Science of the Dark Energy Survey

Josh Frieman

Fermilab and the University of Chicago

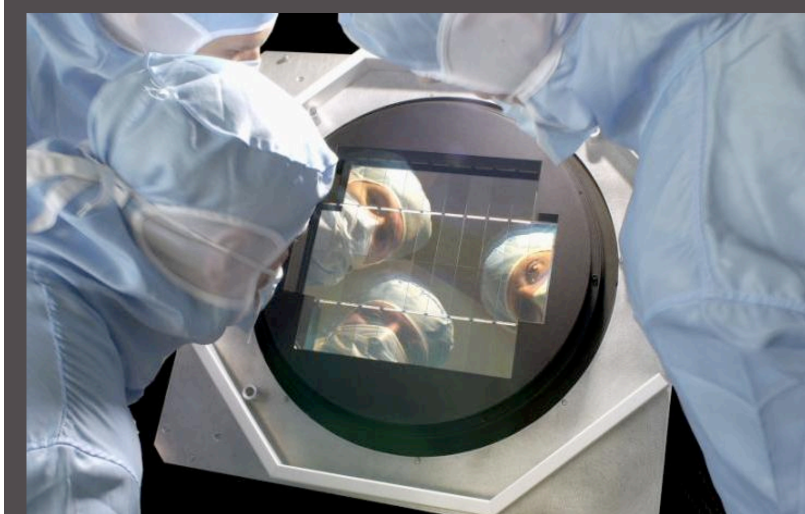
Astronomy 41100
Lecture 3, Oct. 29, 2010

1998-2010 SN Ia Synopsis

- Substantial increases in both quantity and quality of SN Ia data: from several tens of relatively poorly sampled light curves to many hundreds of well-sampled, multi-band light curves from rolling surveys
- Extension to previously unexplored redshift ranges: $z>1$ and $0.1<z<0.3$
- Extension to previously underexplored rest-frame wavelengths (Near-infrared)
- Vast increase in spectroscopic data
- Identification of SN Ia subpopulations (host galaxies)
- Entered the systematic error-dominated regime, but with pathways to reduce systematic errors

Supernova Legacy Survey (2003-2008)

- Observed 2 1-sq deg regions every 4 nights
- ~400+ spectroscopically confirmed SNe Ia to measure *w*
- Used 3.6-meter CFHT/“Megacam”
- 36 CCDs with good blue response
- 4 filters *griz* for good K-corrections and color measurement
- Spectroscopic follow-up on 8-10m telescopes



Megaprime Mosaic CCD camera

Spectra

SN Identification

Redshifts

VLT

120 hr/yr: France/UK
FORS 1&2 for types, redshifts

Magellan

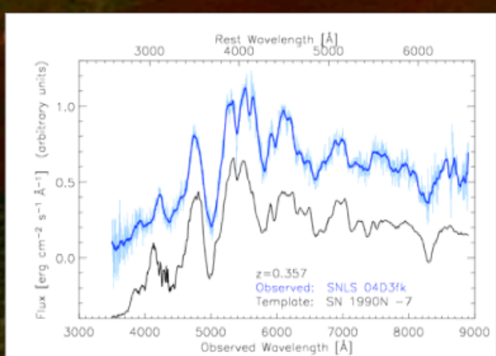
3 nights/yr: Toronto
IMACS for host redshifts

Gemini

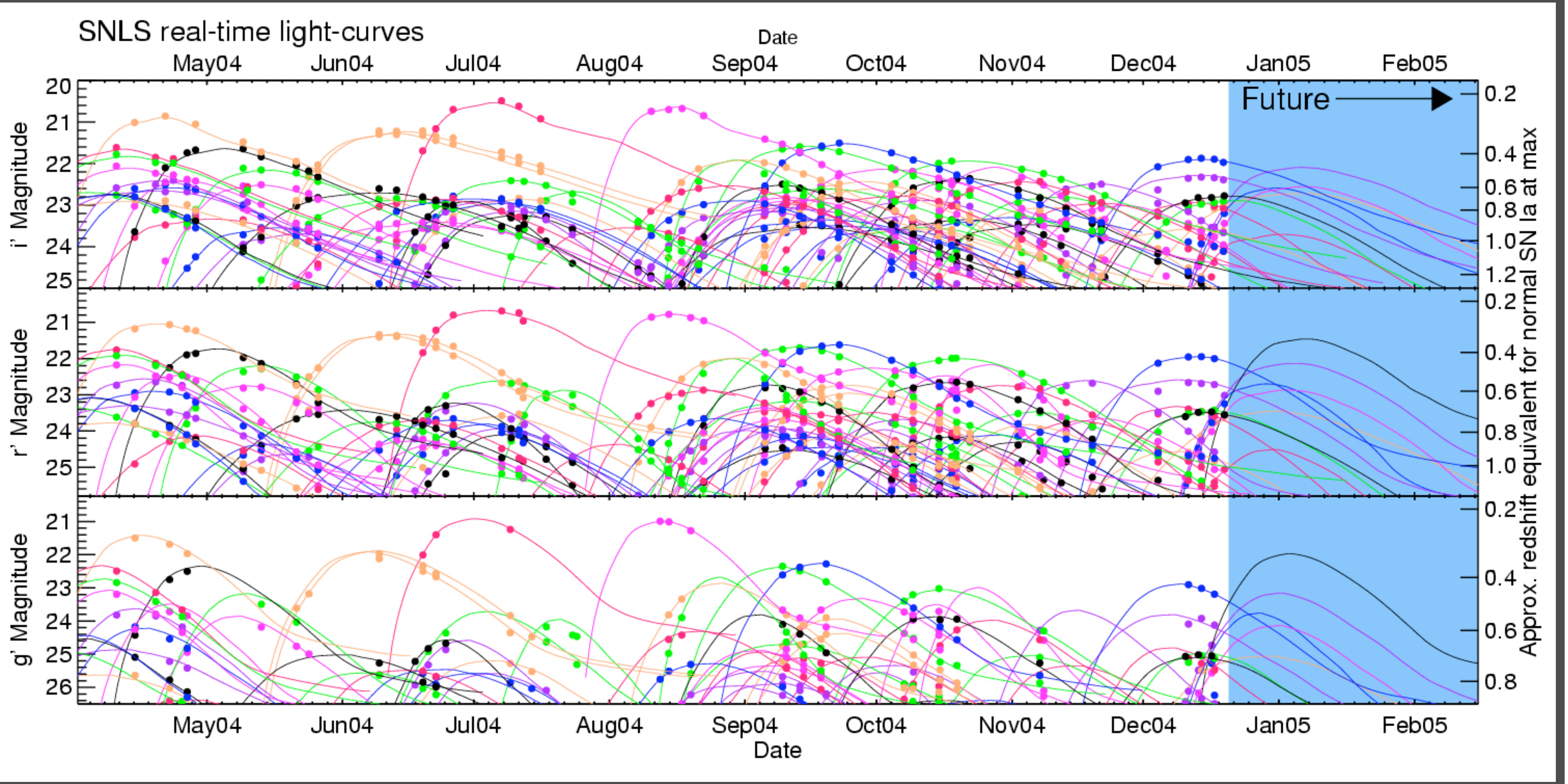
120 hr/yr: Canada/US/ UK
GMOS for types, redshifts

Keck

8 nights/yr: LBL/Caltech
DEIMOS/LRIS for types, intensive study, cosmology with SNe II-P

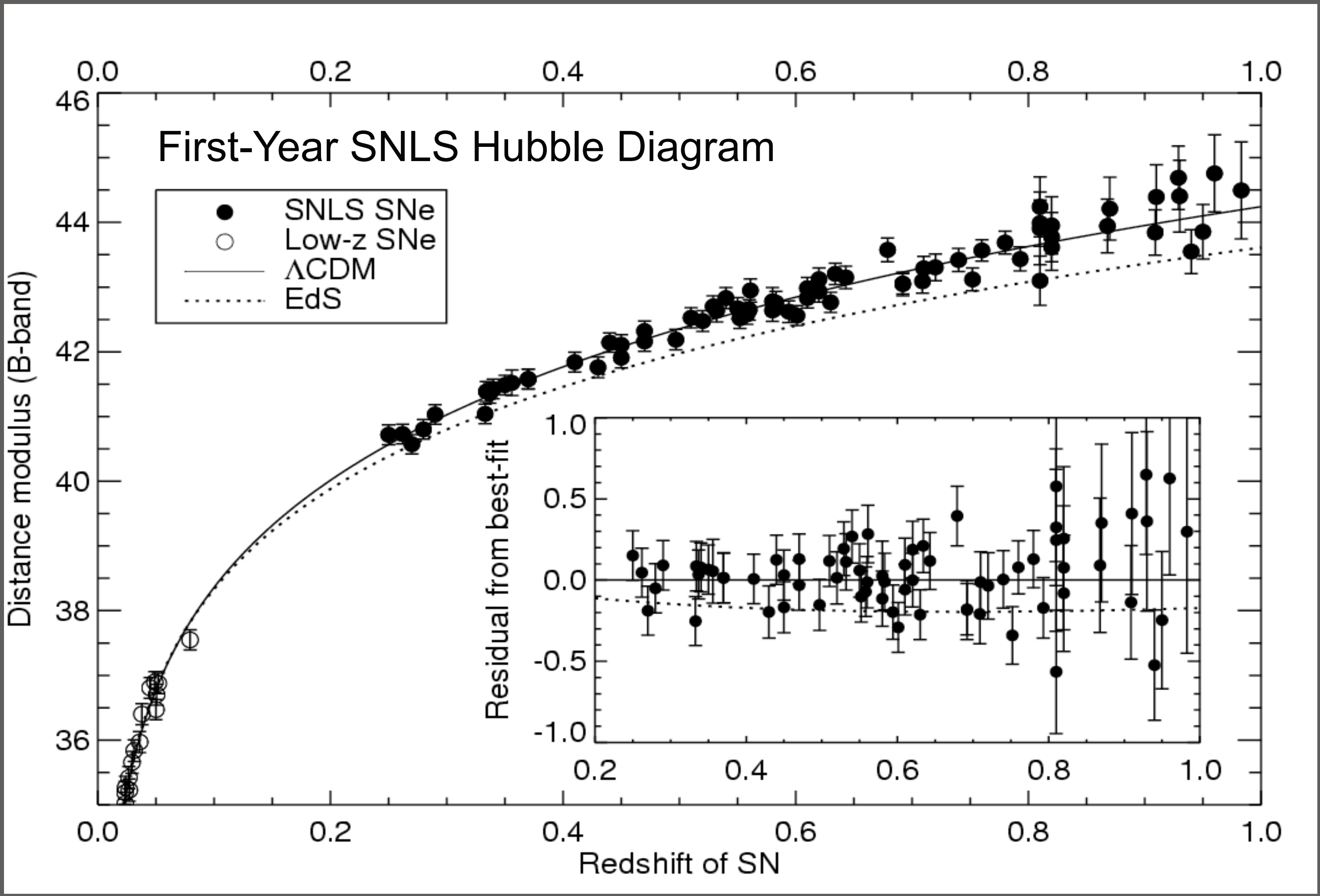


Power of a Rolling Search



SNLS Light curves

SNLS 1st Year Results



Astier et al. 2006

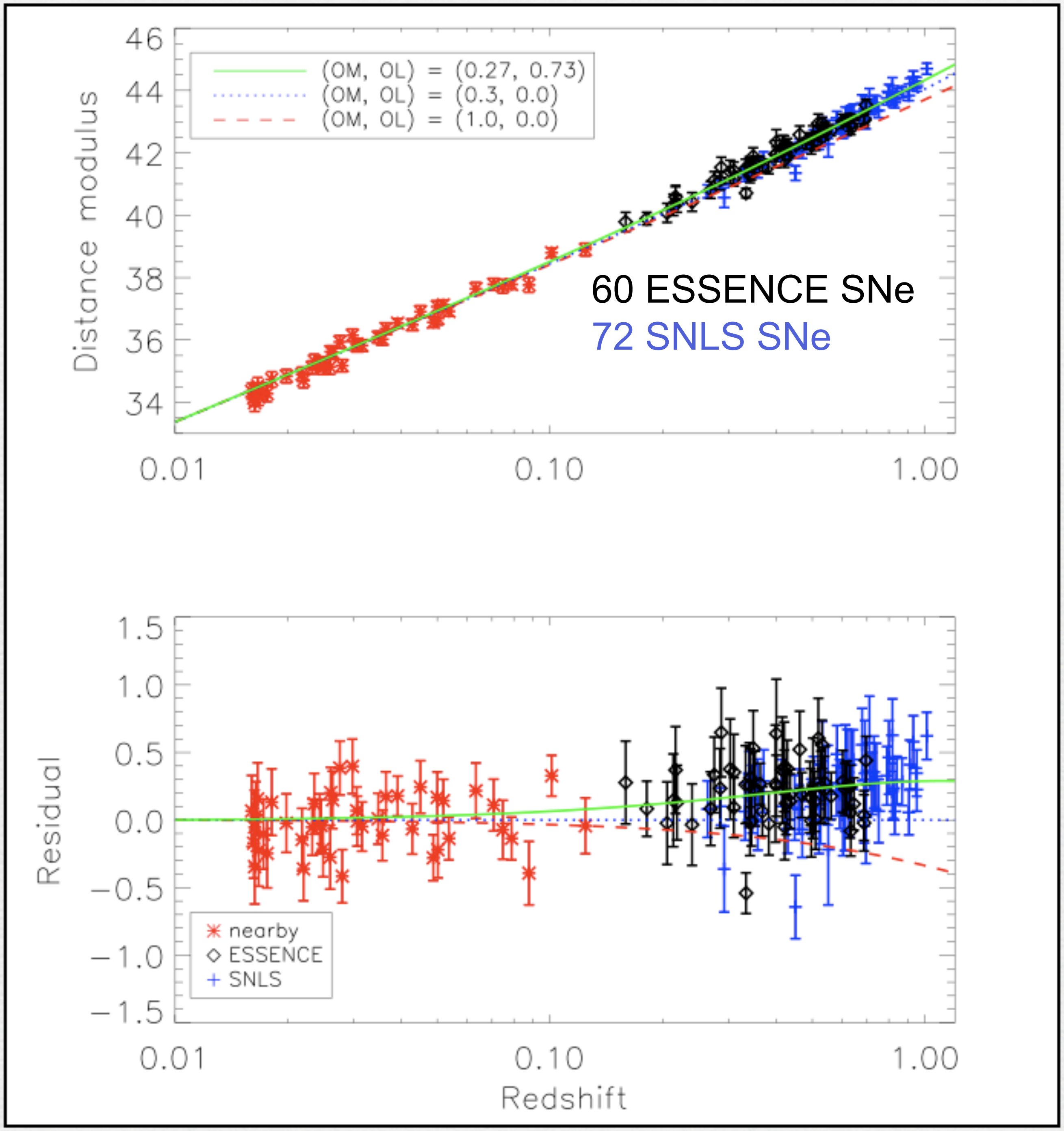
Using 72 SNe from SNLS +40 Low-z

The ESSENCE Survey

- Determine w to 10% or w!=-1
- 6-year project on CTIO 4m telescope in Chile; 12 sq. deg.
- Wide-field images in 2 bands
- Same-night detection of SNe
- Spectroscopy
  - Keck, VLT, Gemini, Magellan
- Goal is 200 SNeIa, 0.2<z<0.8

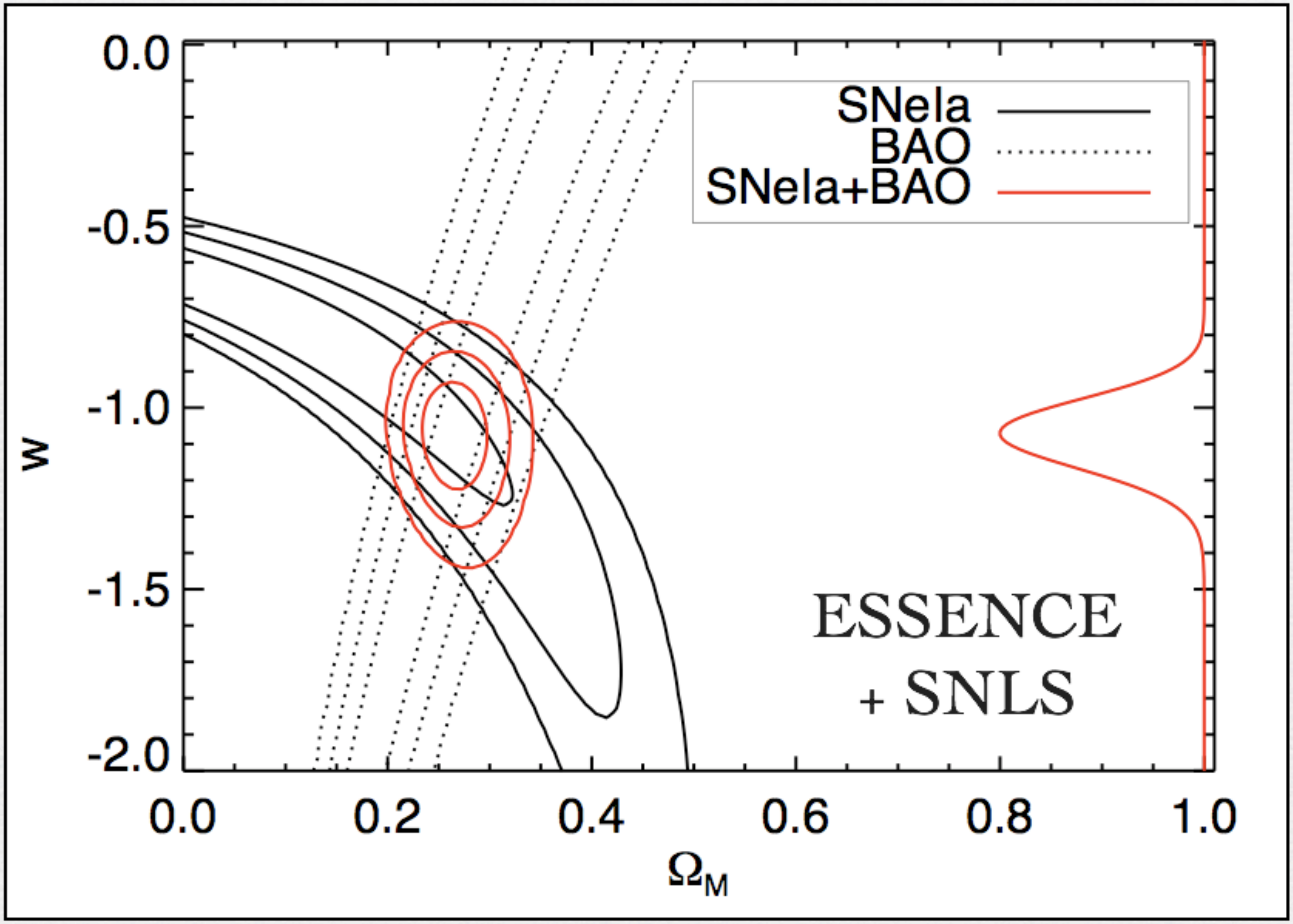
Wood-Vasey, etal (2007), Miknaitis, etal (2007): results from ~60 ESSENCE SNe (+Low-z)

ESSENCE +SNLS Hubble Diagram



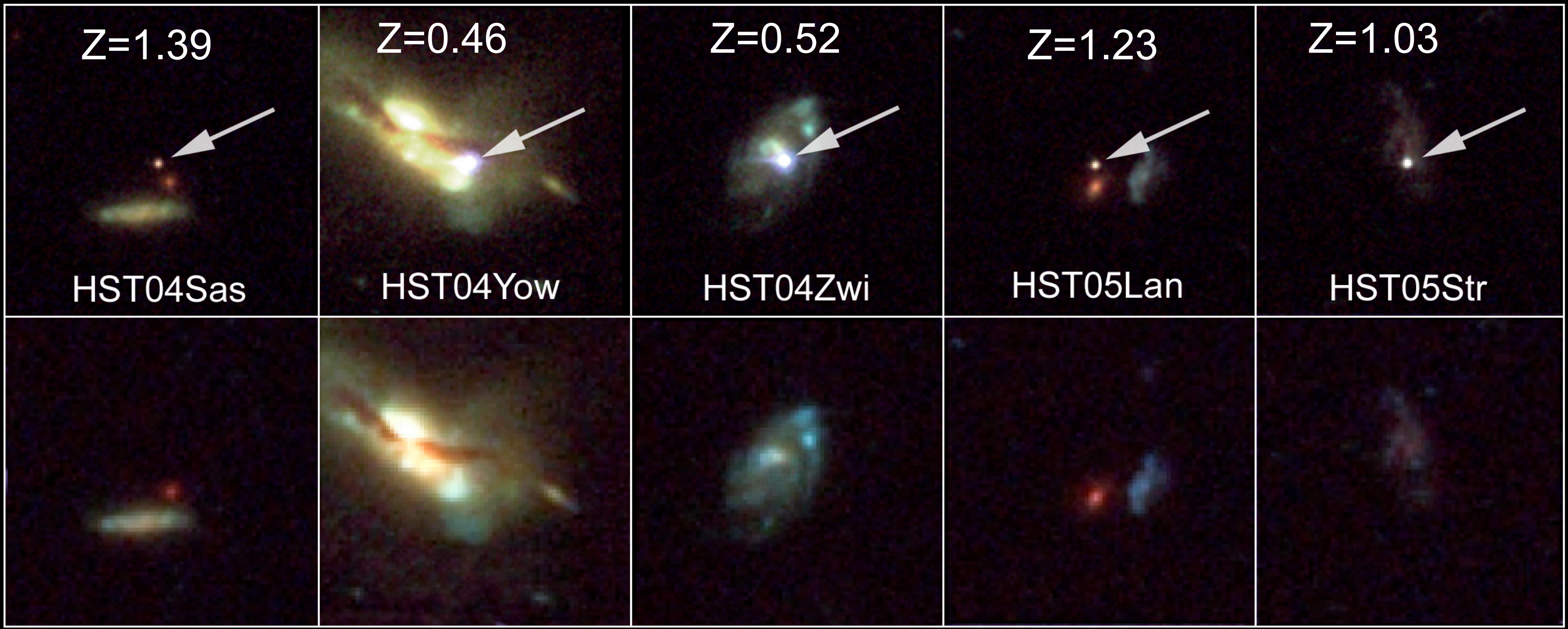
Flat,
constant-w

w=-1.07 +- 0.09 (stat) +- 0.13 (sys)



MLCS2k2.v004

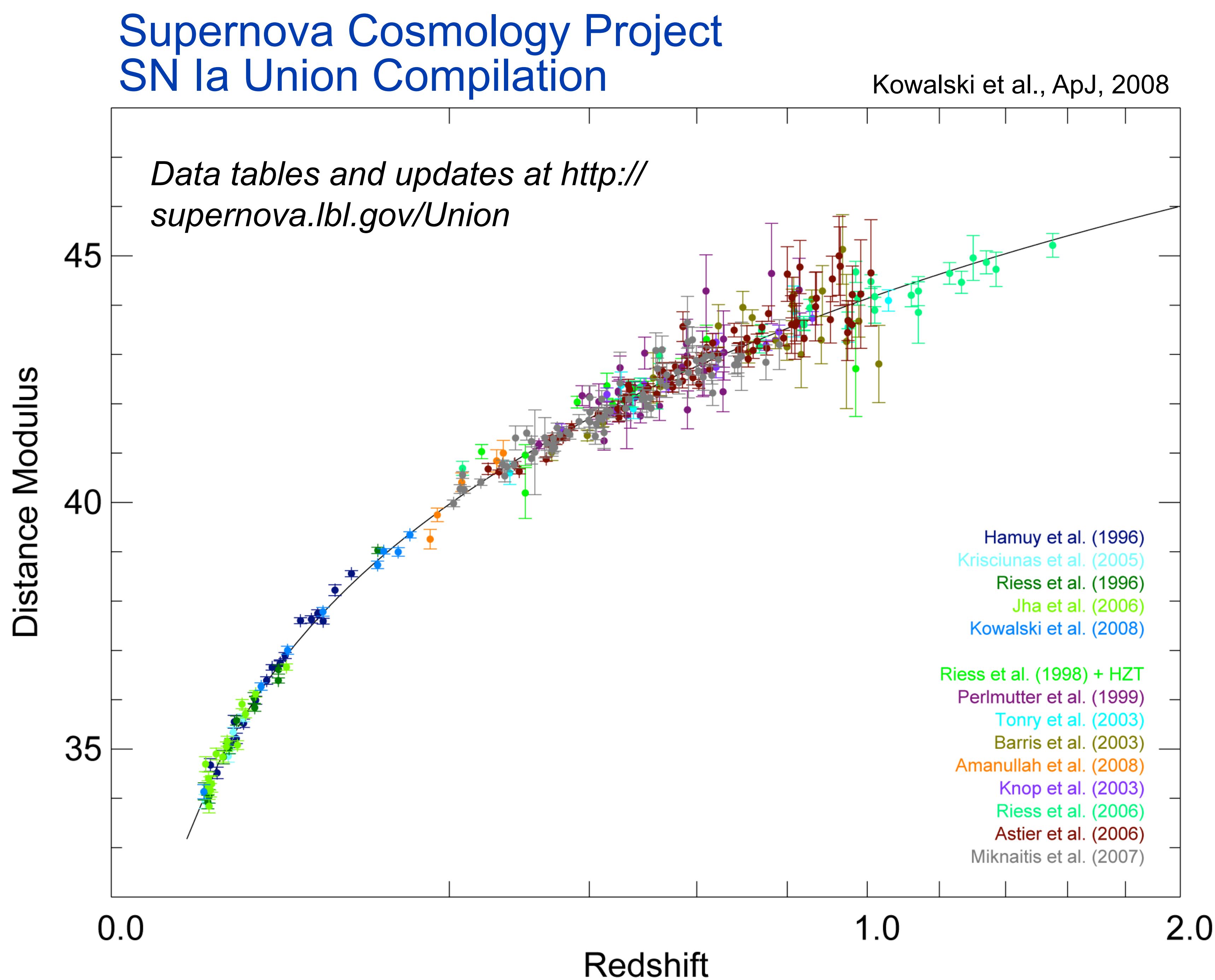
Higher-z SNe Ia from ACS



Host Galaxies of Distant Supernovae
Hubble Space Telescope ▪ Advanced Camera for Surveys

50 SNe Ia, 25 at z>1

Riess, etal


Supernova Cosmology Project
SN Ia Union Compilation
Kowalski et al., ApJ, 2008
Data tables and updates at http://supernova.lbl.gov/Union
Distance Modulus
Redshift
45
40
35
0.0
1.0
2.0
Hamuy et al. (1996)
Krisciunas et al. (2005)
Riess et al. (1996)
Jha et al. (2006)
Kowalski et al. (2008)
Riess et al. (1998) + HZT
Perlmutter et al. (1999)
Tonry et al. (2003)
Barris et al. (2003)
Amanullah et al. (2008)
Knop et al. (2003)
Riess et al. (2006)
Astier et al. (2006)
Miknaitis et al. (2007)

Likelihood Analysis with BAO and CMB Priors

$$-2\ln P_{posterior} = \sum_i \frac{(\mu_i - \mu_{\mathrm{mod}}(z_i; w, \Omega_m, \Omega_{DE})^2}{\sigma_{\mu,i}^2} + \chi_{BAO}^2 + \chi_{CMB}^2$$

where latter terms incorporate BAO and CMB priors:

BAO (SDSS LRG, Eisenstein etal 05):

$$A(z_1; w, \Omega_m, \Omega_{DE}) = \frac{\sqrt{\Omega_m}}{E(z_1)^{1/3}} \left[\frac{1}{z_1\sqrt{|\Omega_k|}} S_k\left(|\Omega_k|^{1/2} \int_0^{z_1} \frac{dz}{E(z)} \right) \right]^{2/3}$$

with

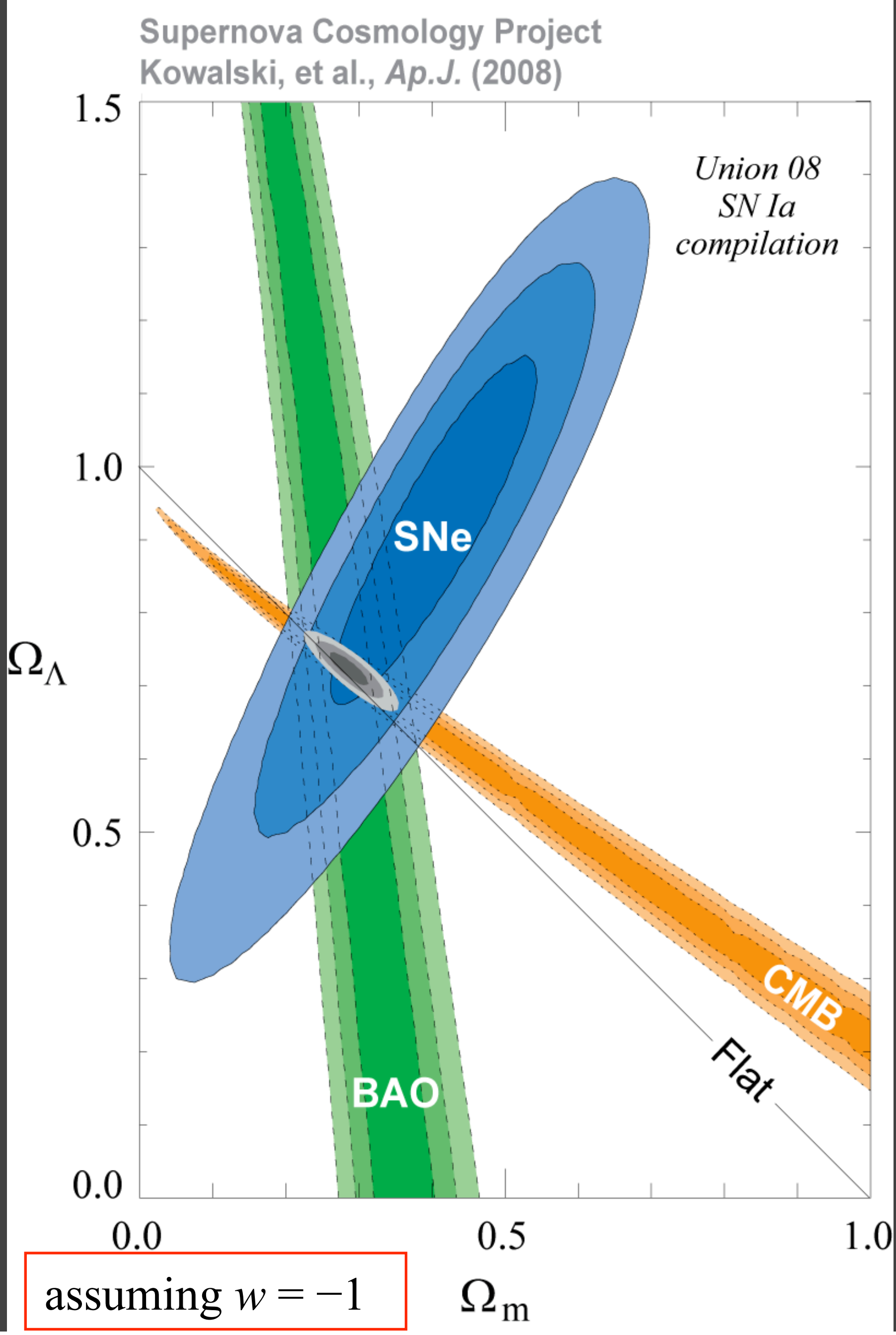
$$\chi_{BAO}{}^2 = [(A(z_1; w, \Omega_m, \Omega_{DE}) - 0.469)/0.017]^2 \text{ for } z_1 = 0.35$$

CMB (WMAP5, Komatsu etal 08):

$$R(z_{CMB}; w, \Omega_m, \Omega_{DE}) = \frac{\sqrt{\Omega_m}}{\sqrt{|\Omega_k|}} \left[S_k\left(|\Omega_k|^{1/2} \int_0^{z_{CMB}} \frac{dz}{E(z)} \right) \right]$$

with

$$\chi_{CMB}{}^2 = [(R(z_{CMB}; w, \Omega_m, \Omega_{DE}) - 1.710)/0.019]^2 \text{ for } z_{CMB} = 1090$$



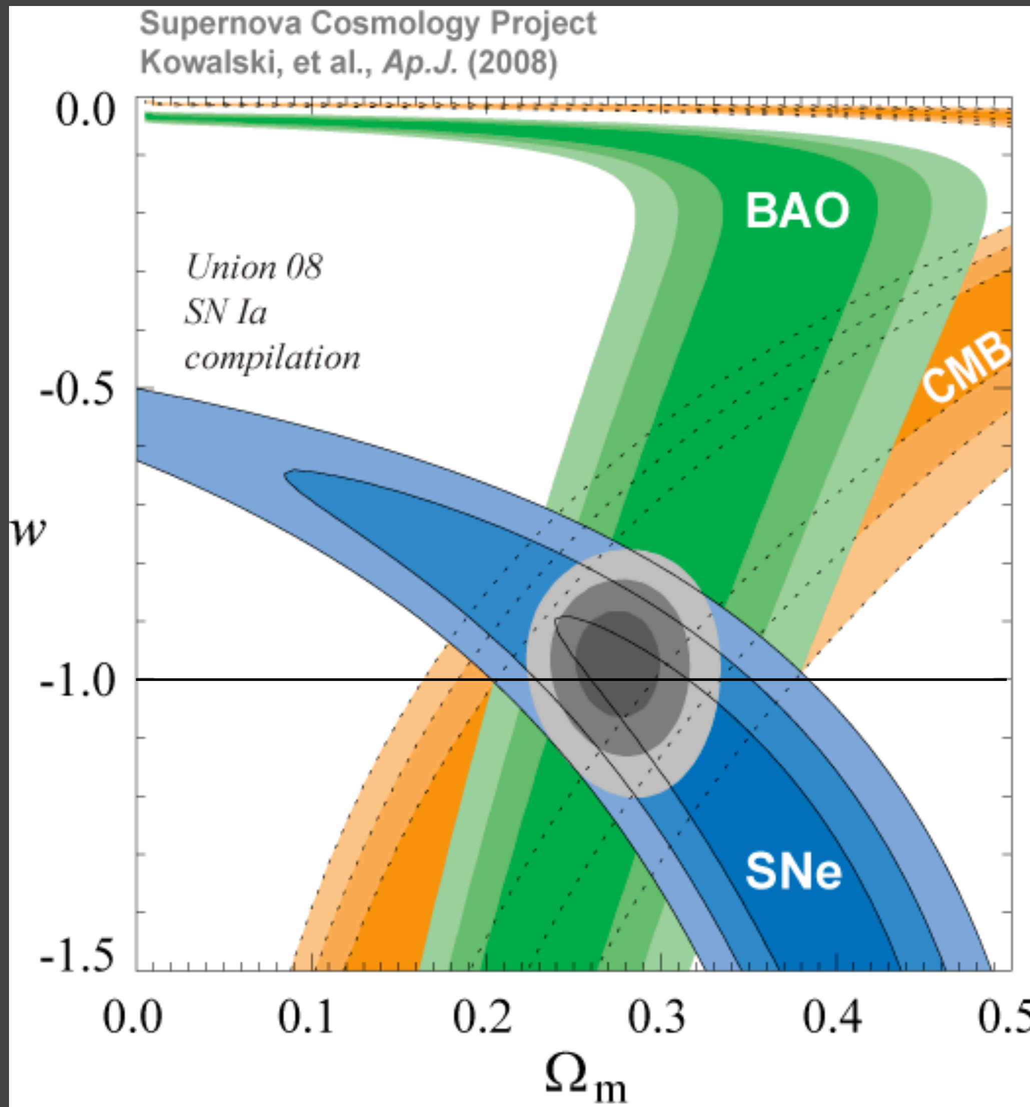
assuming $w = -1$

Recent Dark Energy Constraints

Improved SN constraints

Inclusion of constraints from WMAP Cosmic Microwave Background Anisotropy and SDSS Large-scale Structure (Baryon Acoustic Oscillations)

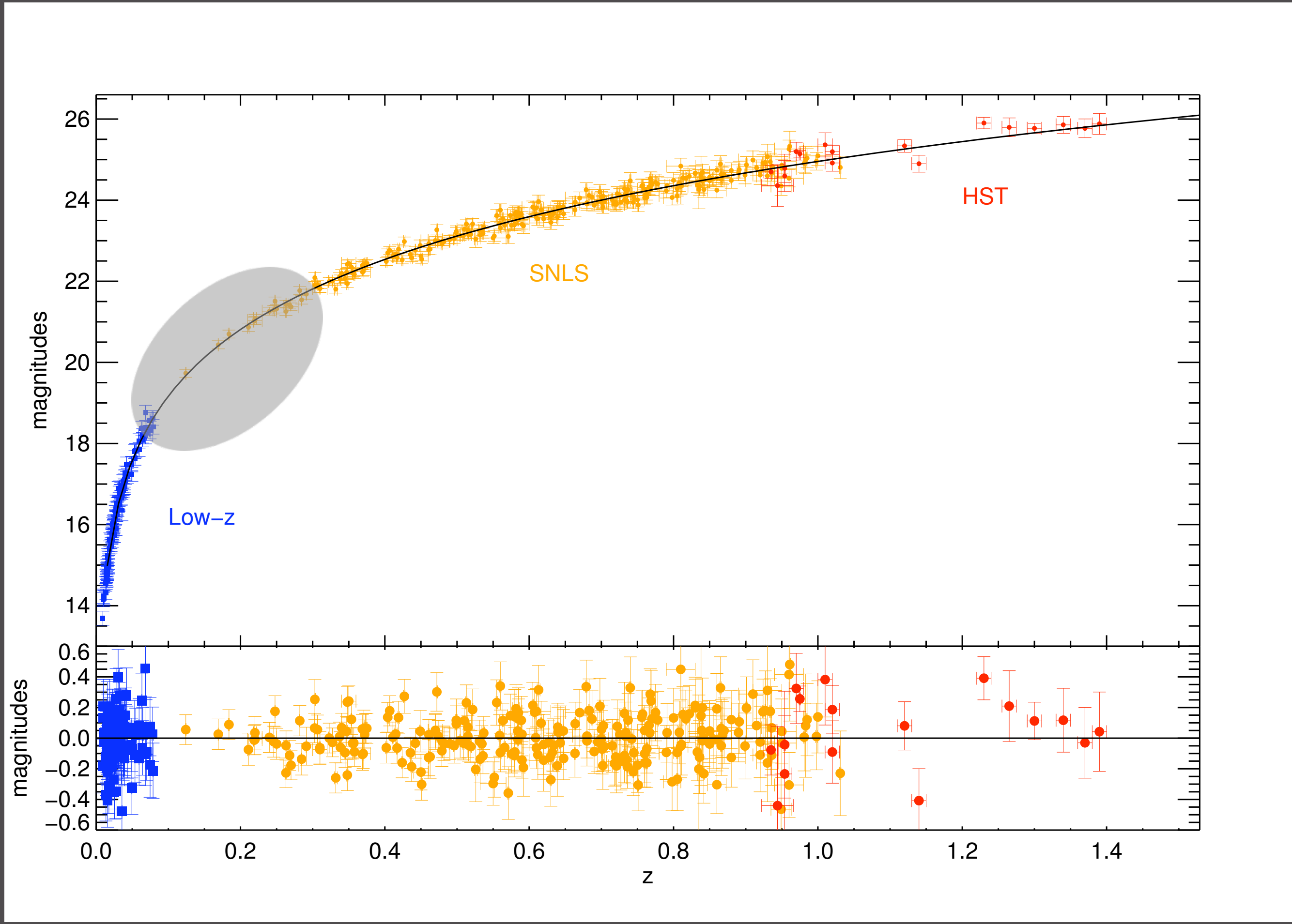
Only statistical errors shown



assuming flat Univ. and constant *w*

Only statistical errors shown

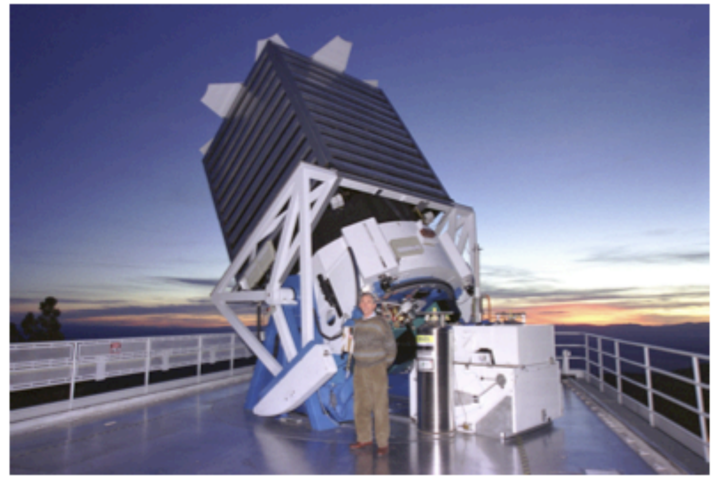
SNLS Preliminary 3rd year Hubble Diagram

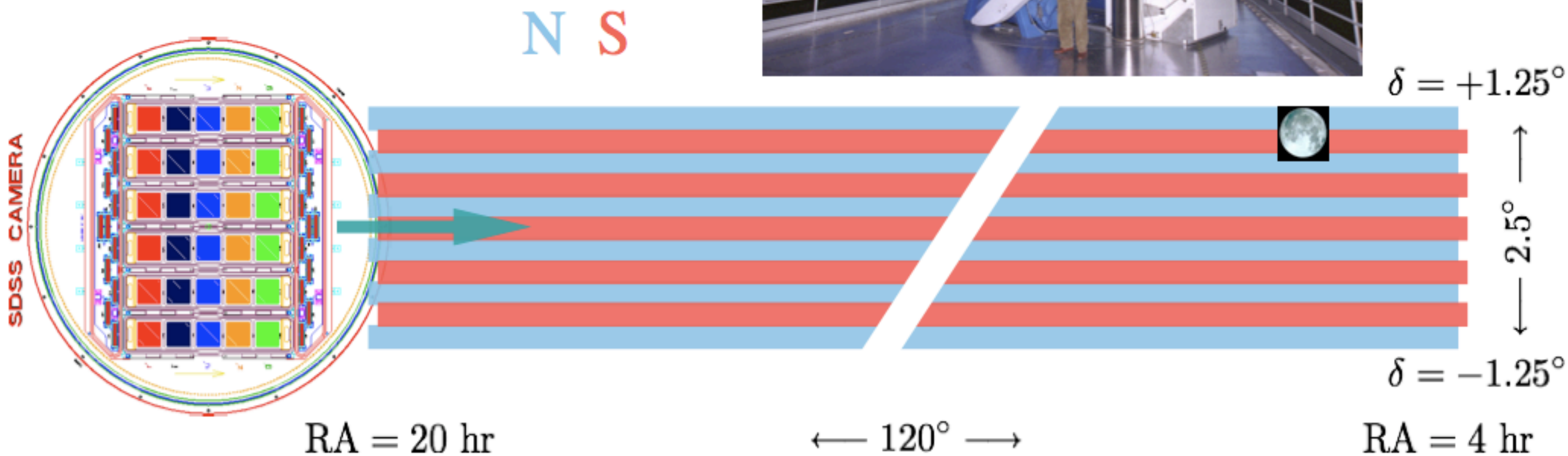


- Conley et al, Guy etal (2010): results with ~252 SNLS SNe
- Independent analyses with 2 light-curve fitters: SALT2, SiFTO

SDSS-II SN Survey

Frieman, et al (2008); Sako, et al (2008)

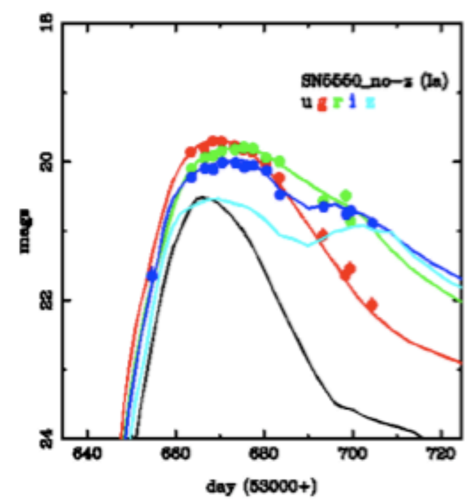




Use the SDSS 2.5m telescope

- September 1 - November 30 of 2005-2007
- Scan 300 square degrees every 2 days
- Obtain densely sampled multi-color light curves
- Results published from 2005 season

Kessler, et al 09; Lampeitl et al 09; Sollerman et al 09



SDSS II Supernova Survey Goals

- Obtain few hundred *high-quality** SNe Ia light curves in the `redshift desert' z~0.05-0.4 for continuous Hubble diagram
- Probe Dark Energy in z regime complementary to other surveys
- Well-observed sample to anchor Hubble diagram, train light-curve fitters, and explore systematics of SN Ia distances
- Rolling search: determine SN/SF rates/properties vs. z, environment
- Rest-frame u-band templates for z >1 surveys
- Large survey volume: rare & peculiar SNe, probe outliers of population

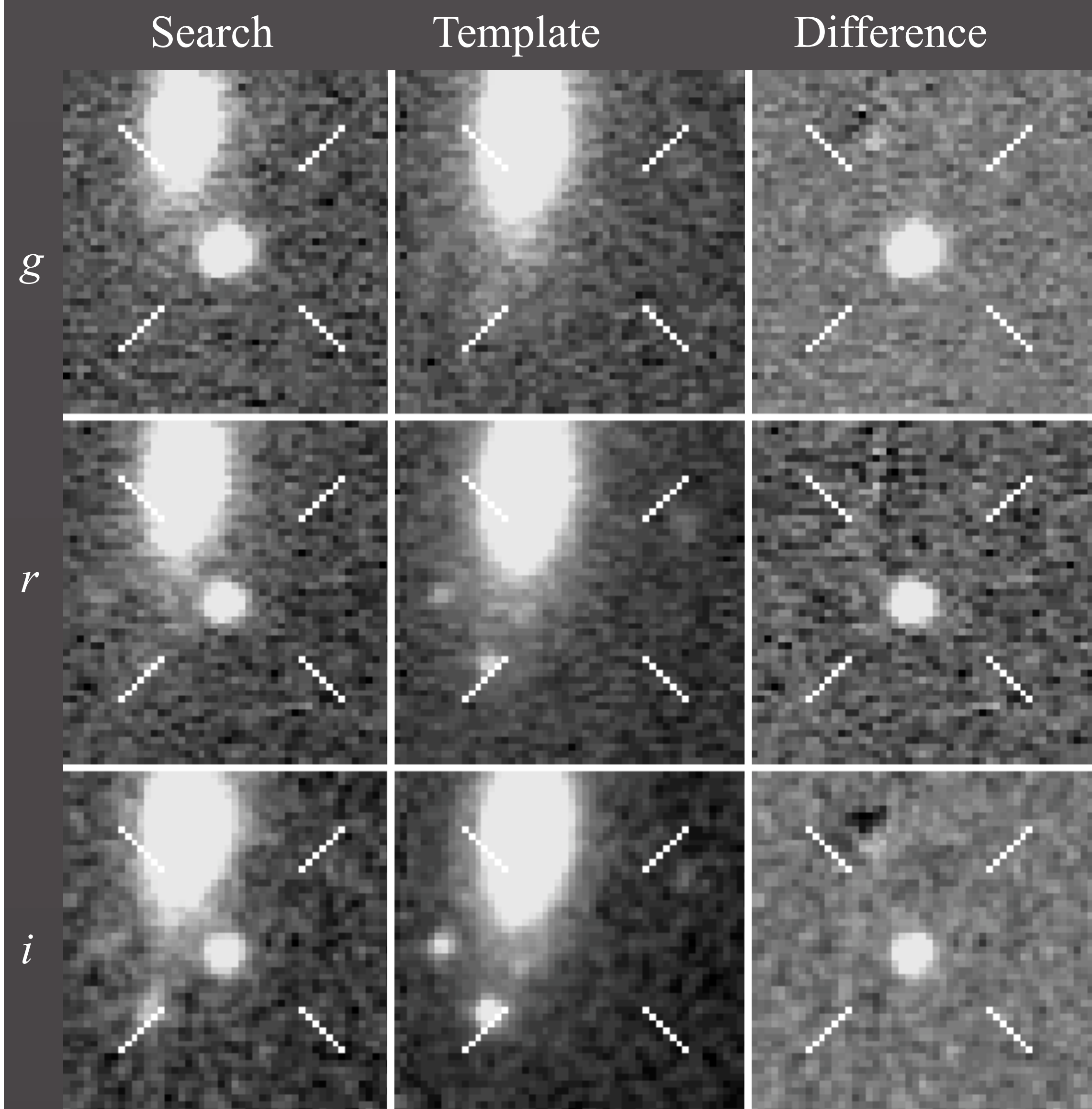
*high-cadence, multi-band, well-calibrated

SDSS-II SN Survey Team

Fermilab	J. Frieman (U Chicago), F. DeJongh, J. Marriner, D. McGinnis, G. Miknaitis
U Chicago	B. Dilday, R. Kessler, M. Subbarao (Adler Planetarium)
APO	J. Barentine, H. Brewington, J. Dembicky, M. Harvanek, J. Krzesinski, B. Ketzeback, D. Long, O. Malanushenko, V. Malanushenko, R. McMillan, K. Pan, S. Saurage, S. Snedden, S. Watters
U Washington	A. Becker, C. Hogan, J. VanderPlas
NMSU	T. Gueth, J. Holtzman
OSU	D. Depoy, J. Marshall, J. Prieto
U Tokyo	M. Doi, K. Konishi, T. Morokuma, N. Takanashi, K. Tokita, N. Yasuda
U Portsmouth	H. Lampeitl, R. Nichol, M. Smith
KIPAC	R. Blandford, S. Kahn, R. Romani, C. Zheng
U Penn	C. D'Andrea, J. Mosher, M. Sako
Rutgers	S. Jha
SAAO	B. Bassett, E. Elson, P. Vaisanen, K. van der Heyden
RIT	M. Richmond
Penn State	D. Schneider
Notre Dame	P. Garnavich
STScI	A. Riess
Wayne State	D. Cinabro, Matt Taylor
SNU	C. Choi, M. Im
HET team	Goettingen (W. Kollatschny), Munich (R. Bender, U. Hopp), U Texas (C. Wheeler, P. Hoeflich)
ESO team	A. Aragon-Salamanca, M. Bremer, F. Castander, C. Collins, A. Edge, A. Goobar, C. Henriksen, G. Leloudas, J. Lucey, J. Mendez, L. Ostman, K. Romer, P. Ruiz-Lapuente, J. Sollerman, M. Stritzinger, M. Turatto R. Miquel, M. Molla, L. Galbany
MDM team	R. Assef, A. Crotts, J. Eastman, M. Eyler, C. Morgan, K. Schlesinger, L. Watson
Subaru team	Y. Ihara
KPNO team	M. Florack, A. Hirschauer, D. O'Connor
Keck team	R. Foley, A. Filippenko

Spectroscopic follow-up telescopes

Searching For Supernovae

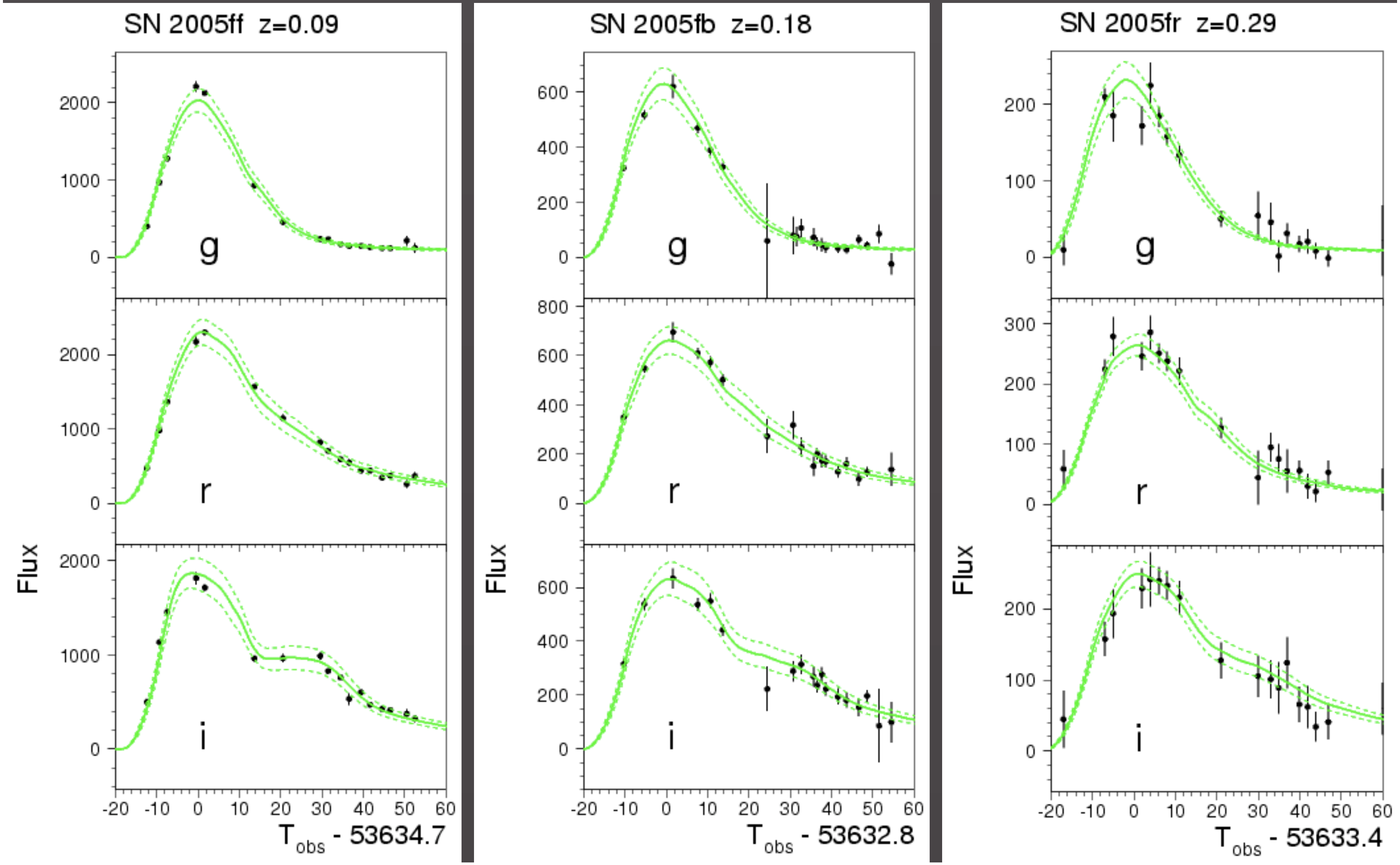


- 193 confirmed Ia
- 2007
  - 175 confirmed Ia

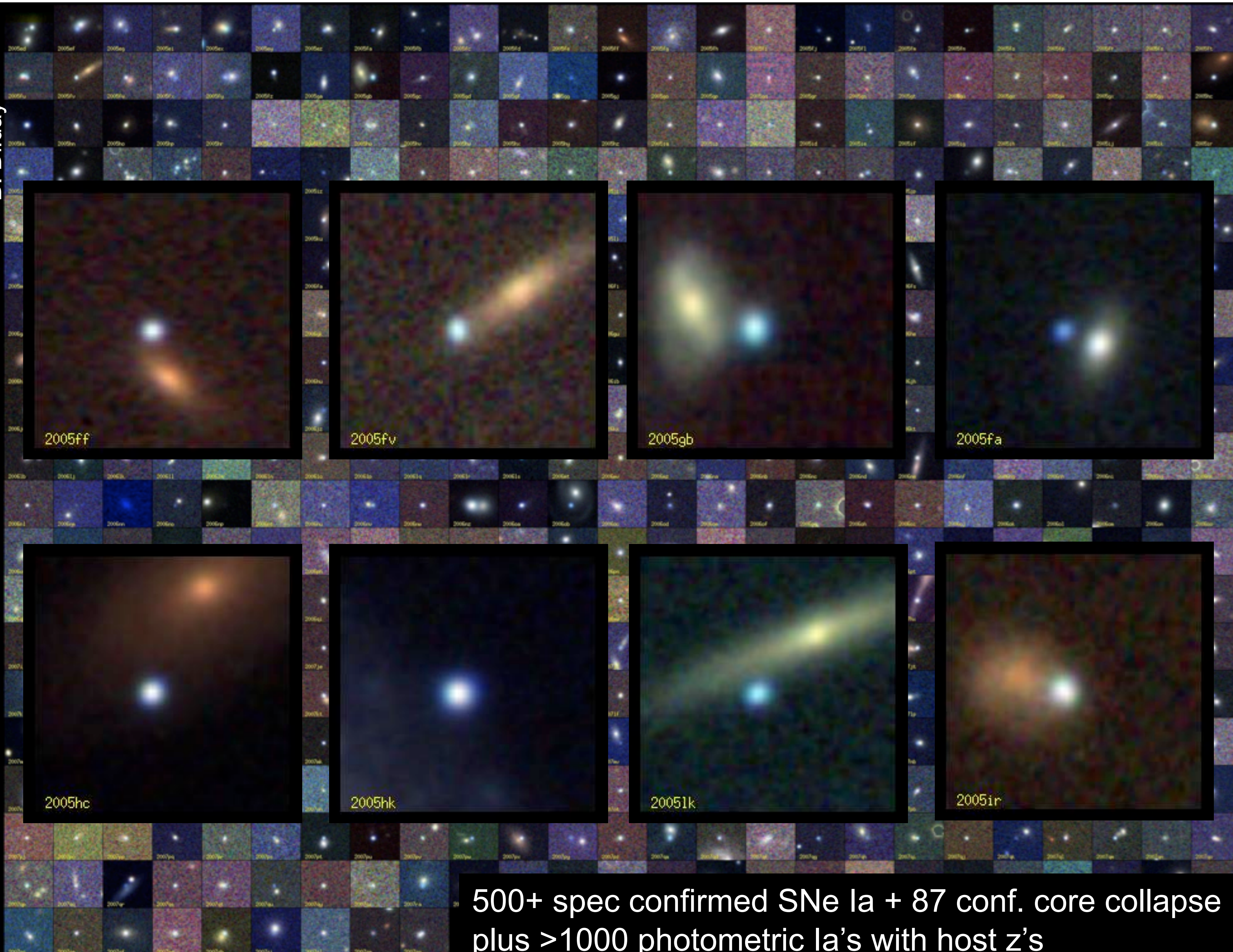
•Positional match to remove movers
•Insert fake SNe to monitor efficiency

SDSS SN Photometry

Holtzman etal (2008)



B. Dilday



500+ spec confirmed SNe Ia + 87 conf. core collapse plus >1000 photometric Ia's with host z's

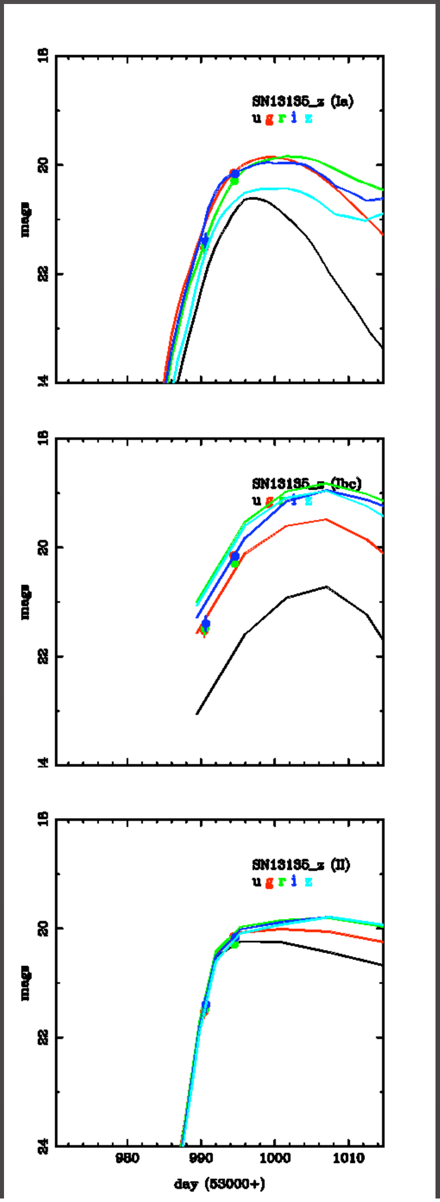
Spectroscopic Target Selection

2 Epochs

SN Ia Fit

SN Ibc Fit

SN II Fit



Sako etal 2008

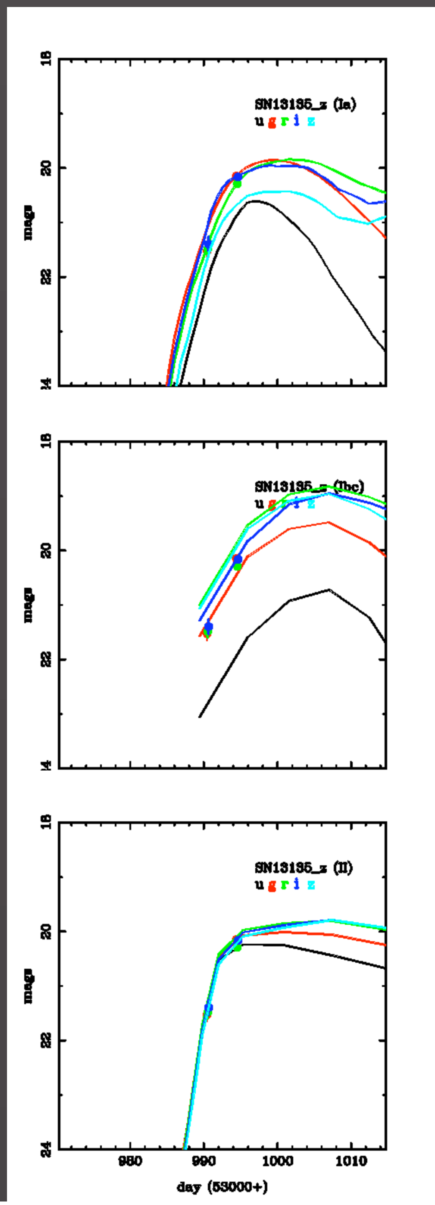
Spectroscopic Target Selection

2 Epochs

SN Ia Fit

SN Ibc Fit

SN II Fit

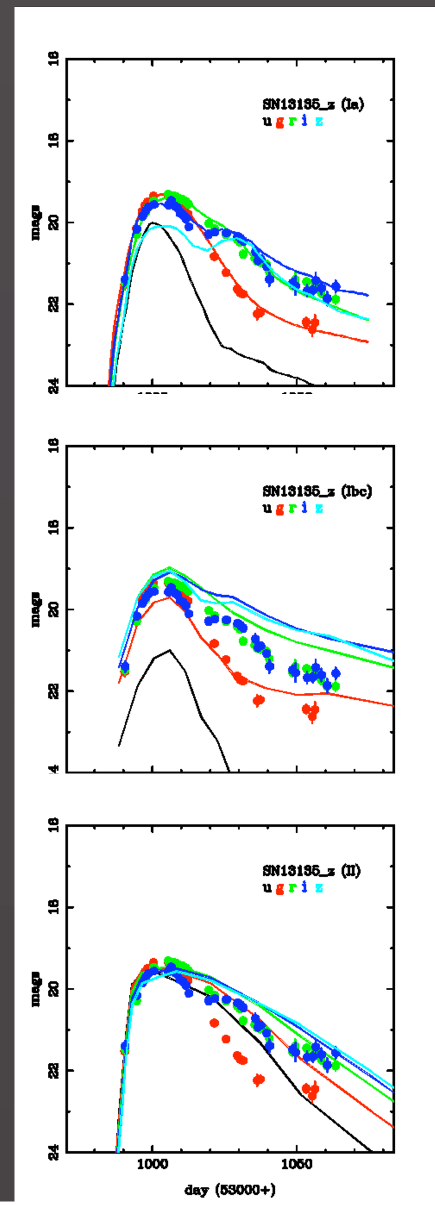


31 Epochs

SN Ia Fit

SN Ibc Fit

SN II Fit



Fit with template library

Classification >90% accurate after 2-3 epochs

Redshifts 5-10% accurate

Sako etal 2008

SN and Host Spectroscopy

MDM 2.4m

NOT 2.6m

APO 3.5m

NTT 3.6m

KPNO 4m

WHT 4.2m

Subaru 8.2m

HET 9.2m

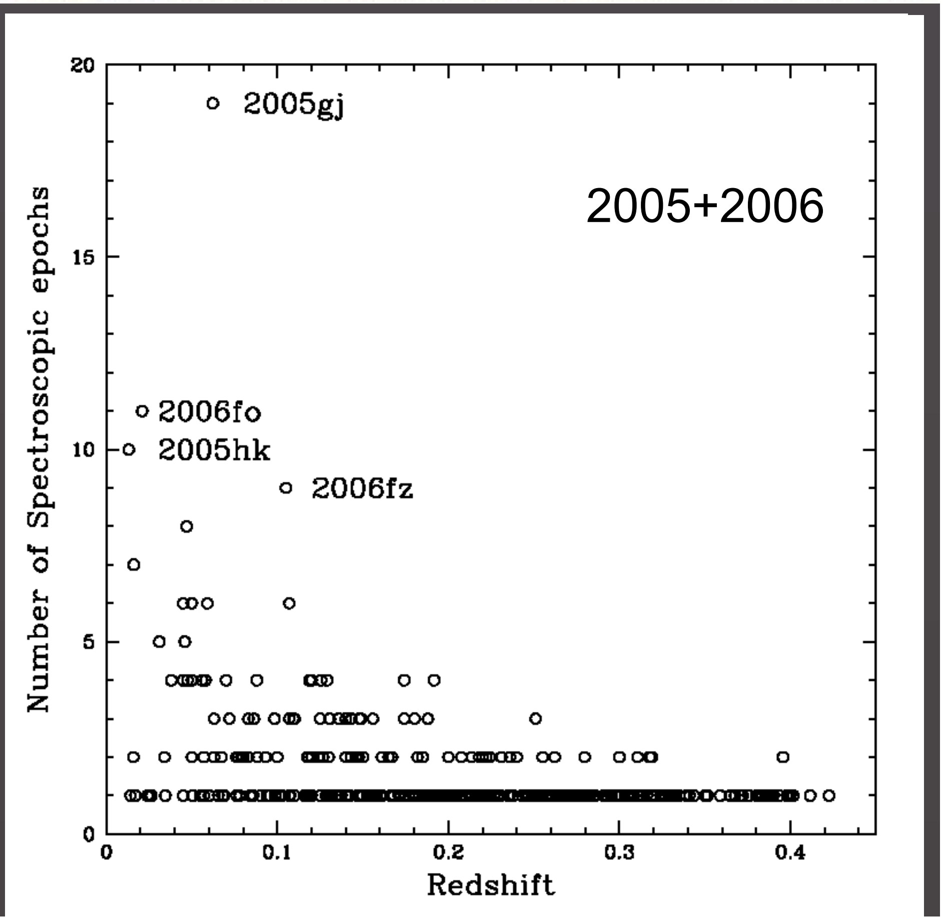
Keck 10m

Magellan 6.5m

TNG 3.5m

SALT 10m   SDSS 2.5m

Determine SN Type and Redshift



Fitting SN Ia Light Curves

- Multi-color Light Curve Shape (MLCS2k2)

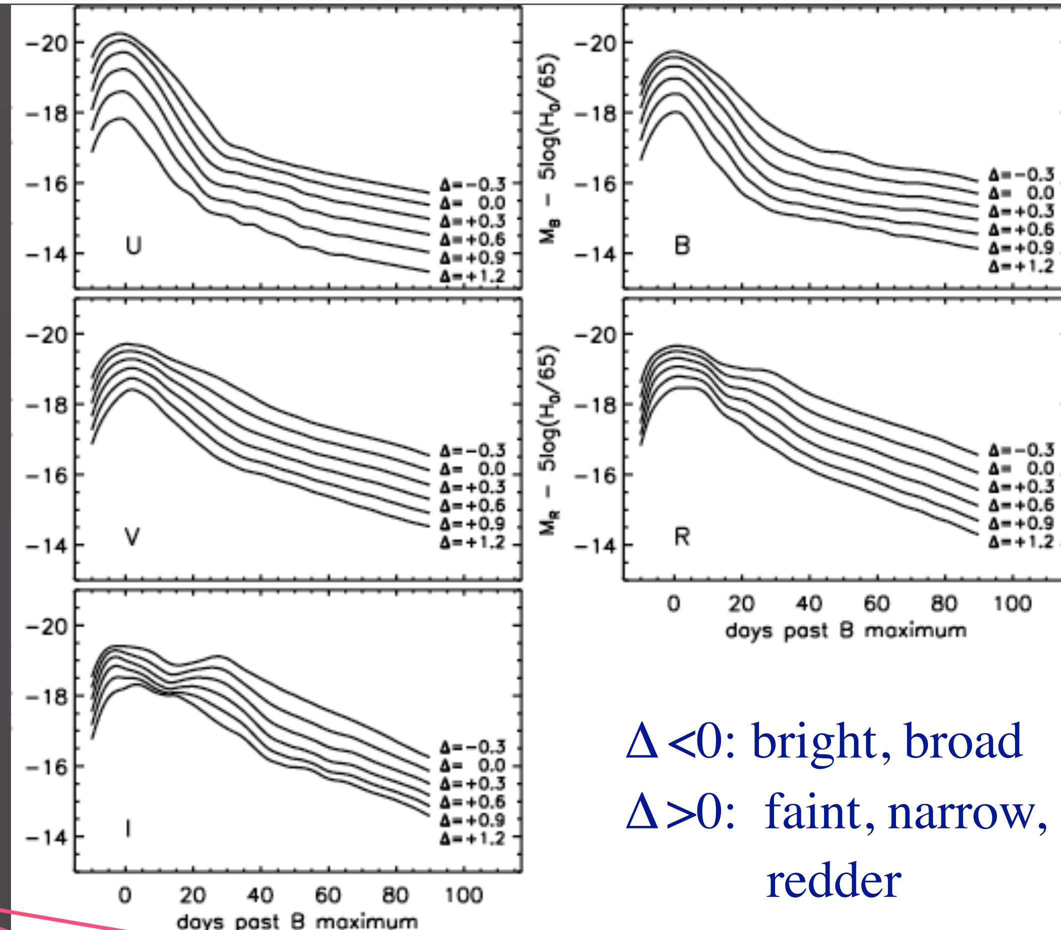
  Riess, etal 96, 98; Jha, etal 2007

- SALT-II

  Guy, etal 05,08

MLCS2k2 Light-curve Templates

in rest-frame $j=UBVRI$;
built from ~100
well-observed, nearby SNe Ia



$\Delta < 0$: bright, broad
$\Delta > 0$: faint, narrow, redder

time-dependent model "vectors"
trained on Low-z SNe

observed passband

$$m^{i}_{\mathrm{mod}}(t-t_0) = \mu + M^{j}(t-t_0) + P^{j}(t-t_0)\Delta + Q^{j}(t-t_0)\Delta^2$$
$$+ K^{ij}(t-t_0) + X^{j}_{host}(t-t_0) + X^{i}_{MW}(t-t_0)$$

fit parameters

Time of maximum   distance modulus   host gal extinction   stretch/decline rate

Host Galaxy Dust Extinction

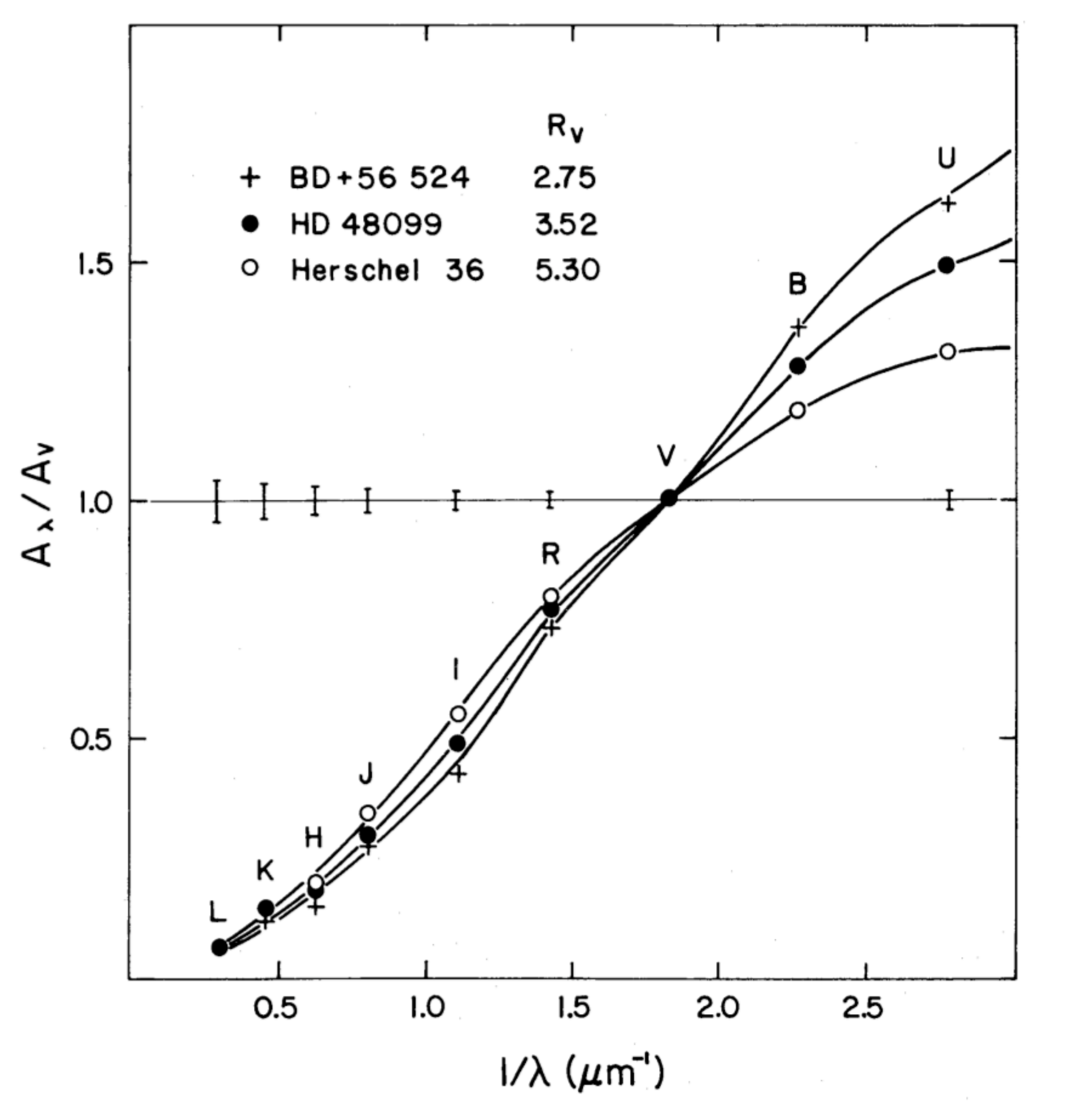
•Extinction:

$$A_\lambda = -2.5\log\left(\frac{f_{obs}(\lambda)}{f_{true}(\lambda)}\right)$$

•Empirical Model for wavelength dependence:

$$\frac{A_\lambda}{A_V} = a(\lambda) + \frac{b(\lambda)}{R_V}$$

•MLCS: A_V is a fit parameter, but R_V is usually fixed to a global value (sharp prior) since it's usually not well determined SN by SN



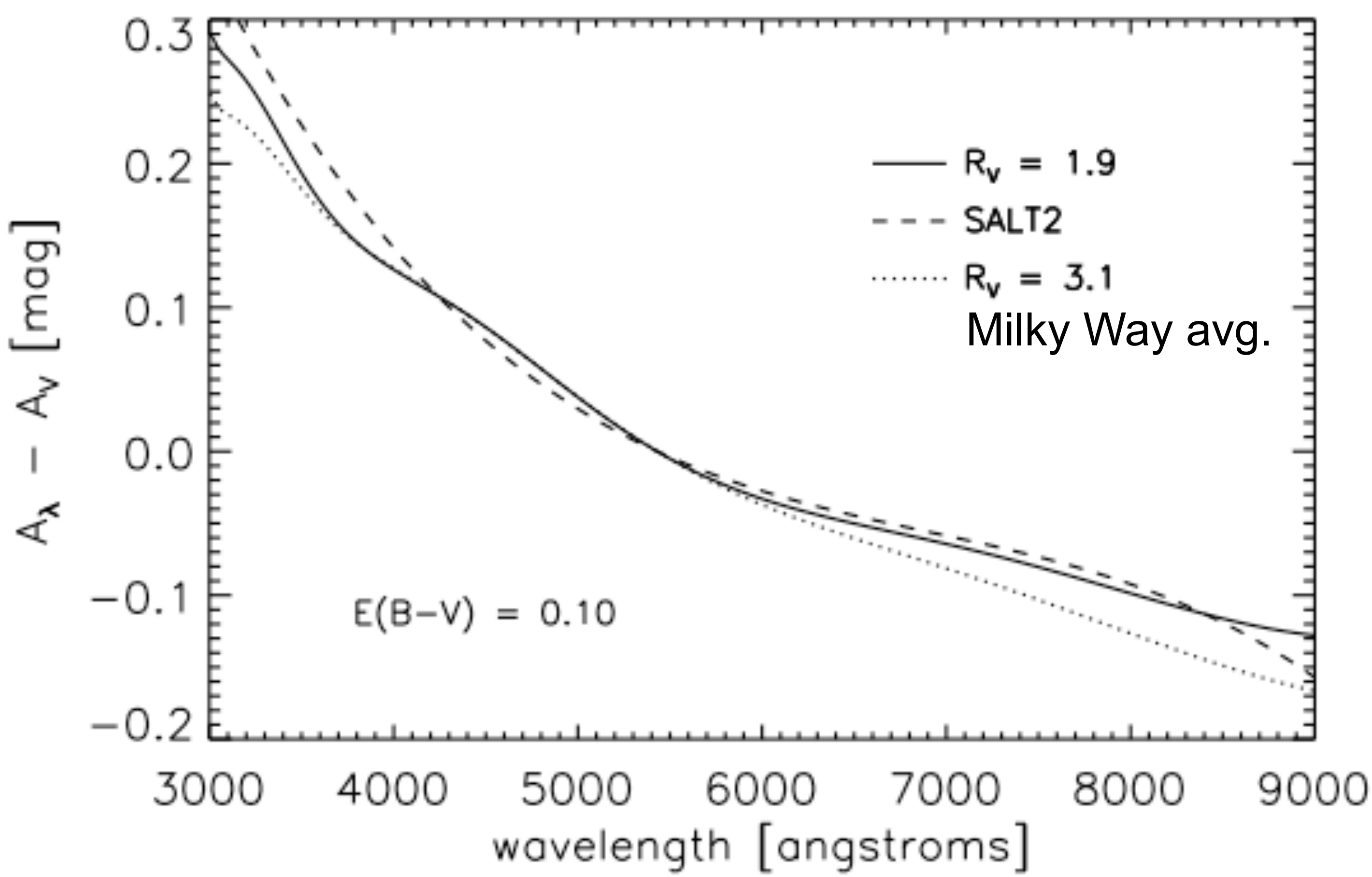
Cardelli etal 89 (CCM)

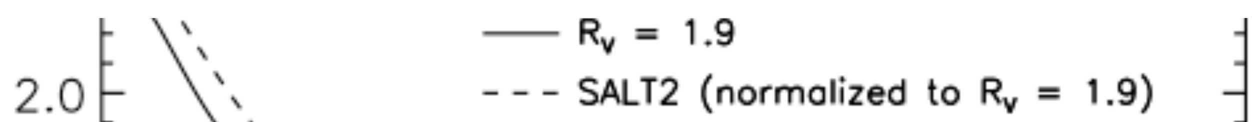
Host Galaxy Dust Extinction

Historically, MLCS used Milky Way average of R_V=3.1

Growing evidence that this doesn't represent SN host galaxy population well

Jha



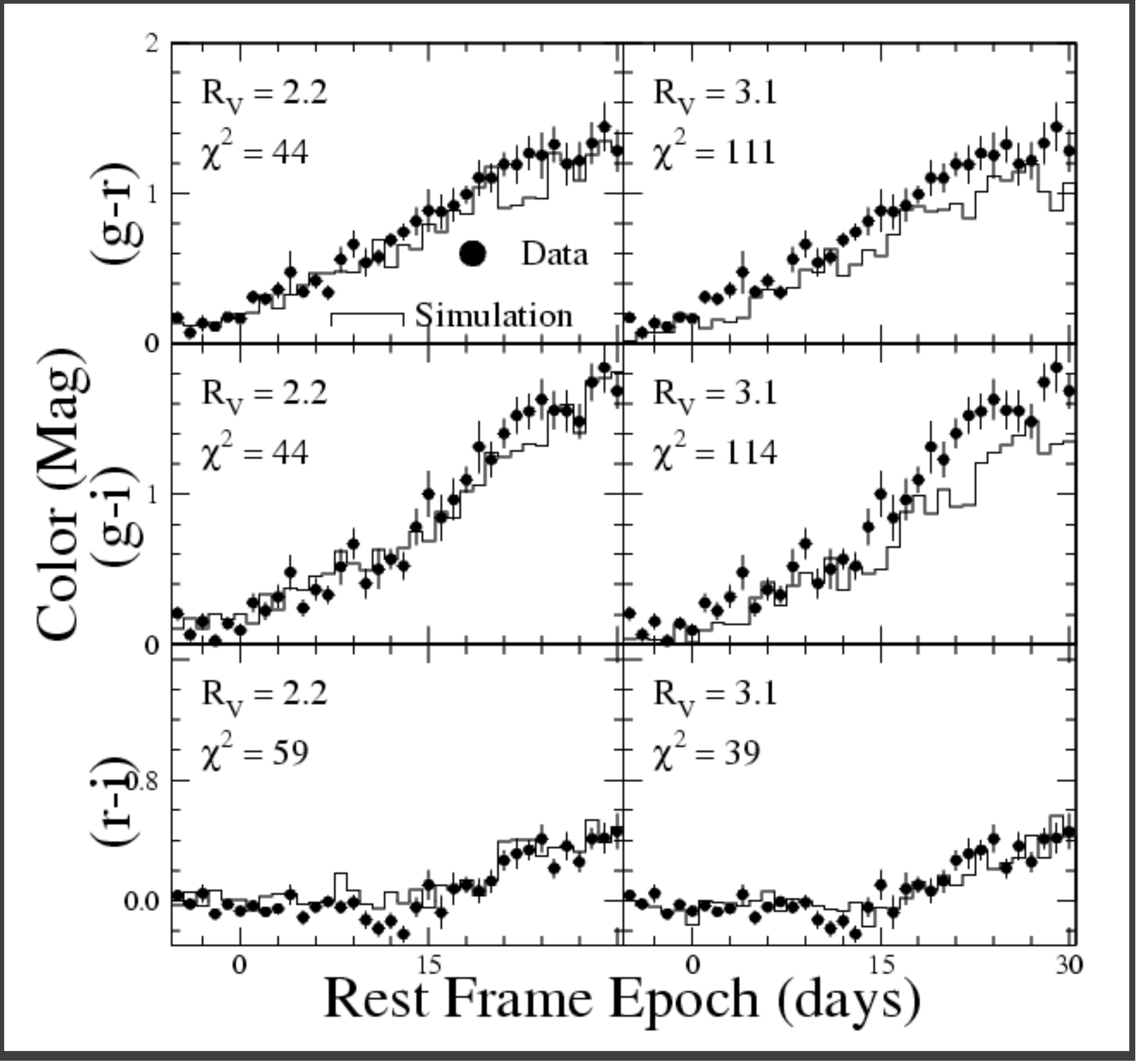


Extract R_V by matching colors of SDSS SNe to MLCS simulations

$$\langle R_V \rangle = \frac{A_V}{E(B-V)} \approx 2$$

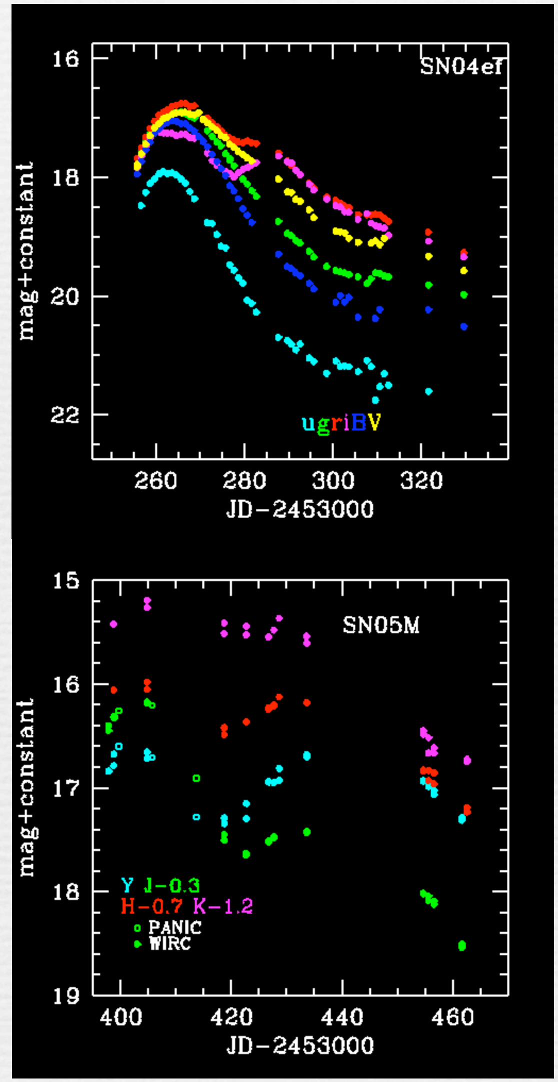
- Use nearly complete (spectroscopic + photometric) sample
- MLCS previously used Milky Way avg R_V=3.1
- Lower R_V more consistent with SALT color law and other recent SN R_V estimates

D. Cinabro

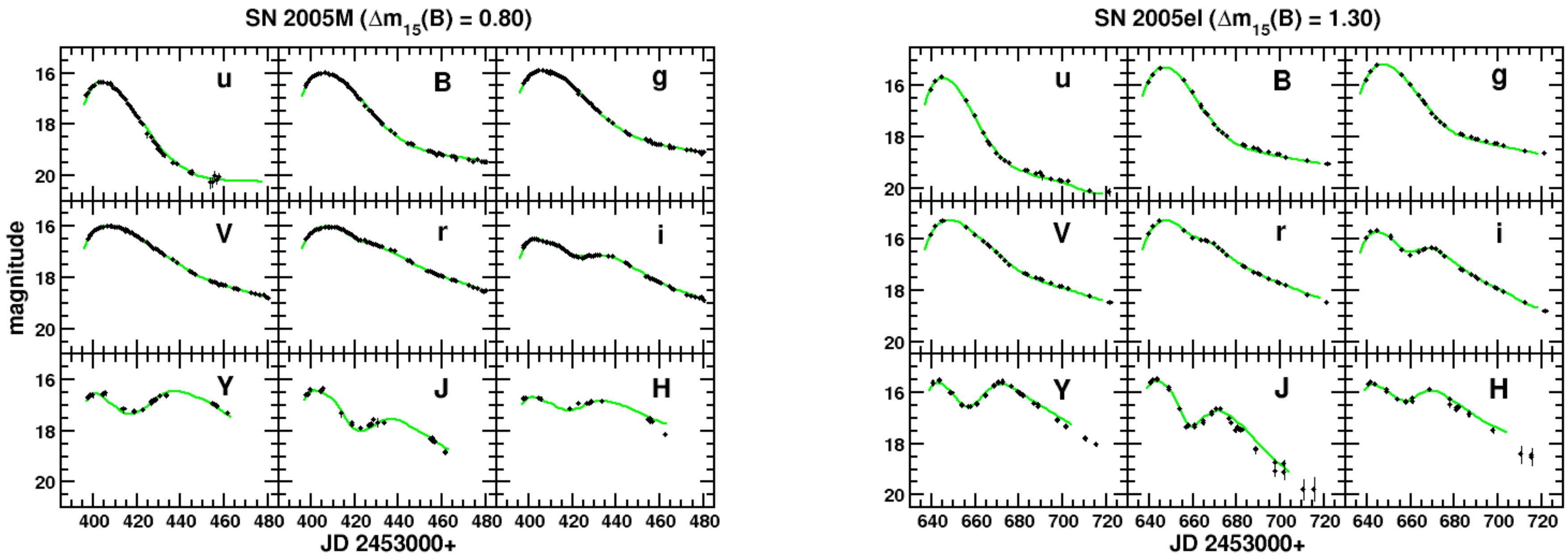


Carnegie Supernova Project: Low-z

- CSP is a follow-up project
- Goal: optical/NIR light-curves and spectro-photometry for
  - > 100 nearby SNIa
  - > 100 SNII
  - > 20 SNIbc
- Filter set: BV + u'g'r'i' + YJHK
- Understand SN physics
- Use as standard candles.
- Calibrate distant SN Ia sample



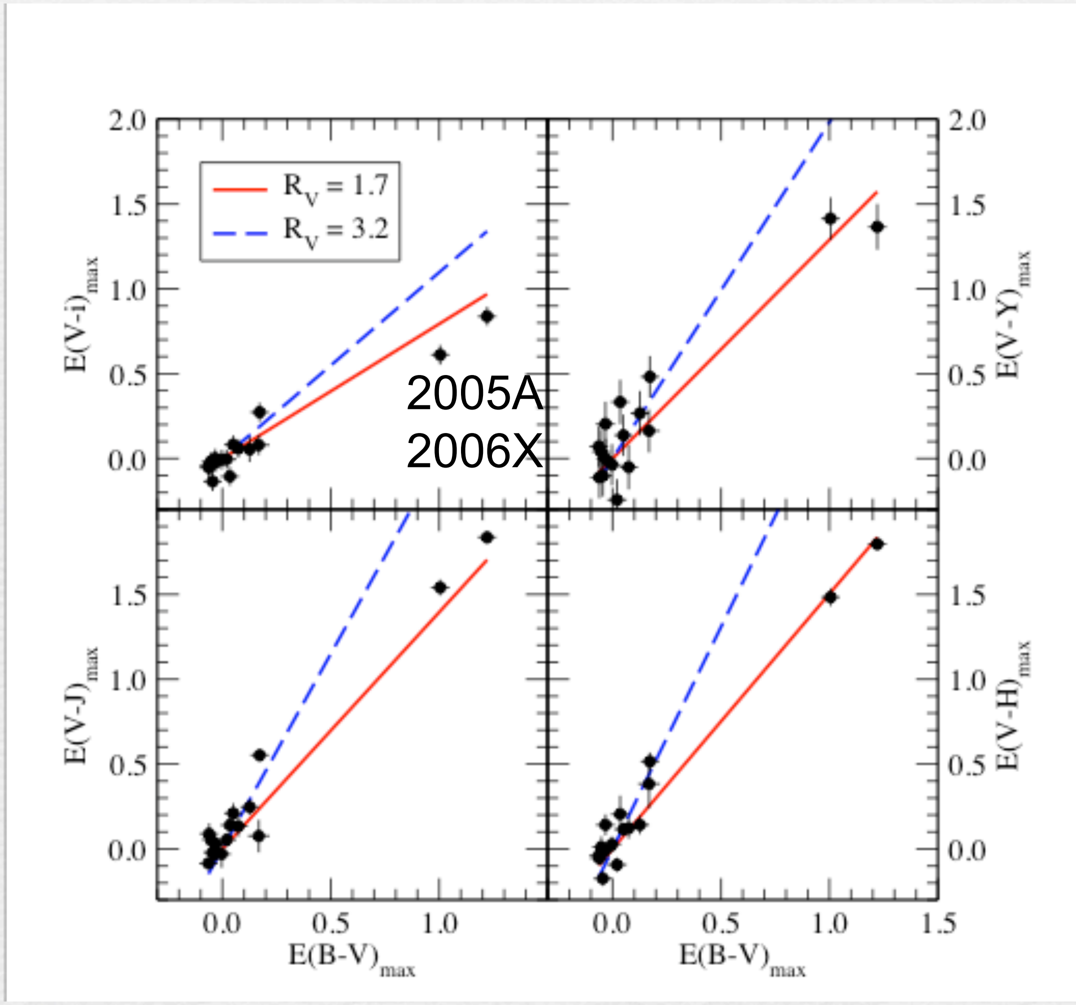
CSP Low-z Light Curves



Folatelli, et al. 2009

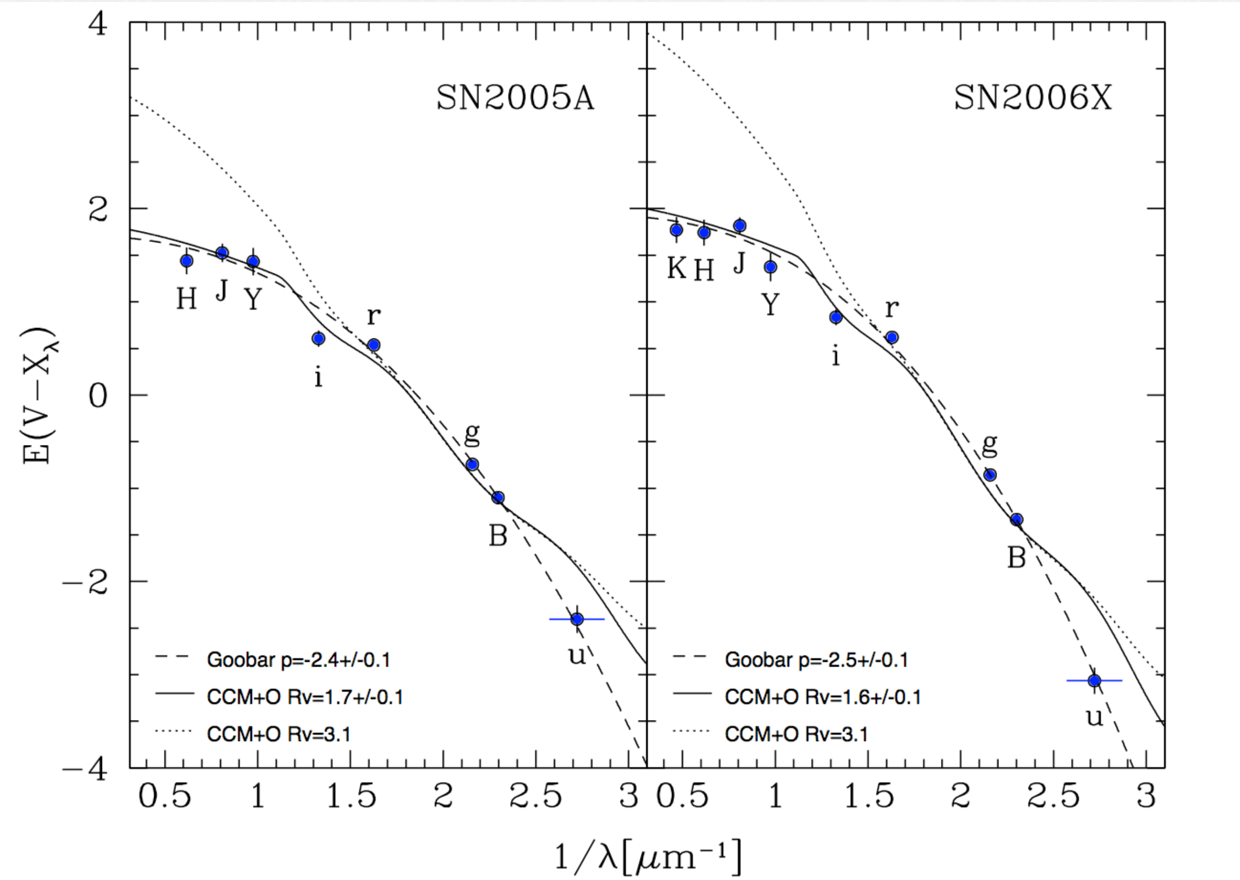
Contreras, et al. 2009: 35 optical light curves (25 with NIR)

Varying Reddening Law?



Folatelli et al. (2009)

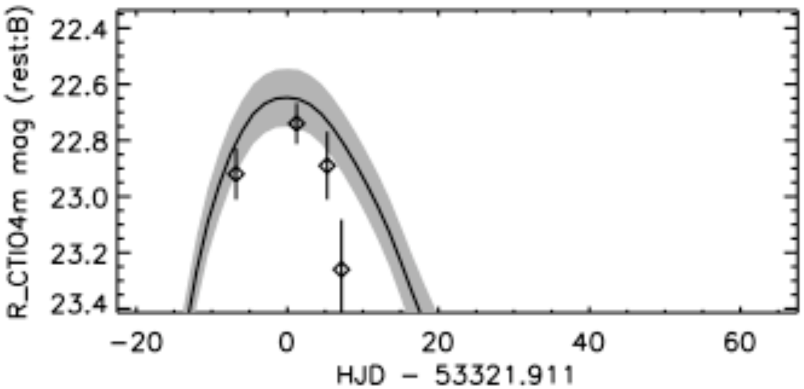
Local Dust?

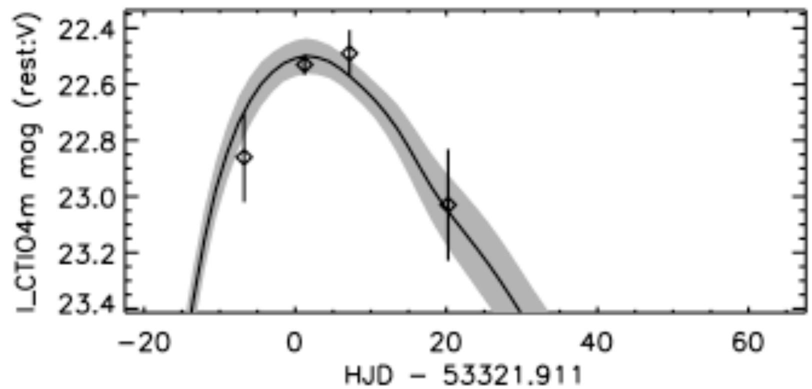


Two Highly Reddened SNe

Goobar (2008): higher density of dust grains in a shell surrounding the SN: multiple scattering steepens effective dust law (also Wang)

Folatelli et al. (2009)





MLCS fit to one of the ESSENCE SNe

h283.v025.nn2

t_0 = 53321.911 R_V = 3.10

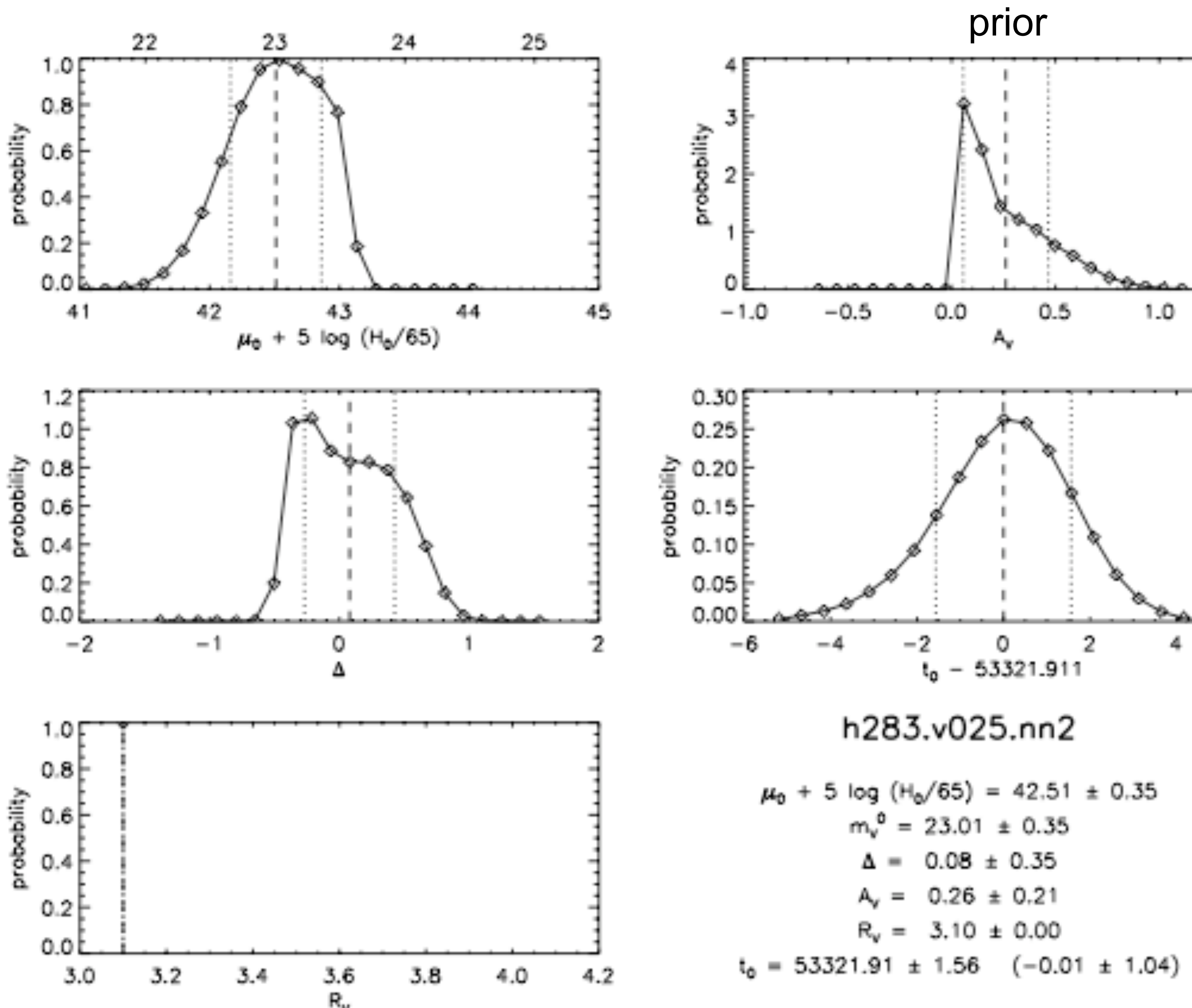
Δ = 0.08 A_V = 0.26

$\mu_0 + 5 \log (H_0/65) = 42.51$

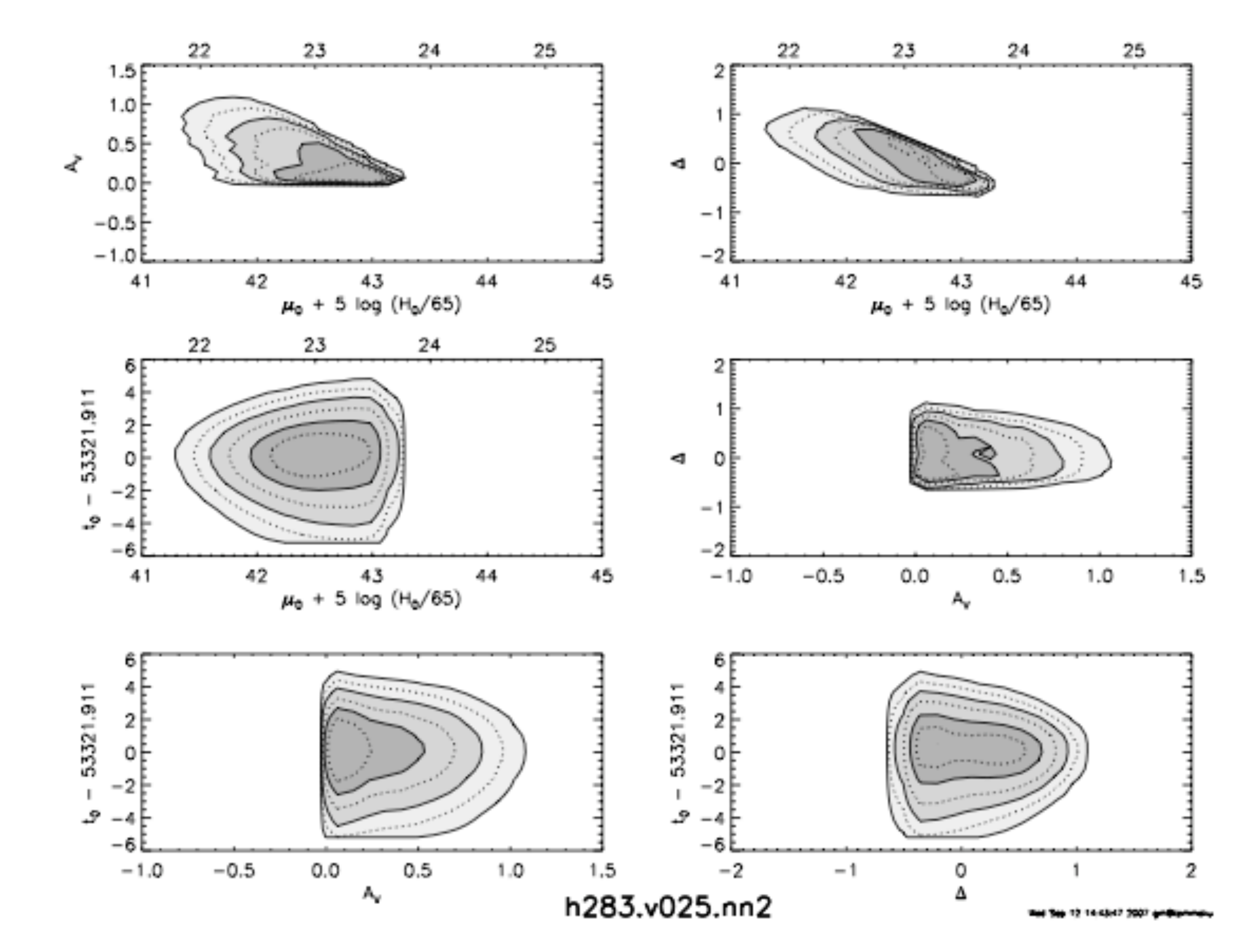
$E(B-V)_{MW}$ = 0.03 z = 0.5020

χ^2/ν = 5.54/4

Marginalized PDFs



μ distribution approximated by Gaussian for cosmology fit



MLCS Likelihood Contours for this object

SALT-II Light-curve Fits

- Fit each light curve using rest-frame *spectral* surfaces:

$$\frac{dF_{\rm rest}}{d\lambda}(t,\lambda) = x_0 \times [M_0(t,\lambda) + x_1 \times M_1(t,\lambda)] \times \exp[c \times CL(\lambda)]$$

light-curve shape

color term

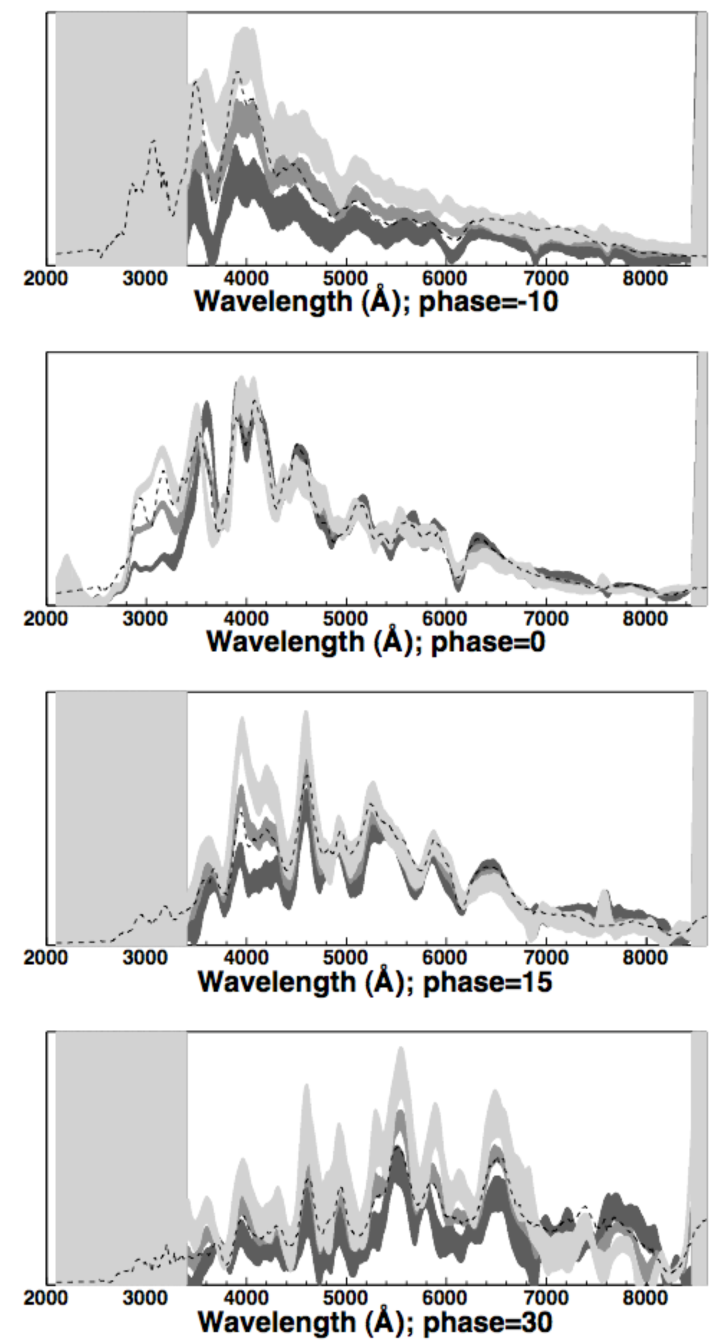
- Light curves fit individually, but distances only estimated globally:

$$\mu_i = m^{*}_{Bi} - M + \alpha \cdot x_{1,i} - \beta \cdot c_i$$

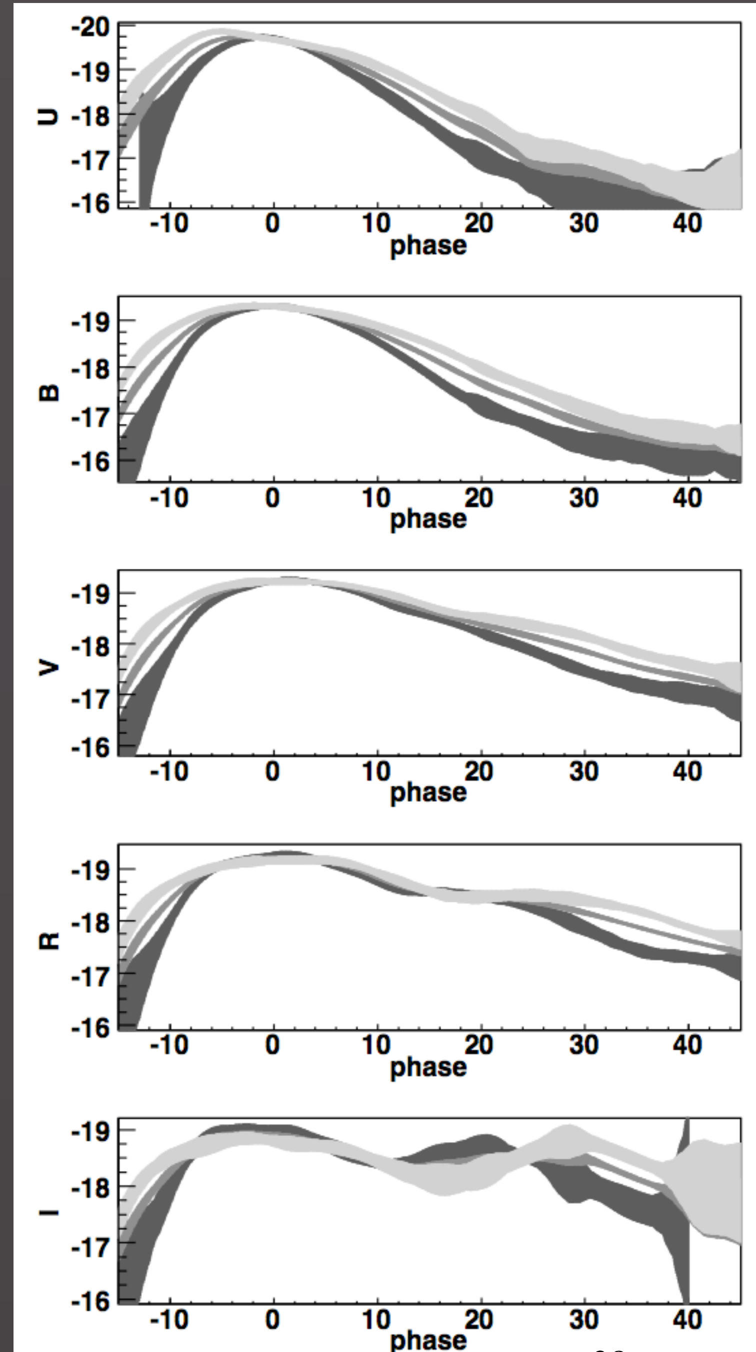
$$\alpha \sim 0.15,\ \beta \sim 2.5$$

Global fit parameters, determined *along with* cosmological parameters by fit to Hubble diagram (so in principle you should not use SALT distance tables to test some other cosmological model)

- Differences from MLCS: not trained just on low-redshift data; flat priors on model parameters; color variations *not* assumed only from dust. *If* dust, then $\beta = R_V + 1$. Find $\beta \sim 2.5$ empirically.



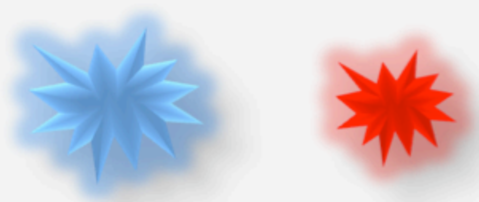
SALT-II templates for x_1=-2,0,2



Color correction: technique matters

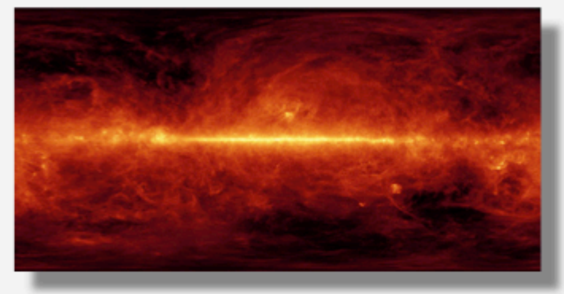
Redder SNe are fainter because of:

Intrinsic SN color



and

Dust extinction



Extinction correction methods:

MLCS: Separate effects of intrinsic color and dust
- Must assume intrinsic SN color distribution with stretch, phase
- Use color to get extinction from assumed dust extinction law

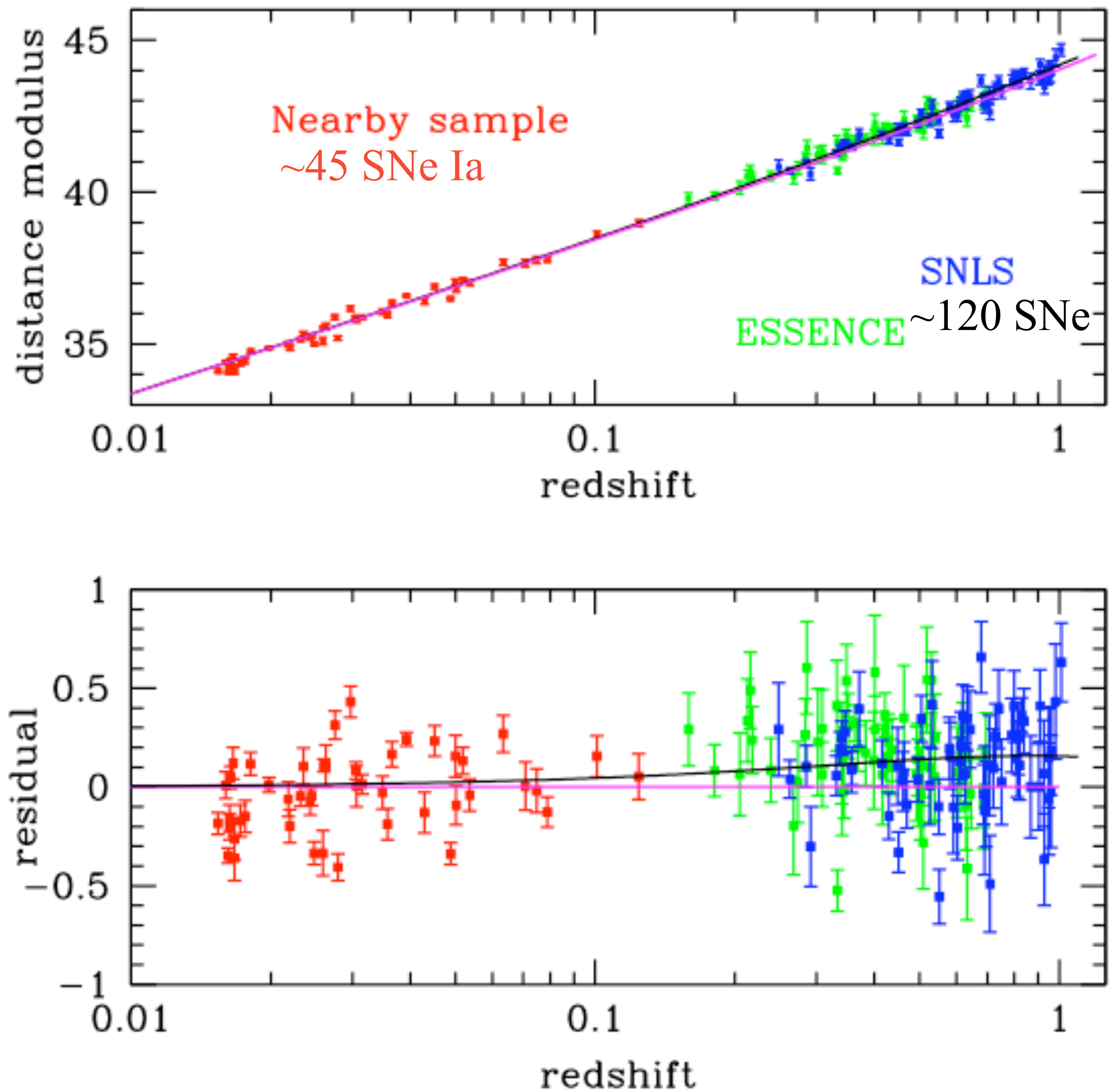
SNLS: Empirical correction

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

$\beta \sim R_B = A_B/E(B-V)$

4.1 if MW dust

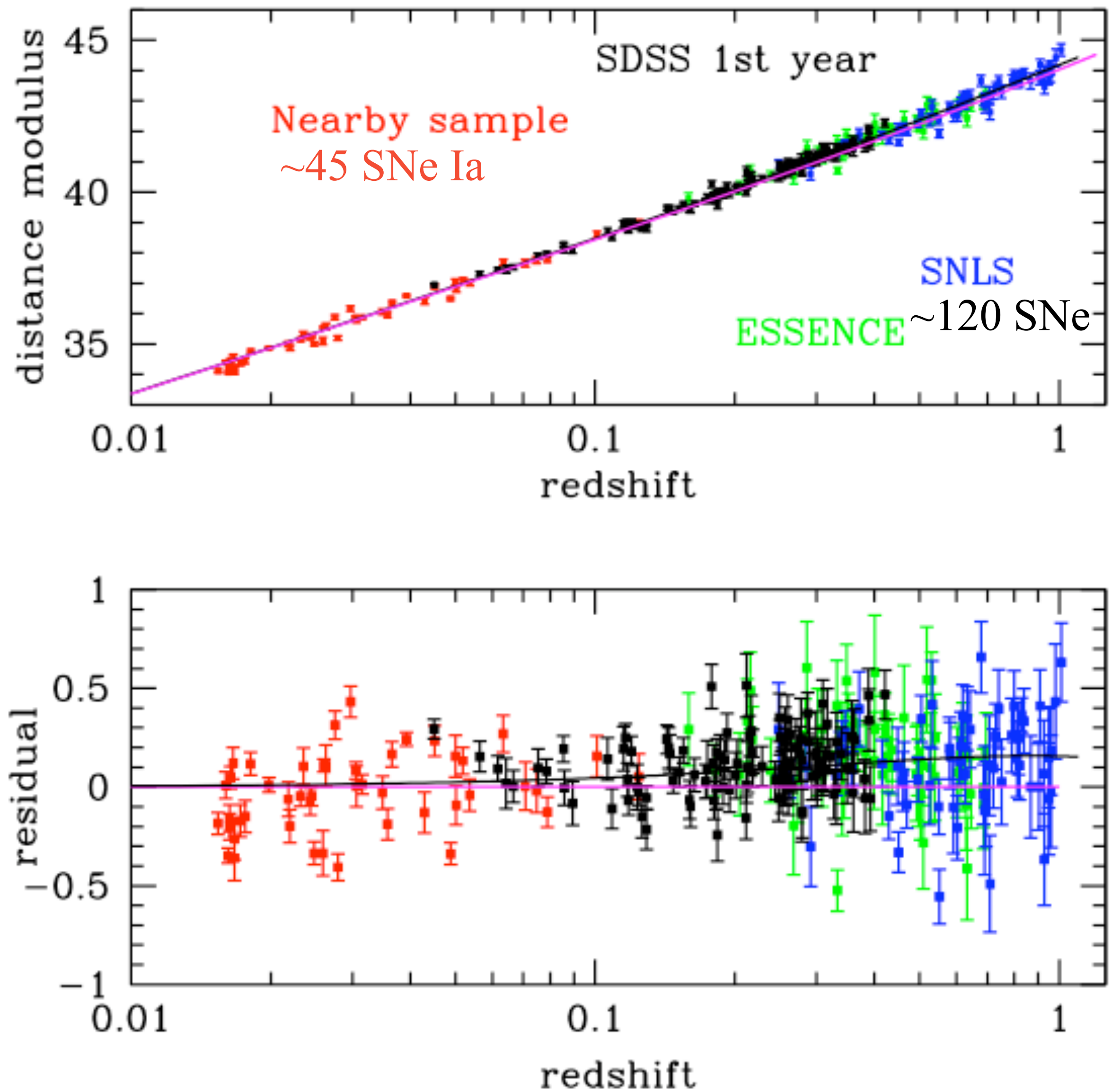
Hubble Diagram



Hubble Diagram with SDSS SNe

103 SNe Ia from first season that pass stringent light-curve quality cuts

Kessler etal (2009)
Lampeitl etal (2009)
Sollerman etal (2009)



SALT MLCS

SDSS only:

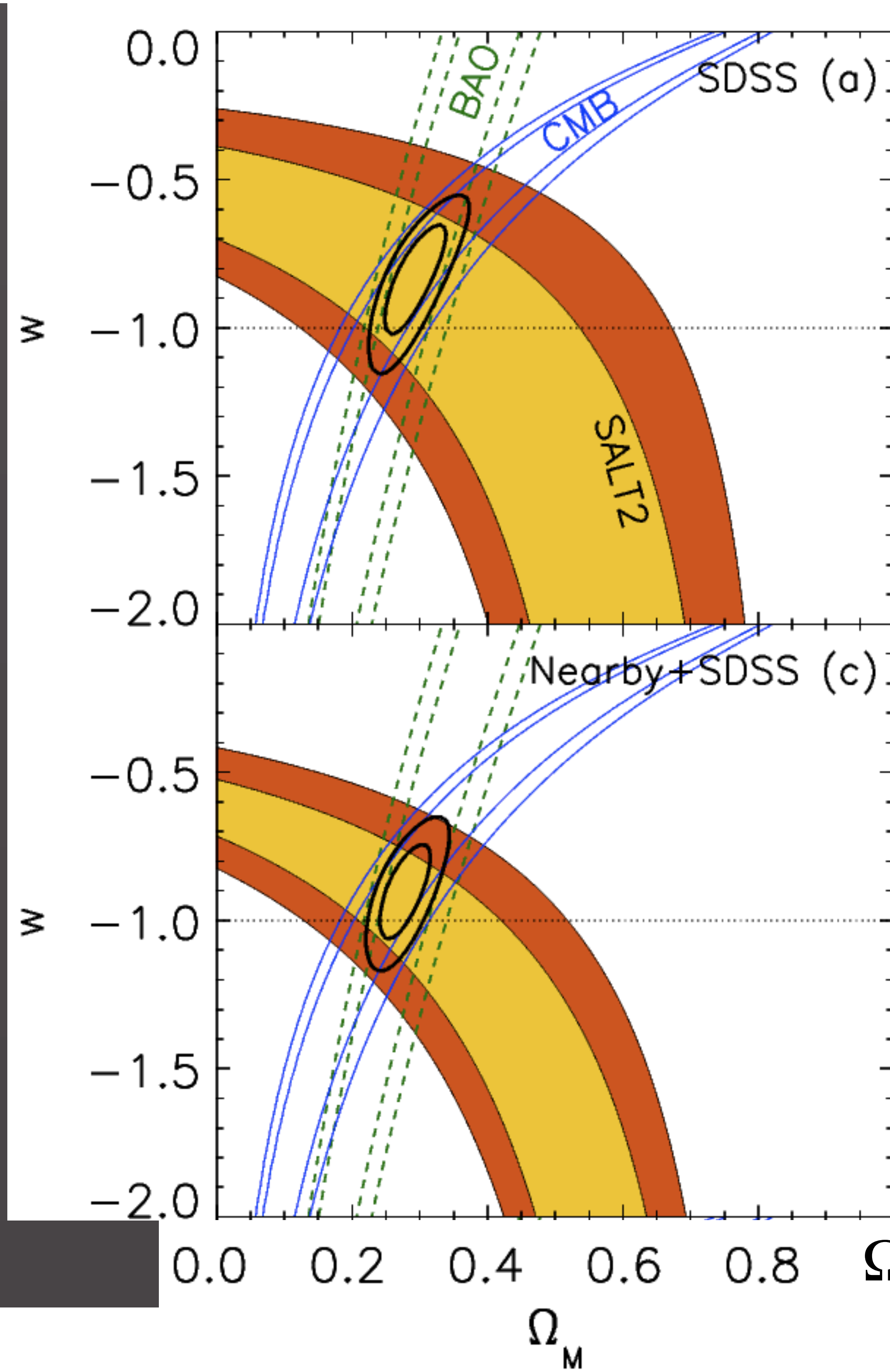
Nearby+SDSS:

MLCS

$$w = -0.93 \pm 0.13(\text{stat})^{+0.10}_{-0.32}(\text{syst})$$

SALT

$$w = -0.92 \pm 0.11(\text{stat})^{+0.07}_{-0.15}(\text{syst})$$



Ω_M

SALT MLCS

Nearby+SDSS:

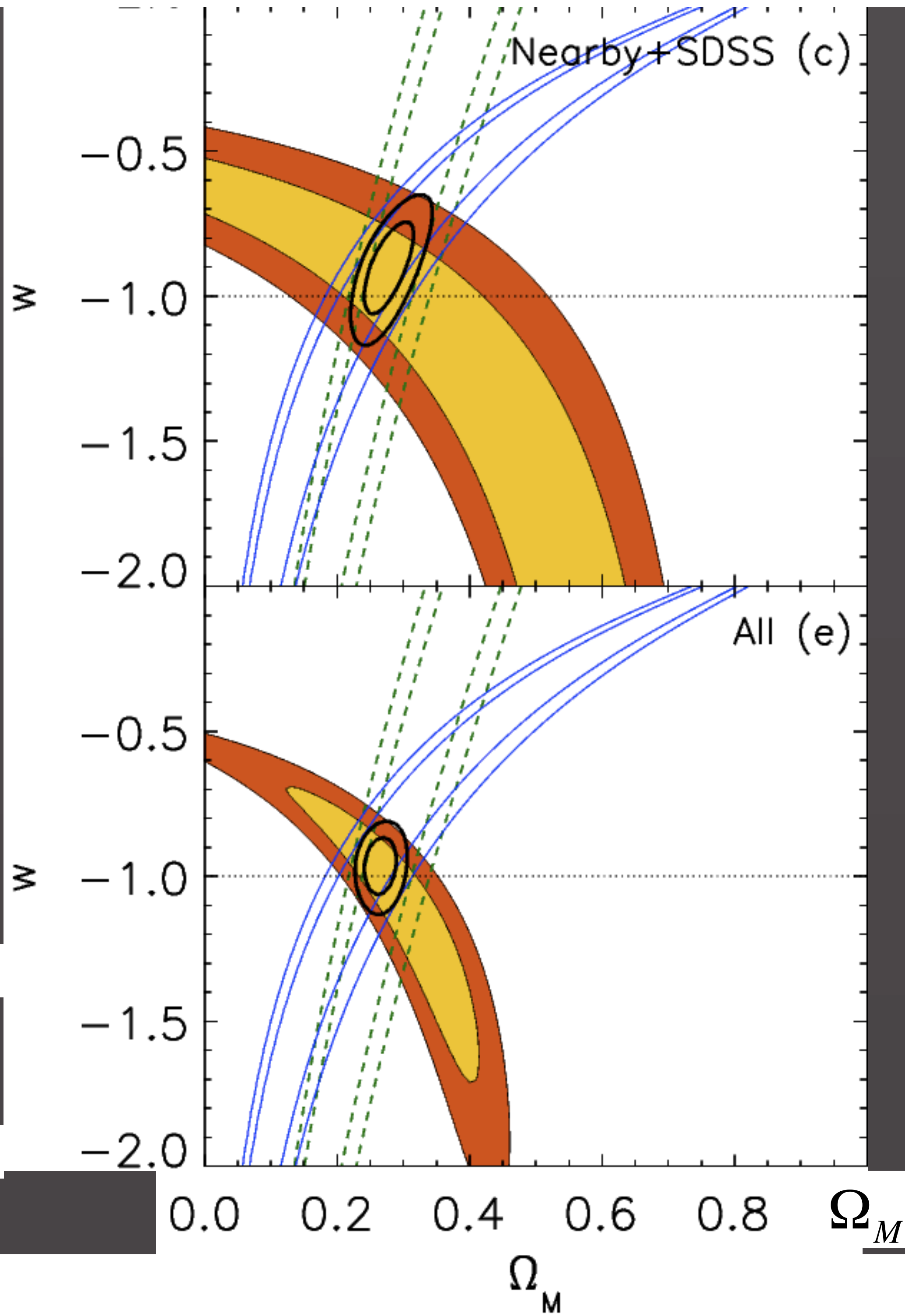
Nearby+SDSS+SNLS +ESSENCE+HST:

MLCS

$w = -0.76 \pm 0.07(\text{stat}) \pm 0.12(\text{syst})$

SALT

$w = -0.96 \pm 0.06(\text{stat}) \pm 0.12(\text{syst})$

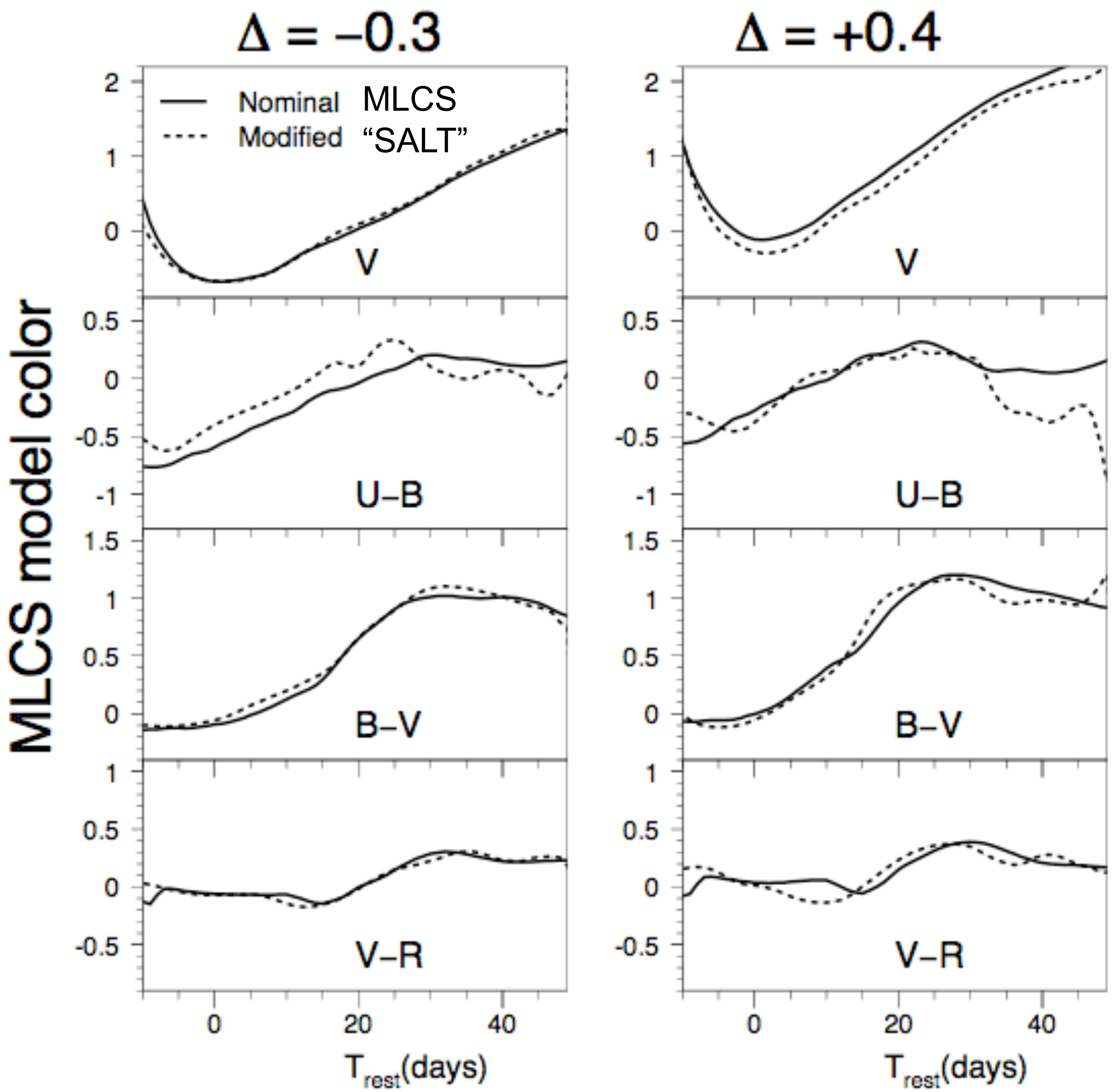


SALT vs MLCS template light curves

Diagnosis:

Large difference in Light-curve model in U-band

Use of prior on extinction in MLCS



A Tale of Two Fitters

MLCS:

• U-band model trained only on low-redshift (observer-frame) U-band data (calibration, atmospheric variations)

• Assumes *all* excess color due to dust extinction (some of it must be); dust prior dominates at high-redshift

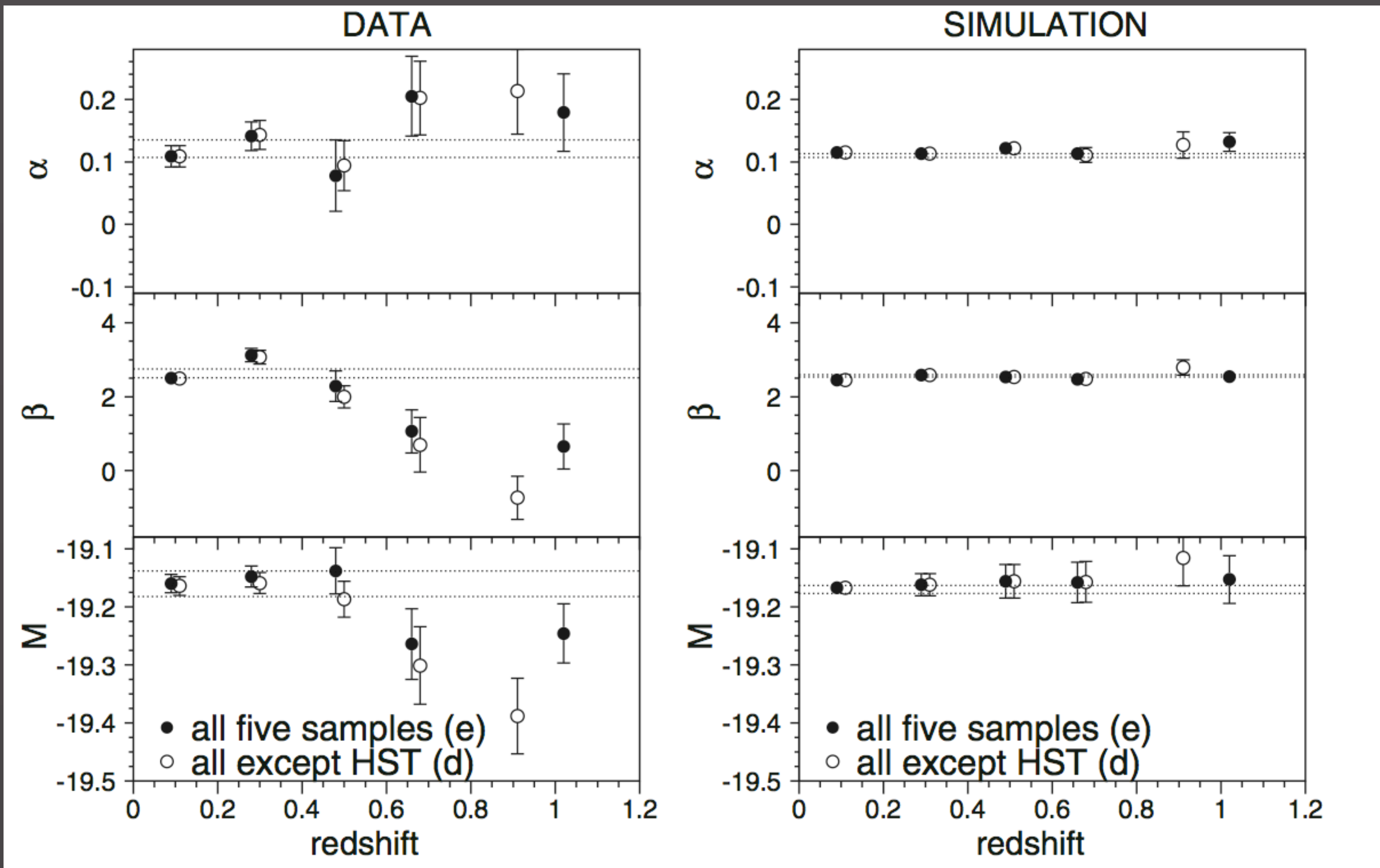
SALT:

• Global fit for color/dust parameter β: minimizing Hubble-scatter can lead to bias

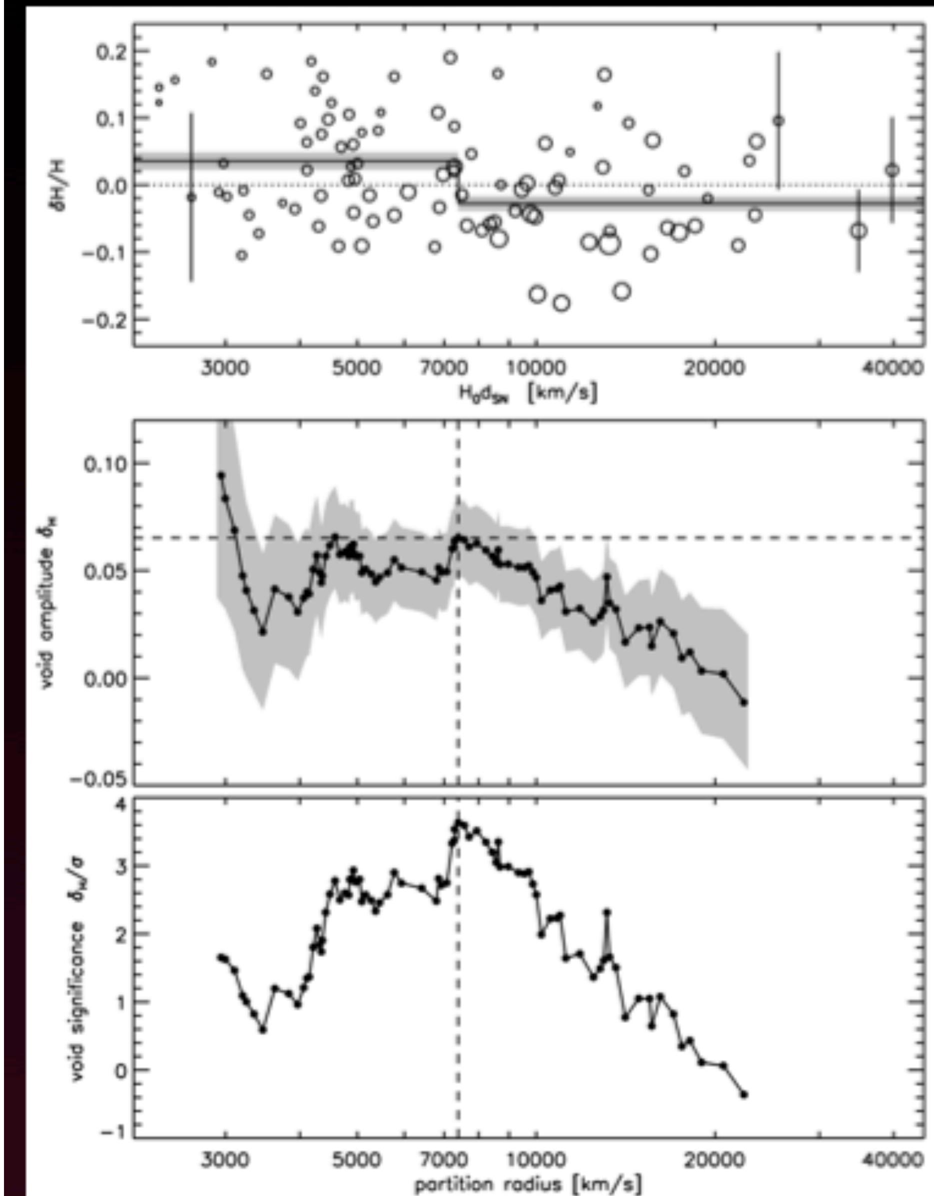
• Trend toward bluer colors at high-z: if allow $\beta(z)$, see strong trend with redshift

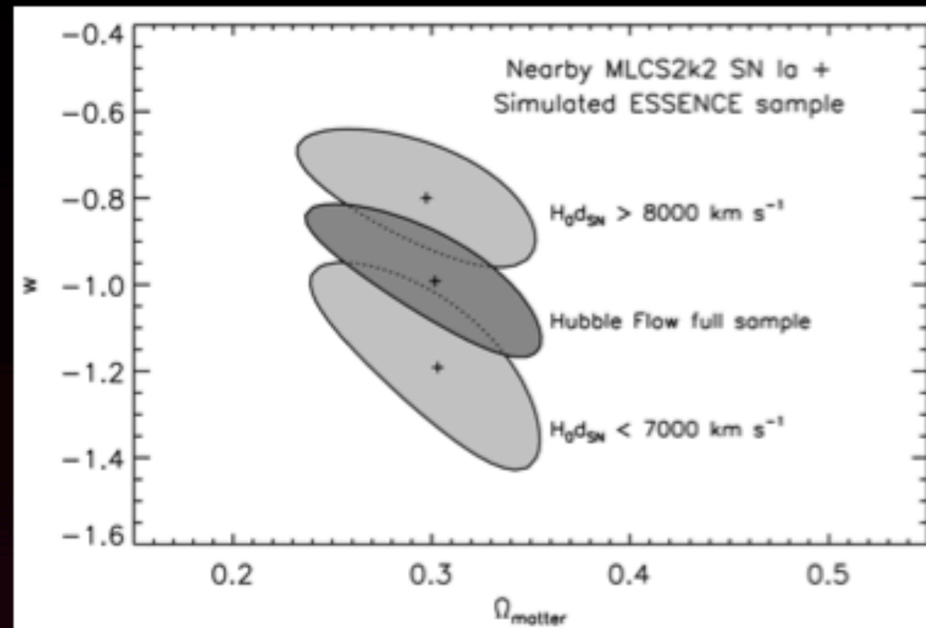
•Retrain and refine the models with newer data

SALT Parameters vs. Redshift



A Hubble Bubble?



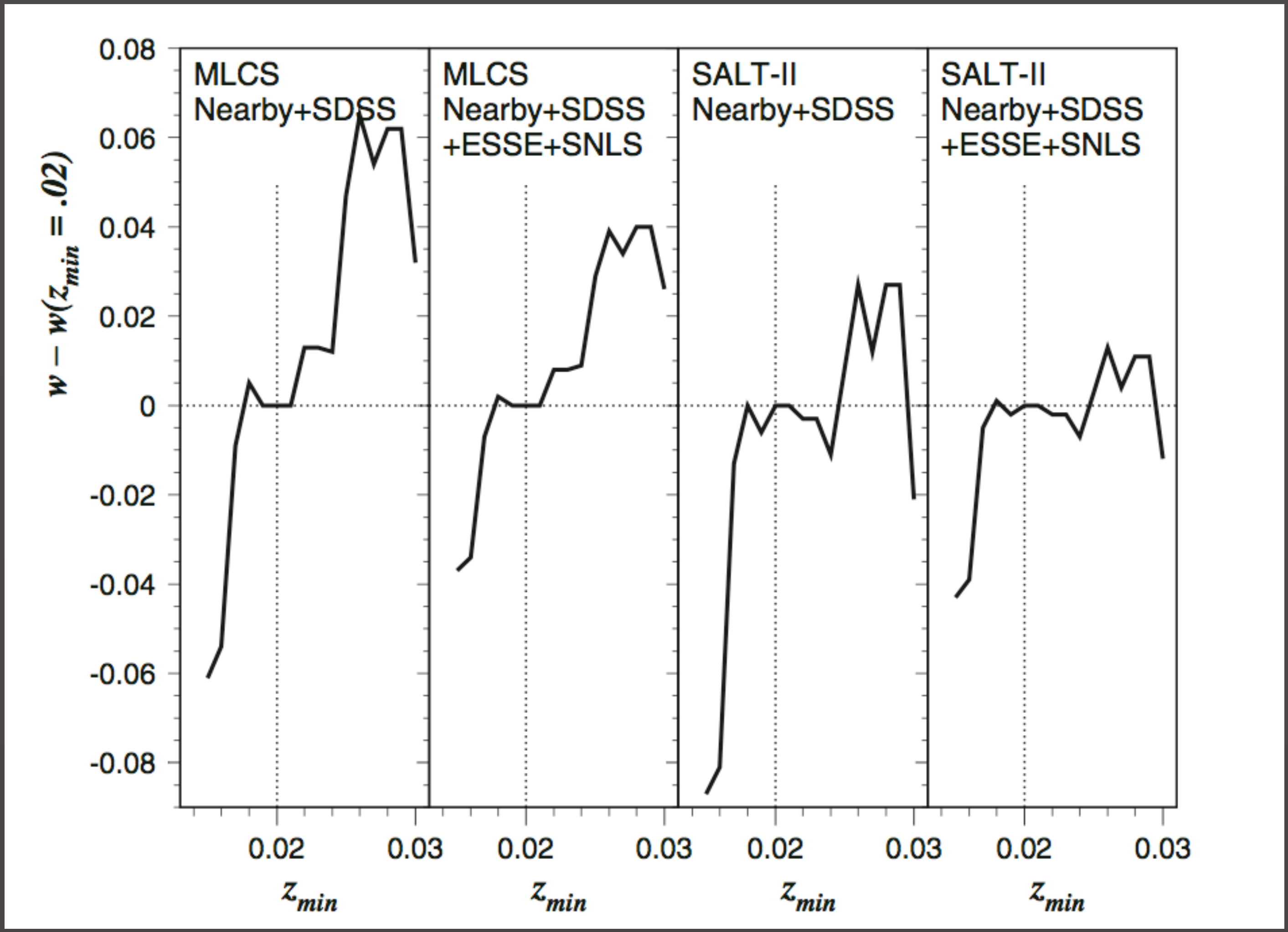


Whatever the cause (real void or systematic effect), this signal is in the low-z data and has a huge impact on measuring w! To proceed we need to check and understand this result.

See also Conley et al 2007: treatment of dust & SN colors

Jha, Riess, & Kirshner (2006)

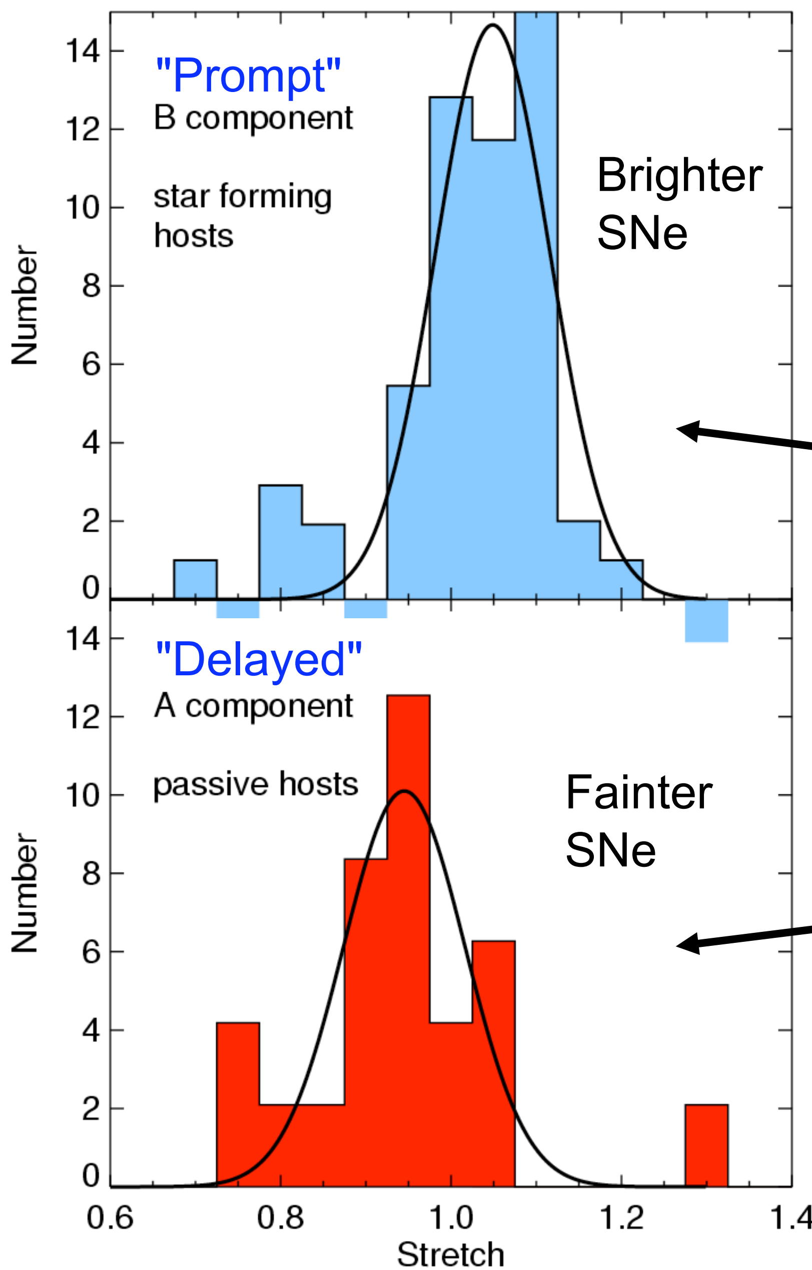
Vary minimum redshift

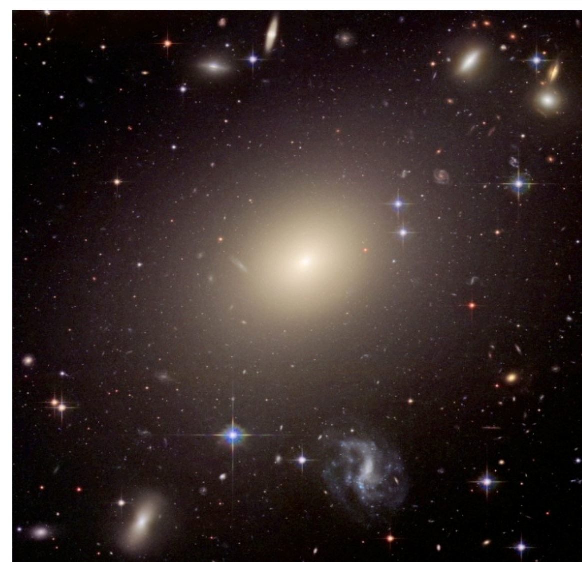


Correlations of SN Ia and Host-galaxy Properties

Host Population correlated with SN Ia Luminosity

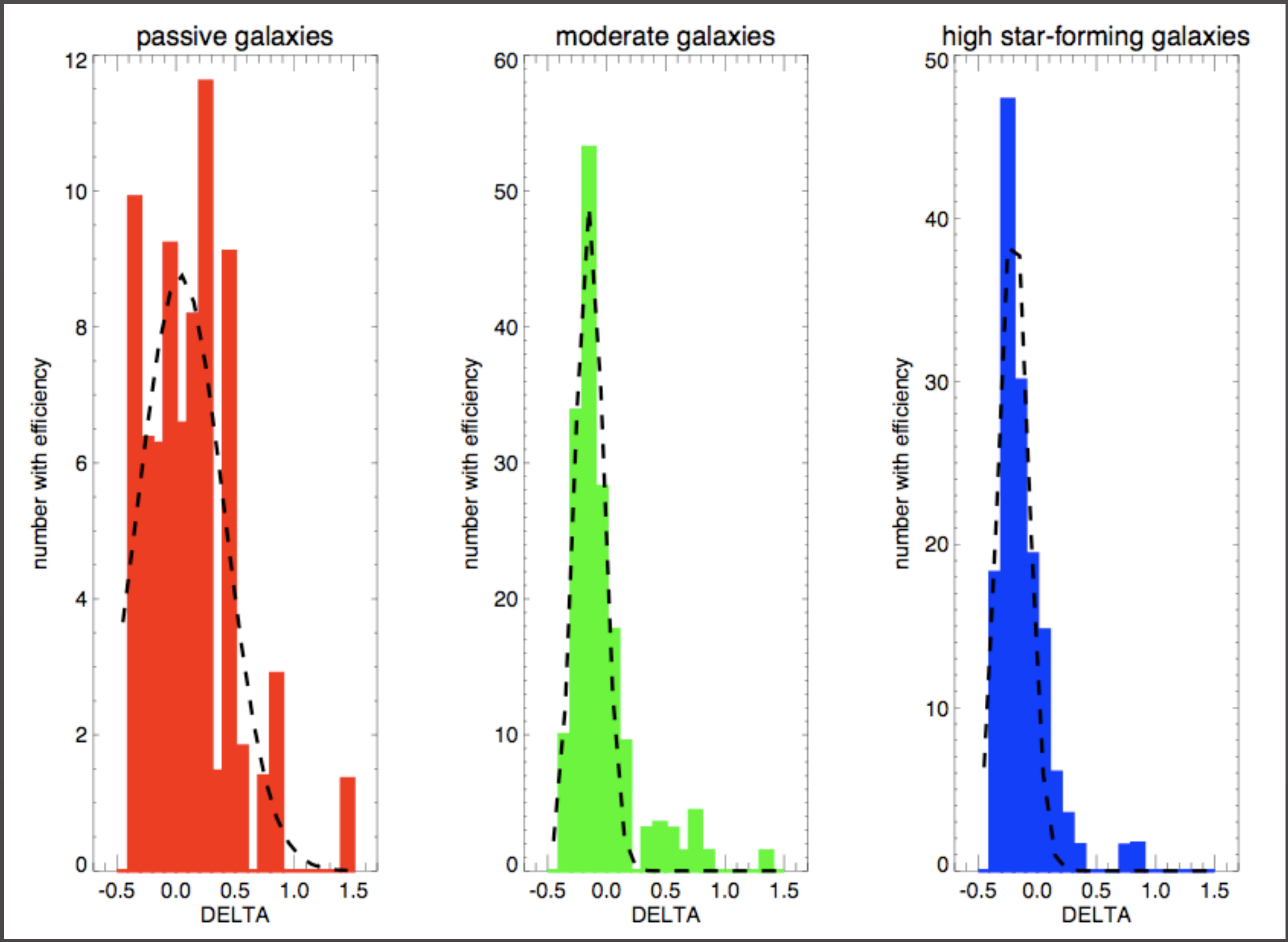
Sullivan et al. 2006, Howell et al. 2007, Jha etal 2007





Also brighter SNe in lower-stellar-mass hosts

SN Ia Luminosity correlates with Host Galaxy Type



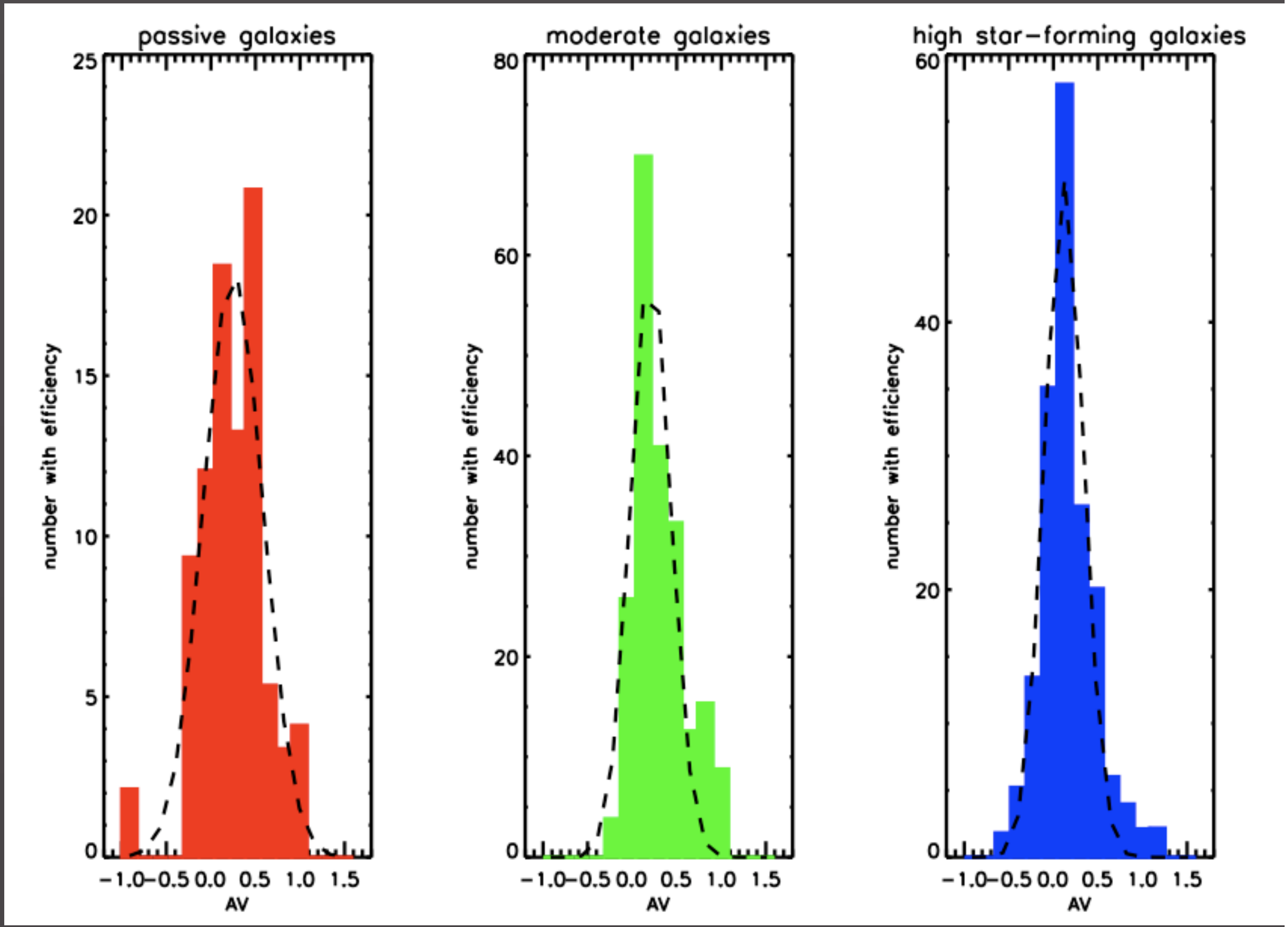
SDSS

Bright SN Luminosity/Decline Rate Faint

Smith et al

SN Ia Color doesn't correlate strongly with Host Galaxy Type

Why aren't `spirals' dustier than `ellipticals'?



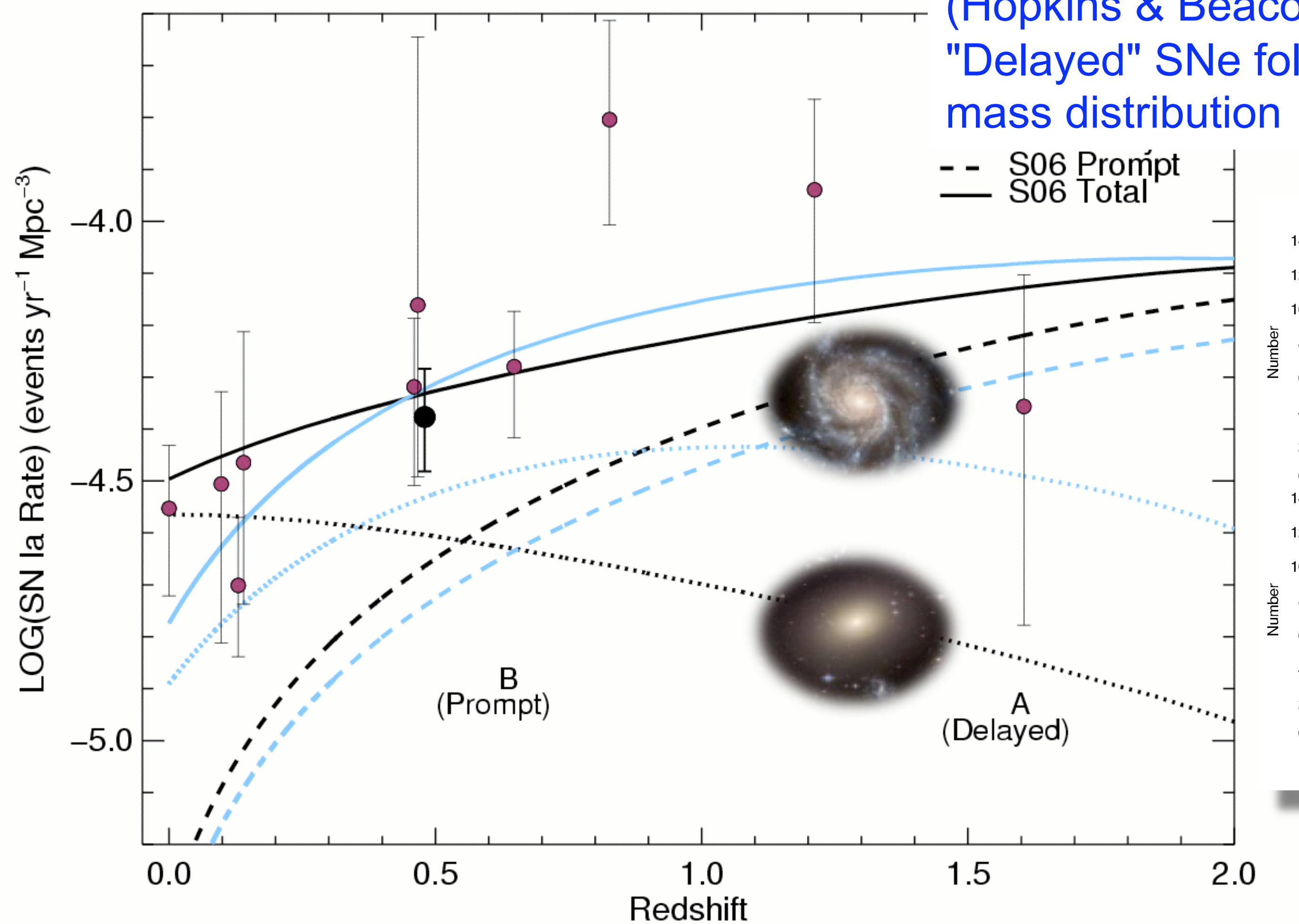
Color/reddening

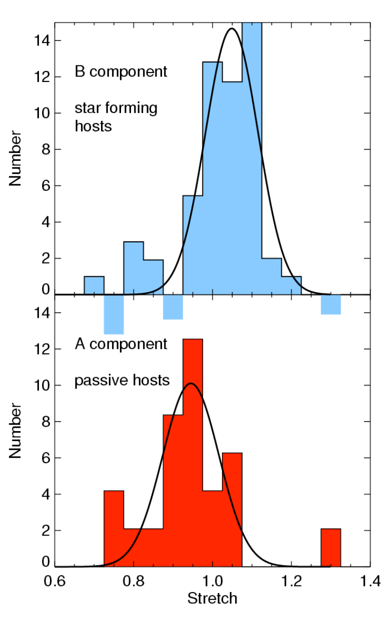
Smith et al

SN Rates vs. redshift

Sullivan et al. 2006, Howell et al. 2007

"Prompt" SNe follow declining cosmic star formation history (Hopkins & Beacom 2006), "Delayed" SNe follow growing stellar mass distribution





Predict relative contribution from each component vs. redshift

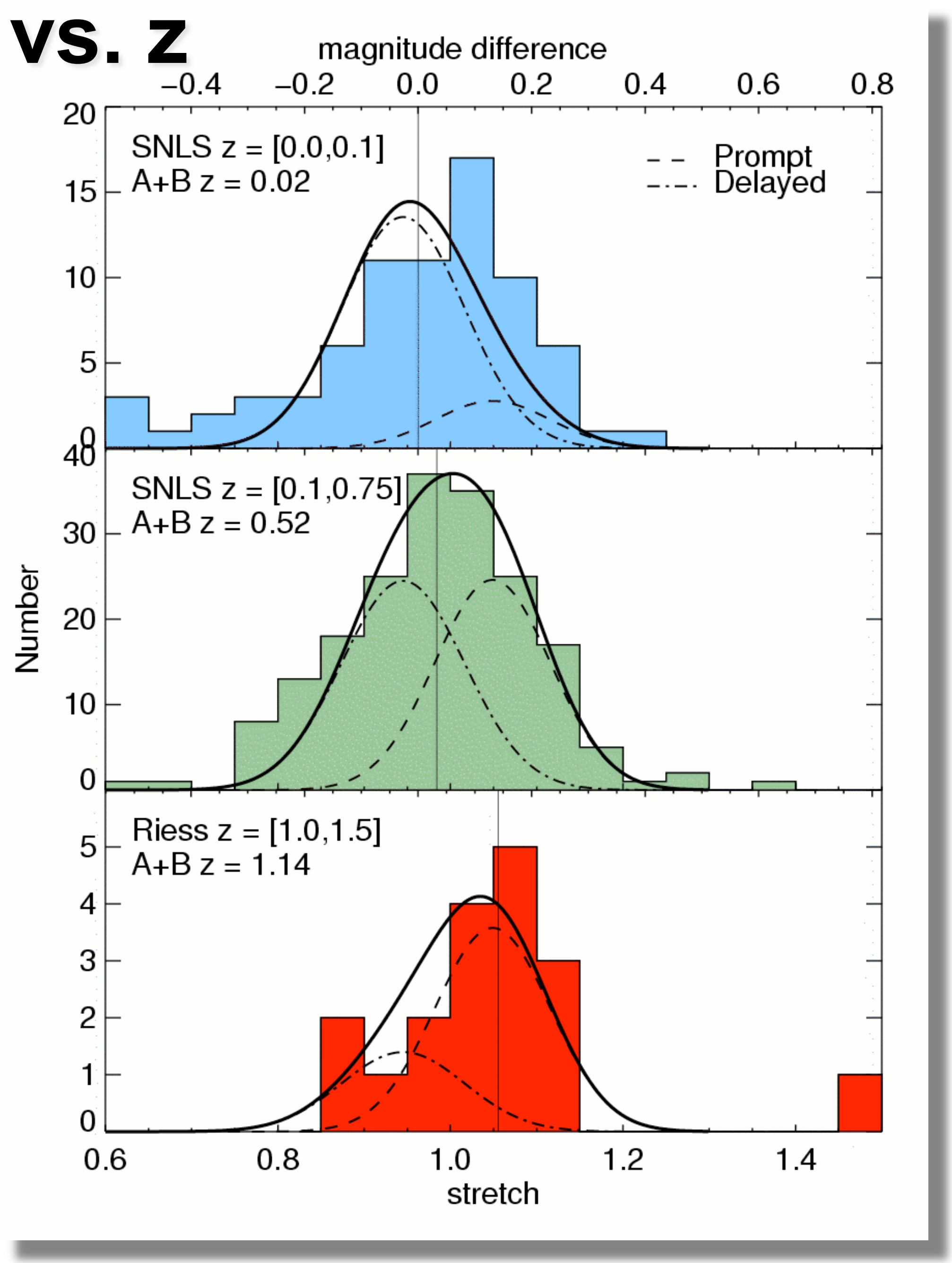
SN population drift vs. z

Howell et al. 2007

Histograms: data
Gaussians: prediction from rates

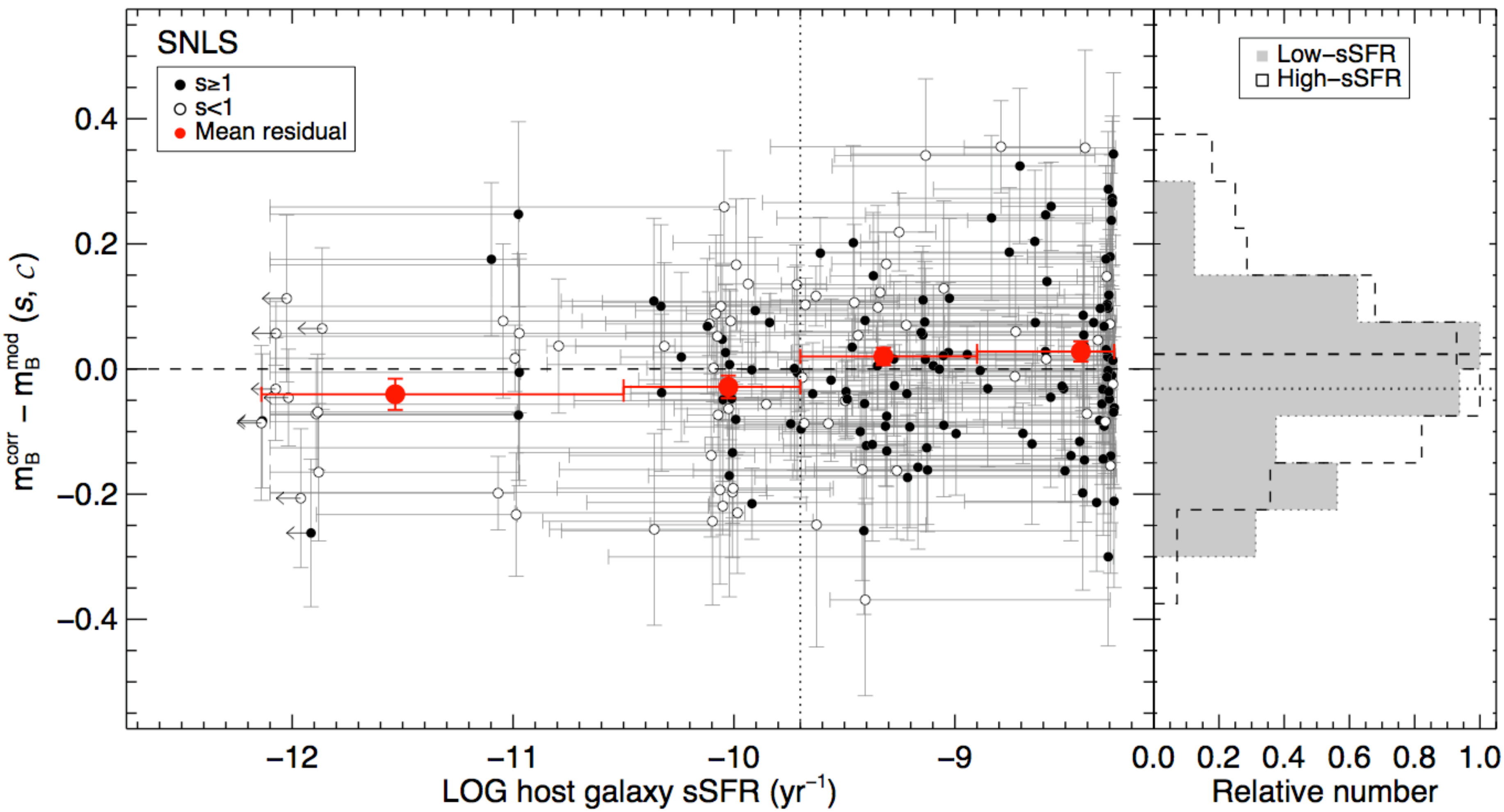
Conclusion: Average stretch, and thus average *observed* brightness of SNe Ia **evolves with redshift.**

Average SN Ia was 12% brighter at z > 1.



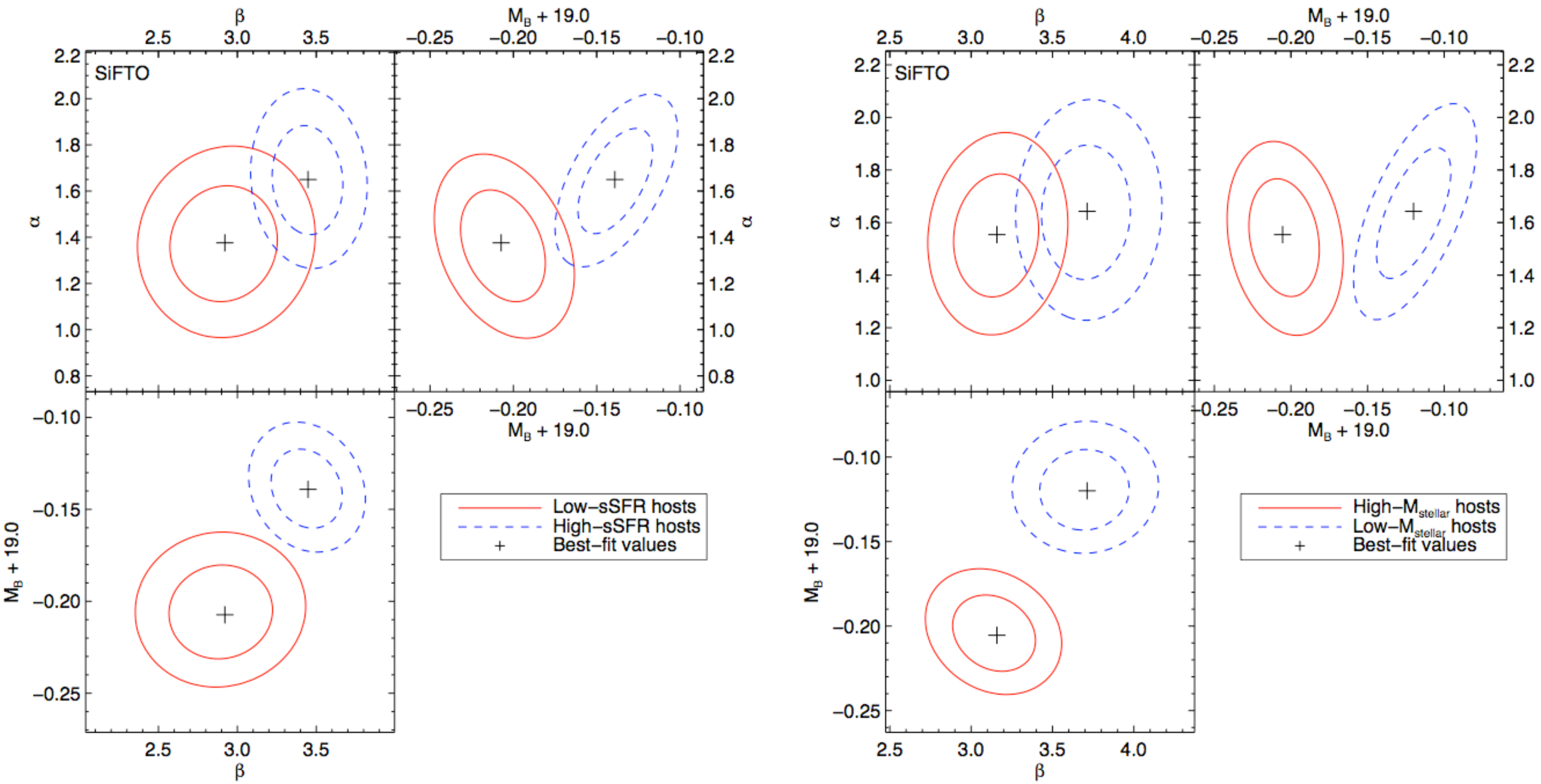
However, if stretch correction works, this population evolution should not affect cosmology

Hubble Residuals vs. Host Galaxy Specific Star Formation Rate



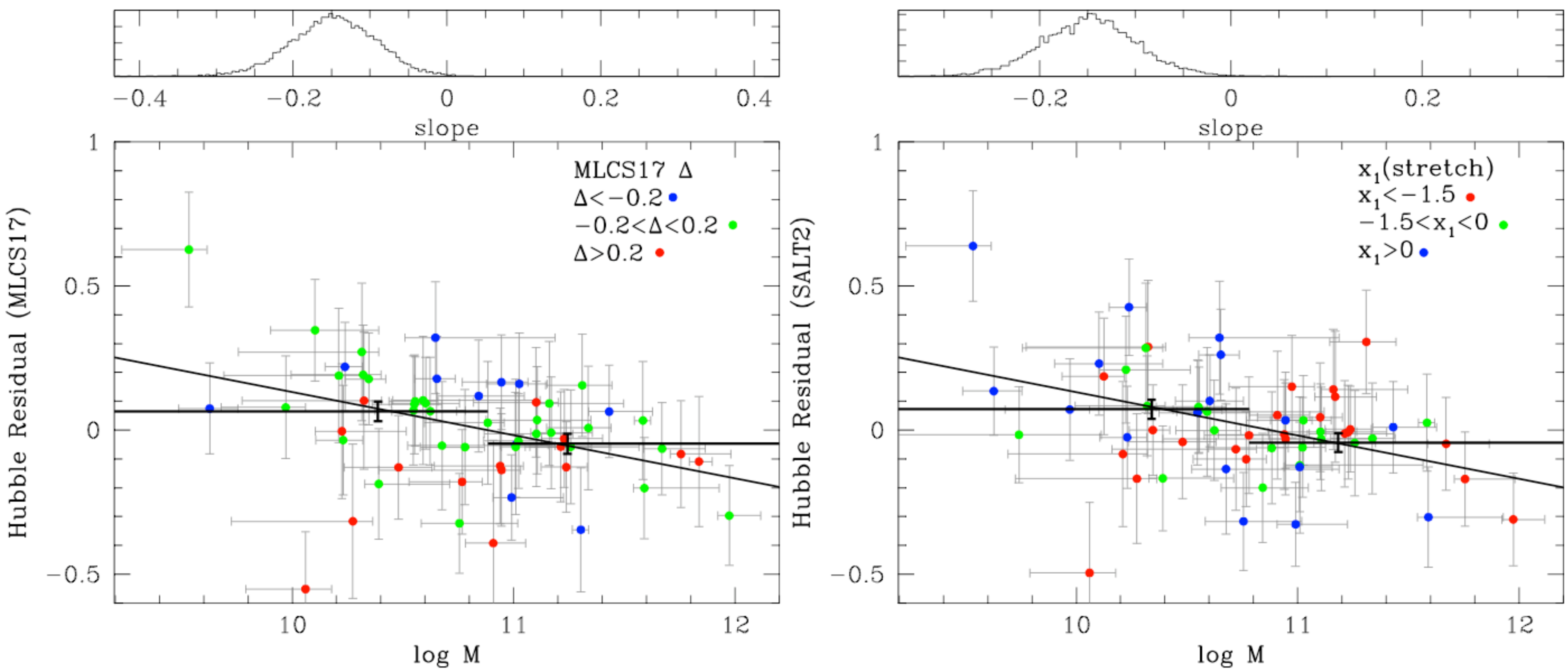
Events of same light-curve shape and color are ~0.08 mag brighter (after LCS correction) on avg. in galaxies with low star-formation rate (or high stellar mass): *opposite* to pre-correction trend

Sullivan etal 10



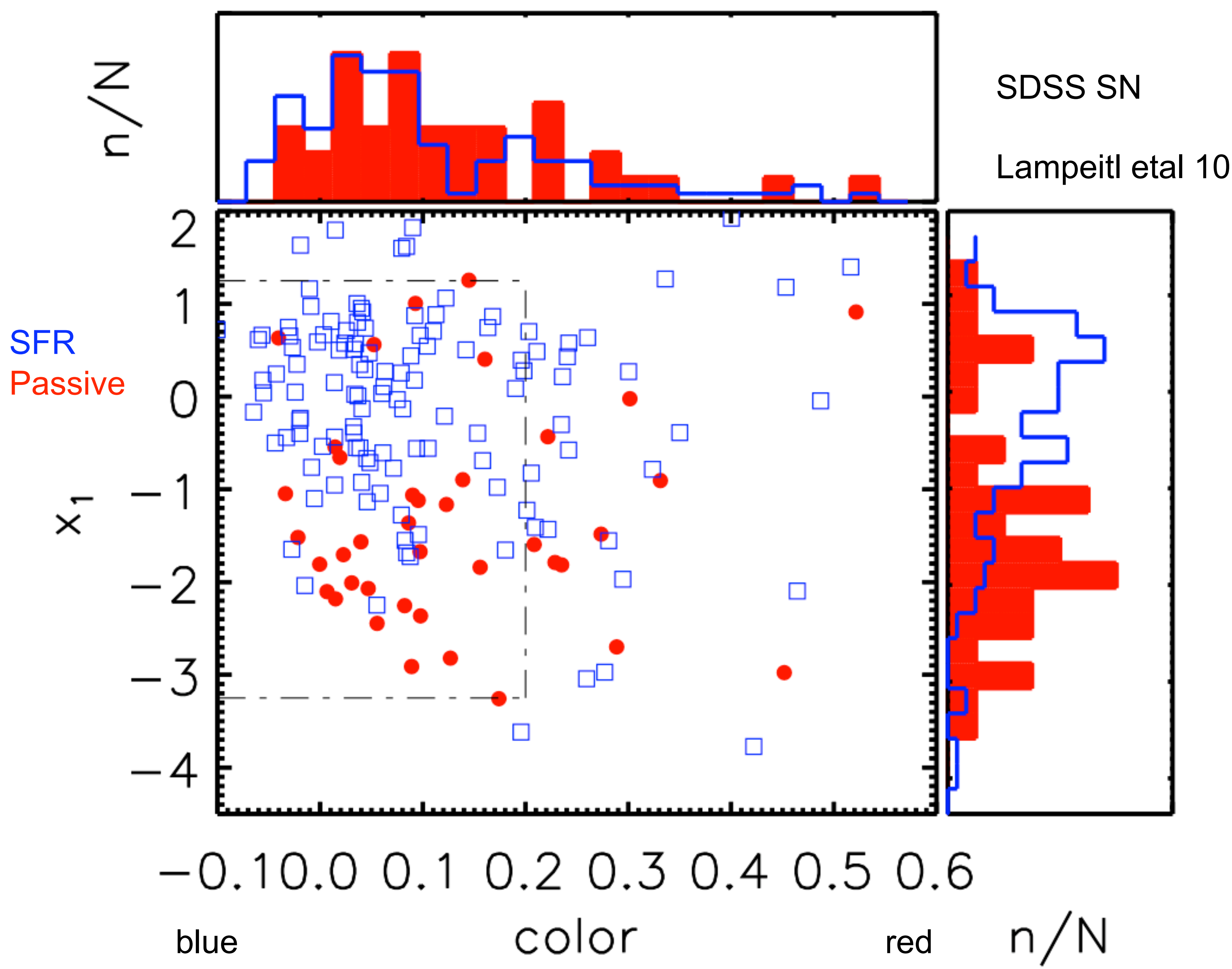
Events of same light-curve shape and color are ~0.08 mag brighter (after LCS correction) on avg. in galaxies with low star-formation rate (or high stellar mass): opposite to pre-correction trend: metallicity effect? Sullivan etal 10

Fit cosmology with 2 populations of M_B: shifts w by~0.04-0.08 with BAO prior

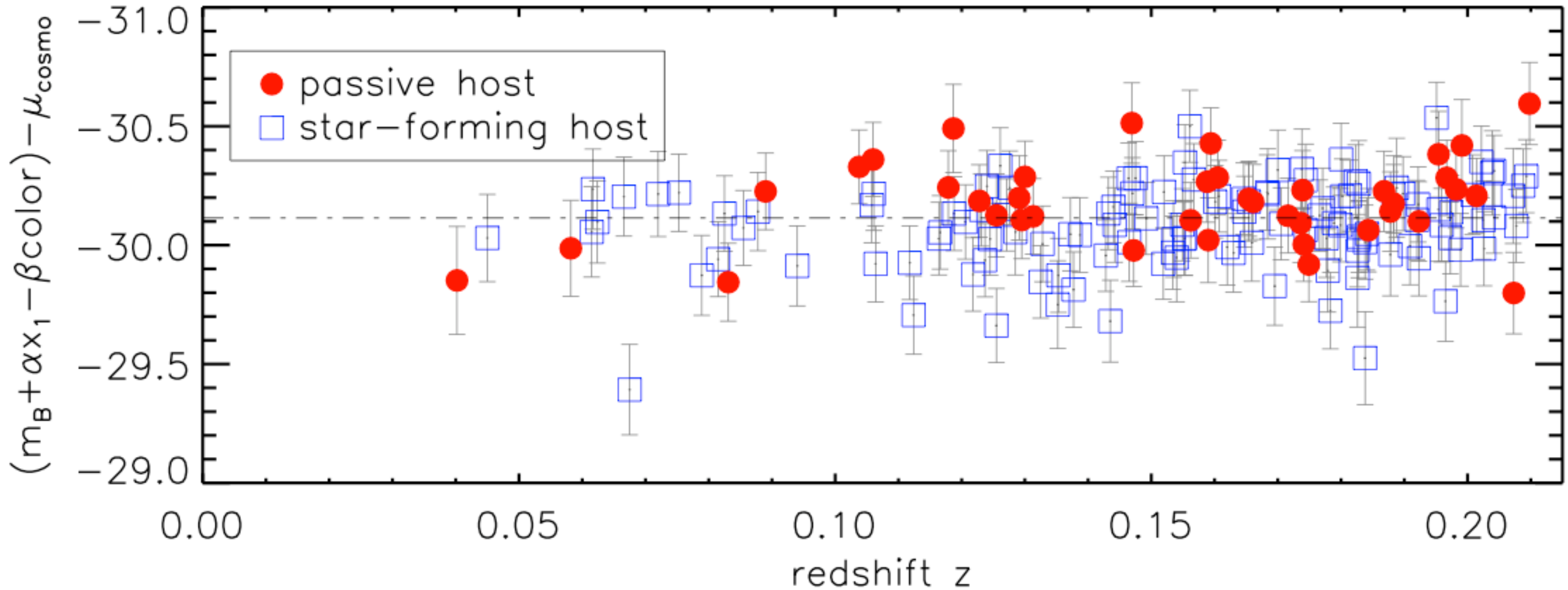


Same trend seen in low-redshift SN Ia sample

Kelly etal 09

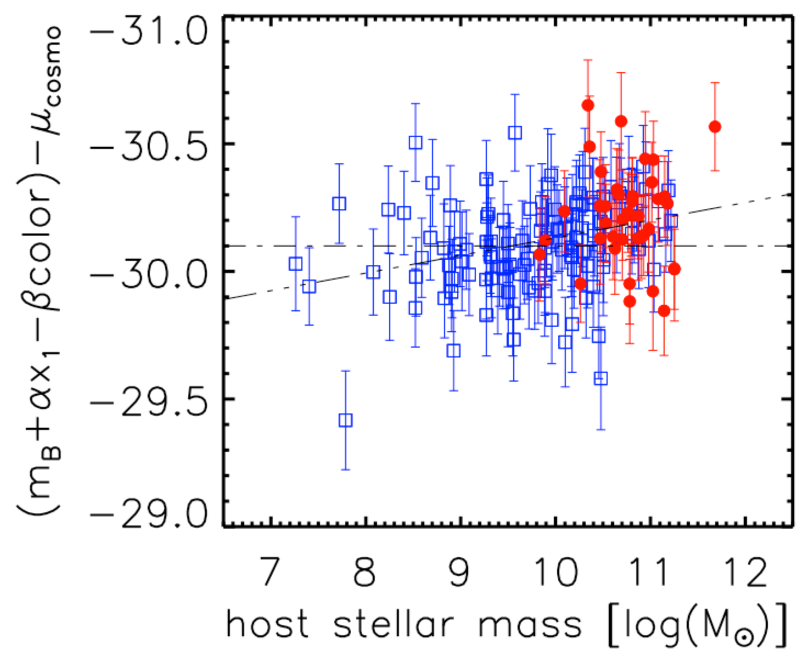


SDSS SN
Lampeitl etal 10
SFR
Passive
n/N
x_1
2
1
0
−1
−2
−3
−4
−0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
blue
color
red
n/N



SDSS SN

Lampeitl etal 10



Systematic Errors (and Controls)

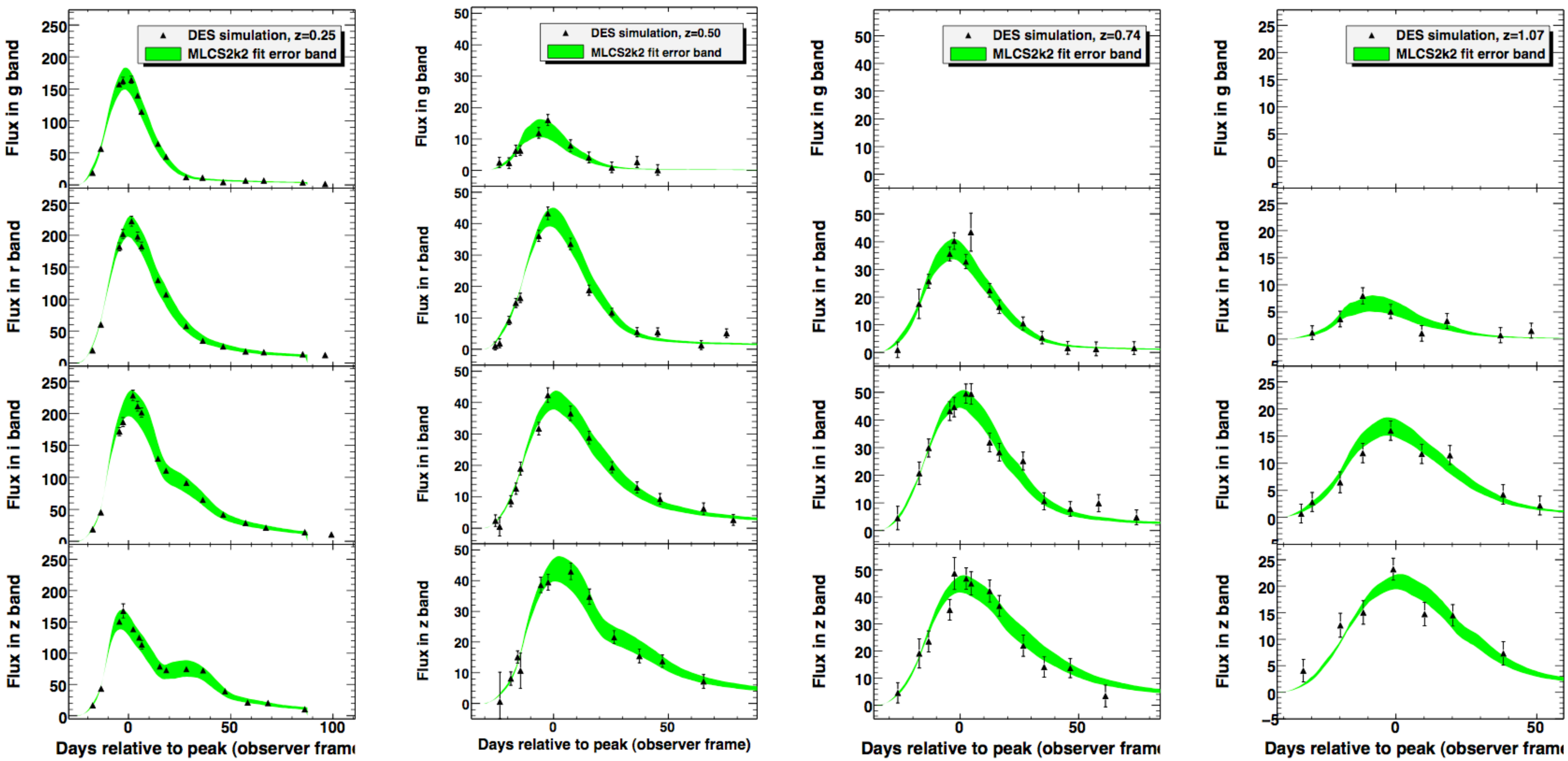
- Dust and SN color variation (multi-λ, NIR, high S/N)
- U-band model discrepancy (retrain with better rest-frame U-band data, e.g., from SDSS SN g-band)
- Minimum redshift effect (model coherent flows; larger, better, low-redshift samples)
- Selection effects (artificial SNe, Monte Carlo simulations)
- Population evolution (SN properties vs host environment)
- Photometric calibration (system response calibration & cross-calibration of systems)
- Sample purity (spectroscopy at least for subsample)
- All (subdivide large samples to cross-check)

The Future is (Mostly) Photometric

- Pan-STARRS, Dark Energy Survey, LSST: thousands to tens of thousands of multi-band light curves to z~1
- Limited spectroscopic resources for follow-up, replace spectroscopic with photometric SN classification
- Very large samples will enable subdivision to study correlations and control systematics
- Photometric-redshift precision at high-z does not critically impact DE constraints but degrades (SN-type) sample purity
- SN spectroscopic subsamples (both Ia and non-Ia) required to quantify purity and define SN Ia color selection. SDSS SN test of photometric classifier: ~92% complete, 5% impurity (M. Sako)

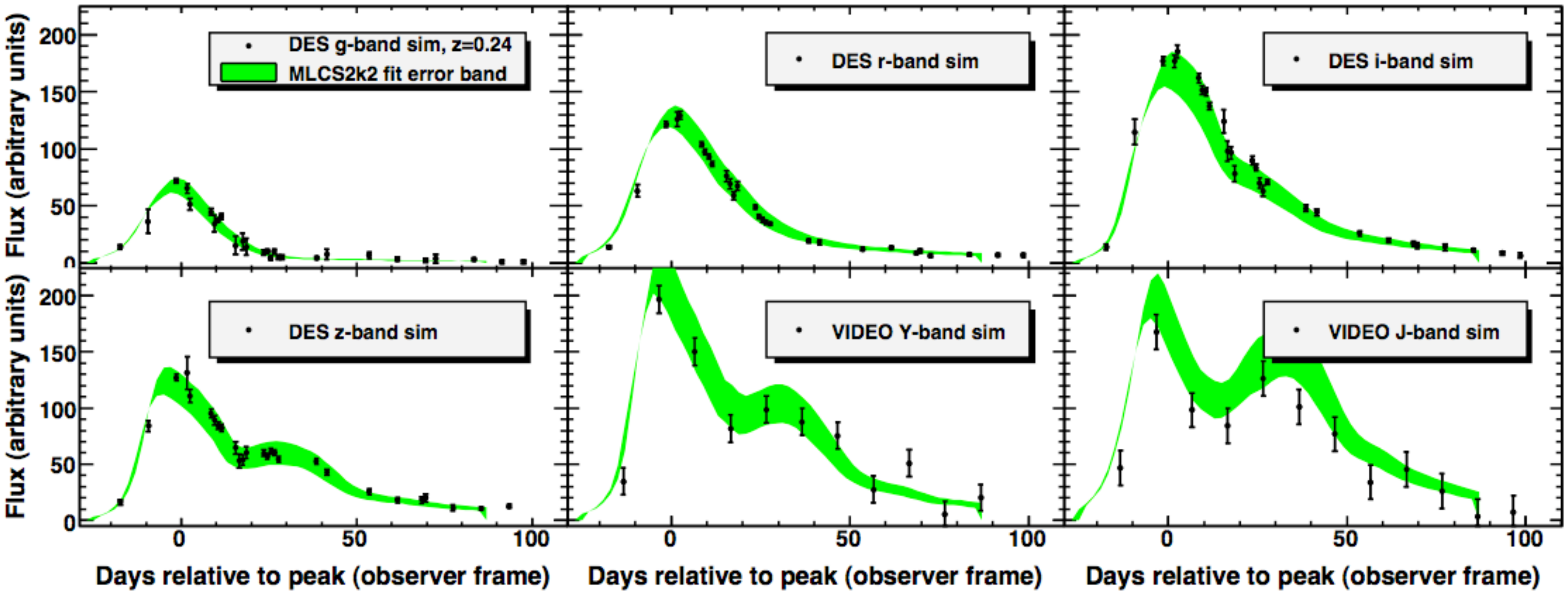
DES SN Simulated Light Curves

DARK ENERGY SURVEY



See Bernstein etal draft DES SN paper on the class website (do not circulate)

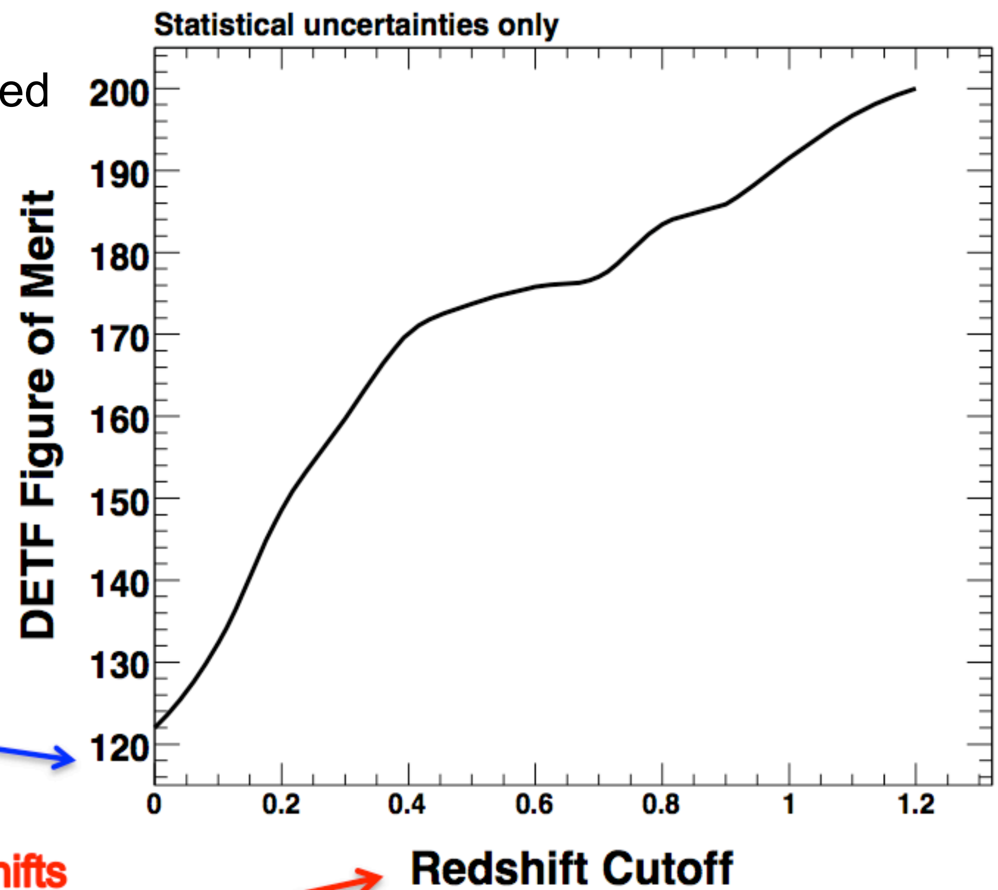
DES + VISTA VIDEO NIR



DARK ENERGY SURVEY

Photometric Redshift Only?

DES simulation:
~3000 well-measured SNe Ia with <z>~0.6



Suppressed 0!

Spectroscopic redshifts below this cutoff. Photometric above.

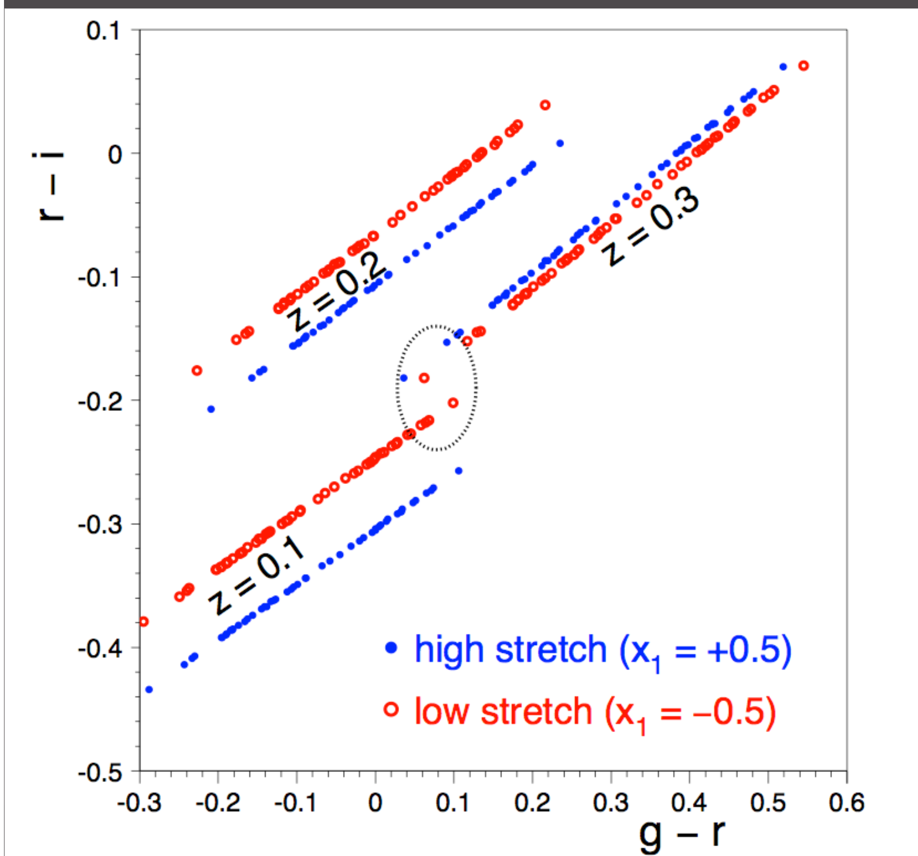
Photometric redshift=SN colors plus galaxy colors

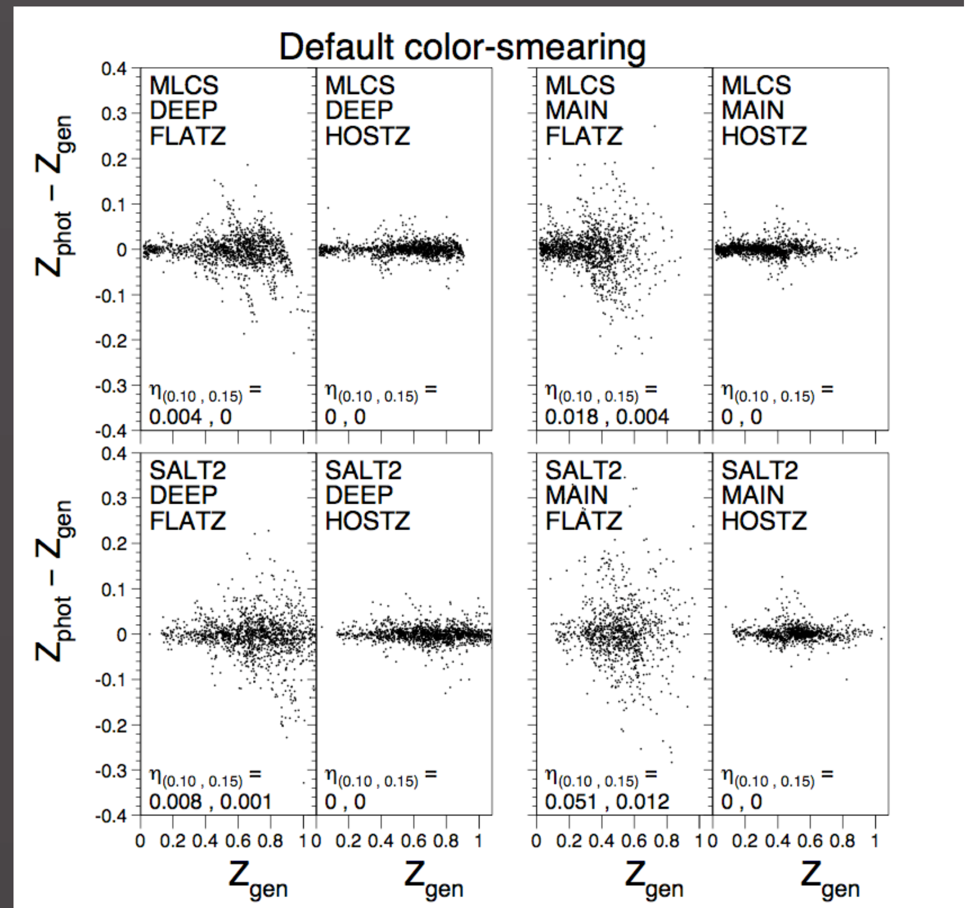
Statistical Errors Only!

DES will obtain host spectroscopic redshifts (improves typing); photo-z cosmology more relevant for LSST

Supernova Photo-z's

Include redshift as a light-curve fit parameter





Kessler, et al 2010

LSST Simulation

Development of Photometric SN Classification Techniques

Blind SN Classification Challenge:

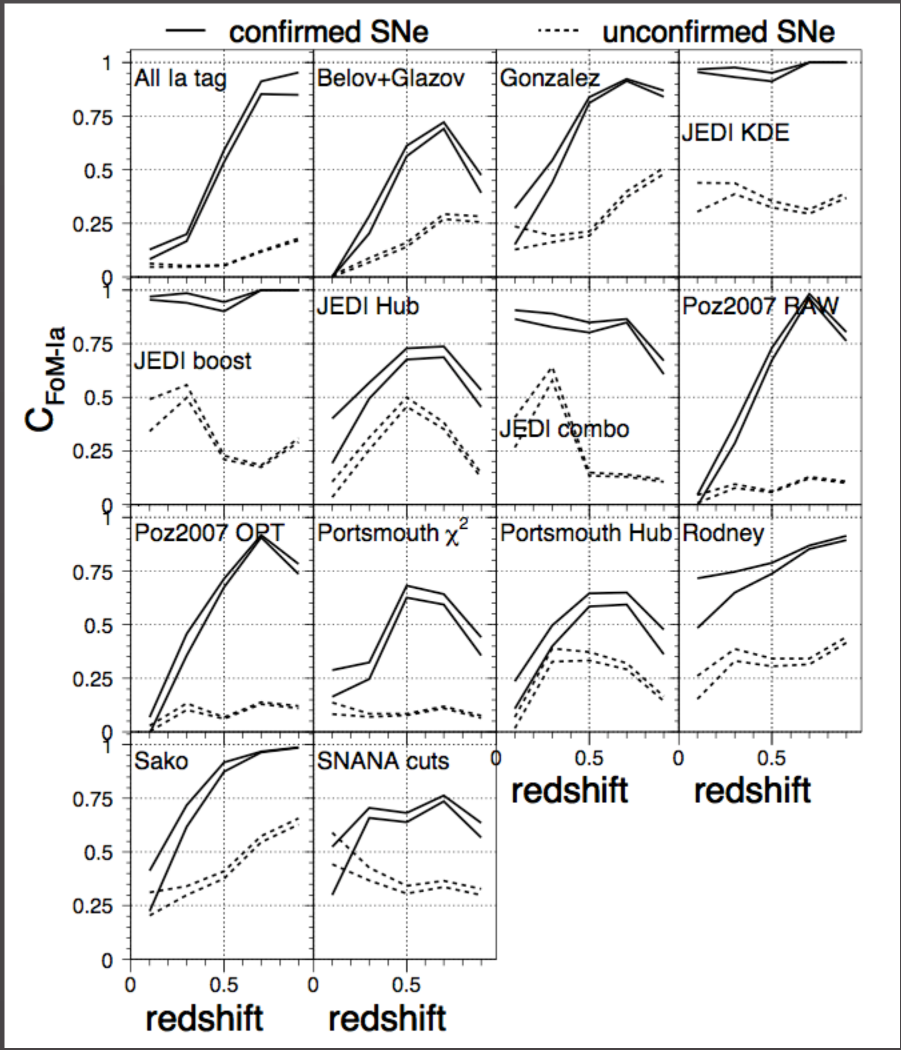
Simulated DES light curves of different SN types

Host photo-z's

Spectroscopically confirmed subsample for training

Cuts: purity vs completeness

Kessler etal 10



Cosmology for Photometric SN samples

Cosmology fits generalized to include probability that a given event is a SN Ia, based on some photometric classification technique.

Will improve results from current SN surveys by including their larger photometric SN Ia datasets

Will be necessary for future surveys, for which spectroscopic classification will be available for only a small fraction of events

Places a premium on characterizing non-Ia populations

Hlozek etal 2010