Type Ia SN Cosmology after the Nobel prize:

Level UP or GAME OVER

Ariel Goobar

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The Nobel Prize in Physics 2011

Saul Perlmutter, ***The Supernova Cosmology Project***
Brian P. Schmidt and Adam G. Riess, ***The High-z Supernova Search Team***
"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

SCP & HZT – December 2011

Two decades of hard work!

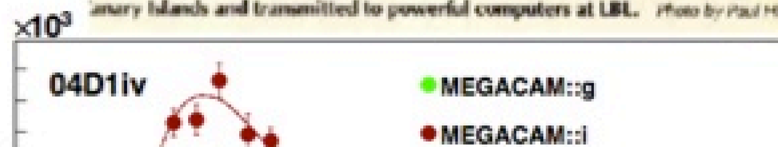
Perlmutter et al 1994

redshifts, thereby allowing one to
shows the $\Omega_M - \Omega_\Lambda$ plane, with
(SCP) (16) and the High-Z Super
compilation based on 557 SNe Ia (
The intermediate- and high-redsh
232 SNe Ia with $0.15 < z \leq 0.55$,
$z > 0.95$. The supernova contours

4. CROSS-CUTTING TEC

The power of the SNe Ia data for
likelihood functions are combine

riel Goobar (seated), Carl Pennypacker, and Saul Perlmutter analyze images icked up by an ultrasensitive electronic camera in a 2.5-meter telescope in the anary Islands and transmitted to powerful computers at LBL. Photo by Paul Hames



Goobar & Leibundgut,
Annual Review of Nuclear and Particle Science **61** (201

Luminosity Distance and parameter *degeneracy*

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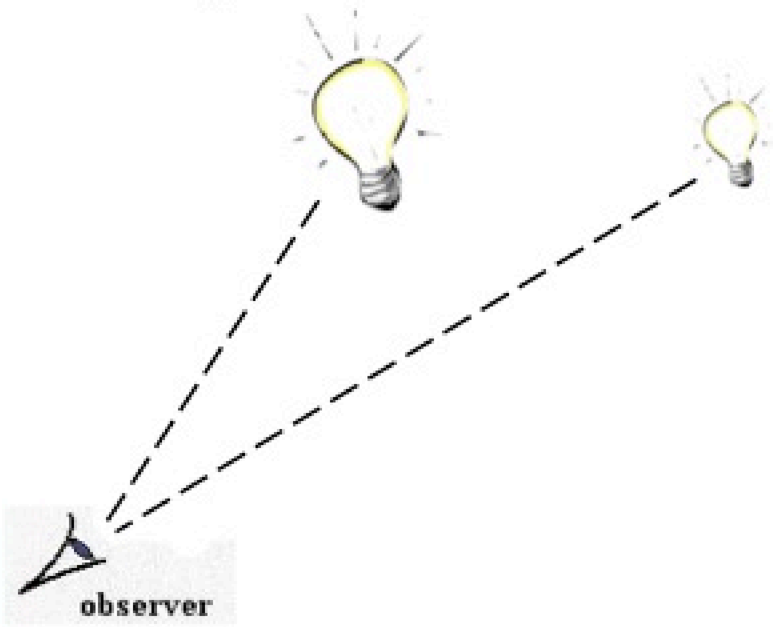
$$d_L = \frac{c \cdot (1 + z_E)}{H_0 \sqrt{|\Omega_K|}} F\left(\sqrt{|\Omega_K|} \int_0^{z_E} \frac{dz}{E(z)} \right)$$

$$E(z) = \left[\Omega_M (1+z)^3 + \Omega_K (1+z)^2 + f(z) \cdot \Omega_X \right]^{1/2}$$

where

$$f(z) = \exp\left[3 \int_0^z \frac{1 + w(x)}{1 + x} dx \right]$$



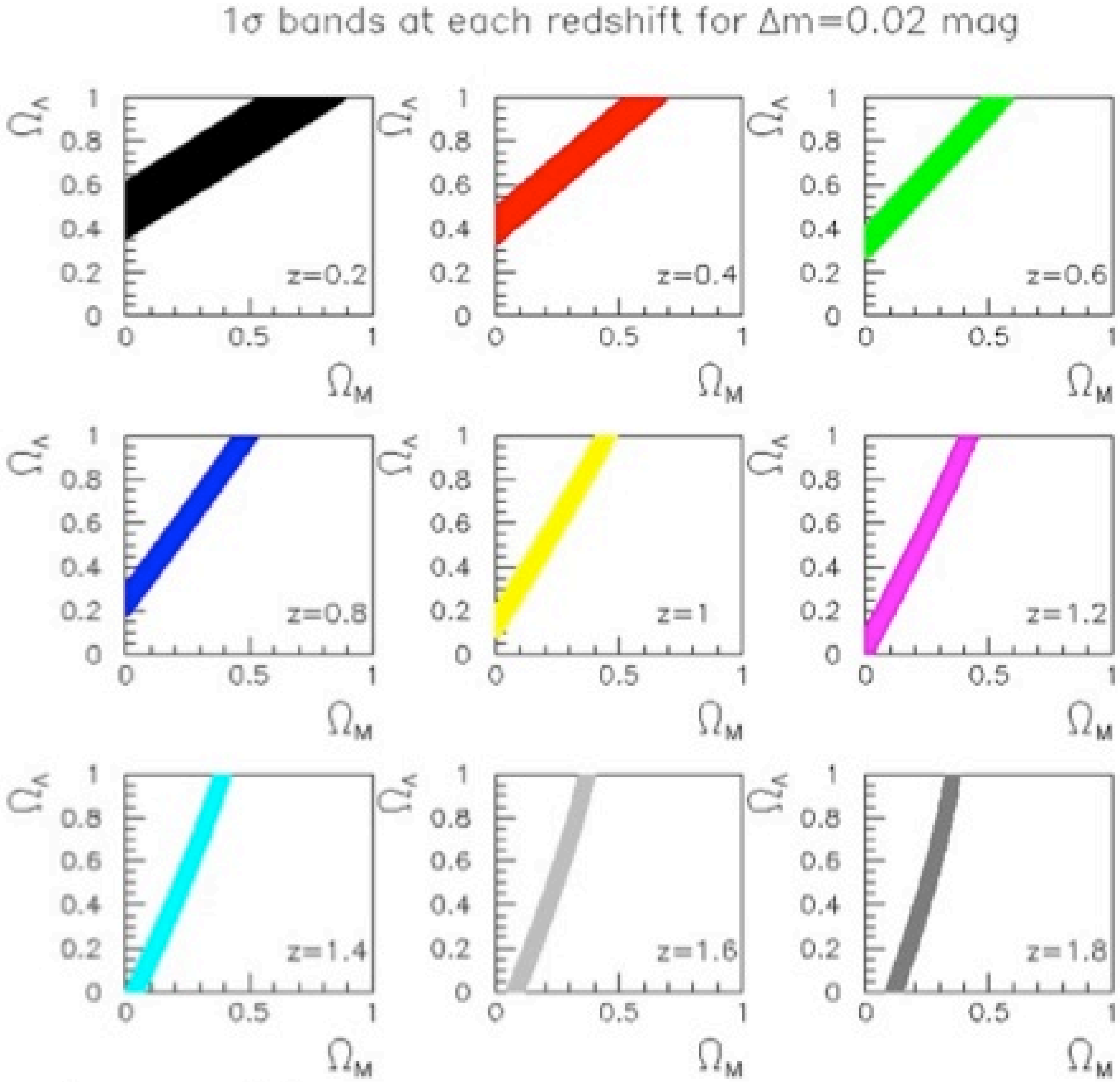
F(x) = sin(x) for a closed universe,

sinh(x) for an open universe and

x for a flat universe.

In the latter case, the Ω_K terms are set to 1

Redshift range



AG & Perlmutter 95

wide lever arm in redshift is key!

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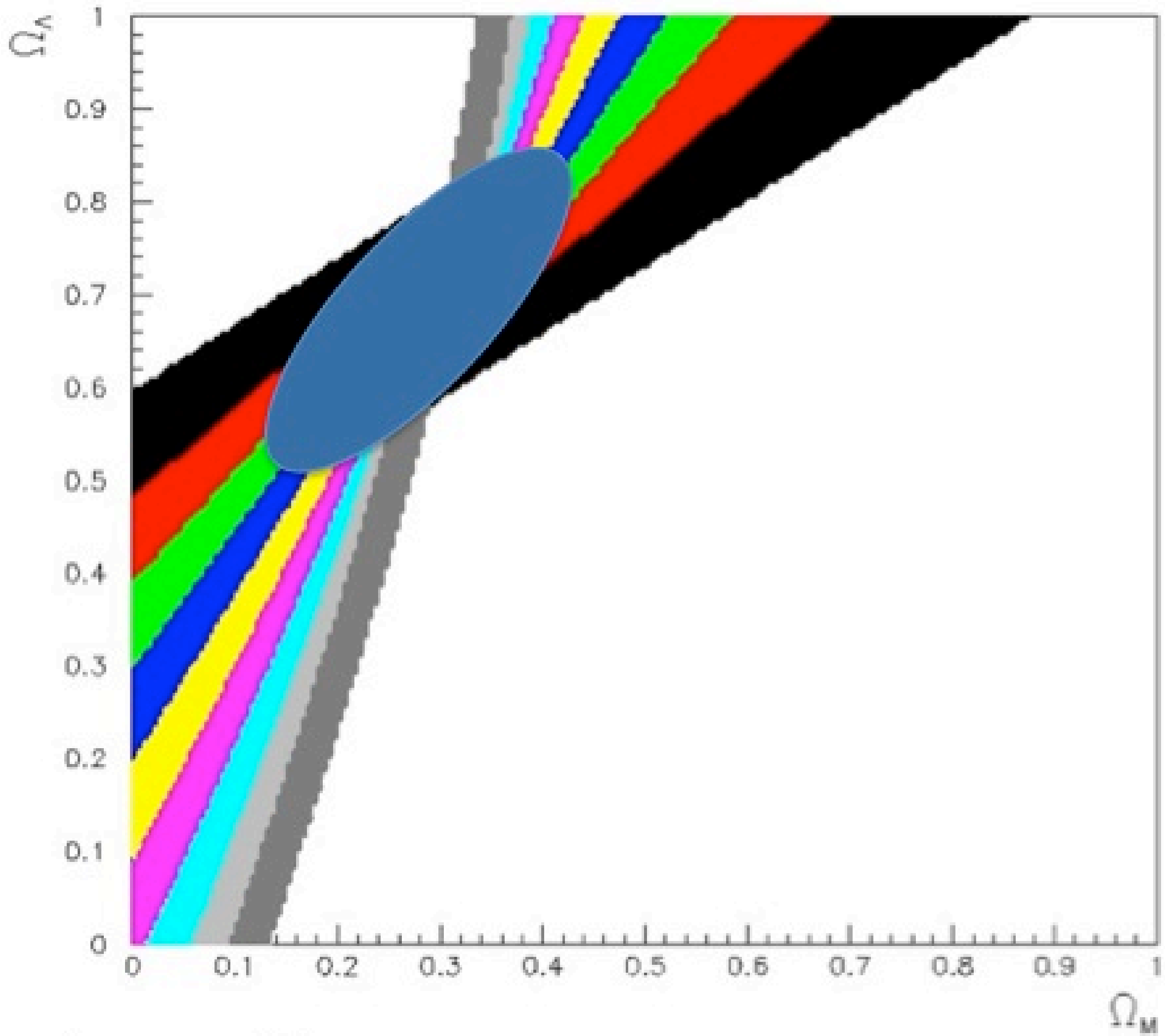
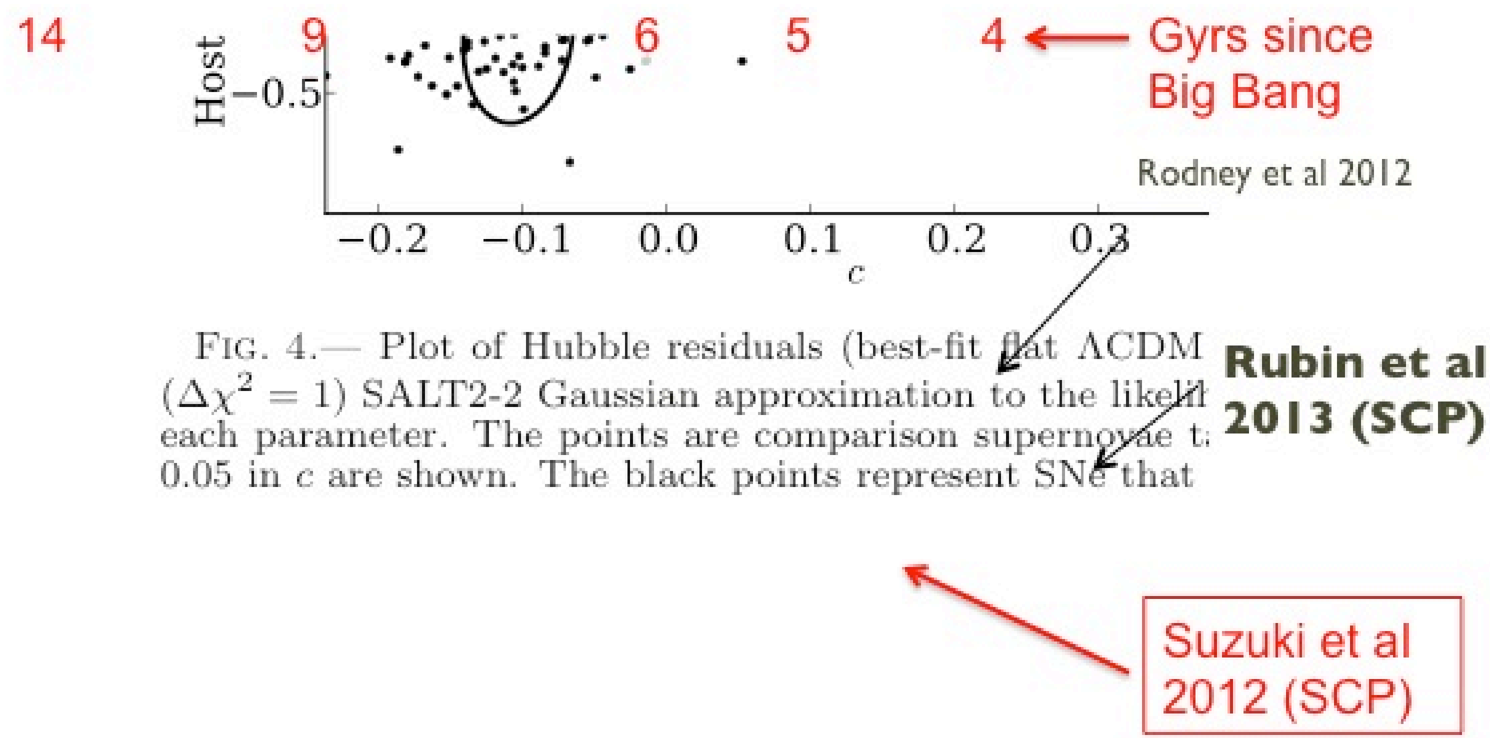


AG & Perlmutter 95

State of the art



Union2.1 data-set + 2 = 582 SNe

State of the art

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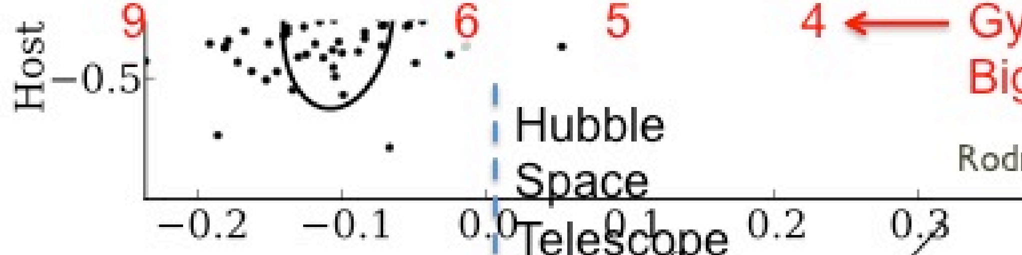
14 9 6 5 4 ← Gyrs since Big Bang



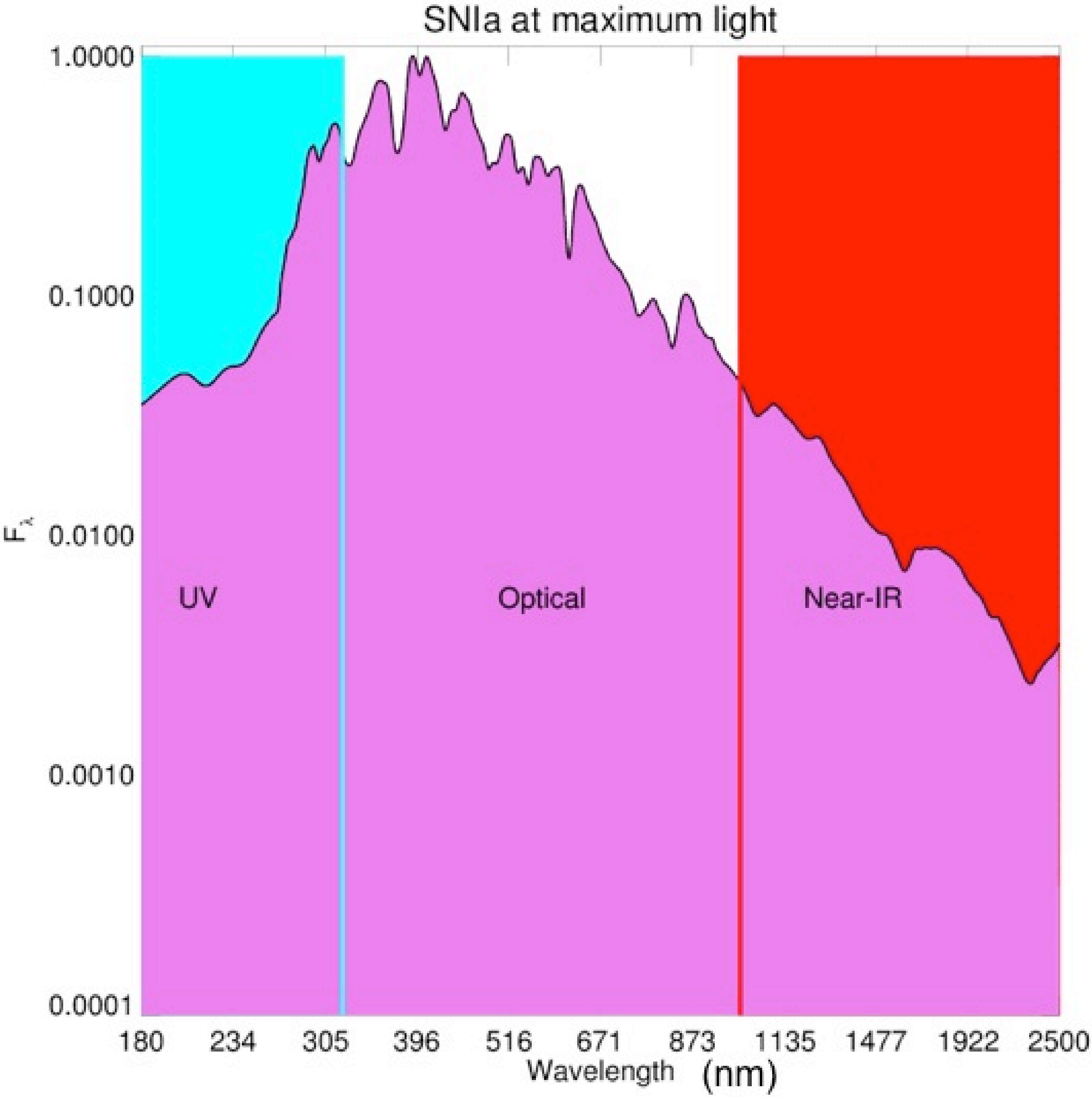
Rodney et al 2012

FIG. 4.— Plot of Hubble residuals (best-fit flat ΛCDM
($\Delta\chi^2 = 1$) SALT2-2 Gaussian approximation to the likeli
each parameter. The points are comparison supernovae t
0.05 in c are shown. The black points represent SNe that

Rubin et al 2013 (SCP)

Suzuki et al 2012 (SCP)

Union2.1 data-set + 2 = 582 SNe



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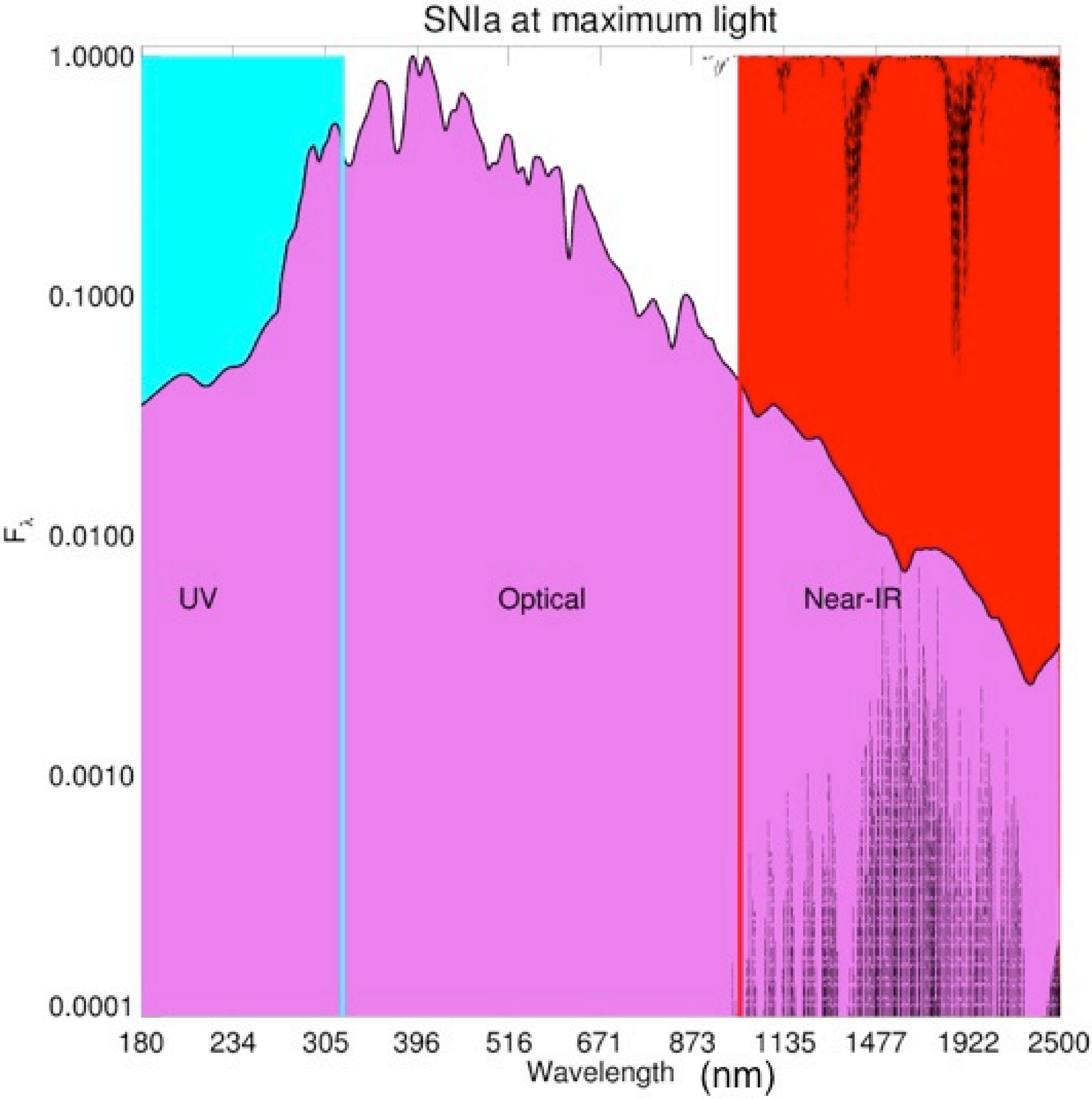

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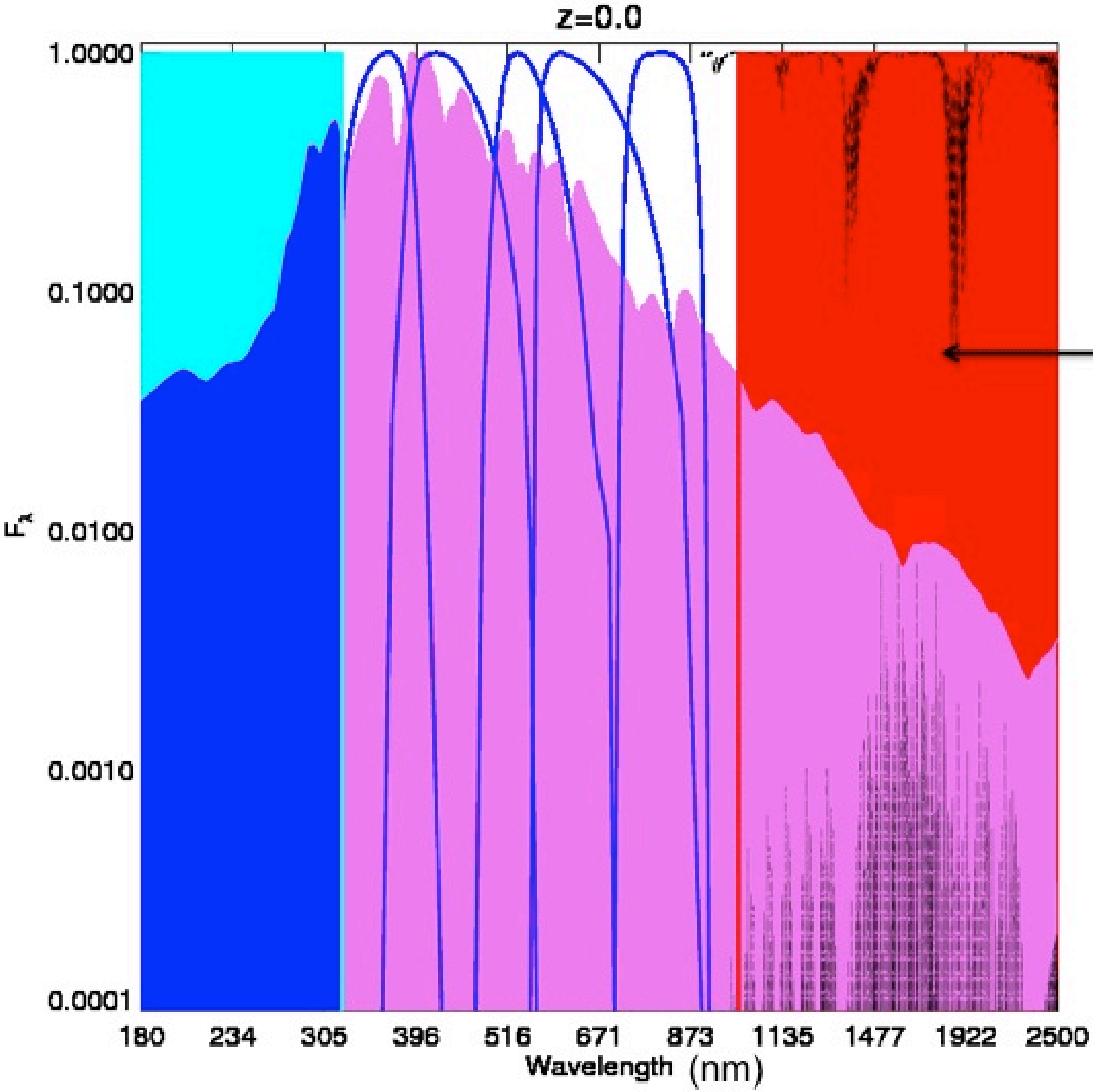

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Mainly from space.

Field of view of Hubble Space Telescope ~**100x smaller** than available for optical ground based surveys.

Is it really Einstein's Λ? Dark Energy EoS, w=p/ρ

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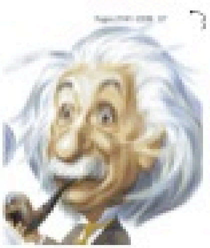
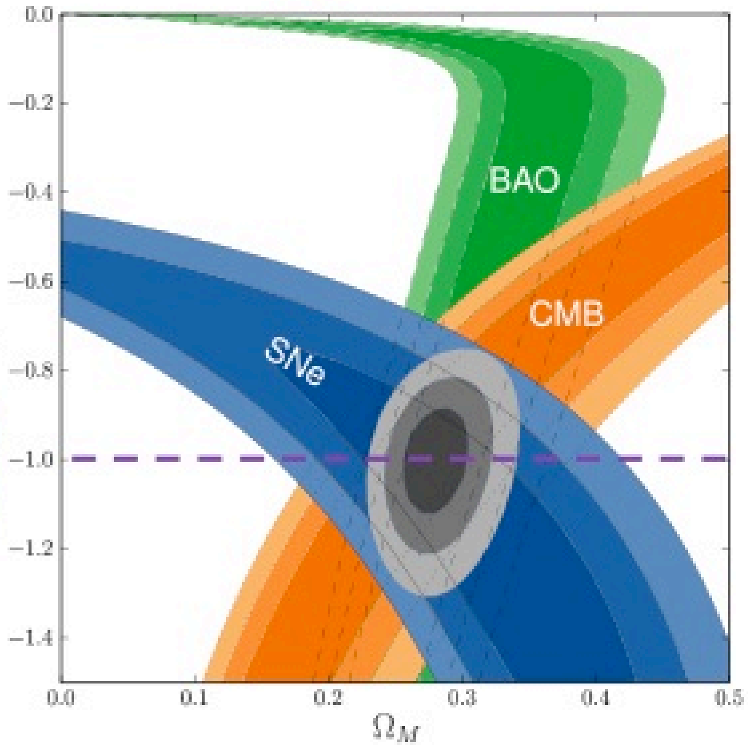
$$\Omega_\Lambda \rightarrow \Omega_{DE} \cdot (1+z)^{3(1+w)}$$

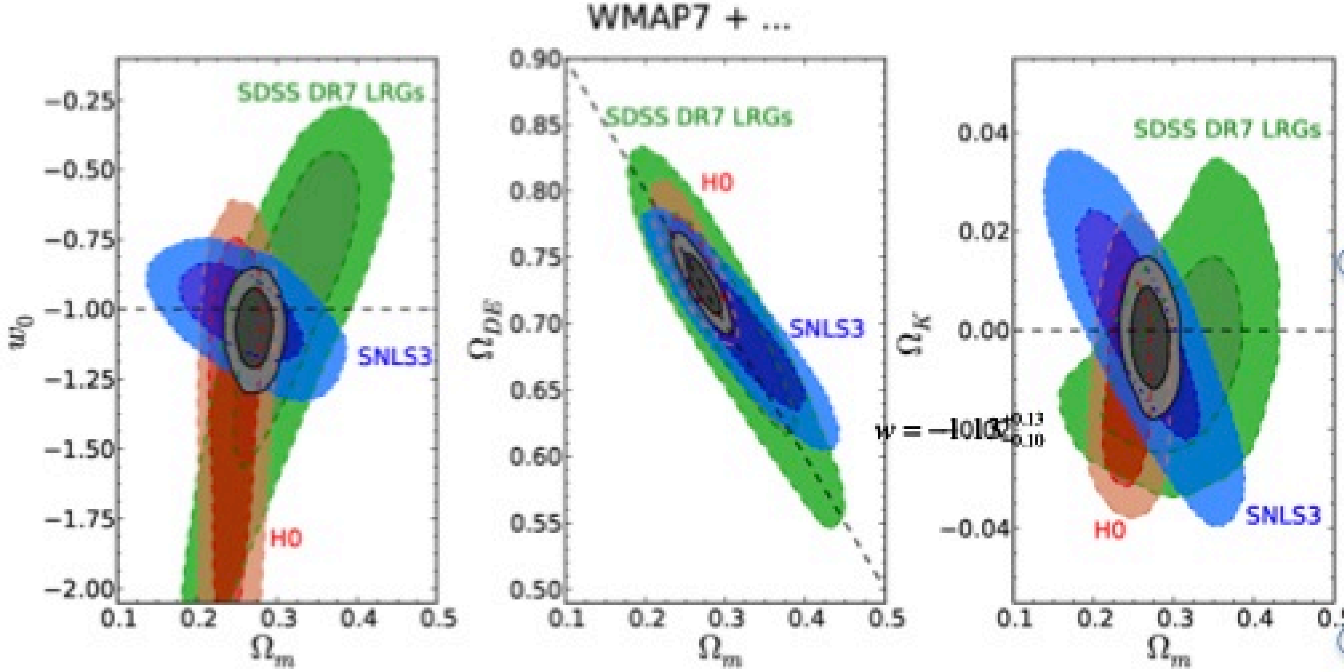




- Λ-hypothesis (w=-1) unchallenged by observations
- **Theoretical understanding still lacking**
- Expected vacuum energy density, ρ_{vac}, has w=-1,but $>10^{56}$ times off!

Amanullah et al 2010

SNLS+WMAP7+BAO/DR7+H_0



Flat:

$$w = -1.061 \pm 0.069$$
$$\Omega_M = 0.269 \pm 0.015$$

Non-Flat:

$$w = -1.069 \pm 0.091$$
$$\Omega_M = 0.271 \pm 0.015$$
$$\Omega_k = -0.002 \pm 0.006$$

Minus SNe:

$$w = -1.412 \pm 0.333$$
$$\Omega_M = 0.259 \pm 0.030$$
$$\Omega_k = -0.009 \pm 0.008$$

Consistent with cosmological constant

Error in w: **<5% (stat)** w/ flatness, ~**7% w/ systematics**

Error is <9% (total) when Ω_k=0 relaxed

SNe remain very important for accuracy on w

Now: BAO+Planck $w = -1.13^{+0.13}_{-0.10}$

Sullivan et al. 2011

Current & Proposed SNIa Surveys

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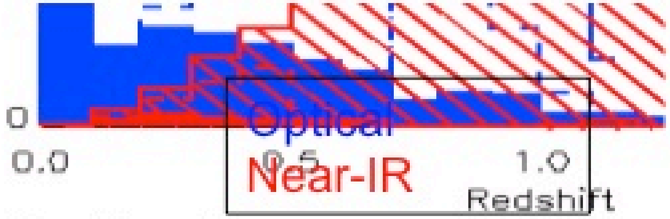


LSST (2020?): 8-m/9 sq.deg
250000/yr

The redshift range and numb
final survey strategy adopted.
over existing SN surveys in te

DES (2012-2016): 4-m/3 sq.deg

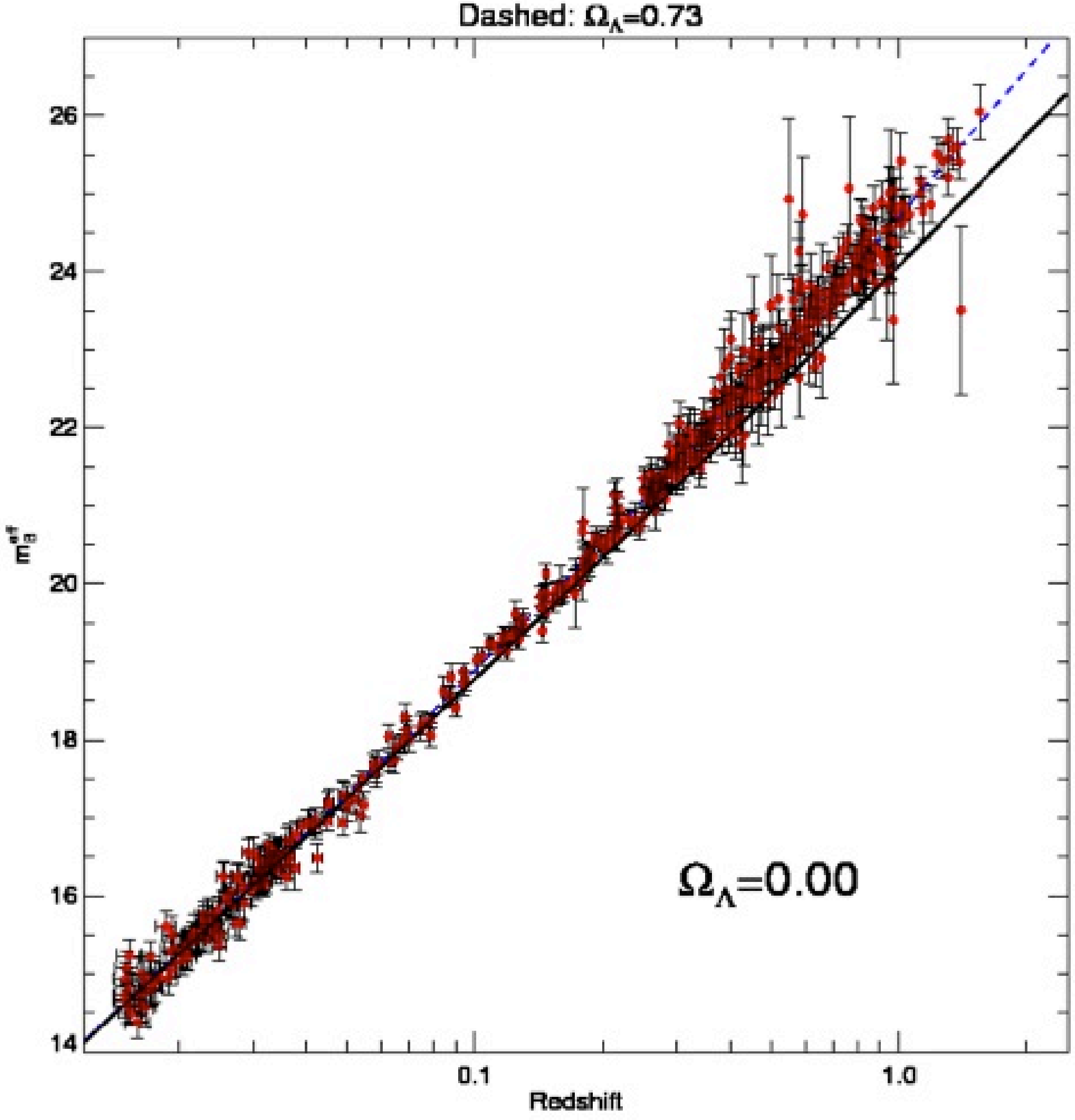
In general, to make a significa
measured distances, which in
(usually more ir
wavelength ran

EUCLID (2020?): 1.2 m/0.5 sq.deg

photometry would be comple
general, SN surveys for cosmo

Amanullah et al 2010 →

Fig. from Hook et al



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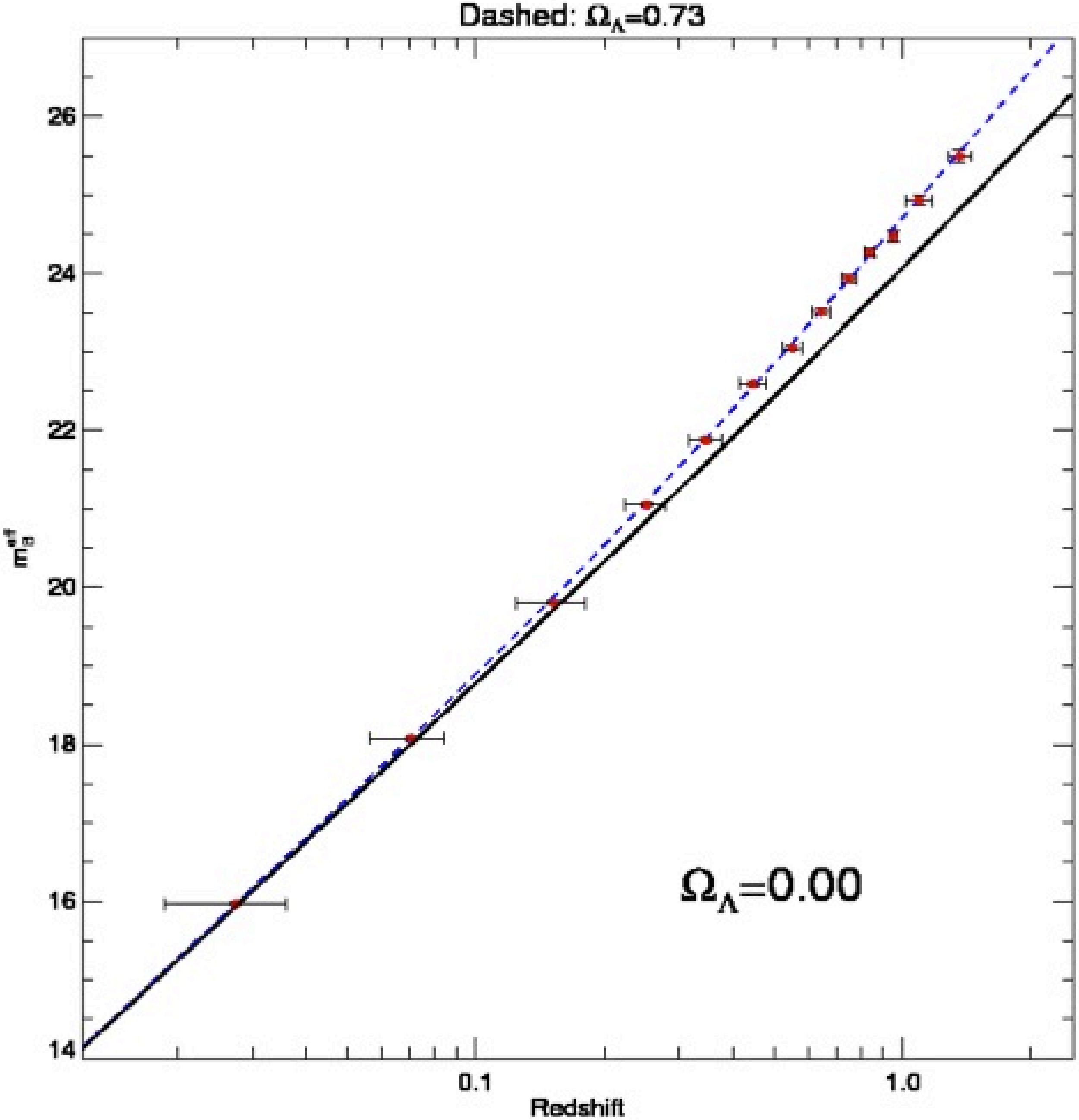
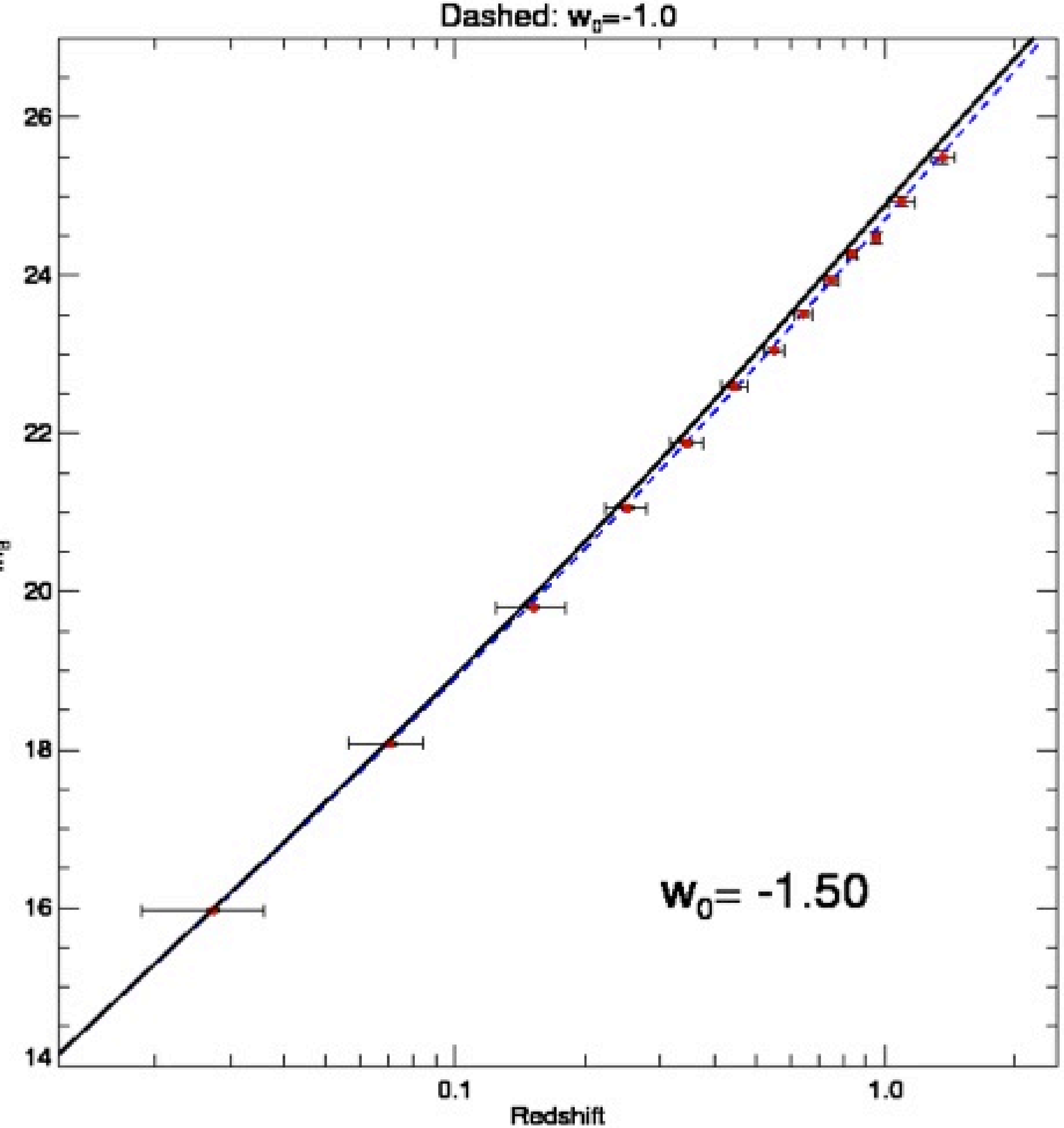
Easy!

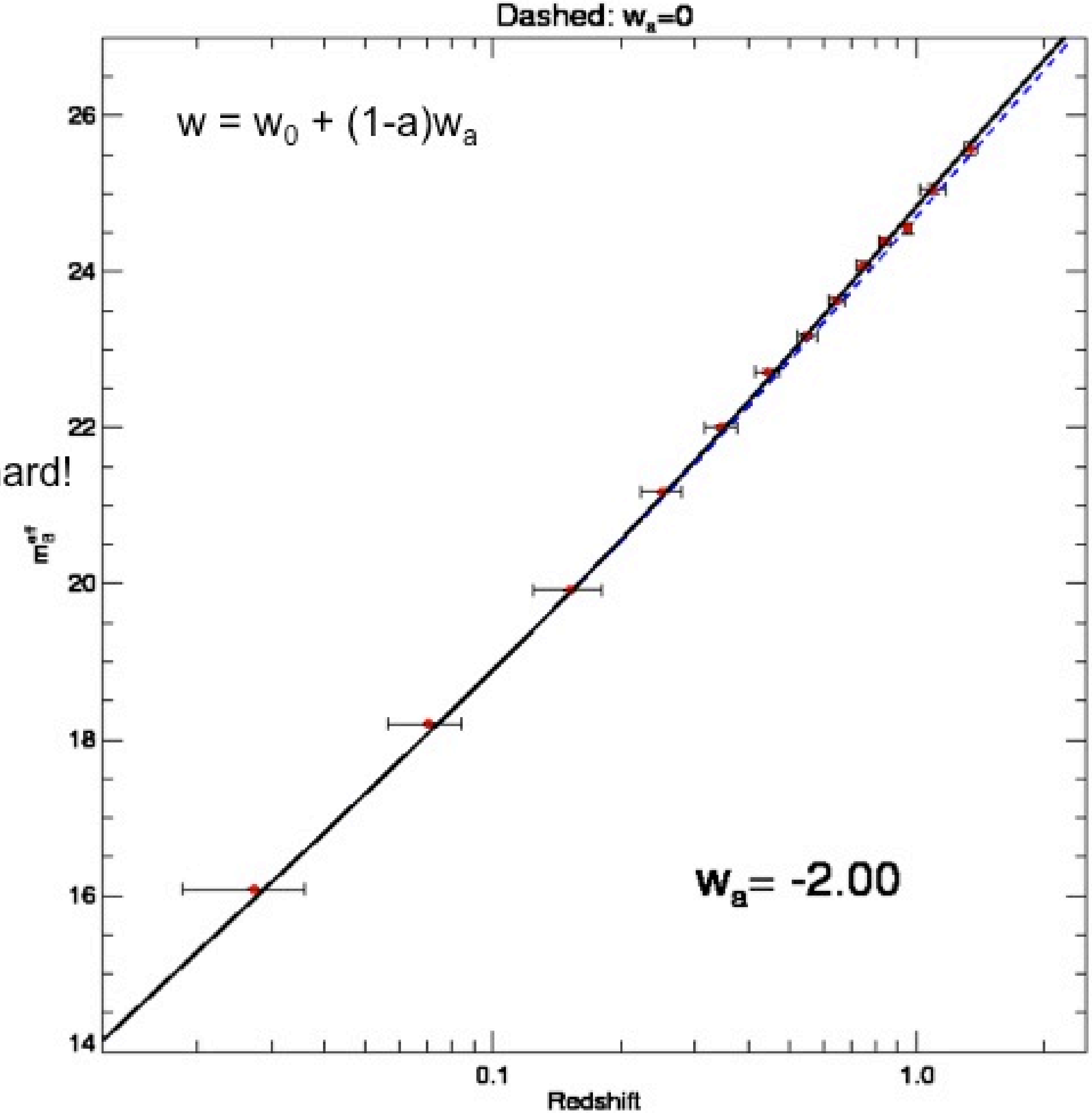


Dashed: Ω_Λ=0.73
26
24
22
20
18
16
14
m_B^{eff}
0.1
1.0
Redshift
Ω_Λ=0.00

Harder!



Really, really hard!



Stage IV forecast (SN+WL+BAO)

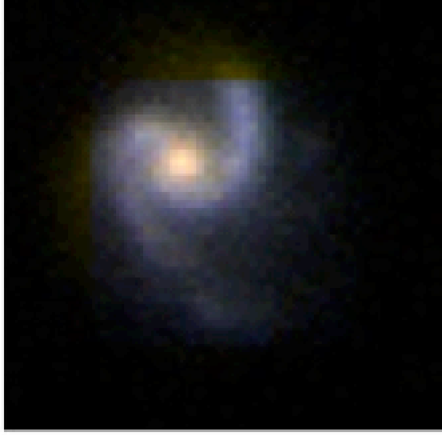
a time-dependent w (the grey bands repr
Goobar & Leibundgut, 2011), and that fu
this quantity. (Both figures adapted from

Amanullah et al
Union 2

$w = w_0 + (1-a)w_a$

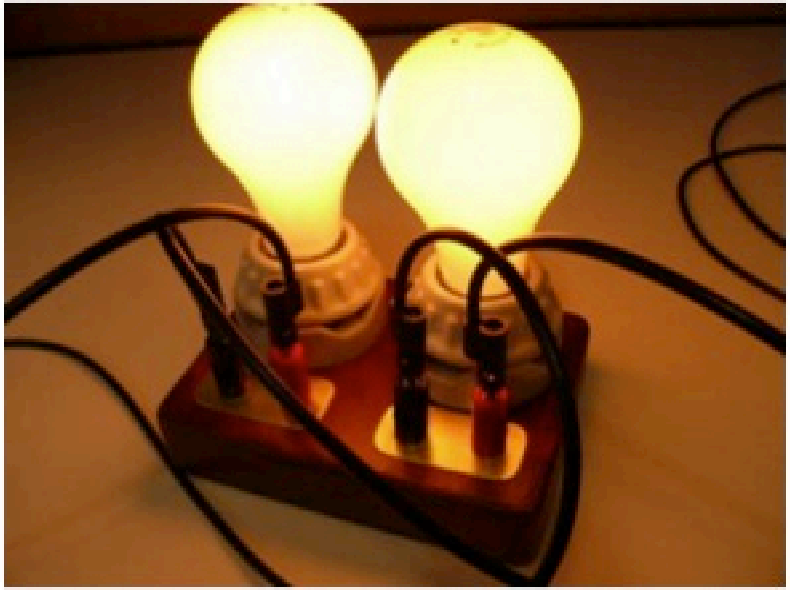
Fig. adapted by
Joel Johansson

Challenges for precision tests of dark energy with SNe Ia: *systematics*



This Talk:

- Dimming by dust along line of sight
- Brightness evolution over cosmic time



Reddening and dimming of SNe Ia

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a) Dust

- Milky Way
- Host galaxy interstellar medium
- Intergalactic medium?
- Circumstellar medium?

b) SN physics

Intrinsic color-brightness relation? Evidence in e.g. Wang et al 2009, Nordin et al 2011, Foley et al 2012,...

- Connection with host galaxy properties: stellar mass, star formation rate,metalicity,age,..., not in this talk!

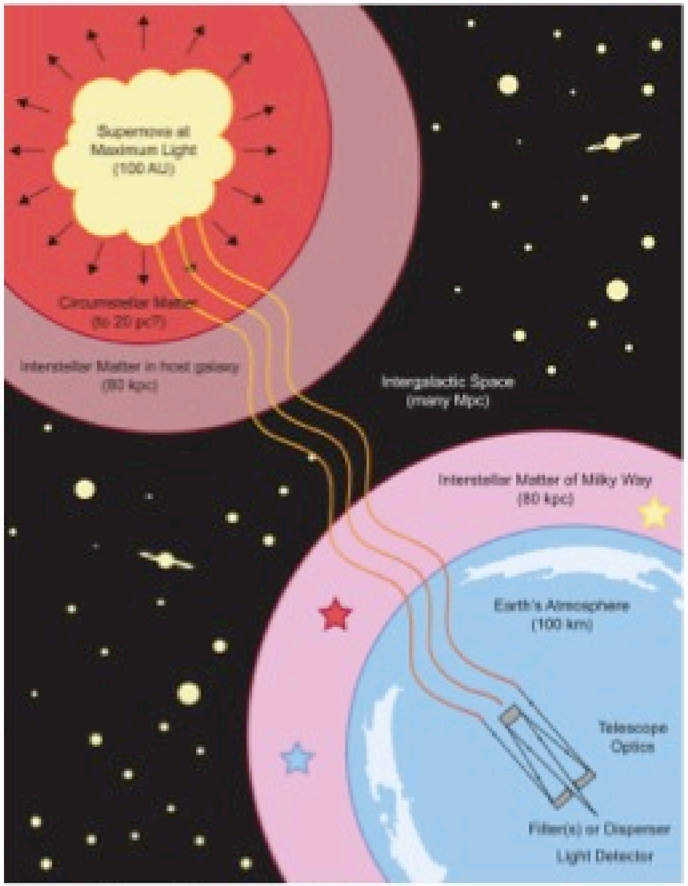

Figure from Kevin Krisciunas

PS: Attenuation by excitation and ionization of atoms negligible in optical and NIR.

Fitting distances from SNIa with SALT

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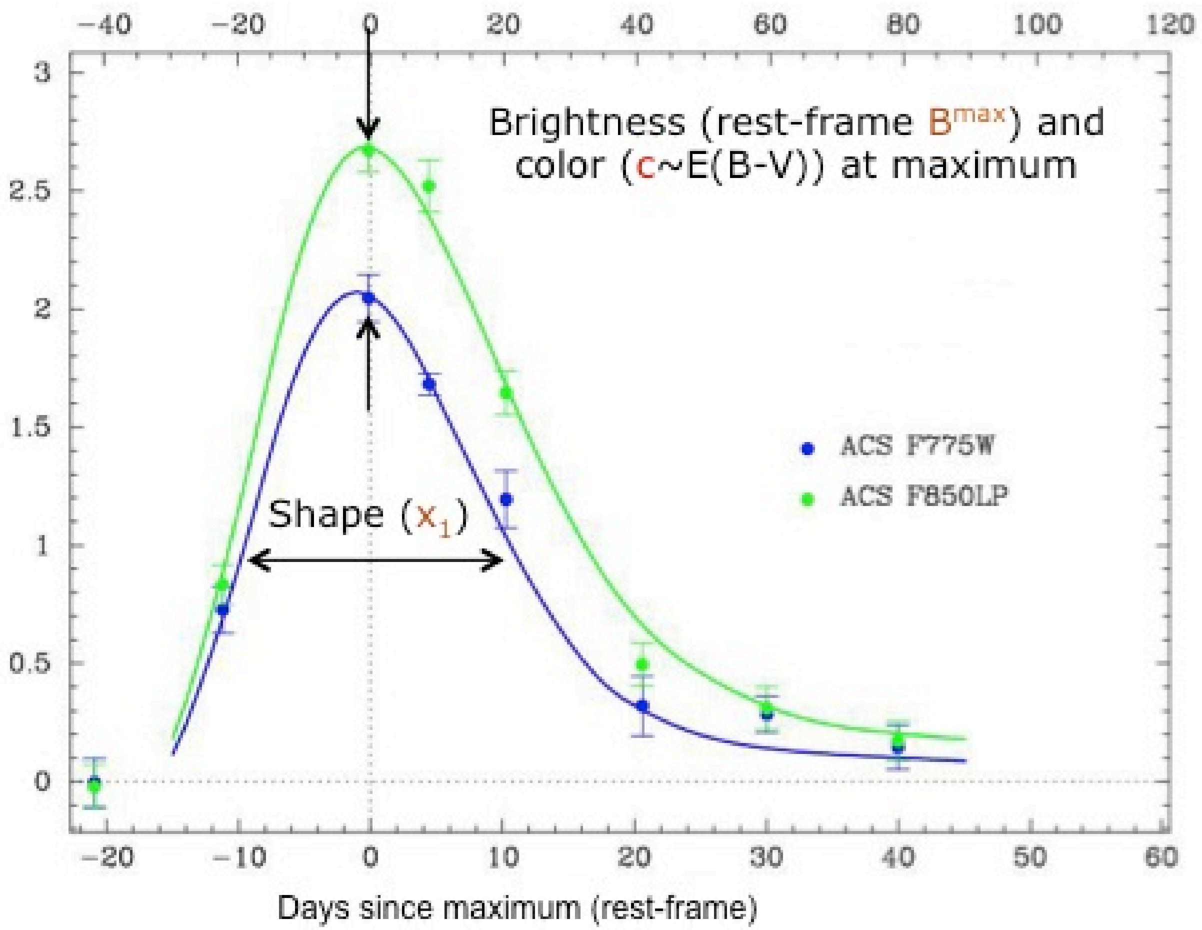
$$B^{\max} - \beta \cdot c + \alpha \cdot x_1 - M_B = 5\log_{10} d_L(\Omega_M, \Omega_X, w; z)$$



Measurements on single Sne

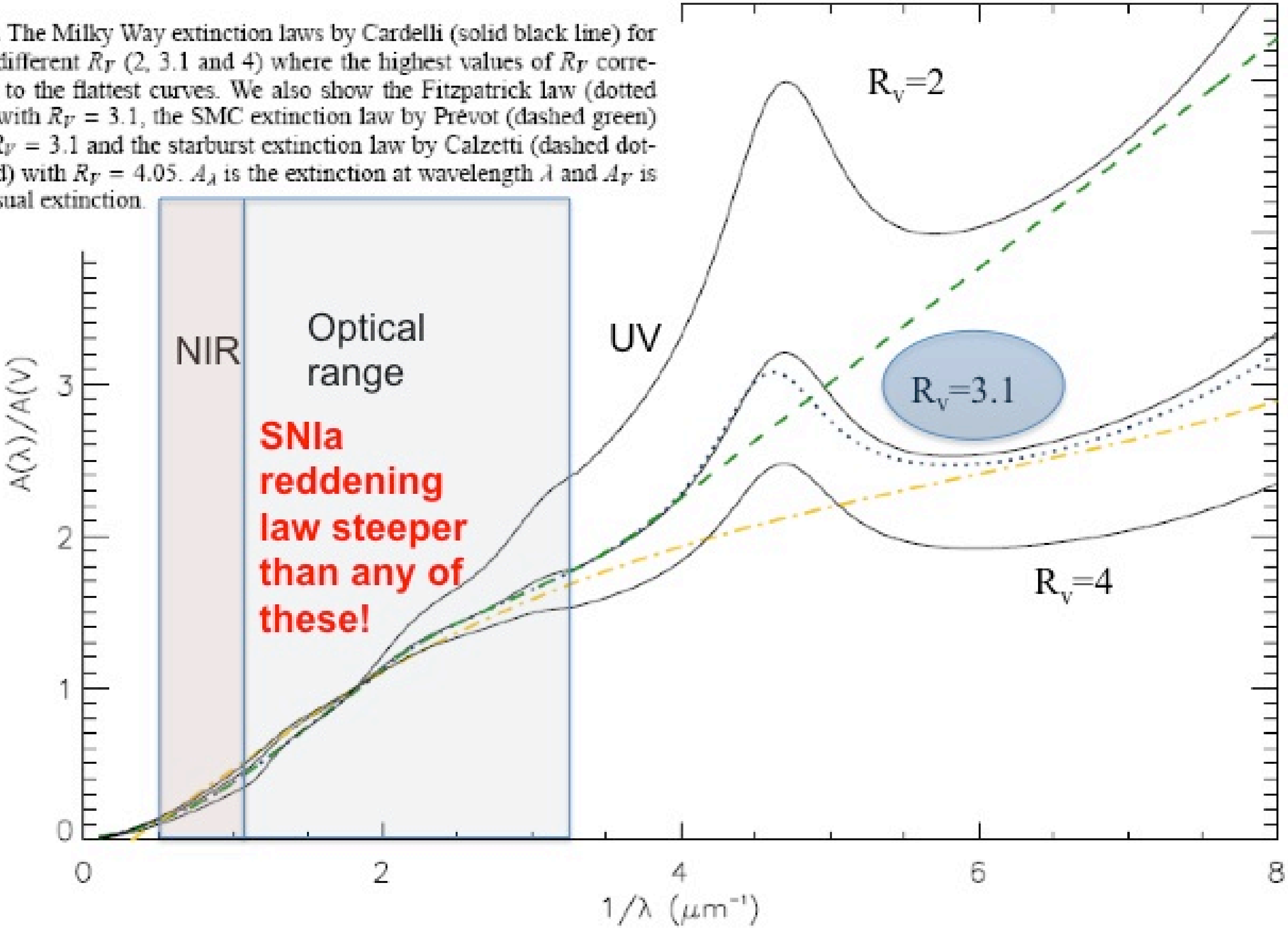
Global fit parameters

Peak brightness can be color and light-curve shape corrected to form a "standard candle.

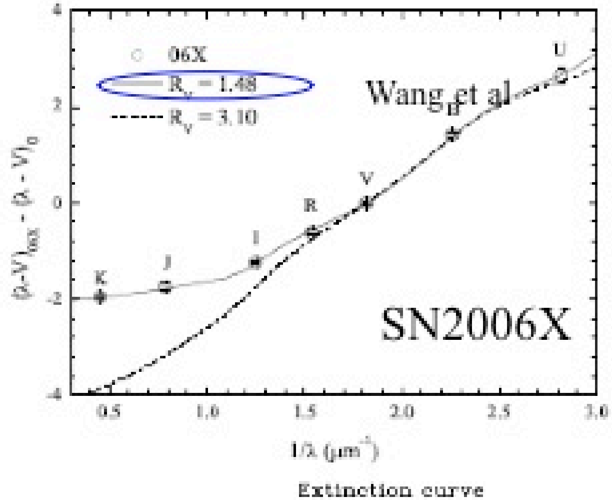
β~2.5 (Amanullah et al. 2010): very unusual reddening coefficient

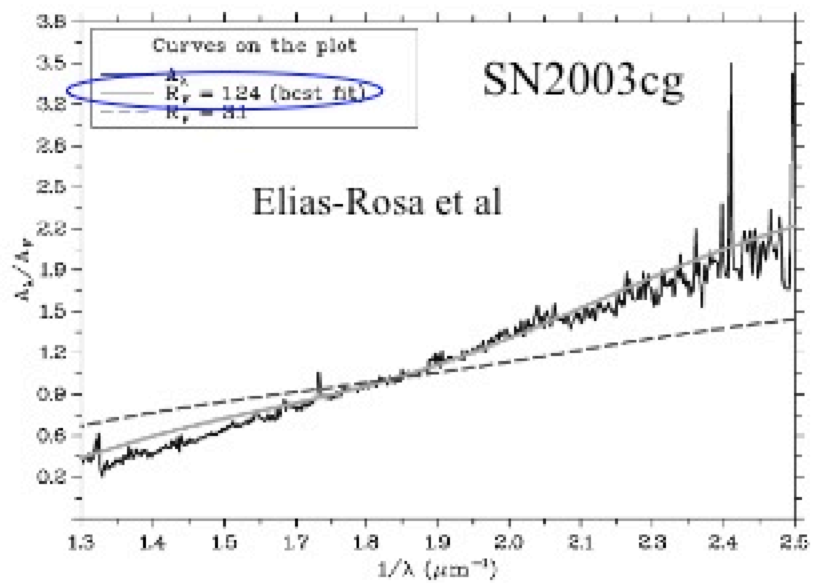
Dust Extinction Laws, $R_V \sim \beta - 1$

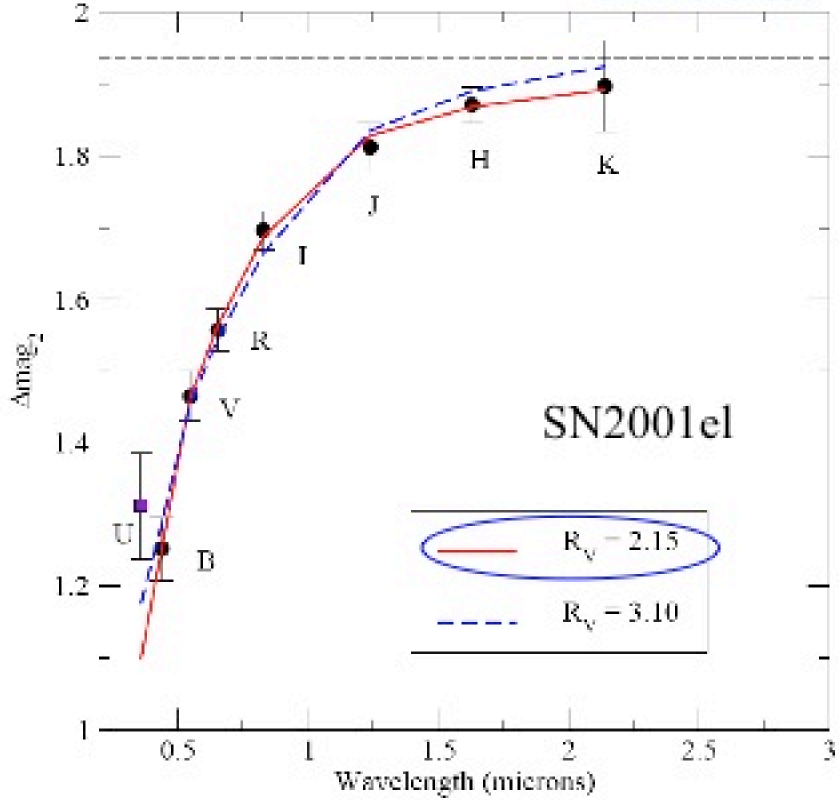
Fig. 1. The Milky Way extinction laws by Cardelli (solid black line) for three different R_V (2, 3.1 and 4) where the highest values of R_V correspond to the flattest curves. We also show the Fitzpatrick law (dotted blue) with $R_V = 3.1$, the SMC extinction law by Prévot (dashed green) with $R_V = 3.1$ and the starburst extinction law by Calzetti (dashed dotted red) with $R_V = 4.05$. A_λ is the extinction at wavelength λ and A_V is the visual extinction.



•Wavelength dependence *is* often quite different for SNIa







But for SN cosmology (so far) assumed all SNe have same reddening law…

Could (part of) reddening be due to dust in ***circumstellar medium***? Connected to progentor system...

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Single degenerate

Double degenerate

CSM more likely in SD scenario

The case for CSM around SNIa

Spectroscopic evidence for shell of CSM ($\sim 10^{16}$-10^{17}cm) for 3 near-by SNIa.

Claim: changing sodium absorption due to changing ionization of CSM, modulated by SN radiation

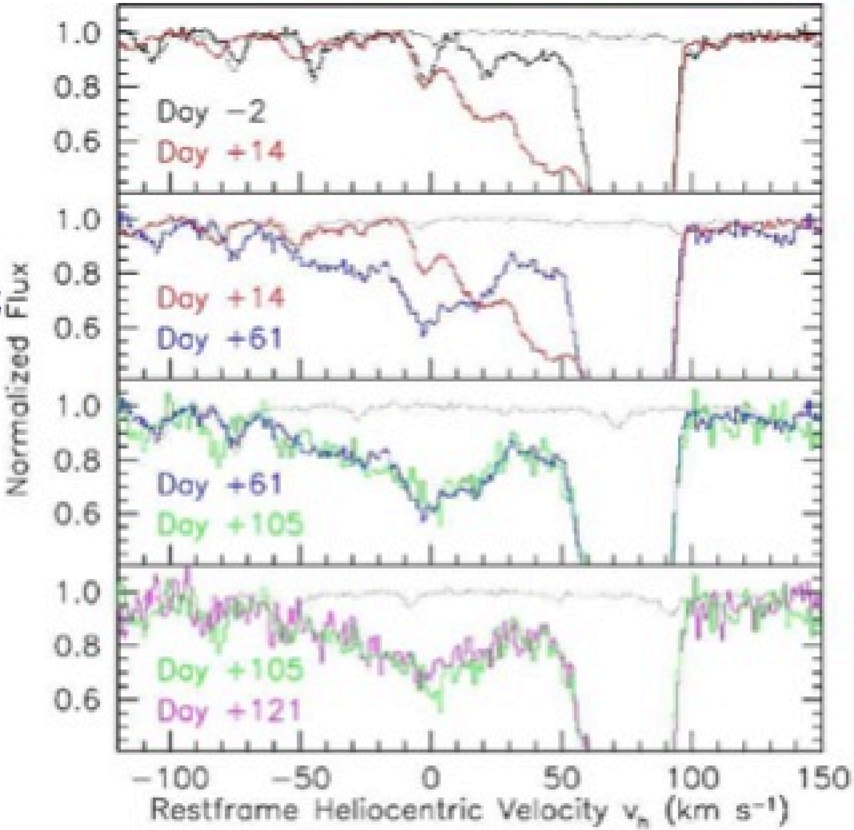
[Ca-atoms locked-up in dust grains]

2006X (Patat et al.); E(B-V)=1.42±0.04, R_v=1.48±0.06 (Wang et al);

1999cl (Blondin et al.), E(B-V)~1.1, R_v~1.8;

2007le (Simon et al.), E(B-V)=0.27, R_v=2.56±0.22

+ see also statistical study in Sternberg et al 2011



PTF 11kx: A Type Ia Supernova with a Symbiotic Nova Progenitor

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There is a consensus that type Ia supernovae (SNe Ia) arise from the thermonuclear explosion of white dwarf stars that accrete matter from a binary companion. However, direct observation of SN Ia progenitors is lacking, and the precise nature of the binary companion remains uncertain. A temporal series of high-resolution optical spectra of the SN Ia PTF 11kx reveals a complex circumstellar environment that provides an unprecedentedly detailed view of the progenitor system. Multiple shells of circumstellar material are detected, and the SN ejecta are seen to interact with circumstellar material starting 59 days after the explosion. These features are best described by a symbiotic nova progenitor, similar to RS Ophiuchi.

SILICATE DUST IN THE ENVIRONMENT OF RS OPHIUCHI FOLLOWING THE 2006 ERUPTION

A. Evans,[1] C. E. Woodward,[2] L. A. Helton,[2] J. Th. van Loon,[1] R. K. Barry,[3] M. F. Bode,[4] R. J. Davis,[5] J. J. Drake,[6] S. P. S. Eyres,[7] T. R. Geballe,[8] R. D. Gehrz,[2] T. Kerr,[9] J. Krautter,[10] D. K. Lynch,[11] J.-U. Ness,[12] T. J. O'Brien,[5] J. P. Osborne,[13] K. L. Page,[13] R. J. Rudy,[11] R. W. Russell,[11] G. Schwarz,[14] S. Starrfield,[12] and V. H. Tyne[1]

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ABSTRACT

We present further *Spitzer Space Telescope* observations of the recurrent nova RS Ophiuchi, obtained over the period 208–430 days after the 2006 eruption. The later *Spitzer* IRS data show that the line emission and free-free continuum emission reported earlier is declining, revealing incontrovertible evidence for the presence of silicate emission features at 9.7 and 18 μm. We conclude that the silicate dust survives the hard radiation impulse and shock blast wave from the eruption. The existence of the extant dust may have significant implications for understanding the propagation of shocks through the red giant wind and likely wind geometry.

Subject headings: binaries: close — binaries: symbiotic — infrared: stars — novae, cataclysmic variables — stars: individual (RS Oph)

Multiple scattering on dust around SNe?

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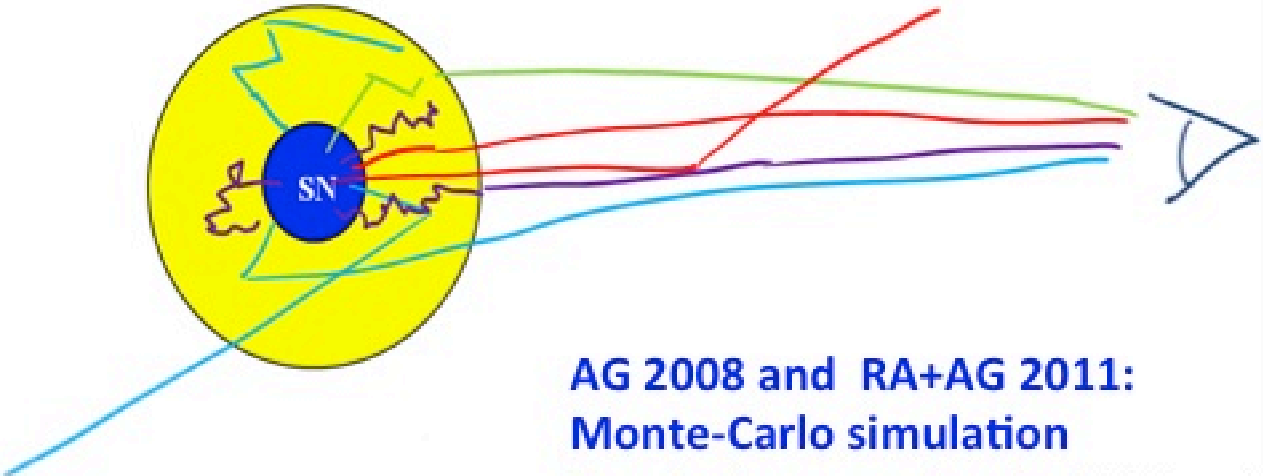
Observed colors after the semi-diffusive shell will be function of:

- **Wavelength dependent cross-sections, albedo and scattering angles**
- **Dust density and CS shell size**



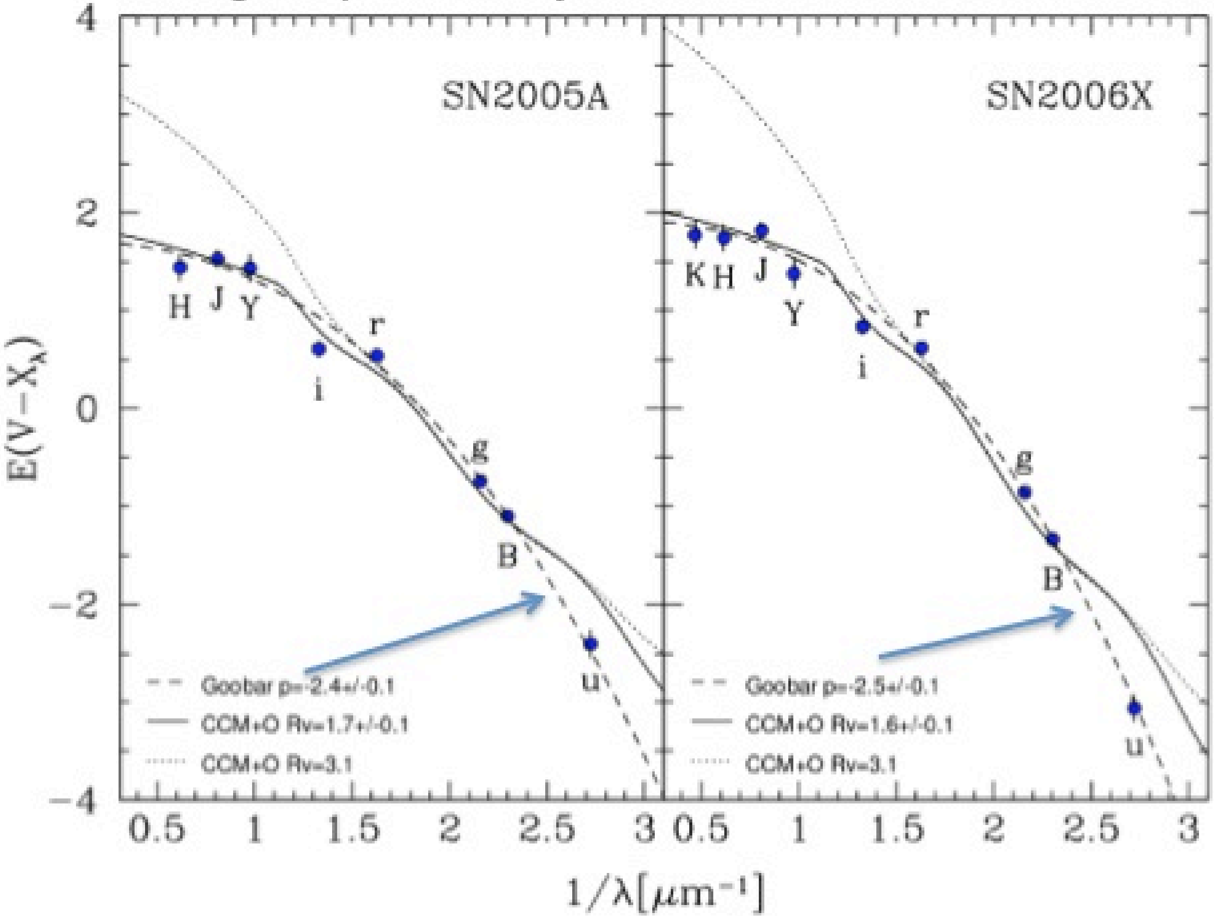
AG 2008 and RA+AG 2011:
Monte-Carlo simulation

Use dust parameters for MW and LMC by:
Draine ApJ 2003, Weingartner & Draine ApJ 2001
(also SMC dust , but mostly absorption, not scattering, at optical wavelengths)

A.Goobar (2008)
R.Amanullah & A. Goobar (2011)

Reddening law from circumstellar dust provides a good fit for highly reddened SNe Ia

Folatelli et al. (2010) –
Carnegie Supernova Project



What about further into the UV?
C19 program – 6 reddened observed

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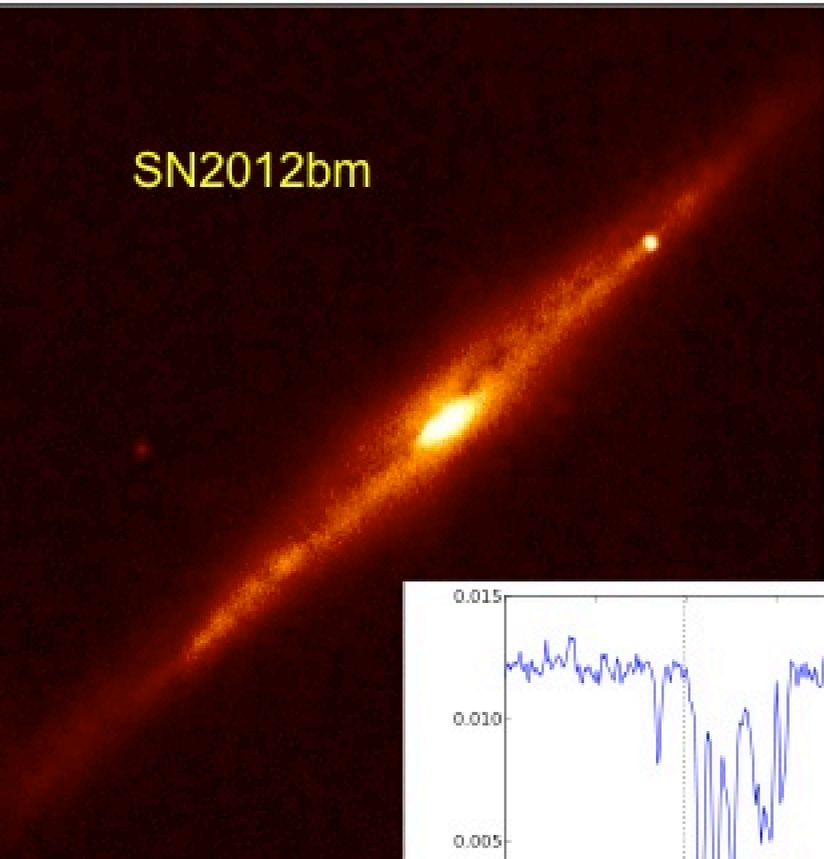

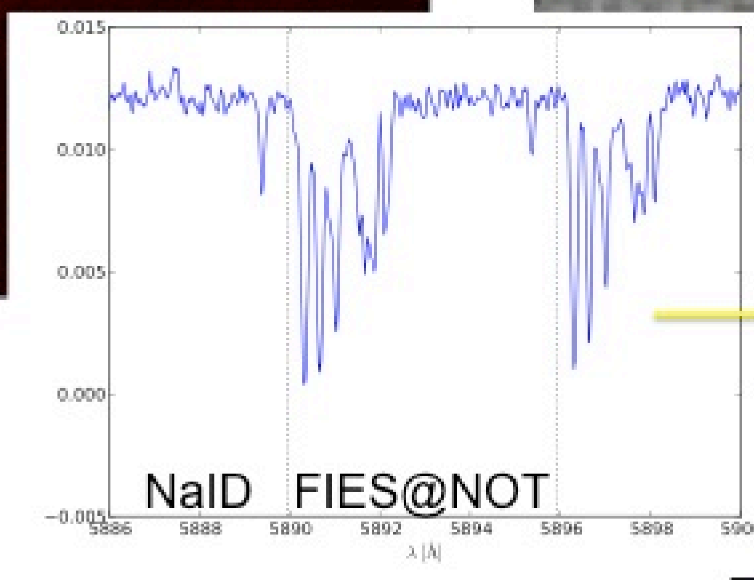

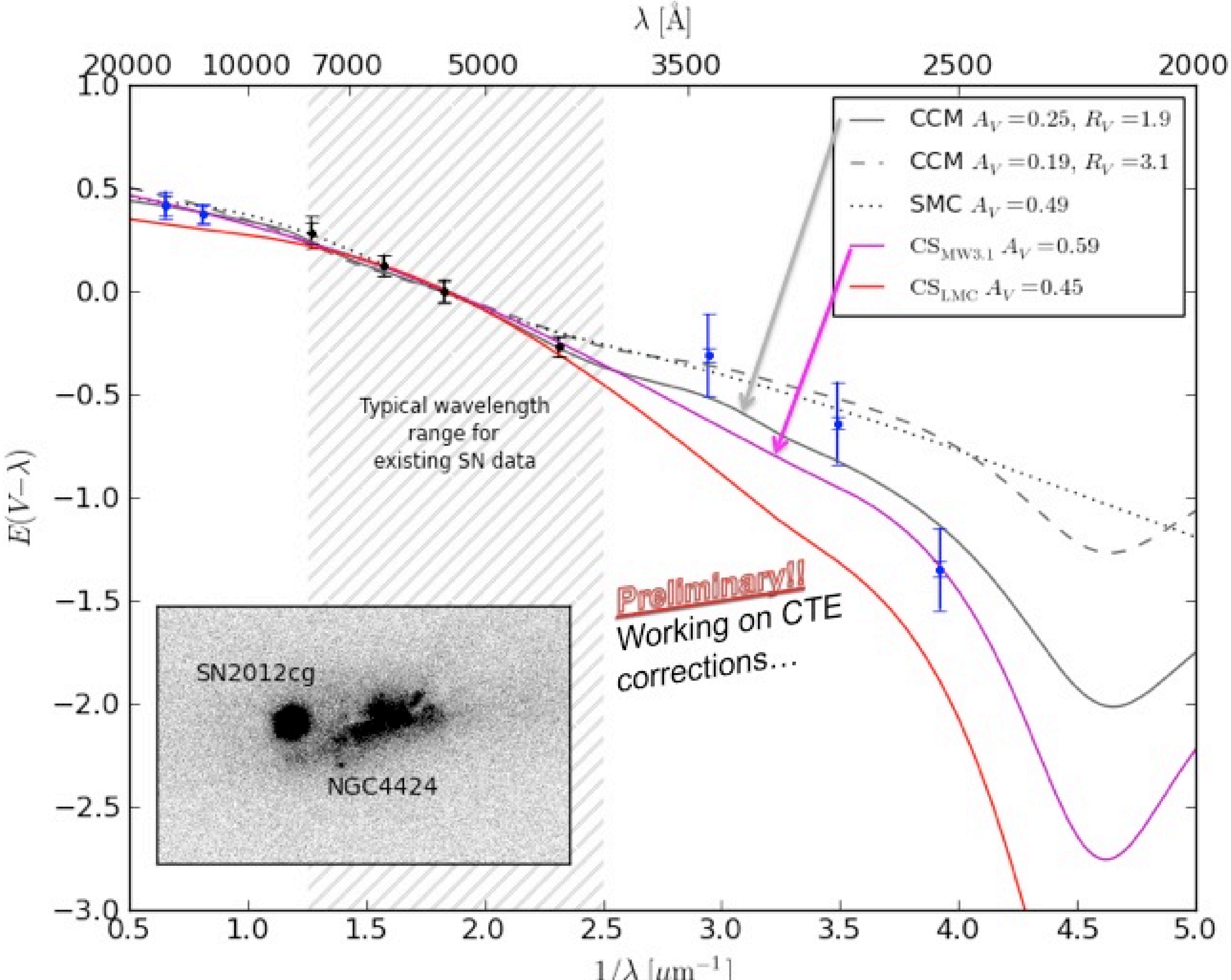

λ [Å]
20000
10000
7000
5000
3500
2500
2000
CCM $A_V = 0.25$, $R_V = 1.9$
CCM $A_V = 0.19$, $R_V = 3.1$
SMC $A_V = 0.49$
$CS_{MW3.1}$ $A_V = 0.59$
CS_{LMC} $A_V = 0.45$
Typical wavelength range for existing SN data
Preliminary!!
Working on CTE corrections...
SN2012cg
NGC4424
$E(V-\lambda)$
$1/\lambda$ [μm^{-1}]

Looking for the smoking gun – *heated dust around the SN??* Herschel observations

..but nothing seen so far, but inconclusive! Work in progress!

Figure 1. *Herschel PACS* 70μm observatio
(top panel), 2011fe (middle panel) and 2012c
The solid circles indicate the position of the s
FWHM of the PSF (6″). The dashed circles a
used for background estimation.

Figure 3. Example of expected IR SEDs of circumstellar
assuming a distance of 6.4 Mpc, $M_d = 7 \times 10^{-3}$ $M_{\odot}$ and T_d
K with graphitic (solid black line) or silicate (dashed black
dust grains of size $a = 0.1\,\mu$m. The dotted black line sh
blackbody spectrum at 10^4 K, scaled to match the NIR
of SN 2011fe 33 days after maximum brightness (Matheson
2012). For comparison, the 5σ detection limits of 3 hr observa
with the *Spitzer Space Telescope* (blue dashed line) and the
Webb Space Telescope (green dashed line) are included. Th
symbols indicate the 3σ upper limits on the flux of SN 201
the PACS 70 μm and 160 μm bands (described in § 2.3).

Johansson, Amanullah & Goobar (2013)

Exploring the highestredshifts – putting the “standard candle” to the test

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Large z-lever arm:
key in studies for evolutionary effects:

At z~1.5, only t~4 Gyrs since Big Bang, i.e., *short lived progenitors*. WDs at very high-z likely to originate from more *massive stars*

- CO mass and the C/O ratio are expected to depend on progenitor mass
- Because of the lower C/O ratio in more massive progenitors, smaller amounts of ^{56}Ni are synthesized.
- ~3% change in peak luminosity per 1 $M_{\odot}$ change in progenitor star.

(Dominguez, Höflich & Straniero, 2001)

Brightness evolution accompanied by changes in SN features?
This would be interesting to probe!
But, does adequate data exist?

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[20] Deceased

of 2 (Vega 26.5). Because the red observed color im plied a possible very-high-redshift SN Ia, we followed i with ACS F850LP and Near Infrared Camera and Multi Object Spectrometer (NICMOS) F110W/ F160W pho tometry, and ACS G800L grism spectroscopy. We nick named the candidate "Mingus" (target SN150G for ou *HST* followup).

The sky in the vicinity of the SN is shown in Figure 1[24] The likely host is the late-type galaxy at redshift 1.71 (se Section 3.2) centered 0.8″ away. This corresponds to onl

[21] HST GO Program 9727
[22] HST GO Program 9728
[23] The reference images for this field come from Program I 9583.
[24] In addition to the other datasets, data from HST GO Pro gram 10339 was used for this figure and the subsequent host-galax analysis.

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11+2 orbits of HST to get spectrum!

Observer Frame Wavelength (Å

FIG. 2.— From top to bottom: the best-fit core-coll (SN1993J, top panel) and the best-fit Type Ia temp plotted at the redshift of the likely host galaxy. The ments are overplotted. The sky level is determined s with the other parameters, as discussed in the text different for the two templates.
Middle panel: 2D SN spectrum, spanning 112 pixels flux visible in the very reddest wavelengths is contam a nearby galaxy.
Lower panels: Extracted WFC3 IR likely host gal with template fit using SDSS galaxy principal comp line). The best-fit (and only reasonable) redshift is 1 that including the ACS grism data for the host (5500 has no effect on the fit. 2D WFC3 spectrum, spanni Some of the flux visible at longer wavelengths than t contamination.

CC SN

Ia

Wavelength range probed with our low-z HST UV spectra

correlation redu elements[25] from values in this pa

[25] This is derive inverse in ρ, summ summing the Taylo

FIG. 4.— Plot of Hubble residuals (best-fit flat ΛCDM $(\Delta\chi^2 = 1)$ SALT2-2 Gaussian approximation to the likeli each parameter. The points are comparison supernovae 0.05 in c are shown. The black points represent SNe that

The spectrum is shown in the bottom pa ure 2, along with the best-fit template deriv ing principal components of SDSS spectra (A 2011). Only one feature is detected at very tical significance: an emission feature at 1 only reasonable match to the spectrum betw 1.0 and 2.0 is one centered on redshift 1.71 the best-fit SN redshift. The emission feat made up of a blend of the [OIII]λλ 4959, blet. No other emission lines are required t the wavelength range of either grism spectrum be a credible template match. We also see sorption from Hγ and Hβ (4340Å, and 4861Å wavelengths, respectively), but at lower sta nificance. As we are not sure which core (or

…and here is the other one!

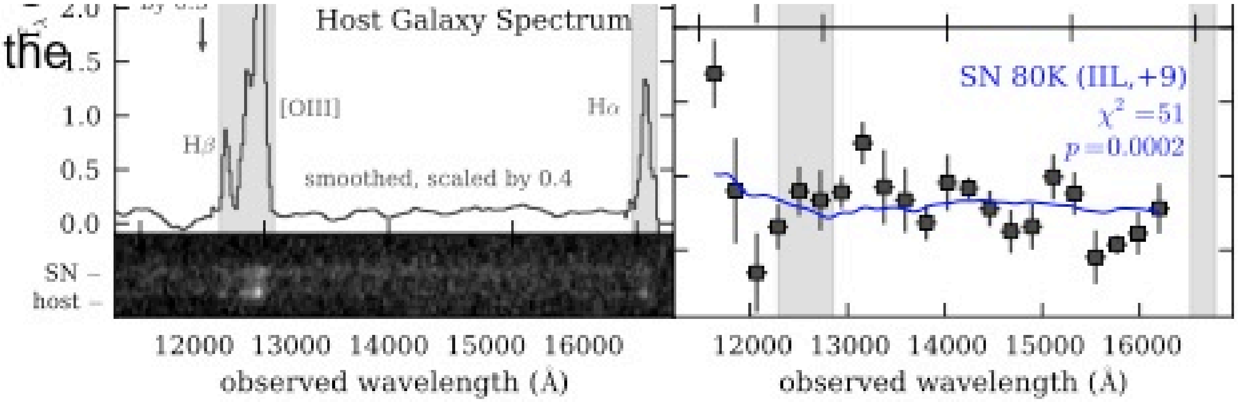


FIG. 6.— The HST G141 grism spectrum of SN Primo. The left side depicts the spectral data reduction process: the bottom shows the 2D grism spectrum, the center panel shows the host-galaxy spectrum, smoothed and shifted as described in the text, and t panel shows the host-subtracted SN spectrum. Grey lines show the unbinned spectrum in rest wavelength for the known redshift $z =$ Solid points show the mean values in 80 Å bins. On the right side, the same binned points are shown in each of the three panels three template spectra overlaid as solid lines for SNe of Type Ia, Ibc, and II. All templates are depicted for the known age of the SN time of the grism observation: 6 rest-frame days past peak brightness. The vertical grey bands indicate regions where the SN spe was contaminated by bright emission lines from the host galaxy: Hβ and [O III] on the blue side, and Hα on the red side.

Signal-to-noise ratio very poor!

This smoothing avoids the introduction of additional noise when this core spectrum is subtracted from the SN. The final host galaxy spectrum – scaled, shifted and smoothed – is shown in the center-left panel of Figure 6). Subtracting this from the spectrum taken at the location of the SN yields the final host-subtracted SN spectrum shown in the upper left panel.

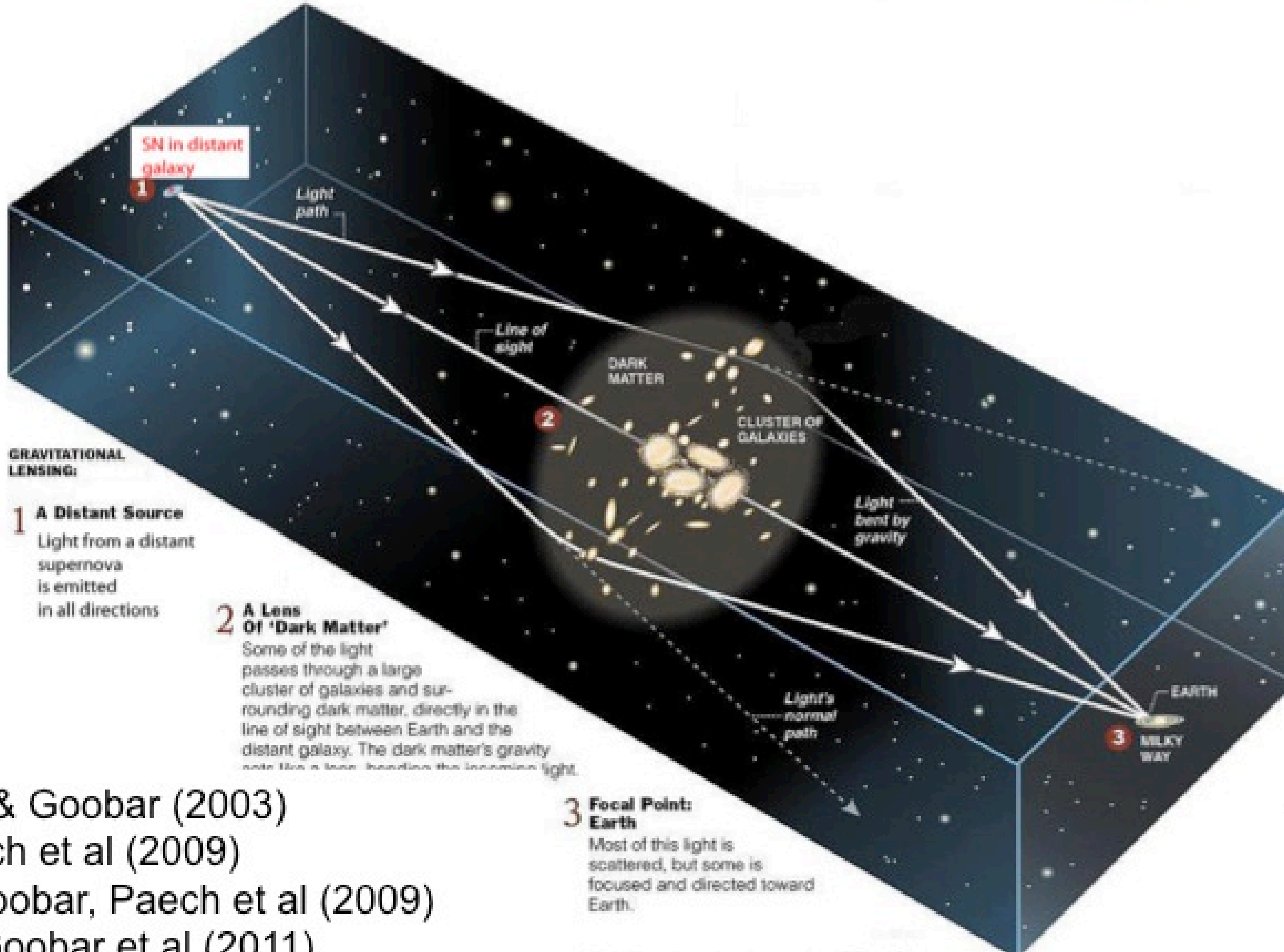
As shown in the upper left panel of Figure 6, the host-subtracted SN spectrum is noisy and spans only ~2000 Å in rest wavelength. The noise in the SN spectrum is characterized by adjacent positive and negative spikes with a width of 50-100 Å (or 20-40 Å in the rest frame). The dispersion of the G141 grism is 46.5 Å pix^{-1}, which we sub-sample to 21.5 Å pix^{-1}. Our analysis here is directed at identifying spectral features of SN sub-classes that are much broader than this in the rest frame. Binning the rest-frame spectrum into wavelength bins of width 80 Å (black points in Figure 6) removes this high frequency noise without obscuring broader features.

6.2. *Spectral Confirmation*

The relatively weak signal in this spectrum is in cient for a pure spectral *classification*, but we argu low that it is enough to provide a spectral *confirm* of this object as a normal Type Ia SN. A true classification would require that the object be ass to a SN (sub)class without any other information, o haps with only weak priors on age and redshift. I case of SN Primo, we have already built up a ser strong classification indicators from the redshift, m tude, color, and light curve shape. Taken together evidence provides a prediction that the grism data sl show spectral features consistent with a SN Ia at ab days past maximum light. We can confirm or refut prediction by testing for the presence of such featu the grism data.

The strongest test of spectroscopic confirmation sl not rely on any information derived from the broad-indicators of Sections 3-5. For example, the grism

Try something else: Nature's own gravitational telescopes!



Gunnarsson & Goobar (2003)
Goobar, Paech et al (2009)
Stanishev, Goobar, Paech et al (2009)
Amanullah, Goobar et al (2011)
Riehm, Mörtsell, Goobar et al (2011)

A1689: magnification map for source at z=2

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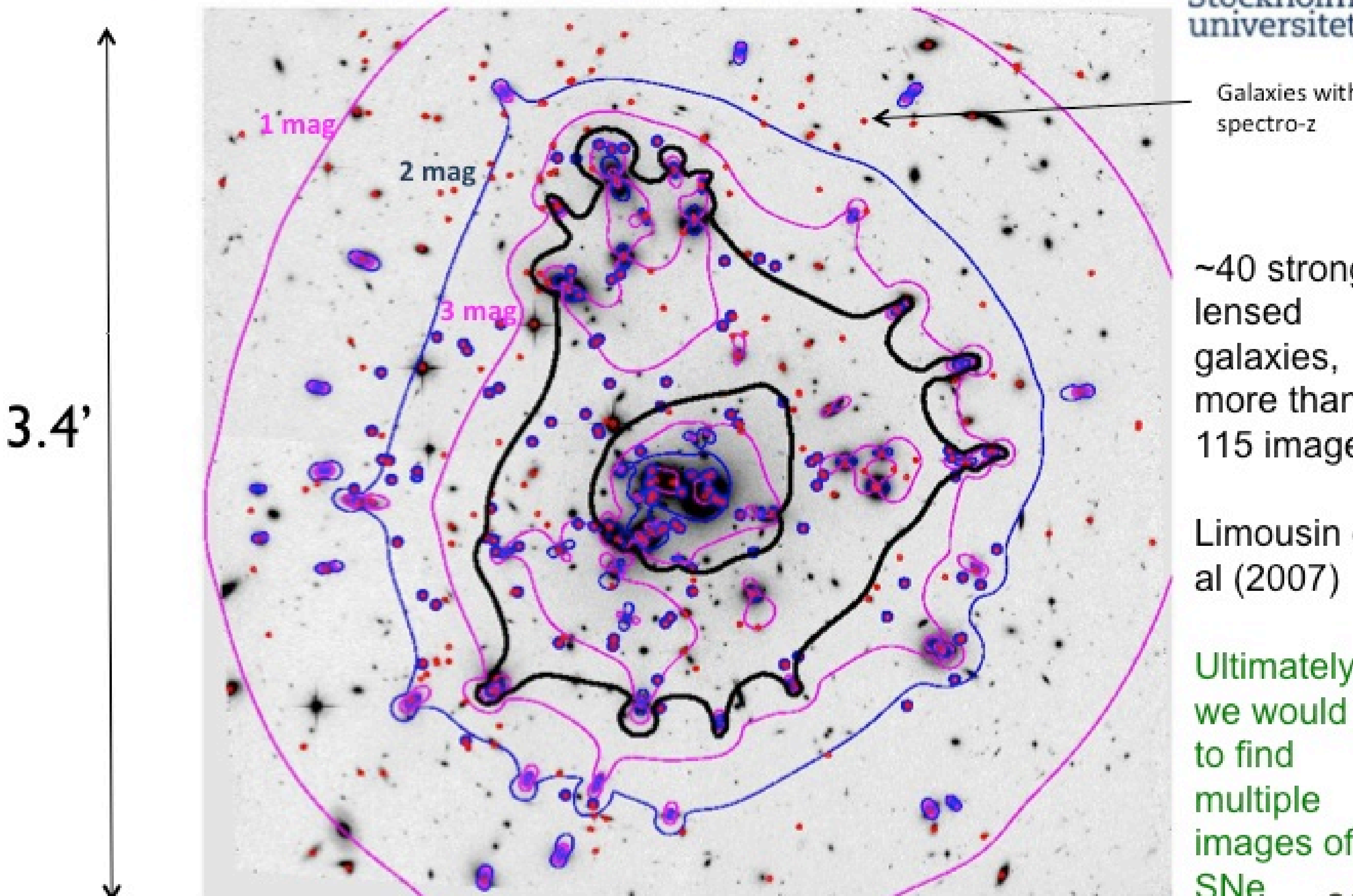
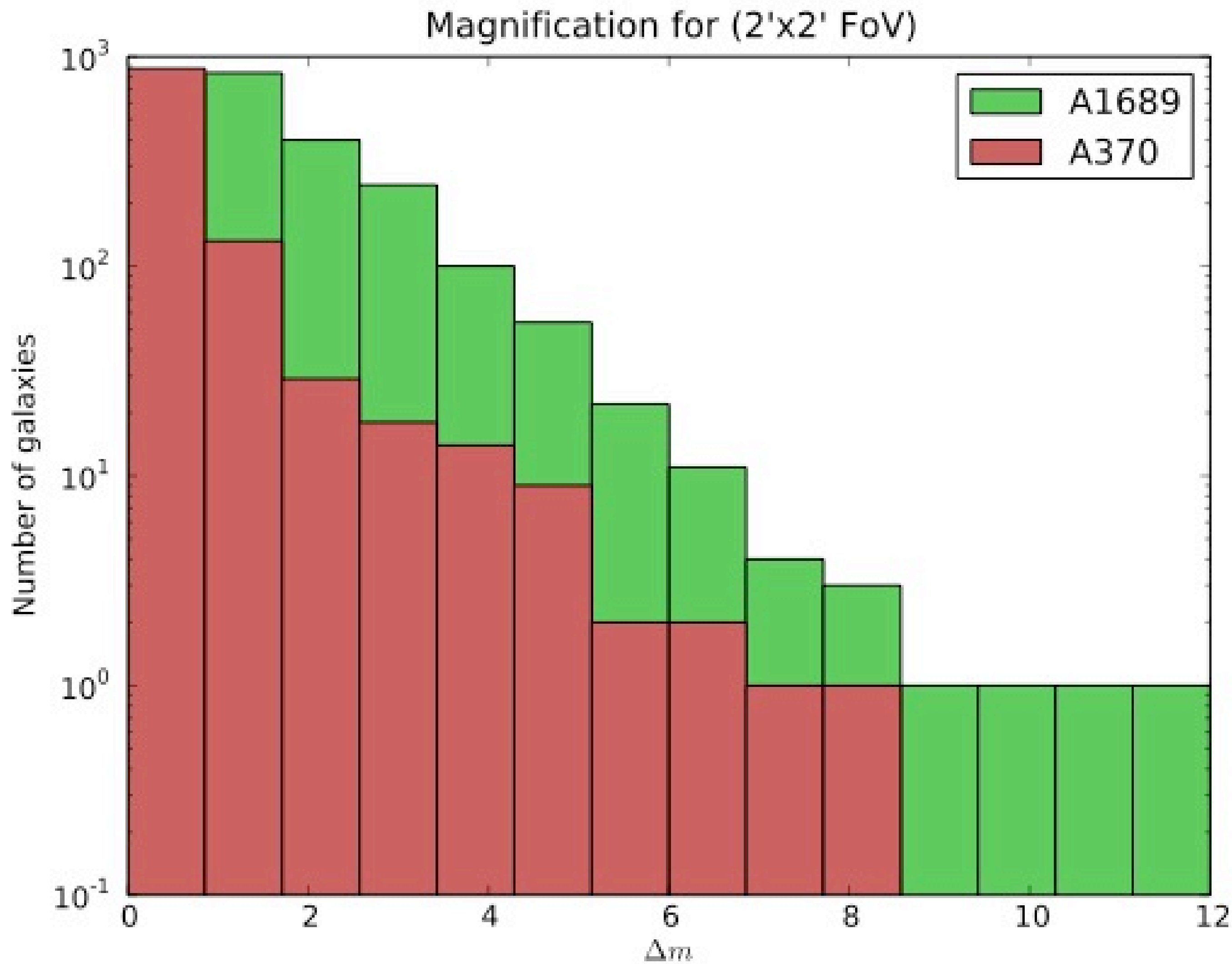


~40 strongly lensed galaxies, more than 115 images!

Limousin et al (2007)

Ultimately, we would like to find multiple images of SNe



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Examples of transients found with 6+17 hs obs at VLT in NIR (Isaac +HAWKI) + optical NOT

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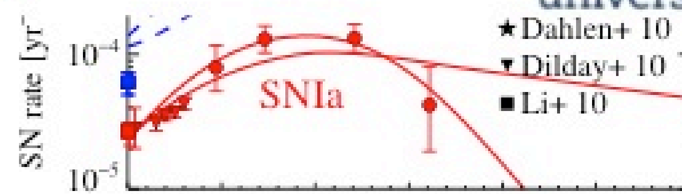
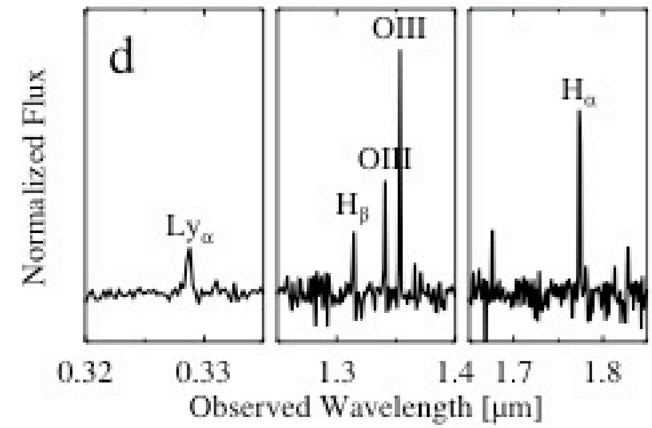
(seven bands) of the galaxy closest (0.5 arcseconds) to the tr
the SN photo-z assuming a IIP template matching SN2001cy
product of the two, yielding $z = 0.59 \pm 0.05$.

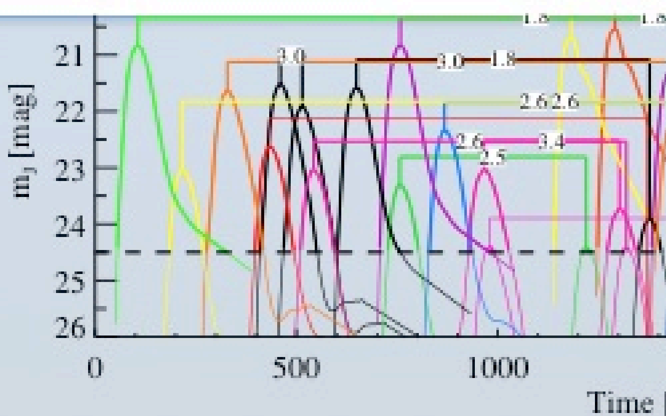
7. Implications for future near-IR surveys

The pilot survey was completed with the ISAAC instr
at VLT, which has a FOV of 2.5'×2.5' and a thresh
~24 mag (Vega) for SZ and J-bands and relatively few ob
tions. We briefly discuss the feasibility of building up light
of lensed SNe behind clusters of galaxies for surveys w
meter class ground-based telescopes and large FOV near
struments, such as HAWK-I at VLT or MOIRCS at Suba
consider a five-year "rolling" search survey, with imaging
at intrevals of 30 days.



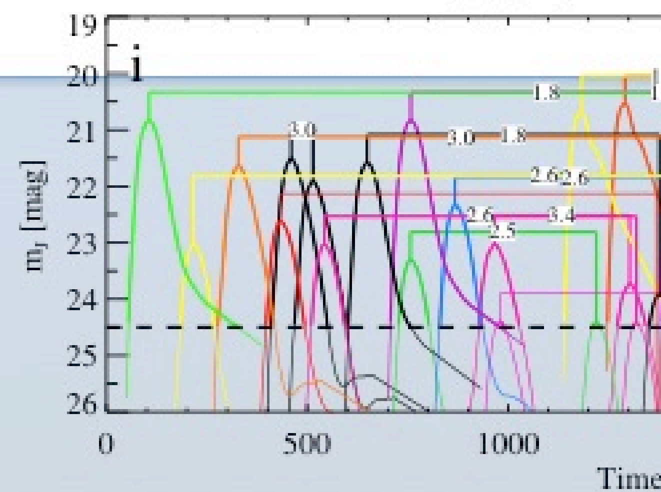
SNIIP
ISAAC z=0.59





Xshooter: host galaxy

μ=4.3±0.3
z=1.703
But not Ia!



Possible to obtain excellent LCs and spectra of high-z lensed SN – even from ground!

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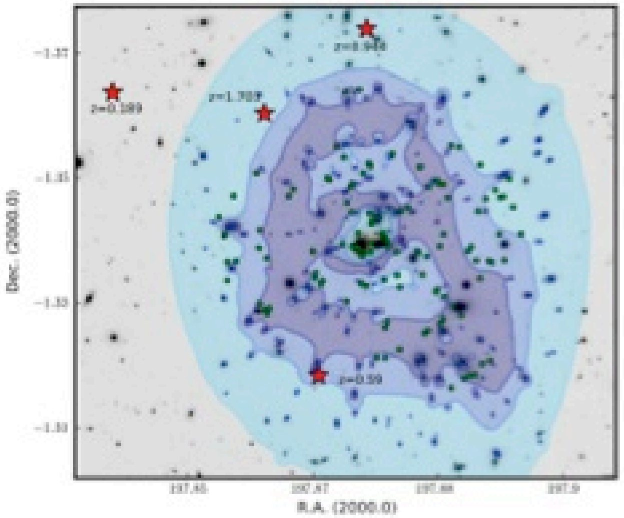
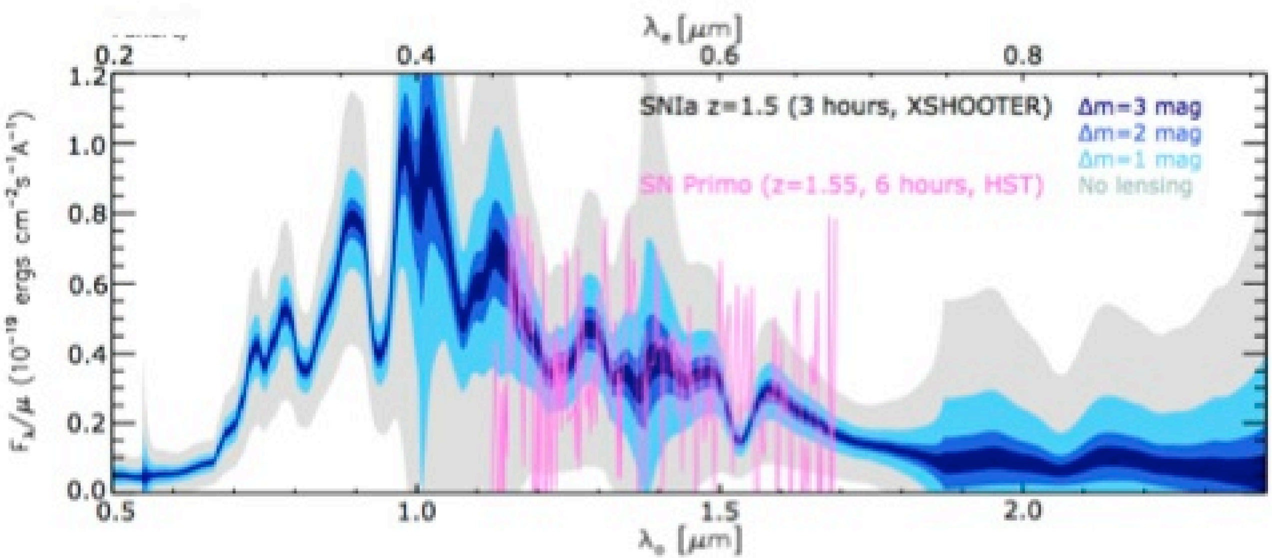


the cosmic concordance Λ-CDM model. As indicated by the blue dots, S
after an investment of more a thousand HST orbits. The expectations f
to the lensing amplification the redshift range is increased and the S/N
accompanying proposal to obtain H-band and spectroscopic ToO follow-u

- 3 -



Program at VLT + proposals submitted to HST, Subaru

Fingers crossed!!

Summary

- Spectacular developments in cosmology using SNe Ia as distance estimators: ~0.10 mag scatter in the Hubble diagram – plenty of room for improvement!
- ~600 objects reaching z=1.7 have been used to establish that the expansion of the Universe is currently accelerating. Is it Einstein's CC or something else?

  Data doesn't quite tell yet, theorists neither!

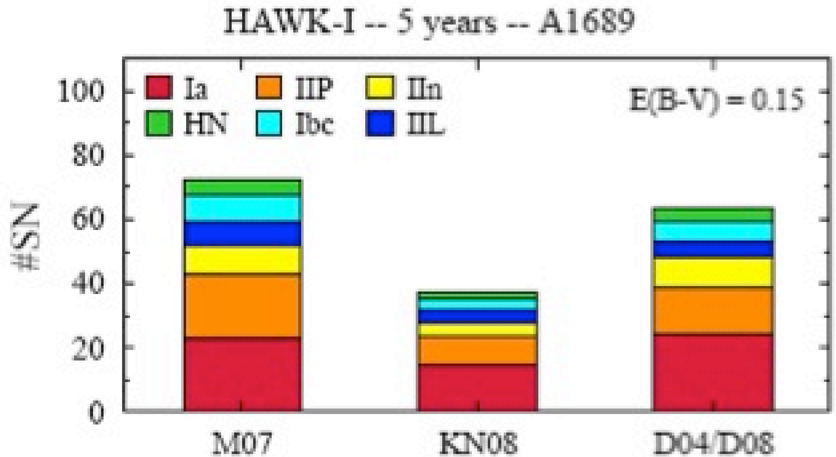
- Major activity in Stockholm (and elsewhere!) to understand reddening and environmental impact of SNIa properties, now also using iPTF survey at Palomar!
- Gravitational telescopes may soon allow us to obtain perform detailed spectroscopic studies of SNeIa

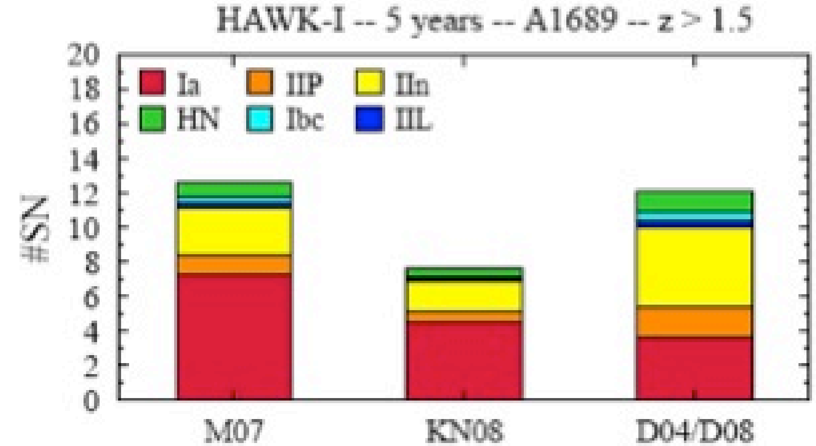
  

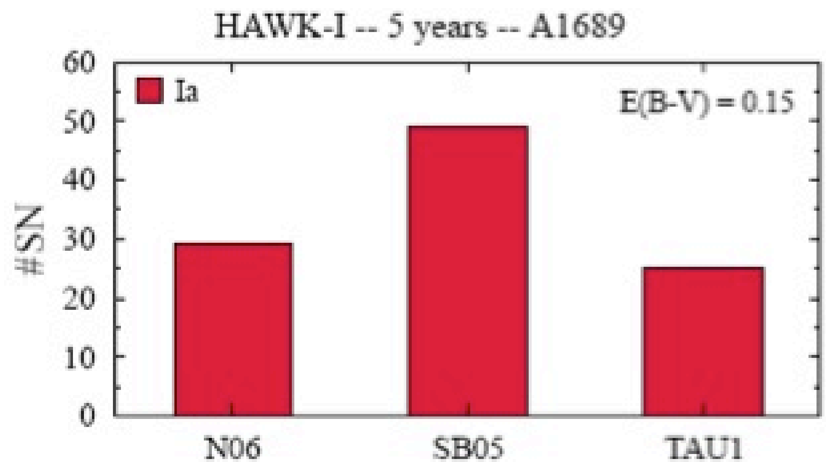
Thank You!

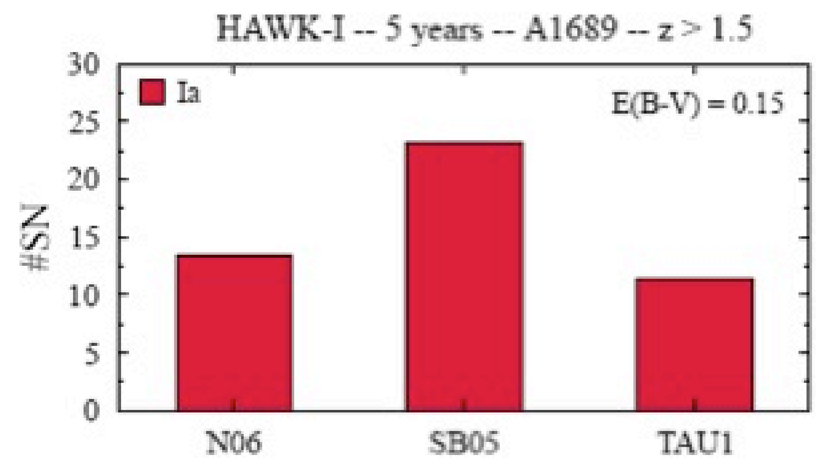
Predictions for 5-year Monitoring of A1689...

A handful of good z>1.5 spectra would be very exciting!

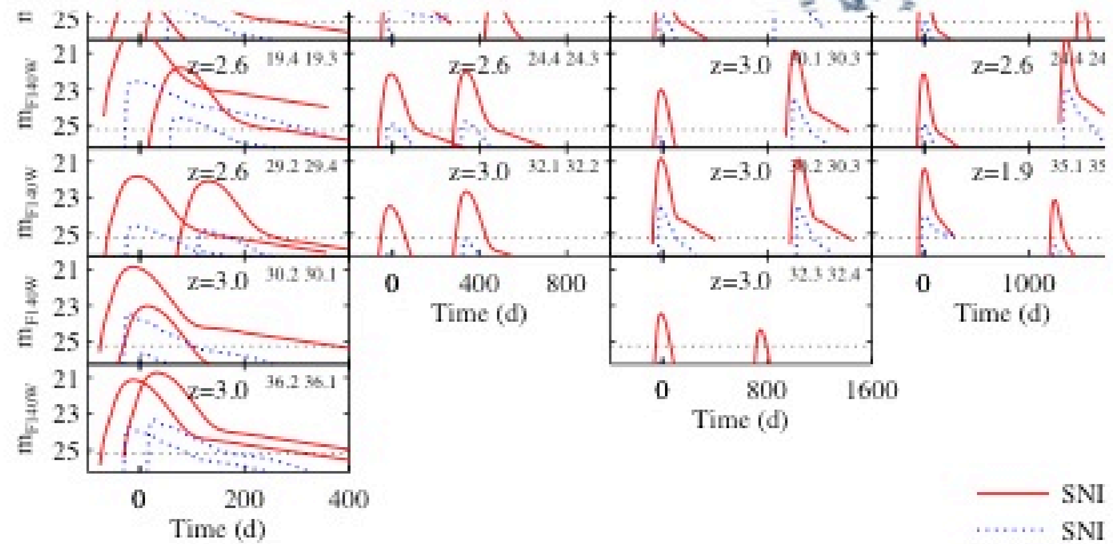








And with some luck... multiple images and independent way to measure cosmological distances, including H_0



rule out realizations producing deviant magnifications. The precision of the magnification measurements are ultimately limited by the intrinsic scatter in the brightness of SNe Ia after corrections for lightcurve shape and color, about 0.1 mag in the rest-frame optical wavelength region (Conley et al. 2011). We do not anticipate any additional sources of error due to the cluster in the line of sight. E.g., observing at near-IR wavelengths ensures that corrections from dust in the (low-z) cluster are small, especially since galaxy clusters are relatively dust-free environments, see Dawson et al. (2009) and references therein. Thus, a SN Ia exploding in any of the background galaxies behind the cluster could be used to put constraints on the lensing potential. As discussed in Paper II, we expect to detect ~ 20–30 SNe Ia (depending on the underlying rates estimates) to be detectable, e.g., in a 5 year monthly survey at VLT. In order to assess the power of this method, we investigate the strength of the tween the optimized model parameters and the m different positions behind the cluster.

Figure 3 shows the absolute value of the co cients for the predicted magnification and the fr eters as a function of position for an image at The parameters shown are those describing the ter clumps (Clump 1 and Clump 2) and the clus ing relations ($L^* r_{cut}$ and $L^* \sigma$) in the model of close to 1 implies a very strong correlation whi coefficient close to 0 implies no correlation. As Fig. 3, the free parameters differ in the strength tion with the predicted magnification both with the position behind the cluster. The dependence tion strength on redshift is very weak. In genera

Riehm et al 2011

Dust in the CS Medium?

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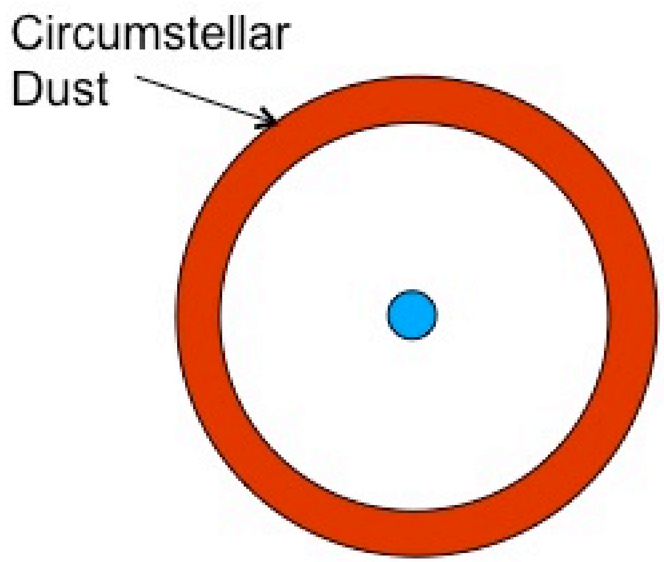
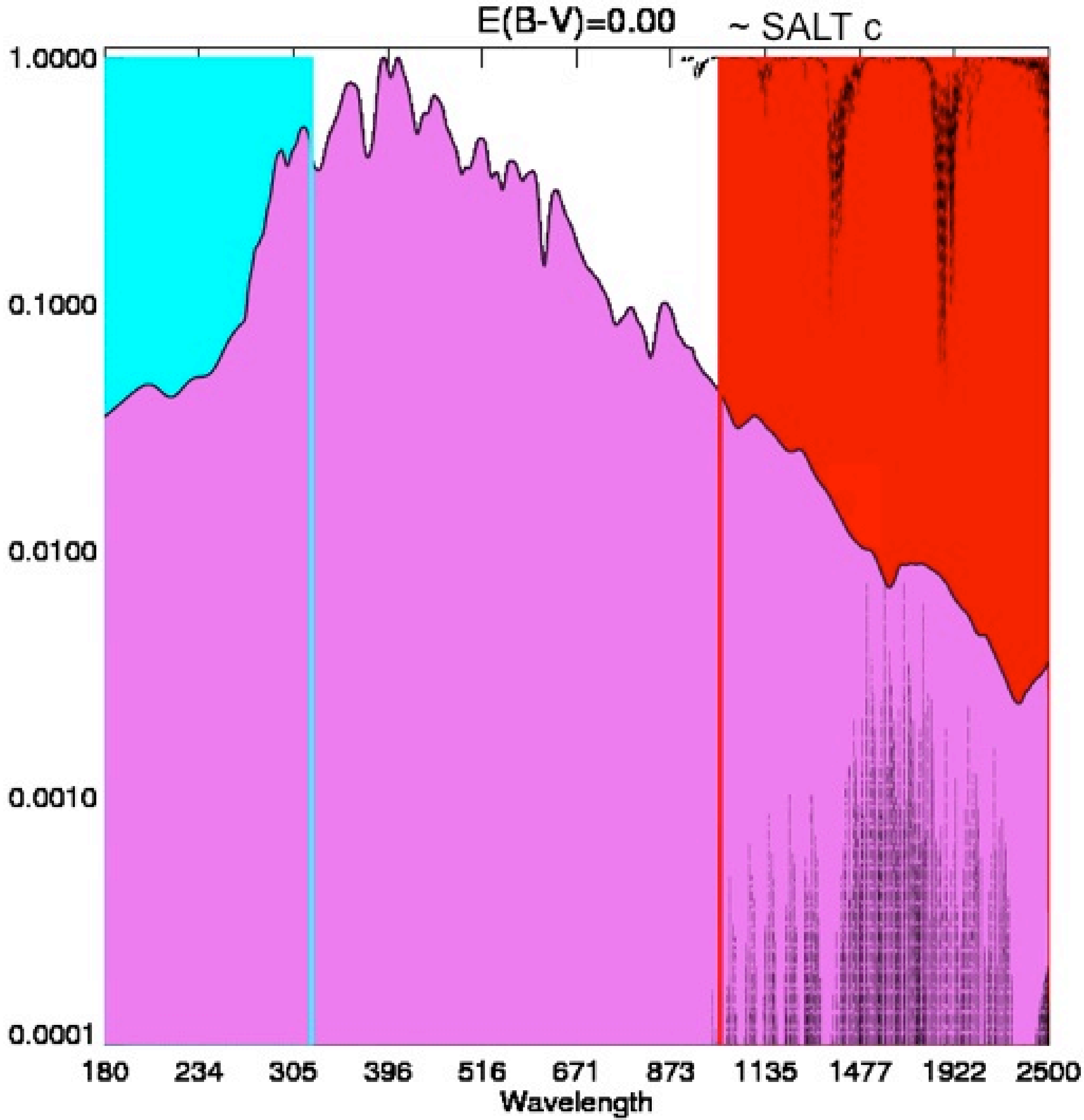


Evaporation radius ~10^{16} cm, 4 light-days



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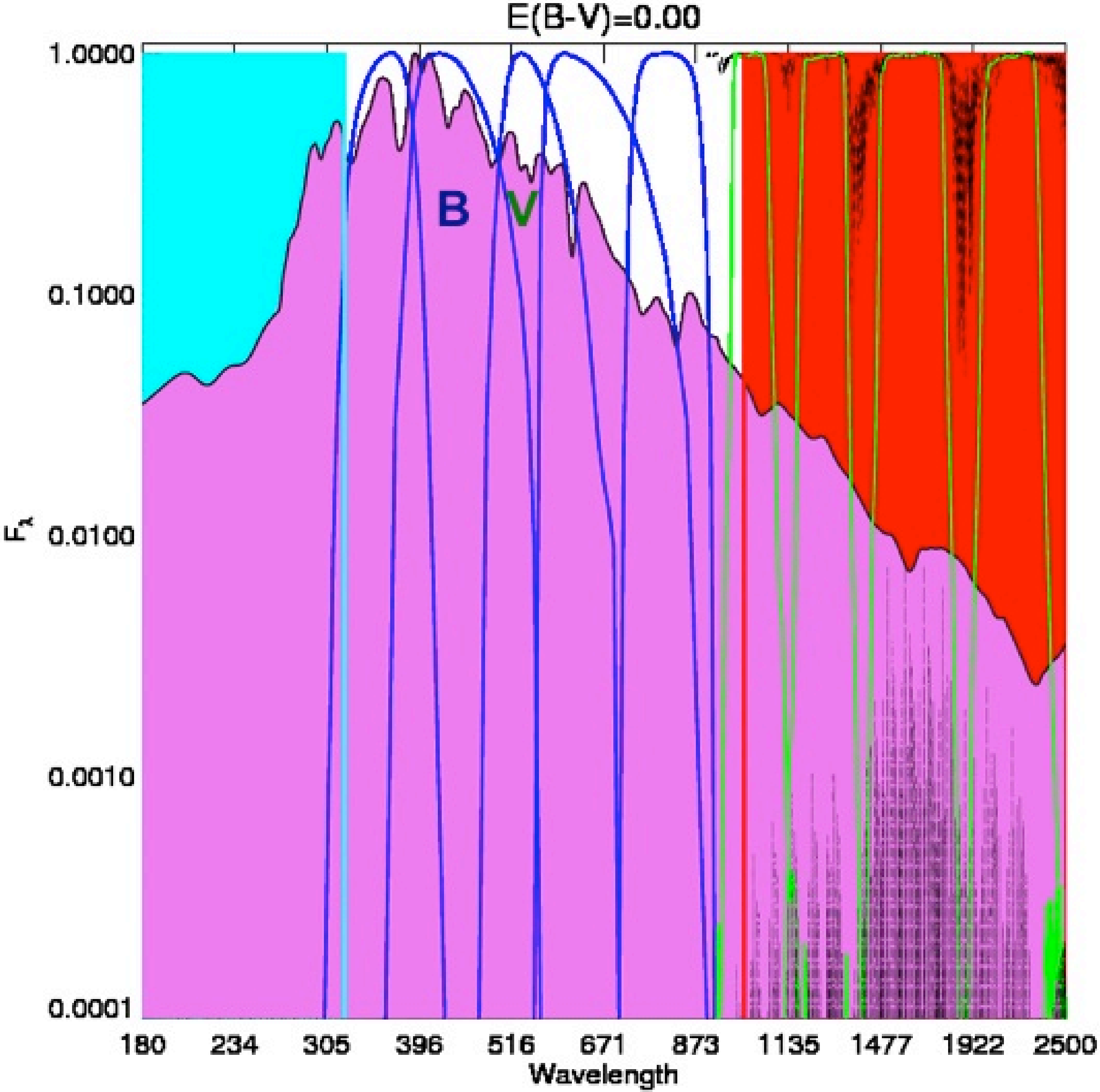
Assuming extinction curve as for Milky Way



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Assuming extinction curve as for Milky Way

Sizeable corrections!

Annu. Rev. Nucl. Part. Sci. 2011.61:251-
by Stockholm University - Libr

Figure 6

(*a*) Peak color–versus–peak luminosity and (*b*) light-curve shape–versus–luminosity (aft
correlations of Type Ia supernovae (SNe Ia). Shown are light-curve fits to the rest-frame *E*
observations of 685 SNe Ia (69) covering a redshift range of 0.025 < z < 1.4. The clear co
to correct the distances and to provide a significant reduction in the scatter. The color has
corrected for Milky Way reddening.

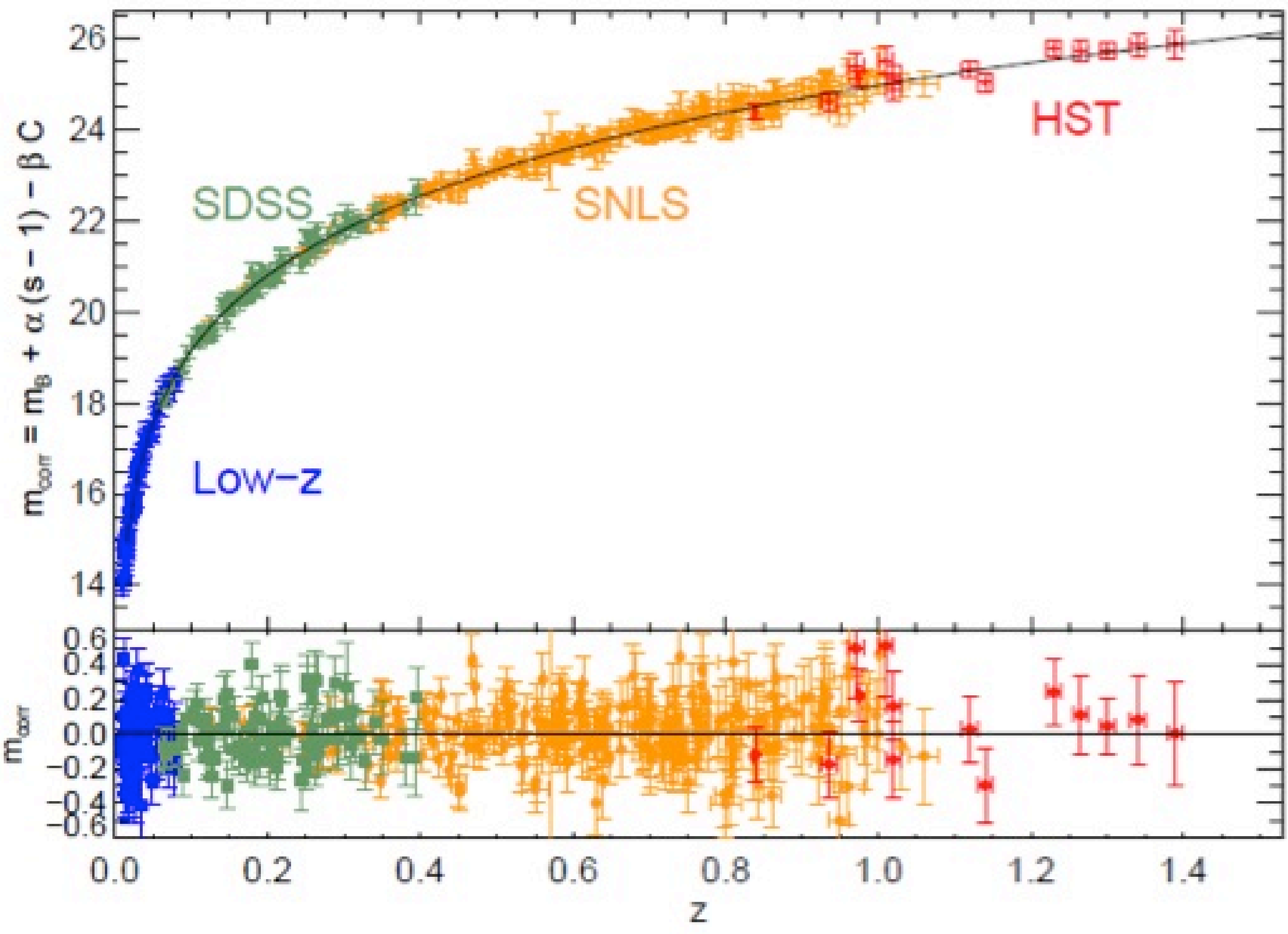
often computed as the relative magnitude attenuation between the rest-fram
band. **Figure 6** shows the empirical color brightness– and light-curve shape–
used to standardize SNe Ia.

Because these measurements are done with fixed-filter pass bands, regardles
redshift, the measured fluxes correspond to different parts of the rest-frame spect
estimates rely on flux ratios of the same rest-frame filters; therefore, a *K* correc
transfer the observed flux into the rest frame for comparison with local objects. D
cant spectral evolution, high signal-to-noise spectroscopic observations would be
flux point—a daunting task! However, given the uniformity of SNe Ia, spectral te
to compute *K* corrections. These templates are made of well-sampled, low-nois
of SNe Ia, mostly at low redshift. Any potential reddening is determined throug

supernovae typically display a slightly slower evolution.

www.annualreviews.org • SN Co

Conley et al 2011



Implications on lightcurve shape – LC width becomes a func of shell radius and width

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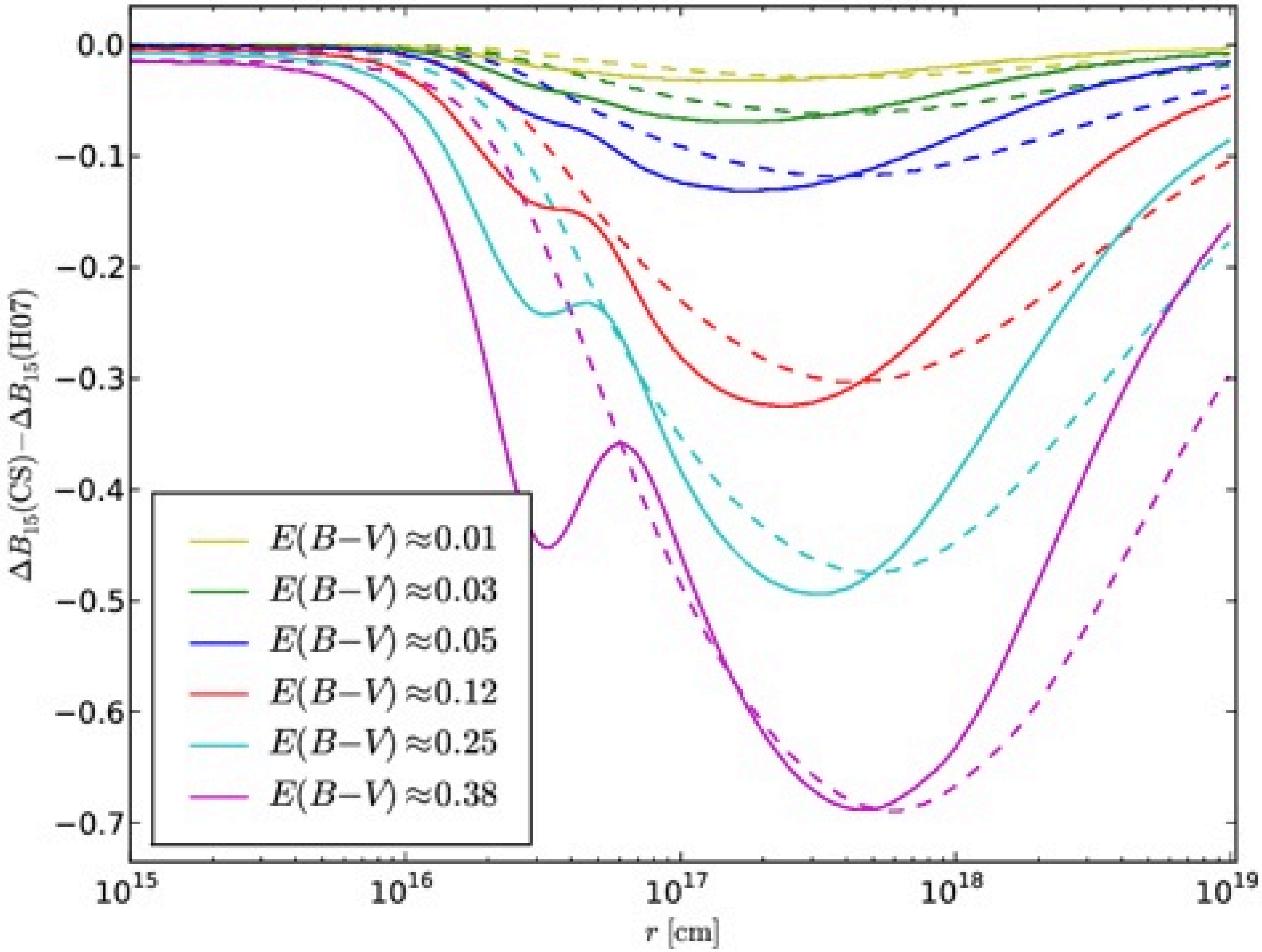

Amanullah & AG

Time-dependent color excess: blue photons arrive later, SN gets bluer at late times

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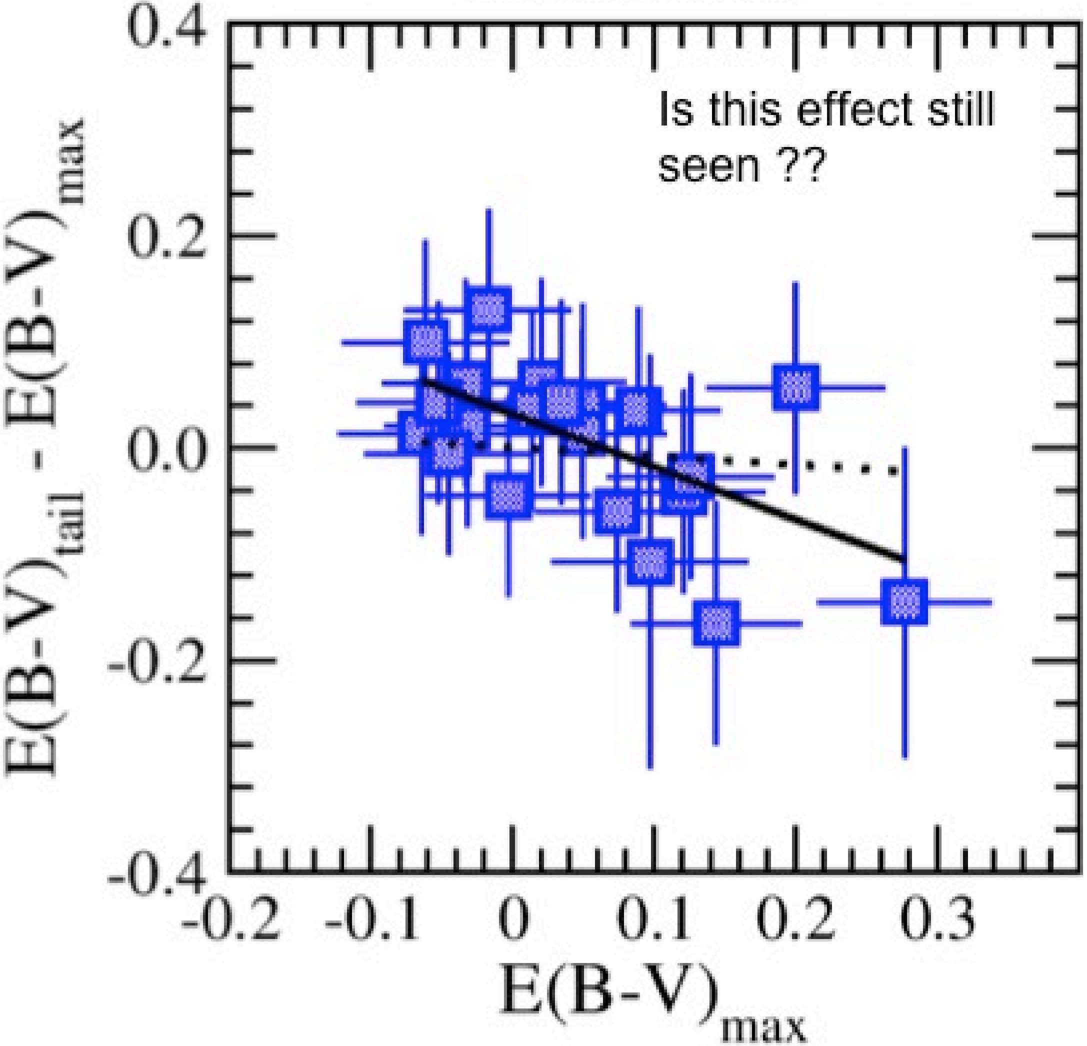
Folatelli et al. (2010)



Prediction:

some perturbation of SN features, since we get to a mixture of epochs

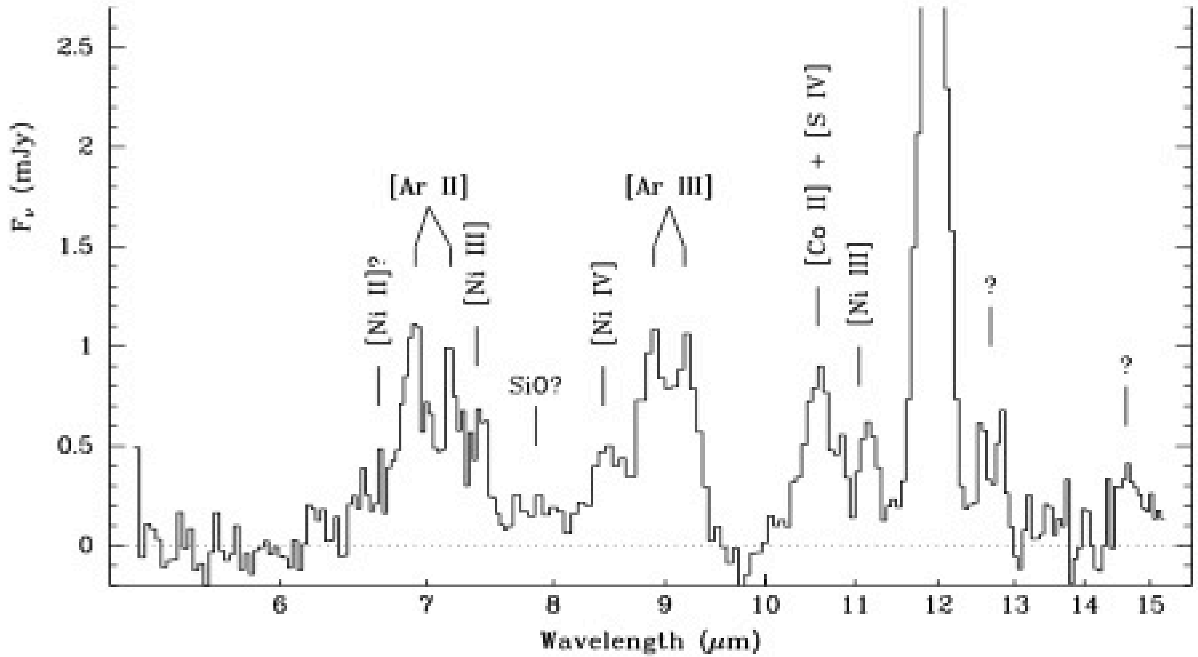


FIG. 2.— The observed mid-infrared spectrum of SN 2005df. Wavelengths are shown as vacuum coordinates in the observer's frame, and are plotted on a logarithmic scale so that the observed line width is proportional to the velocity line width throughout the large wavelength span. See text for discussion of line identifications.

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Gerardy et al (2007)

Power-law

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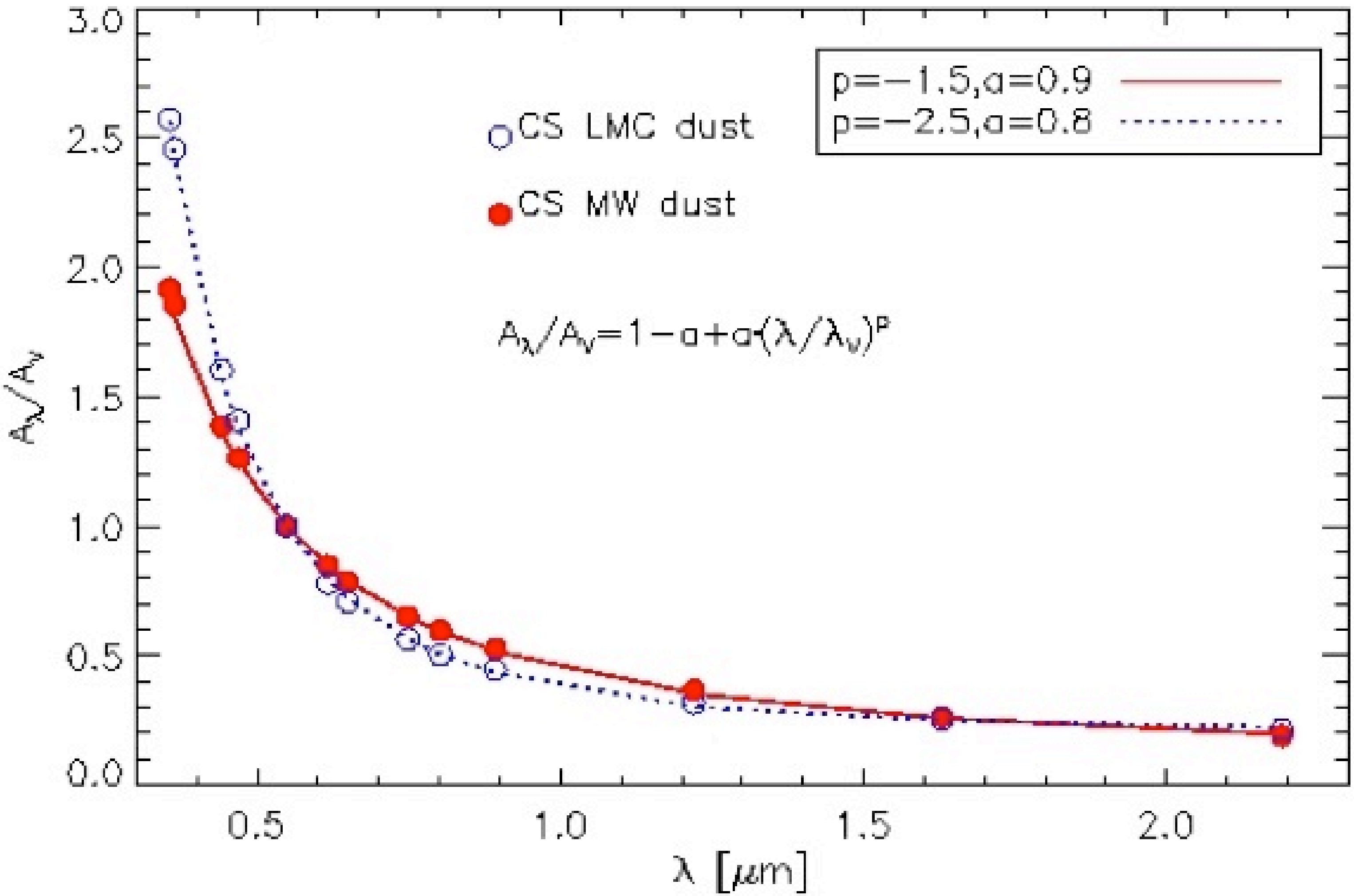

State of the art at highest-z from HST

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et al. 2001). This object was found in a passive host with an old stellar population, strongly suggesting it is a SN Ia. However, there is no reliable spectroscopic measurement of the SN, it has only a sparsely observed light curve, and the host redshift relies on a photo-z and a questionable single-line detection. More and better observations are clearly needed before any inferences about the high-z SN Ia population can be drawn.

Collectively, the SN Ia samples out to $z \approx 1.5$ are consistent with a description of dark energy as the cosmological constant, $w(z) = -1$ (Riess et al. 2007; Hicken et al. 2009; Sullivan et al. 2011; Suzuki et al. 2011). Figure 1 shows a recent collection of $\sim$ 500 SNe Ia from Conley et al. (2011), with distances plotted relative to the best-fit ΛCDM cosmology. Histograms on the lower edge show the redshift range of each contributing survey. With the addition of the Wide Field Camera 3 infrared detector (WFC3-IR) on *HST*, a new window has been opened, allowing the detection of SNe Ia at $z > 1.5$. This very high redshift regime provides an excellent laboratory in which to test for possible evolution of the SN Ia population (Riess & Livio 2006).

with these constraints would affect the obse magnitudes at $z > 1.5$ by less than 0.1 mag. that a larger deviation in the peak magnitud SNe would provide evidence for evolution of population.

Riess & Livio (2006) considered SN Ia proge els that predict a decrease in the observed nosity for objects with a higher initial proge due to changes in the internal C/O ratio at explosion (Domínguez et al. 2001; Hoeflich e If such an effect exists, then we might expec signature becoming apparent in the SN Ia po $z > 1.5$: the universe is <4 Gyr old at thes so low-mass stars are still on the main seq thus the SN Ia progenitor stars must necessar massive.

The high-z SN Ia sample also provides an constraint on progenitor models through th ment of SN Ia rates. Binary stellar populat sis combined with models of SN Ia explosion can provide a prediction for the delay-time (DTD) that should be observed for the SN Ia population at any redshift. Convolving thi DTD with measurements of the cosmic sta

ESO "pilot": ISAAC (6 hs, Y) and HAWK-I (17 hs, J) on A1689

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+ Archival data from FORS2, HST
+ Optical Monitoring in NOT 2.5m
+ Unrelated ESO program in parallel with our HAWKI obs: Ks + NB1060 (1.06 μm)

Gravity gives, gravity takes: focusing means also smaller survey area.

est redshift SNe can now be moved to longer wavelengths, th
avoiding the difficulties involved with restframe UV observ
tions, and extending the potential for supernova discoveries, e
pecially Type Ia supernovae, beyond $z > 2$. A feasibility stud
of the potential to build up lightcurves of lensed SNe with larg
and deeper surveys shows that this is a very exciting path f
new discoveries. The equivalent of a five-year monthly surv
of a single very massive cluster with the HAWK-I camera
VLT would yield 40 – 70 lensed SNe, most of them with goo
lightcurve sampling. Thus, a dedicated multi-year NIR rollin
search targeting several massive clusters would lead to a hig
rate of very high-z SN discoveries, thus making this approa
complementary to deep optical space-based SN surveys (Rie
et al., 2007) as well large field-of-view optical SN searches, e.
(Poznanski et al., 2007).

Although very rare, multiple images of strongly lensed SN
are within reach of such a survey and could offer potentially e
citing tests of cosmological parameters as well as improvemen
to the cluster mass modeling.

Acknowledgments

We would like to thank Peter Nugent for providing lightcur
and spectral templates used in this analysis. Filippo Mannuc
is also thanked for making his SN rate predictions available
us. We are also grateful to Dovi Poznanski for providing us wi

SNIa cosmology v2012.6

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- Acceleration of the Universe has been established, but what is the nature of the Dark Energy causes it?
- Is it Einstein's Cosmological Constant, Λ, in spite of its unnaturalness?
- If DE = Λ then it must be constant in space and time (vacuum energy)
- EoS $w = p/\rho$ (=-1) for Einstein's Λ
- SNIa cosmology among few techniques to find out!

Dust in intergalactic medium?

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imizing the residuals in the Hubble diagram. Accord
Equation 11, a component of cosmic dust with $\beta_{\rm d} = 4$
bias the distance modulus estimate by

$$\delta m_{\rm bias}(z = 0.5) \simeq 0.01 \text{ mag} .$$

Given the simple scaling relations derived in §2.1, th
in turn bias the inferred $\Omega_{\rm M}$ value by $\delta\Omega_{\rm M} \simeq 0.01$.
translates into a $\sim 3\%$ bias for $\Omega_{\rm M} \simeq 0.3$. Below we qu
this effect more accurately, using existing data.

2.3 Application to the Union supernova sam

We now investigate the impact of cosmic dust on a rec
pernova dataset: the "Union" sample (Kowalski et al.
These authors have combined various supernova sa
compiling a "clean" dataset of 307 SNe with 0.015
1.55 which they used to infer cosmological paramete
straints.

Using Equation 6, we sample the parameter spac
strained by this dataset for two cosmological models,

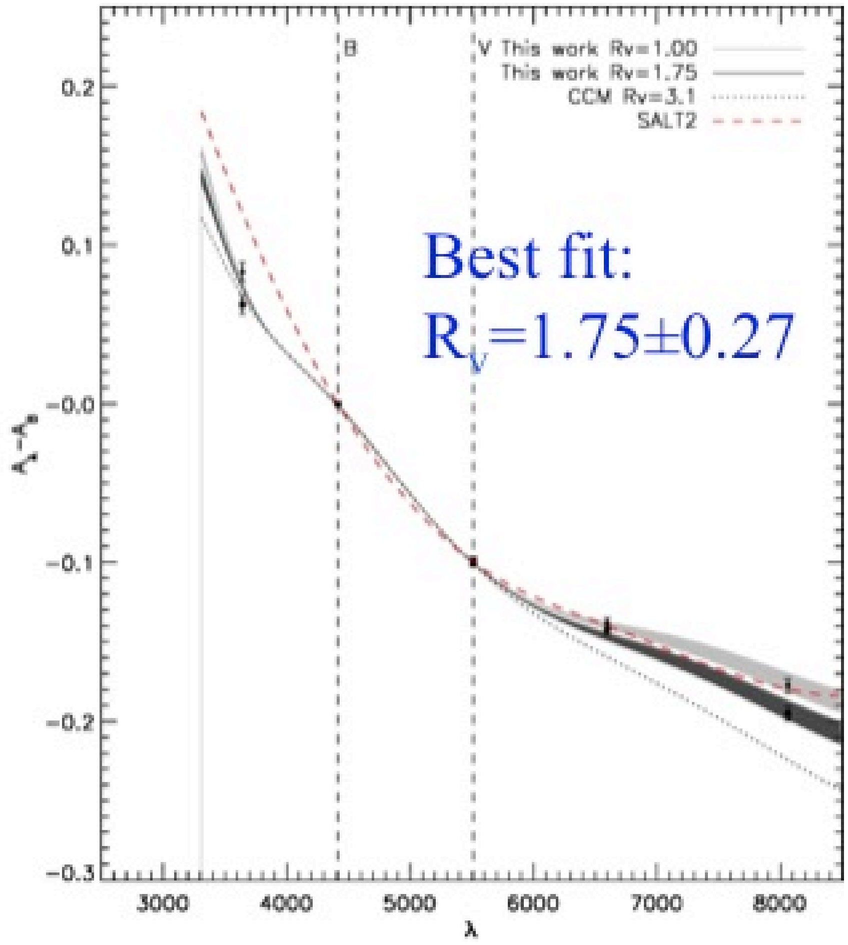
Issue for *high-precision* high-z cosmology

Negligible at low-z: not related to "low" R_V problem

Menard, Kilbinger & Scranton (2009)

Systematic uncertainties? No big deal…

Low R_v no matter how you look...



Nobili & Goobar (2008)

Re-evaluated intrinsic colors of 80 near-by SNe, e.g. dependence on stretch, and found that a consistent picture emerged for R_v~1.75

supernovae typically display a slightly slower evolution.

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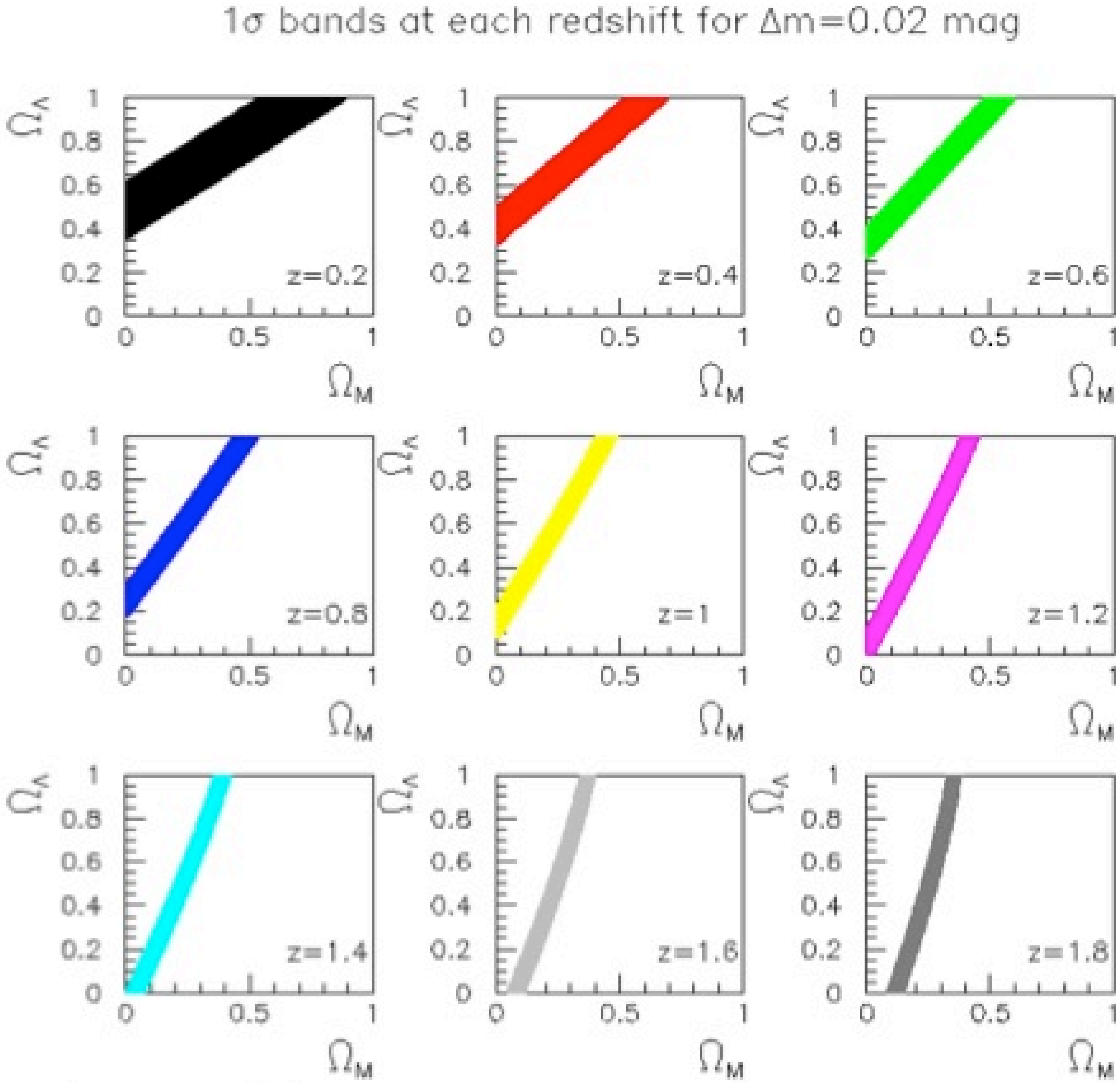
Summary

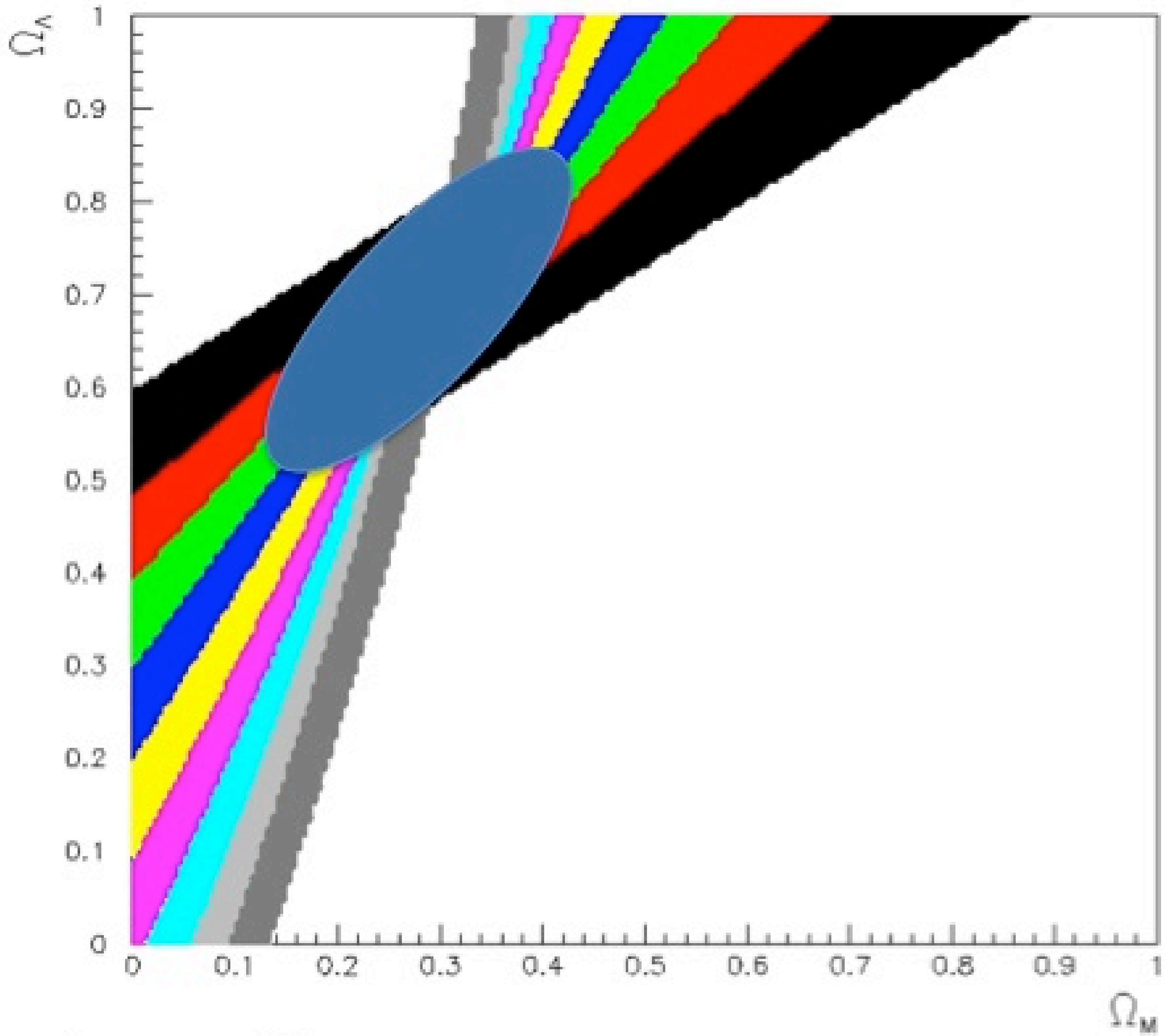
- Spectacular breakthroughs in cosmology using SNe Ia as distance estimators in spite of limited understanding of progenitor system and line-of-sight effects: ~0.10 mag scatter in the Hubble diagram today.
- We are starting tf dust in line of sight vs SN intrinsic properties.
- Studies of lensed SNe are very promising to explore SN properties at z~1.5 and beyond: it is feasible!
- Addressing these systematic effects holds great promise for significant improvements on precision of w_{DE}: DES,PanSTARRS, LSST, and possibly EUCLID would provide huge statistics.
- Caution: no clear theoretical guidance for what precision is required for next breakthrough.

Redshift range



AG & Perlmutter 95

wide lever arm in redshift is key!



AG & Perlmutter 95