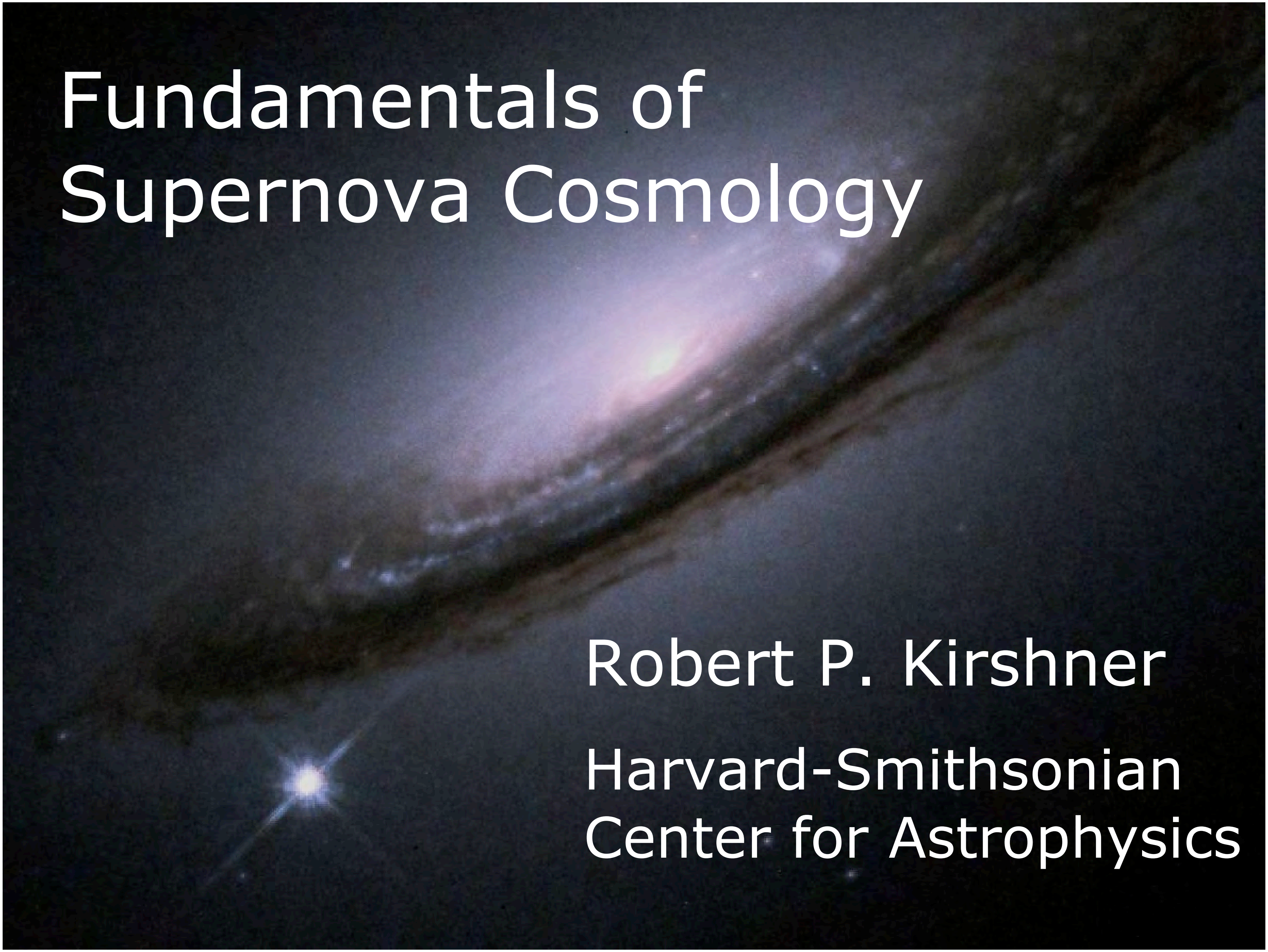
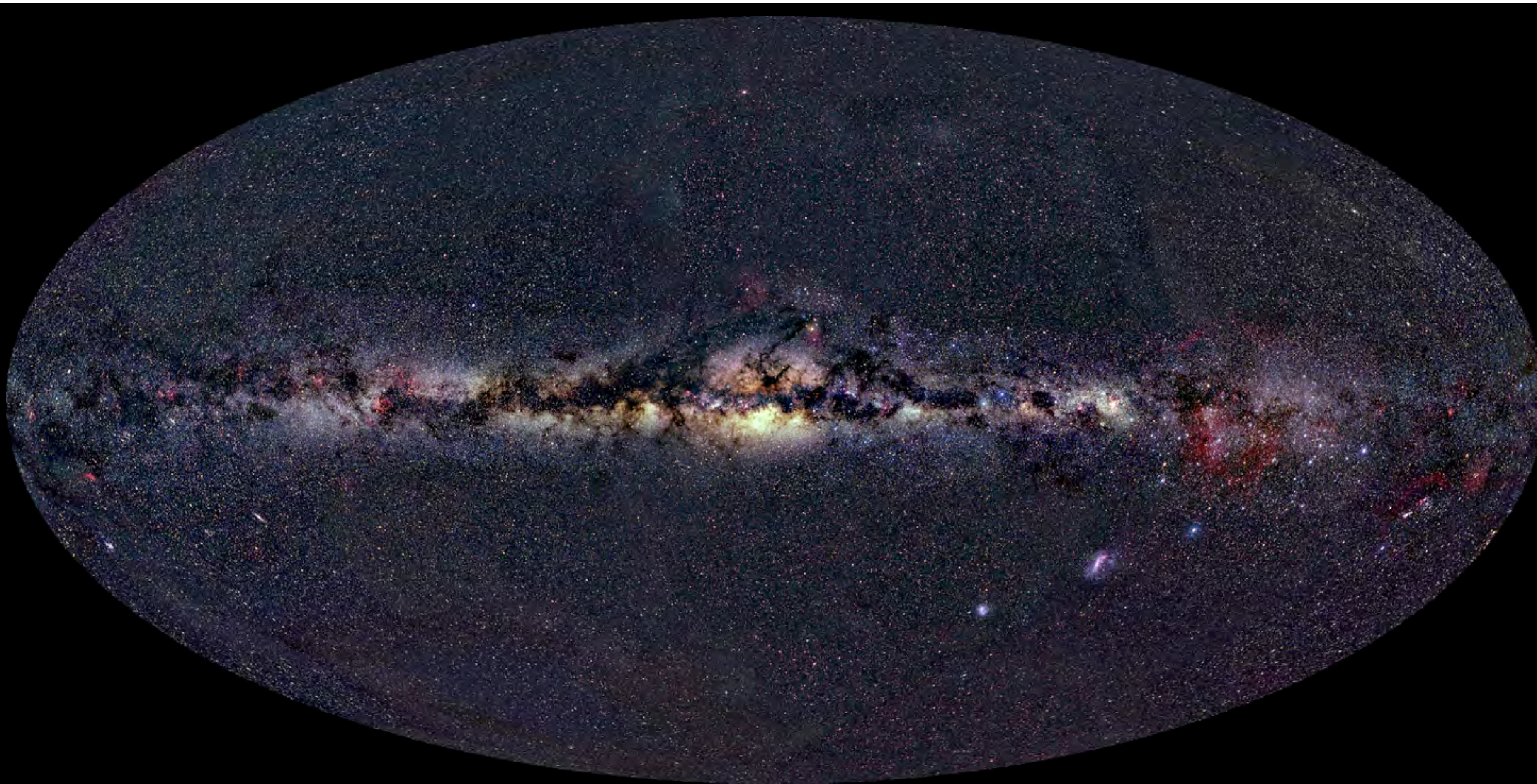


Fundamentals of Supernova Cosmology

Robert P. Kirshner

Harvard-Smithsonian
Center for Astrophysics



The Milky Way

In 1917 = The Universe

Today = 1 in 10^{11}

1917:

Einstein stuck in the cosmological constant to make a static Universe.

theory of relativity lies nearest at hand; whether, from the standpoint of present astronomical knowledge, it is tenable, will not here be discussed. In order to arrive at this consistent view, we admittedly had to introduce an extension of the field equations of gravitation which is not justified by our actual knowledge of gravitation. It is to be emphasized, however, that a positive curvature of space is given by our results, even if the supplementary term is not introduced. That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars.

“Universe” = Milky Way Galaxy

Supernovae & Cosmology

Shapley-Curtis Debate (1921)

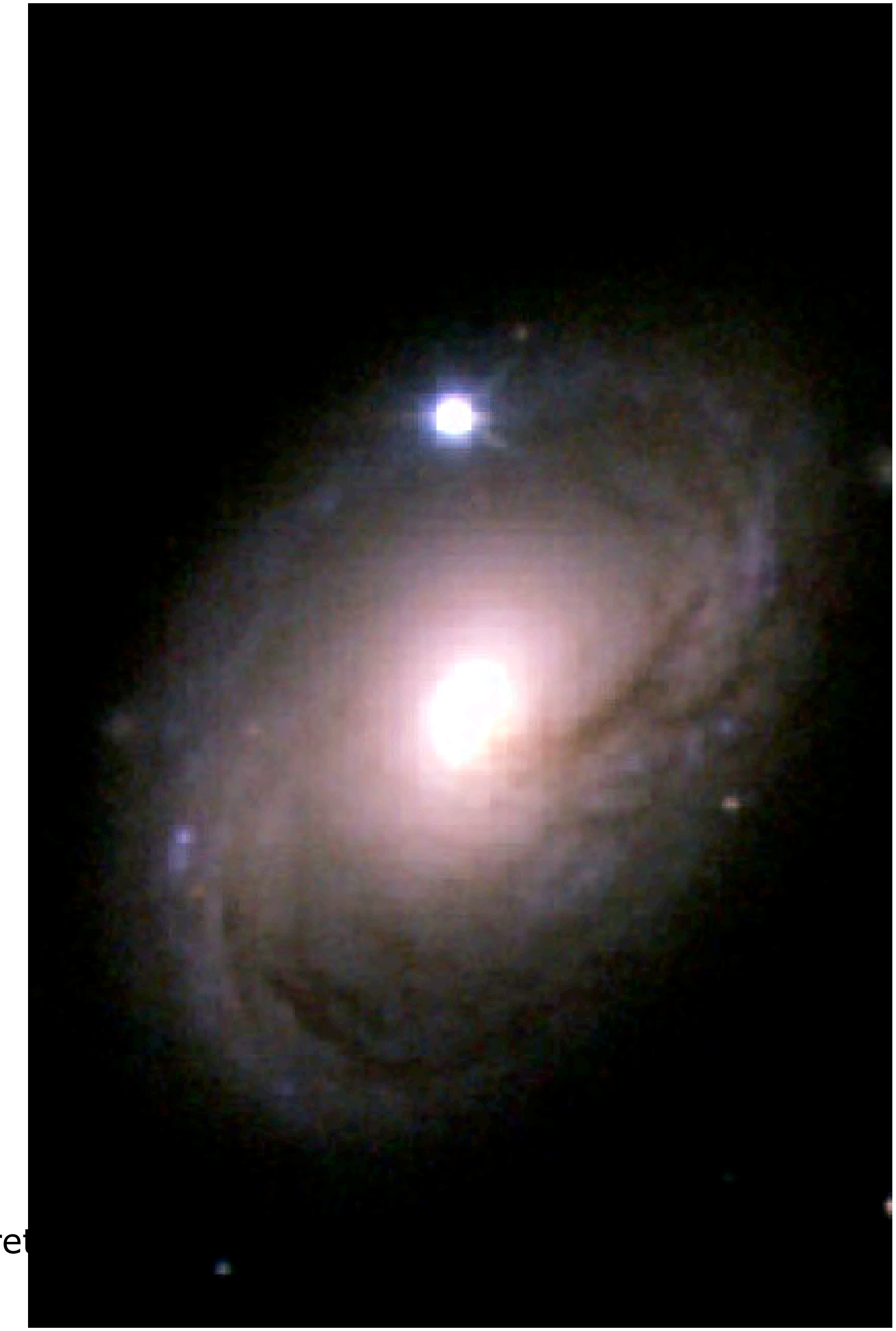
Shapley:

S Andromeda (SN 1885) M= -16?

“out of the question”

Curtis:

“the dispersion of novae may be 10 magnitudes…a division into two classes may not be impossible”



Supernovae & Cosmology

Hubble (1929)

“a mysterious class of exceptional novae which attain luminosities that are respectable fractions of the total luminosities of the systems in which they appear.''

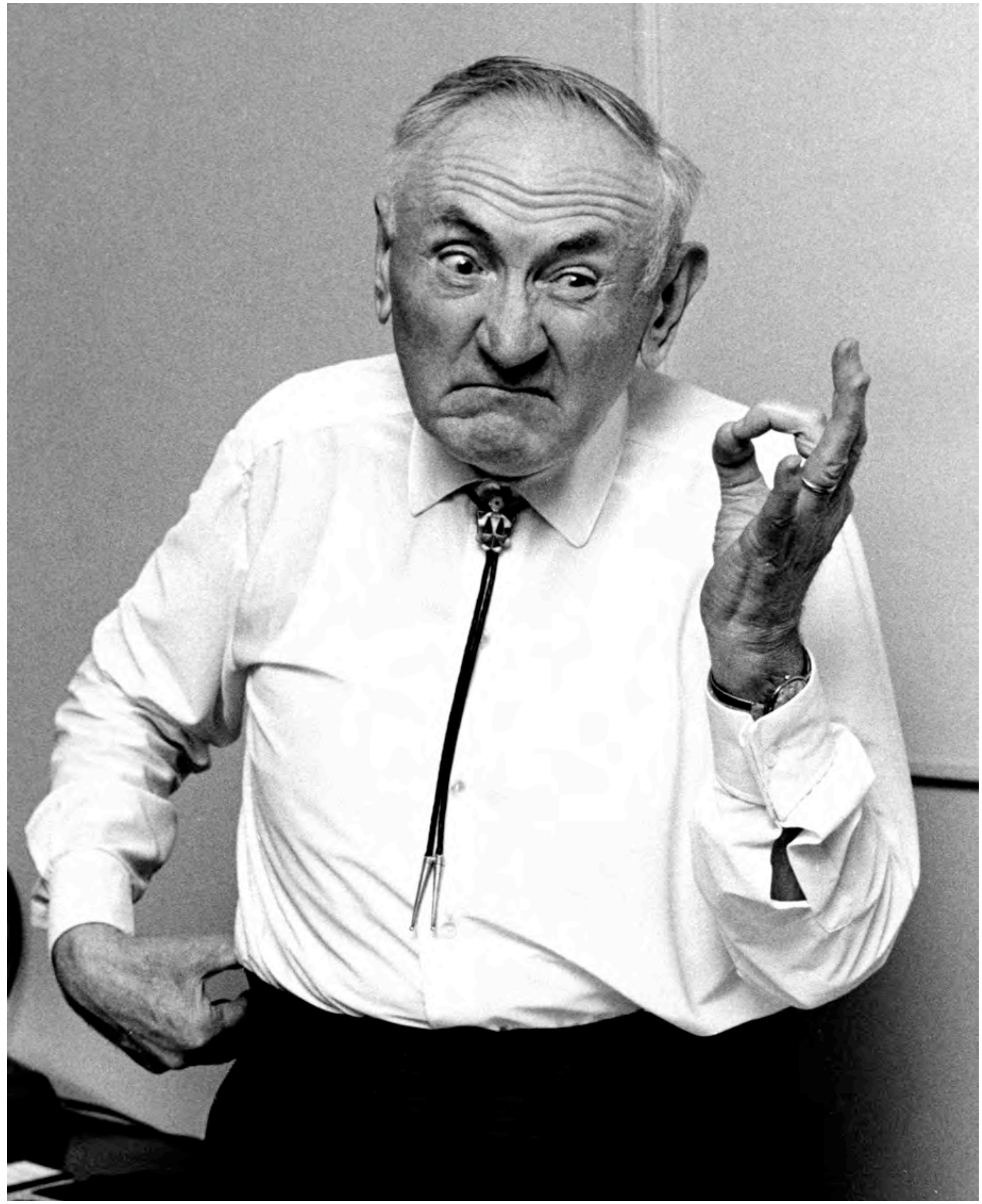
Fritz Zwicky--
Supernova Visionary!

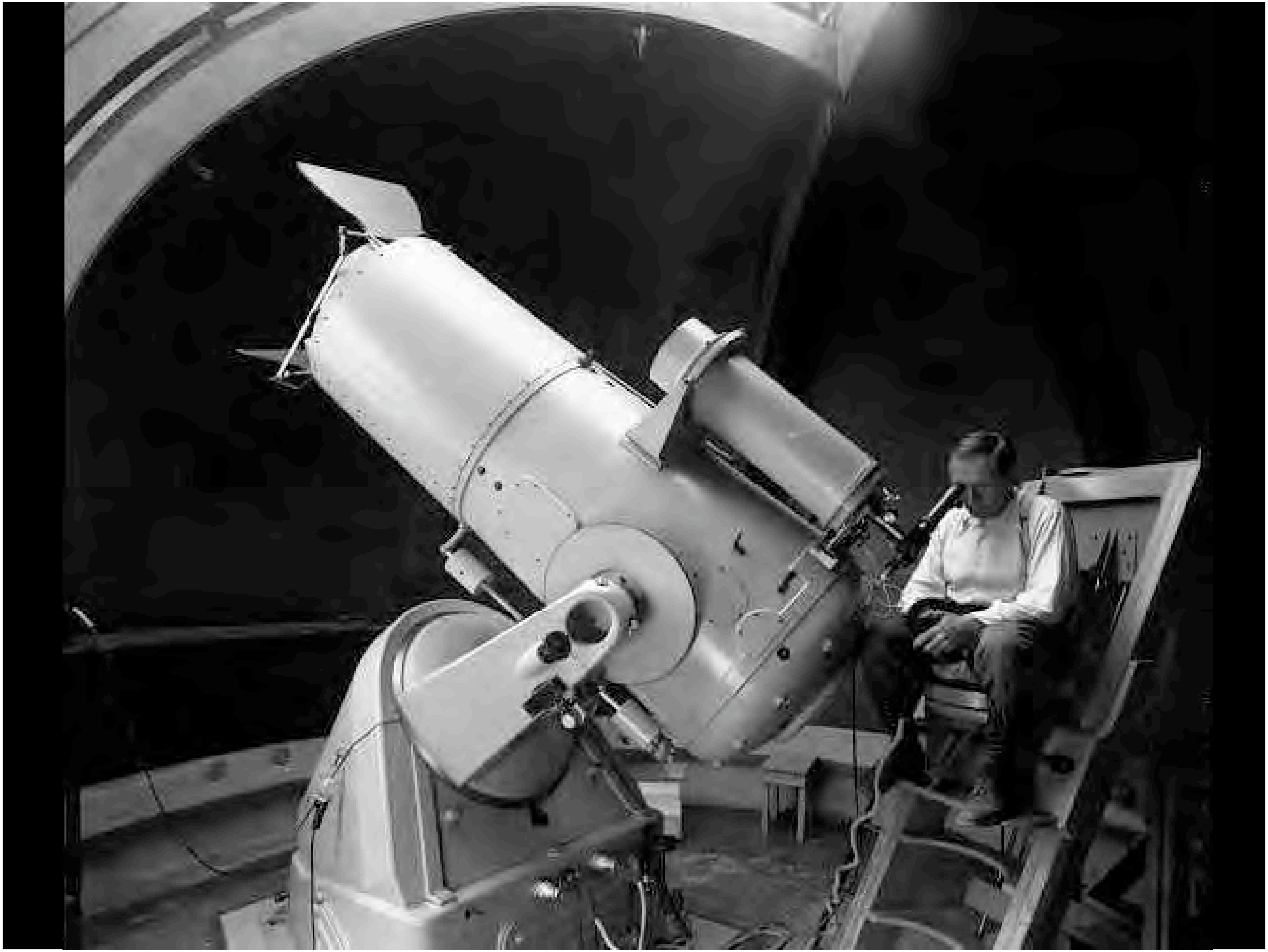
SN Ia:
thermonuclear explosion of a white dwarf

SN II:
collapse to neutron star or black hole

{Also Ib & Ic:

All the SN Tom Abel was talking about have a core collapse and are powered by gravity





Type Ia supernovae

Exploding stars ~ 4 x 10^9 Suns

~1 SNIa /century in a galaxy

~30 per second in the Universe!

July 3, 2008

Kowal (1968)

1-σ ~ 0.6 mag

Speculated that supernova distances to individual objects might eventually be known to 5-10%

"[i]t may even be possible to determine the second-order term in the redshift-magnitude relation when light curves become available for very distant supernovae."

DES OF SUPERNOVAE 1023

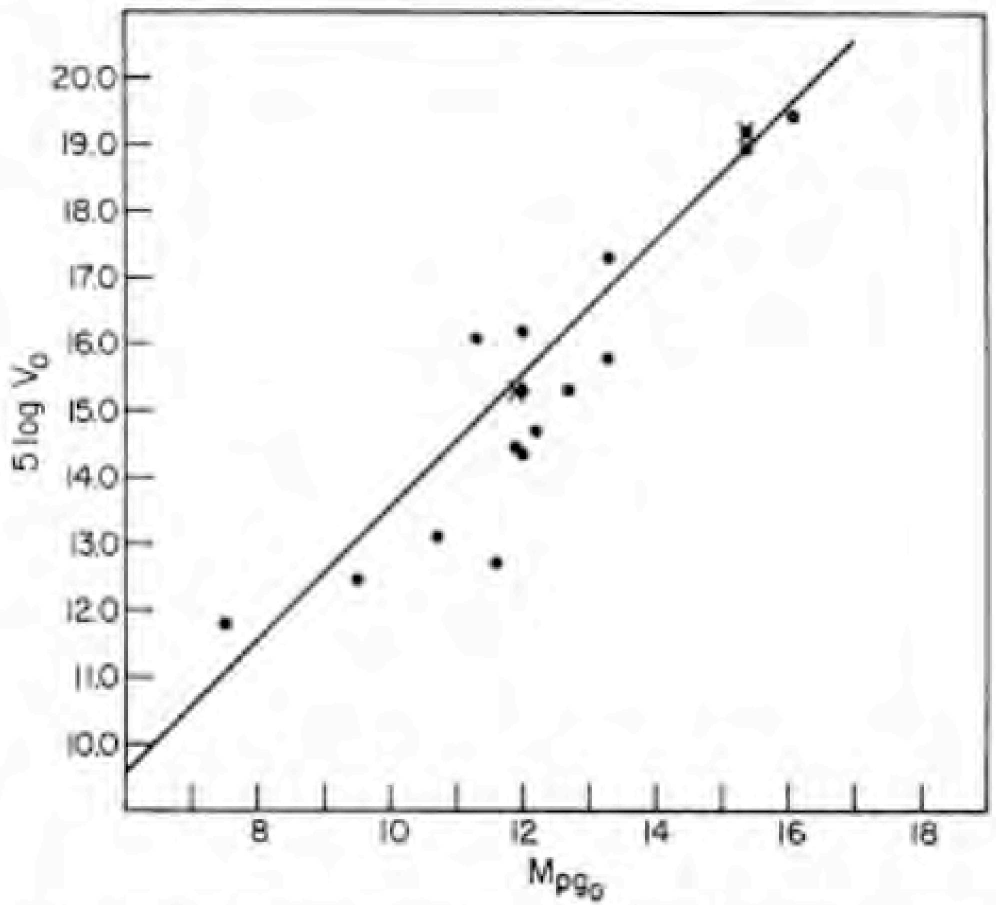
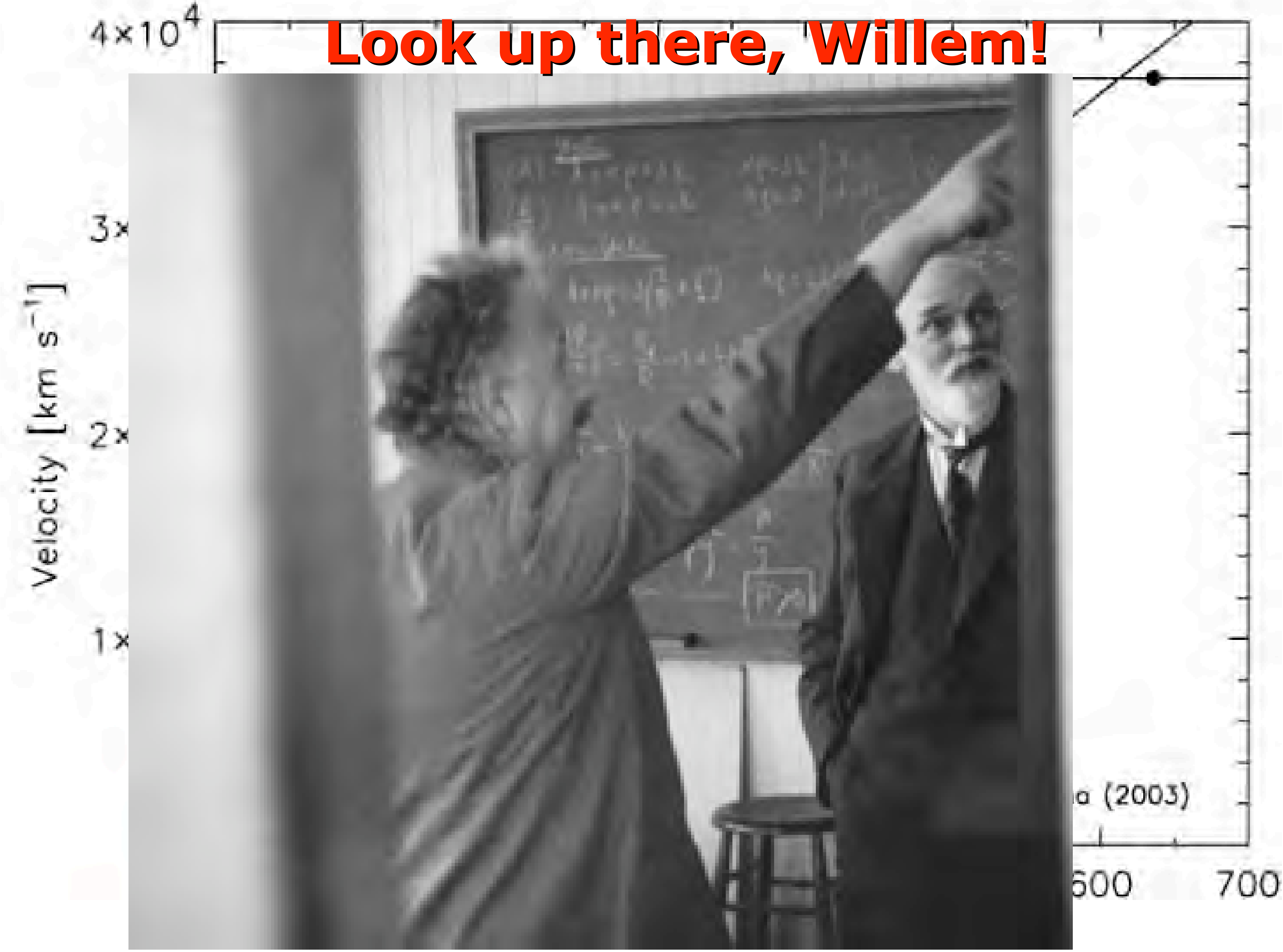


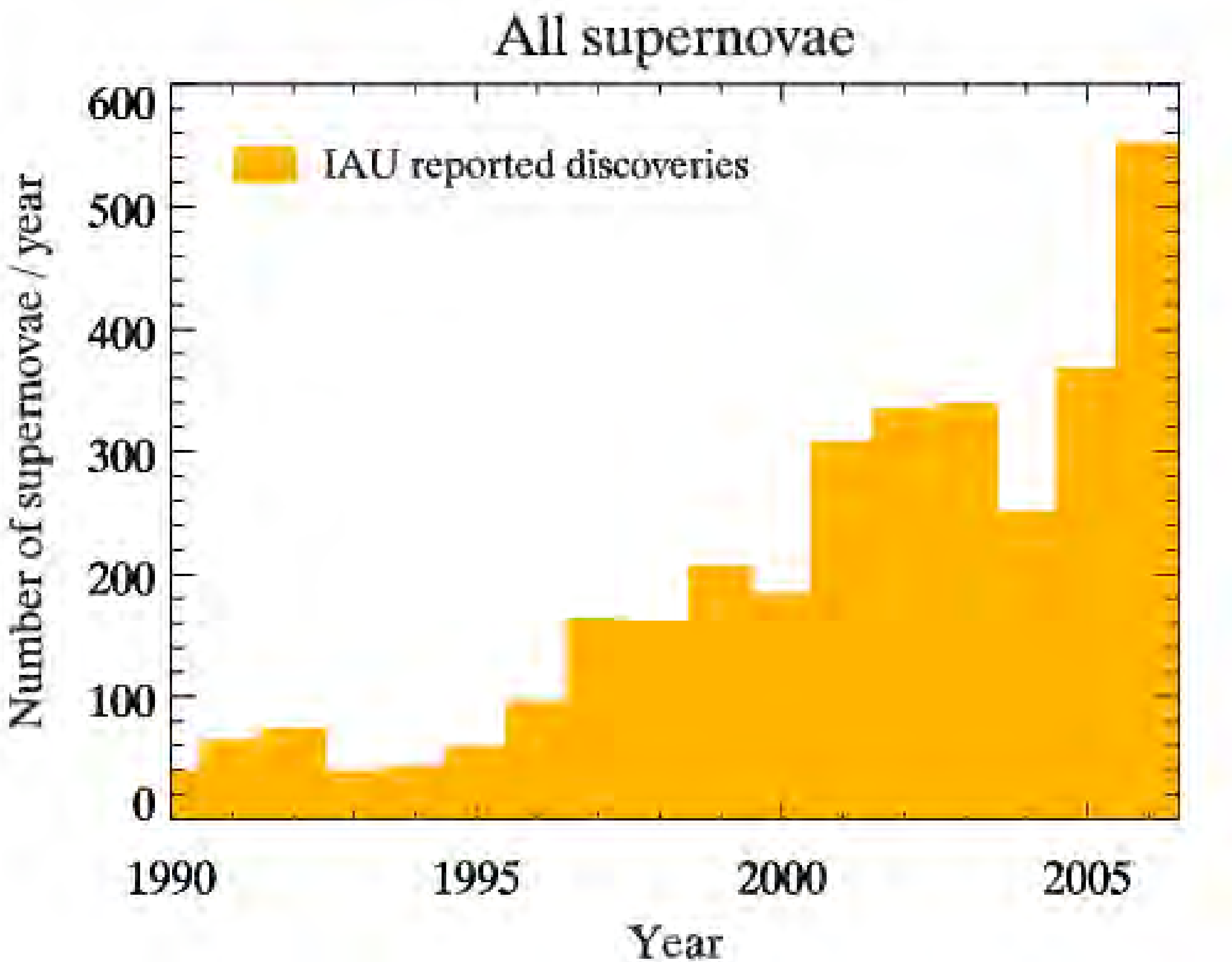
FIG. 1. The redshift–magnitude relation for supernovae of type I. The dots refer to individual supernovae, and the crosses represent averages for the Virgo and Coma clusters, as explained in the text.

Look up there, Willem!



Supernovae by the 1000s

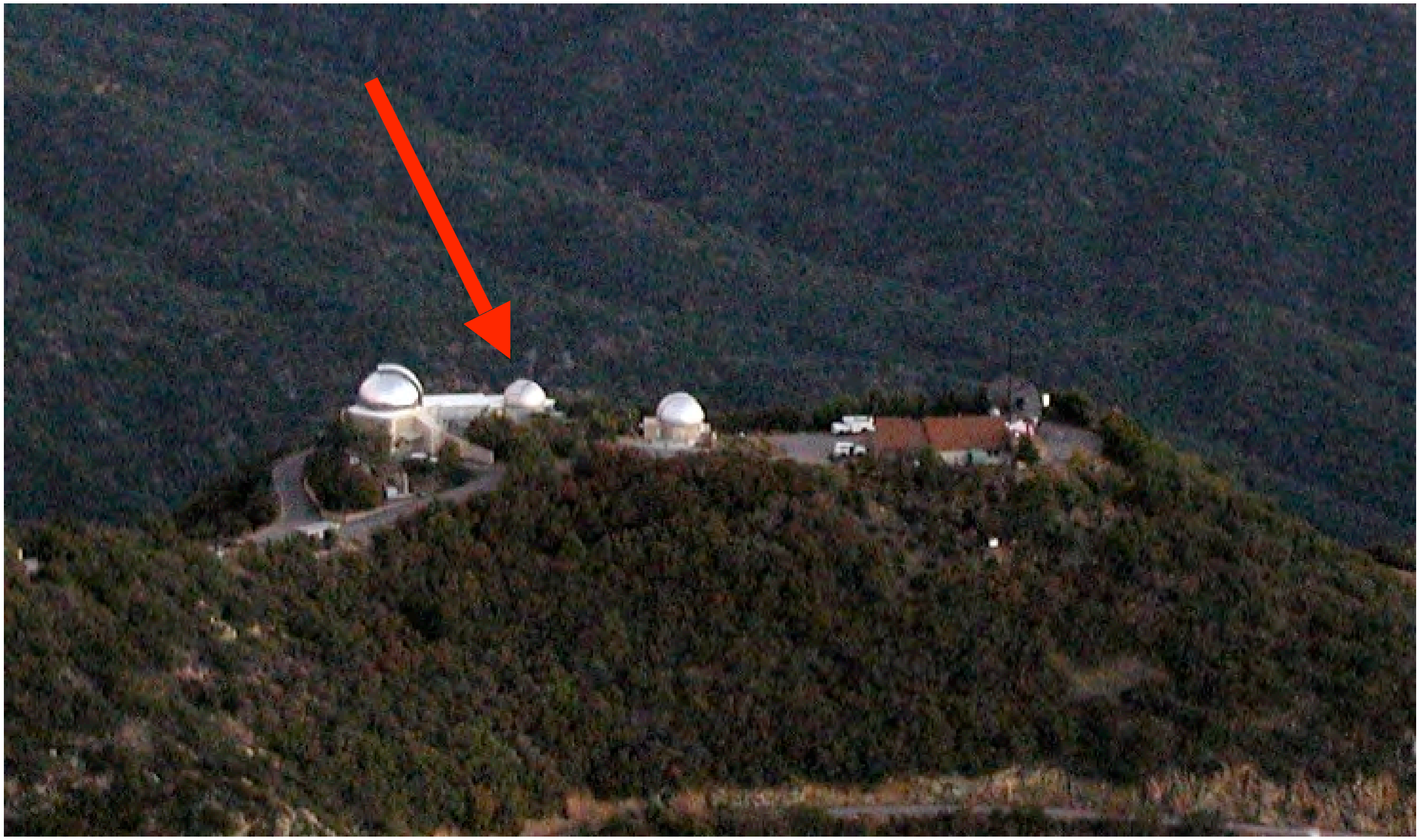
4081 SNe since 1006 (~60% since 2000)



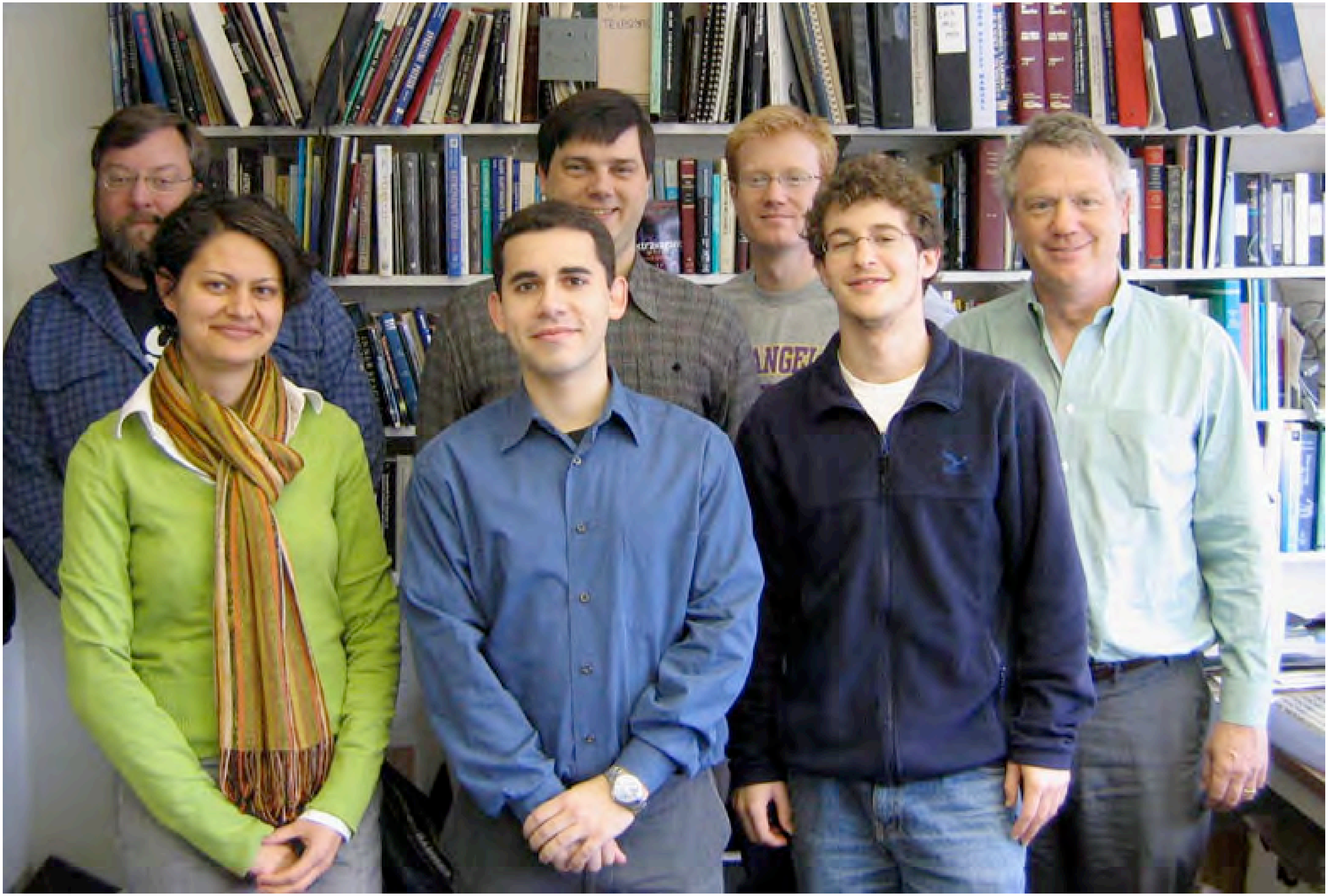
~50% discovered by amateurs

~300++ SNe/year (in IAU circulars)

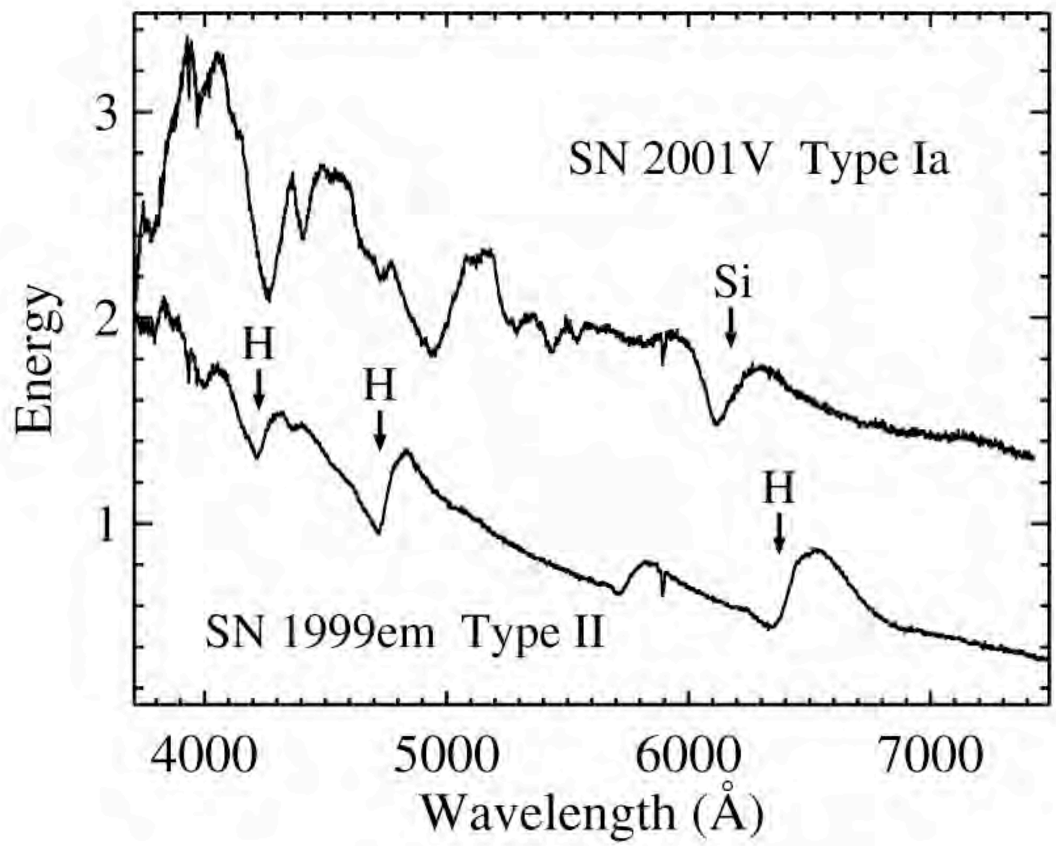
CfA:
Following up with light curves



CfA Supernova Group



Determining the Type



IAU Circulars (IAUC,CBET)

Discovery (7 Mar 2007)
Announcement (8 Mar 2007)

Circular No. 8822

Central Bureau for Astronomical Telegrams
INTERNATIONAL ASTRONOMICAL UNION

Mailstop 18, Smithsonian Astrophysical Observatory, Cambridge, MA 02138, U.S.A.
IAUSUBS@CFA.HARVARD.EDU or FAX 617-495-7231 (subscriptions)
CBAT@CFA.HARVARD.EDU (science)
URL http://cfa-www.harvard.edu/iau/cbat.html ISSN 0081-0304
Phone 617-495-7440/7244/7444 (for emergency use only)

SUPERNOVAE 2007ag–2007as

Thirteen apparent supernovae have been discovered on unfiltered CCD frames and reported to the Central Bureau: 2007ag, 2007ao, and 2007ap by T. Puckett (cf. *IAUC* 8814; 2007ag and 2007ao with R. Gagliano, and 2007ap with A. Kroes); 2007an by M. Migliardi (via A. Dimai; cf. *IAUC* 8667); 2007ar by G. Duszanowicz (cf. *IAUC* 8789); 2007as by P. Luckas, O. Trondal, and M. Schwartz (cf. *IAUC* 8789); and the rest by W. Li (cf. *IAUC* 8813; 2007aj–2007al with D. R. Madison, 2007am with N. Joubert, and 2007aq with D. Winslow). Discovery observations:

SN	2007 UT		α_{2000}	δ_{2000}	Mag.	*Offset*
2007ag	Mar.	7.29	10 01 35.99	+21 36 42.0	18.0	4".0 E, 15".5 N
2007ah	Mar.	6.13	4 02 18.50	+25 49 06.8	17.8	0".4 W, 4".9 N
2007ai	Mar.	6.53	16 12 53.74	−21 37 48.7	18.0	9".4 E, 24".5 S
2007aj	Mar.	3.43	12 47 54.45	+54 00 37.2	16.4	130" W, 47" S
2007ak	Mar.	10.16	5 20 40.75	+ 8 48 16.0	18.2	13".1 S
2007al	Mar.	10.28	9 59 18.48	−19 28 25.8	16.6	3".9 W, 2".0 S
2007am	Mar.	11.36	10 46 33.62	+13 45 09.3	17.8	20".1 W, 7".3 N
2007an	Mar.	10.98	11 58 33.72	+27 27 01.2	17.5	24" W, 7" S
2007ao	Mar.	13.38	14 16 49.74	+10 48 24.1	17.7	47" W, 2".4 S
2007ap	Mar.	13.45	15 56 23.06	+16 30 57.9	15.5	8".0 W, 26".3 S
2007aq	Mar.	13.21	8 48 22.03	+18 19 32.6	18.0	38" W, 20" S
2007ar	Mar.	12.92	13 24 04.93	+58 33 02.4	17.5	7".4 W, 7".6 N
2007as	Mar.	13.61	9 27 36.01	−80 10 39.2	15.8	12".1 W, 4".8 N

Additional information is available on the following *Electronic Telegrams*: 2007ag in UGC 5392, *CBET* 868 and 874 (type-Ib, discovered near maximum light); 2007ah in UGC 2931, *CBETs* 869 and 878 (type-II, discovered just past explosion); 2007ai in MCG −04-38-4, *CBETs* 870 and 880 (type-Ia, discovered just before maximum); 2007aj, *CBETs* 871 and 873 (type-Ia, discovered near maximum); 2007ak in UGC 3293, *CBETs* 875 and 881 (type-IIn); 2007al, *CBETs* 875 and 878 (type-Ia, discovered near maximum); 2007am in NGC 4367, *CBETs* 877 and 884 (type-II, discovered ~ 10 days past explosion); 2007an in NGC 4017, *CBETs* 882 and 896 (type-II); 2007ao in NGC 5532, *CBETs* 883 and 892 (subluminous type-Ia, discovered ~ 10 days past peak); 2007ap in MCG +03-41-3, *CBET* 883; 2007aq in IC 2409, *CBETs* 885 and 889 (type-II, discovered ~ 3.5 weeks past explosion); 2007ar in MCG +10-19-62, *CBETs* 886 and 889 (type-Ia, discovered just past maximum); 2007as in ESO 18-G18, *CBET* 888

2007 March 19 *Daniel W. E. Green*

Spectrum 1.5m+FAST (9 Mar 2007)
Classification (10 Mar 2007)

Electronic Telegram No. 874
Central Bureau for Astronomical Telegrams
INTERNATIONAL ASTRONOMICAL UNION
M.S. 18, Smithsonian Astrophysical Observatory, Cambridge, MA 02138, U.S.A.
IAUSUBS@CFA.HARVARD.EDU or FAX 617-495-7231 (subscriptions)
CBAT@CFA.HARVARD.EDU (science)
URL http://cfa-www.harvard.edu/iau/cbat.html

SUPERNOVA 2007ag IN UGC 5392

S. Blondin, M. Modjaz, R. Kirshner, and P. Challis, Harvard-Smithsonian Center for Astrophysics, report that a spectrum (range 350-740 nm) of 2007ag (cf. CBET 868), obtained on Mar. 10.34 UT by R. Hutchins with the F. L. Whipple Observatory 1.5-m telescope (+ FAST), shows it to be a type-Ib supernova around maximum light. The spectrum shows conspicuous lines of He I (rest 447.1 and 587.6 nm) and is most similar to that of the type-Ib supernova 2005hg (cf. CBET 271) at one day before maximum light. The spectrum appears to be slightly reddened, although interstellar Na I absorption at the redshift of the host galaxy cannot be reliably detected due to the moderate signal-to-noise ratio. A comparison plot can be seen at the following URL:
http://www.cfa.harvard.edu/oir/Research/supernova/spectra/sn2007ag_comp.gif

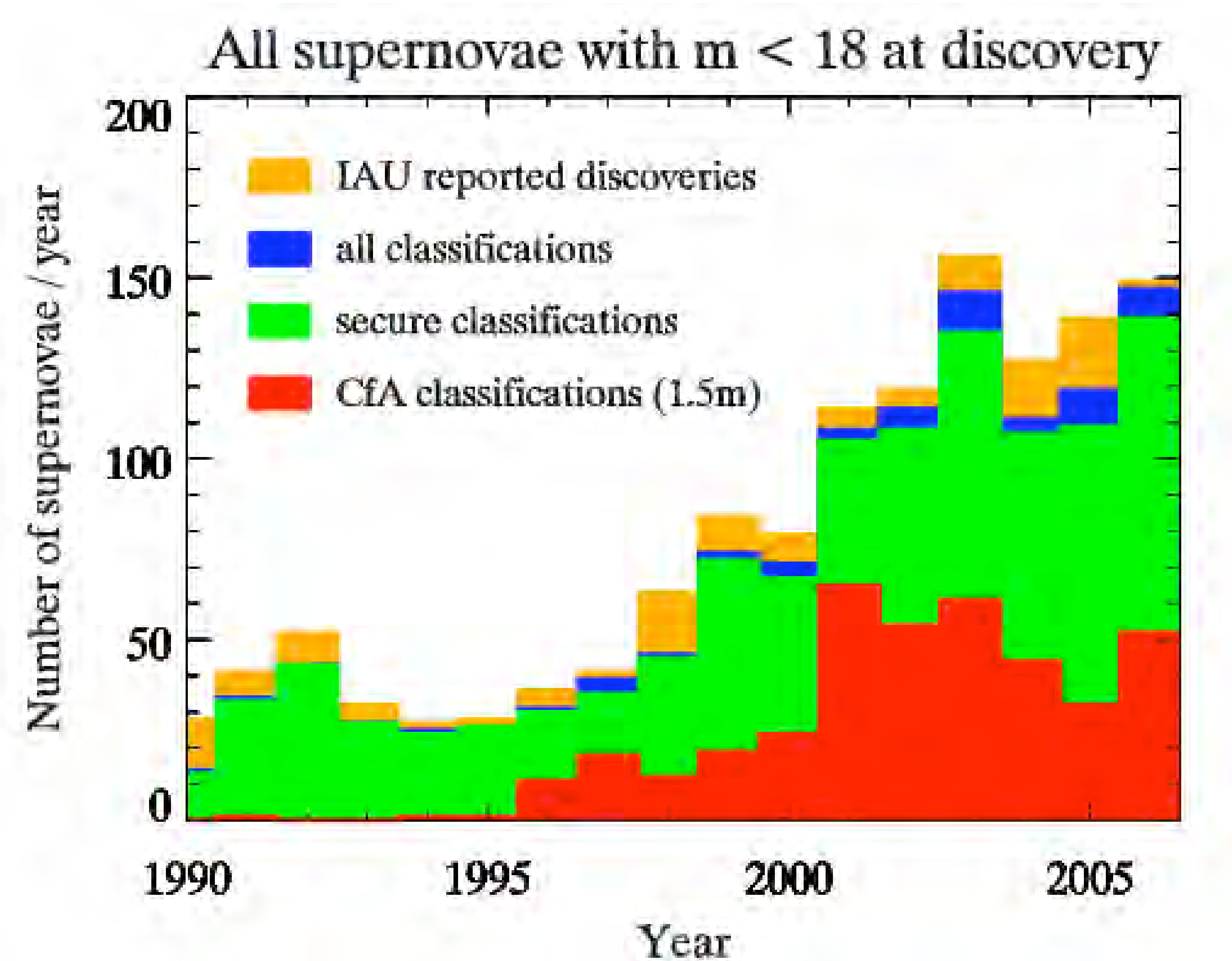
NOTE: These 'Central Bureau Electronic Telegrams' are sometimes superseded by text appearing later in the printed IAU Circulars.

2007 March 10 (CBET 874) Daniel W. E. Green
Green

Crete

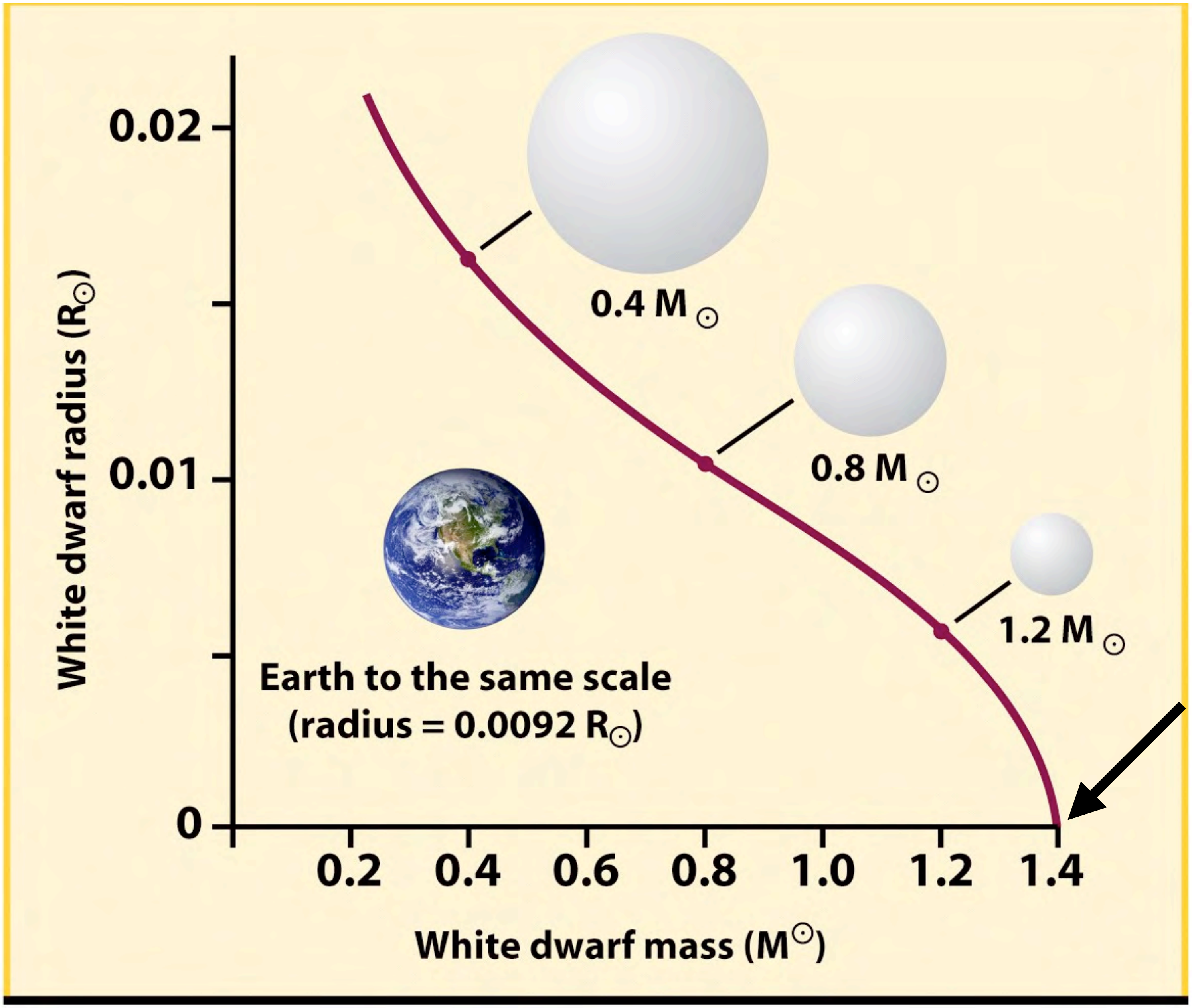
Credit: Dan Green (CfA)

Supernovae by the 1000s



~150 SNe/year
(m<18 at discovery)

1/3+ classifications
by CfA astronomers



This is really weird--- as you take matter away from a white dwarf, the star gets BIGGER

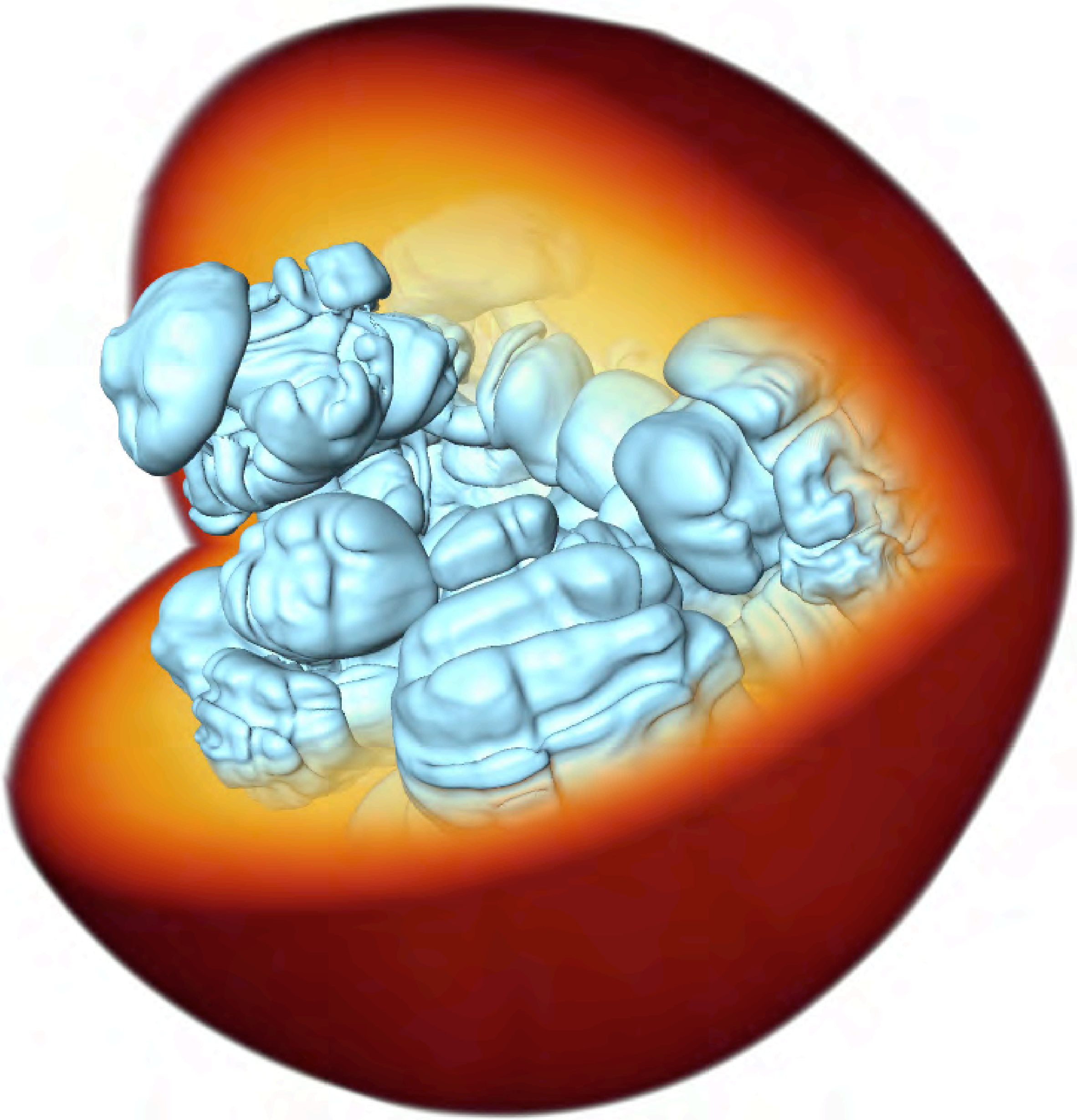
This is even weirder-- what happens if you put more mass on a 1.4 M_{sun} white dwarf?

Mass and radius for a white dwarf

White dwarf density ~ 10^9 kg/m^3

~ 1 ton/cm^3 (1 hippo mass/teaspoon)

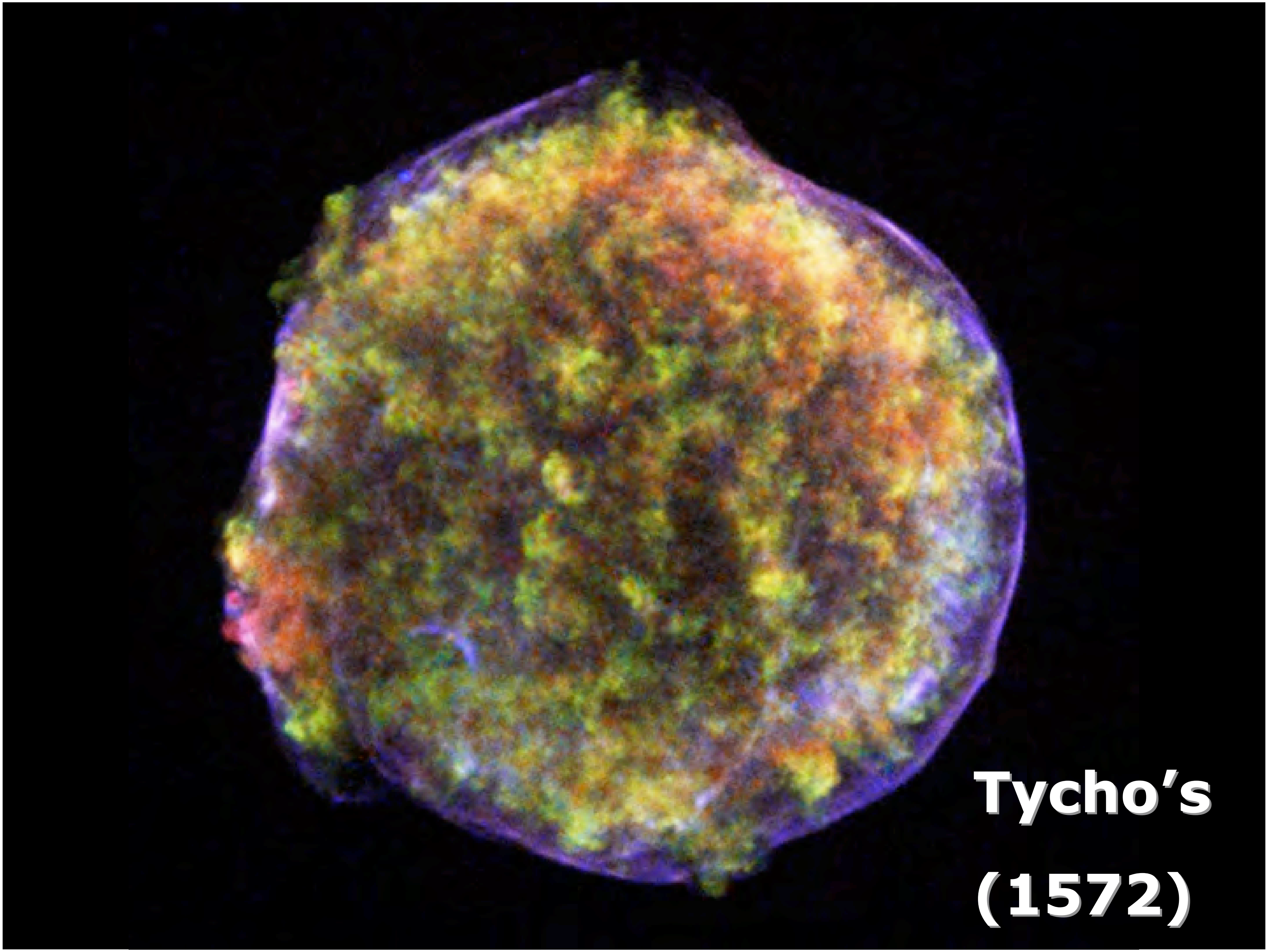
~ Mass of the Sun/ Volume of the Earth



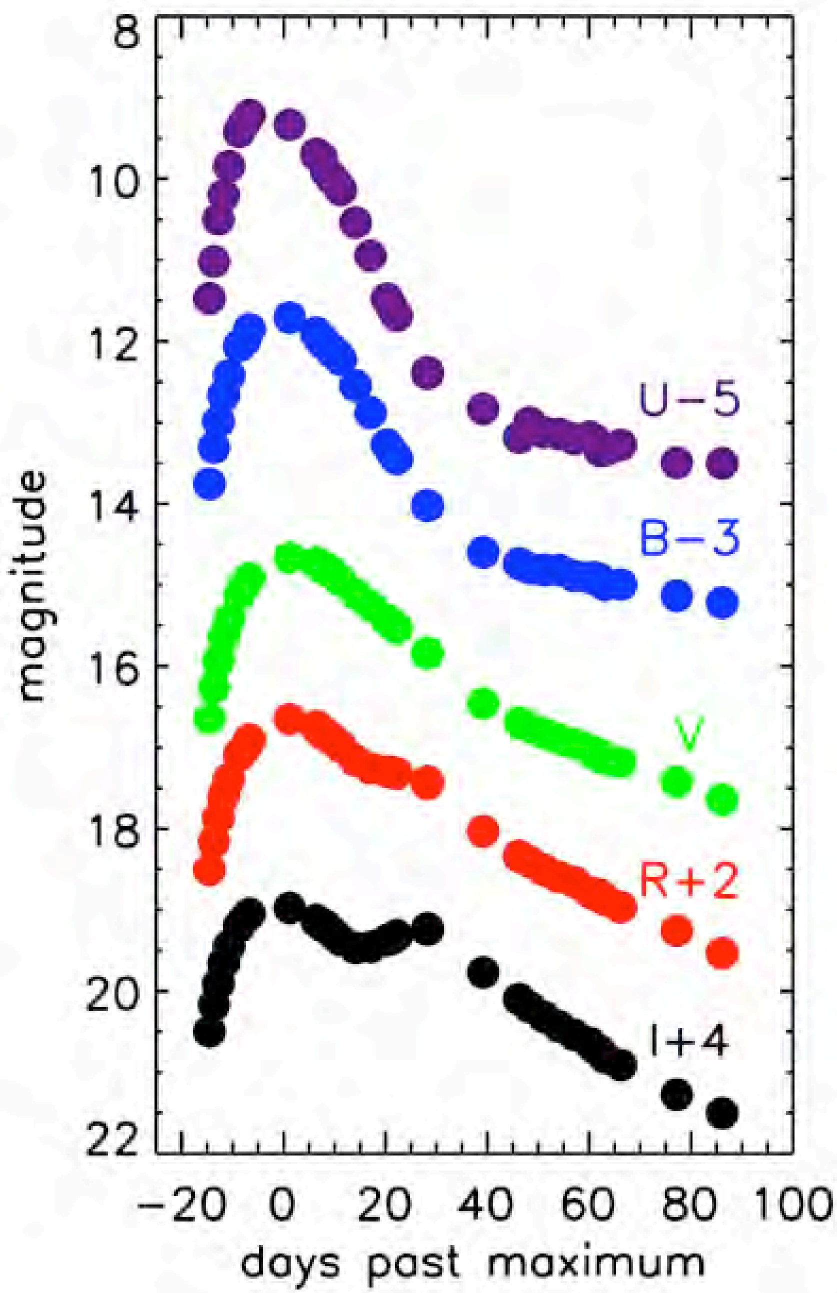
Type Ia SN: exploding white dwarfs

From crinkled flames grow lumpy supernovae

Perhaps there's a variation in the ^{56}Ni production


Tycho's
(1572)


Manufactured in
supernovae!
MAINE
MAUDIE



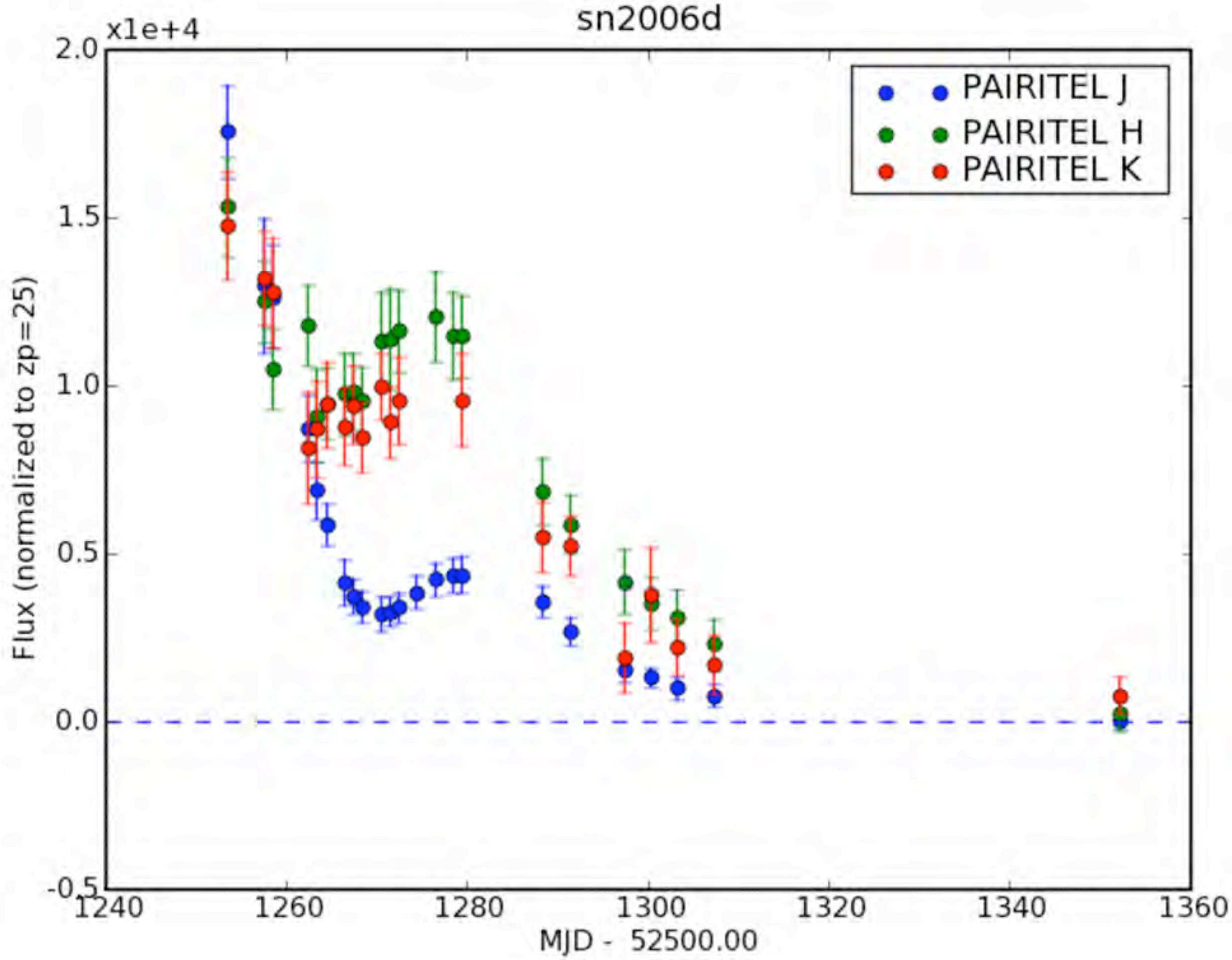
e

Light Curves: Clues to Luminosity

Most likely related to ^{56}Ni produced in the explosion

Riess, Press & Kirshner (1995, 1996)

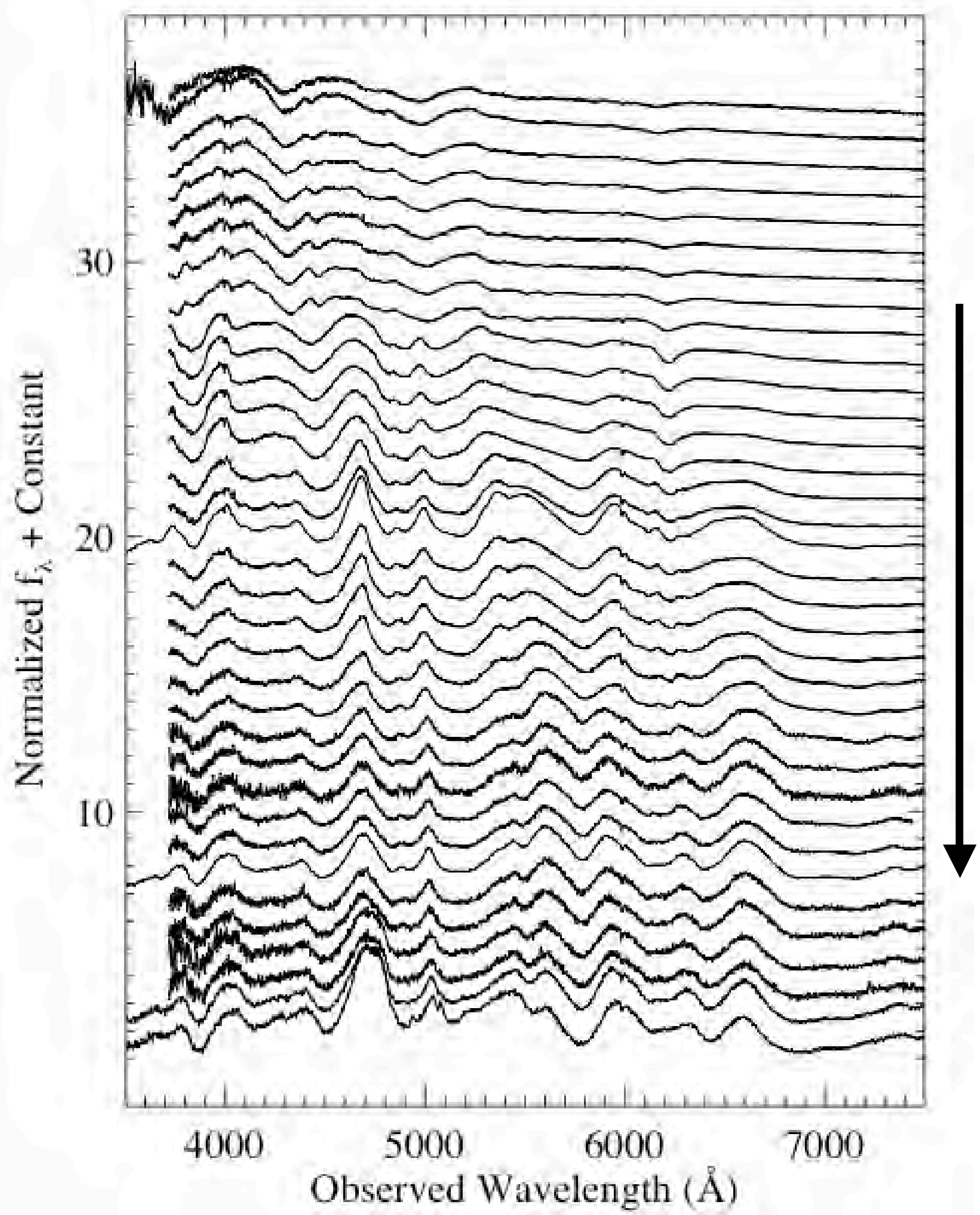
Goal: better distances, determination of extinction by dust



Good work in the IR by robotic telescope!

Needs no encouragement or food.

Former 2MASS, automated by Josh Bloom



Time series of spectra for a SN Ia

Spectra are similar at a given age, but not identical

SNID: Blondin & Tonry (2007)

Fe seen at late times

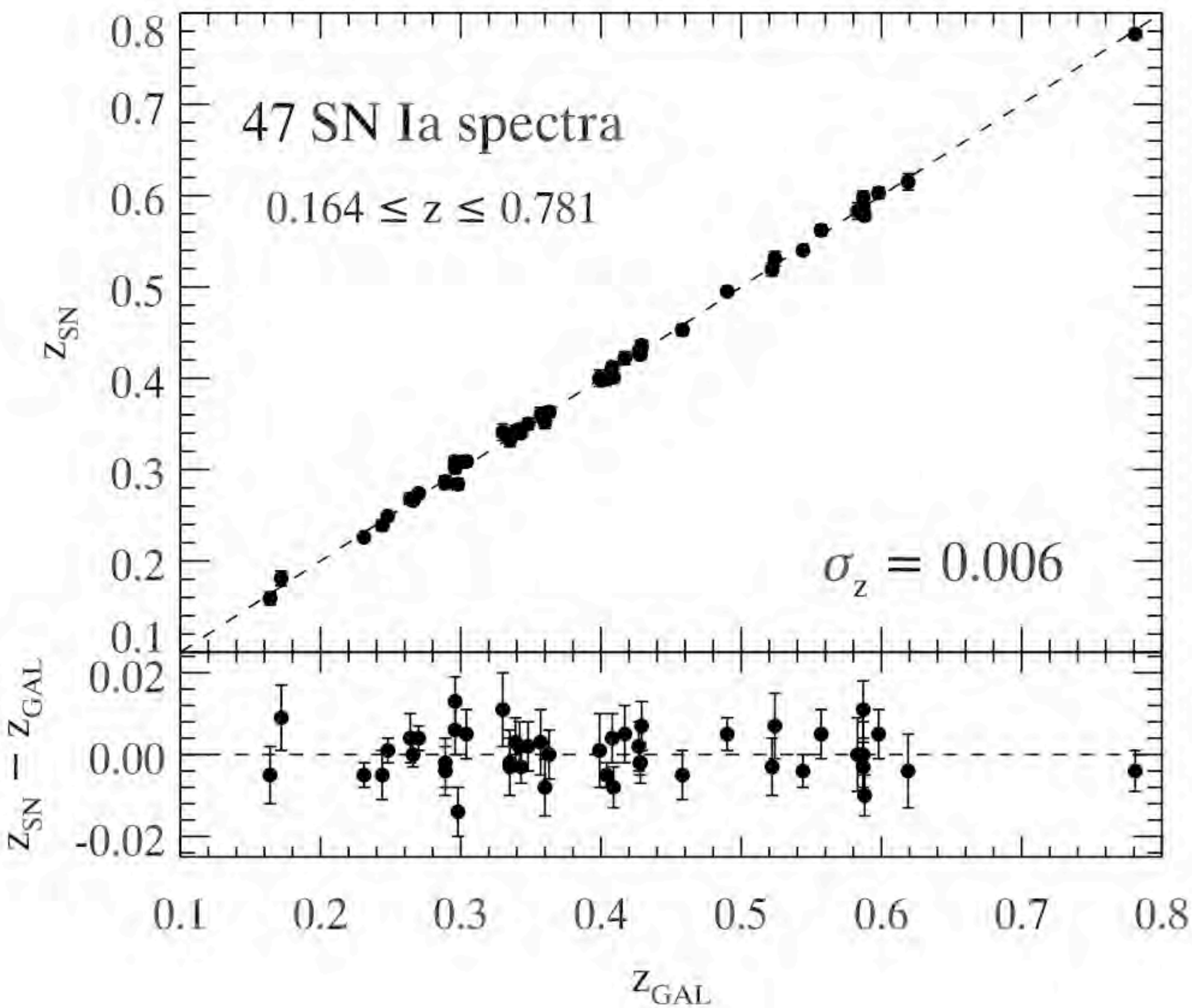
Matheson et al. (2008)

787 spectra of 55 SN Ia in

http://www.cfa.harvard.edu/supernova/SNarchive.html

2211 spectra of 413 SN Ia -- Blondin

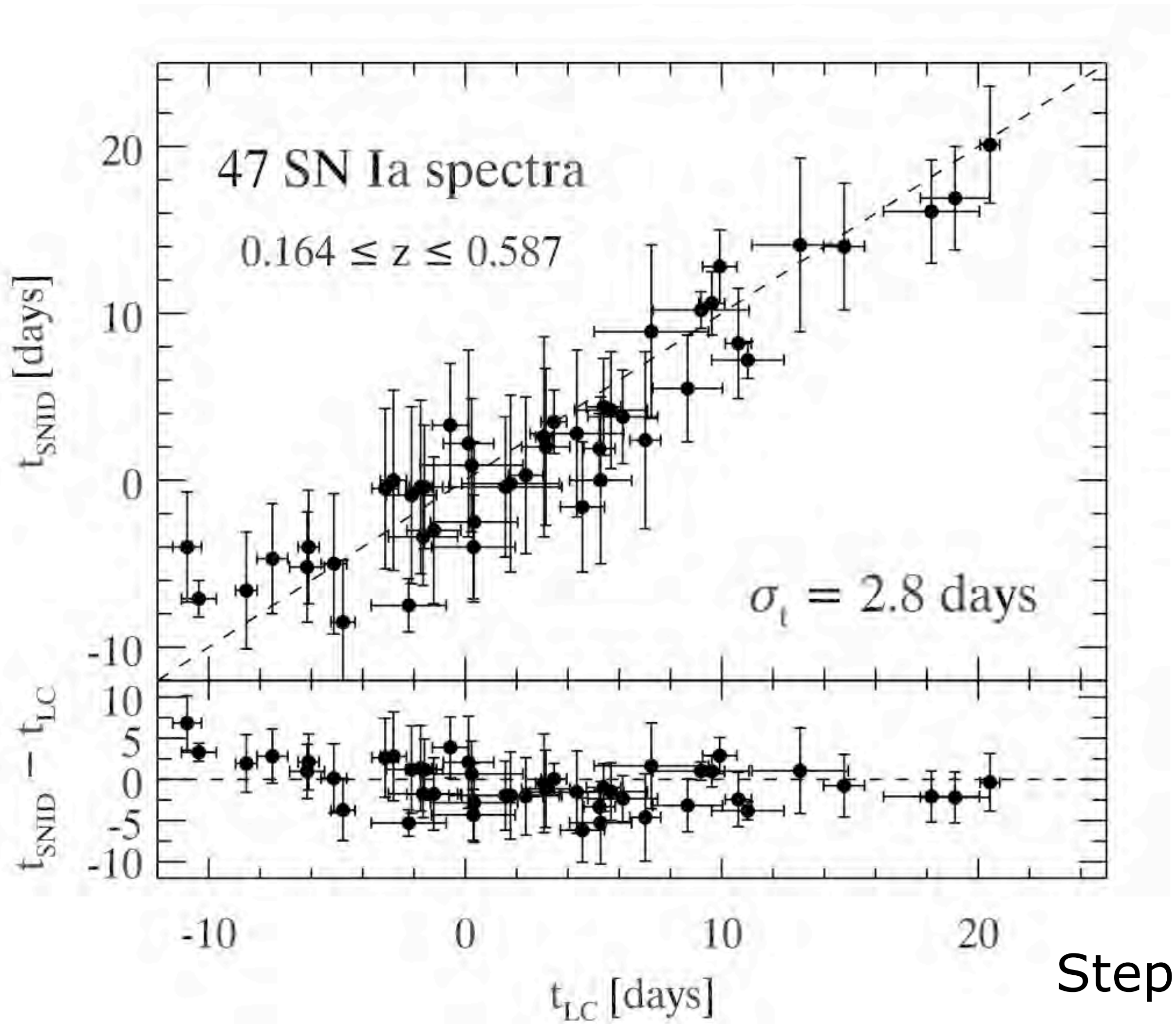
Using the supernova spectrum to measure the galaxy redshift



July

Stephane Blondin

Using the galaxy spectrum to measure the age of the supernova



Stephane Blondin

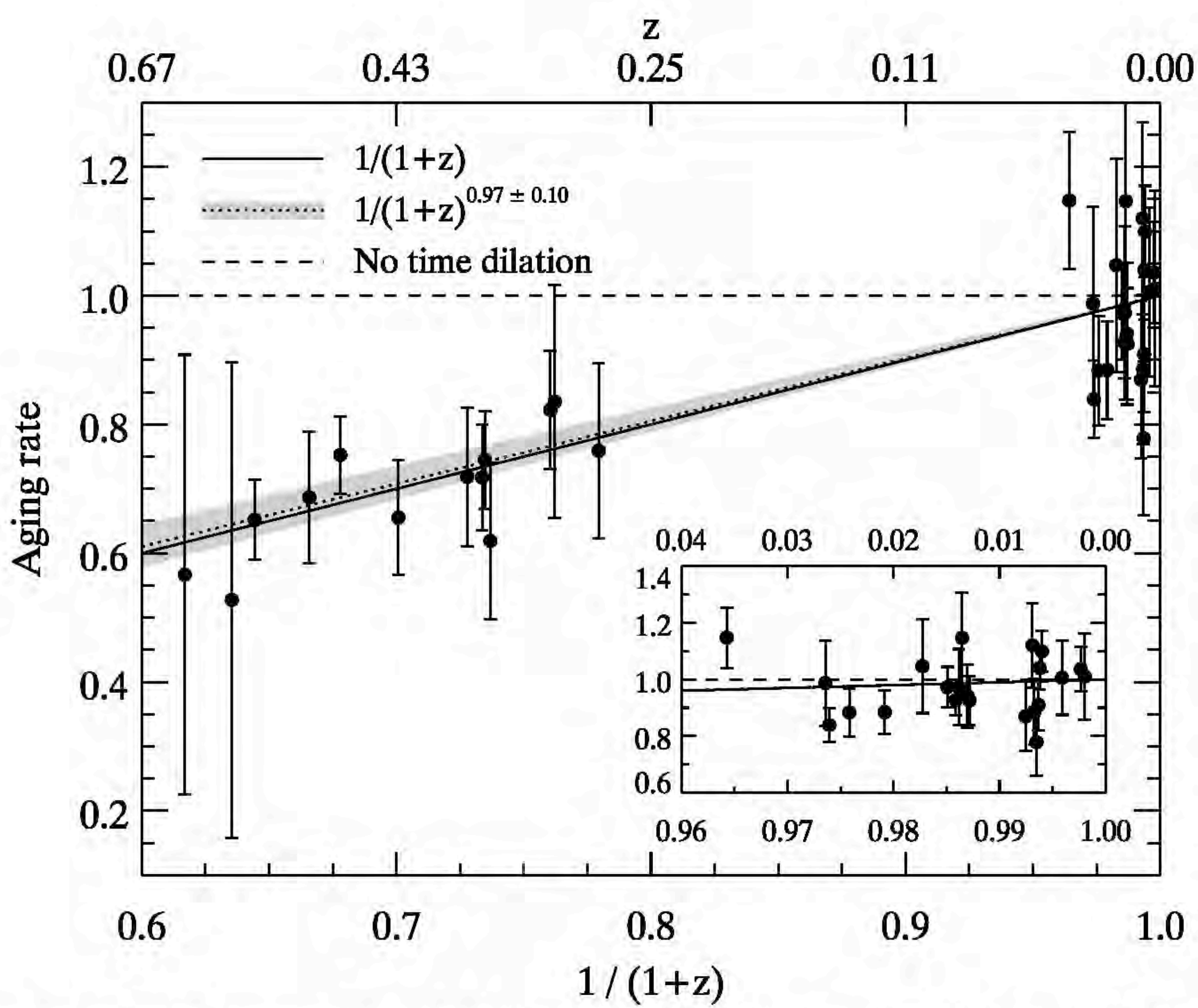
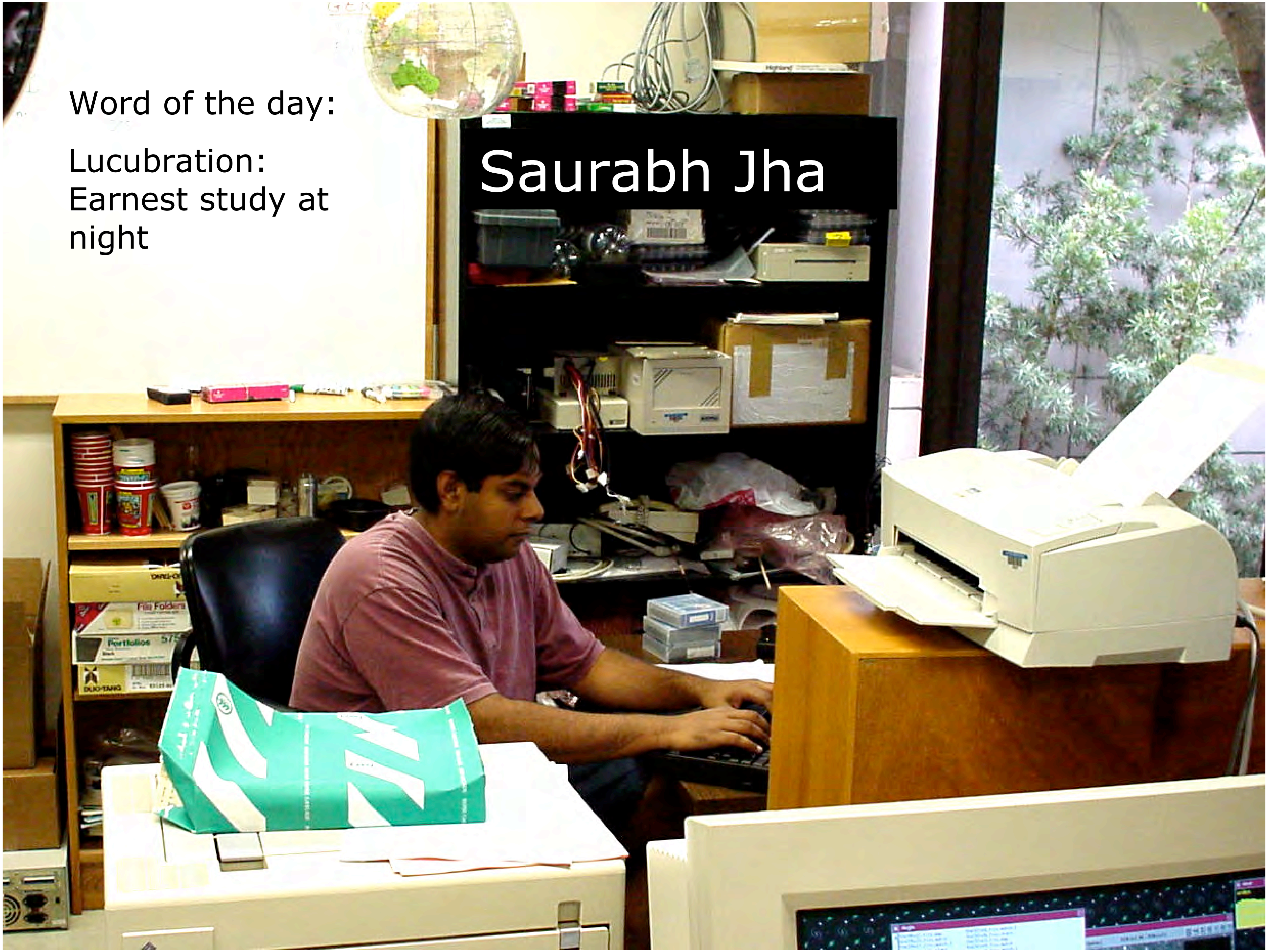


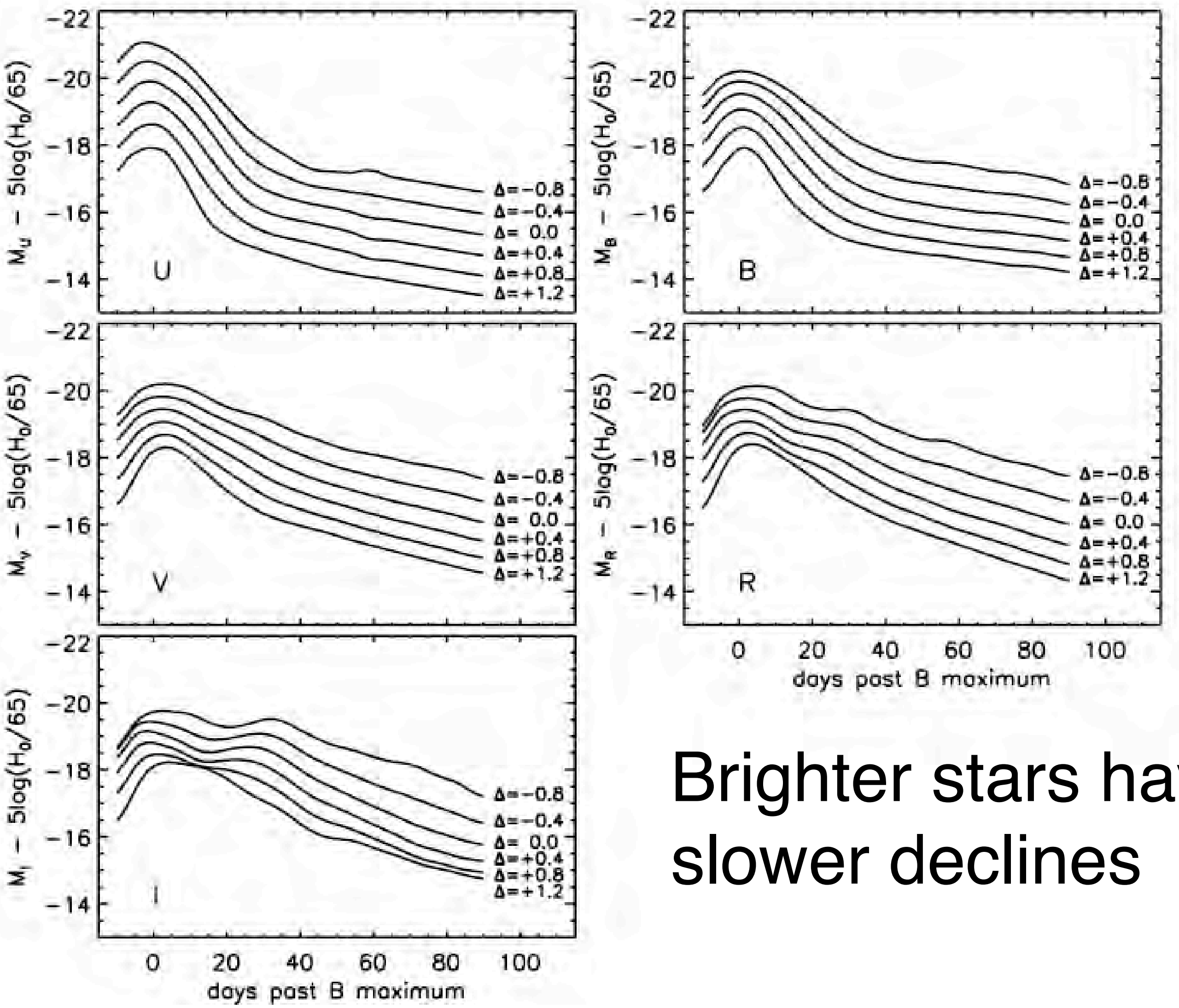
FIG. 8.— Apparent aging rate versus $1/(1+z)$ for the 13 high-redshift ($0.28 \leq z \leq 0.62$) and 22 low-redshift ($z < 0.04$) SNe Ia in our sample. Overplotted are the expected $1/(1+z)$ time dilation (solid line) and the best-fit $1/(1+z)^b$ model (with $b = 0.97 \pm 0.10$; dotted

Time Dilation ~(1 + z) from Spectra

Blondin et al. 2008 astro-ph 0804.3595

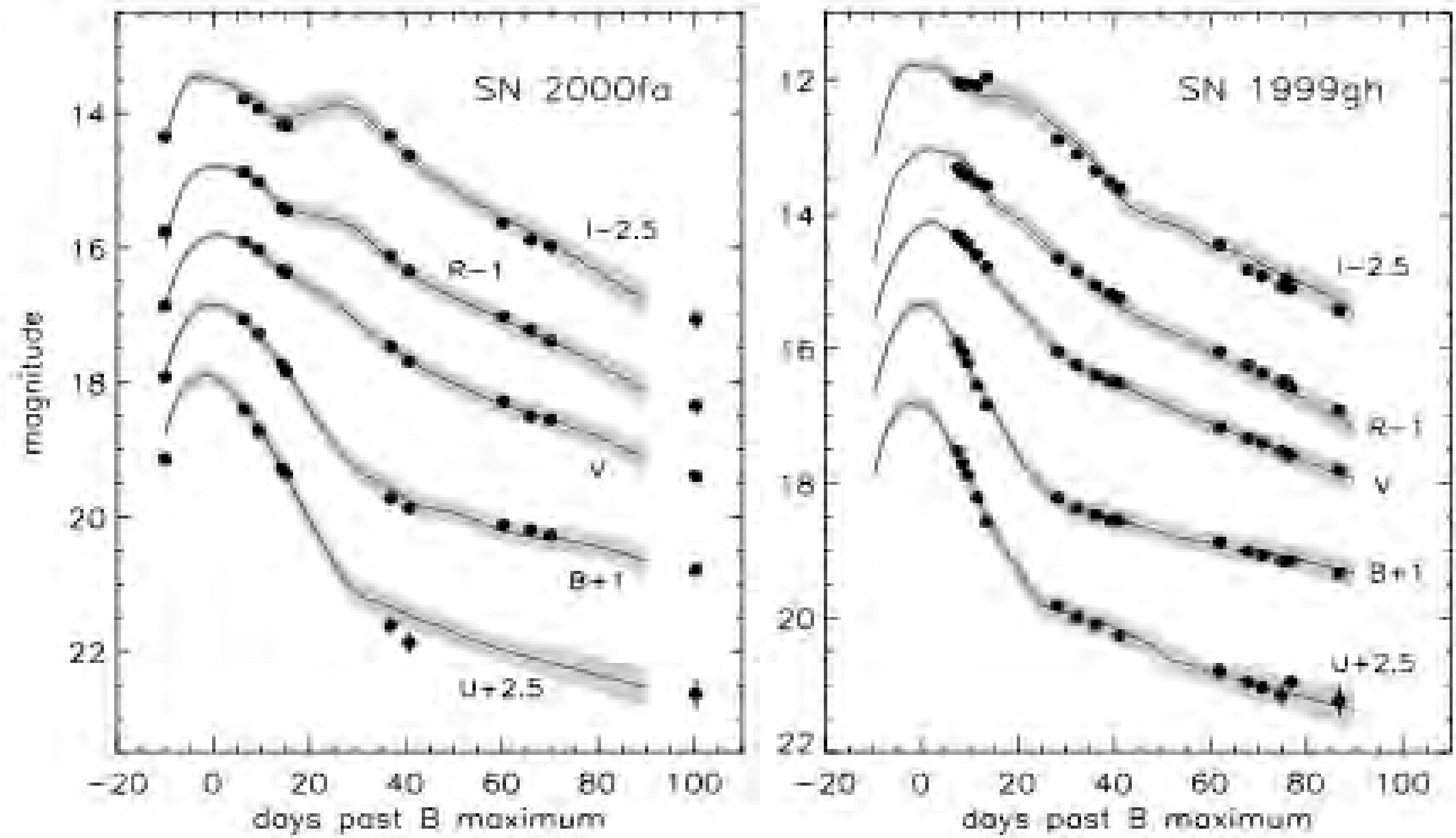

Word of the day:
Lucubration:
Earnest study at night
Saurabh Jha

Light Curve Shapes => L

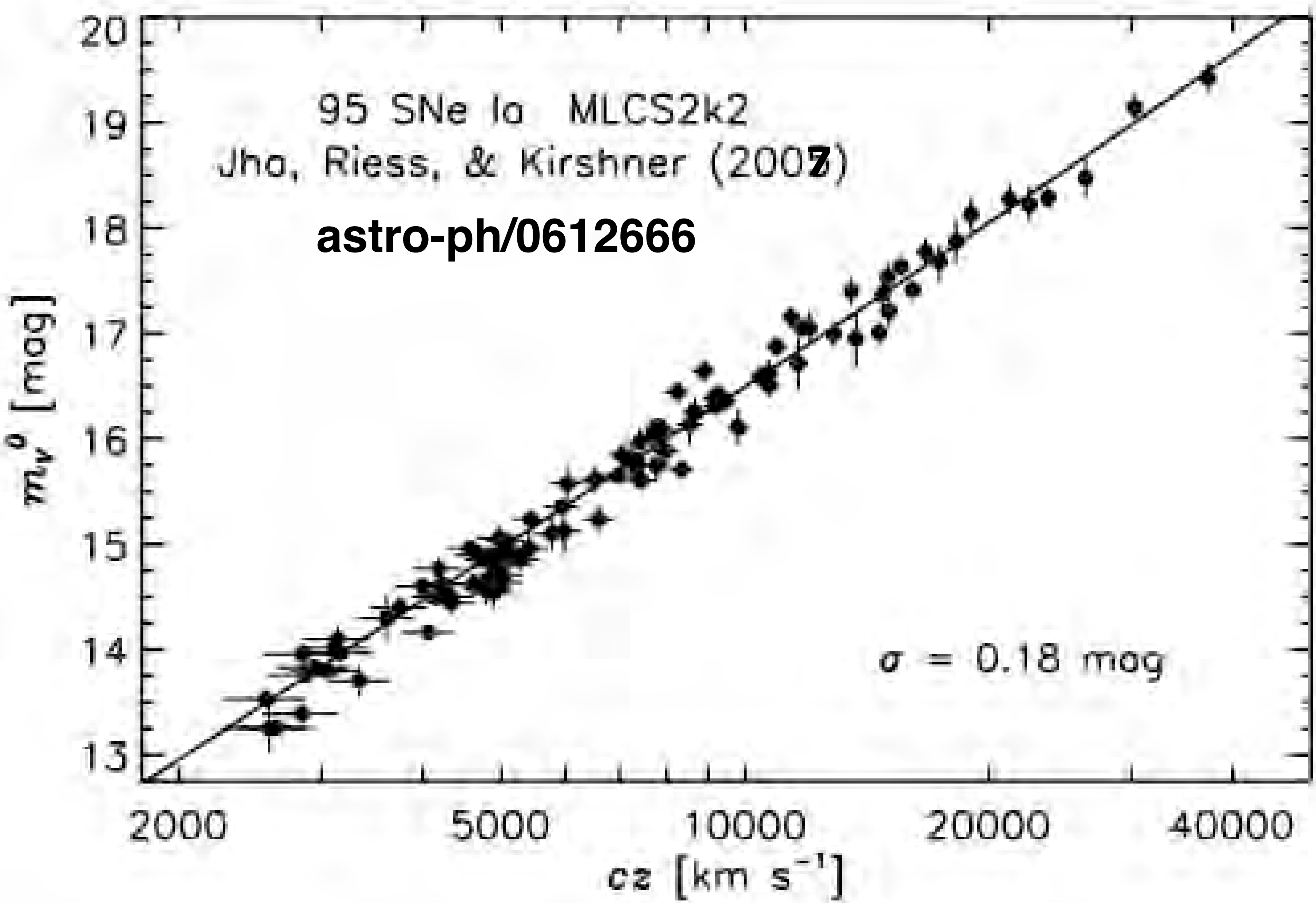


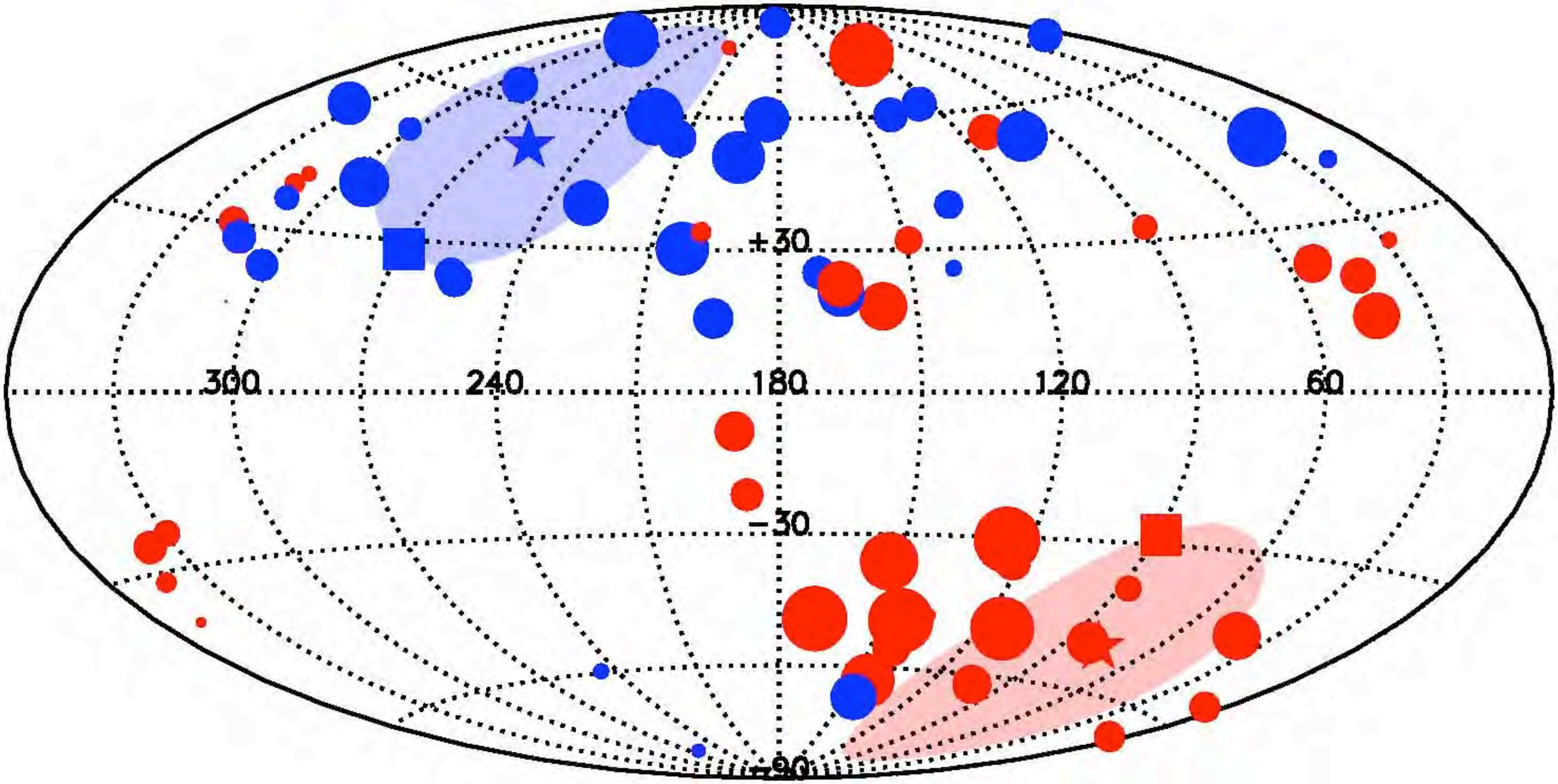
Brighter stars have slower declines

Jha, Riess & Kirshner astro-ph0612666 MLCS2K2



Other approaches work, too: Stretch, SALT, Lifan Wang's C-MAGIC; Δm_{15}

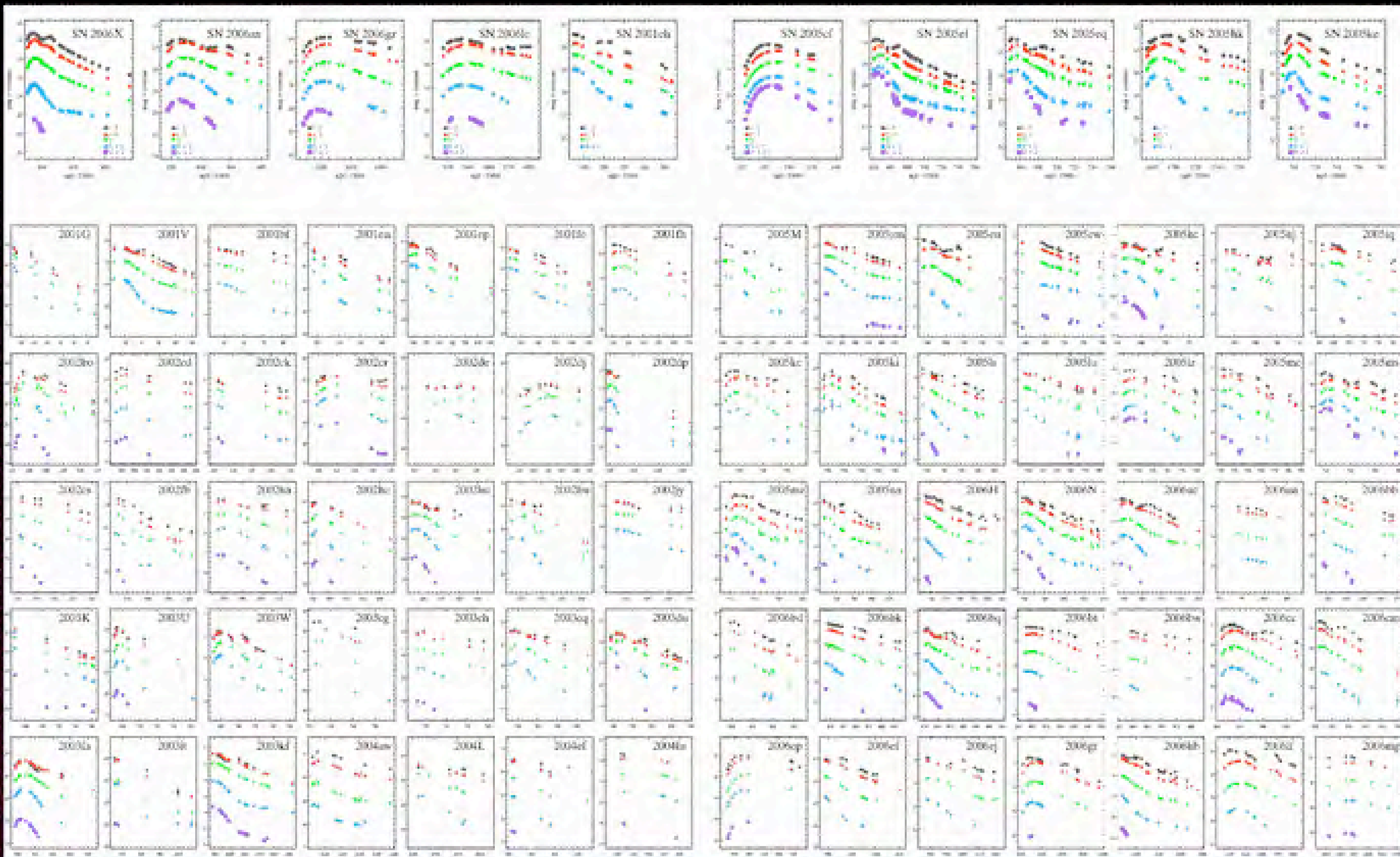

95 SNe Ia MLCS2k2
Jha, Riess, & Kirshner (2007)
astro-ph/0612666
σ = 0.18 mag
m_V^0 [mag]
cz [km s^{-1}]
20
19
18
17
16
15
14
13
2000
5000
10000
20000
40000



MLCS2k2 69 SN Ia Local Group frame

1500 km s^{-1} ≦ $H_0 d_{SN}$ ≦ 7500 km s^{-1}

Follow-up at FLWO: CfA III



Coming soon: KAIT, Carnegie, SN Factory

Hicken et al. (2007)

Why are some SN Ia brighter than others?

- Chemical composition?
- Age?
- Chance?

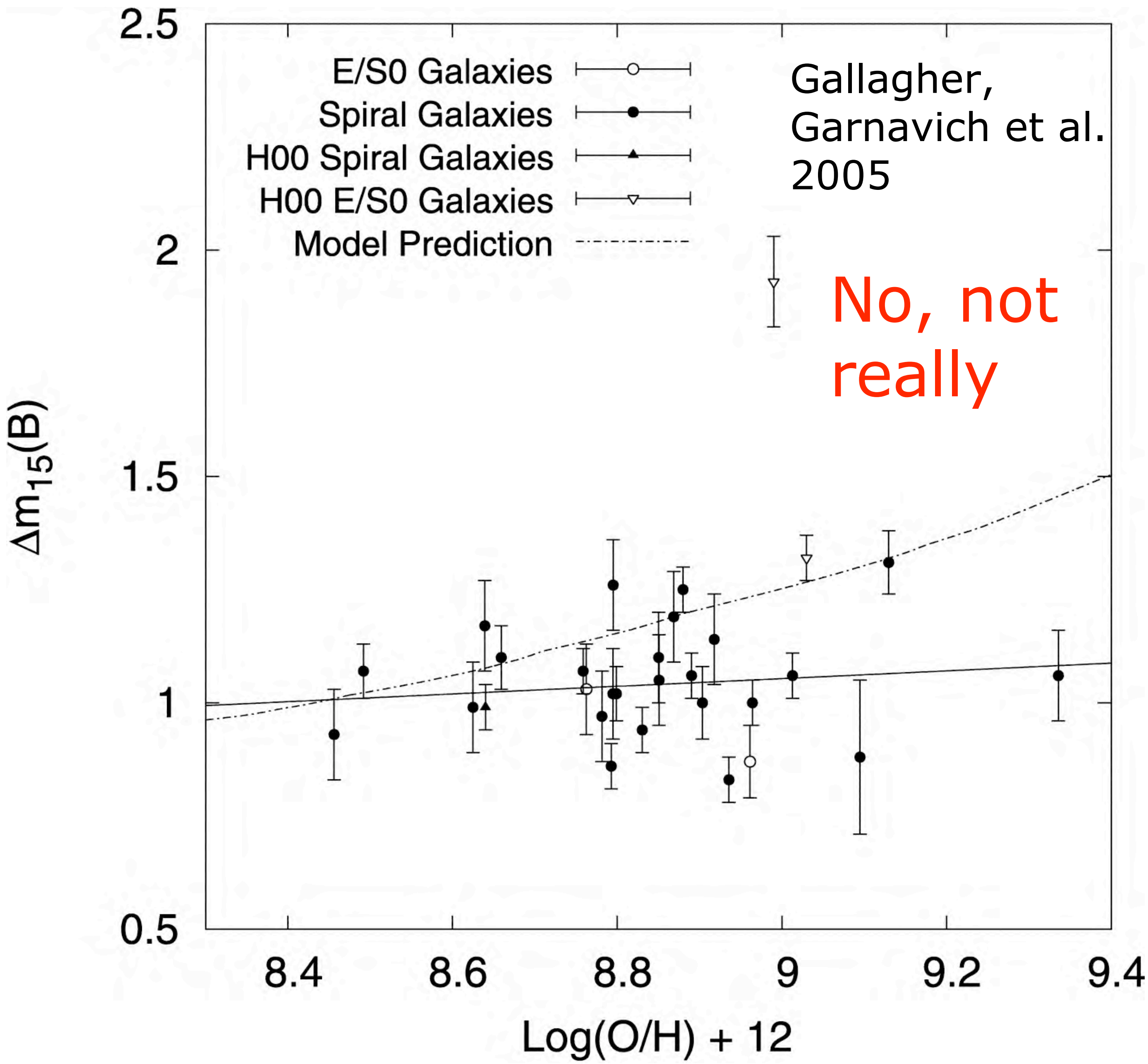
This is important for cosmology and can be studied locally.

Chemistry?

Look at galaxy chemistry-- do the SN Ia show the effect predicted?

high metallicity => low luminosity?

Dim



Bright

Poor

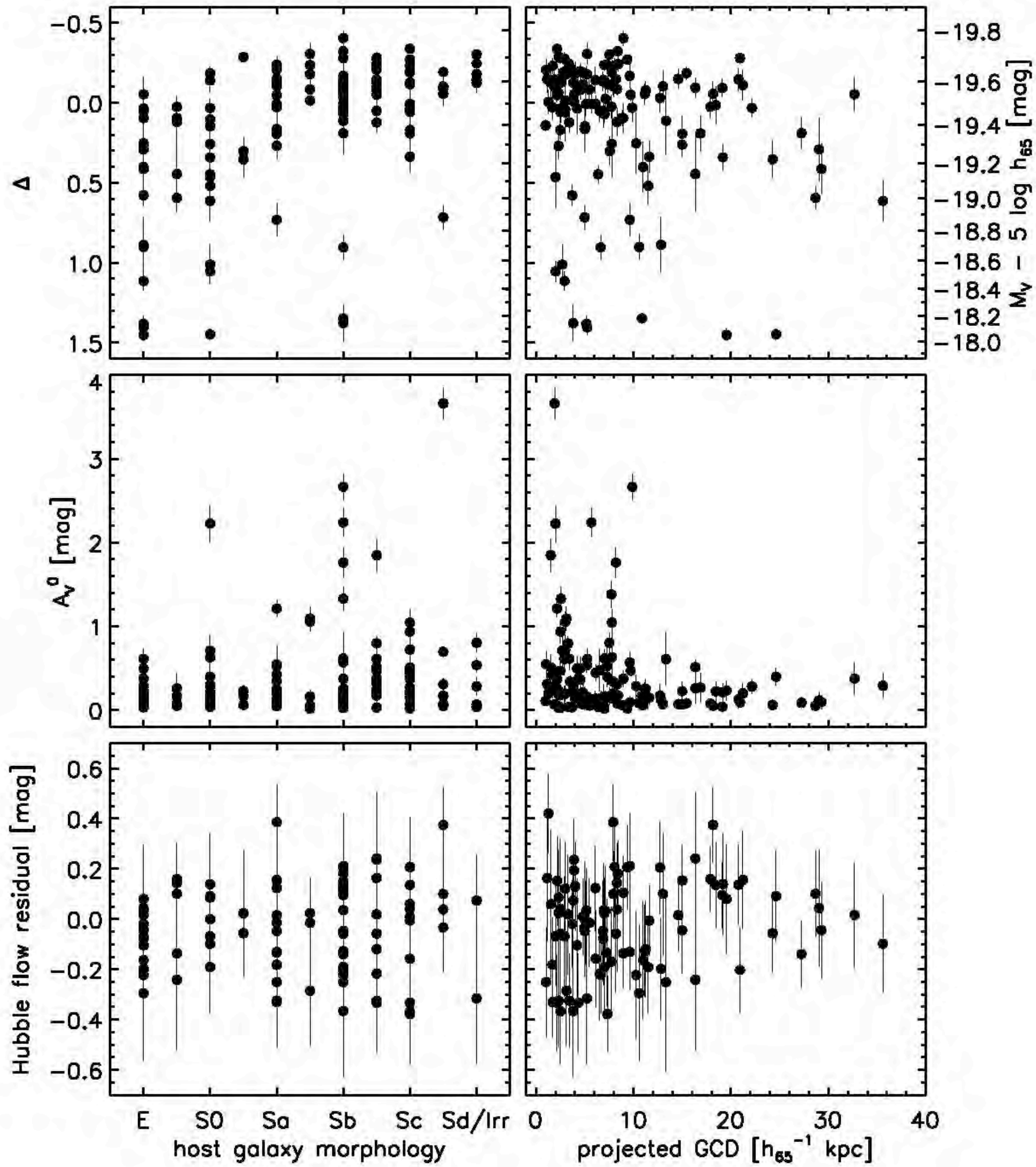
Rich

Age?

Look at galaxy morphology-- SN Ia found in sprials (both old and young stars) and in ellipticals (where most of the stars are old)

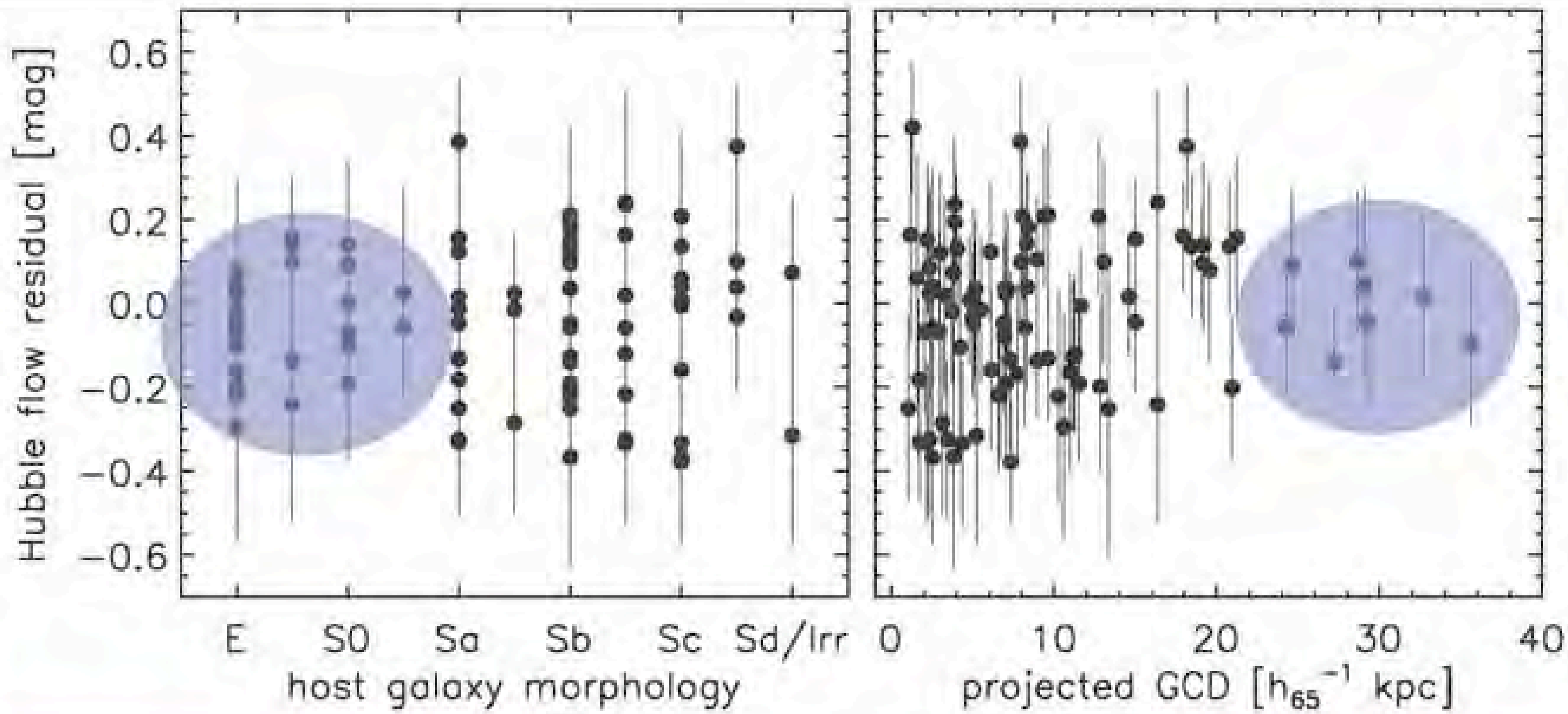
There are **real** systematic differences between the supernovae in spirals and ellipticals

At the present level of precision, MLCS2K2 copes well with these effects



Sharpening our precision tools

Jha, Riess, & Kirshner (2006)



Are we battling the fog of dust?

Intrinsic dispersion of subsamples could be much lower: 3% distances?

➔ *we need more nearby objects!*

The CfA Spectroscopic Archive

http://www.cfa.harvard.edu/cfa/oir/Research/supernova/

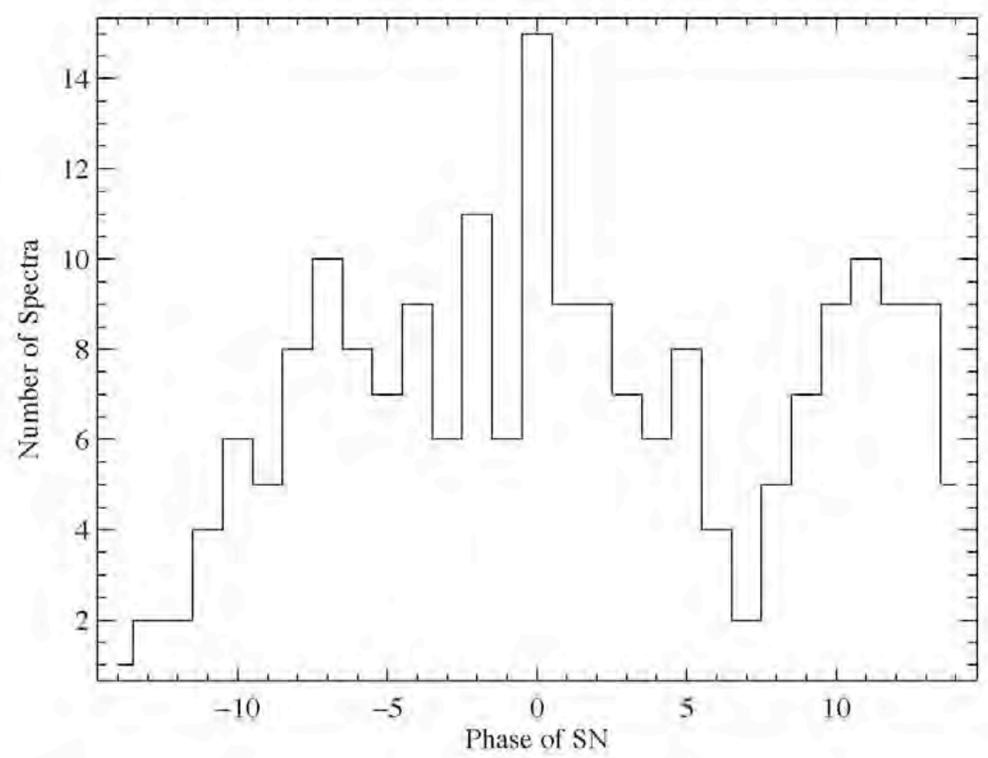
In the works:

1875 spectra of 363 SN Ia

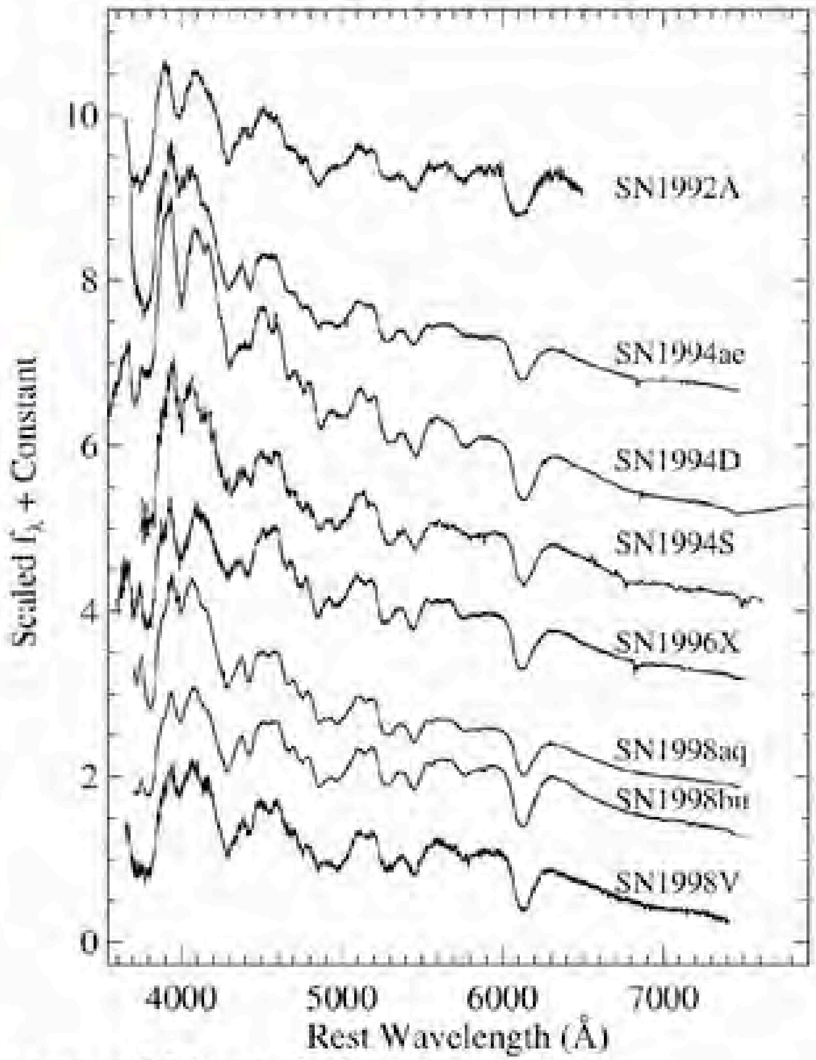
524 spectra of 106 SN Ib/Ic/IIb

574 spectra of 242 SN II

Some observed quite early!



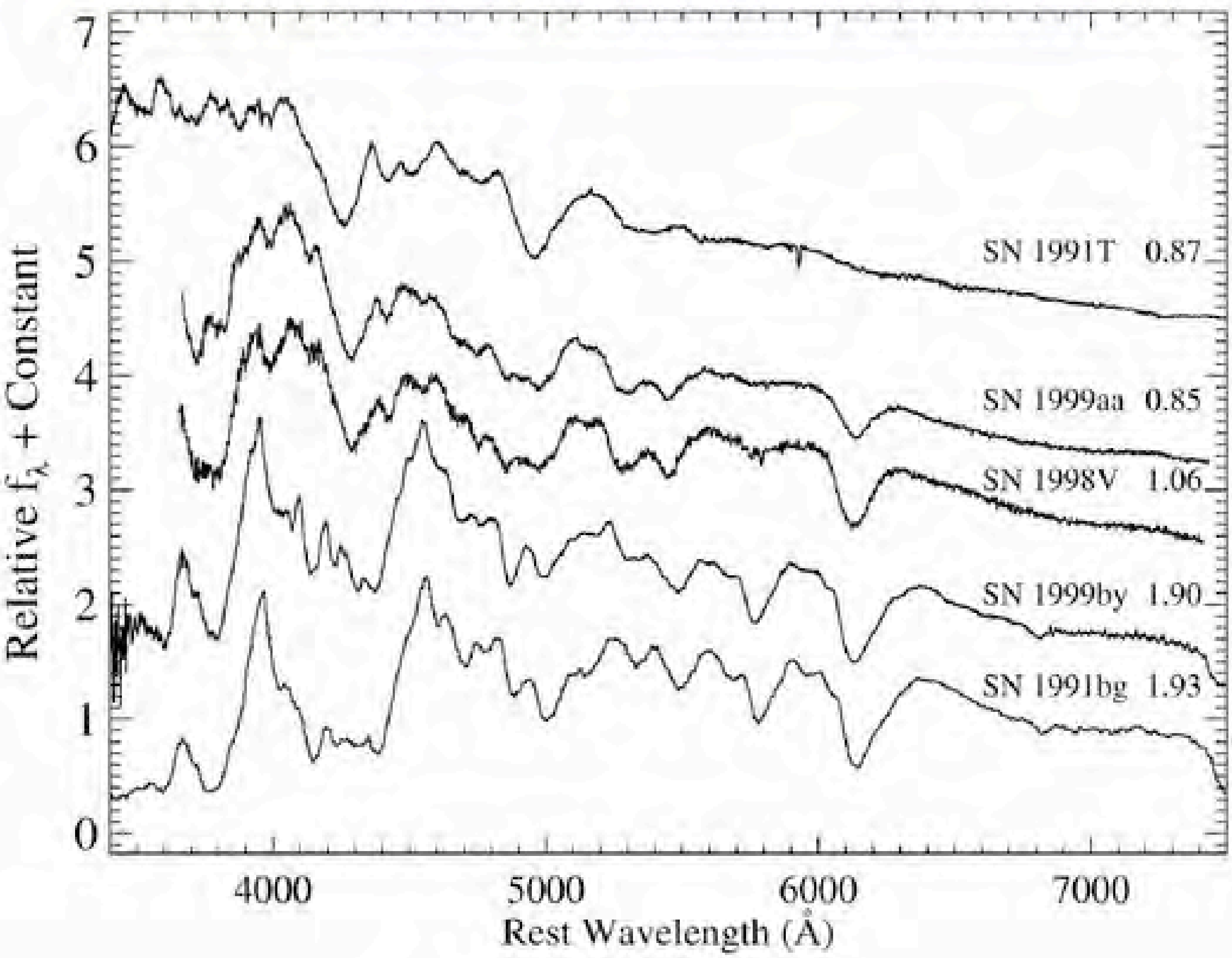
Once upon a time all Type Ia SNe were alike



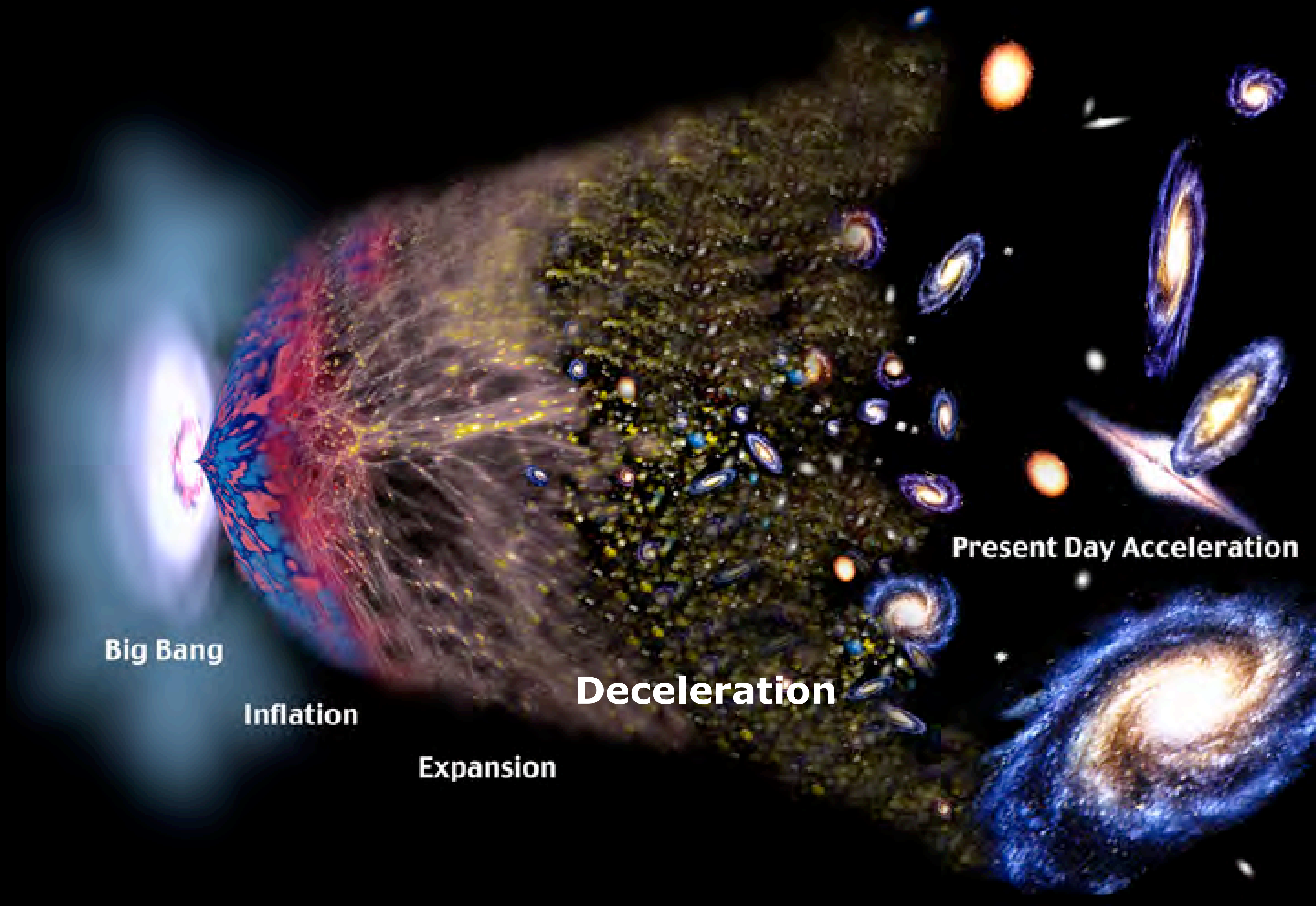
d) Similarities in the Spectra of Type I Supernovae

It has often been suggested that spectra of Type I supernovae show remarkable similarities. We have available excellent data to investigate this question. With reference to SN 1972e in NGC 5253, it can be seen from figures 6 and 7 that the spectrum

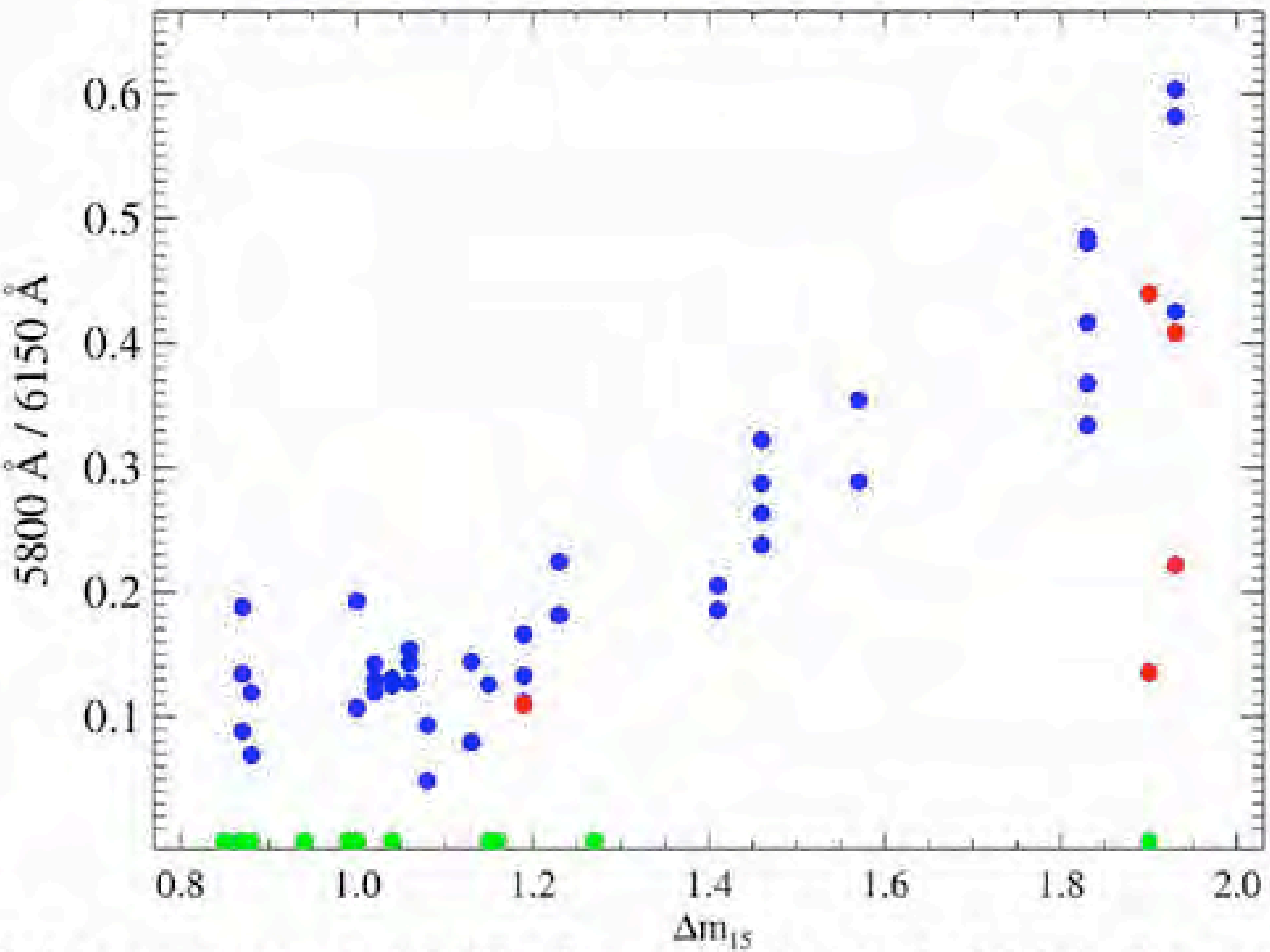
Spectra and Light-Curve Shape



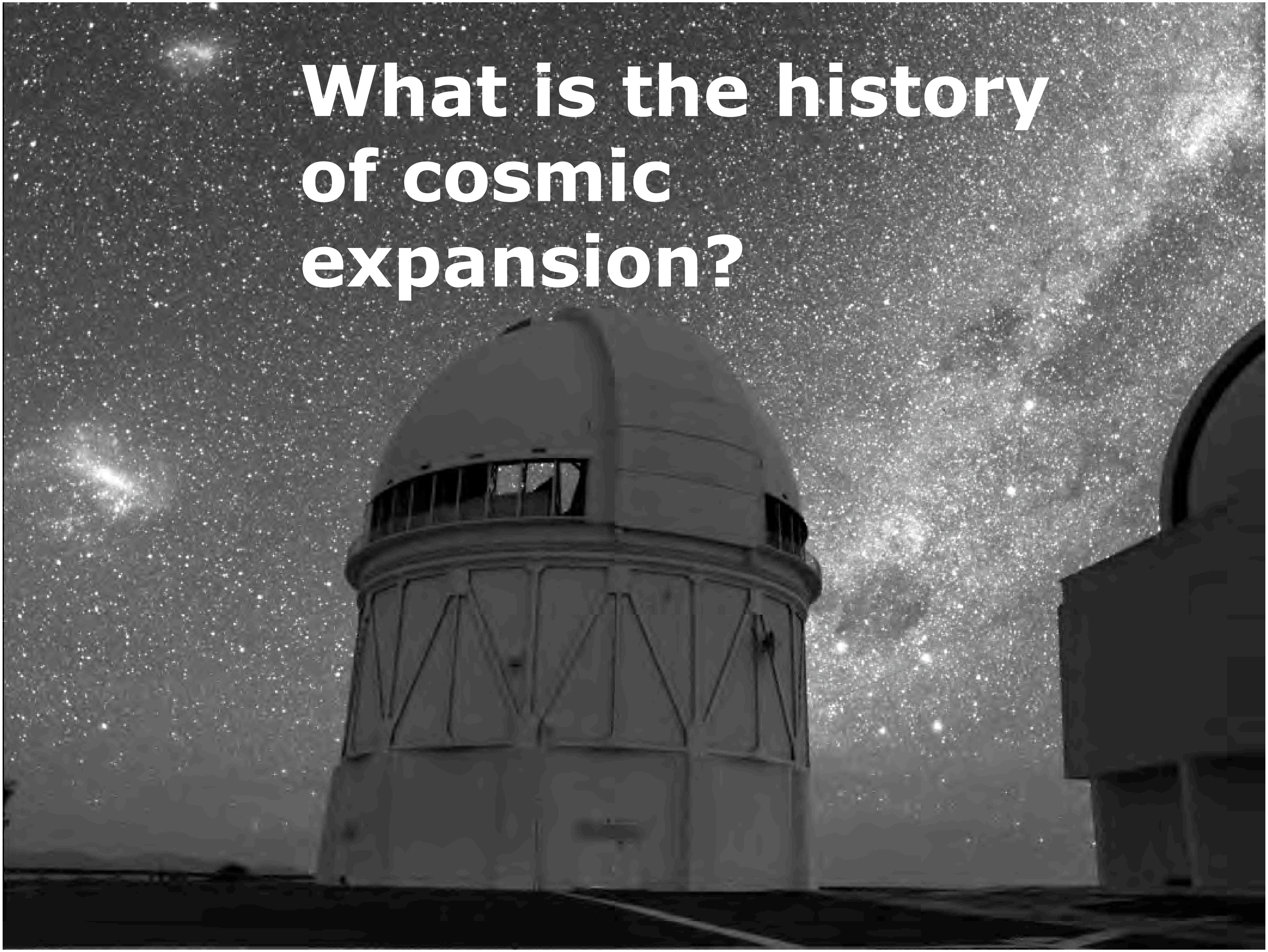
Cosmic Deceleration from Dark Matter, then Acceleration from Dark Energy!



Strength of 5800Å Feature

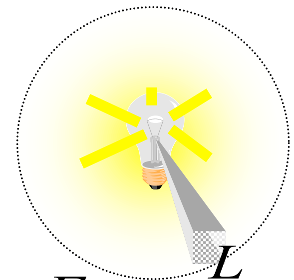


cf. Nugent et al. 1995, Garnavich et al. 2004, Bongard et al. 2006


What is the history
of cosmic
expansion?

Luminosity Distance

$$D_L = \sqrt{\frac{L}{4\pi F}}$$



$$F = \frac{L}{4\pi D^2}$$

Observer infers distance to an object with redshift z from the observed flux.

$$D_L = \frac{c}{H_0}(1+z)\left|\kappa_0\right|^{-1/2} S\left\{\left|\kappa_0\right|^{1/2}\int_0^z dz'\left[\sum_i \Omega_i (1+z')^{3+3w_i} - \kappa_0 (1+z')^2\right]^{-1/2}\right\}$$

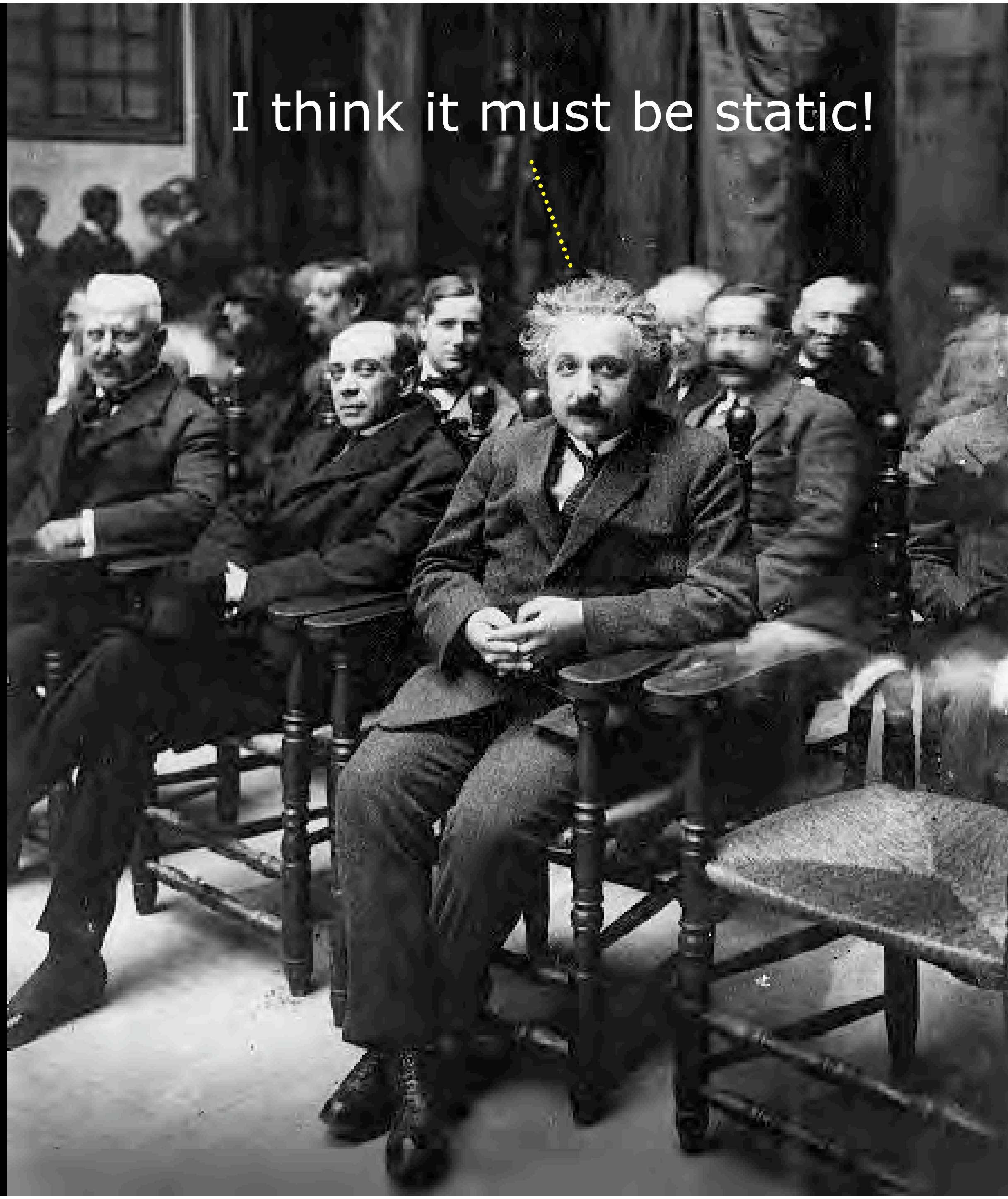
$$\kappa_0 = \left(\Omega_{tot} = \sum_i \Omega_i\right) - 1$$

$$S(x) = \begin{cases} \sin(x) & \mathrm{k} = 1 \\ x & \mathrm{k} = 0 \\ \sinh(x) & \mathrm{k} = \text{-}1 \end{cases}$$

1852

Daguerrotype of the Moon

Detectors accumulate light over a period of time & provide a durable record


I think it must be static!

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)[2]. 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.

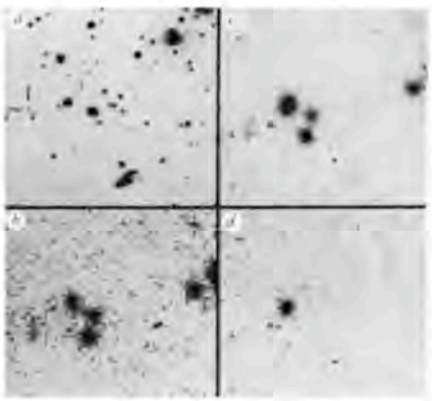


FIG. 1 Detection of the candidate supernova in the distant cluster AC118. *a*, 1-hour V exposure on the Danish 1.5-m telescope on 30 August 1986. *b*, 30 × 30-arcsec enlargement of *a* around the galaxy containing the event. *c*, Same enlargement of a 1-hour V exposure taken on 8 and 9 August 1988. *d*, 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

detailed spectra of SN1981B (ref. 15) and introduces a transformation error of ≤0.2 mag over the period concerned, an uncertainty less than the noise errors of Table 1. Figure 3 shows the rest-frame *B* light curve together with a template light-curve derived from nearby type Ia supernovae[16] shifted to fit the

statistics would therefore allow some interesting constraints to

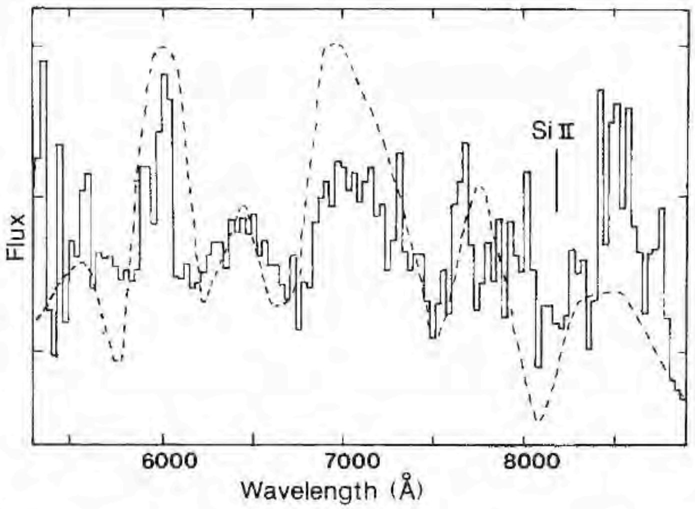


FIG. 2 Spectrum (solid line) of the galaxy in the cluster AC118, containing the supernova obtained by Hewett and Warren on 19 August 1988. The dashed line shows a spectrum of the nearby type Ia supernova 1981B 17 days after maximum redshifted to $z = 0.31$. The redshifted 6,150-Å feature is visible at 8,060 Å.

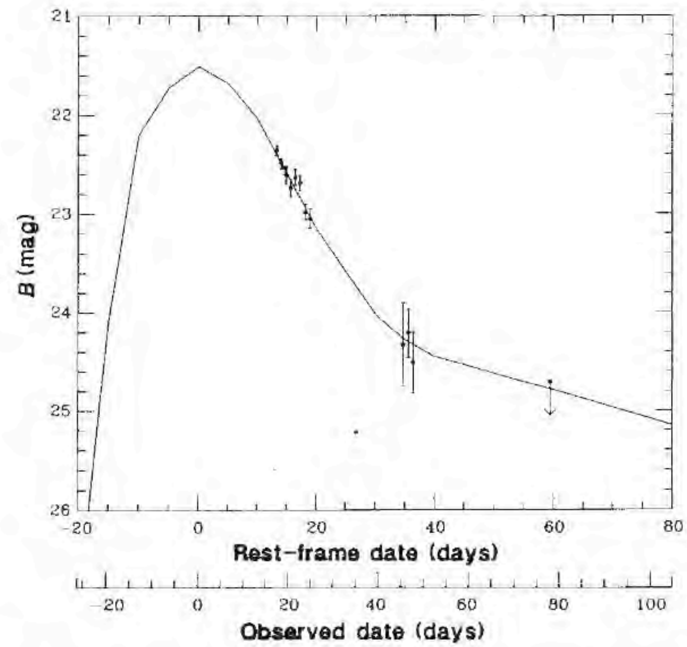
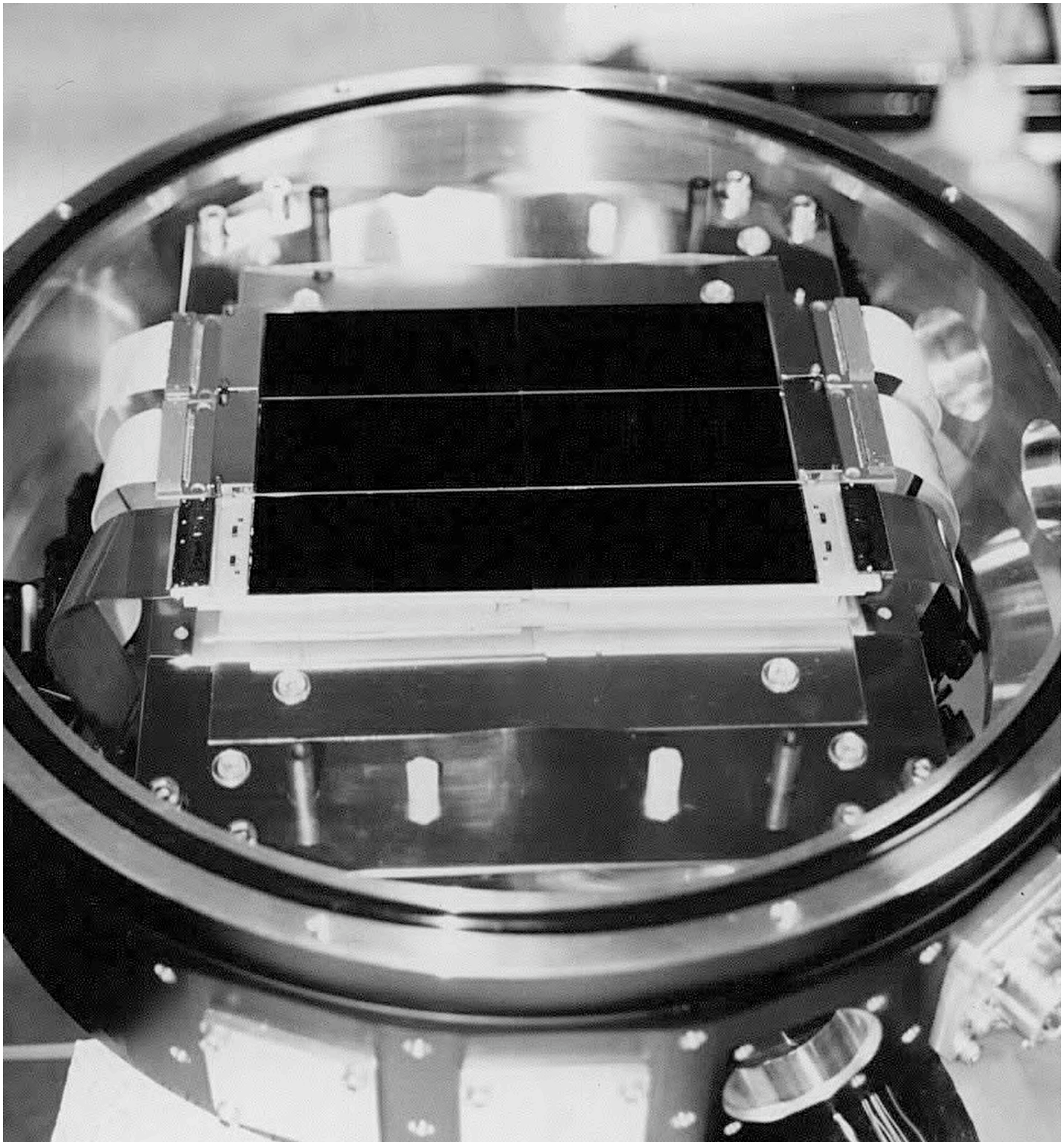


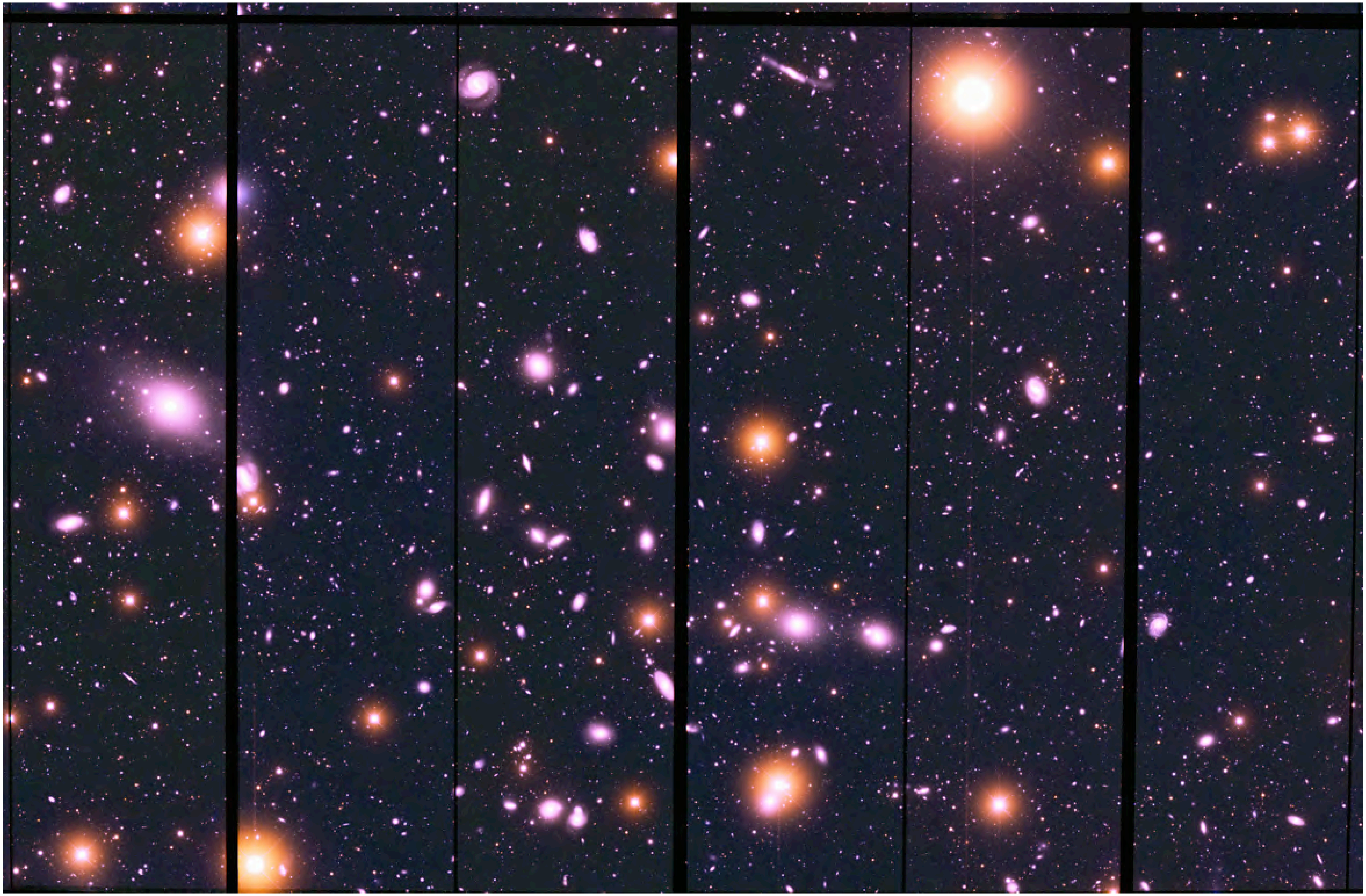
FIG. 3 Rest-frame *B* light curve of the AC118 supernova (points), uncorrected for extinction, compared with a standard light curve for a type Ia supernova (solid line)[16]. $t = 0$ is chosen to coincide with the estimated epoch of maximum light.

Actual data not so wonderful, and the rate with a small CCD on a 1.5 m telescope was 1 per year. But the ideas were there!



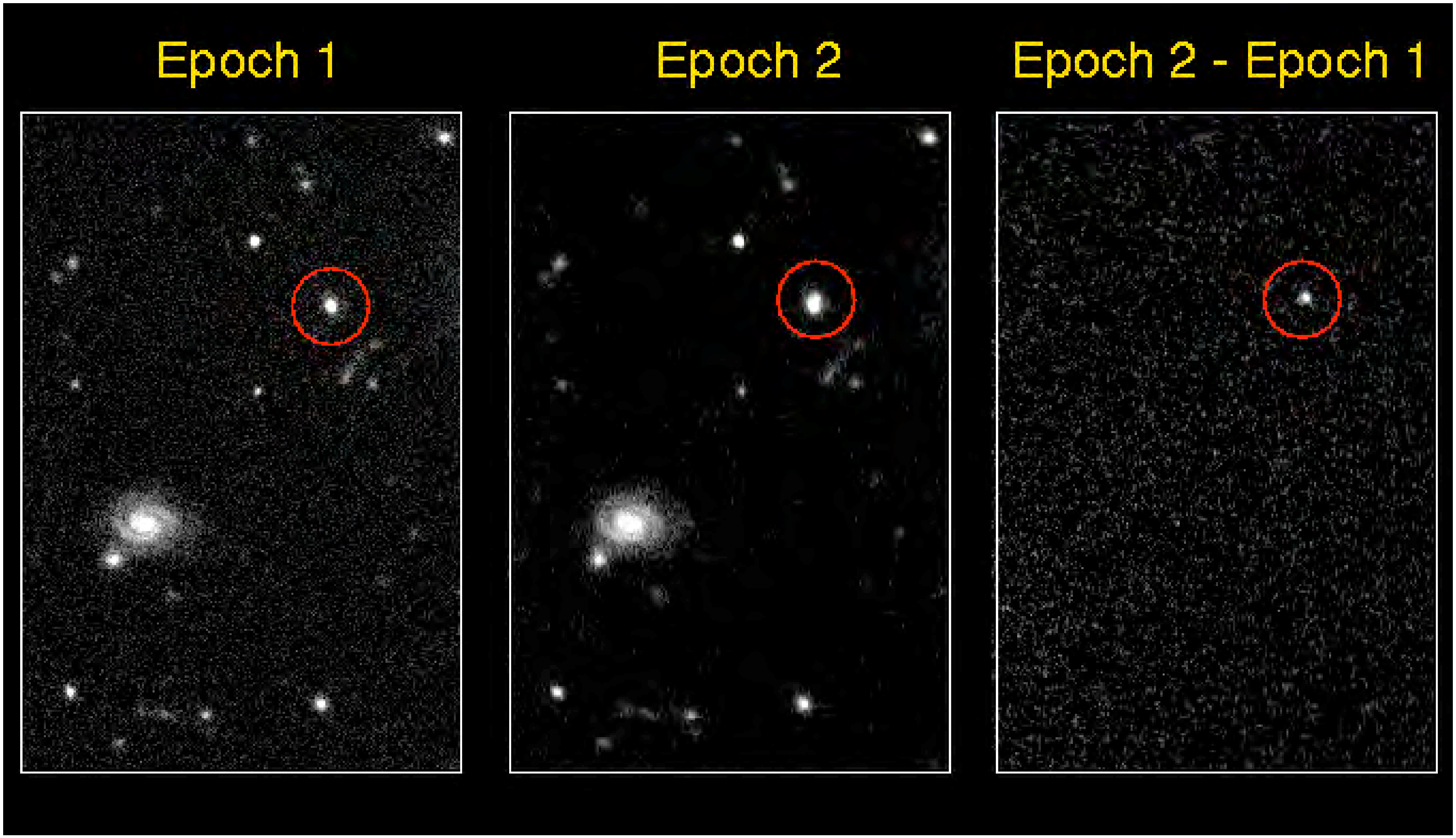
Giant Electronic Cameras Improve Searches

1/100 years ~ 1/5000 weeks => 5000 galaxies

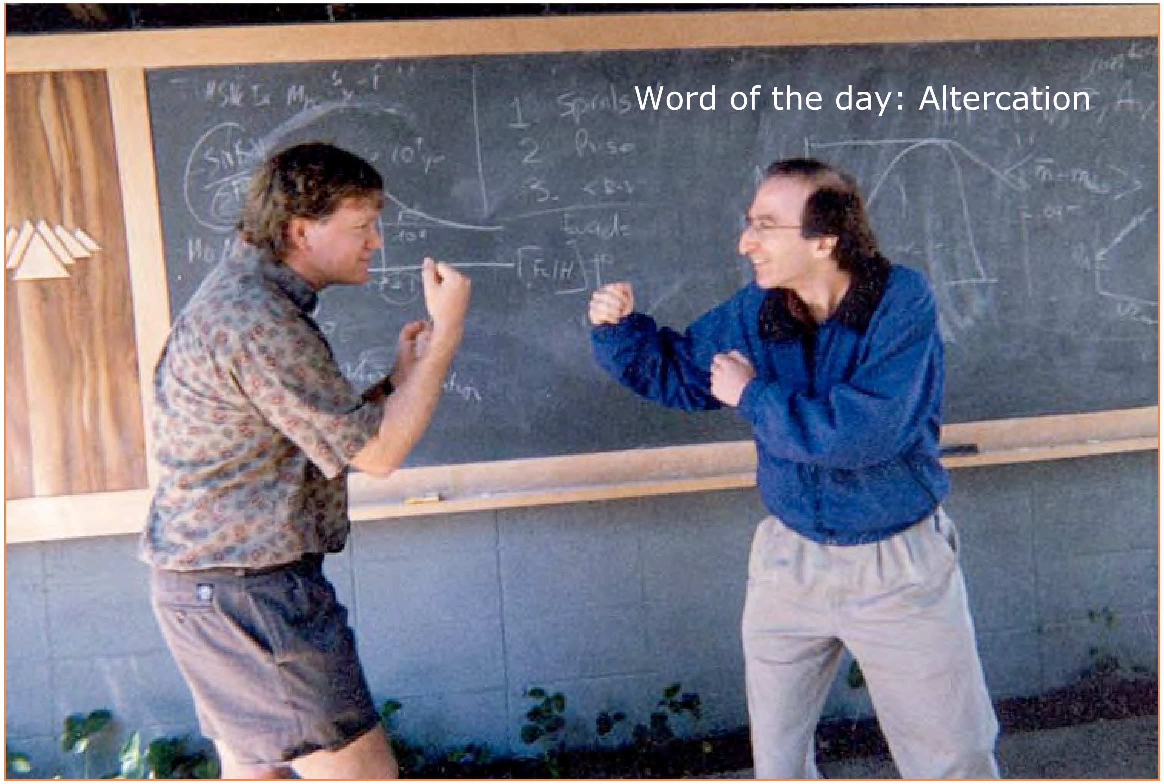


Brian Schmidt explains to his thesis advisor how easy this will be

Searching by Subtraction



High-Z Supernova Search Team



The High-Z Team

- Brian Schmidt (ANU)
- Nick Suntzeff, Bob Schommer, Chris Smith (CTIO)
- Mark Phillips (Carnegie)
- Bruno Leibundgut and Jason Spyromilio (ESO)
- Bob Kirshner, Peter Challis, Tom Matheson (Harvard)
- Alex Filippenko, Weidong Li, Saurabh Jha (Berkeley)
- Peter Garnavich, Stephen Holland (Notre Dame)
- Chris Stubbs (UW)
- John Tonry, Brian Barris (University of Hawaii)
- Adam Reiss (Space Telescope)
- Alejandro Clocchiatti (Catolica Chile)
- Jesper Sollerman (Stockholm)

The High-Z SN Search

Crete

The Supernova Cosmology Project

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C. Pennypacker

The High-Z SN Search

The Astrophysical Journal, 483:565–581, 1997 July 10

July 1997 Ap.J.

SCP: No Λ

MEASUREMENTS[1] OF THE COSMOLOGICAL PARAMETERS Ω AND Λ FROM THE FIRST SEVEN SUPERNOVAE AT $z \geq 0.35$

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(The Supernova Cosmology Project)

Received 1996 August 26; accepted 1997 February 6

ABSTRACT

We have developed a technique to systematically discover and study high-redshift supernovae that can be used to measure the cosmological parameters. We report here results based on the initial seven of more than 28 supernovae discovered to date in the high-redshift supernova search of the Supernova Cosmology Project. We find an observational dispersion in peak magnitudes of $\sigma_{M_B} = 0.27$; this dispersion narrows to $\sigma_{M_B,\mathrm{corr}} = 0.19$ after "correcting" the magnitudes using the light-curve "width-luminosity" relation found for nearby ($z \leq 0.1$) Type Ia supernovae from the Calán/Tololo survey (Hamuy et al.). Comparing light-curve width-corrected magnitudes as a function of redshift of our distant ($z = 0.35$–0.46) supernovae to those of nearby Type Ia supernovae yields a global measurement of the mass density, $\Omega_M = 0.88^{+0.69}_{-0.60}$ for a $\Lambda = 0$ cosmology. For a spatially flat universe (i.e., $\Omega_M + \Omega_\Lambda = 1$), we find $\Omega_M = 0.94^{+0.34}_{-0.28}$ or, equivalently, a measurement of the cosmological constant, $\Omega_\Lambda = 0.06^{+0.28}_{-0.34}$ (<0.51 at the 95% confidence level). For the more general Friedmann-Lemaître cosmologies with independent Ω_M and Ω_Λ, the results are presented as a confidence region on the Ω_M-Ω_Λ plane. This region does not correspond to a unique value of the deceleration parameter q_0. We present analyses and checks for statistical and systematic errors and also show that our results do not depend on the specifics of the width-luminosity correction. The results for Ω_Λ-versus-Ω_M are inconsistent with Λ-dominated, low-density, flat cosmologies that have been proposed to reconcile the ages of globular cluster stars with higher Hubble constant values.

Subject headings: cosmology: observations — distance scale — supernovae: general

1. INTRODUCTION

The classical magnitude-redshift diagram for a distant standard candle remains perhaps the most direct approach for measuring the cosmological parameters that determine the fate of the cosmic expansion (Sandage 1961, 1989). The first standard candles used in such studies were first-ranked cluster galaxies (Gunn & Oke 1975; Kristian, Sandage, & Westphal 1978) and the characteristic magnitude of the cluster galaxy luminosity function (Abell 1972). More recent measurements have used powerful radio galaxies at higher redshifts (Lilly & Longair 1984; Rawlings, Lacey, & Eales 1994). Both the early programs (reviewed by Tammann 1983) and the recent work have proved particularly important for the understanding of galactic evolution but are correspondingly more difficult to interpret as measurements of cosmological parameters. The Type Ia supernovae (SN

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

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B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7]
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Received 1998 March 13; revised 1998 May 6

ABSTRACT

We present spectral and photometric observations of 10 Type Ia supernovae (SNe Ia) in the redshift range $0.16 \leq z \leq 0.62$. The luminosity distances of these objects are determined by methods that employ relations between SN Ia luminosity and light curve shape. Combined with previous data from our High-z Supernova Search Team and recent results by Riess et al., this expanded set of 16 high-redshift supernovae and a set of 34 nearby supernovae are used to place constraints on the following cosmological parameters: the Hubble constant (H_0), the mass density (Ω_M), the cosmological constant (i.e., the vacuum energy density, Ω_Λ), the deceleration parameter (q_0), and the dynamical age of the universe (t_0). The distances of the high-redshift SNe Ia are, on average, 10%–15% farther than expected in a low mass density ($\Omega_M = 0.2$) universe without a cosmological constant. Different light curve fitting methods, SN Ia subsamples, and prior constraints unanimously favor eternally expanding models with positive cosmological constant (i.e., $\Omega_\Lambda > 0$) and a current acceleration of the expansion (i.e., $q_0 < 0$). With no prior constraint on mass density other than $\Omega_M \geq 0$, the spectroscopically confirmed SNe Ia are statistically consistent with $q_0 < 0$ at the 2.8 σ and 3.9 σ confidence levels, and with $\Omega_\Lambda > 0$ at the 3.0 σ and 4.0 σ confidence levels, for two different fitting methods, respectively. Fixing a "minimal" mass density, $\Omega_M = 0.2$, results in the weakest detection, $\Omega_\Lambda > 0$ at the 3.0 σ confidence level from one of the two methods. For a flat universe prior ($\Omega_M + \Omega_\Lambda = 1$), the spectroscopically confirmed SNe Ia require $\Omega_\Lambda > 0$ at 7 σ and 9 σ formal statistical significance for the two different fitting methods. A universe closed by ordinary matter (i.e., $\Omega_M = 1$) is formally ruled out at the 7 σ to 8 σ confidence level for the two different fitting methods. We estimate the dynamical age of the universe to be 14.2 ± 1.7 Gyr including systematic uncertainties in the current Cepheid distance scale. We estimate the likely effect of several sources of systematic error, including progenitor and metallicity evolution, extinction, sample selection bias, local perturbations in the expansion rate, gravitational lensing, and sample contamination. Presently, none of these effects appear to reconcile the data with $\Omega_\Lambda = 0$ and $q_0 \geq 0$.

Key words: cosmology: observations — supernovae: general

THE ASTROPHYSICAL JOURNAL, 517:565–586, 1999 June 1

MEASUREMENTS OF Ω AND Λ FROM 42 HIGH-REDSHIFT SUPERNOVAE

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(THE SUPERNOVA COSMOLOGY PROJECT)
Received 1998 September 8; accepted 1998 December 17

ABSTRACT

We report measurements of the mass density, Ω_M, and cosmological-constant energy density, Ω_Λ, of the universe based on the analysis of 42 type Ia supernovae discovered by the Supernova Cosmology Project. The magnitude-redshift data for these supernovae, at redshifts between 0.18 and 0.83, are fitted jointly with a set of supernovae from the Calán/Tololo Supernova Survey, at redshifts below 0.1, to yield values for the cosmological parameters. All supernova peak magnitudes are standardized using a SN Ia light-curve width-luminosity relation. The measurement yields a joint probability distribution of the cosmological parameters that is approximated by the relation $0.8\Omega_M - 0.6\Omega_\Lambda \approx -0.2 \pm 0.1$ in the region of interest ($\Omega_M \lesssim 1.5$). For a flat ($\Omega_M + \Omega_\Lambda = 1$) cosmology we find $\Omega_M^{flat} = 0.28^{+0.09}_{-0.08}$ (1 σ statistical) $^{+0.05}_{-0.04}$ (identified systematics). The data are strongly inconsistent with a $\Lambda = 0$ flat cosmology, the simplest inflationary universe model. An open, $\Lambda = 0$ cosmology also does not fit the data well: the data indicate that the cosmological constant is nonzero and positive, with a confidence of $P(\Lambda > 0) = 99\%$, including

High-Z Team

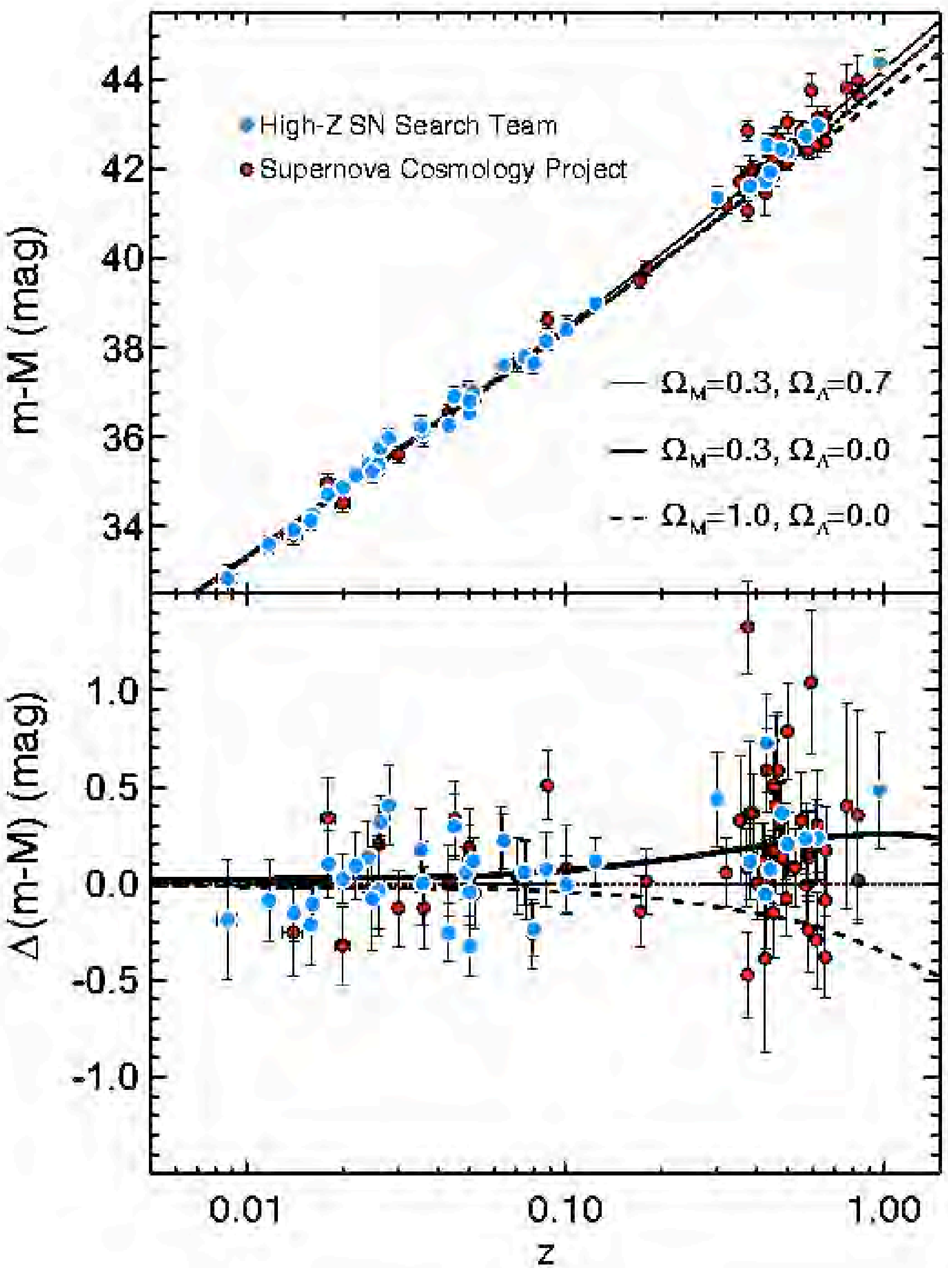
Astronomical Journal

1998 September

SCP

Astrophysical Journal

1999 June



1998 Data:

Riess et al. (1998)

Perlmutter et al. (1999)

Evidence for cosmic acceleration: 20% dimmer than expected

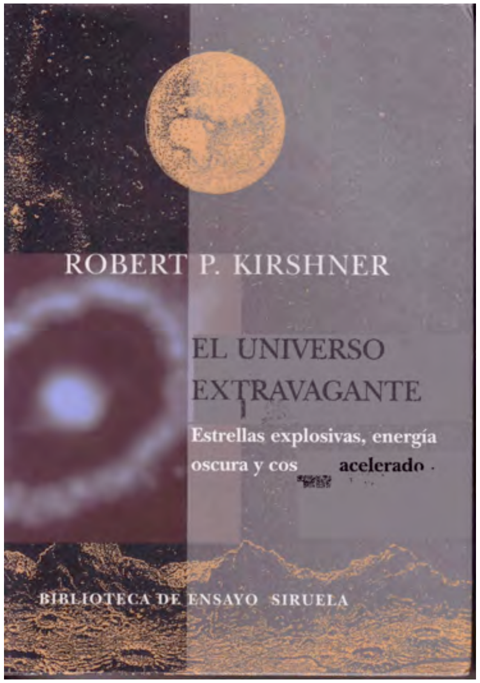
N/σ^2 comparable

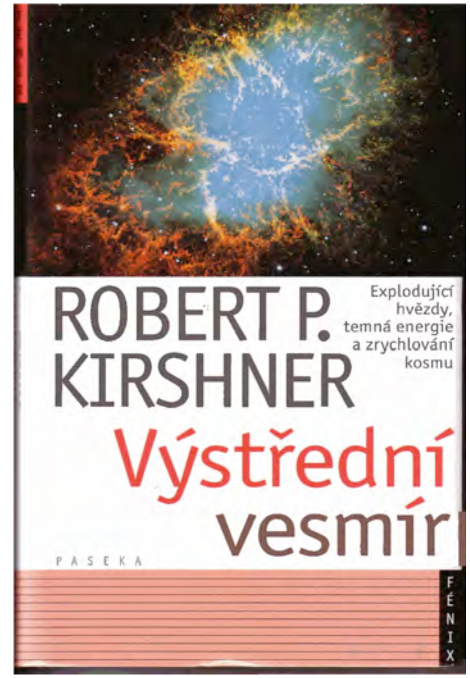

MAINE
AUG
0233161
XLR8N U
MAINE
08
6728349
Vacationland

Big News in 1998!

Λ

Very small compared to expectations, but not zero!





If you can’t get enough of these matters… I can’t recommend a better book

http://cfa-www.harvard.edu/~rkirshner/whowhatwhen/Thoughts.htm

ESSENCE Results

Miknatis et al (2007)

astro-ph/0701043

Wood-Vesey et al. (2007)

astro-ph/0701041

See also SNLS

Astier et al. (2005)

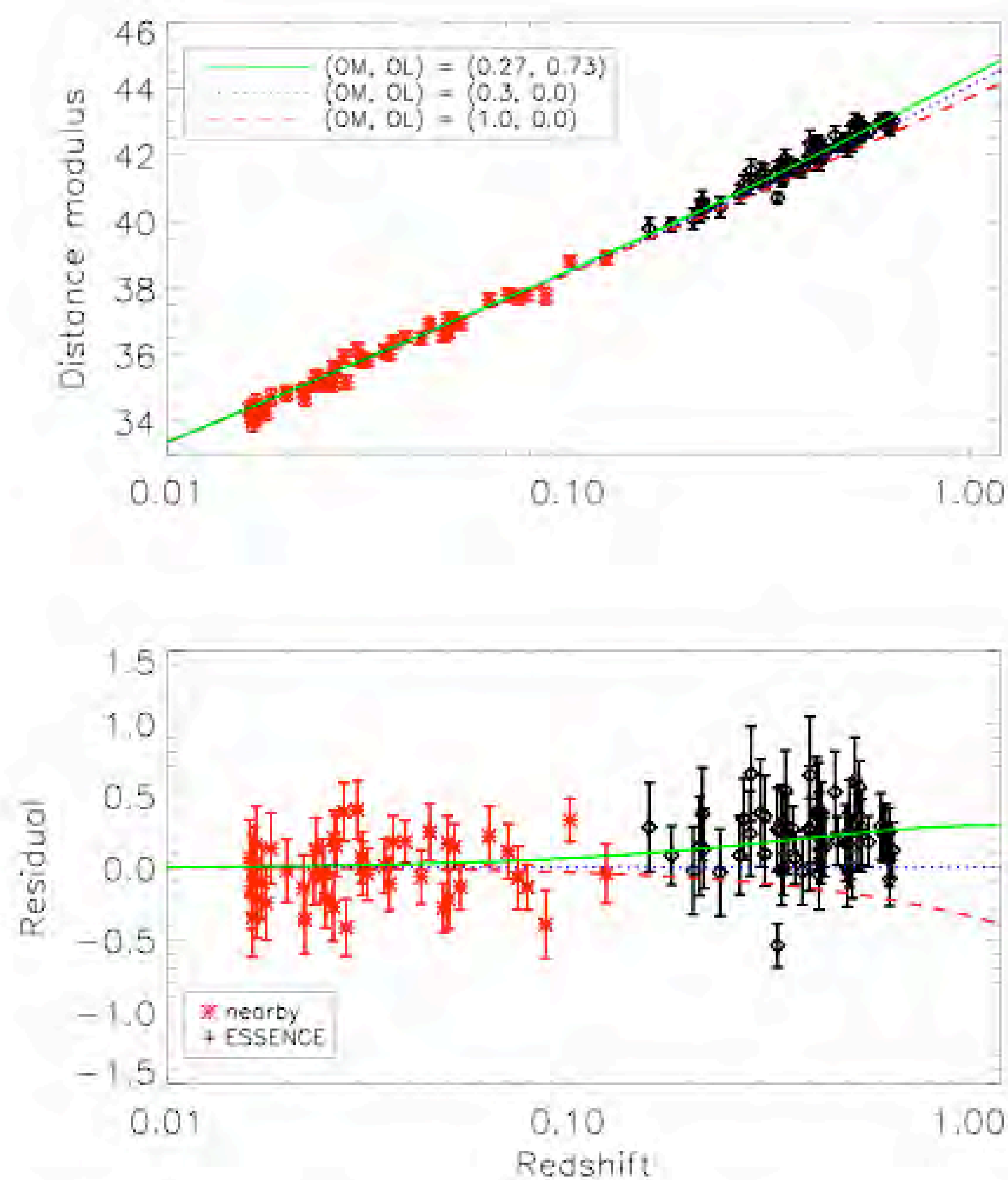


Fig. 8.— Luminosity distance modulus versus redshift for the ESSENCE and nearby SNe Ia for MLCS2k2 with the "glosz" A_V prior. For comparison the overplotted solid line and residuals are for a $(w, \Omega_M, \Omega_\Lambda) = (-1, 0.27, 0.73)$ Universe.

General Relativity

For GR, pressure counts as a source of gravitation

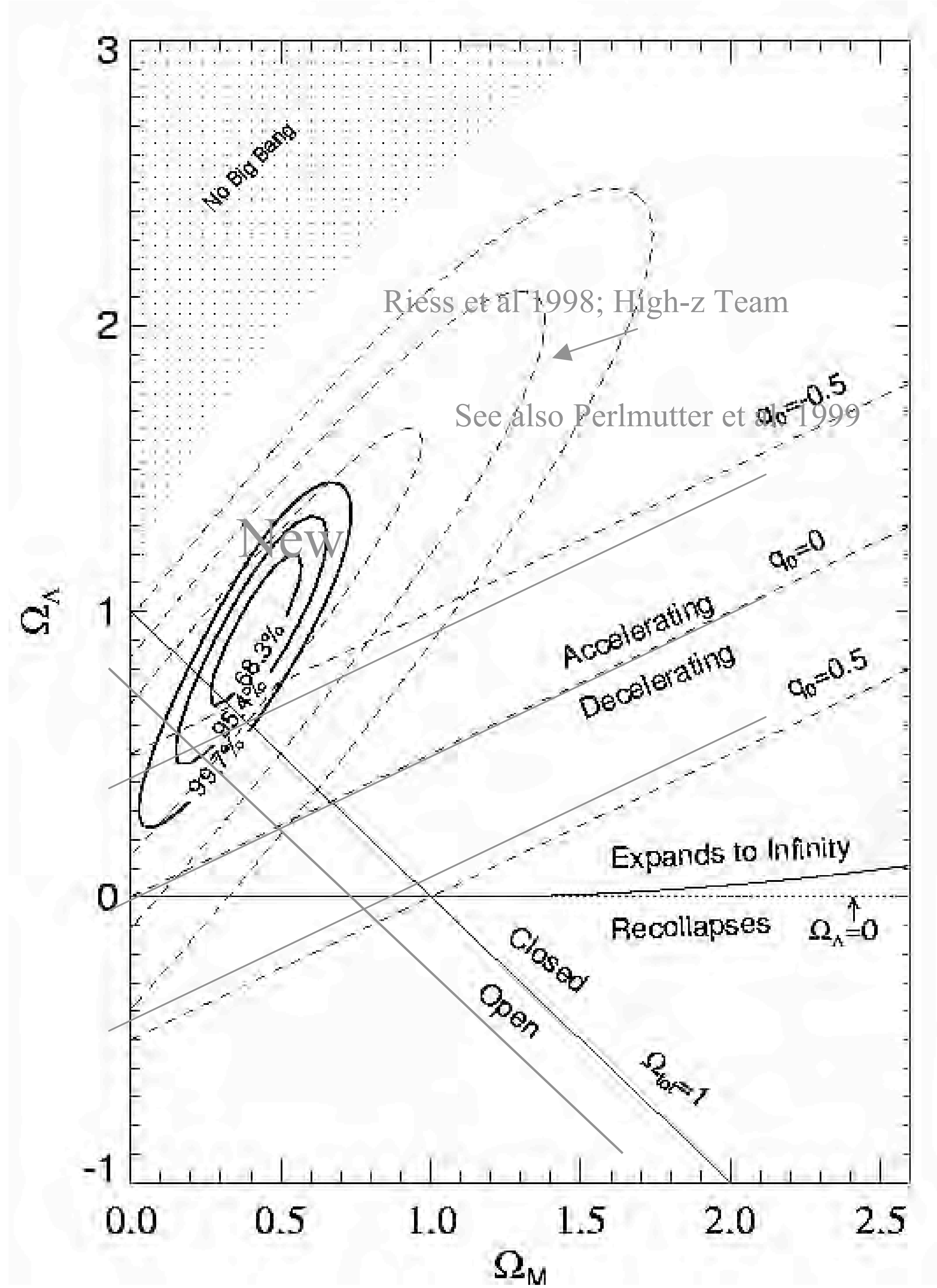
$a''/a = -4\pi G/3\ (\rho + 3P/c^2)$

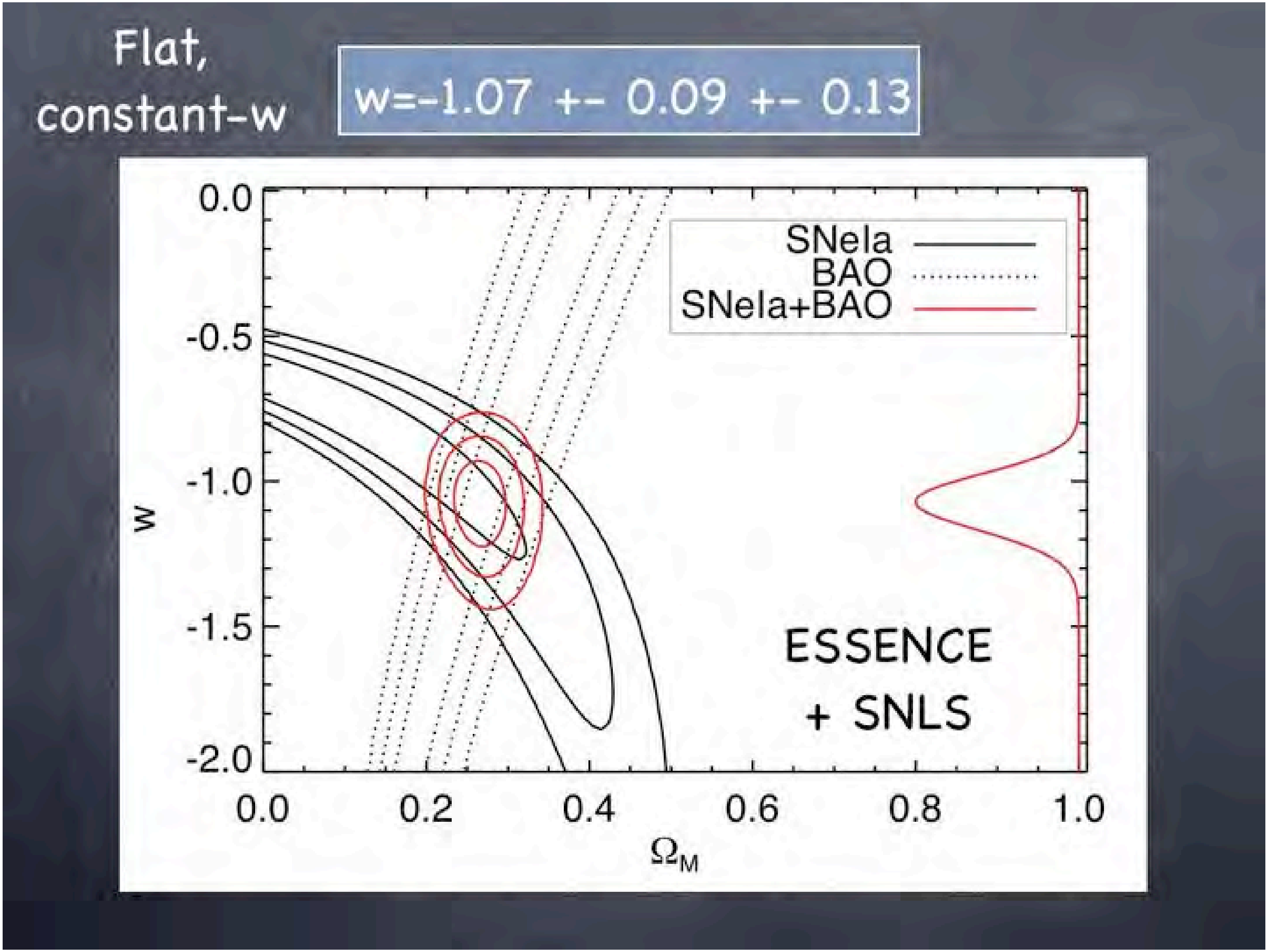
Ordinarily, $a'' < 0$

But… if $(\rho + 3P/c^2)<0$, a'' is positive! You can get cosmic acceleration from negative pressure ($w < -1/3$)

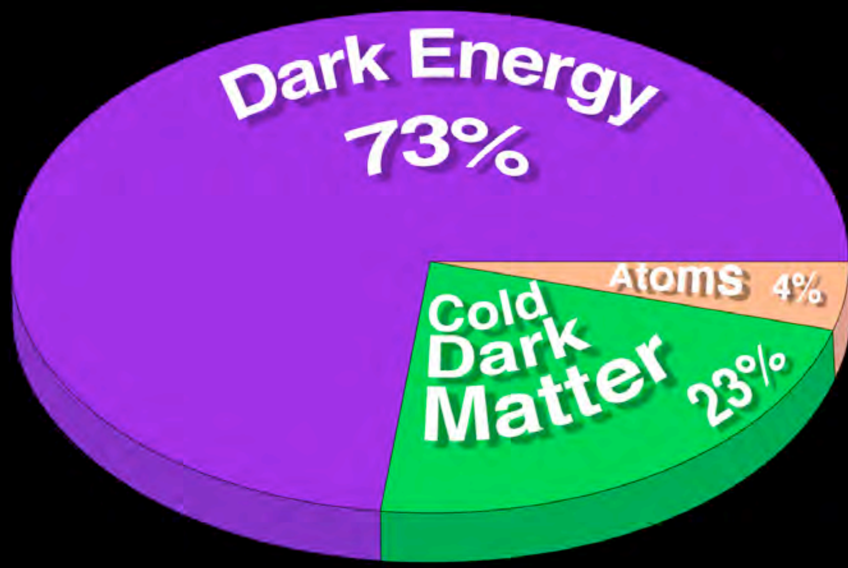
Updated Constraints

Factor of 7 improvement from 1998 by building up the samples and extending the redshift range




Flat,
constant-w
w=-1.07 +- 0.09 +- 0.13
SNeIa
BAO
SNeIa+BAO
ESSENCE
+ SNLS
0.0
-0.5
-1.0
-1.5
-2.0
w
0.0
0.2
0.4
0.6
0.8
1.0
ΩM

Not Your Father's Universe!



ESSENCE Results

Miknatis et al (2007)

astro-ph/0701043

Wood-Vesey et al. (2007)

astro-ph/0701041

See also SNLS

Astier et al. (2005)

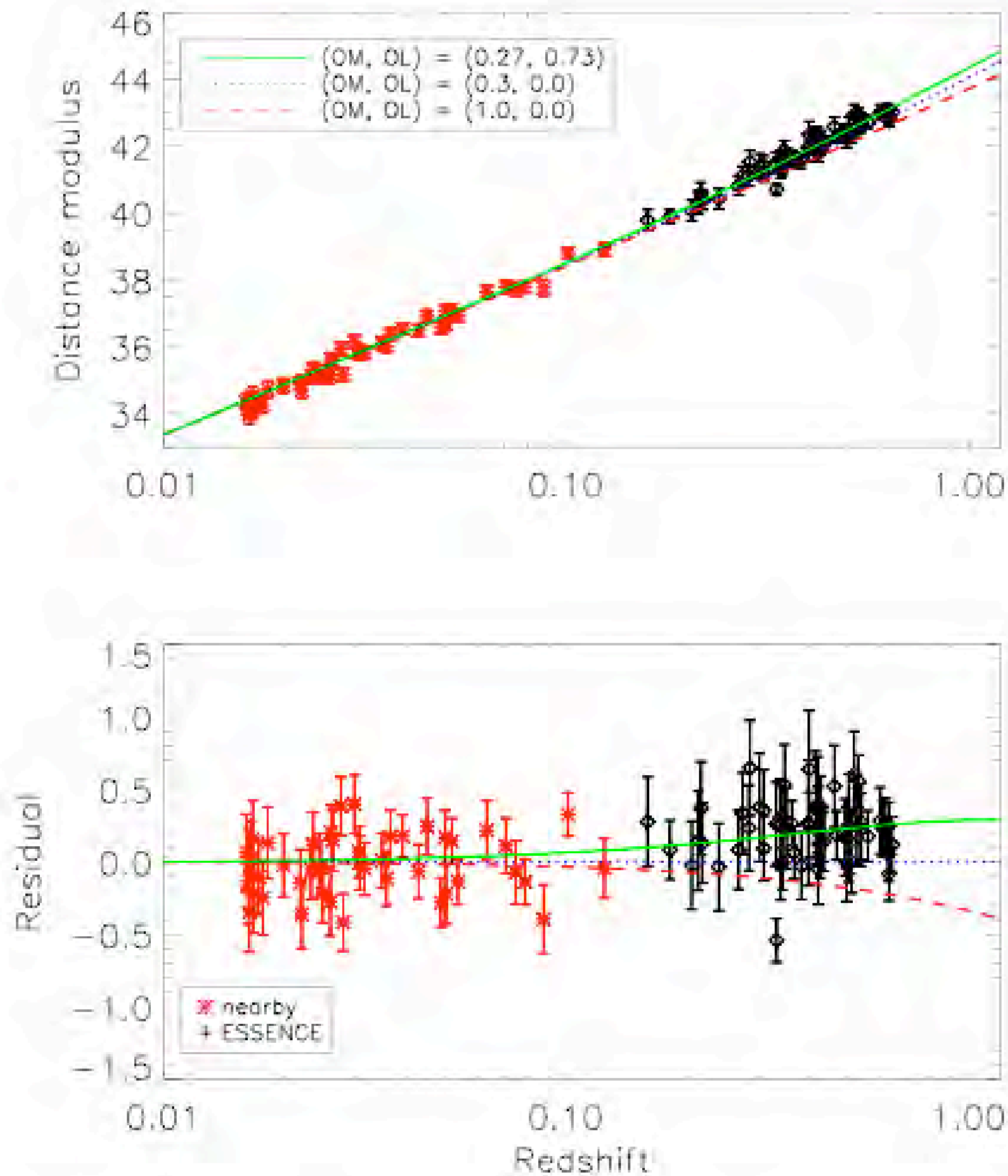
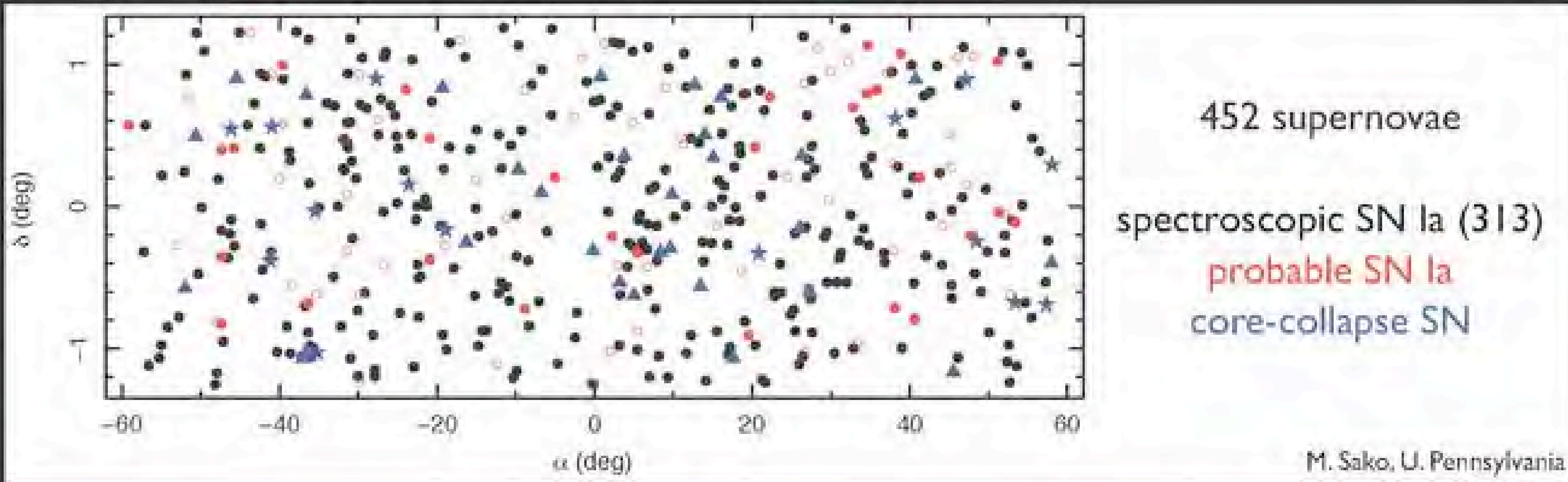
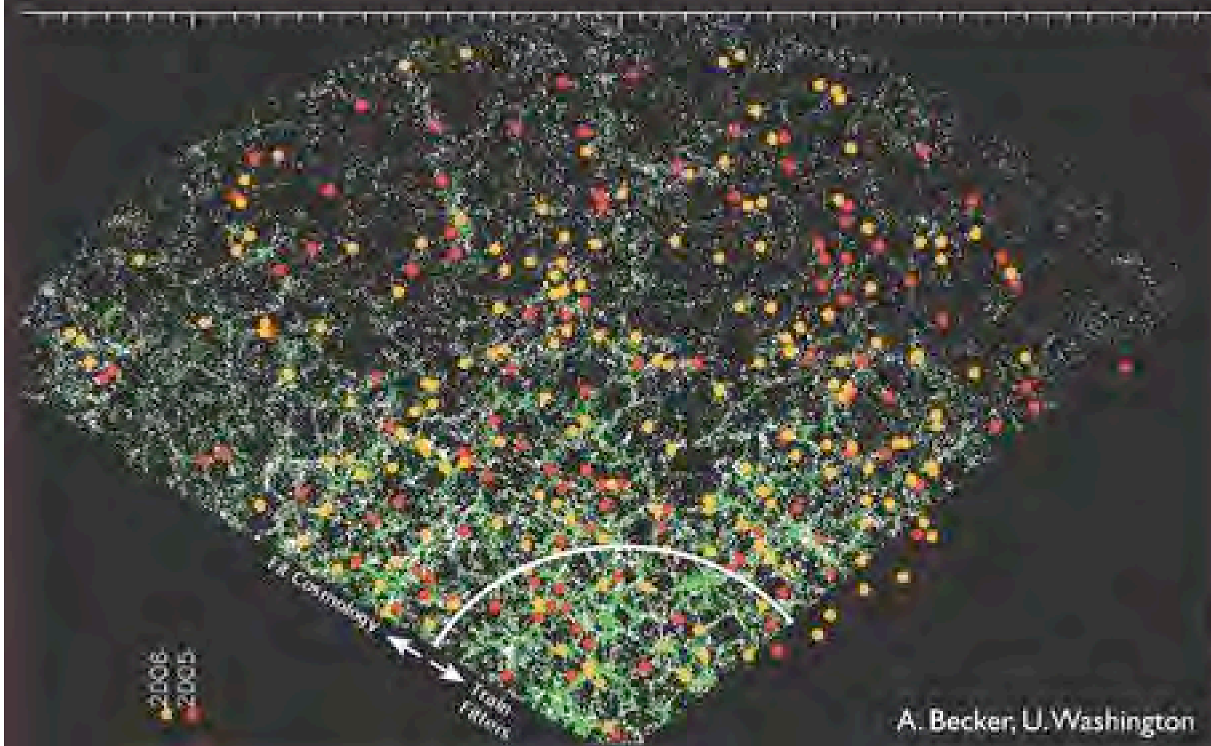


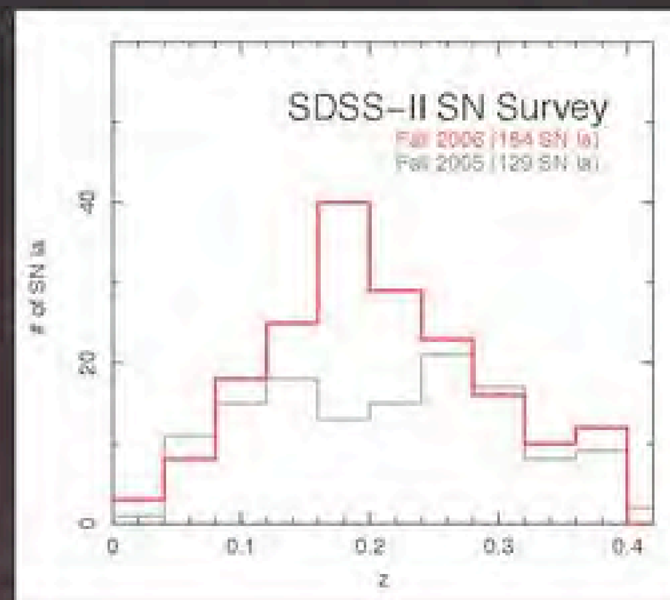
Fig. 8.— Luminosity distance modulus versus redshift for the ESSENCE and nearby SNe Ia for MLCS2k2 with the "glosz" A_V prior. For comparison the overplotted solid line and residuals are for a $(w, \Omega_M, \Omega_\Lambda) = (-1, 0.27, 0.73)$ Universe.



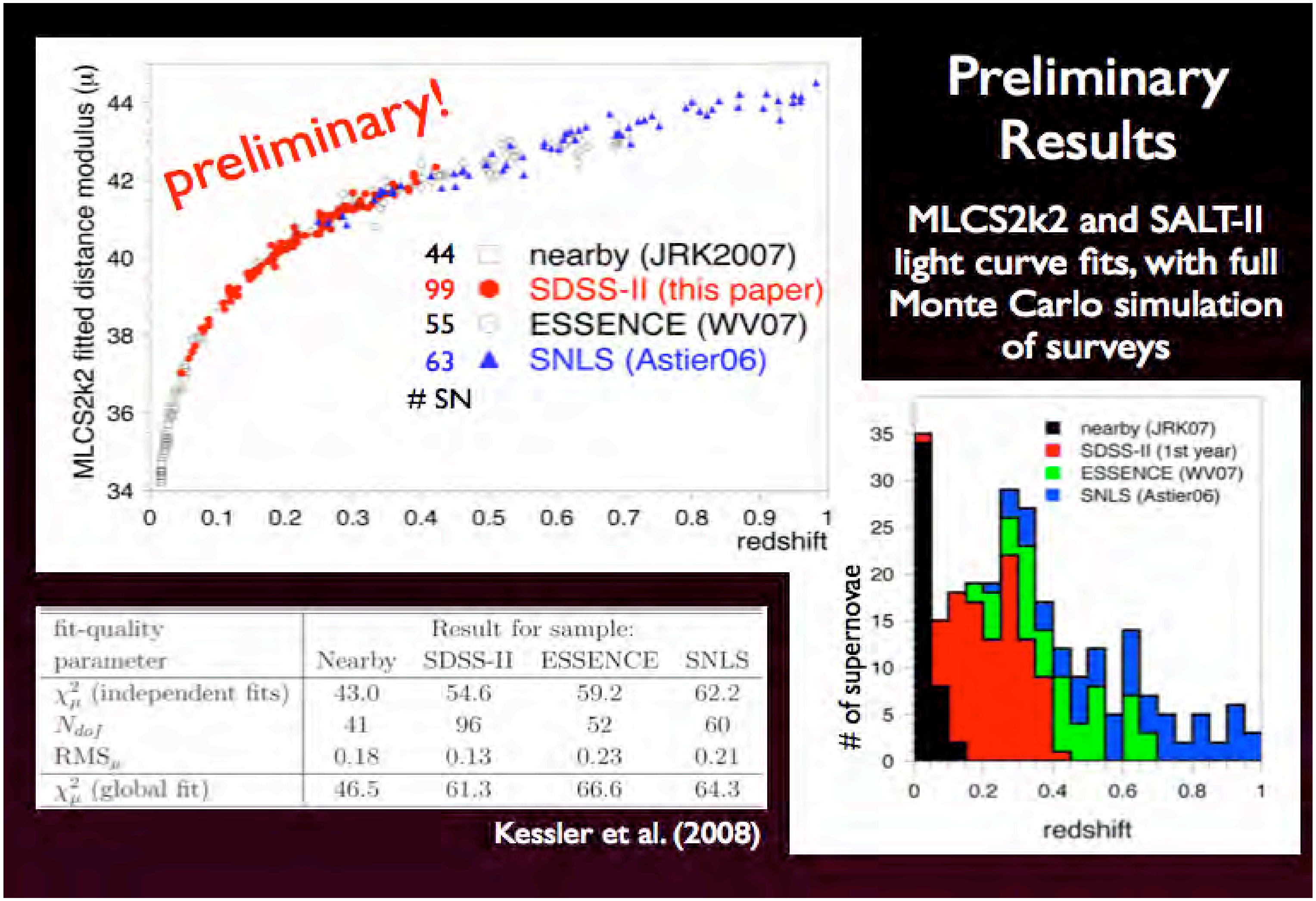
452 supernovae
spectroscopic SN Ia (313)
probable SN Ia
core-collapse SN
δ (deg)
α (deg)
M. Sako, U. Pennsylvania



Fit Cosmology
Train Filters
2006
2005
A. Becker, U. Washington

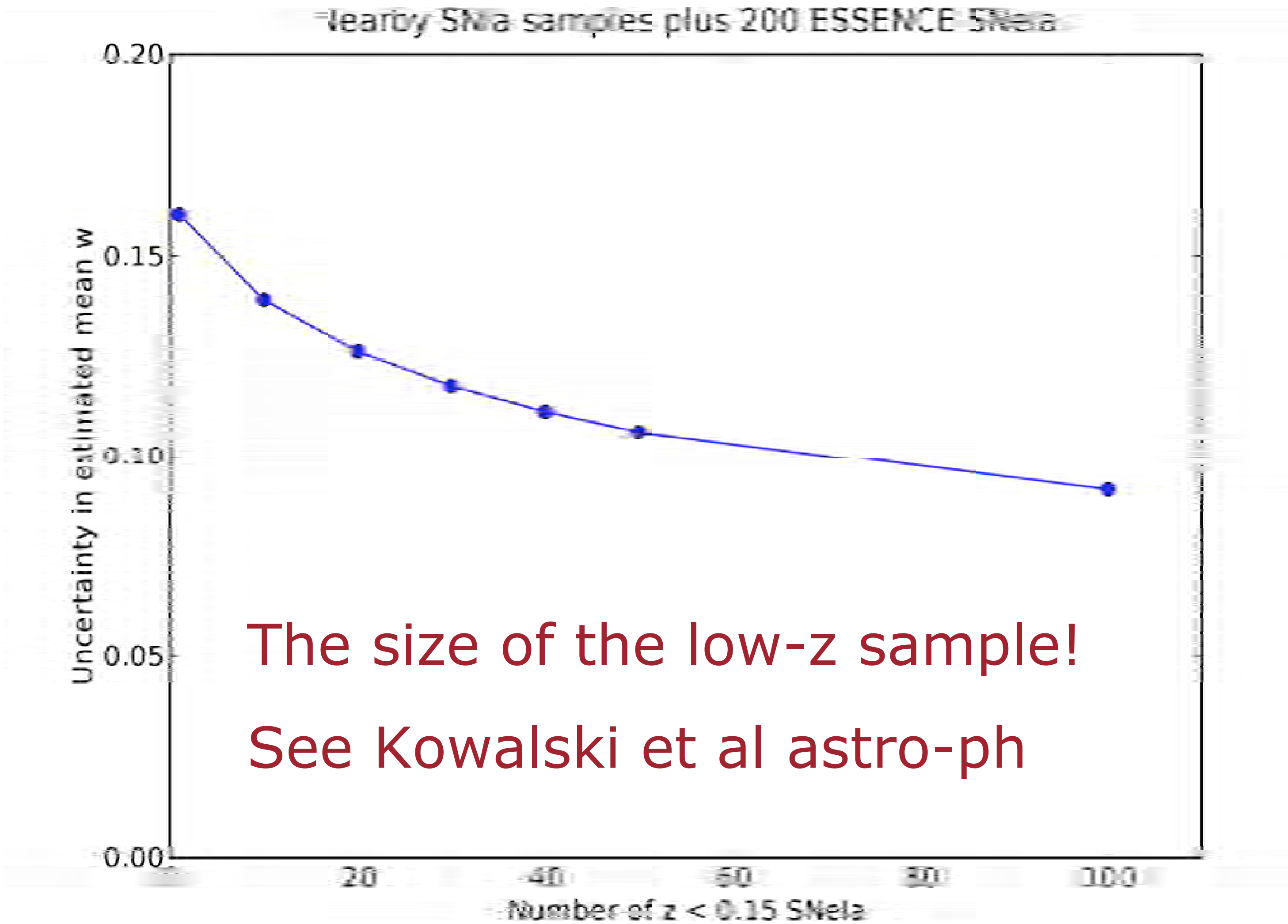


SDSS-II SN Survey
Fall 2006 (184 SN Ia)
Fall 2005 (129 SN Ia)
# of SN Ia
z



Today’s State of Play: N~100 (from S. JHA)

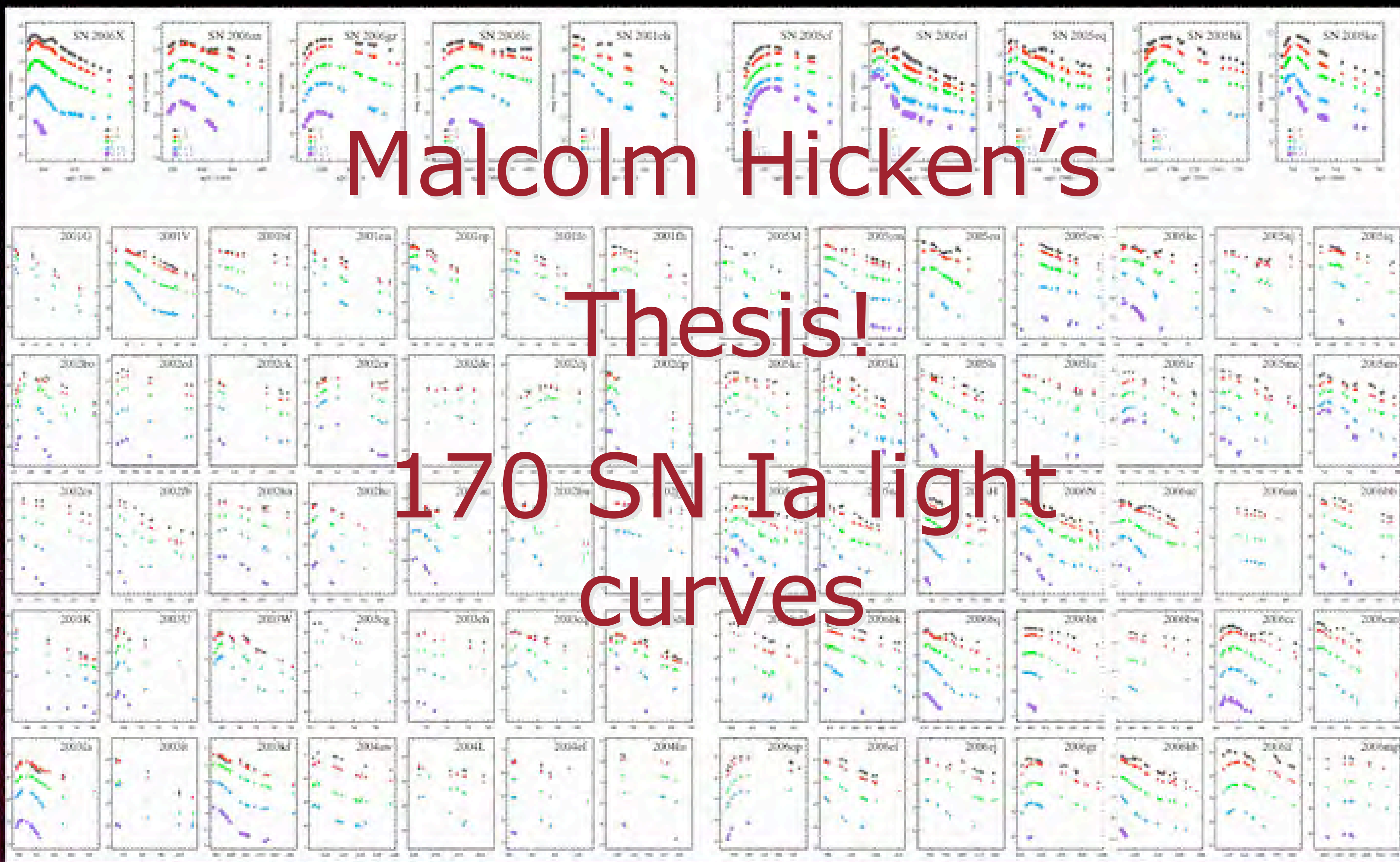
What limits the precision of the measurement?



The size of the low-z sample!

See Kowalski et al astro-ph

Follow-up at FLWO: CfA III



Malcolm Hicken’s Thesis!

170 SN Ia light curves

Hicken et al. (2007)

Coming soon: KAIT, Carnegie, SN Factory

Systematic Errors: the name of this game!

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

(Wood-Vasey et al., astro-ph/070141)

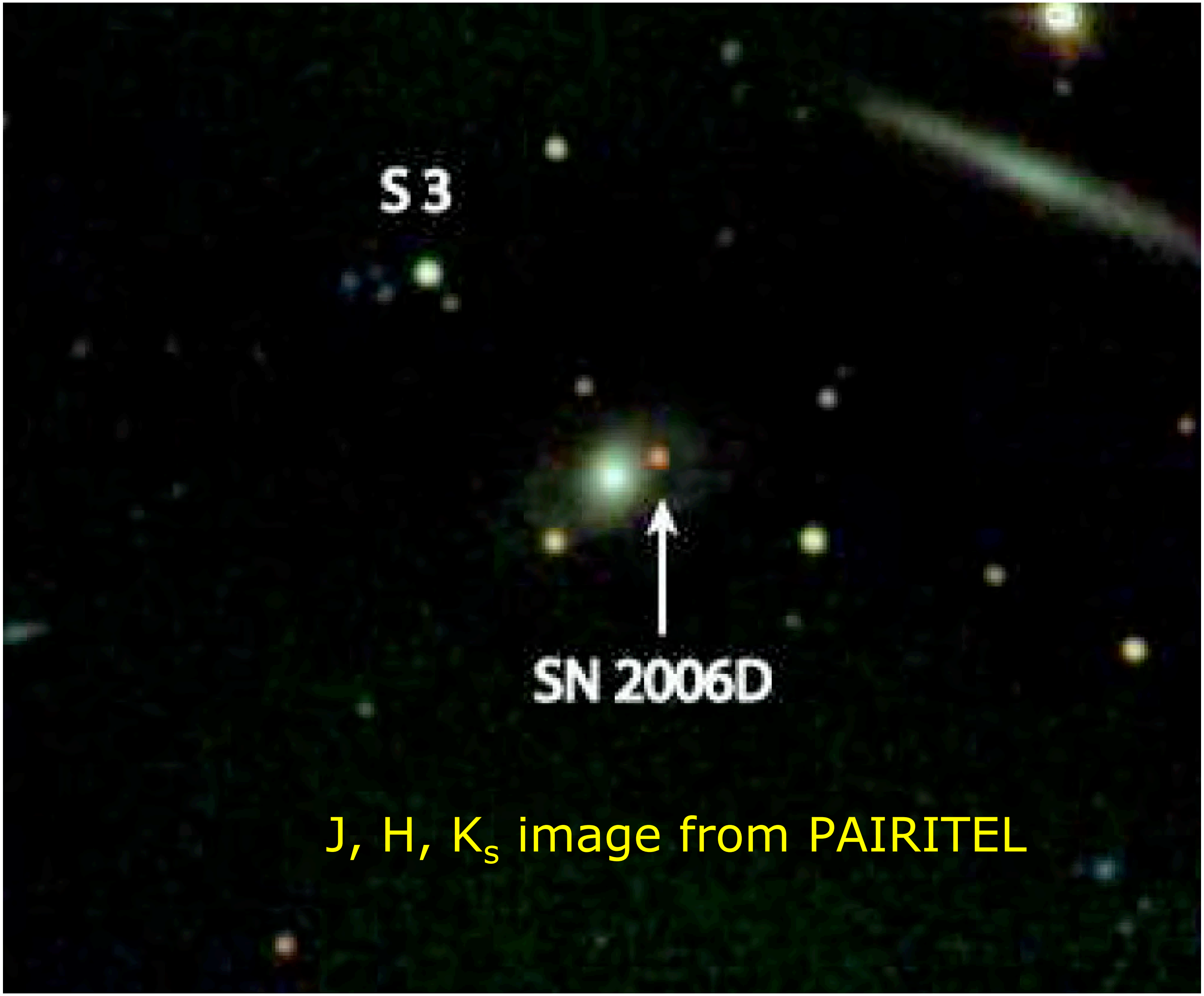
Something to avoid!

What is to be done?

Observe in the (near) infrared: JHK_s

The SN Ia behave very uniformly (who knew?)

Dust extinction goes $\sim 1/\lambda$, so it should be only $\sim 1/4$ as large


S3
SN 2006D
J, H, K_s image from PAIRITEL

Ongoing efforts to build up low-z IR samples!

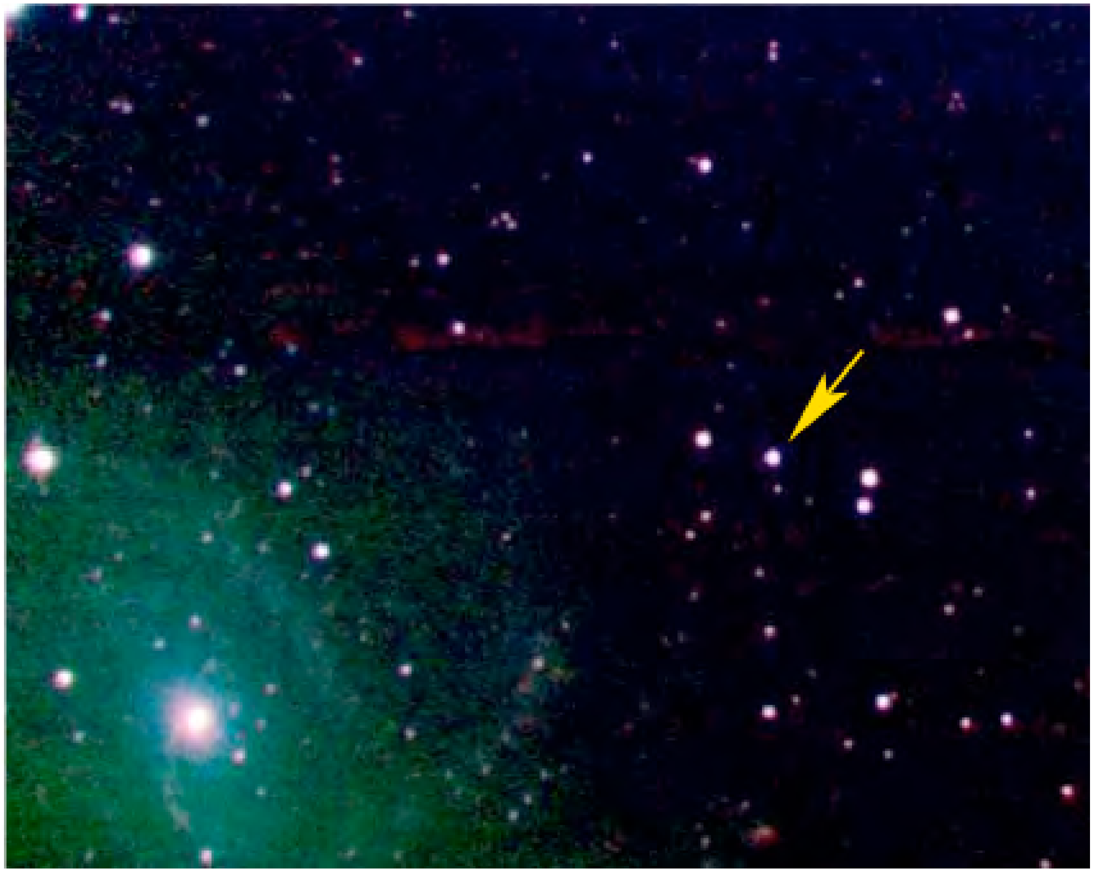
Carnegie Supernova Project:

http://csp1.lco.cl/~cspuser1/CSP.html

CfA: Pairitel

Robotic 2MASS

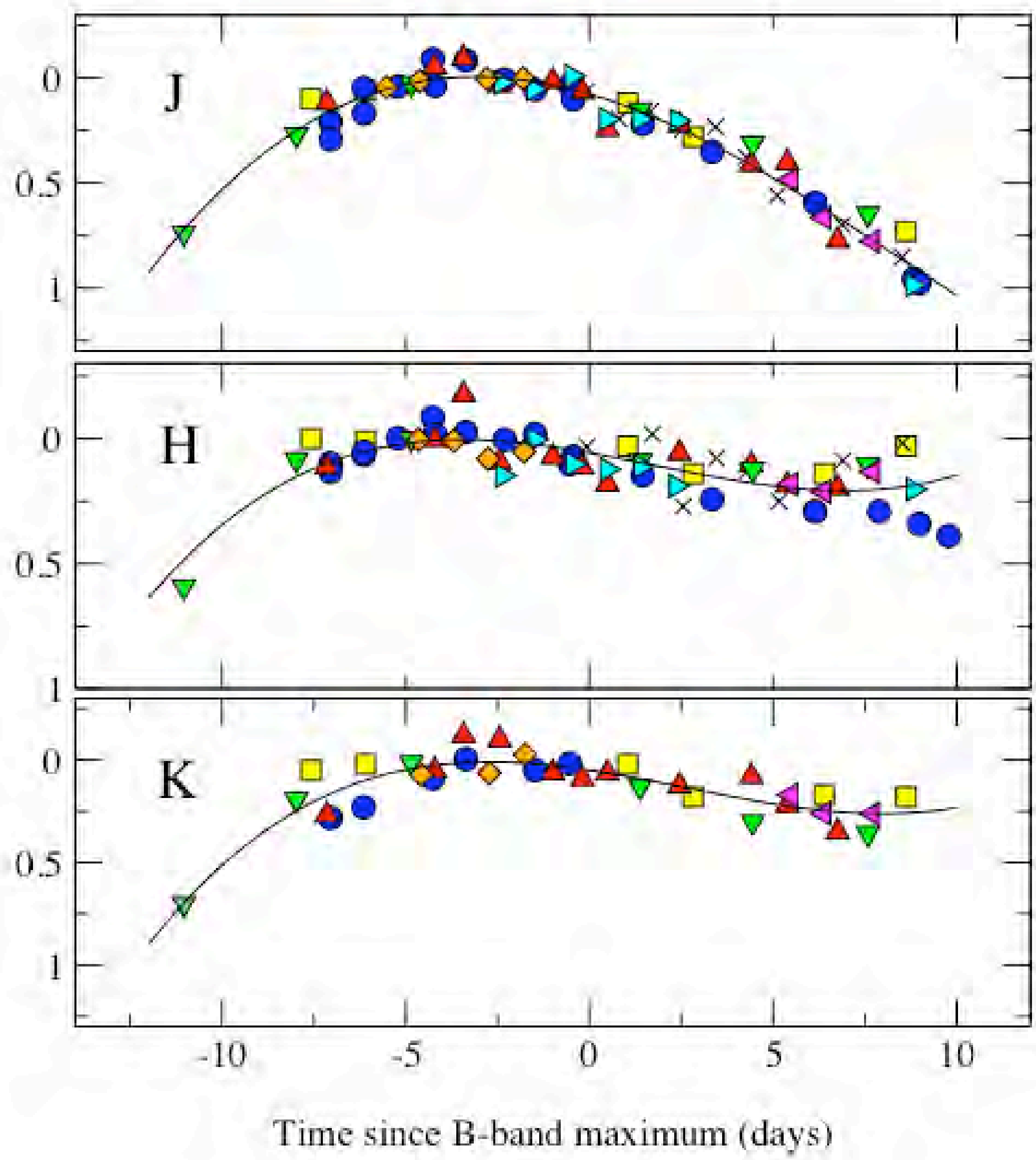
JHK_s



July 3, 2008

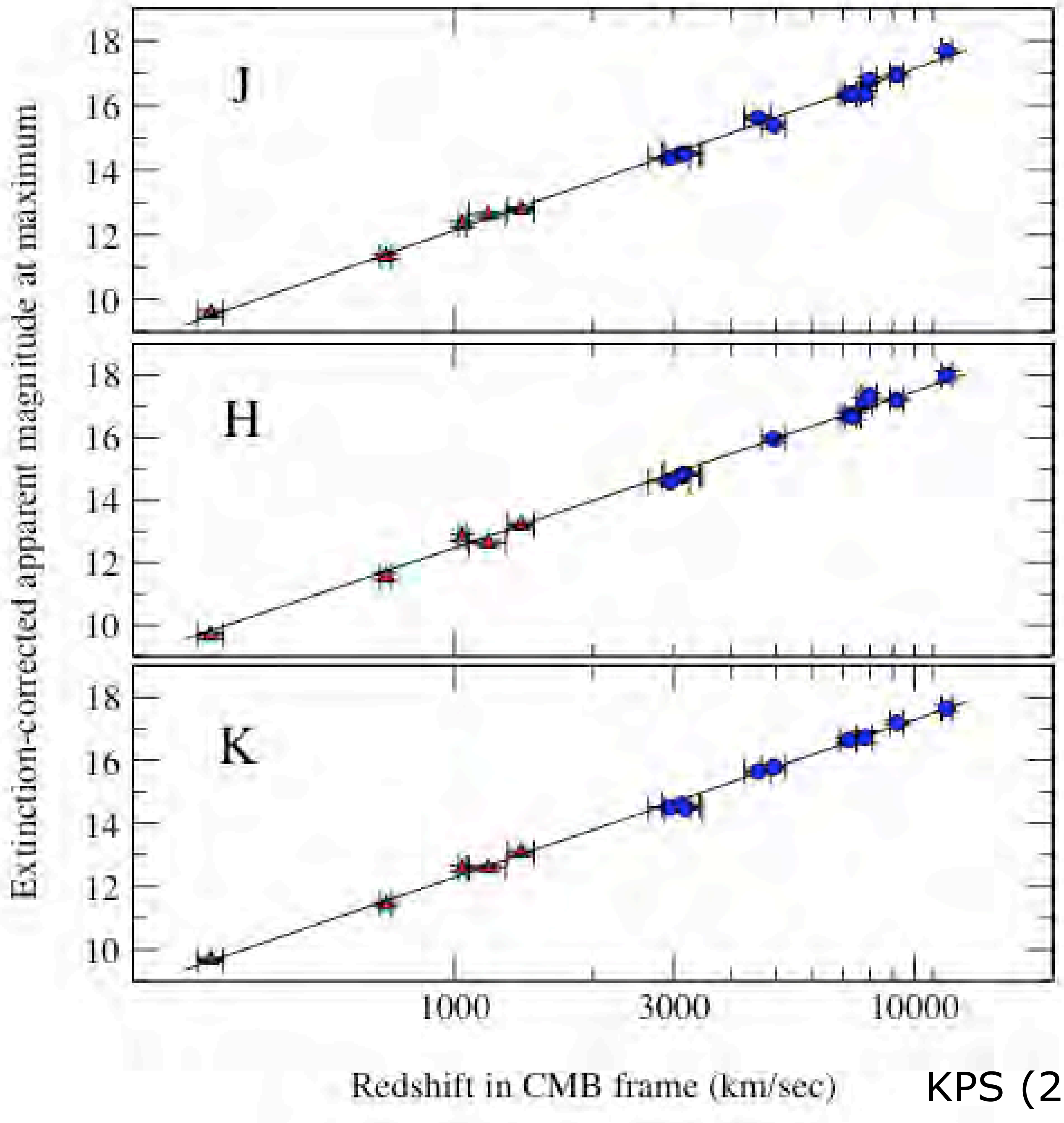
Infrared Light Curves: More Homogeneous!

Krisciunas, Phillips, & Suntzeff Ap.J. Letters 602, 81 (2004)

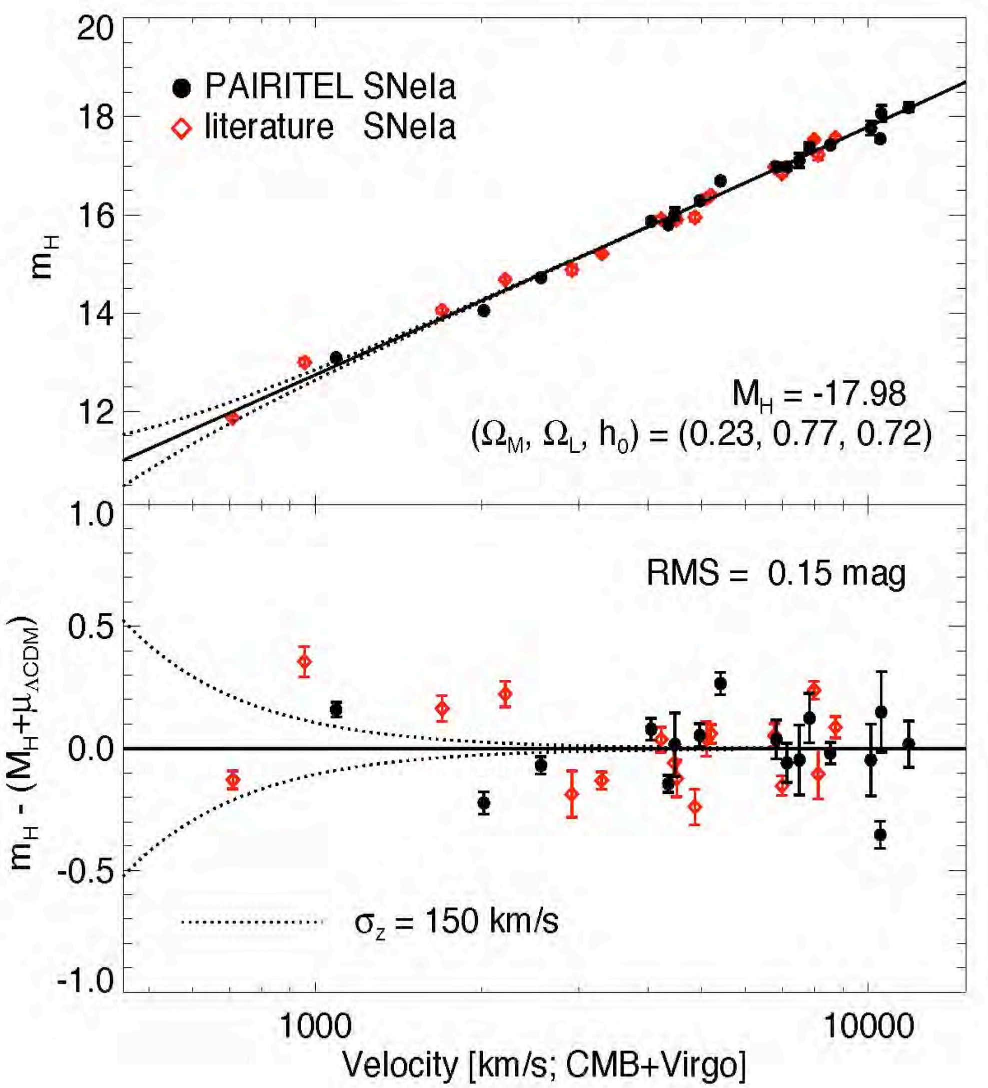


July 3,

Infrared Hubble Diagrams



KPS (2004)



Even if you make **no correction** for light curve shape or for dust-- the IR Hubble diagram has scatter that is no larger than for UBVRI light curves after all the corrections of MLCS!

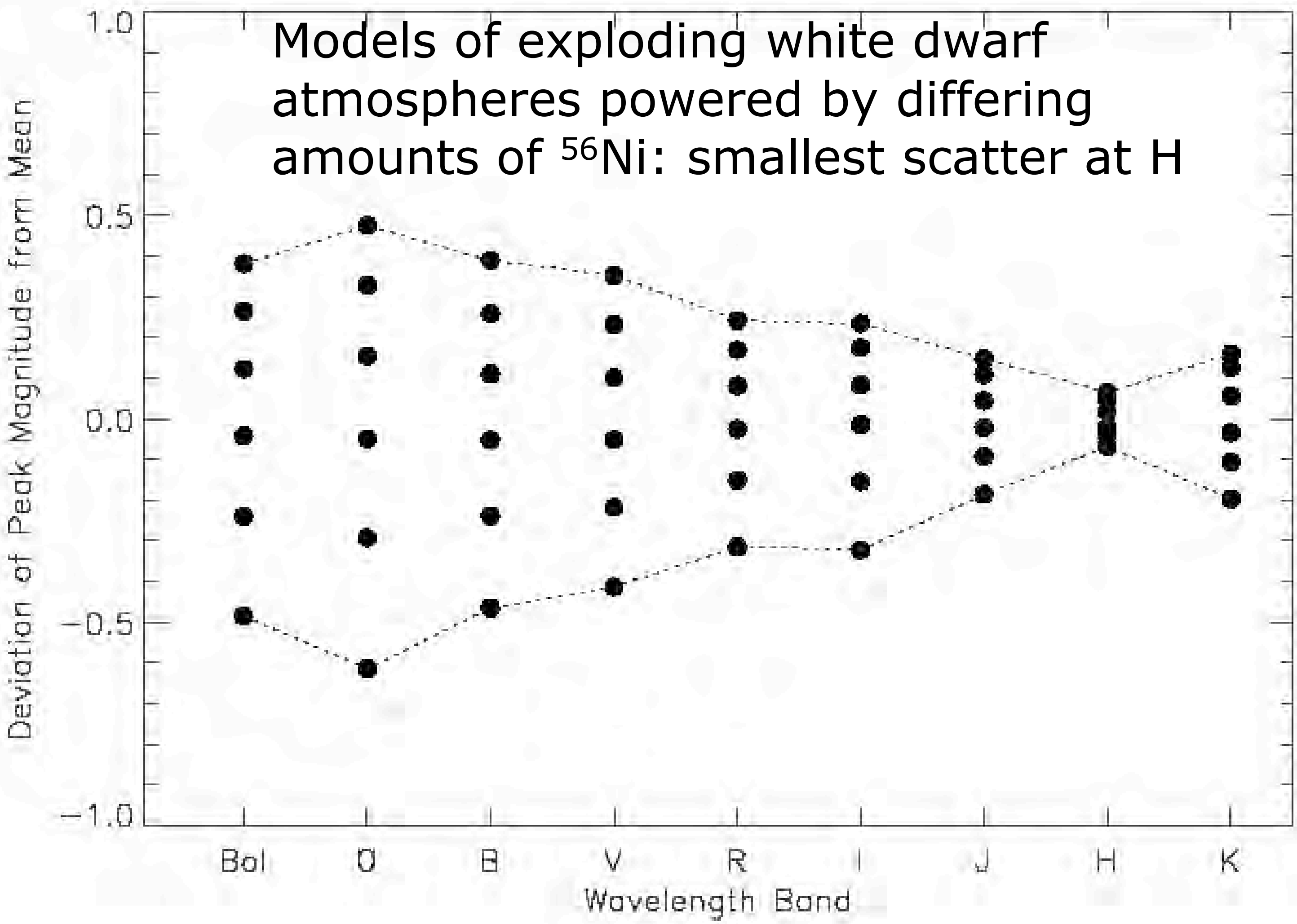
We can do better: (Kaisey Mandel)

Construct an optimum template light curve

Take the 3 IR light curves into account simultaneously

Use the optical + IR data to determine dust properties

Believe no observation without a theory-- Eddington

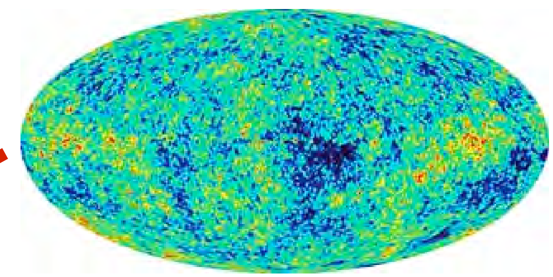


Dan Kasen (2006)

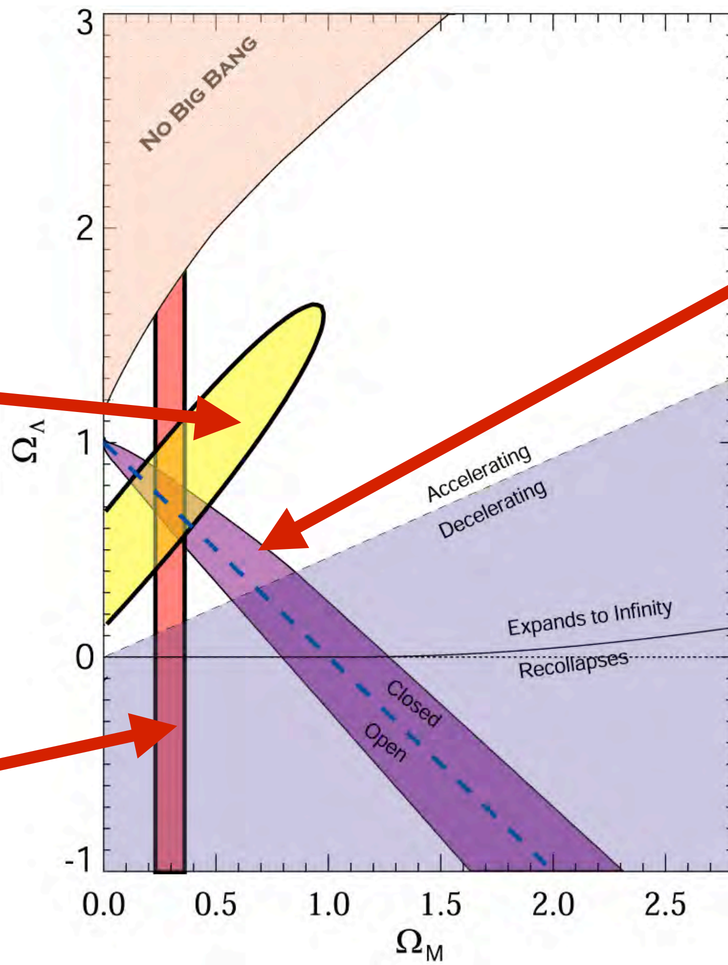
OK, Dark Energy is Real…

SNe Ia

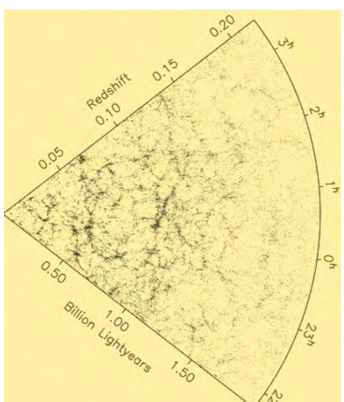
CMB(WMAP)

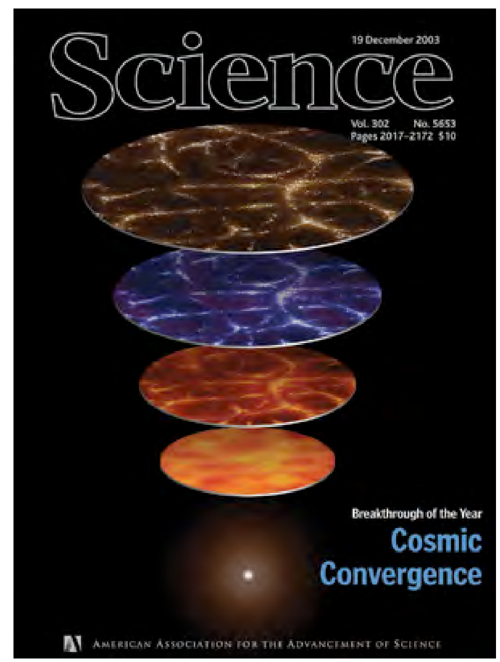


+ ISW, X-ray Clusters



LSS

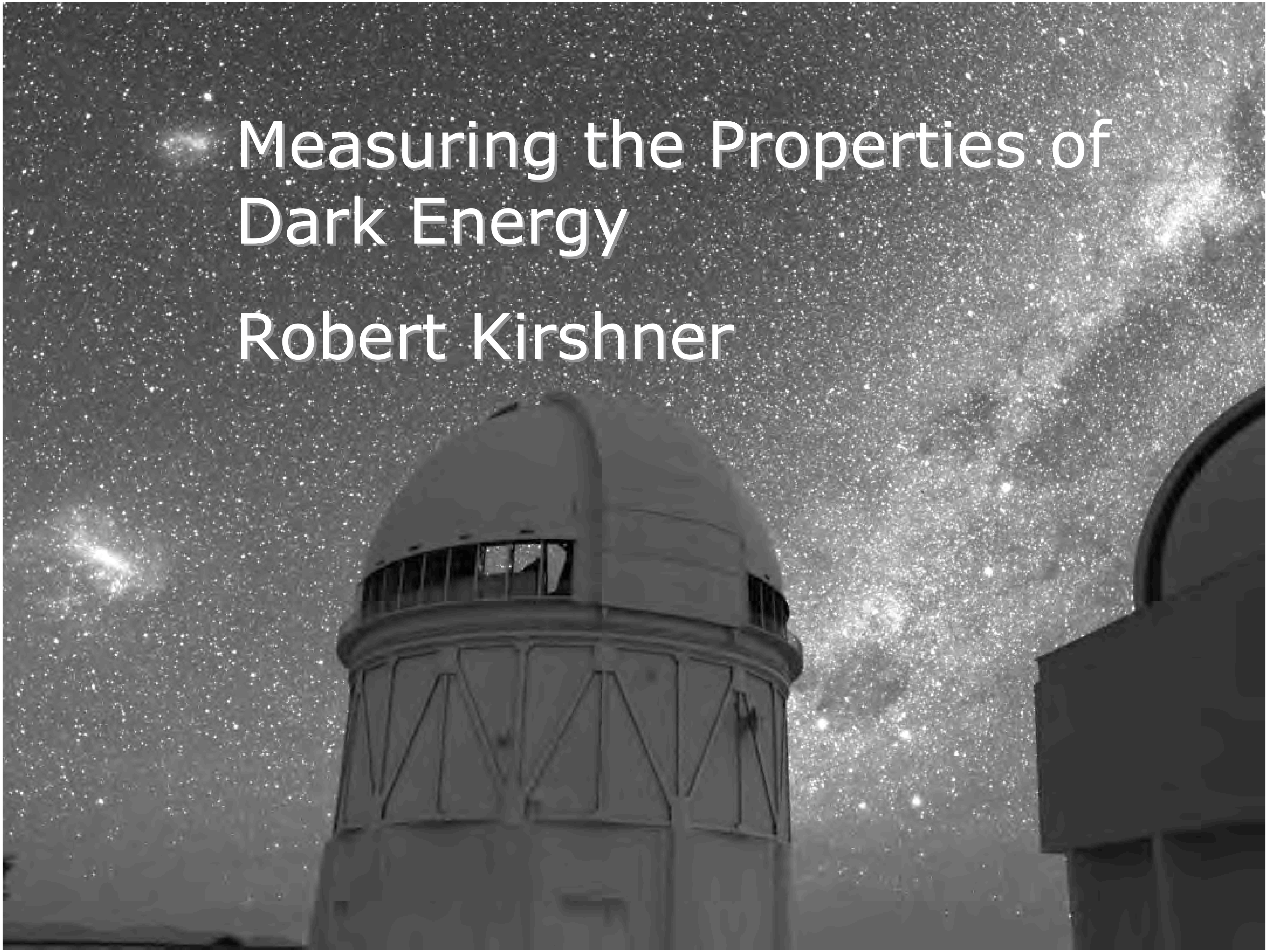




But what is it?

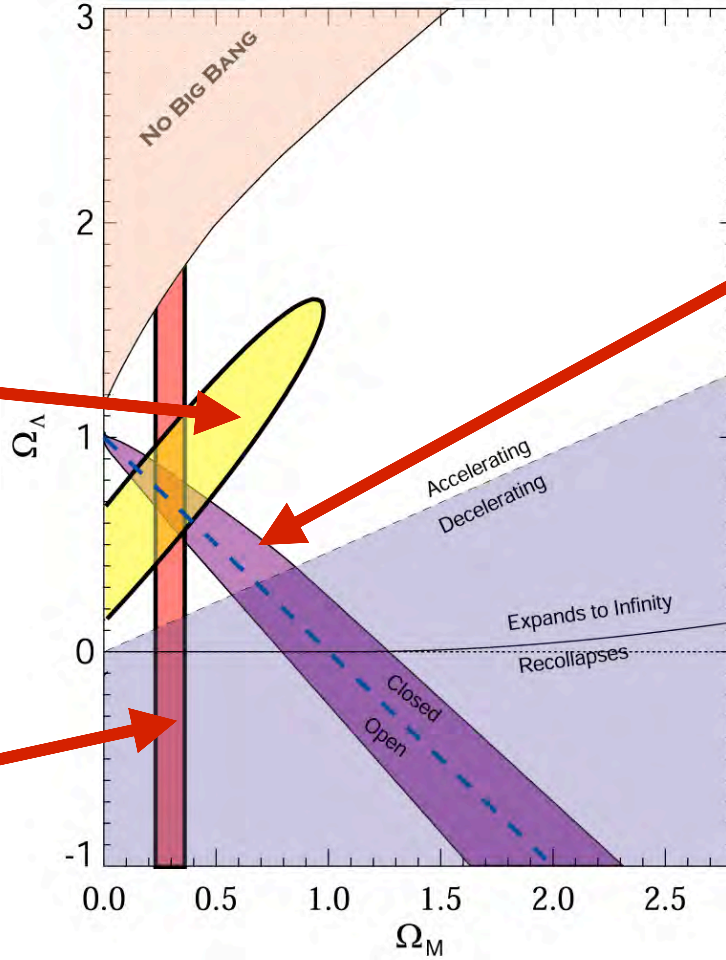
Measuring the Properties of Dark Energy

Robert Kirshner

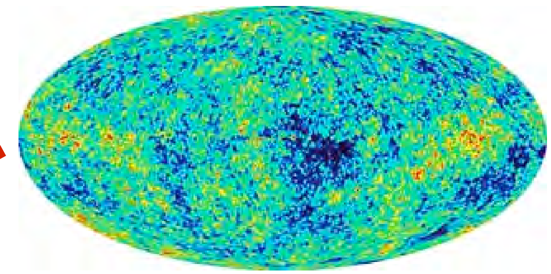


OK, Dark Energy is Real…

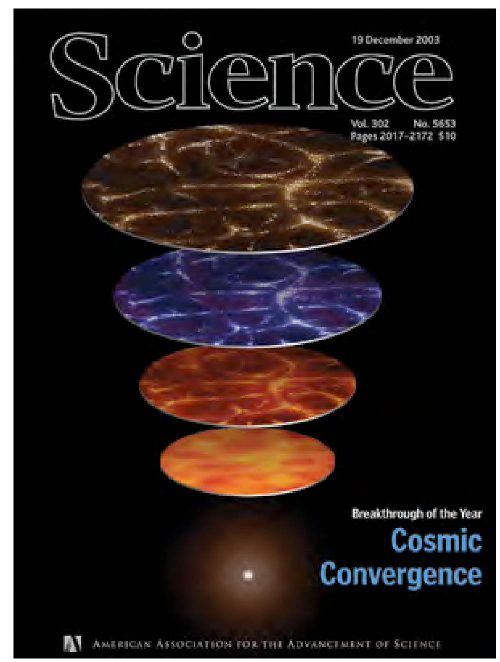
SNe Ia



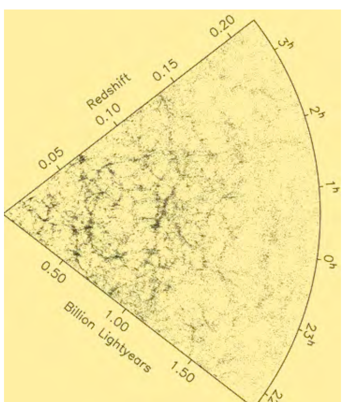
CMB(WMAP)



+ ISW, X-ray Clusters



LSS



But what is it?

Google ‘Dark Energy’!

“These specialized processes are also responsible for the very distinct odor of Dark Energy!”

Einstein's View on Λ

"An increase in the precision of data …will enable us in the future to fix its sign and determine its value." 1932

Thinking about dark energy:

a(t), the cosmic scale factor

- a″~ **-**($\rho + 3$P), so you expect **deceleration** when P is negligible or when P is positive.
- But, P does not have to be positive! The cosmological constant has negative P.
- If P<-1/3ρ, a″ >0-- you get **acceleration!**

The Equation of State: w

For dark energy

$\rho = R^{-3(1+w)}$; $w = P/\rho$

Regular matter: w= 0; $\rho = R^{-3}$

Radiation w=1/3, $\rho = R^{-4}$

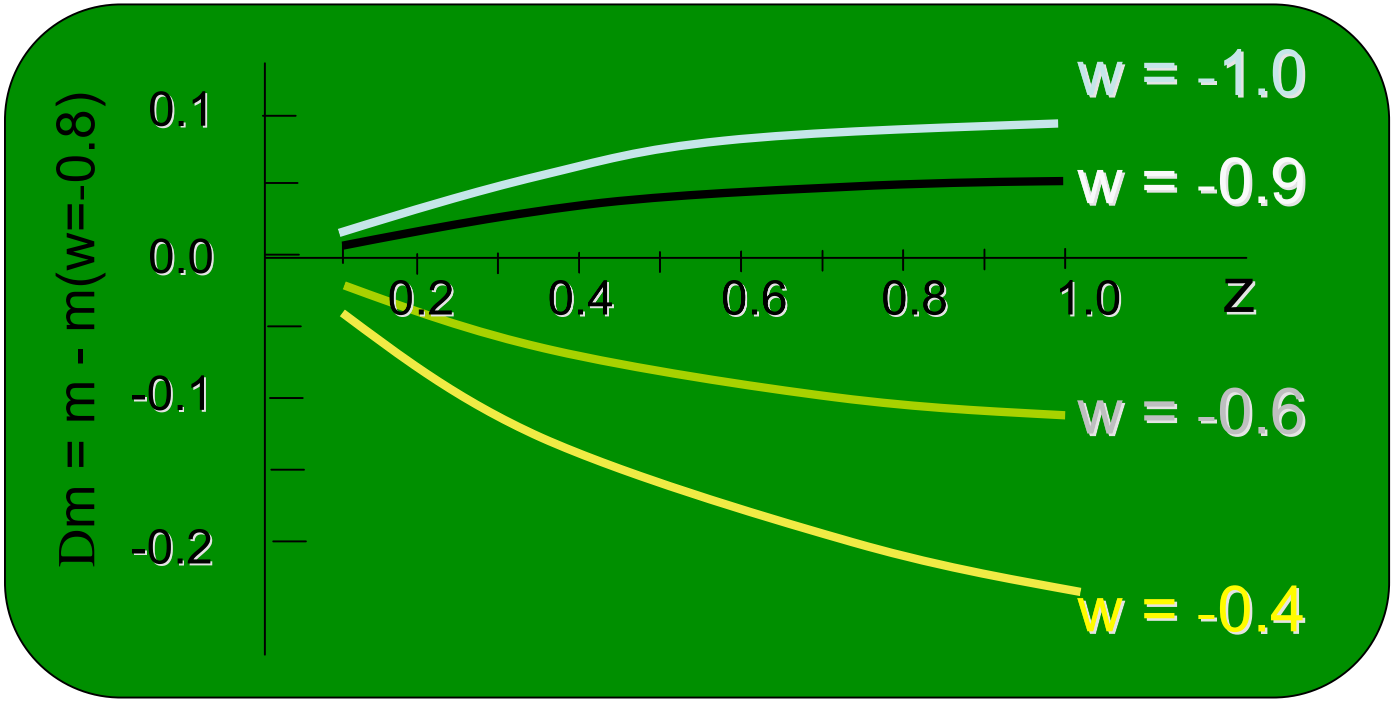
Cosmological Constant $\rho = R^0 \Rightarrow w = -1$

Other possiblities--

w(z) "quintessesnce"

Variations on GR (Dvali et al 2000)

Measuring the Equation of State



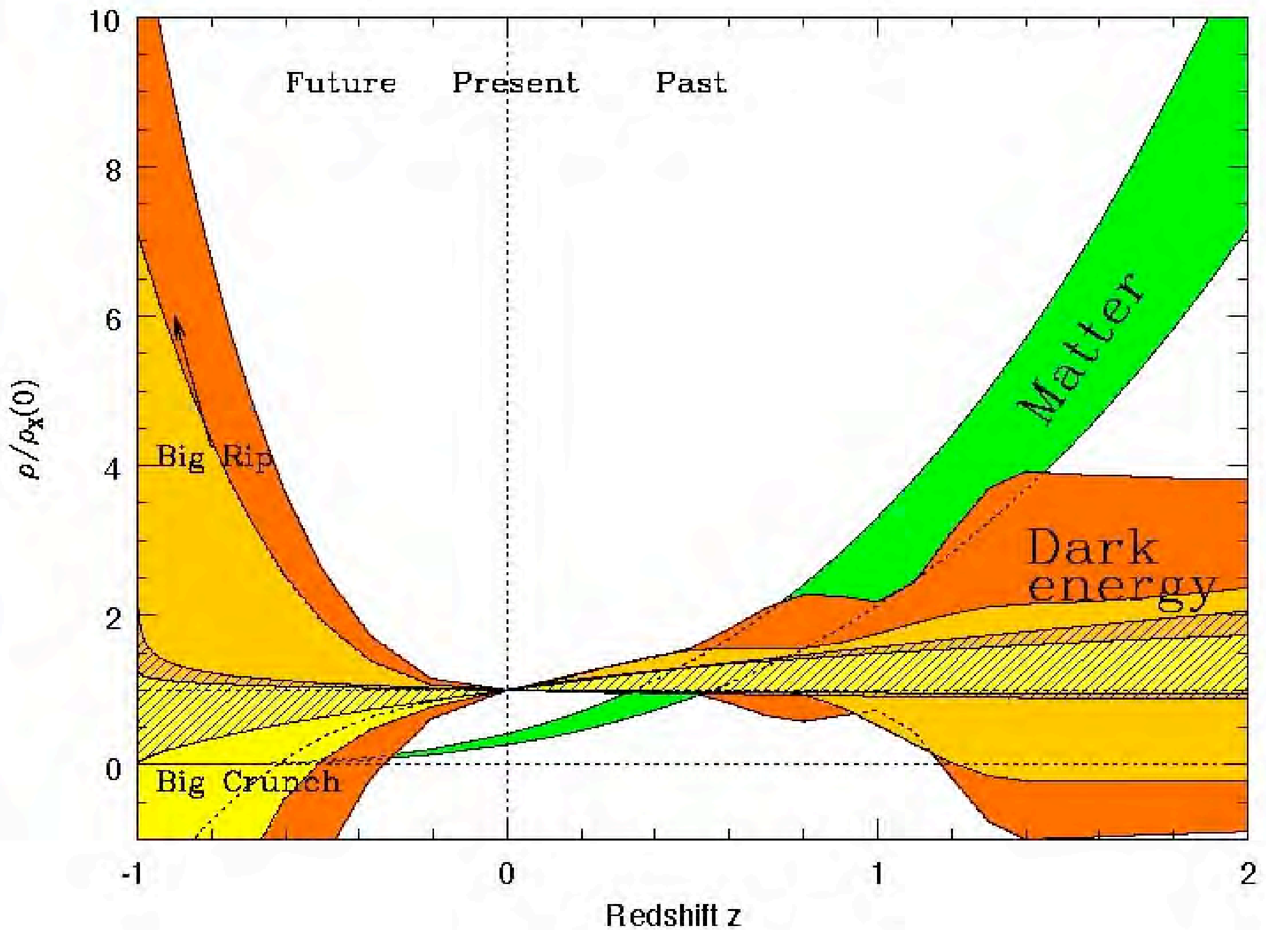
For $\Delta w \sim 0.1$, the difference in apparent SN brightness ~0.05 mag

SN scatter~0.15 mag, $0.15/N^{1/2}$

N~100 => 3σ

Most of the signal by z ~0.4

Past and Future of Dark Energy



Wang & Tegmark (2004)

The ESSENCE Survey

- Determine the properties of dark energy-- Λ or not?
- 6-year project on CTIO 4m telescope in Chile; 12 sq. deg.
- Half of the night, every 2nd night, for 3 months!
- Same-night detection of supernovae
- Goal is 200 SNeIa, $0.2<z<0.8$
- Data and SNIa made public in real time

Crete

Hardware for real-time reductions

Dual networks
- 1 Gb/sec compute link
- 100 Mb/s admin link

10 compute nodes
- 2 x 1.2 GHz CPUs
- 1 GB RAM each
- 300 GB local IDE disk

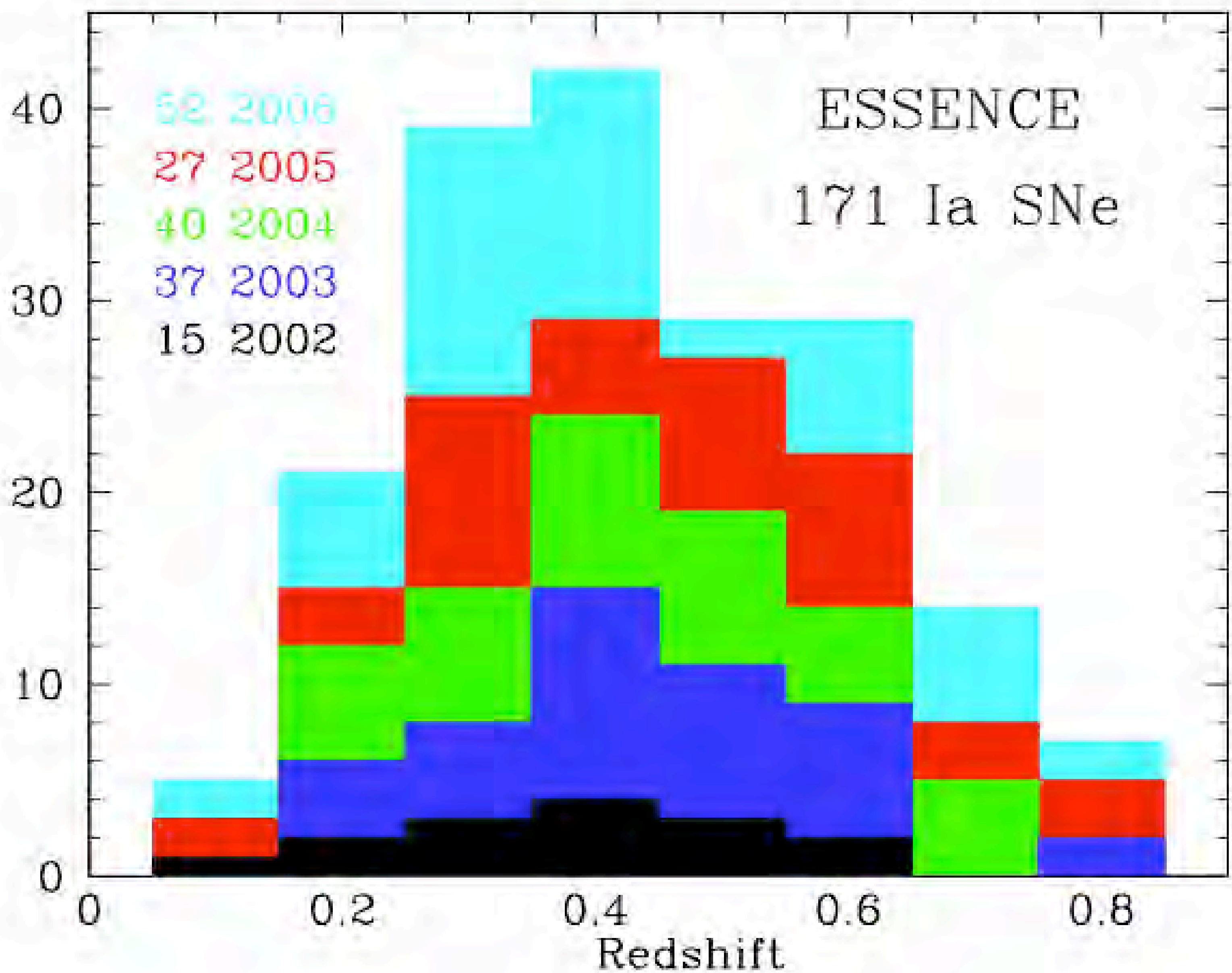
1 TB SCSI RAID disk array

2 TB IDE RAID disk array

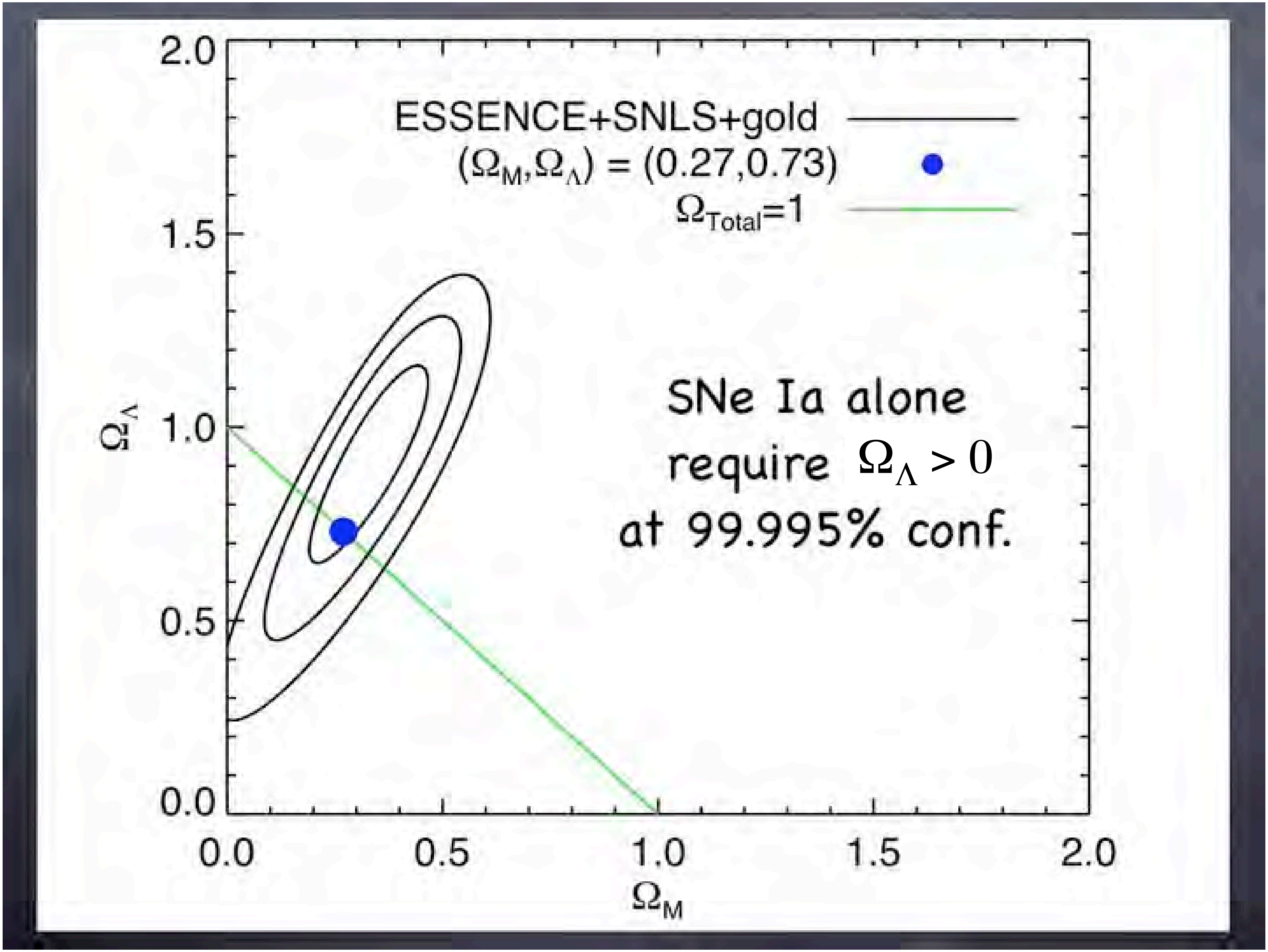
Crete

ESSENCE Survey Team

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



52 2006
27 2005
40 2004
37 2003
15 2002
ESSENCE
171 Ia SNe
40
30
20
10
0
0
0.2
0.4
0.6
0.8
Redshift

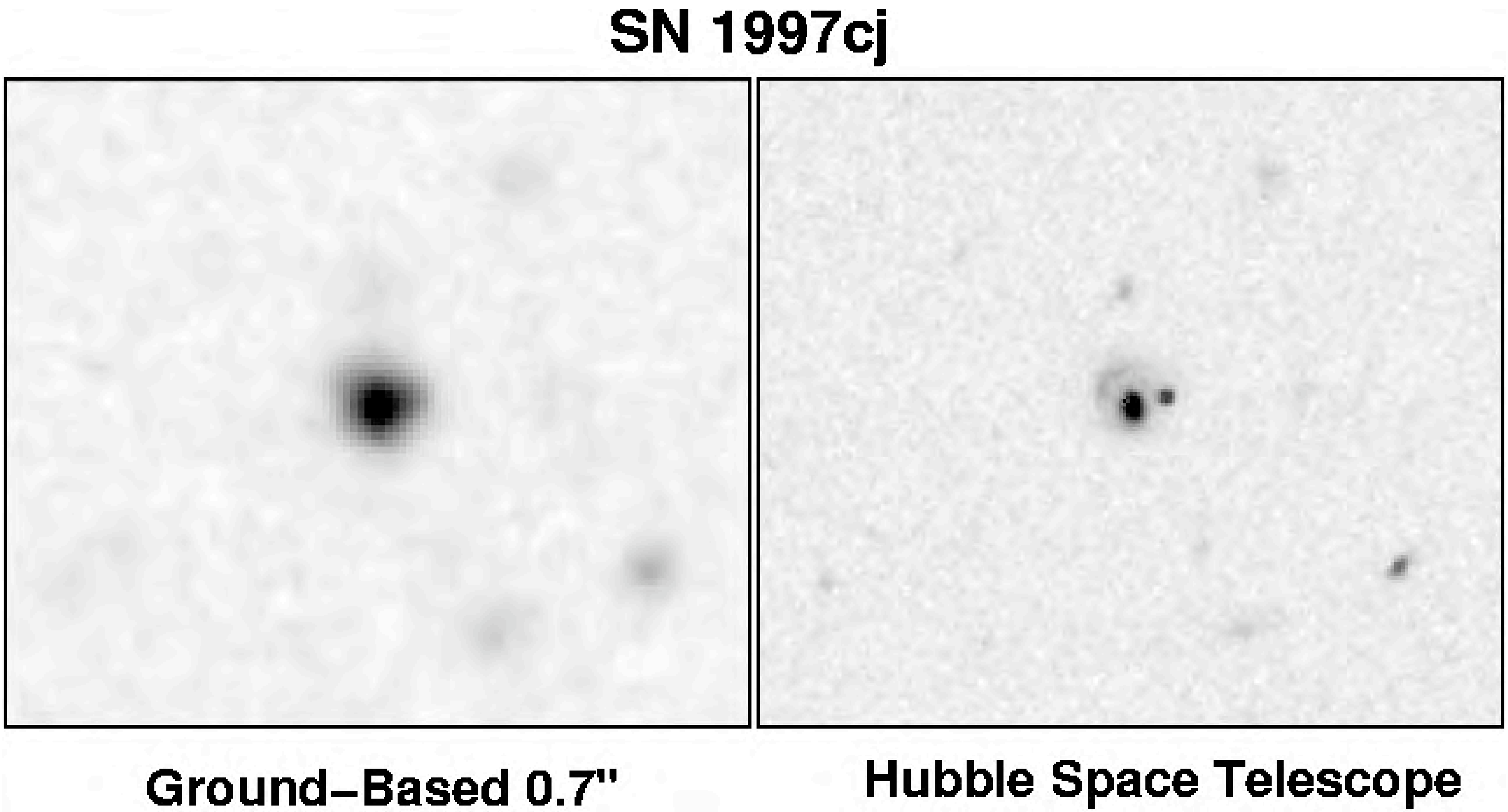


ESSENCE+SNLS+gold
$(\Omega_M,\Omega_\Lambda) = (0.27,0.73)$
$\Omega_{Total}=1$
SNe Ia alone
require $\Omega_\Lambda > 0$
at 99.995% conf.
Ω_Λ
Ω_M
0.0
0.5
1.0
1.5
2.0

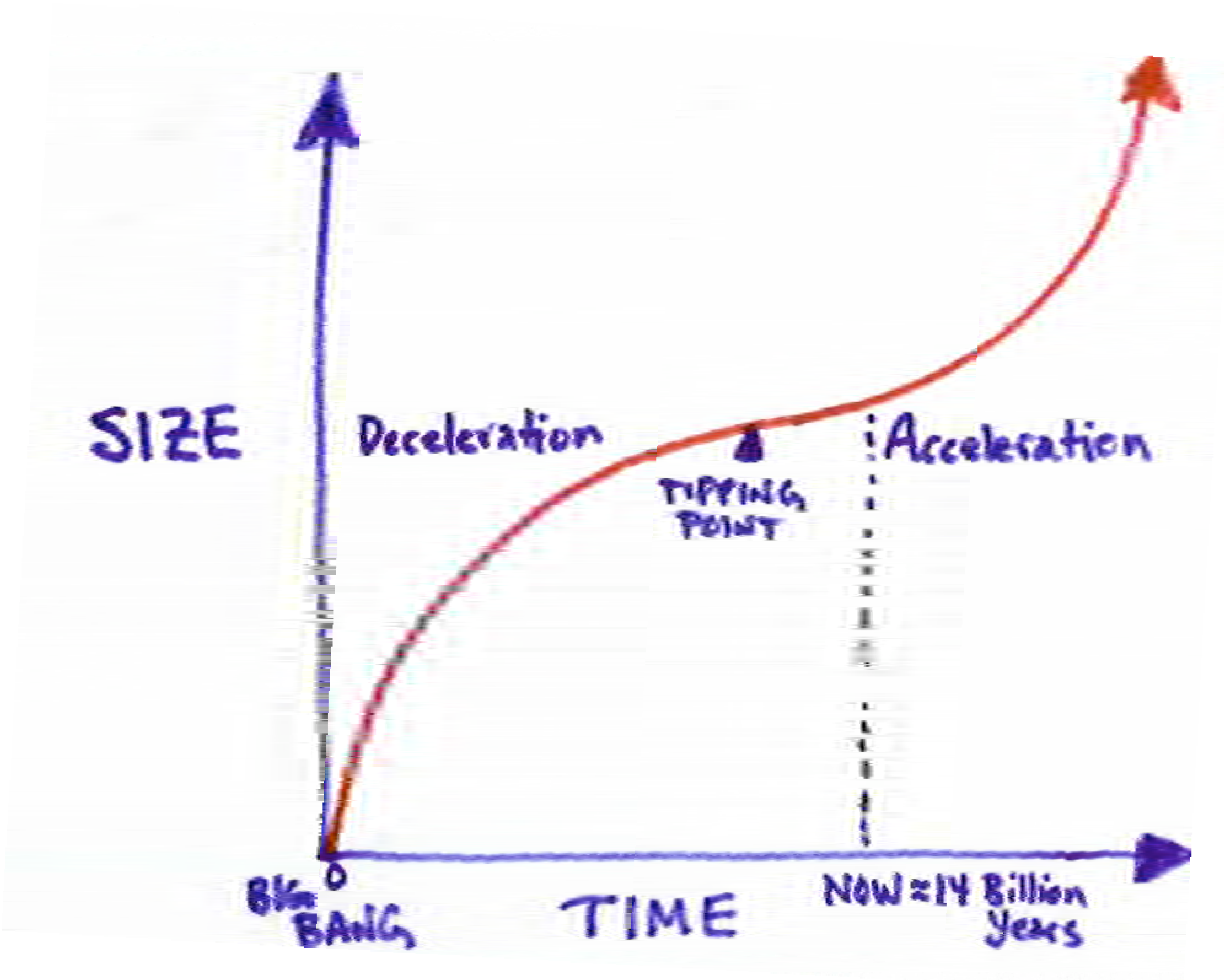
Searching for Supernovae with HST

Back to the age of ***de***celeration

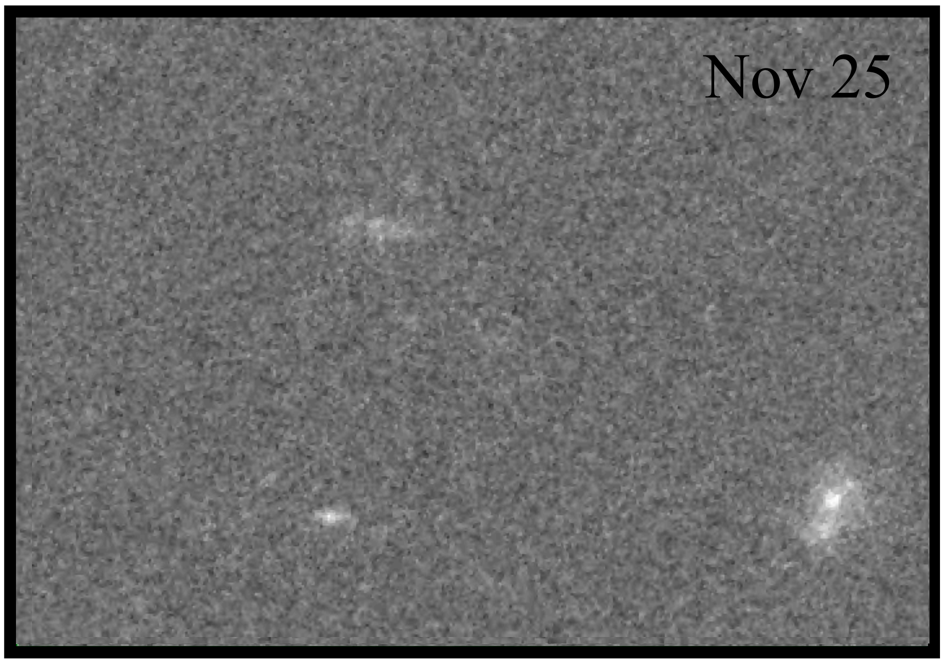
The sharper image!

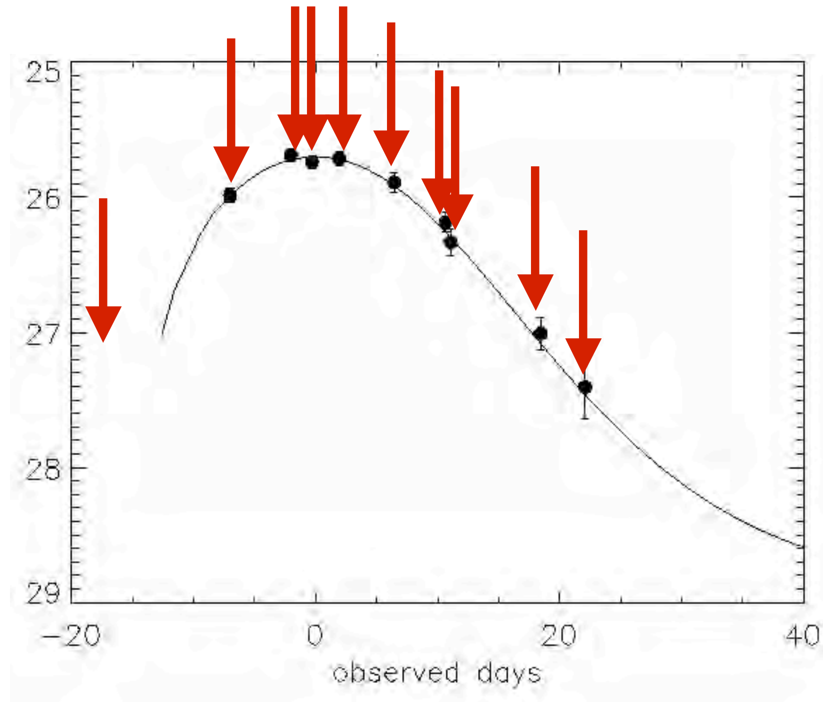


Expansion History of the Universe

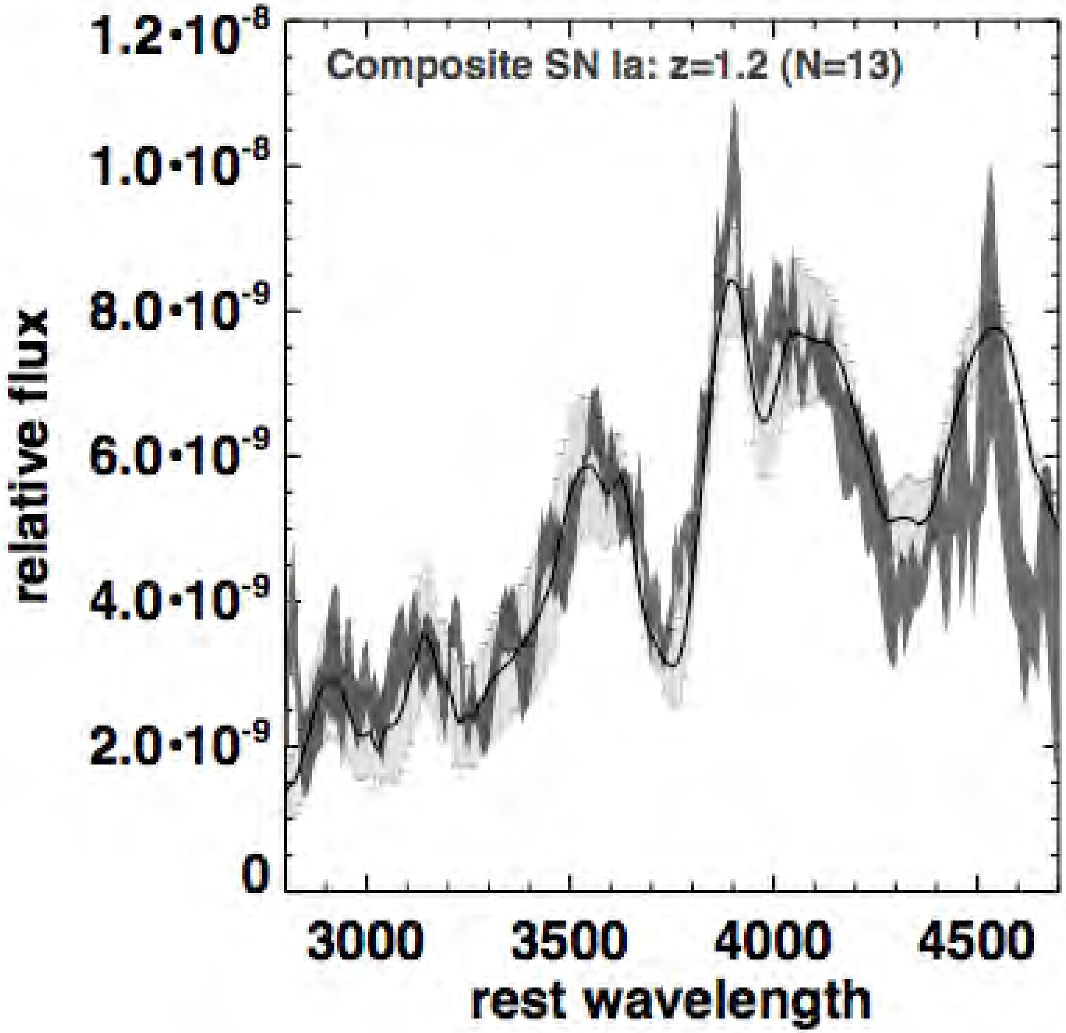


The Rise and Fall

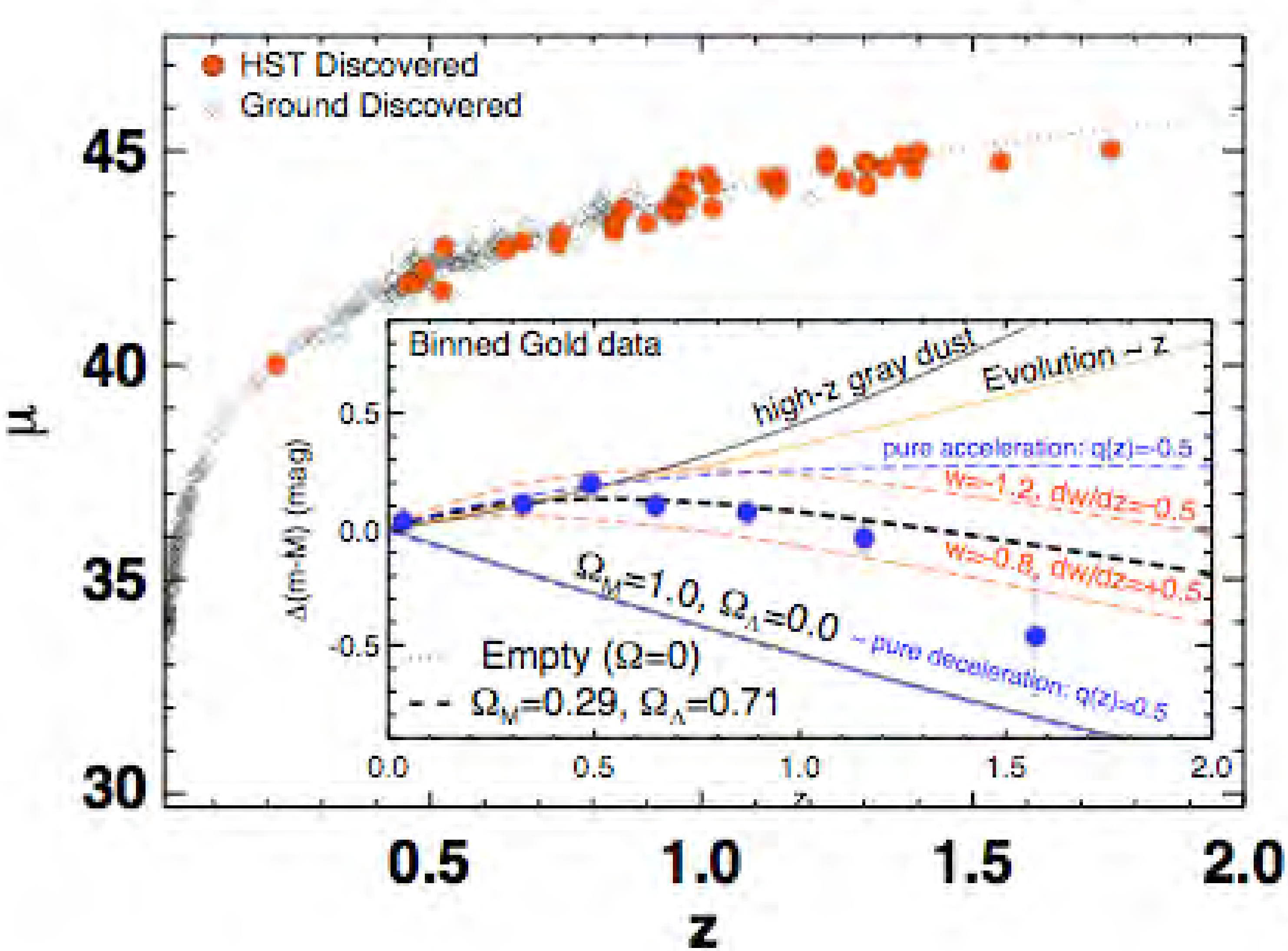




No difference between nearby and distant supernovae



Evidence for Slowing Down before Speeding Up from HST: Riess et al (2007)



Jι

A 'Cosmic Jerk' That Reversed the Universe

By DENNIS OVERBYE

CLEVELAND, Oct. 10 — Astronomers said on Friday that they had determined the time in cosmic history when a mysterious force, "dark energy," began to wrench the universe apart.

Five billion years ago, said Dr. Adam Riess, an astronomer at the Space Telescope Science Institute in Baltimore, the universe experienced a "cosmic jerk." Before then, Dr. Riess said, the combined gravity of the galaxies and everything else in the cosmos was resisting the expansion, slowing it down. Since the jerk, though, the universe has been speeding up.

The results were based on observations by a multinational team of astronomers who used the Hubble Space Telescope to search exploding stars known as Type 1a supernovas, reaching back in time three-quarters of the way to the Big Bang, in which the universe was born. The results should help quell remaining doubts that the expansion of the universe is really accelerating, a strange-sounding notion that has become a pillar of a new and widely accepted model of the universe as being full of mysterious dark matter and even more mysterious dark energy.

"This gives great confidence that we've been on the right track," said Dr. Riess, who announced his results at a meeting here on the Future of Cosmology sponsored by the Center for Education and Research in Cosmology and Astrophysics at Case Western Reserve University and the Kavli Institute.

Dr. Lawrence M. Krauss, an astrophysicist at Case Western, called the turnaround from slowing down to speeding up important confirmation.

"The big surprise," Dr. Krauss said, "would have been if it hadn't happened."

Dr. Joseph Lykken, a physicist at the Fermi National Accelerator Laboratory, known as Fermilab, in Batavia, Ill., said, "I could go home now and be happy."

Knowing how and when the jerk occurred, astronomers said, was an important step in figuring out just what the dark energy is.

"He gave us information about when the universe hit the gas pedal," said Dr. Michael S. Turner, a cosmologist at the University of Chicago who is director of mathematics and

Marty Katz for The New York Times

Dr. Adam Riess, who reported yesterday on the speeding and expanding universe, at the Space Telescope Science Institute in Baltimore.

The goal was to measure how much the universe was being slowed by the collective gravity of the cosmos and determine whether the universe would go on forever or recollapse in a "Big Crunch" on one distant day.

The groups found, though, that nearby supernovas looked dimmer than they should, implying that the universe was growing faster than expected, speeding up, under the influence of some form of antigravity — perhaps embedded in the fabric of spacetime itself.

The results were buttressed by studies of radiation left over from the Big Bang that suggested that two-thirds of the mass-energy of the universe resided in this dark energy.

"But there was always a nagging doubt," Dr. Riess told his colleagues.

'Dark energy' made the universe speed up 5 billion years ago.

If that was the case, supernovas even

collaborators found Hubble observations of a supernova 10 billion years in the past. It proved to be anomalously bright, lending credence to the idea that a dark energy had taken over some time in between.

"But a single object is just not robust enough," he said. For the last year, he and his colleagues have used the Hubble in collaboration with a large galaxy survey known as Goods to find distant supernovae.

"We found lots of weapons of mass destruction," he said, showing Hubble pictures of some exploding with the brilliance of small galaxies 8 billion to 10 billion light-years away.

More important, they were brighter than expected. When he plotted their velocities against distance, or time in the past, Dr. Riess found that the universe had to have changed direction, from slowing to speeding up, over a period of time five billion years ago, the so-called cosmic jerk, using the technical term for a change in acceleration.

"It's great to see it," Dr. Riess said.

In Dr. Lykken's words, and as borne out by discussions at the meeting here, "theorists don't have a clue" about the identity of the dark energy that is so important.

Evidence for a change in cosmic acceleration: **cosmic jerk**

Future:

Acceleration without end?

Big rip?

2008: HST Servicing
WFC 3, COS

S103E5204 1999:12:22 16:32:29

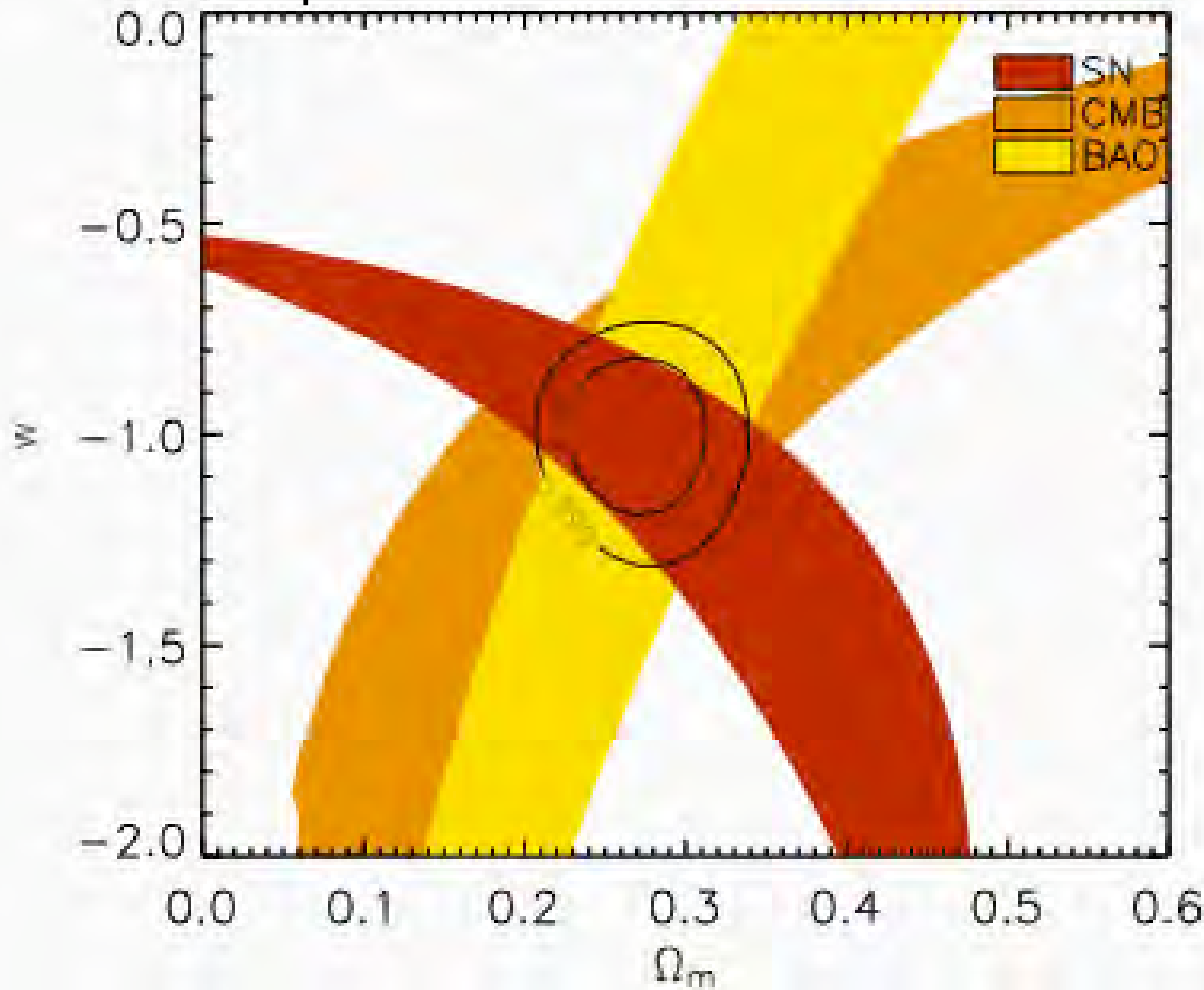
Davis et al. astro-ph/0701510

Testing Models with Baysean Information Criteria

TABLE 1
SUMMARY OF MODELS

Model	Abbrev.[a]	Parameters[b]	Section
Flat cosmo. const.	FΛ	Ω_m	4.1.1
Cosmological const.	Λ	Ω_m, Ω_Λ	4.1.2
Flat constant w	Fw	Ω_m, w	4.1.3
Constant w	w	Ω_m, Ω_k, w	4.1.4
Flat w(a)	Fwa	Ω_m, w_0, w_a	4.2.1
DGP	DGP	Ω_k, Ω_{r_c}	4.3.1
Flat DGP	FDGP	Ω_{r_c}	4.3.2
Cardassian	Ca	Ω_m, q, n	4.4
Flat Gen. Chaplygin	FGCh	A, α	4.5.1
Gen. Chaplygin	GCh	Ω_k, A, α	4.5.1
Flat Chaplygin	FCh	A	4.5.2

Nothing more complicated than the cosmological constant is justified by the present data



J

And some things just don't fit.

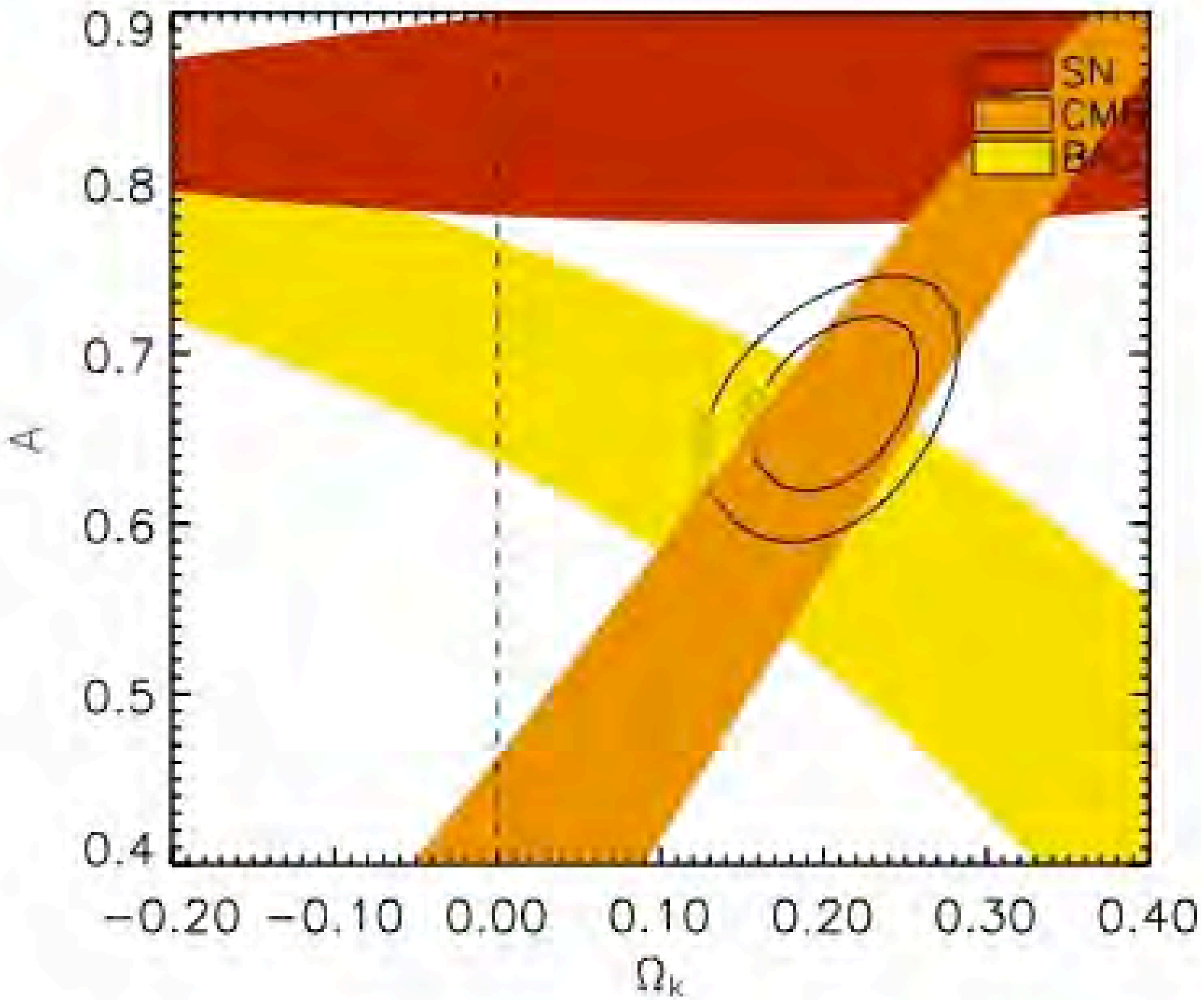
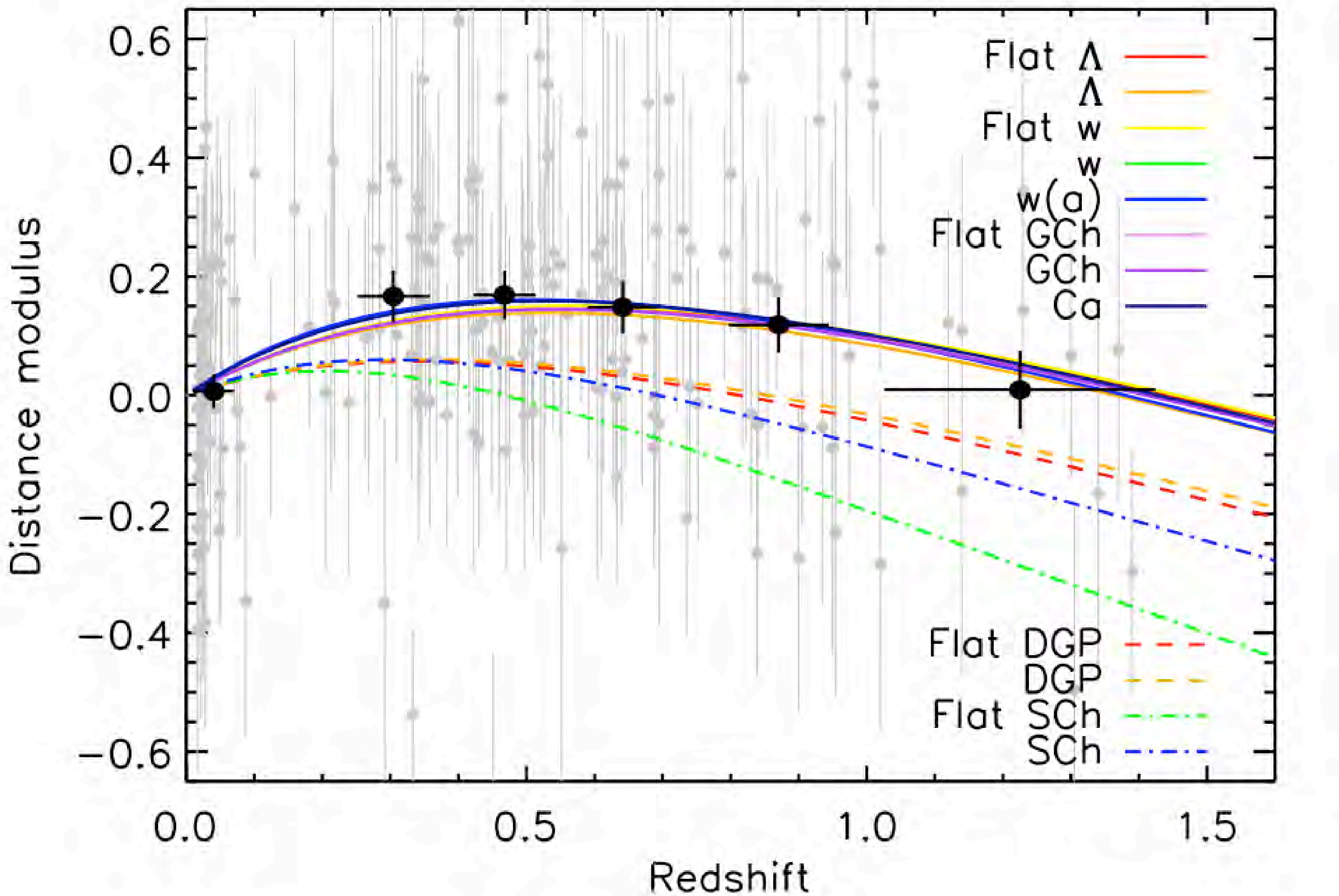
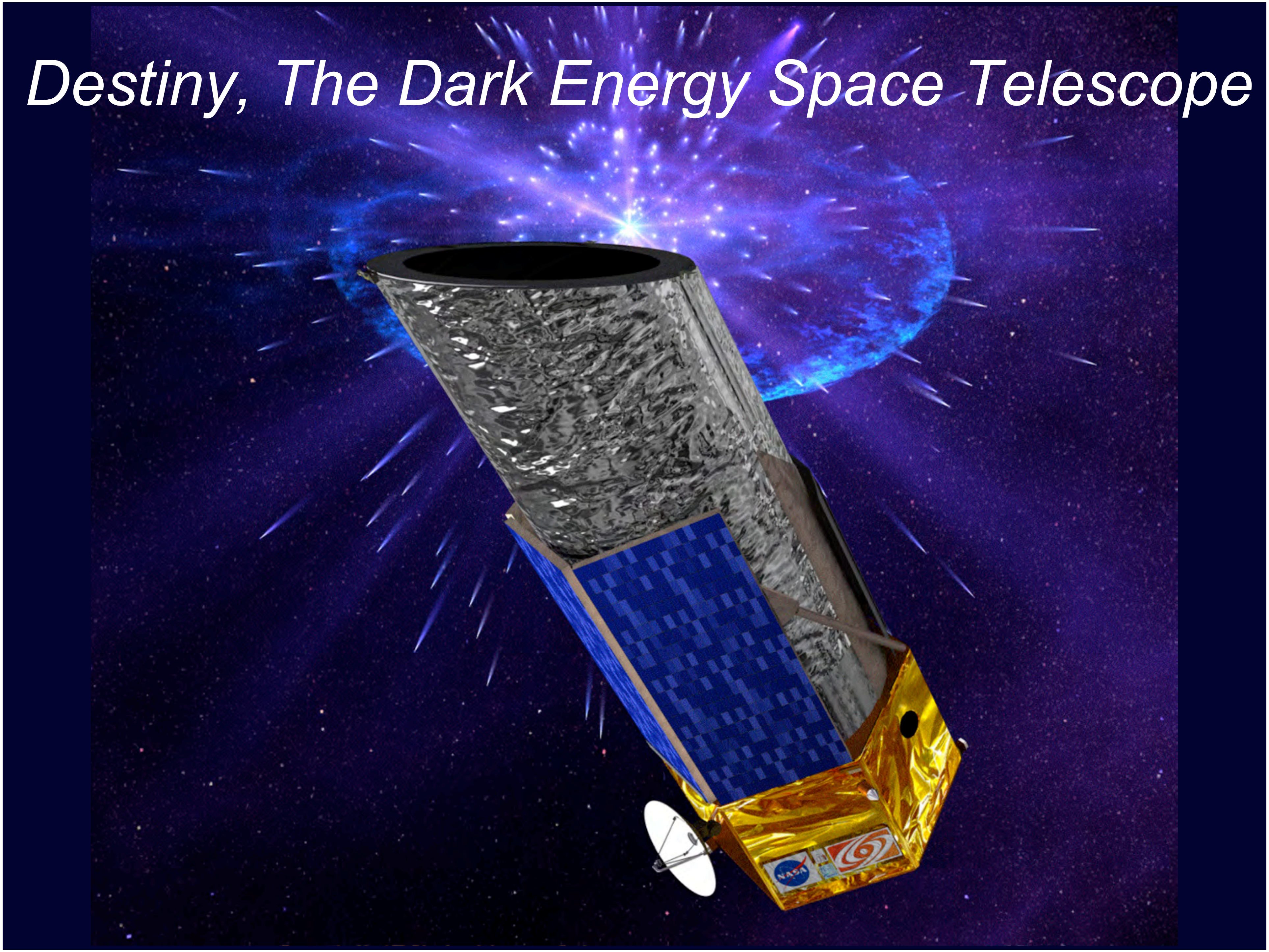


FIG. 6.— Standard Chaplygin gas (Sect 4.5.2). The dashed line shows the flat version of the model. Clearly this model is a very poor fit to the data. The subtleties of information criteria are not required to determine that this model is disfavored.



And some things just don't fit, no matter how you turn the knobs.

Destiny, The Dark Energy Space Telescope

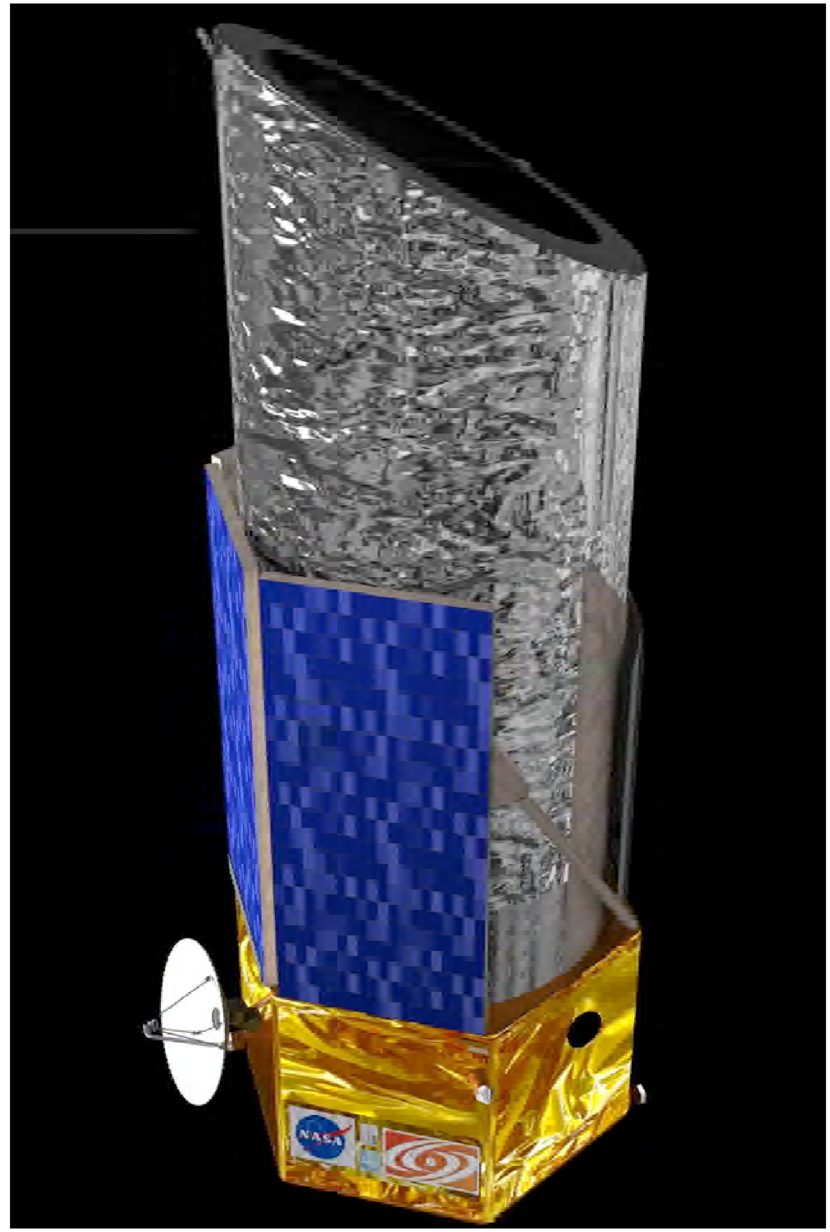


Science Goals

- Determine the expansion history of the Universe to 1% accuracy in $\Delta z = 0.1$ bins over the last 10^{10} yr.
- Constrain Dark Energy equation of state parameters w_0 to 0.05 and w_a to 0.20.

DESTINY: Tod Lauer (PI)

- 1.65m telescope at L2
- H2RG Infrared Array
- SNIa survey over > $3°^2$
- WL survey $1000°^2$
- NIR imaging $0.85\ \mu m < \lambda < 1.7\ \mu m$
- Imaging Spectrograph with $\lambda / \Delta\lambda \sim 75$



Ideas for DESTINY

- Do in space only what must be done in space - use the ground based observations of 2012.
- All spectra all the time. Complete spectro-photometric time series on all SN events.
- Highly automated survey - no time critical operations.

Last Month's "World Sample" from Kowalski et al.

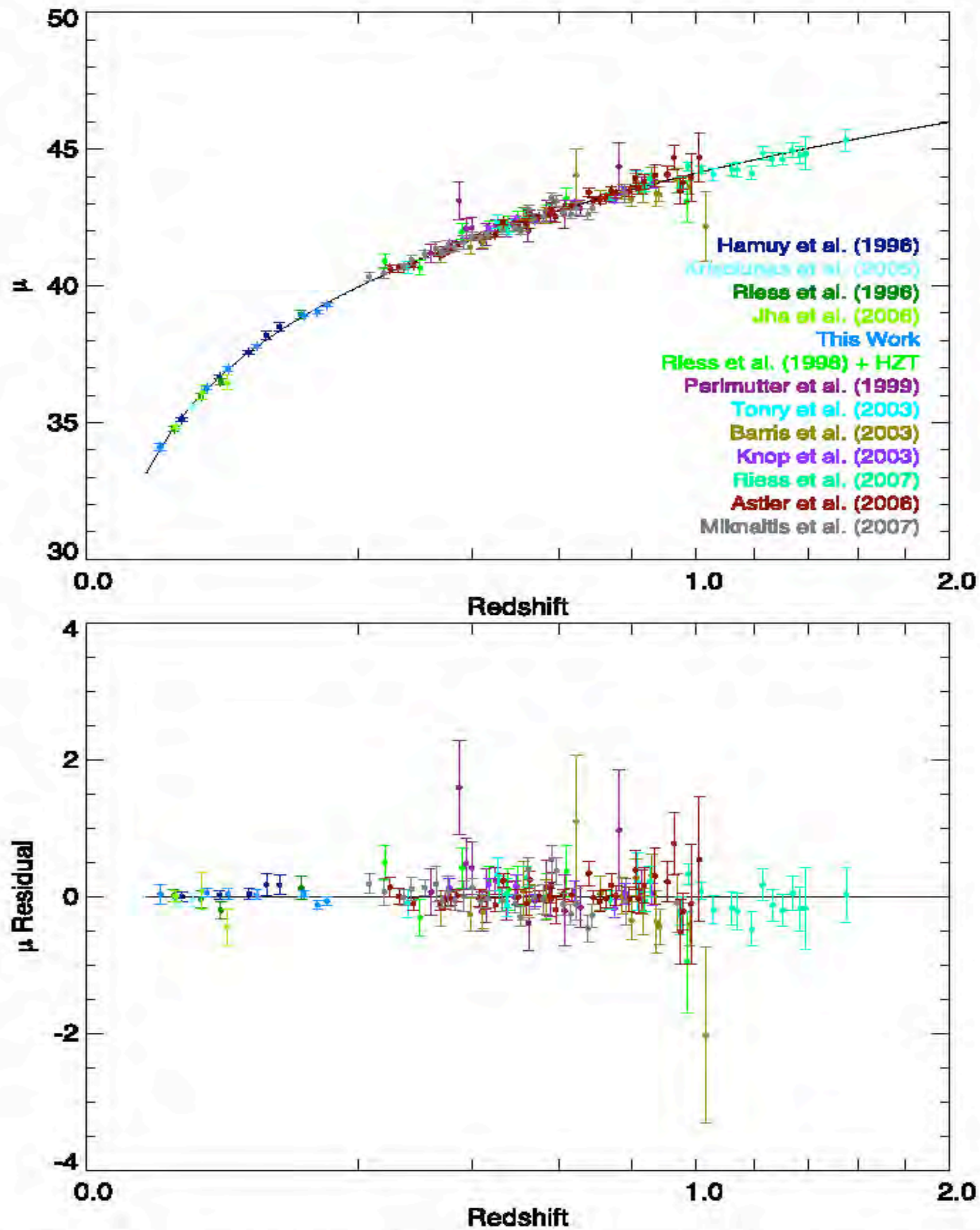
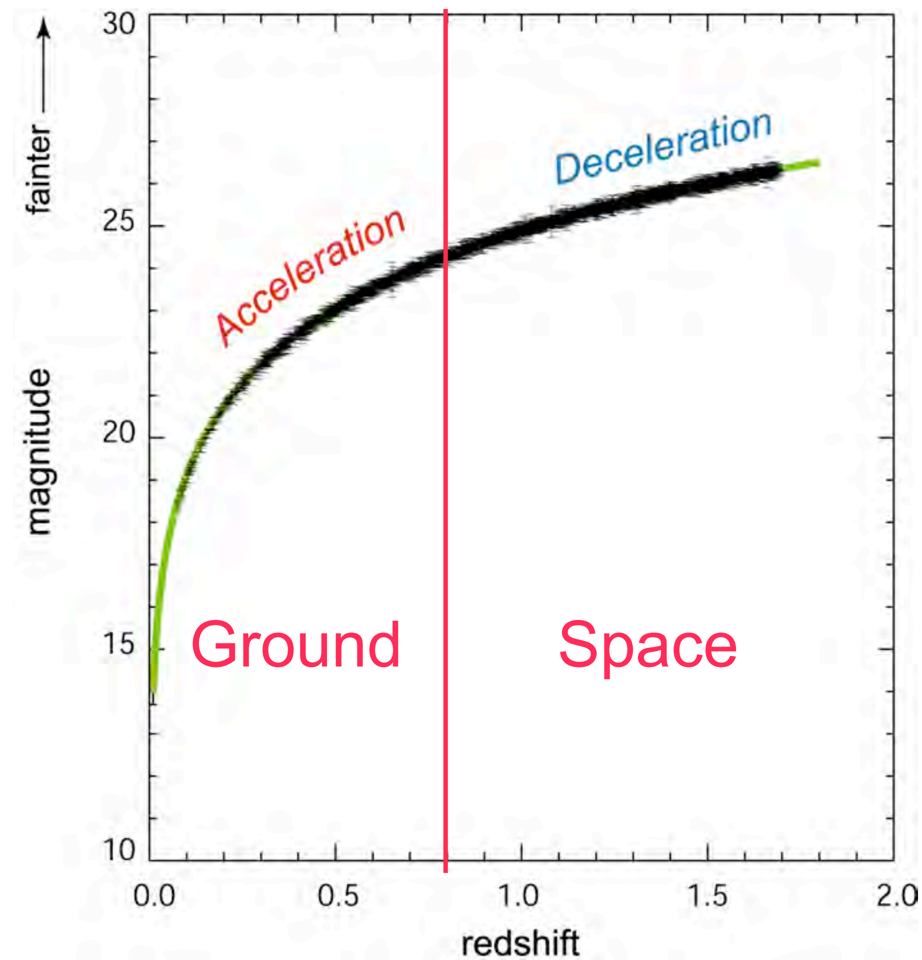


FIG. 10.— Top: Binned Hubble diagram (bin-size $\Delta z = 0.01$). Bottom: Binned residuals from the best fitting cosmology.

July 3, 2008

Why go to high redshifts?

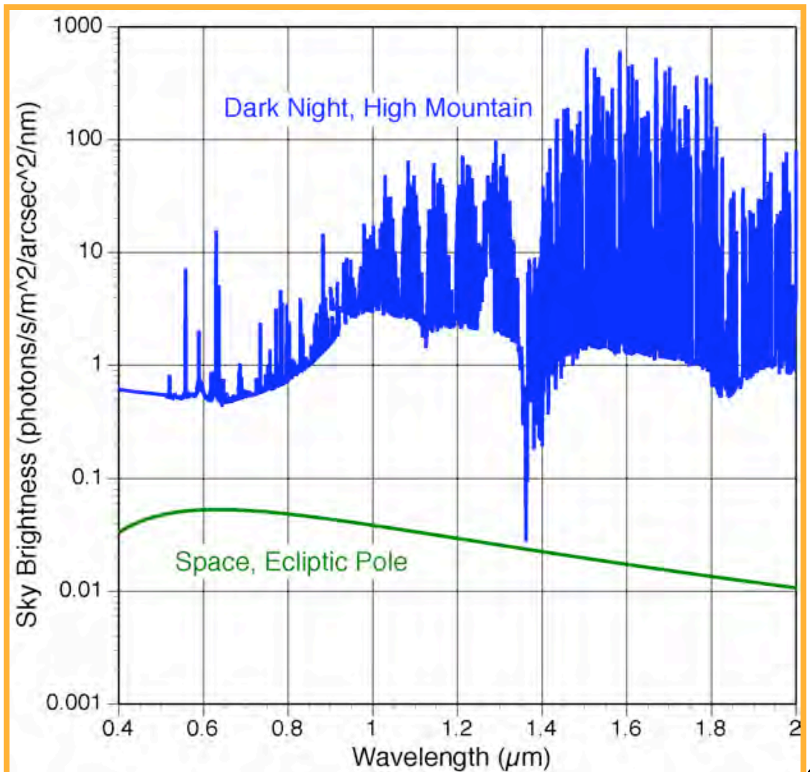
Dark energy can be detected at low redshift, but precise constraints on the DE equation of state requires measurements in both the acceleration and deceleration epochs.

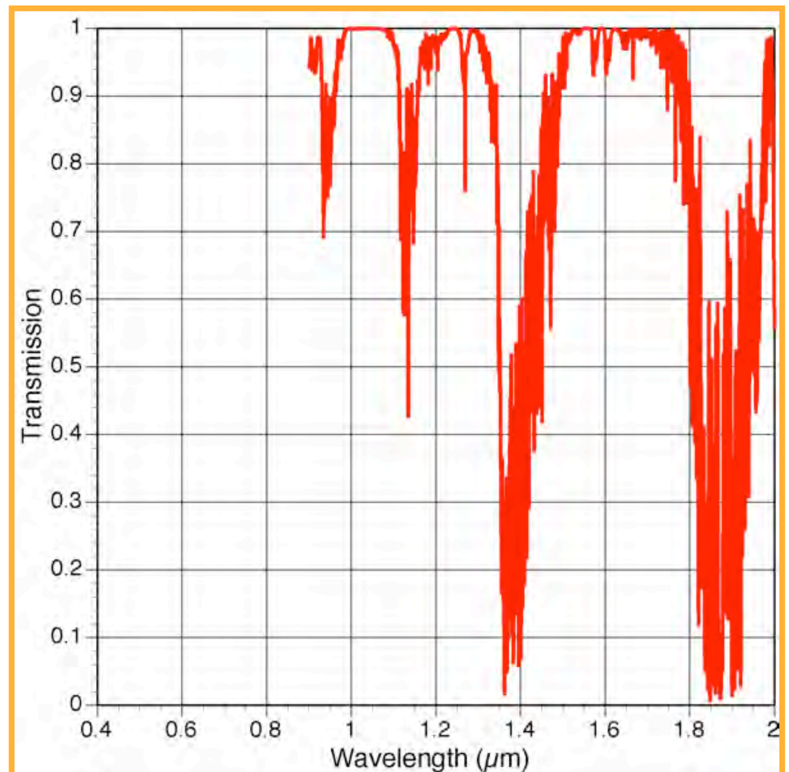


Only in space

Crucial near-infrared observations at the required photometric accuracy are impossible from the ground

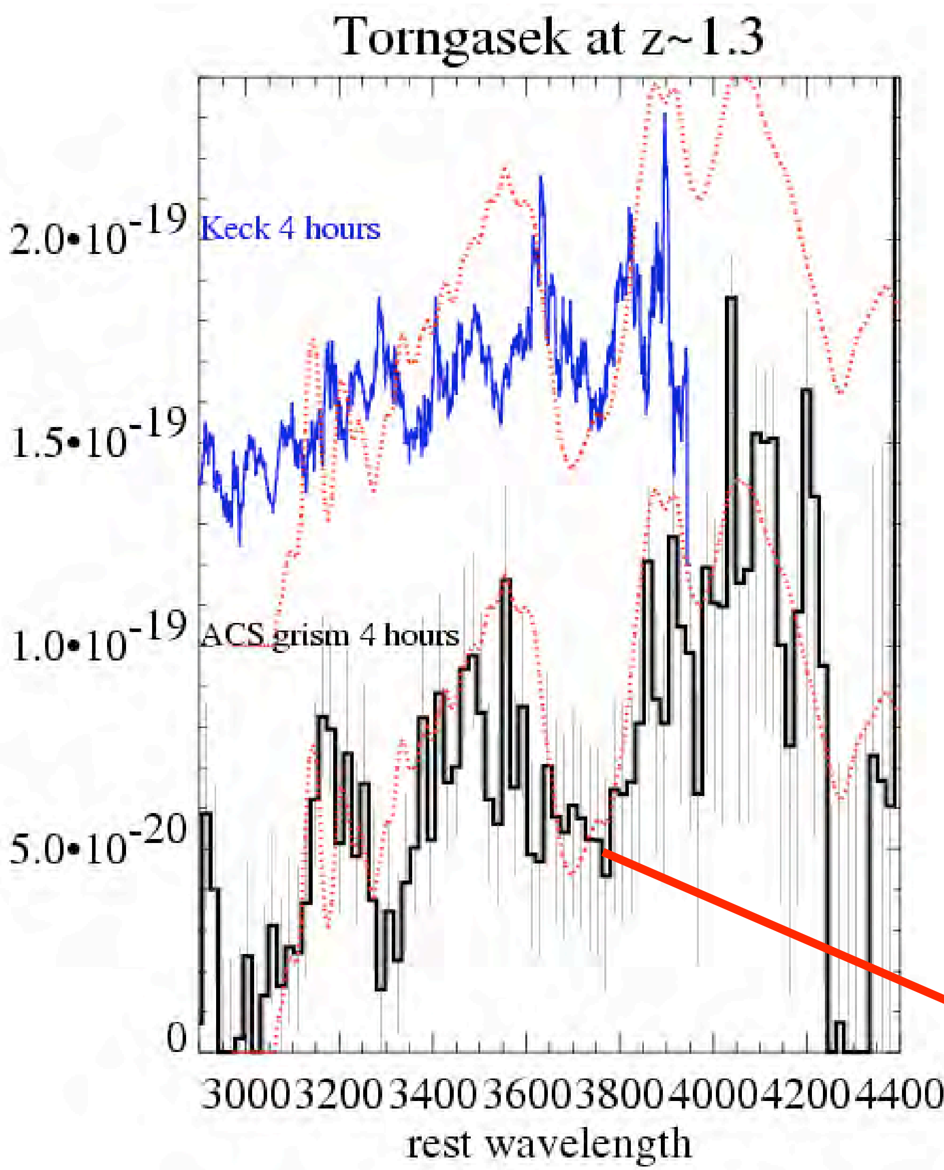
- Sky is very bright in NIR: >100x brighter than in visible
- Sky is not transparent in NIR: absorption due to water is very strong and extremely variable

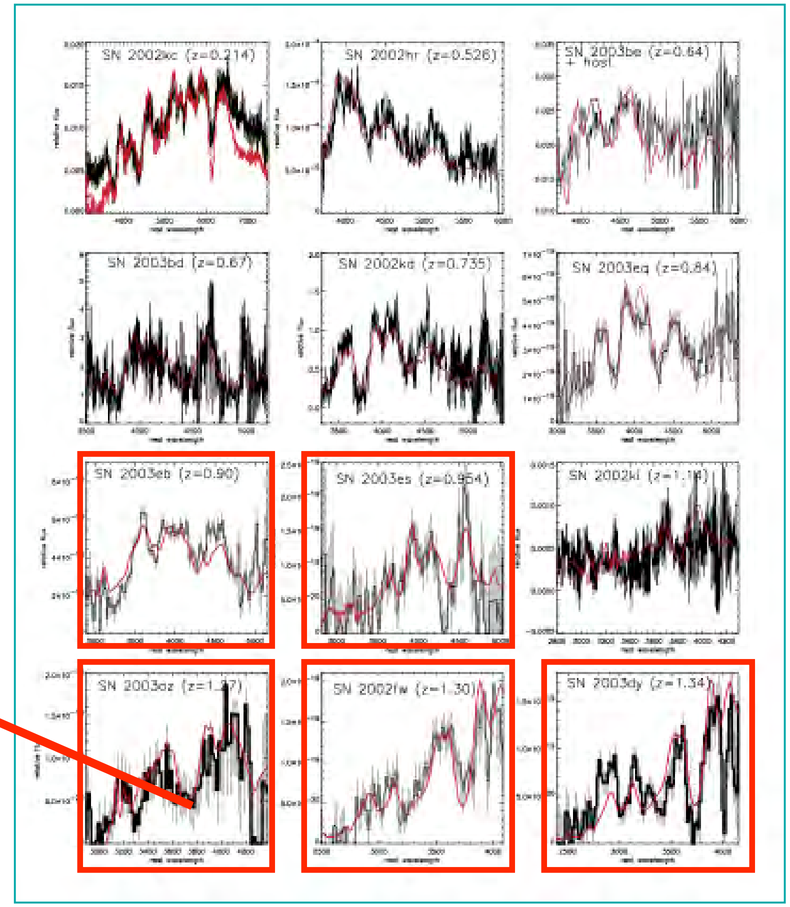




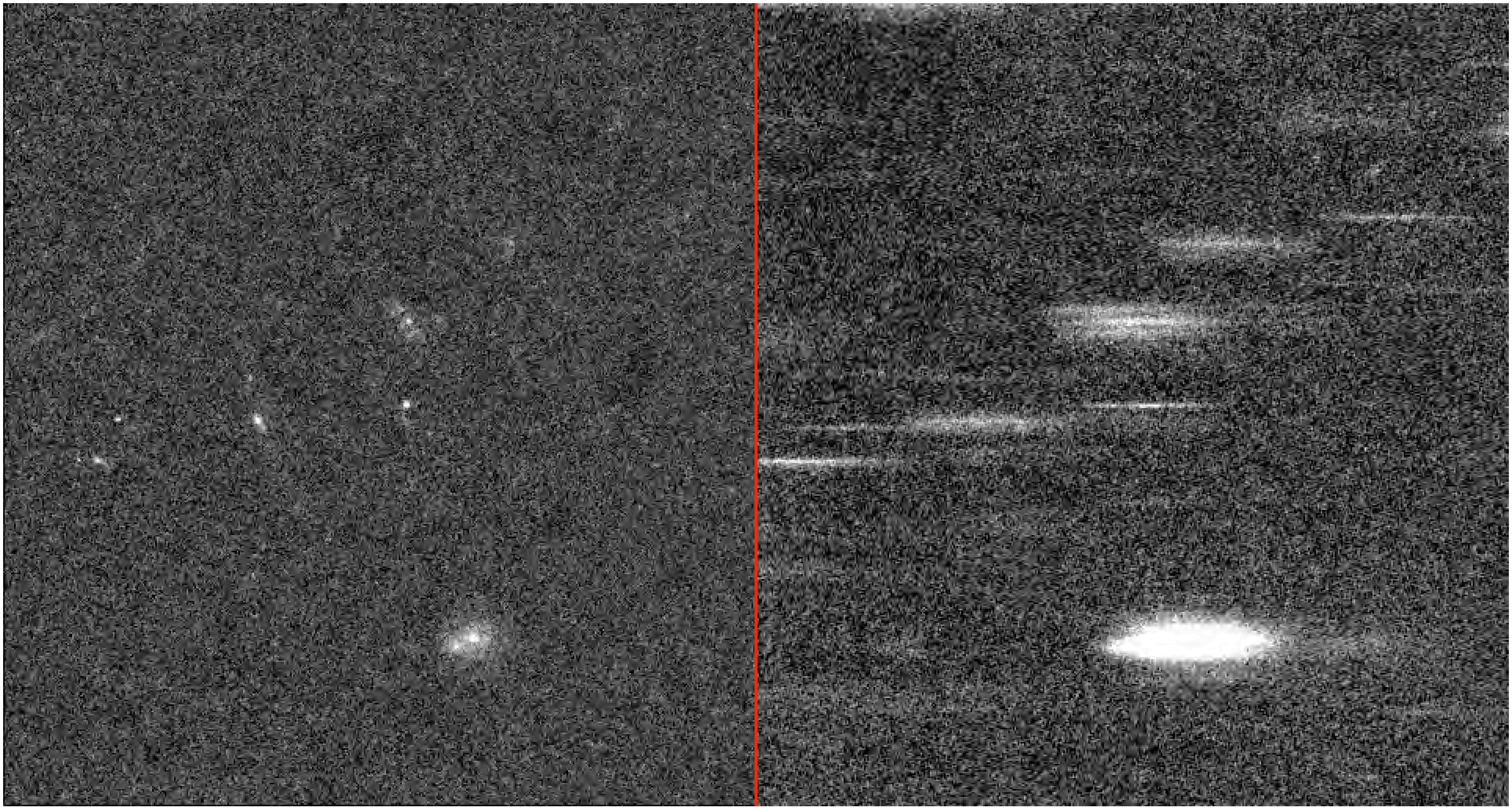
Data from Gemini Observatory & ATRAN: Lord (1992)

Riess et al. (2004) obtained ACS grism spectra of z ~ 1.3 SN Ia



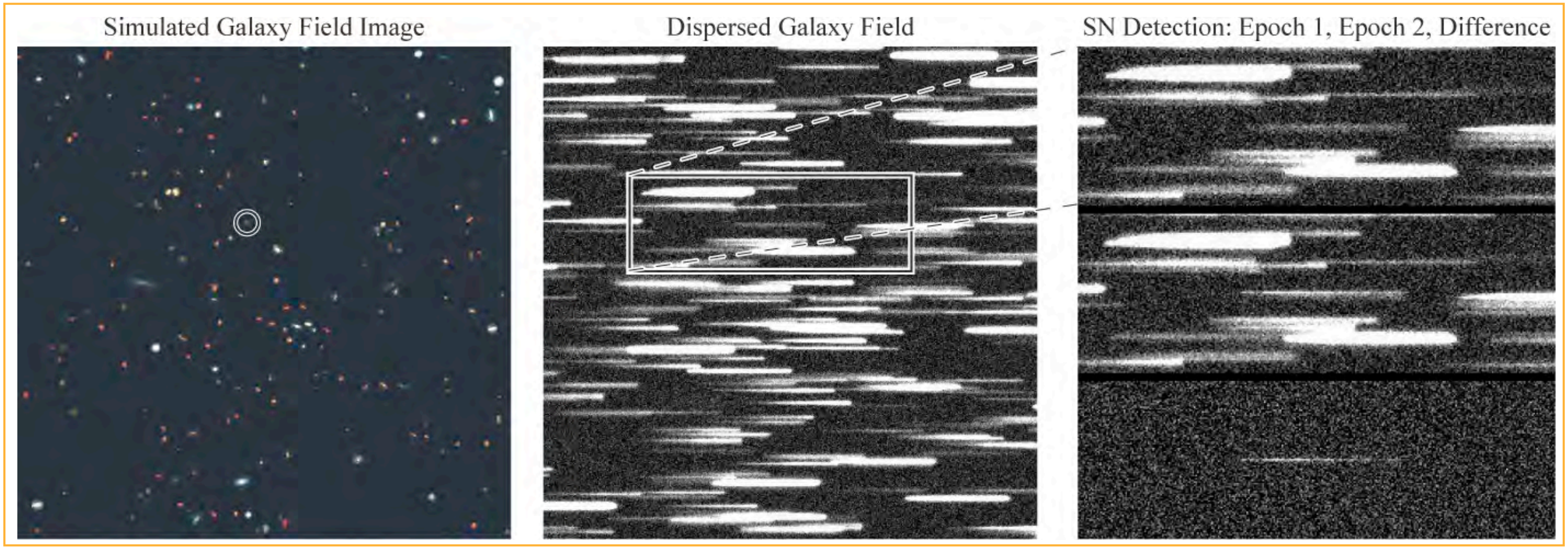


ACS Grism Images of SN2002FW (z = 1.30)



Riess et al. (2004)

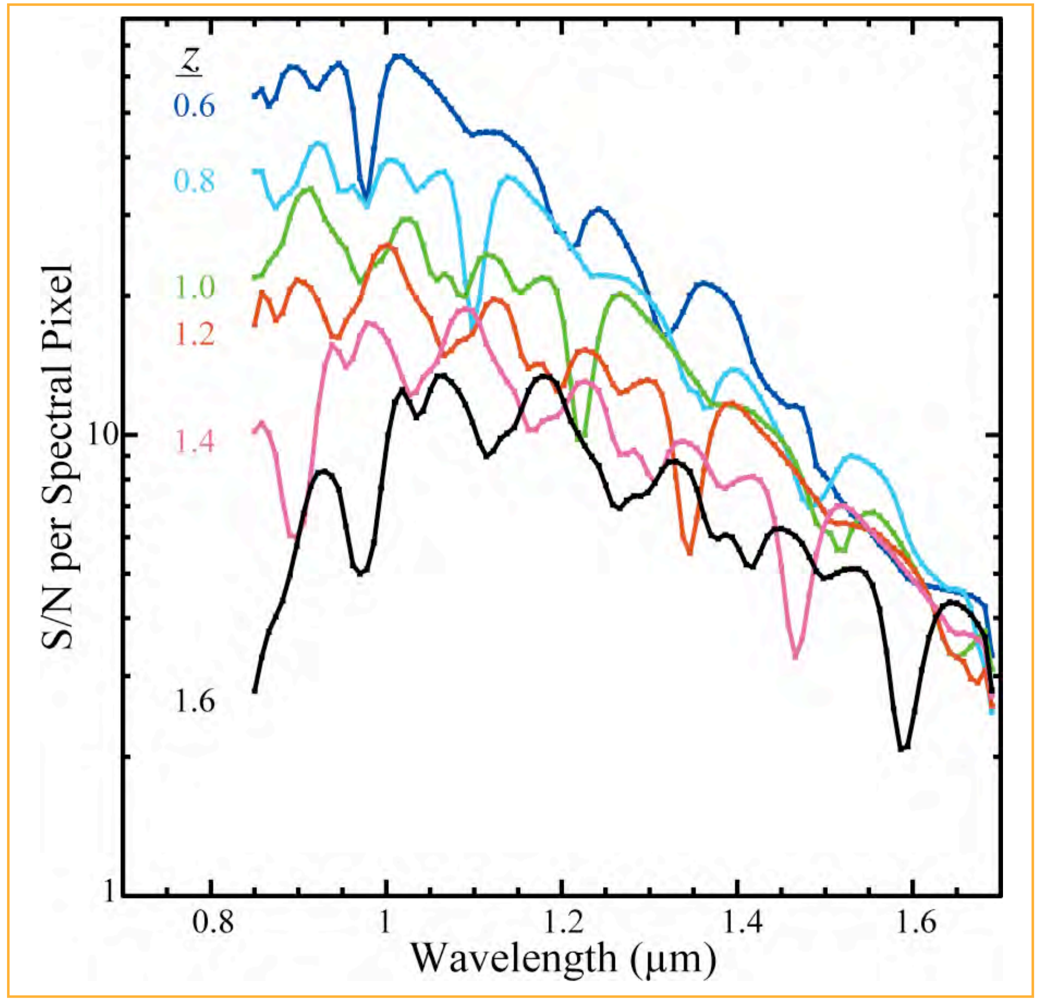
Supernova Observations



1. Filter: locate SN & host galaxy
2. Dispersed mode: spectral time series
3. Difference & extract SN spectrophotometry

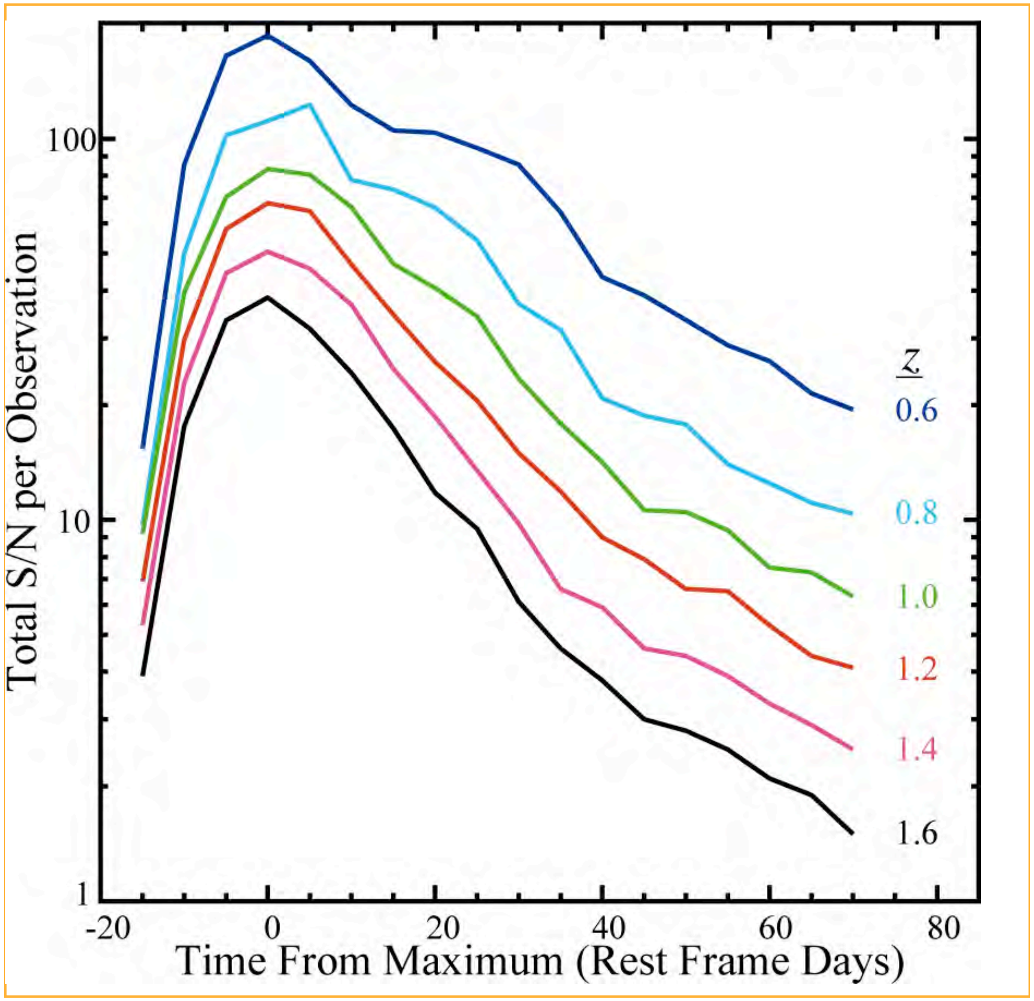
Supernova Spectra

- Simultaneous spectrum & photometry = redshift & brightness
- Redshift from 615nm SiII line
- Equal precision & more accuracy than broadband filters alone



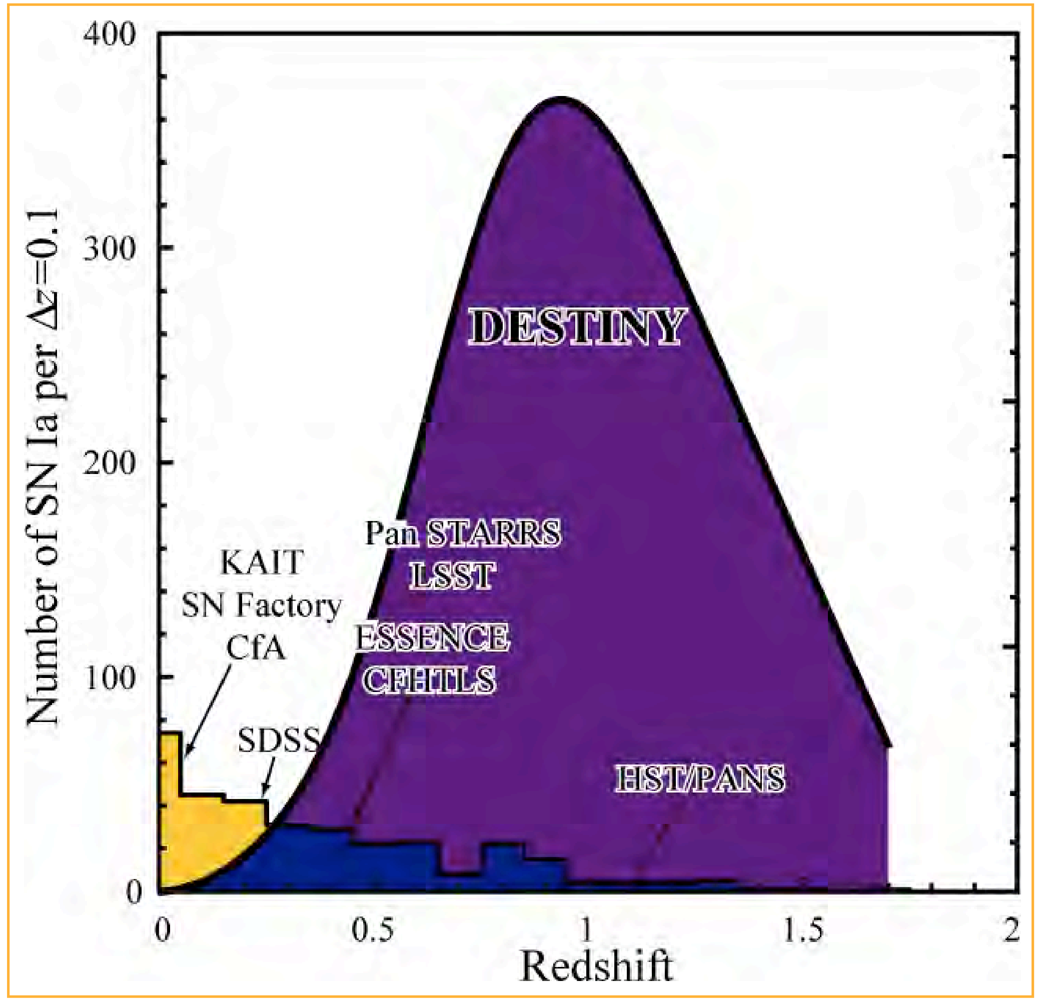
Supernova Light Curves

- Always get photometry around maximum light
- Sample every 5 days

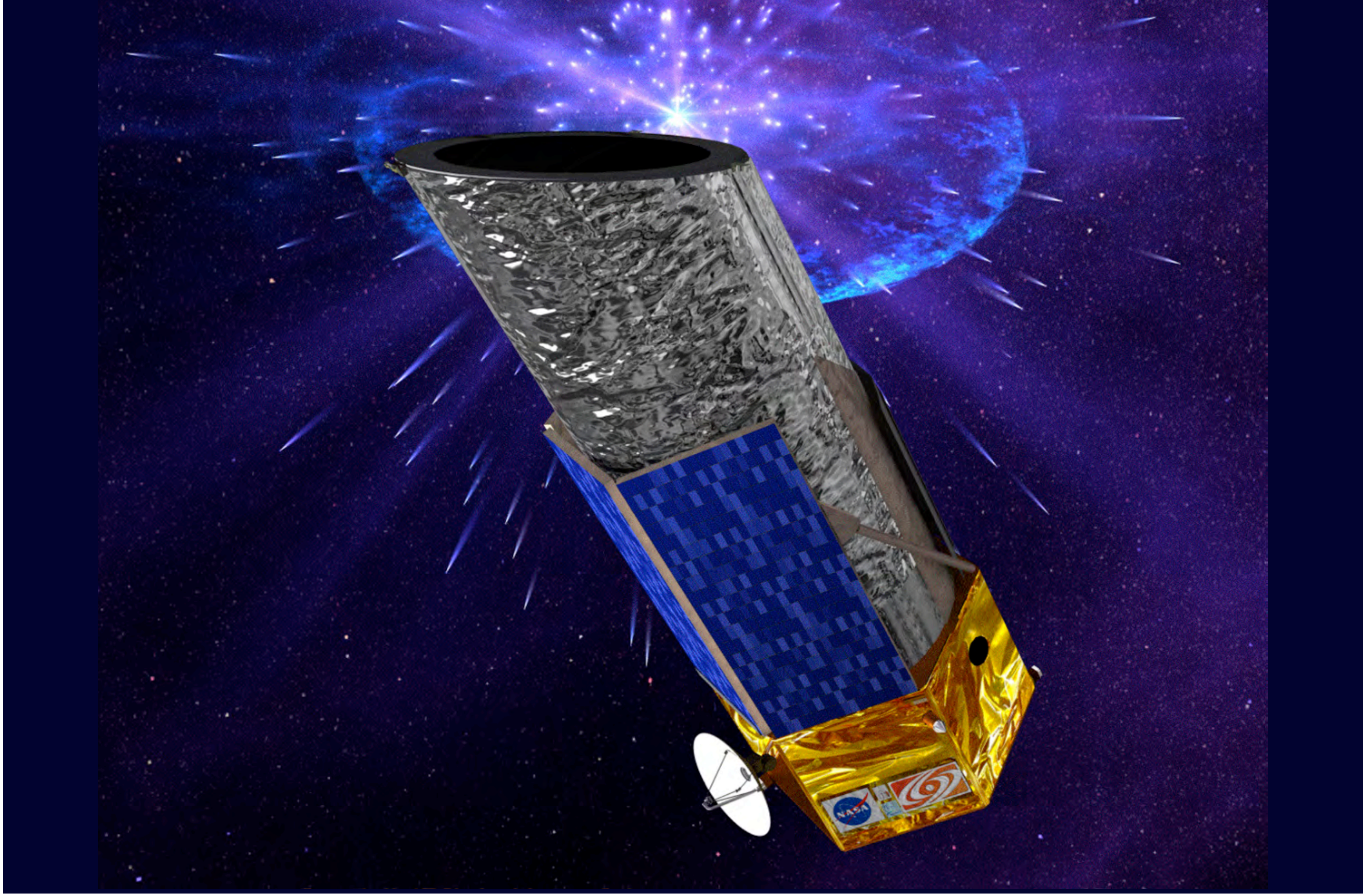


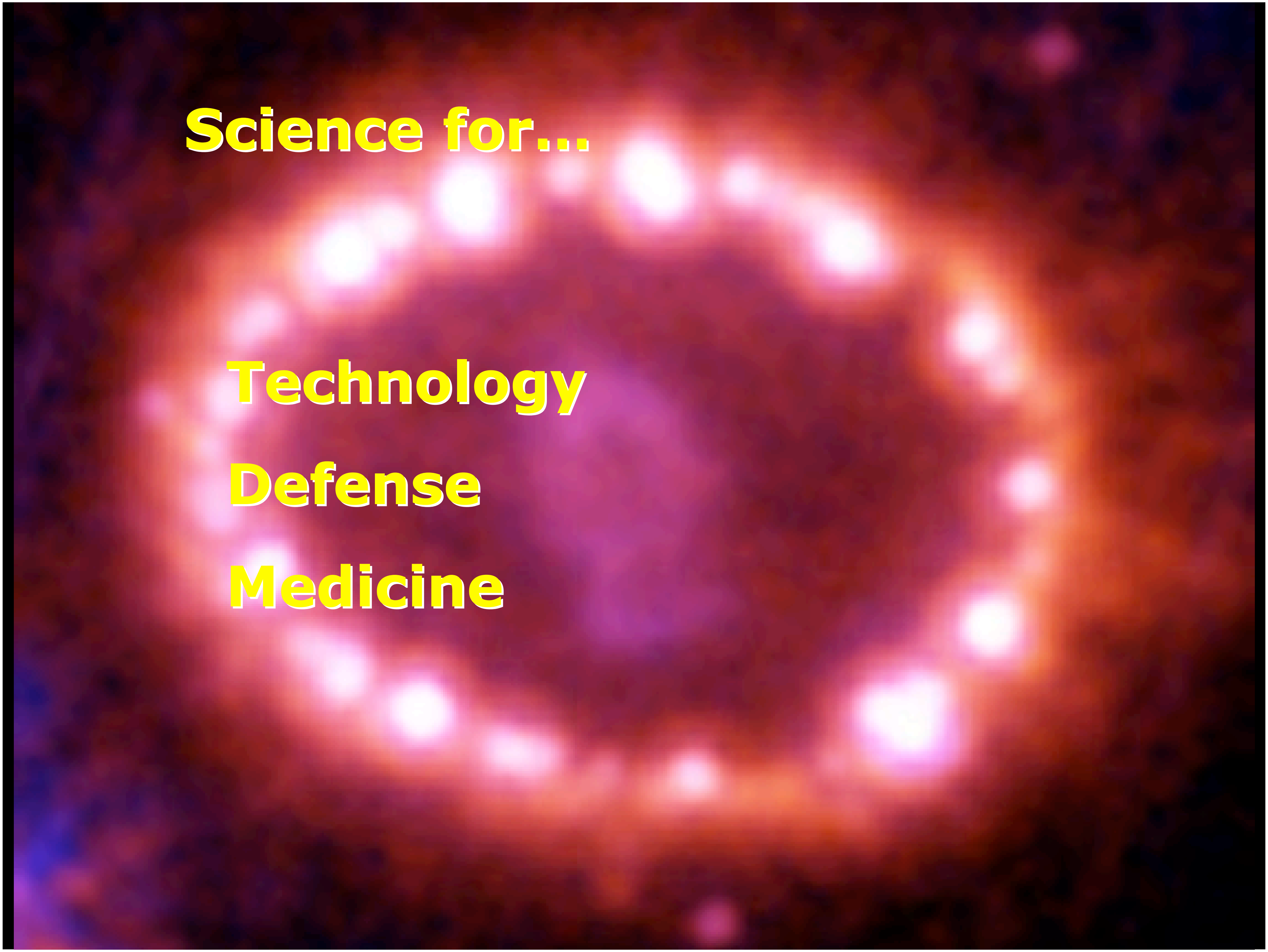
Supernova Survey

- Present day & ongoing surveys find hundreds
- Destiny will find >3000 SN in 2 yrs.
- Most at z~1; requires 3.2 deg^2 survey area

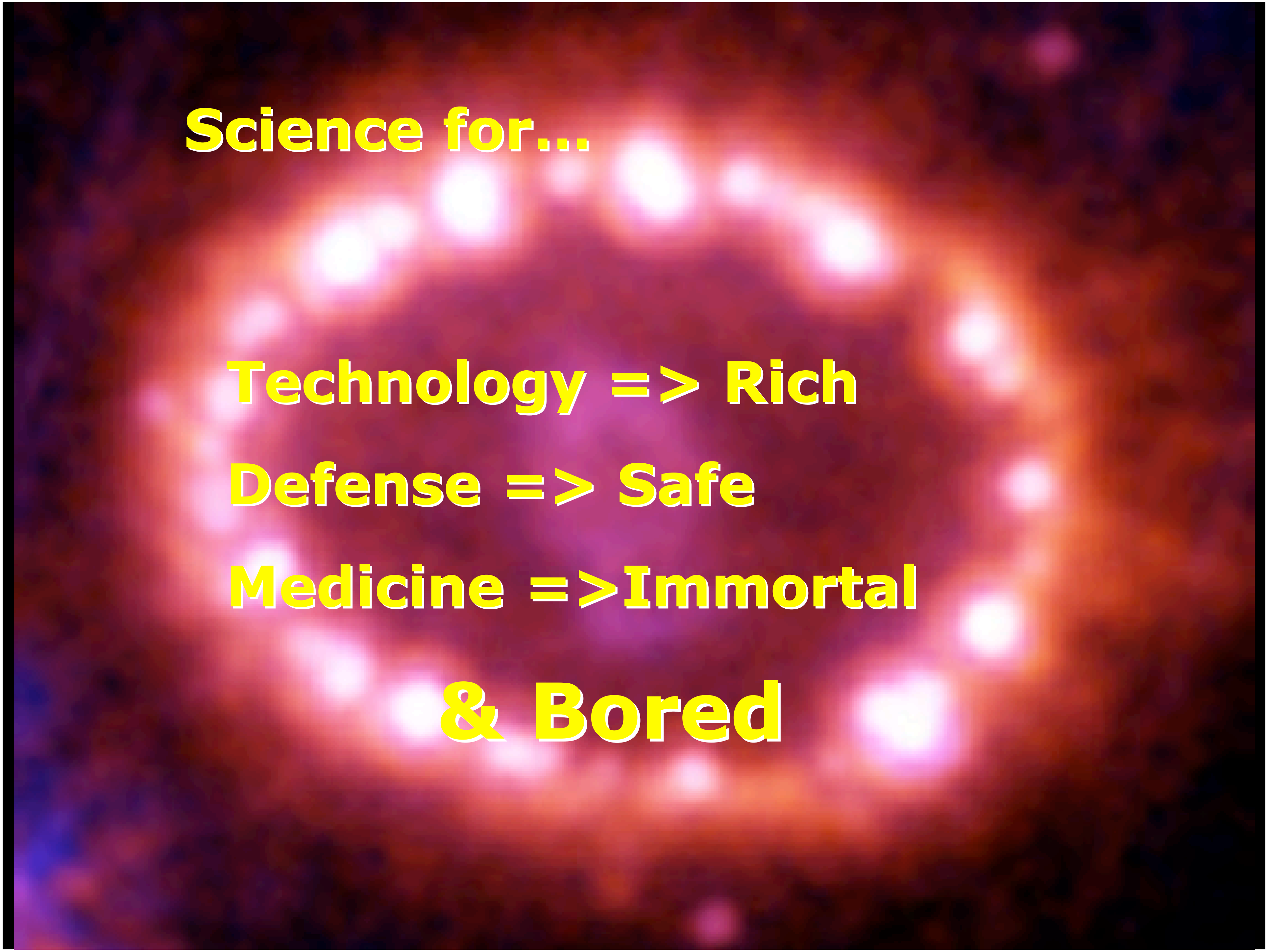


Destiny, The Dark Energy Space Telescope



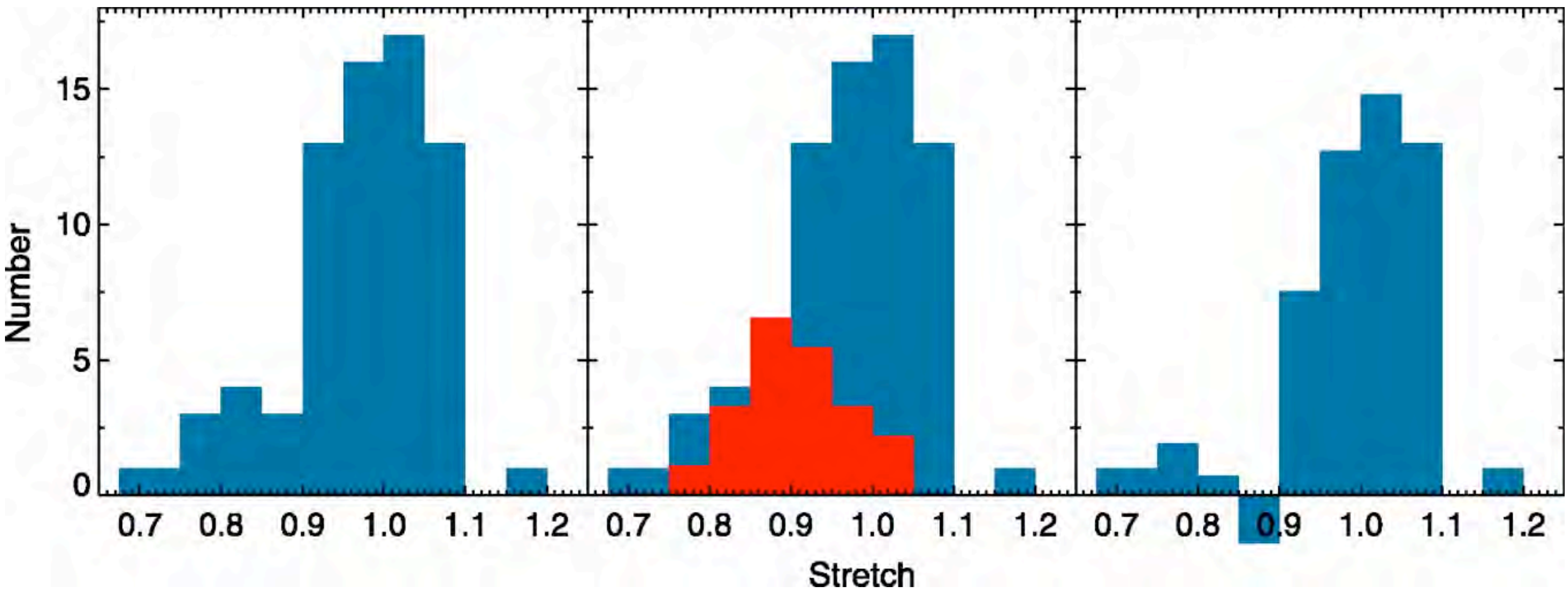

Science for…
Technology
Defense
Medicine


Science for…
Technology => Rich
Defense => Safe
Medicine =>Immortal


Science for…
Technology => Rich
Defense => Safe
Medicine =>Immortal
& Bored


Science for…
The joy of finding out
how the world works

Sullivan et al. Ap.J. 648, 868 (2006)



SNLS: as if ALL the fast (and dim) supernovae are associated with the old stars and ALL the slow (and bright) supernovae are the result of current star formation

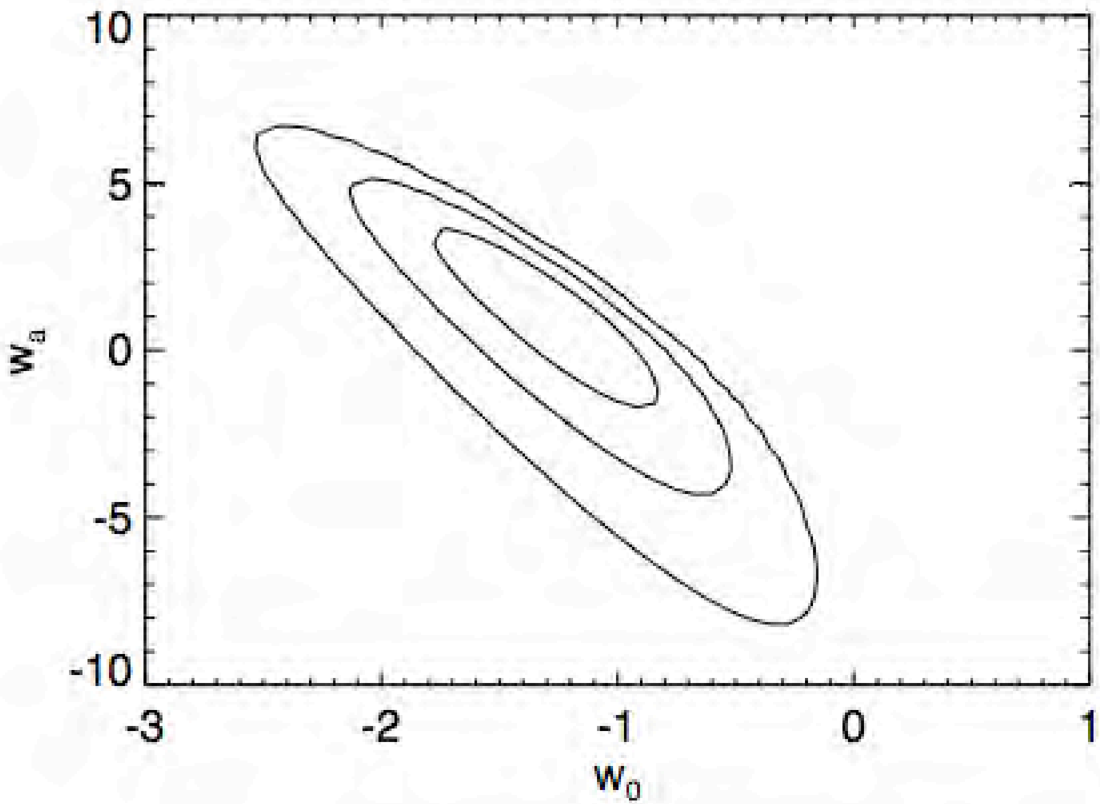
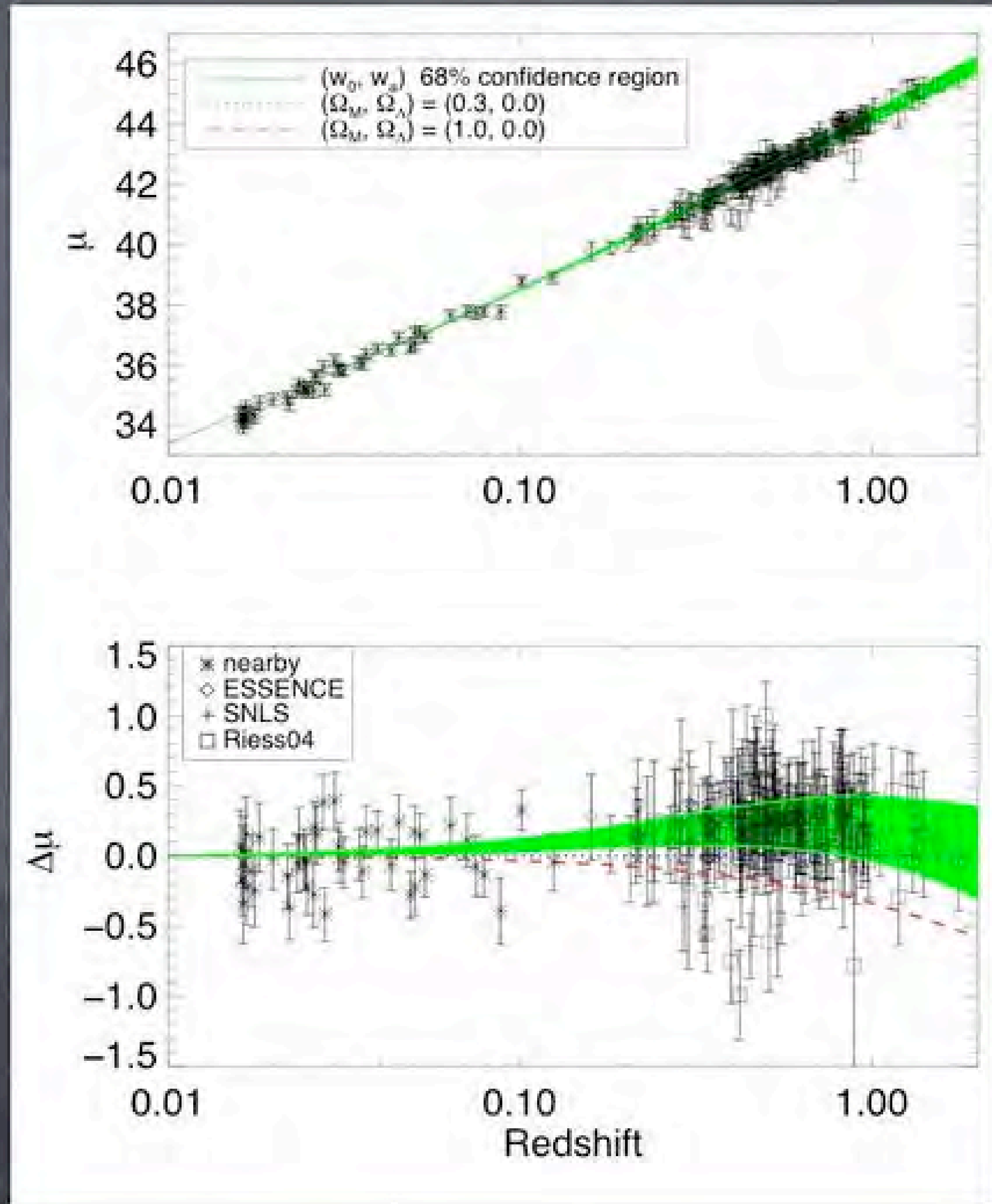


Fig. 20.— Combined constraints on (w_0, w_a) using the MLCS2k2 fit results for the ESSENCE SNe Ia analyzed here in combintation with the nearby SNe Ia, SNLS SNe Ia, and the Riess "gold" sample. We have used an additional constraint of $\Omega_M = 0.27 \pm 0.03$.

Global SNIa Hubble Diagram

Hamuy 1996a,b
Riess 1998
Perlmutter 1999
Riess 1999
Riess 2001
Tonry 2003
Knop 2003
Barris 2004
Riess 2004
Clochiatti 2005
Astier 2006
Jha 2006



SHOES

[redacted]

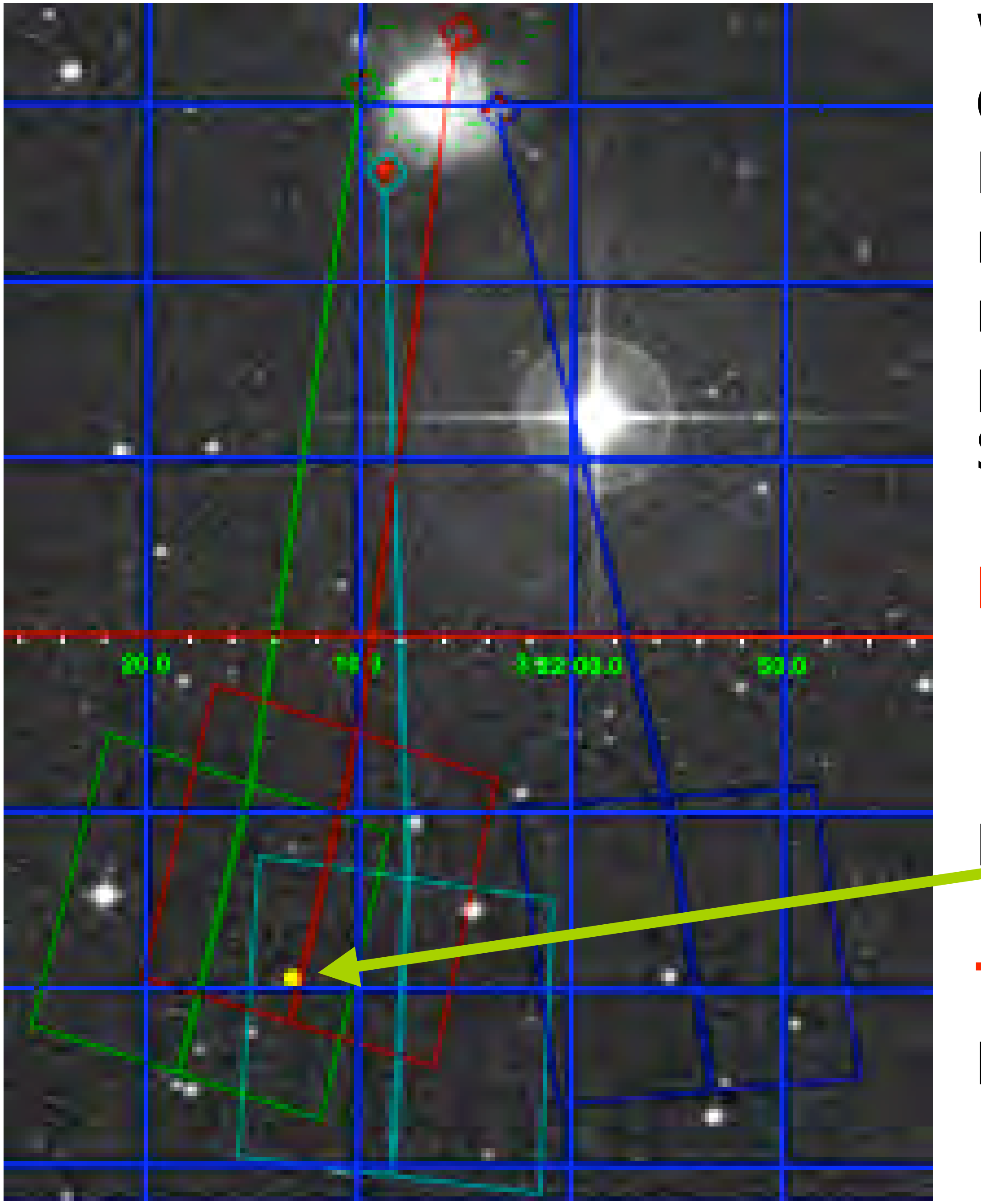
Supernovae, HO, for the Equation of State

P.I. Riess (STScI), Stetson (HIA),
Macri (NOAO), Ferguson(STScI)
Strolger (W. Kentucky), Tonry (UH)
Filippenko (UCB), Jha (Stanford),
Li (UCB), Kirshner, (CfA)
Challis, (CfA), Casertano, (STScI)
Livio (STScI),Mobasher (STScI)

HST Cycle 15

Two Programs in Parallel for Dark Energy

- Get H_o to 4% precision
- Collect (more) HST-unique SNe Ia at z>1



While collecting Cepheids with NICMOS to measure reddening-free magnitudes…search in parallel with ACS for SN Ia at z>1…

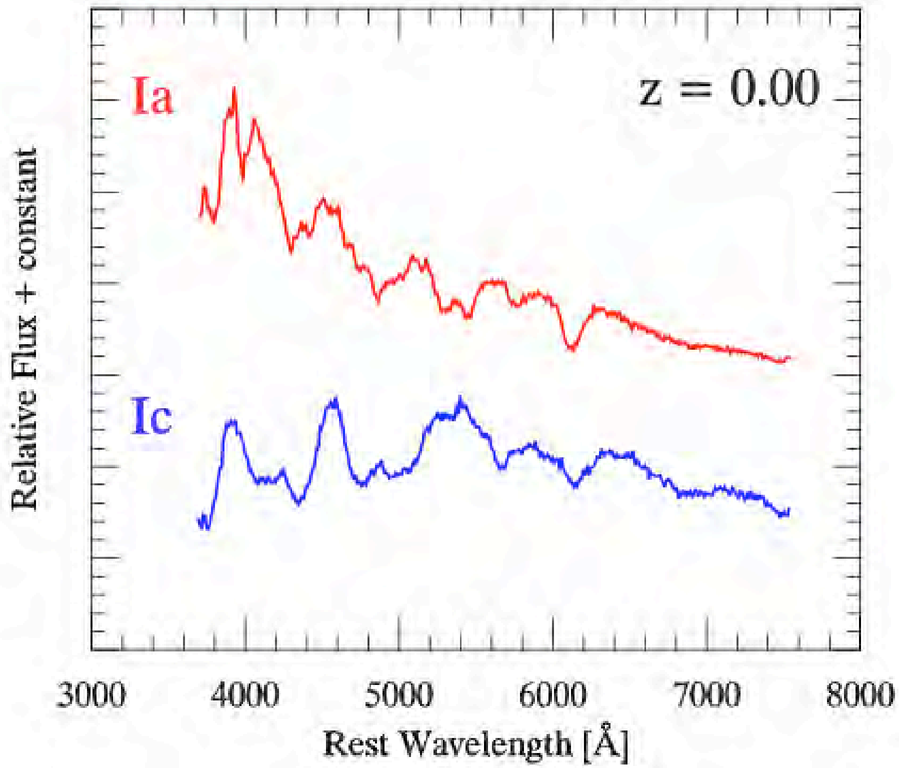
How cool is that?

SN Ia, "Boots", z=1
Found Aug 13, 2006

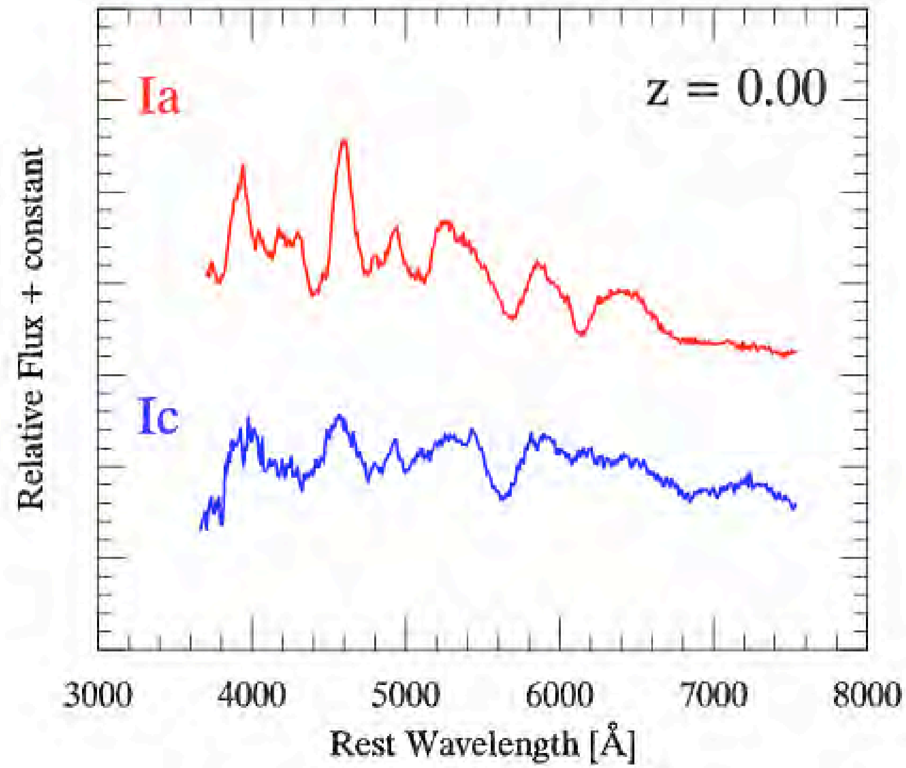
Two Dark Energy probes for price of one!

SN Ia *vs.* SN Ic

At maximum light

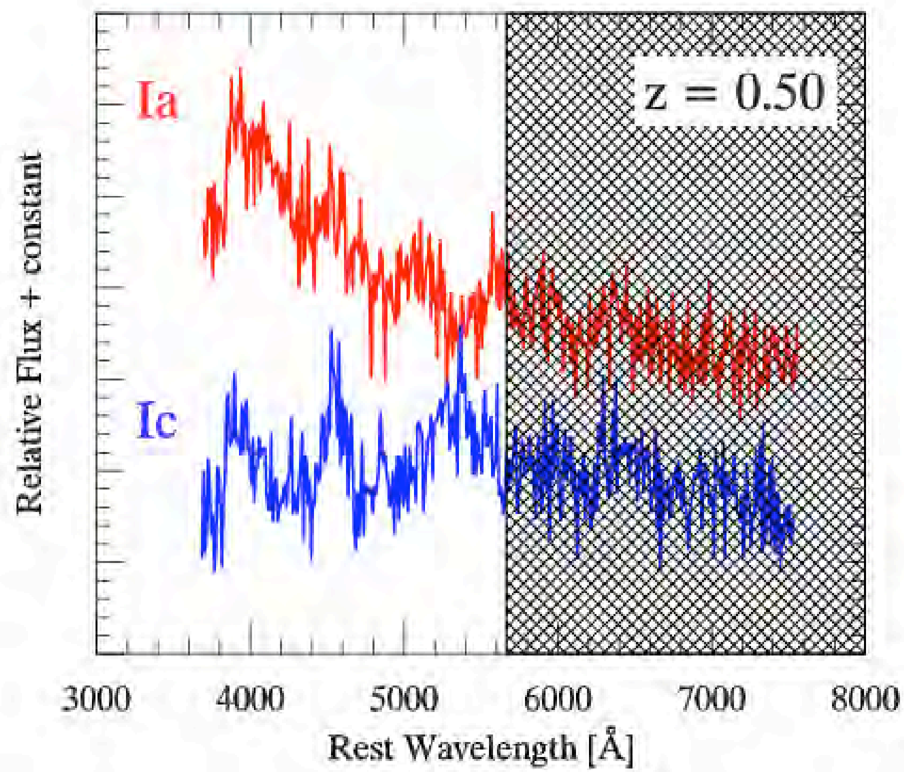


Two weeks past maximum

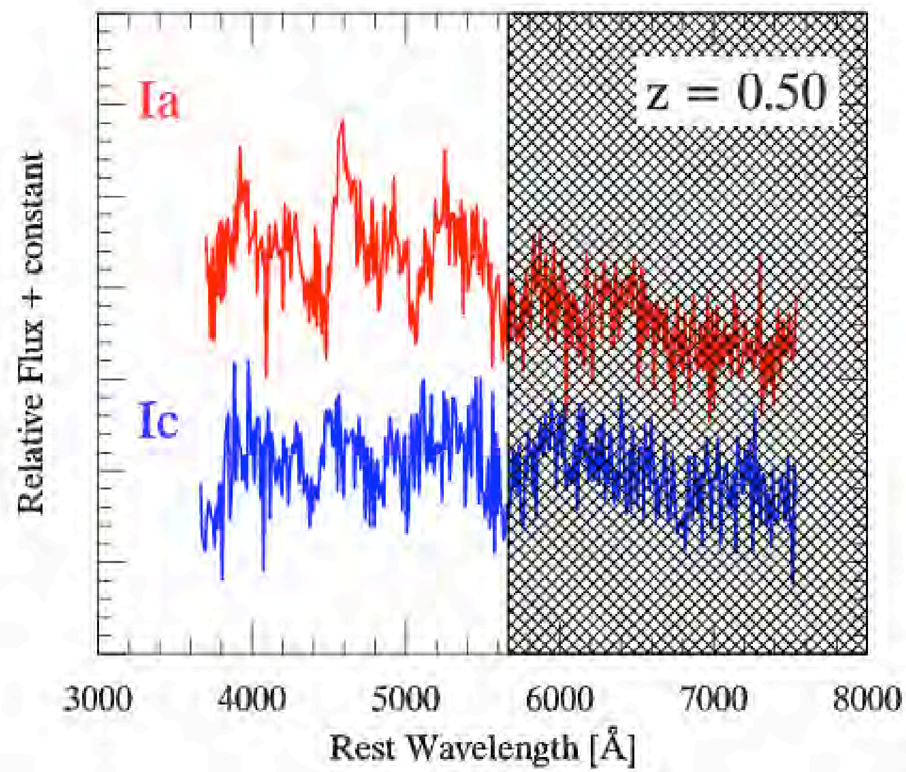


SN Ia *vs.* SN Ic

At maximum light

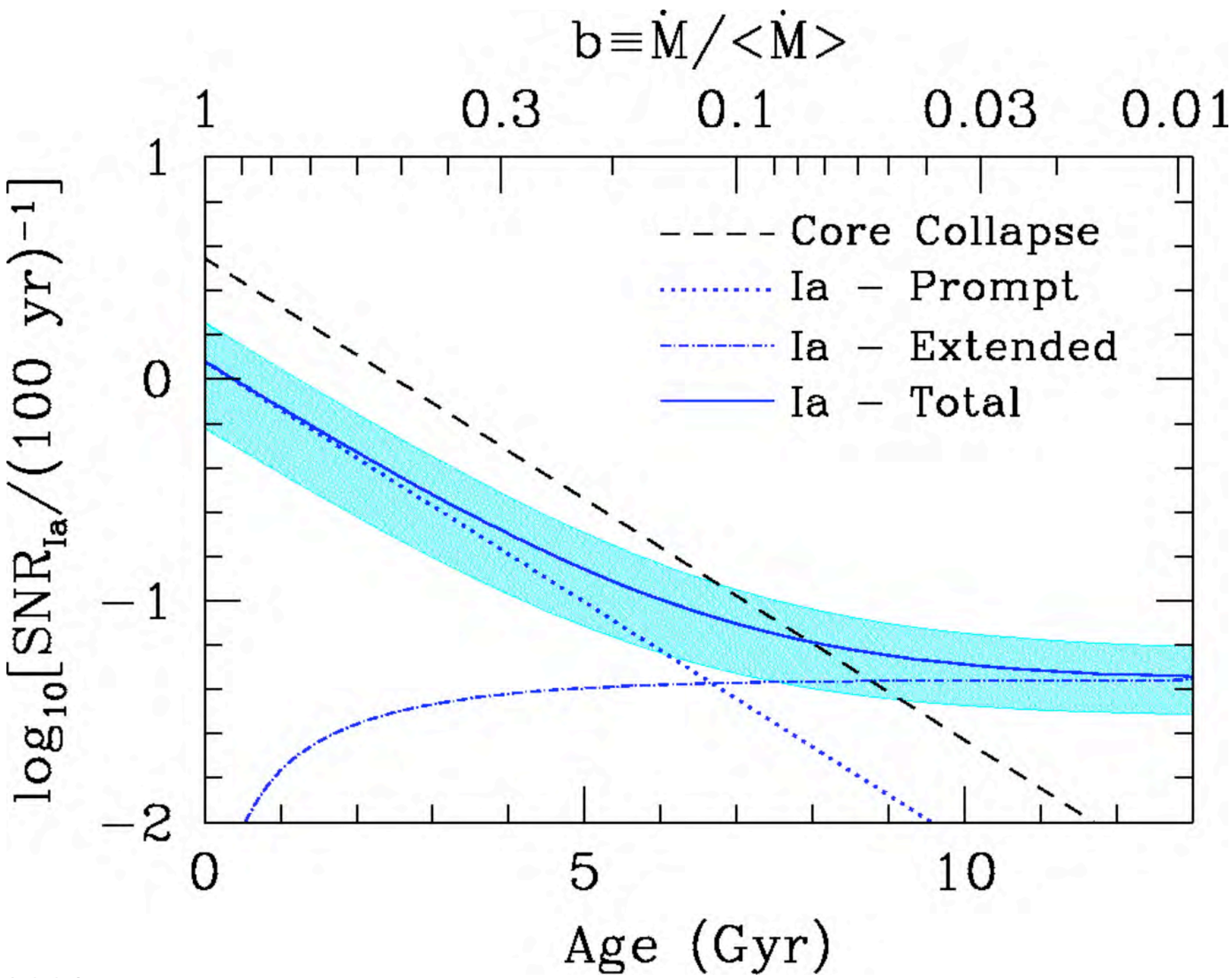


Two weeks past maximum

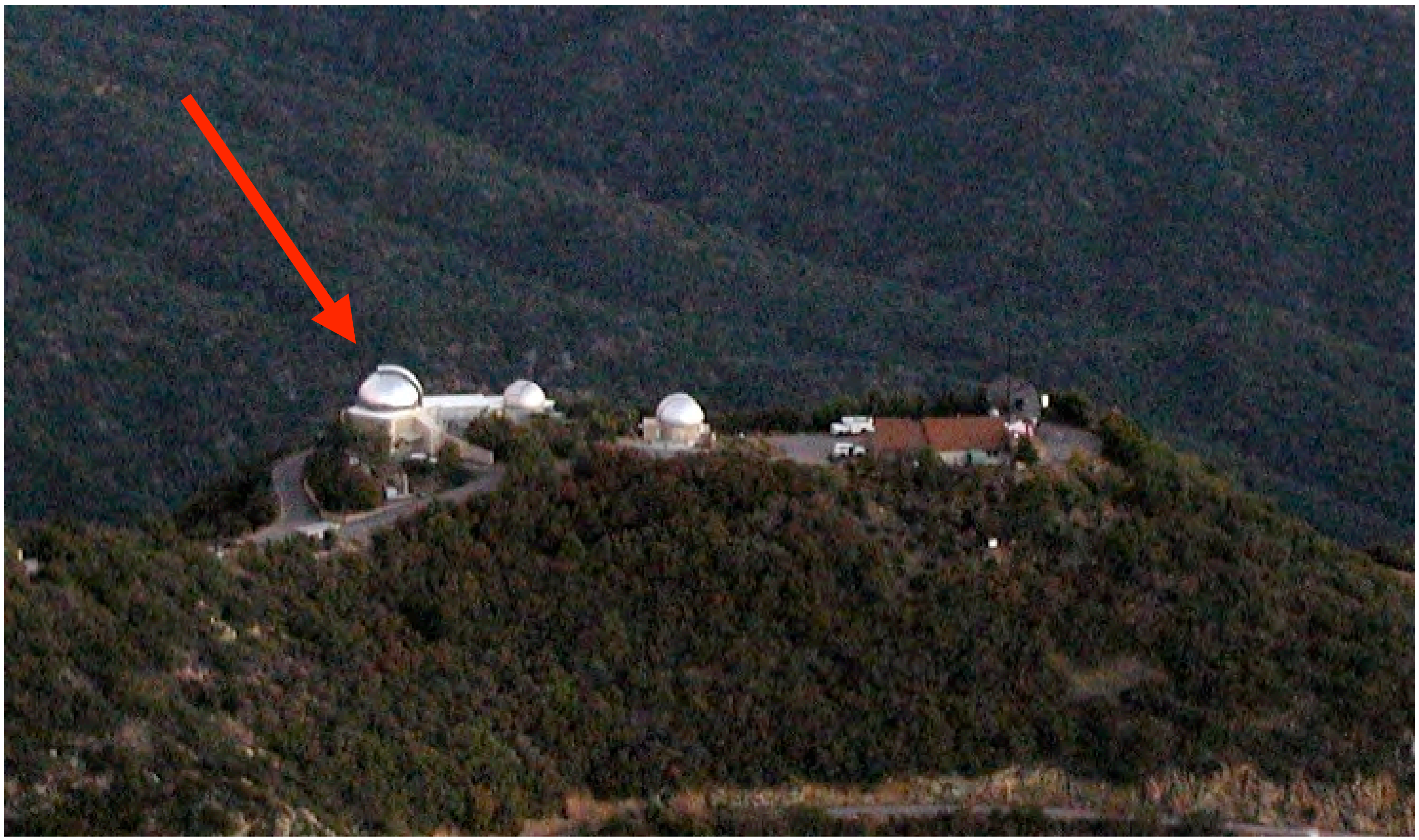


Blondin et al., in prep

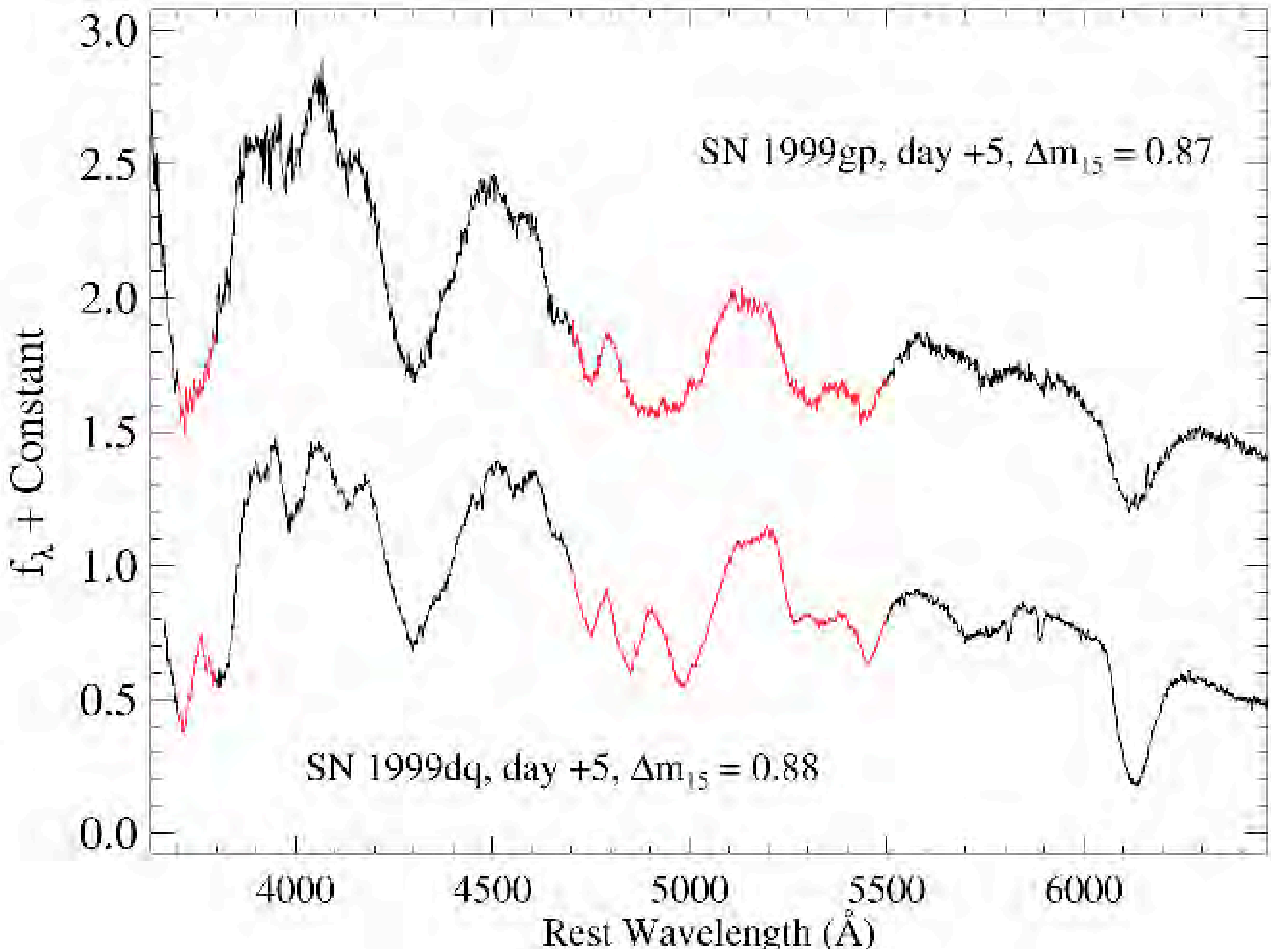
Scannapieco & Bildsten Ap.J. Letters 629, L85 (2005)



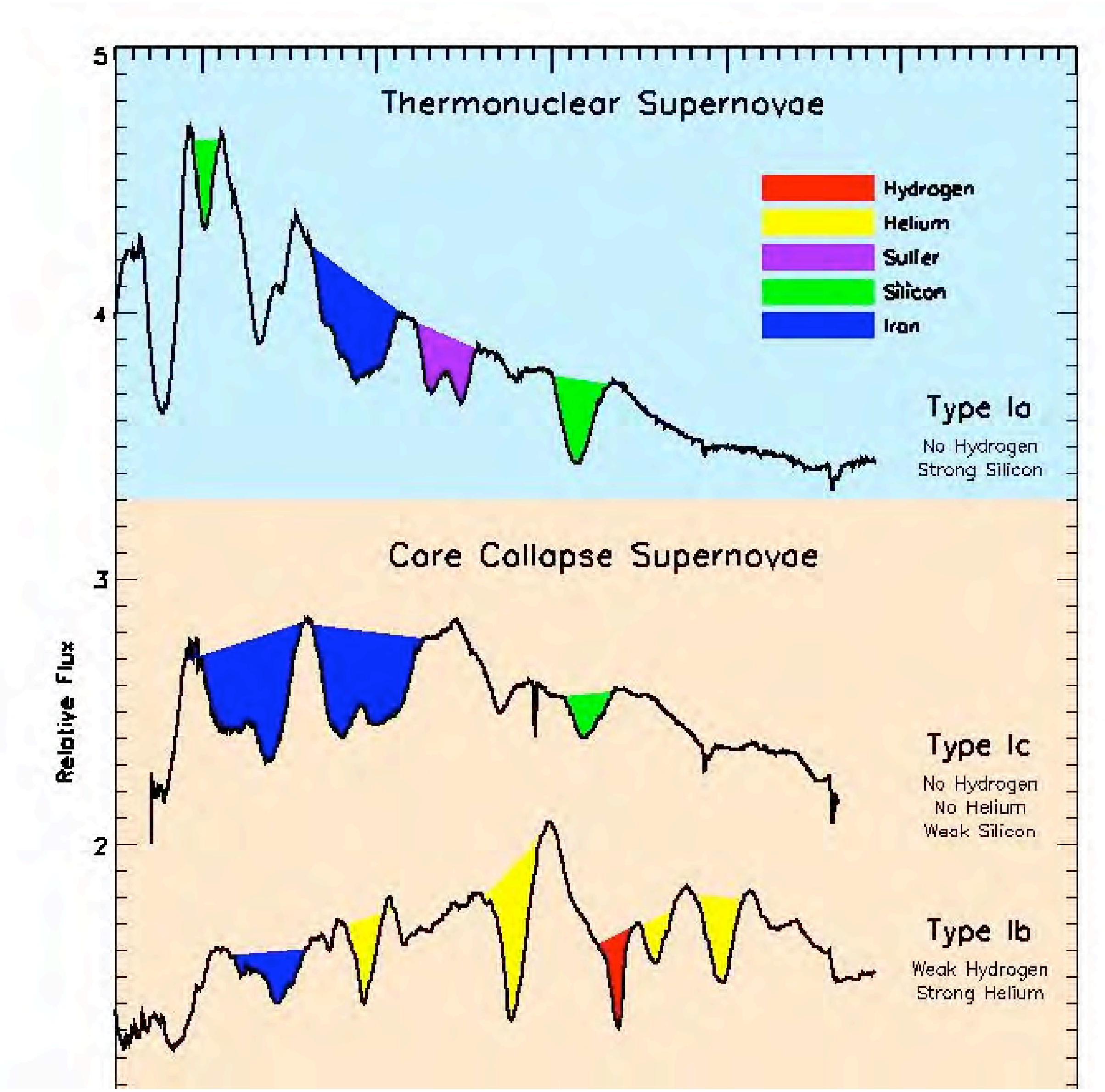
F.L. Whipple Observatory: Following up with spectra



What is the origin of these variations?

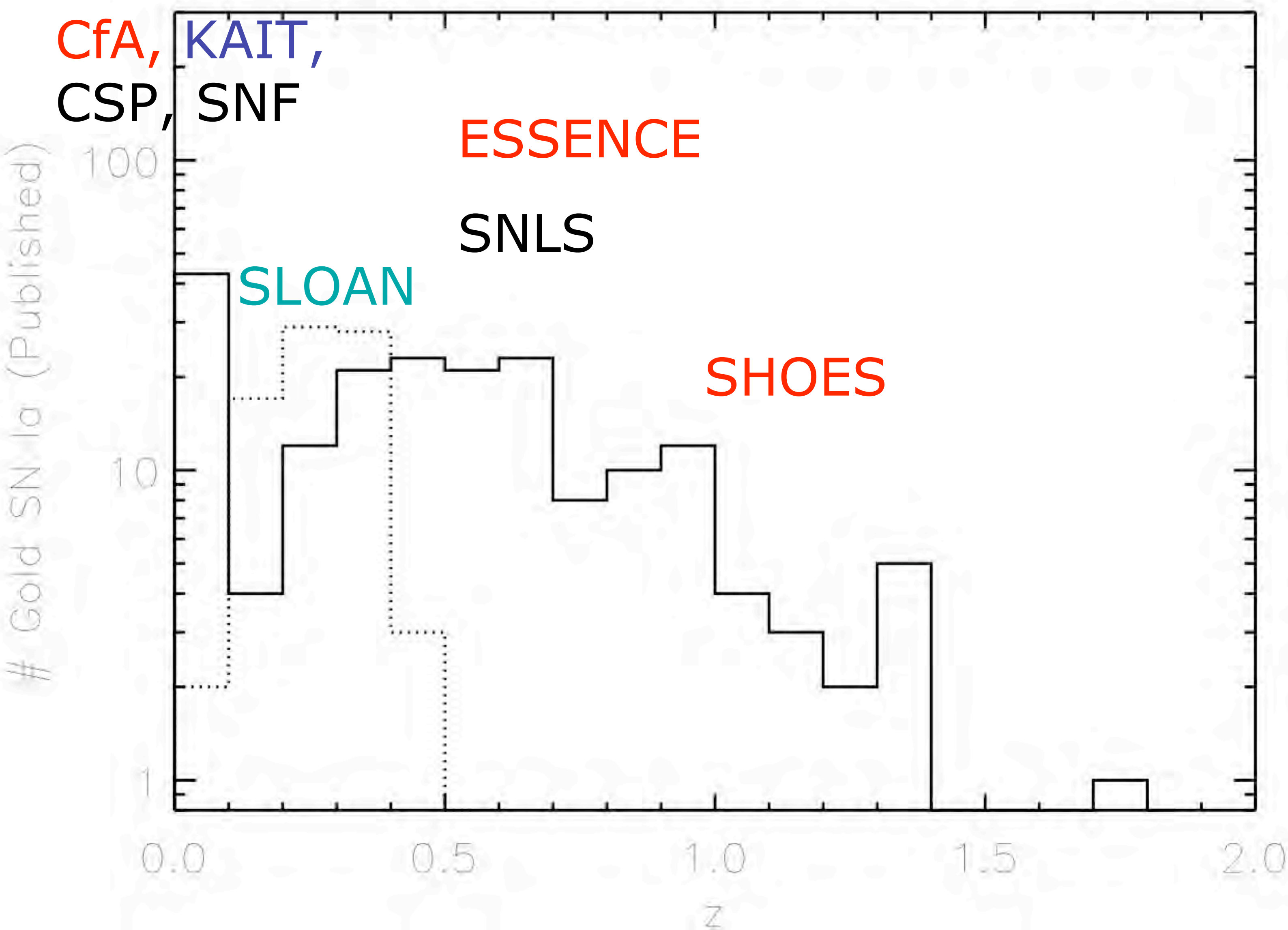


Classifying Spectra



Credit: Dan Kasen

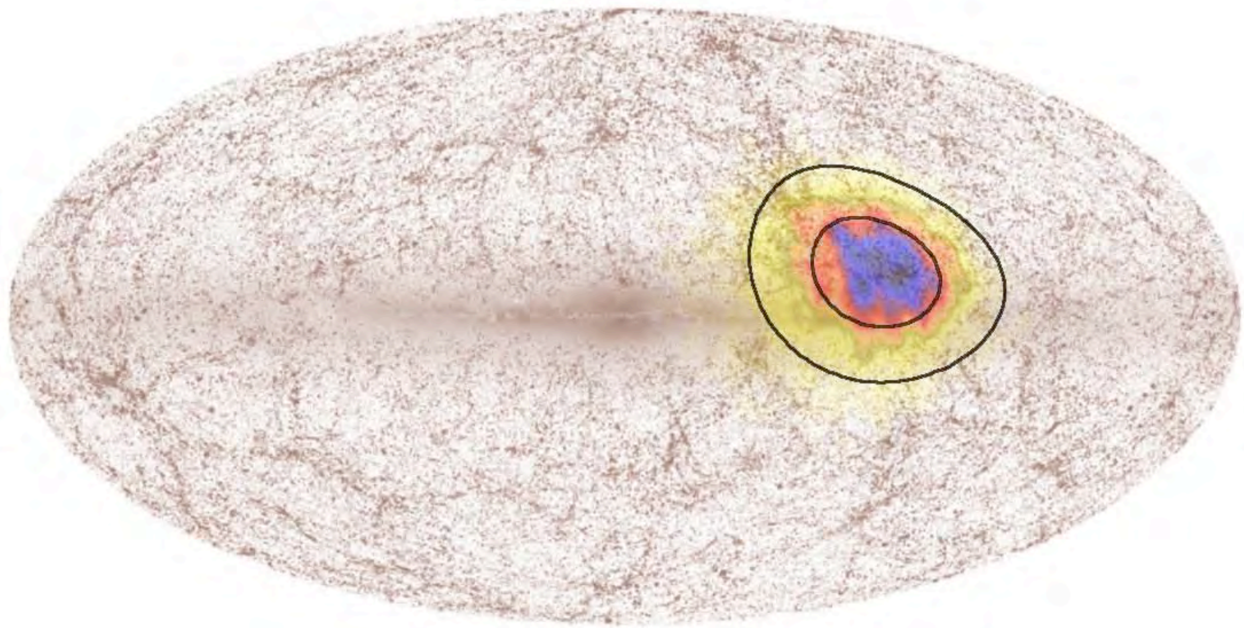
The Current State of the Art



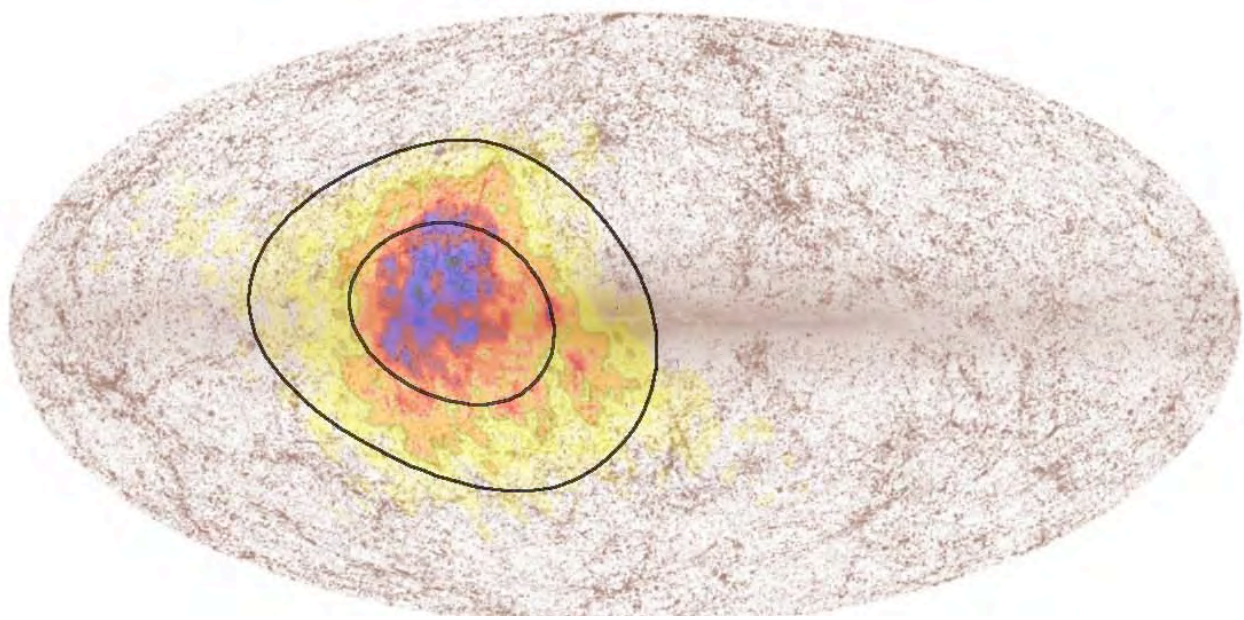
Adam Riess

From astro-ph/0612137: Haugboelle et al.

Dipole

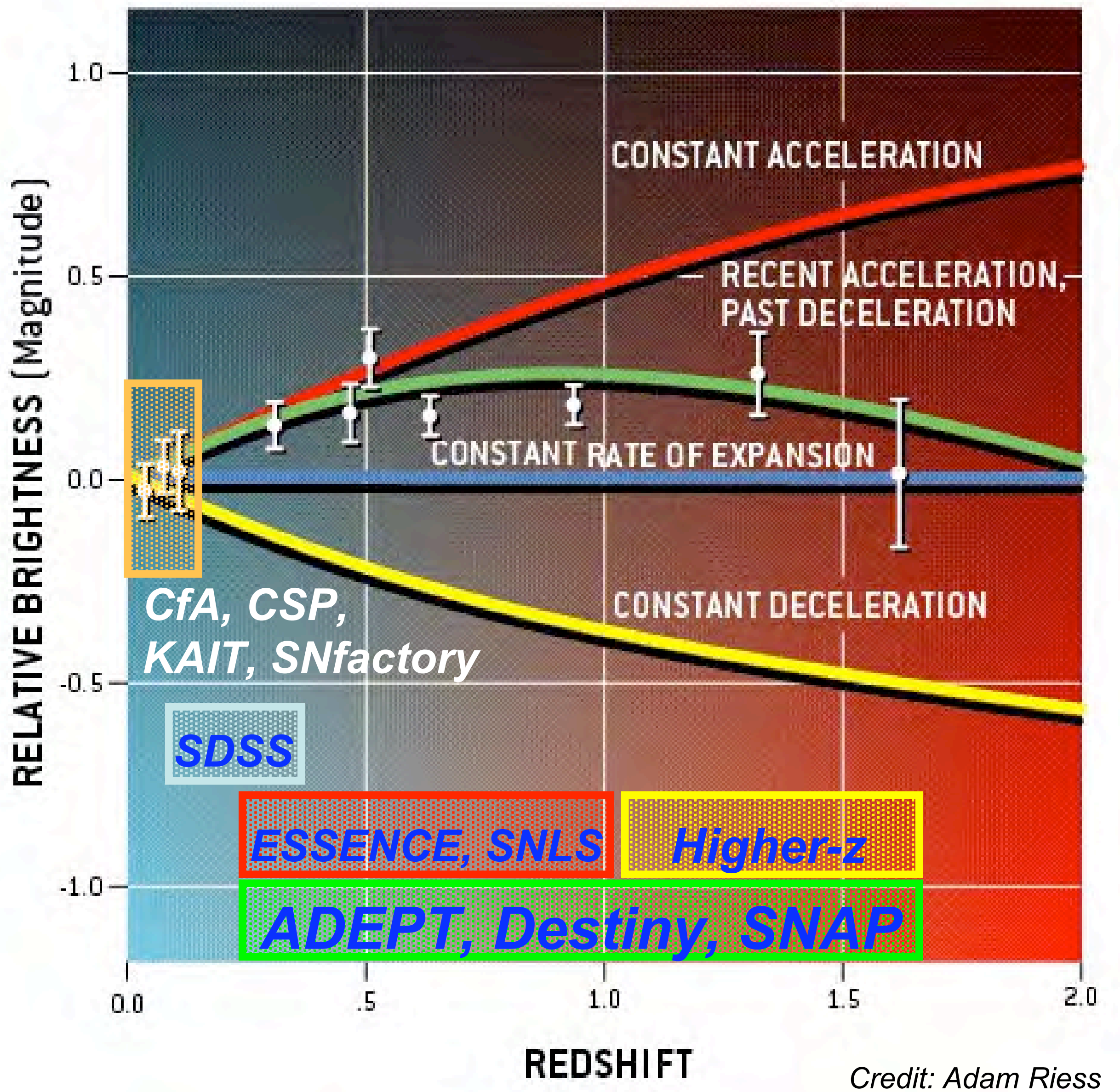


Quadrupole



July

SN Ia and "Dark Energy"



Credit: Adam Riess

1998-1999: $\Omega_\Lambda > 0$

High-Z Team, SCP

2006-2007: $w = -1$

SNLS, ESSENCE, Higher-z

2008-2015+: $w' = 0$?

Pan-STARRS, LSST

ADEPT, Destiny, SNAP

Constraints from supernovae alone Kowalski et al.

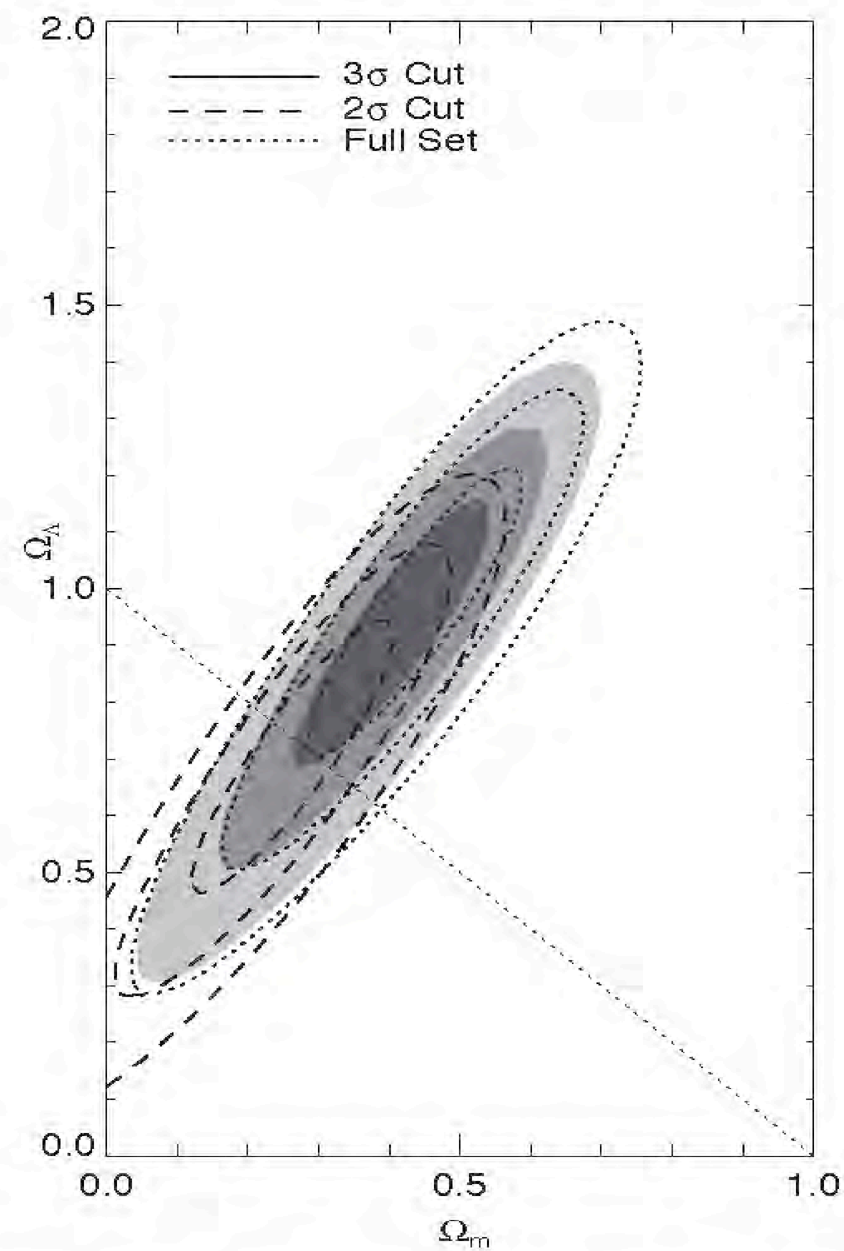
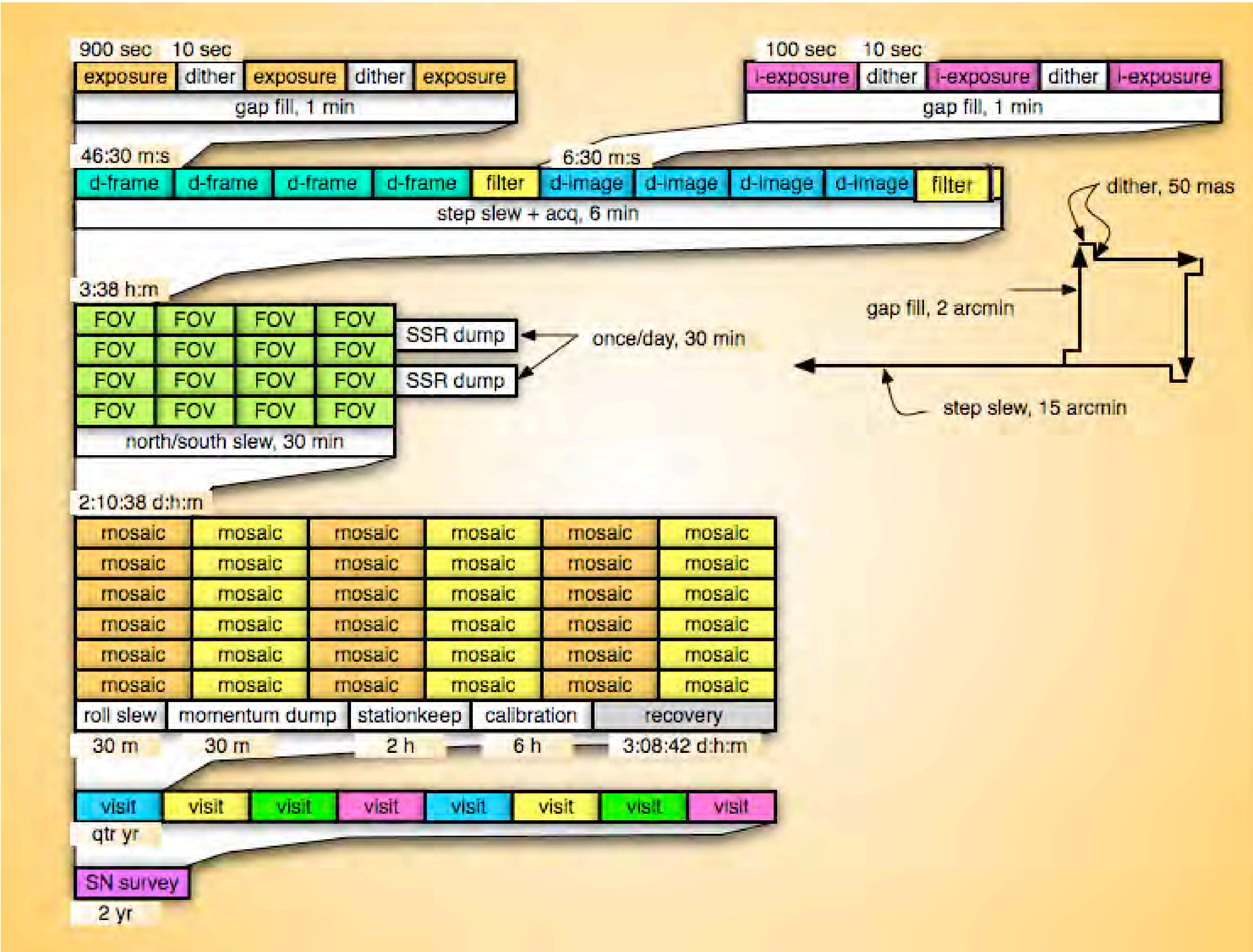
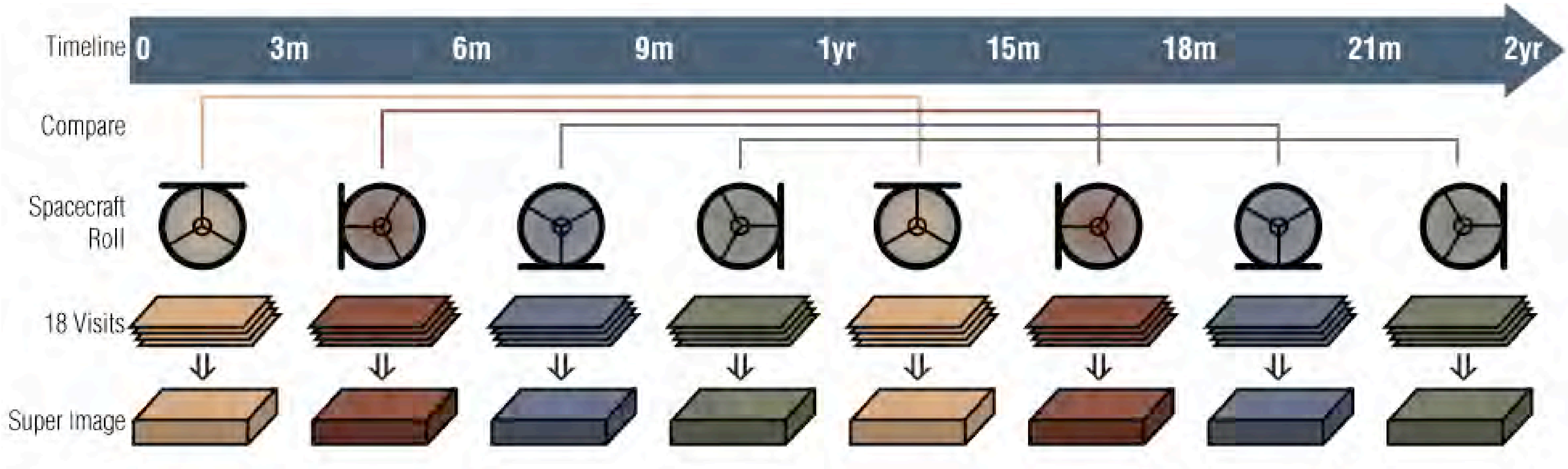


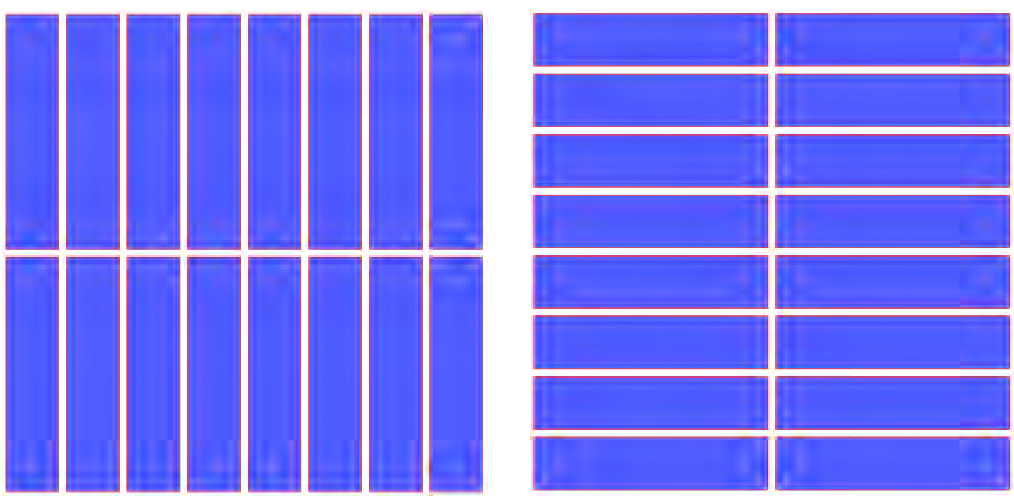
FIG. 11.— 68.3 %, 95.4 % and 99.7% confidence level contours on Ω_Λ and Ω_M plane from the Union SNe set. The result from



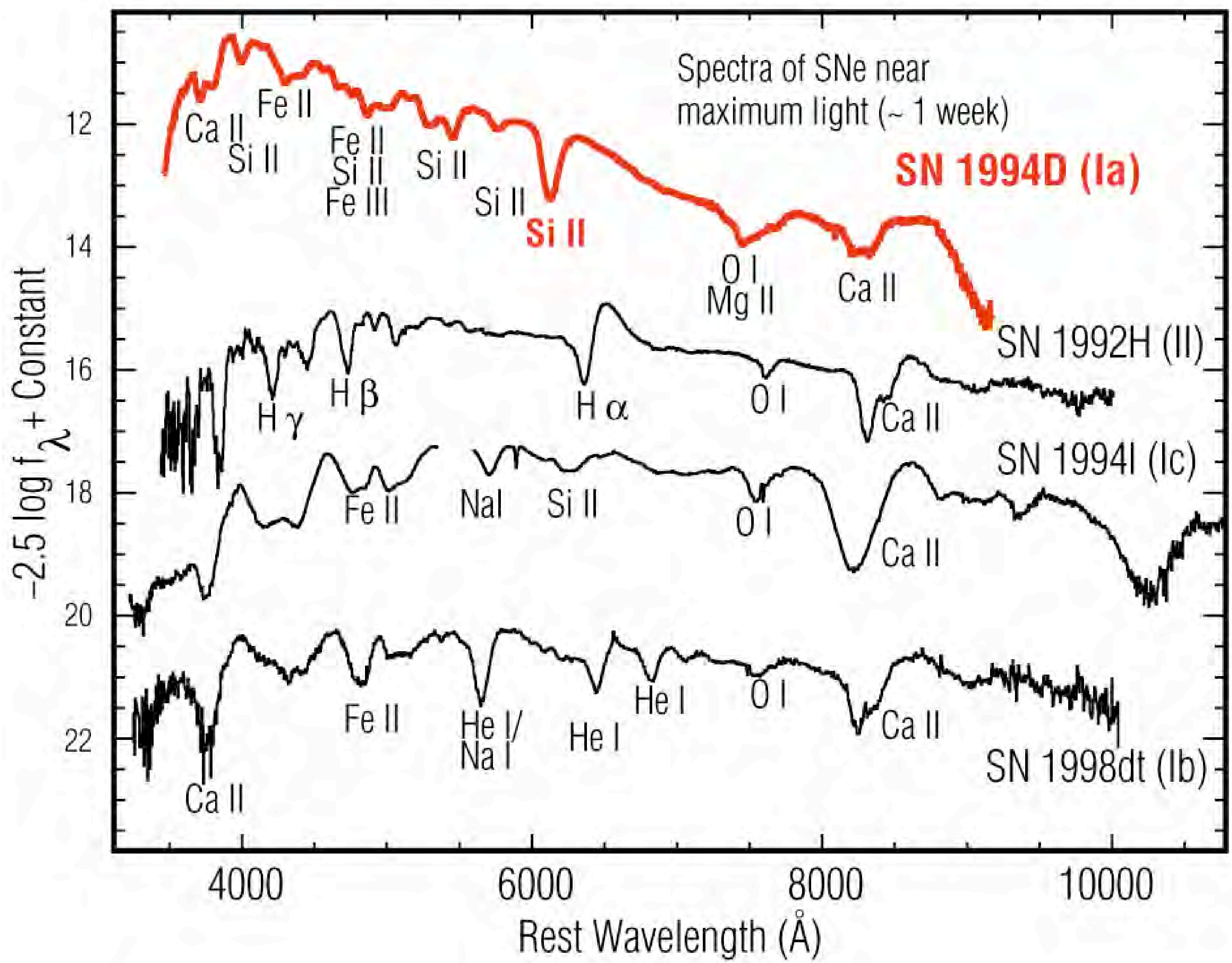
900 sec
10 sec
exposure
dither
exposure
dither
exposure
gap fill, 1 min
100 sec
10 sec
i-exposure
dither
i-exposure
dither
i-exposure
gap fill, 1 min
46:30 m:s
6:30 m:s
d-frame
d-frame
d-frame
d-frame
filter
d-image
d-image
d-image
d-image
filter
step slew + acq, 6 min
dither, 50 mas
gap fill, 2 arcmin
step slew, 15 arcmin
3:38 h:m
FOV
SSR dump
SSR dump
once/day, 30 min
north/south slew, 30 min
2:10:38 d:h:m
mosaic
roll slew
momentum dump
stationkeep
calibration
recovery
30 m
30 m
2 h
6 h
3:08:42 d:h:m
visit
qtr yr
SN survey
2 yr

Supernovae Survey Plan





Survey area is a contiguous Mosaic of Destiny FOVs. Orientation rolls by 90° every 3 months. Dithering will fill in chip gaps and ensure Nyquist sampling.


Spectra of SNe near
maximum light (~ 1 week)
SN 1994D (Ia)
SN 1992H (II)
SN 1994I (Ic)
SN 1998dt (Ib)
Ca II
Si II
Fe II
Fe II
Si II
Fe III
Si II
Si II
Si II
O I
Mg II
Ca II
H γ
H β
H α
O I
Ca II
Fe II
NaI
Si II
O I
Ca II
Ca II
Fe II
He I/
Na I
He I
He I
O I
Ca II
12
14
16
18
20
22
4000
6000
8000
10000
Rest Wavelength (Å)
−2.5 log f_λ + Constant