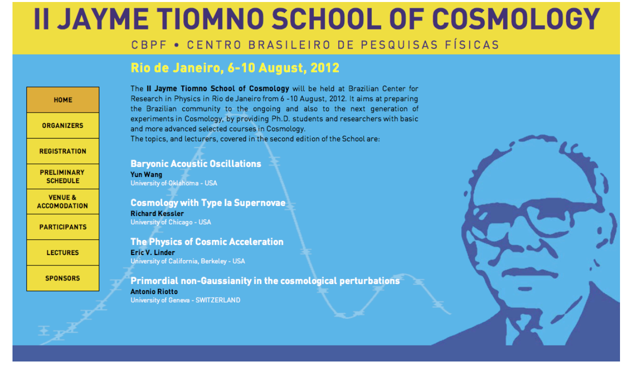


Lectures on Cosmology with Type Ia Supernovae:

Dark Energy Measurements with SNIa

R.Kessler (U.Chicago)

II Jayme Tiomno School of Cosmology

Rio de Janeiro, Brazil

Aug 6-10, 2012

Overview

- Discovery of Dark Energy (1998)
- HST SNIa, z>1 (2004)
- SNLS (2005)
- ESSENCE (2007)
- CSP (2009)
- SDSS (2009)
- SNLS again (2011)
- SDSS + SNLS collaboration

Who has the best logo ?

The High-Z SN Search

SCP Supernova Cosmology Project

SNLS SuperNova Legacy Survey

SDSS/SNLS Joint Light Curves Analysis

SDSS

Pan-STARRS

Javalambre
Physics of the Accelerating Universe
Astrophysical
Survey

CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

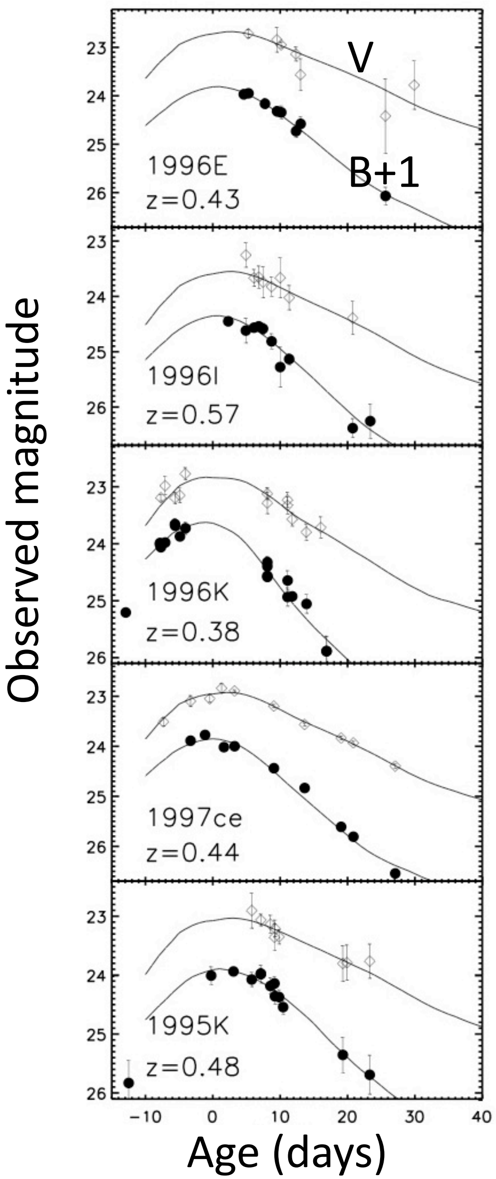
THE DARK ENERGY SURVEY

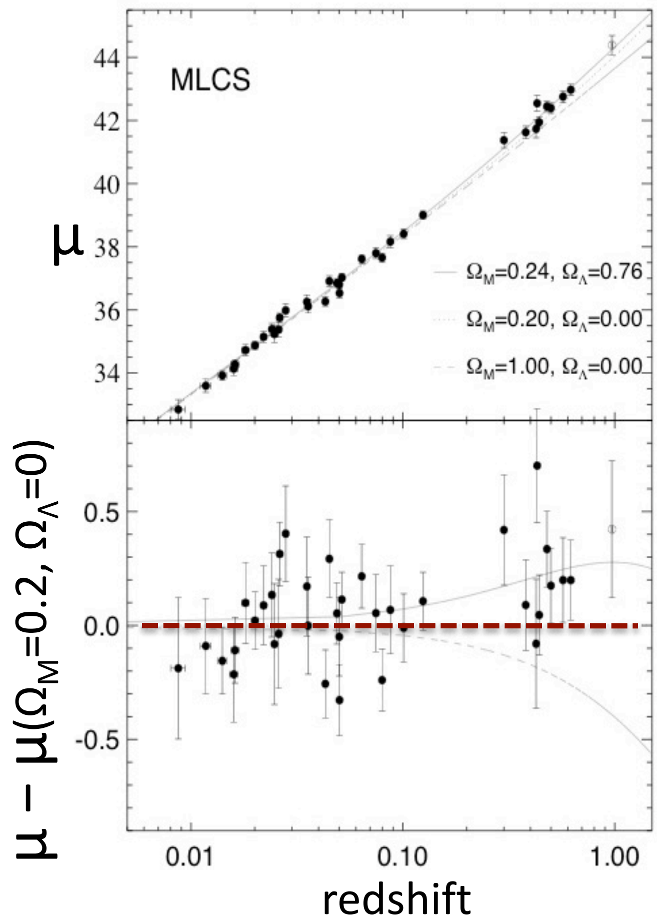
LSST
Large Synoptic Survey Telescope
the widest, fastest, deepest eye of the new digital age

Discovery of Dark Energy:

Riess et al., AJ 116, 1009, (1998)

The High-Z SN Search



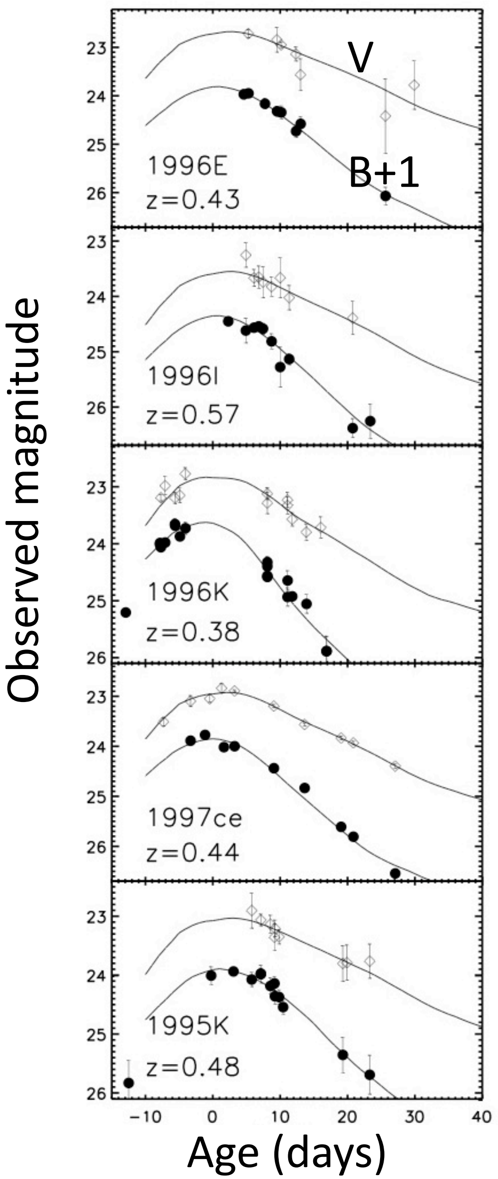


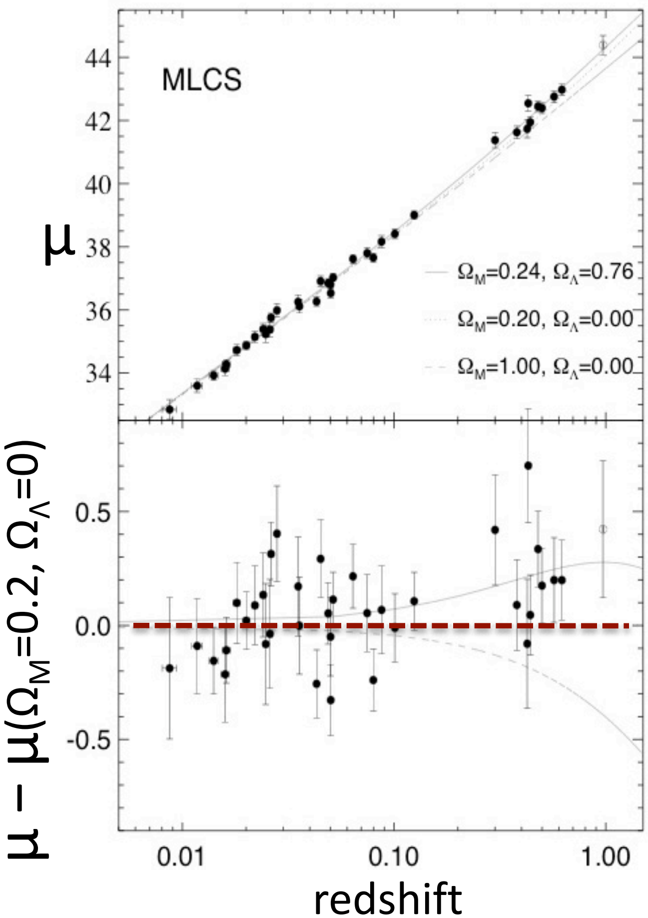
Exercise

Plot these curves of

$\mu - \mu(\Omega_M= 0.2,\ \Omega_\Lambda = 0)$

Discovery of Dark Energy: The High-Z SN Search

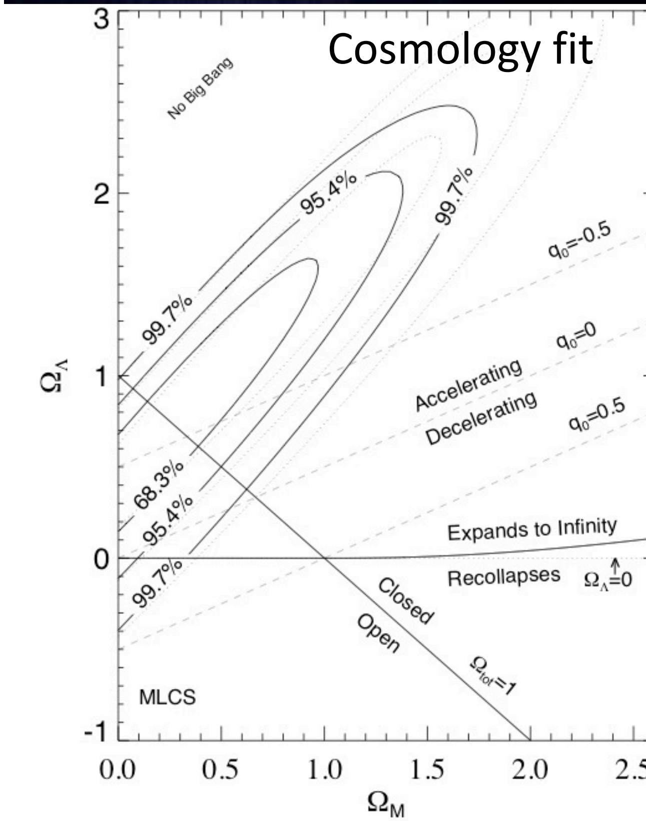




Ω_M= 0.24, Ω_Λ = 0.76

Ω_M= 0.20, Ω_Λ = 0.00

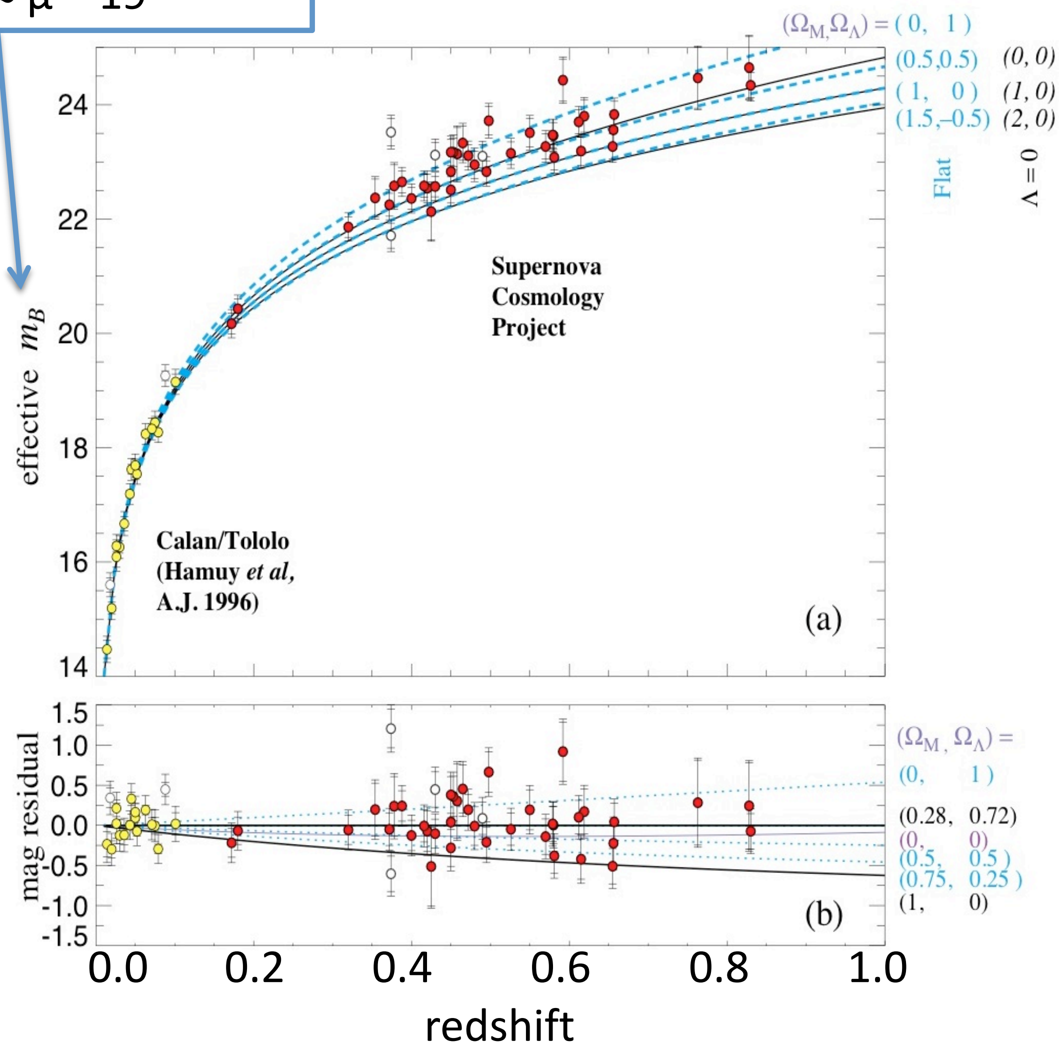
Ω_M= 1.00, Ω_Λ = 0.00

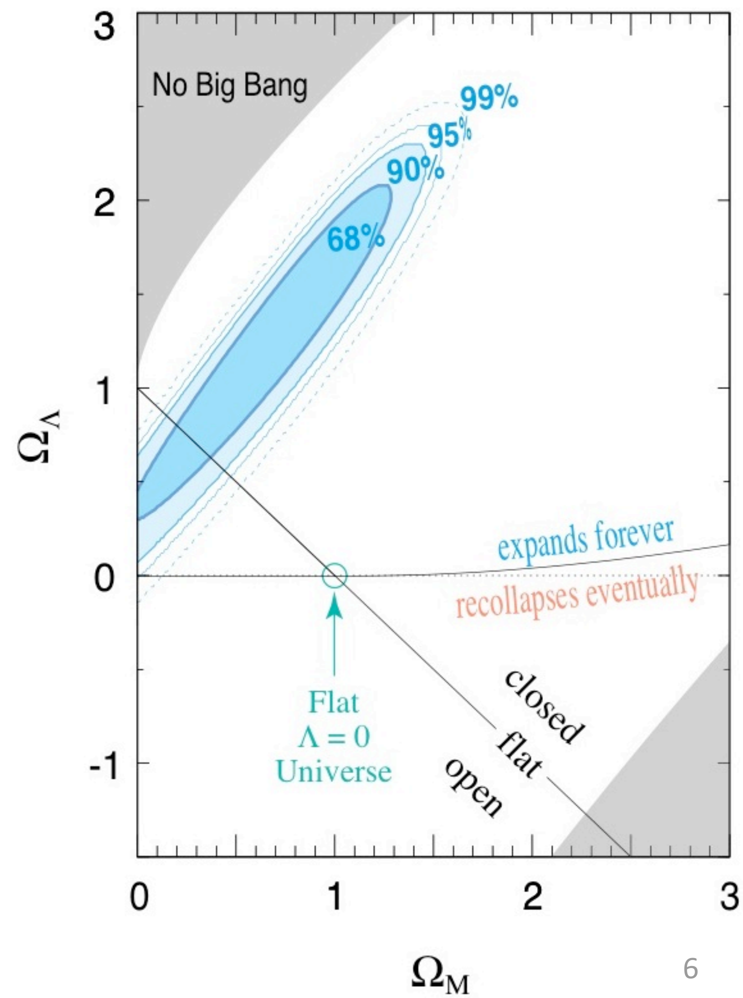


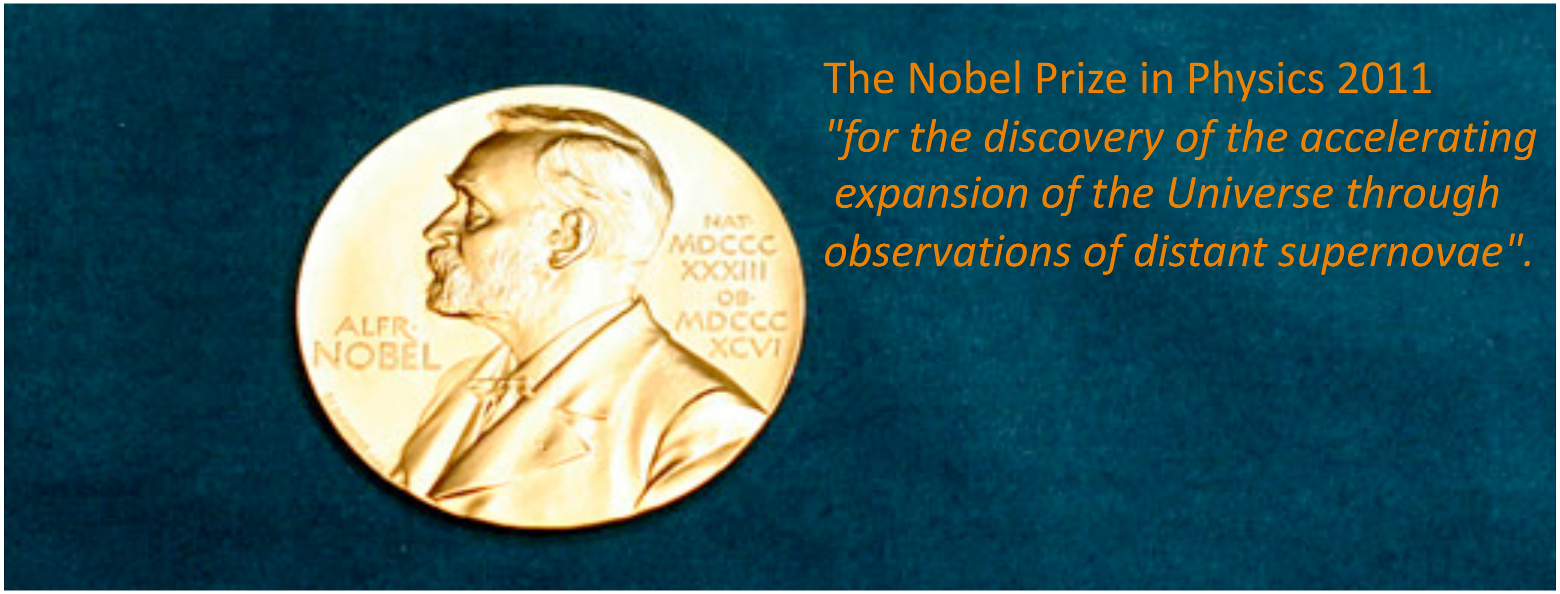
SCP Supernova Cosmology Project

Obserbed mag:
μ + abs-SNmag
≈ μ − 19

Perlmutter et. al., AJ, 517, 565 (1999)







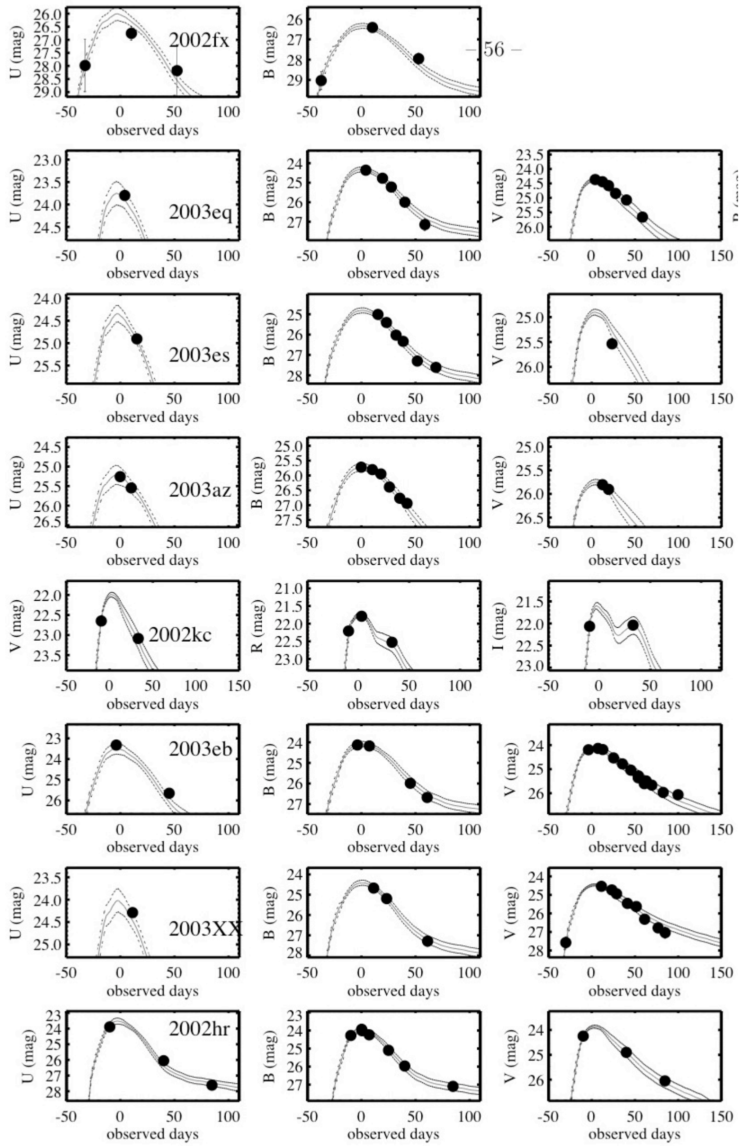
Saul Perlmutter

Brian P. Schmidt

Adam G. Riess

HST: z>1 (Riess et al. ,ApJ 607, 665, 2004)

U B V



z =1.40

z =0.84

z =0.95

z =1.27

z =0.22

z =0.90

z =0.

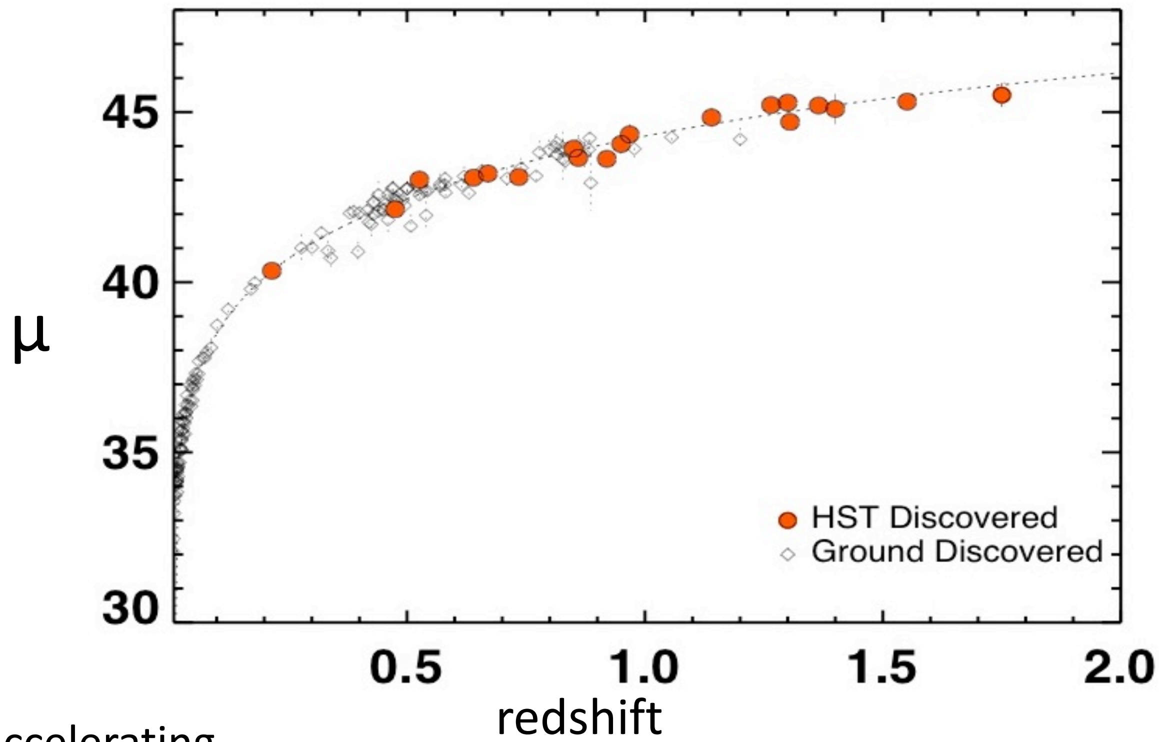
z =0.53

Half of 16 light curves are shown.

Signal-to-noise is excellent, but sampling is marginal … 0 or 1 pre-max epochs.

Goal: look for 'cosmic jerk'

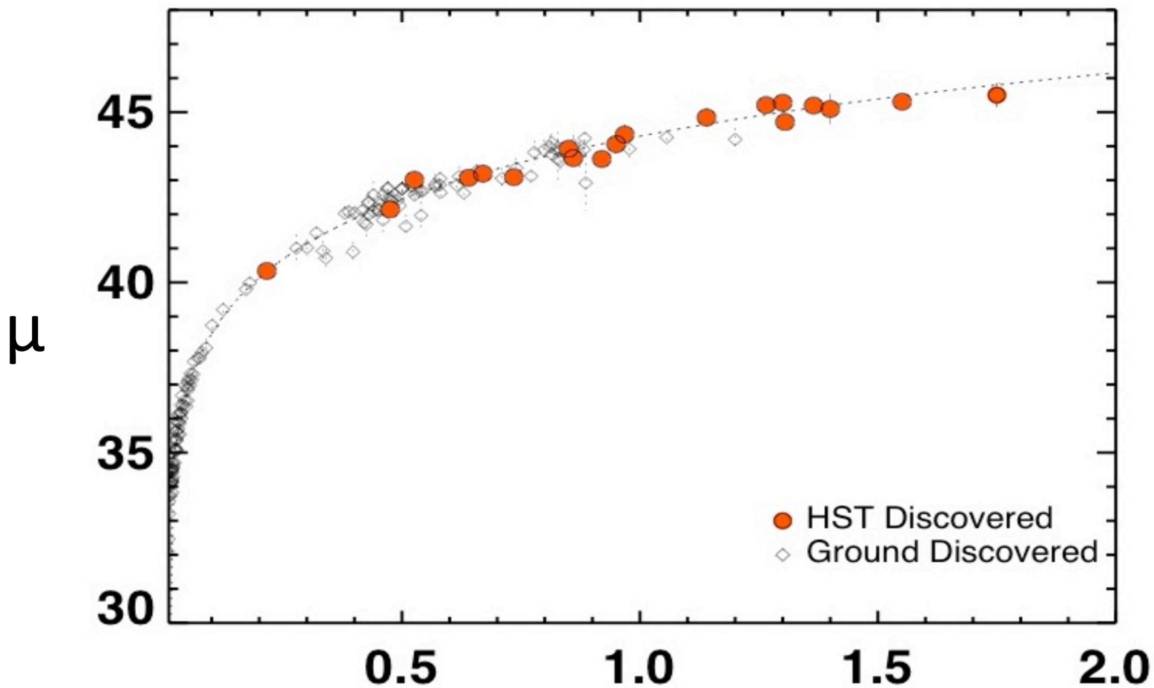
HST: z>1



Accelerating
at low redshifts

Deccelerating
at high redshifts

HST: z>1

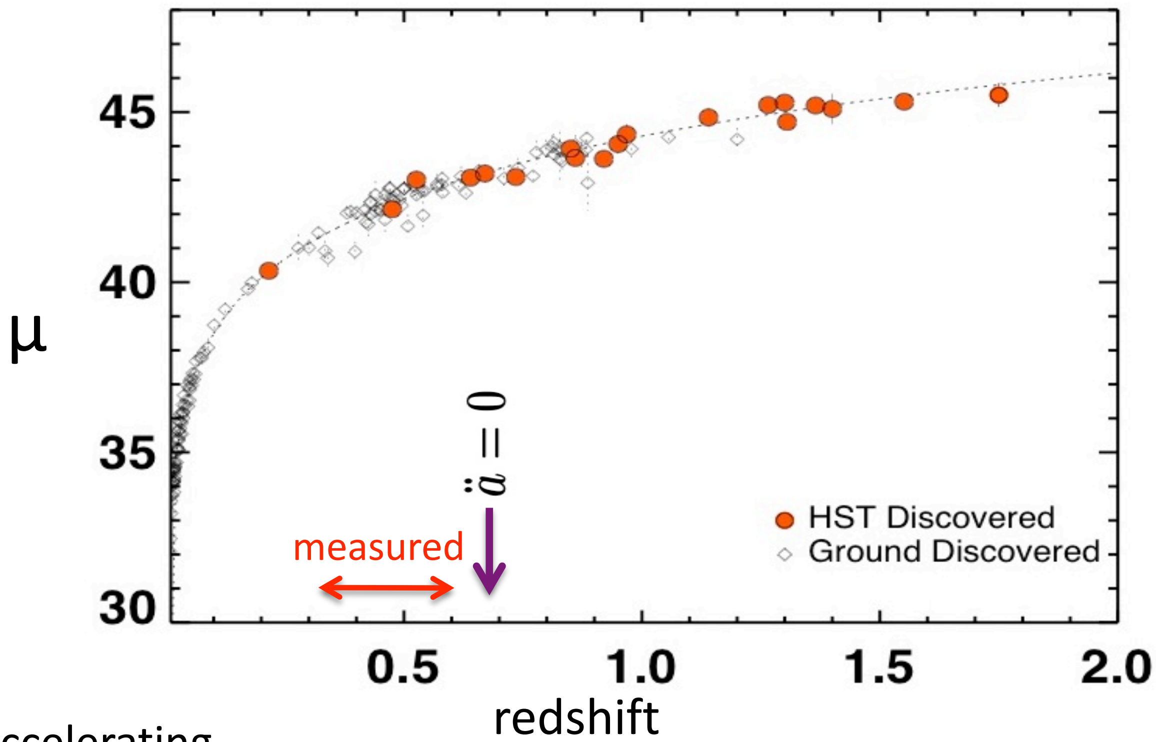


Accelerating
at low redshifts

Where is the transition ?
Also called 'cosmic jerk'

Deccelerating
at high redshifts

HST: z>1



Exercise 

use 2nd Friedman equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i \rho_i(1+3w_i)$$

to show that

$$\ddot{a} = 0 \ \text{ when } \ z = 0.67$$

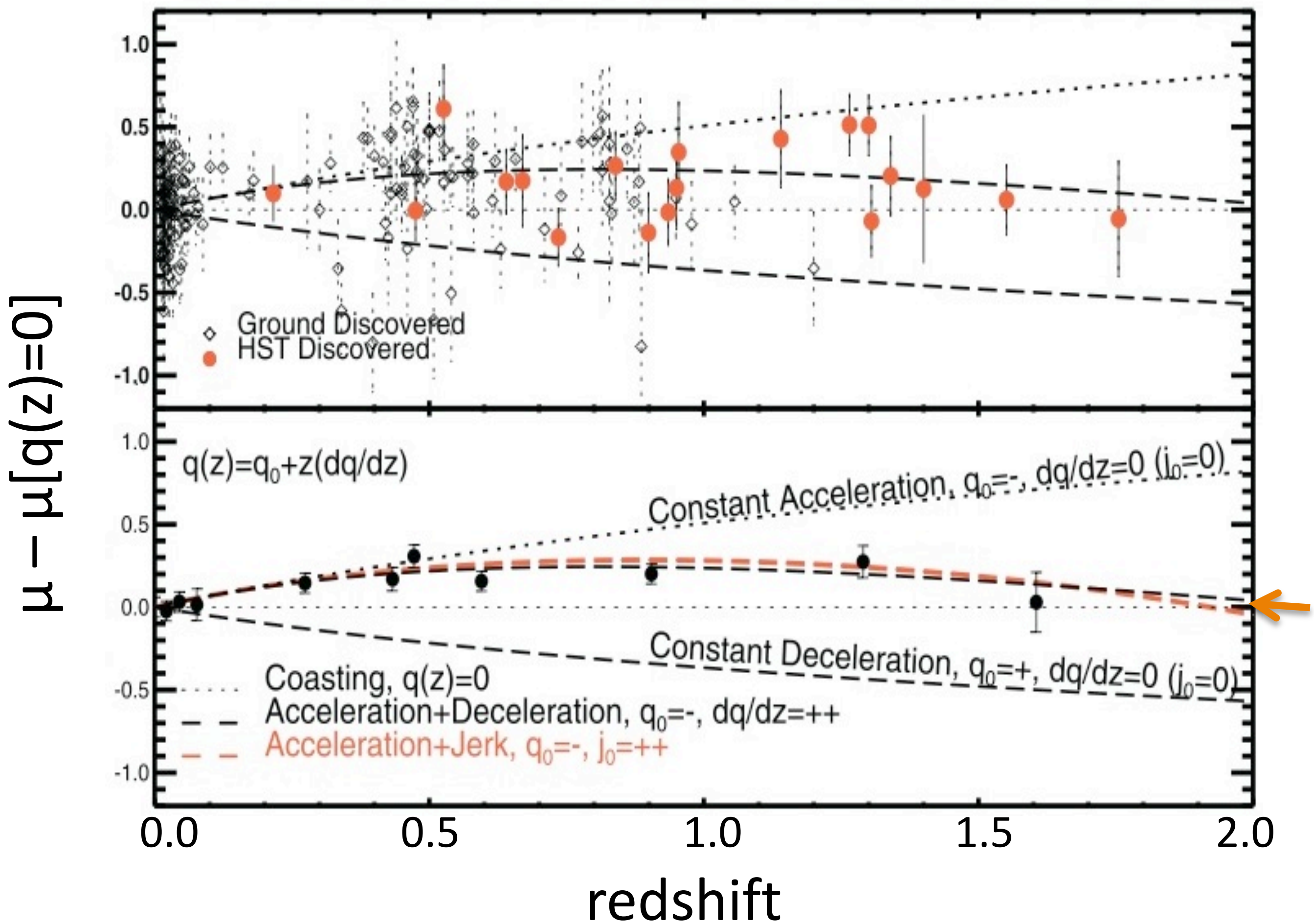
(Ω_M=0.3 Ω_Λ=0.7).
Why different than measurement ?

Accelerating
at low redshifts

Where is the transition ?
Also called 'cosmic jerk'

Deccelerating
at high redshifts

HST: z>1

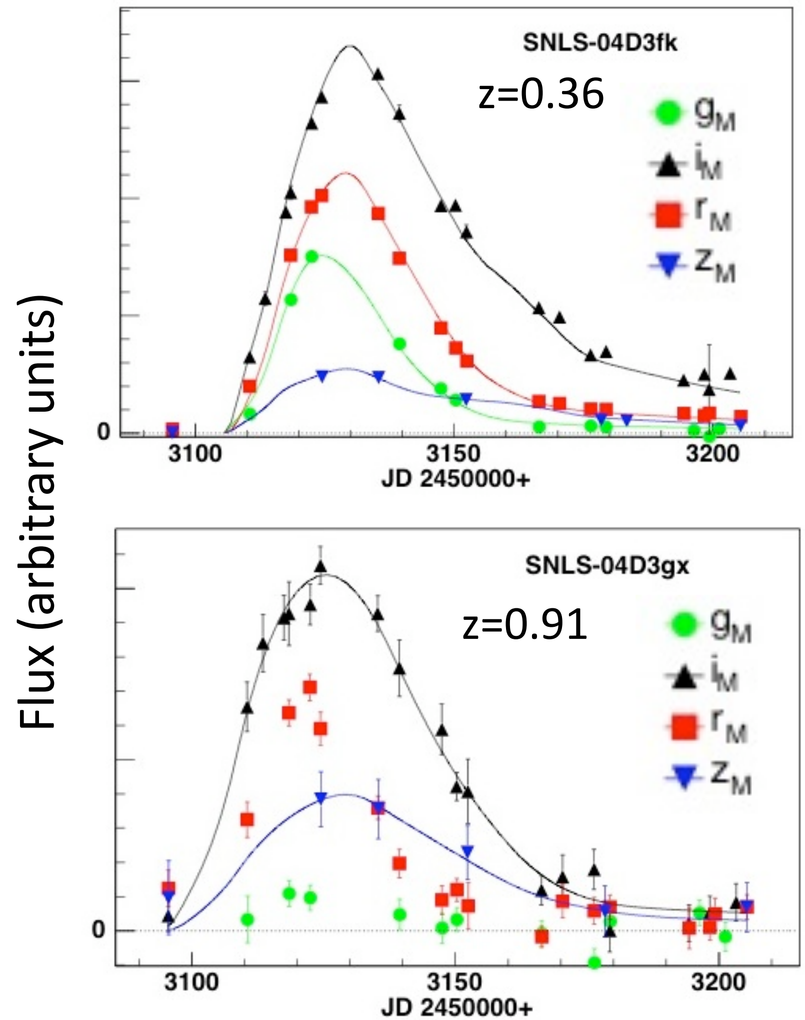


Decceleration, then acceleration

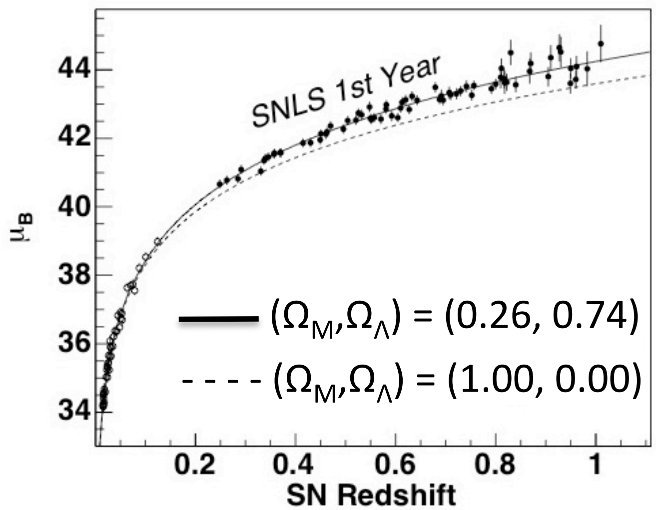
SNLS SuperNova Legacy Survey

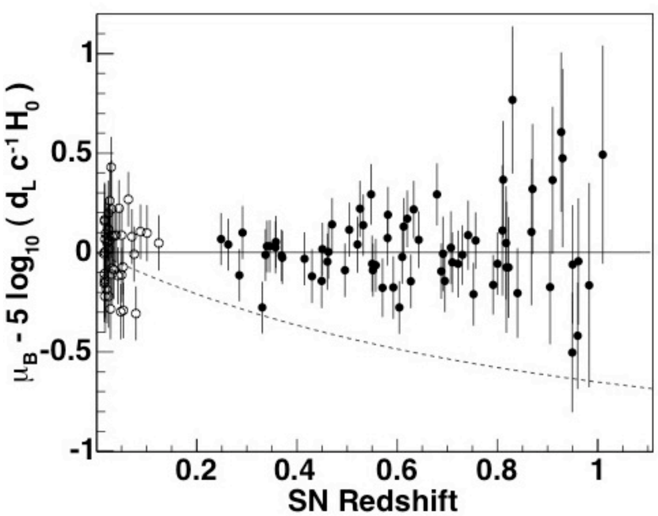
Astier et. al., A&A 447, 31 (2006)

- First serious measurement of the dark energy equation-of-state parameter w.
- traditional nearby SNe Ia with 70 new high-redshift SN from CFHT.
- Systematic uncertainties.
- BAO prior from SDSS (Eisenstein et al, 2005).
- Transition to new era of survey strategy: repeat imaging of same fields every few days (can go back to catch early light curve)

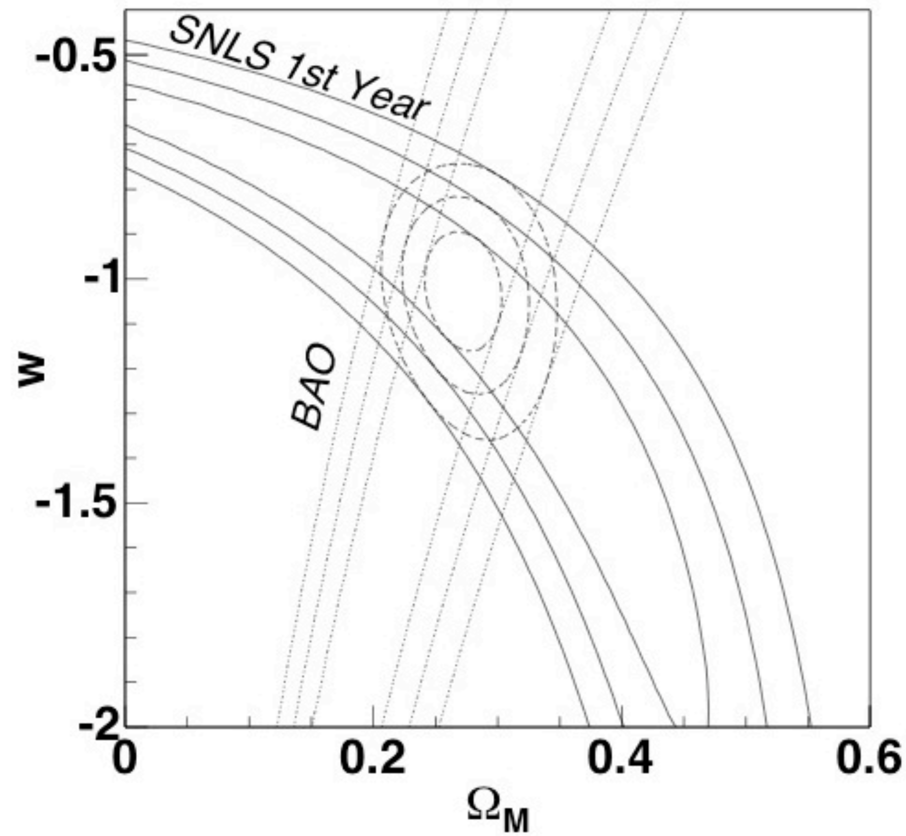


SNLS SuperNova Legacy Survey





$w = -1.023 \pm 0.090(\text{stat}) \pm 0.054(\text{syst})$

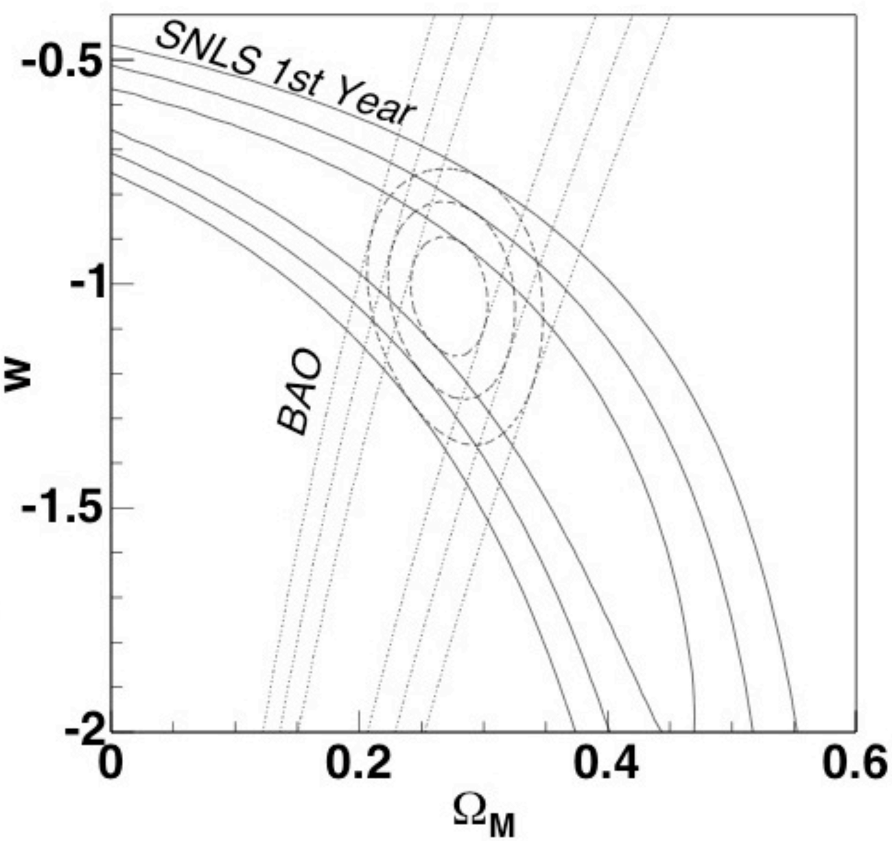


SNLS SuperNova Legacy Survey

$w = -1.023 \pm 0.090(\text{stat}) \pm 0.054(\text{syst})$

Source	$\sigma(\Omega_M)$ (flat)	$\sigma(\Omega_{tot})$	$\sigma(w)$	$\sigma(\Omega_M)$ (with BAO)	$\sigma(w)$ (with BAO)
Zero-points	0.024	0.51	0.05	0.004	0.040
Vega spectrum	0.012	0.02	0.03	0.003	0.024
Filter bandpasses	0.007	0.01	0.02	0.002	0.013
Malmquist bias	0.016	0.22	0.03	0.004	0.025
Sum (sys)	0.032	0.55	0.07	0.007	0.054
Meas. errors	0.037	0.52	0.09	0.020	0.087
U-B color(stat)	0.020	0.10	0.05	0.003	0.021
Sum (stat)	0.042	0.53	0.10	0.021	0.090

Table 6 Summary of uncertainties in the derived cosmological parameters. The dominant systematic uncertainty arises from the photometric calibration, itself dominated by the i_M and z_M band contributions.



ESSENCE (CTIO):

Wood-Vasey et al., ApJ 666, 694 (2007)

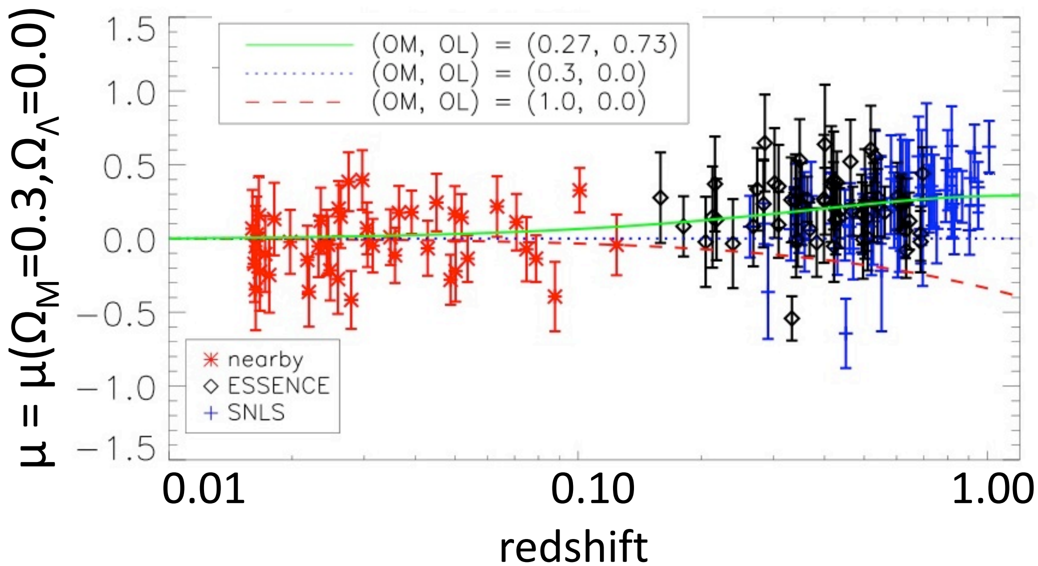
Similar in spirit to SNLS, but only two filters (R,I) instead of four filters for SNLS.

First MLCS fits with efficiency included in A_V prior

Avoids rest-frame UV region.

Having only one color results in larger systematic uncertainty compared to SNLS:

$\mathcal{w} = -1.05 \pm 0.13(\text{stat}) \pm 0.13(\text{syst})$



CSP: Carnegie Supernova Project

Freedman et. al., ApJ 704, 1036 (2009)

Goal:
Hubble diagram up to redshift z < 0.7 using rest-frame i-band (7500 A)

Benefit:
Reduced sensitivity to host-galaxy extinction and/or intrinsic reddening.

Challenge:
Infrared observations are difficult due to sky noise

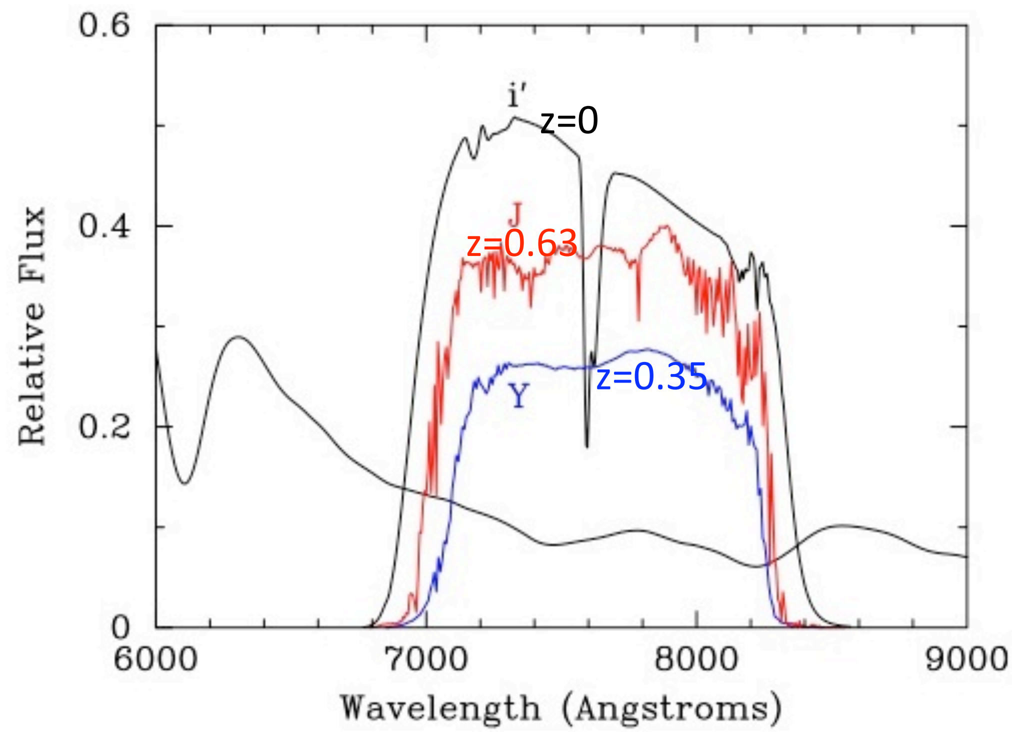


Figure 2. Filter response functions for the Y (blue) and J (red) bands blueshifted by 0.35 and 0.63, respectively. Rest-frame i band is plotted in black. The absorption feature at $\lambda \sim 7600$ Å is telluric O_2. Crossing the entire figure, the SED of a typical SN Ia at maximum (Hsiao et al. 2007) is also shown in black.

Illustration of Benefit.

Exercise 

: For the discovery papers (Riess 98, Perlmutter 99, Riess 2004) the primary rest-frame bands are U & B. For CSP the primary rest-frame band is i.

Assuming host-galaxy extinction follows the Cardeli,Clayton,Mathis (1989) extinction law, R_V=2 and mean A_V=0.3, compare the average extinction in U,B and i.

NASA/ESA/Hubble: Dark lanes of dust in Centaurus A.

Illustration of Challenge

Exercise  : Exposure Time Calculator, i vs. J band

Consider the following observing conditions for $\boldsymbol{i}$ and $\boldsymbol{J}$ bands, with central wavelengths of 7500 Å and 12500 Å, respectively.

- sky brightness ($\boldsymbol{m_{\rm sky}}$) is 19.3 mag/asec^2 and 15.8 mag/asec^2 for $\boldsymbol{i}$ and $\boldsymbol{J}$, respectively.
- A 20^{th} magnitude source delivers $\boldsymbol{N_{\rm pe}^{20} = 100}$ photoelectrons per second (for both bands).
- Aperture radius $\boldsymbol{r = 0.7''}$, and assume 100% of source-signal is contained.

To obtain a specified signal-to-noise ratio (SNR), show that the exposure time $\boldsymbol{T}$ is given by

$$T = \mathrm{SNR}^2 \left[\frac{1 + A \cdot 10^{0.4(M_{\rm SN} - m_{\rm sky})}}{10^{0.4(Z_{\rm pe} - M_{\rm SN})}} \right]$$

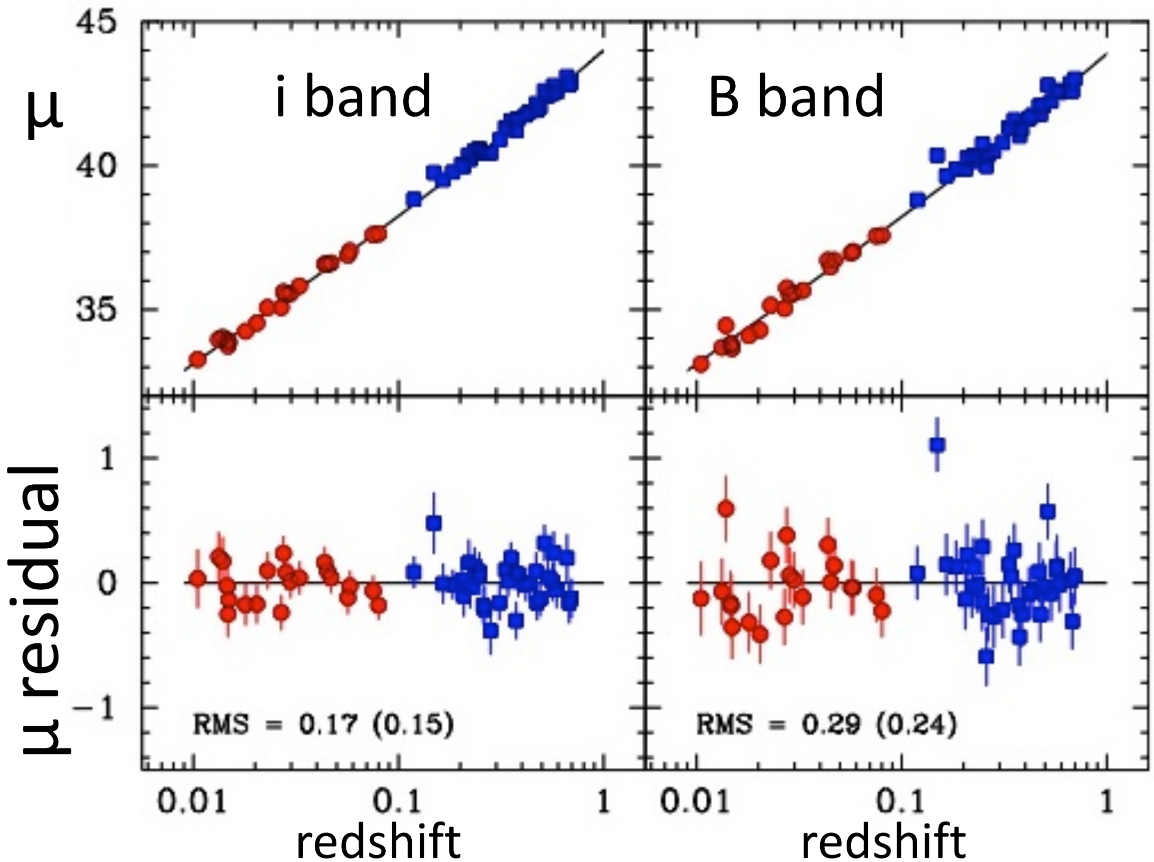
where $\boldsymbol{M_{\rm SN}}$ is the SN magnitude, $\boldsymbol{A = 4\pi r^2}$ is the photometric aperture area, and $\boldsymbol{Z_{\rm pe} = 20 + 2.5\log_{10}(N_{\rm pe}^{20})}$.

For $\boldsymbol{M_{\rm SN} = 23}$, show that the exposure times for the $\boldsymbol{i}$ and $\boldsymbol{J}$ band are 12 minutes and 5 hours, respectively. Why is there such a big difference ?

At redshift z=0.7, i & J map into which rest-frame bands ?

CSP: Carnegie Supernova Project

NOT corrected for reddening

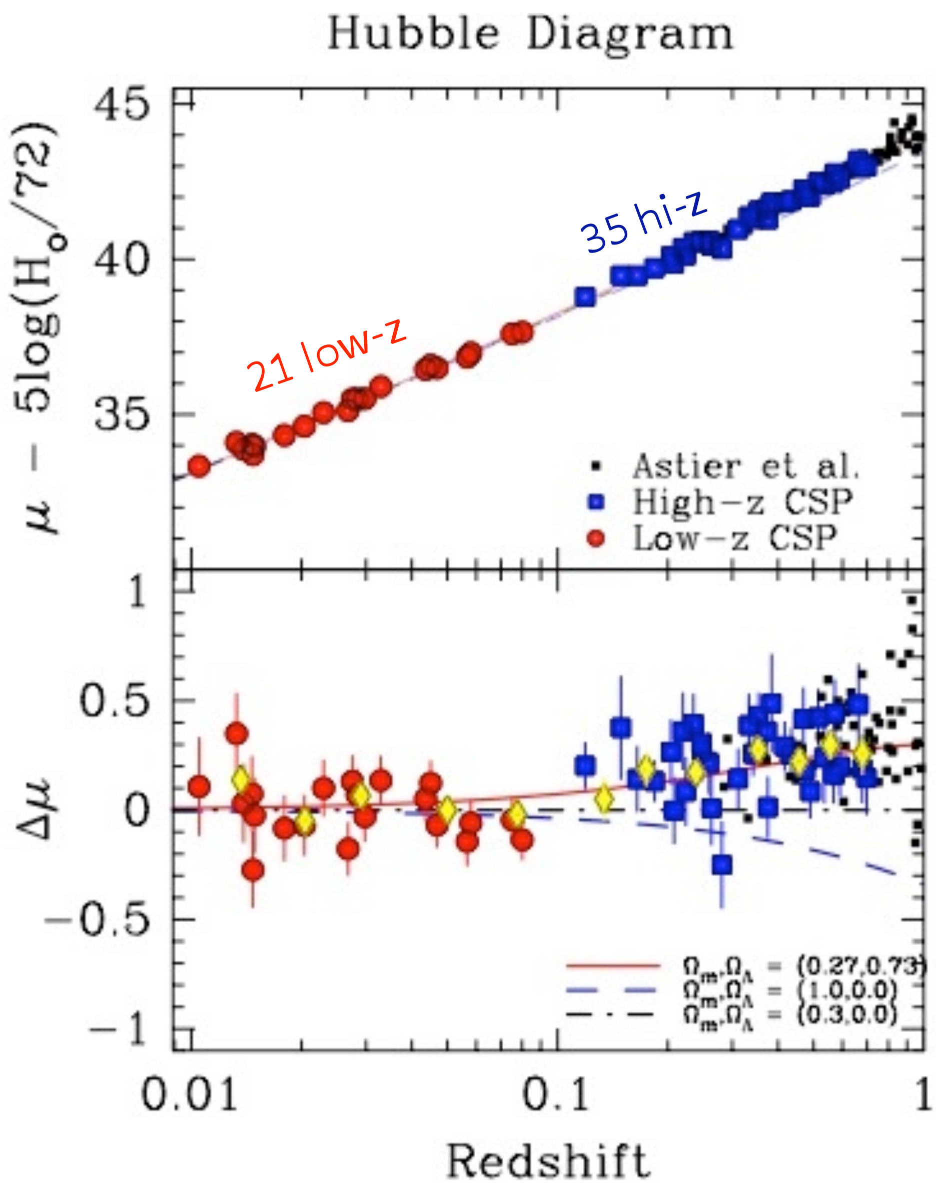


Exercise 

Following up the exercise from 2 slides back, show that the ratio $RMS_B/RMS_i \approx 3$ if all scatter is from host galaxy extinction with $R_V=2$.

Why do we expect the measured rms-ratio (in CSP) to be smaller than 3 ?

CSP: Carnegie Supernova Project



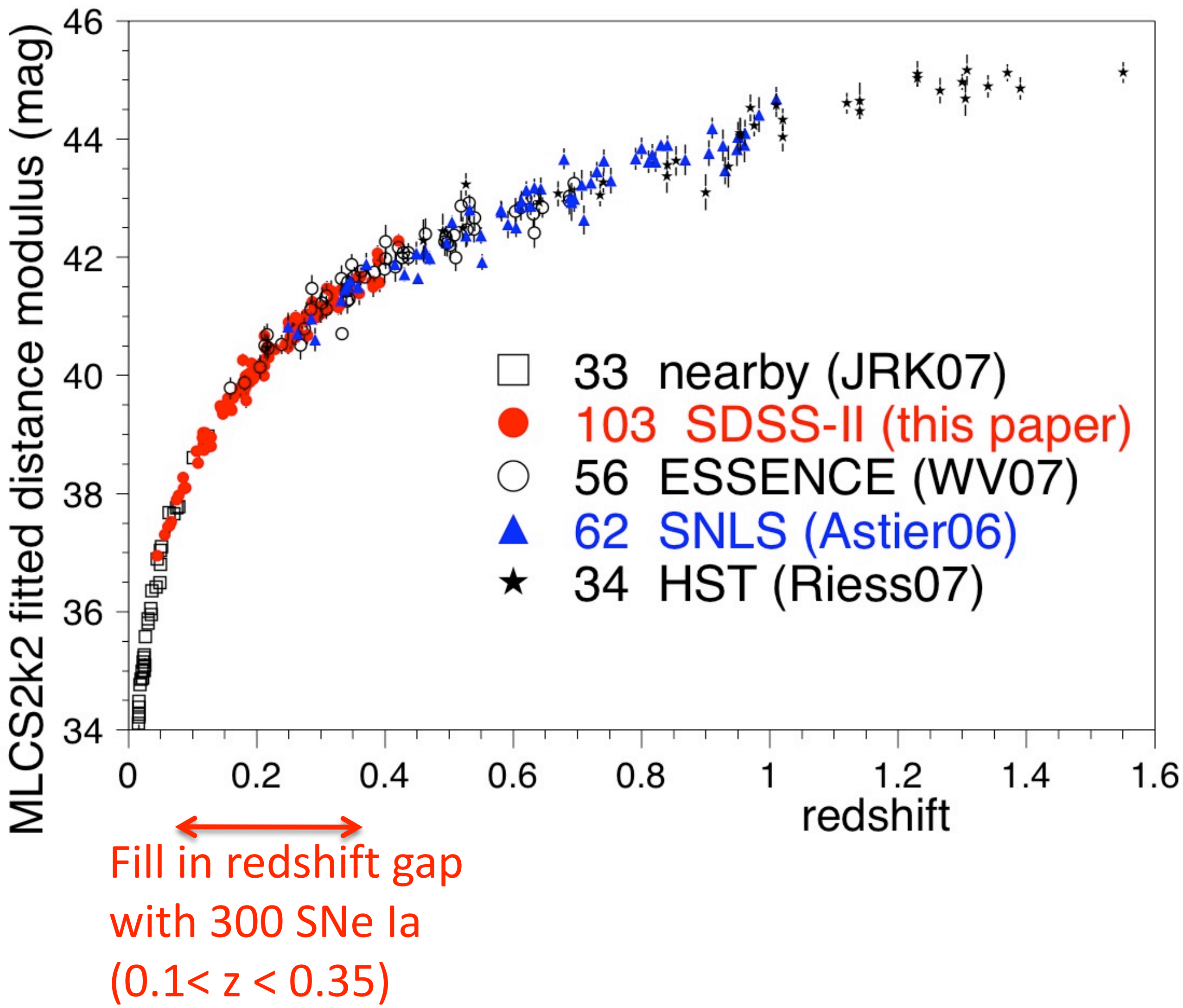
w = −1.05 ± 0.13(stat) ± 0.09(syst)

Largest systematic error is calibration

Also find host-galaxy extinction parameter R_V = 1.8, notably smaller than for Milky Way(R_V=3.1)

Sloan Digital Sky Survey-II

Kessler et. al., ApJS, 185, 32, (2009)



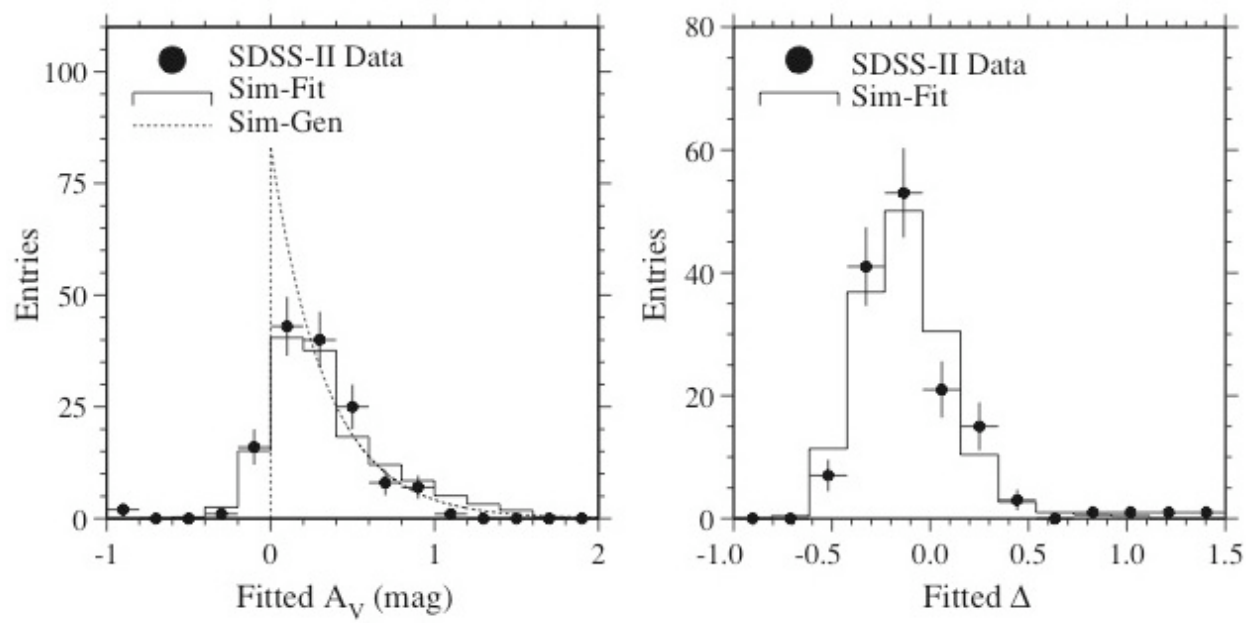
Extensive simulations to determine prior $P(A_V)$ for mlcs2k2.

Compare SALT2 vs. mlcs2k2.

Results are systematics-limited

Sloan Digital Sky Survey-II

For host-galaxy extinction (mlcs2k2), $R_V = 2.2 \pm 0.5$, somewhat lower than for Milky Way (R_V=3.1) and consistent with CSP value.

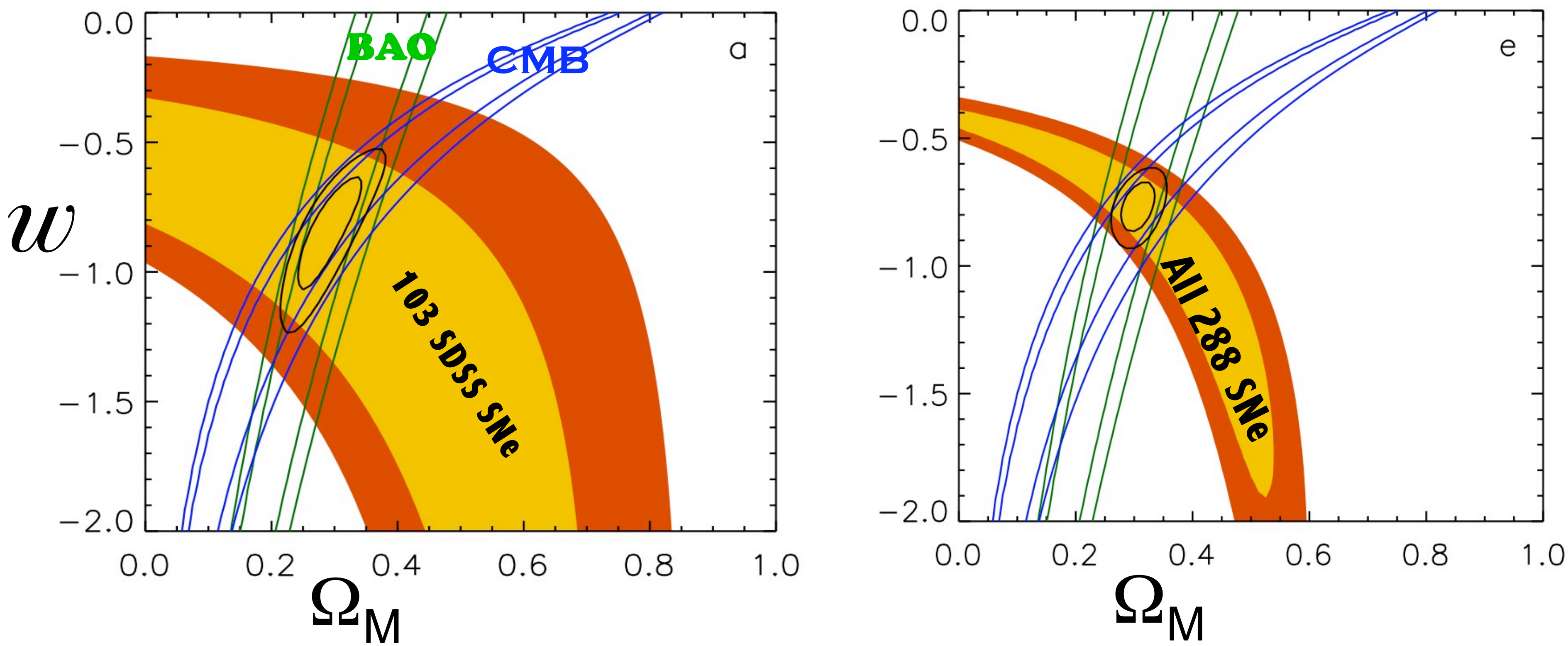


Also measured parent distributions for A_V and Δ
-> part of prior

Cosmology Fit

- Priors: BAO, CMB, flat universe
- Float w and Ω_M

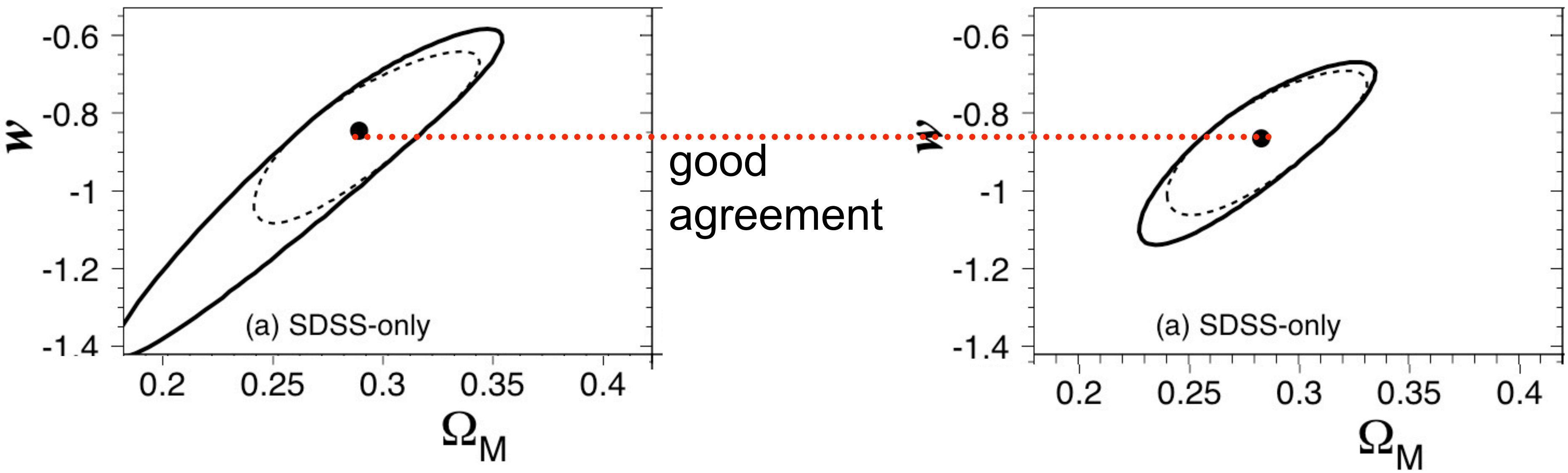
68% + 95% stat-error contours (MLCS)



Results:

— total error
- - stat error

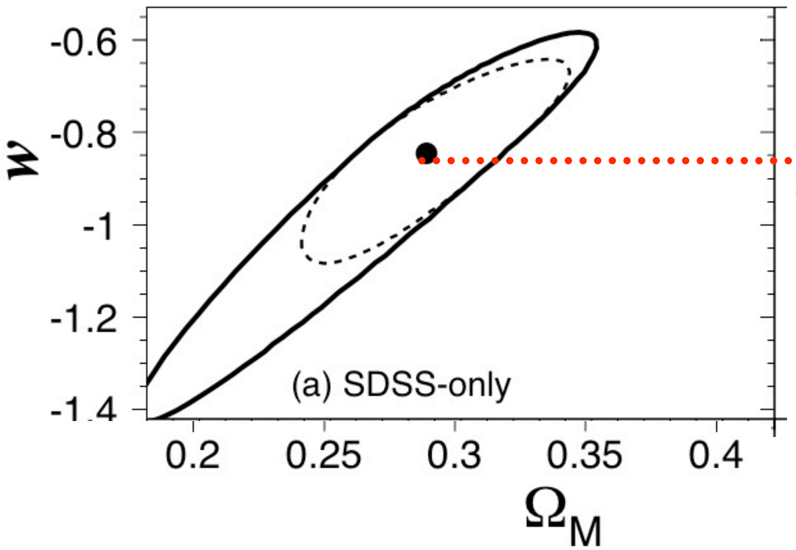
MLCS **SALT-II**



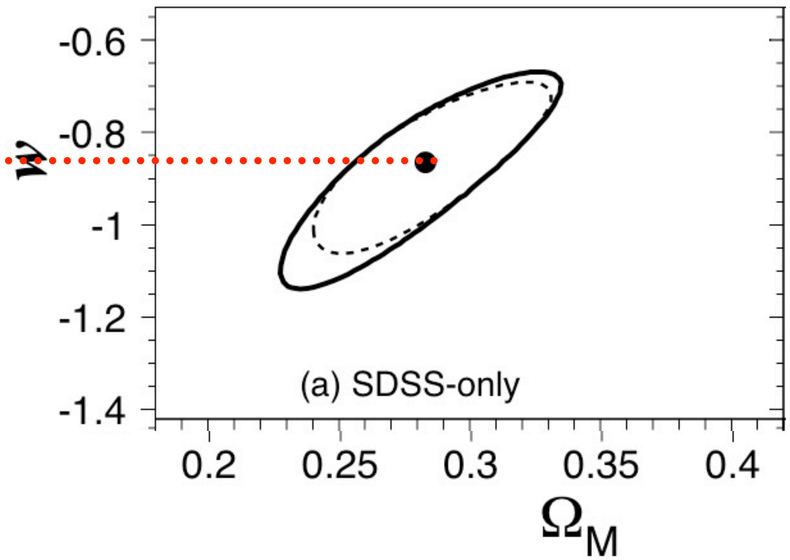
Results:

— total error
- - stat error

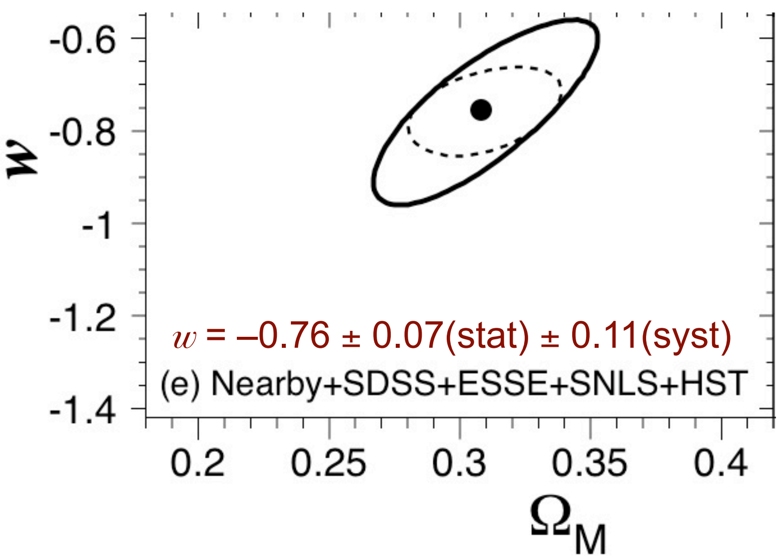
MLCS



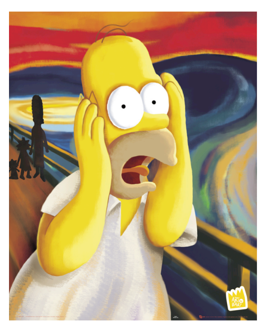
SALT-II

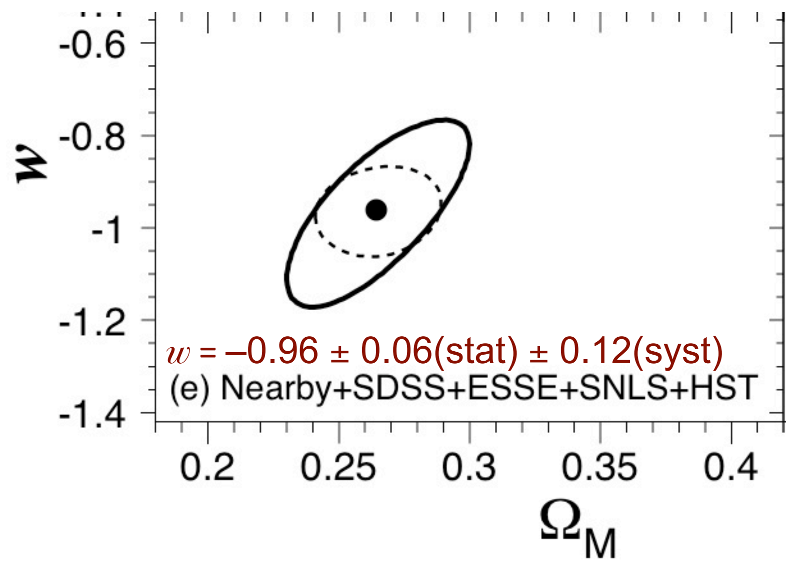


good agreement



Δw ~.2





SALT2-mlcs2k2 Discrepancy

- Discrepancy traced to
  1. model disagreement in UV region
  2. mlcs2k2 prior requiring $A_V > 0$

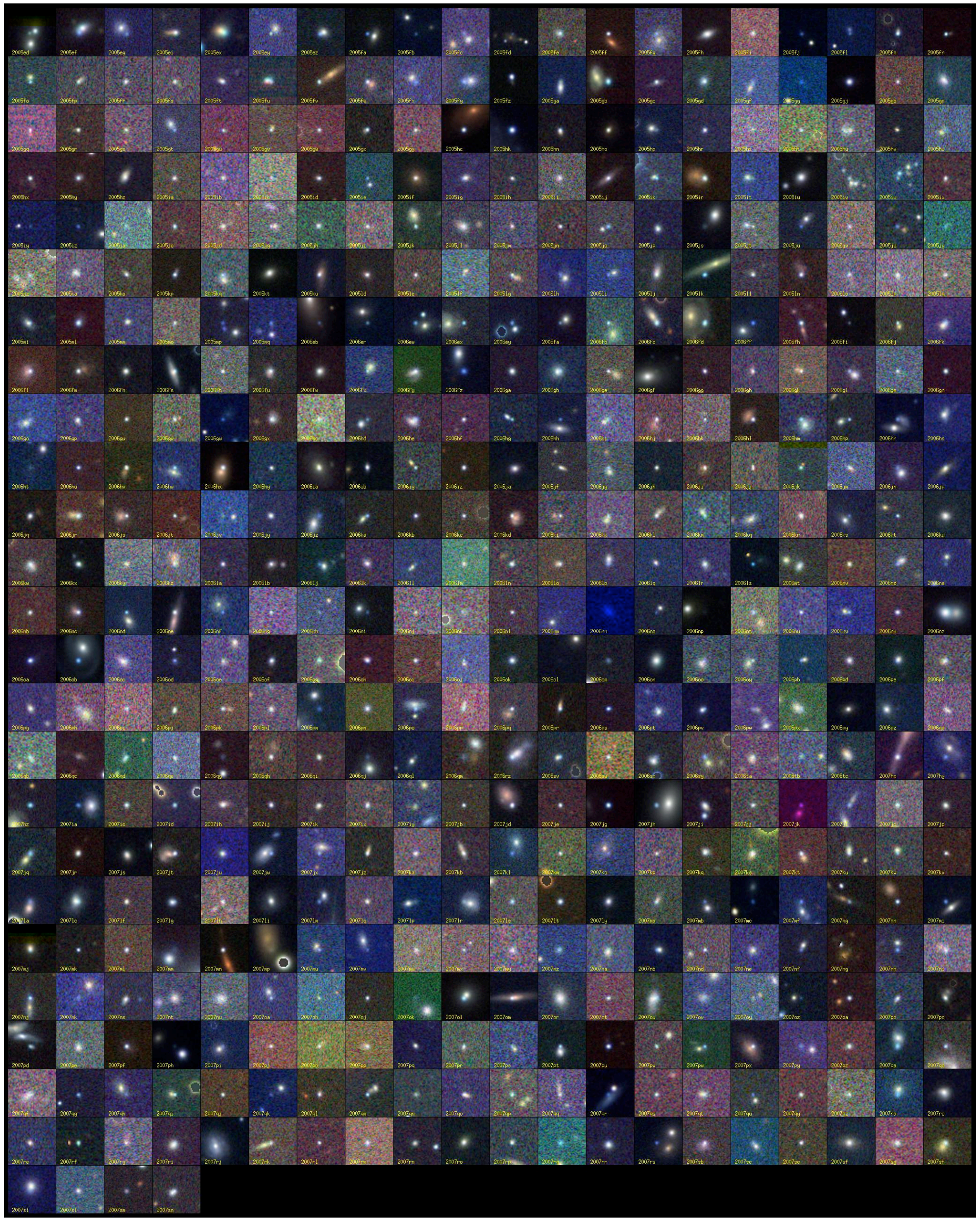
SALT2-mlcs2k2 Discrepancy

- Discrepancy traced to
  1. model disagreement in UV region
  2. mlcs2k2 prior requiring $A_V > 0$

• mlcs2k2 UV region trained only with observer-frame U band at low redshift
-> difficult calibration

* SALT2 UV region trained with multiple observer-frame bands at higher redshift
-> less sensitive to U band calibration issues.

Artistic Results from SDSS SN

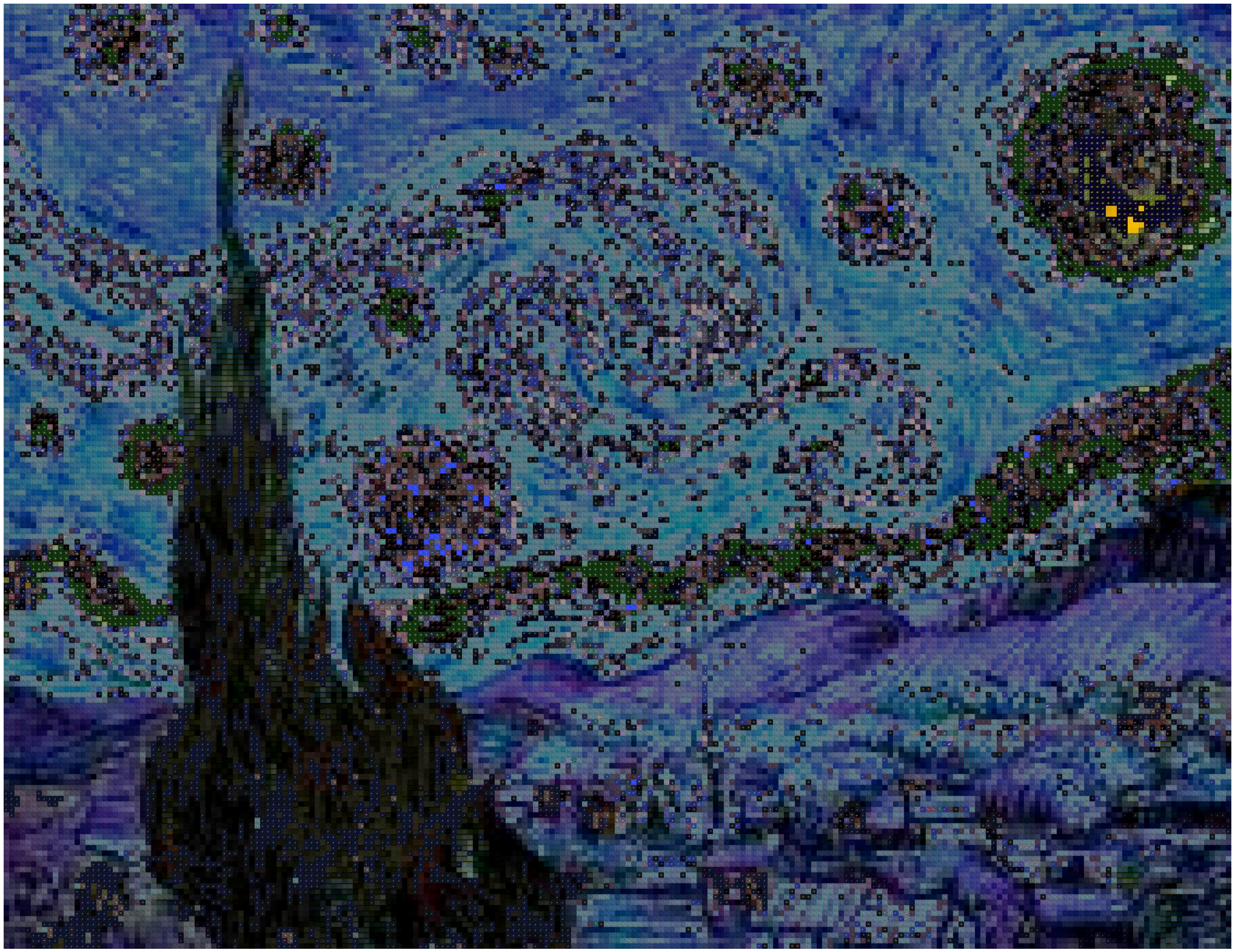


SDSS SN Gallery
created by grad-student
B. Dilday for AAS 2005 poster.

Image has appeared in

- National Geographic (Mar 2007)
- Hoshi Navi
  (Japanese astro magazine)
- AAS Calendars 2006
- Chemistry , 5th Edition ??

Artistic Results from SDSS SN



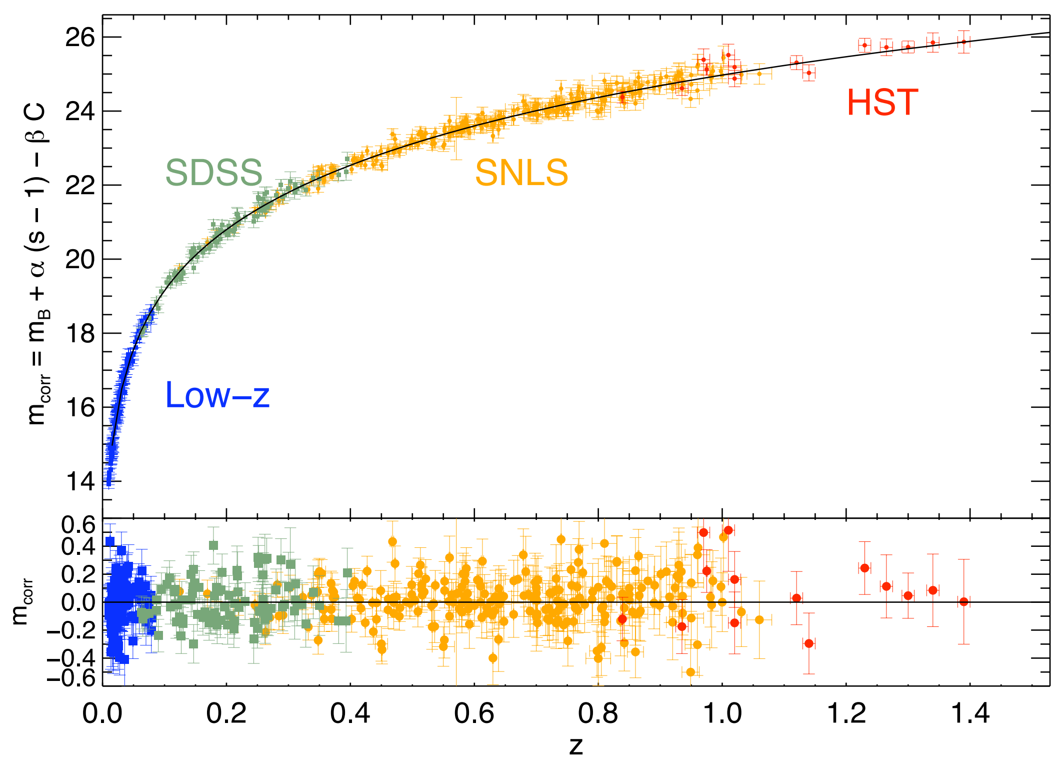
This one didn't sell.

SNLS3 SuperNova Legacy Survey

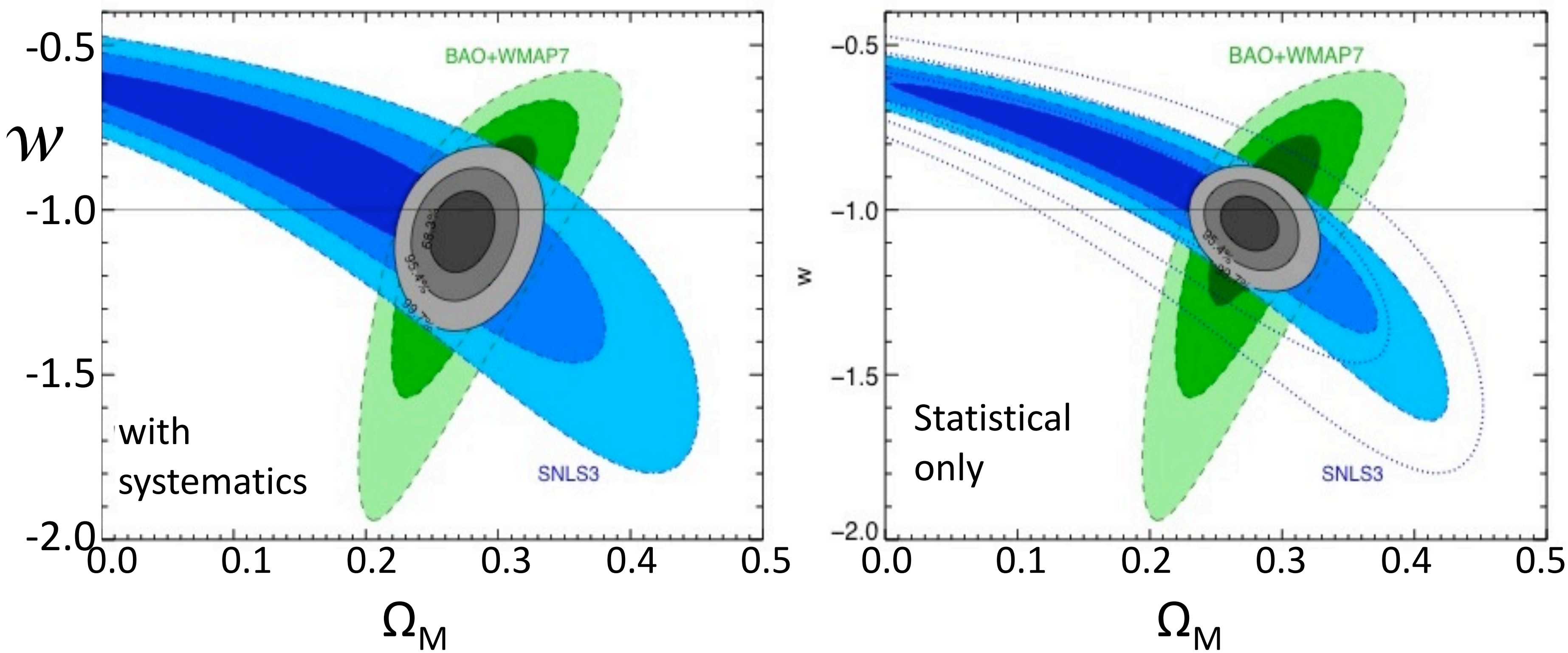
3-season results

Regnault et al., A&A 506, 999 (2009)
Guy et. al., A&A 523, 7 (2010),
Conley et. al., ApJS, 192, 1(2011)
Sullivan et. al., ApJ 737, 102 (2011)

- 472 SN (half from SNLS)
- 4 major publications to describe analysis and results
- Systematic uncertainty dominated by calibration



SNLS3 SuperNova Legacy Survey



$$w = -1.068 \pm 0.055(\text{stat}) \pm 0.060(\text{syst})$$

SNLS3 SuperNova Legacy Survey

New features in this analysis:

- Banana contours including systematic uncertainties
- Correction for host-galaxy mass correlation with Hubble residual (as large as total systematic error)
- Peculiar velocity correction allowing relaxed redshift cut z > 0.01 for nearby SN (previous cuts z > 0.02 – 0.03)
- Calibration corrects for large (15%) non-uniformity of filter transmissions across MEGACAM focal plane
- Many publicly availably SN Ia discarded due to inadequate calibration.

JLA

Rather than combing data from published papers, **SDSS & SNLS** are collaborating to share data, software, and expertise in a joint collaboration.

Three ‘***systematics***’ papers in preparation …

Calibration
(Lect. 4, slide 23)

Potential biases from SALT2 training: based on simulations of photometry + spectra (Lect. 3, slide 13)

←

Models of intrinsic brightness variations in SNIa