Constraining Dark Energy: First Results from the SDSS-II Supernova Survey

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(adapted from presentation by Josh Frieman)

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1998-2009 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 (NIR)
- Vast increase in spectroscopic data
- Identification of SN Ia subpopulations (host galaxies)
- Entered the systematic error-dominated regime, but with pathways to reduce sys. errors

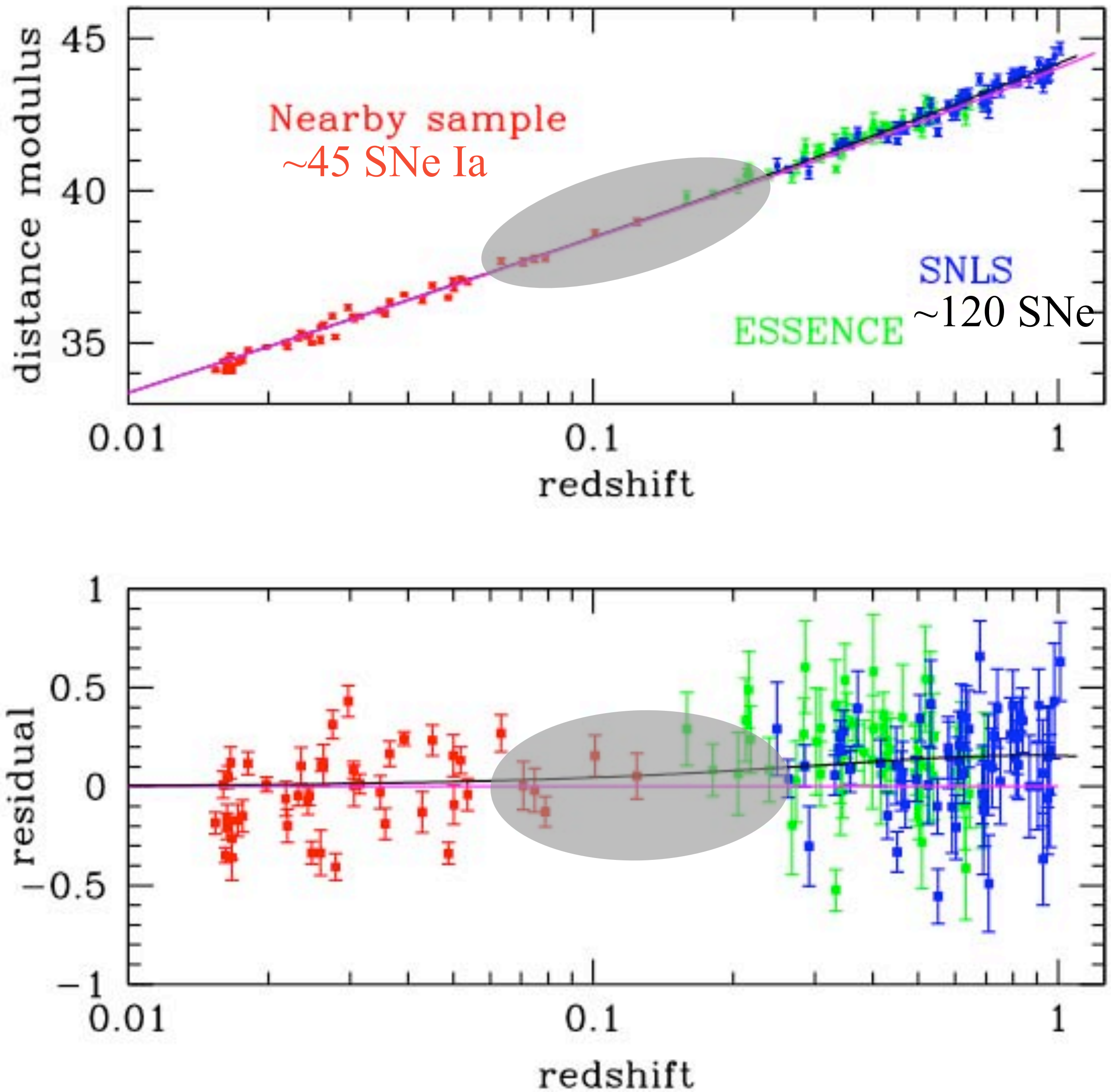
ESSENCE

- Wood-Vasey, etal
- Miknaitis, etal

SNLS

- Astier, etal

But redshift desert remains



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
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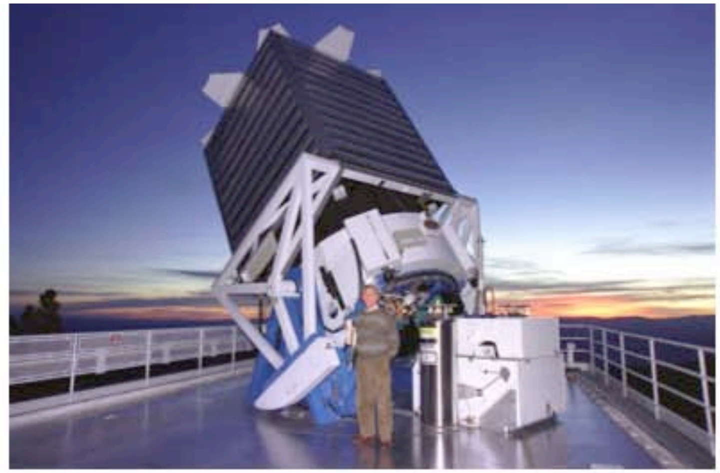
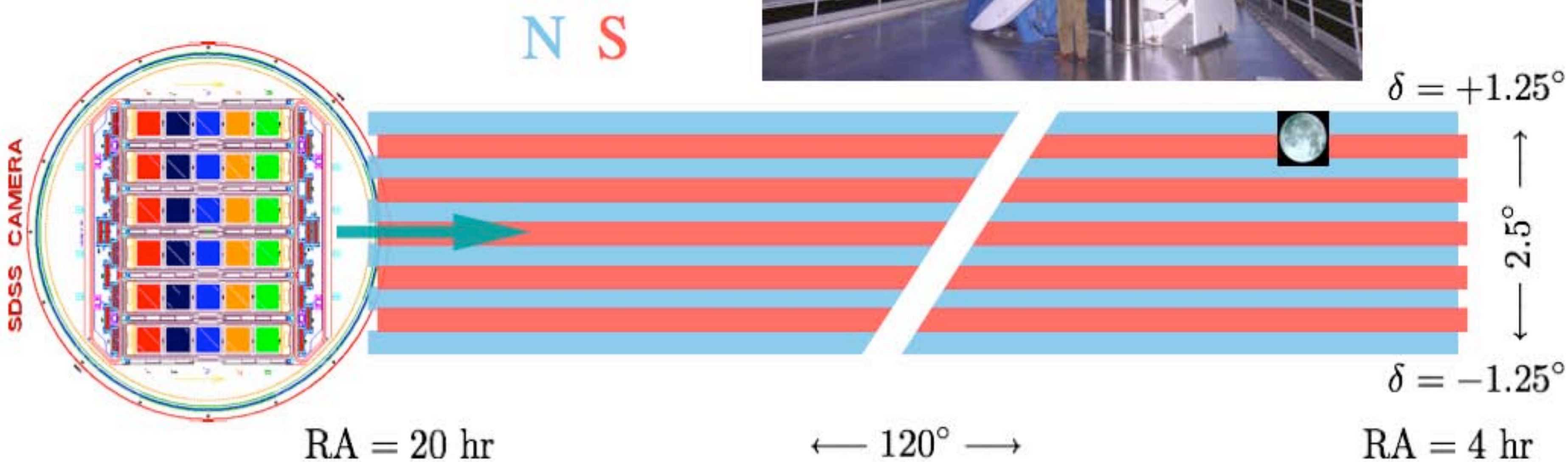
U Washington	A. Becker, C. Hogan, J. VanderPlas
NMSU	T. Gueth, J. Holtzman
OSU	D. Depoy, J. Marshall, J. Prieto
U Tokyo	M. Doi, K. Konishi, T. Morokuma, N. Takanashi, K. Tokita, N. Yasuda
U Portsmouth	H. Lampeitl, R. Nichol, M. Smith
KIPAC	R. Blandford, S. Kahn, R. Romani, C. Zheng
U Penn	C. D'Andrea, 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

SDSS-II SN Survey

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

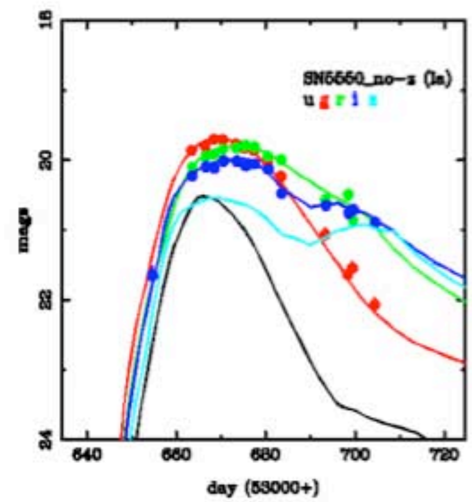




Use the SDSS 2.5m telescope

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

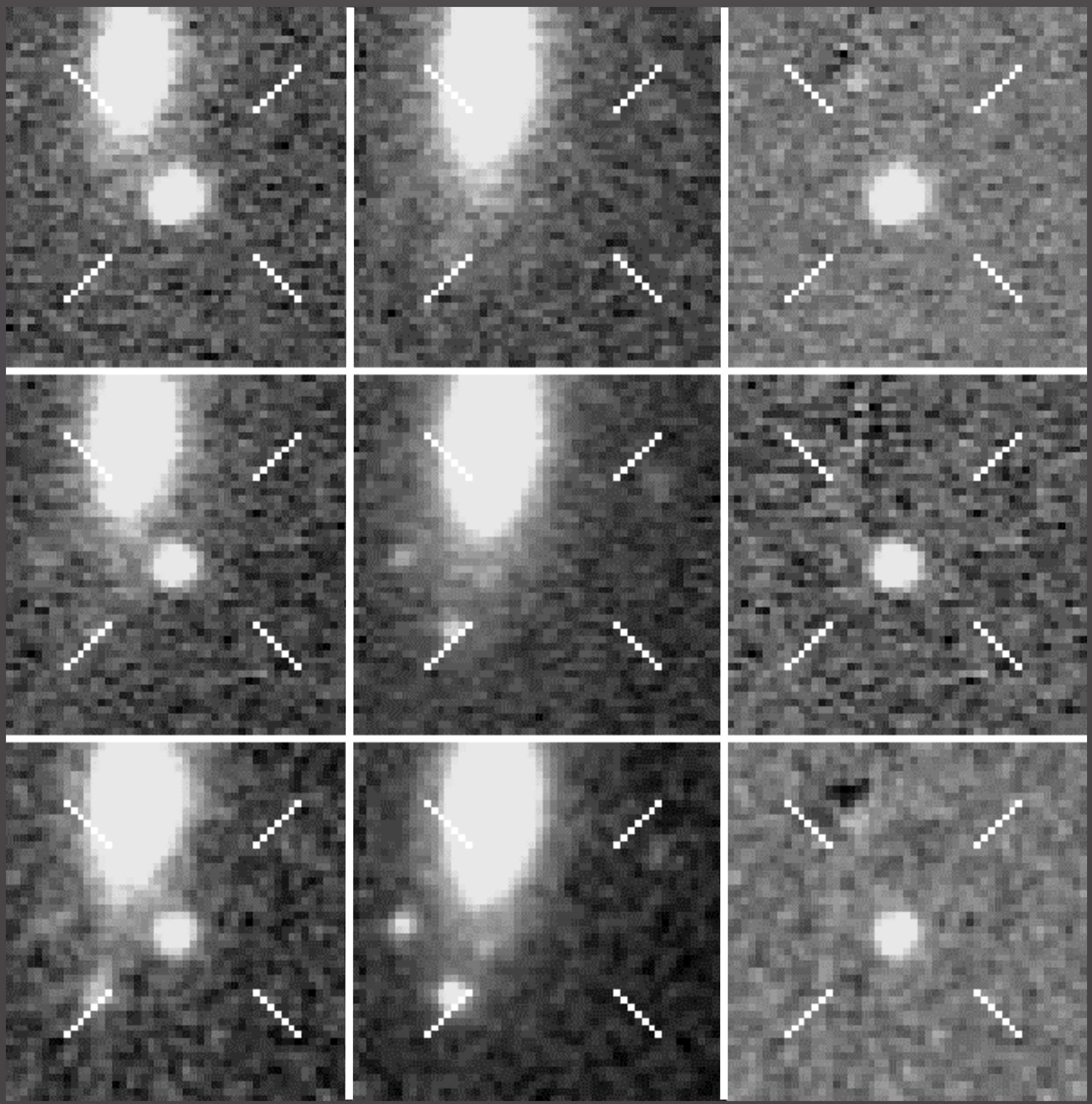
Kessler, et al 09; Lampeitl et al 09; Sollerman et al 09



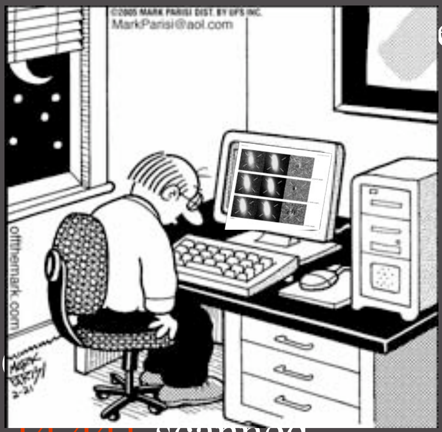
Searching For Supernovae

Search Template Difference

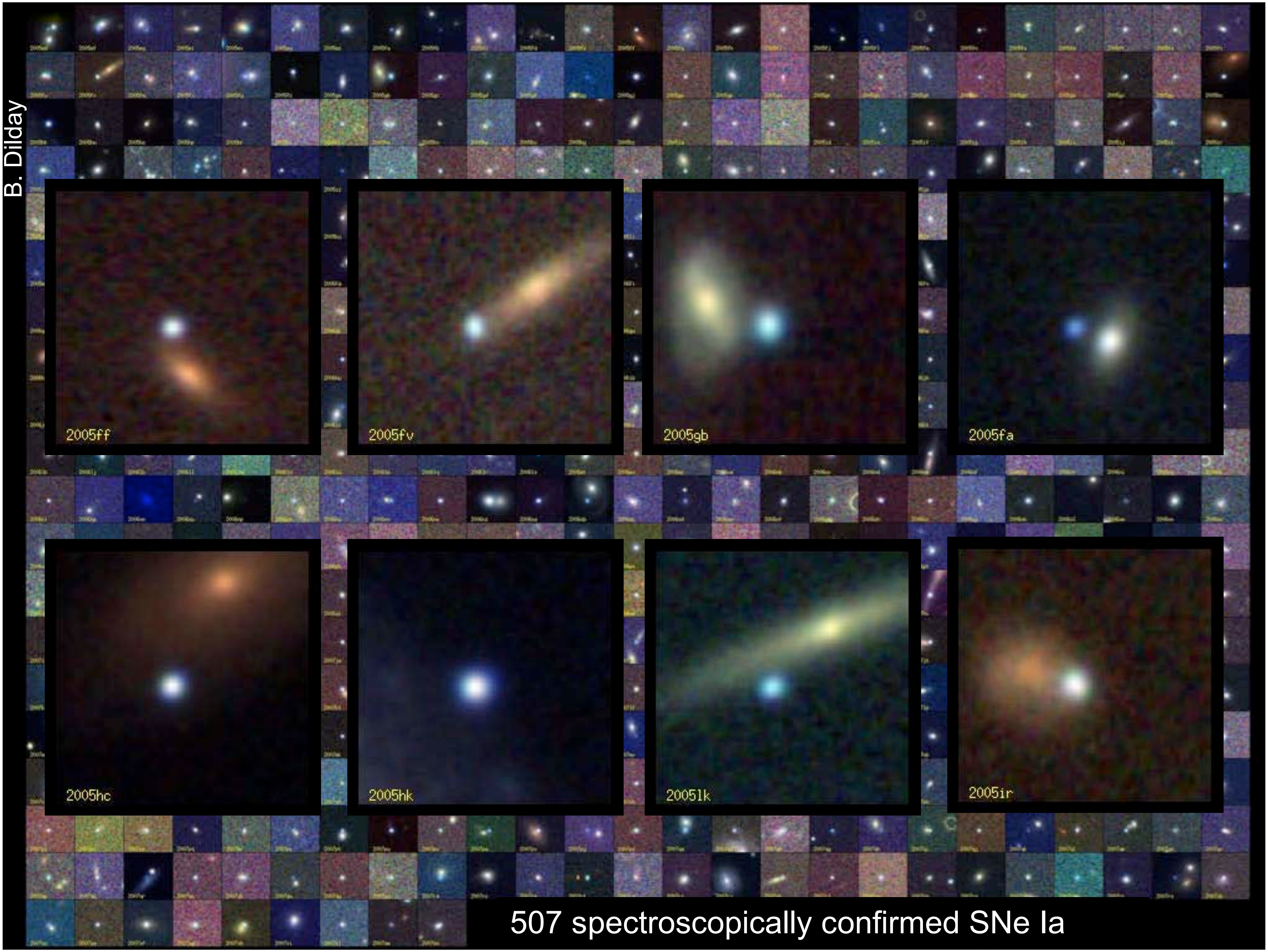
g r i



- 2005
  - ...ed
  -
  -
- 200
  - 14,441 scanned
  - 3,694 candidates
  - 193 confirmed Ia
- 2007
  - 175 confirmed Ia

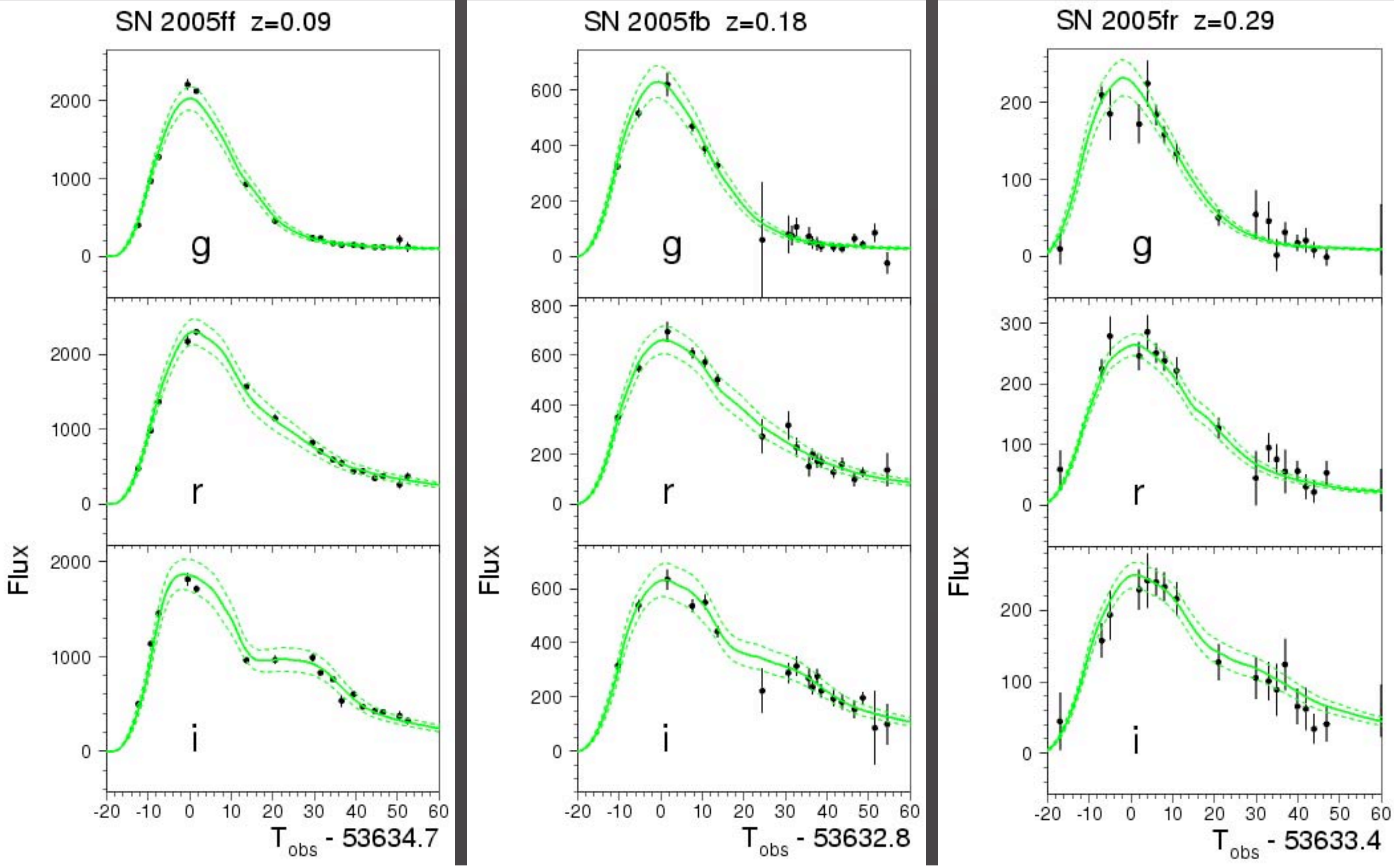


•Positional match to remove movers
•Insert fake SNe to monitor efficiency


B. Dilday
2005ff
2005fv
2005gb
2005fa
2005hc
2005hk
2005lk
2005ir
507 spectroscopically confirmed SNe Ia

SDSS SN Photometry

Holtzman etal (2008)



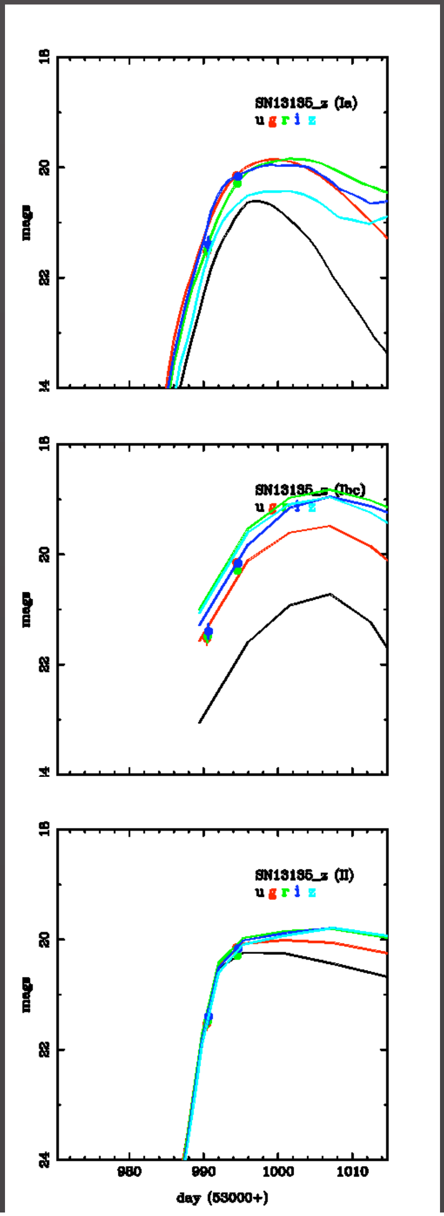
Spectroscopic Target Selection

2 Epochs

SN Ia Fit

SN Ibc Fit

SN II Fit



Sako etal 2008

Spectroscopic Target Selection

2 Epochs

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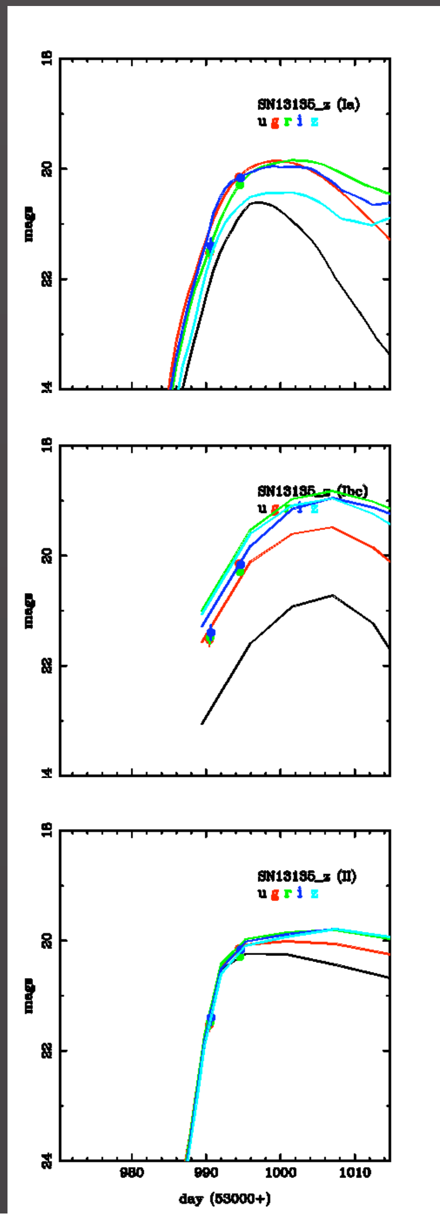
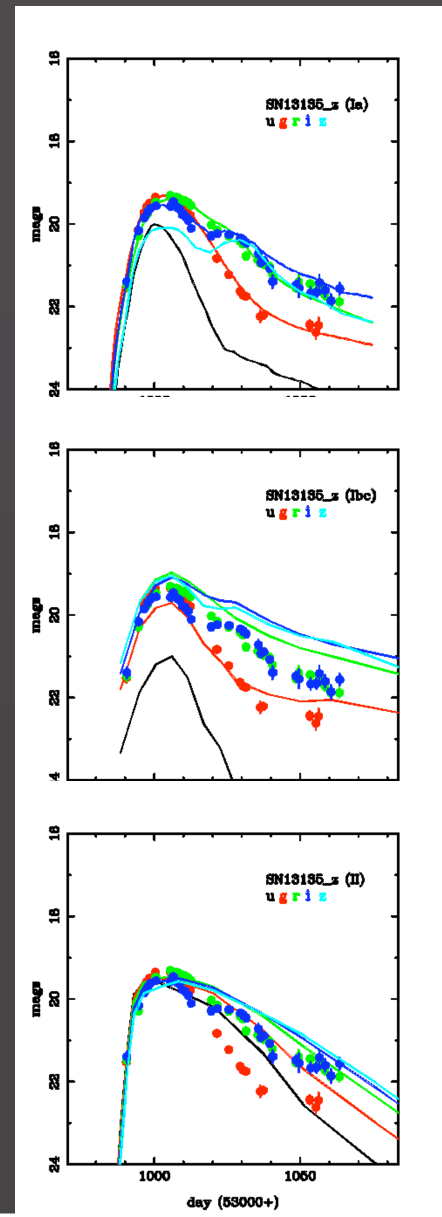


31 Epochs

SN Ia Fit

SN Ibc Fit

SN II Fit



Fit with template library

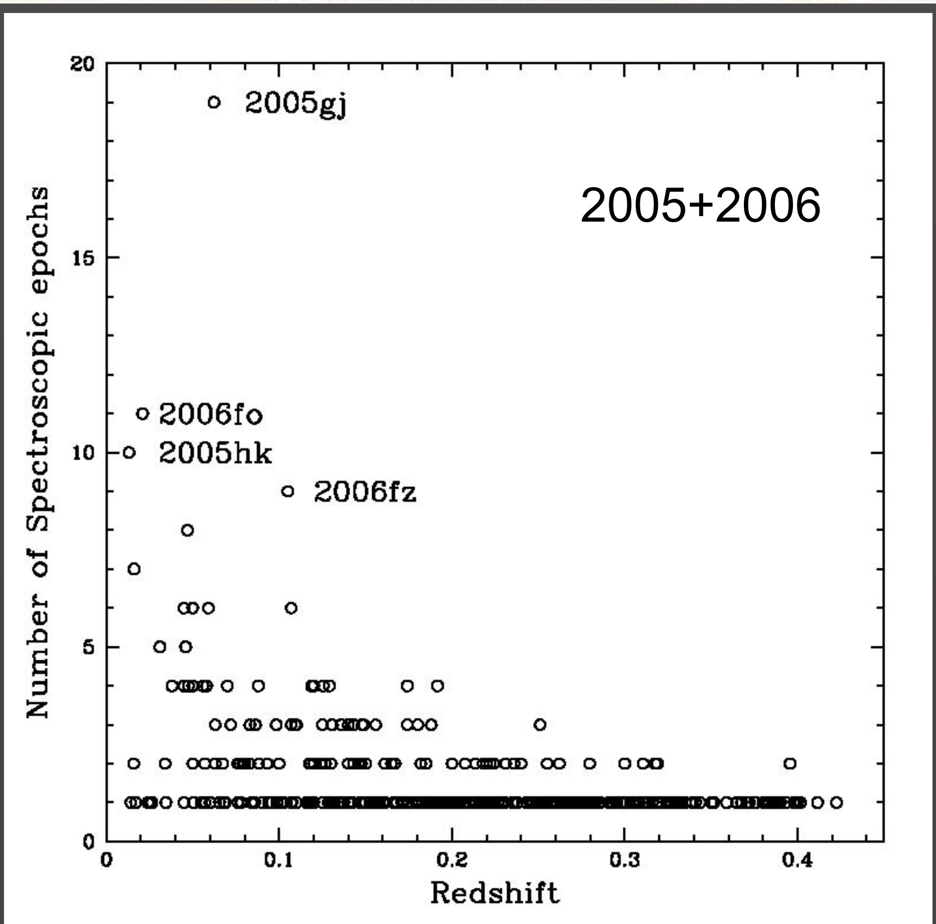
Classification >90% accurate after 2-3 epochs

Redshifts 5-10% accurate

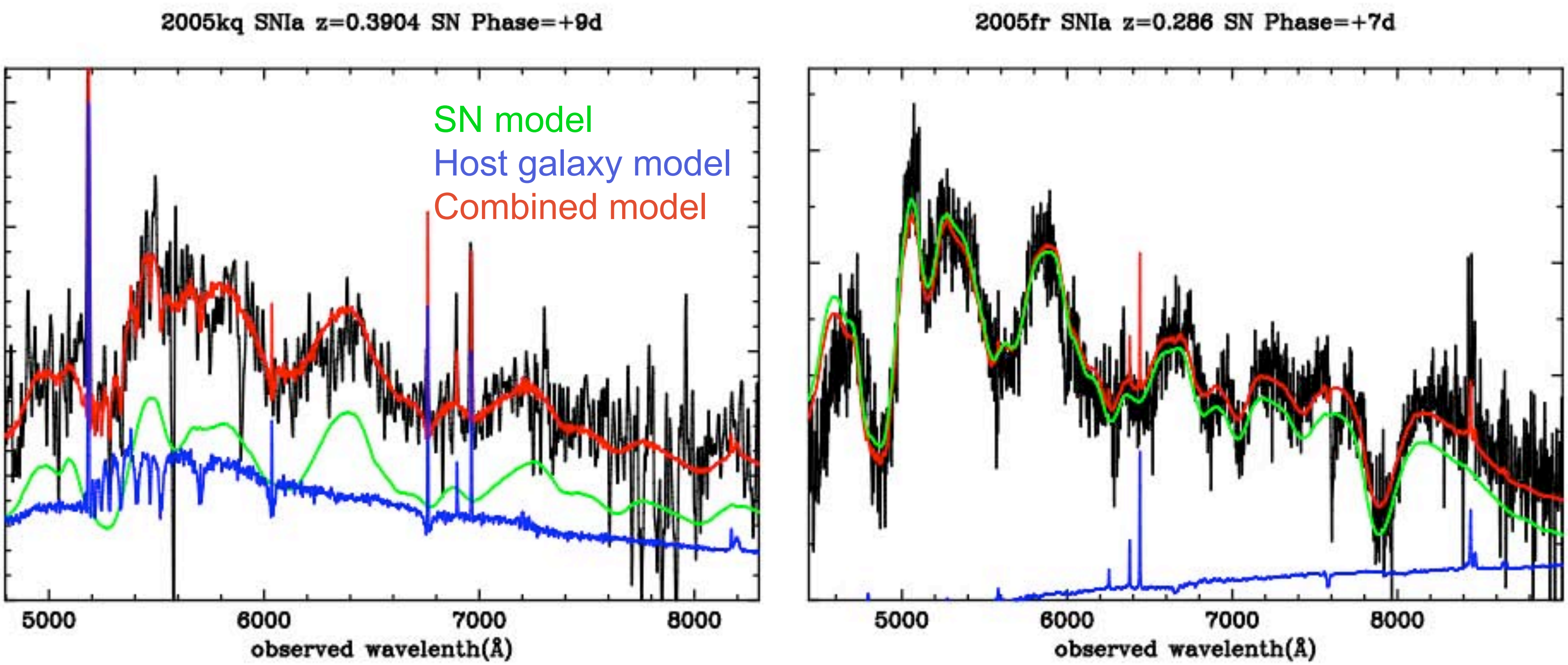
Sako etal 2008

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 6m
- TNG 3.5m
- SALT 10m



Spectroscopic Deconstruction



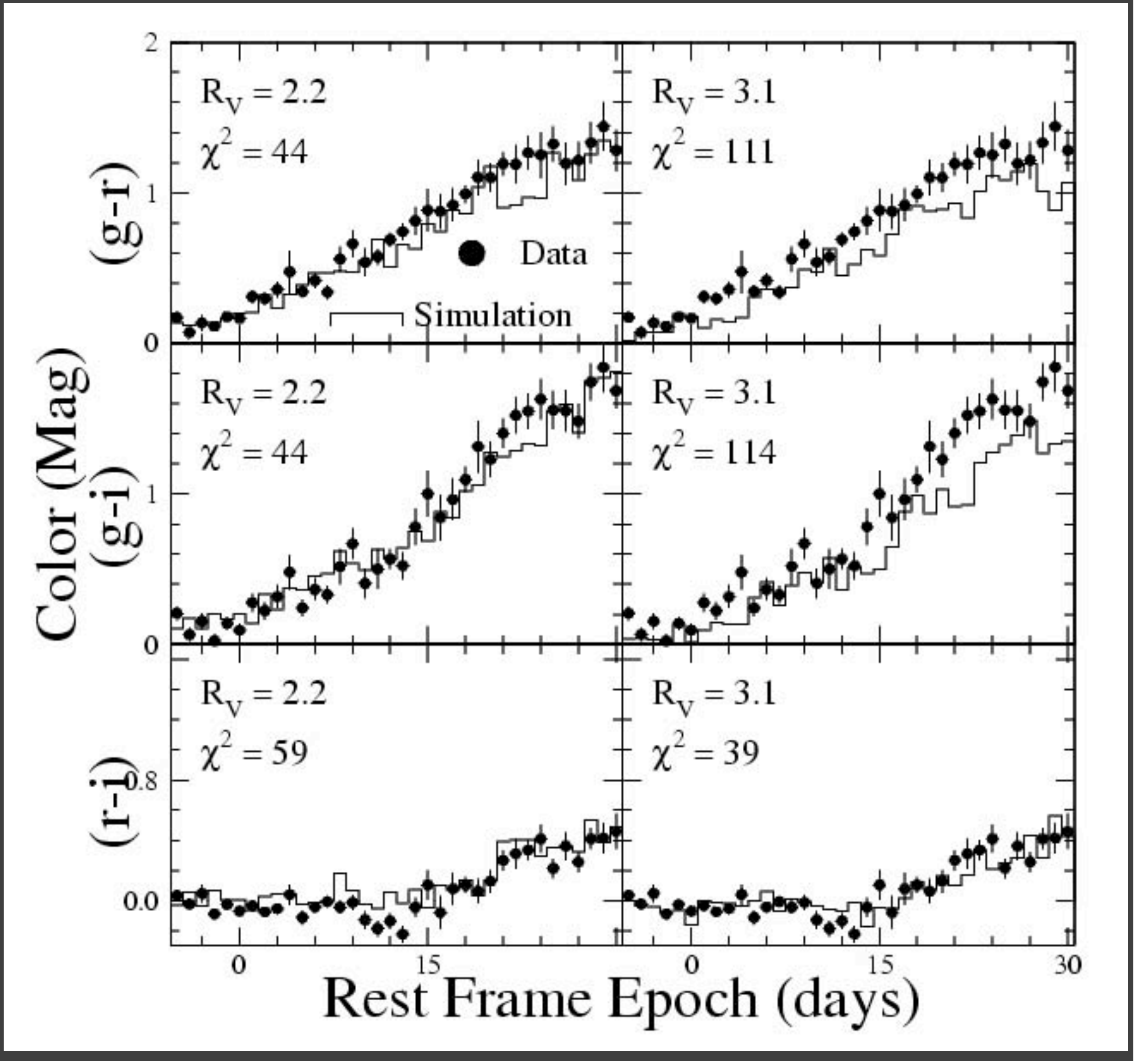
Zheng, et al (2008)

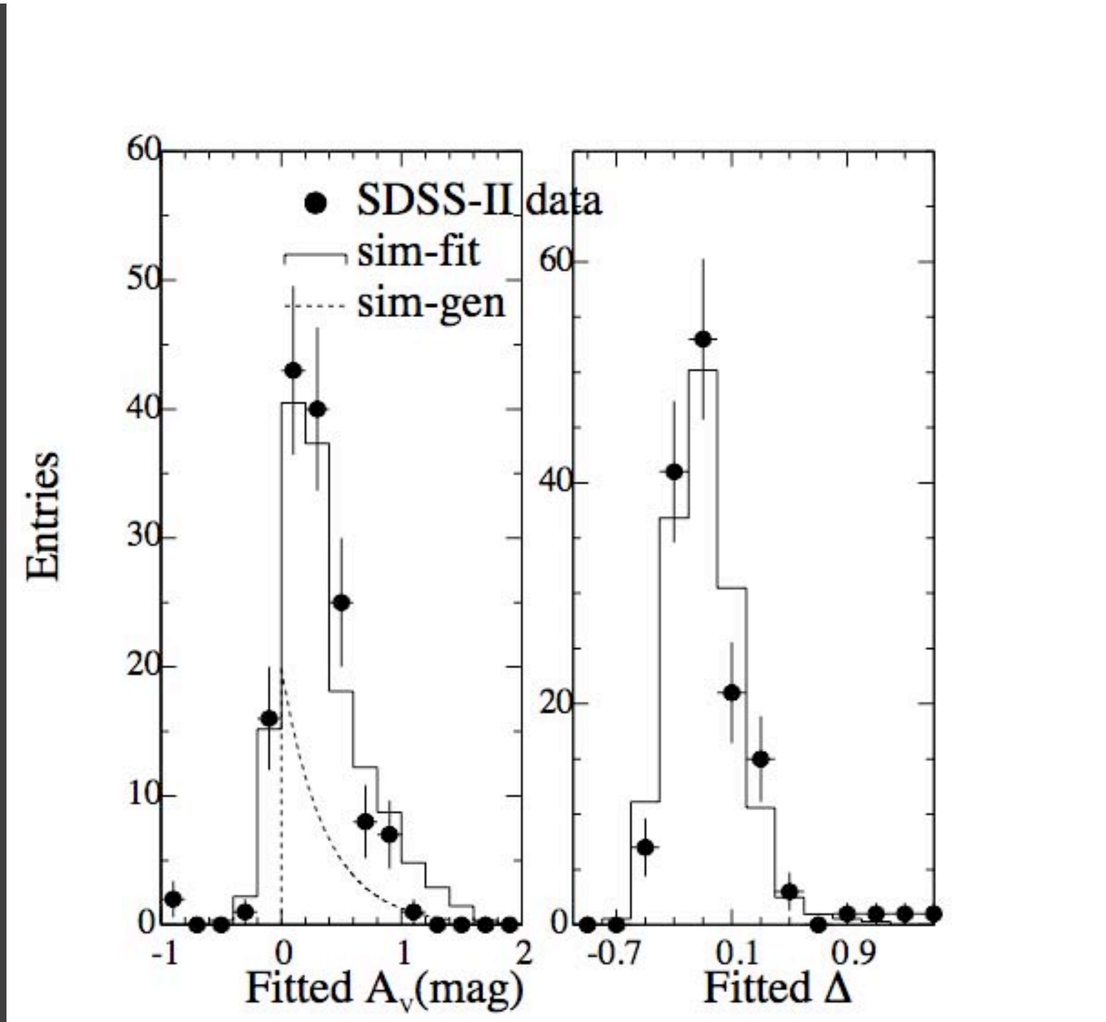
Extract R_V by matching colors of SDSS SNe to MLCS simulations

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

- MLCS previously used Milky Way avg R_V=3.1
- Lower R_V more consistent with SALT color law

D. Cinabro

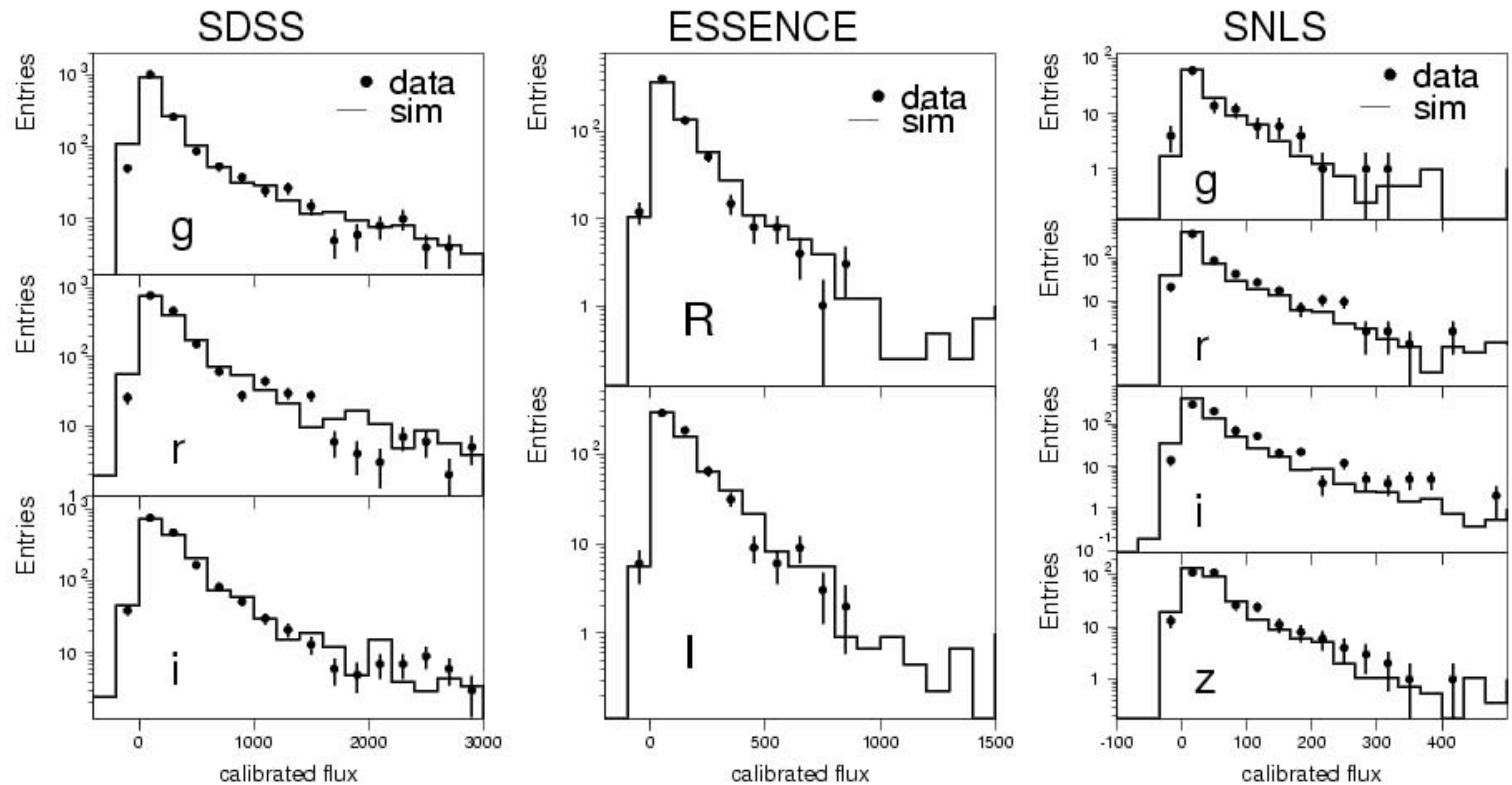




$$\chi^2_{MLCS} = \sum_i \frac{\left[F_i^{data} - F_i^{\mathrm{mod}}(t_0,\Delta,A_V,\mu)\right]^2}{\sigma_i^2} - 2\ln\left(P(A_V)P(\Delta)\varepsilon(z,A_V,\Delta)\right)$$

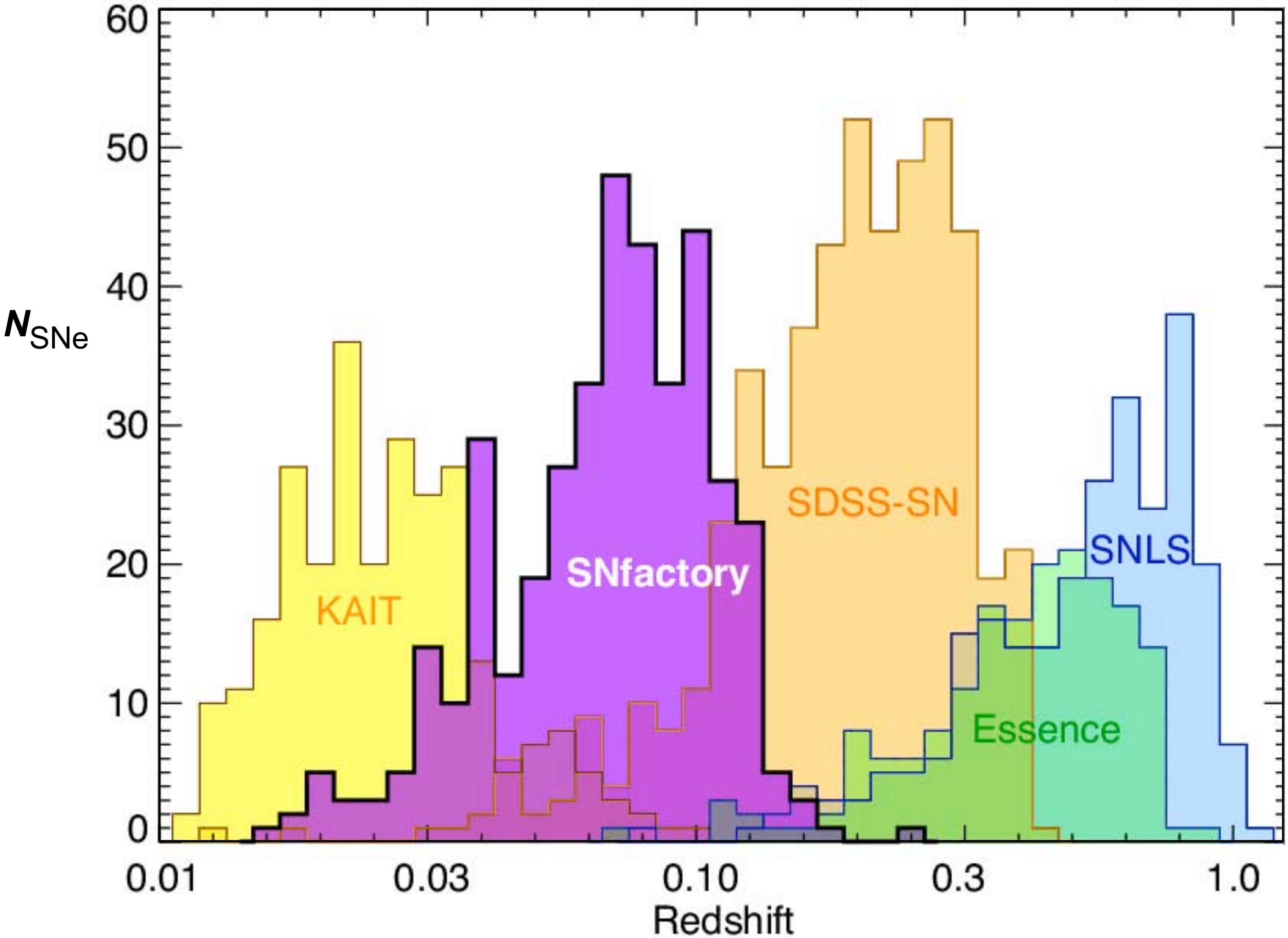
Determine priors and efficiencies from data and Monte Carlo simulations

Monte Carlo Simulations match data distributions

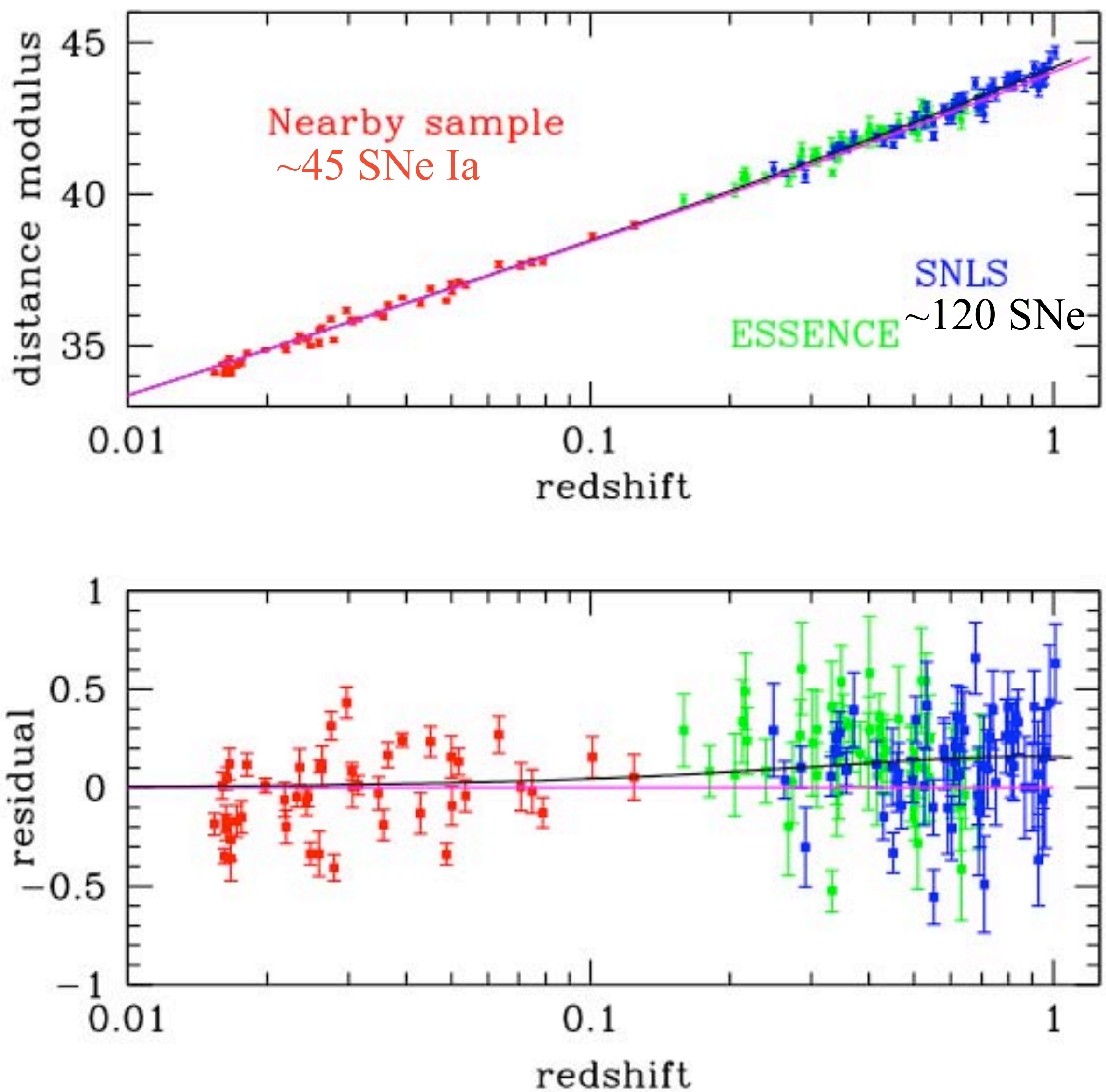


Use recorded observing conditions (local sky, zero-points, PSF, etc)

Number of Type Ia
Supernova Discoveries

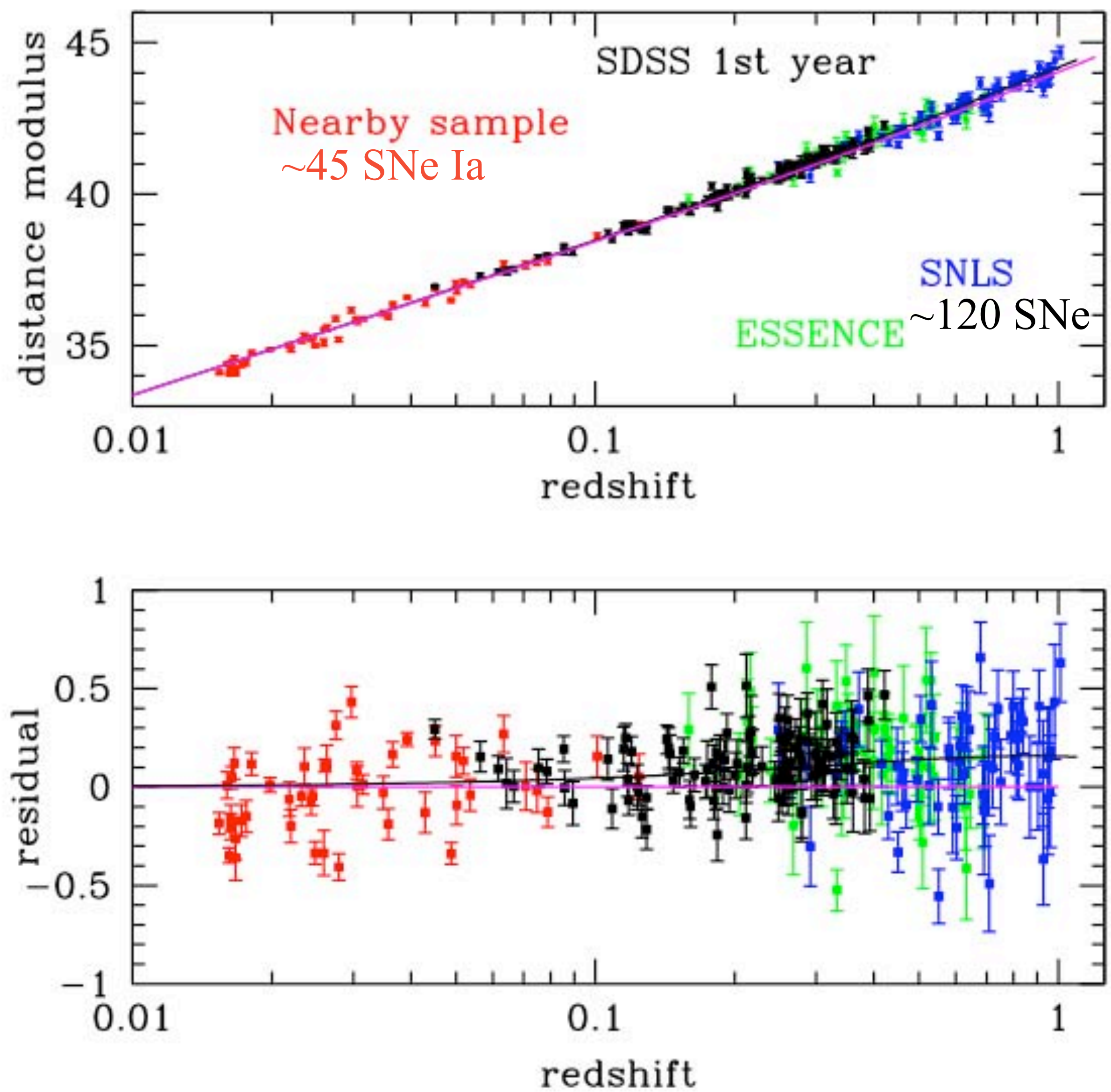


Hubble Diagram



Hubble Diagram with SDSS SNe

103 SNe Ia from first season



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

A Tale of Two Fitters

MLCS (Multicolor Light Curve Shape; MLCS2k2, Jha, 2002):

• 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 (Spectral Adaptive Lightcurve Template, Guy et al 2005):

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

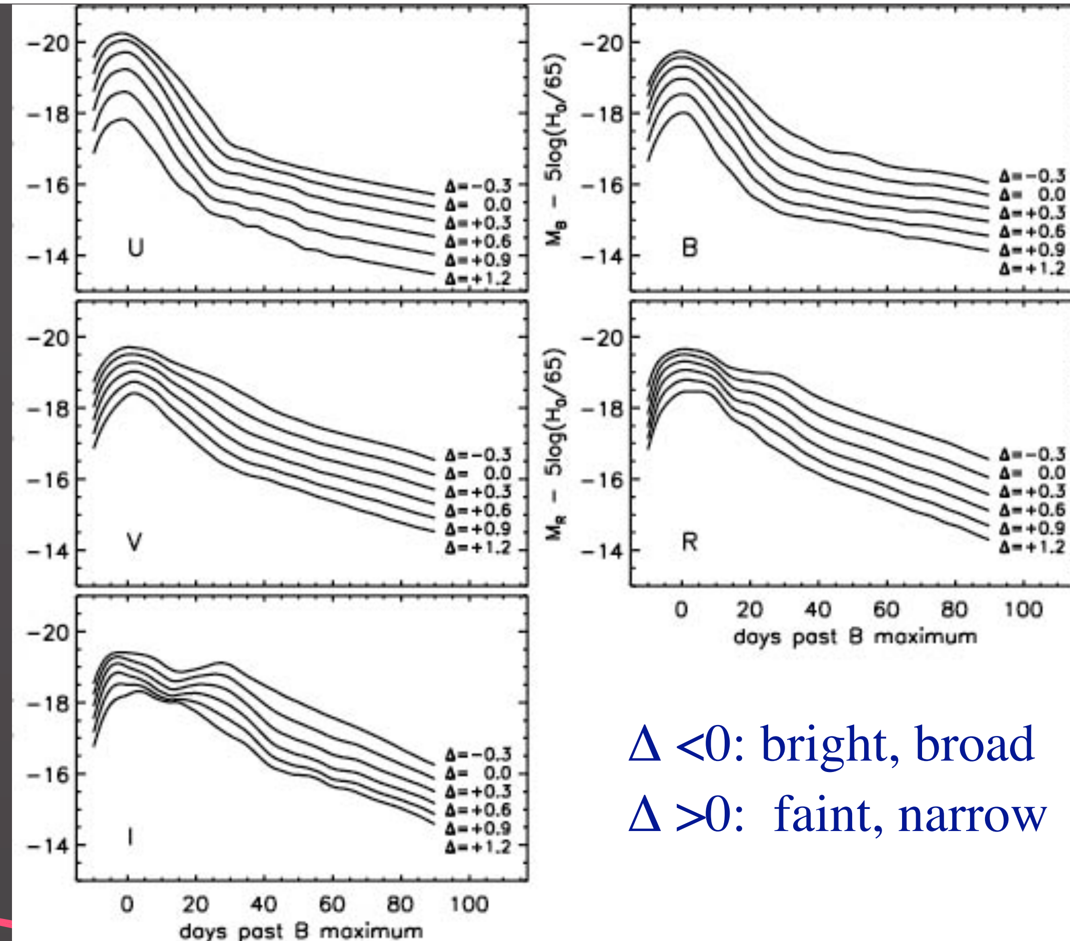
• Trend toward bluer colors at high-z: if allow $\beta(z)$, see strong trend with redshift

•Retrain and refine the models with newer data

Correct Distance Estimates for Brightness-decline relation and dust extinction

MLCS2k2 Light-curve templates

Jha, etal (2007)



Δ <0: bright, broad

Δ >0: faint, narrow

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

$$\vec{m}_X(t - t_0) = \vec{M}_X^0 + \mu_0 + \vec{\zeta}_X\,(\alpha_X + \beta_X/R_V)\,A_V^0 + \vec{P}_X\Delta + \vec{Q}_X\Delta^2,$$

fit parameters

(plus K-corrections)

Time of maximum | distance modulus | dust law | extinction | stretch/decline rate

Guy et al

SALT-II Light-curve Fits

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

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

light-curve shape

color term

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

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

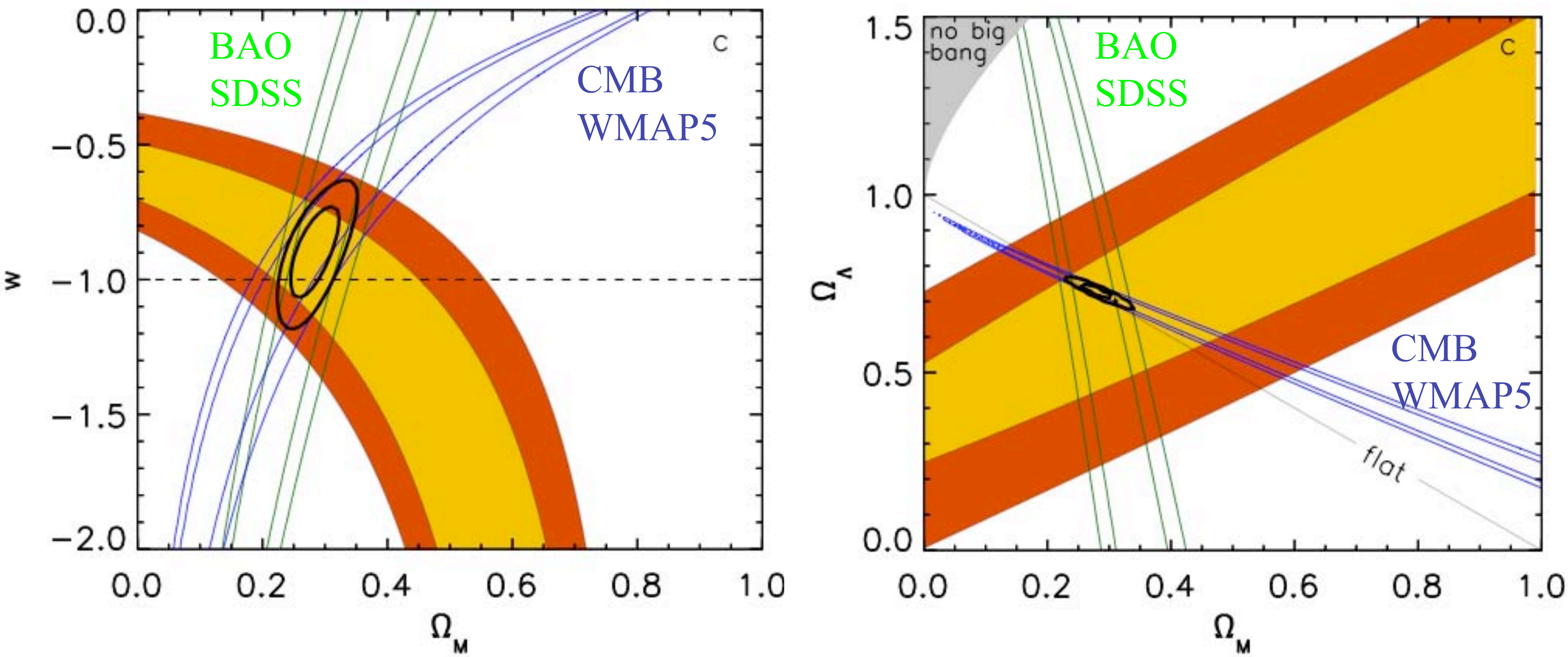
Global fit parameters, determined *along with* cosmological parameters

•Differences from MLCS: not trained just on low-redshift data; flat priors on model parameters, espec. color; color variations not assumed to come only from dust

SDSS+Nearby SNe Only

SALT-II

$$w = -0.93 \pm 0.11(\text{stat})^{+0.07}_{-0.16}(\text{syst})$$

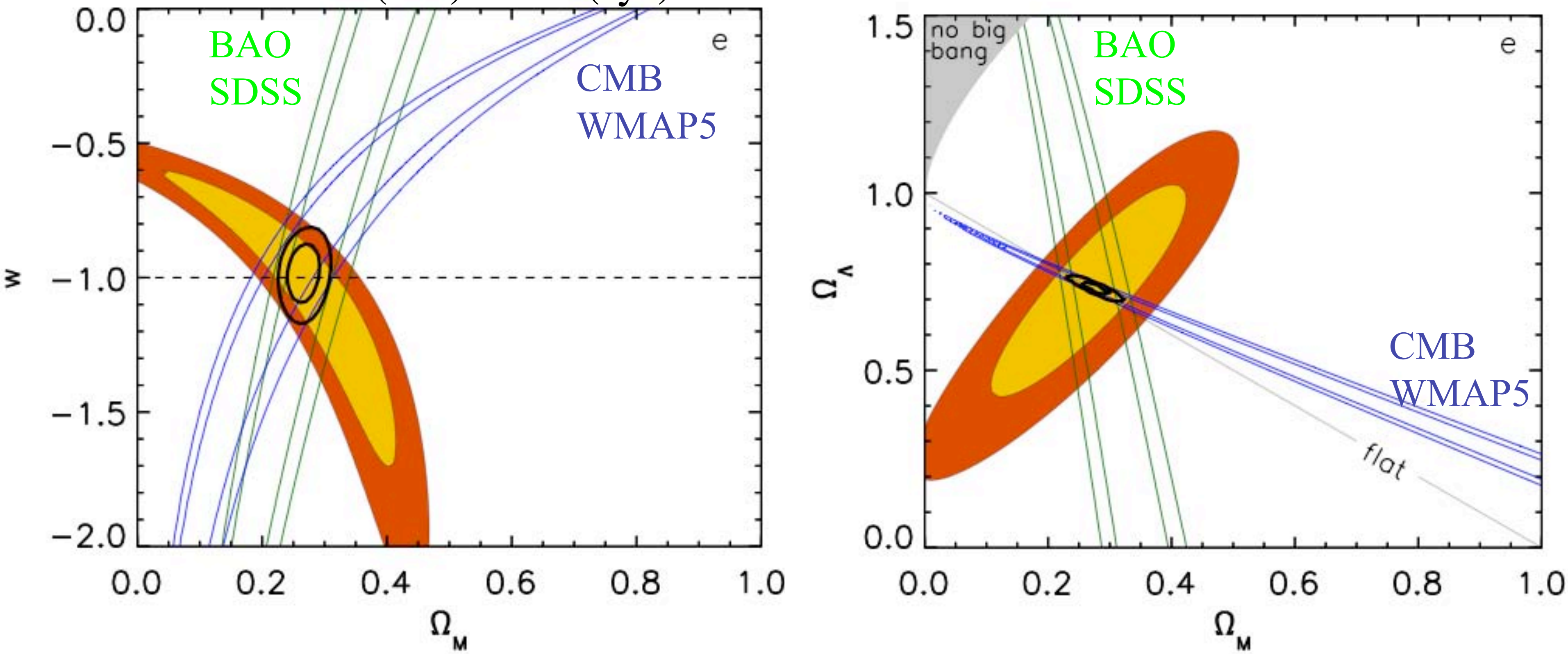


SDSS+Nearby+SNLS+ESSENCE+HST

SALT-II

$$w = -0.97 \pm 0.07(\text{stat}) \pm 0.12(\text{syst}) \text{ SALT}$$

$$= -0.76 \pm 0.07(\text{stat}) \pm 0.12(\text{sys}) \text{ MLCS}$$

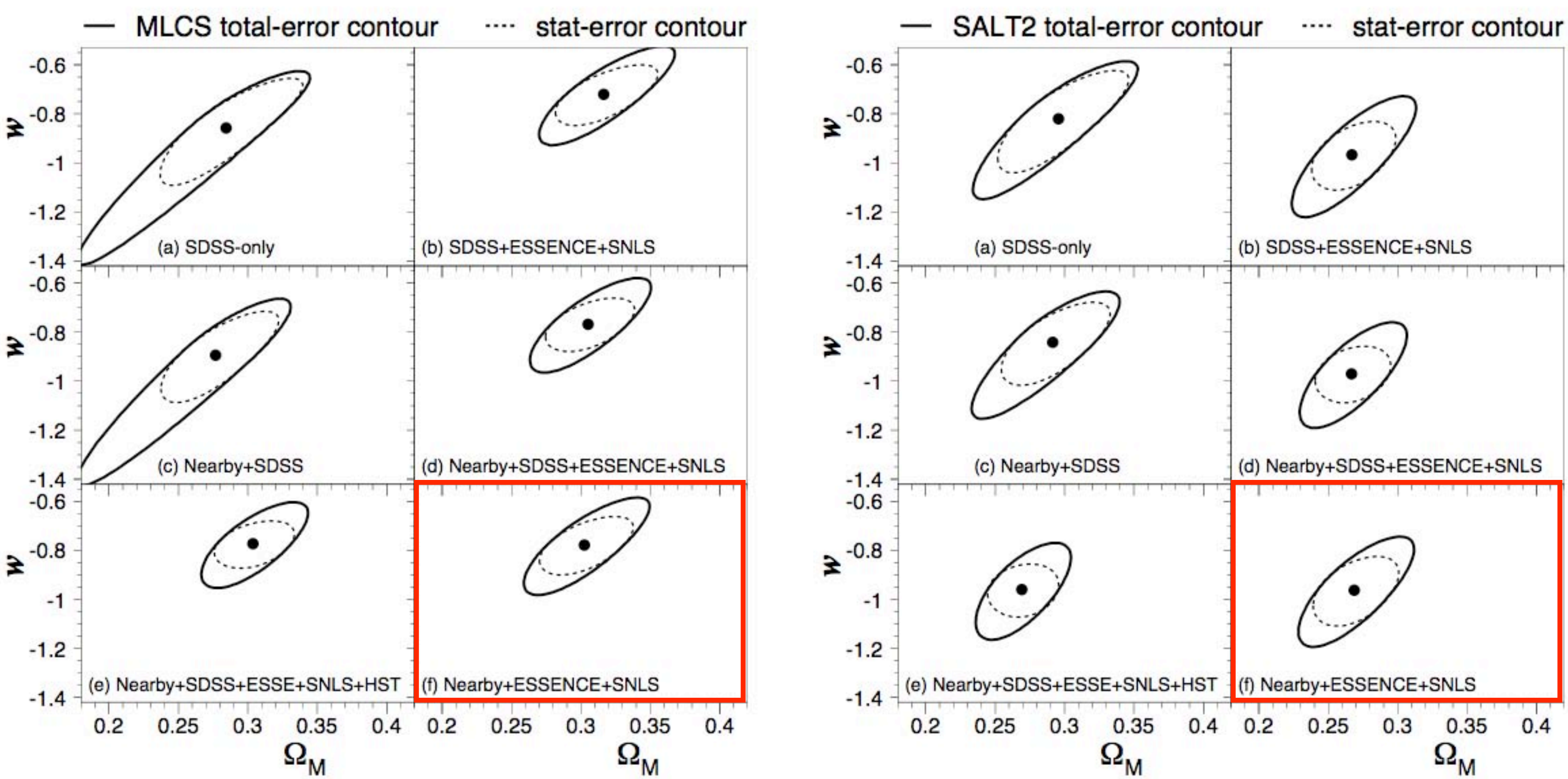


SALT2 distance moduli for SNLS SNe systematically higher than MLCS

Systematic Errors are Dominant

SN+BAO+CMB constraints

MLCS vs. SALT discrepancy is NOT associated with SDSS SNe

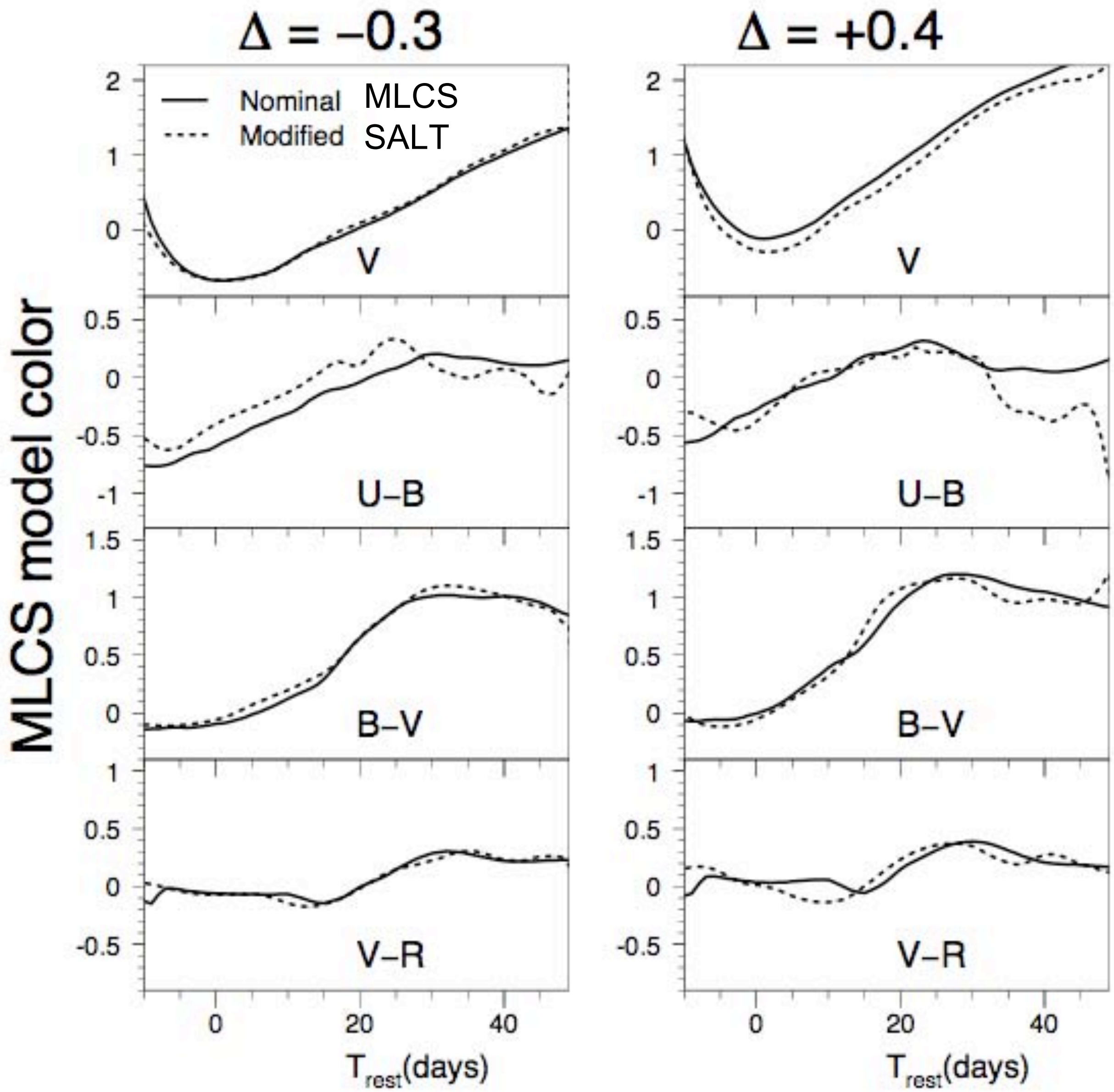


SALT vs MLCS template light curves

Diagnosis:

Large difference in Light-curve model in U-band

Use of prior on extinction in MLCS



Systematic Errors (and Controls)

- Dust and SN color variation (multi-λ, NIR, high S/N)
- Selection effects (artificial SNe, Monte Carlo simulations)
- Population evolution (SN properties vs host environment)
- Photometric calibration (system calibration (lasers, etc) & cross-calibration of systems)
- Sample purity (spectroscopy)
- All (subdivide large samples to cross-check)
- Clear pathway to progress

The Future is (Mostly) Photometric

- Pan-STARRS, Dark Energy Survey, LSST: thousands to hundreds of thousands of SN 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)

Conclusions

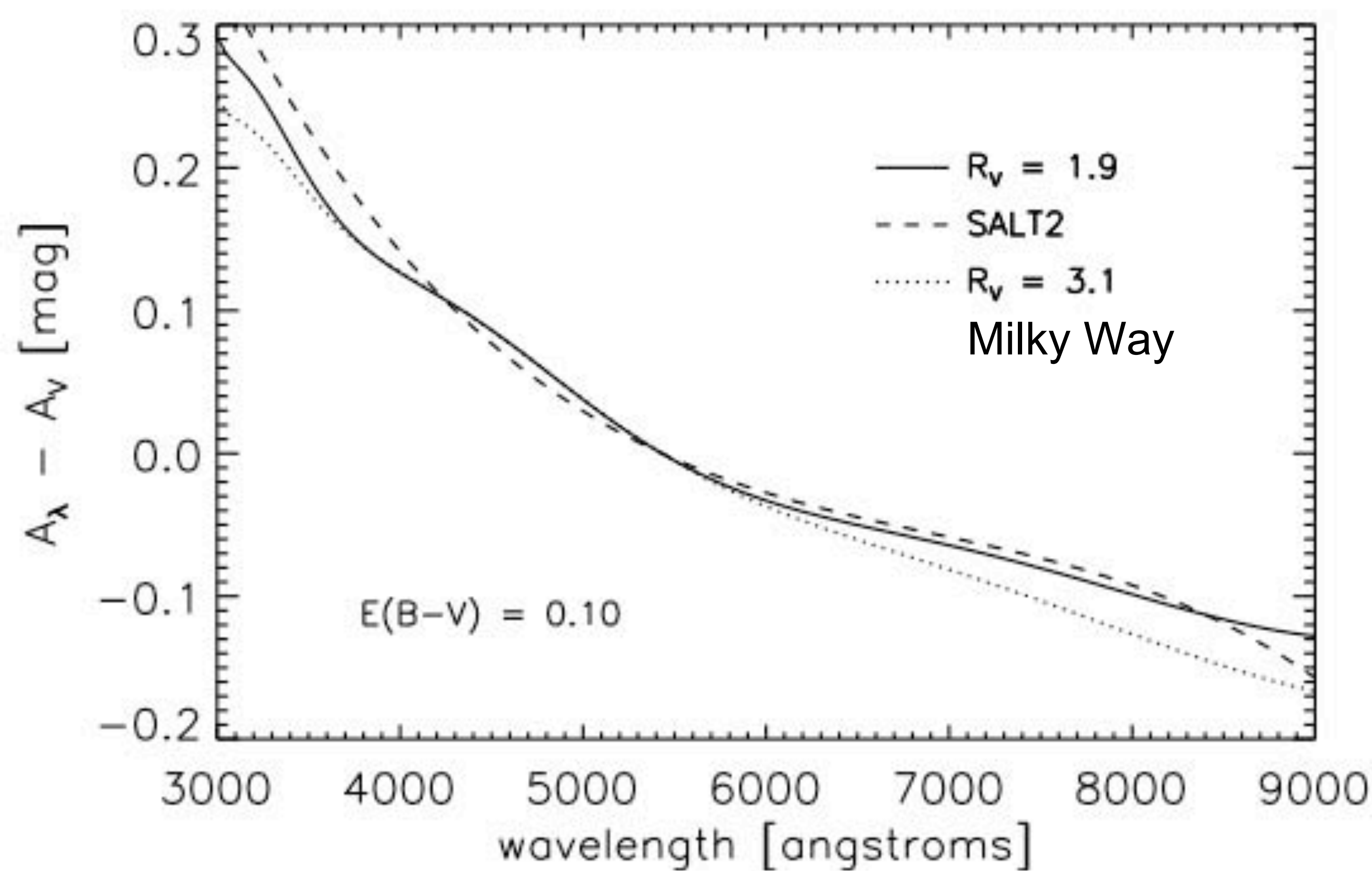
• Robust evidence for cosmic acceleration from Supernovae and other probes

•Systematic errors pose challenges to reaching greater precision in dark energy properties

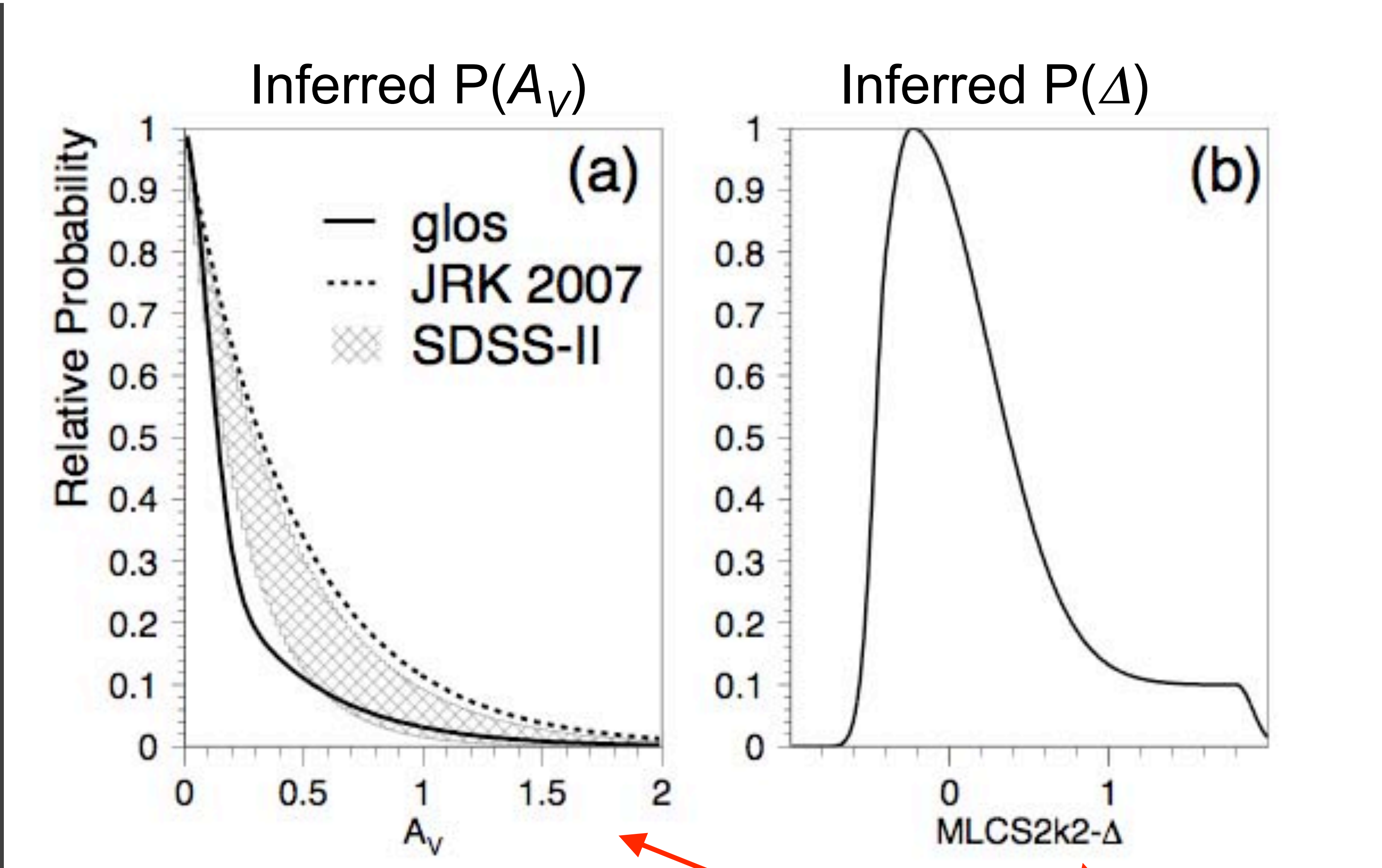
•We have data in hand to help resolve these issues for SNe: retraining light-curve models using SDSS, CSP, CfA, SNF,…

• Future experiments will/must be designed to control systematic errors and exploit complementarity of multiple probes: HETDEX, DES, PanSTARRS, PAU, LSST, JDEM,…

Dust Extinction Law: R_V



Jha



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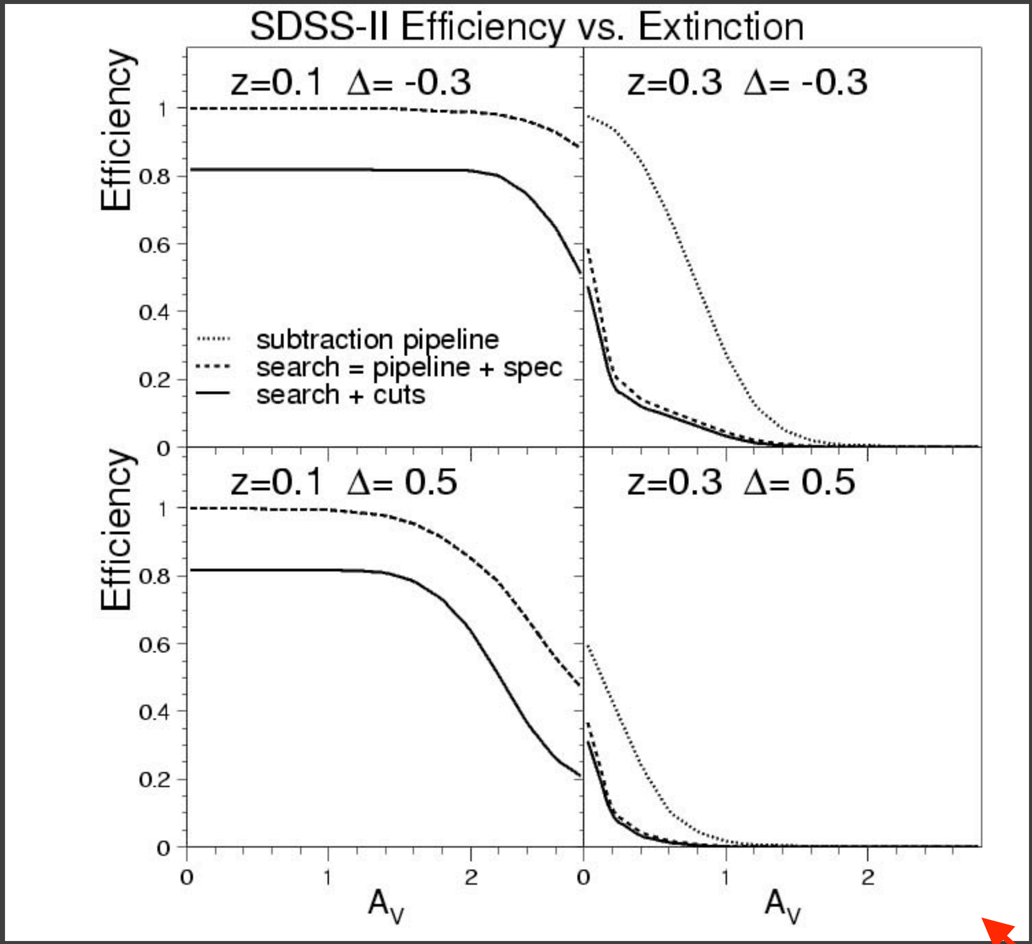
Determine priors and efficiencies from data and Monte Carlo simulations

Determine Survey Efficiencies



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