Measuring the Expansion History of the Universe: Results from the SDSS-II Supernova Survey

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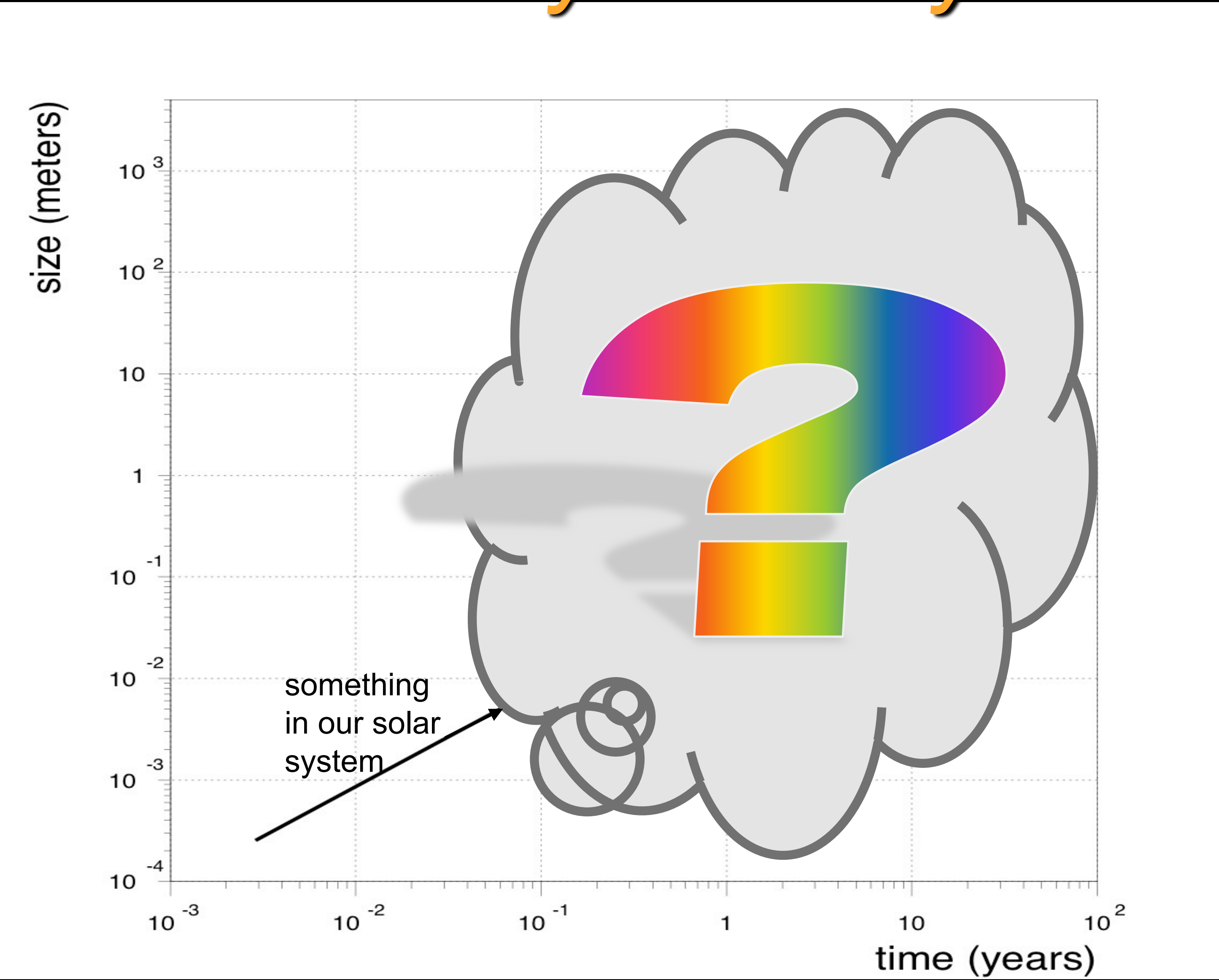
Contents

- Intro/Hubble Diagrams
- The SDSS-II Supernova Survey
- Analysis
- Results & Systematic Issues

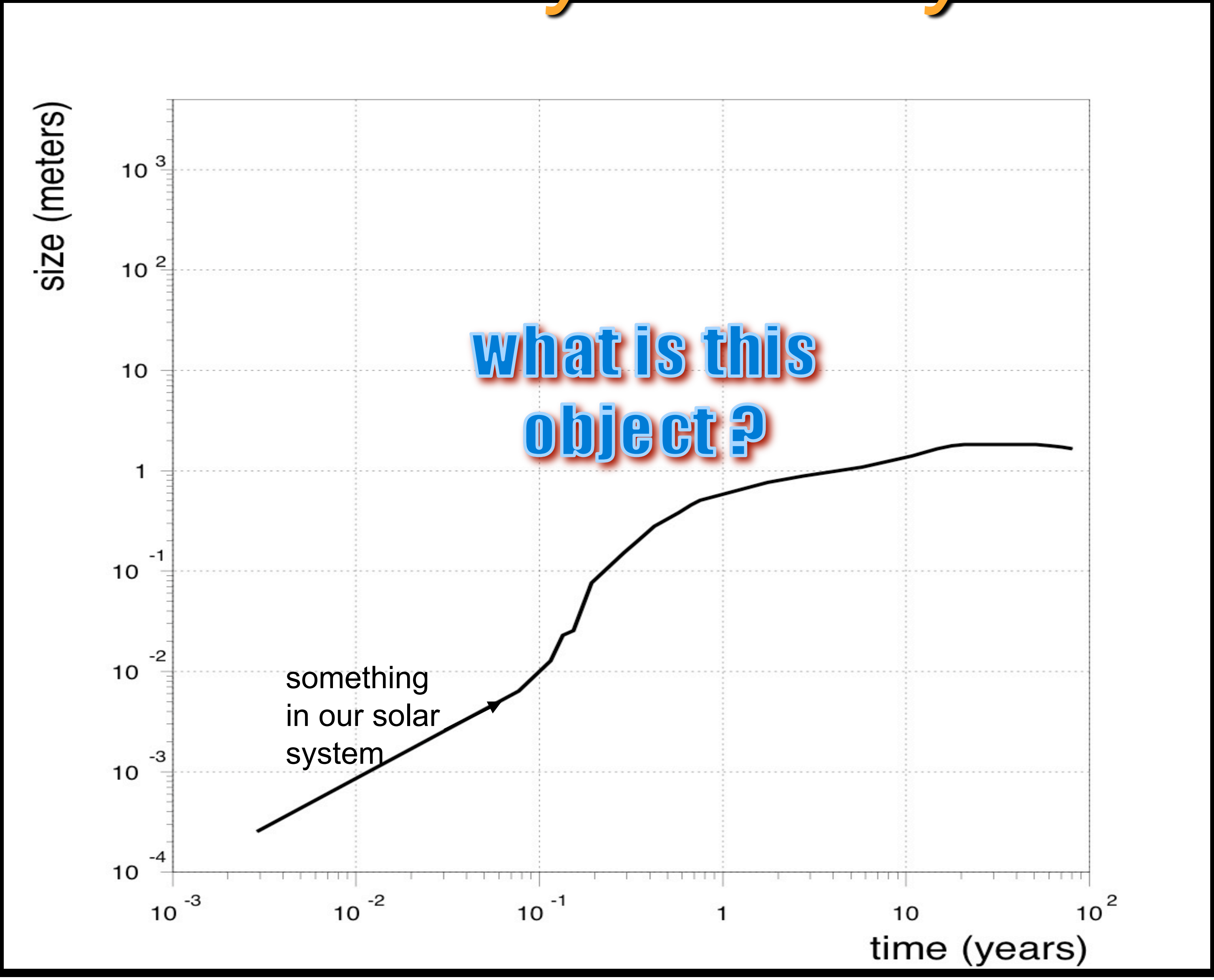
Primary Motivation for Supernova Surveys:

measure expansion history of the Universe: in particular, the role of dark energy

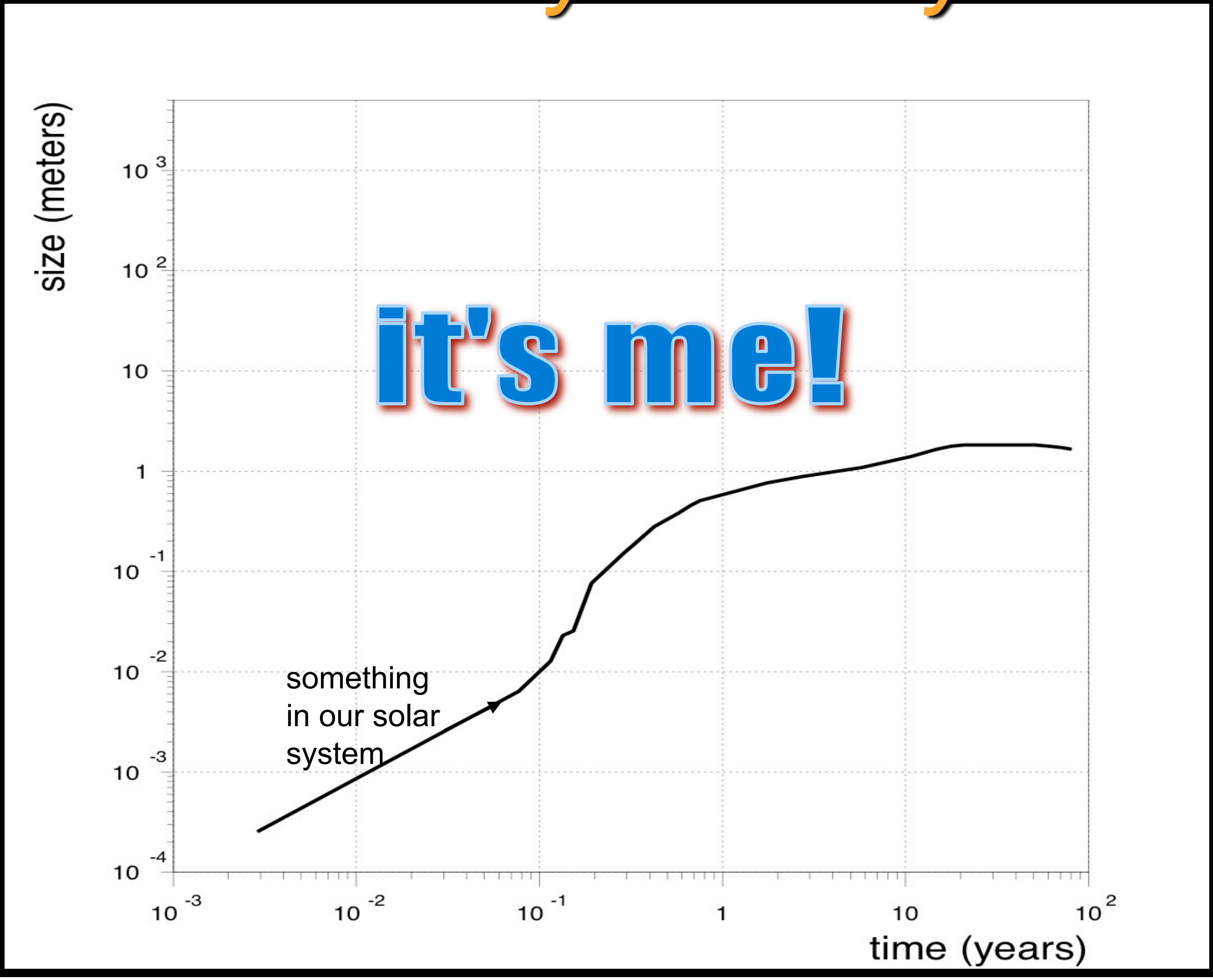
Understanding Expansion History is Tricky



Understanding Expansion History is Tricky



Understanding Expansion History is Tricky



Fun Facts About Dark Energy

- $\rho_\Lambda = 10^{-29}$ g/cm^3 everywhere.
- Earth volume contains 0.01g of dark energy.
- Dark energy increases Earth's orbit by 0.1μm; Pluto's orbit is increased by 1μm.
- Gravity and dark energy roughly cancel for Milky-Way and Andromeda galaxies (but galaxy-cluster gravity wins)
- $\Omega_\Lambda = 0.7$ today
- $\Omega_\Lambda/\Omega_M \sim 2.3$ today (compare $\Omega_\gamma / \Omega_M < 10^{-4}$).
- $\Omega_\Lambda = \Omega_M$ at $z=0.3$ (3-4 billion years ago).
- Undetectable in terrestrial experiments (so far).
- Nobody knows what dark energy (or dark matter) is.

Expansion Basics

$$H(z)^2 = H_0^2 \, \Sigma_i \, \Omega_i \, (1+z)^{3(1+w)}$$

Notes:

- Ω_i **are energy density fractions relative to critical density (Ω_{TOT} = 1)**
- w **is the pressure/density ratio (p/ρ)**
- $R = 1/(1+z)$ **is the "universal scale factor"**
- **To determine expansion history, must measure the** Ω_i **and** w_i **.**

Expansion Basics

$$H(z)^2 = H_0^2 \, \Sigma_i \, \Omega_i \, (1+z)^{3(1+w)}$$

Source of expansion	**w**	**Evolution with z**	**Ω at z=0**
Matter (dark, baryon, relic ν)	$v^2/c^2 \sim 0$	$\Omega_M(1+z)^3$	0.3
Radiation (CMB)	$+1/3$	$\Omega_\gamma(1+z)^4$	$\sim 10^{-5}$
Cosmological constant (?)	-1	Ω_Λ = constant	0.7
Curvature	$-1/3$	$\Omega_k(1+z)^2$	< few %

Methods to Measure H(z)

$$H(z)^2 = \Sigma_i \, \Omega_i \, (1+z)^{3(1+w)}$$

Method	**Difficulties**
brightness vs. redshift	Large dispersion in brightness. Evolution ? Dust ?
count galaxy clusters vs redshift.	Need to know cluster-mass selection function.
galaxy clustering; power spectrum or clumpiness	galaxy vs. dark matter clustering
Weak lensing	Systematics of galaxy-shear measurements

Methods to Measure H(z)

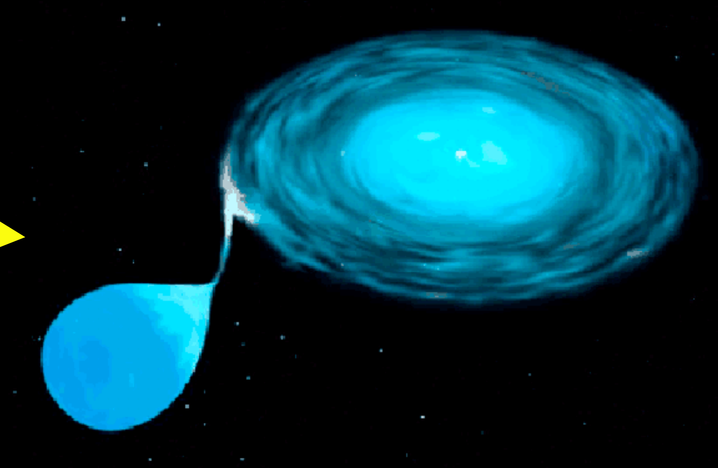
$$H(z)^2 = \Sigma_i\ \Omega_i\ (1+z)^{3(1+w)}$$

Method	Difficulties
brightness vs. redshift for **SN Ia**	~~Large dispersion in brightness.~~ Evolution ? Dust ?

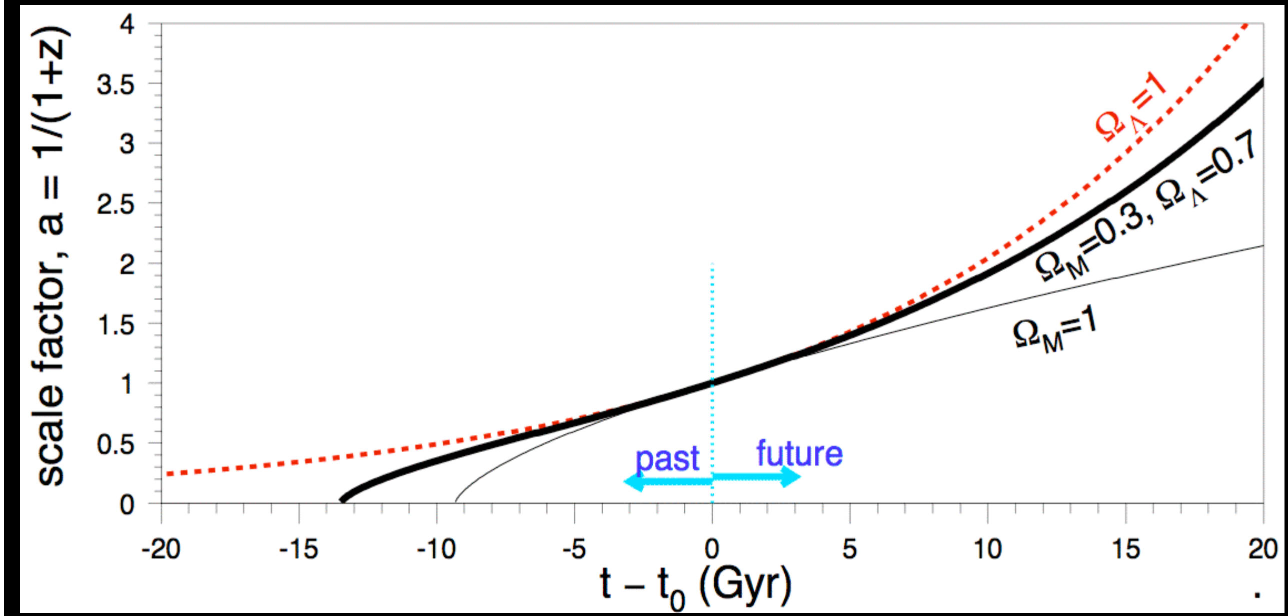
Natural dispersion ~ factor of 2 :
reduced to 15% after ‘width-luminosity’ correction (Phillips 1993)

Supernova Classifications

Supernova type	Hydrogen, Helium	Silicon	Core collapse
Ia	No, no	Yes	No
Ib	No, yes	No	Yes
Ic	No, yes	No	Yes
II	Yes, yes	No	Yes

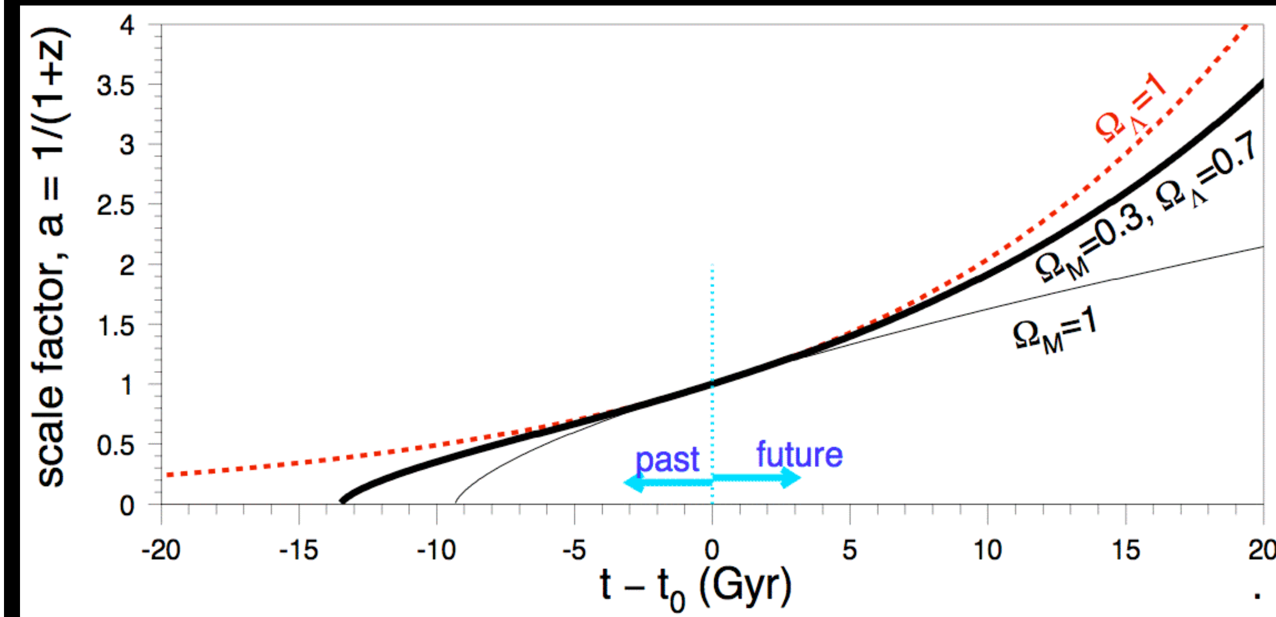


Hubble Diagram Basics

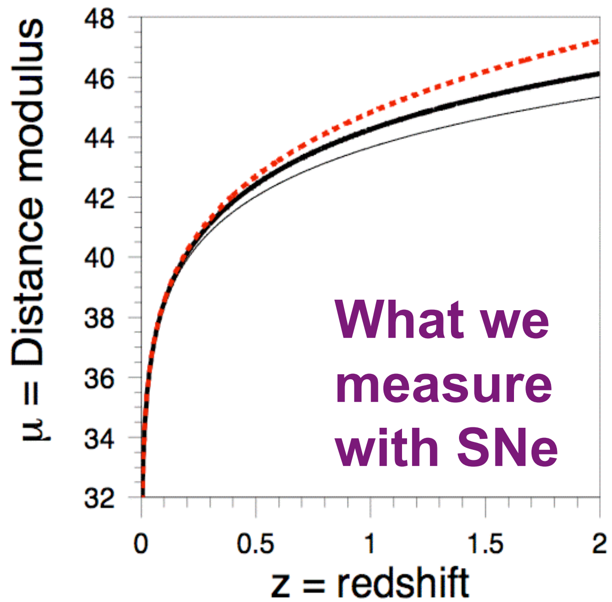


Expansion history depends on w, Ω_Λ and Ω_M

Hubble Diagram Basics



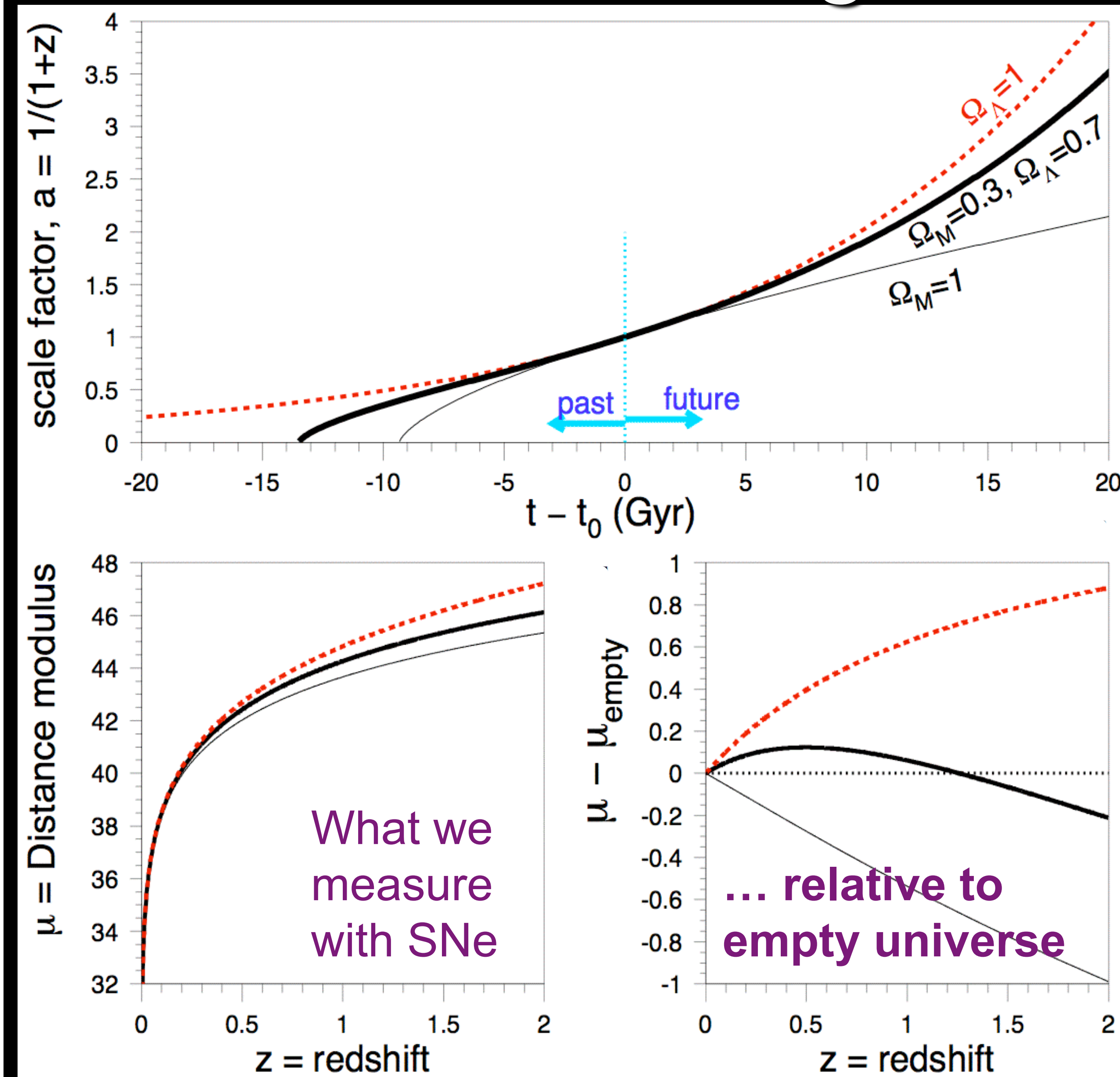
Expansion history depends on w, Ω_Λ and Ω_M



Flux $\propto \mathscr{L}/4\pi d_L^2$.

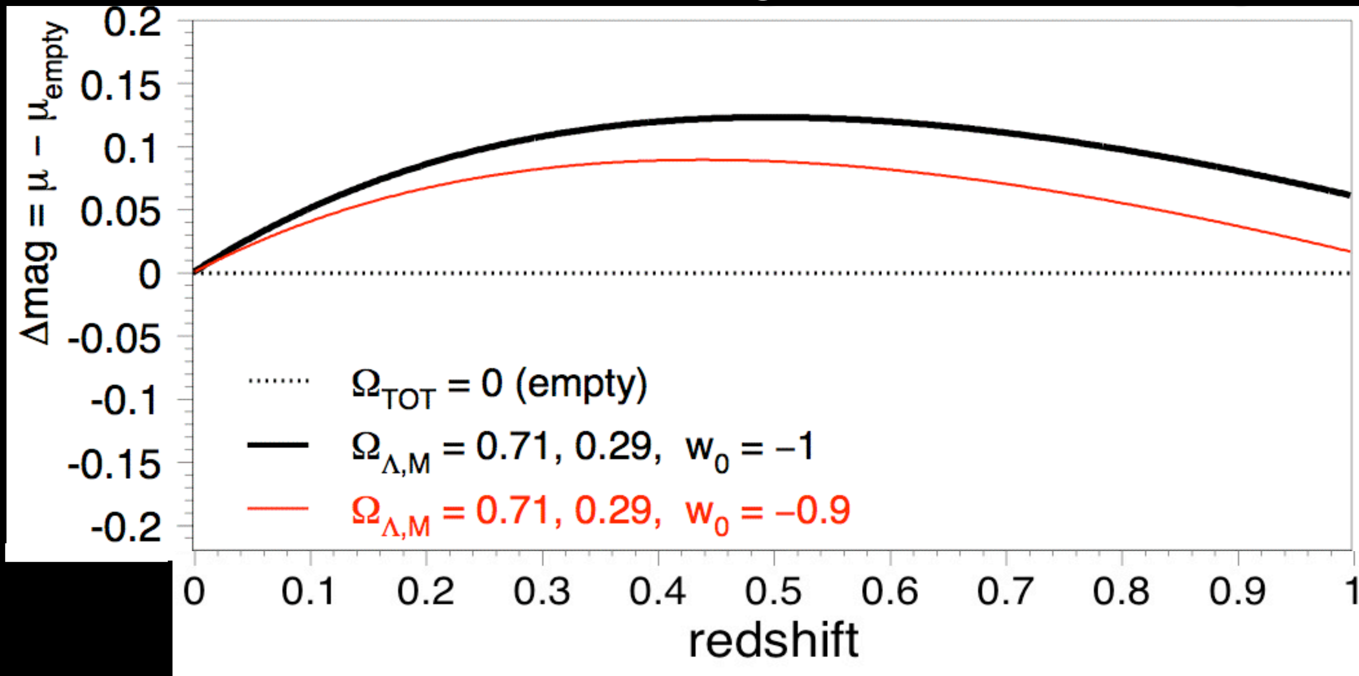
$d_L = (1+z)\int dz/H(z,\Omega_M,\Omega_\Lambda,w)$
for flat universe.
Distance modulus: $\mu=5\log(d_L/10pc)$

Hubble Diagram Basics

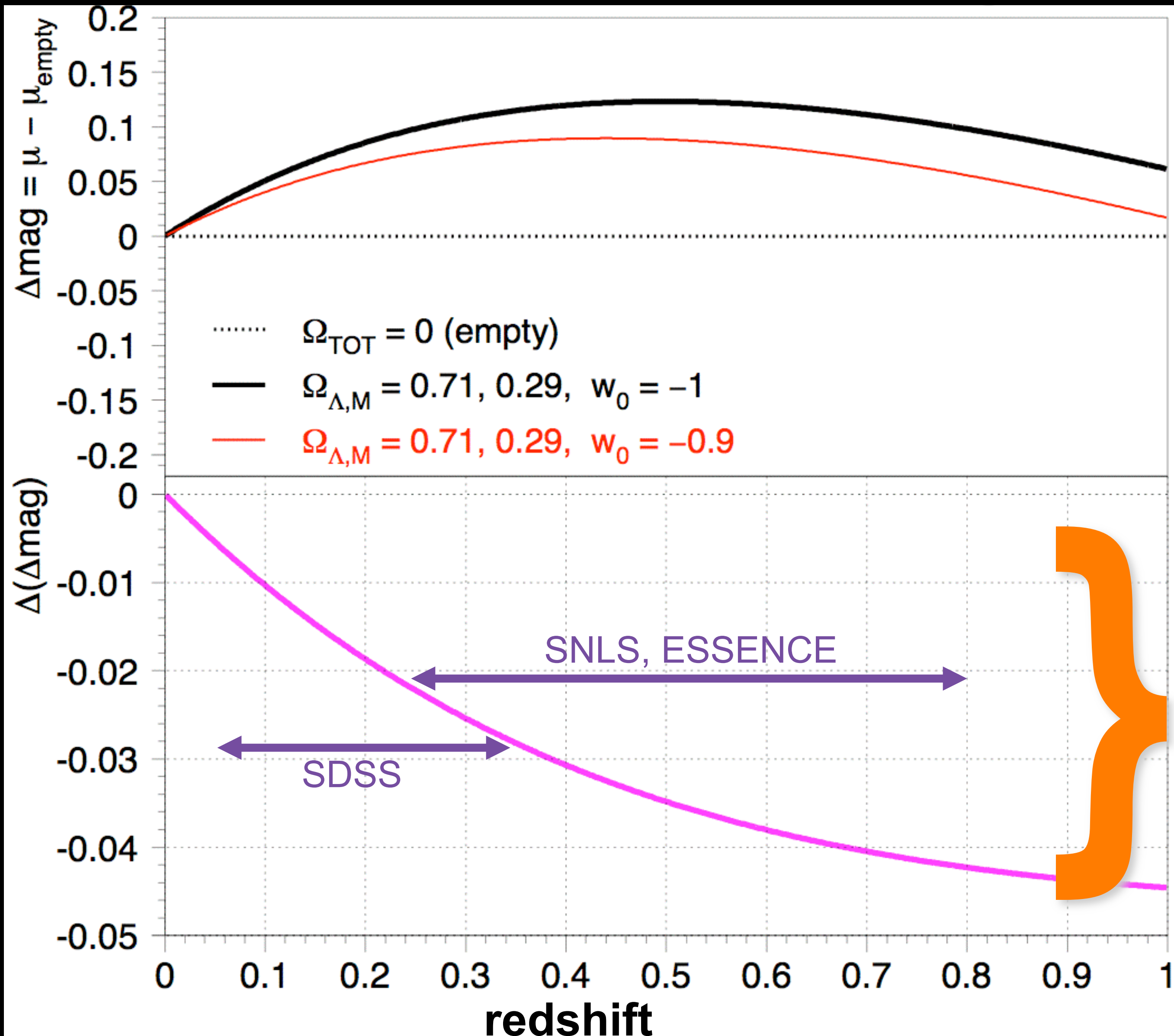


Expansion history depends on w, Ω_Λ and Ω_M

w-sensitivity with Supernova



w-Quest with Supernova

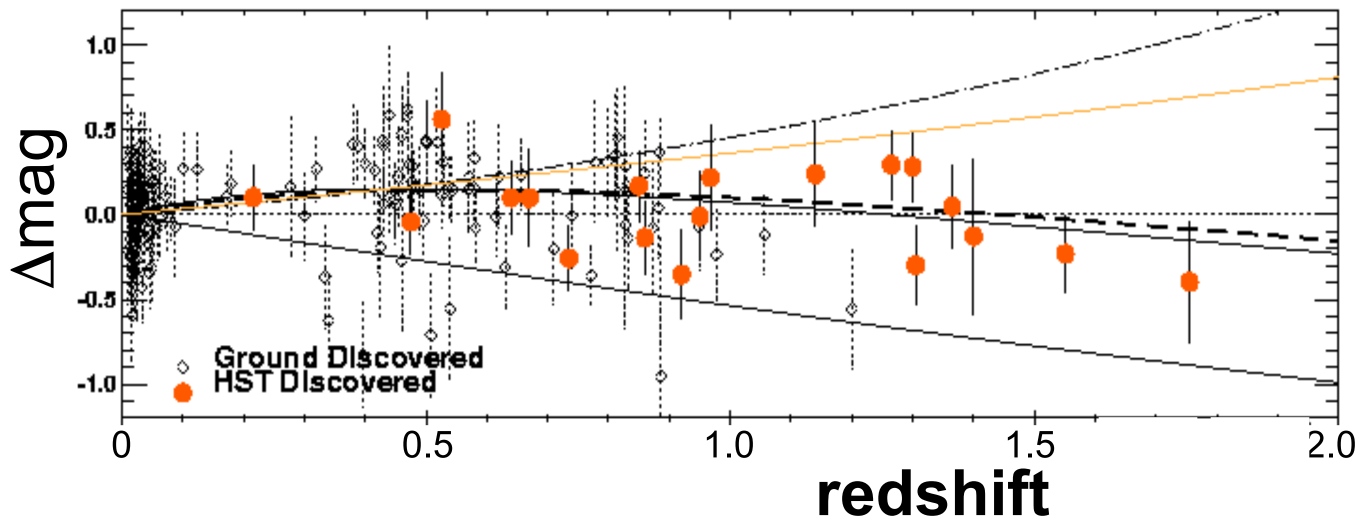


w = –0.9 gives 4% variation from w = –1

Data Overview

SN Ia Hubble diagram: compilation from Riess et. al., AJ 607 (2004)

includes data from Calan Tololo, HZT, SCP, CfA, Higher-Z, ACS.

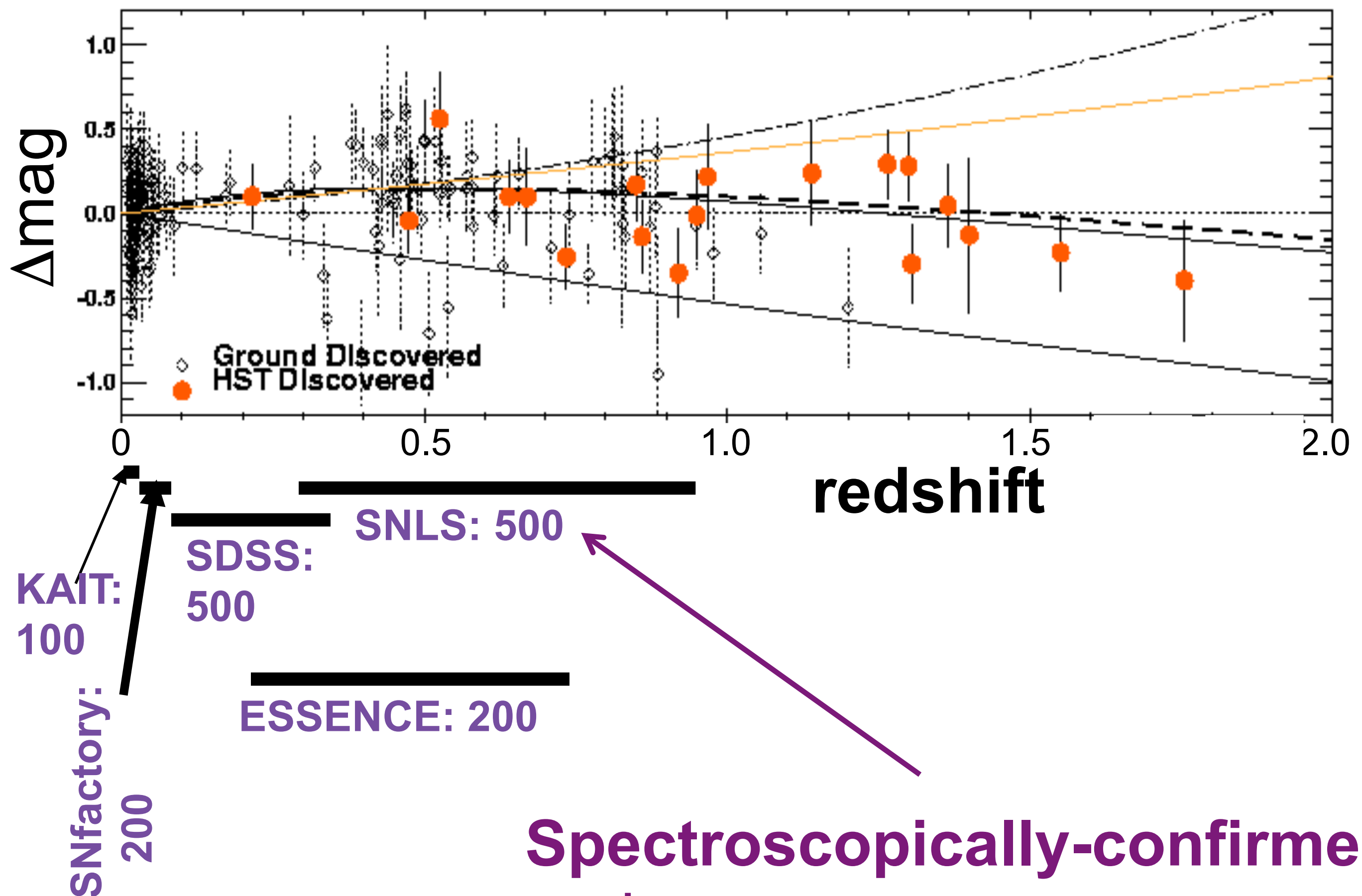


1st generation surveys:
Discovery of accelerated expansion
and w within 20% of −1

Data Overview

SN Ia Hubble diagram: compilation from Riess et. al., AJ 607 (2004)

includes data from Calan Tololo, HZT, SCP, CfA, Higher-Z, ACS.

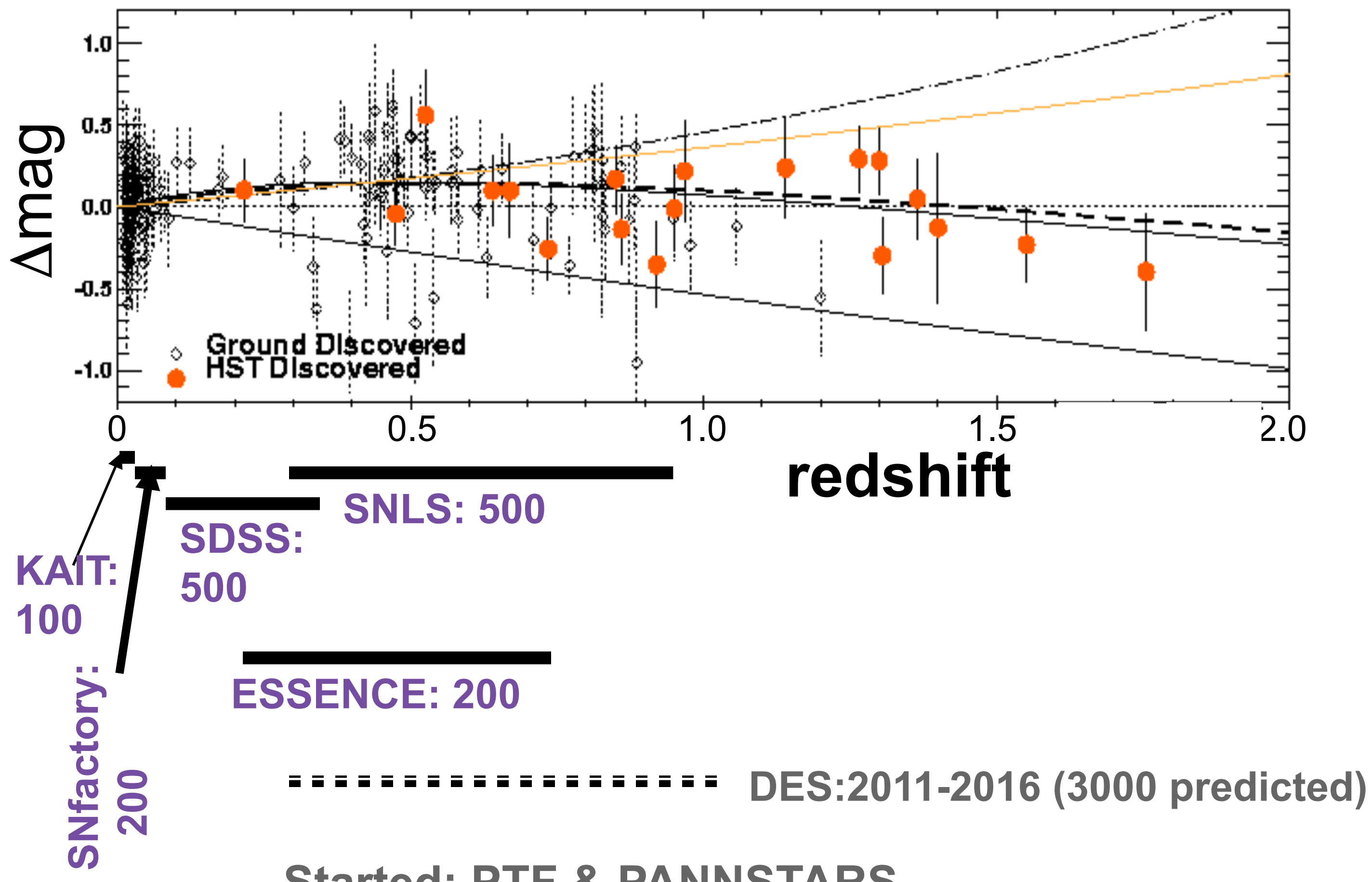


Spectroscopically-confirmed (2nd generation surveys)

Data Overview

SN Ia Hubble diagram: compilation from Riess et. al., AJ 607 (2004)

includes data from Calan Tololo, HZT, SCP, CfA, Higher-Z, ACS.



Started: PTF & PANNSTARS
Future: DES, LSST, JDEM …

Meet the SDSS-II Supernova Team

The Sloan Digital Sky Survey-II Supernova Survey: Technical Summary

AJ 135, 338 (2008)

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SDSS-II Supernova Survey: Sep 1 - Nov 30, 2005-2007

(1 of 3 SDSS projects for 2005-2008)

GOAL:

Few hundred high-quality type Ia SNe lightcurves in redshift range 0.05-0.35

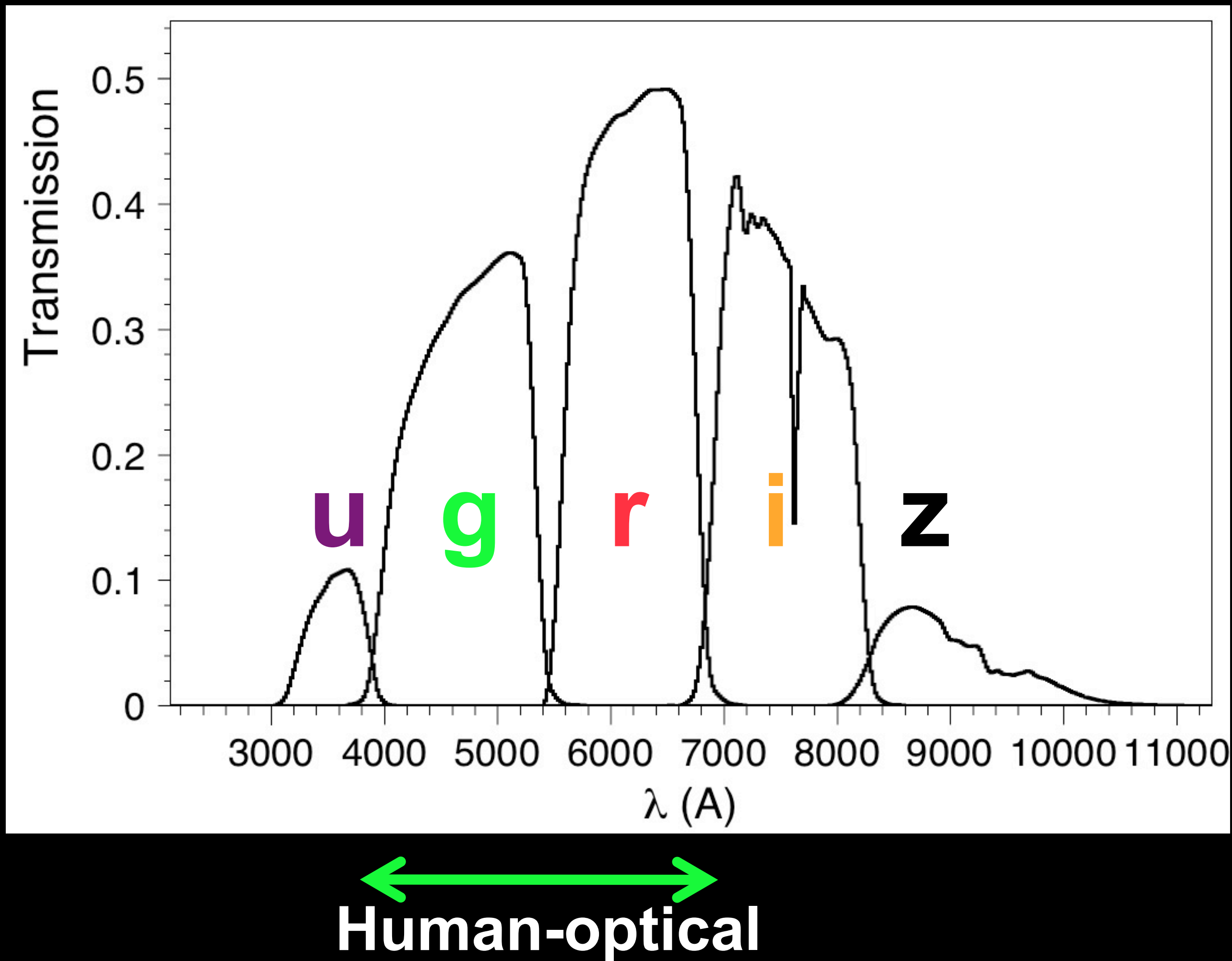
SAMPLING:

~300 sq deg in ugriz (3 million galaxies every two nights)

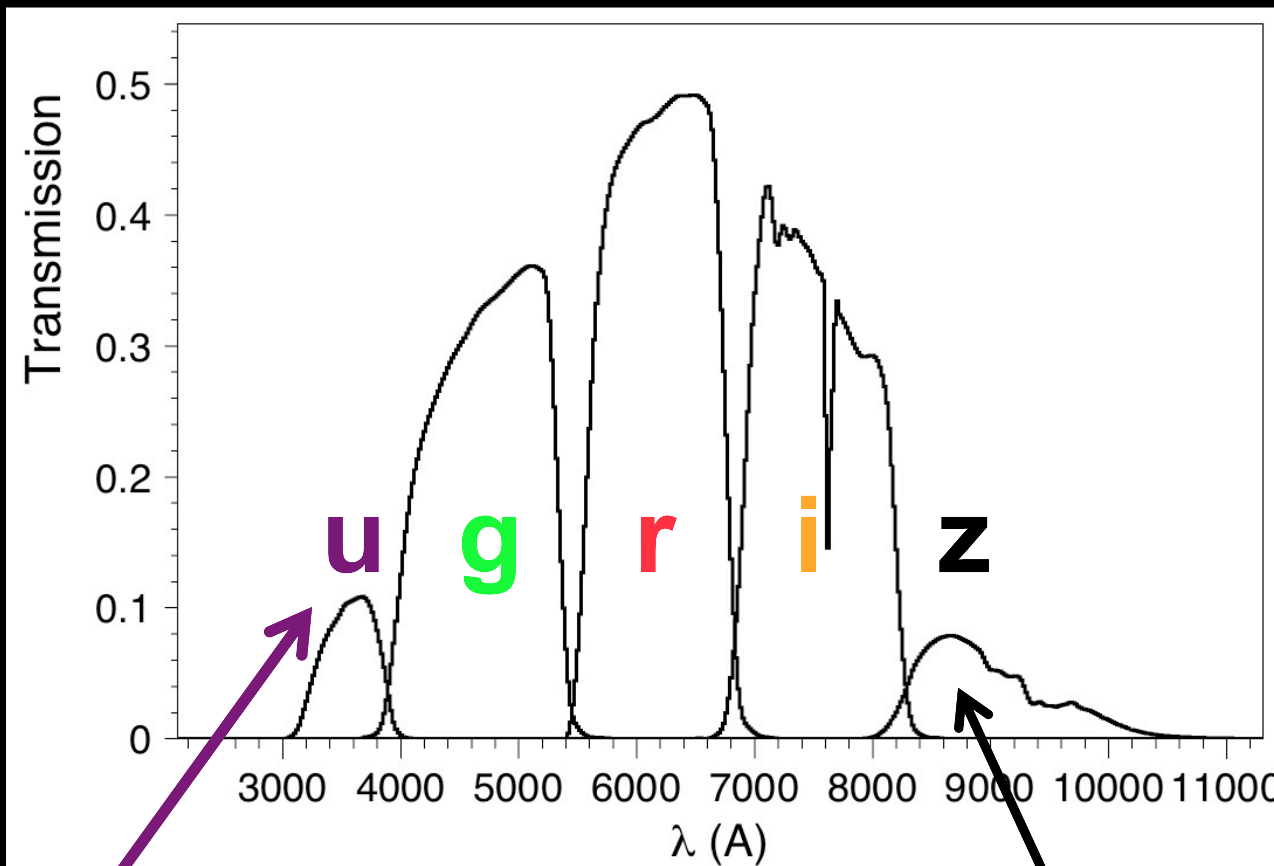
SPECTROSCOPIC FOLLOW-UP:

HET, ARC 3.5m, MDM, Subaru, WHT, Keck, NTT, KPNO, NOT, SALT, Magellan, TNG

SDSS Filters



SDSS Filters



u: strong atmospheric absorption

Human-optical

z: low CCD efficiency, large sky background

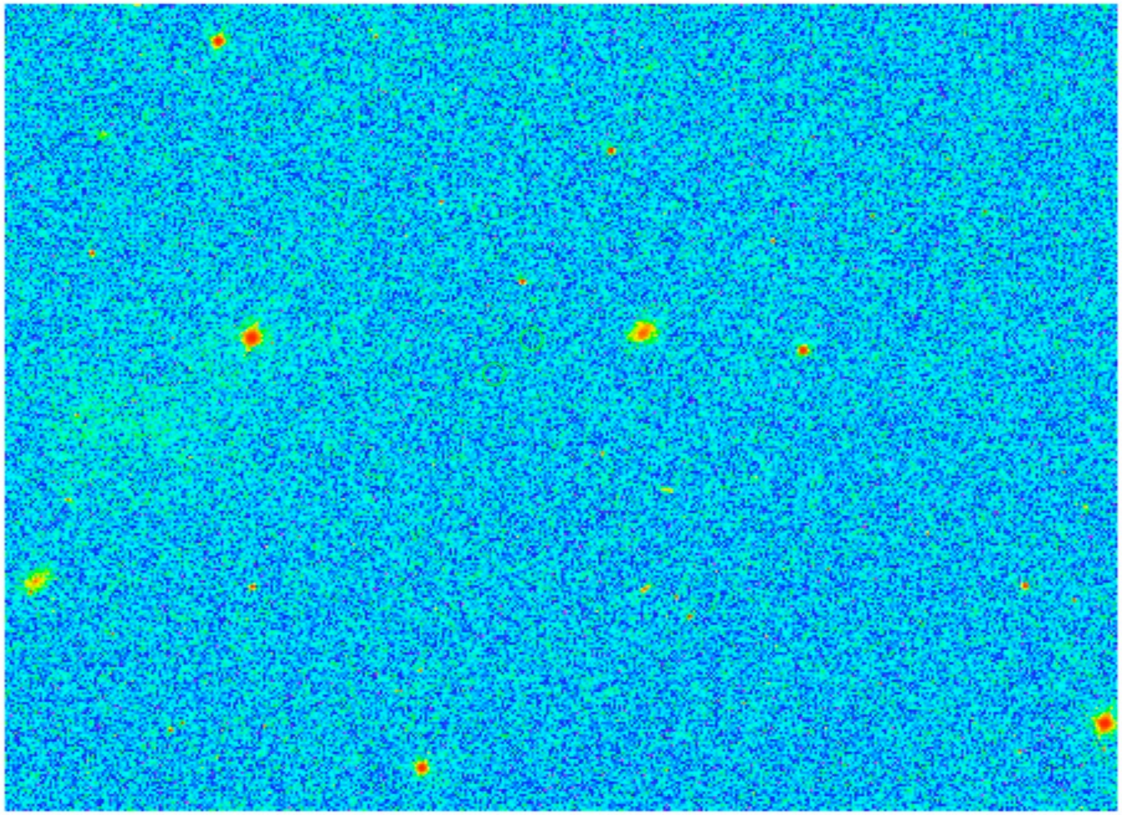
SDSS Data Flow

One full night collects 4000 fields (800/filter)

Each 'search' field is compared to a 2-year old 'template' field … things that go "boom" are extracted for human scanning.

Ten dual-CPU servers at APO process g,r,i data in ~ 20 hrs.

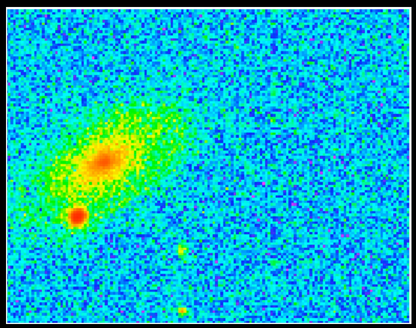
one raw g-field (0.15^0)

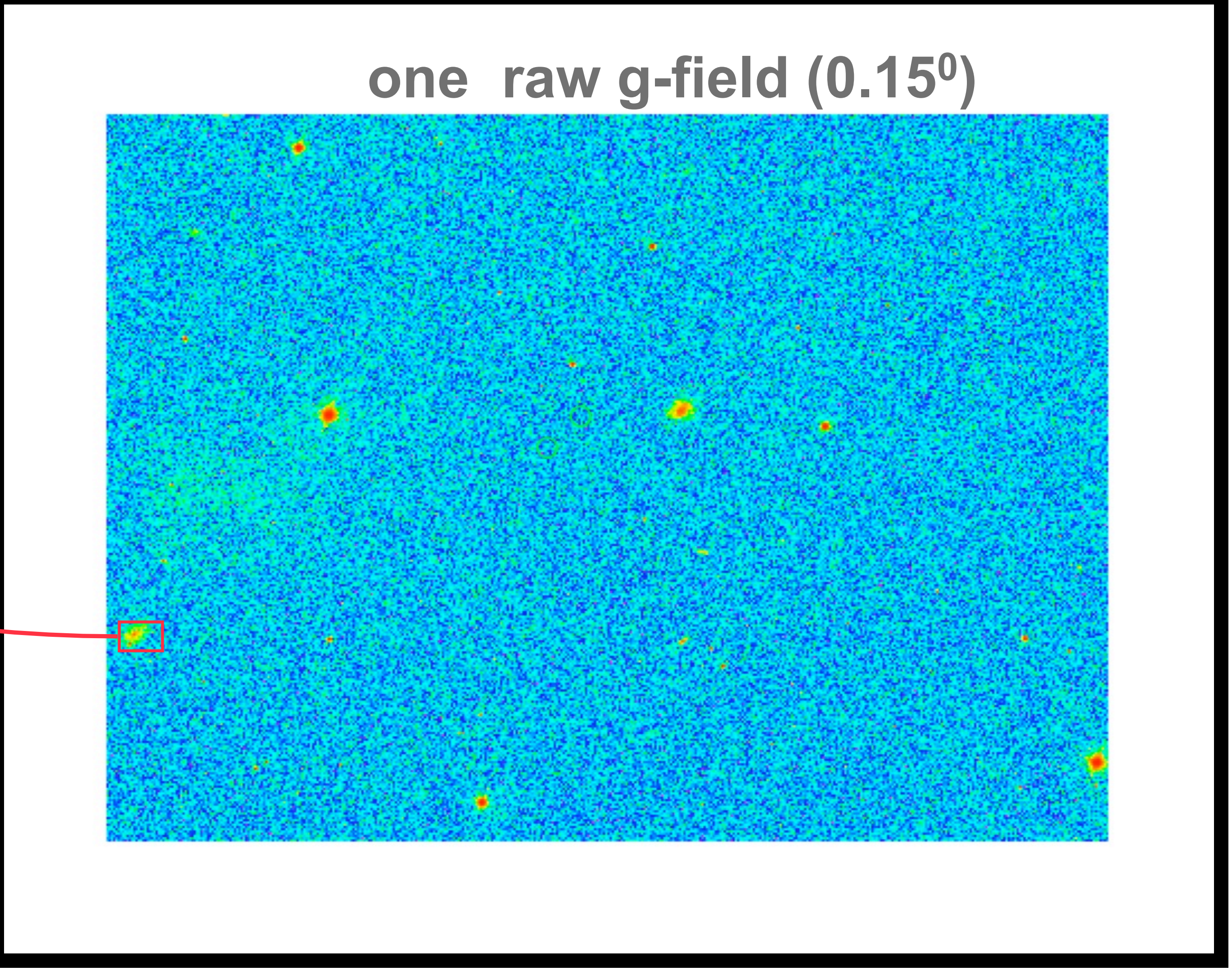


(can you find a confirmed SN Ia ?)

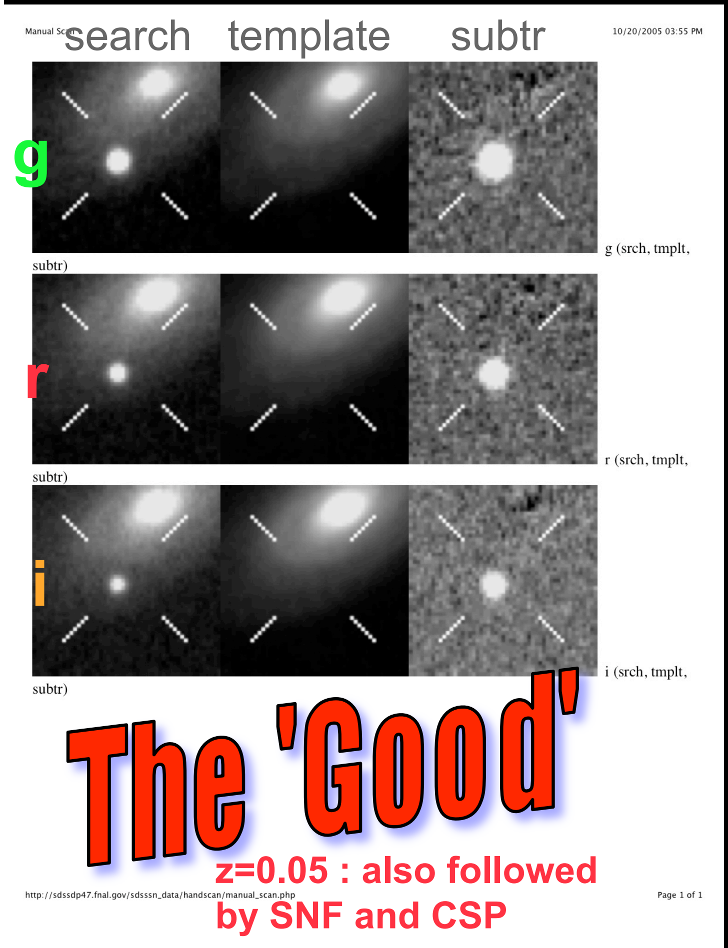
SDSS Data Flow

One full night collects 4000 fields (800/filter)

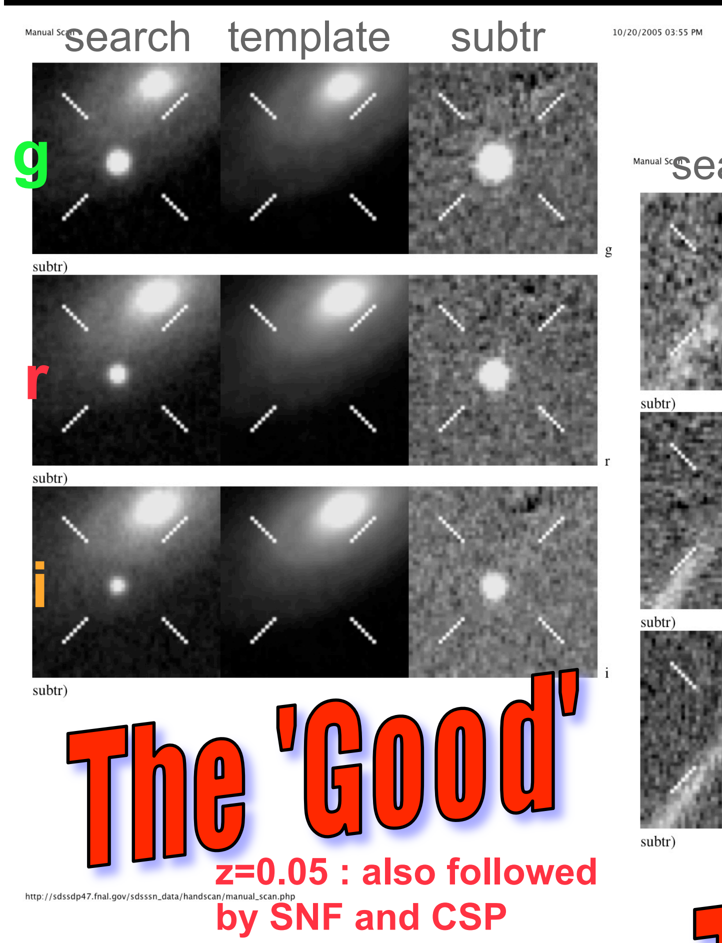




SDSS Manual Scanning



SDSS Manual Scanning



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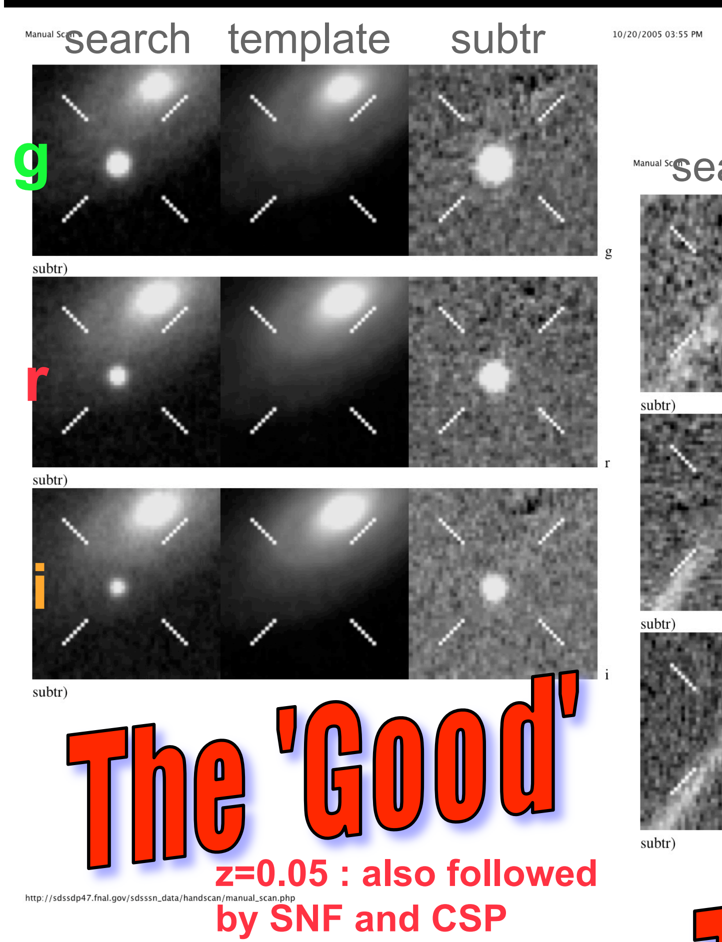
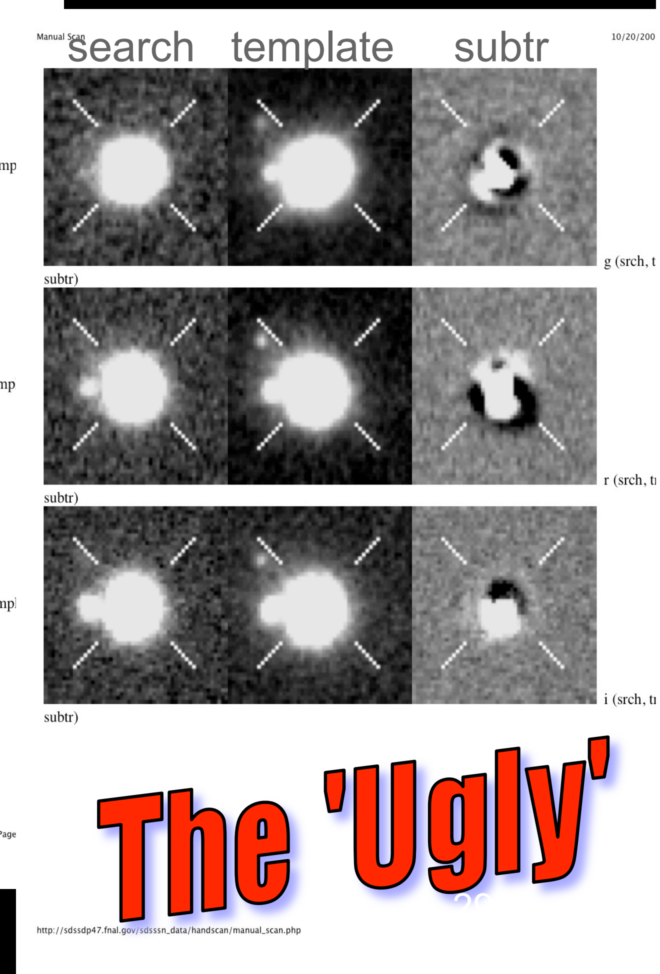
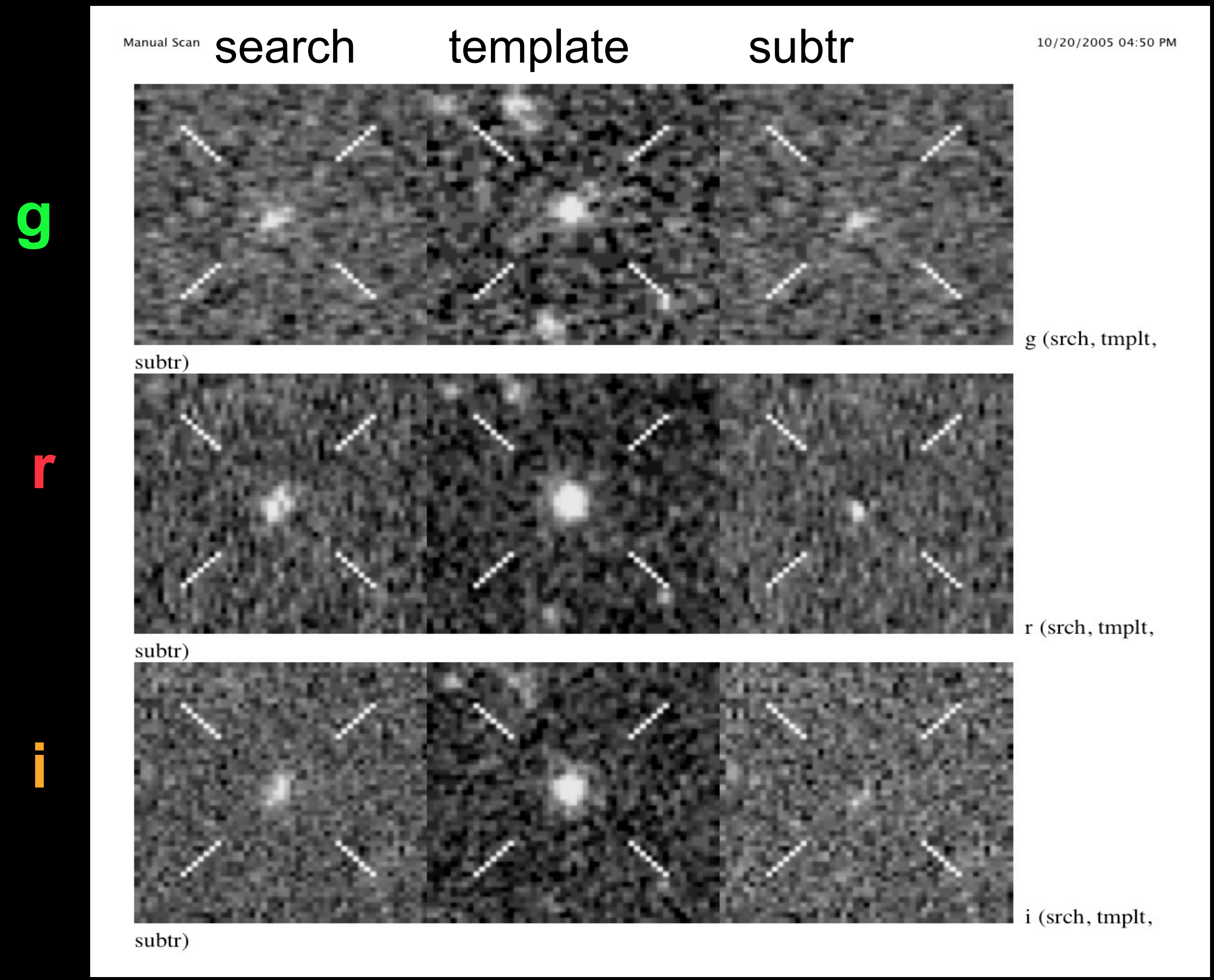




Typical SN Candidate

z = 0.36



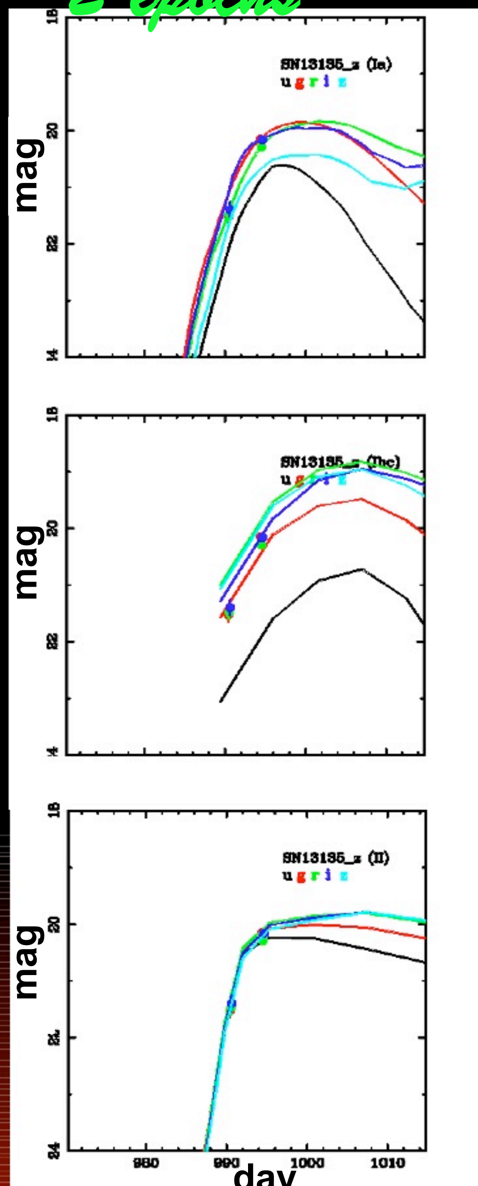
Lightcurve Fits Update in Real Time

2 epochs

SN Ia Fit
$\chi^2 = 1.8$

SN Ibc Fit
$\chi^2 = 39$

SN II Fit
$\chi^2 = 6.6$

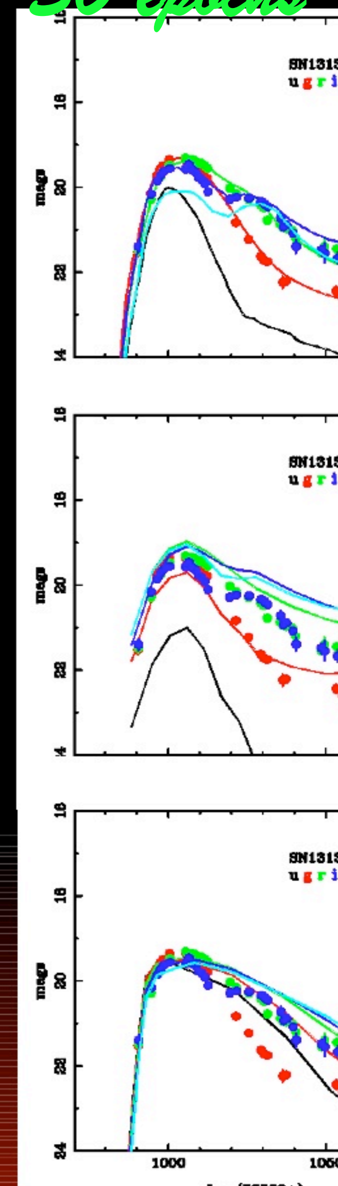


30 epochs

SN Ia Fit
$\chi^2 = 8.8$

SN Ibc Fit
$\chi^2 = 352$

SN II Fit
$\chi^2 = 57$



Lightcurve Fits Update in Real Time

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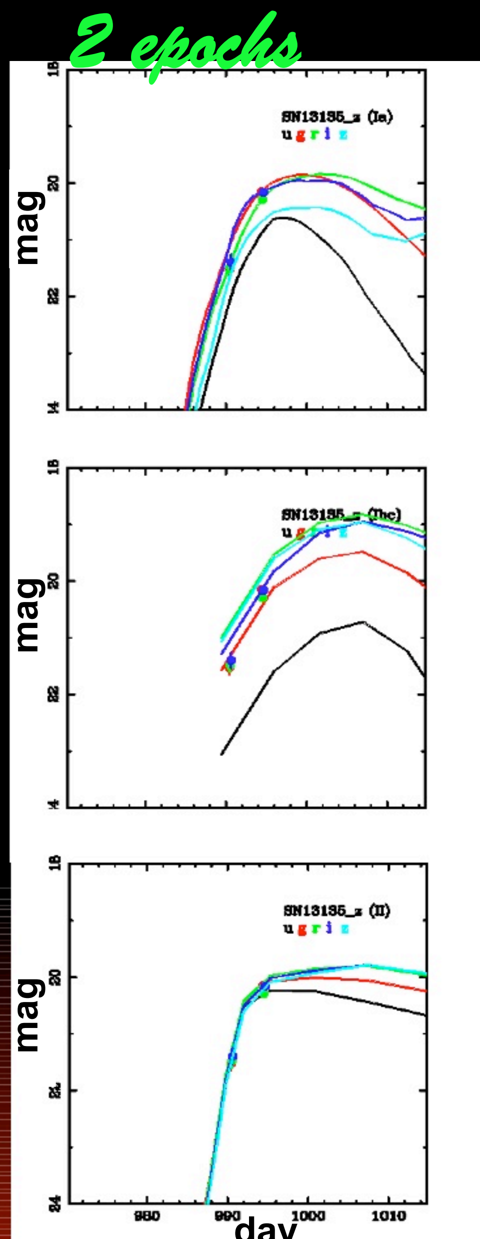
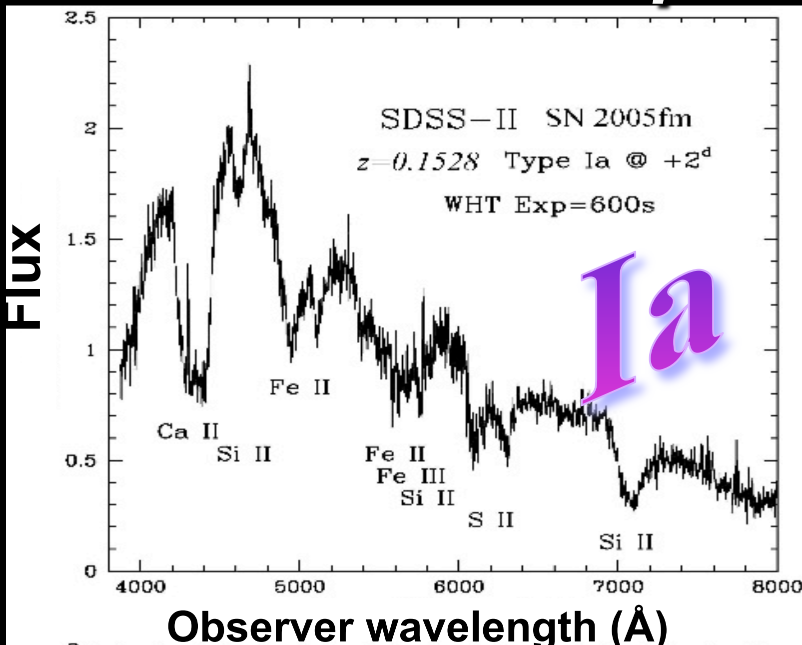
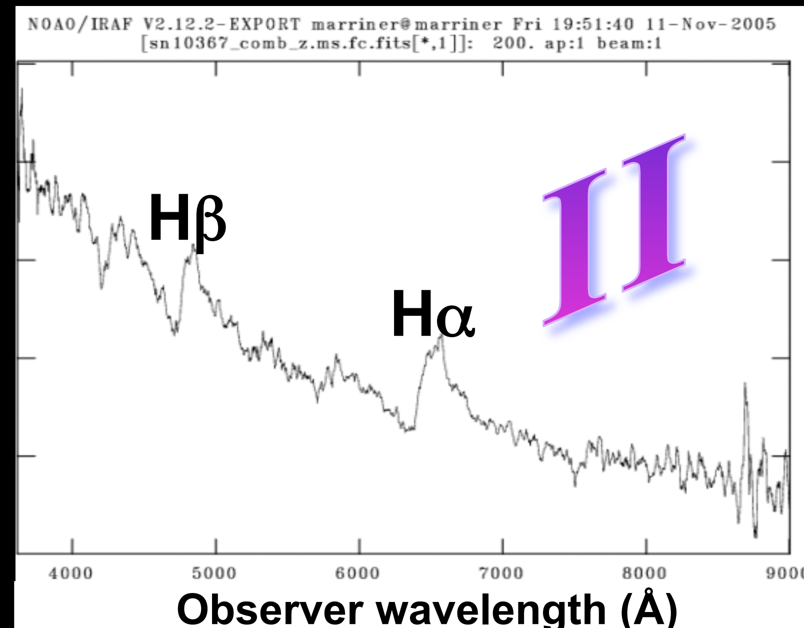
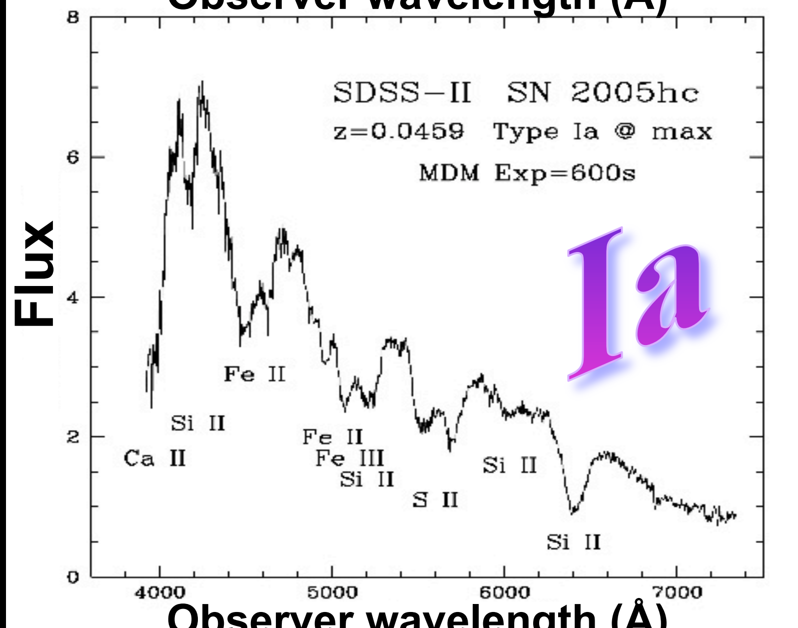


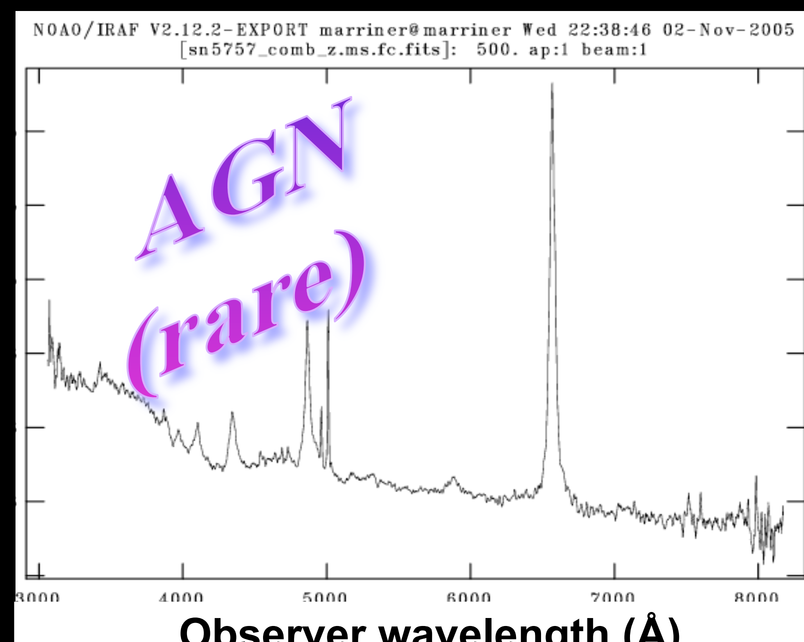
> 90% of photometric Ia candidates were spectroscopically confirmed to be SN Ia

Follow-up Spectral id









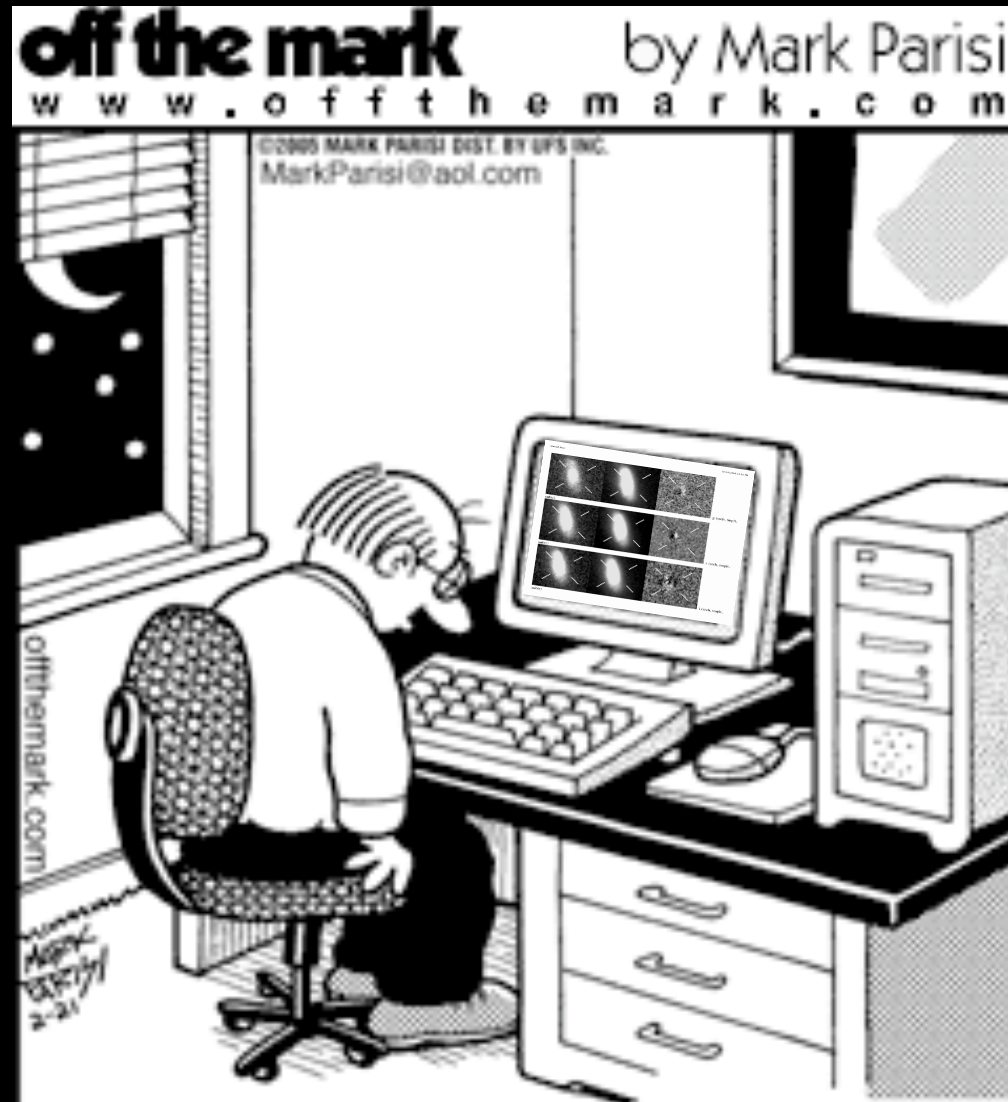
Survey Scan Stats

Sako et al., AJ 135, 348 (2008)

We visually scanned more than 100,000 candidates and discovered > 1000 SN Ia

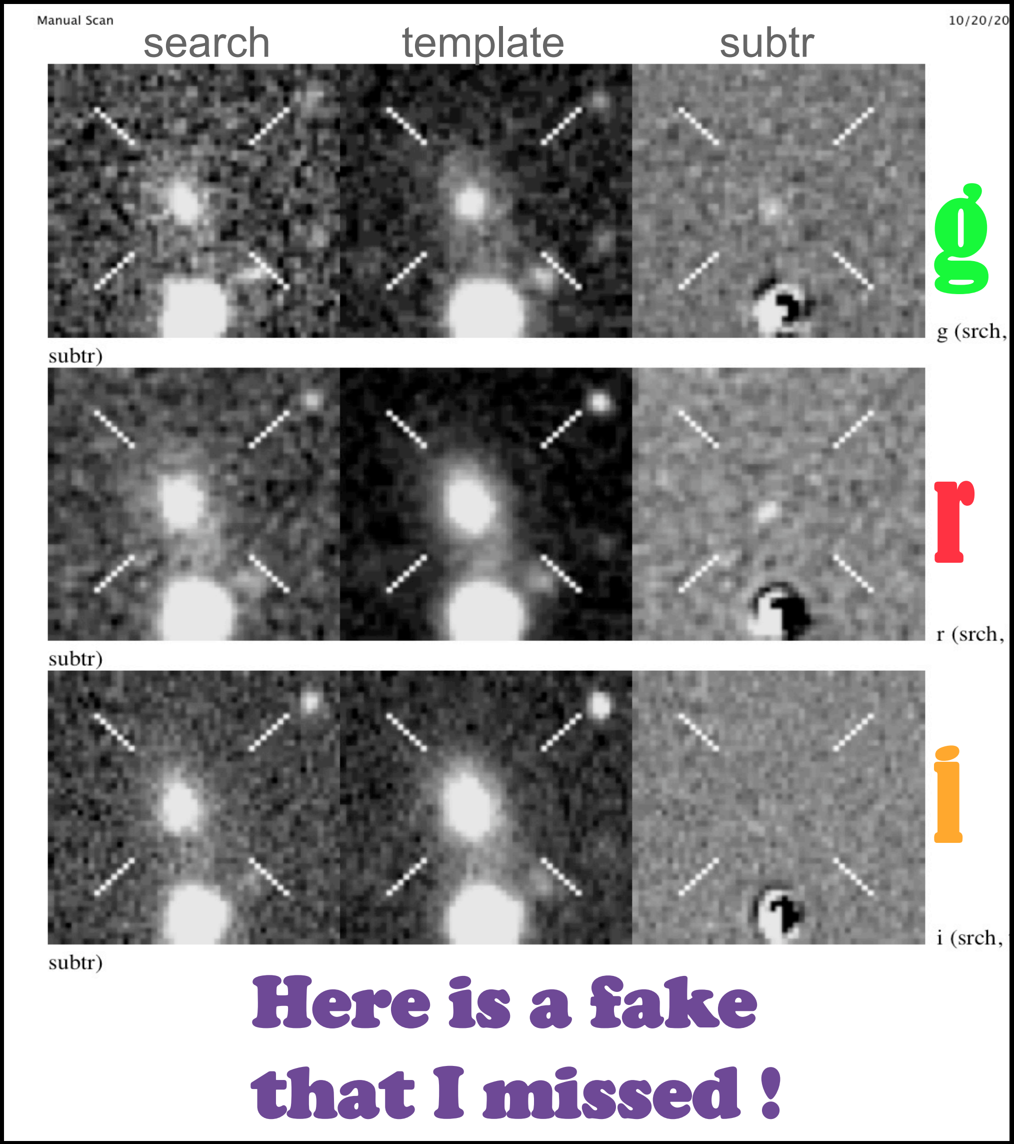
… 500 were spec-confirmed

... BOSS is getting host-galaxy spec-z for the rest



SN Fakes

Fake SN Ia were inserted into the images in real time to measure software & scanning efficiencies.



Analysis

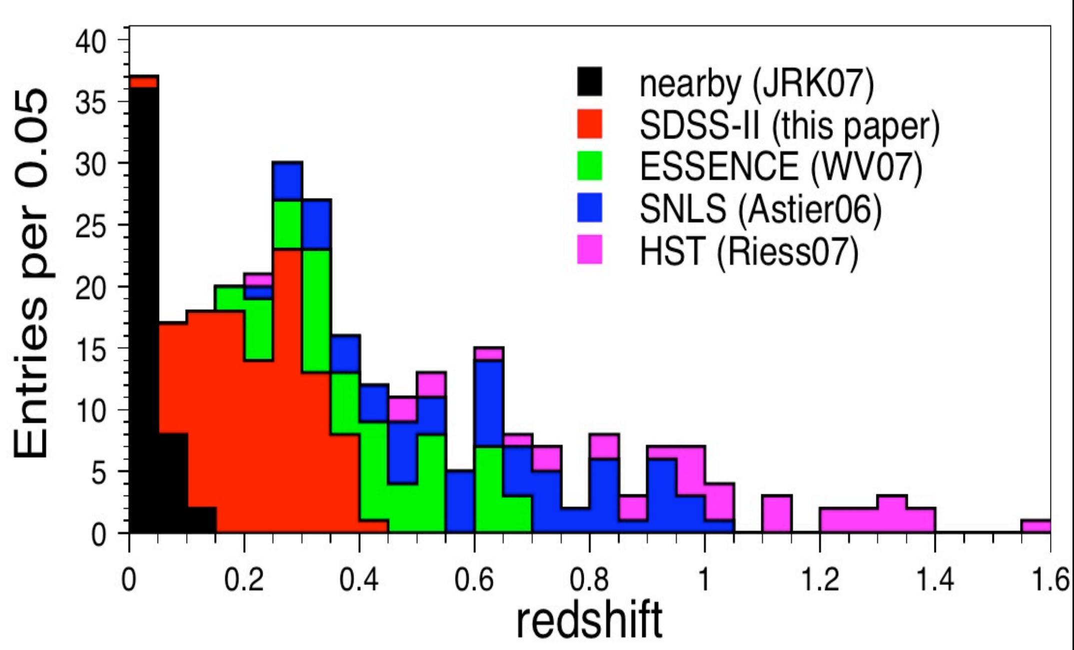
- Methods & results:
  arXiv:0908.4274 or ApJS 185, 32 (2009)
- All software (fitters & sim) is public:
  arXiv:09084280 or PASP 121, 1028 (2009)
- All SDSS-II light curves are public
  arXiv:0908.4277 or AJ 136, 2306 (2008)

SN papers becoming "Methodology" papers as surveys contribute smaller fraction of total SNe Ia

- Astier06: SNLS contributes ~ 70 of 110
- Kowalski 2008:
  contributes 8 of 307 SNe Ia
- SDSS-II 2009: contributes 103 of 288

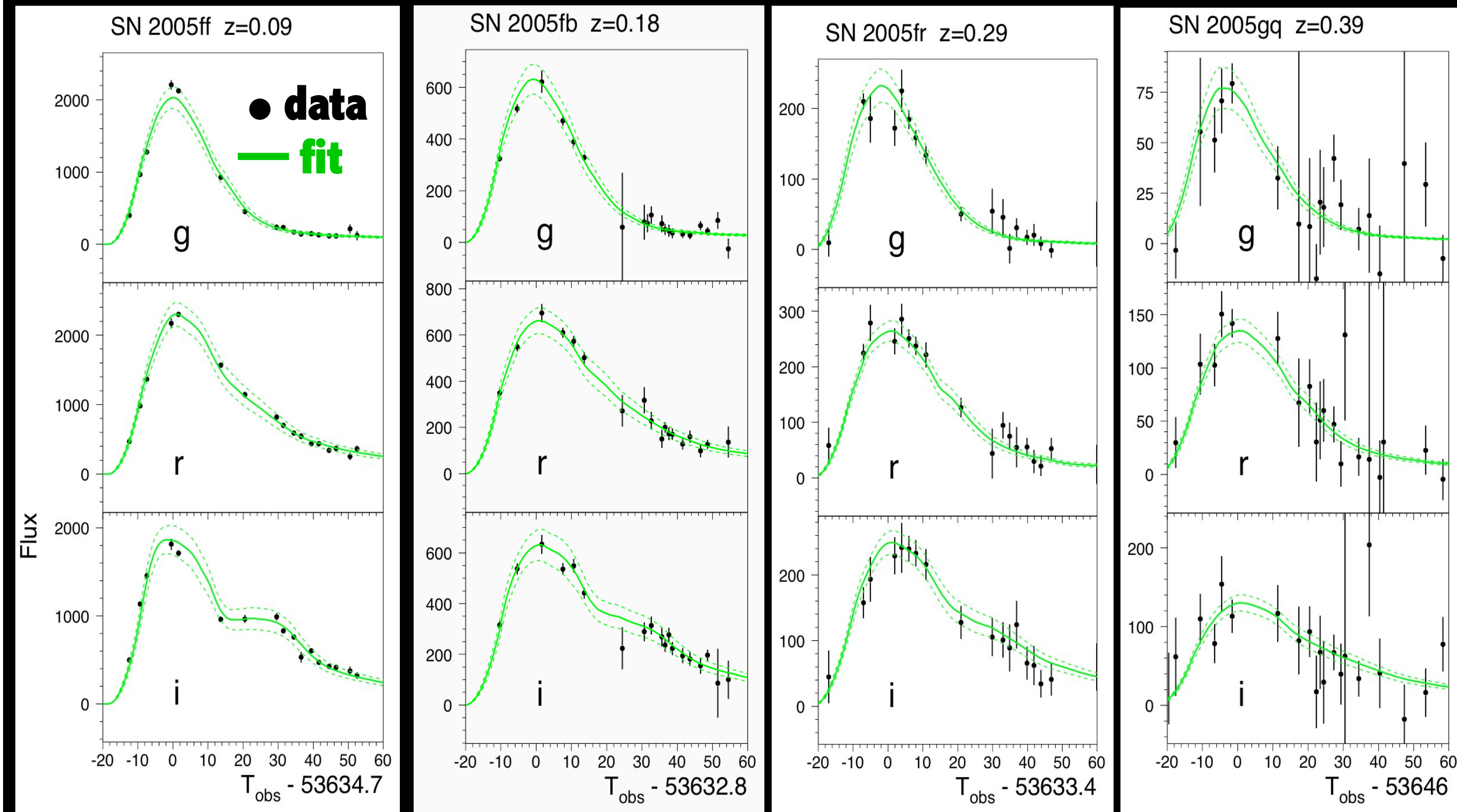
SDSS Hubble Diagram Analysis: Samples Include

- SDSS-II 1st season (103)
- Nearby SNe from literature (33)
- SNLS 1st season (62)
- ESSENCE (56)
- HST (34)



SDSS ***gri*** *Light Curves:*

$\langle N_{measure} \rangle$ = 48 per SN



SN Light Curve Sampling

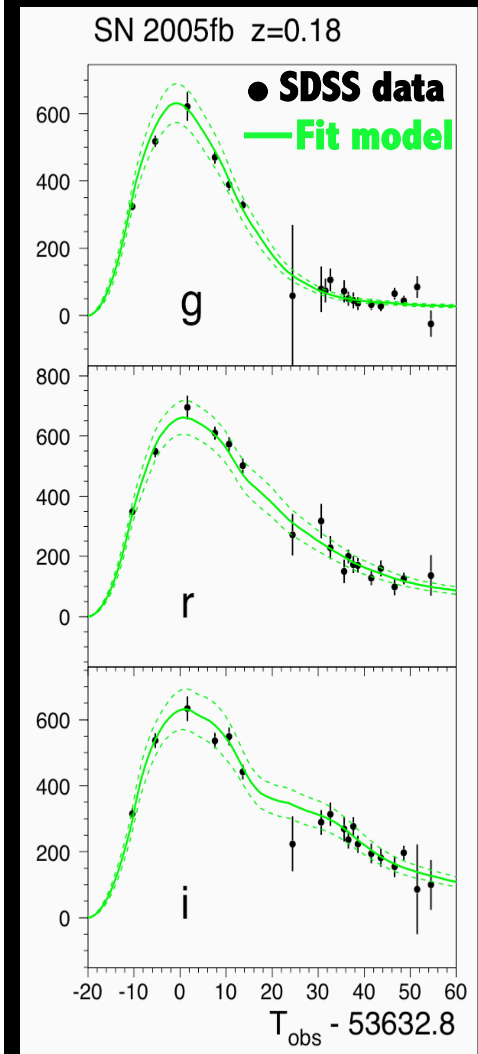
Table 2: Redshift range, number of SNe passing selection cuts, and mean number of measurements for each SN sample.

sample (obs passbands)	redshift range	N_{SN}[a]	$\langle N_{meas} \rangle$[b]
Nearby ($UBVRI$)	0.02 – 0.10	33	52
SDSS-II (gri)	0.04 – 0.42	103	48
ESSENCE (RI)	0.16 – 0.69	56	21
SNLS ($griz$)	0.25 – 1.01	62	27
HST (F110W, F160W, F606W, F775W, F850LP)	0.21 – 1.55	34	11

[a] Number of SNe Ia passing cuts.

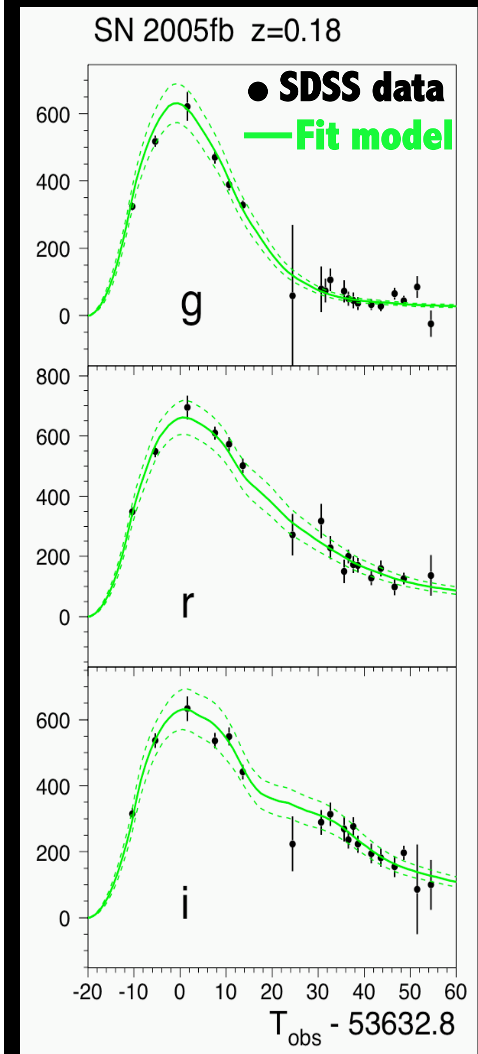
[b] Average number of measurements per SN Ia, in the interval $-15 < T_{\rm rest} < +60$ days.

Lightcurve Fit Overview



- **Fit data to parametric model (or template) to get light curve shape and color.**
- **"Training" relates shape and color to "standardized" intrinsic luminosity (mag) at peak**

Lightcurve Fit Overview



- **Fit data to parametric model (or template) to get light curve shape and color.**
- **"Training" relates shape and color to "standardized" intrinsic luminosity (mag) at peak**

Distance-modulus (μ) =
Observed mag –
Intrinsic mag

Light Curve Fit Overview

- Use both MLCS2k2 & SALT2 methods without retraining ==>

  use essentially as-is

- Make necessary & obvious improvements to implementation, but not to underlying method.

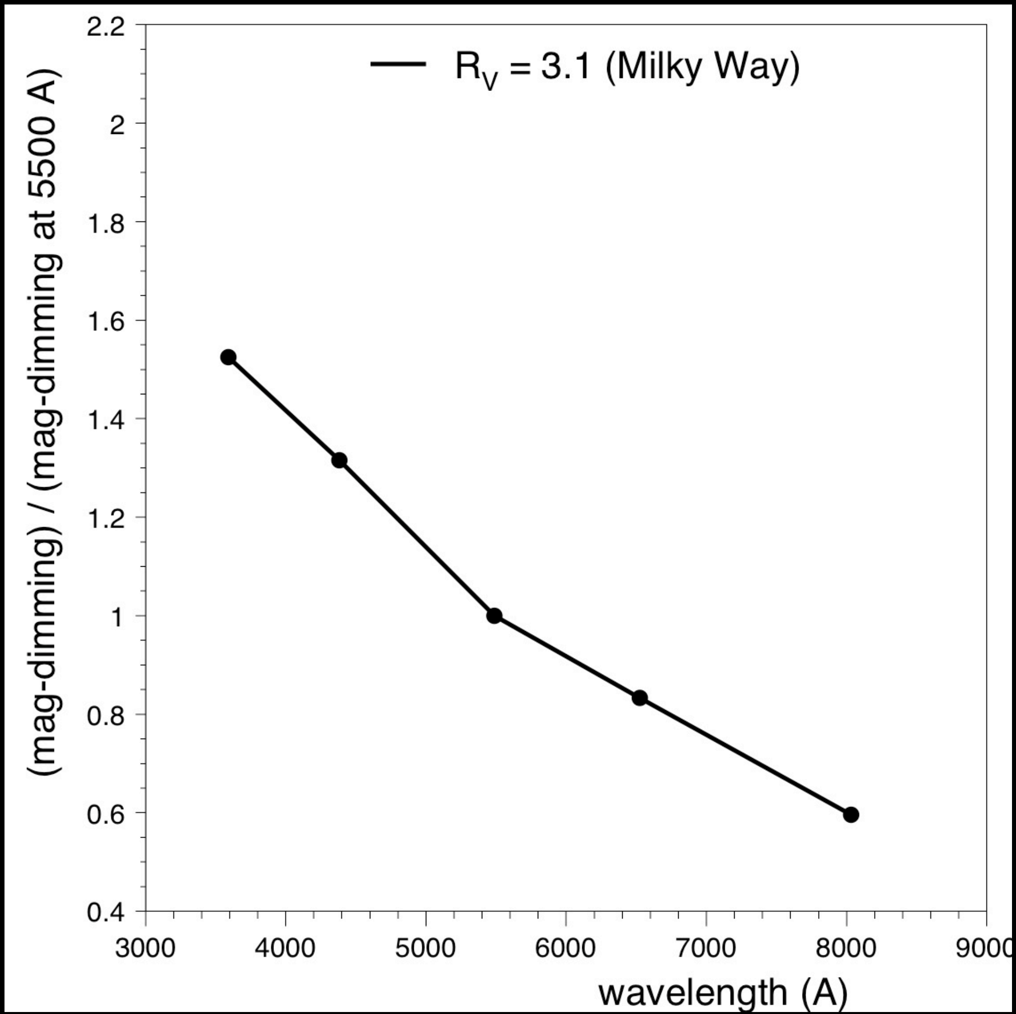
- Identify problems & evaluate systematic uncertainties.

Analysis with available light curve fitters:

- **MLCS (A.Riess)**:
  - assumes color variations are ONLY from host-galaxy extinction.
  - Prior enforces positive extinction: $A_V > 0$

- **SALT2 (J.Guy)**:
  - color variations are not untangled from SN and host-galaxy extinction
  - no prior (bluer is always brighter)

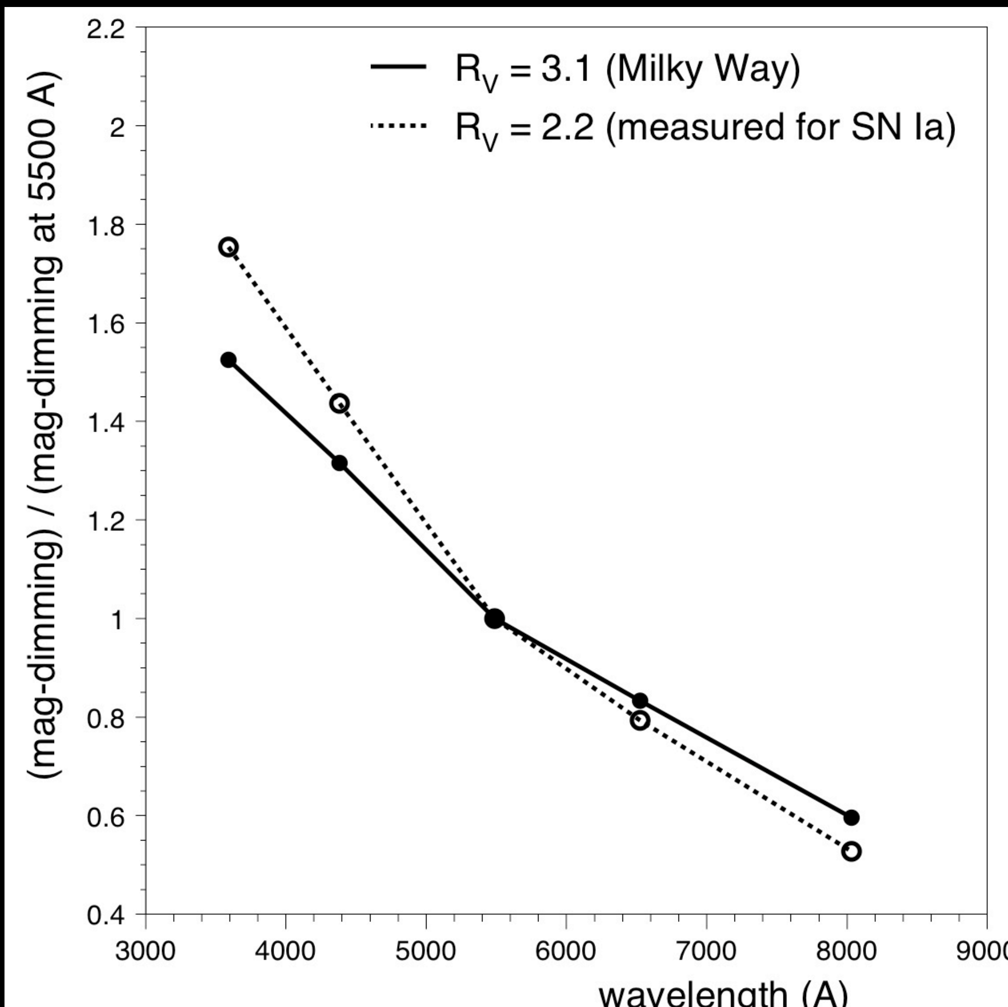
Color Variations: SN or host-galaxy Dust ?



Original MLCS (Riess et al.) assumed host-galaxy extinction is the same as in Milky Way: R_V = 3.1 & CCM89

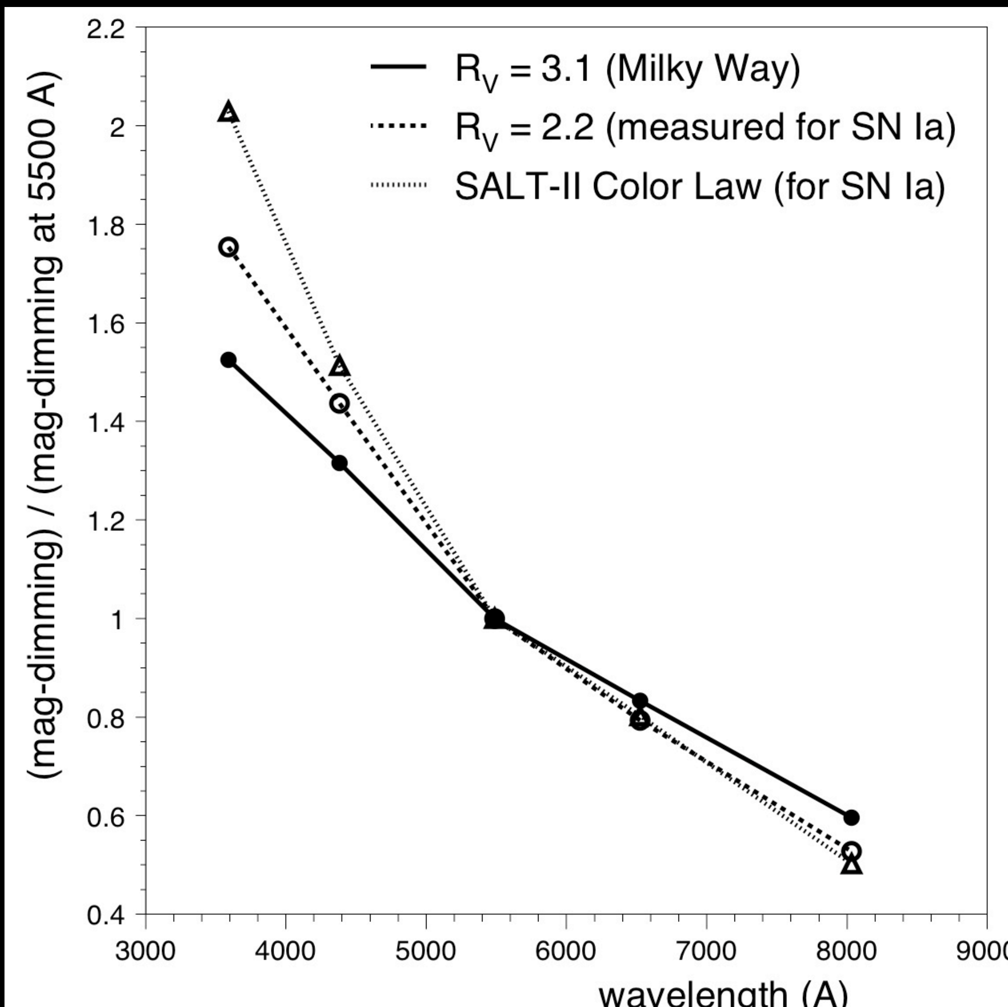
Dust scatters blue light more, hence extincted objects appear reddened.

Color Variations: SN or host-galaxy Dust ?



Many recent analyses find R_V ~ 2 ➔ more extinction in UV region (compared to R_V = 3.1)

Color Variations: SN or host-galaxy Dust ?



Empirical SN color law (SALT-II, Guy 2007) finds even more dimming in UV region (no assumption about dust)

Changes in MLCS Implementation

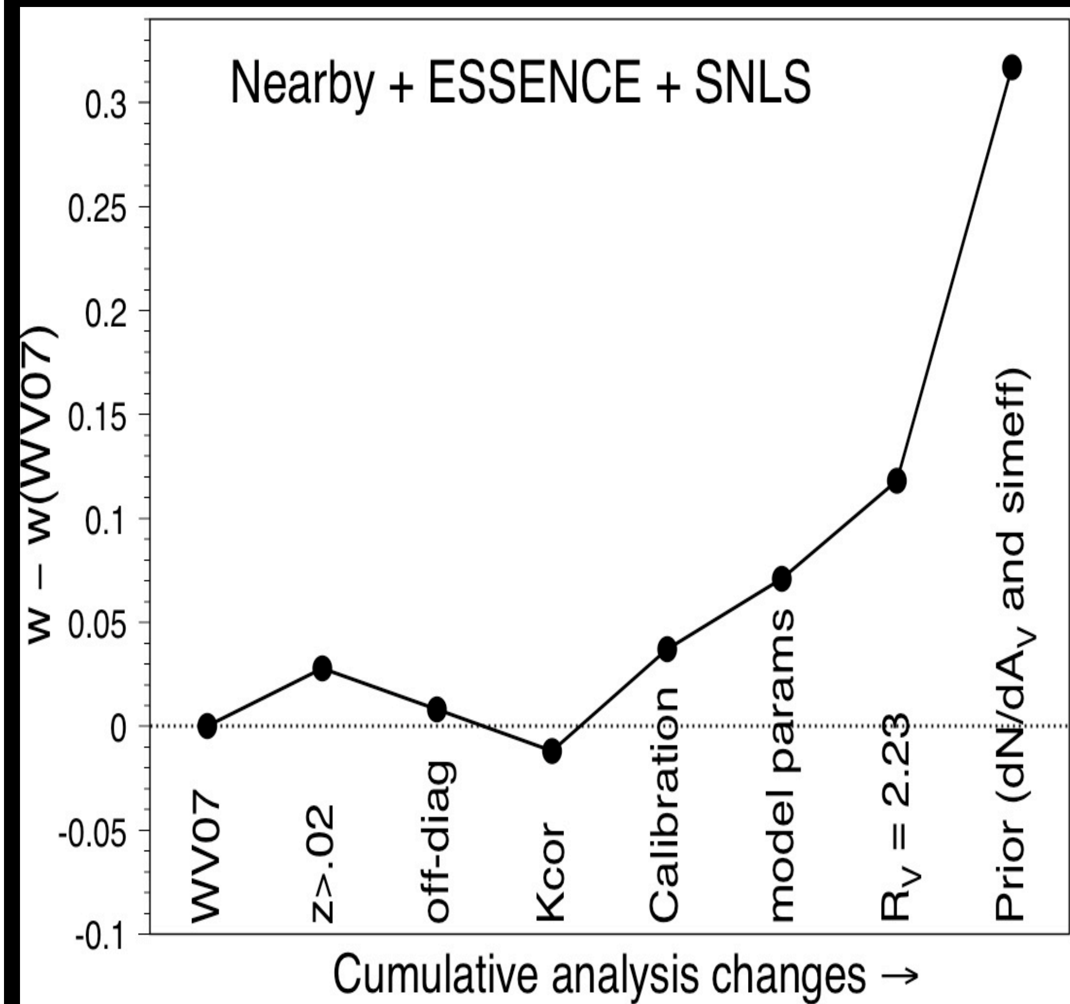
(no changes in training or philosophy)

- Host galaxy dust properties are measured with SDSS SNe (instead of assumptions)

- Account for spectroscopic efficiency in fitting prior ➜ big effect at high-z end of each survey

- Fit in flux (not mag)

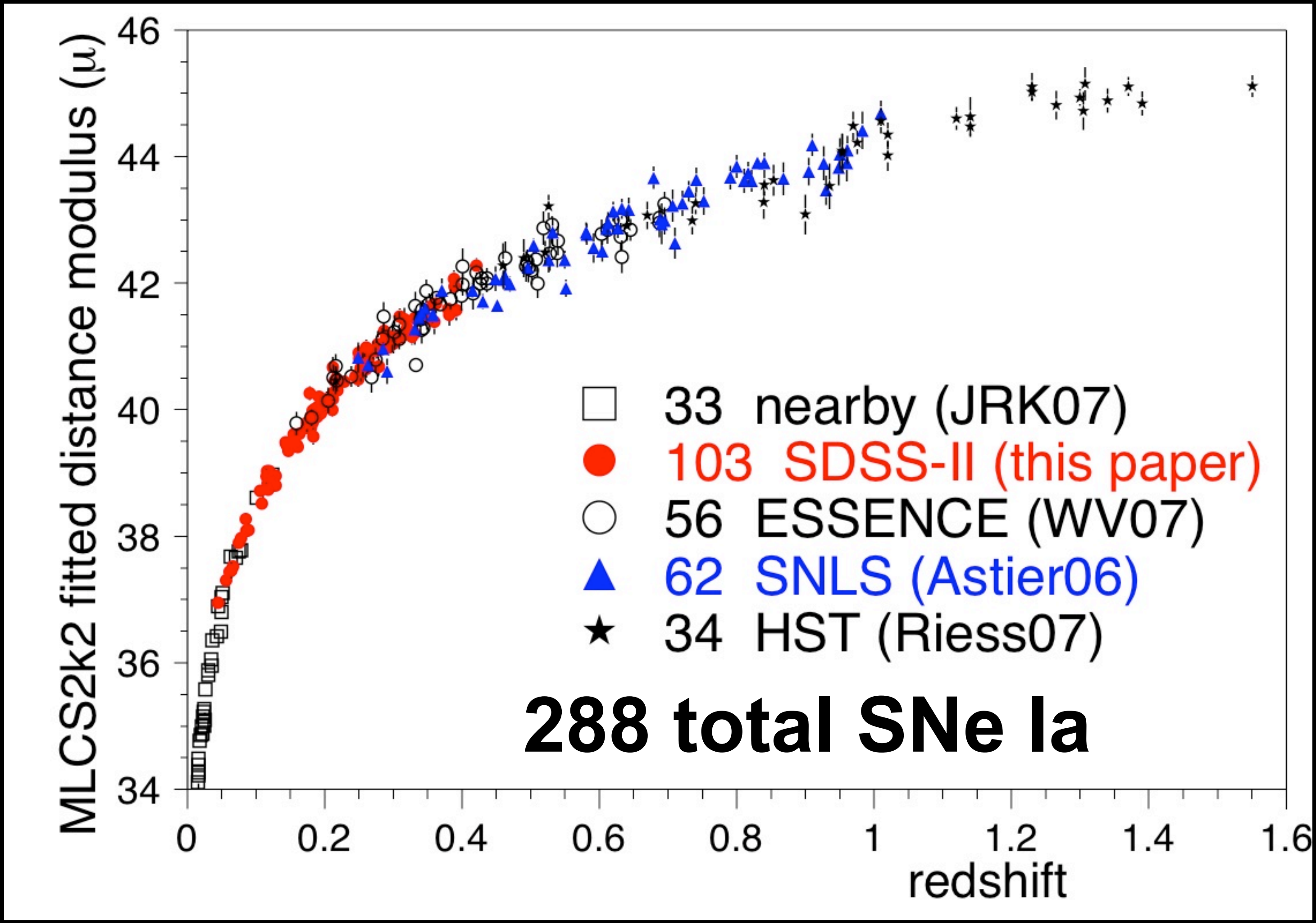
Impact of MLCS Changes (δw ~ 0.3 compared to WV07)



Wood-Vasey et al, 2007: previous MLCS-based analysis from ESSENCE collaboration

Results …

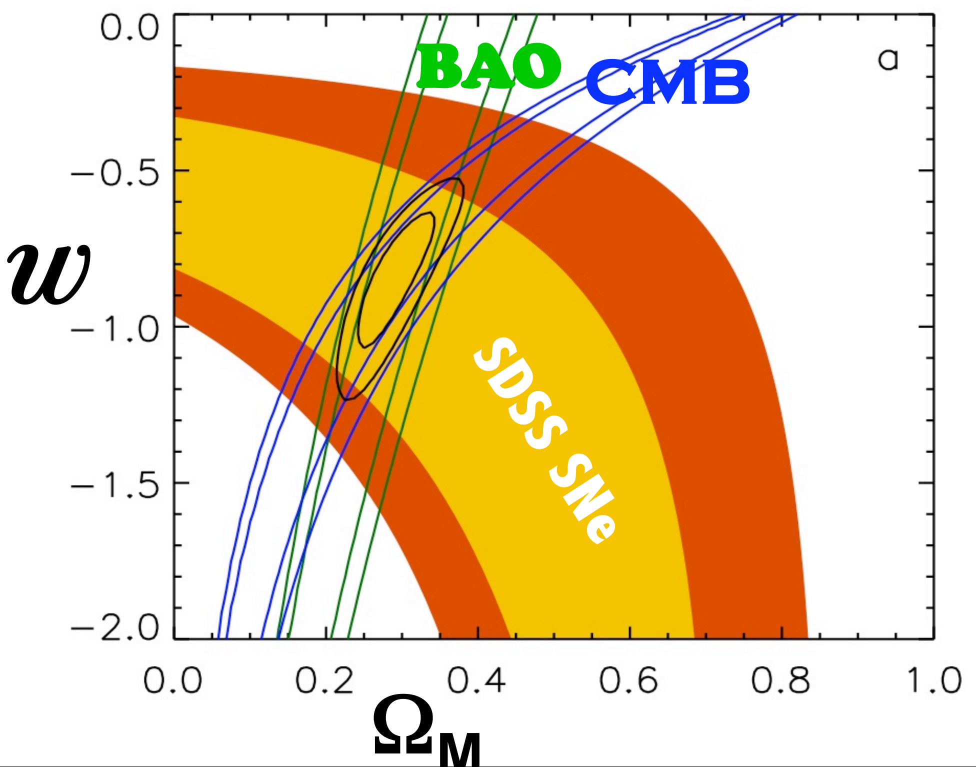
Combine SDSS SNe with Published Samples

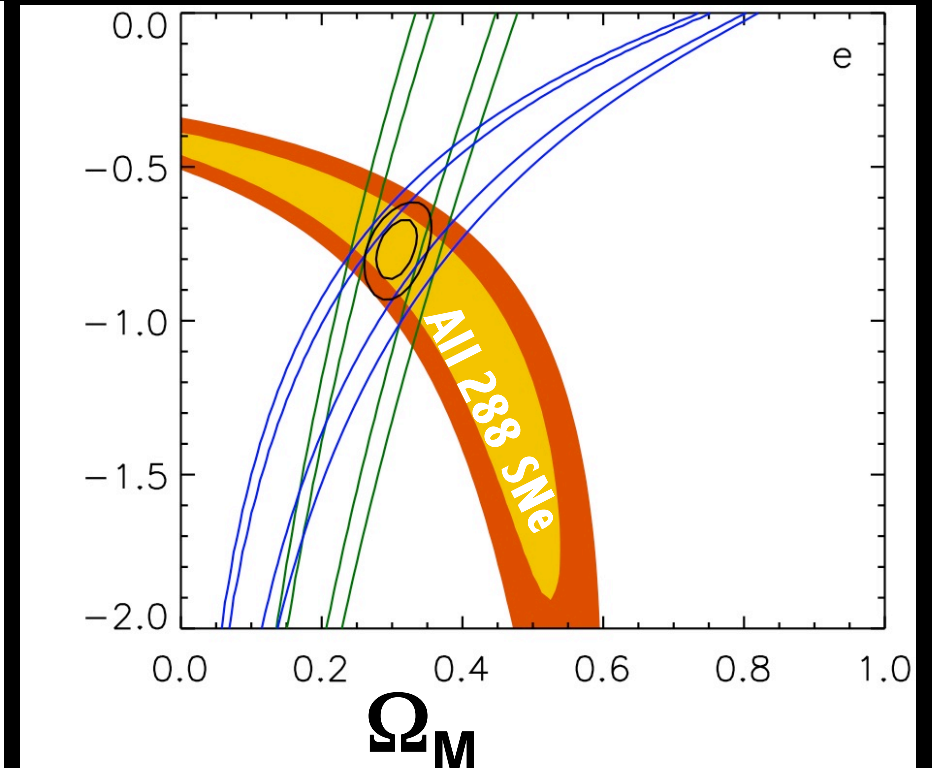


Cosmology Fit

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

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

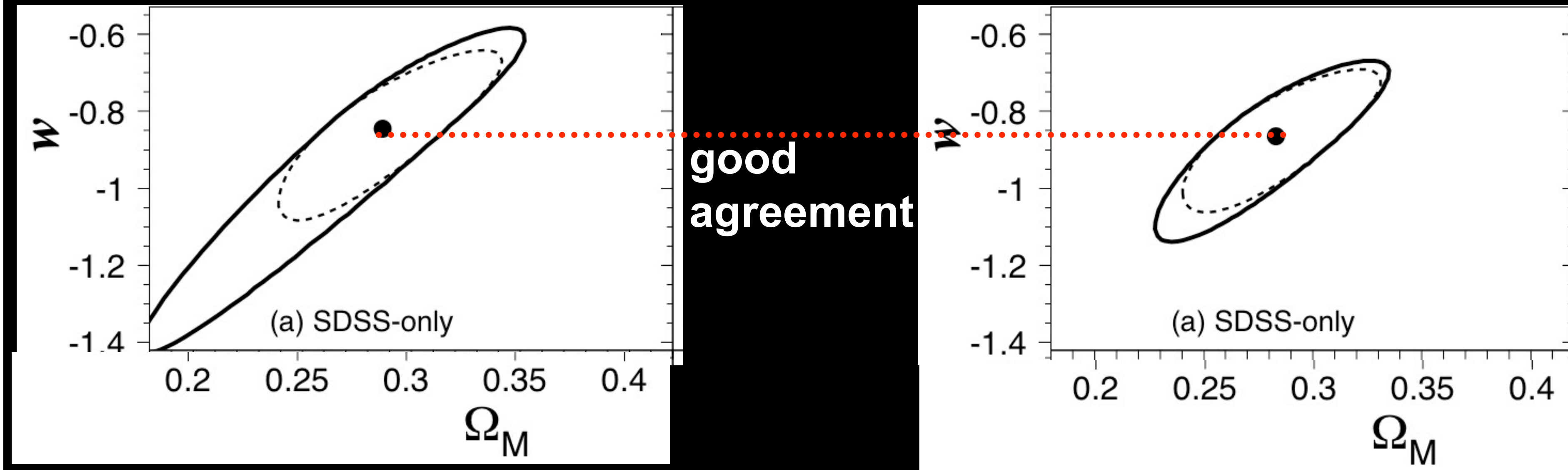




Results:

— total error
- - stat error

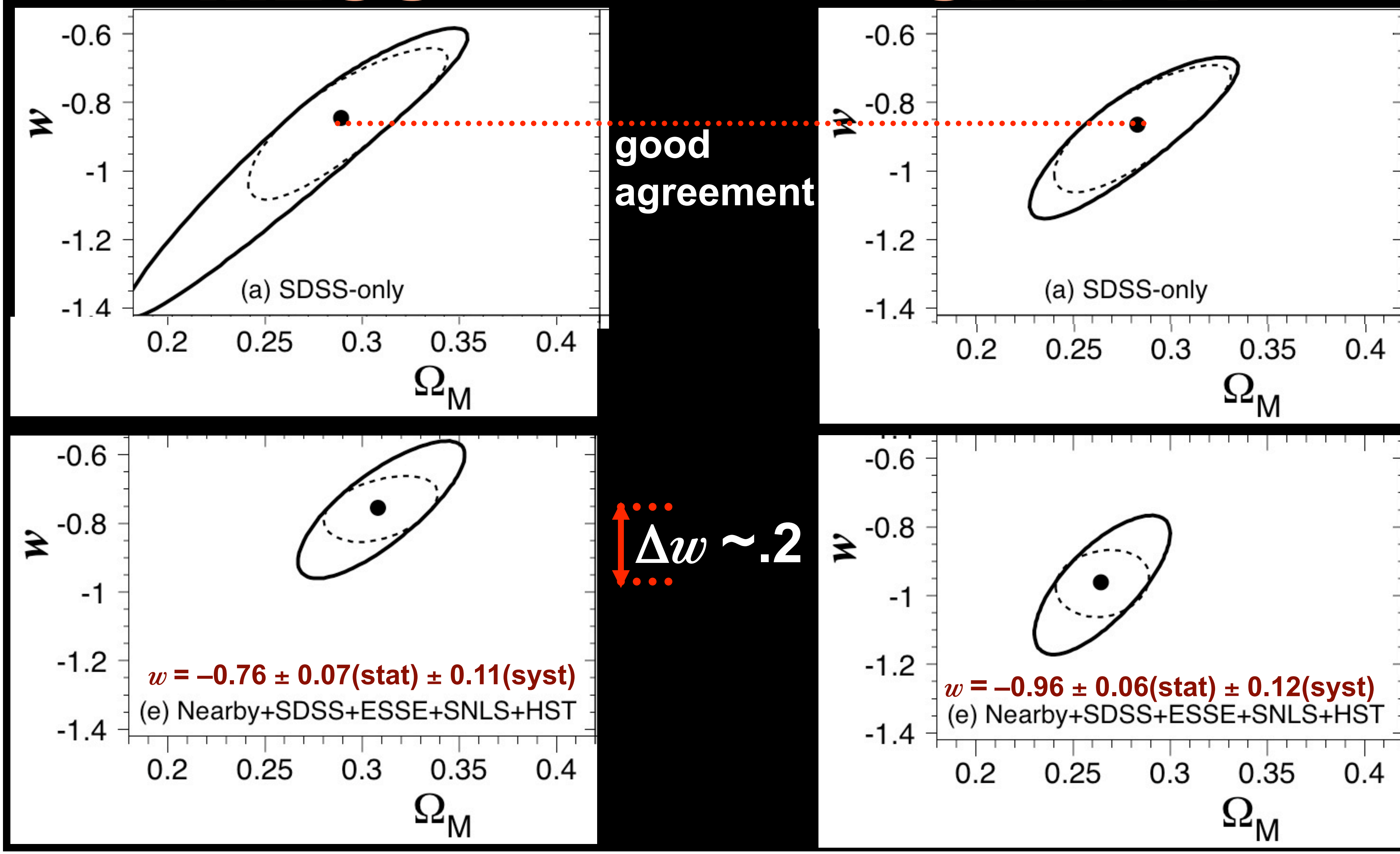
MLCS SALT-II



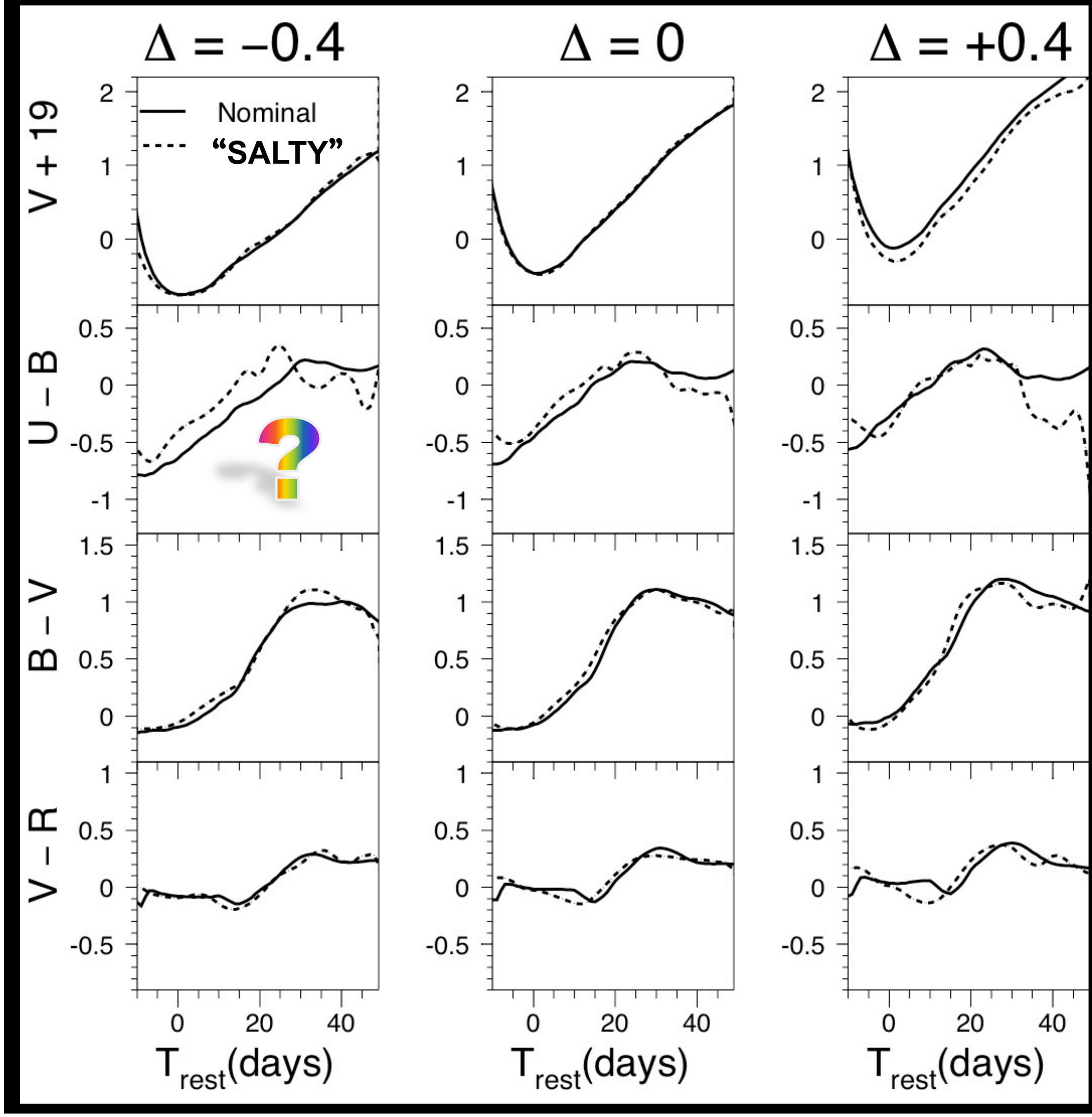
Results:

— total error
- - stat error

MLCS **SALT-II**



Tracing the SALT2 - MLCS Discrepancy: Model mags



Translate SALT2 SED surface (λ vs. Trest) into "SALTY" MLCS model parameters; i.e., train MLCS with SALT2 SED surface.

➔

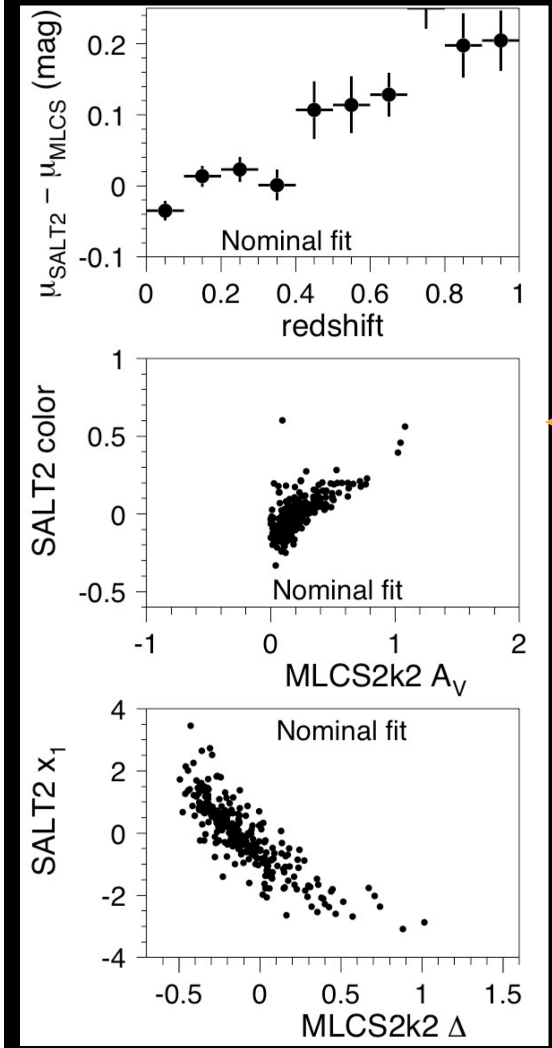
UV region is discrepant by ~ .1 mag

Tracing the SALT2 - MLCS Discrepancy: Color Variations

MLCS assumes color variations are only from host-galaxy extinction → can only redden: bluer is NOT always brighter.

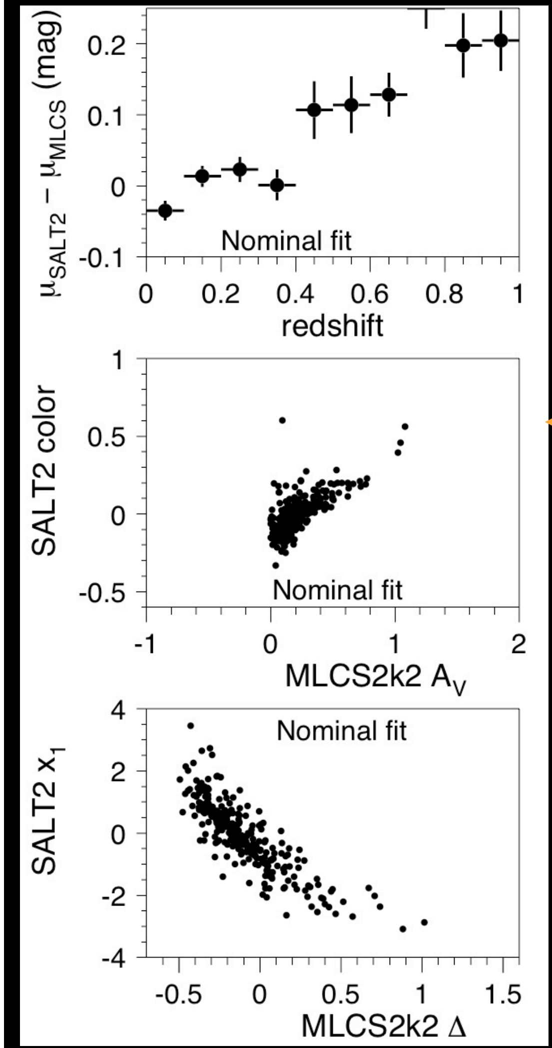
SALT-II makes no assumption about color variations: bluer is always brighter.

Tracing the SALT2 - MLCS Discrepancy



SALT2
vs.
Nominal MLCS

Tracing the SALT2 - MLCS Discrepancy



SALT2

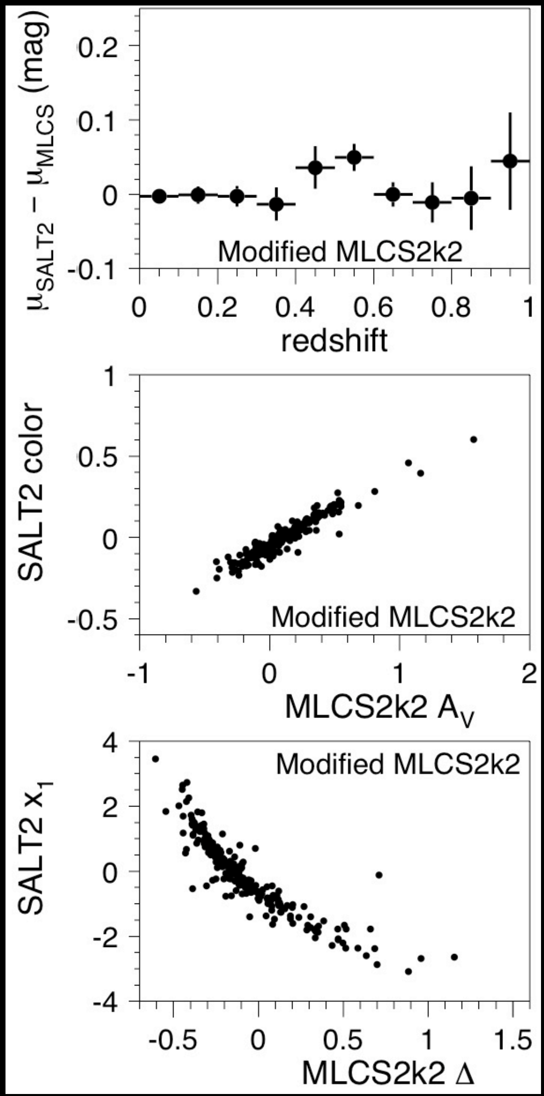
vs.

Nominal MLCS

vs.

SALTY MLCS

(allows $A_V < 0$ & thus bluer is brighter)



Tracing the SALT2 - MLCS Discrepancy

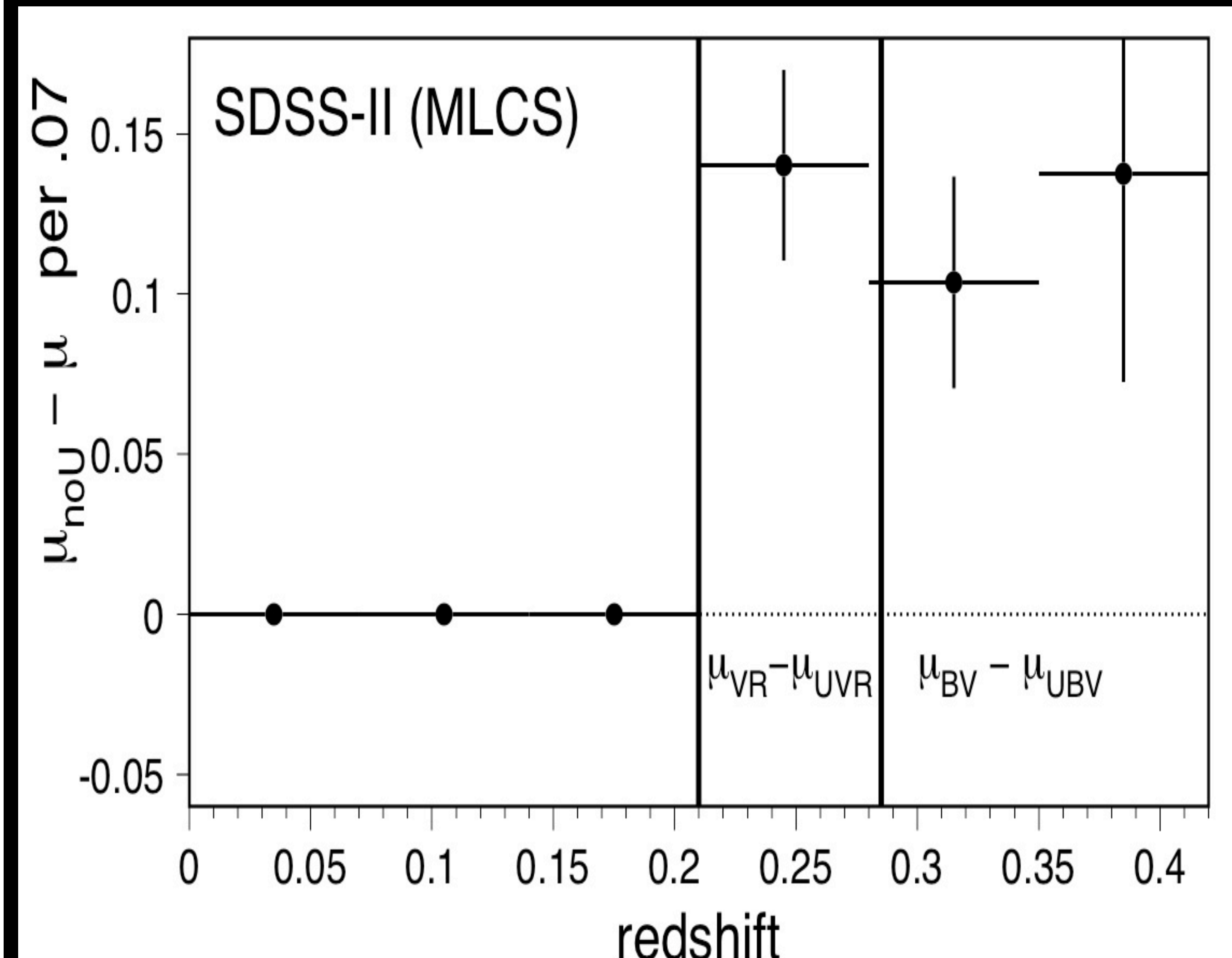
- Using SALTY-MLCS and removing A_V prior (i.e, allow A_V <0) → w shifts by –0.2 and agrees with SALT2 result.

- Either change alone makes small change in w: need both changes

- This test does not suggest that either method is right or wrong; only illustrates sources of discrepancy.

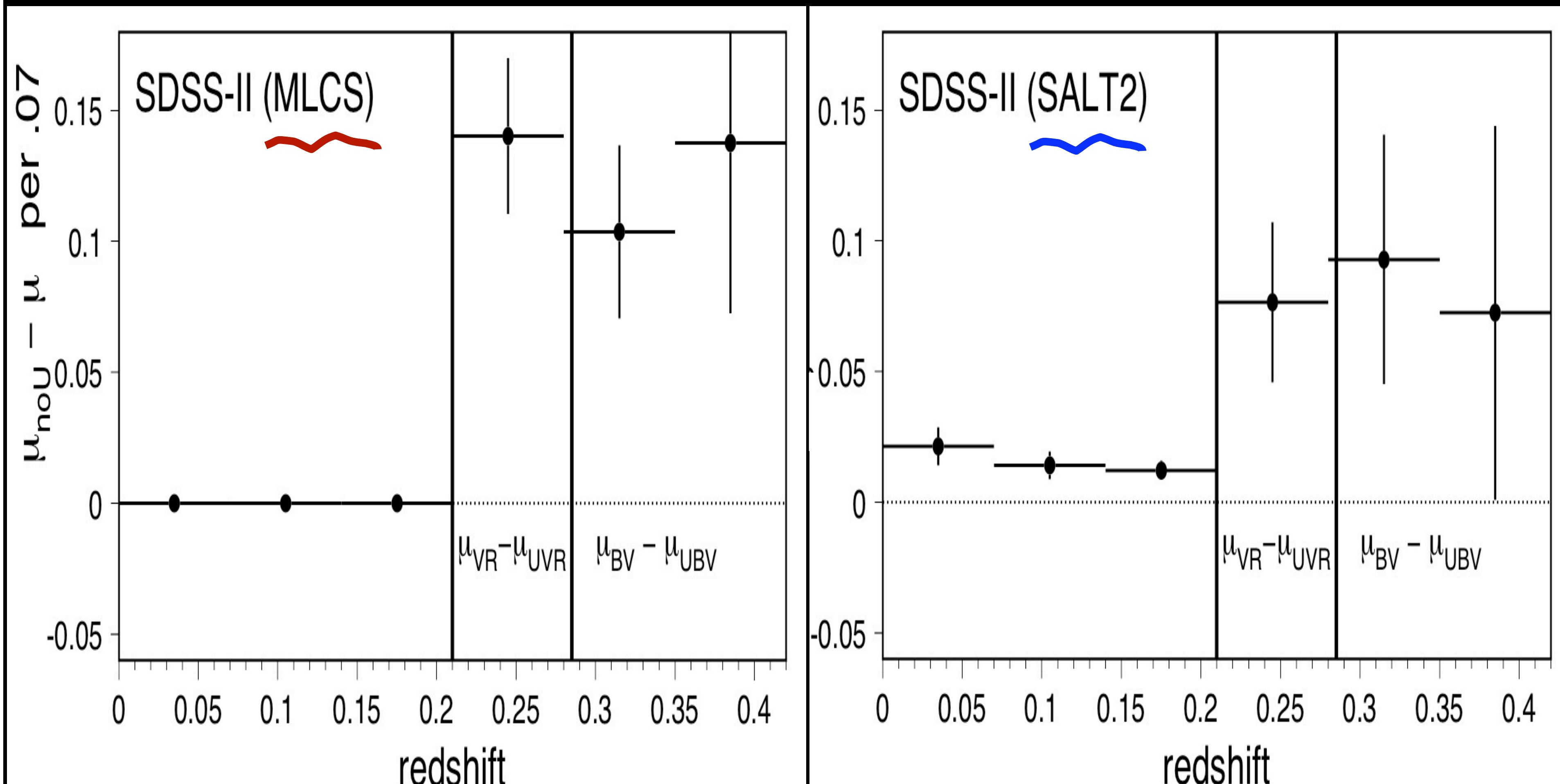
Systematics Issues with UV Region …

Large U-band Systematic for SDSS SNe



Source of largest systematic error.

Large U-band Systematic for SDSS SNe



UV-region

- Evidence points to problem with rest-frame UV in Nearby ($z < 0.1$) sample.
- UV observations from earth are difficult to calibrate (darn ozone)
- MLCS is sensitive to nearby UV observations because only nearby SNe are used for training.
- SALT-II uses SNe at all redshifts for training

  ➔ less sensitive to nearby UV problems.

UV-region

- SDSS-II SN sample ideally suited to study rest-frame UV region:
  - few dozen SNe with u → **UV** ($z < 0.1$)
  - hundreds with g → **UV** ($z > 0.2$)

Very well calibrated !

Summary

- Cosmology analysis of 1st season SDSS SNe Ia is finished;

  unresolved issues ➜ systematic errors
- "improved" MLCS and "standard" SALT-II give discrepant results for w: traced to UV model and assumption of color variations.
- UV model problem very clear with SDSS SNe; dominates systematic error.
  SDSS data ideal to study UV region.
- Starting SDSS-II/SNLS collaboration to reduce calibration systematics by using overlapping fields (and get rid of ancient nearby SNe)