Constraint on the Cosmological Constant Parameter from Type Ia Supernovae Survey

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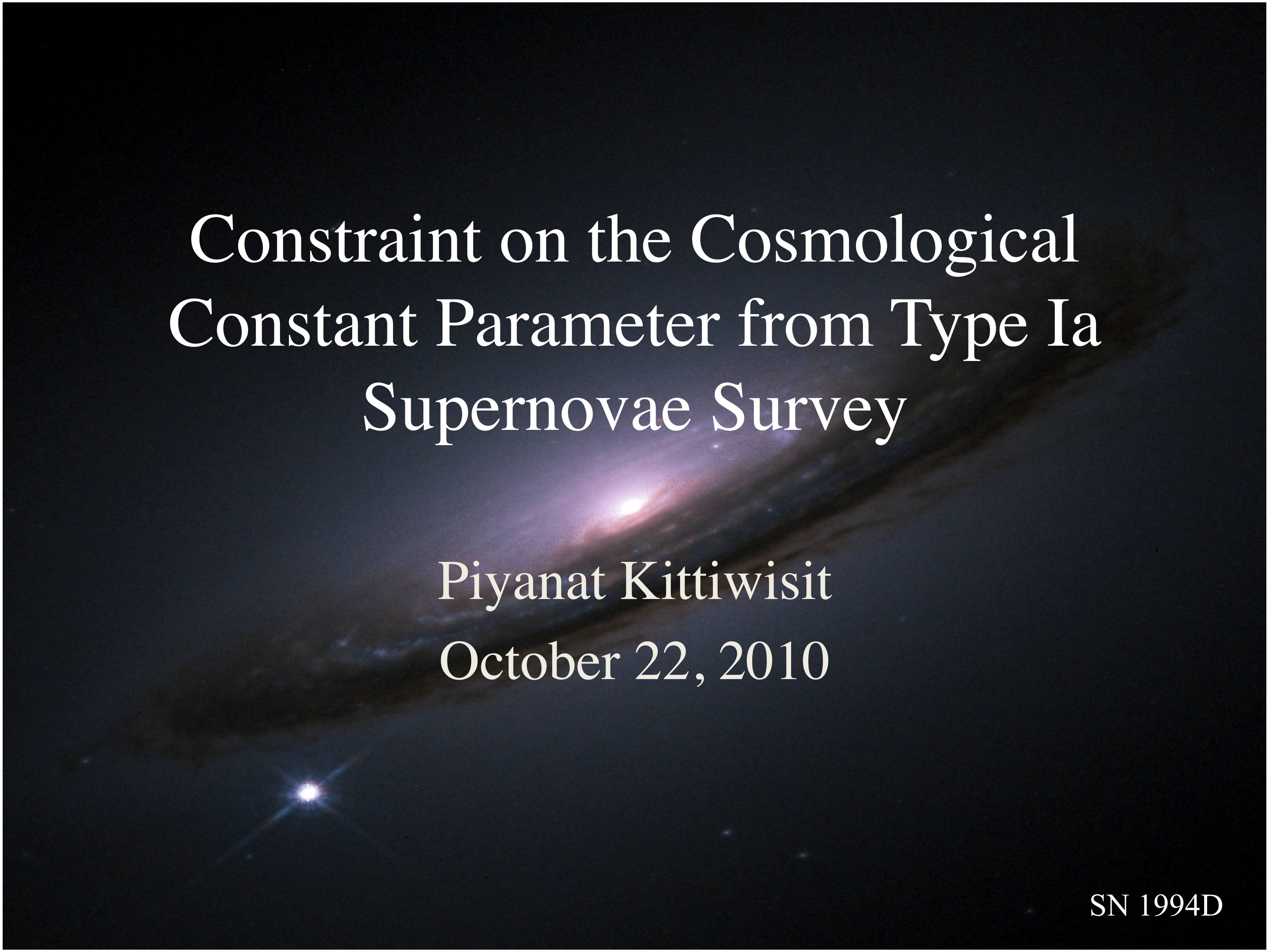
October 22, 2010

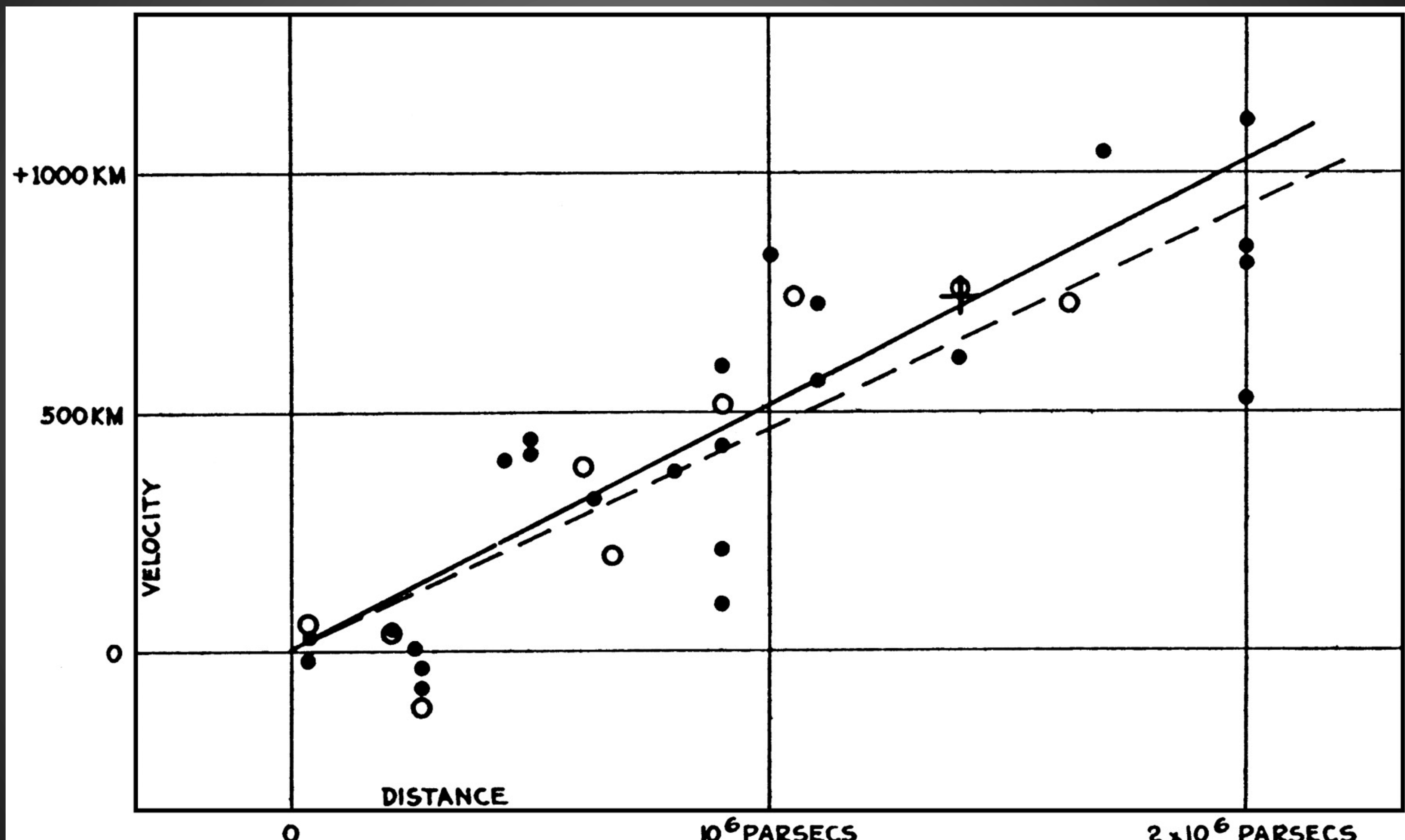


SN 1994D

Outline

- Expansion of the Universe
  - Hubble Diagram
  - Riess, A 1998
- Cosmological Constant
  - Einstein's Lamda
  - Equation of State Parameter
- Type Ia Supernova
- Supernova Search
- Hicken, M 2009
  - Data
  - Lightcurve Fitting
  - Result & Error Discussion
- Future

Expansion of the Universe



Kirshner R P PNAS 2004;101:8-13

Accelerating Expansion

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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ABSTRACT

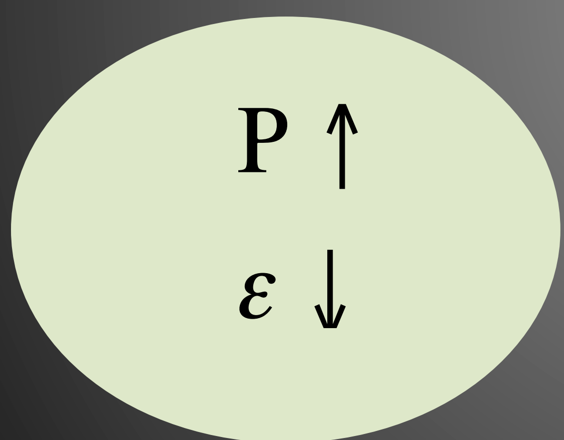
We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior

Cosmological Constant

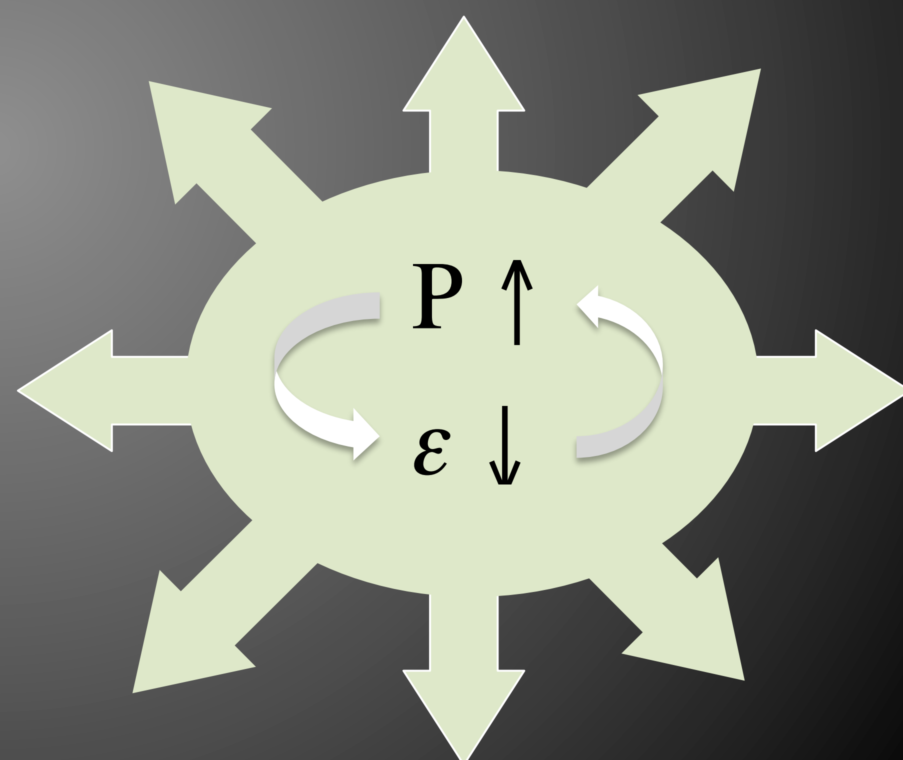
- The Greek letter Λ introduced by Einstein to create a static model of the universe from his theory of general relativity
- Drop out after Hubble shows that the universe is expanding
- Come back again after Riess et al. discovery in 1998!

Cosmological Constant

- Uniformly distributed component of the universe with equation of state $P = \omega\varepsilon = -\varepsilon$



Expanding Universe



Accelerating Expansion

Type Ia Supernovae (SN Ia)

- Supernovae explosion from mass-accreting white dwarf
- Uniform intrinsic luminosity M~19.5

$$\mu = m - M \propto Log(D)$$

- Can be observed at high redshifts (z~1)

Artist's rendition of a white dwarf accumulating mass from a nearby companion star. This type of progenitor system would be considered singly-degenerate.

Image courtesy of David A. Hardy, © David A. Hardy/www.astroart.org.

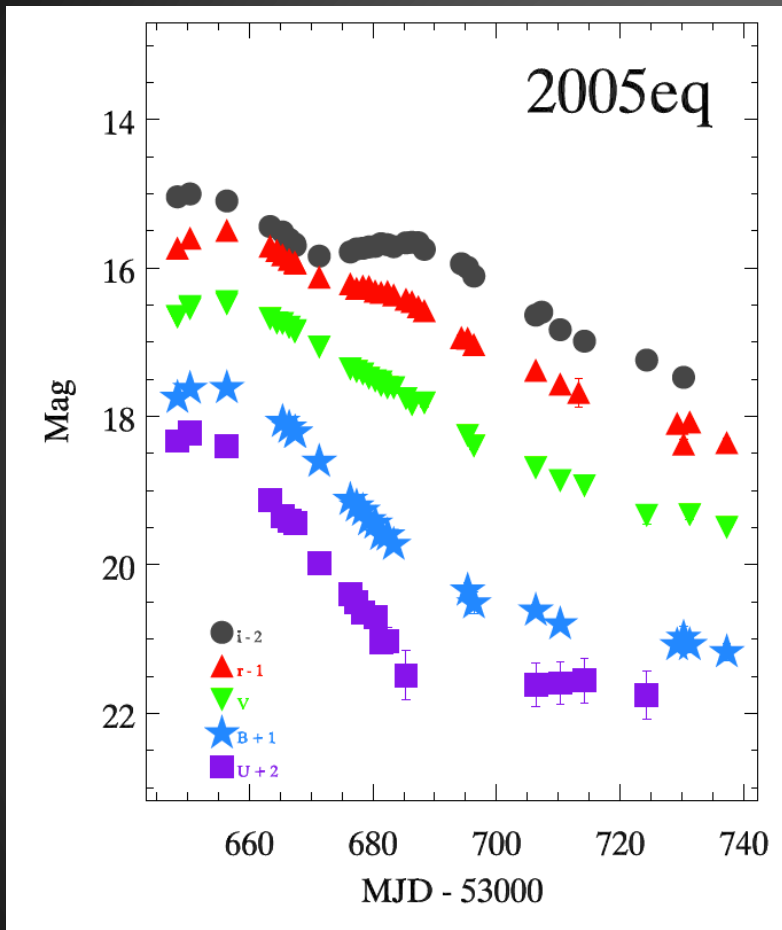
Supernovae Search

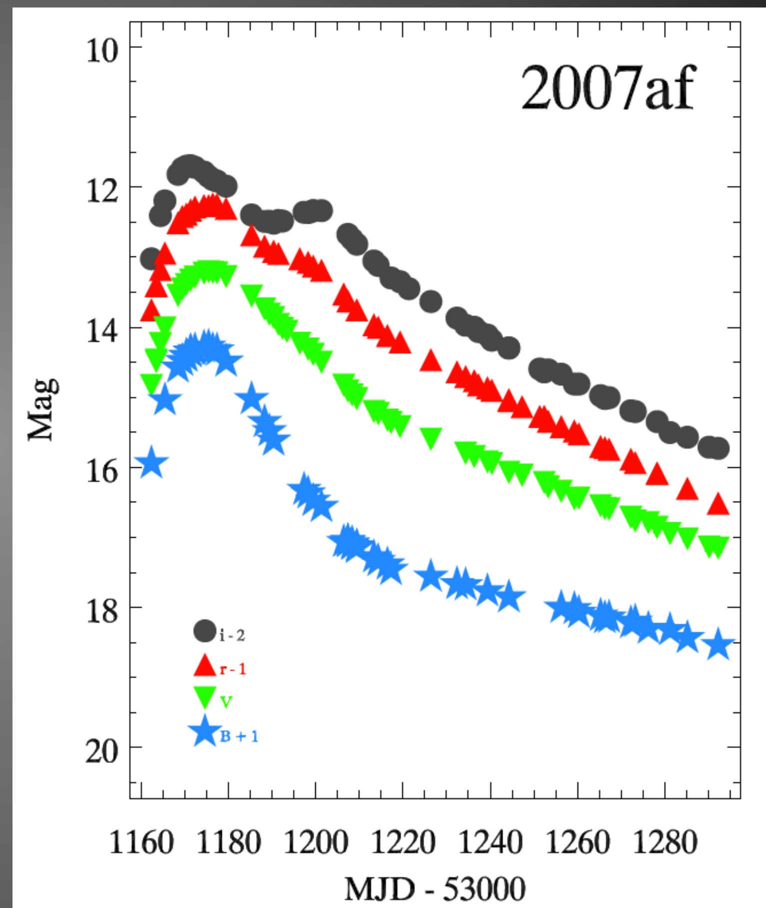
- 2 Main Internationally Collaborate Groups
  - High-z SN Search
  - Supernova Cosmology Project
- Past & Current Projects
  - ESSENCE (Equation of State: SupErNovae trace Cosmic Expansion, Cerro Tololo)
  - SLSN (Supernovae Legacy Survey, Hawaii)
  - SDSS (Apache Point)
  - KAIT (Katzman Automatic Imaging Telescope, Berkeley)
  - Pan-STARS (Panoramic Survey Telescope & Rapid Response System, Hawaii)

Hicken, M et al 2009

- Combine CfA3 sample with sample from Kowalski et al. 2008 to calculate cosmological constant equation of state parameter, w
- Observation
  - From 2001-2008
  - F. L. Whipple Observatory with two 1.2m Telescope on UBVRI or UBVr'I' filters
  - Over 11500 observation
  - End up with 185 useful objects
    - SN phenomena are unpredictable, so you have to observe routinely

Lightcurve

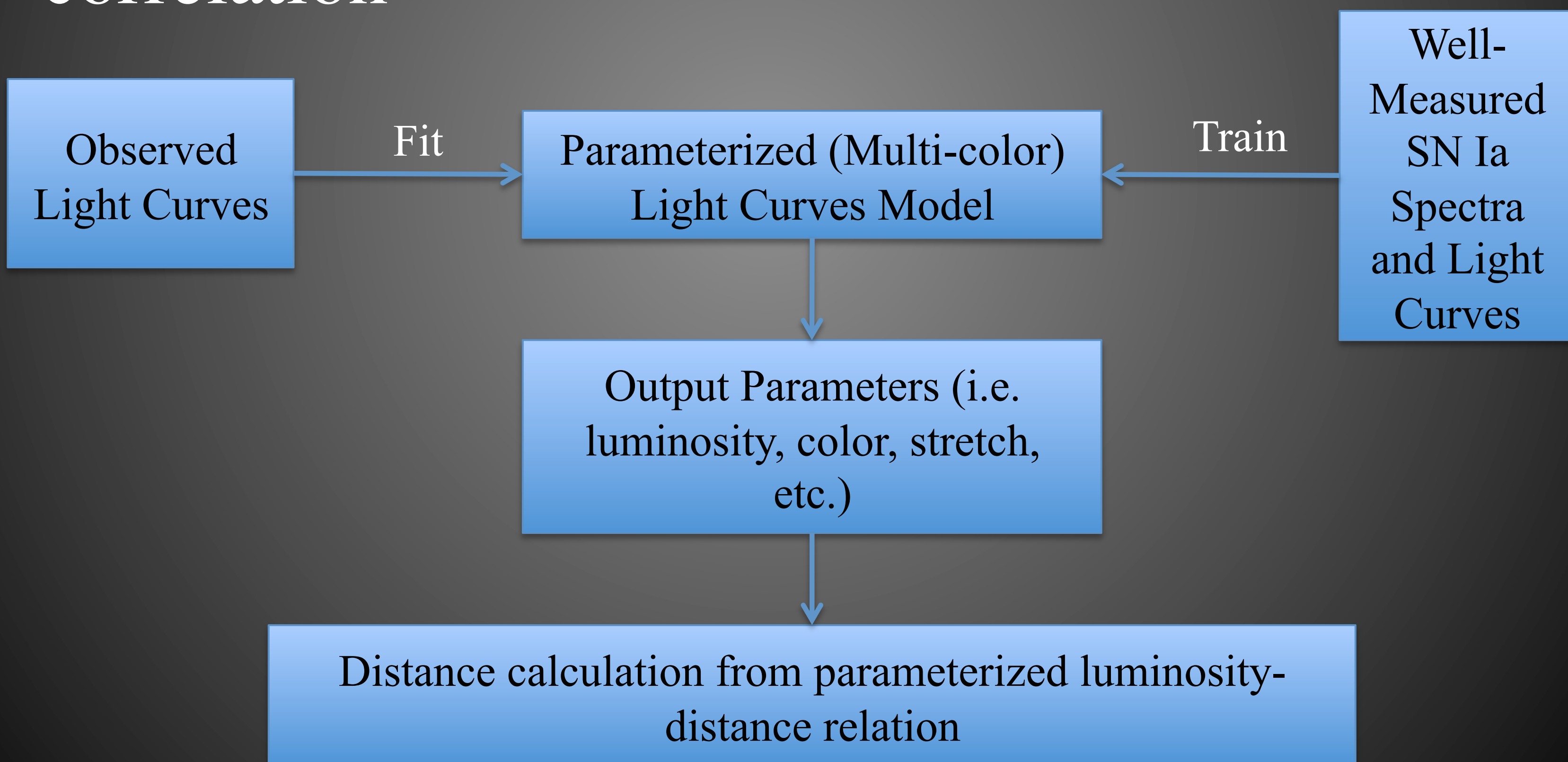




2 better light curves from CfA3 sample. Error bars are smaller than symbols in most case. U + 2, B + 1, V, R/r−1, and I/I−2 have violet, blue, green, red, and black symbols, and are ordered from bottom to top in each plot. (Hicken et al 2009a)

Getting Distance

- Light curve fitting – shape, luminosity correlation



Getting Distance

- SALT, SALT2 : Spectral Adaptive Light Curve Template (Guy et al. 2005, 2007)
  - SALT use spectral template developed by Nugent et al. to reproduce UBVR light curves
  - No SN-1991bg-like objects (Strong Ti II lines)
  - Fit for
    - Time of B-band maximum light, t_0
    - Time stretch factor, s
    - Color parameter, $c = (B\text{-}V)|_{t=Bmax}+0.057$ (host-galaxy dust reddening)
  - Get distance from parameterized distance-luminosity relation

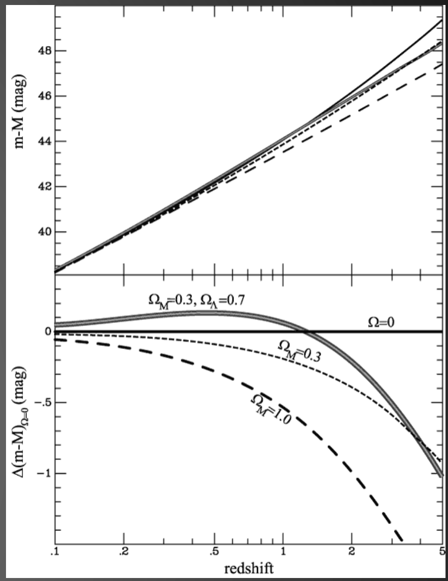
$$\mu_B = m_B^{\max} - M + \alpha(s-1) - \beta c$$

  - SALT2 use spectrum derived from the sample of nearby and faraway SN Ia spectra and light curves

Getting Distance

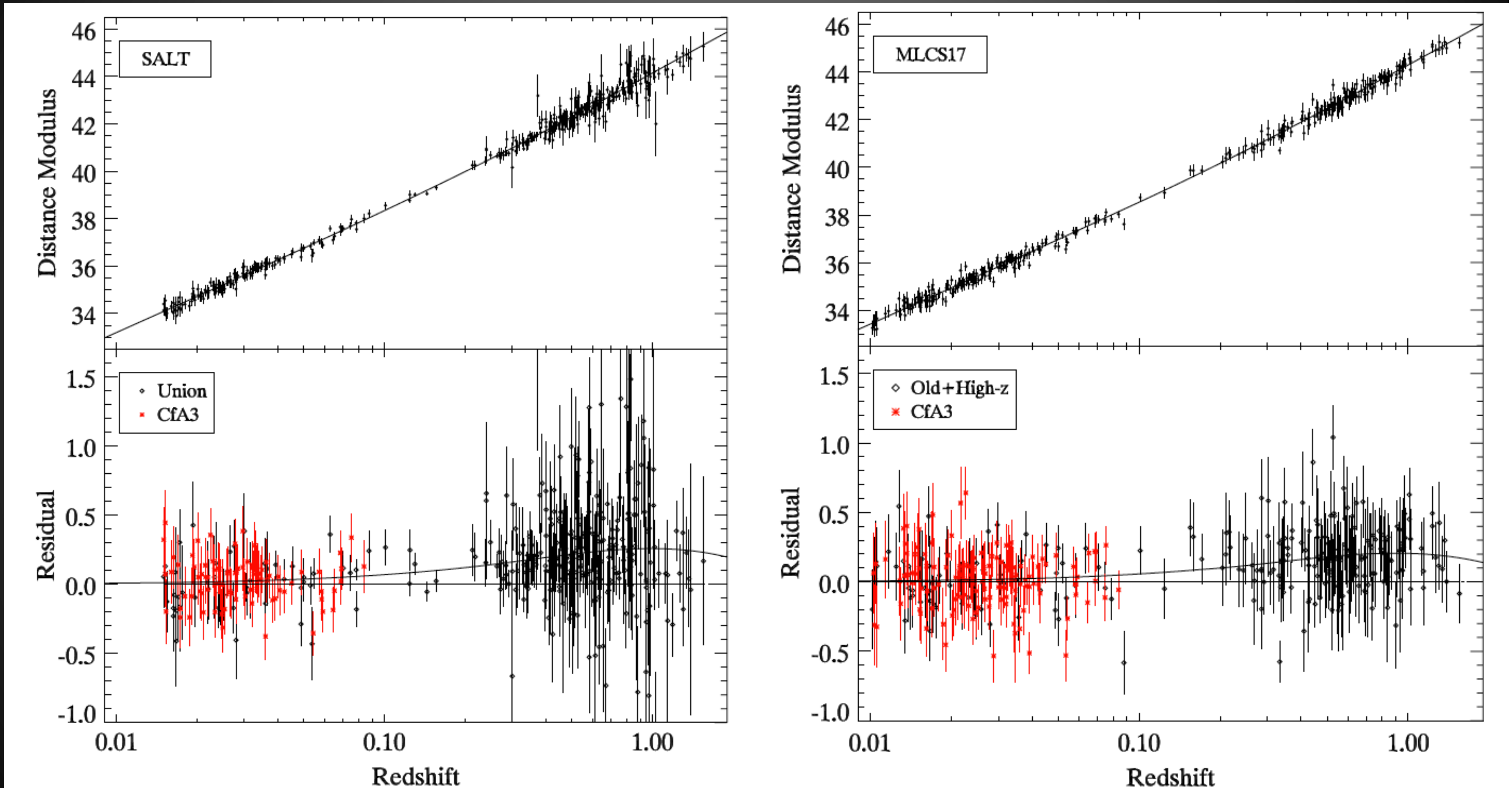
- Light curve fitting – shape, luminosity correlation.
  - MLCS2k2 : Multicolor Light-curve Shapes (Jha et al. 2003, 2005, Riess et al. 1996, 1998)
    - Fit based on multiple color rather than distance-independent parameters
    - Δ – luminosity correction parameter
    - Allow dust extinction, A_v
  - There are many others …
    - Δm_{15} relation B band decline in the first 15 days (Phillips 1993, Hamuy et al. 1996, Phillips et al. 1999)
    - Stretch (Perlmutter et al. 1997, 1999, Goldhaber et al. 2001)
    - MAGIC (Wang et al. 2003)

Result and Error



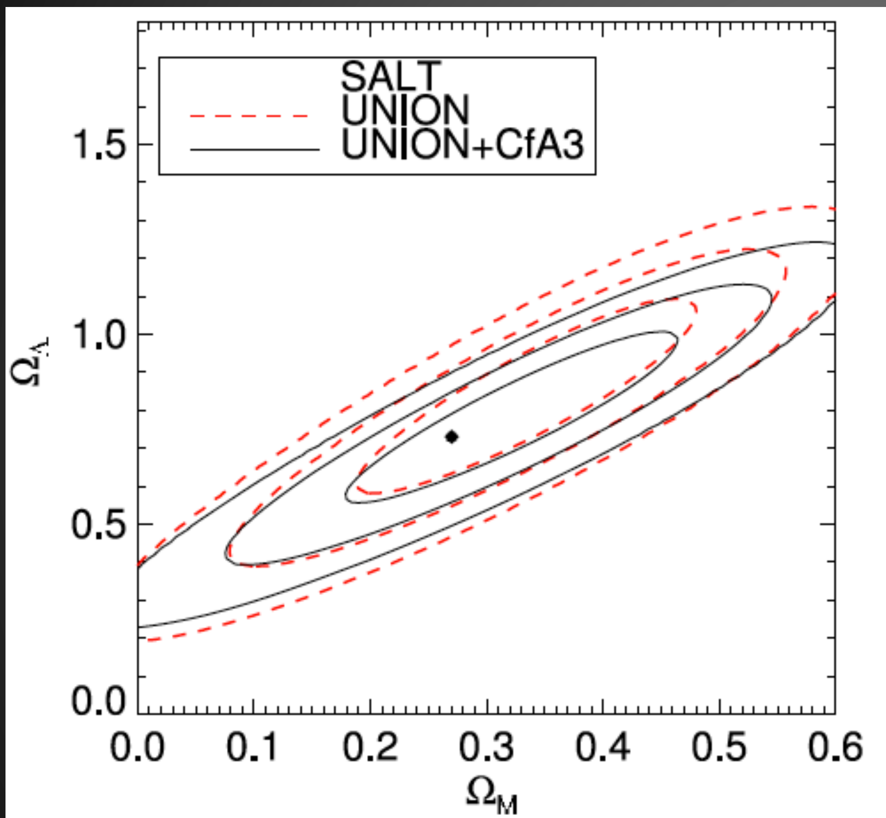
- The most (boring) and tedious part.
- Cosmology model (Ω_M, Ω_Λ, w)
- Check for uncertainty from
  1. Consistency of the four fitters
  2. Find the best cuts
  3. Error from Hubble bubble – difference of H_0 in space
  4. Host-galaxies morphology dependency

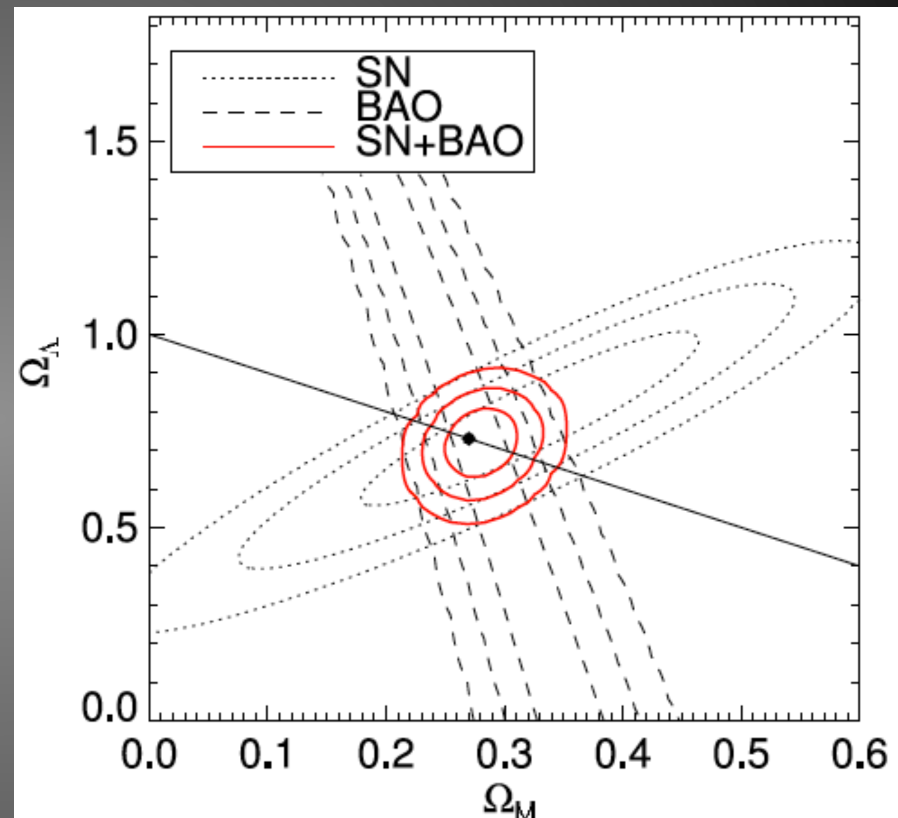
Cosmology Model



Top: w.r.t. $\Omega_M = 0.27$, $\Omega_\Lambda = 0$. Bottom: with best-fit cosmology model. SALT has more scatter at high z.

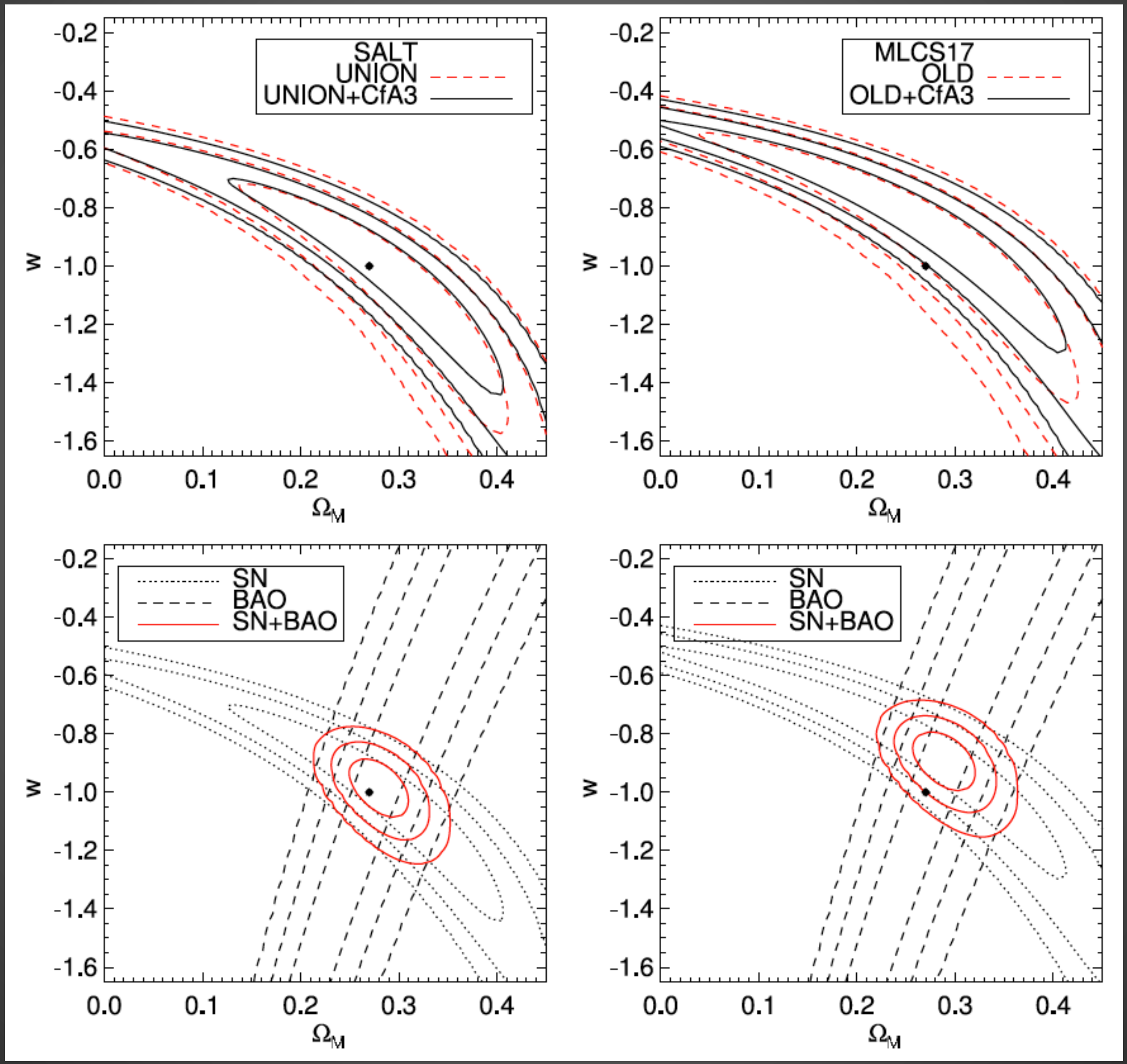
Cosmology Model





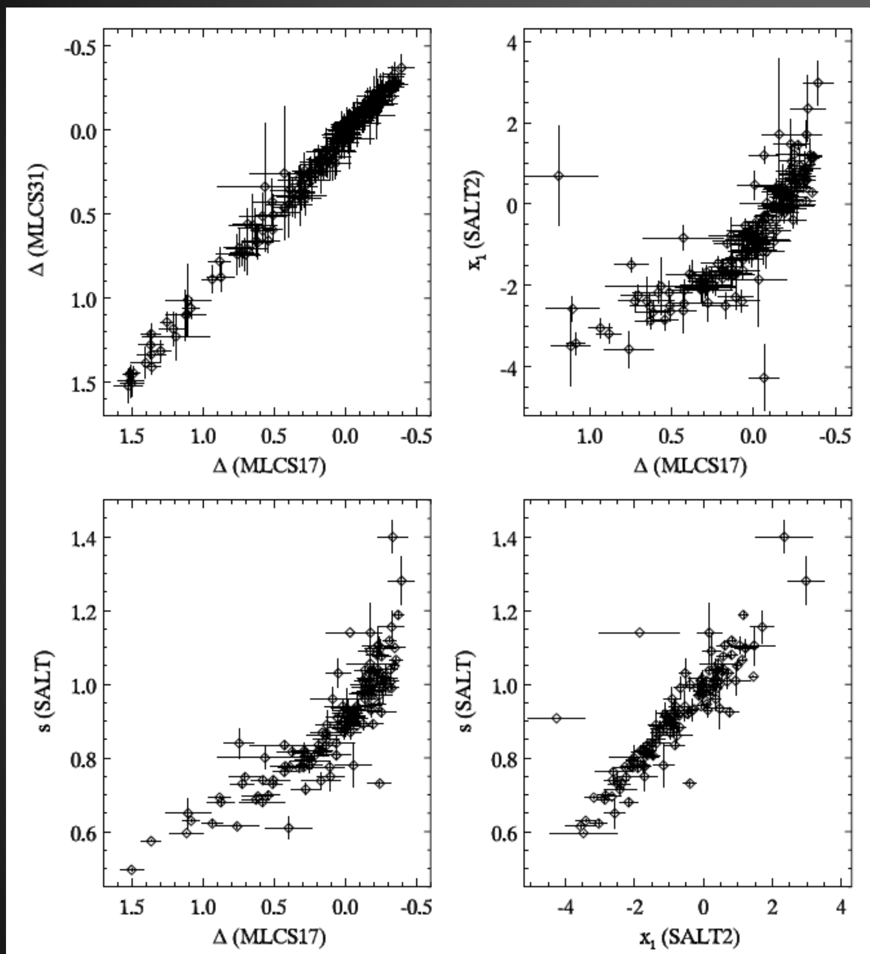
$1 + w = 0$. Adding CfA3 narrows contour along Ω_Λ.
Black dot show $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$.

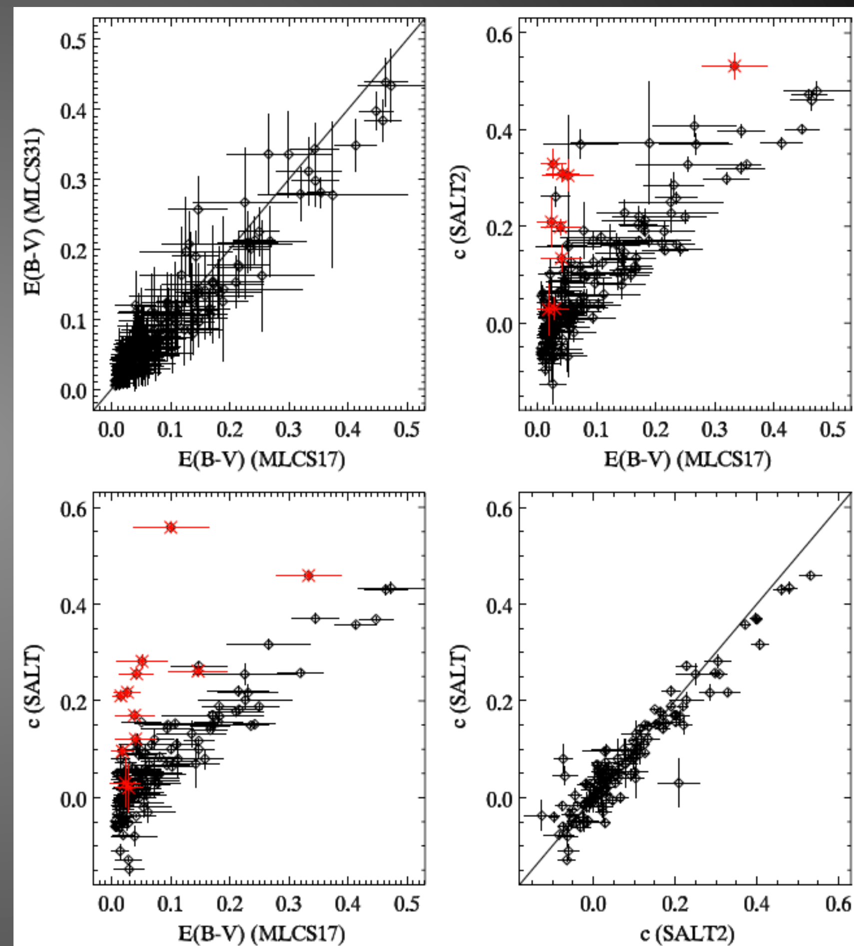
Cosmology Model



Black dot show w = -1, $\Omega_M = 0.27$, $\Omega_\Lambda = 0$

Fitter Consistency

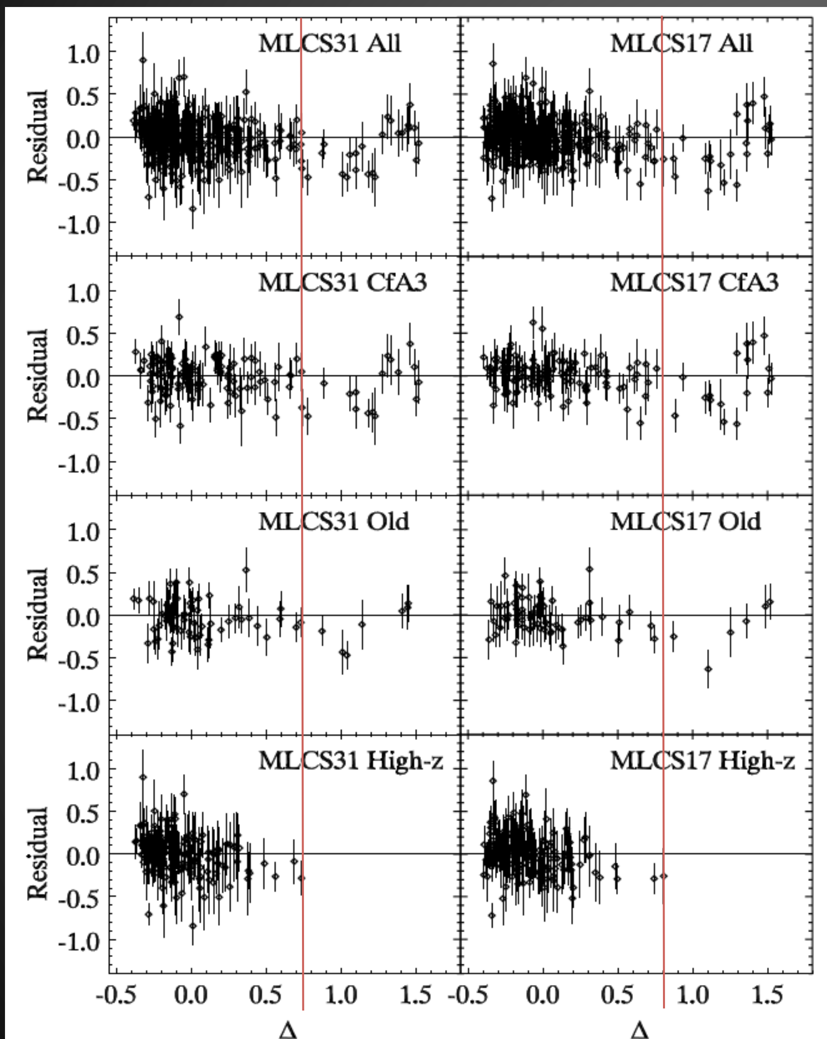


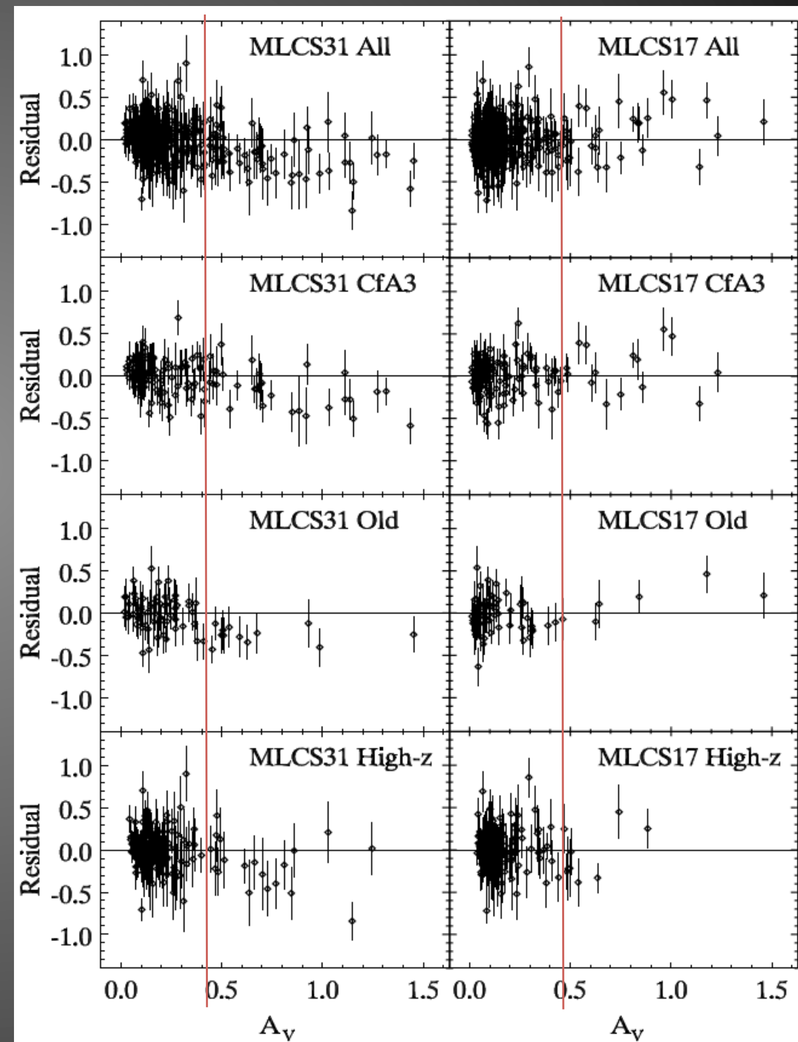


4 on the Left: Light-curve shape parameters. MLCS and SALT agree well

4 on the Right: Color parameters. SALT vs MLSC shows SN Ia that are intrinsically blue but suffer from host-galaxy reddening (bottom left of the plots). Red asterisk are red object.

Best Cuts

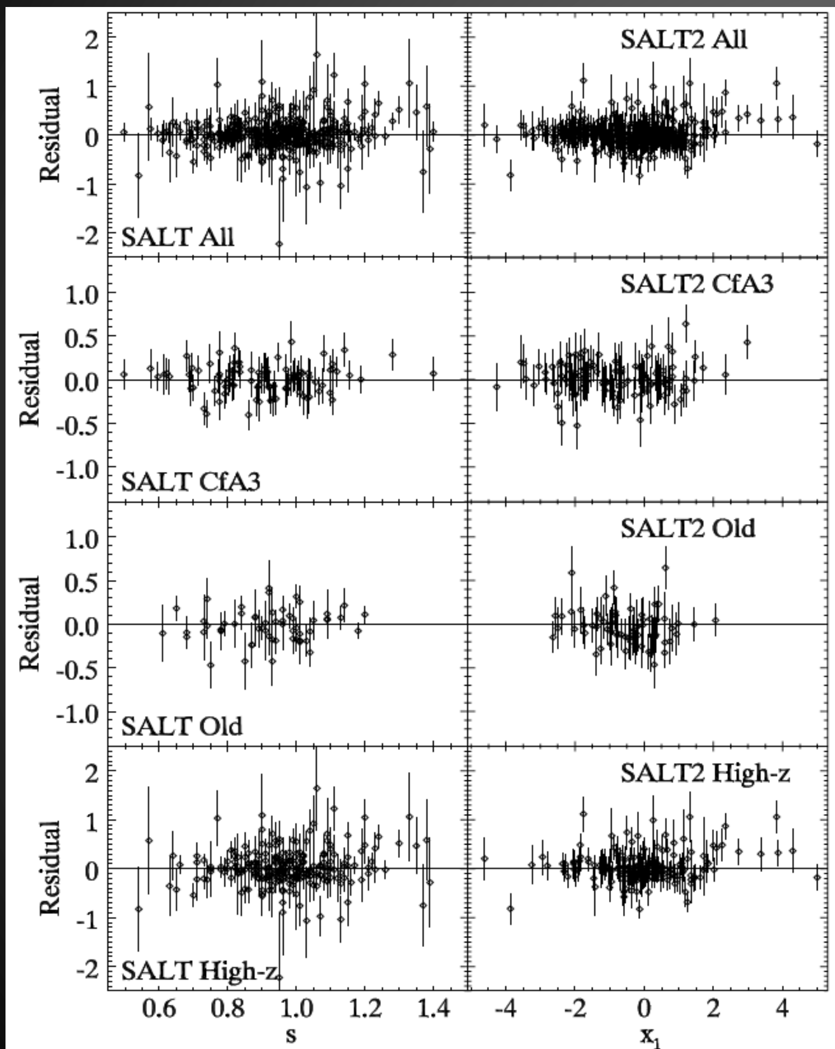


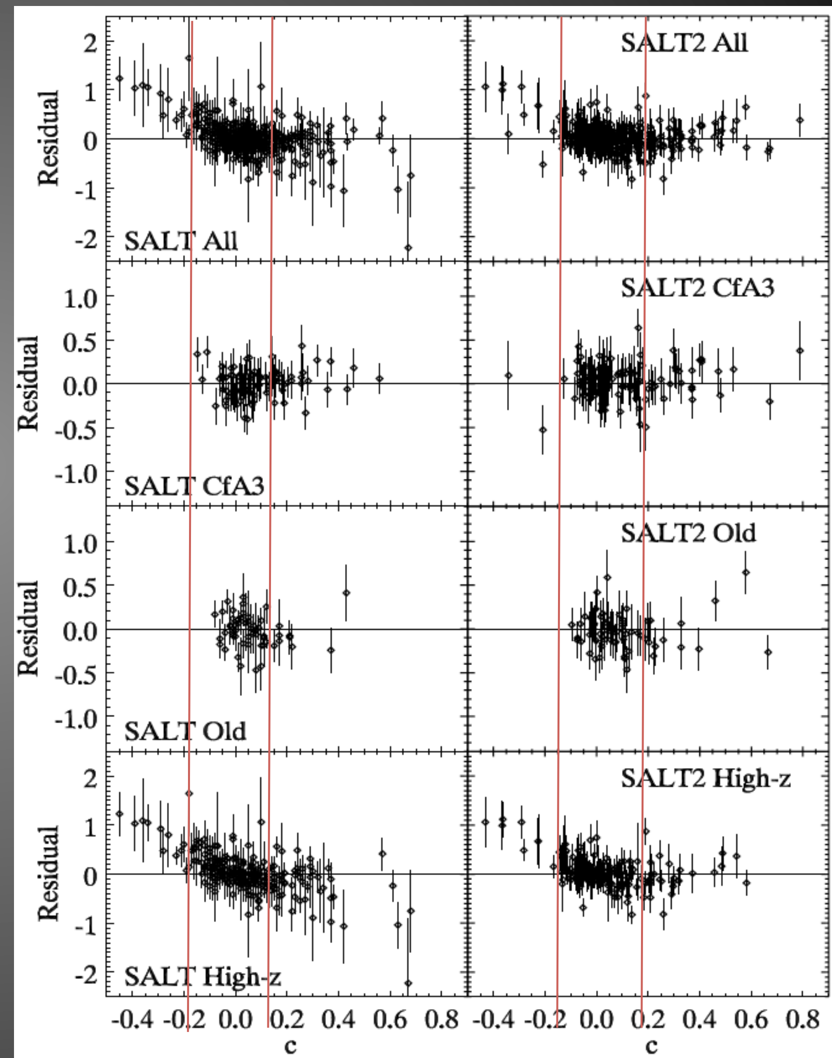


$\Delta \geq 0.7$

$A_v \leq 0.5$

Best Cuts





-0.1 < c < 0.2

Hubble Bubble

- Local void – non-uniform (locally) dark energy (Zehavi et al. 1998)
- Terminology
  - Deviation from Hubbel's Law
    - $u = H_0 d$
    - $\delta H/H = (u_{fit} - u_{light\text{-}curve})/u_{light\text{-}curve}$
  - Void amplitude
    - divide sample into bins based on redshifts and calculate H_0 for the bins
    - $\delta_H = (H_{inner} - H_{outer})/H_{outer}$

Hubble Bubble

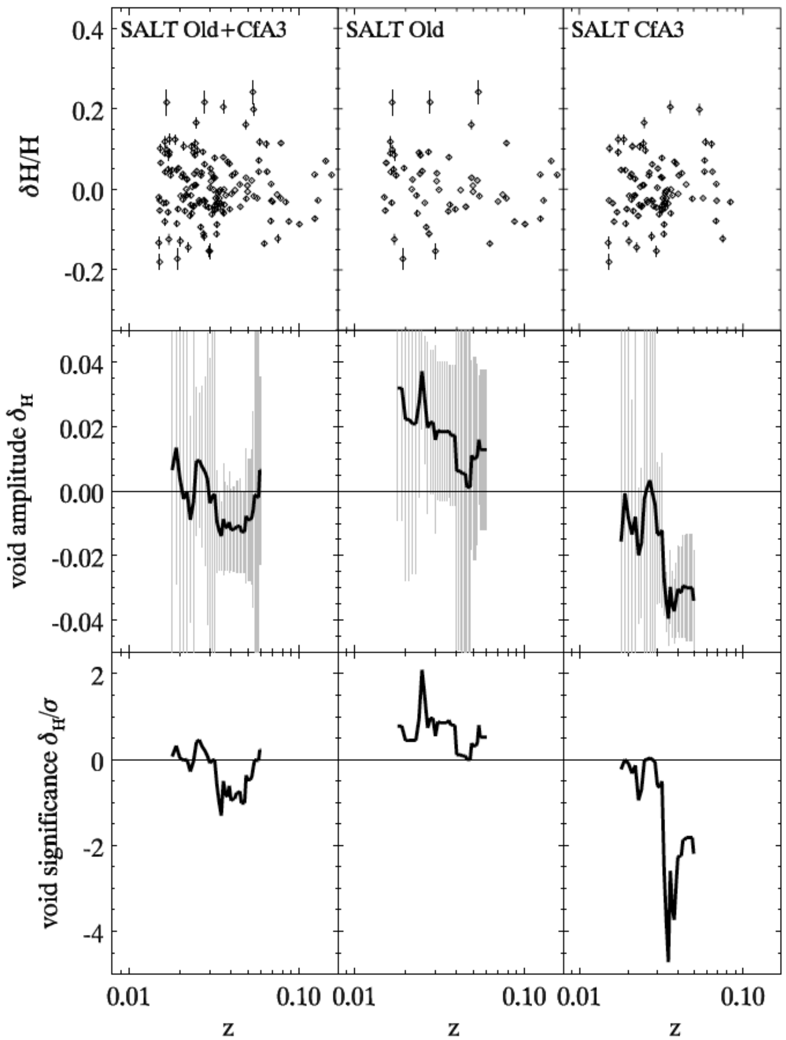


Figure 16. Hubble bubble for SALT. A negative but insignificant Hubble bubble is present in the OLD+CfA3 sample.

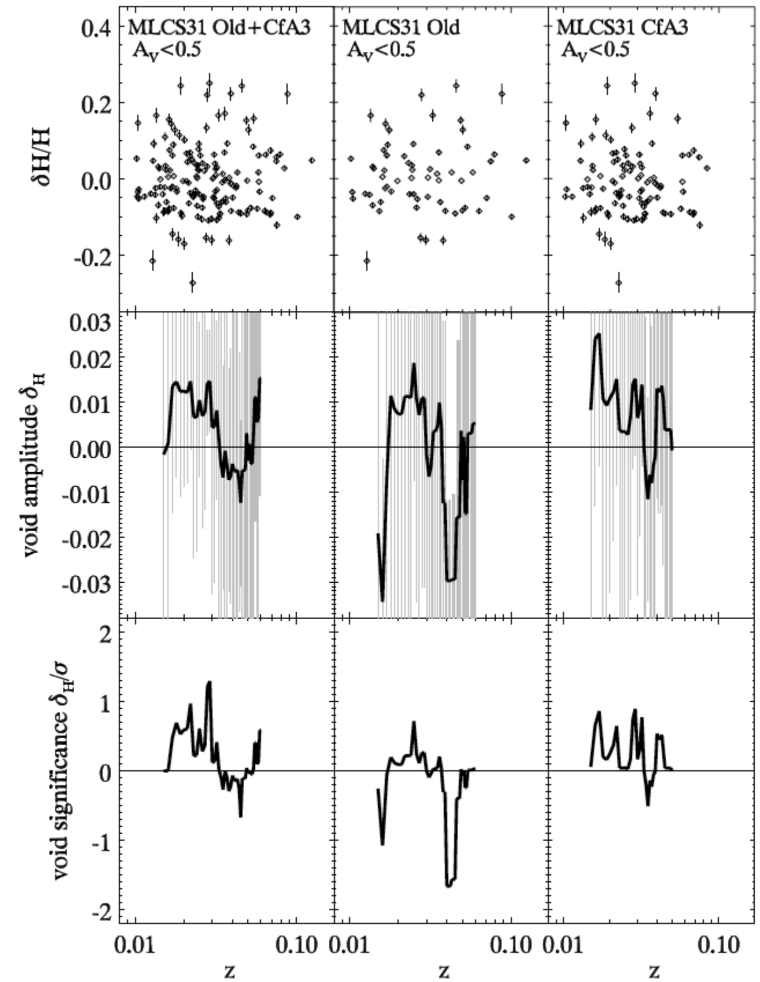


Figure 17. After a cut at $A_V = 0.5$, the positive Hubble bubble for MLCS31 is now insignificant.

Host-galaxies Morphology Effect

Standard Deviation and Weighted Means of Hubble Residuals by Host-Galaxy Morphology

Fitter	Morph	N	StdDev	WMEAN	RelativeWM	σ_{WM}
SALT	E-S0	21	0.170	−0.0641	−0.0712	0.0366
	S0a-Sc	63	0.173	0.0071	0.0	0.0224
	Scd/Sd/Irr	9	0.064	0.0506	0.0435	0.0602
SALT2	E-S0	26	0.208	−0.0686	−0.0490	0.0411
	S0a-Sc	72	0.163	−0.0196	0.0	0.0242
	Scd/Sd/Irr	14	0.108	0.0717	0.0913	0.0560
MLCS31	E-S0	19	0.166	−0.0187	−0.0405	0.0432
	S0a-Sc	59	0.172	0.0218	0.0	0.0234
	Scd/Sd/Irr	9	0.118	0.1367	0.1149	0.0583
MLCS17	E-S0	21	0.186	−0.0521	−0.0537	0.0416
	S0a-Sc	64	0.155	0.0016	0.0	0.0221
	Scd/Sd/Irr	10	0.109	0.1138	0.1122	0.0538
Average	E-S0		0.182		−0.0536	0.0406
	S0a-Sc		0.166		0.0	0.0230
	Scd/Sd/Irr		0.100		0.0905	0.0571
Diff.	Scd-Irr−E-S0				0.1441	0.0701

Notes. For these results, SN Ia with $0.7 < \Delta < 1.2$ and $A_V > 0.5$ have been excluded from MLCS31 and MLCS17. SN Ia with $-0.1 < c < 0.2$ from SALT/2 have been included. N is the number in each bin. Relative WM is the weighted mean relative to the S0a-Sc bin. The Scd/Sd/Irr bin has the smallest average standard deviation while the E-S0 bin has the largest. The mean of Hubble residuals of the Scd/Sd/Irr hosts is greater by 2σ than that of the E-S0 bin.

Conclusion

- Old+CfA3 sample gives $1+w=0.013^{+0.066}_{-0.068}$, improving systematic error by ~20%.
- The four fitters are relatively consistent, but there is still room to improve for reducing systematic error.
- Applying different fitters on Old+CfA3 data lead to consistent 1+w, but the best cuts, $-0.1 < c < 0.2$ for SALT, and $A_v \leq 0.5$ and $\Delta \geq 0.7$ for MLCS, are applied.
- Negligible Hubble bubble effect
- SN Ia in Scd/Sd/Irr host-galaxies are fainter than in E/S0 host-galaxies, suggesting that they are from different population.
- Systematic uncertainties are the largest uncertainty.
  - Need to improve photometry.
  - Fitter that can better take care of reddening by dust and effect from host-galaxies population.

Future

- WFIRST will observe 2000+ SN Ia with $0.3 < z < 1.7$
- LSST will find $\sim 10^5$ SN Ia with $z < 0.7$
- JWST will be able to study SN Ia beyond $z \approx 2$
- But … what will come after we finally measure $1+w = 0.000000000000000000$….?

Question?