Distance Precision with Type Ia Supernovae

The Carnegie Supernova Project

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IPMU

January 6th 2011

Outline

Importance of Supernovae

Astrophysical relevance

- *Death* of a star $\longrightarrow$ Stellar evolution
- Chemical enrichment of the ISM
- Energetics of the ISM $\longrightarrow$ Trigger of star formation

Cosmology

- Powerful distance indicators (SNe Ia)
- Discovery of *dark energy*
- Theory still has to explain this
  - What is the equation of state of dark energy?
  - Does it vary with cosmic time?

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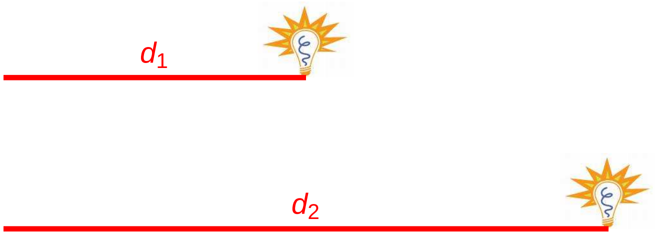
Type Ia SNe as Distance Indicators

- Standard candle $\longrightarrow$ Luminosity distance

F_1



$$F_2 = F_1 \left(\frac{d_1}{d_2} \right)^2$$

- Requires an external calibration of the luminosity

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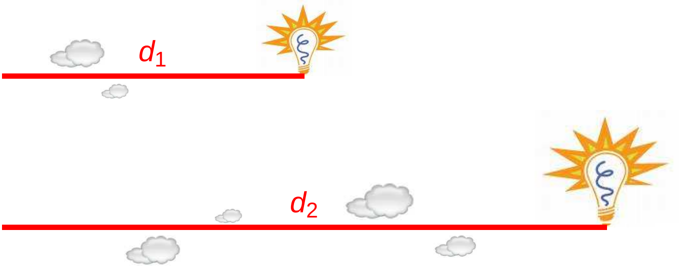

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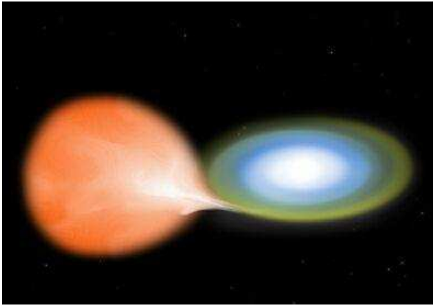
Type Ia SNe as Distance Indicators

Physical picture of SNe Ia

- Binary system with a CO white dwarf
- Mass transfer
- Thermonuclear runaway at Chandrasekhar mass



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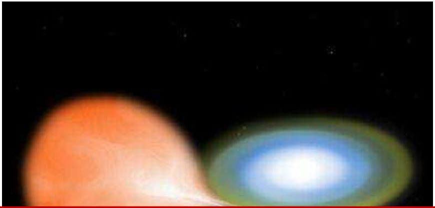


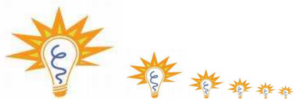
Pending questions

- What is the companion star?
- What is the explosion mechanism?

Type Ia SNe as Distance Indicators

Advantages of SNe Ia as distance indicators

- Luminous
- Ubiquitous
- Identifiable
- Homogeneous



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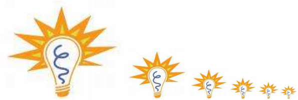
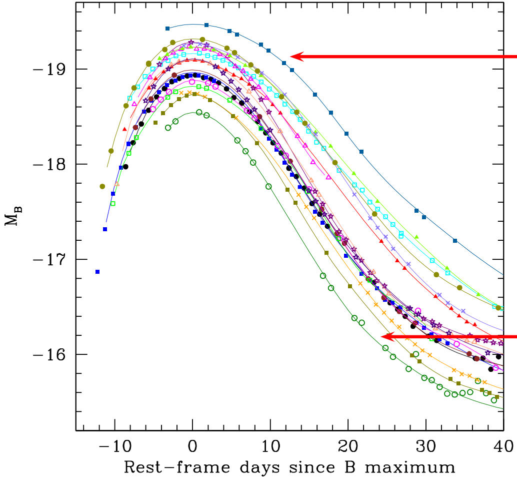


Calibration of SNe Ia as *Standardized Candles*

- Brighter SNe evolve more slowly
- Mass and distribution of radioactive isotopes

- *B*-band decline rate, $\Delta m_{15}(B)$



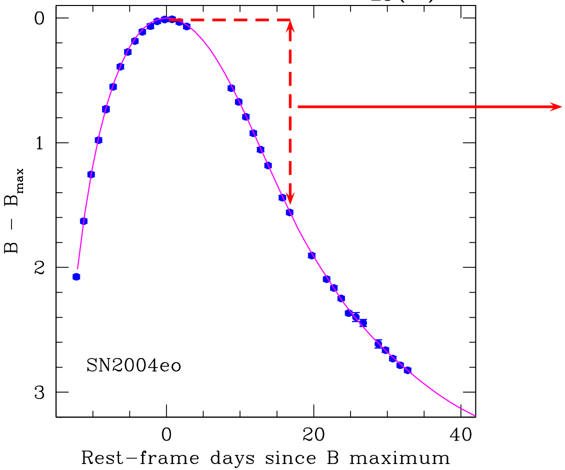
wider = more luminous

narrower = less luminous

(CSP data)

Luminosity – Decline Rate Relation

- *B*-band decline rate, $\Delta m_{15}(B)$



$\Delta m_{15}(B)$ Phillips (1993)

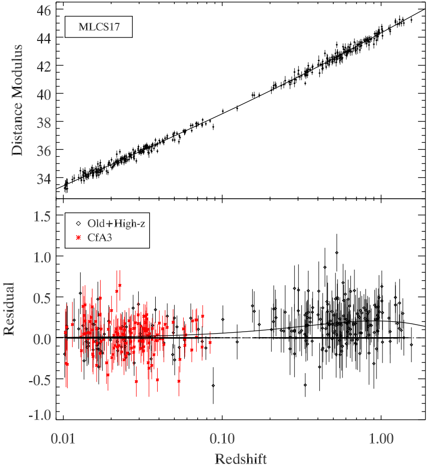
$$M_{\rm max} = f[\Delta m_{15}(B)]$$

Phillips et al. (1999)

SN Ia Cosmology

Hubble diagram

- Low- and high-z SNe
- Fit for cosmological parameters (Ω_M, Ω_Λ)



Hicken et al. (2009)

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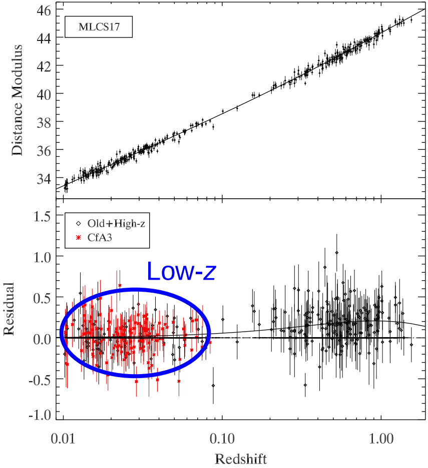
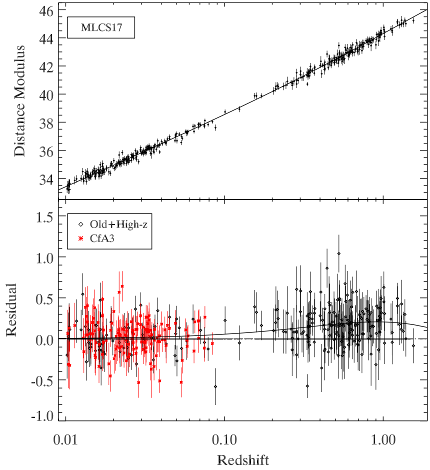


Hicken et al. (2009)

SN Ia Cosmology

Possible hindrances

- Extinction
- Evolution / metallicity
- Photometric calibration
- K-corrections
- Gravitational lensing



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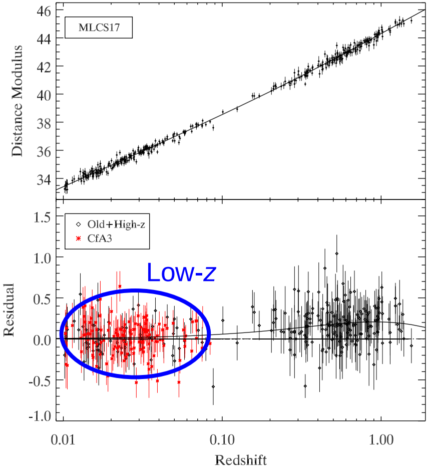
- Large local sample
- Multi-band observations
- Controled photometric system
- Spectroscopic studies



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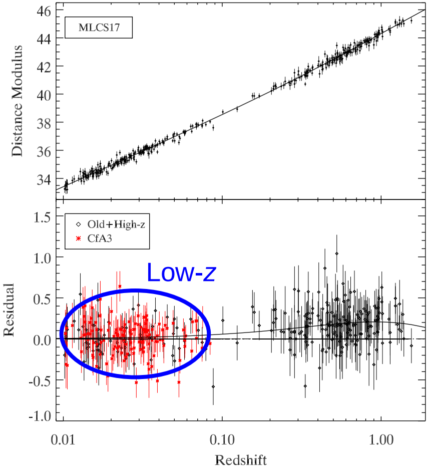


Hicken et al. (2009)

The Carnegie Supernova Project

(low redshift)

Swope 1-m

du Pont 2.5-m

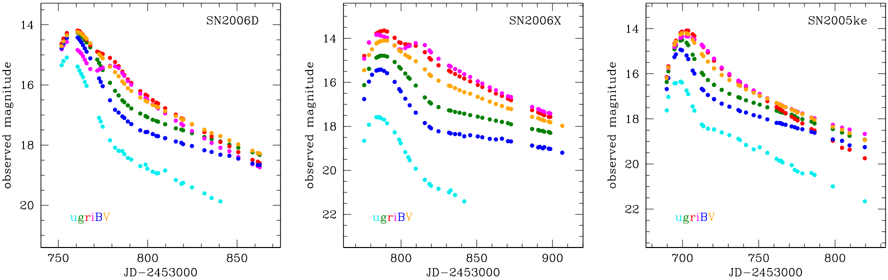
Magellan 6.5-m

Between 2004 – 2009 followed:

	Ia	II	Ib/c
SNe	130	93	26

Data set (first release)

- 35 Type Ia SNe
- Well-understood, uniform photometric system
  - Optical: $u'g'r'i'$ and BV
  - NIR: $YJH(K_s)$
- Excellent coverage and sampling
- Complemented with spectroscopy (Folatelli et al. in prep.)



CSP Light Curves (Contreras et al. 2010)

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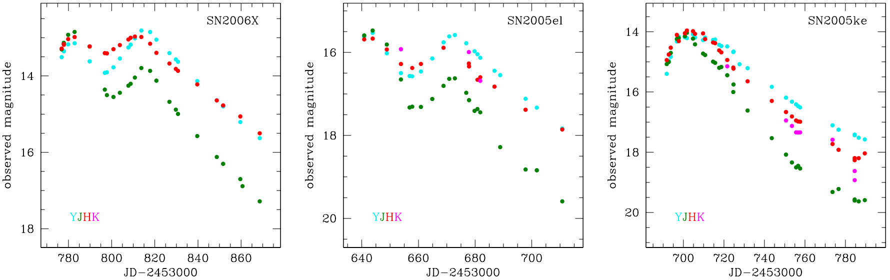
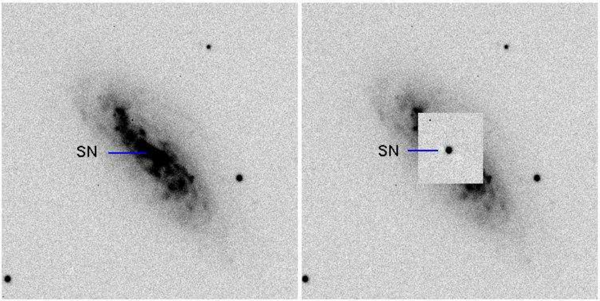


CSP Light Curves (Contreras et al. 2010)

Background subtraction

- Images of the host galaxy obtained $\sim$ one year later
- Alignment, psf matching, flux scaling and subtraction
- Significant improvement in signal

SN 2004fc in g'



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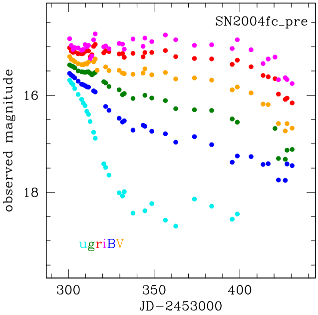
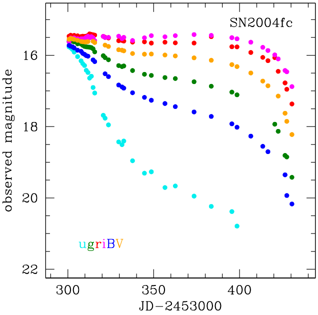
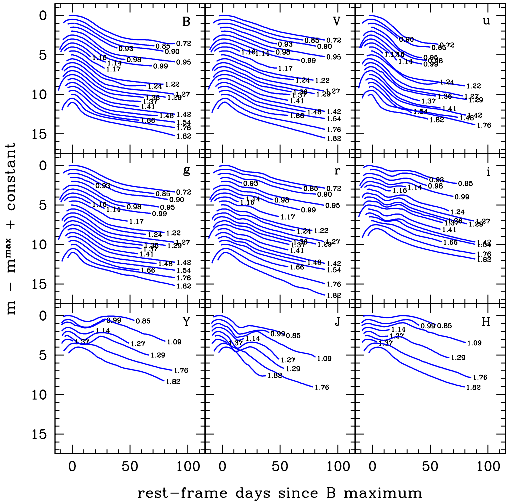
Before



After



Light curve templates in u’g’r’i’BVYJH:



Light-curve parameters

- $t_{\max}$, $m_{\max}$, $\Delta m_{15}(B)$
- Set of template LC’s
- Useful for fitting any other SNe (Burns et al. 2011)

Intrinsic SN Colors

- Selection of SNe with low reddening
  - SNe in E/S0 galaxies or far from S galaxies
  - Absence of interstellar Na I in early-time spectra
- Uniform late-time evolution Lira (1995) $\longrightarrow E(B-V)_{\rm tail}$
- At maximum light $\longrightarrow$ Slight dependence on $\Delta m_{15}(B)$

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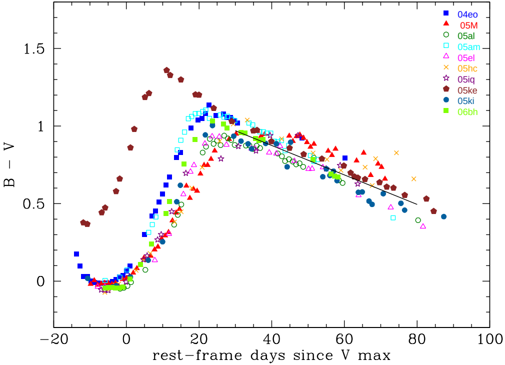

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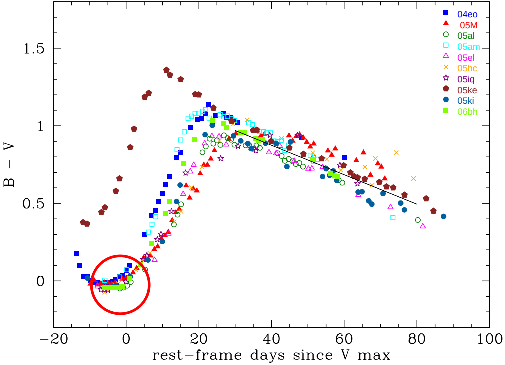
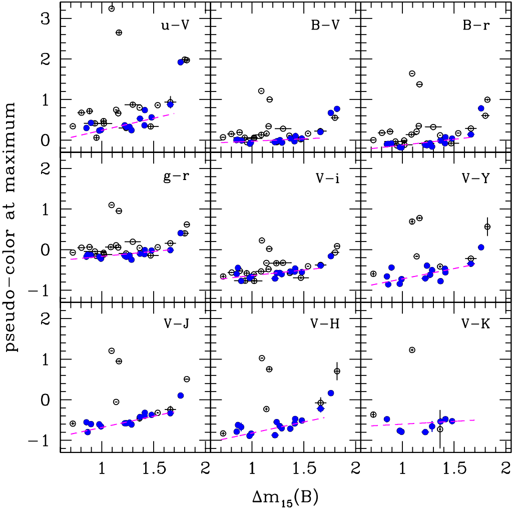


Color Excesses

Color indices

- From magnitudes at maximum
- Corrected for MW extinction
- Various color combinations
- Linear fits to unreddened SNe
- $\Delta m_{15}(B) < 1.7$

Colors at maximum light:



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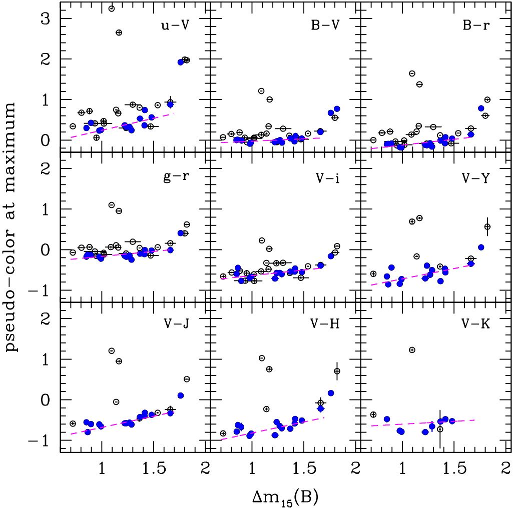
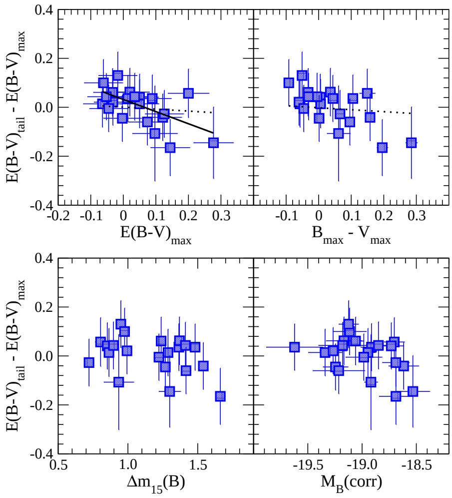


Color Excesses

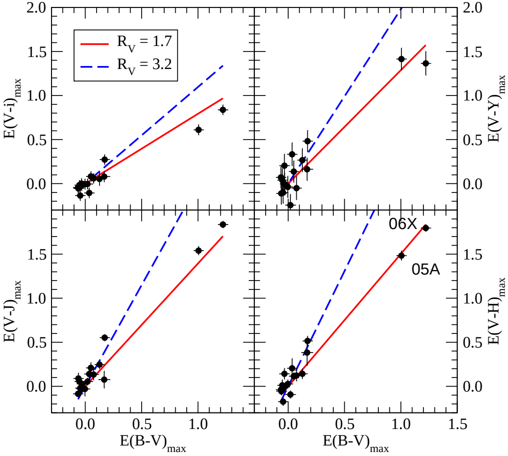
$E(B-V)$ at maximum and at tail:



Maximum vs. tail

- Systematic differences
- Is this non-dust reddening?
- Is it time-varying extinction?

Extinction Law



Fits for R_V

- From optical–NIR colors
- We study the extinction law
- Slopes determined by $R_V = A_V / E(B - V)$
- Reddening law (Cardelli et al. 1989): $A_\lambda / A_V = a_\lambda + b_\lambda / R_V$
- Moderately reddened: $R_V = 3.2 \pm 0.4$
- Heavily reddened: $R_V = 1.69 \pm 0.05$

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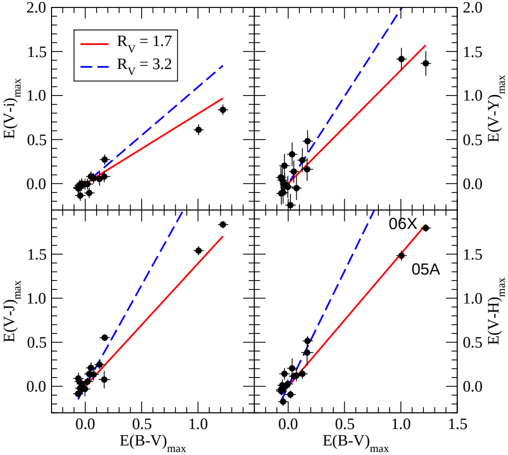

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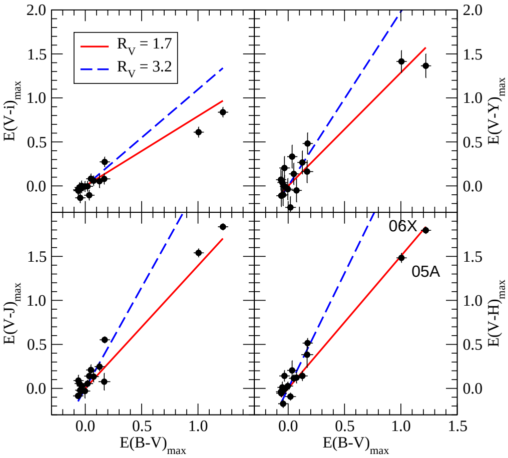

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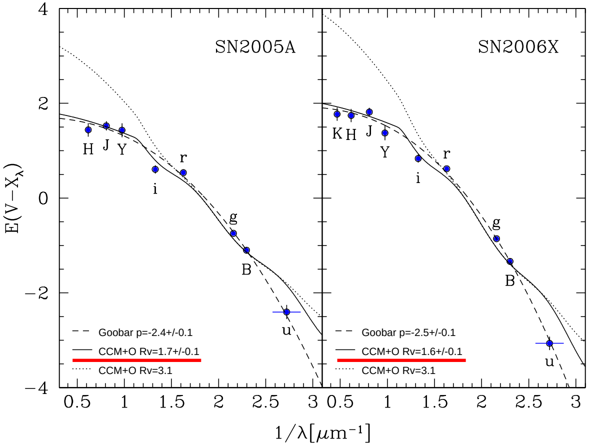
Extinction Law

Heavily reddened SNe

- Two SNe with $E(B-V) \gtrsim 1$
- $R_V \sim 1.7$
- Importance of NIR data
- Evidence of peculiar extinction
- Circumstellar dust

Goobar (2008)



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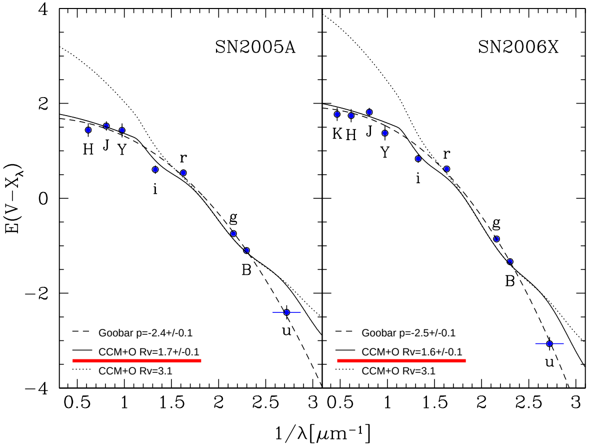

SNe Ia as Standardized Candles

- Hubble-flow distances with H_0, Ω_M, Ω_Λ for SNe with $z > 0.01$

$$d_L(z; H_0, \Omega_M, \Omega_\Lambda) = \frac{c}{H_0}\left[z + \frac{1}{2}\left(\Omega_\Lambda - \frac{\Omega_M}{2} + 1\right) z^2\right]$$

- Bilinear relation between peak luminosity in any band X, decline rate $\Delta m_{15}(B)$, and color excess $E(Y-Z)$

$$\mu_X = m_X - M_X(0) - b_X[\Delta m_{15}(B) - 1.1] - R_X^{YZ} E(Y-Z)$$

- Input data: μ_X, m_X, $\Delta m_{15}(B)$ and $E(Y-Z)$ for all SNe
- $\Delta m_{15}(B) < 1.7 \longleftarrow$ "Normal" SNe Ia
- $R_X^{YZ} \longrightarrow R_V$
- χ^2 fit with added *instrinsic* dispersion σ_{SN}

$$\chi^2\left(M_X(0), b_X, R_X^{YZ}; \sigma_{SN}\right) = \sum_{i=1}^{N} \frac{(\mu_{X\,i} - \bar{\mu}_X)^2}{\sigma_i^2 + \sigma_{SN}^2}$$

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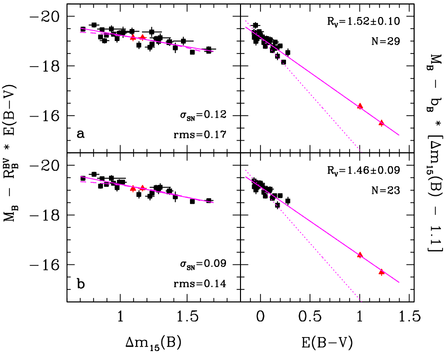
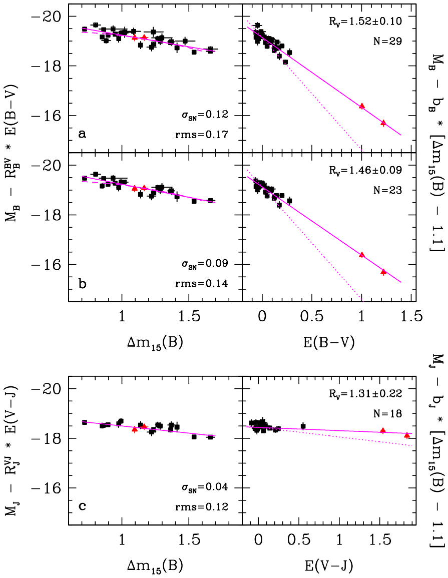


Fit Results

- B vs. $E(B-V)$
  - RMS $\sim$ 0.15 mag
  - $\sigma_{SN} \sim$ 0.1 mag
  - $R_V \sim$ 1.5
    even without most reddened SNe
- J vs. $E(V-J)$
  - RMS = 0.12 mag
  - $\sigma_{SN} \sim$ 0.04 mag
  - slight dependence on $\Delta m_{15}(B)$
  - $R_V \sim$ 1.5
- $\sim$ 7% dispersion in distance

SNe Ia as Standardized Candles



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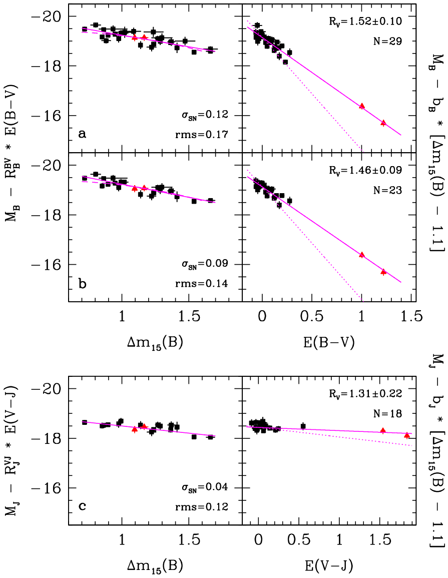

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Contradiction with color escess analysis

- R_V is small ($\sim$ 1–2) even for moderate reddening
- This was also found before by other SN teams
- Are we *only* measuring host-galaxy reddening?
- There may a dispersion in SN colors which depends on luminosity but not on decline rate

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SNe Ia as Standardized Candles

- Alternative approach Tripp (1998)
- Luminosity versus decline rate and color $(m_Y - m_z)$

$$\mu_X = m_X - M_X(0) - b_X[\Delta m_{15}(B) - 1.1] - \beta_X^{YZ}(m_Y - m_Z)$$

- All SNe can be used (all $\Delta m_{15}(B)$ values)
- No assumption on intrinsic colors
- However β_X^{YZ} could be associated with R_V
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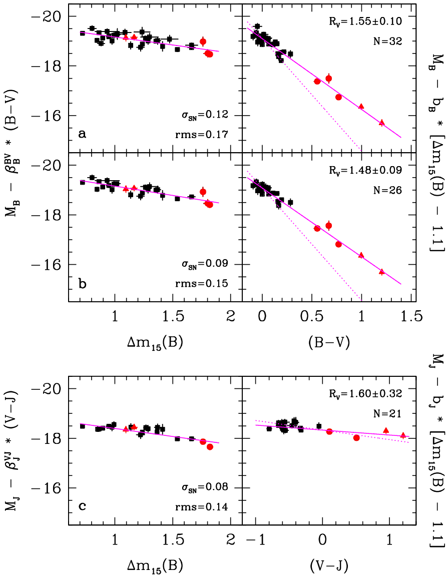
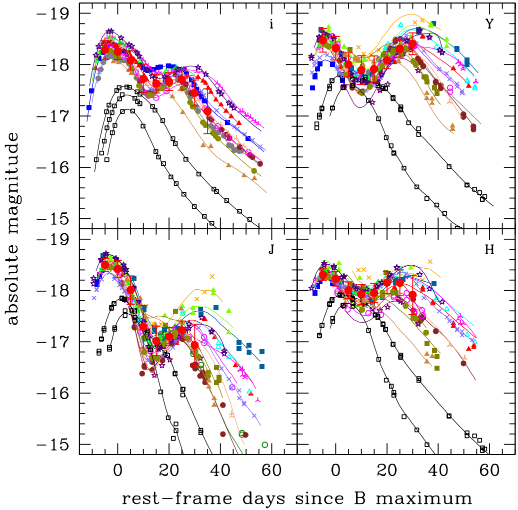


Fit Results

- B vs. $(B - V)$
  - RMS $\sim$ 0.15 mag
  - σ_{SN} $\sim$ 0.1 mag
  - Fast-declining SNe fall on fit
  - R_V $\sim$ 1.5
- J vs. $(V - J)$
  - RMS $\sim$ 0.15 mag
  - σ_{SN} $\sim$ 0.08 mag
  - slight dependence on $\Delta m_{15}(B)$
  - R_V $\sim$ 1.5
- $\sim$ 7% dispersion in distance

Absolute Magnitudes in NIR



Advantages of NIR

- Small reddening correction
- No correction for decline rate

Precision at maximum (mag)

i'	Y	J	H
0.25	0.24	0.18	0.19

- Local NIR minimum as a good standard candle
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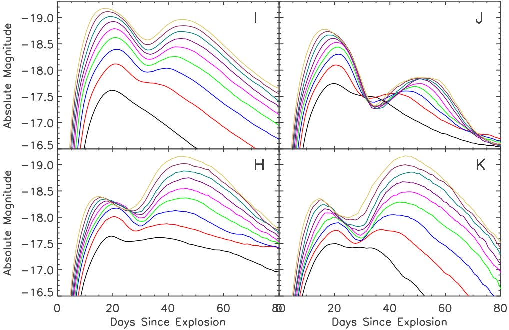

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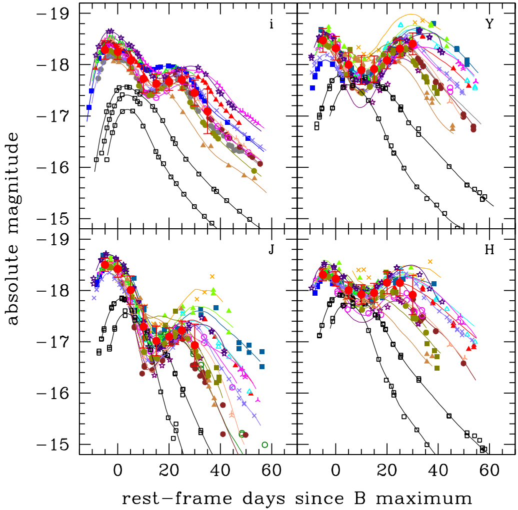

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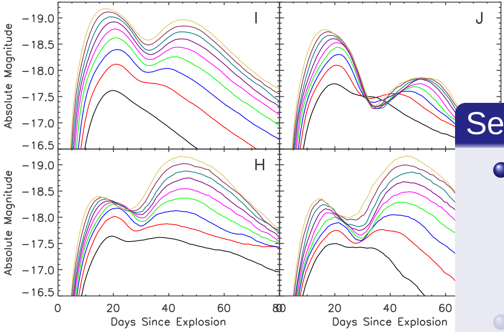

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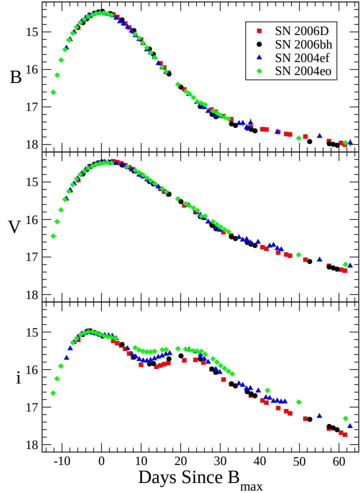
Secondary NIR maximum

- Theory:
  Time and strength of 2nd max determined by ^{56}Ni mass and therefore by $\Delta m_{15}(B)$
- Data:
  Identical B-band and different i'-band LCs
- Is this due to mixing/metallicity/geometry?
- Could this serve to reduce the scatter in the Hubble diagram?

NIR Diversity

Four SNe Ia with $\Delta m_{15}(B) \approx 1.4$:



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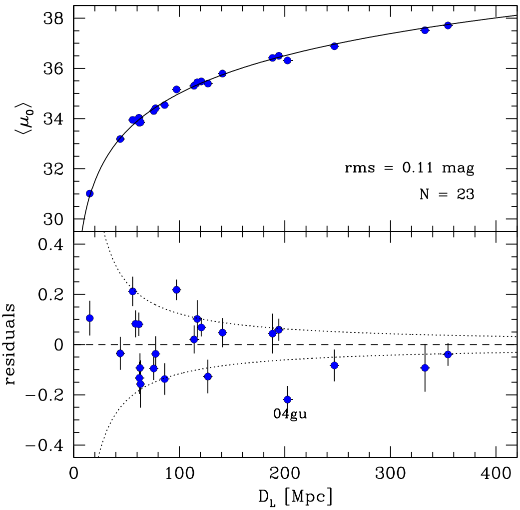

Results

- 23 best-observed SNe with $z > 0.01$
- Combined RMS $= 0.11$ mag
- No significant improvement compared with individual bands
- Strong correlation of residuals in all bands
- Probably due to peculiar velocities
- Actual precision could be 0.06–0.09 mag in $u'g'r'i'BV$ ($\sim$3%–4% in distance)

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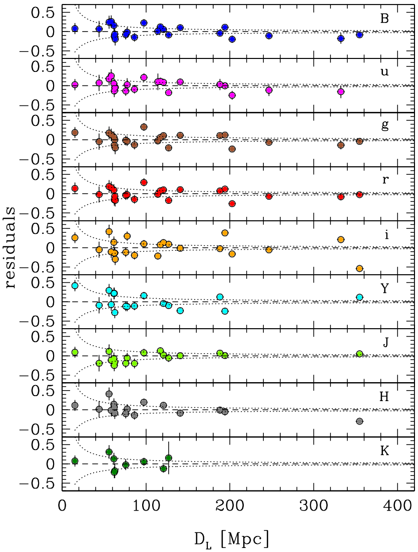

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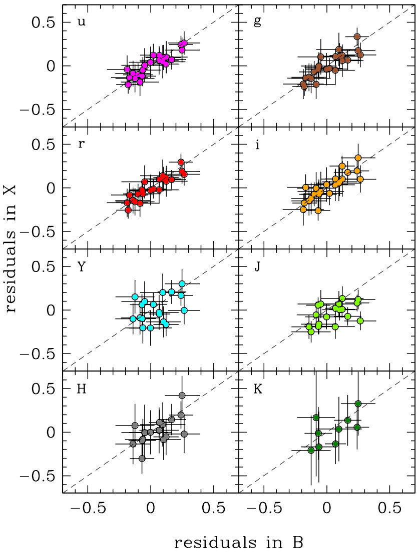

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Summary

- Precision cosmology requires high-quality SN samples at low z
- Superb $u'g'r'i'BVYJHK_s$ light curves of the CSP allow us to:
  - Build LC templates
  - Study intrinsic SN Ia colors
  - Characterize the host-galaxy extinction law
  - Fit SN Ia luminosities
- SNe Ia as *standardized candles* are possibly as precise as 3%–4% in distance
- *Standard candle* precision in the NIR may be of $\sim$10%

- Folatelli+ 2010, AJ, 139, 120; Contreras+ 2010, AJ, 139, 519
- $\sim$90 SNe Ia in forthcoming CSP papers