Supernovae and the Accelerating Universe

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can't get no respect...

8 *Bassett and Hlozek. 2009*

$H(z)$ using almost completely linear physics (unlike SNIa for example which involve highly complex, nonlinear, poorly understood stellar explosions). In addition, they offer the as yet unproven possibility of delivering constraints on growth though the change in the amplitude of the power spectrum. The time-dependence of the matter density perturbations, $\delta\rho/\rho$ obeys the equation

COSMOLOGY

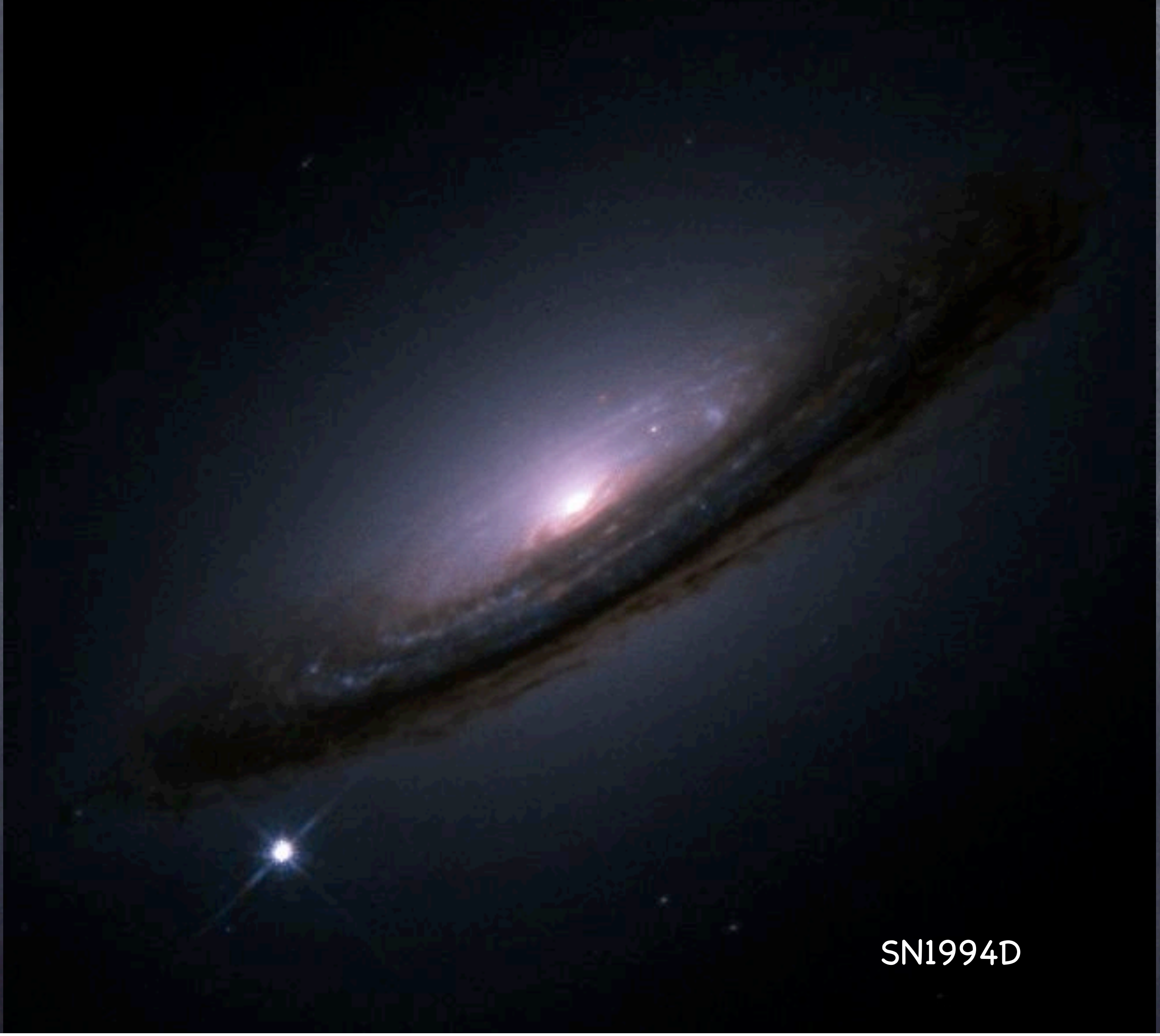
Dark is the new black

Richard Massey

Rival experimental methods to determine the Universe's expansion are contending to become the fashionable face of cosmology. Fresh theoretical calculations make one of them the hot tip for next season.

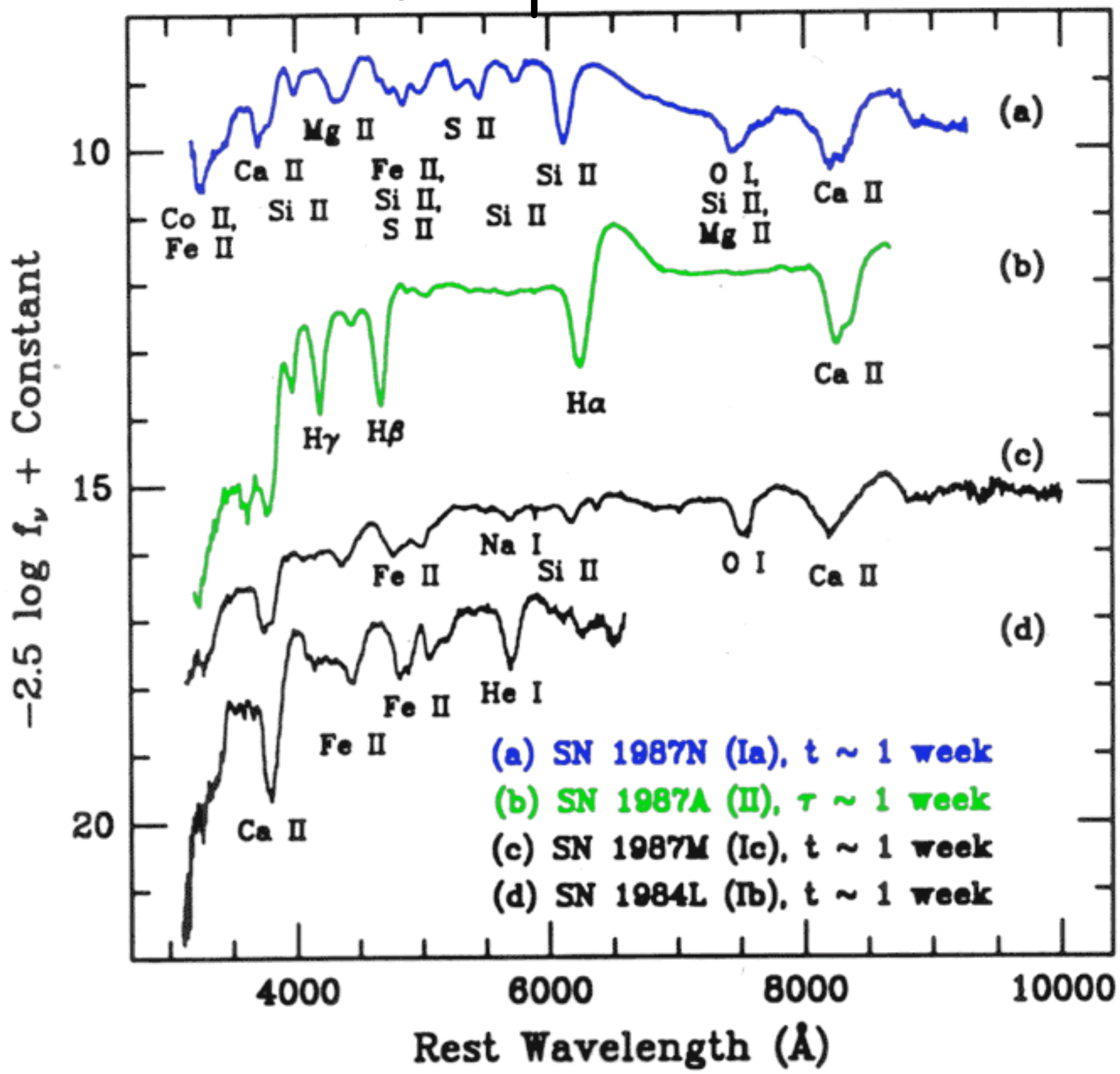
Earth. However, the accelerating expansion of the Universe means that distant supernovae have already receded farther from us and look even fainter. Initial enthusiasm for using supernovae as cosmic distance indicators, and thus as a probe of the Universe's expansion, garnered vast allocations of time on ground- and space-based telescopes, and triggered the first plans for a dedicated, all-sky successor to the Hubble Space Telescope. Unfortunately, the explosions were later found to depend on the stars' environment and ingredients, which evolve over cosmic time. Such effects can be parameterized only to a certain precision, and the technique is falling out of fashion.

Supernovae



P. Challis
CfA & NASA

SN spectra



Type Ia

Core Collapse

Type Ib/c & Type II

SN SEDs

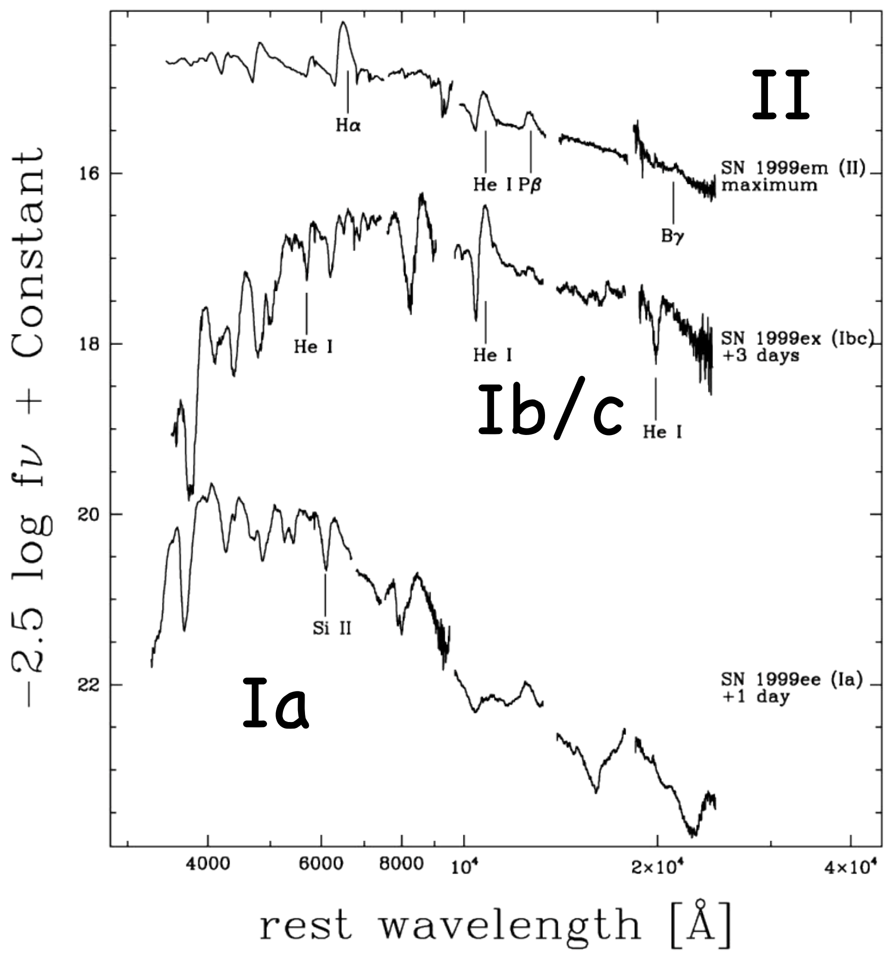
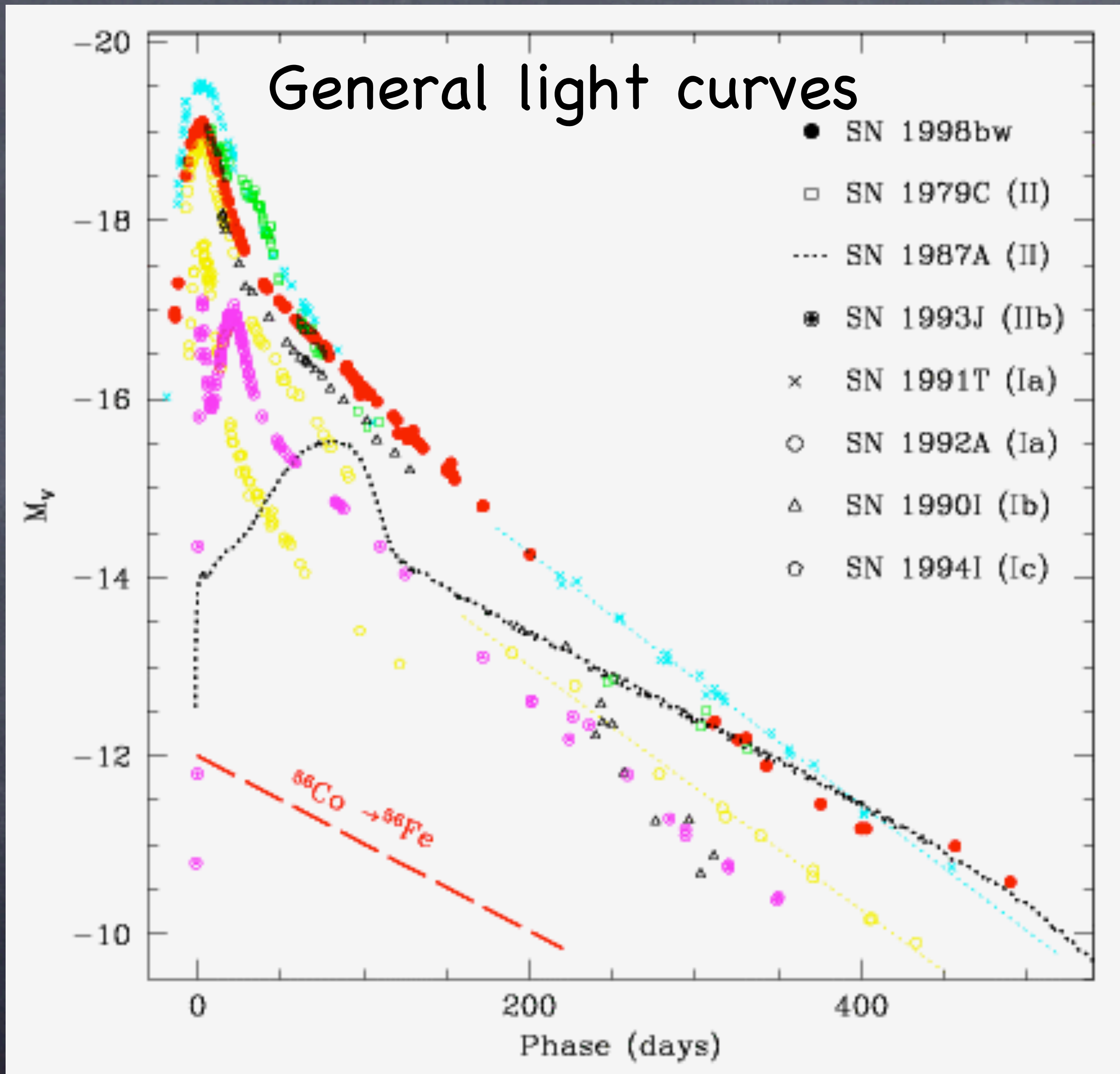


Fig. 13.— Combined optical and IR maximum-light spectra of the Type II SN 1999em, the Type Ib/c SN 1999ex, and the Type Ia SN 1999ee.

General light curves



^{56}Ni →
^{56}Co →
^{56}Fe

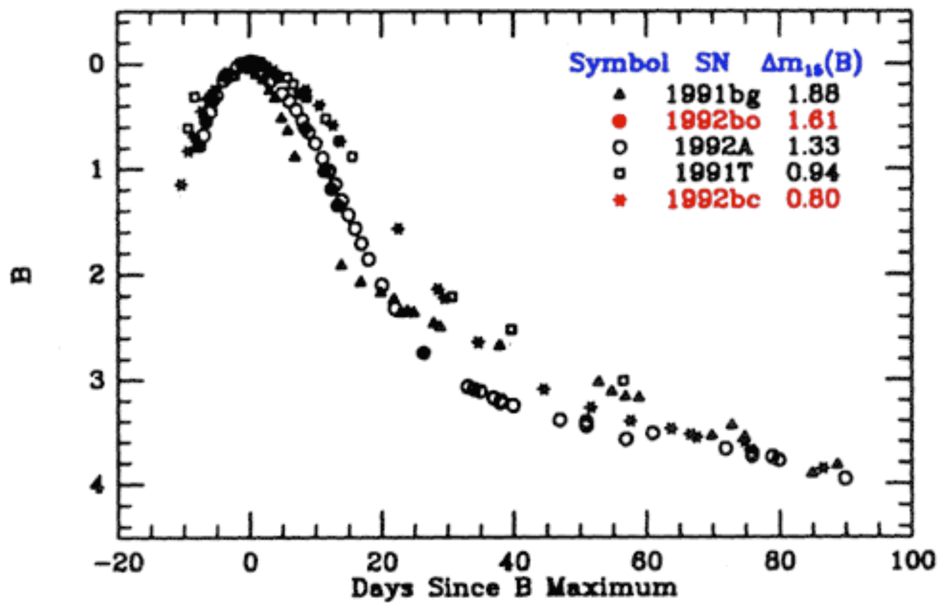
Leibundgut & Suntzeff 98

One parameter family

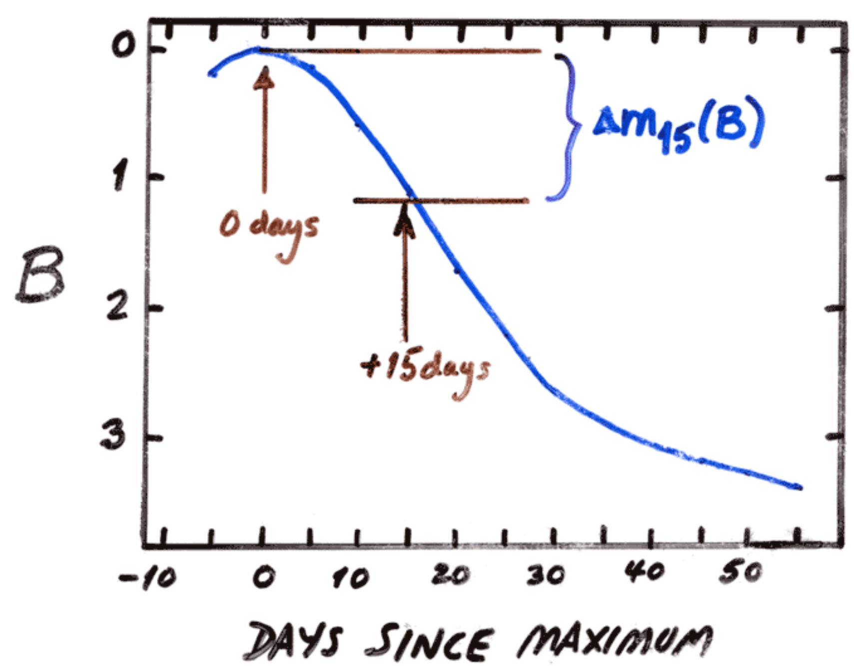
Color

Rate of decline

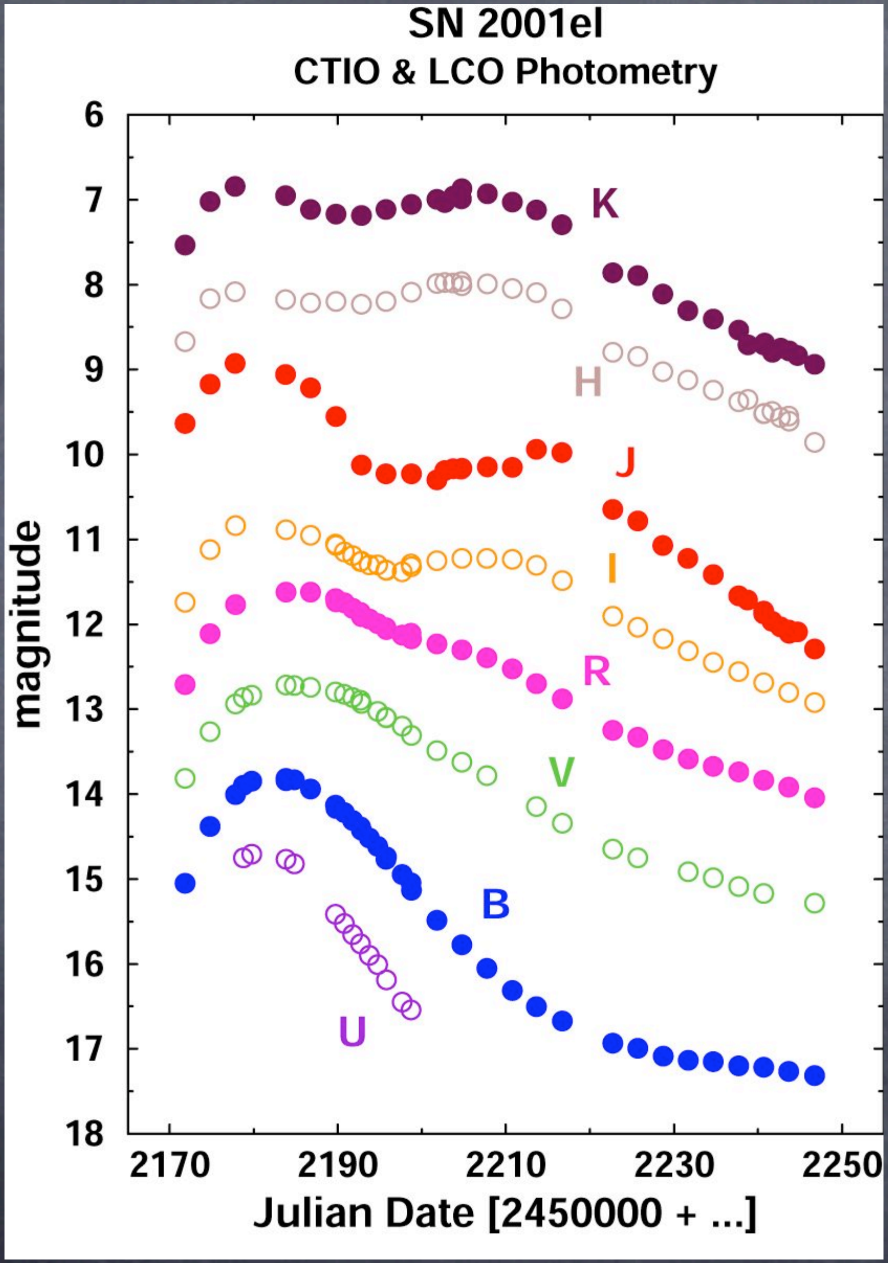
Peak brightness



Suntzeff (1996)



Phillips (1993)

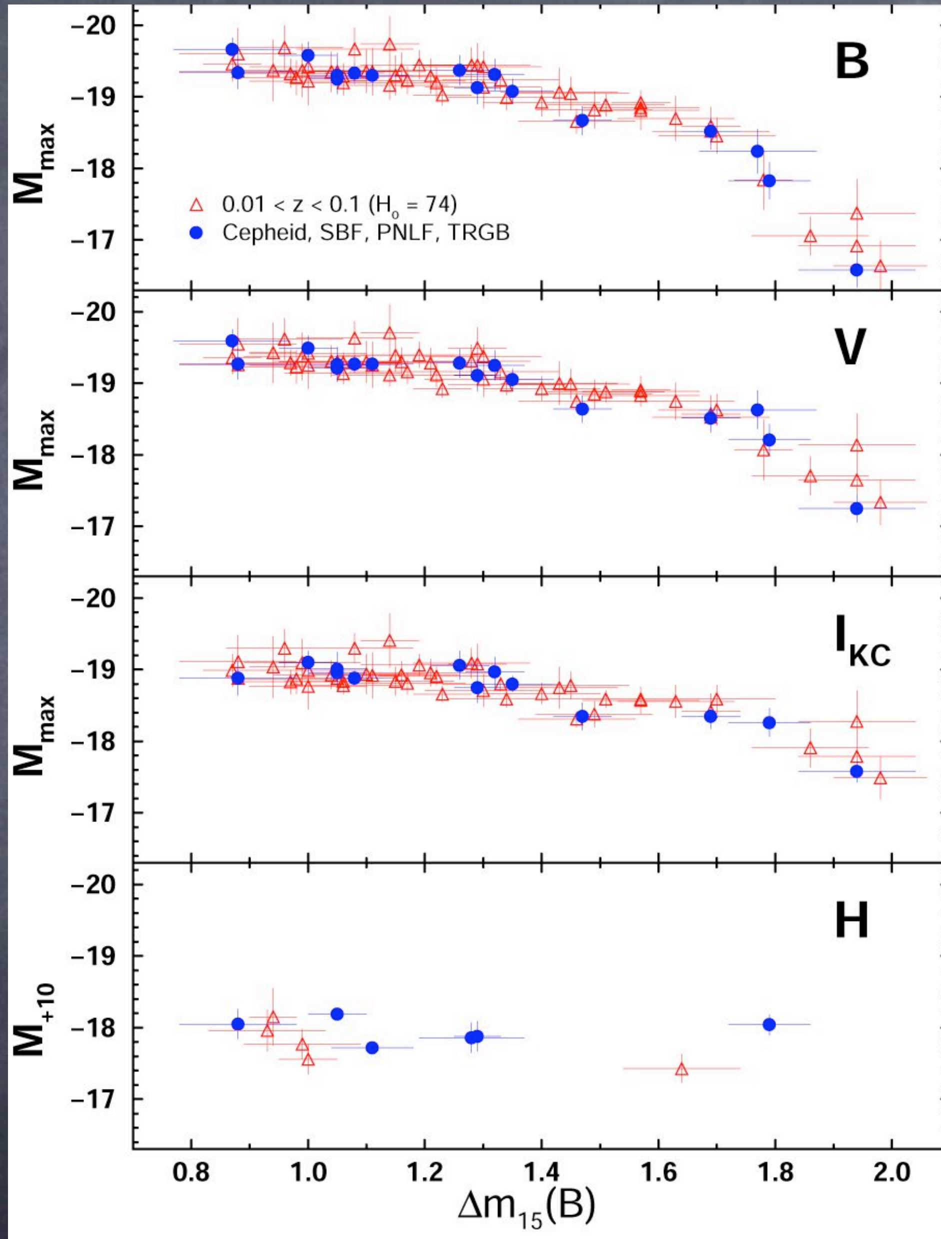


Secondary max due to $Fe^{++} \Rightarrow Fe^{+}$

mystery - where is $Fe^{+} \Rightarrow Fe^{0}$??

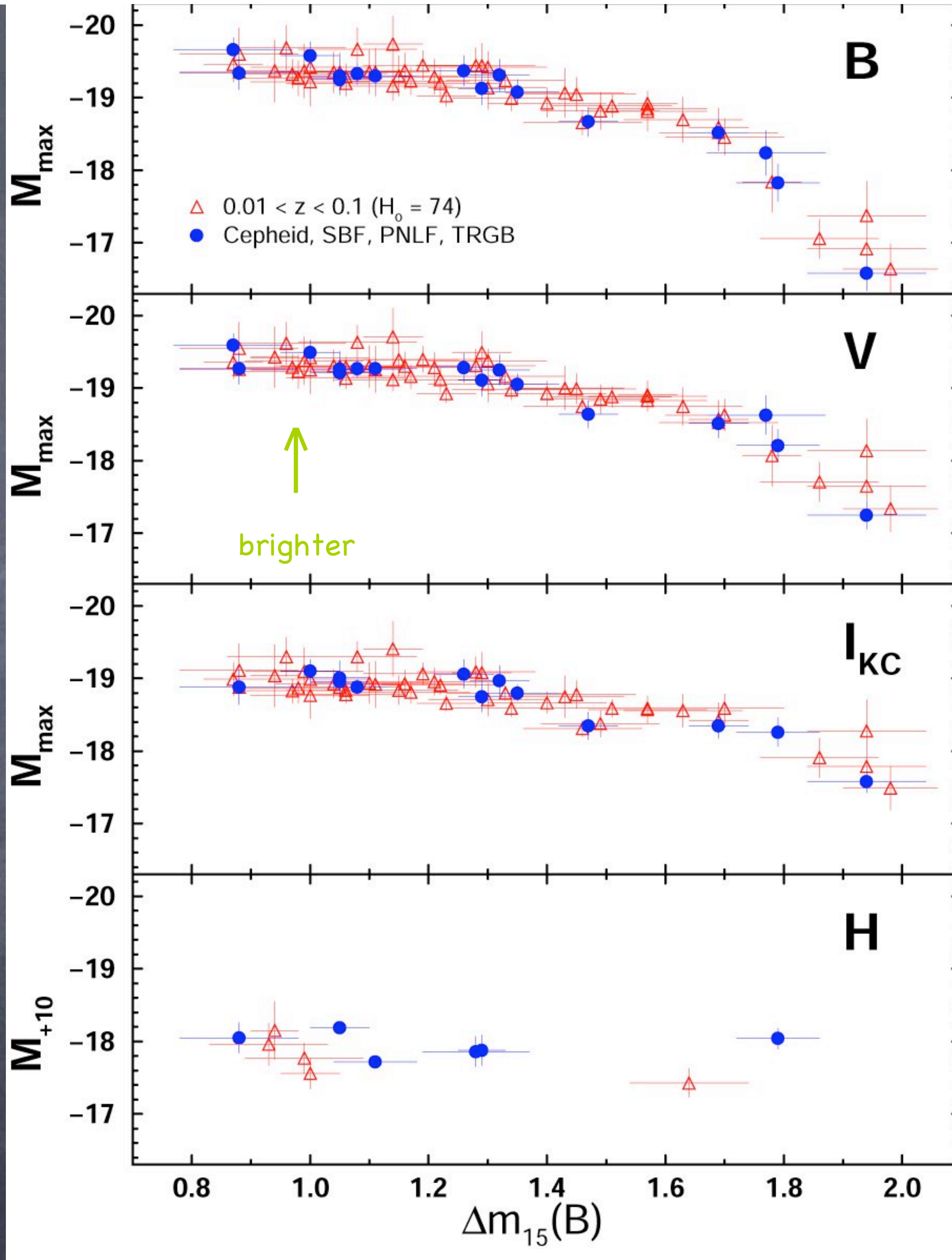
⇑

Luminosity



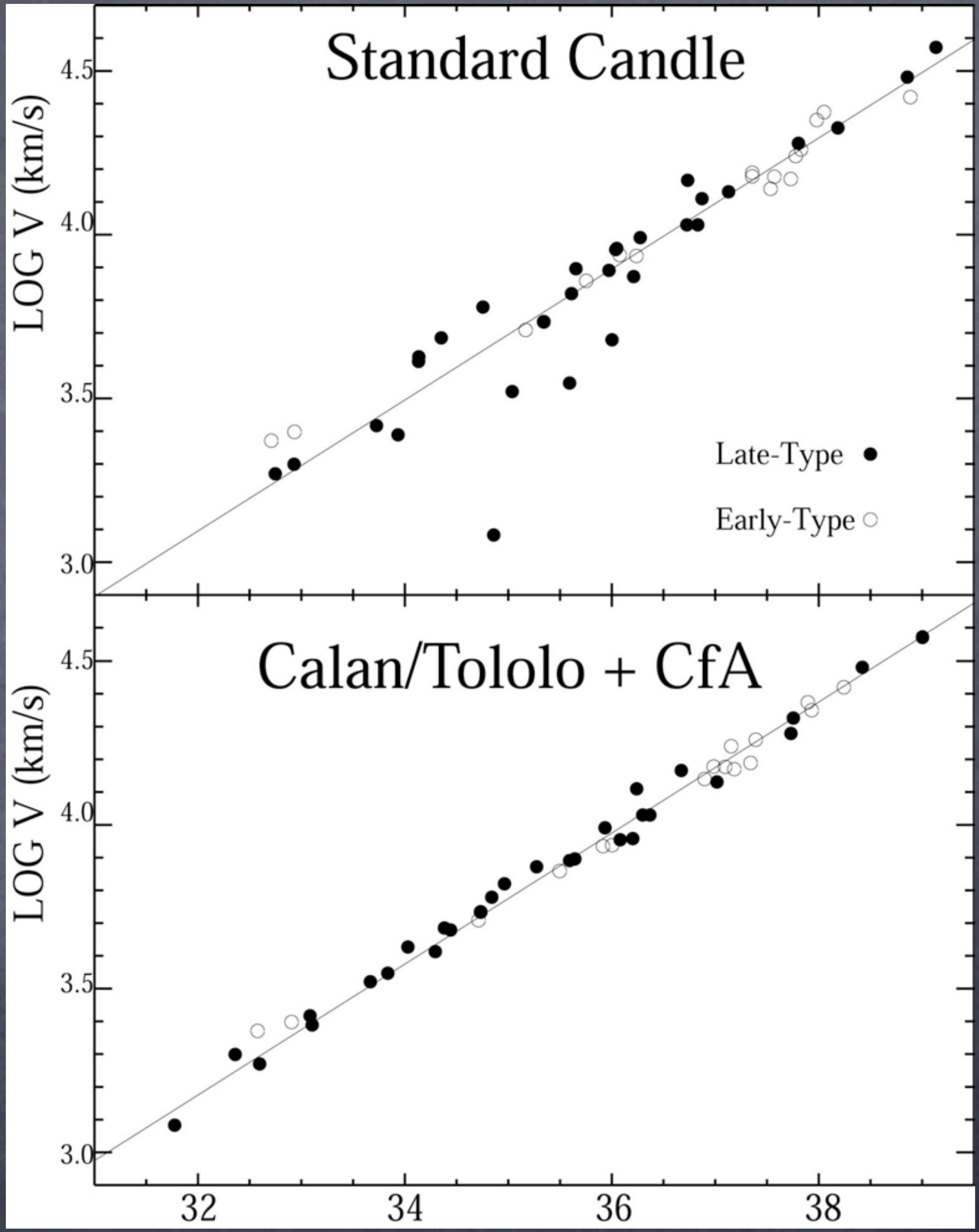
⇐standard candle??
Krisciunas et al 2003

Absolute magnitudes of Type Ia SNe



H, K probable standard candles →

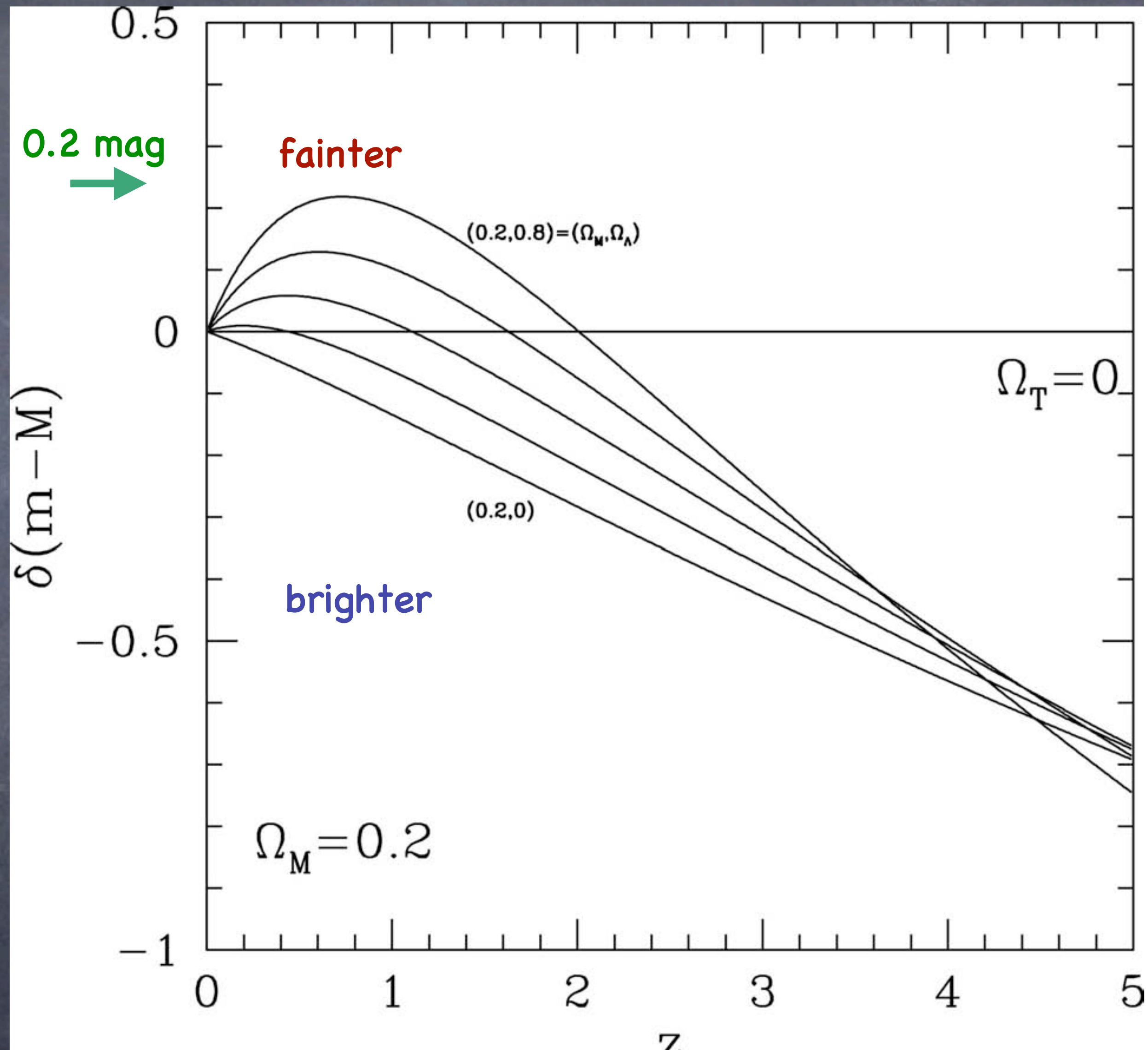
Effects of correction to Δm_{15}



Distance Modulus II

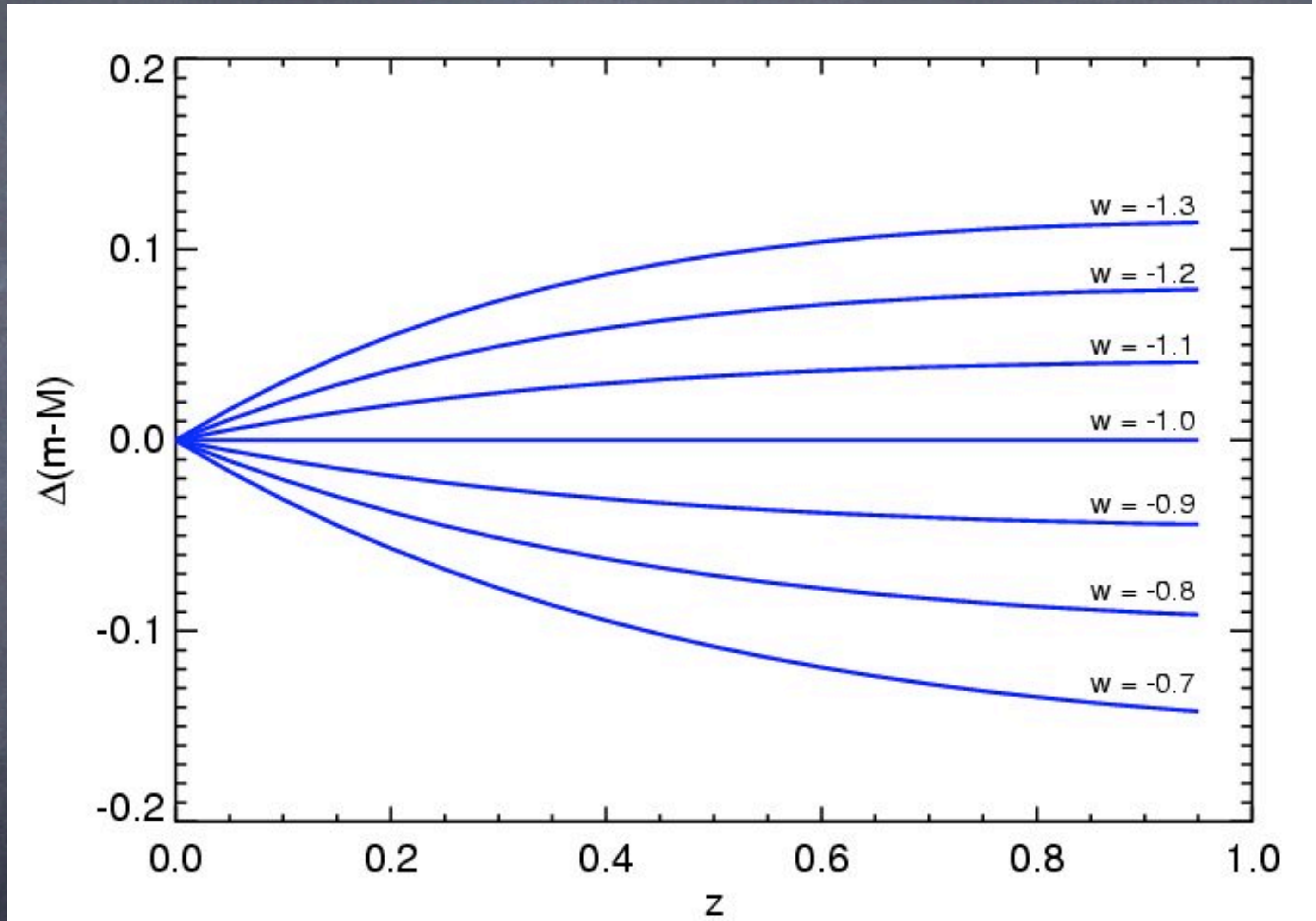
Peak effect for L is at about z~0.8.

We are looking for about a 0.25m effect.



Equation-of-State Signal

Assume
$P = w\rho c^2$



Difference in apparent SN brightness vs. z
Ω_Λ=0.70, flat cosmology

The Basic Question:

Is a cosmological constant model consistent with the data?

Is $w=-1$?

The ESSENCE Survey

- Determine w to 10% or w!=-1
- 6-year project on CTIO/NOAO 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
- Data and SNeIa public real-time

ESSENCE Survey Team

Claudio Aguilera	CTIO/NOAO	Bruno Leibundgut	ESO
Andy Becker	Univ. of Washington	Weidong Li	UC Berkeley
Stéphane Blondin	Harvard/CfA	Thomas Matheson	NOAO
Peter Challis	Harvard/CfA	Gajus Miknaitis	Fermilab
Ryan Chornock	UC Berkeley	Jose Prieto	OSU
Alejandro Clocchiatti	Univ. Católica de Chile	Armin Rest	NOAO/CTIO
Ricardo Covarrubias	Univ. of Washington	Adam Riess	STScI/JHU
Tamara Davis	Dark Cosmology Center	Brian Schmidt	ANU/Stromo/SSO
Alex Filippenko	UC Berkeley	Chris Smith	CTIO/NOAO
Arti Garg	Harvard University	Jesper Sollerman	Stockholm Obs.
Peter Garnavich	Notre Dame University	Jason Spyromilio	ESO
Malcolm Hicken	Harvard University	Christopher Stubbs	Harvard University
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Robert Kirshner	Harvard/CfA	John Tonry	Univ. of Hawaii
Kevin Krisciunas	Texas A&M	Michael Wood-Vasey	Harvard/CfA

ESSENCE Summary

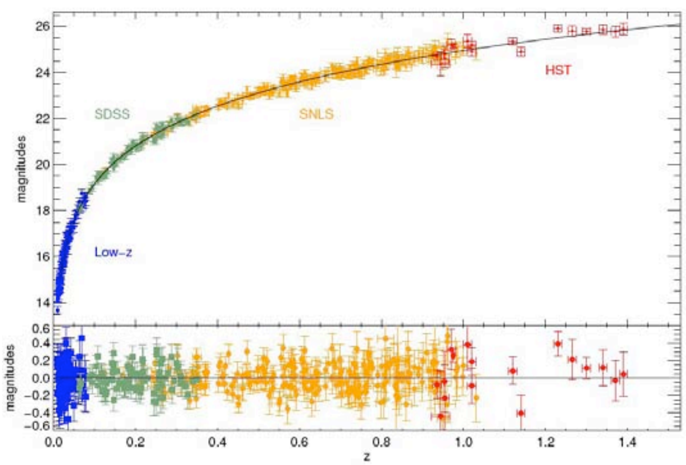
- 200 SNeIa from 2002-2007
- 200 good light curves (Wood-Vasey, et al 2009)
- Data from Keck, Gemini, VLT, CTIO, HST

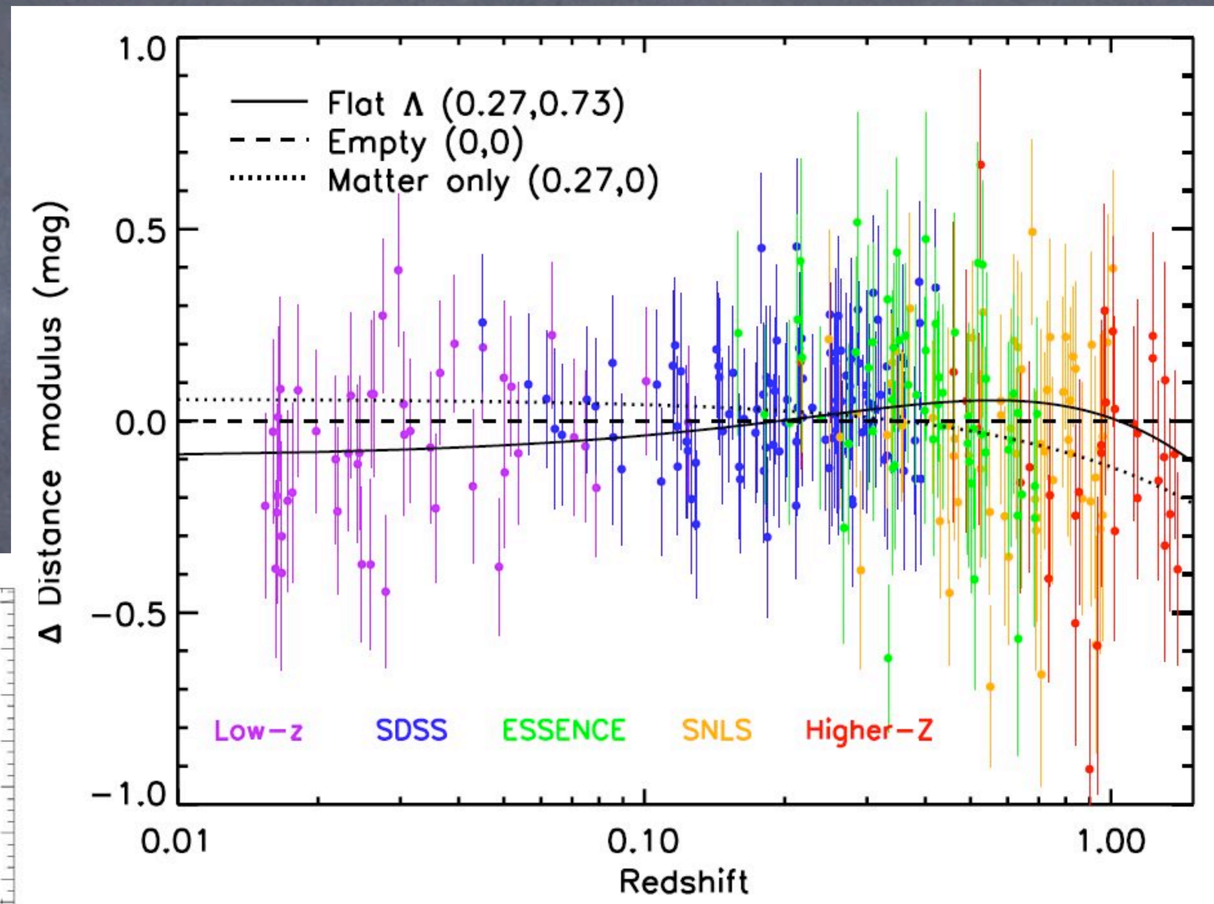
Gold⇒Union⇒Constitution⇒ whatthe**** set

SDSS SN plot

Lesson in plotting

⇓



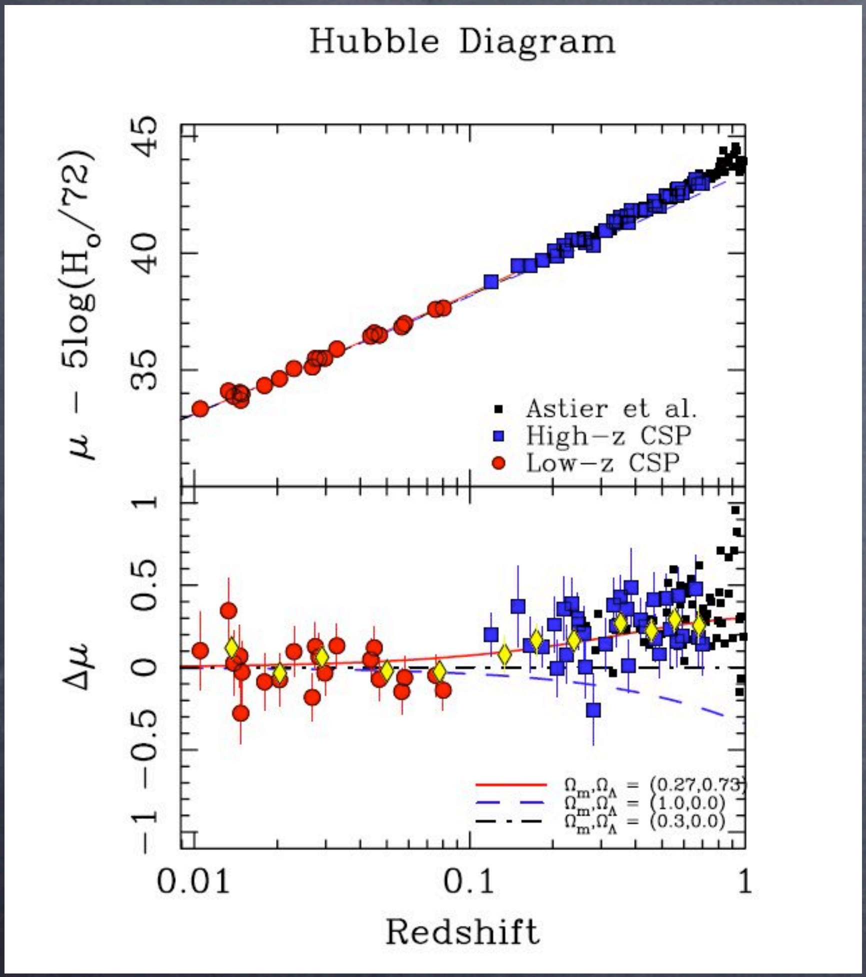


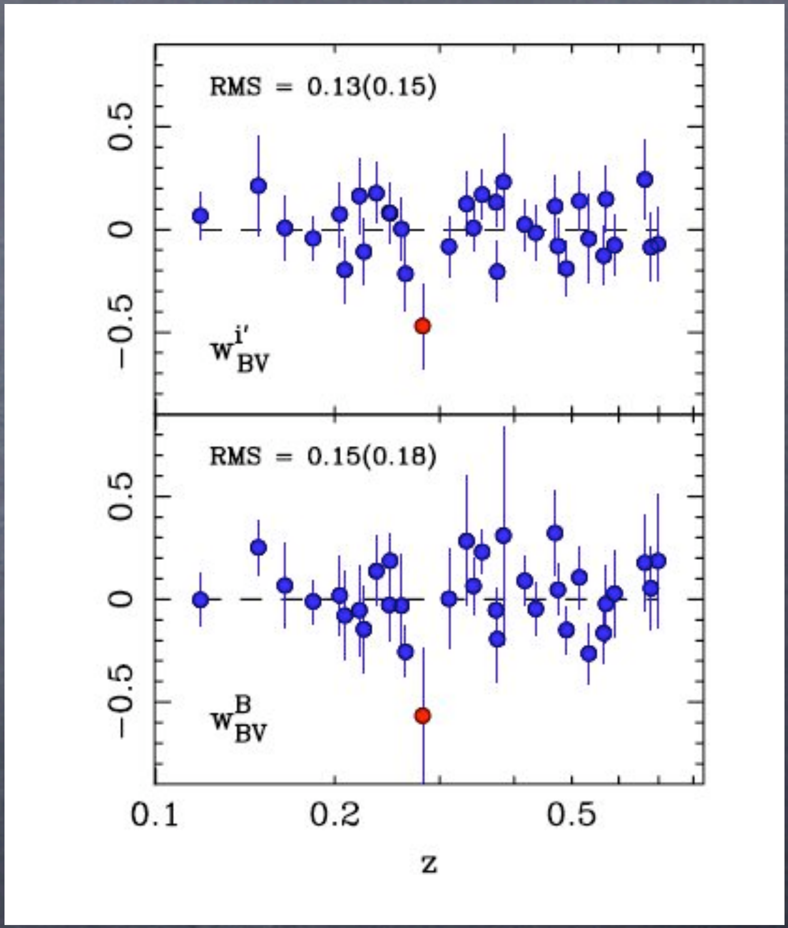
Being from Texas, I suggest the Confederate Set is next

Carnegie Supernova Project

- Phillips, Freedman, Hamuy, Madore, Burns, Follatelli, Cadenas, Suntzeff

High-z project





I-band measurements

Cosmology fits

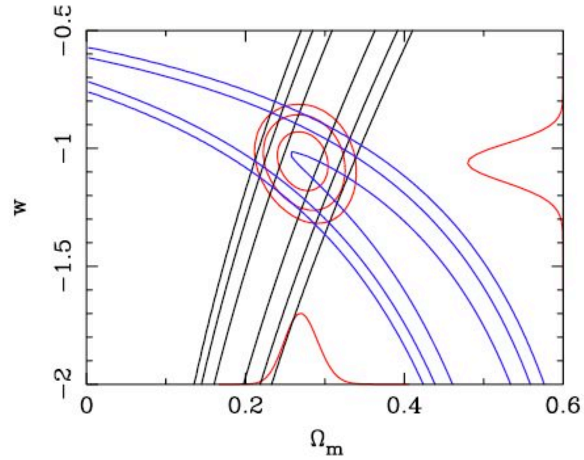


Fig. 18.— Combining the CSP constraints with baryonic acoustic oscillations (Eisenstein et al. 2005) and assuming $\Omega_k = 0$. The CSP and BAO data combined are consistent with a value of $w = -1.05 \pm 0.08$ (statistical) ± 0.08 (systematic) and $\Omega_m = 0.27 \pm 0.02$ (statistical). Our 68%, 95%, and 99% confidence intervals are shown as solid blue (banana-shaped) contours. The constraints from baryon acoustic oscillations (Eisenstein et al. 2005) are shown as solid black contours and the combined confidence intervals are shown as red contours. The 1-D marginalized probabilities for each parameter are plotted as red lines on the axes.

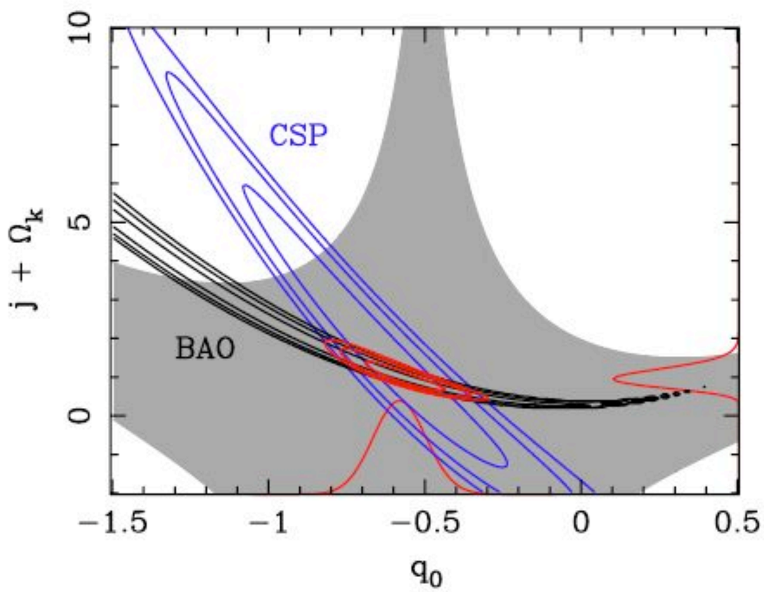


Fig. 19.— The sum (j_k) of the jerk (j) and curvature parameter (Ω_k) as a function of the deceleration parameter (q_0). The grey shading indicates the region where the luminosity distance expansion is valid, as described in the text. The best-fit values including both baryon acoustic oscillation and the CSP data are $j_k = 1.08 \pm 0.25$ (statistical) ± 0.27 (systematic) and $q_o = -0.61 \pm 0.08$ (statistical) ± 0.09 (systematic) at the 95% confidence level. The 1-D marginalized probabilities for each parameter are plotted as red lines on the axes.

Carnegie Low-z Sample

- 5-year project, 270n per year on 1m Swope + nights on Magellan, du Pont, VLT
- Ending 2009 (around now)
- *ugriBVYJH*(K_s). K_s with WIRC on duPont
- Spectra where we can [more hot spectrographs on 2m telescopes are needed]
- Follow all types with z≤0.08 (if caught early)
- 200 Sne with 100 Type Ia

What we are trying to do

- So many data samples with so many methods of analysis have confused us
- We want to “rewrite” history, that is, start with a clean data set and redo our analyses to find the weaknesses of our techniques.
- Purely phenomenological guided by simple physics
- Basic parameter - Δm_{15}, *measured from the light curves, NOT from a black box program*
- Measure photometry in the natural system with measured precise transmission functions
- Ultimately the goal is an accuracy of <1% in distance for cosmology with no systematics.

Summary of Sample

The fifth and final low-z CSP observing campaign is now nearly complete. To date, observations have been obtained of a total of 327 SNe. Of these, 253 (77%) were selected for follow-up observations. Table 1 shows the classifications of these. The final row of the table gives our original expectation of how many SNe would be observed per campaign. As may be seen, *the CSP has fully achieved its goal of obtaining high-quality optical light curves in five years of ~100 SNe Ia, ~100 SNe II, and ~25 SNe Ib/Ic.*

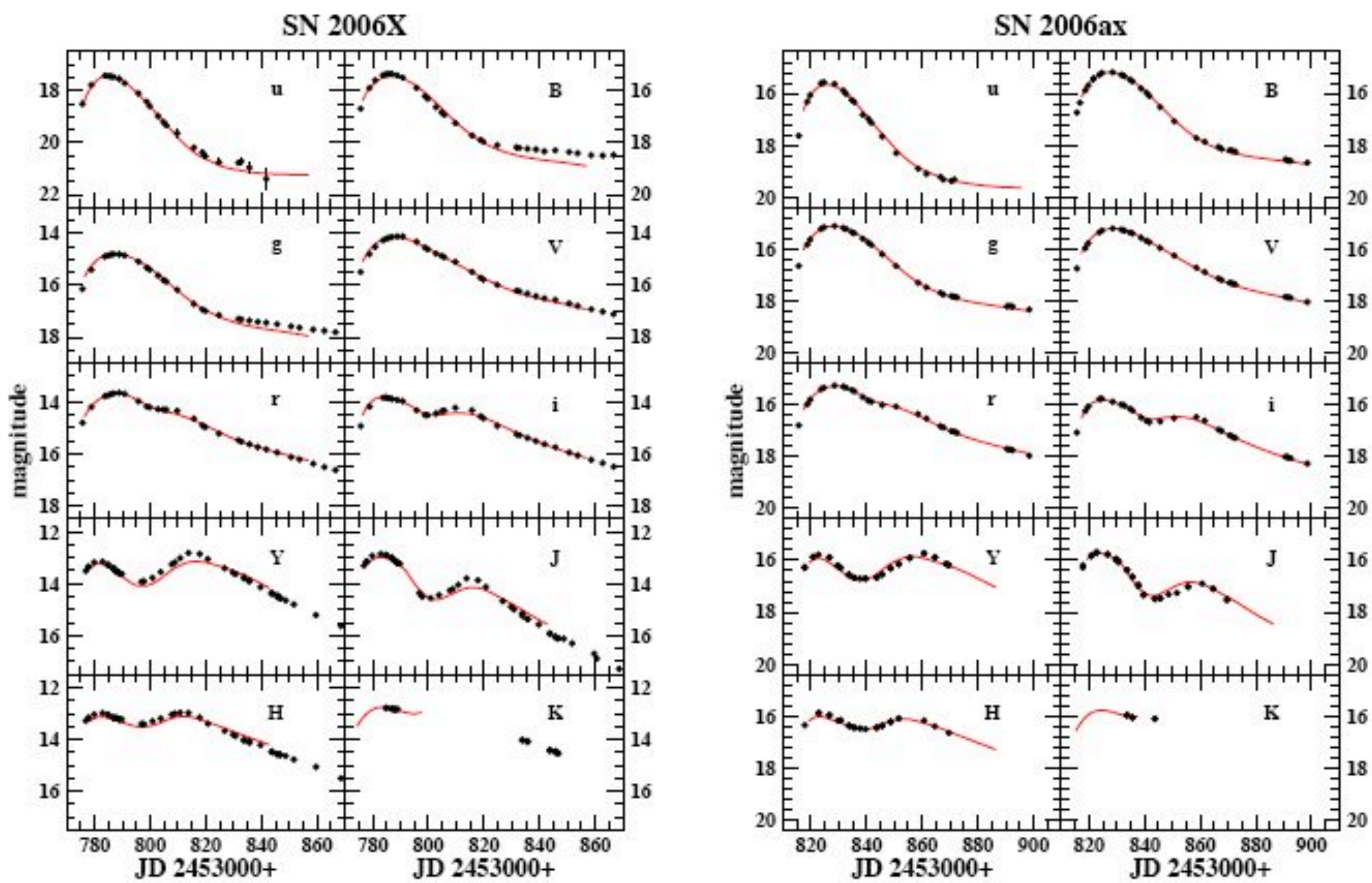
Table 1 Low-z SNe Followed by the CSP

	Ia	**II**	**Ib/Ic/IIb**	**Total**
Total	**129**	**93**	**31**	**253**
Expected	100	100	25	225

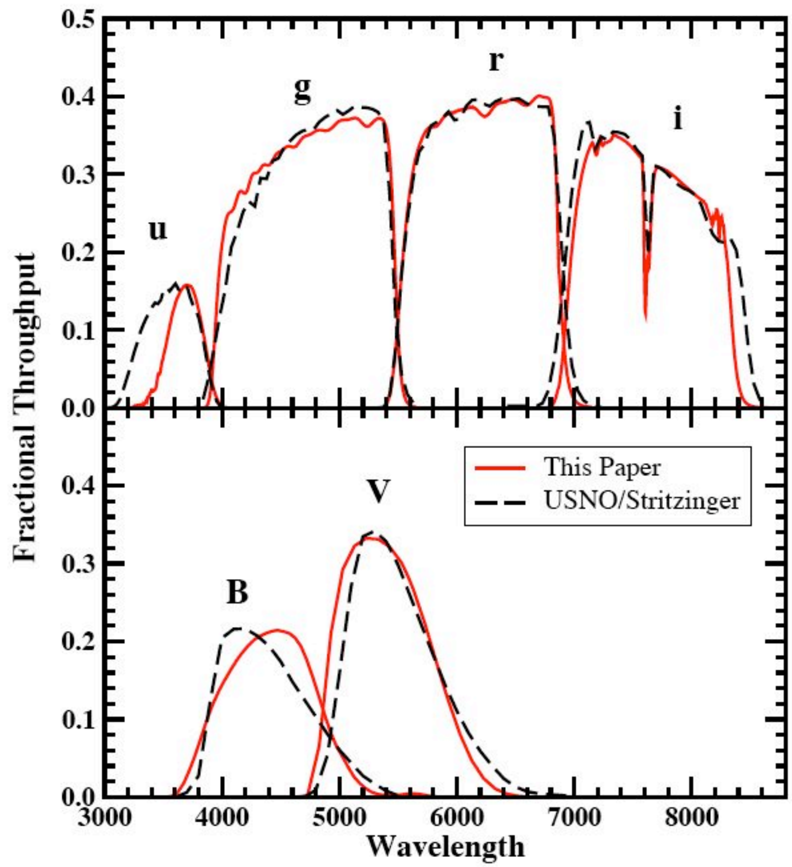
First Release

Contreras, C. et al 2009 arXiv:0910.3330V1

35 Type Ia, 5559 *ugriBV* optical φ, 1043 NIR *YJHK*$_s$ φ

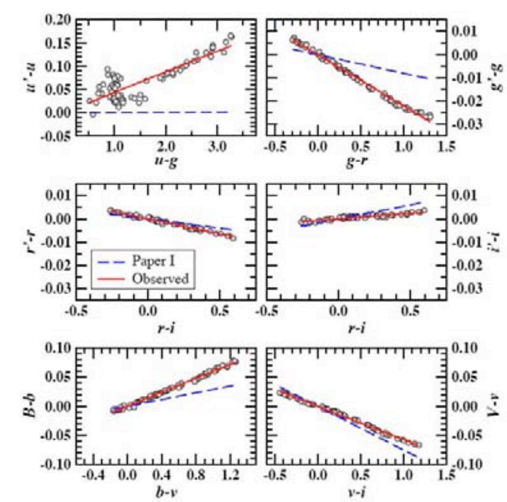


Natural System φ



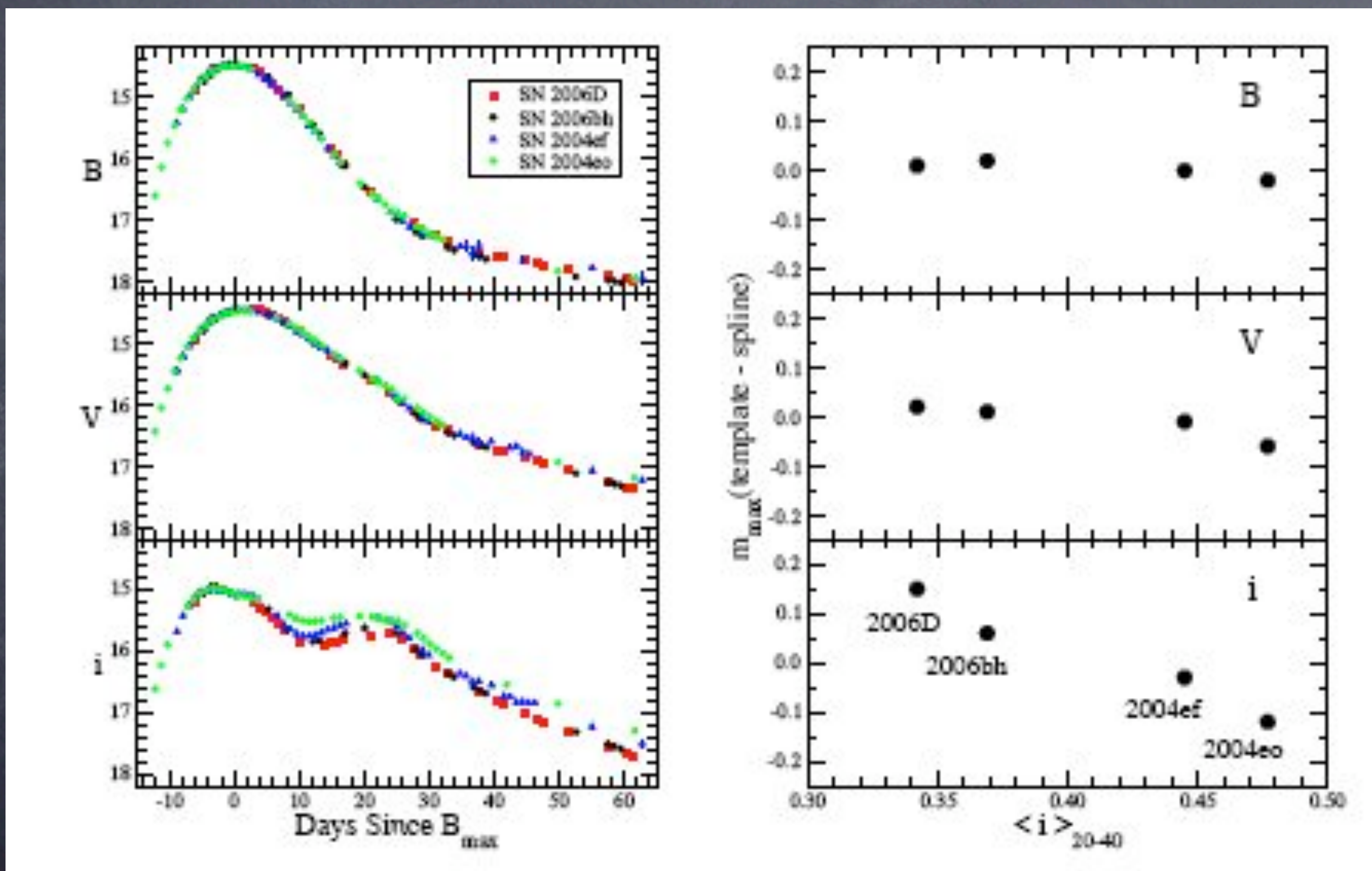
Contreras *et al.* Fig. 8

Definition of photometric zero-points



Contreras *et al.* Fig. 7

Second Parameter

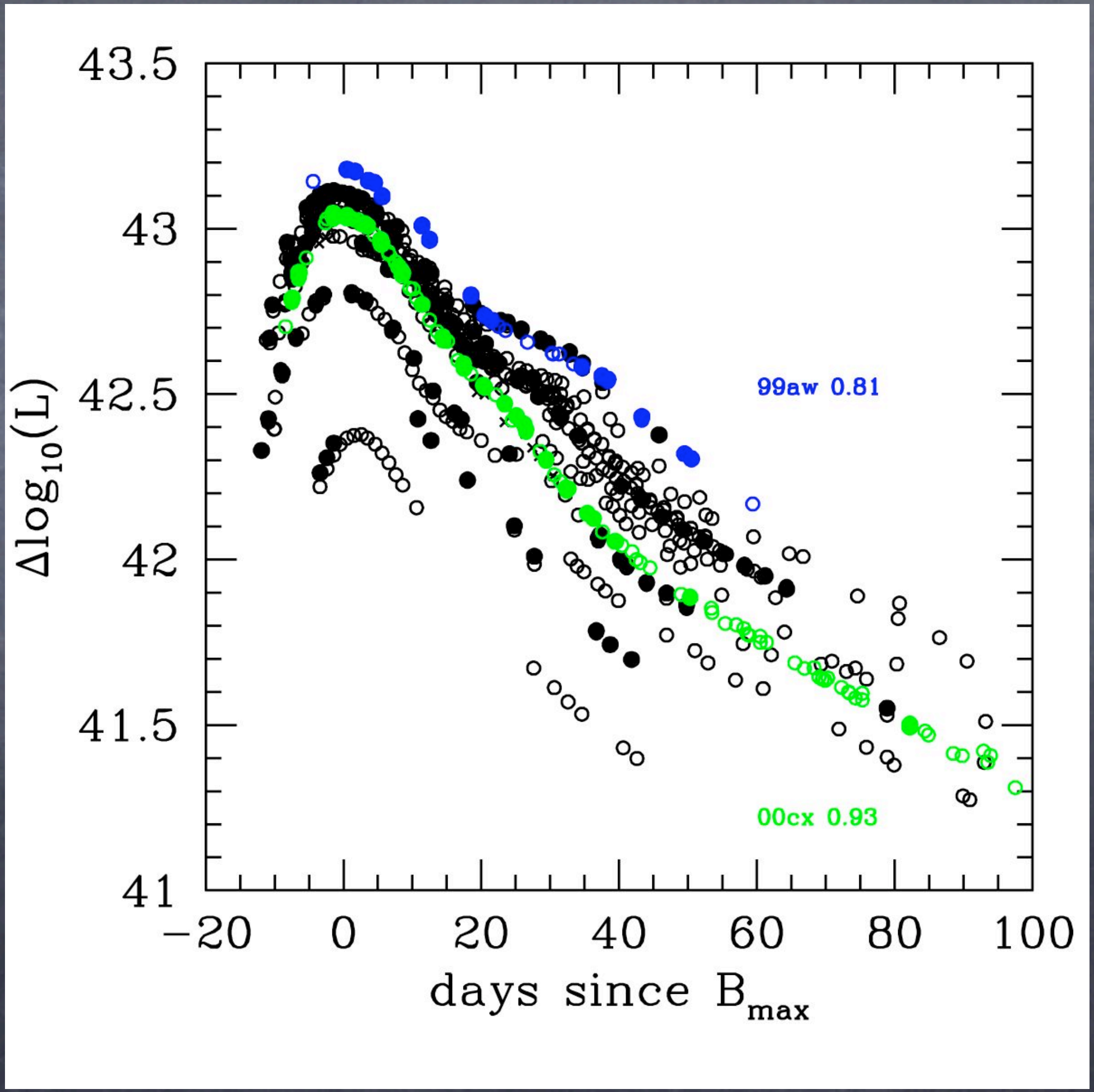


Same

Δm_{15}

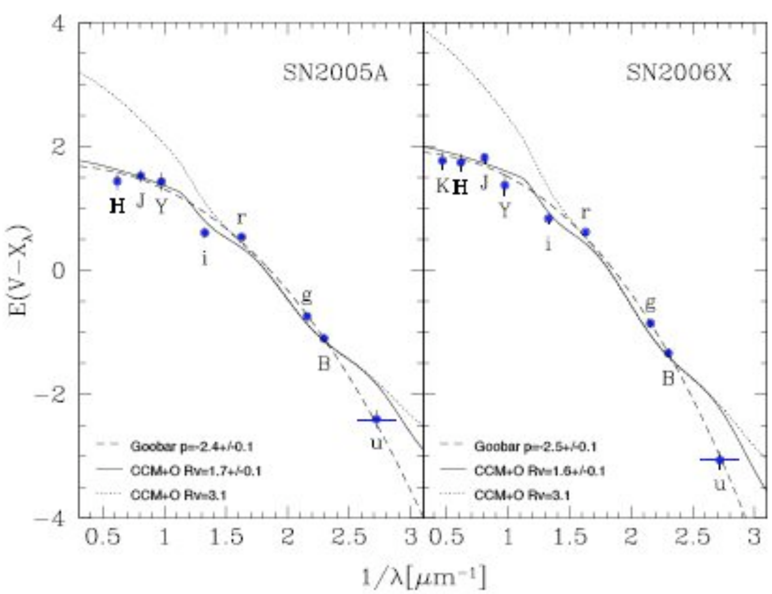
Bolometric light curves

The secondary maximum is not tightly correlated with the peak luminosity.



Reddening

R_V = 1.7 or 3.1??
Wang, Goobar suggestion



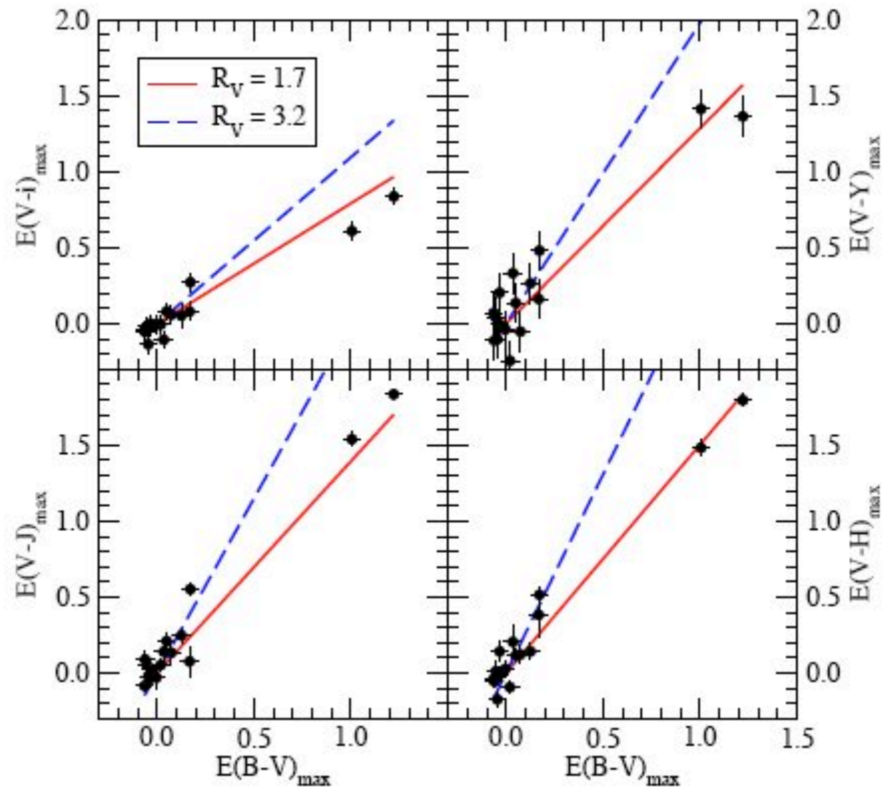


Fig. 13.— Comparison of color-excess estimates $E(V-X)_{max}$, for $X \equiv iYJH$, with $E(B-V)_{max}$ for the best-observed SNe. The solid red lines represent the slope which corresponds to the average fit value of $R_V = 1.7$, found using the whole set of points. The dashed blue lines indicate the slope predicted by a value of $R_V = 3.2$, which is the averaged fit value found when excluding the two highly reddened SNe (the two points farthest to the right in the plots.)

Distances to 3%

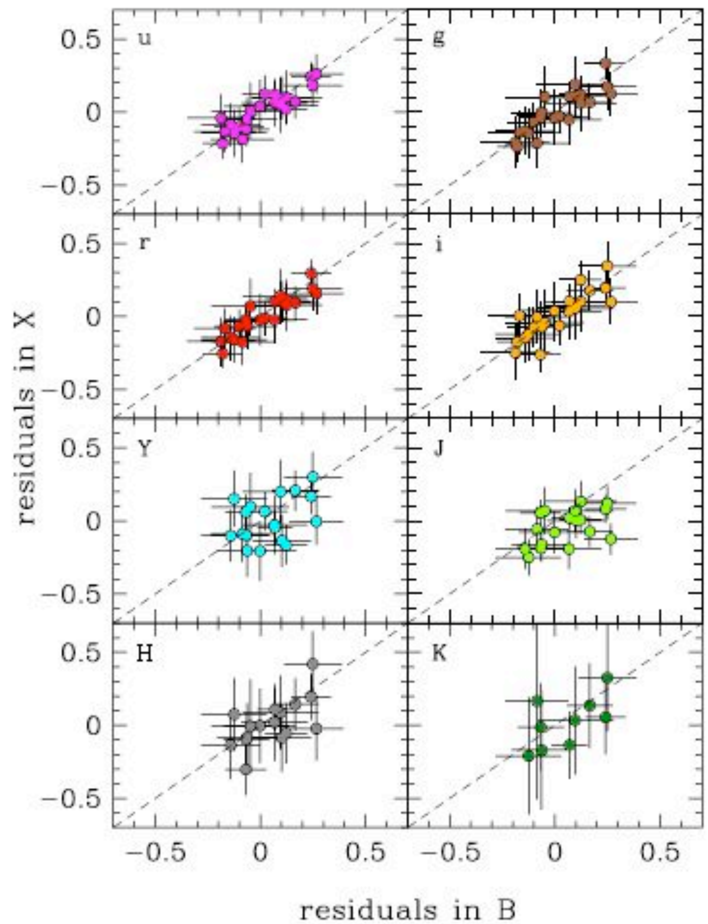
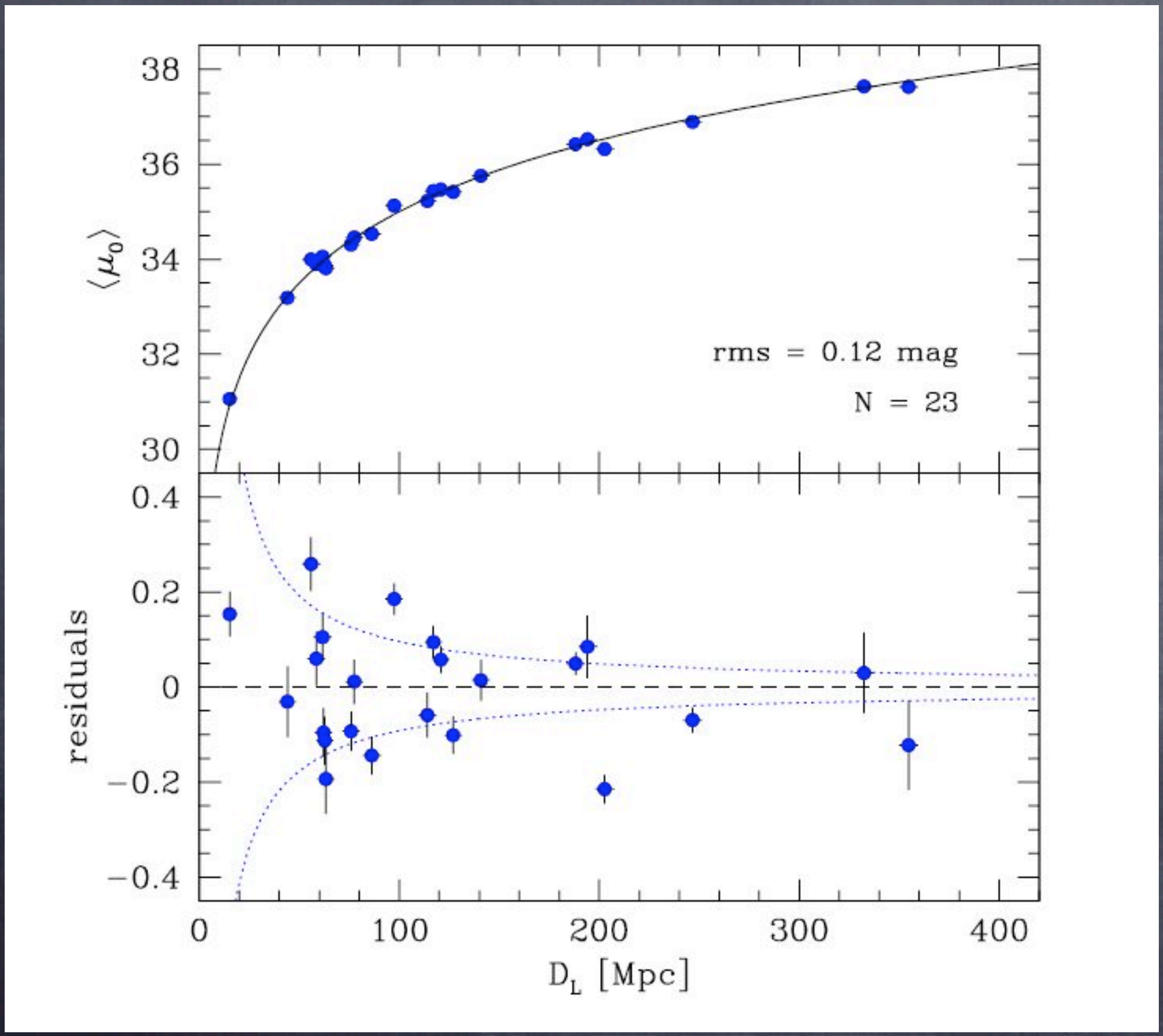


Fig. 20.— Residuals in the distance moduli calculated in band X, where $X = ugriYJHK$, plotted versus the residuals in the B-band distance moduli. Note the significant correlation between these.

Hubble Diagram



δm=0.12

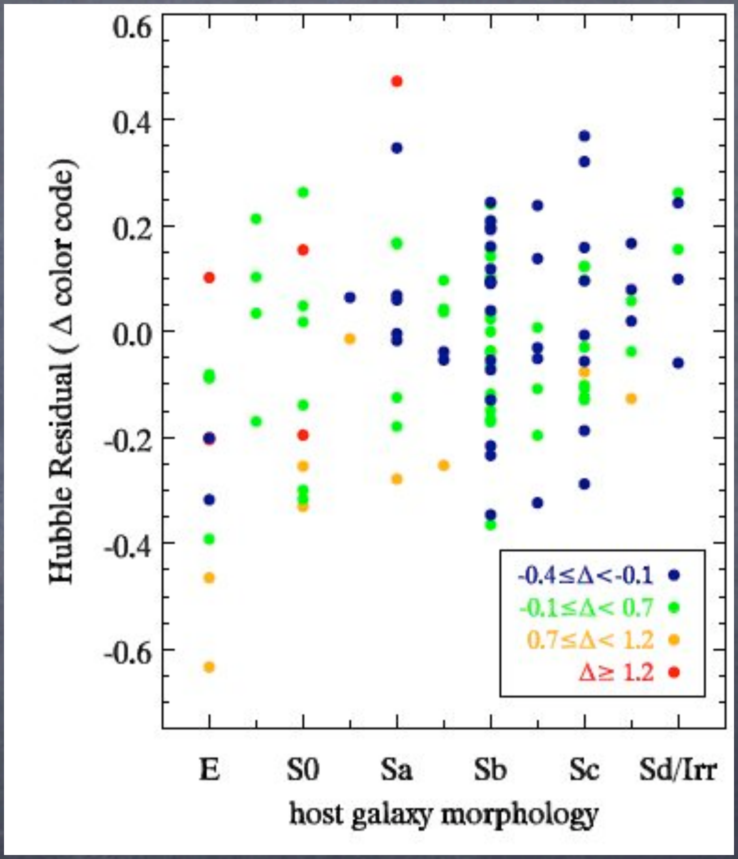
δz=0.001

Hicken et al 2009

state parameter, w. The CfA3 sample is added to the Union set of Kowalski et al. (2008) to form the Constitution set and, combined with a BAO prior, produces $1 + w = 0.013^{+0.066}_{-0.068}(0.11 \text{ syst})$, consistent with the cosmological constant. The CfA3 addition makes the cosmologically-useful sample of nearby SN Ia between 2.6 and 2.9 times larger than before, reducing the statistical uncertainty to the point where systematics play the largest role. We use four light curve fitters to test for systematic differences: SALT, SALT2, MLCS2k2 ($R_V = 3.1$), and MLCS2k2 ($R_V = 1.7$). SALT produces high-redshift Hubble residuals with systematic trends versus color and larger scatter than MLCS2k2. MLCS2k2 overestimates the intrinsic luminosity of SN Ia with $0.7 < \Delta < 1.2$. MLCS2k2 with $R_V = 3.1$ overestimates host-galaxy extinction while $R_V \approx 1.7$ does not. Our investigation is consistent with no Hubble bubble. We also find that, after light-curve correction, SN Ia in Scd/Sd/Irr hosts are intrinsically fainter than those in E/S0 hosts by 2σ, suggesting that they may come from different populations.

A difficult diagram to understand

2σ separation between blue and orange points??



Potential sources of systematic error

- Flux calibrations
- Bias in distance determination codes
- Extinction
    - Host galaxy
    - Our Galaxy
    - Atmosphere
- Extinction law
- Passband errors
    - K corrections
    - Photometry normalization
- Nonlinearity in flux measurements

More Potential Systematics

- “Hubble bubble” trouble
- Gravitational lensing
- Evolutionary effects in SNe
- Biases in low redshift sample
- Search efficiency/selection

Table 5. Potential Sources of Systematic Error on the Measurement of w

Source	dw/dx	Δx	Δ_w	Notes
Phot. errors from astrometric uncertainties of faint objects	1/mag	0.005 mag	0.005	
Bias in diff im photometry	0.5 / mag	0.002 mag	0.001	
CCD linearity	1 / mag	0.005 mag	0.005	
Photometric zeropoint diff in R,I	2 / mag	0.02 mag	0.04	
Zpt. offset between low and high z	1 / mag	0.02 mag	0.02	
K-corrections	0.5 / mag	0.01 mag	0.005	
Filter passband structure	0 / mag	0.001 mag	0	
Galactic extinction	1 / mag	0.01 mag	0.01	
Host galaxy R_V	0.02 / R_V	0.5	0.01	"glosz"
Host galaxy extinction treatment	0.08	prior choice	0.08	different priors
Intrinsic color of SNe Ia	3 / mag	0.02 mag	0.06	interacts strongly with prior
Malmquist bias/selection effects	0.7 / mag	0.03 mag	0.02	"glosz"
SN Ia evolution	1 / mag	0.02 mag	0.02	
Hubble bubble	$3/\delta H_{\text{effective}}$	0.02	0.06	
Gravitational lensing	$1/\sqrt{N}$ / mag	0.01 mag	< 0.001	Holz & Linder (2005)
Grey dust	1 / mag	0.01 mag	0.01	
Subtotal w/o extinction+color	···	···	0.082	
Total	···	···	0.13	
Joint ESSENCE+SNLS comparison	···	···	0.02	photometric system
Joint ESSENCE + SNLS Total	···	···	0.13	

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

Photometric Calibration Critical!

- 3% absolute offset in overall ZP with respect to nearby SNIa sample
  - Δzp = 0.03 => Δw = 0.05
- 3% relative offset in color ZP
  - Δcolor = 0.03 => Δw = 0.10

(Δw = change in the marginalized mean value of w)

SNe and GRB's

Wright (2007)

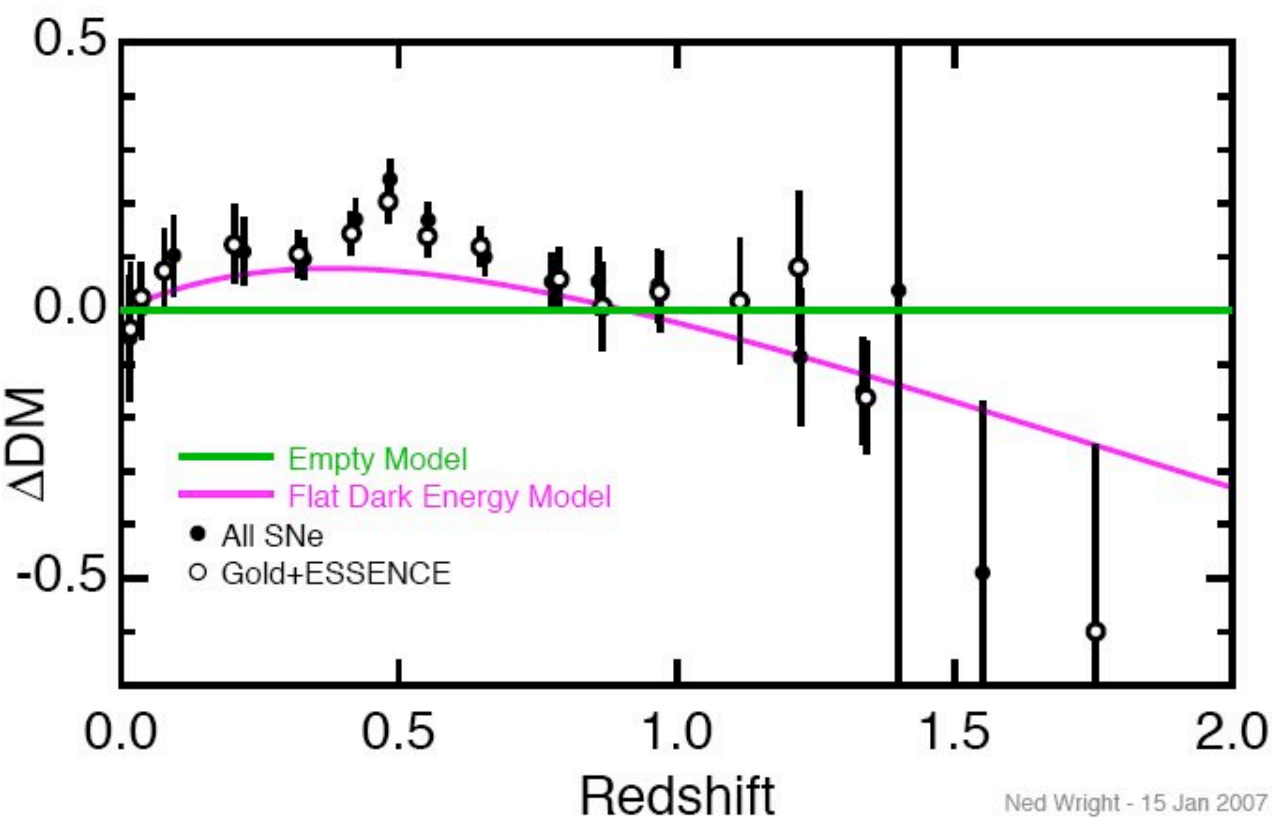


Fig. 2.— Binned supernova data *vs.* redshift compared to a flat ΛCDM model with $\Omega_M = 0.369$. The filled circles are binned points from the full dataset, while the open circles have omitted the "Silver" subset.

Higher-Z SN Team

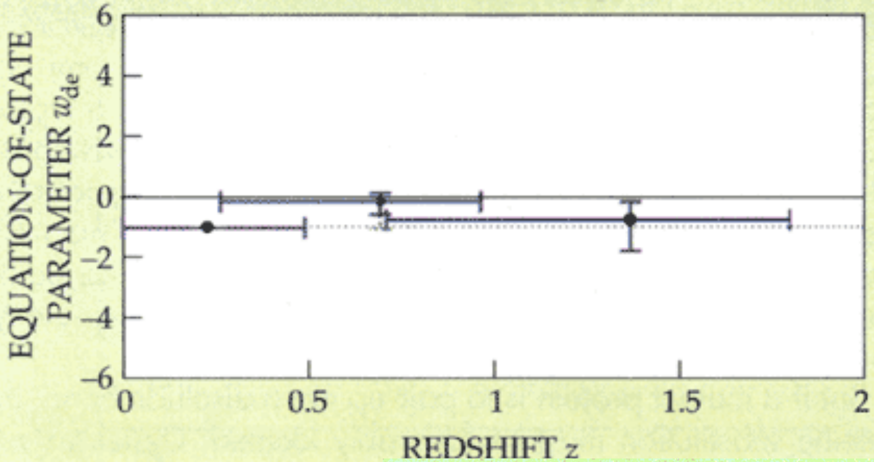


Figure 3. Evolution of w_{de}, the dark energy's ratio of pressure to energy density, as determined from the supernova data. Negative pressure tends to accelerate the cosmic expansion. If the dark energy is the vacuum energy of Einstein's cosmological constant, w_{de} is −1 forever (dotted line). Competing quintessence models let w_{de} change over time. The Higher-Z team concludes, with 98% confidence, that w_{de} was already negative from redshift 1.8 to 1.0, that is, from 10 to 6 billion years ago. (Adapted from ref. 3.)

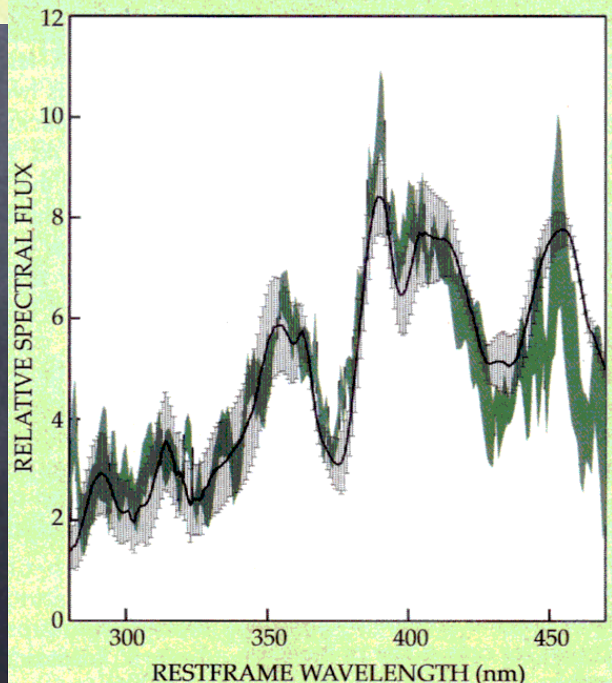


Figure 4. Ancient and recent spectra of type 1a supernovae show no evolutionary change over 10 billion years. The green band is a composite spectrum of the Higher-Z team's 13 best-measured supernovae with redshifts *z* above 1, transformed into each exploding star's rest frame. The black curve with gray error bars is a template used to verify the type 1a designation for supernovae with redshifts less than 0.1, which would have exploded within the past billion years or so. (Adapted from ref. 3.)

Riess, et al (2007)

Summary

- The accelerating Universe poses a significant challenge to theory, experiment and observation.
- Current goal: w to 10%
- The SNIa data are consistent with a flat Universe with a cosmological constant.

Closing thoughts

- The scale of dark matter
- DETF and future measures of dark energy
- The Hubble constant
- Why are we wasting our time with w′???