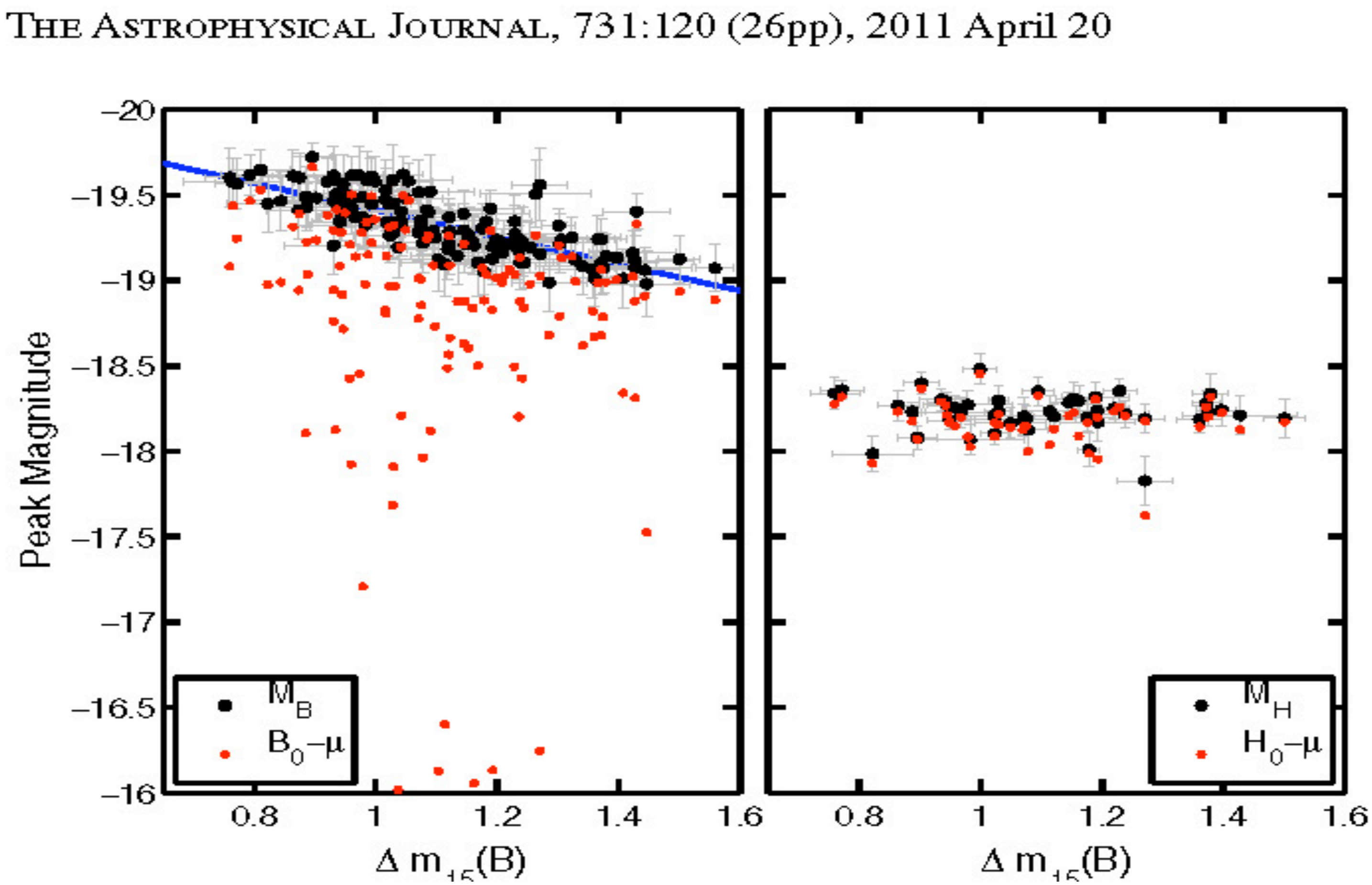
The Past, Present, and Future of Supernova Cosmology

Robert P. Kirshner

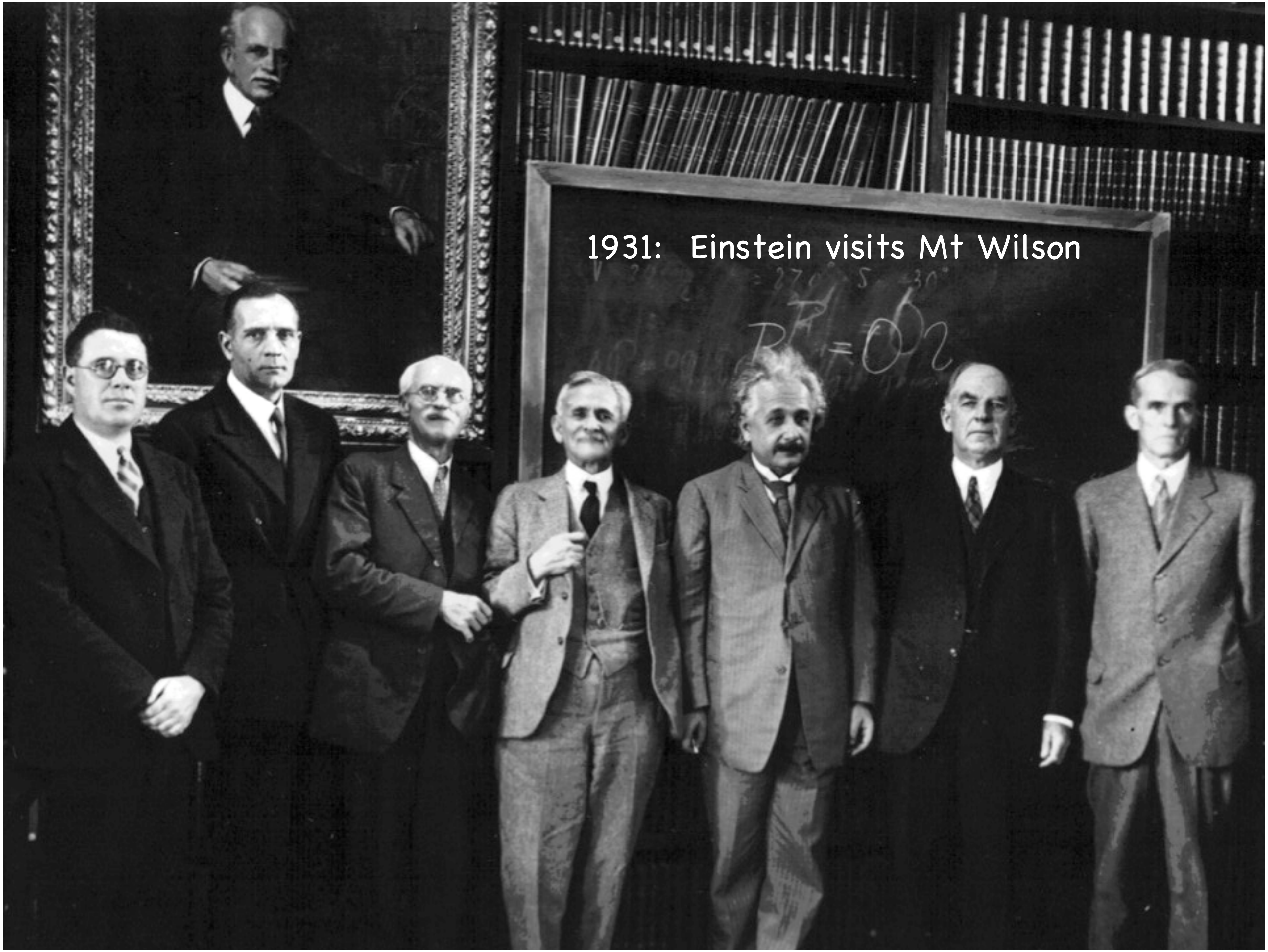
Harvard University

Most important slide

At H-band (1.6μ) SN Ia really are standard candles (and there's much less trouble with dust!)



The Past


1931: Einstein visits Mt Wilson

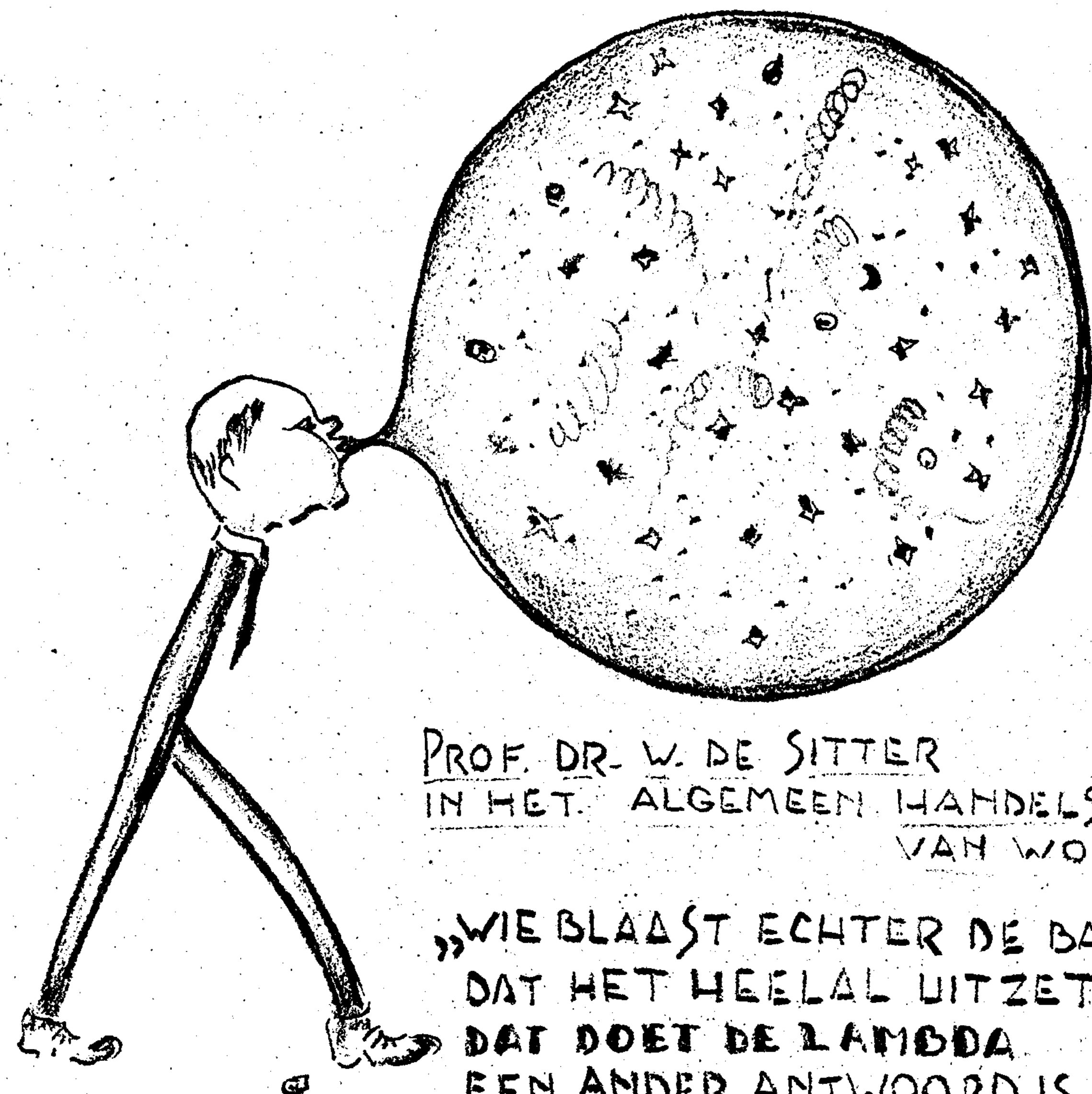
Einstein & de Sitter banish Λ in 1931

They didn’t just set Λ=0, they ***excluded*** it from their formalism!

“Einstein-de Sitter”
Flat, critically dense Universe
$\Omega = 1$

Always expanding, always **decelerating**

Λ as the source of cosmic expansion: DeSitter in 1930



PROF. DR. W. DE SITTER
IN HET ALGEMEEN HANDELSBLAD*
VAN WOENSDAG 9 JULI 1930

„WIE BLAAST ECHTER DE BAL OP? WAT MAAKT
DAT HET HEELAL UITZET, OF OPZWELT?
DAT DOET DE LAMBDA
EEN ANDER ANTWOORD IS NIET TE GEVEN"

"Who however blows up the ball? What makes the Universe expand or swell up?
That is done by the Lambda.
An other answer cannot be given."

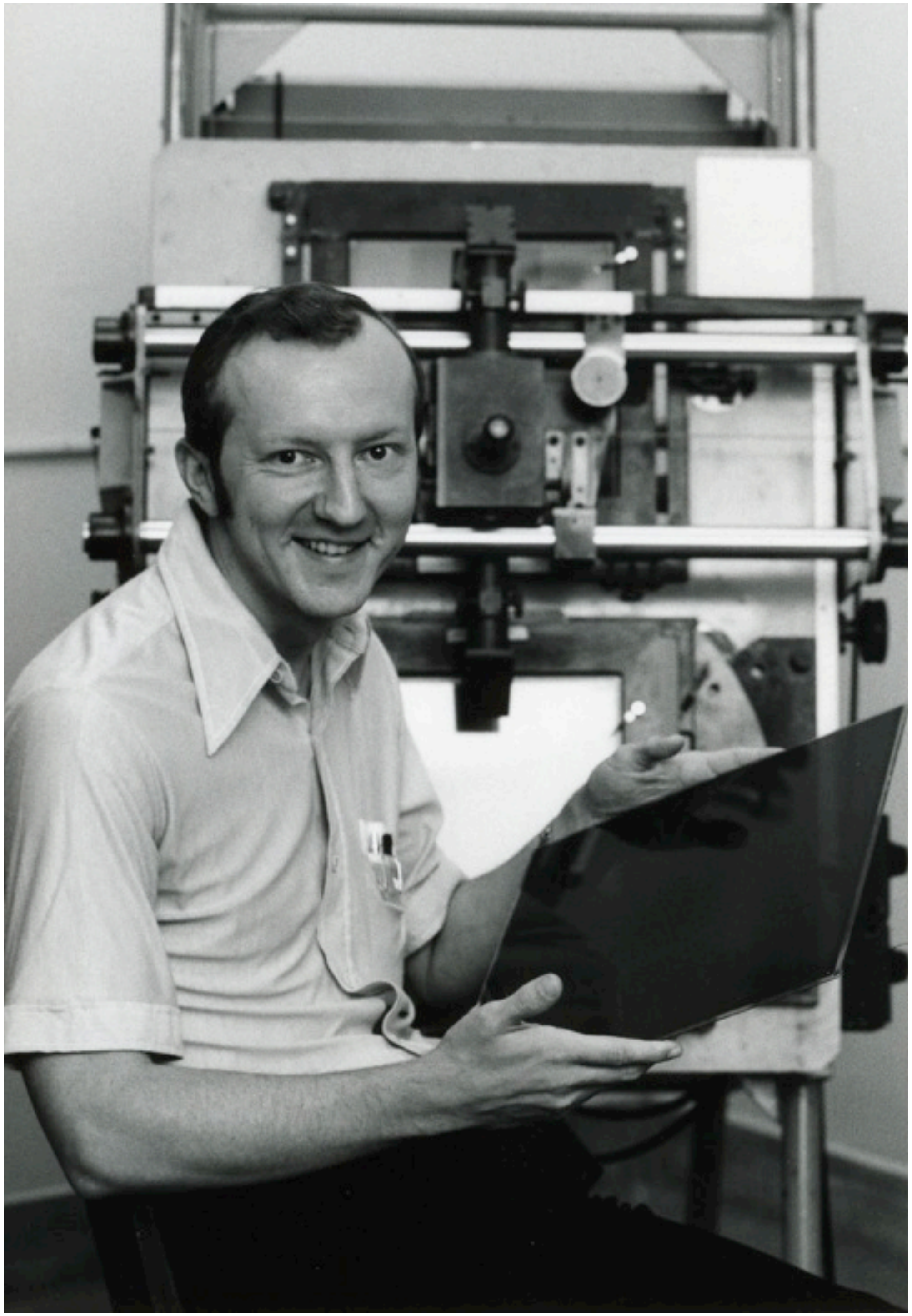
** A well known daily newspaper*

Thanks to Jim Peebles

Georges Lemaître S.J. + MIT Ph.D.

"Everything happens as though the energy *in vacuo* would be different from zero…we associate a pressure $p = -\rho c^2$ to the density of energy ρc^2 of vacuum. This is essentially the meaning of the cosmological constant λ."

PNAS 20, 12 (1934)



The Beginning of Supernova Cosmology

Charlie Kowal

Note the imaging technology of 1968!

Monthly searches in the dark of the moon at Palomar with 48” and 18”

Kowal (1968)

✓ Had distances good to ~30% from SN I

Speculated that individual measurements might be good to 5-10%

“It may even be possible to measure the second-order term in the redshift-magnitude relation when light curves become availab for very distant supernovae

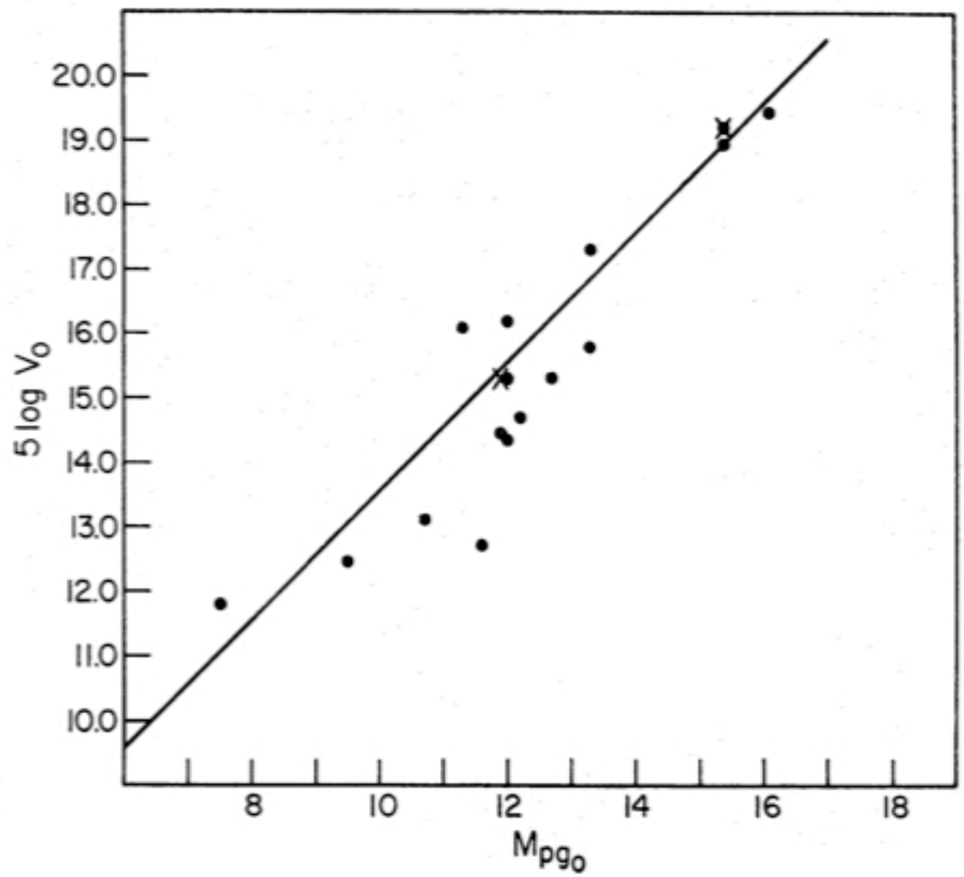
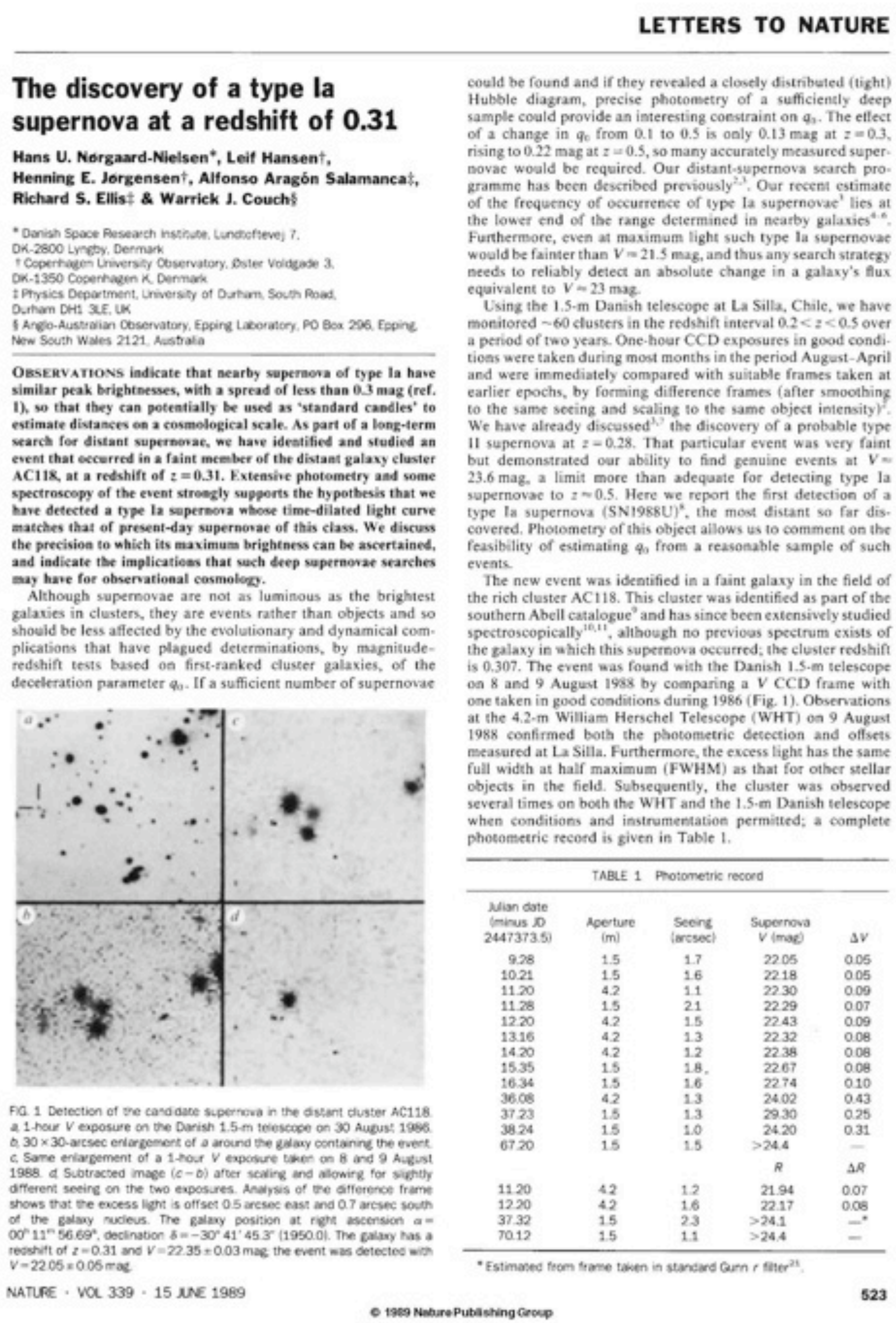


FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.



The discovery of a type Ia supernova at a redshift of 0.31

Hans U. Nørgaard-Nielsen*, Leif Hansen†, Henning E. Jørgensen†, Alfonso Aragón Salamanca‡, Richard S. Ellis‡ & Warrick J. Couch§

* Danish Space Research Institute, Lundtoftevej 7, DK-2800 Lyngby, Denmark
† Copenhagen University Observatory, Øster Voldgade 3, DK-1350 Copenhagen K, Denmark
‡ Physics Department, University of Durham, South Road, Durham DH1 3LE, UK
§ Anglo-Australian Observatory, Epping Laboratory, PO Box 296, Epping, New South Wales 2121, Australia

OBSERVATIONS indicate that nearby supernova of type Ia have similar peak brightnesses, with a spread of less than 0.3 mag (ref. 1), so that they can potentially be used as 'standard candles' to estimate distances on a cosmological scale. As part of a long-term search for distant supernovae, we have identified and studied an event that occurred in a faint member of the distant galaxy cluster AC118, at a redshift of $z = 0.31$. Extensive photometry and some spectroscopy of the event strongly supports the hypothesis that we have detected a type Ia supernova whose time-dilated light curve matches that of present-day supernovae of this class. We discuss the precision to which its maximum brightness can be ascertained, and indicate the implications that such deep supernovae searches may have for observational cosmology.

Although supernovae are not as luminous as the brightest galaxies in clusters, they are events rather than objects and so should be less affected by the evolutionary and dynamical complications that have plagued determinations, by magnitude-redshift tests based on first-ranked cluster galaxies, of the deceleration parameter q_0. If a sufficient number of supernovae could be found and if they revealed a closely distributed (tight) Hubble diagram, precise photometry of a sufficiently deep sample could provide an interesting constraint on q_0. The effect of a change in q_0 from 0.1 to 0.5 is only 0.13 mag at $z = 0.3$, rising to 0.22 mag at $z = 0.5$, so many accurately measured supernovae would be required. Our distant-supernova search programme has been described previously[2,3]. Our recent estimate of the frequency of occurrence of type Ia supernovae[3] lies at the lower end of the range determined in nearby galaxies[4-6]. Furthermore, even at maximum light such type Ia supernovae would be fainter than $V \approx 21.5$ mag, and thus any search strategy needs to reliably detect an absolute change in a galaxy's flux equivalent to $V \approx 23$ mag.

Using the 1.5-m Danish telescope at La Silla, Chile, we have monitored ~60 clusters in the redshift interval $0.2 < z < 0.5$ over a period of two years. One-hour CCD exposures in good conditions were taken during most months in the period August–April and were immediately compared with suitable frames taken at earlier epochs, by forming difference frames (after smoothing to the same seeing and scaling to the same object intensity)[7]. We have already discussed[3,7] the discovery of a probable type II supernova at $z = 0.28$. That particular event was very faint but demonstrated our ability to find genuine events at $V \approx 23.6$ mag, a limit more than adequate for detecting type Ia supernovae to $z \approx 0.5$. Here we report the first detection of a type Ia supernova (SN1988U)[8], the most distant so far discovered. Photometry of this object allows us to comment on the feasibility of estimating q_0 from a reasonable sample of such events.

The new event was identified in a faint galaxy in the field of the rich cluster AC118. This cluster was identified as part of the southern Abell catalogue[9] and has since been extensively studied spectroscopically[10,11], although no previous spectrum exists of the galaxy in which this supernova occurred; the cluster redshift is 0.307. The event was found with the Danish 1.5-m telescope on 8 and 9 August 1988 by comparing a V CCD frame with one taken in good conditions during 1986 (Fig. 1). Observations at the 4.2-m William Herschel Telescope (WHT) on 9 August 1988 confirmed both the photometric detection and offsets measured at La Silla. Furthermore, the excess light has the same full width at half maximum (FWHM) as that for other stellar objects in the field. Subsequently, the cluster was observed several times on both the WHT and the 1.5-m Danish telescope when conditions and instrumentation permitted; a complete photometric record is given in Table 1.

FIG. 1 Detection of the candidate supernova in the distant cluster AC118. *a*, 1-hour V exposure on the Danish 1.5-m telescope on 30 August 1986. *b*, 30 × 30-arcsec enlargement of *a* around the galaxy containing the event. *c*, Same enlargement of a 1-hour V exposure taken on 8 and 9 August 1988. *d*, Subtracted image ($c - b$) after scaling and allowing for slightly different seeing on the two exposures. Analysis of the difference frame shows that the excess light is offset 0.5 arcsec east and 0.7 arcsec south of the galaxy nucleus. The galaxy position at right ascension $\alpha = 00^h 11^m 56.69^s$, declination $\delta = -30° 41' 45.3''$ (1950.0). The galaxy has a redshift of $z = 0.31$ and $V = 22.35 \pm 0.03$ mag; the event was detected with $V = 22.05 \pm 0.05$ mag.

TABLE 1 Photometric record

Julian date (minus JD 2447373.5)	Aperture (m)	Seeing (arcsec)	Supernova V (mag)	ΔV
9.28	1.5	1.7	22.05	0.05
10.21	1.5	1.6	22.18	0.05
11.20	4.2	1.1	22.30	0.09
11.28	1.5	2.1	22.29	0.07
12.20	4.2	1.5	22.43	0.09
13.16	4.2	1.3	22.32	0.08
14.20	4.2	1.2	22.38	0.08
15.35	1.5	1.8	22.67	0.08
16.34	1.5	1.6	22.74	0.10
36.08	4.2	1.3	24.02	0.43
37.23	1.5	1.3	29.30	0.25
38.24	1.5	1.0	24.20	0.31
67.20	1.5	1.5	>24.4	—
			R	ΔR
11.20	4.2	1.2	21.94	0.07
12.20	4.2	1.6	22.17	0.08
37.32	1.5	2.3	>24.1	—*
70.12	1.5	1.1	>24.4	—

* Estimated from frame taken in standard Gunn r filter[21].

Like the Vikings, the Danes were there a long time ago! 1989

SN1988U:

SN Ia z=0.31

For cosmology!

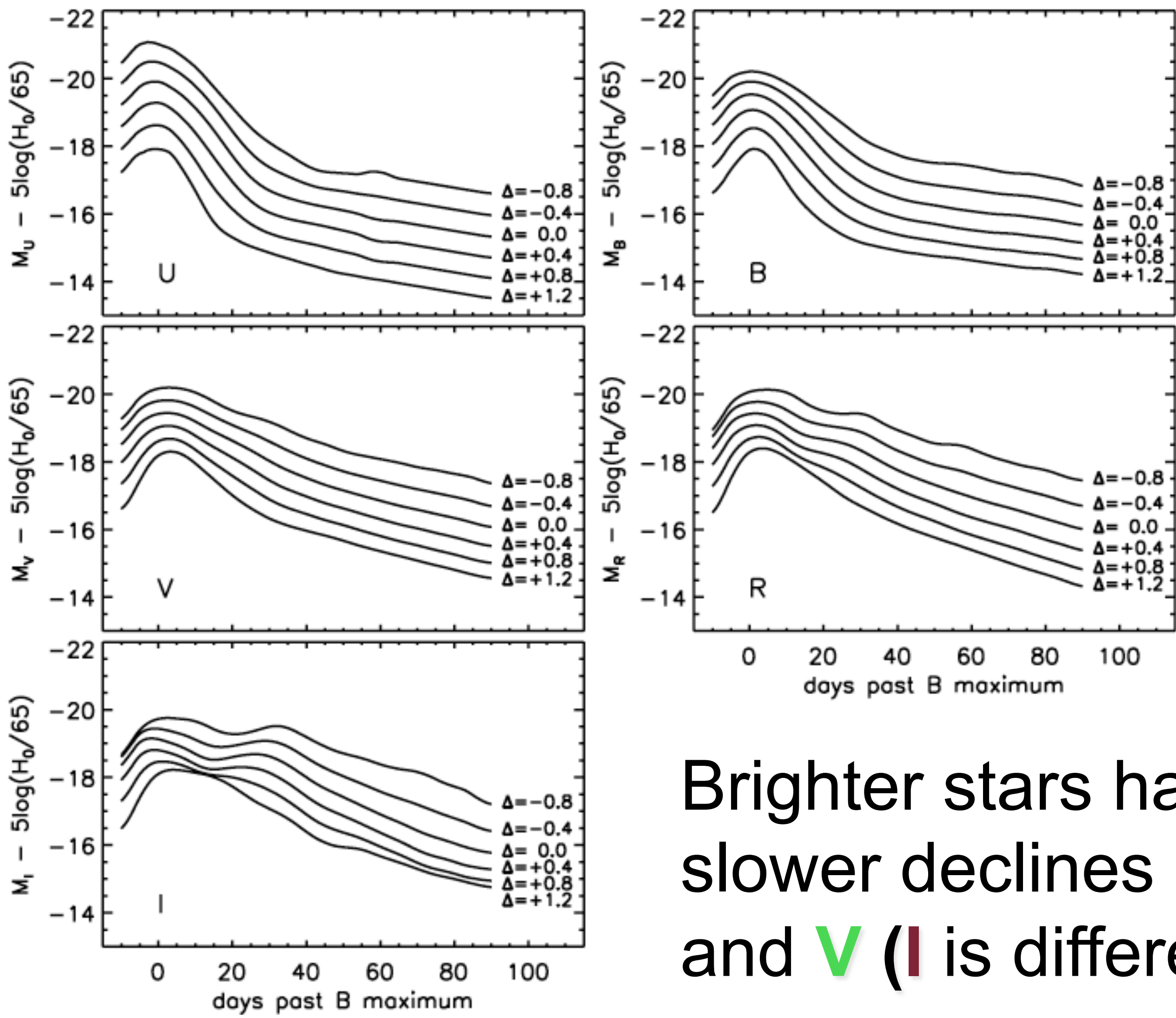
Real-time image registration, scaling,subtraction

Monthly searches

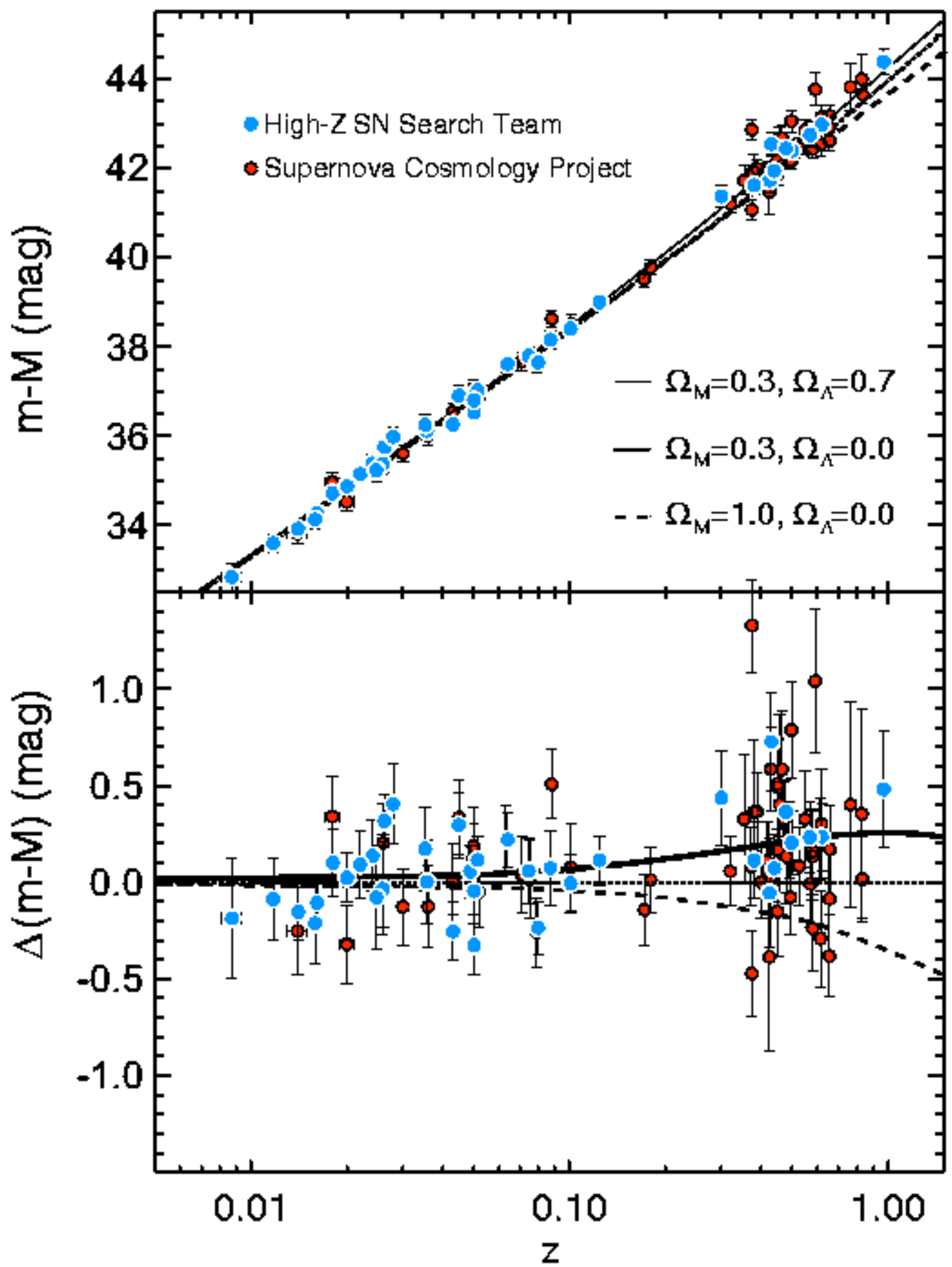
Scheduled follow-up

Light Curve Shapes => L

Mark Phillips (1992)



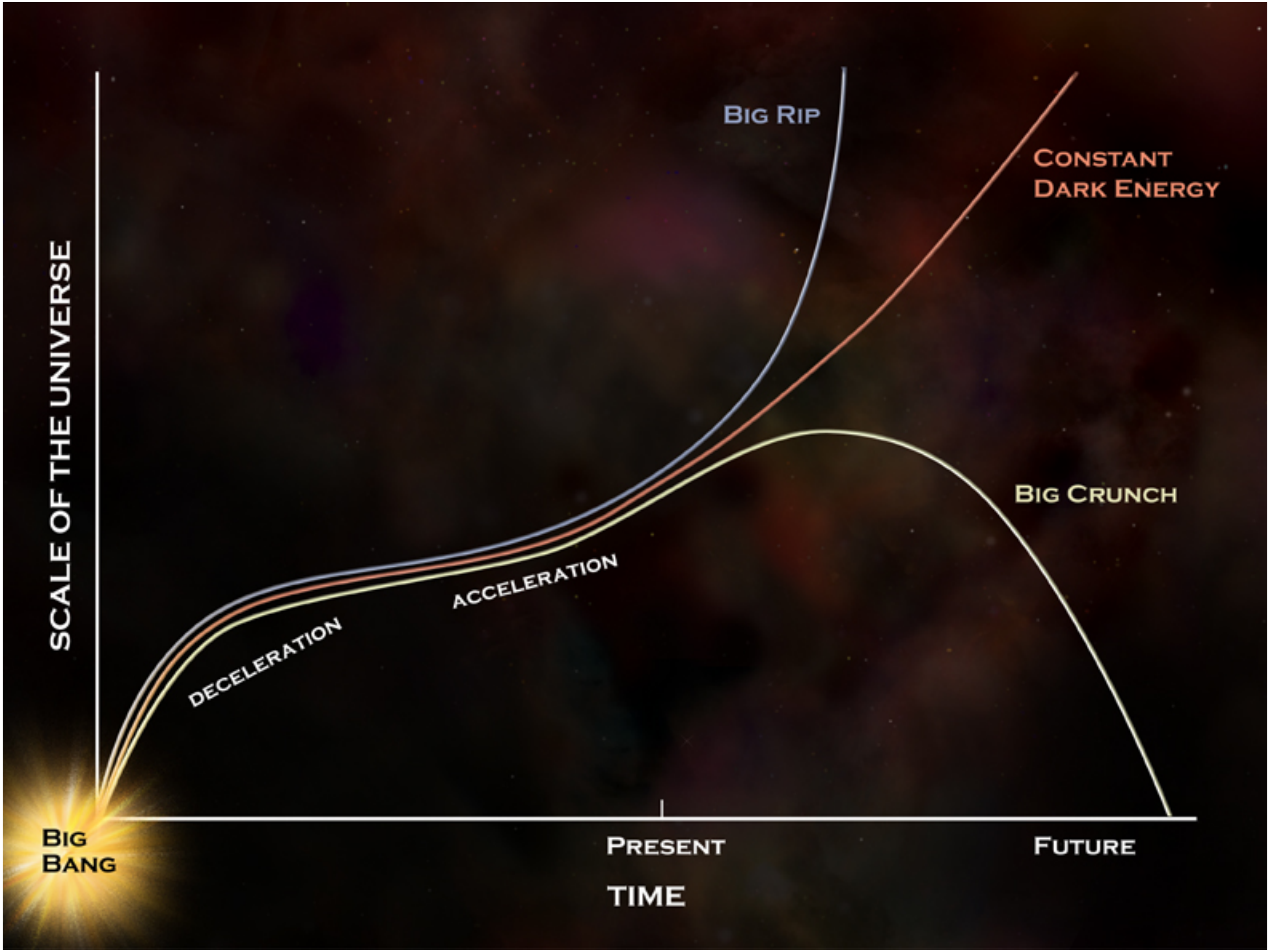
Brighter stars have slower declines in **B** and **V** (**I** is different)



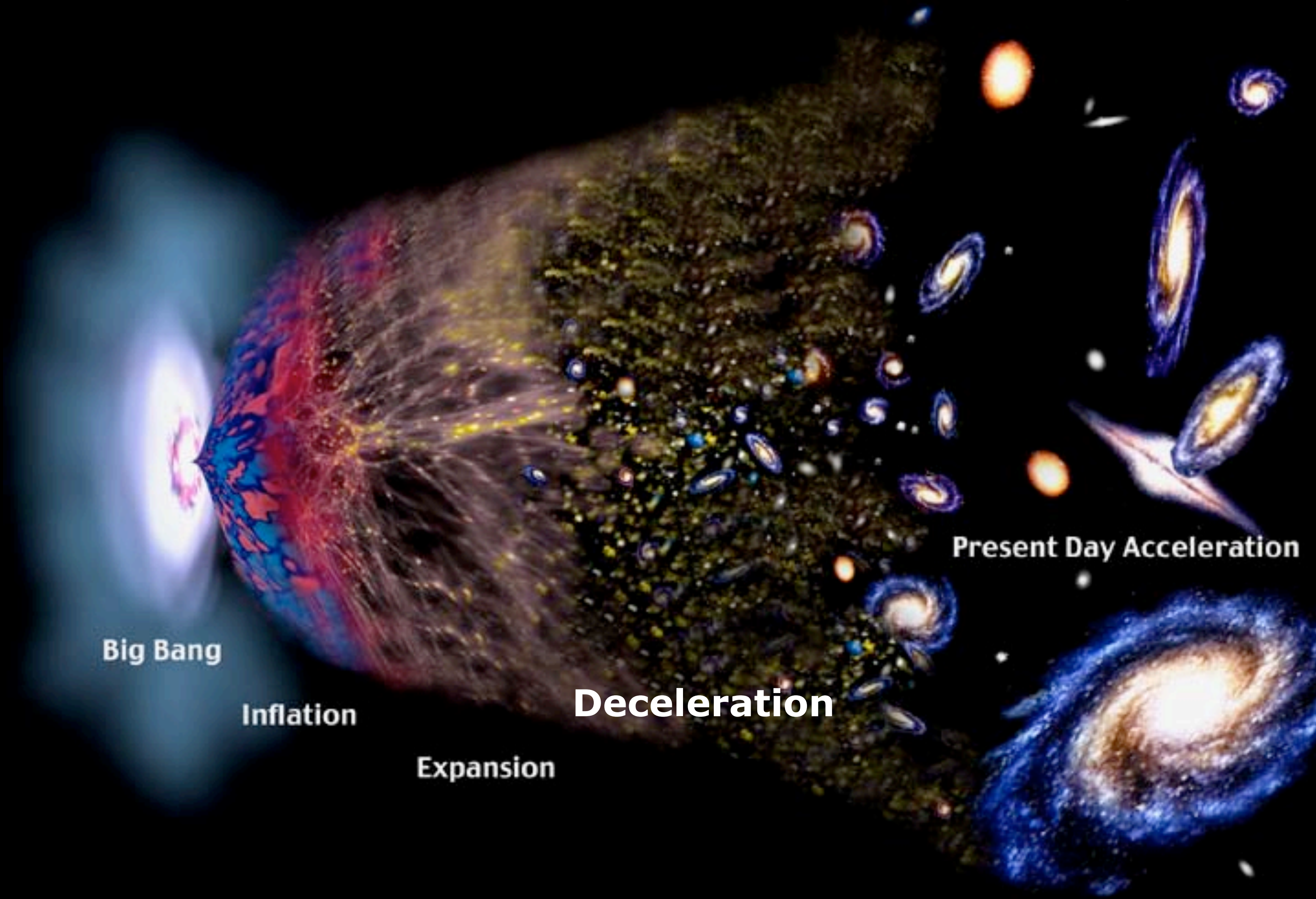
1998 Data:

Evidence for cosmic acceleration: 20% dimmer than expected

Scatter for one measurement <20%, so a handful gave 3-sigma results


Big Rip
Constant
Dark Energy
Big Crunch
Acceleration
Deceleration
Scale of the Universe
Big
Bang
Present
Future
Time

Cosmic Deceleration from Dark Matter, then Acceleration from Dark Energy!



The Present

Curiously, into 2009, the biggest statistical error in SN cos due to the sm e low-z sample

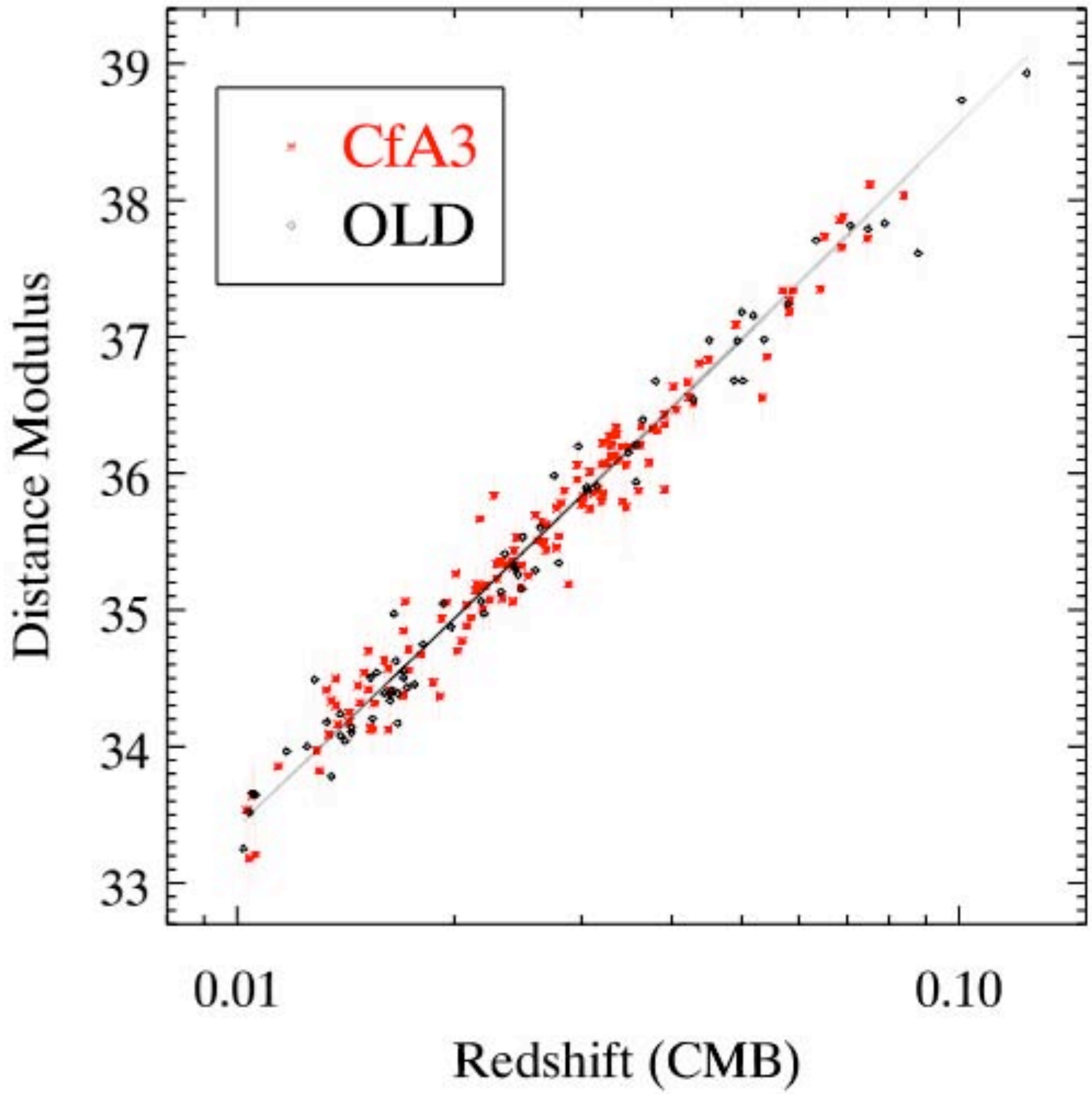
This ha remedi fA3 sample

Hicken et al. ApJ 700, 331 (2009)

185 Type I Light Curves

Hicken et al. ApJ 700, 1097 (2009)

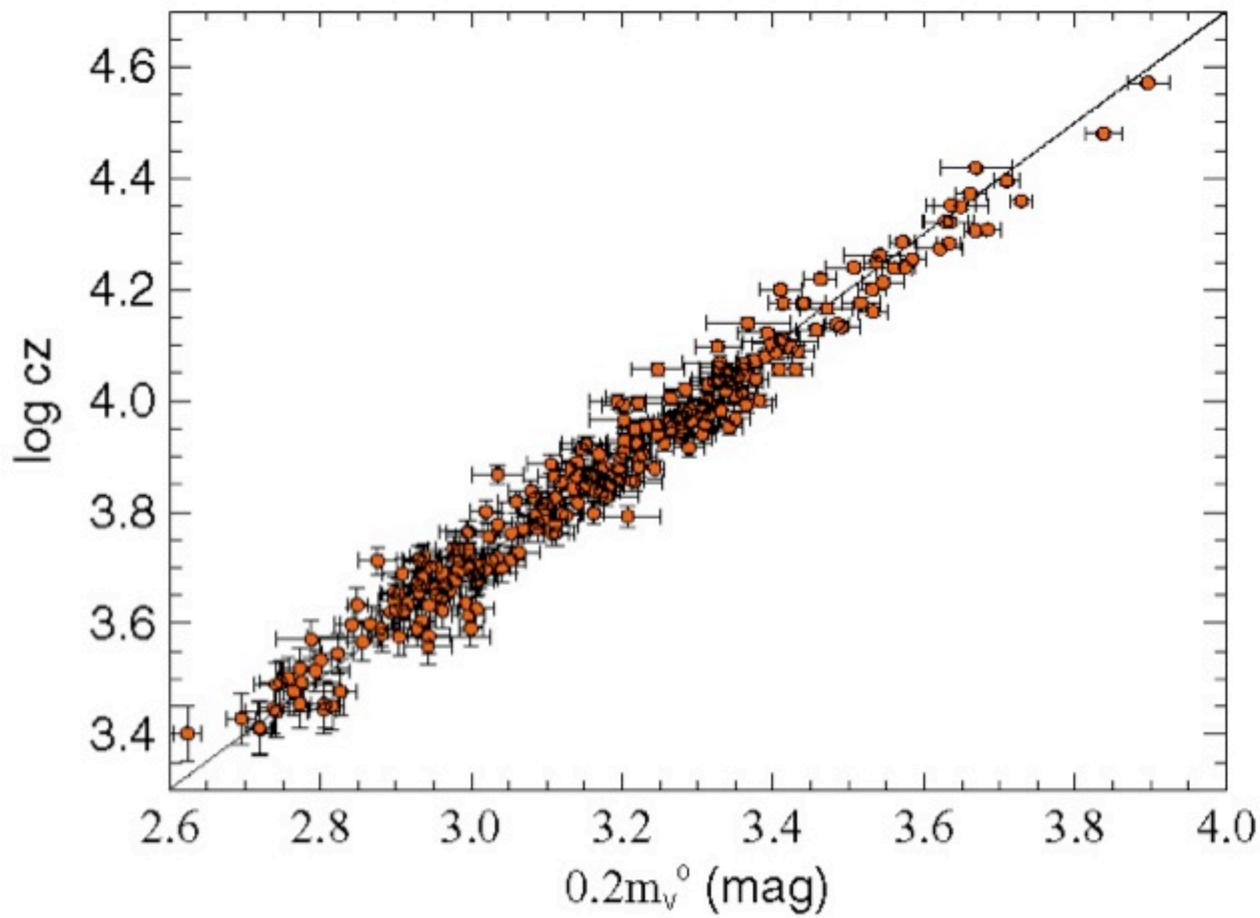
Improved Dark Energy Constraints




Dust both dims and reddens

The intercept is well-determined: H_o

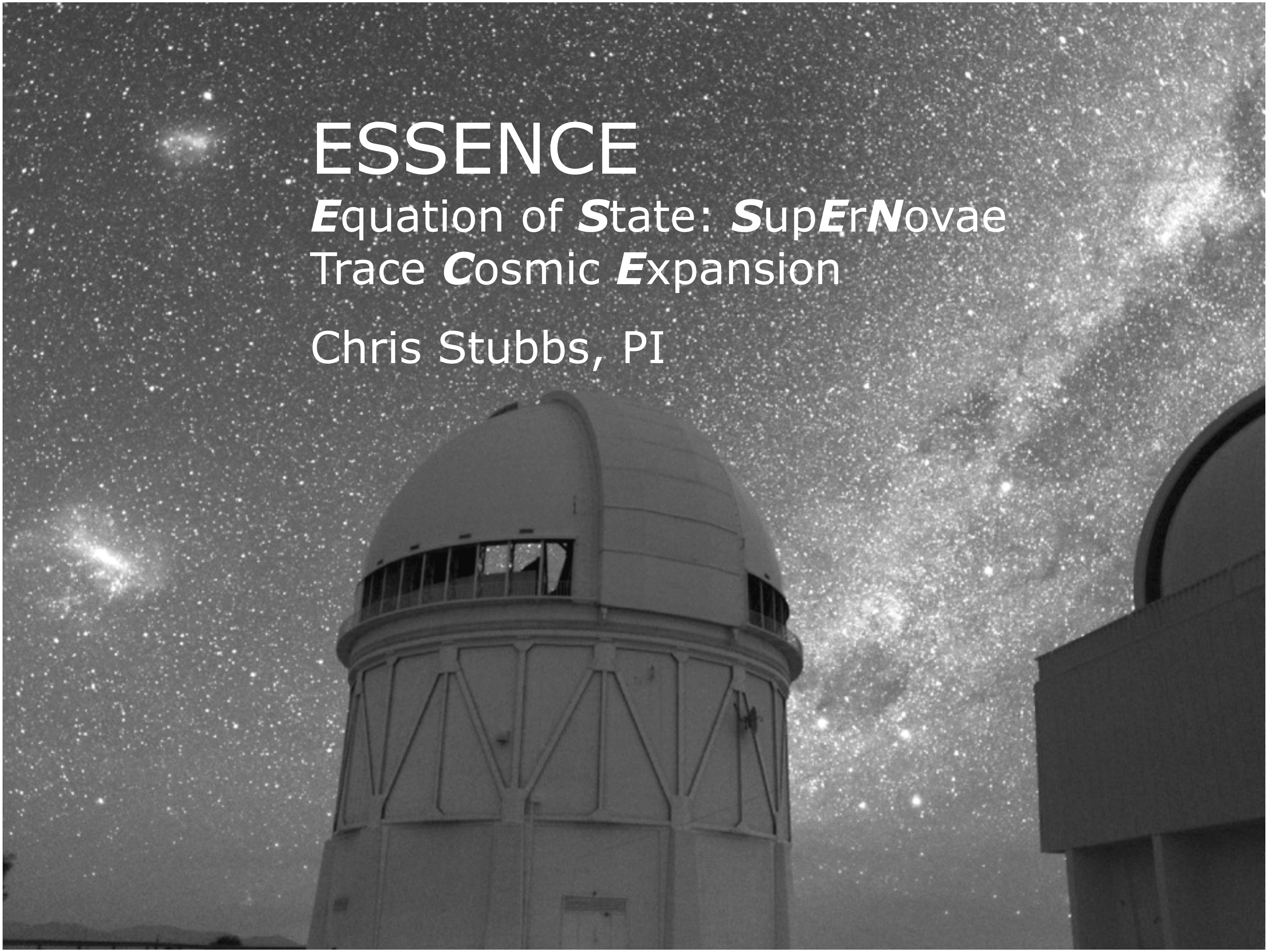
253 SN Ia used to calibrate the Hubble expansion, H_0=73.8+/-2.4, a 3.3% measurement including systematics (Riess et al. 2011): 0.5% attributed to this diagram!



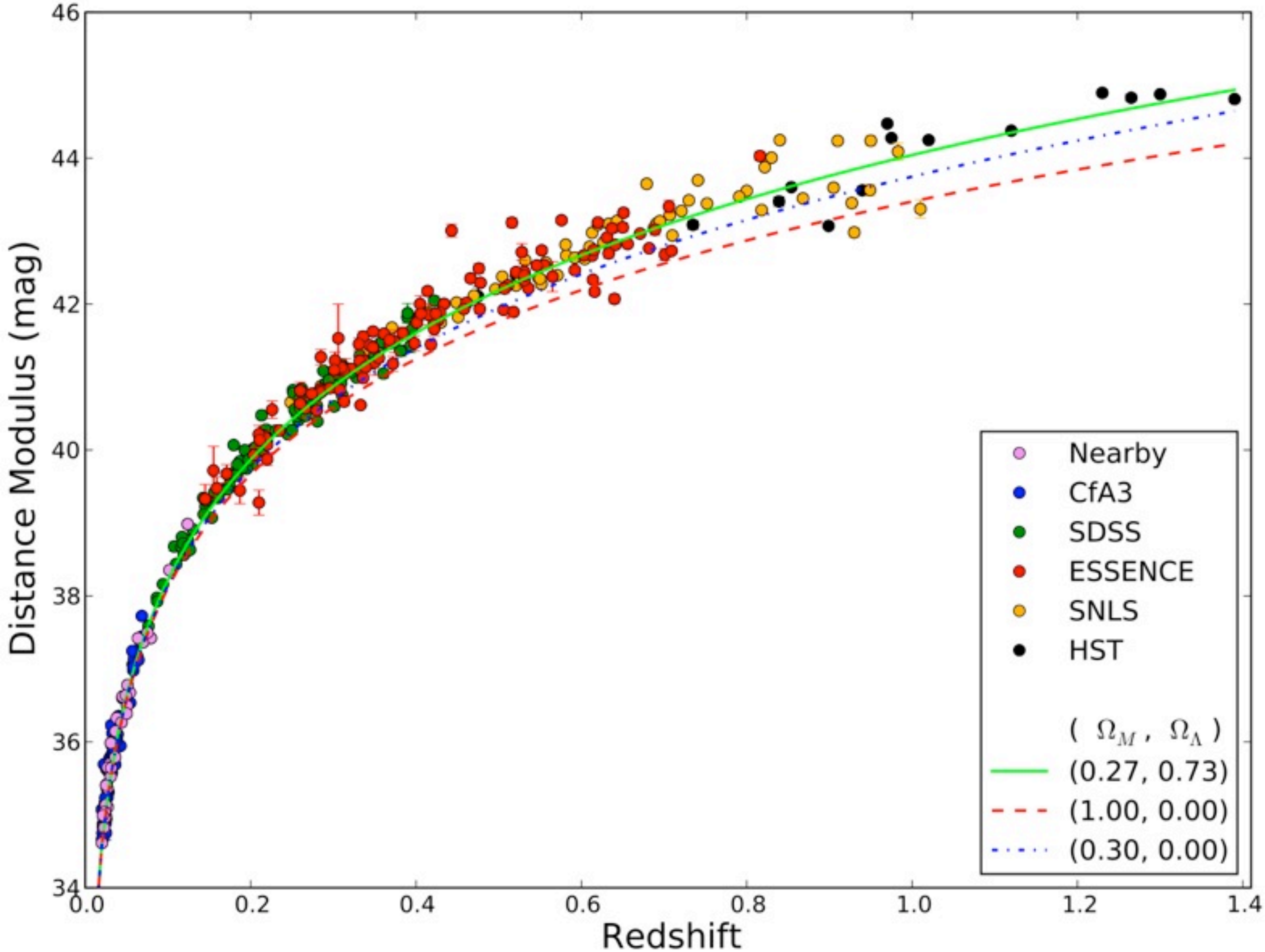
ESSENCE

Equation of ***S***tate: ***S***up***E***r***N***ovae Trace ***C***osmic ***E***xpansion

Chris Stubbs, PI



Full ESSENCE sample is coming soon!



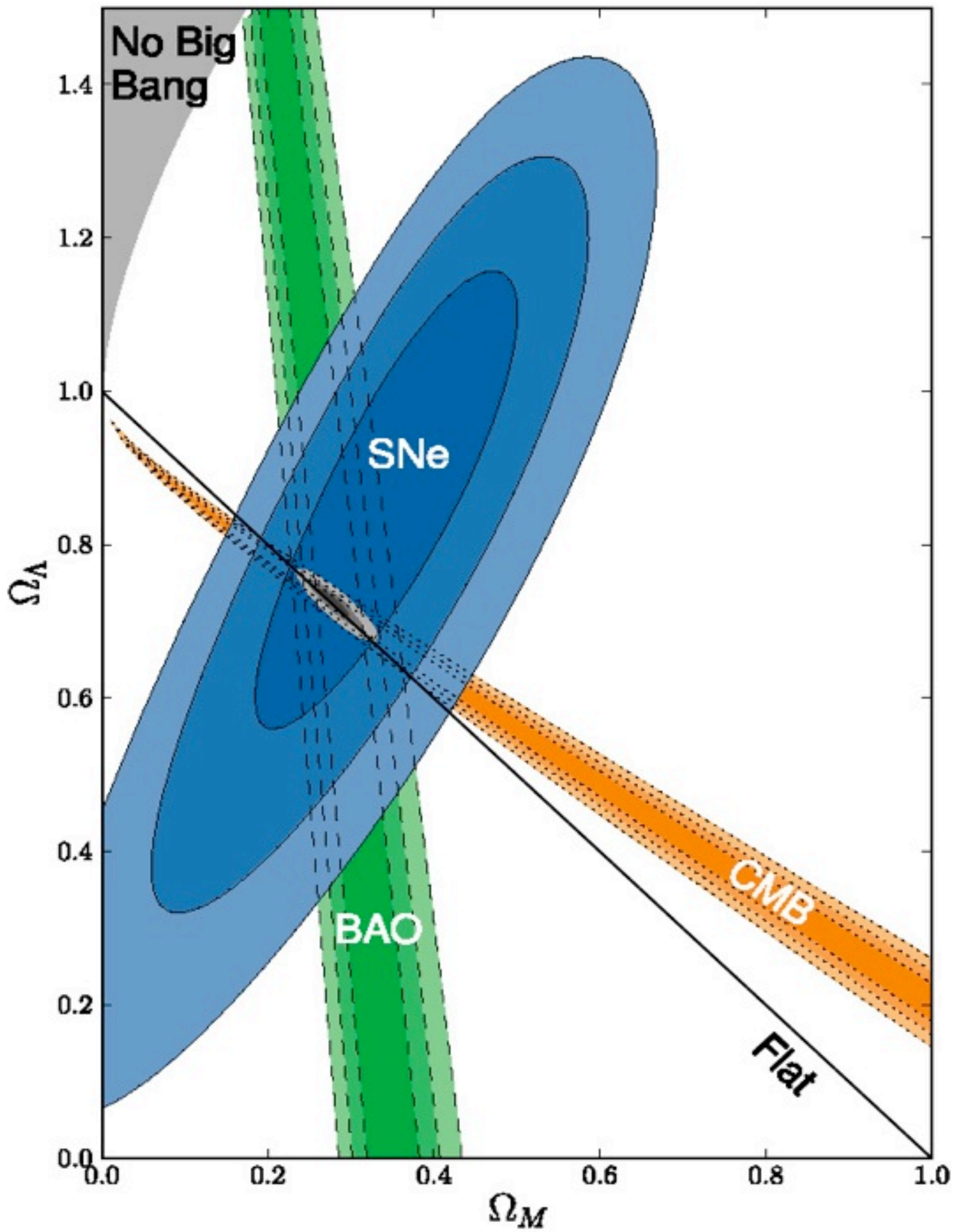


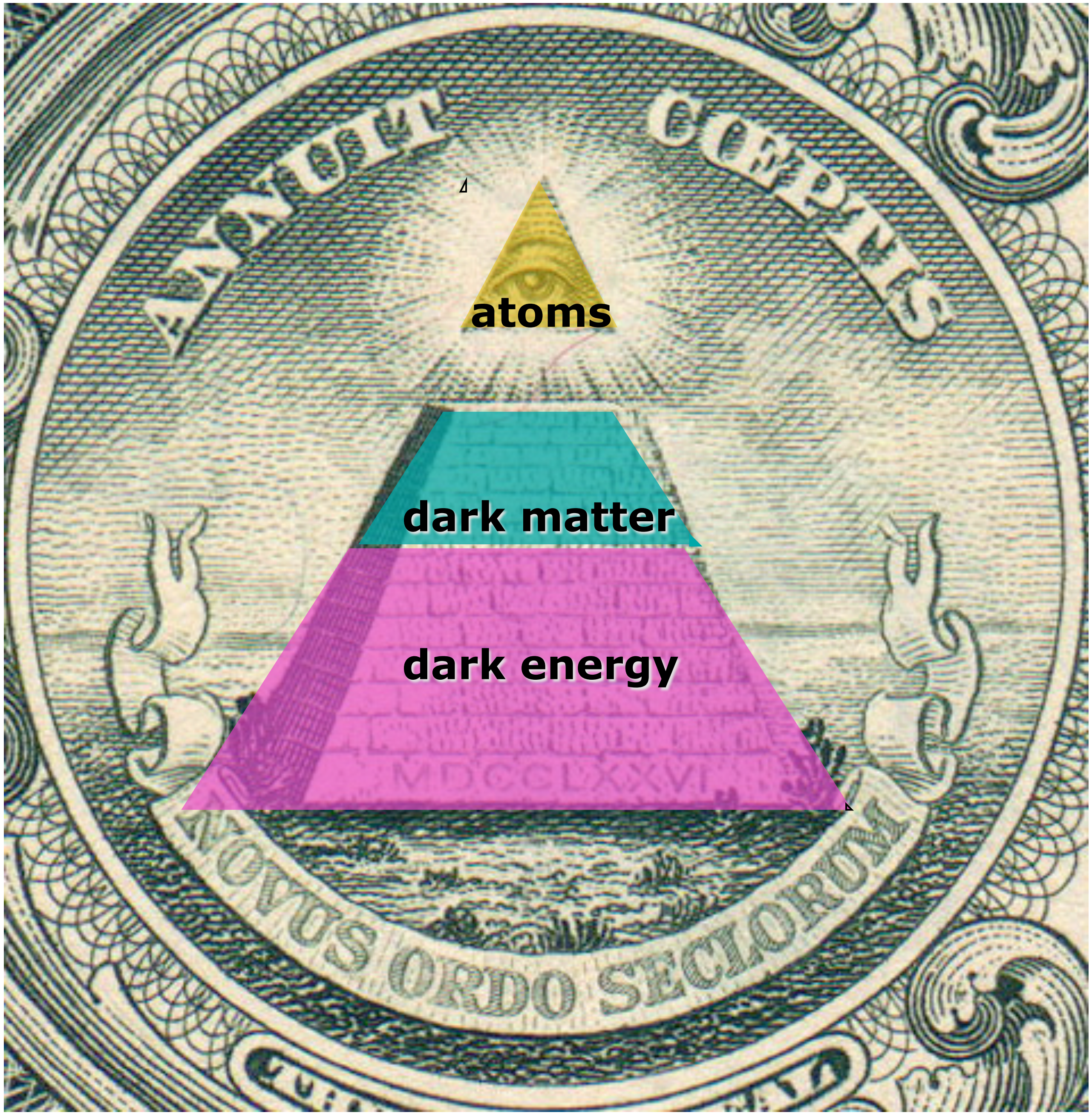
Figure from Amanullah et al. (2010)

Based on Low z: (Calan-Tololo + CfA1 +CfA2 + CfA3 + Sloan) + 8 from SCP (Kowalski 2008)

ESSENCE + SNLS + Higher-Z+ 6 from SCP (from 2001!)

"Union 2"

Ω_m = 0.28 +/- 0.01
Ω_Λ = 0.72


ANNUIT CŒPTIS
atoms
dark matter
dark energy
MDCCLXXVI
NOVUS ORDO SECLORUM

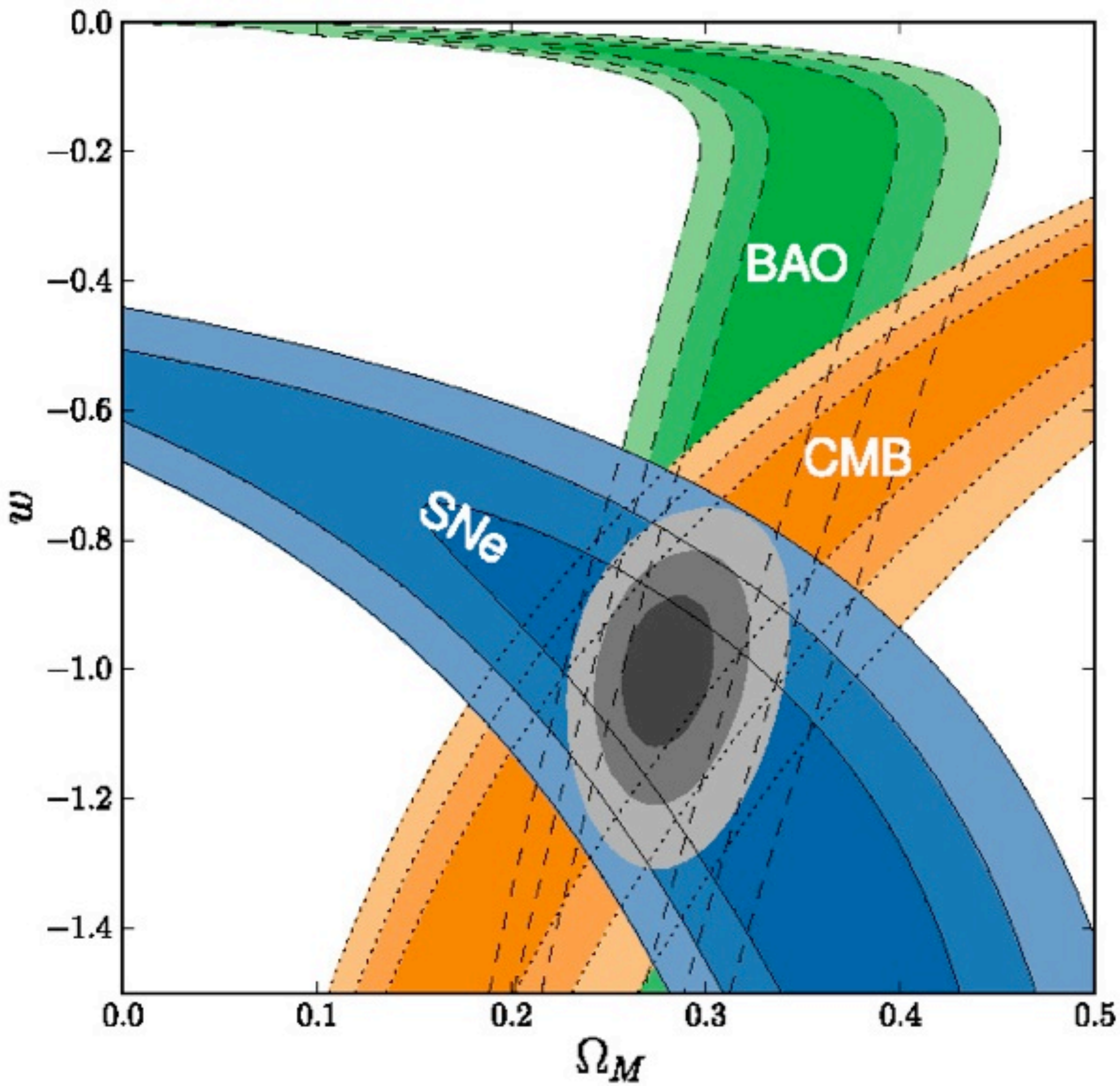


Figure from Amanullah et al. (2010)

$1 + w = -0.04 \pm 0.06$ **+/- 0.10 (sys)**

Consistent with a cosmological constant--but how do we diminish the systematic errors?

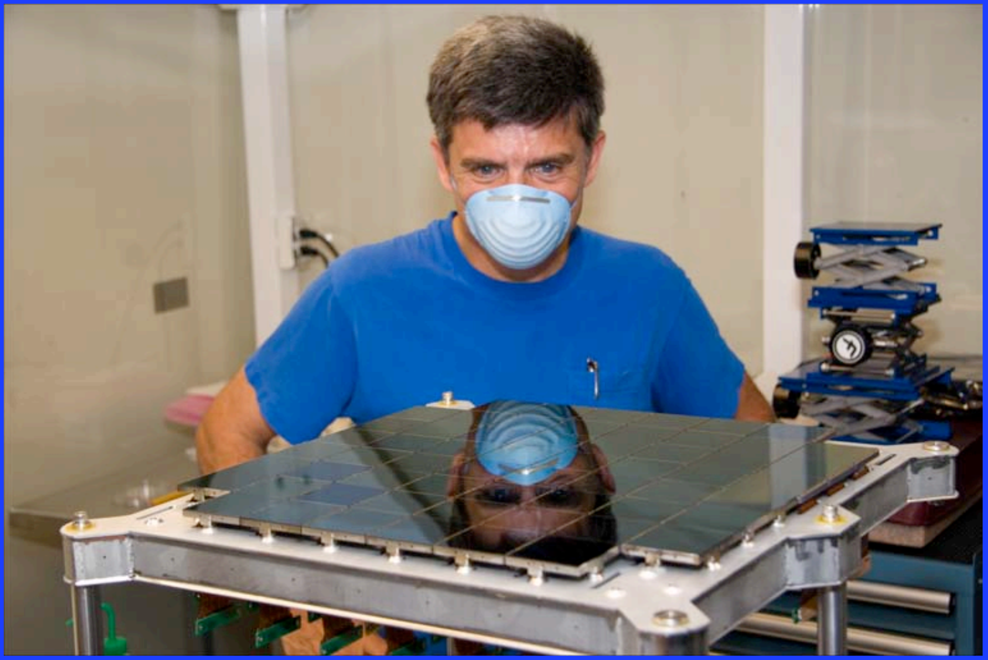
Can we use information about host galaxies, from spectra?
Can we avoid problems with dust?

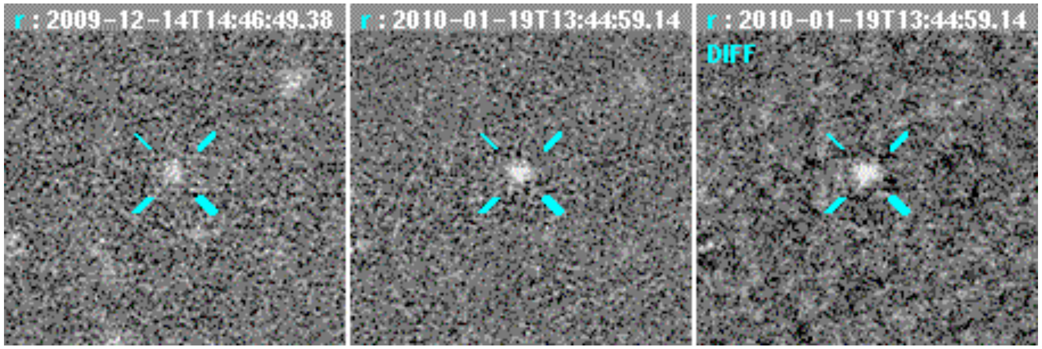
Most promising:
NIR observations

Pan-STARRS

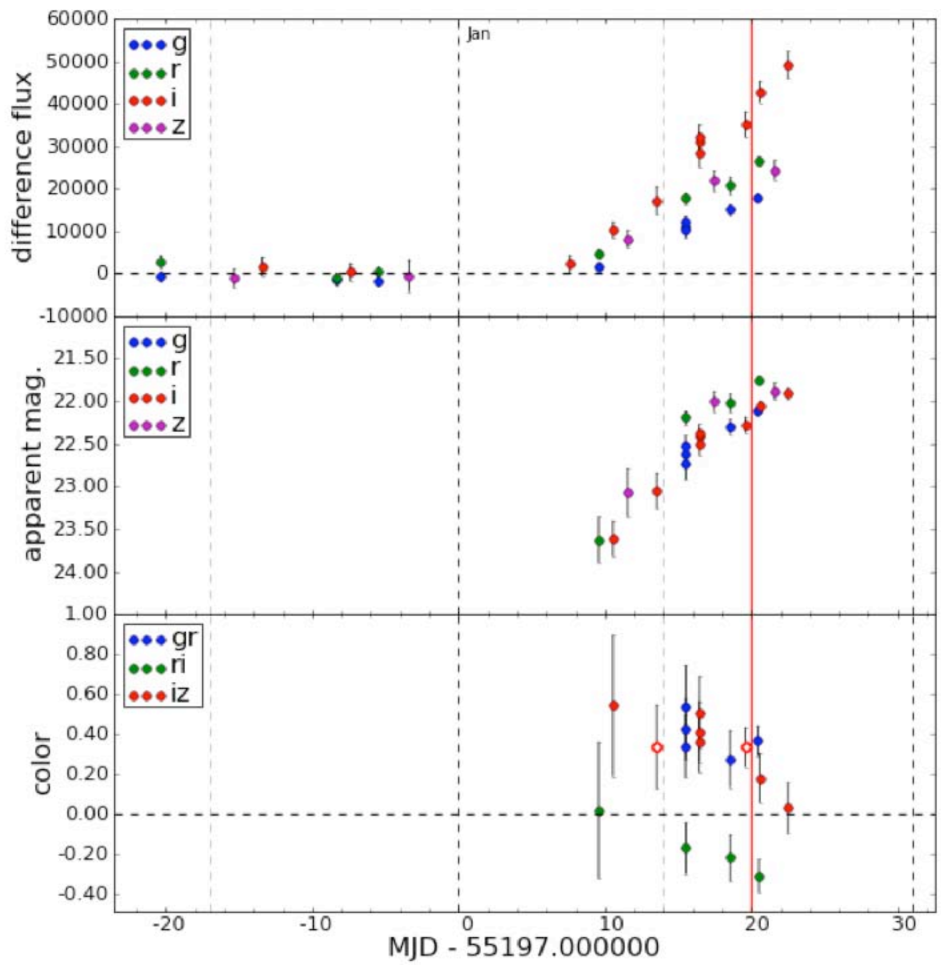
Medium-Deep Fields

Good light curves at z~0.4
Real production now
7 square degrees
0.26 "/pixel





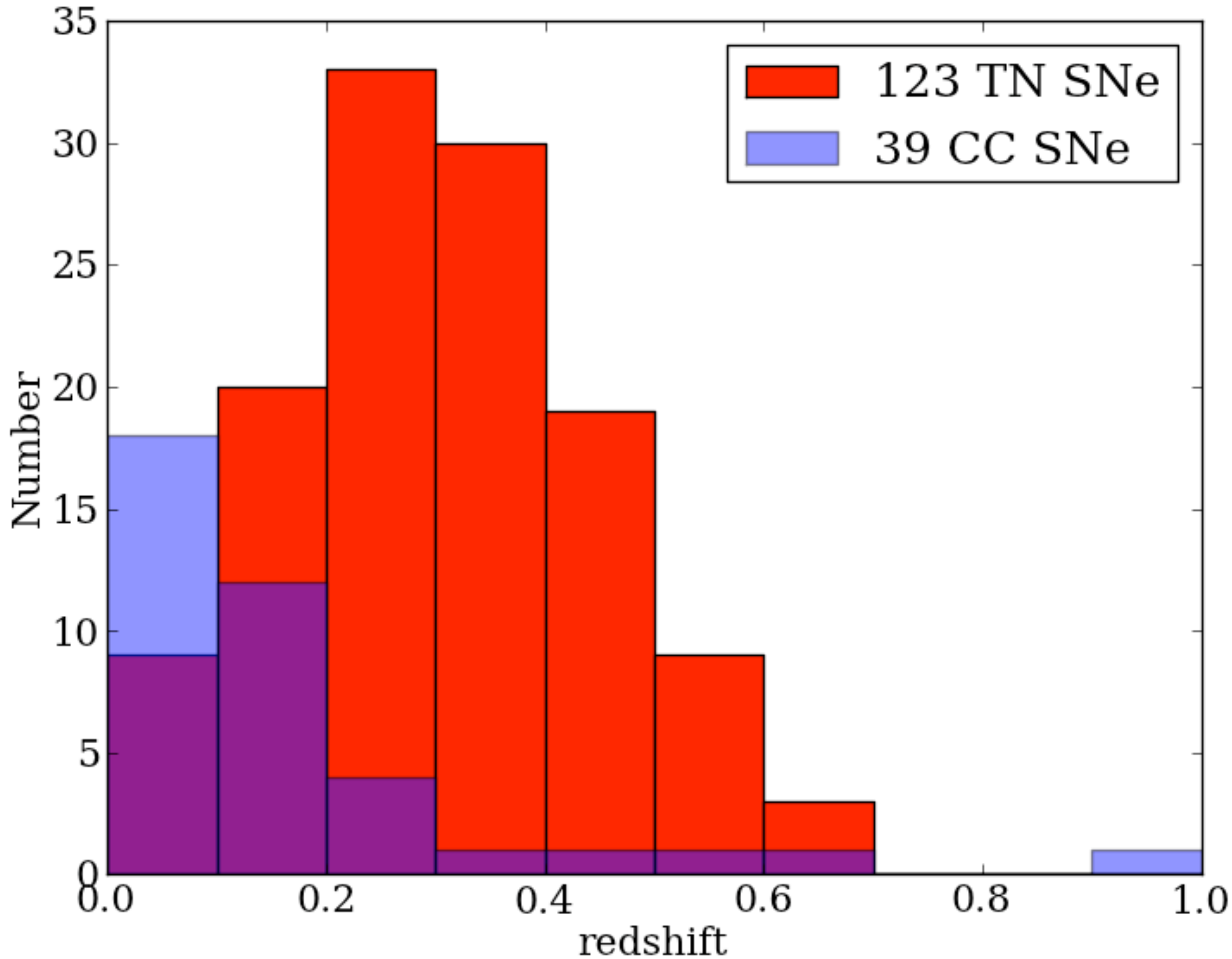
PS1
Medium
Deep
Field



4 day
cadence
m~23

z~0.31

several days
before
maximum
light



Spectra from Magellan, MMT, Gemini

Key to the RAISIN program to get restframe IR of SN Ia

Mount Hopkins: CfA Supernova Program

Can Spectra Help?

Stéphane Blondin (CPPM, Marseilles)

Has used the CfA Spectral Archive as an independent test, and has explored some other ways of using spectra.

~250 SN Ia, 2000 spectra

Do spectra improve distance measurements of Type Ia supernovae?

S. Blondin[1], K. S. Mandel[2], and R. P. Kirshner[2]

[1] Centre de Physique des Particules de Marseille (CPPM), CNRS/IN2P3, 163 avenue de Luminy, 13288 Marseille Cedex 9, France e-mail: blondin@cppm.in2p3.fr
[2] Harvard-Smithsonian Center for Astrophysics (CfA), 60 Garden Street, Cambridge, MA 02138, USA

Received XXX; accepted XXX

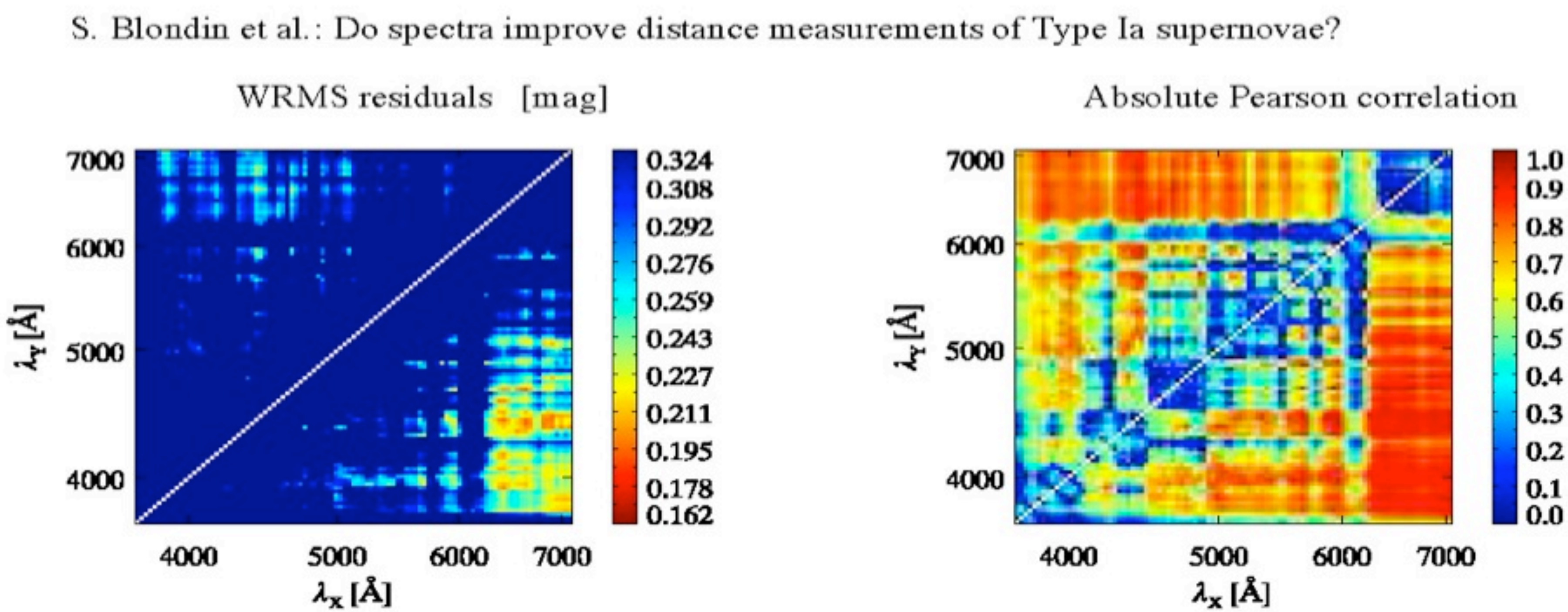
ABSTRACT

We investigate the use of a wide variety of spectroscopic measurements to determine distances to low-redshift Type Ia supernovae (SN Ia) in the Hubble flow observed through the CfA Supernova Program. We consider linear models for predicting distances to SN Ia using light-curve width and color parameters (determined using the SALT2 light-curve fitter) and a spectroscopic indicator, and evaluate the resulting Hubble diagram scatter using a cross-validation procedure. We confirm the ability of spectral flux ratios alone at maximum light to reduce the scatter of Hubble residuals by ~ 10% [weighted rms, or WRMS = 0.189 ± 0.026 mag for the flux ratio $\mathcal{R}(6630/4400)$] with respect to the standard combination of light-curve width and color, for which WRMS = 0.204 ± 0.029 mag. When used in combination with the SALT2 color parameter, the color-corrected flux ratio $\mathcal{R}^c(6420/5290)$ at maximum light leads to an even lower scatter (WRMS = 0.175 ± 0.025 mag), although the improvement has low statistical significance ($< 2\sigma$) given the size of our sample (26 SN Ia). We highlight the importance of an accurate relative flux calibration and the failure of this method for highly-reddened objects. Comparison with synthetic spectra from 2D delayed-detonation explosion models shows that the correlation of $\mathcal{R}(6630/4400)$ with SN Ia absolute magnitudes can be largely attributed to intrinsic color variations and not to reddening by dust in the host galaxy. We consider flux ratios at other ages, as well as the use of pairs of flux ratios, revealing the presence of small-scale intrinsic spectroscopic variations in the iron-group dominated absorption features around ~ 4300 Å and ~ 4800 Å. The best flux ratio overall is the color-corrected $\mathcal{R}^c(4610/4260)$ at $t = -2.5$ d from maximum light, which leads to ~ 30% lower scatter (WRMS = 0.143 ± 0.020 mag) with respect to the standard combination of light-curve width and color, at ~ 2σ significance. We examine other spectroscopic indicators related to line-profile morphology (absorption velocity, pseudo-equivalent width etc.), but none appear to lead to a significant improvement over the standard light-curve width and color parameters. We discuss the use of spectra in measuring more precise distances to SN Ia and the implications for future surveys which seek to determine the properties of dark energy.

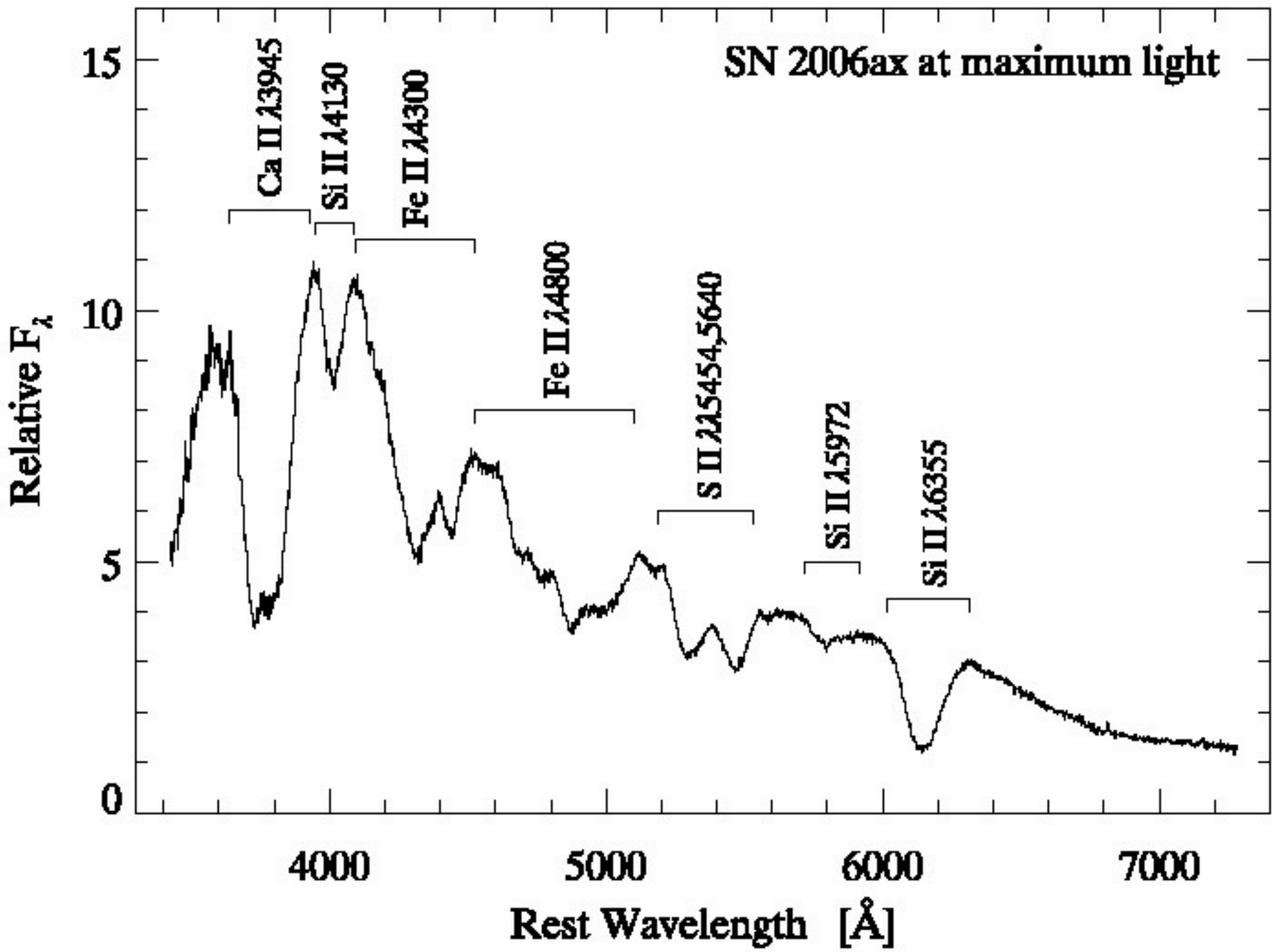
Key words. supernovae: general — cosmology: observations

A & A 526, 81 (2011)

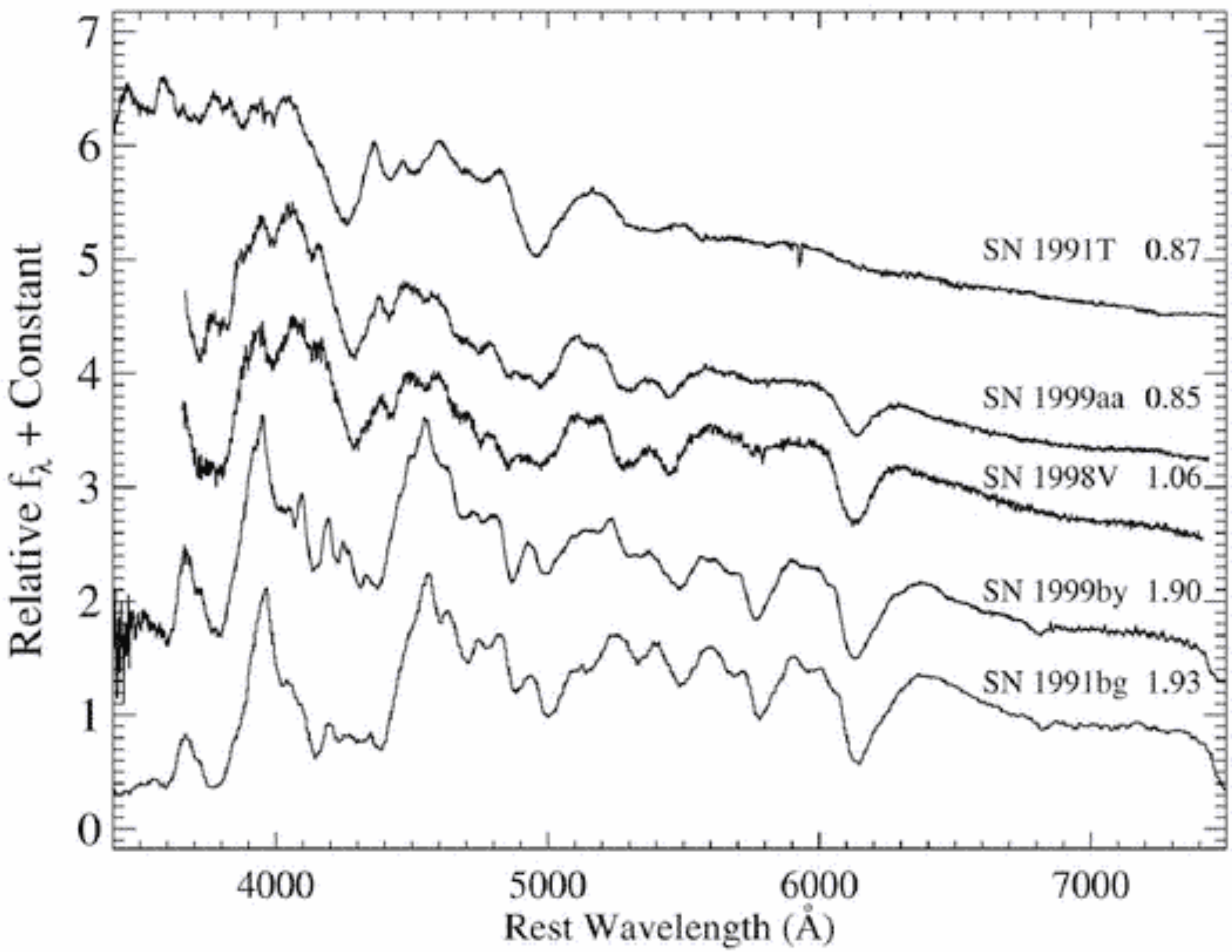
We' ve looked for spectral features that are correlated with reduced scatter in the Hubble diagram
(see also Bailey et al. A & A 500, 117 (2009))

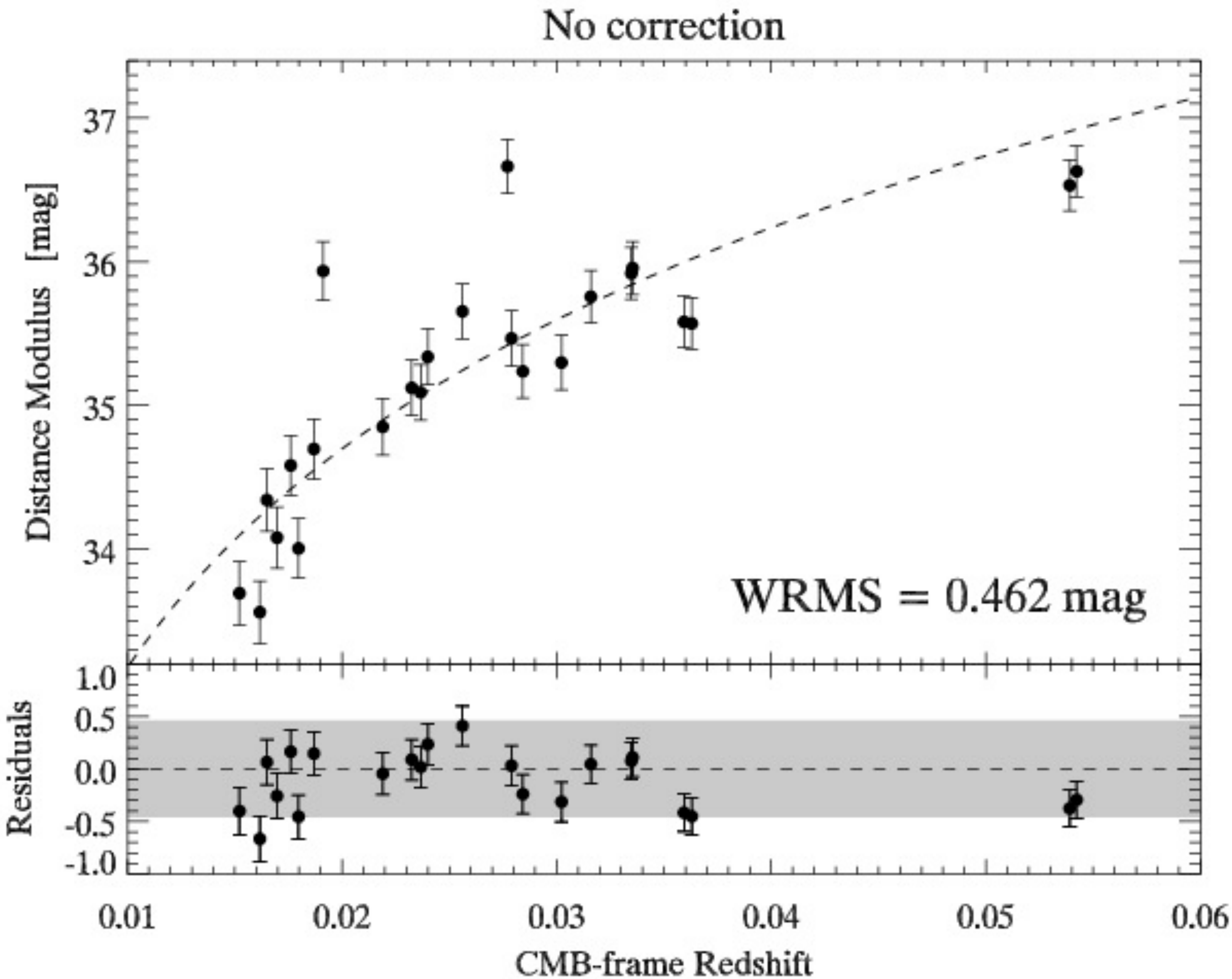


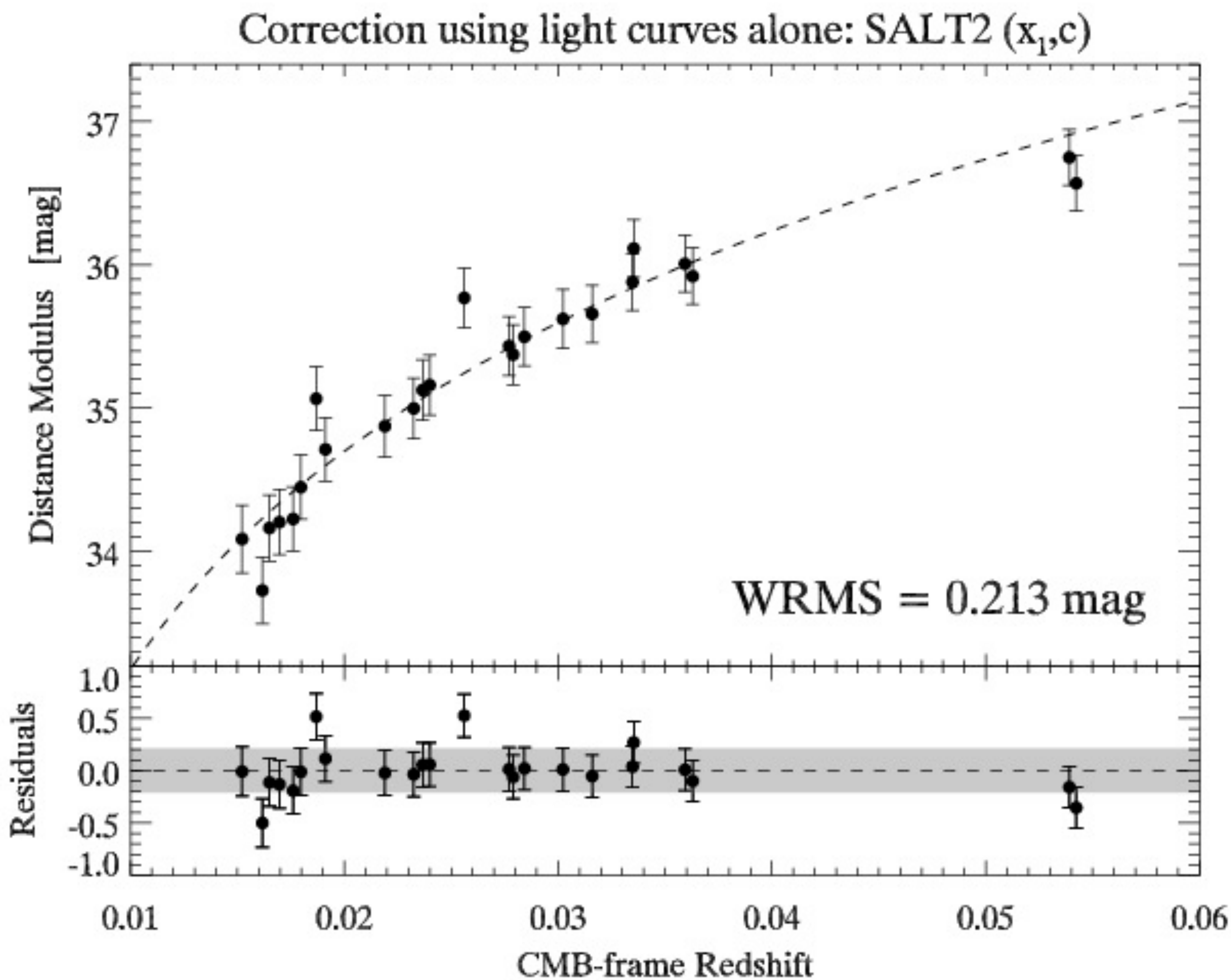
And we have looked at spectral features whose astrophysics we understand



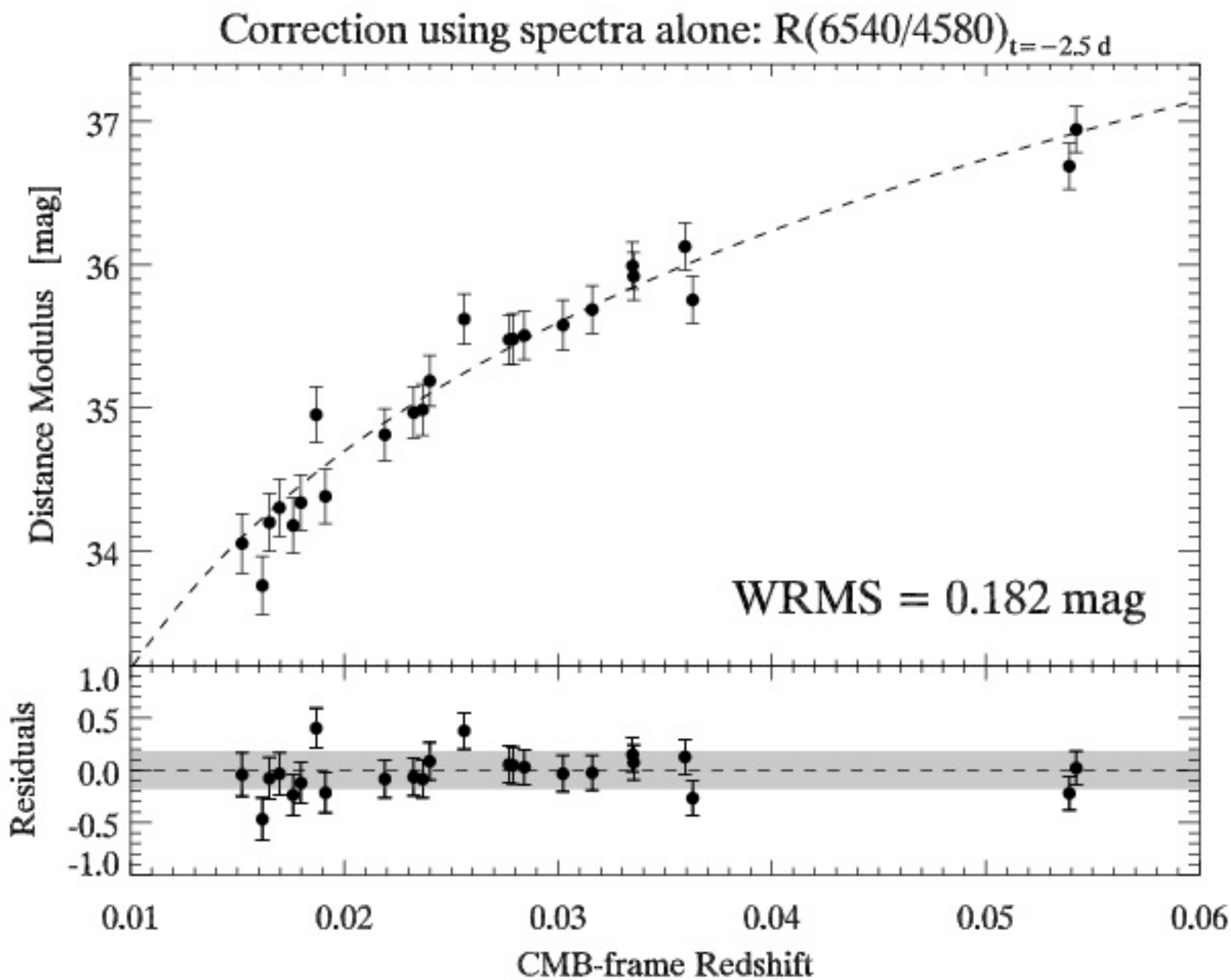
Spectra and Light-Curve Shape

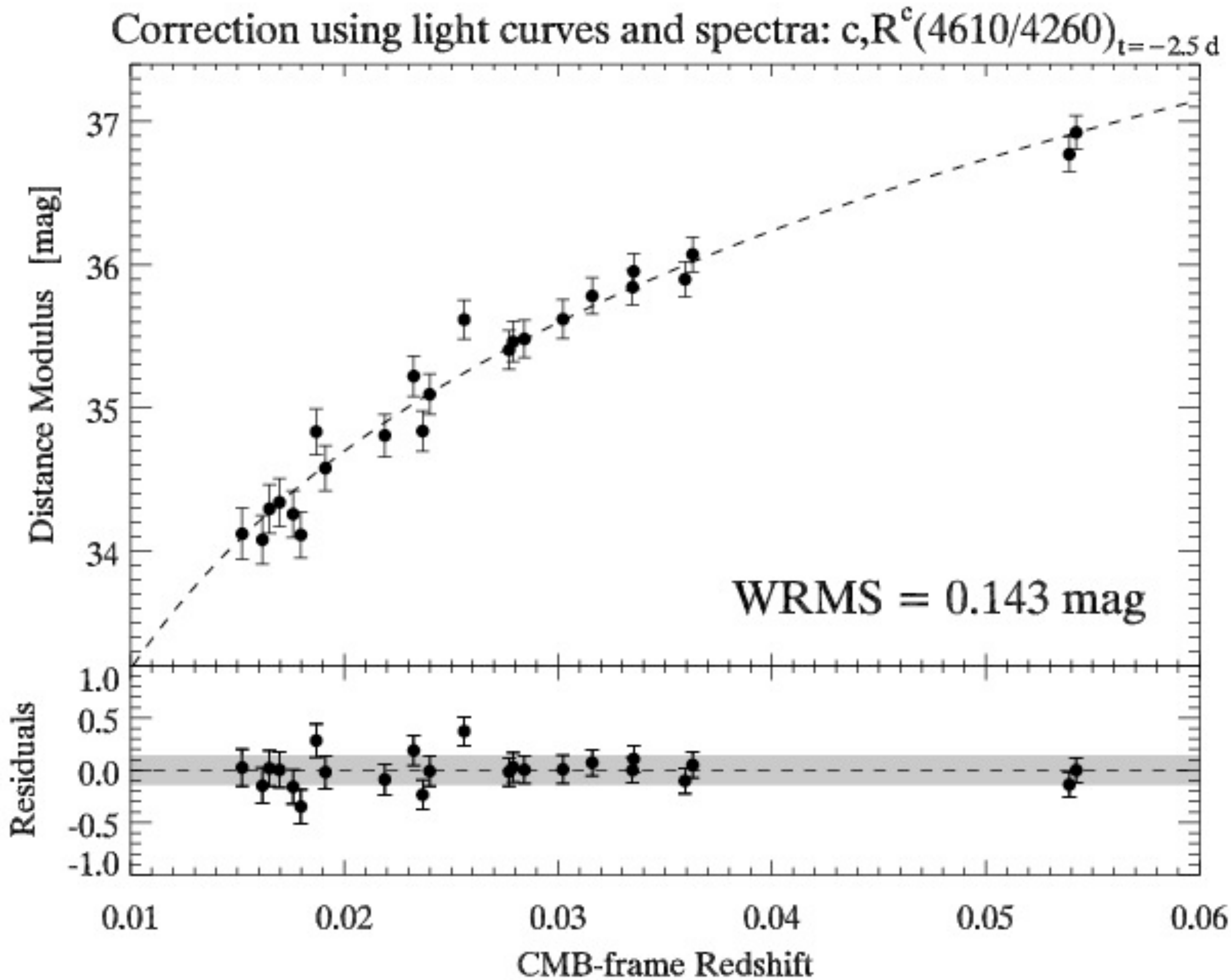



No correction
Distance Modulus [mag]
37
36
35
34
WRMS = 0.462 mag
Residuals
1.0
0.5
0.0
-0.5
-1.0
0.01
0.02
0.03
0.04
0.05
0.06
CMB-frame Redshift



Correction using light curves alone: SALT2 (x1,c)
Distance Modulus [mag]
37
36
35
34
WRMS = 0.213 mag
Residuals
1.0
0.5
0.0
-0.5
-1.0
0.01
0.02
0.03
0.04
0.05
0.06
CMB-frame Redshift


Correction using spectra alone: R(6540/4580)$_{t=-2.5\ d}$
Distance Modulus [mag]
37
36
35
34
WRMS = 0.182 mag
Residuals
1.0
0.5
0.0
-0.5
-1.0
0.01
0.02
0.03
0.04
0.05
0.06
CMB-frame Redshift



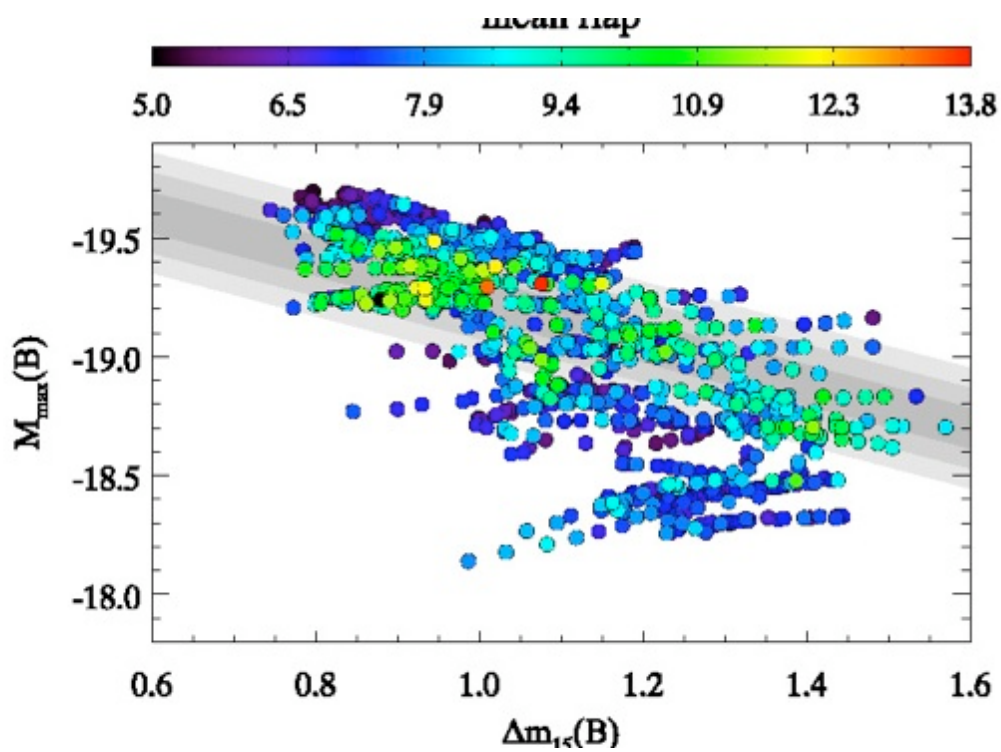
Correction using light curves and spectra: c,R^c(4610/4260)_t=−2.5 d
Distance Modulus [mag]
37
36
35
34
WRMS = 0.143 mag
Residuals
1.0
0.5
0.0
-0.5
-1.0
0.01
0.02
0.03
0.04
0.05
0.06
CMB-frame Redshift

Spectra and Light Curves

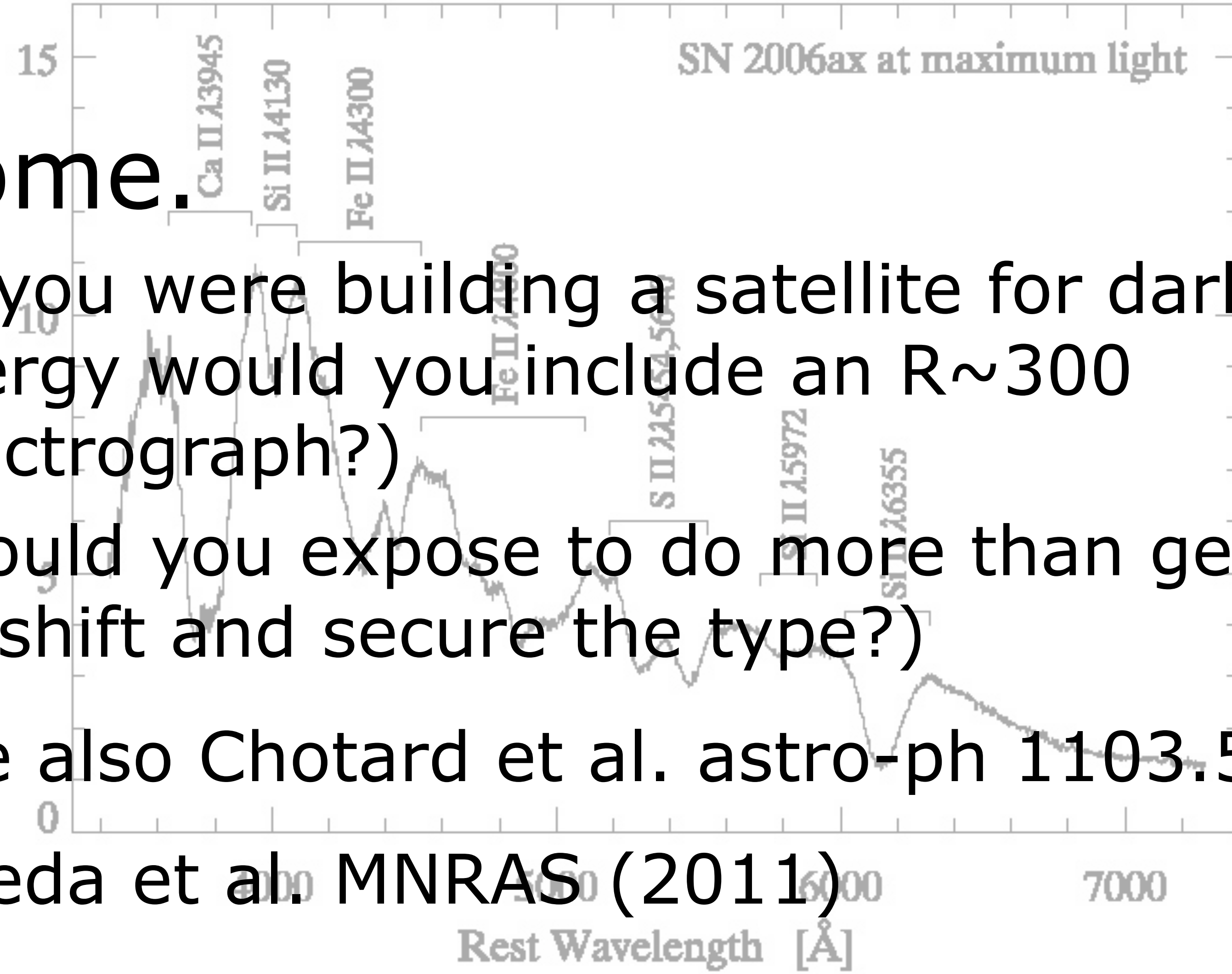
Models form a sequence that spans the observed relation-- but do the spectra look right?

Yes and no.

Blondin et al. MNRAS in press



Can Spectra Help?



Some.

(If you were building a satellite for dark energy would you include an R~300 spectrograph?)

(Would you expose to do more than get the redshift and secure the type?)

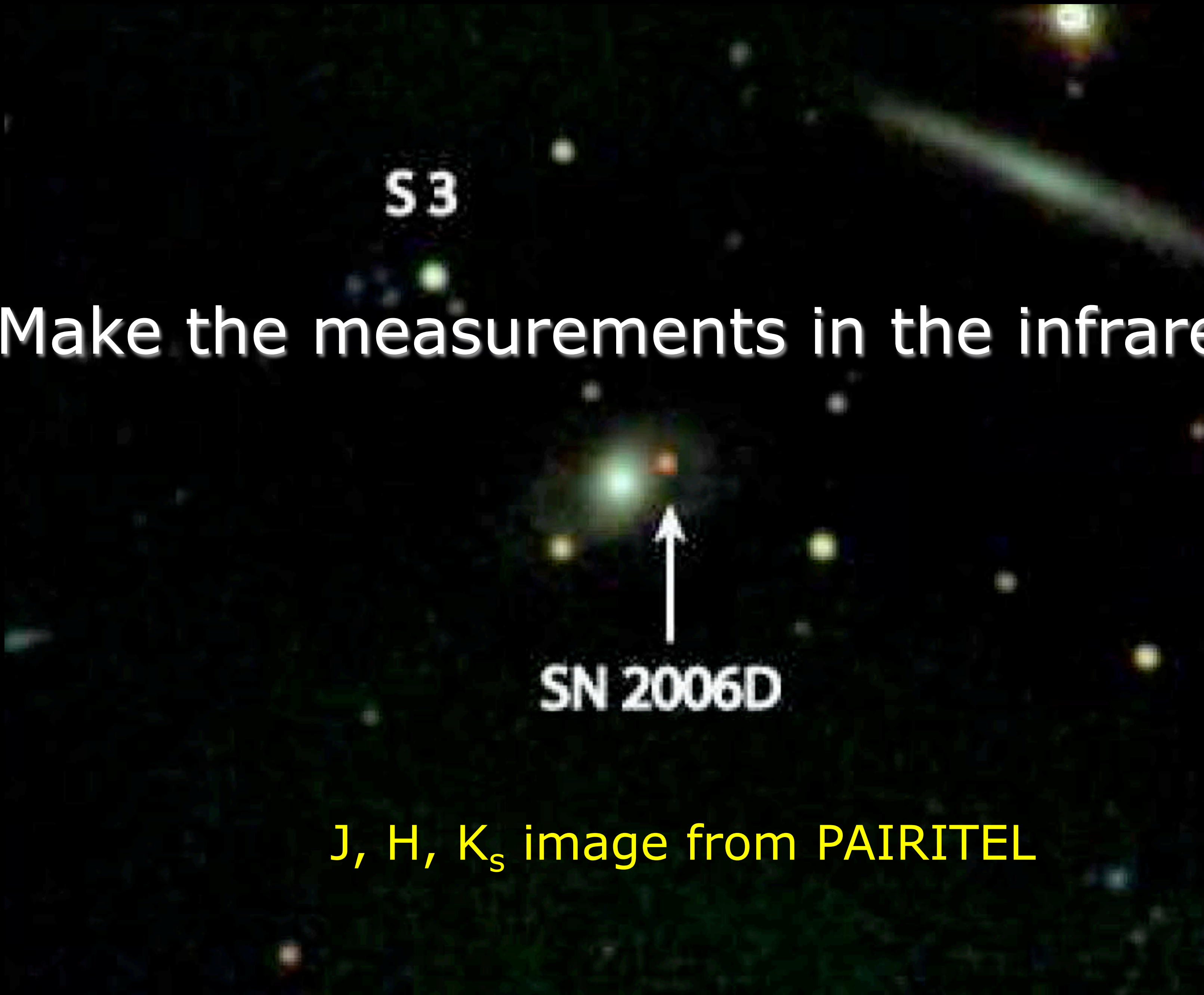
See also Chotard et al. astro-ph 1103.5300

Maeda et al. MNRAS (2011)

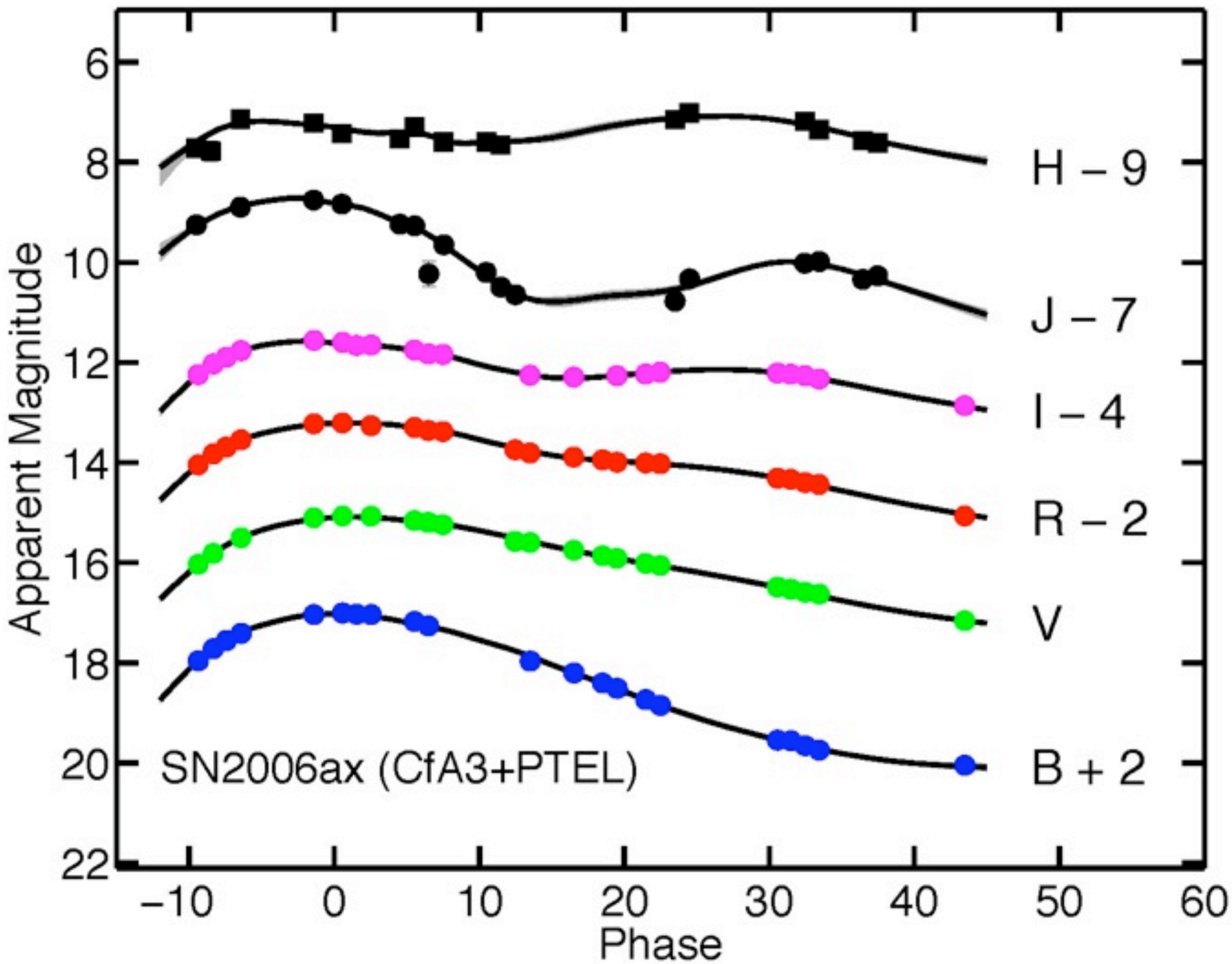
The biggest uncertainties now are **systematic errors** and the worst of these come from dust and light curve fitters

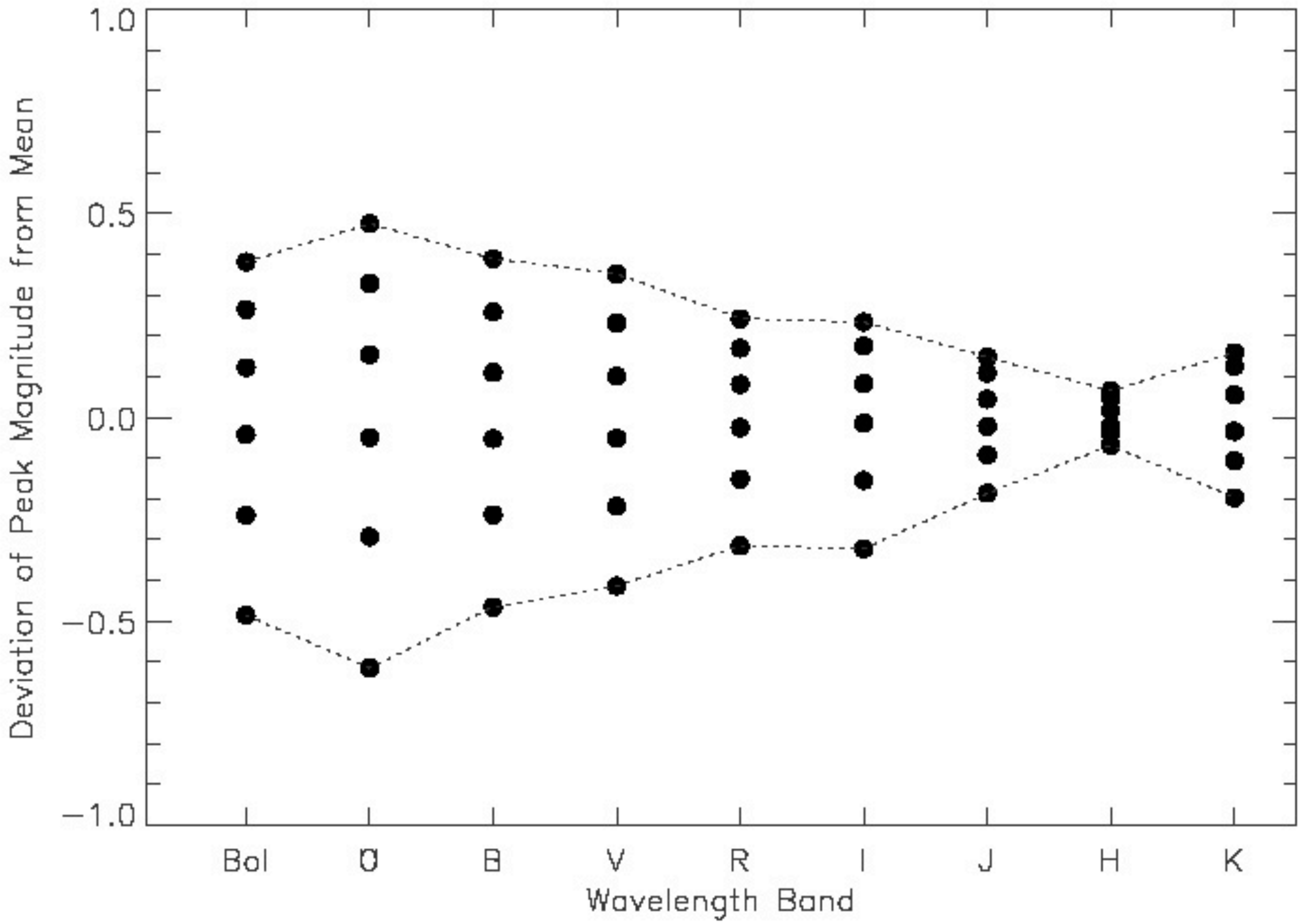
Dust both dims and reddens -- but less so in the infrared

Make the measurements in the infrared!



J, H, K_s image from PAIRITEL


Apparent Magnitude
Phase
H – 9
J – 7
I – 4
R – 2
V
B + 2
SN2006ax (CfA3+PTEL)
6
8
10
12
14
16
18
20
22
−10
0
10
20
30
40
50
60



Theory by Dan Kasen (2006)- expect smallest variance in the IR: Pioneering work by Krisciunas & CTIO group shows this is actually true! CfA: Wood-Vasey et al. 2008

Kaisey Mandel

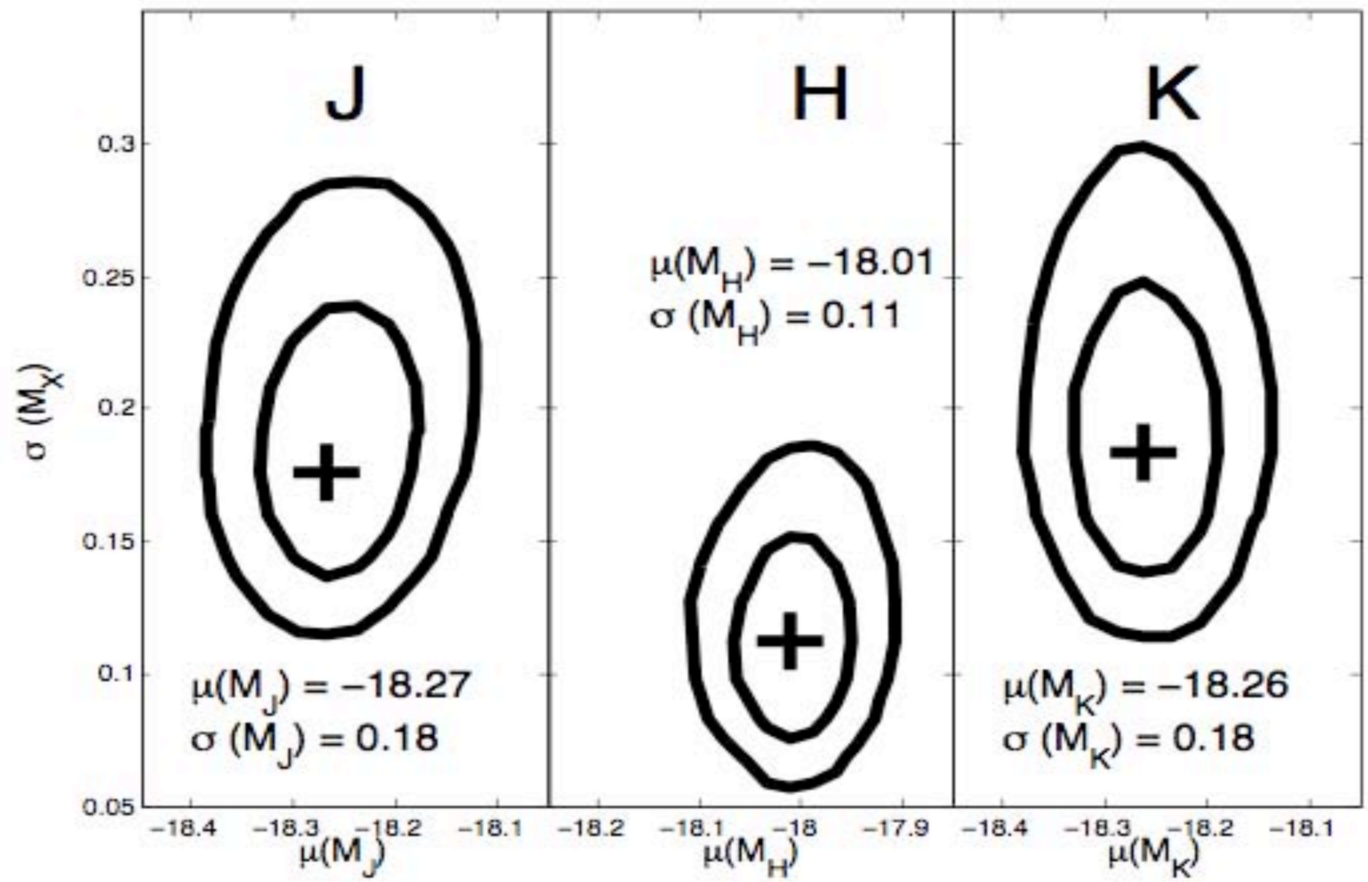
Using a Bayesian model to combine optical and IR data for SN Ia, predict distances, and determine dust properties.

Needs Job!

BayeSN inference : Kaisey Mandel

ApJ 704, 629 (2009)

ApJ 731, 120 (2011)



H-band (1.6 microns) works best

IR + Optical

Get **better distances** & learn about **properties of the dust** by using observations over the range from B (0.4 μ) to K (2.2μ)

We want to know the ratio of absorption to color change (we measure colors but want to know absorption)

Milky Way dust R_v = 3.1 =A_v/ E(B-V), but hints are that SN dust is not the same (${R_v}$ = 1.7 !)

Uses optical and IR data from CfA and CSP

THE ASTROPHYSICAL JOURNAL, 731:120 (26pp), 2011 April 20 doi:10.1088/0004-637X/731/2/120

TYPE Ia SUPERNOVA LIGHT CURVE INFERENCE: HIERARCHICAL MODELS IN THE OPTICAL AND NEAR-INFRARED

KAISEY S. MANDEL, GAUTHAM NARAYAN, AND ROBERT P. KIRSHNER
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; kmandel@cfa.harvard.edu
Received 2010 November 23; accepted 2011 February 1; published 2011 April 1

ABSTRACT

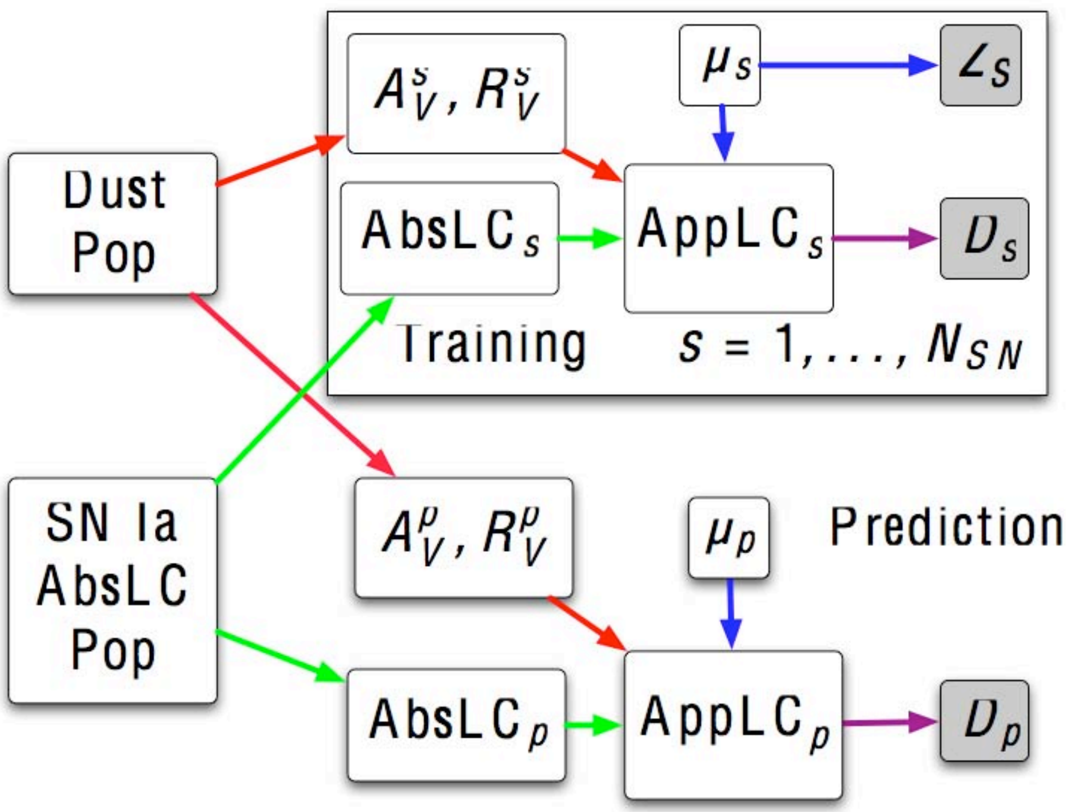
We have constructed a comprehensive statistical model for Type Ia supernova (SN Ia) light curves spanning optical through near-infrared (NIR) data. A hierarchical framework coherently models multiple random and uncertain effects, including intrinsic supernova (SN) light curve covariances, dust extinction and reddening, and distances. An improved BAYESN Markov Chain Monte Carlo code computes probabilistic inferences for the hierarchical model by sampling the global probability density of parameters describing individual SNe and the population. We have applied this hierarchical model to optical and NIR data of 127 SNe Ia from PAIRITEL, CfA3, Carnegie Supernova Project, and the literature. We find an apparent population correlation between the host galaxy extinction A_V and the ratio of total-to-selective dust absorption R_V. For SNe with low dust extinction, $A_V \lesssim 0.4$, we find $R_V \approx 2.5$–2.9, while at high extinctions, $A_V \gtrsim 1$, low values of $R_V < 2$ are favored. The NIR luminosities are excellent standard candles and are less sensitive to dust extinction. They exhibit low correlation with optical peak luminosities, and thus provide independent information on distances. The combination of NIR and optical data constrains the dust extinction and improves the predictive precision of individual SN Ia distances by about 60%. Using cross-validation, we estimate an rms distance modulus prediction error of 0.11 mag for SNe with optical and NIR data versus 0.15 mag for SNe with optical data alone. Continued study of SNe Ia in the NIR is important for improving their utility as precise and accurate cosmological distance indicators.

Key words: distance scale – methods: statistical – supernovae: general

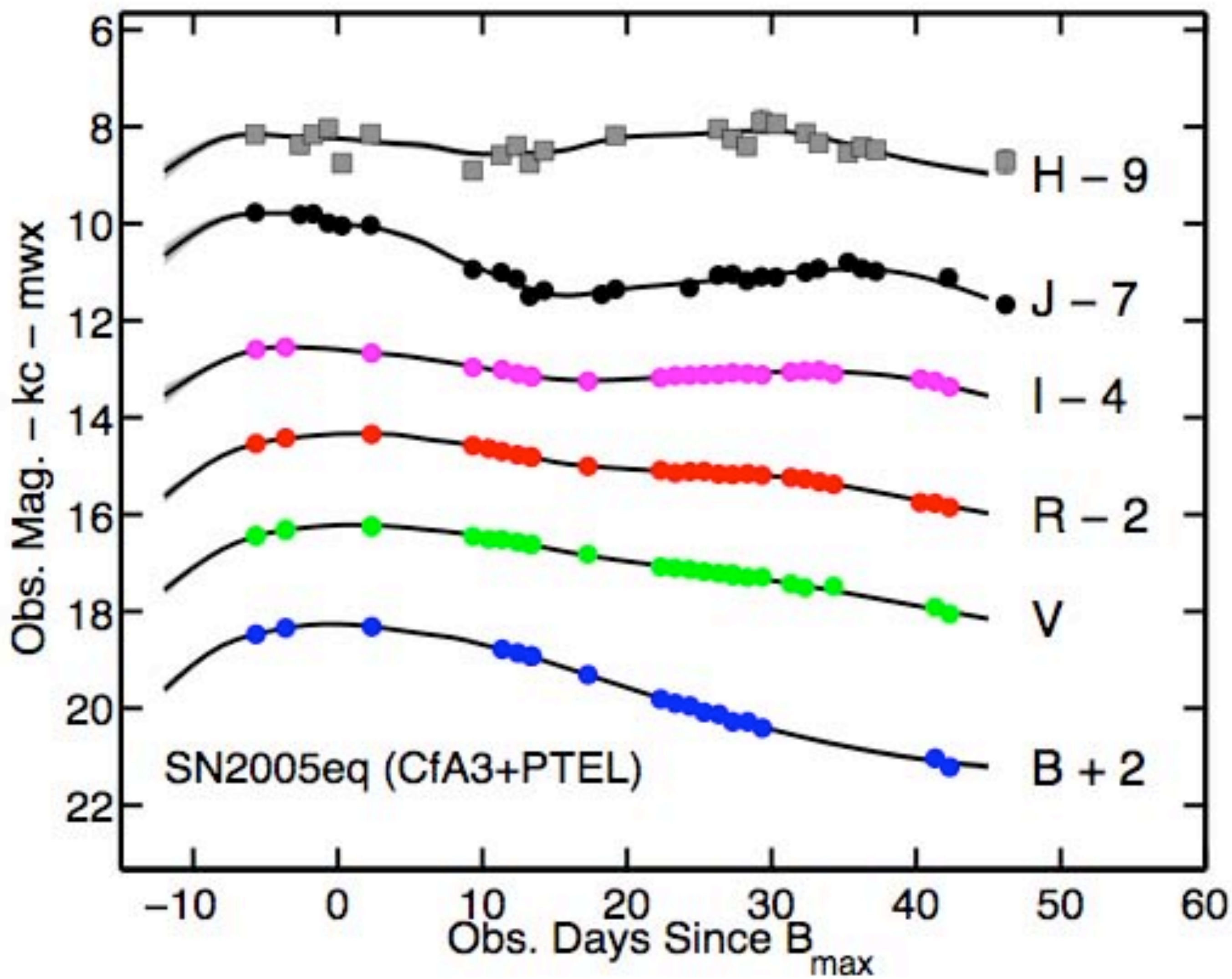
Modeling SN Ia Light Curves:

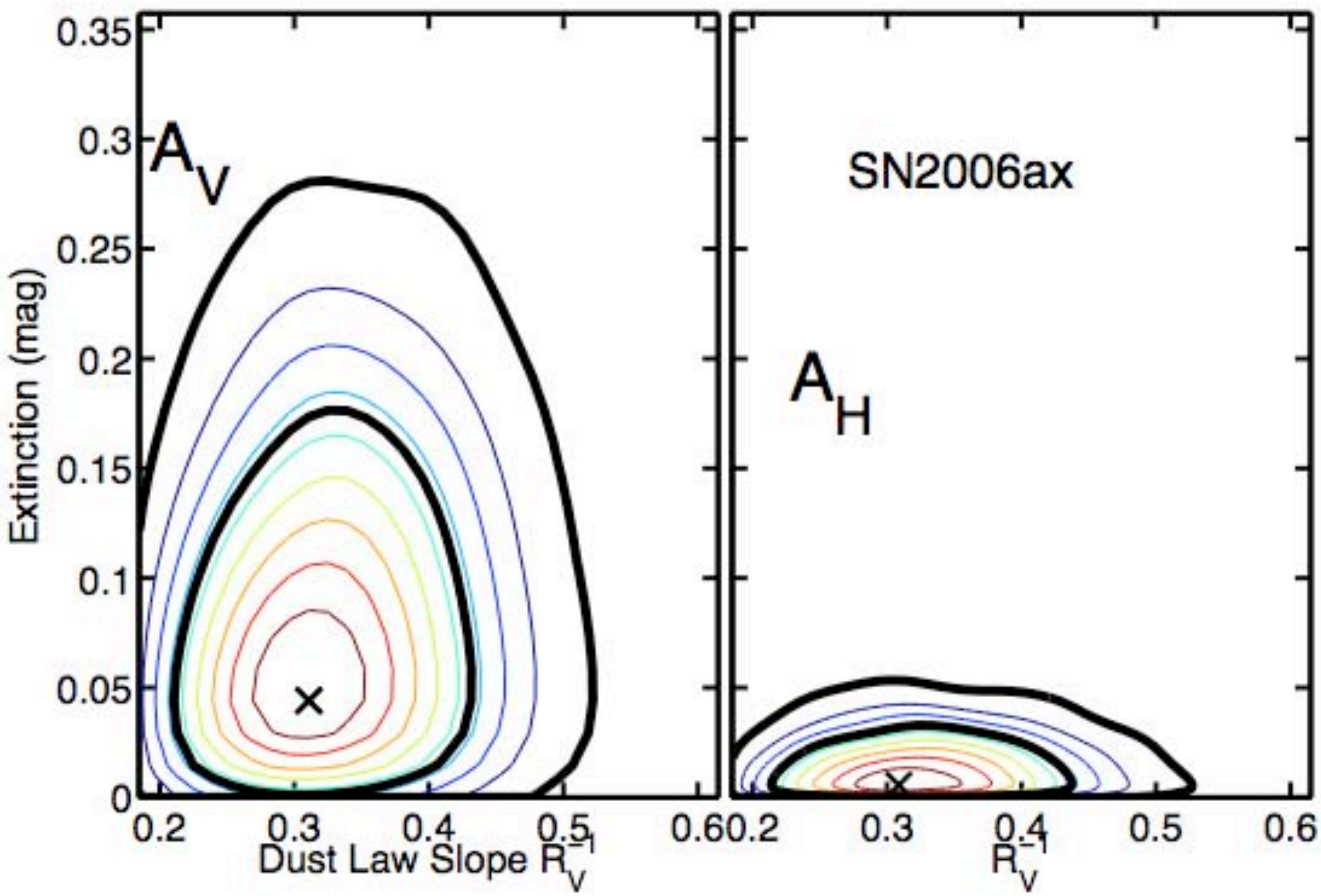
Using the Optical + IR to learn about dust and distance

Kaisey Mandel, RPK & Gautham Narayan



Andy Friedman thesis-- will have ~80 NIR light curves from PAIRITEL

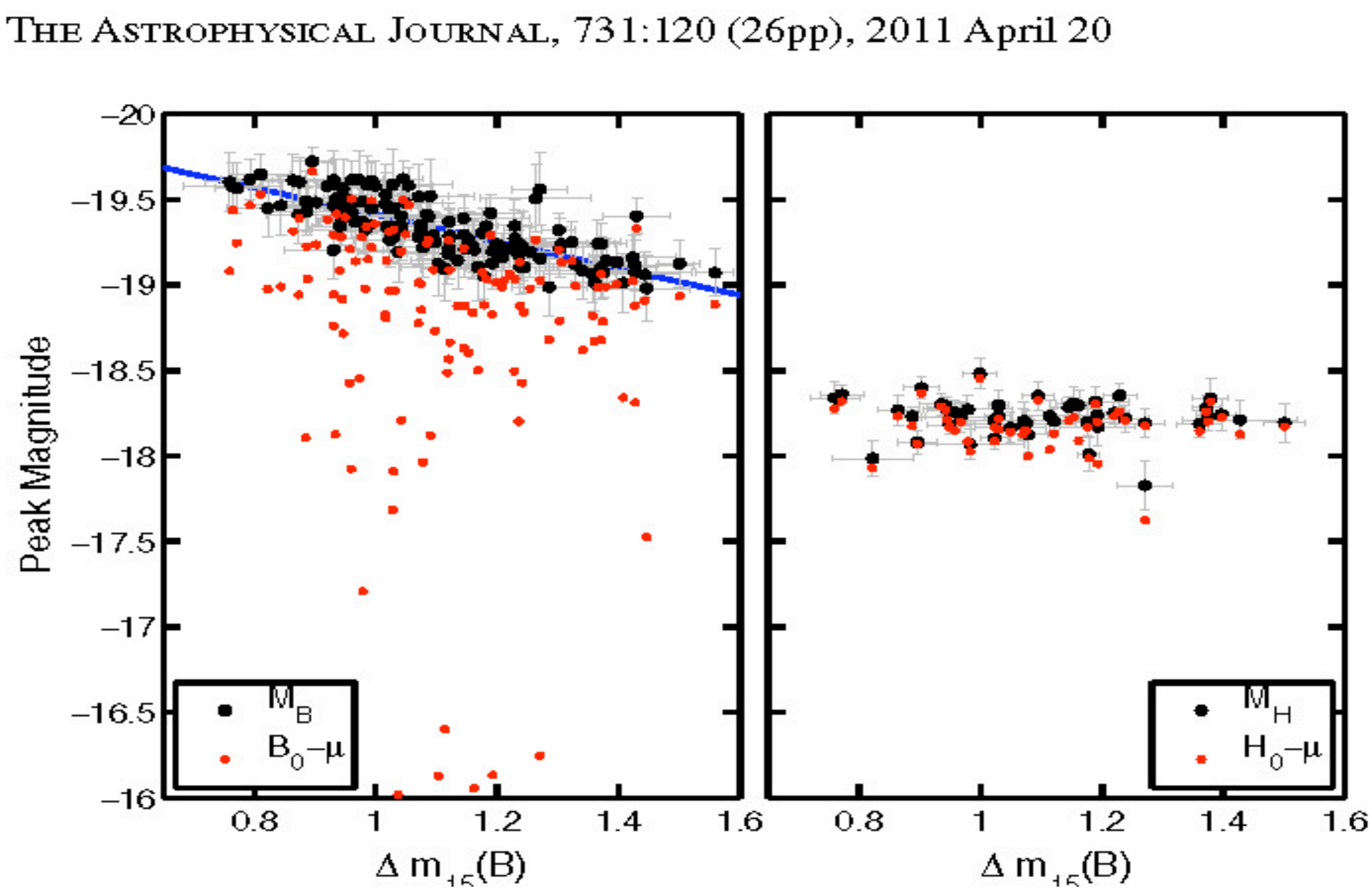




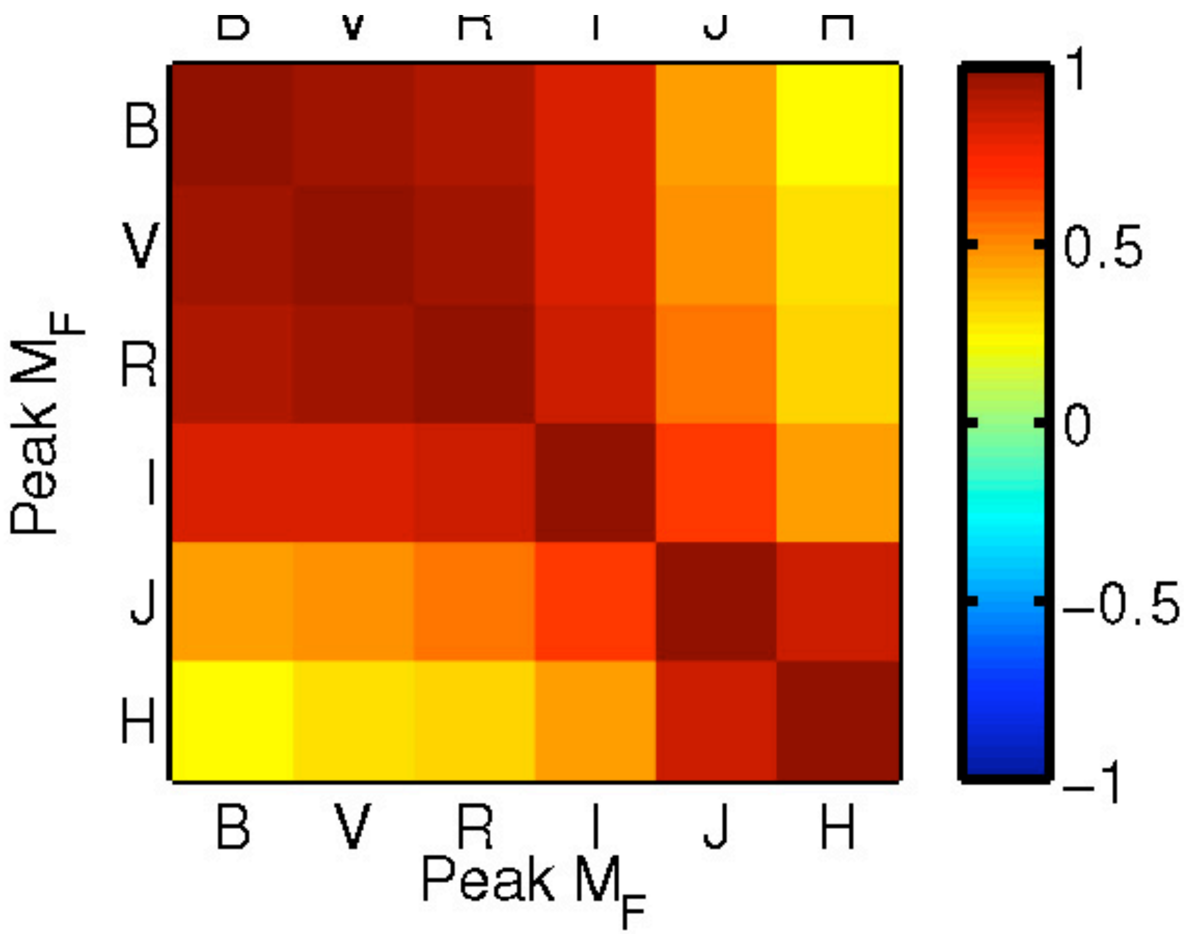
A_V
SN2006ax
A_H
Extinction (mag)
Dust Law Slope R_V^-1
R_V^-1
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.2
0.3
0.4
0.5
0.6

Optical: standardizable candles

IR: standard candles! (and less trouble with dust!)



The IR is not strongly correlated with the Optical



Odd thing:

R_v looks ~3.1 for low extinction

R_v looks lower when extinction is high (different mechanism?)

See also Folatelli AJ 109, 120 (2010)

MANDEL, NARAYAN, & KIRSHNER

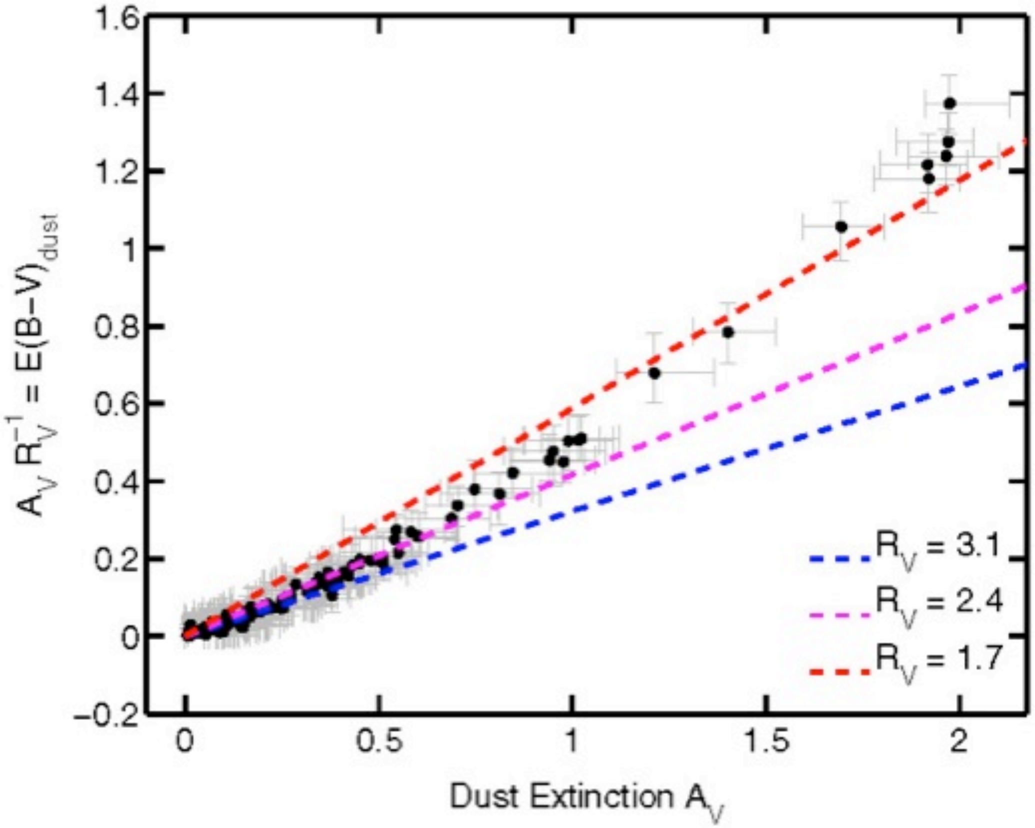
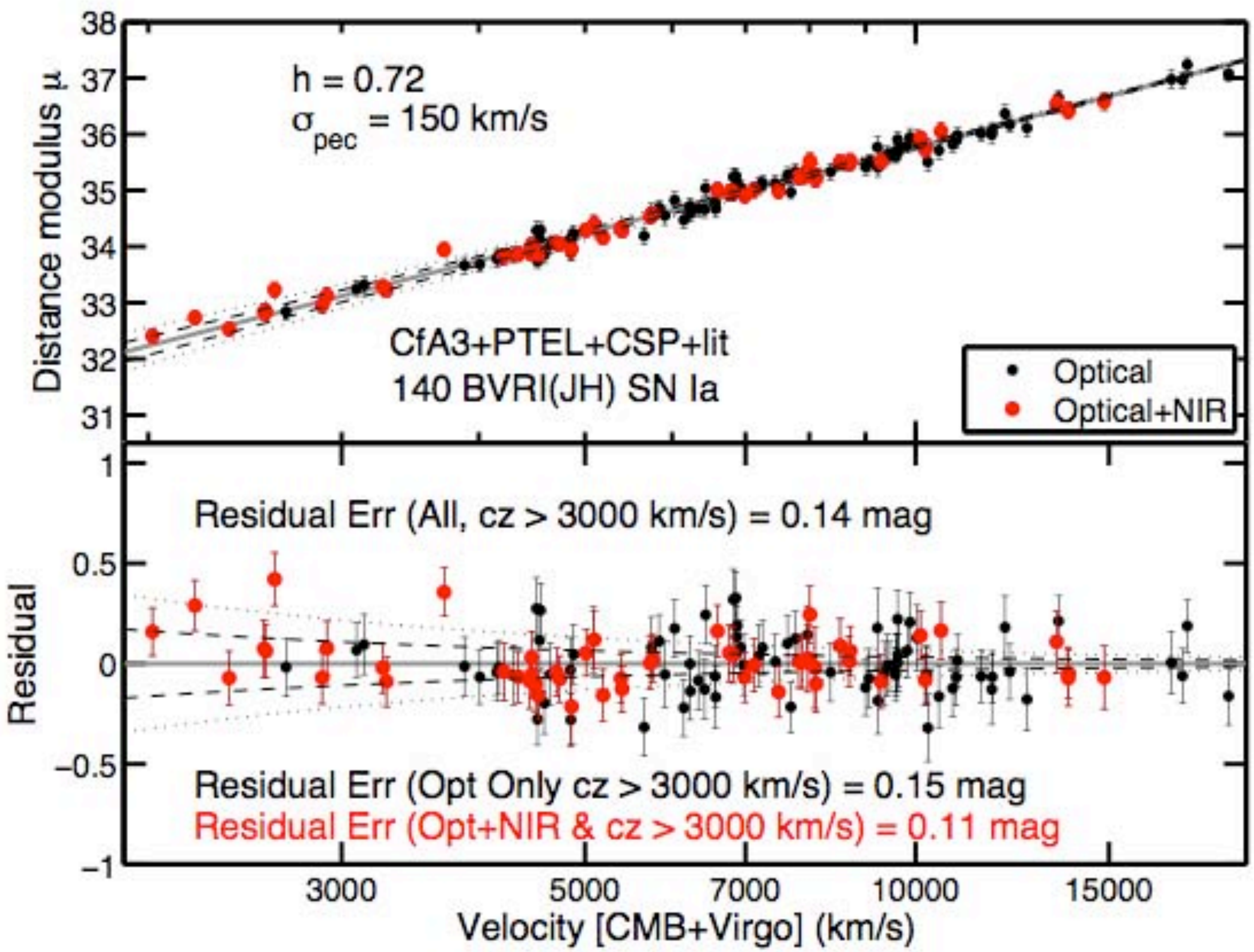


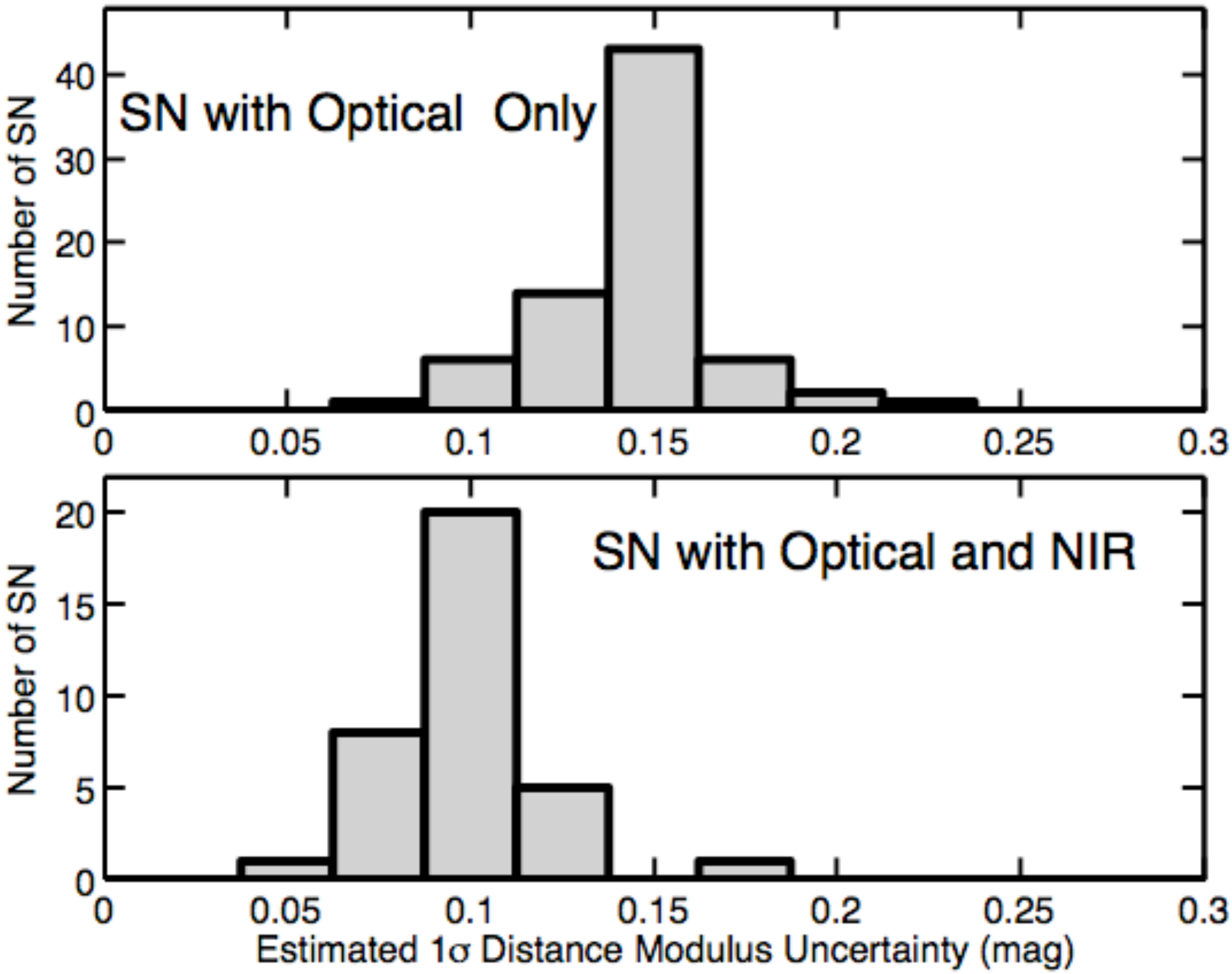
Figure 10. Marginal posterior estimates of inferred color excess $E(B-V)$ due to host galaxy dust vs. inferred extinction A_V, assuming the linear correlation

The Payoff



h = 0.72
σ_{pec} = 150 km/s
CfA3+PTEL+CSP+lit
140 BVRI(JH) SN Ia
Optical
Optical+NIR
Distance modulus μ
Residual Err (All, cz > 3000 km/s) = 0.14 mag
Residual Err (Opt Only cz > 3000 km/s) = 0.15 mag
Residual Err (Opt+NIR & cz > 3000 km/s) = 0.11 mag
Residual
Velocity [CMB+Virgo] (km/s)
38
37
36
35
34
33
32
31
1
0.5
0
−0.5
−1
3000
5000
7000
10000
15000

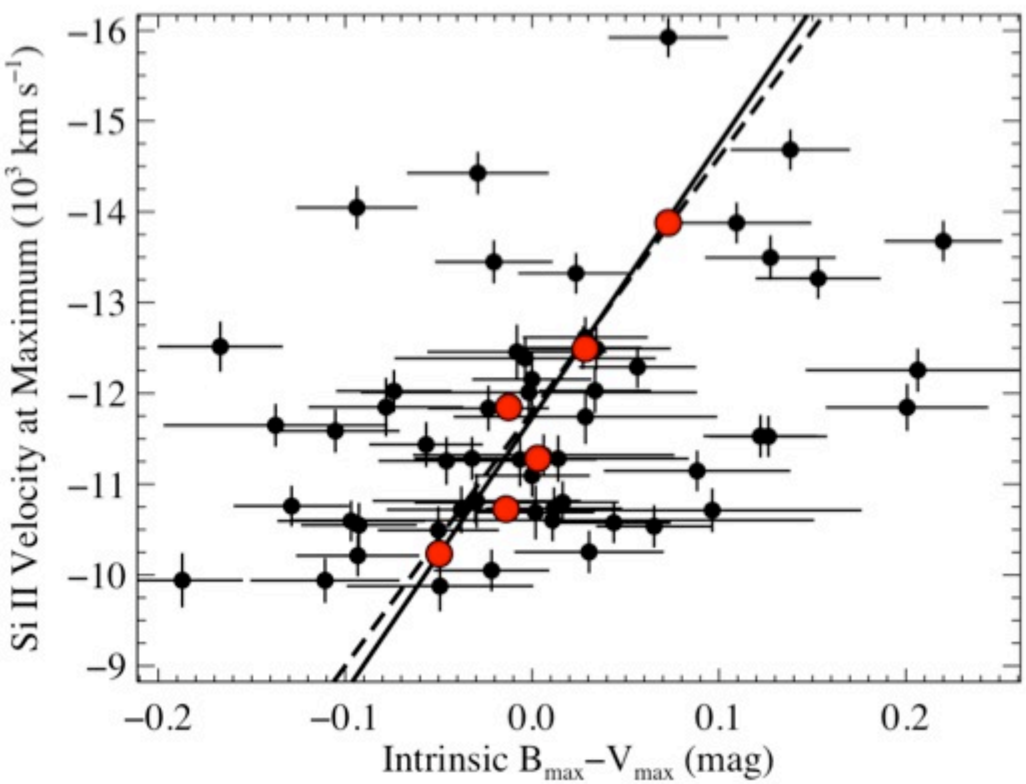
Could we get this advantage for the high-z supernovae? RAISIN



Measuring Ejecta Velocity Improves Type Ia Supernova Distances

Foley & Kasen ArXiv1011.4517

B-V color and velocity are correlated

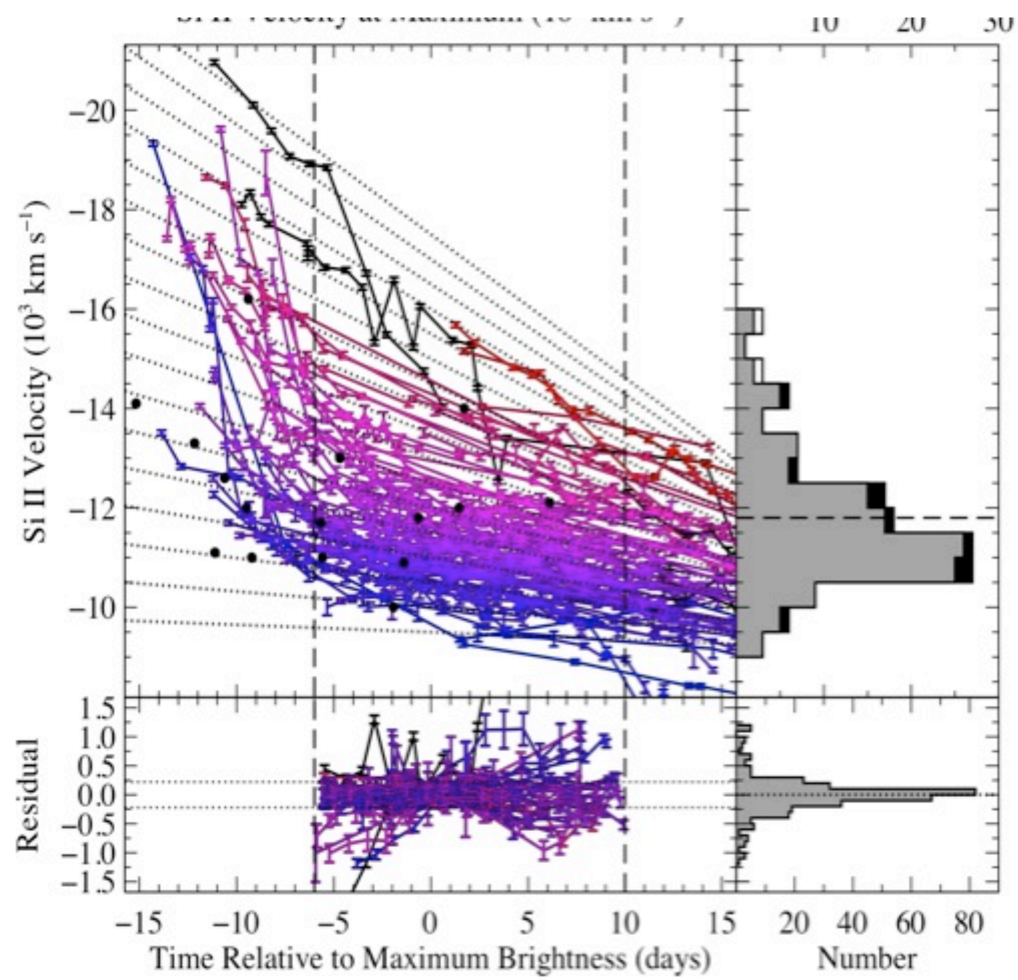


Ryan Foley

Clay Fellow at CfA

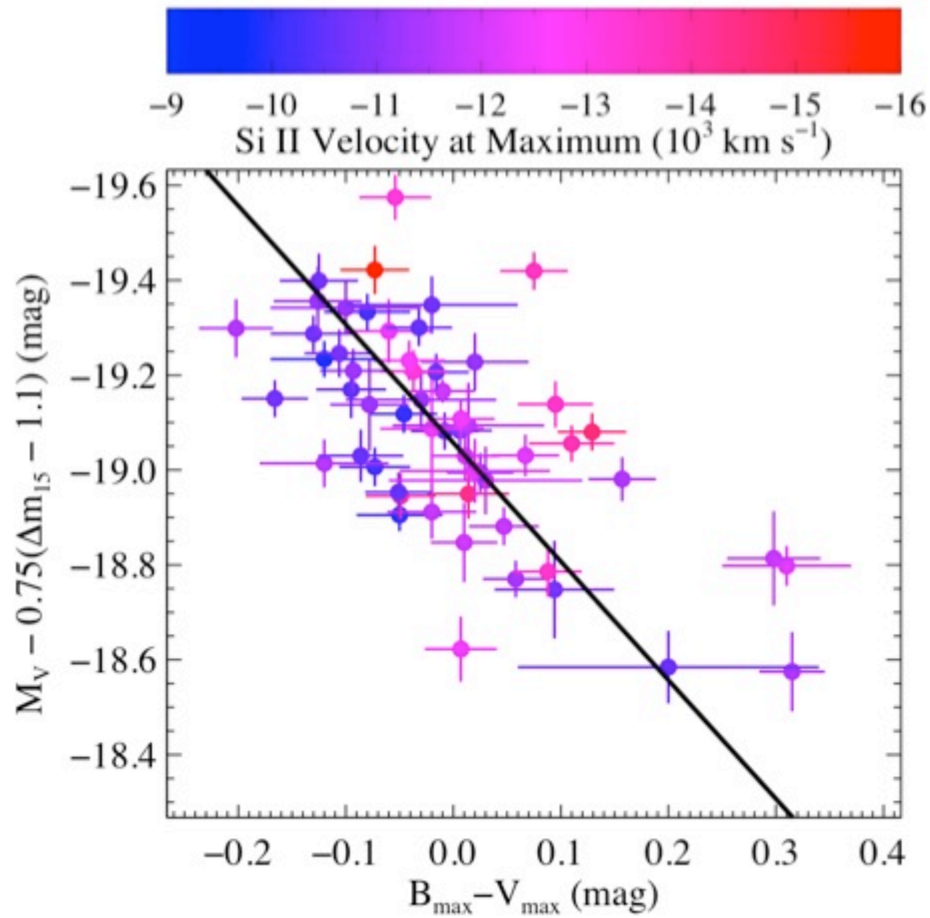
The CfA data are helpful because there are spectra at many epochs

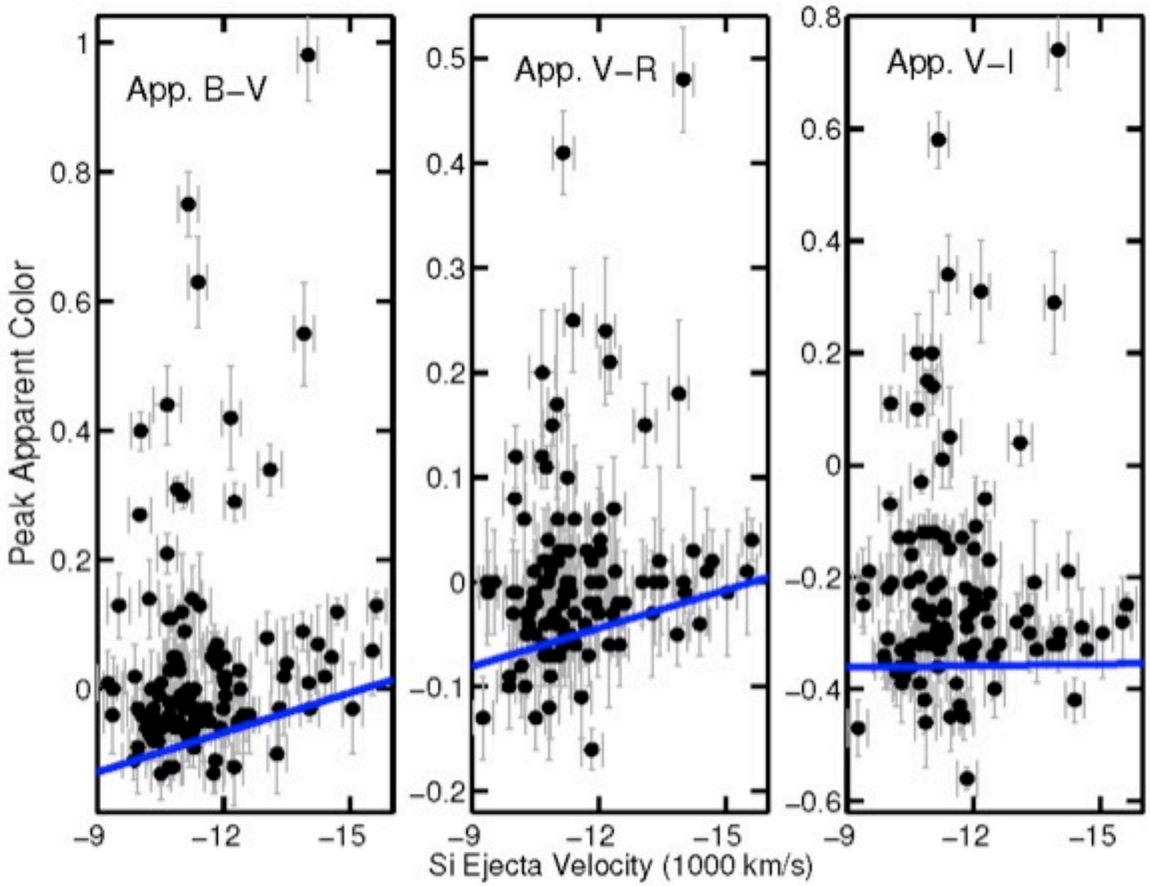
This permits a good interpolation to v (max)



Velocity is correlated with B-V color and these help account for **departures** from the light curve shape

Use BayeSN!





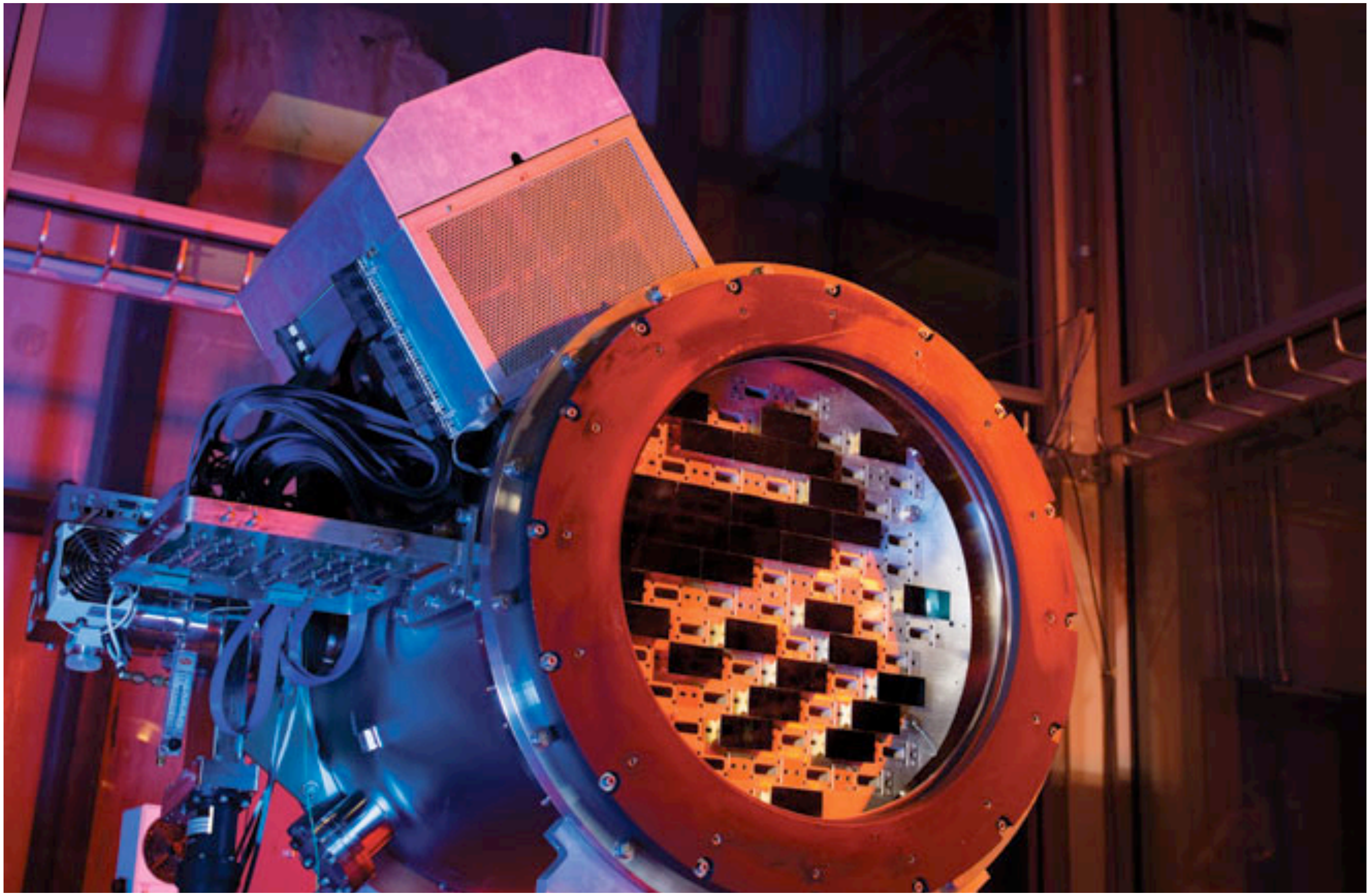
Using Kaisey's BayeSN method- there is definitely a correlation between B-V color and ejecta velocity as measured in the Si II lines

Applying this decreases the prediction error to ~0.12 mag

The Future

Skymapper-- a (small) southern Sloan

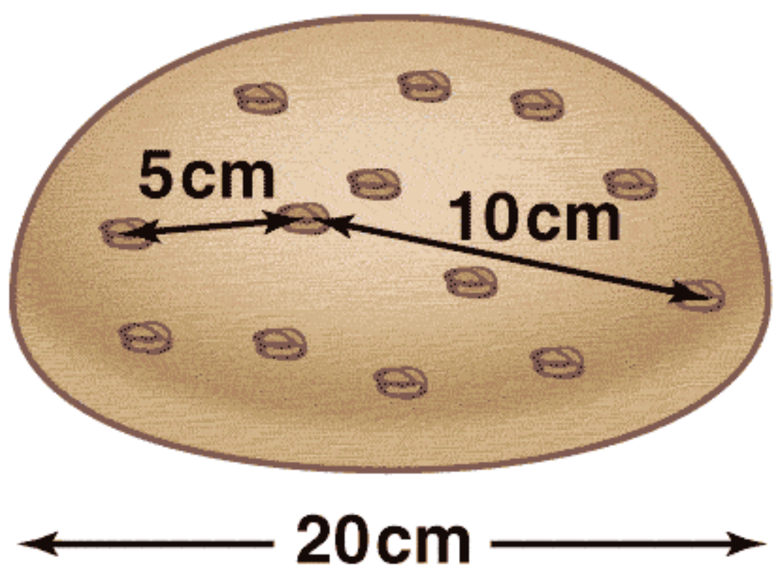
Dark Energy Survey



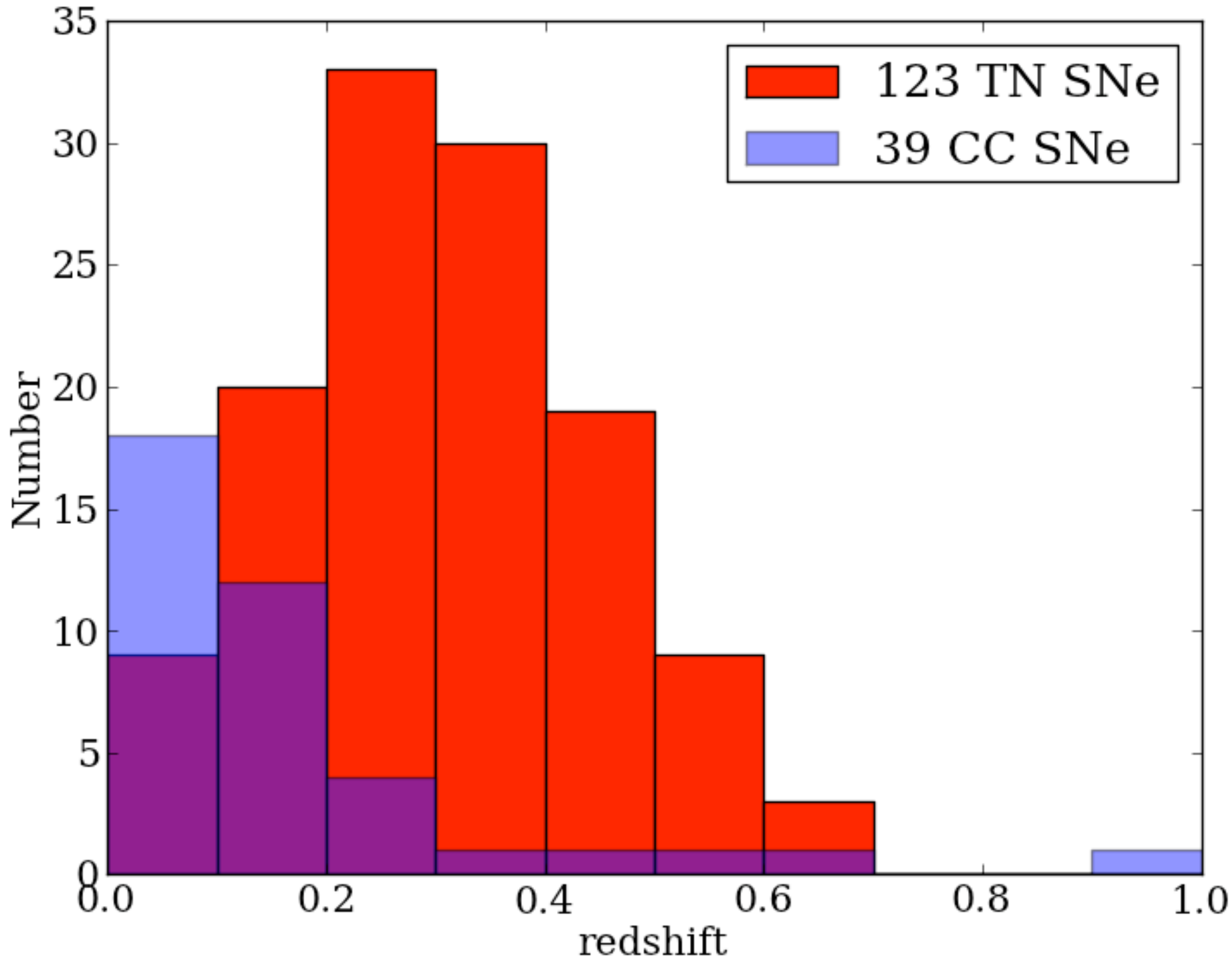
Fermilab project hopes to uncover why universe expansion is accelerating

BY **KEVIN DANNA** NOV 03, 2010

Use WFC3 to get rest frame IR of moderate redshift SN Ia!
SNIA in the IR = RAISIN

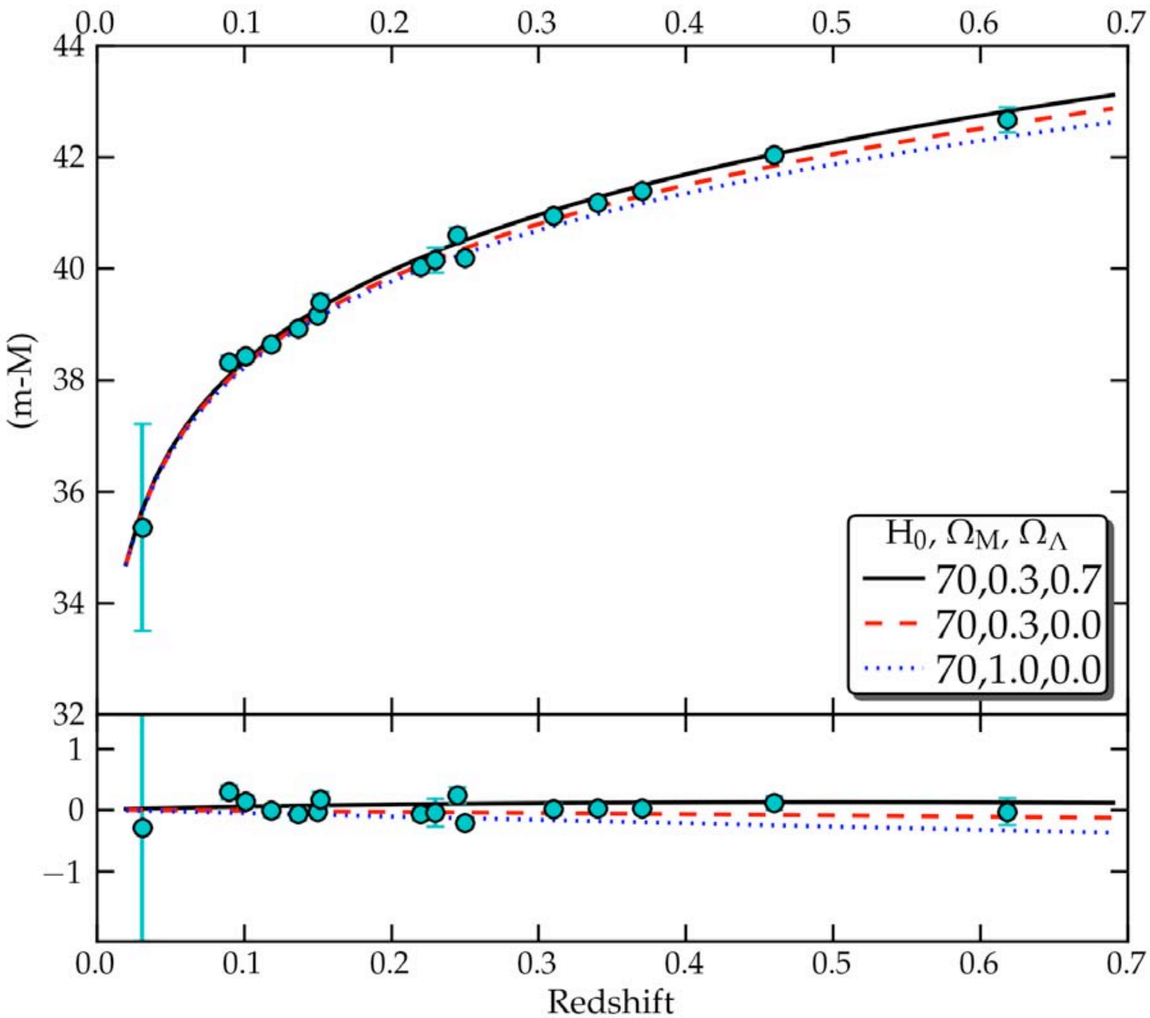


MAP990404



Spectra from Magellan, MMT, Gemini

Key to the RAISIN program to get restframe IR of SN Ia-- inspired by CSP

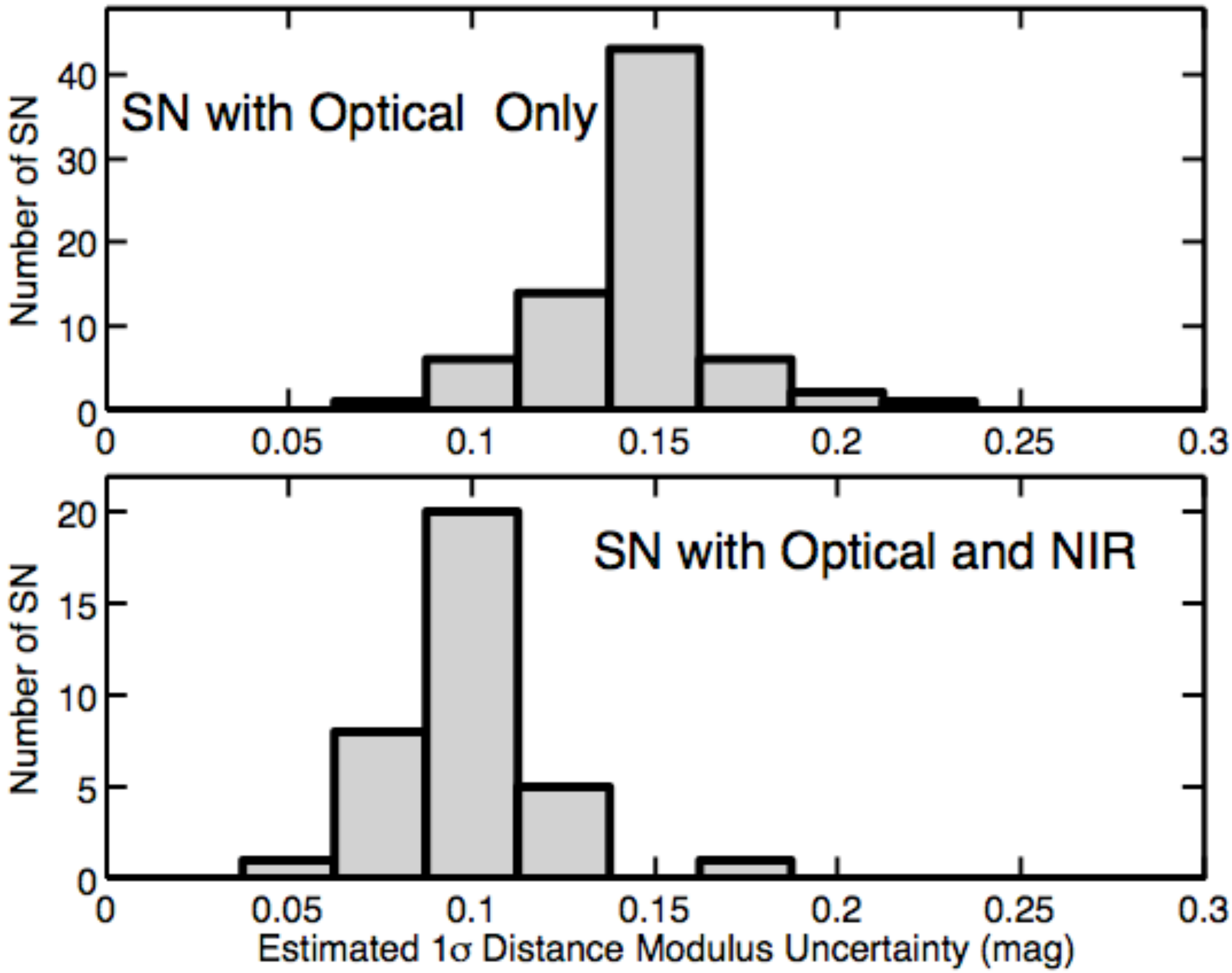


One month of panSTARRS also finds an accelerating universe!

Very big range in redshift all with a single system.

Select a sample to minimize systematics.

Could we get this advantage for the high-z supernovae?



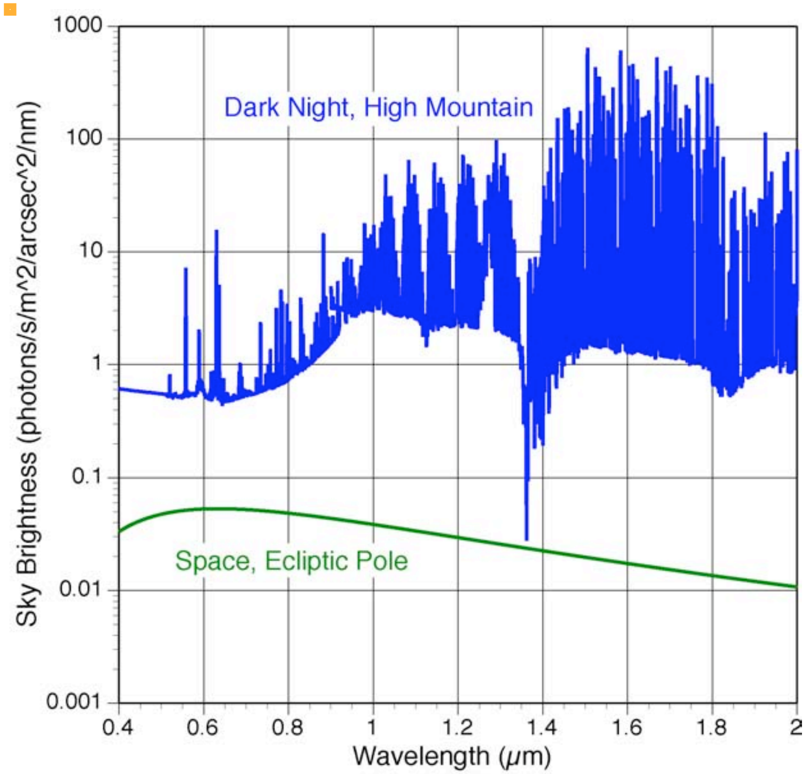
Only in space!

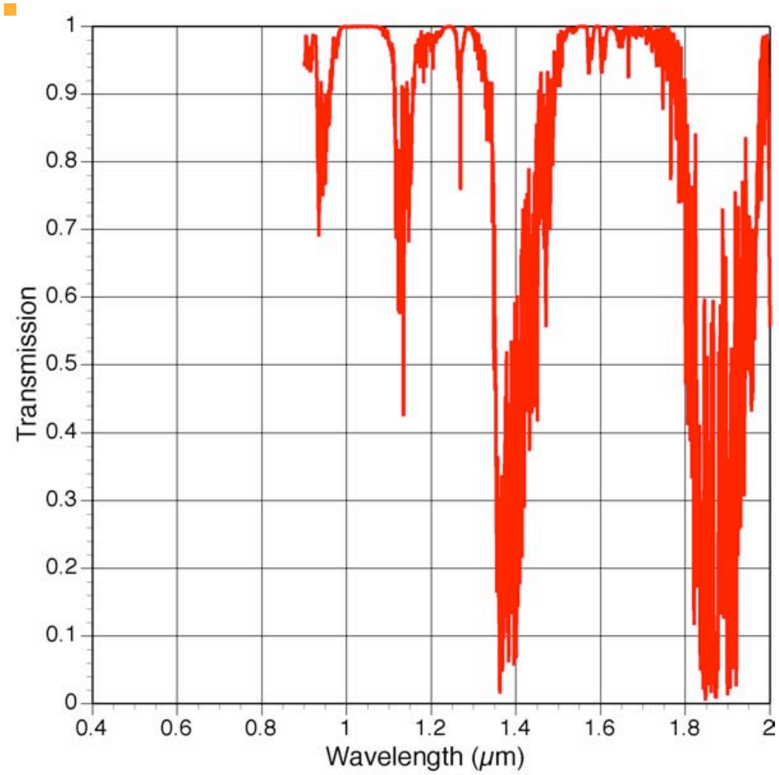
Rest frame IR measurements of z~1 supernovae are not possible from the ground

Go as far into the IR as technically feasible!

Sky is very bright in NIR: >100x brighter than in space

Sky is not transparent in NIR: absorption due to water is very strong and extremely variable





Odd thing:

R_v looks ~3.1 for low extinction

R_v looks lower when extinction is high (different mechanism?)

See also Folatelli

MANDEL, NARAYAN, & KIRSHNER

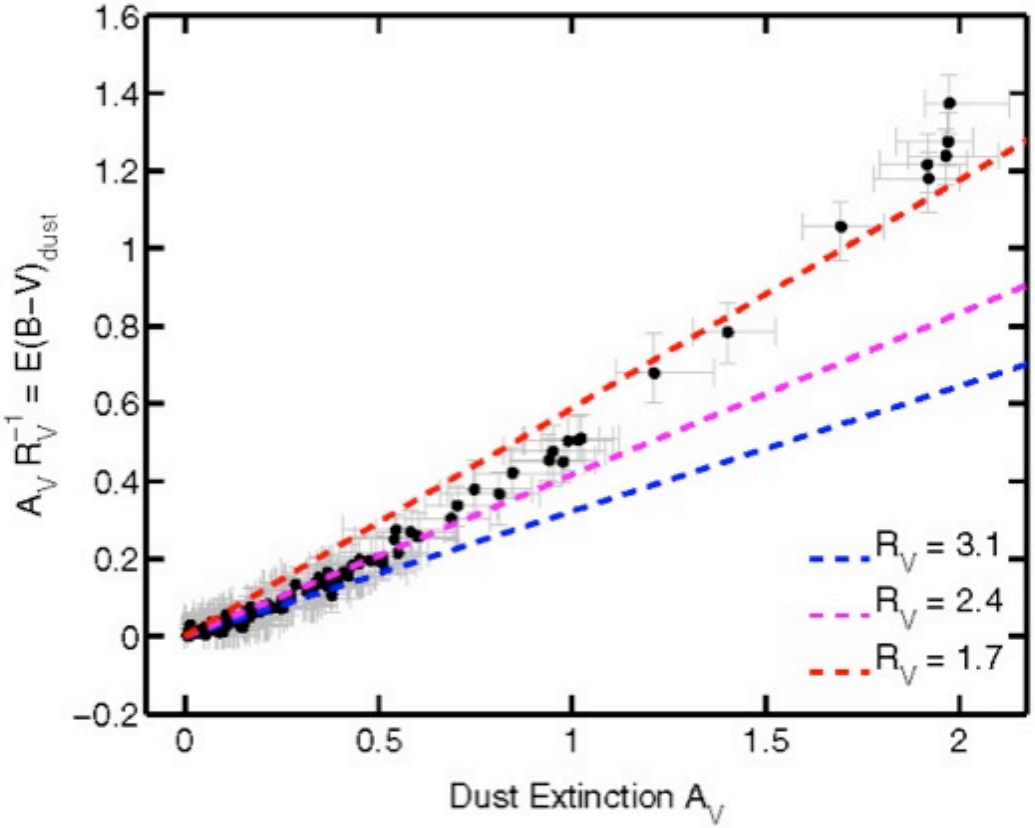
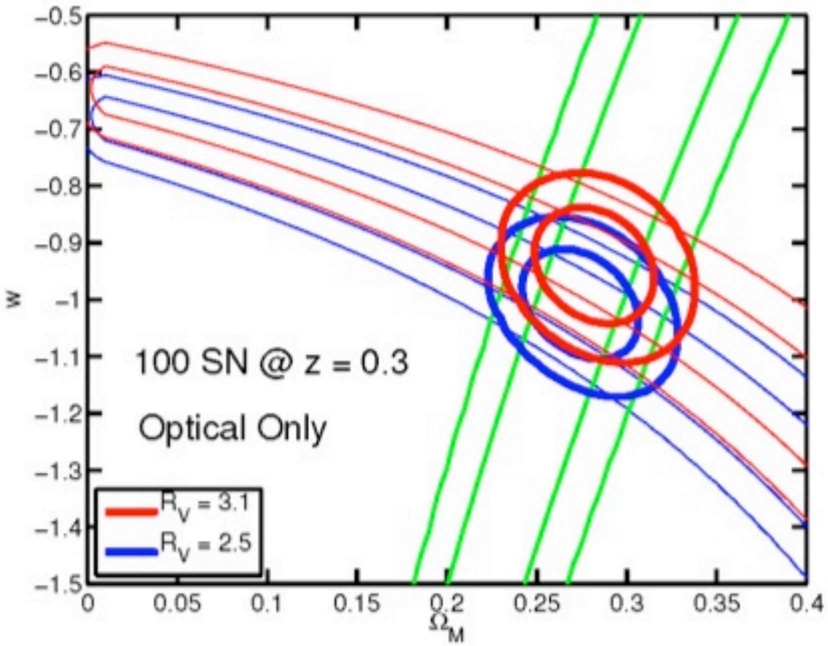
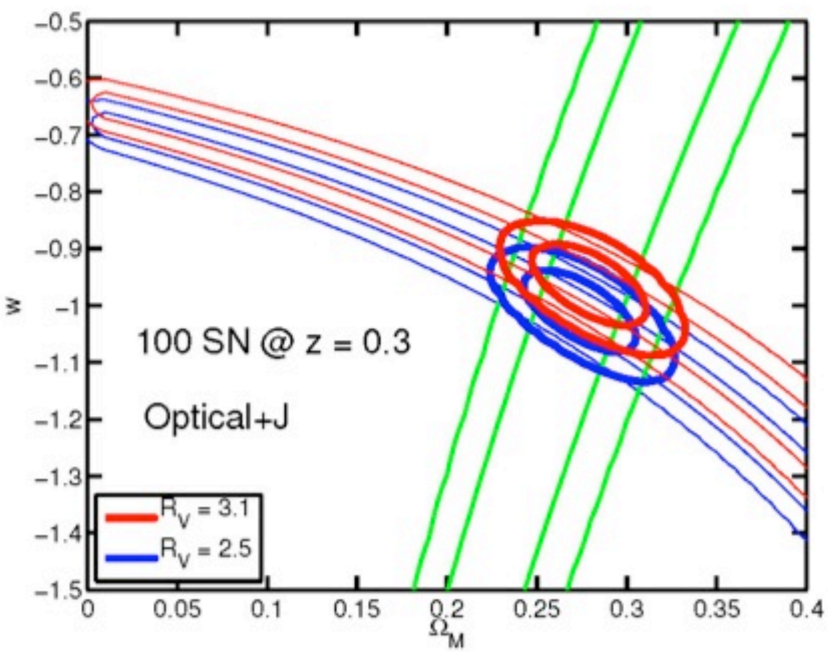


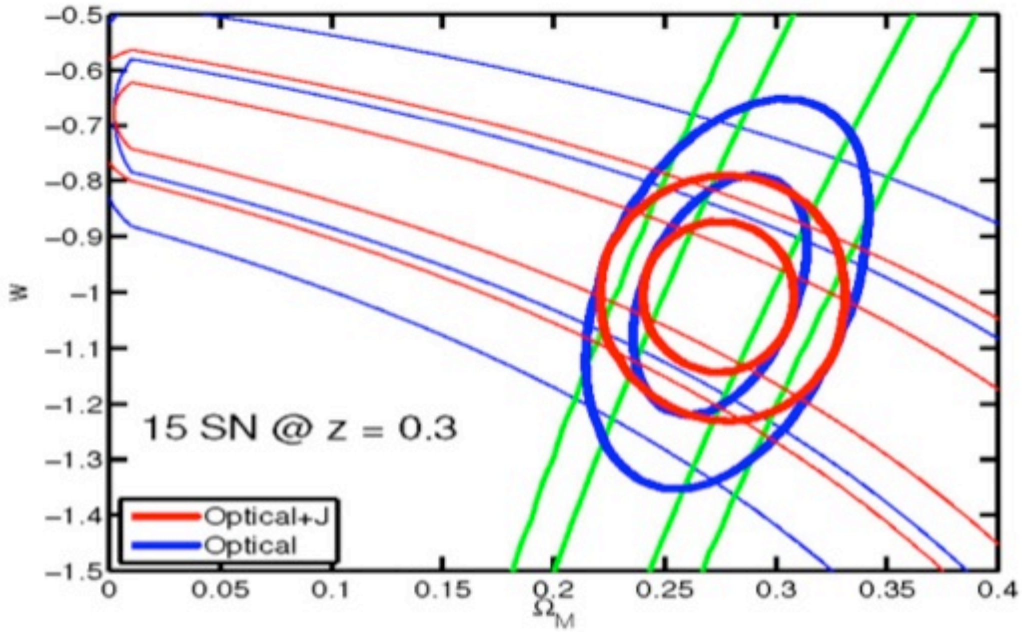
Figure 10. Marginal posterior estimates of inferred color excess $E(B-V)$ due to host galaxy dust vs. inferred extinction A_V, assuming the linear correlation



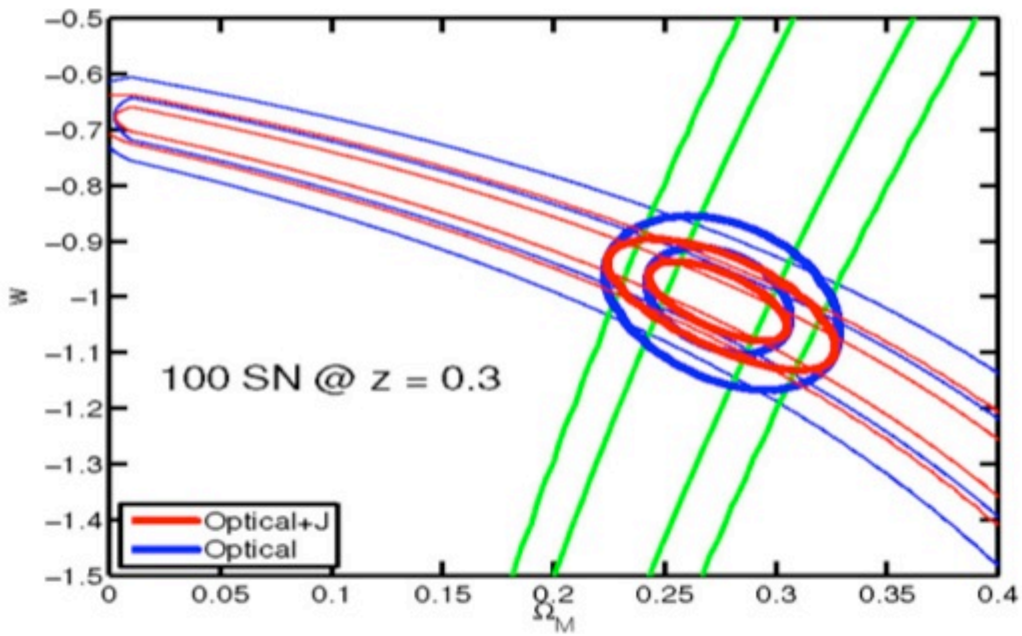
Uncertainty in extinction law produces uncertainty in dark energy!



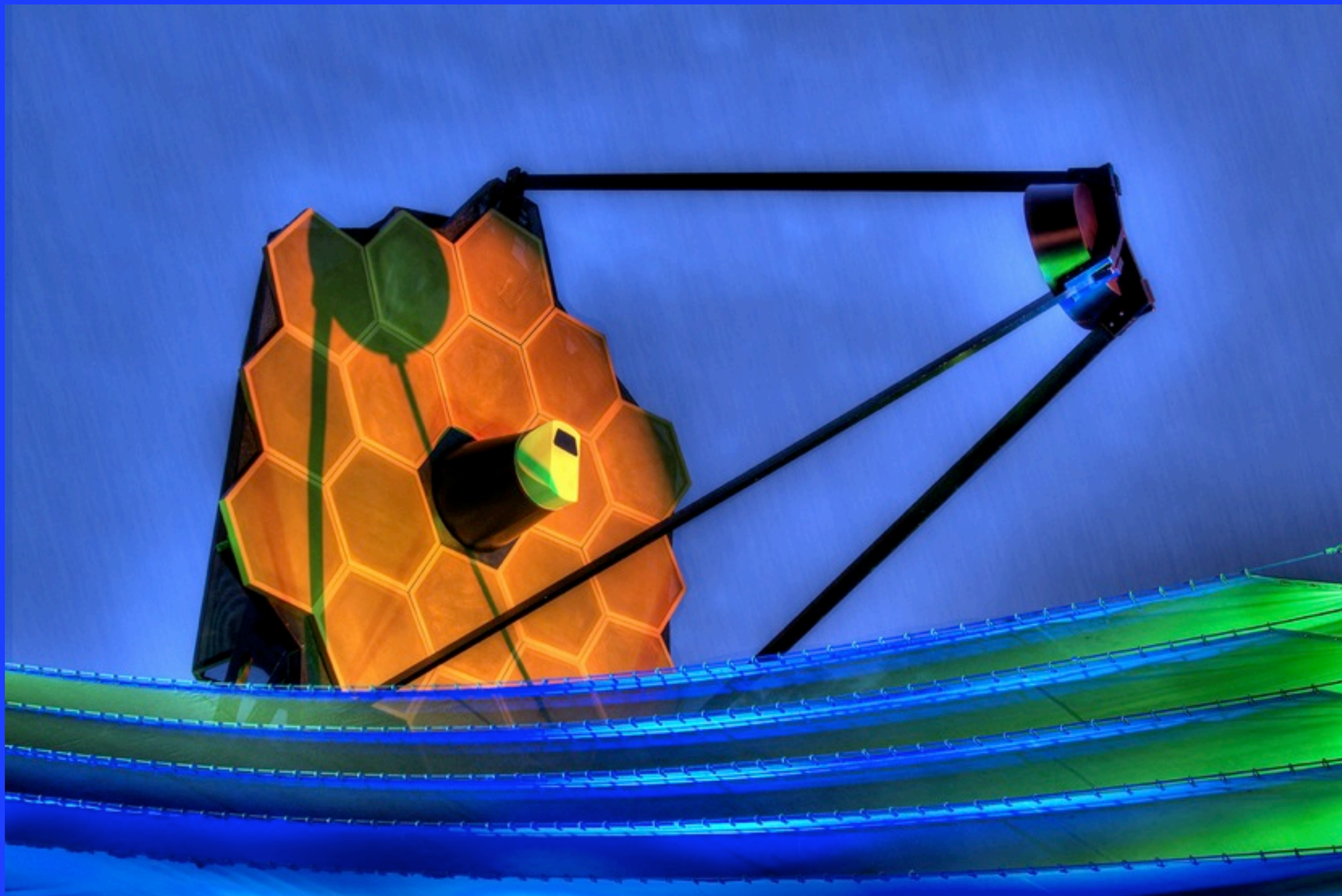
Adding the IR really helps



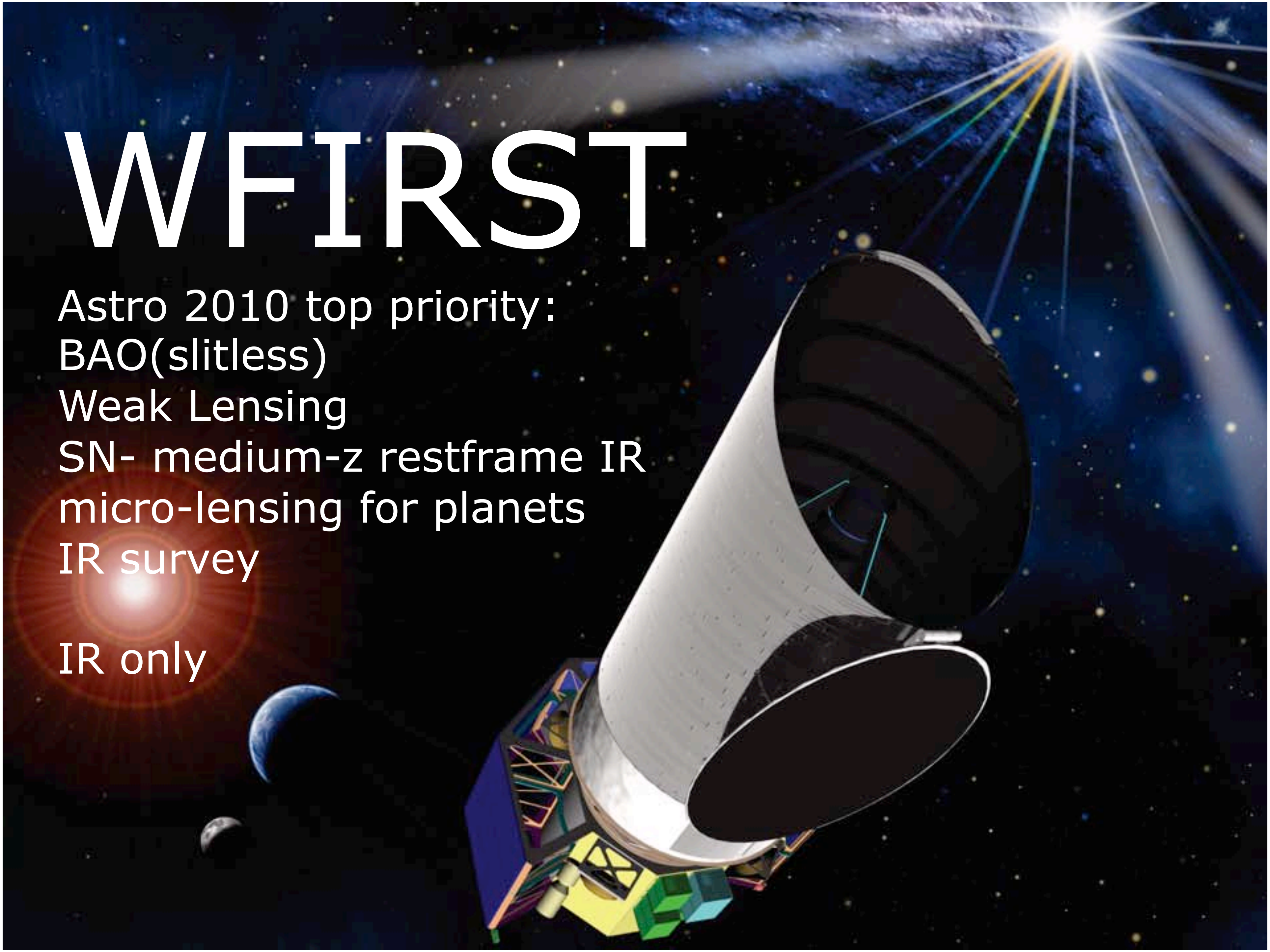
A pilot sample (next HST Cycle)



A real contribution to our knowledge of dark energy



JWST will be excellent for the rest frame IR of SN Ia at 0.2< z <1


WFIRST
Astro 2010 top priority:
BAO(slitless)
Weak Lensing
SN- medium-z restframe IR
micro-lensing for planets
IR survey
IR only

First wide-field survey telescope