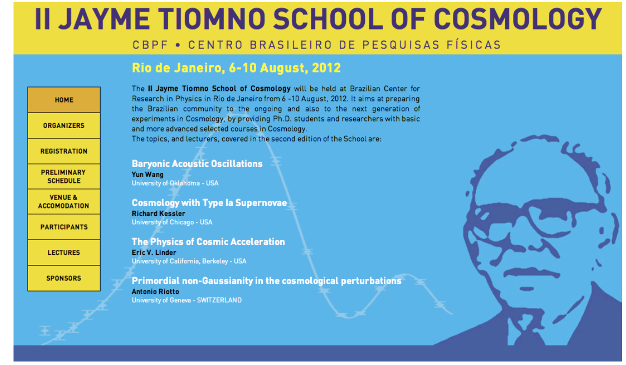

Lectures on Cosmology with Type Ia Supernovae: **Measuring the Distance Modulus**

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Rio de Janeiro, Brazil

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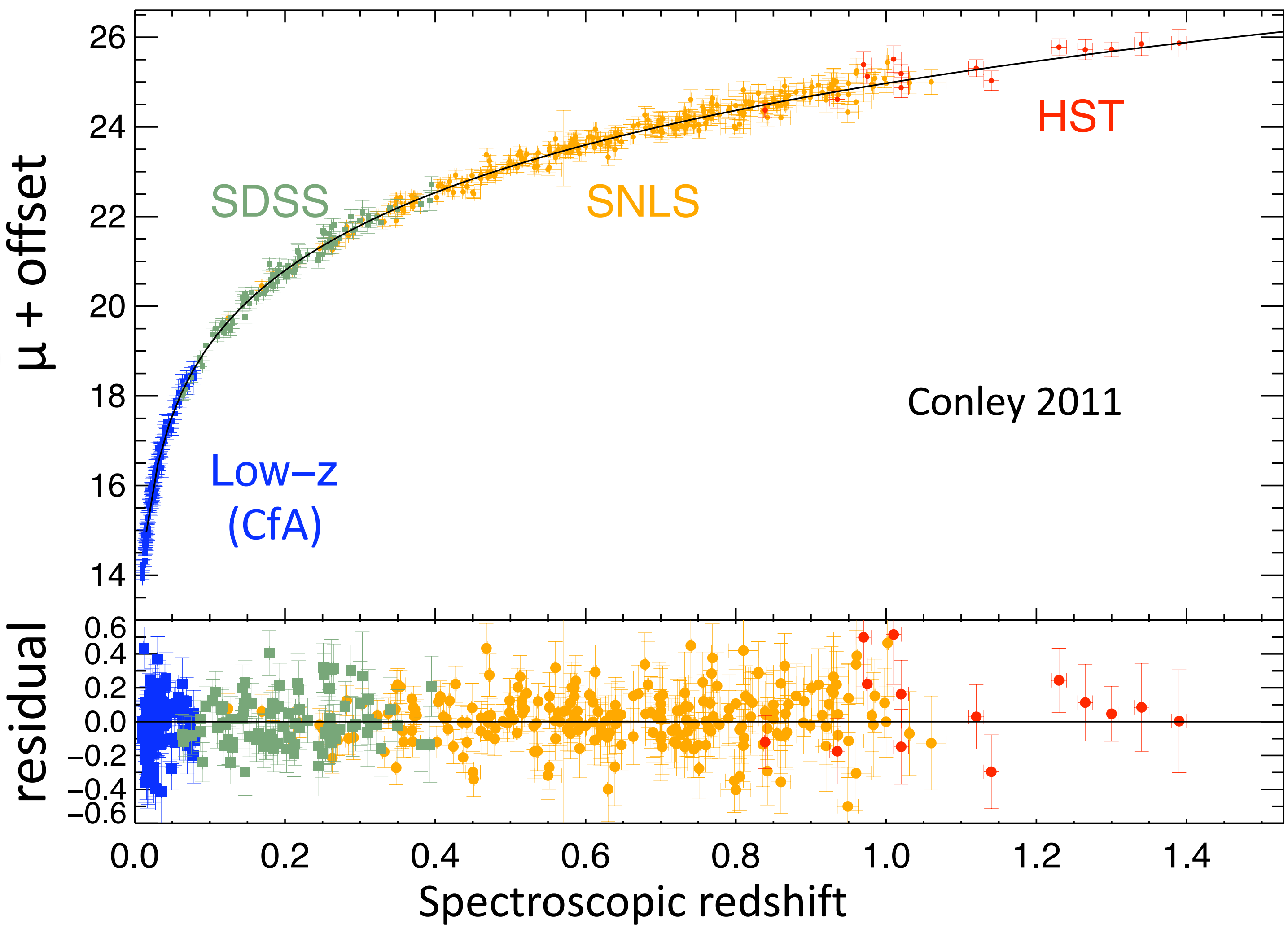
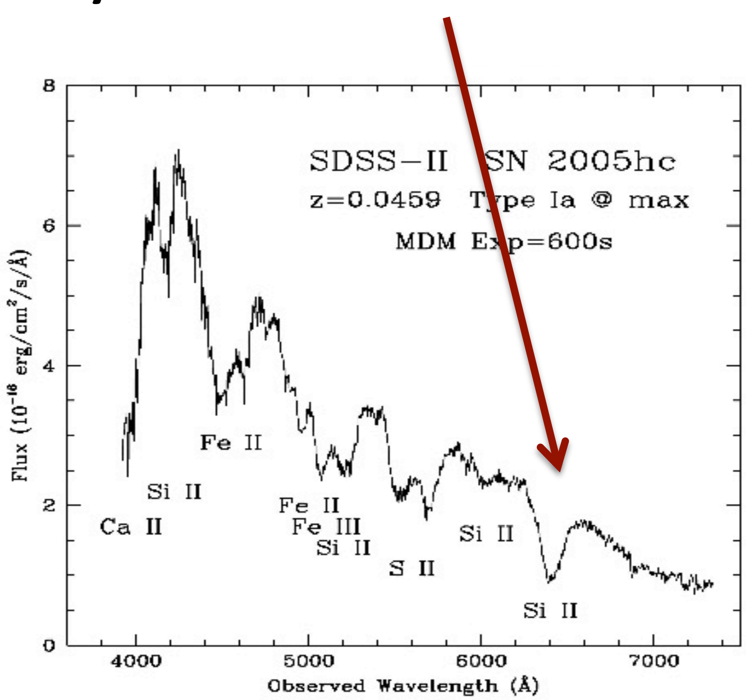
SN Ia Hubble Diagram

Focus: how to measure this ?



Why use SNIa to Measure μ ?

- Bright (absolute peak mag ≈ −19.5)
- Standardizable brightness to about 10%
- Easy to identify via Si II feature in spectrum



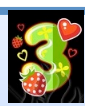
Measuring μ

Consider "Bolometric" SN mags (M) and uniform efficiency vs. λ for the atmosphere and telescope. Ignore Galactic extinction.

$$M_{Earth} = M_{source} + \mu$$

- M_{Earth} ↑ Mag measured on Earth
- M_{source} ↑ mag @ 10pc
- μ ↑ dimming due to light travel thru expanding universe

If M_{source} is constant, the analysis is easy: $\mu = M_{Earth} - M_{source}$

Exercise  : if M_{source} is mis-measured by a constant mag-shift δm, show that the μ-dependence on w, Ω_M,Ω_Λ is unchanged if H_0 -> H_0 x $10^{\delta m/5}$.

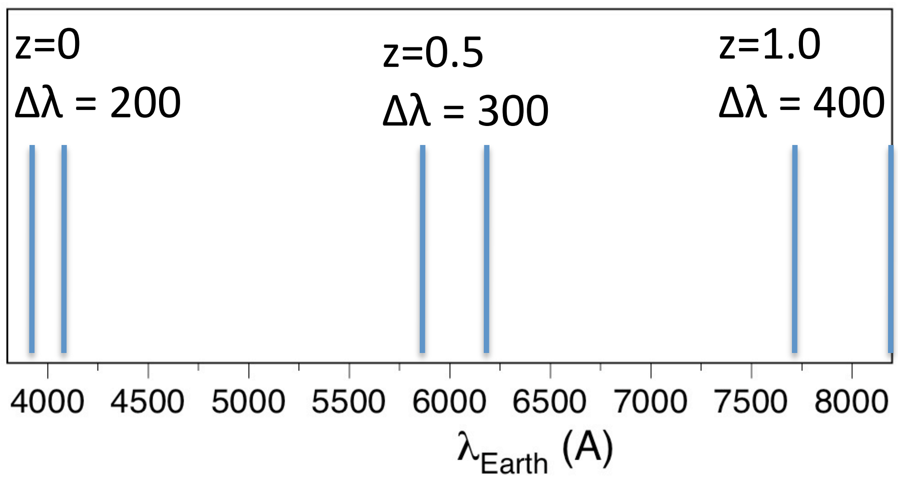
Measuring μ

$\mu = M_{Earth} - M_{source}$ is too simplistic because:

- Efficiency(Atmosphere + telescope) depends on λ_{Earth}. SNe at different redshift deliver rest-frame fluxes at different λ_{Earth} -> different efficiency at each redshift. This 'calibration' effect is currently the largest source of systematic error.
- SN light is reddened if it scatters thru circumstellar and/or host galaxy dust.
- SN light reddens as it scatters thru Milky Way.
- SN flux changes with time and we cannot measure mag at exactly the same rest-frame epoch for all SNe.
- M_{source} is not constant, even at the same epoch !!
  Needs empirical correction based on light curve shape (Phillips 1993) and color (Riess 98, Tripp 98).

Illustration of Calibration Bias

Imagine ideal spectroscopic measurements to select peak flux corresponding to rest-frame λ_{rest}=4000 A with 200 A width

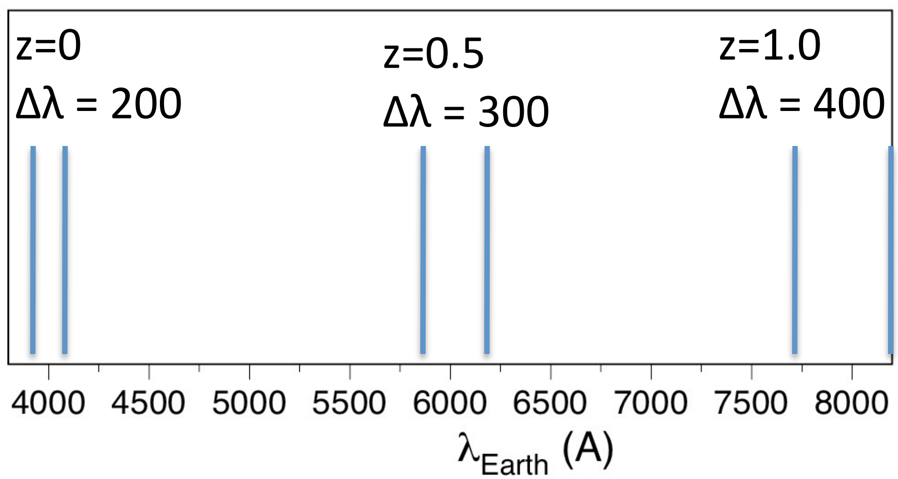


If efficiency (ε_{spec}) vs. λ is known,

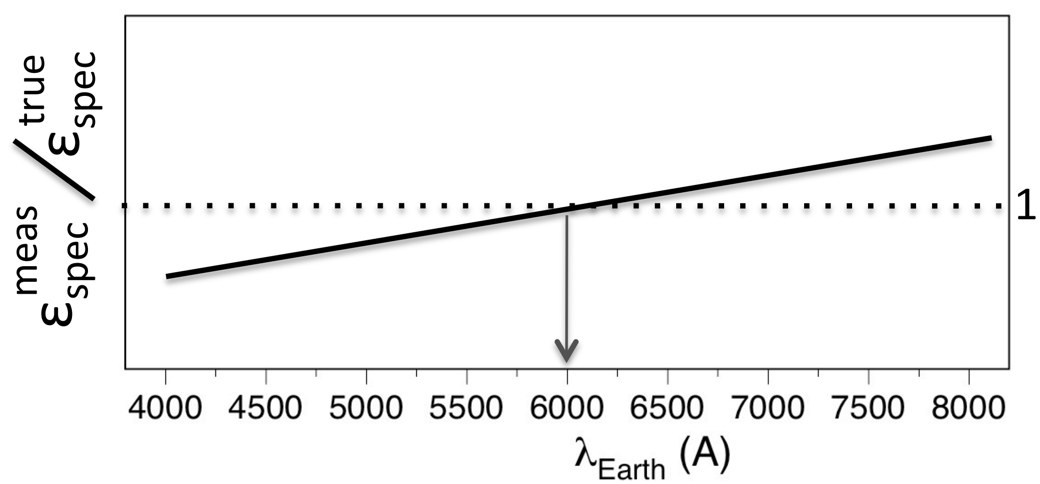
$M_{Earth} = -2.5\log_{10}(F_{Earth}/\varepsilon_{spec})$ and

$\mu = M_{Earth} - M_{source}$ works for Hubble diagram.

Illustration of Calibration Bias

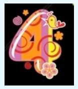


Suppose efficiency is mis-measured;



Define $\Delta\varepsilon_{spec}$ = fractional mis-measured efficiency variation from 4000-8000

Illustration of Calibration Bias

Exercise  : show that

$$\left(\frac{D_L{}^{\text{bias}}}{D_L{}^{\text{true}}}\right)^2 = \left\{1 + \frac{\Delta\epsilon_{\text{spec}}}{\Delta\lambda_{\text{Earth}}}\left[(1+z)\lambda_{\text{rest}} - \bar{\lambda}_{\text{Earth}}\right]\right\}^{-1}$$

where

$$\begin{aligned} \Delta\lambda_{\text{Earth}} &= 8000 - 4000 = 4000\ \text{Å} \\ \lambda_{\text{rest}} &= 4000\ \text{Å} \\ \bar{\lambda}_{\text{Earth}} &= 6000\ \text{Å} \\ z &= \text{redshift} \end{aligned}$$

Setting $\Omega_\Lambda = 1 - \Omega_M$ determine the biased parameters w and Ω_M by fitting the biased Hubble diagram ($\mu_{bias} = 5\log10(D_L{}^{bias}/10)$) with an unbiased μ-function.
Use equal weighting in each redshift bin.
Show that $dw/\Delta\varepsilon_{spec} = 5$
-> 1% effic bias results in .05 bias on w.

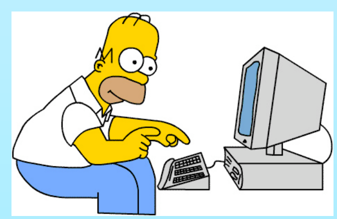
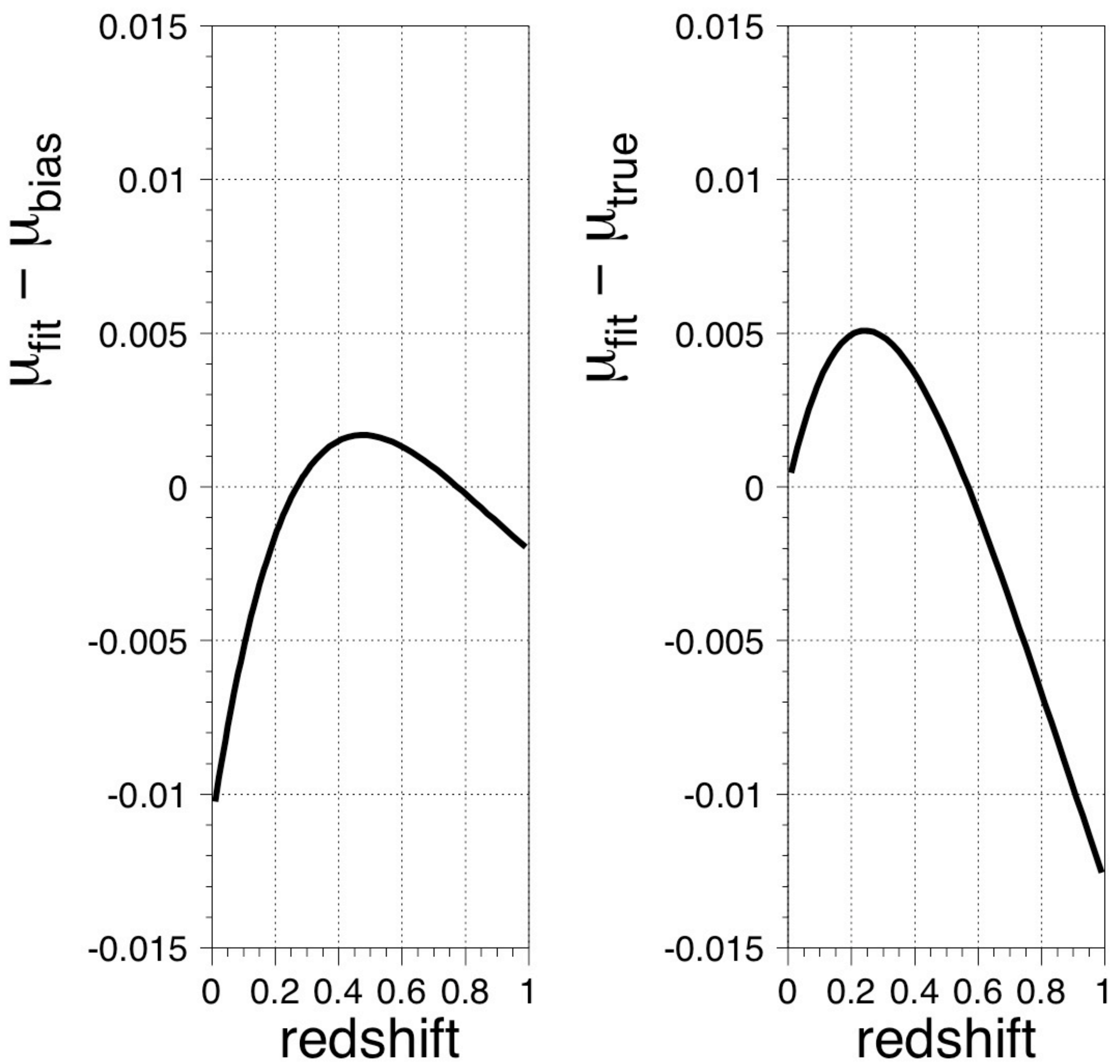


Illustration of Calibration Bias:

fit results with $\Delta\varepsilon_{spec} = 0.02$ and w-bias=0.1



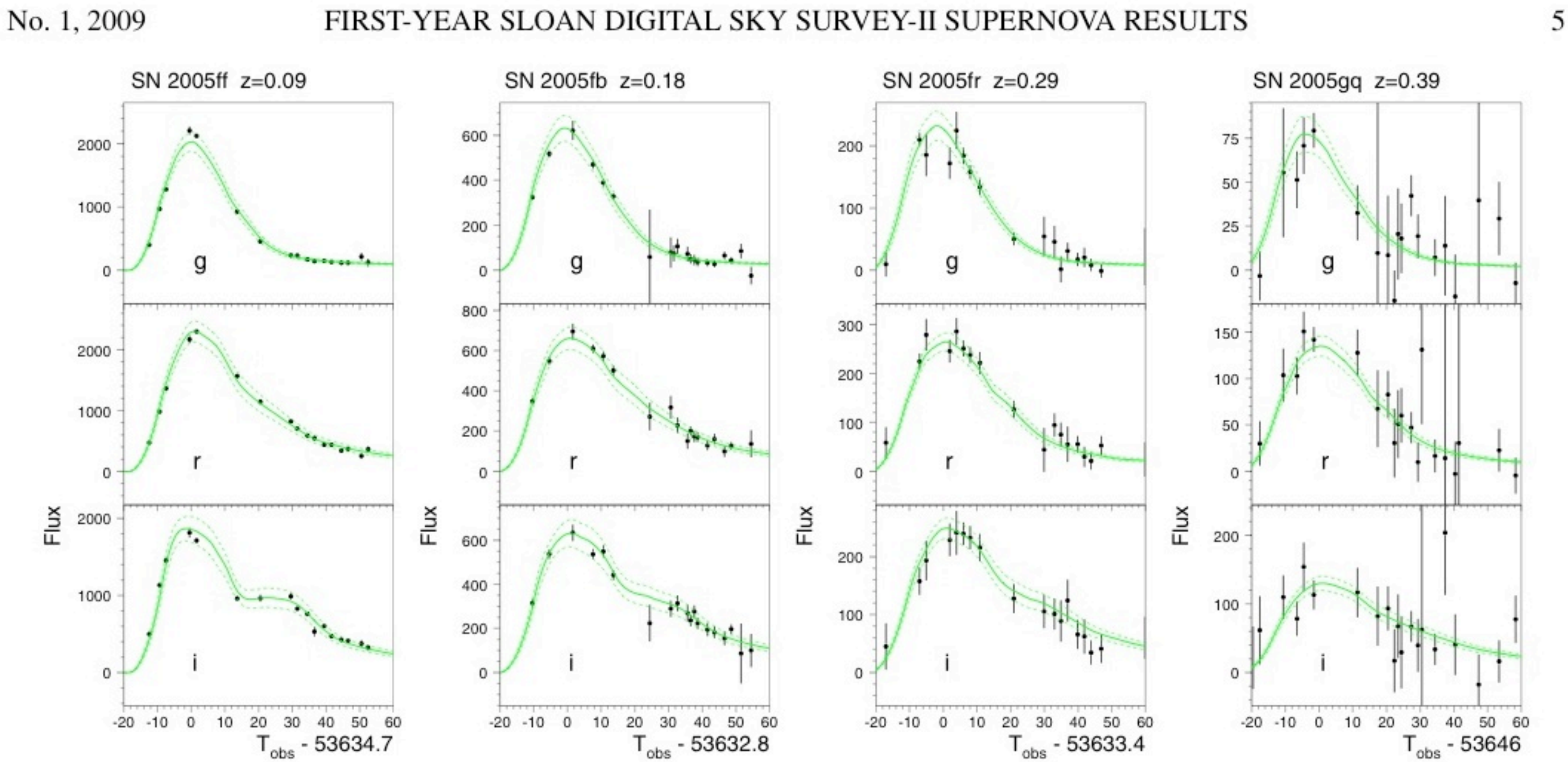
Exercise

In this fit a .018 mag μ-variation gives w-bias of 0.1 …

But earlier (Lect.1) a 0.04 mag μ-variation shifts w by the same 0.1 …

Explain this paradox.

Measuring μ: Light Curve Fitting

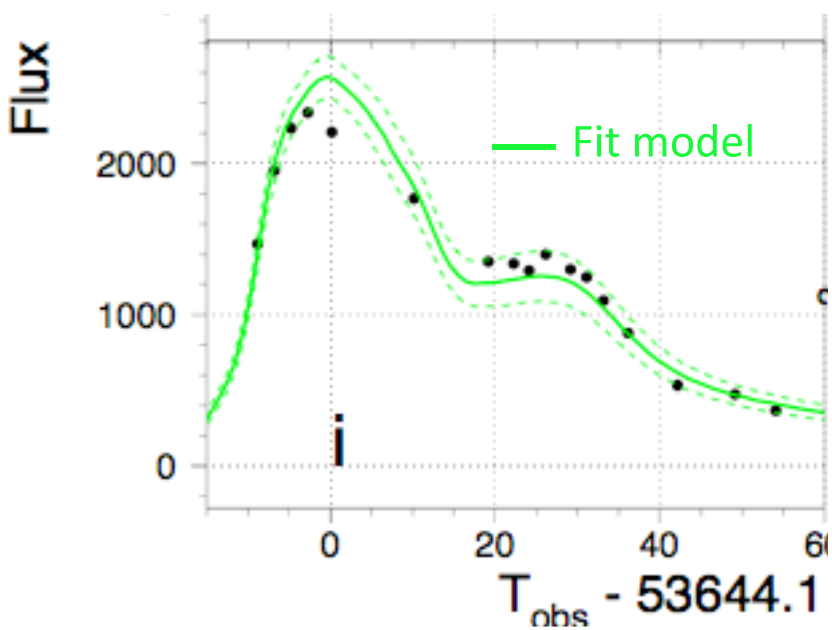


- Data

-- Result of light curve fit

Lightcurve Fit (LCFIT): Brief Overview

- Fit data to parametric model (or template) to get shape and color.
- Use shape and color to "standardize" intrinsic luminosity.



Jargon: "SN Training"

is the procedure for determining the relation between shape+color and intrinsic luminosity

Lightcurve Fit (LCFIT): Brief Overview

- Fit data to parametric model (or template) to get shape and color.
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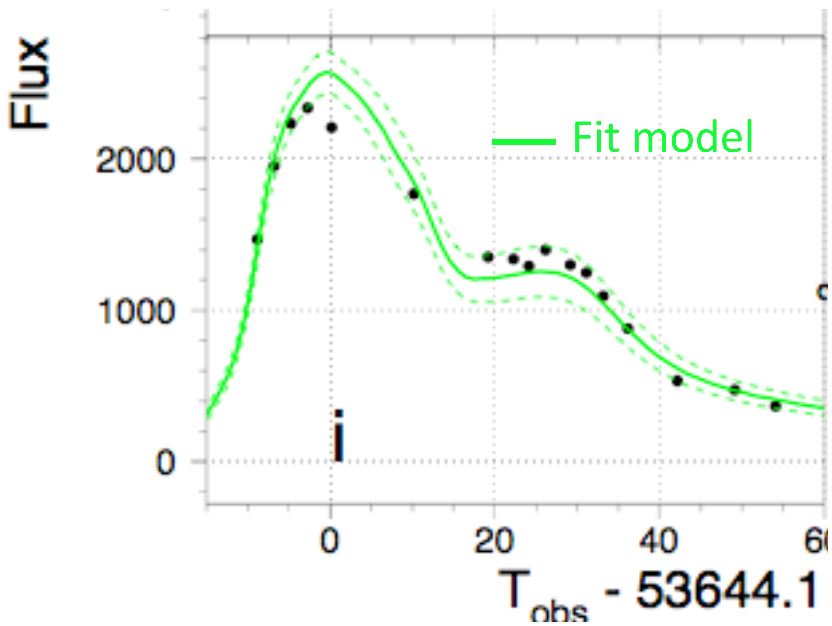

Distance-modulus (μ) = Observed mag – Intrinsic mag

LCFIT chi-squared

$$\chi^2 = \sum_{e,f} \frac{[F_{\mathrm{data}(e,f)} - F_{\mathrm{model}(e,f)}]^2}{\sigma^2_{\mathrm{data}(e,f)} + \sigma^2_{\mathrm{model}(e,f)}}$$

← Fit in flux space to avoid undefined mags when flux is small or negative.

$$\begin{aligned} e &= \text{epoch index} \\ f &= \text{filter index} \\ F_{\mathrm{model}(e,f)} &= 10^{0.4m_{(e,f)}} \end{aligned}$$

← Compute model-mag and convert to model flux

Exercise 6: qualitatively explain what happens in a LCFIT If epochs with low signal-to-noise ratio are excluded from the fit; i.e., fitting in magnitudes instead of flux.

LCFITs

- There are two general strategies for LCFITs:

1) rest-frame model mags + K-corrections:
   mlcs2k2 (Jha,Riess,Kirshner ApJ 659, 122 2007)
   SNooPy optical+IR, (Burns et al., AJ 141, 19, 2011)
2) rest-frame spectral model :
   SALT2 (Guy et. al., A&A 466, 11, 2007)

LCFIT Model with Rest-Frame Mags

$$\left.\begin{aligned} m_{(e,f_1)} &= (\bar{m}_B^{\rm rest} + \Delta m_B^s + \Delta m_B^c) + K_{Bf_1} + \mu + X_{\rm MW}^{f_1} \\ m_{(e,f_2)} &= (\bar{m}_V^{\rm rest} + \Delta m_V^s + \Delta m_V^c) + K_{Vf_2} + \mu + X_{\rm MW}^{f_2} \\ m_{(e,f_3)} &= (\bar{m}_R^{\rm rest} + \Delta m_R^s + \Delta m_R^c) + K_{Rf_3} + \mu + X_{\rm MW}^{f_3} \end{aligned}\right\}_e$$

↑ ...

model mag for obs-frame in filter f

Lots of terms ....
let's go through them quickly,
them again slowly.

LCFIT Model with Rest-Frame Mags

$$\left.\begin{aligned} m_{(e,f_1)} &= (\bar{m}_B^{\text{rest}} + \Delta m_B^s + \Delta m_B^c) + K_{Bf_1} + \mu + X_{\text{MW}}^{f_1} \\ m_{(e,f_2)} &= (\bar{m}_V^{\text{rest}} + \Delta m_V^s + \Delta m_V^c) + K_{Vf_2} + \mu + X_{\text{MW}}^{f_2} \\ m_{(e,f_3)} &= (\bar{m}_R^{\text{rest}} + \Delta m_R^s + \Delta m_R^c) + K_{Rf_3} + \mu + X_{\text{MW}}^{f_3} \end{aligned}\right\}_e$$

↑ …

model mag for obs-frame in filter f

↑ Avg rest-frame mag

↑ Stretch corr: $\alpha_{e,X} \times s$ (X=B,V,R)

↑ Color Corr: $A_V \times CL(\lambda, R_B)$ c x $CL(\lambda, \beta_B)$

LCFIT Model with Rest-Frame Mags

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\end{aligned}\right\}_e$$

...

- model mag for obs-frame in filter f
- Avg rest-frame mag
- Stretch corr: $\alpha_{e,X} \times s$ (X=B,V,R)
- Color Corr: $A_V \times CL(\lambda, R_B)$ c x $CL(\lambda, \beta_B)$
- K-cor with color-warped spectrum
- Distance modulus
- Galactic Extinction (Milky Way)

LCFIT Model with Rest-Frame Mags

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...

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- Color Corr: $A_V \times CL(\lambda,$ … c x CL($\lambda,$ …
- K-cor with color-
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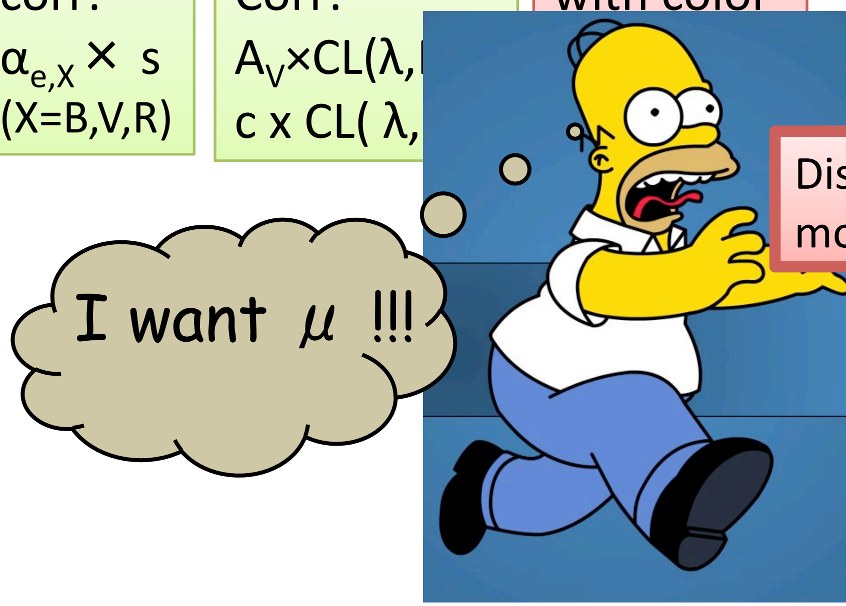

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...

- model mag for obs-frame in filter f
- Avg rest-frame mag
- Stretch corr: $\alpha_{e,X} \times s$ (X=B,V,R)
- Color Corr: $A_V \times CL(\lambda, R_B)$ / $c \times CL(\lambda, \beta_B)$
- K-cor with color-warped spectrum
- Distance modulus
- Galactic Extinction (Milky Way)

	Stretch	Color	K-cor	Distance	Galactic
Training params (fixed):	$\alpha_{e,X}$	$CL(\lambda, R_B)$	data+calc		Dust Map
Fit params for each SN:	s	A_V or c		μ	

LCFIT Model with Rest-Frame Mags

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↑ ...

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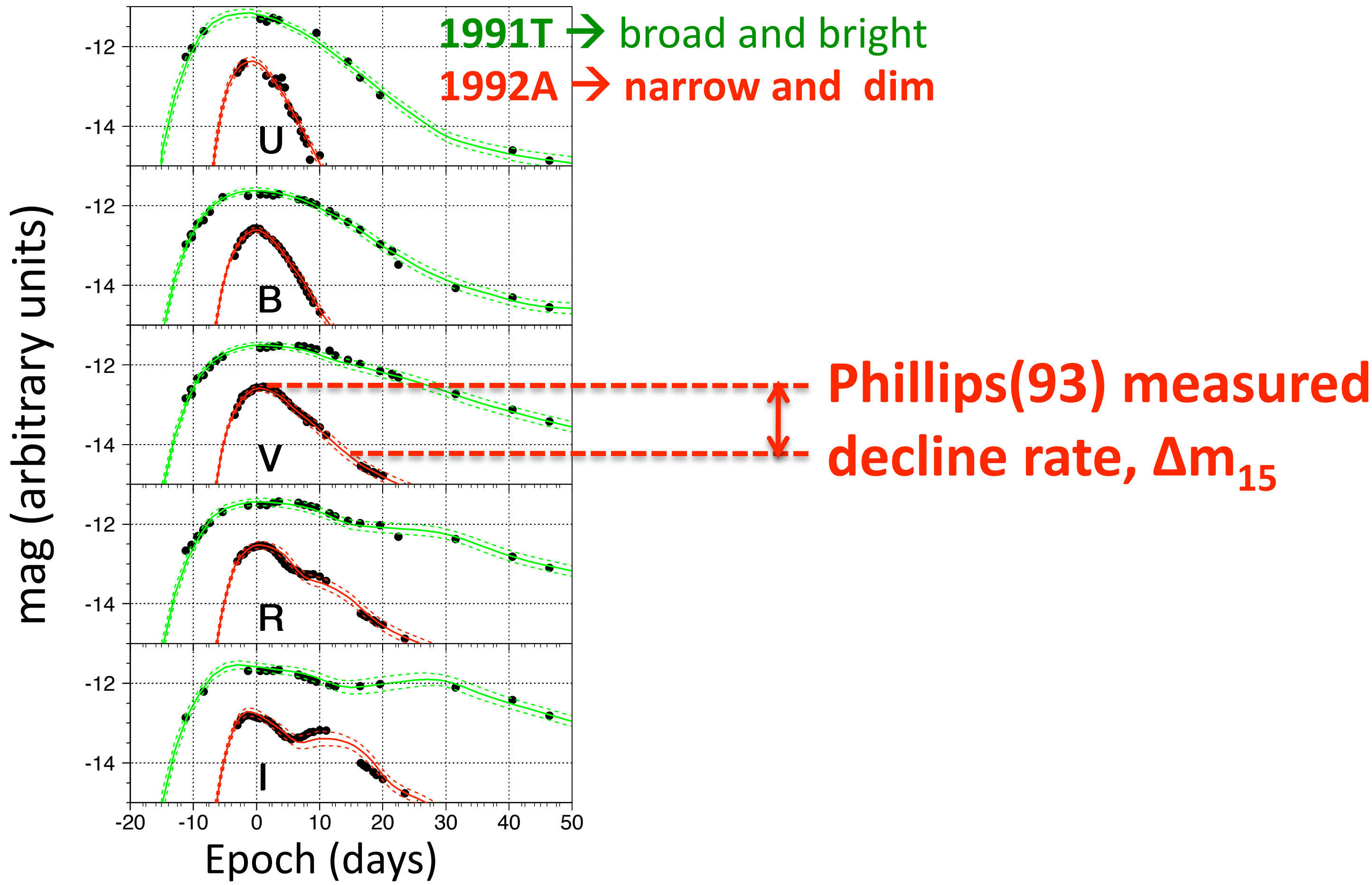
Lots of terms ....
let's go through them again, slowly.

LCFIT Model with Rest-Frame Mags

$$m_{(e,f_1)} = (\bar{m}_B^{\rm rest} + \Delta m_B^s + \Delta m_B^c) + K_{Bf_1} + \mu + X_{\rm MW}^{f_1}$$

Describes "shape":
broader is brighter.

Stretch corr



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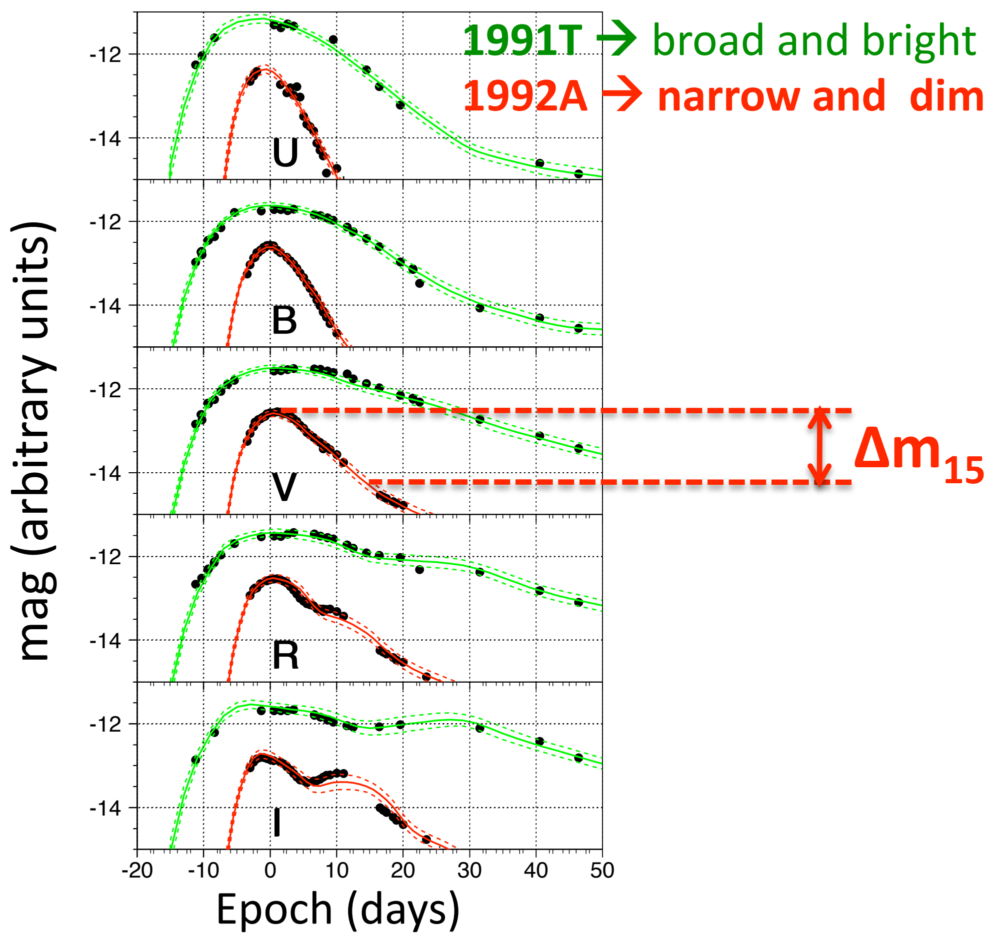


M. Phillips, ApJ 413, 105 (1993)

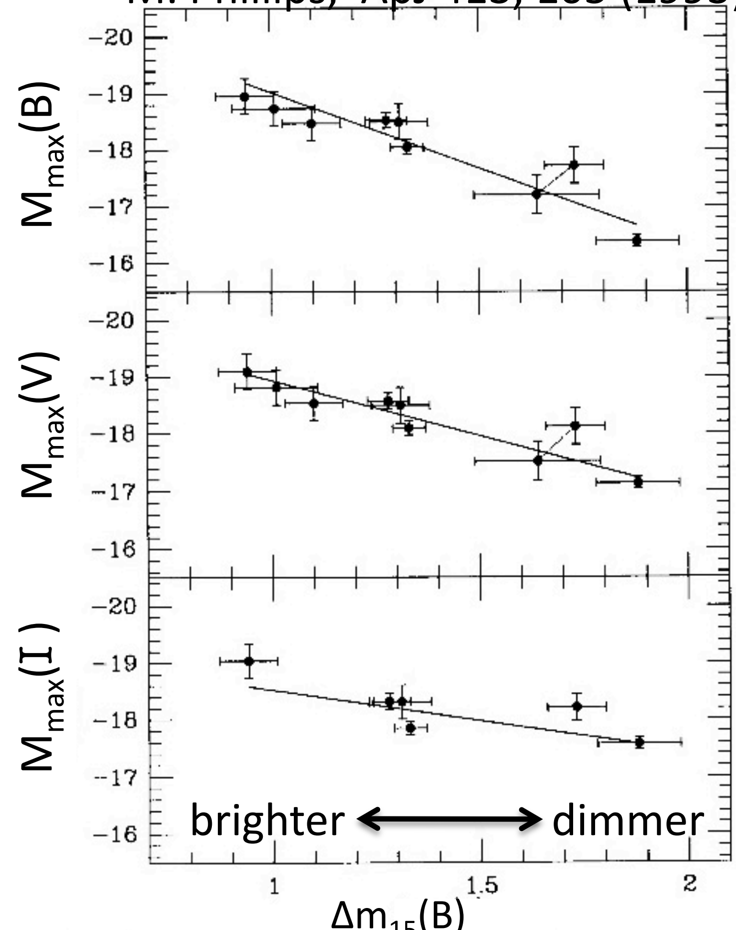


FIG. 1.—Decline rate–peak luminosity relation for the nine best-observed SN Ia's. Absolute magnitudes in *B*, *V*, and *I* are plotted vs. $\Delta m_{15}(B)$, which measures the amount in magnitudes that the *B* light curve drops during the first 15 days following maximum.

LCFIT Model with Rest-Frame Mags

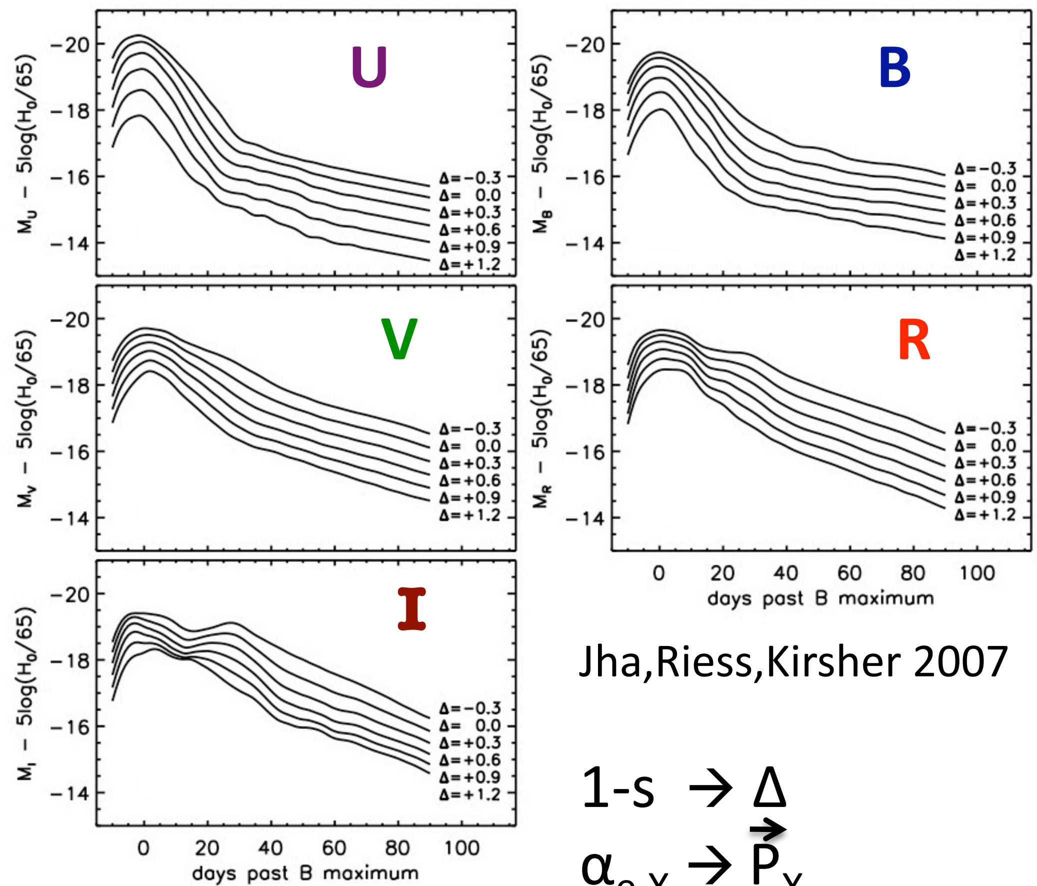
$$m_{(e,f_1)} = (\bar{m}_B^{\text{rest}} + \Delta m_B^s + \Delta m_B^c) + K_{Bf_1} + \mu + X_{\text{MW}}^{f_1}$$

Stretch corr: $\alpha_{e,X} \times s$

Describes "shape" or "stretch" (s): broader is brighter.

Beware: template-stretch works OK in **U**,**B**,**V** but not in redder (R,I) bands because of 2nd bump.

Instead of template-stretch, $\alpha_{e,F}$ depend on epoch and filter; they are determined from training on nearby SNe Ia.



Jha,Riess,Kirsher 2007

$1\text{-}s \rightarrow \Delta$

$\alpha_{e,X} \rightarrow \vec{P}_X$

Fig. 7.— MLCS2k2 intrinsic *UBVRI* light curve templates, $\vec{M}_X = \vec{M}_X^0 + \vec{P}_X\Delta + \vec{Q}_X\Delta^2$, shown a range of luminosity and light-curve shape from $\Delta = -0.3$ (brighter) to $\Delta = +1.2$ (fainter).

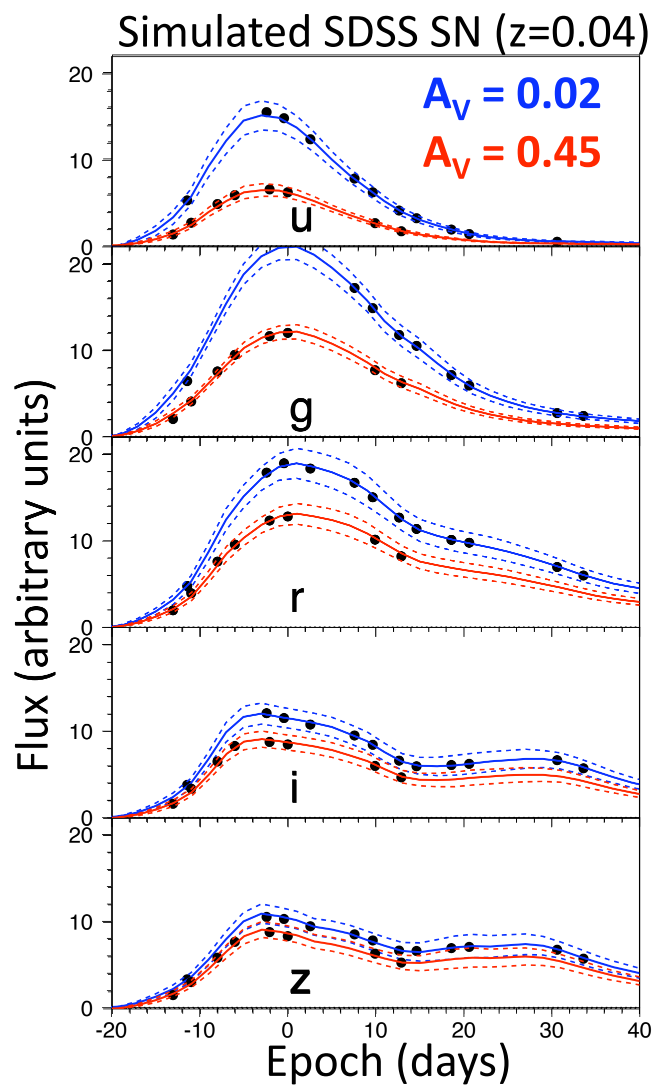
LCFIT Model with Rest-Frame Mags

$$m_{(e,f_1)} = (\bar{m}_B^{\rm rest} + \Delta m_B^s + \Delta m_B^c) + K_{Bf_1} + \mu + X_{\rm MW}^{f_1}$$

Color Corr:
$A_V \times CL(\lambda, R_B)$
$c \times CL(\lambda, \beta_B)$

Increasing c,A_V --> redder and dimmer

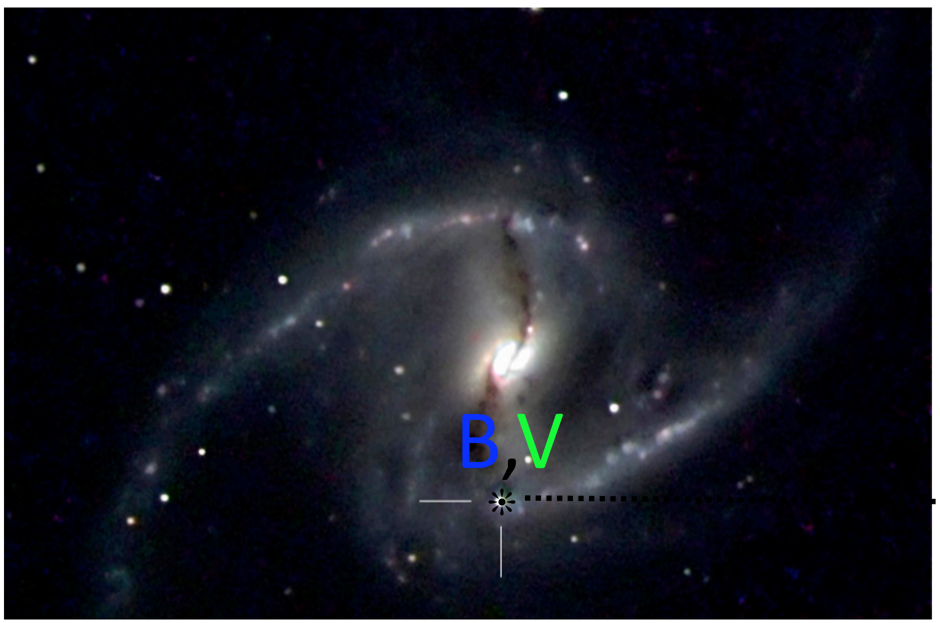
Decreasing c, A_V --> bluer and brighter.



Dust Law: $R_V = A_V/E(B-V)$ and $CL(\lambda)$ from

Cardelli, Clayton, Mathis ApJ, 345, 245 (1989)

Blue light scatters more →
extincted objects appear redenned.



$B+\Delta B$, $V+\Delta V$

earth

$$E(B-V) = \Delta B - \Delta V$$

LCFIT Model with Rest-Frame Mags

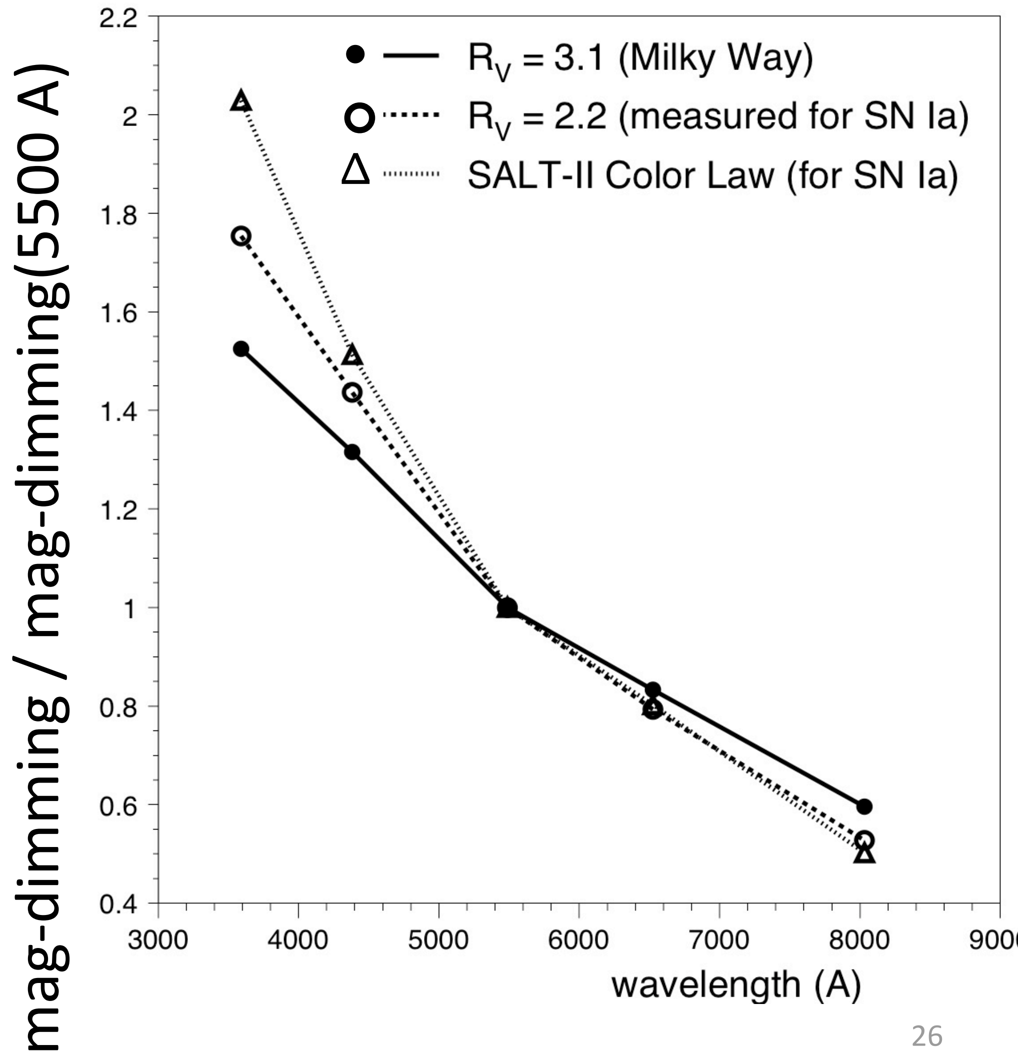
$$m_{(e,f_1)} = (\bar{m}_B^{\mathrm{rest}} + \Delta m_B^s + \Delta m_B^c) + K_{Bf_1} + \mu + X_{\mathrm{MW}}^{f_1}$$

Color Corr:
$A_V \times CL(\lambda, R_B)$
$c \times CL(\lambda, \beta_B)$

Original assumption for mlcs:
$A_V > 0$ is from host-galaxy extinction.
$CL(\lambda)$ assumed to be the same as Galactic color law with $R_V = 3.1$ (Cardelli,Clayton,Mathis 1989)

Relaxed assumption in SALT-II.
$CL(\lambda)$ determined from SNIa training and no (c>0) prior.

Different $CL(\lambda)$ choice makes notable difference !



LCFIT Model with Rest-Frame Mags

$$m_{(e,f_1)} = (\bar{m}_B^{\rm rest} + \Delta m_B^s + \Delta m_B^c) + K_{Bf_1} + \mu + X_{\rm MW}^{f_1}$$

K-cor with color-warped spectrum

K-correction ≈
−2.5 × log[SEDFlux(obs-f_1) / SEDflux(rest-B)]

Determined from spectral template that is WARPED such that **synthetic colors** from WARPED spectrum match the **model colors**.

$$\begin{aligned} m_B^{\rm synth} - m_V^{\rm synth} &= (\bar{m}_B^{\rm rest} + \Delta m_B^s + \Delta m_B^c) \\ &- (\bar{m}_V^{\rm rest} + \Delta m_V^s + \Delta m_V^c) \\ m_V^{\rm synth} - m_R^{\rm synth} &= (\bar{m}_V^{\rm rest} + \Delta m_V^s + \Delta m_V^c) \\ &- (\bar{m}_R^{\rm rest} + \Delta m_R^s + \Delta m_R^c) \\ &\ldots \end{aligned}$$

LCFIT Model with Rest-Frame Mags

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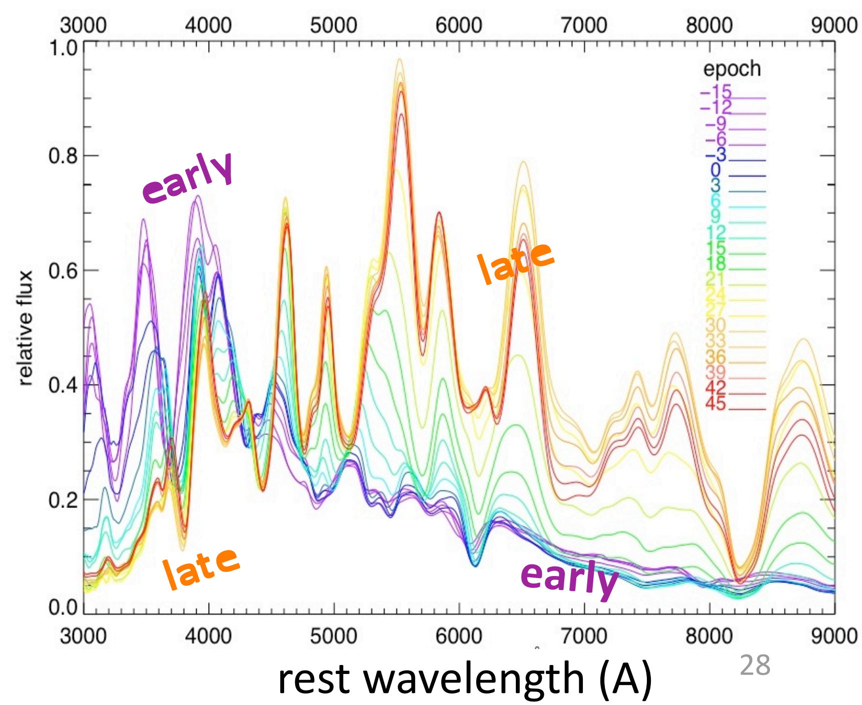
Hsiao et. al., ApJ 663 , 1187 (2007)



LCFIT Model with Rest-Frame Mags

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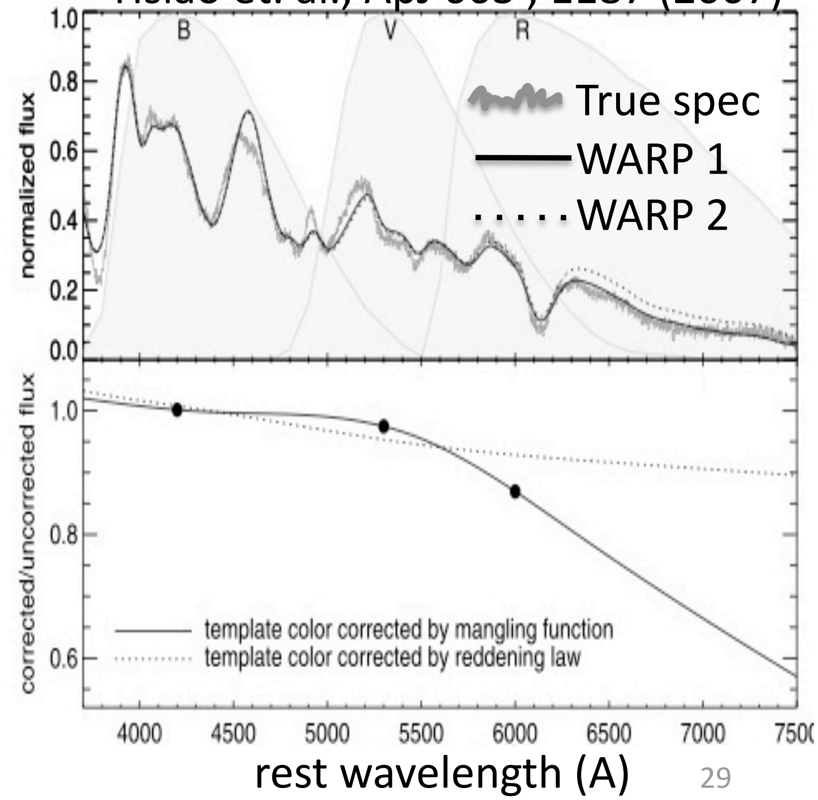
Hsiao et. al., ApJ 663 , 1187 (2007)



LCFIT Model with Rest-Frame Mags

$$m_{(e,f_1)} = (\bar{m}_B^{\text{rest}} + \Delta m_B^s + \Delta m_B^c) + K_{Bf_1} + \mu + X_{\text{MW}}^{f_1}$$

K-cor with color-warped spectrum

K-correction ≈
−2.5 × log[SEDFlux(obs-f_1) / SEDflux(rest-B)]

Determined from spectral template that is WARPED such that **synthetic colors** from WARPED spectrum match the **model colors**.

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Note:
during the LCFIT minimization, SED WARP is done for each fitting step in which s & c are varied.
➔ can be CPU intensive

LCFIT Model with Rest-Frame Mags

$$m_{(e,f_1)} = (\bar{m}_B^{\rm rest} + \Delta m_B^s + \Delta m_B^c) + K_{Bf_1} + \mu + X_{\rm MW}^{f_1}$$

K-cor with color-warped spectrum

Nugent, Kim, Perlmutter, PASP 114, 803 (2002) : see appendix

$$K_{Bf_1}^{\rm energy} = -2.5\log_{10}\left[\frac{\int f_\lambda(\lambda/(1+z))T_{f_1}(\lambda)d\lambda}{\int (1+z)f_\lambda(\lambda)T_B(\lambda)d\lambda}\right] -2.5\log_{10}\left[\frac{\int \mathcal{Z}_B(\lambda)T_B(\lambda)d\lambda}{\int \mathcal{Z}_{f_1}(\lambda)T_{f_1}(\lambda)d\lambda}\right]$$

- $f_\lambda(\lambda)$ = **WARPED** SN SED ($dE/d\lambda$).
- $\mathcal{Z}(\lambda)$ = SED of reference (AB,Vega,BD17 ...)
- $T_X(\lambda)$ = energy-transmission vs. λ for filter X.

Exercise 

what is the K-corr formula for photon-count filter transmissions ,

$K_{\rm Bf1}^{\rm count}$

SN Model-Metamorphosis (mag-model → spectral model)

$$m_{(e,f)} = (\bar{m}_B^{\rm rest} + \Delta m_B^s + \Delta m_B^c) + K_{Bf} + \mu + X_{\rm MW}^f$$

$$\Delta m_B^s = -\alpha_{e,B}(s-1)$$
$$\Delta m_B^c = \mathrm{CL}(\lambda) \times \mathbf{c}$$

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$$\Delta m_B^c = \text{CL}(\lambda) \times \text{c} \longrightarrow (\widehat{\text{CL}}(\lambda) + \beta)\text{c}$$

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$$\begin{aligned} \Delta m_B^s &= -\alpha_{e,B}(s-1) \longrightarrow -(\hat{\alpha}_{e,B} + \alpha)(s-1) \\ \Delta m_B^c &= {\rm CL}(\lambda) \times {\rm c} \quad \longrightarrow (\widehat{\rm CL}(\lambda) + \beta){\rm c} \end{aligned}$$

$\downarrow$ (after rearranging terms)

$$\begin{aligned} m_{(e,f)} &= \left[\bar{m}_B^{\rm rest} - \hat{\alpha}_{e,B}(s-1) + \widehat{\rm CL}(\lambda) \times c + K_{Bf}\right] \\ &+ [\mu - \alpha(s-1) + \beta c] + X_{\rm MW}^f \end{aligned}$$

- $\hat{\alpha}_{e,B}$ are shape parameters for B band.
- $\widehat{\rm CL}(\lambda)$ describes λ-dependence.
- α, β are global mag-correction parameters. (global $\rightarrow$ all epochs and λ)

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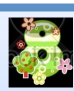
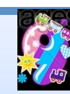
Question  : why does K_{Bf} Depend only on the terms inside the first [ ] ?

Question  : since α,β > 0, explain the (−/+) sign of these terms.

Transform observed mag to flux: $F_{e,f} \sim 10^{-0.4m_{(e,f)}}$

$$F_{e,f} = A^{f}_{MW} x_0 10^{-0.4(\bar{m}^{\mathrm{rest}}_{B} - \hat{\alpha}_{e,B}(s-1) + c\mathrm{CL}(\lambda) + \mathrm{K_{Bf}})}$$

- $x_0 \equiv 10^{-0.4(\mu - \alpha(s-1) + \beta c)}$
- A^{f}_{MW} is fraction of light passing through our Galaxy.

e = epoch

f = filter

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$$F_{e,f} = A^f_{MW} x_0 10^{-0.4(\bar{m}_B^{\rm rest} - \hat{\alpha}_{e,B}(s-1) + c{\rm CL}(\lambda) + {\rm K_{Bf}})}$$

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f = filter

Exercise: 10

using K_{Bf} in counts and $A^f_{MW} = 1$, show that

$$F_{e,f} = x_0(1+z) \int d\lambda \, [\lambda f_\lambda(e,\lambda) T_f(\lambda(1+z))]$$
$$\times \left\{ \frac{10^{-0.4[\bar{m}_B^{\rm rest} - \hat{\alpha}_{e,B}(s-1) + c{\rm CL}(\lambda)]}}{\int d\lambda[\lambda f_\lambda(e,\lambda) T_B(\lambda)]} \right\} \times \hat{F}_{(e,f,B)}$$
$$= x_0(1+z) \hat{F}_{(e,f,B)} \int d\lambda \, [\lambda f_\lambda(e,\lambda) T_f(\lambda(1+z))]$$

Exercise: 11

show that $\hat{F}_{(e,f,B)}$ does not depend on SN properties.

Exercise:

explain why the term in {} drops out.

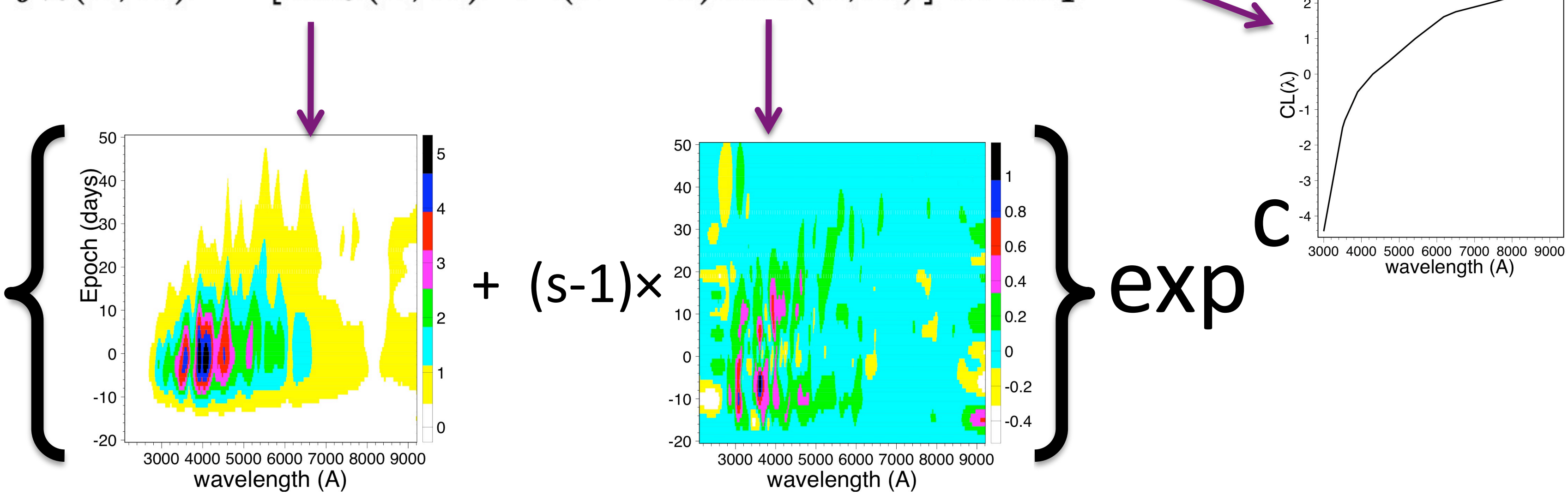
SALT-II Model

Leaving out the $\hat{F}_{(e,f,B)}$-zeropoint term,

$$F_{e,f} = x_0(1+z)\int d\lambda\,[\lambda f_\lambda(e,\lambda)T_f(\lambda(1+z))]\ .$$

The SALT-II model (Guy 2007, 2010) is described by a spectral time-series,

$$f_\lambda(e,\lambda) = [M_0(e,\lambda) + (s-1)M_1(e,\lambda)] \times \exp^{c\mathrm{CL}(\lambda)}$$



Distances from SALT-II

$$x_0 \equiv 10^{-0.4(\mu - \alpha(s-1) + \beta c)}$$

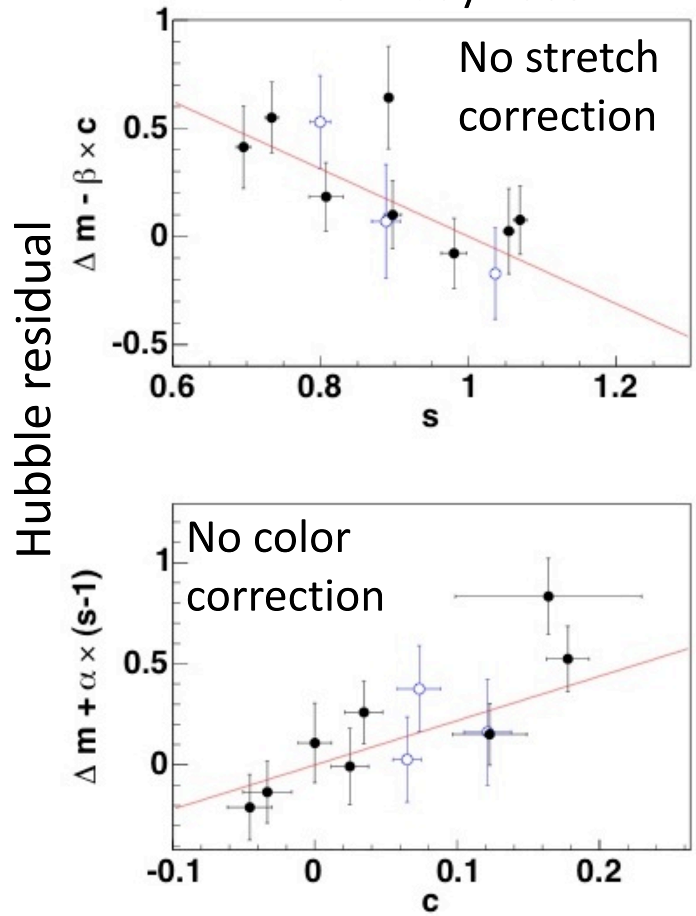
For each SN we fit for $\mathbf{x_0, s, c}$.

$$\mu = -2.5\log(x_0) + \alpha(s-1) - \beta c$$

Original method: simultaneous Hubble-fit for cosmological parameters, and α and β.

Disadvantage: distances are tied to best-fit cosmology parameters.

from Guy 2005



Distances from SALT-II

$$\underline{x_0} \equiv 10^{-0.4(\mu - \alpha(\underline{s}-1)+\beta\underline{c})}$$

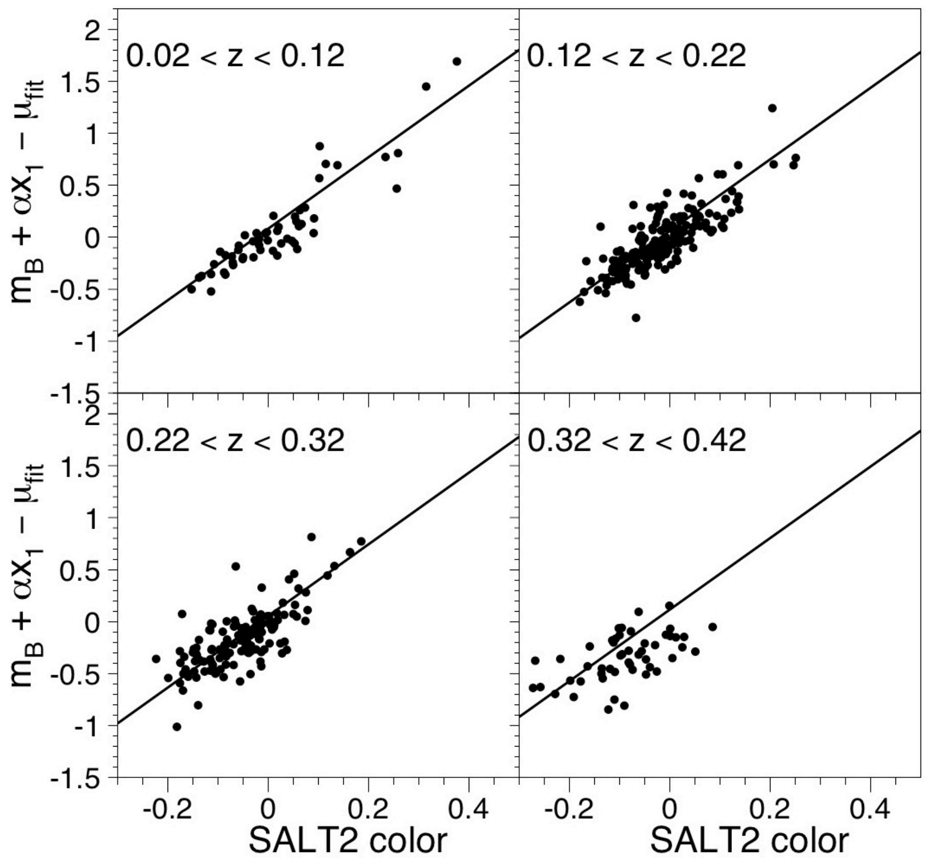
Newer method
(Marriner et al, ApJ 740, 72, 2011)

Basic idea:
fit $m_z + \beta c$ in **redshift bins**.
Require same β in each z-bin,
but allow different offsets m_z .
Do same for α. Discard the m_z
as nuisance params.

$$\mu = m_B + \alpha(s\text{-}1) - \beta c$$

$$m_B = -2.5\log_{10}(x_0)$$

SDSS-II data



Comparison of Lightcurve Fit Methods

property	**MLCS2k2 (Jha 2007)**	**SALT2 (Guy07)**
rest-frame model	U,B,V,R,I mag vs. t	Spectral components vs. t
color variations	Assumes host-galaxy extinction from dust	Measured in training (no assumptions)
Fitting prior	Extinction $A_V > 0$	none
K-correction	warp composite SN Ia spectrum to match model colors	not needed
Training	z<0.1: shape and lumin. U band problems.	All redshifts, shape only. Rest-frame UV OK from higher redshifts.
Distance μ	Fit param for each SN	After global fit for α, β

Comparison of Lightcurve Fit Methods: Comments

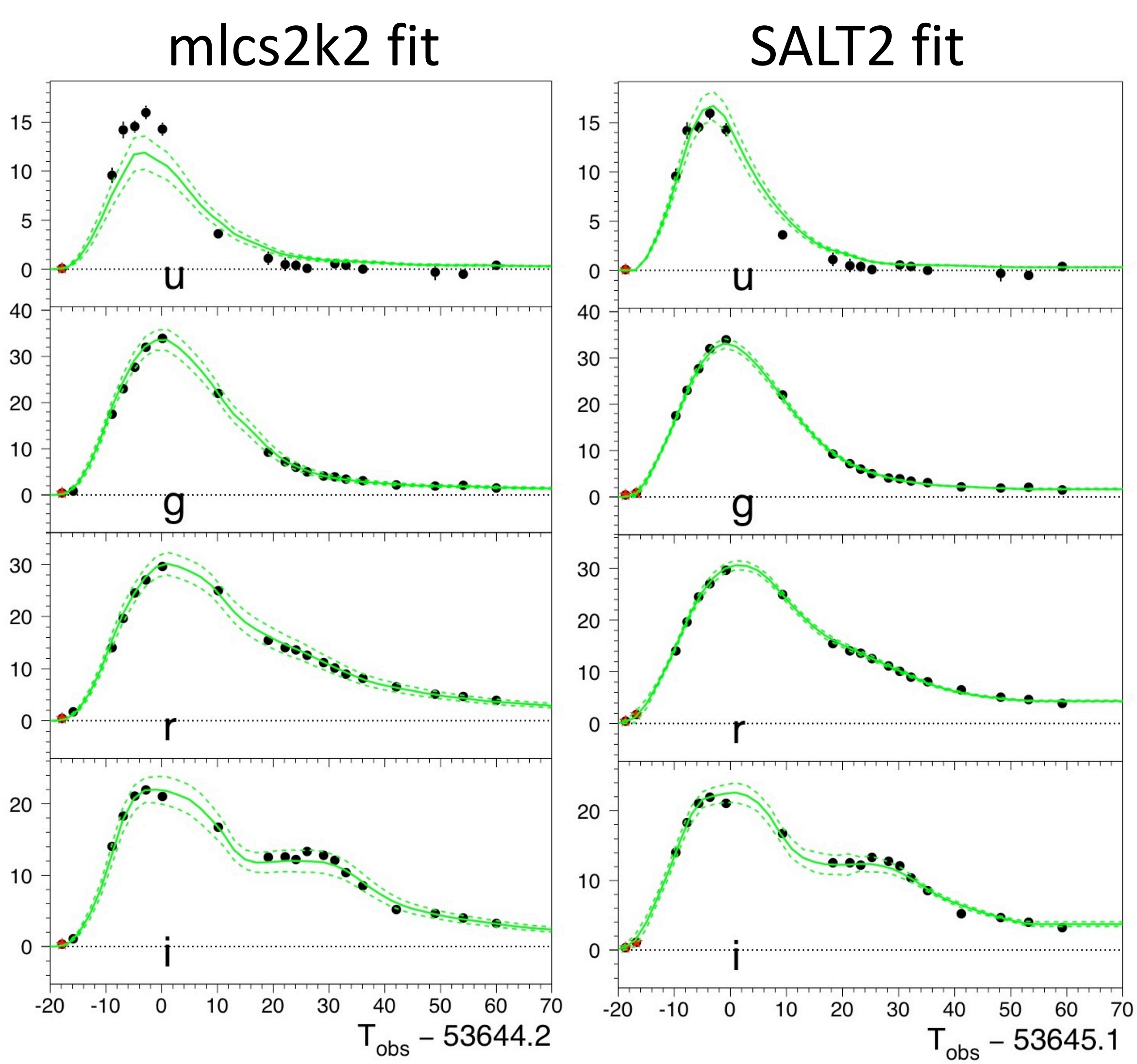
In SALT-II, α and β could be fixed by nearby SNe (like mlcs2k2), but a choice was made to determine them from a global fit.

In mlcs2k2, we could do a global fit for analogous (α,β) parameters, but a choice was made to fix them based on nearby SNe.

Several global fits have been done for R_V (analog of β), resulting in $R_V \approx 2$ (instead of 3.1 for Milky Way).

Model Difference Hard to See Visually

(except in UV … more on this later)



SDSS SN 2005gb (z=0.09) fit with both models.

PRIORS in LCFIT chi-squared

$$\chi^2 = \sum_{e,f} \frac{[\boldsymbol{F}_{\mathrm{data}(e,f)} - \boldsymbol{F}_{\mathrm{model}(e,f)}]^2}{\boldsymbol{\sigma}^2_{\mathrm{data}(e,f)} + \boldsymbol{\sigma}^2_{\mathrm{model}(e,f)}} - 2\ln P(s^{\mathrm{fit}}, A_V^{\mathrm{fit}})$$

$P(s^{\mathrm{fit}}, A_V^{\mathrm{fit}})$ = probability of observing fitted stretch and host-galaxy extinction.

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All analyses using extinction prior have made the approximation that $P \approx P(s^{\mathrm{true}},A_V^{\mathrm{true}})$ with
P = (parent population) x (MC efficiency)

Correct treatment should marginalize over $P(s^{\mathrm{true}},A_V^{\mathrm{true}})$ to estimate $P(s^{\mathrm{fit}},A_V^{\mathrm{fit}})$.

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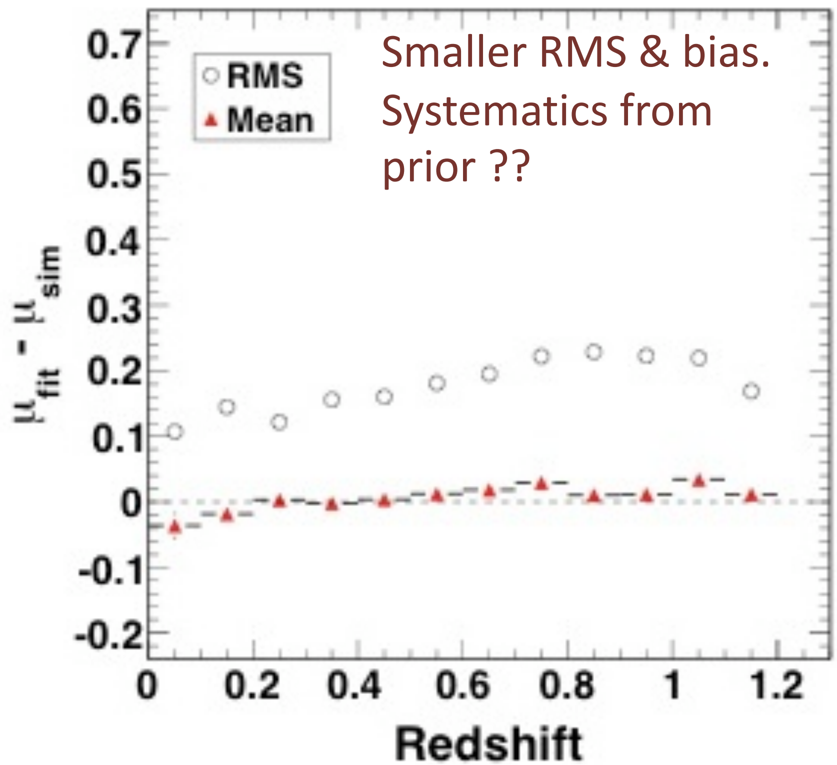
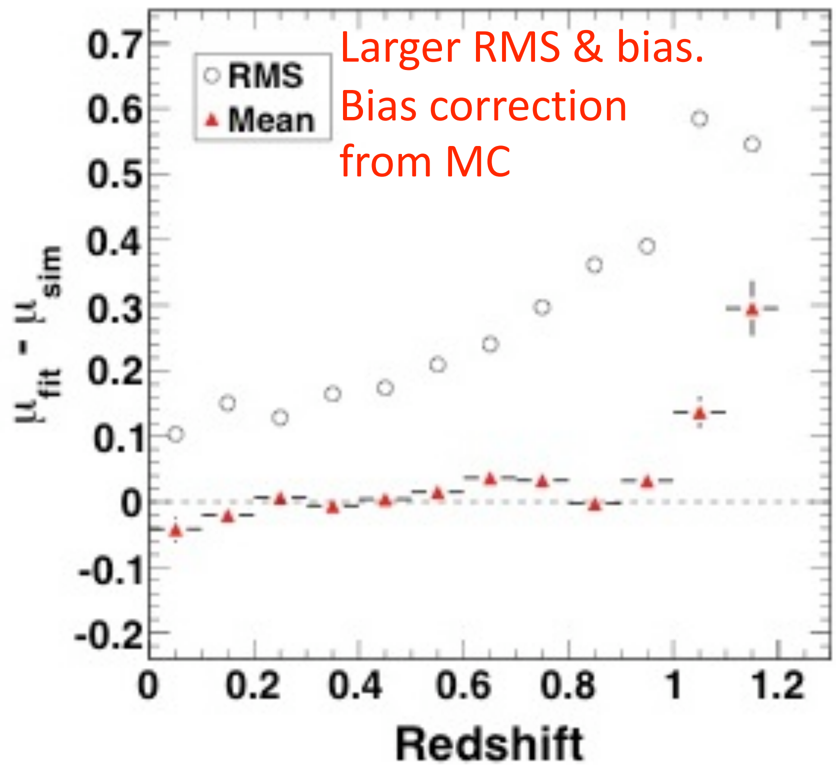
DES-SN Strategy paper (Bernstein et al, ApJ 753, 152, 2012):
Fitting simulations with mlcs2k2.

$P(A_V > 0)$ =
$\exp(-A_V / 0.33)$ x (DES efficiency) vs. $P(A_V) = 1$ (pos or neg A_V)





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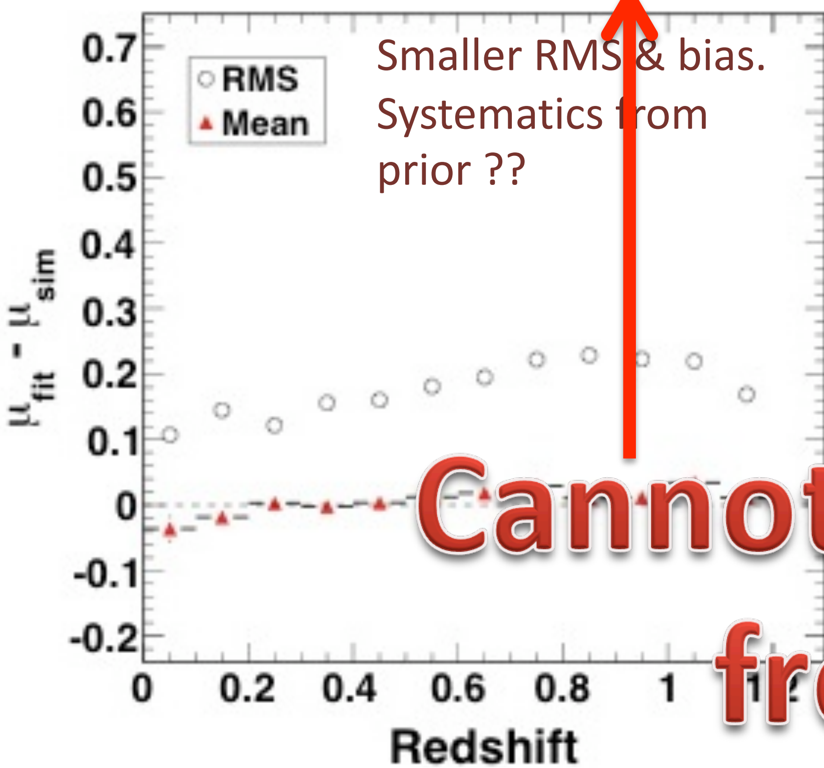
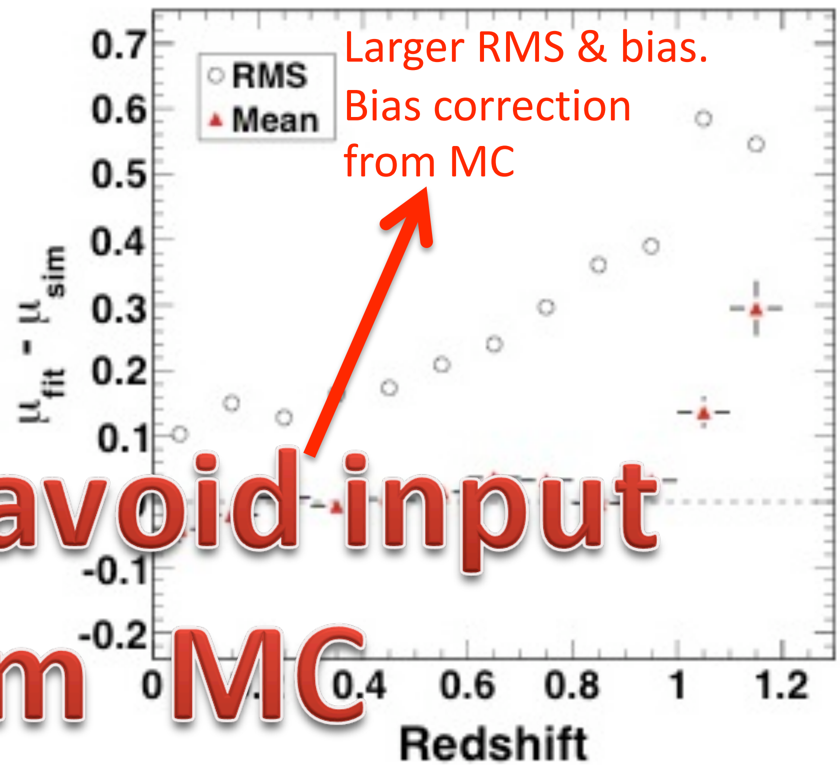




Cannot avoid input from MC

Malmquist Bias

Exercise 

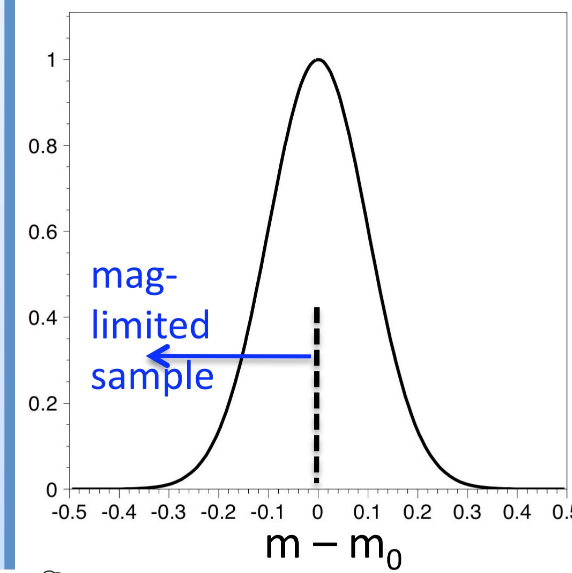
Consider ideal SN with s=1 and c=0
(no color or stretch dependence).

At fixed redshift, peak mag = $m_0 + \Delta$ where m_0 is fixed and Δ is a random "intrinsic scatter" shift from a Gaussian distribution with sigma σ_m = 0.1 mag.

If distances are computed from the bright half with $m < m_0$, show that the μ-bias is $\sigma_m (2/\pi)^{1/2}$ = 0.08 mag.

Extra credit: numerically evaluate bias for

- $m < m_0 + \sigma_m$ (deeper) -> μ-bias = $0.3\sigma_m$ = 0.03 mag
- $m > m_0 - \sigma_m$ (shallower) -> μ-bias = $1.5\sigma_m$ = 0.15 mag



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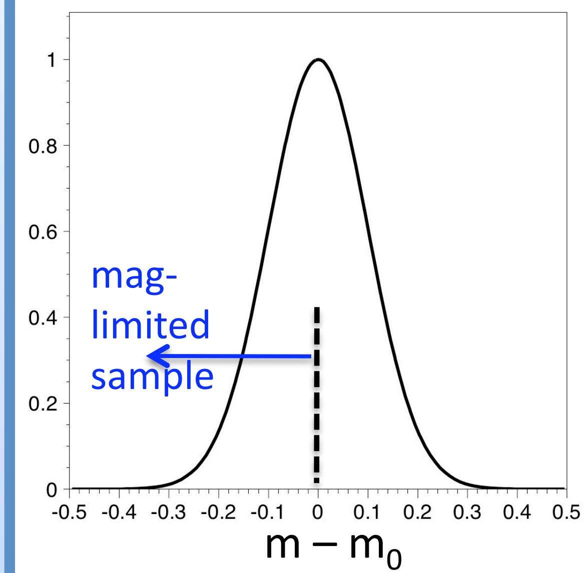

μ-bias is caused from dispersion (intrinsic + measurement error) combined with magnitude (or signal-to-noise) limit.

Malmquist Bias

In general the μ-bias cannot be numerically integrated.

The μ-bias is determined from a **Monte Carlo simulation** with a detailed treatment of the observing conditions and telescope efficiency in each passband.

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The μ-bias is determined from a **Monte Carlo simulation** with a detailed treatment of the observing conditions and telescope efficiency in each passband.

BEWARE: this bias depends on the selection criteria (spectroscopic + software cuts), and hence must be evaluated for each specific analysis.

Ideally the SN sample is defined by software cuts that are easy to model; larger uncertainties arise if SN sample is defined by unknown spectroscopic selection function.

Malmquist Bias

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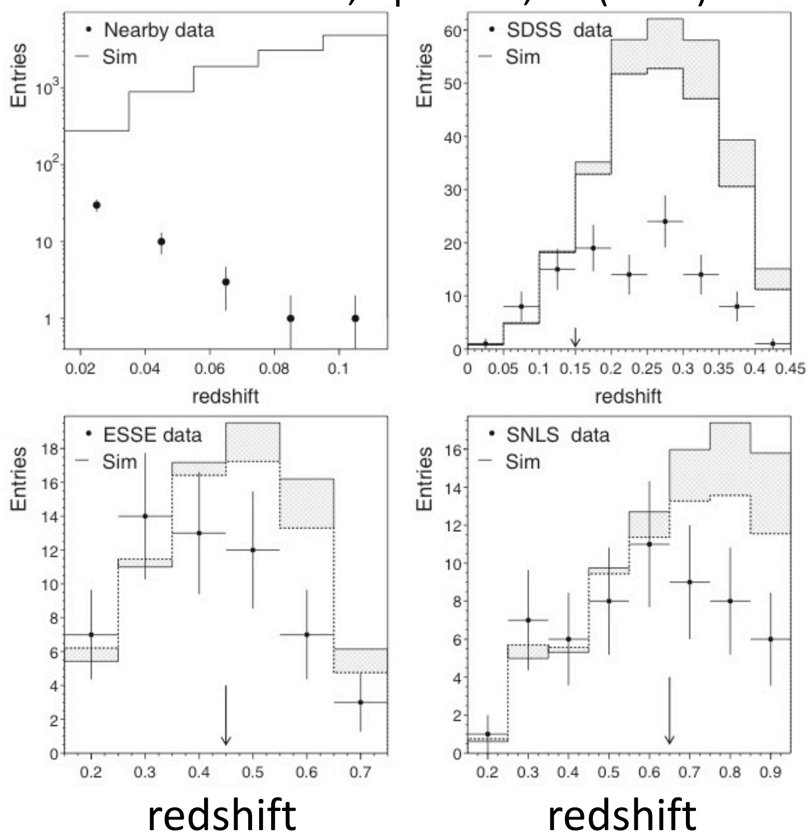
Kessler et al., ApJS 185, 32 (2009)



Each simulation (histogram) models software cuts only, ignoring spectroscopic selection (shaded area shows uncertainty).

Dots show spectroscopically-confirmed data with all selection cuts.

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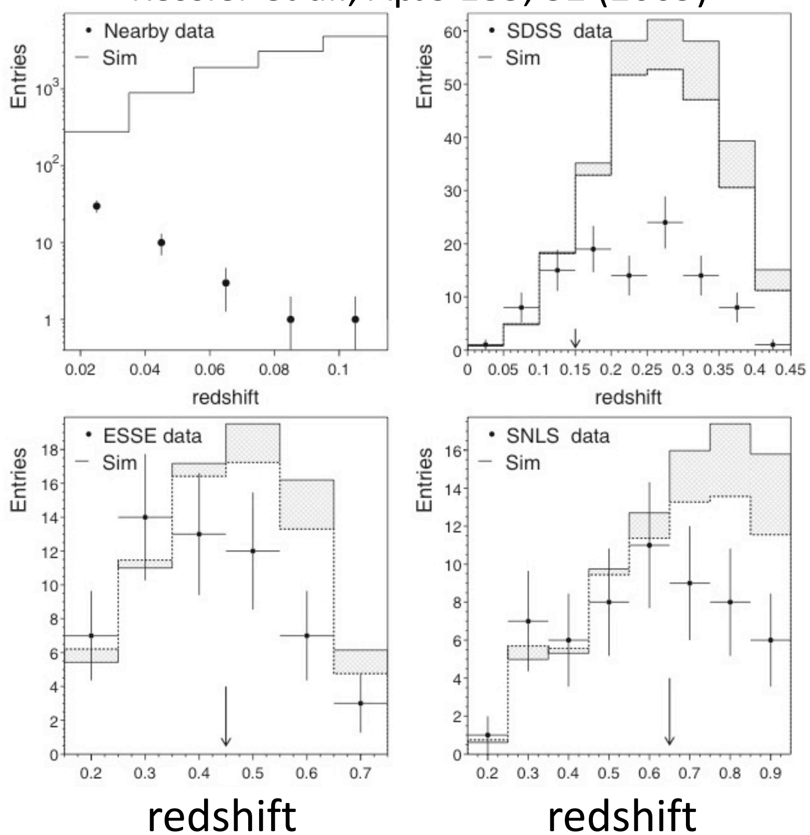

Spec-efficiency modeled by fitting trial functions to data/MC ratios. See example below for SDSS.

```
# Spectro-Efficiency for SDSS-II SNIa sample.
# IF (g-r) < 0.15
# SPECEFF = 1
# IF 0.15 < (g-r) < 0.30
# SPECEFF(r < 19) = 1
# SPECEFF(r > 19) = 1/[1 + (r-19)]^{1.120}
# IF (g-r) > 0.30
# SPECEFF(r < 19) = 1
# SPECEFF(r > 19) = 1/[1 + (r-19)]^{1.762}
```

by V. Braganca

Malmquist Bias

- How to check simulation of Malmquist bias ?
- Compare data to MC for mean color/stretch vs. redshift

Malmquist Bias

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