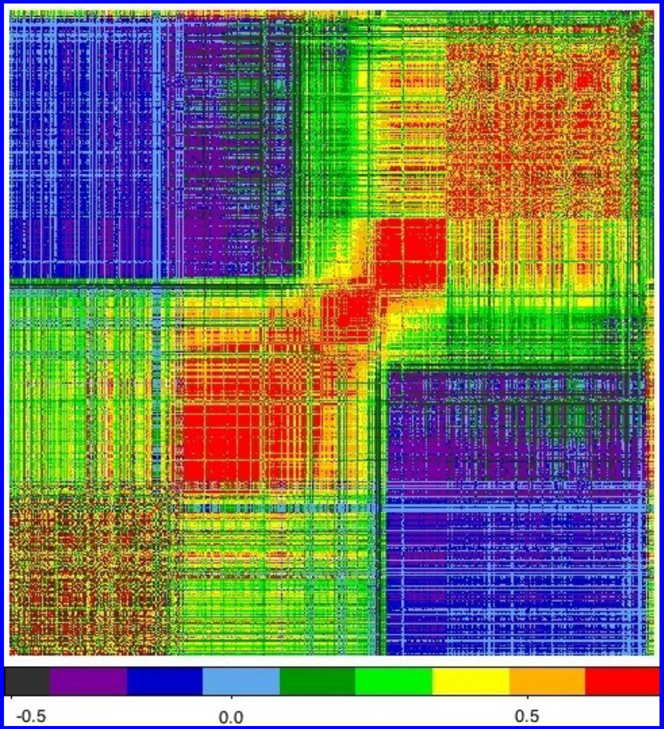
Supernova Cosmology

where is the systematic floor ?



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Why worrying (now) about systematics?

SN cosmology is conceptually simple,

and (mostly) a relative measurement ($\Omega_{i,}$ w)

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

And subject to z dependent (known) systematics

- 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?

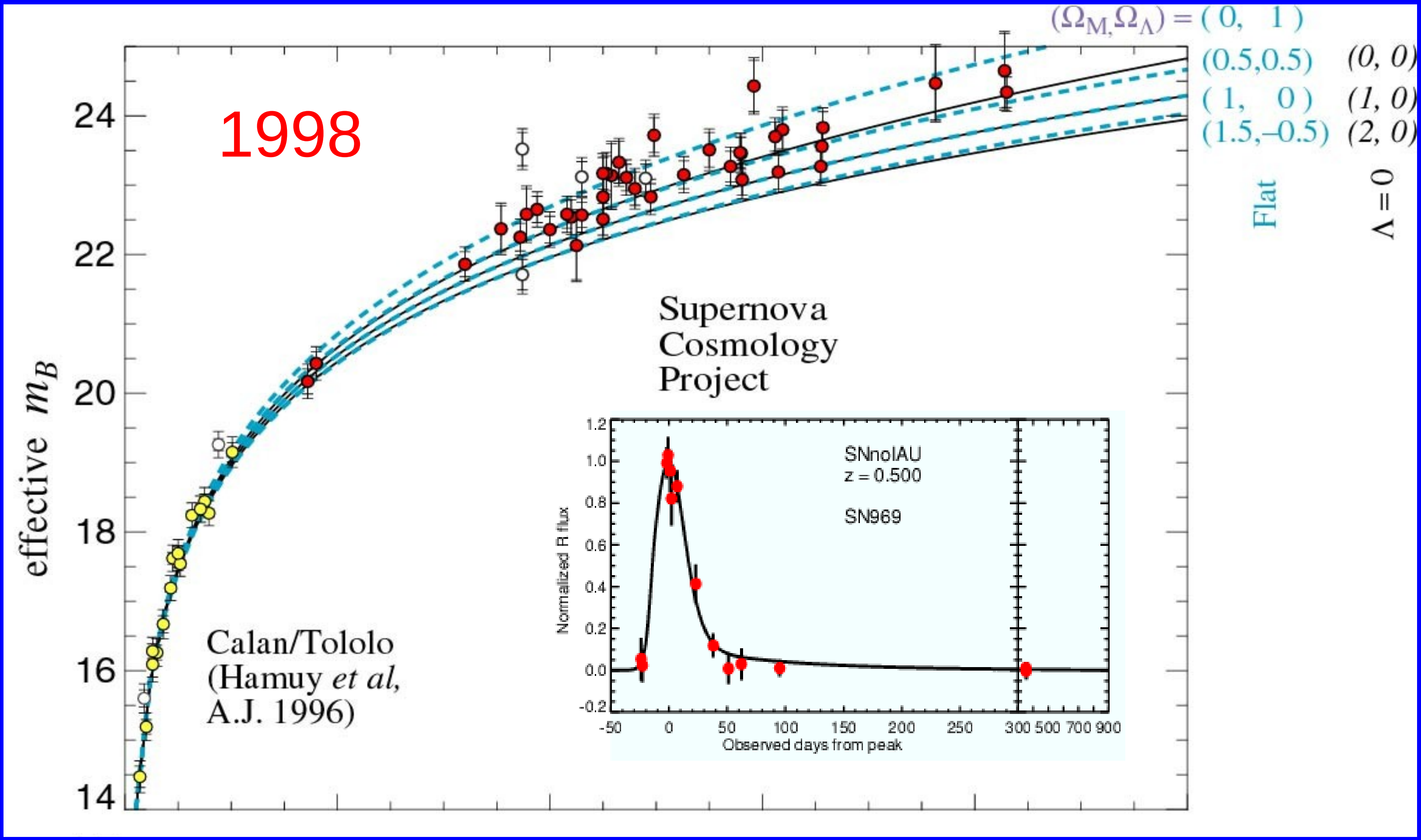
There is an indication that the constraints on dark energy parameters are different when different methods are used to fit the light curves of Type Ia supernovae (Hicken et al. 2009b; Kessler et al. 2009). We also found that the parameters of the minimal 6-parameter ΛCDM model derived from two compilations 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 $\sim$

WMAP-7

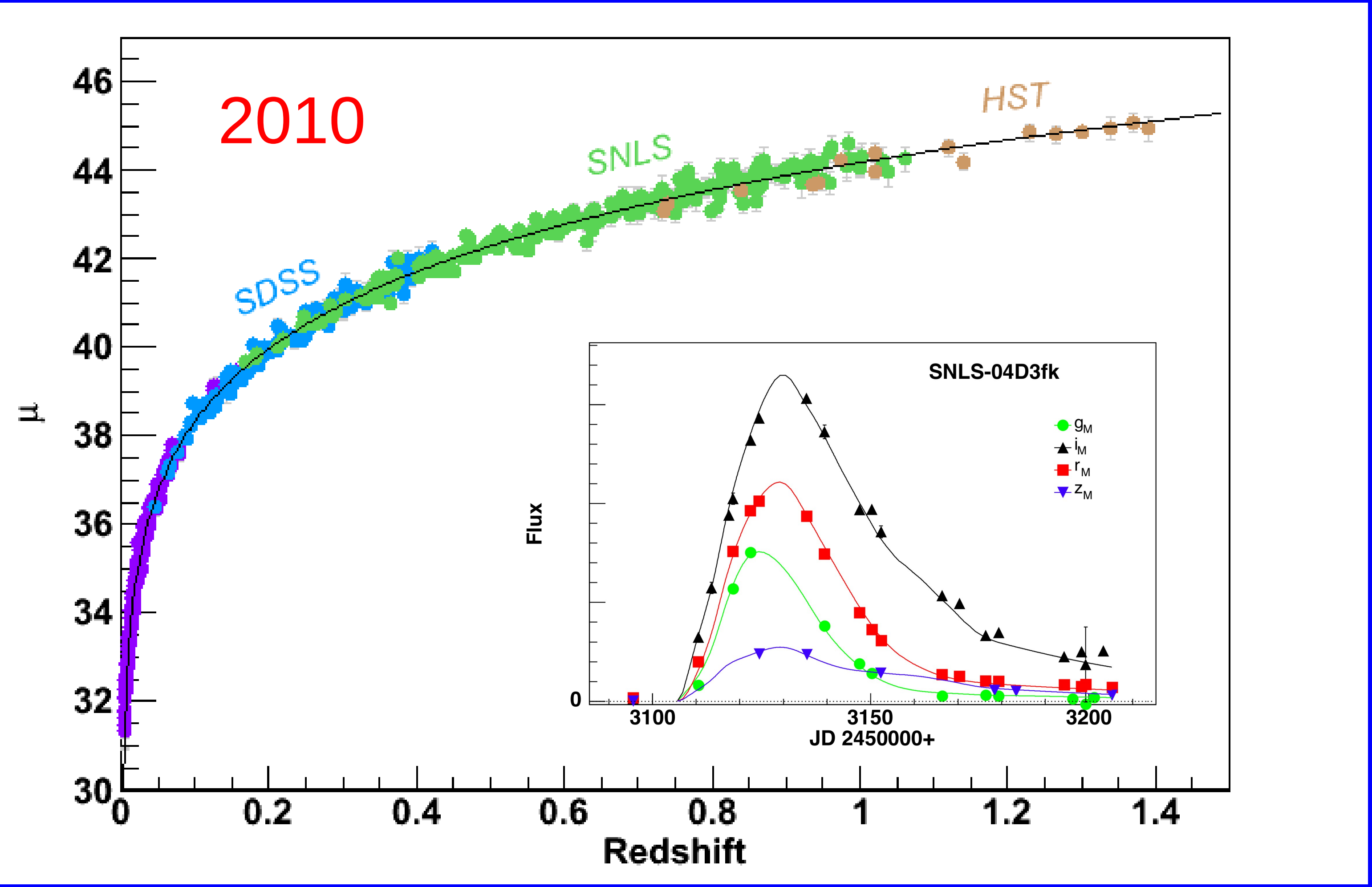
(Komatsu et al, 2010)

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.

Systematic floor reached ?



Systematic floor reached ?



Where is the systematic floor ?

- SN Cosmology in 3 slides
- Tracking systematics
- Latest SN cosmological constraints
- What's coming next ?

Credit

Many plots shown here are borrowed from:

A. Conley, J. Guy, N. Regnault, M. Sulivan

See also papers

N. Regnault et al. A&A, 2009

J. Guy et al. A&A 2010, accepted

A. Conley et al. APJ 2010, submitted

M. Sulivan et al. APJ 2010, in prep

I - SN Cosmology in 3 slides

Experimental Principle

2 observables :
flux: f
Redshift: z

$d_L^2 = L/4\pi f$

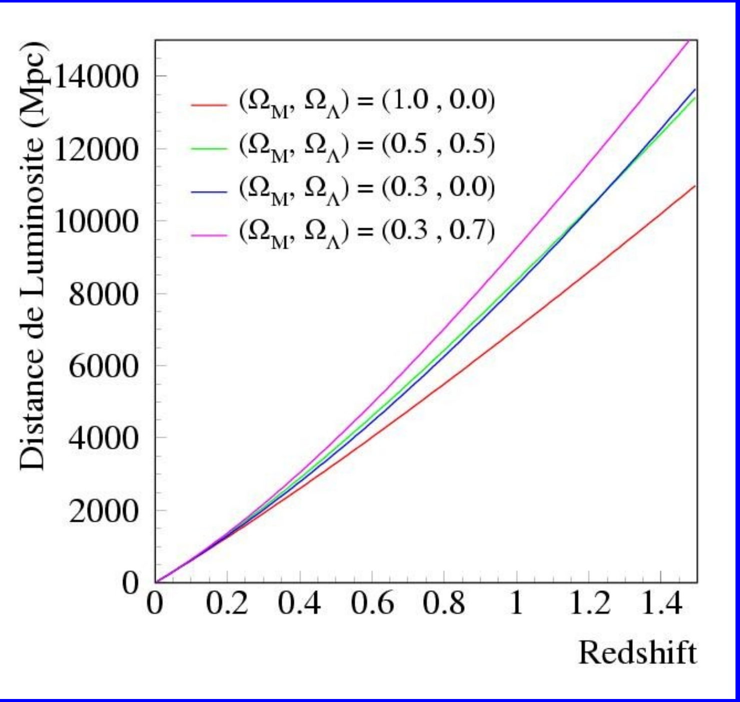
Use SN Ia as distance indicators to measure the Luminosity distance d_L

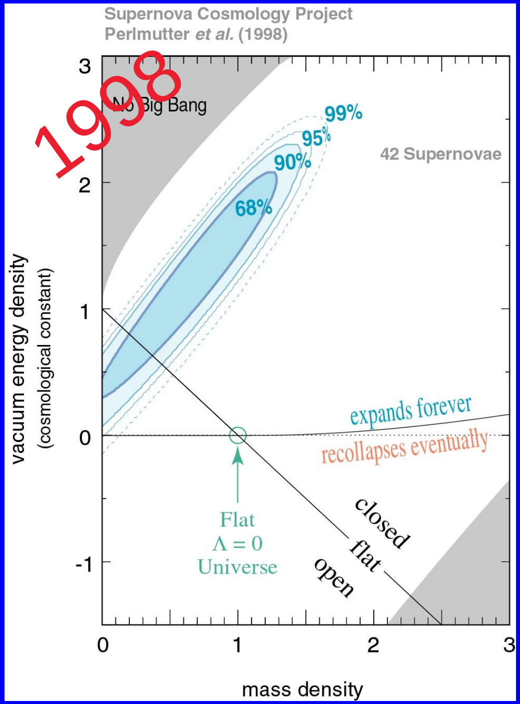
d_L is sensitive to the expansion rate and to the Energy content of the Universe

Cosmology with SN Ia

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

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



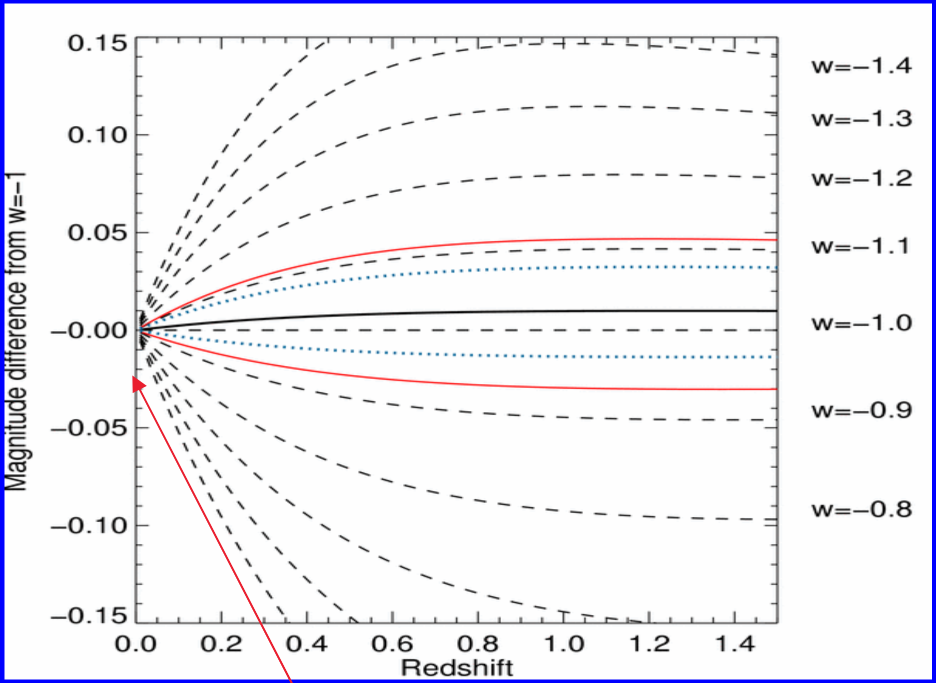


Favor a non zero Λ

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

Measurement ingredients:

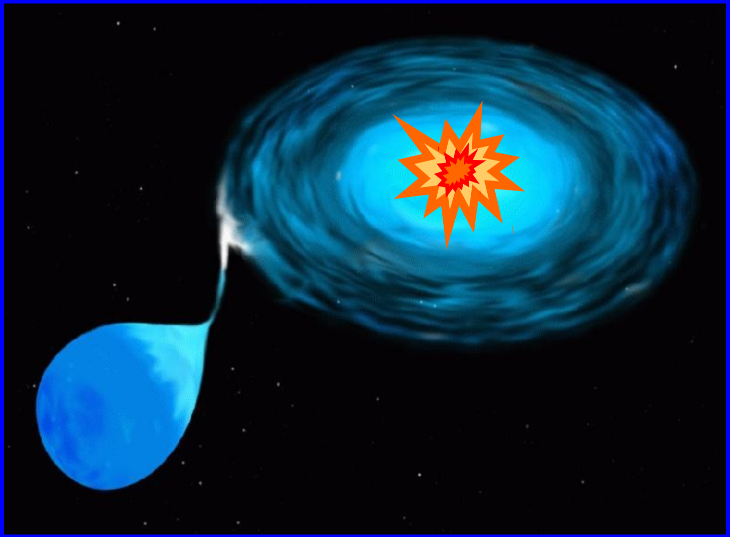
- Low-z SNe
- High-z SNe

∀ Ω_M prior or constraint -> BAO

SNe Ia are good cosmological tools

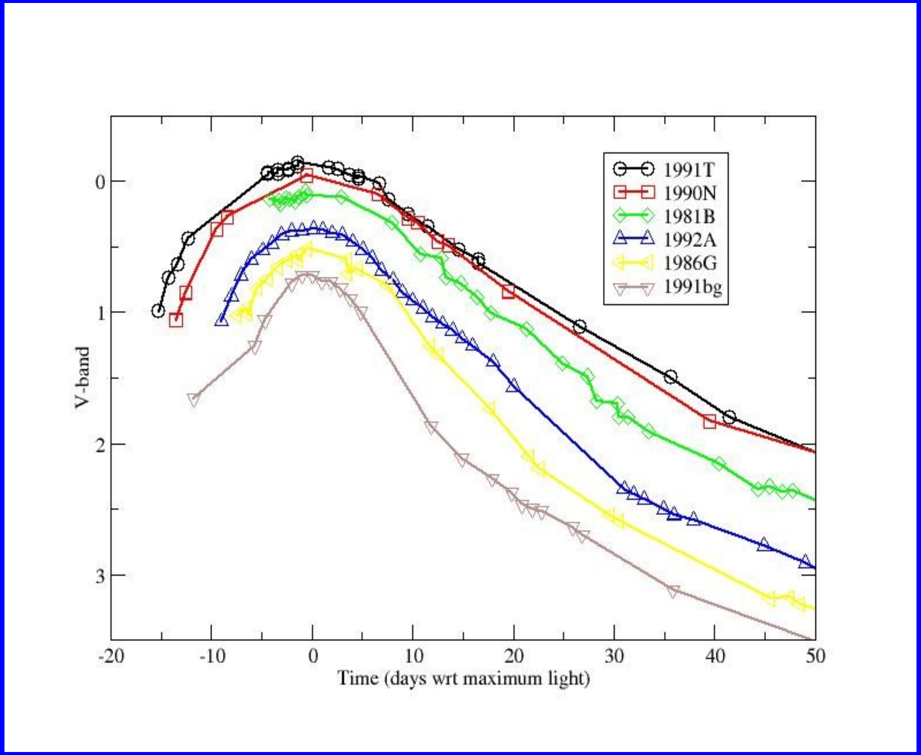
Very Luminous events

⇒ visible at cosmological distances



Show little luminosity dispersion

But they are NOT standard candles

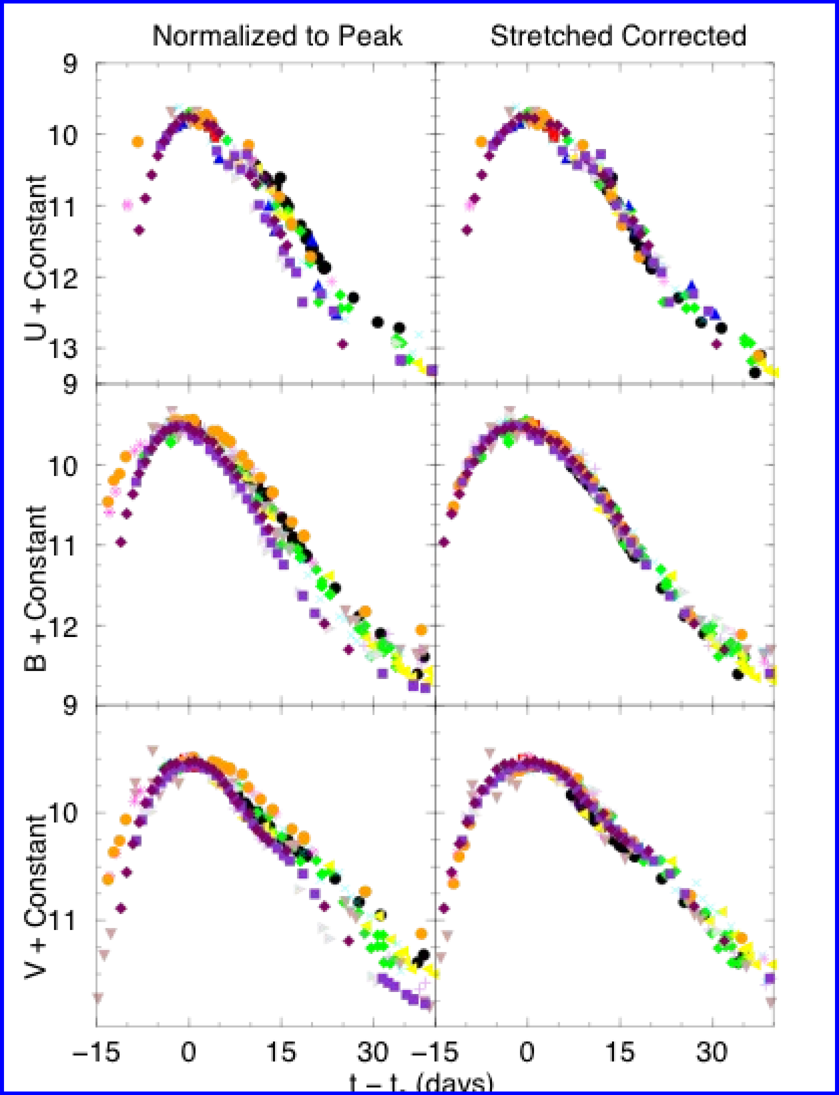


Calibrating supernovae

SNe Ia show Light Curve shape 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



Cosmology with SNe Ia

An empirical approach

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

Resframe apparent magnitude at maximum

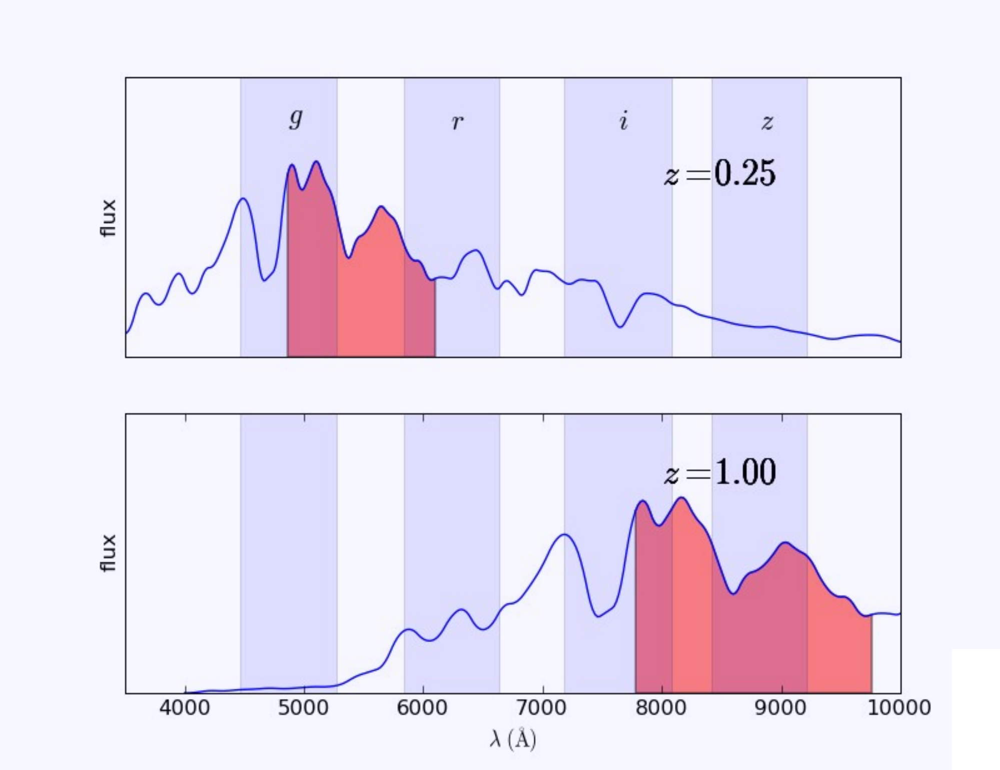
Absolute magnitude at maximum

Light curve shape correction

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

II - Tracking Systematics

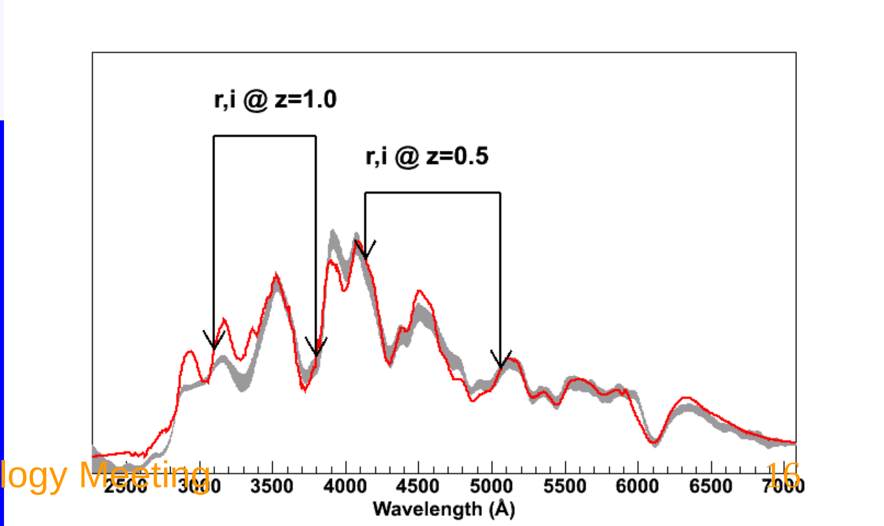
Extracting mb, s and c from observations



SN restframe fluxes at different redshifts

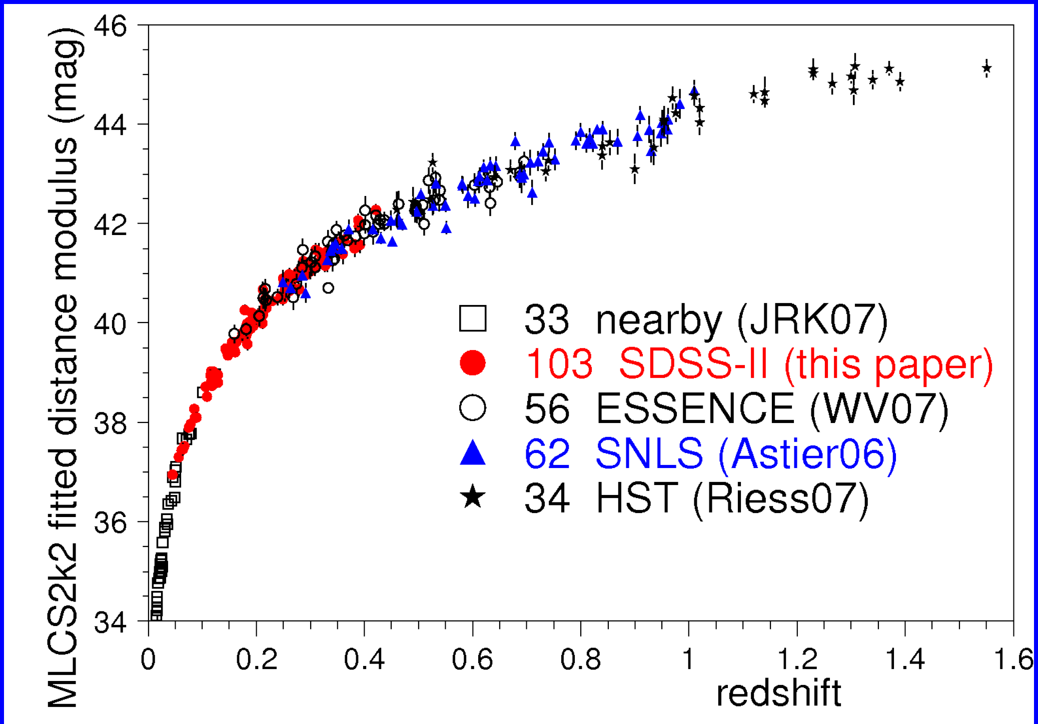
→ empirical model to interpolate between photometric measurements

→ Trained on sets of nearby & distant SNe



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

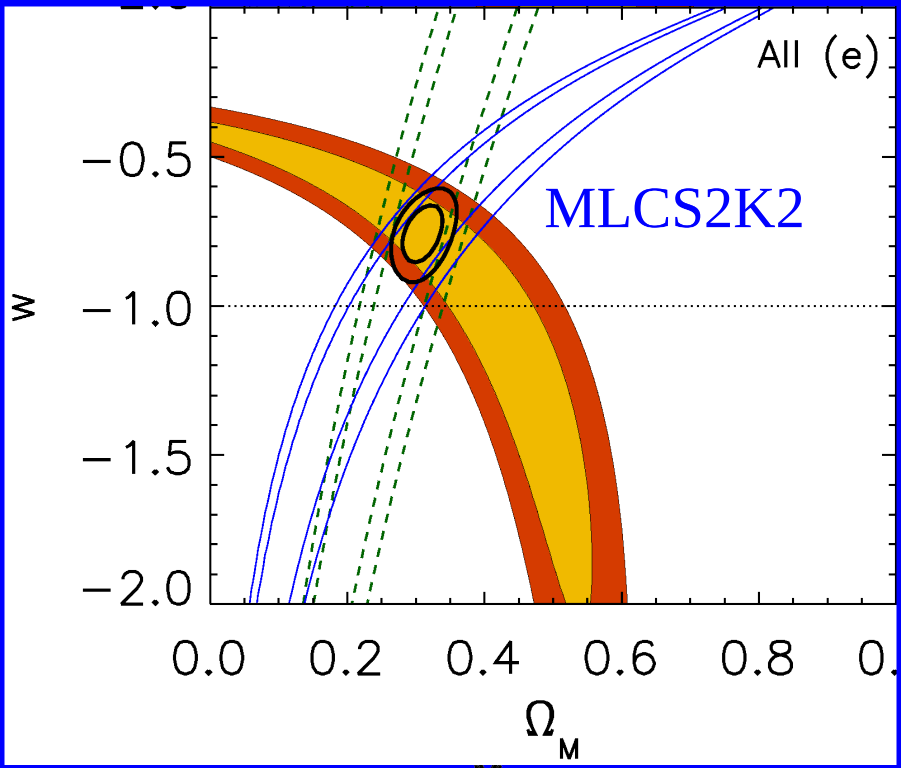
Analysis performed with two LC fitters:

MLCS2k2 (Jha et al, 07)

SALT2 (Guy et al, 07)

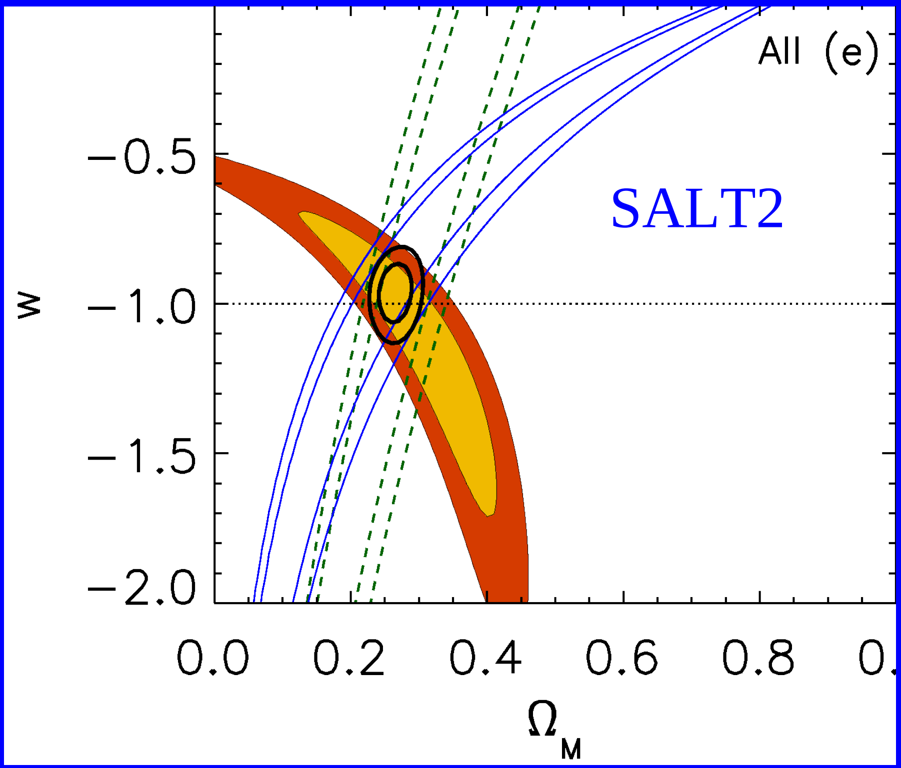
→ thorough comparison of two lightcurve fitters / distance estimators.

Discrepancies between methods ?



w = -0.76 ± 0.07 (stat)

± 0.11 (sys)



w = -0.96 ± 0.06 (stat)

± 0.12 (sys)

SALT2 versus MLCS2K2

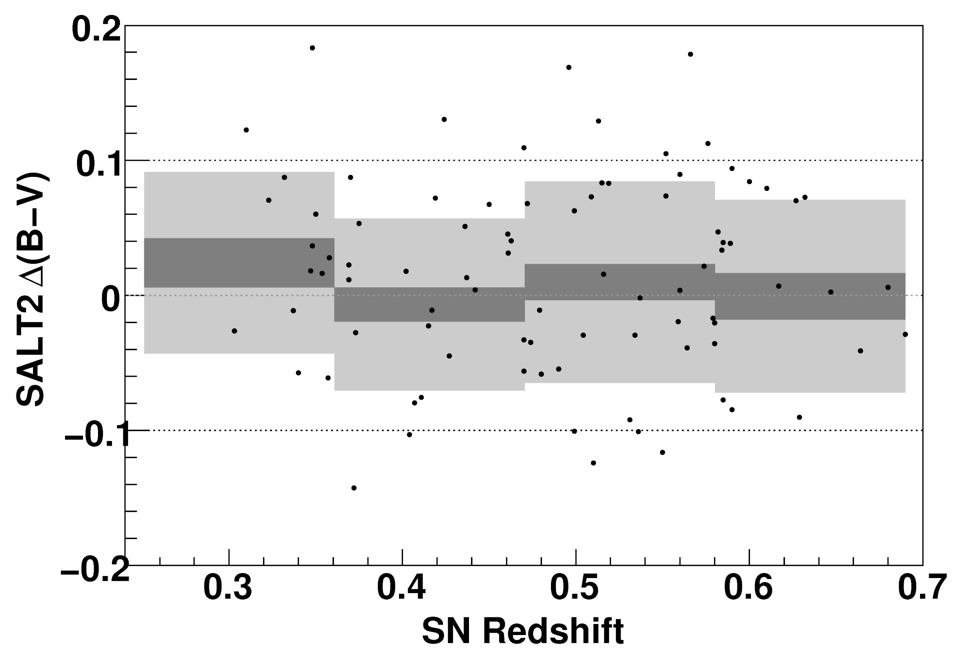
	SALT2	MLCS2K2
Distance Estimate	Fitted along with the cosmology (no distance information in the model)	Directly from the model (trained on SNe with known distances)
Training sample	Well measured nearby and distant SNe (SNLS) (→ u-band constraints)	Well measured nearby SNe, with known distances.
K-corrections	Built in the model	External K-corrections applied to the data.
Color vs. luminosity	No assumption on the nature of the color-luminosity relation.	Assumes all the color-luminosity relation captured in the model. Additional color variation → reddening by dust

Tracking syst. differences

As noted earlier, there is strong evidence of systematic discrepancies in rest-frame U-band between the nearby and higher-redshift samples. These discrepancies are reflected in the differences between the MLCS2K2 and SALT–II U-band models, differences that account for part of the cosmological parameter disagreement between the two models. The other major contributor to the cosmological disagreement is the differing treatment of SN color variation in the two models. There is a trend toward negative apparent SALT–II color at high-redshift within the SNLS sample. SALT–II and MLCS2K2 with a flat-A_V prior assign these blue events large intrinsic luminosities and therefore large distance moduli. By contrast, MLCS2K2 with the nominal A_V prior identifies these events as having $A_V \sim 0$ and assigns them lower luminosities and distances. As illustrated in Fig. 19, the nominal MLCS2K2 interpretation of these events is consistent with the observed color distributions, so it is not obvious which model is correct.

(Kessler et al, 2009)

The “U-band anomaly”



Resframe color (with UV) – (no UV)

→ no visible effect as a function of z

- SNLS-3: new calibration + new SALT-2 training.

→ Better agreement between SNLS – SDSS data.

→ Larger dispersion (0.1 mag RMS) in the U band when fitting nearby data.

- Large uncertainties on ground-based U-band obs
- Variable Atmosph cutoff at 350 nm → effective passbands not well known

SN Ia colors

- 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

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

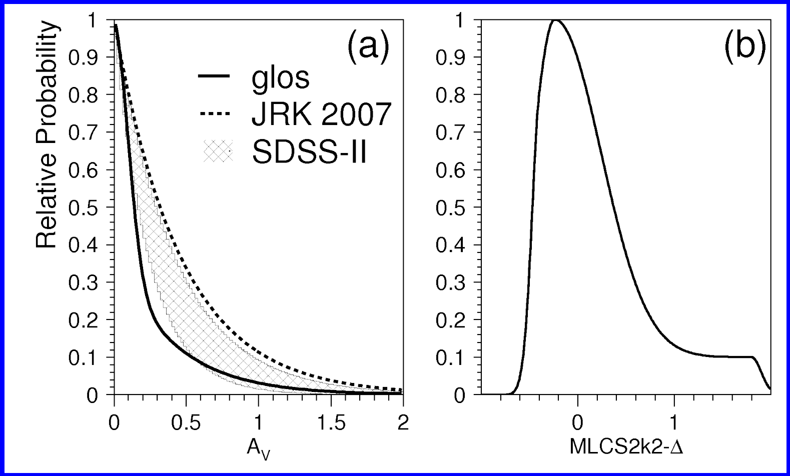
R_B ~4.1 for MW dust

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

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

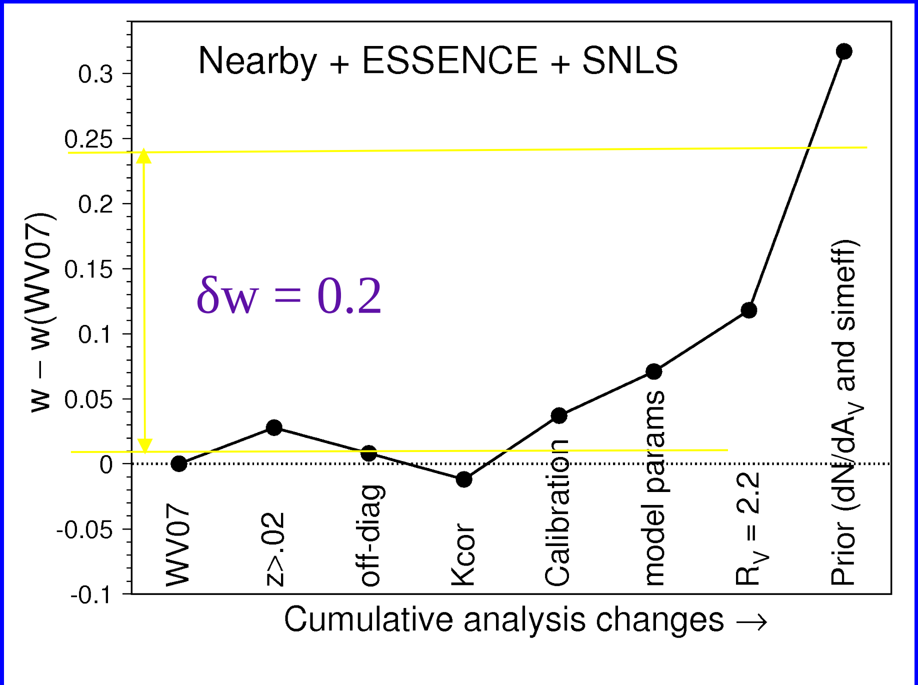
→ no a-priori knowledge of the SN intrinsic colors (variability)

Effect of Prior on SN Ia colors



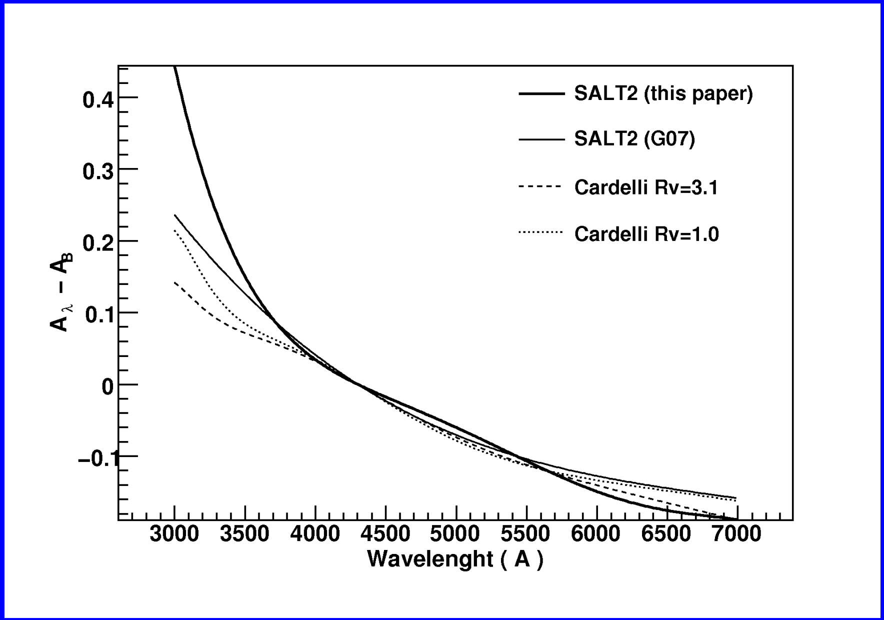
- MLCS2K2 interpret the color variability as extinction by dust → prior to ensure $A_\lambda > 0$

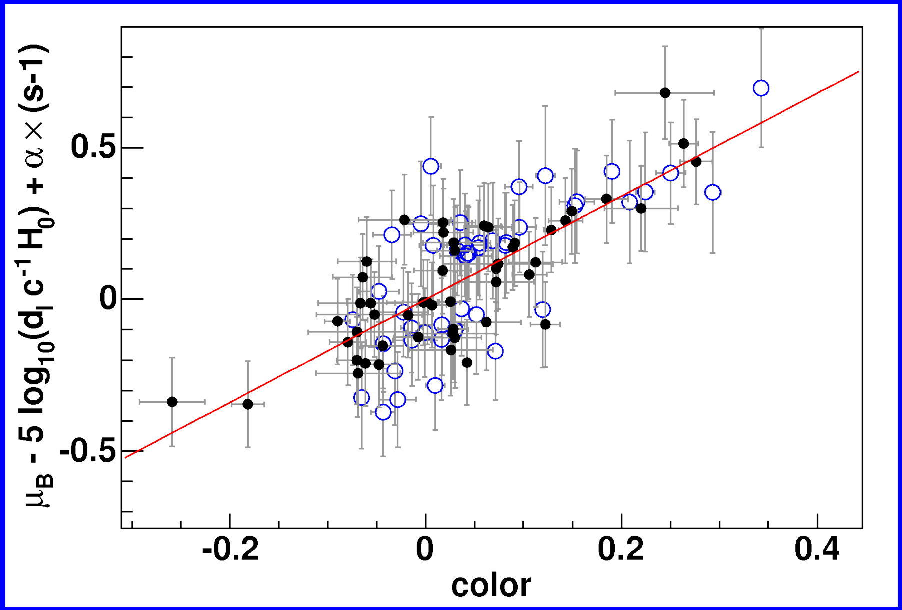
- Redshift dependent bias
- Strong effect on the cosmological parameter determination
- Explains ~ half of the discrepancies



(Kessler et al, 2009)

SN Ia colors





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

- For SNe Ia the total to selective extinction ratio

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

Conclusion : LC fitters difference is not a systematic uncertainty

Origins of the "discrepancy" well identified

(1) Model restframe UV calibration

→ disappears with improved photometric calibration

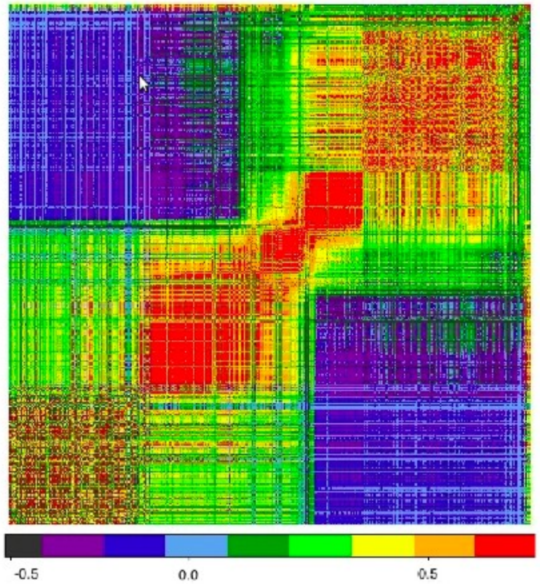
(2) Treatment of the color variability of the SNe Ia.

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

Other possible systematics

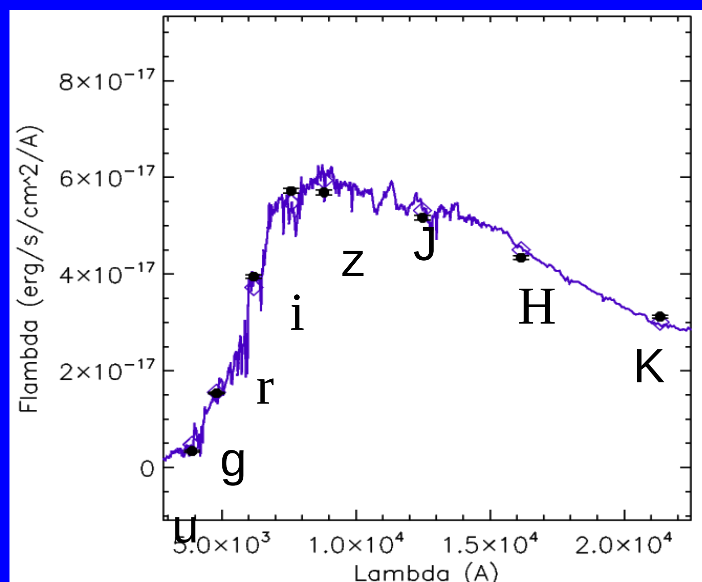
- Peculiar velocities for low-z SNe
- Contamination by Core collapse SNe for high-z SNe
- **Evolution of color-luminosity relation with redshift**
- **Evolution of SNe with z : age of stellar population or metallicity**
- Gravitational magnification

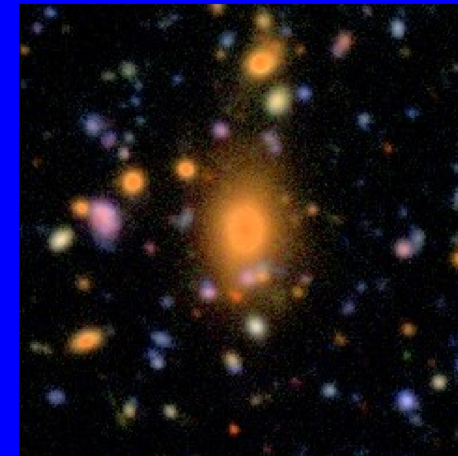
- about 200 different systematics (S_k) identified.
- Conversion of those systematics into a covariance matrix of SNe distance moduli (μ_i) $C_{sys,ij} = \sum_k \frac{\partial \mu_i}{\partial S_k} \frac{\partial \mu_j}{\partial S_k} (\Delta S_k)^2$

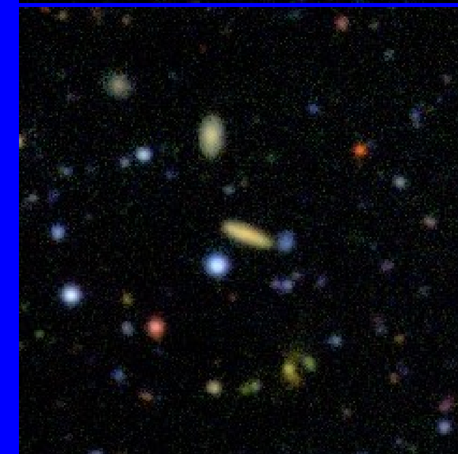


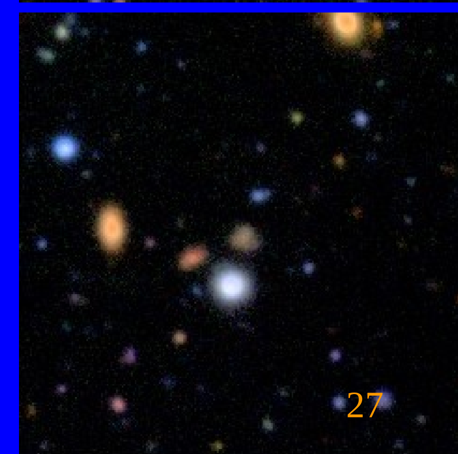
SN Ia host galaxies

- **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

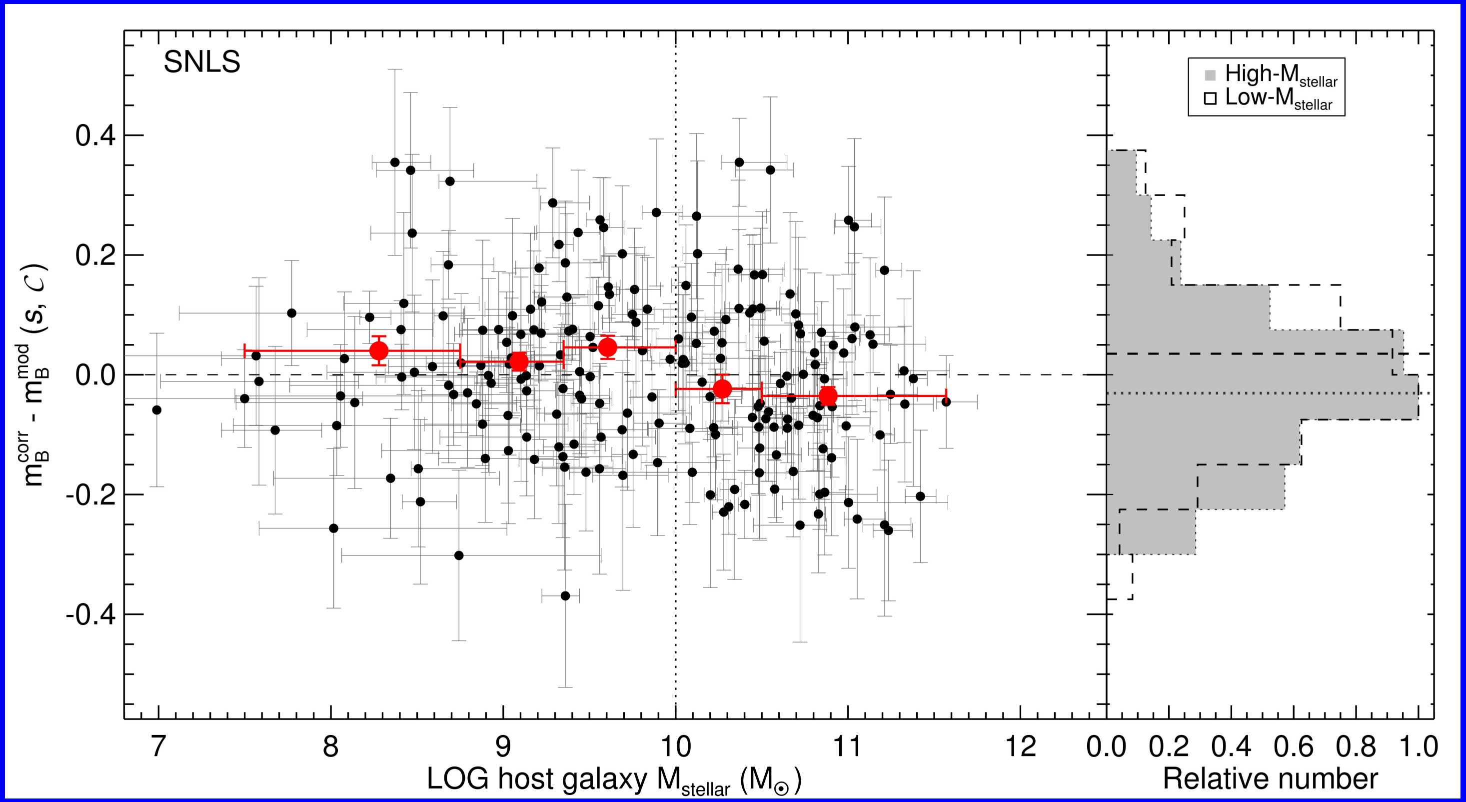








Hubble residuals versus host mass



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

Cosmological analysis

Two ways to proceed:

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

$$\mu_B = m_B - M_B + a(s-1) - bc + gH$$

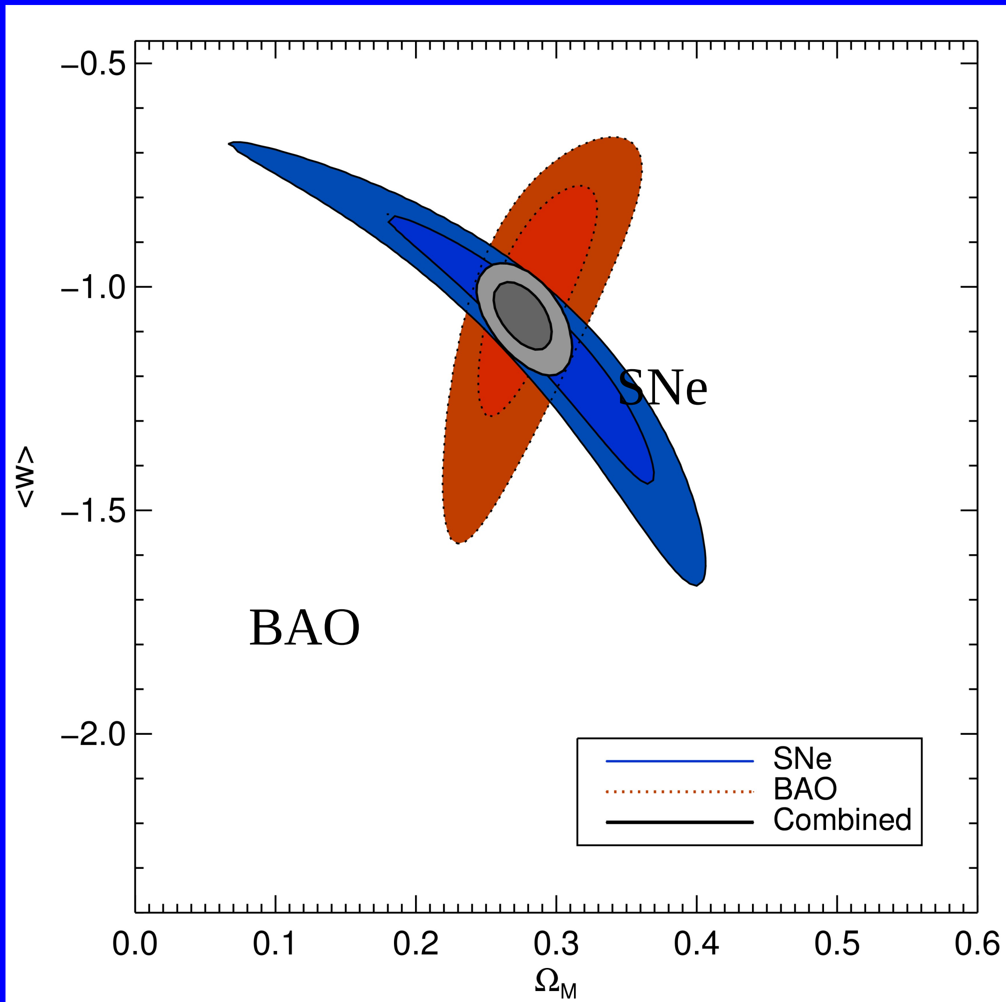
– *Requires very precise measure of H, and robust errors*

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

$$\mu_B = m_B - M_B^1 + a(s-1) - bc \quad \text{when } H < H_{\text{split}}$$

$$m_B = m_B - M_B^2 + a(s-1) - bc \quad \text{when } H \geq H_{\text{split}}$$

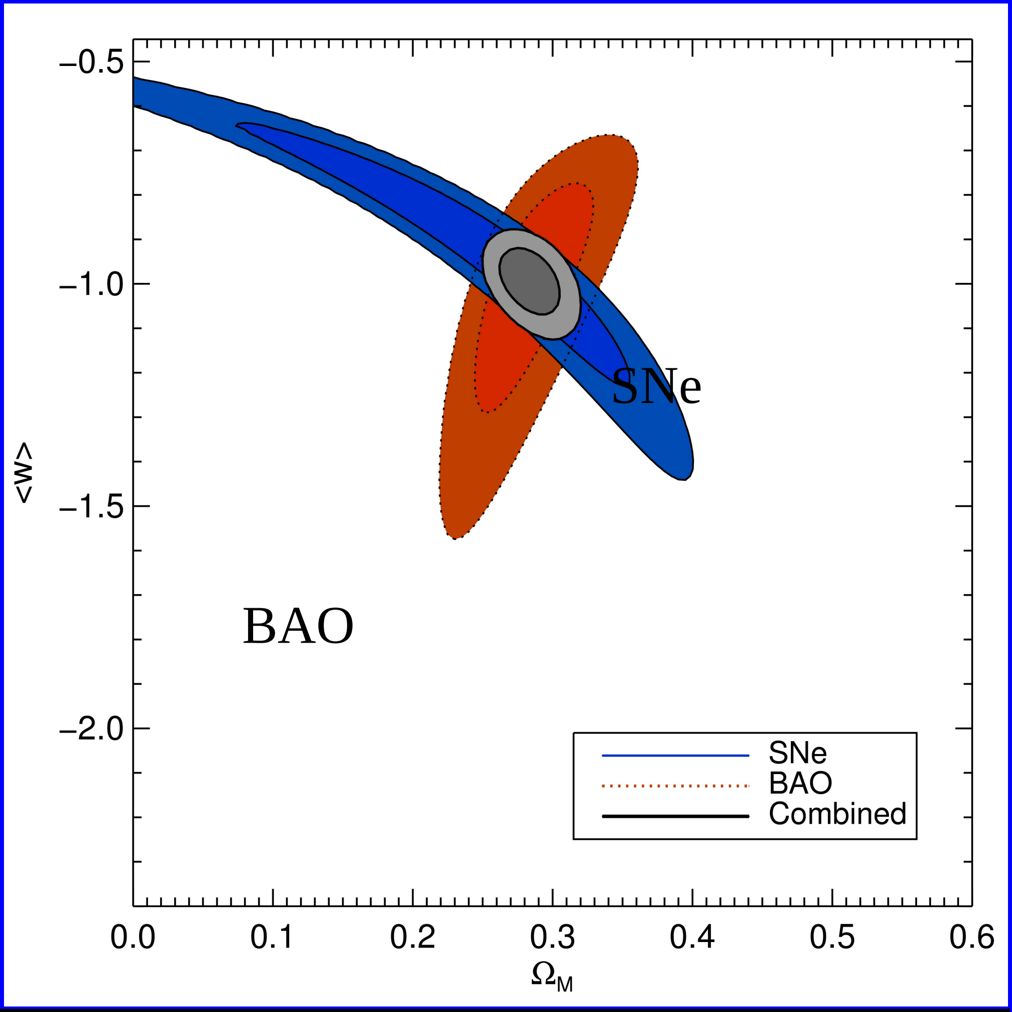
SNLS3 Cosmological Constraints



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 3yr Analysis

- Statistics x 3.5 71 → ~ 280
- Two independent analyses (control of systematics) performed in Canada & France
  - → SN photometry
  - → photometric calibration
  - → light curve fitters SALT2 + SiFTO (Conley et al, 2008)
- 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

Photometric Calibration

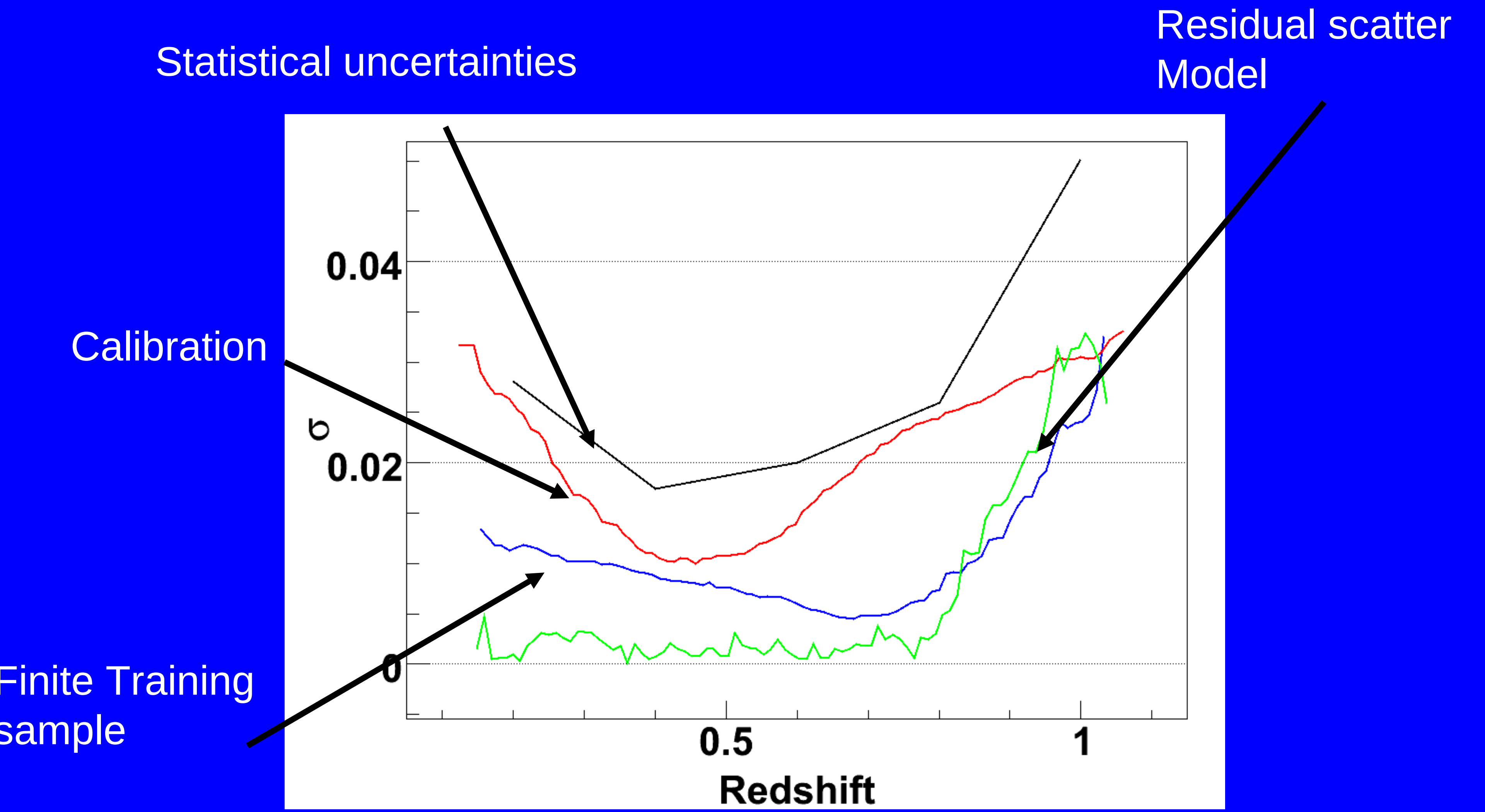
- Magnitude systems do *not* define their physical flux scale → rely on a fundamental standard with known magnitudes and spectrum to convert magnitudes into physical fluxes

$$\Phi = 10^{-0.4(m - m_{ref})} \times \int S_{ref}(\lambda) T(\lambda) d\lambda$$

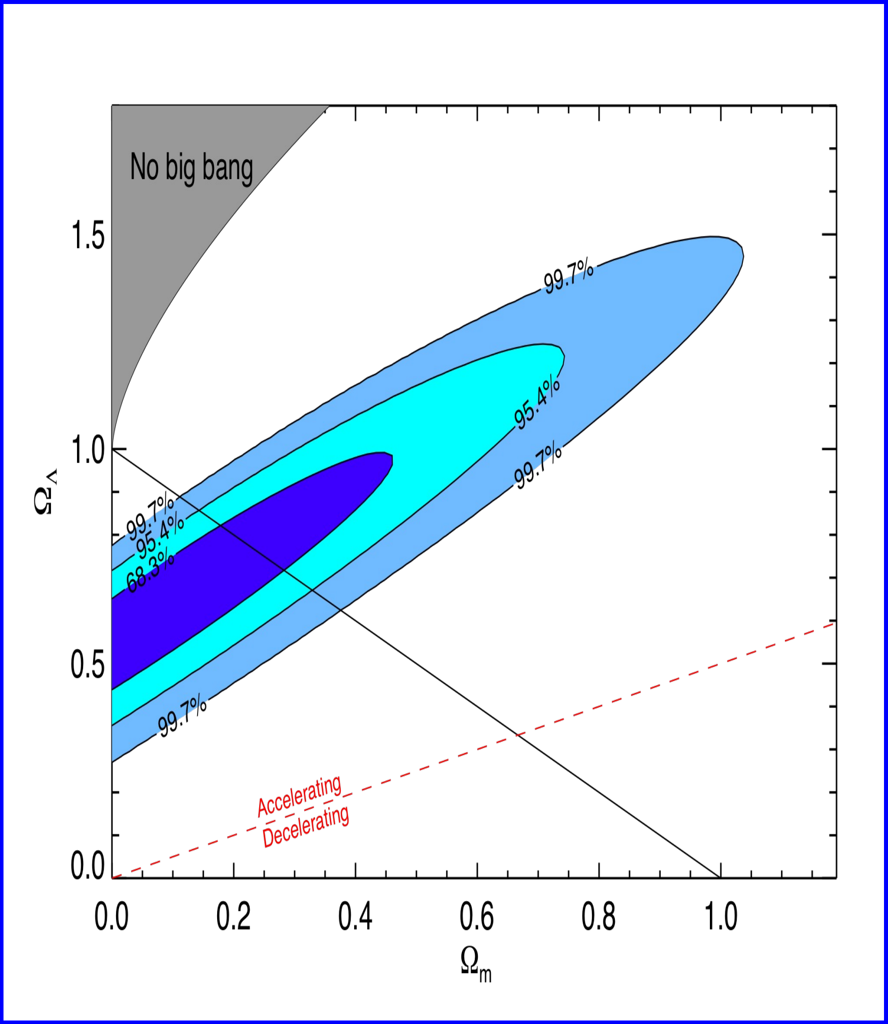
- The HST has selected 5 primary standards (pure hydrogen WD). Models of these stars' spectra are used to calibrate the HST instruments.
- Calibration then propagated to a larger network of secondary standards. SNLS uses one of them, BD +17 4708, as a fundamental flux standard.
- Uncertainties on flux calibration: ~0.005 (gri), ~0.02(z)

(Regnault et al, 2009)

Syst. uncertainties on <μ> [dz=0.2]



LCDM SN only constraints [stat+syst]



Acceleration detected at >99.999% confidence – including systematic effects

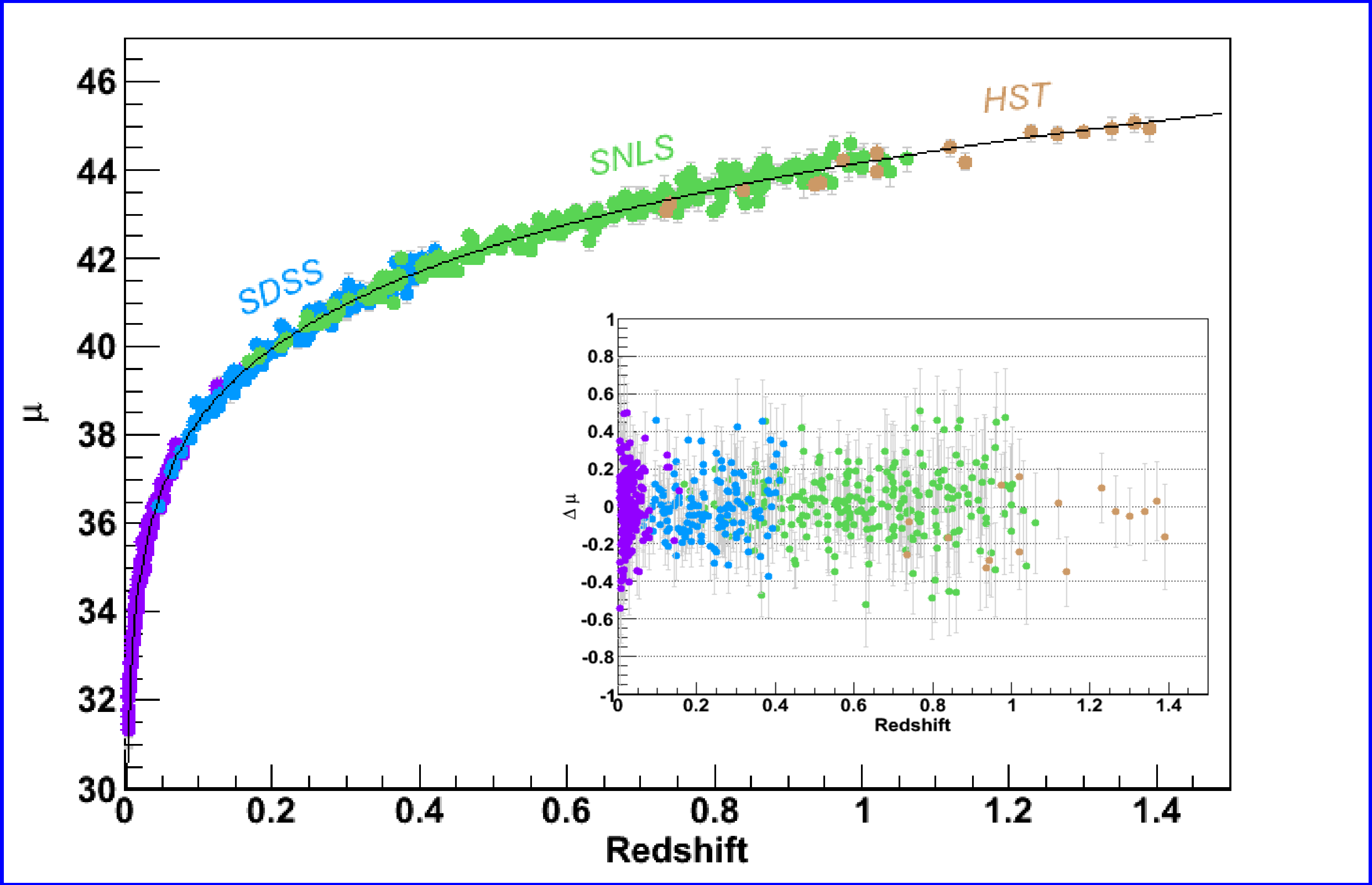
Combined SN sample

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

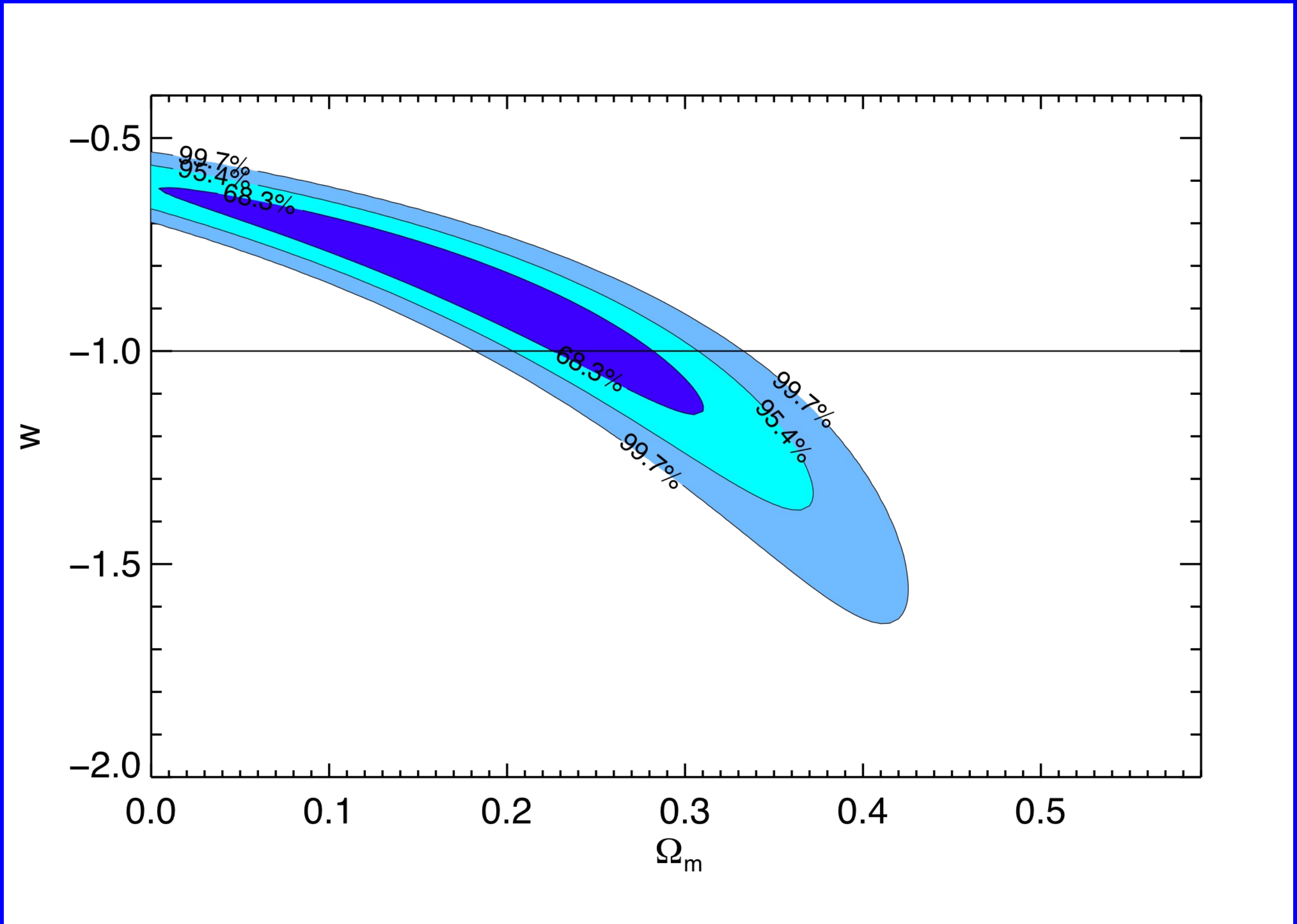
More systematic uncertainties for each survey:

- calibration
- survey incompleteness (Malmquist bias)

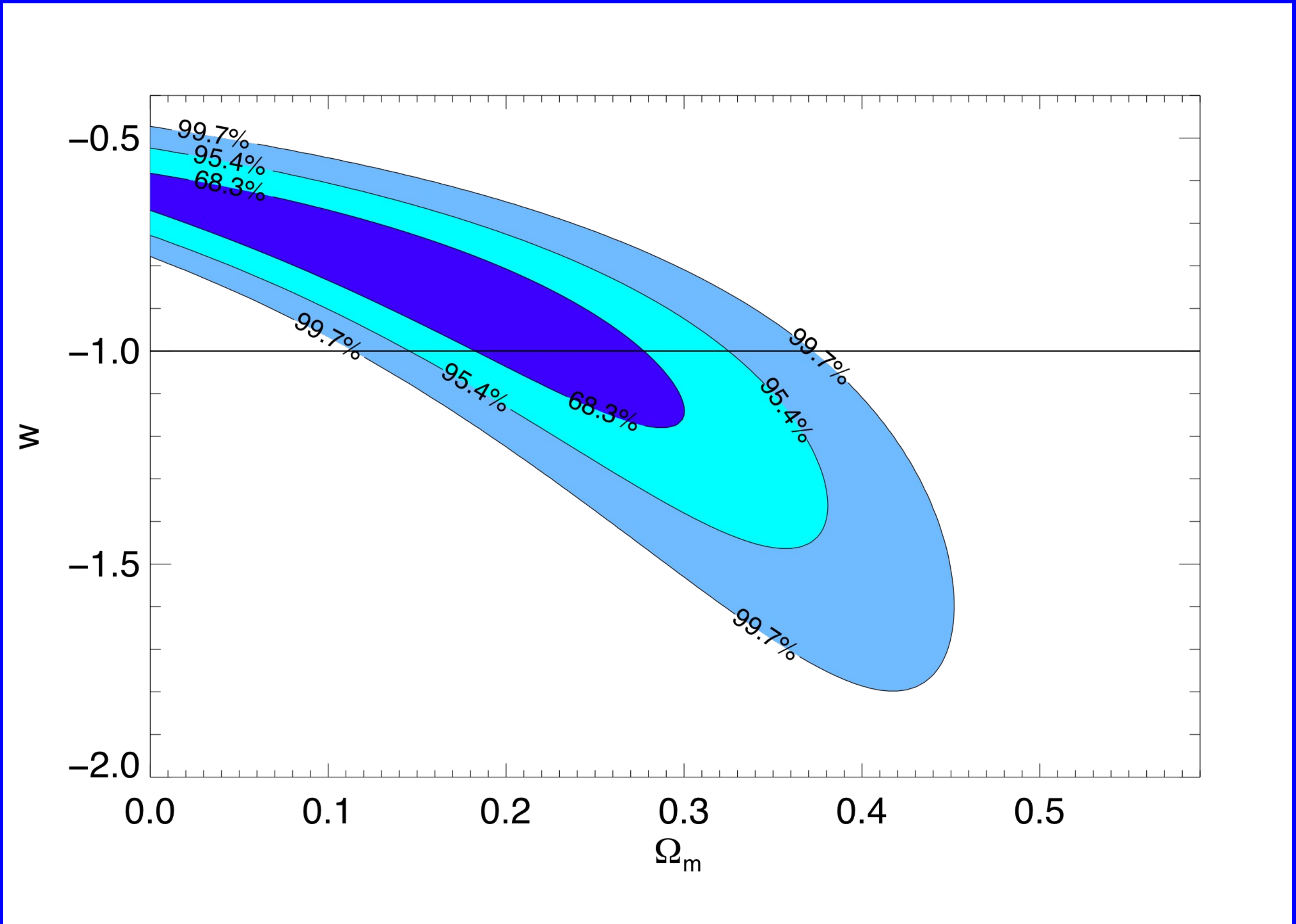
Combined Hubble diagram



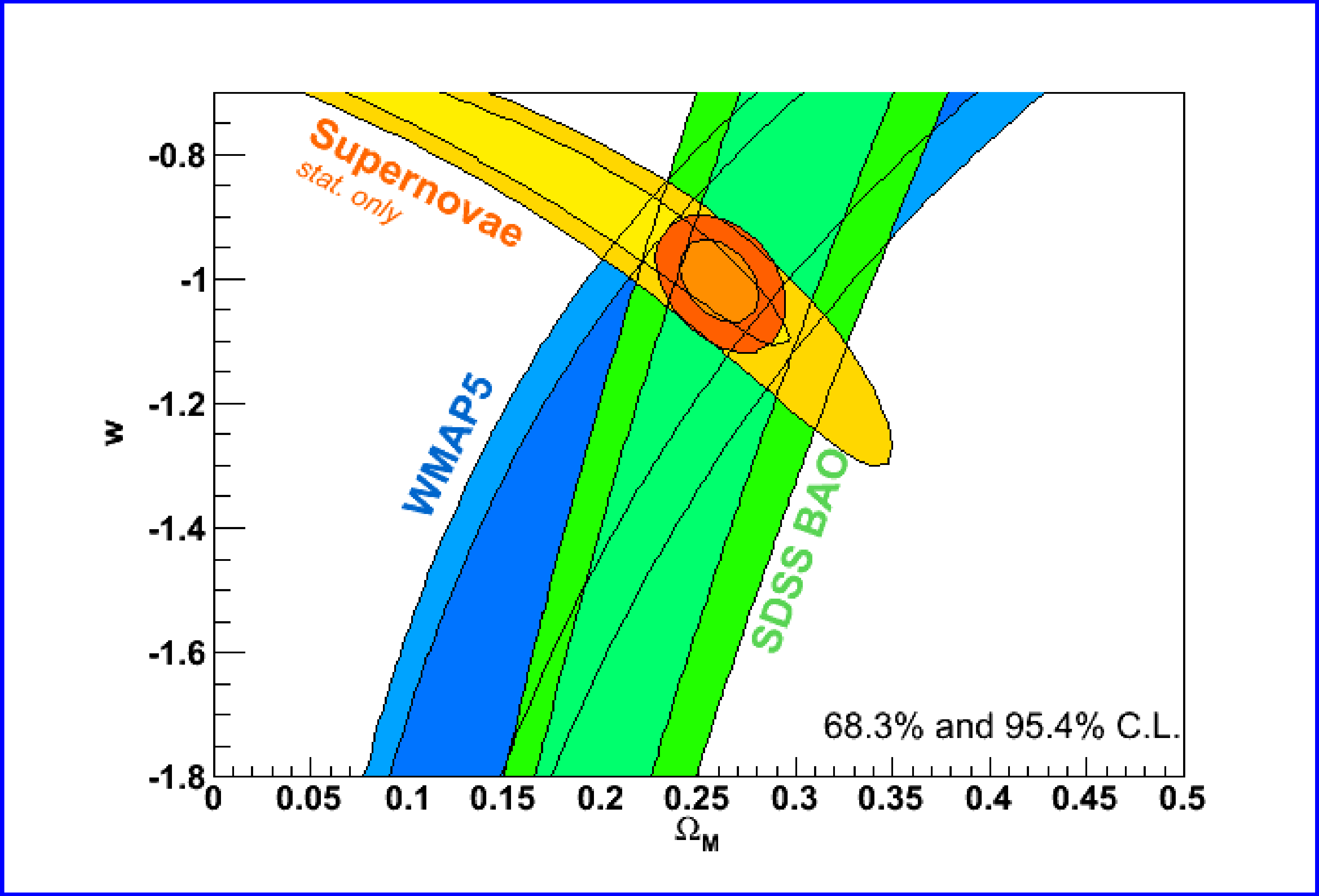
SN only constraints on w



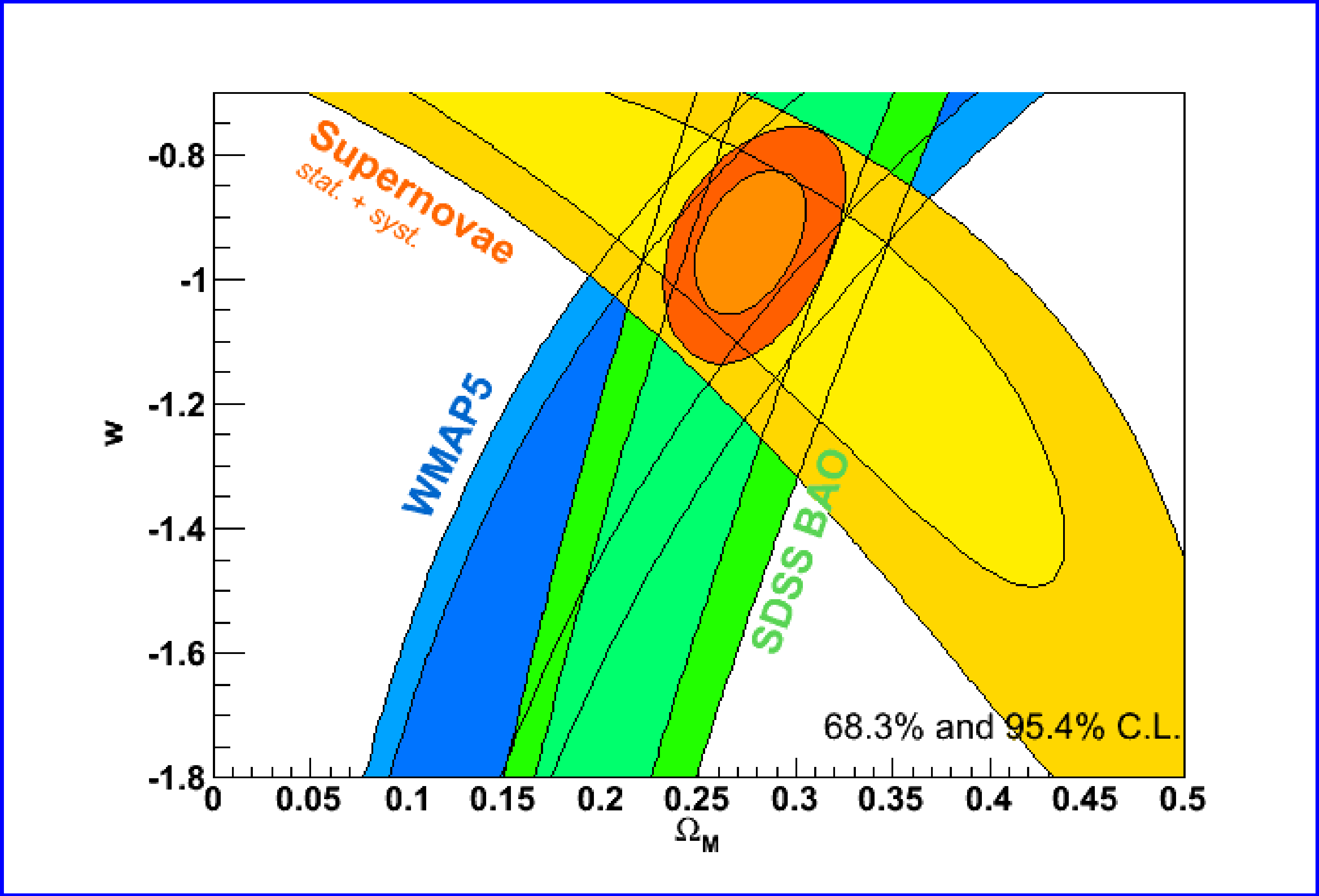
SN only constraints on w



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



(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

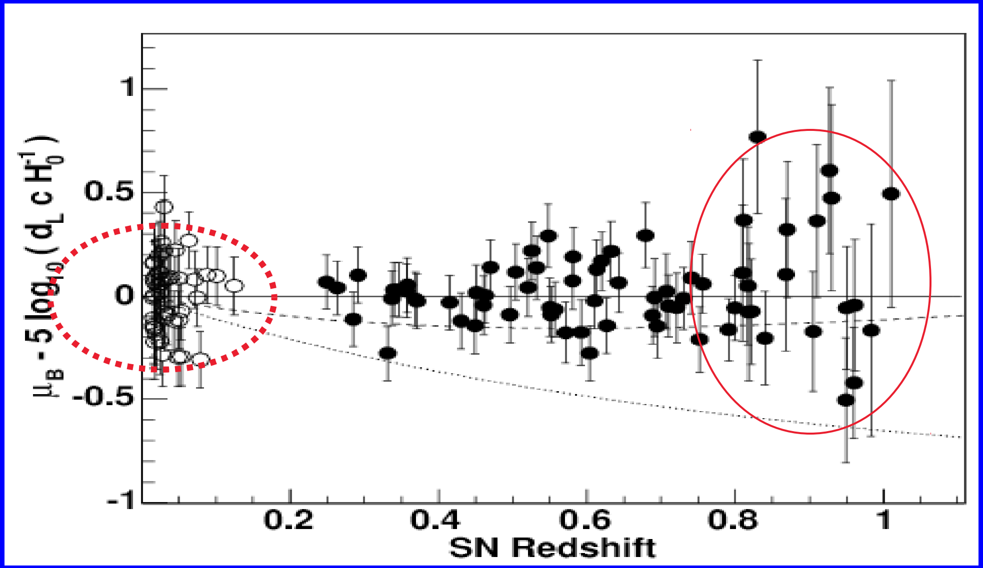
Future SN programs

By 2012 SDSS+SNLS

- will optimistically reach δw (w=cte)~0.05
- obtain no (significant) constraints on w' (wa)

and will (most probably) reached their systematic floor

=> Improving on these « 2nd generation » SN survey results will very difficulty



« 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 difficulty to significantly improve on precision

Stage IV ground based SN projects

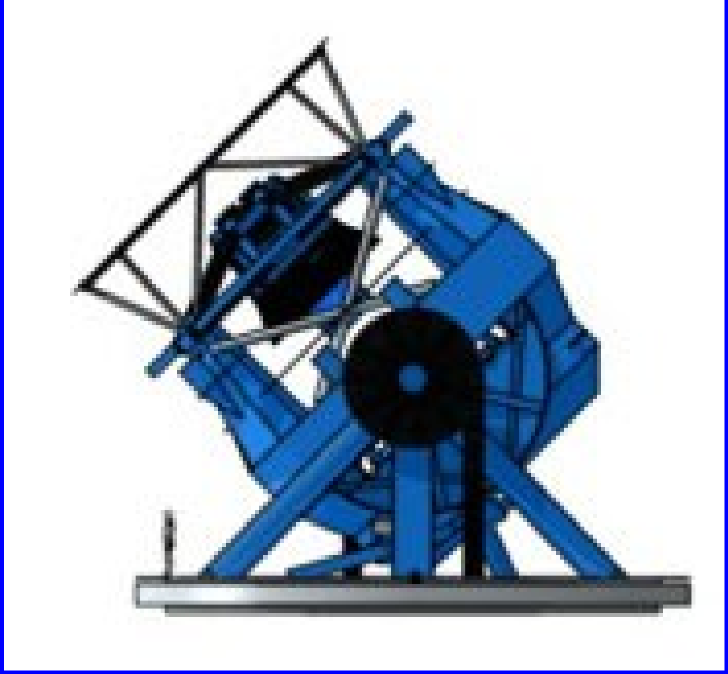
- Pan Starrs 4 :

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

- LSST :

One 8m telescope with
9 deg2 fov

=> 250000 SN/an !

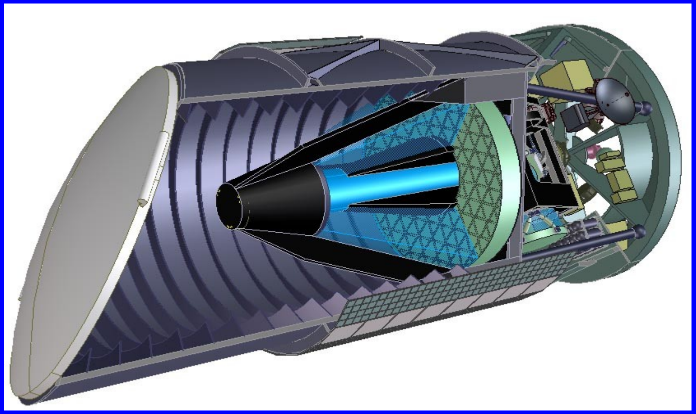


by 2020?

- 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 remain excellent distance indicators

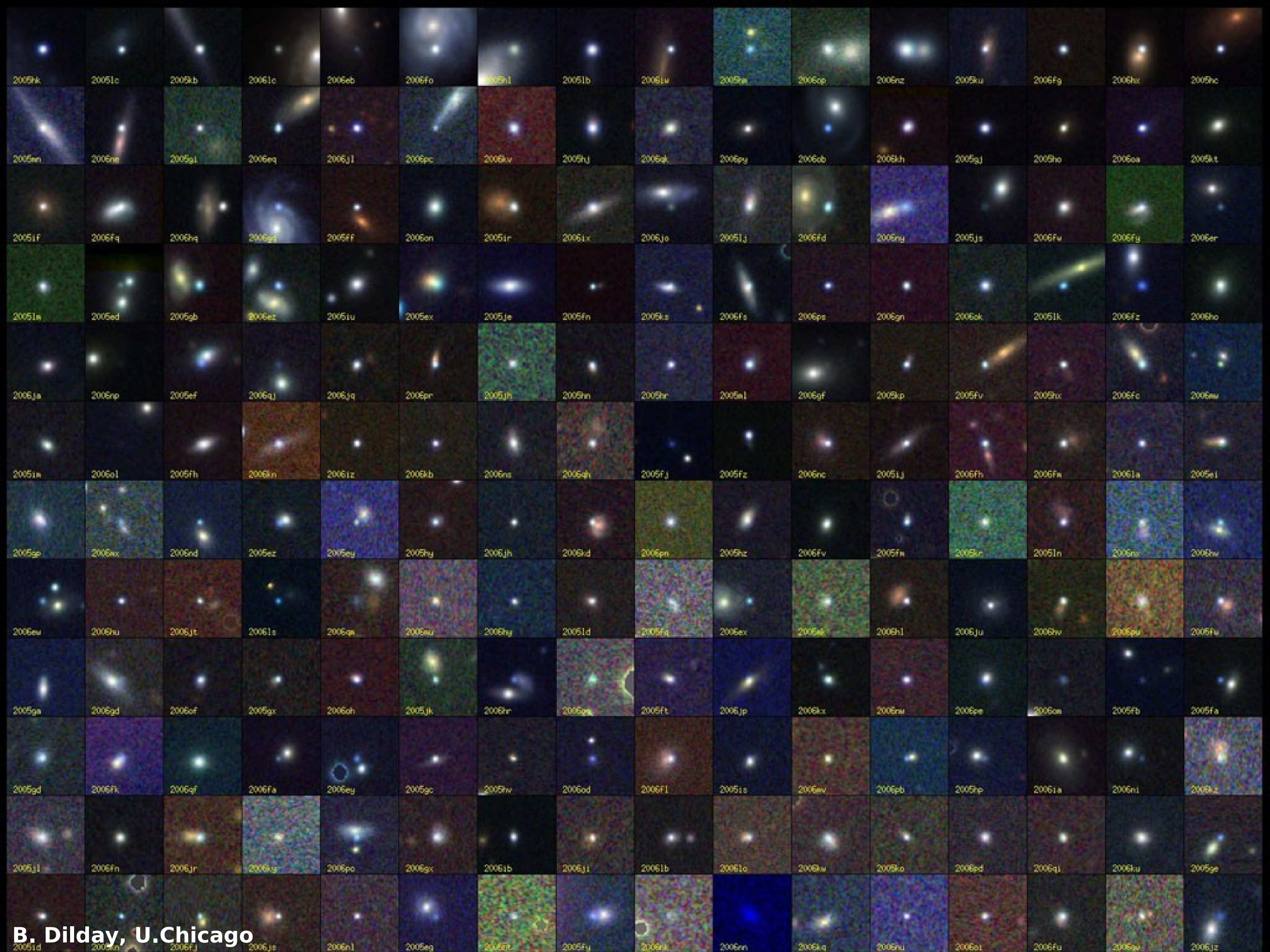
- Current projects are getting more and higher quality data toward building a systematic limited Hubble diagram with ~1000 SN Ia with an expected precision on w (flat Univ., constant) of

+/- 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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