Jesper Sollerman

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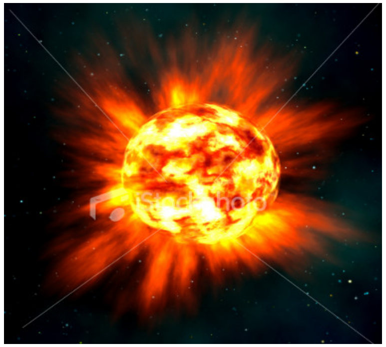
Supernovae - Gamma-Ray Bursts - Cosmology Connection....

Jesper Sollerman, June 4 2012, Finnish Astronomers' Days



Supernovae - Gamma-Ray Bursts - Cosmology Connection....

Jesper Sollerman, June 4 2012, Finnish Astronomers' Days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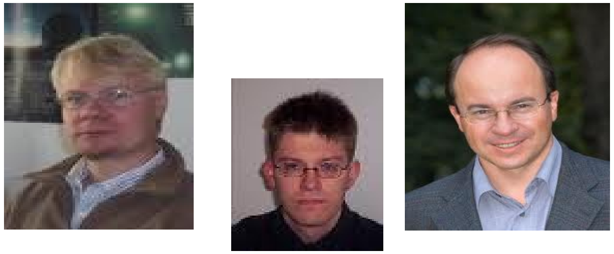
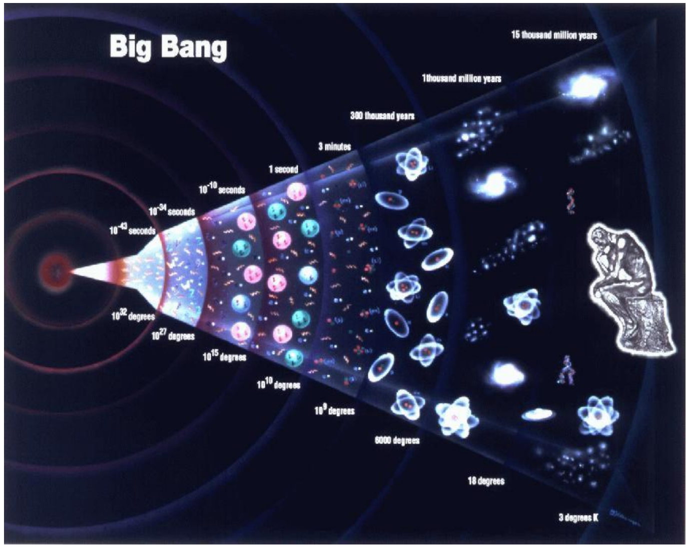
Supernovae - Gamma-Ray Bursts - Finland Connection....





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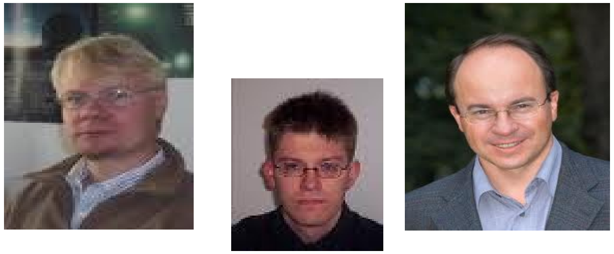
Supernovae - Gamma-Ray Bursts - Finland Connection....



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SNe Ia

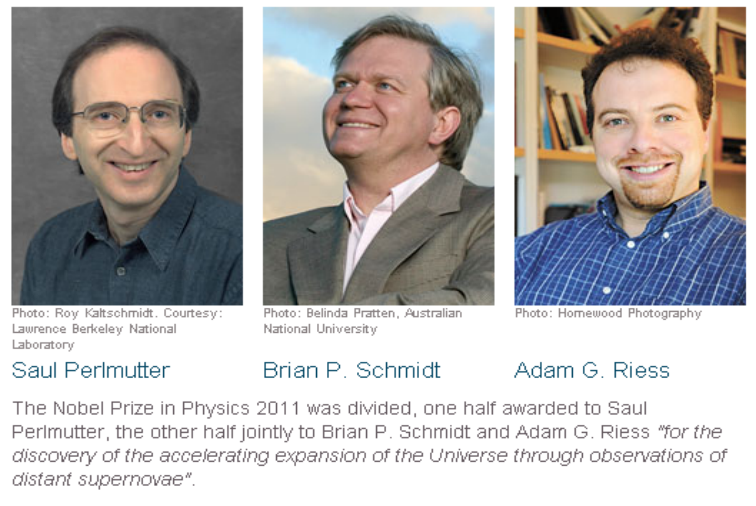


Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Photo: Belinda Pratten, Australian National University

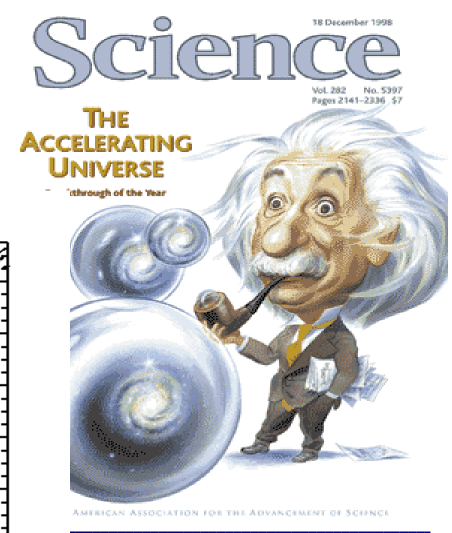
Photo: Homewood Photography

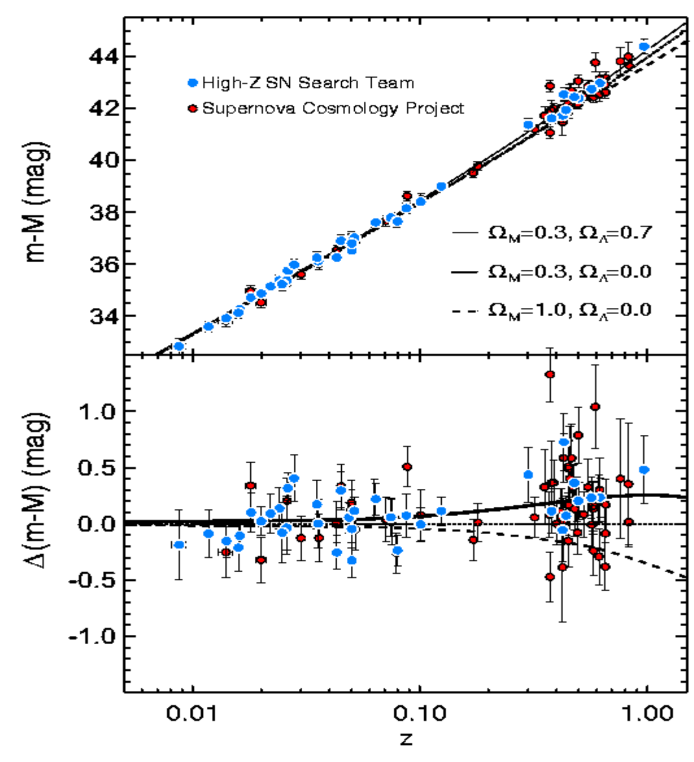
Saul Perlmutter

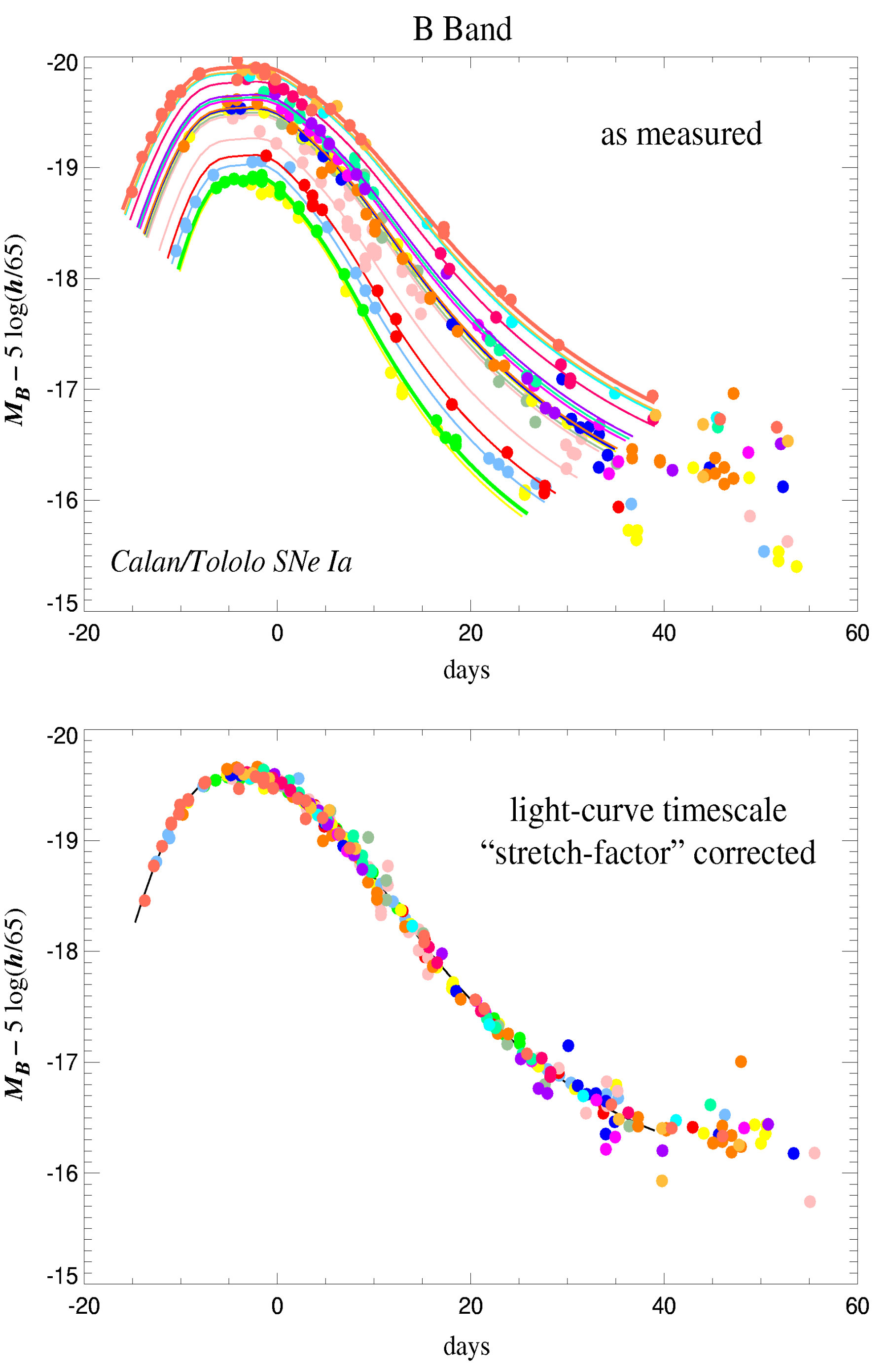
Brian P. Schmidt

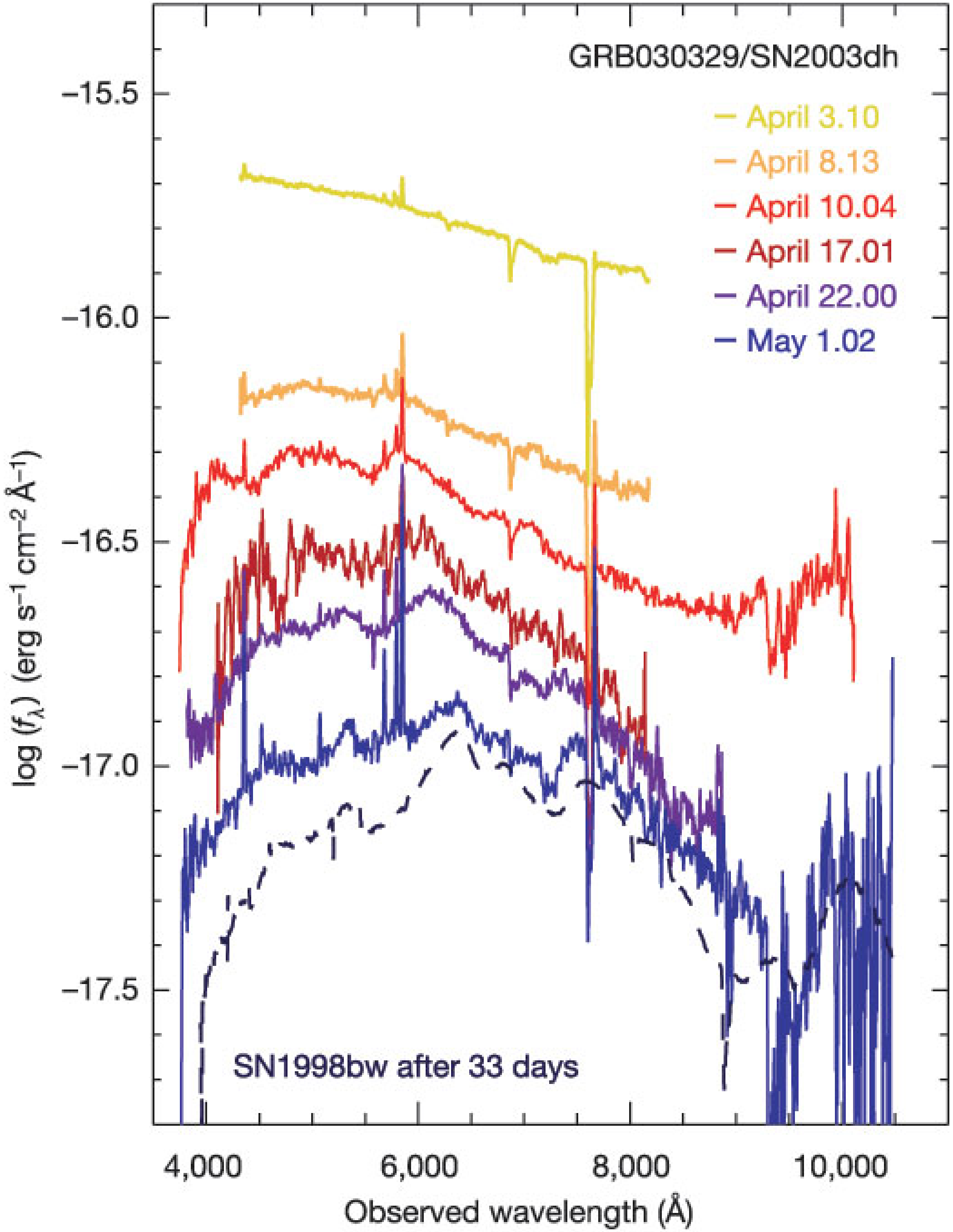
Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.









Hjorth, Sollerman, Möller, et al. 2003, Nature 423, 847

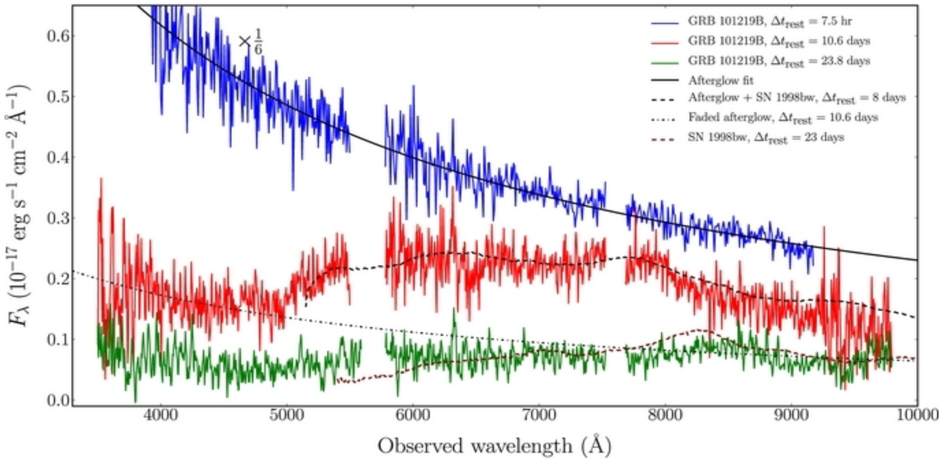
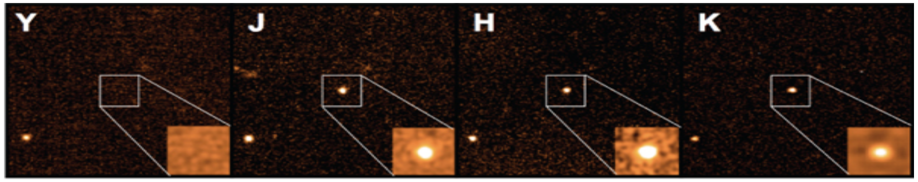


Figure 3 from *Spectroscopic Evidence for SN 2010ma Associated with GRB 101219B*
Sparre, Sollerman, Fynbo, et al. 2011 ApJ 735 L24



NR Tanvir *et al. Nature* **461**, 1254-1257 (2009)

KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2011 with one half to **Saul Perlmutter**, and the other half to **Brian P. Schmidt** and **Adam G. Riess** "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae".

Nobel Prize 2011 **in Physics**

Written in the stars

"Some say the world will end in fire; Some say in ice…"*

What is the ultimate fate of the Universe? Probably it will end in ice. This year's Nobel Laureates studied several dozen exploding stars, called supernovae, in faraway galaxies and have discovered that the expansion of the Universe is speeding up. The accelerating expansion of the Universe is one of the greatest enigmas in physics today.

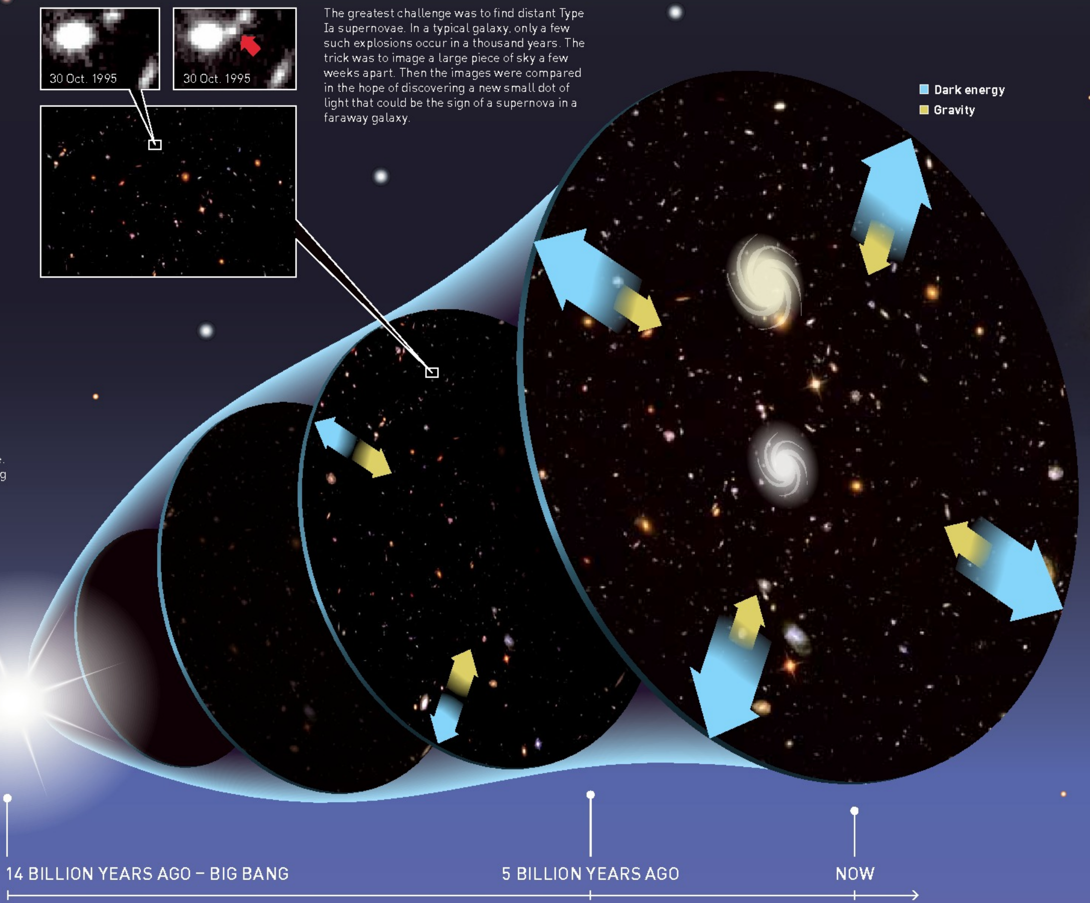
Saul Perlmutter headed one of the research teams, the Supernova Cosmology Project, initiated in 1988. Brian Schmidt headed another team of scientists, which, towards the end of 1994, launched a competing project, the High-z Supernova Search Team, in which Adam Riess was to play a crucial role.

The two research teams raced each other to map the Universe by discovering the most distant supernovae, stellar explosions in space. They hoped to reveal our cosmic fate by finding signs that the expansion of the Universe was slowing down. What they discovered was the opposite – the expansion is accelerating.

Saul Perlmutter
U.S. citizen. Born 1959 in Champaign-Urbana, IL, USA. Professor of Astrophysics, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, USA.

Brian P. Schmidt
U.S. and Australian citizen. Born 1967 in Missoula, MT, USA. Distinguished Professor, Australian National University, Weston Creek, Australia.

Adam G. Riess
U.S. citizen. Born 1969 in Washington, DC, USA. Professor of Astronomy and Physics, Johns Hopkins University and Space Telescope Science Institute, Baltimore, MD, USA.



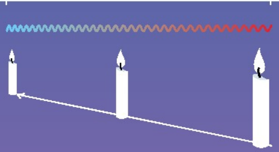
The greatest challenge was to find distant Type Ia supernovae. In a typical galaxy, only a few such explosions occur in a thousand years. The trick was to image a large piece of sky a few weeks apart. Then the images were compared in the hope of discovering a new small dot of light that could be the sign of a supernova in a faraway galaxy.

← Supernova 1994D in the outskirts of its galaxy NGC 4526. A supernova is a stellar explosion that, during a few weeks, can outshine its home galaxy.

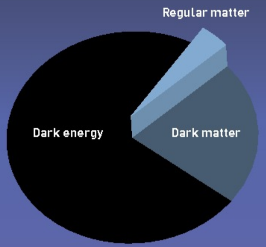
The expansion started with the Big Bang. During the first several billion years, the expansion slowed down due to gravitation from matter. However, about 5 billion years ago, when the unknown dark energy became dominant over matter, the expansion began to accelerate.

The researchers hoped to reveal the fate of the Universe by establishing how far away supernovae are from Earth and how much the Universe has expanded since they exploded.

All Type Ia supernovae shine with similar brightness, a property that makes them useful as "standard candles" to measure the distances to their home galaxies. The dimmer the supernova light, the farther away its galaxy.



When the galaxies are carried away, imbedded in the expanding Universe, the wavelength of light becomes longer and thus redder. This so-called redshift is useful in measuring how much the Universe has expanded since the light was emitted.



Cosmic puzzle. An unknown so-called dark energy is believed to be responsible for the accelerating expansion. Together with invisible "dark" matter the dark energy constitutes 95 percent of the Universe. Only the remaining 5 percent is regular matter that makes up galaxies, stars, flowers and humans.

FURTHER READING! Information on the Nobel Prize in Physics 2011: *http://kva.se/nobelprizephysics2011* and *http://nobelprize.org* **POPULAR SCIENCE ARTICLES:** ● **Leibundgut, B., Sollerman, J.** [2001] A Cosmological Surprise: the Universe Accelerates, *Europhysics News*, vol. 32, nr 4. ● **Perlmutter, S.** [2003] Supernovae, Dark Energy and the Accelerating Universe, *Physics Today*, vol. 56, no. 4. ● **Krauss, L.M., Turner, M.S.** [2004] A Cosmic Conundrum, *Scientific American*, 23 August. ● **Riess, A.G., Turner, M.S.** [2008] The Expanding Universe: From Slowdown to Speedup, *Scientific American*, 12 January. ● **Appell, D.** [2008] Dark Forces at Work, *Scientific American*, 21 April. **WEBSITE:** ● Runaway Universe, *www.pbs.org/wgbh/nova/universe/* **BOOKS:** ● **Livio, M.** [2000] *The Accelerating Universe*, Wiley, New York. ● **Goldsmith, D.** [2000] *The Runaway Universe*, Perseus Books, Cambridge MA. ● **Panek, R.** [2011] *The Four Percent Universe: Dark Matter, Dark Energy, and the Race to Discover the Rest of Reality*, Houghton Mifflin Harcourt. **SCIENTIFIC ARTICLES:** ● **Riess, A.G. et al.** [1998] Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant, *Astronomical Journal*, 116, 1009-1038. ● **Perlmutter, S. et al.** [1999] Measurement of Ω and Λ from 42 High-Redshift Supernovae, *Astrophysical Journal*, 517, 565-586. ● **Perlmutter, S., Schmidt, B.P.** [2003] Measuring Cosmology with Supernovae, *Lecture Notes in Physics* , 598, 195.

FOOTNOTE: *Robert Frost, *Fire and Ice*, 1920.

PHOTO: Saul Perlmutter portrait, Lawrence Berkeley National Laboratory; Brian P. Schmidt portrait, The Australian National University; Adam G. Riess portrait, Will Kirk/The Johns Hopkins University; Supernova 1994D, Hubble Space Telescope.

Editors: Lars Bergström, Olga Botner, Lars Brink, Börje Johansson, The Nobel Committee for Physics, The Royal Swedish Academy of Sciences, Rahman Amanullah and Jesper Sollerman, Stockholm university, Joanna Rose/Joanna Rose Vet, Science writer, Annika Moberg, Editor, The Royal Swedish Academy of Sciences. Illustration: Johan Jarnestad/Swedish Graphics Layout: Ritator Tryck: Åtta45

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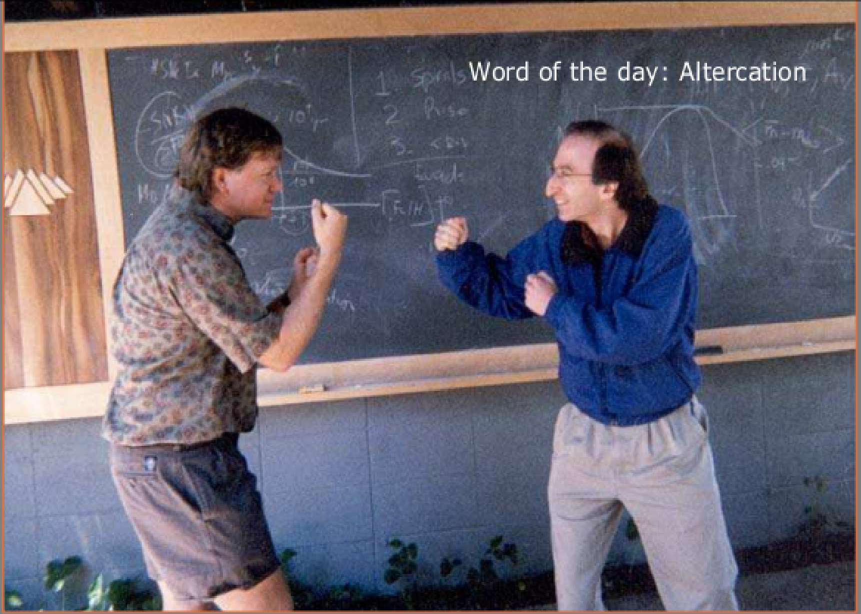
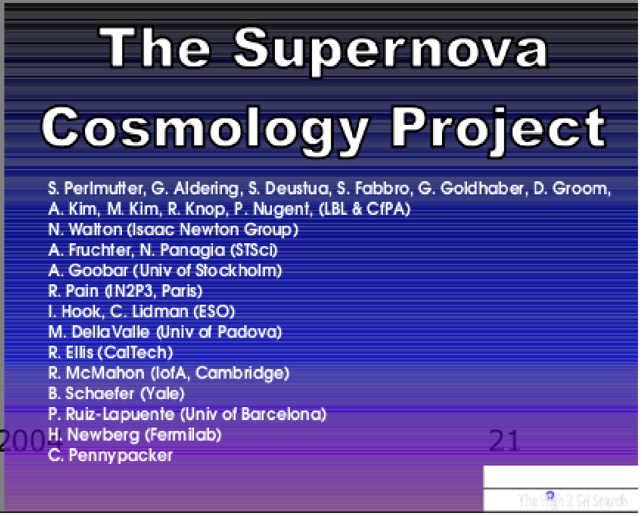


Word of the day: Altercation

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



The Supernova Cosmology Project

S. Perlmutter, G. Aldering, S. Deustua, S. Fabbro, G. Goldhaber, D. Groom, A. Kim, M. Kim, R. Knop, P. Nugent, (LBL & CfPA)
N. Walton (Isaac Newton Group)
A. Fruchter, N. Panagia (STScI)
A. Goobar (Univ of Stockholm)
R. Pain (IN2P3, Paris)
I. Hook, C. Lidman (ESO)
M. DellaValle (Univ of Padova)
R. Ellis (CalTech)
R. McMahon (IofA, Cambridge)
B. Schaefer (Yale)
P. Ruiz-Lapuente (Univ of Barcelona)
H. Newberg (Fermilab)
C. Pennypacker

The High-Z SN Search

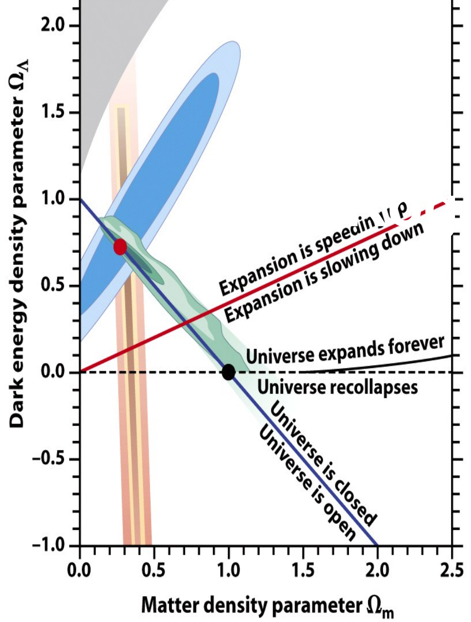


Figure 26-19
Universe, Eighth Edition

er A. Freedman • William J. Kaufmann III

Universe

Eighth Edition

CHAPTER 26

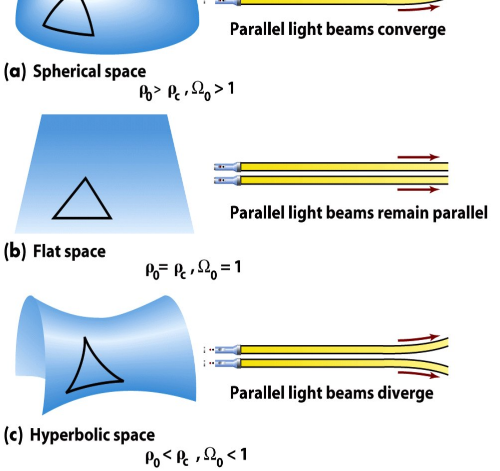


Figure 26-15
Universe, Eighth Edition

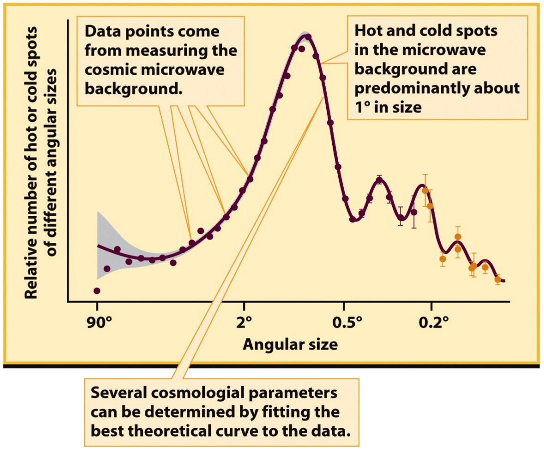
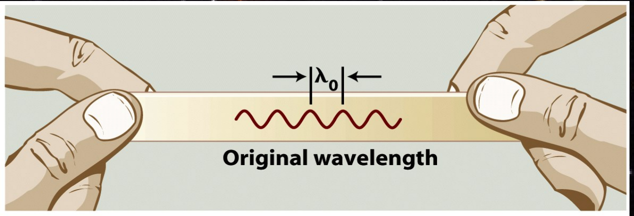
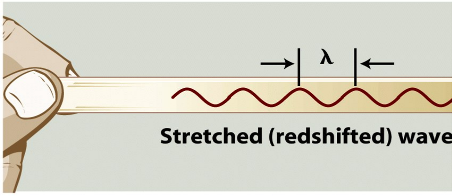


Figure 26-21
Universe, Eighth Edition



(a) A wave drawn on a rubber band ...



(b) ... increases in wavelength as the rubber

Figure 26-4
Universe, Eighth Edition

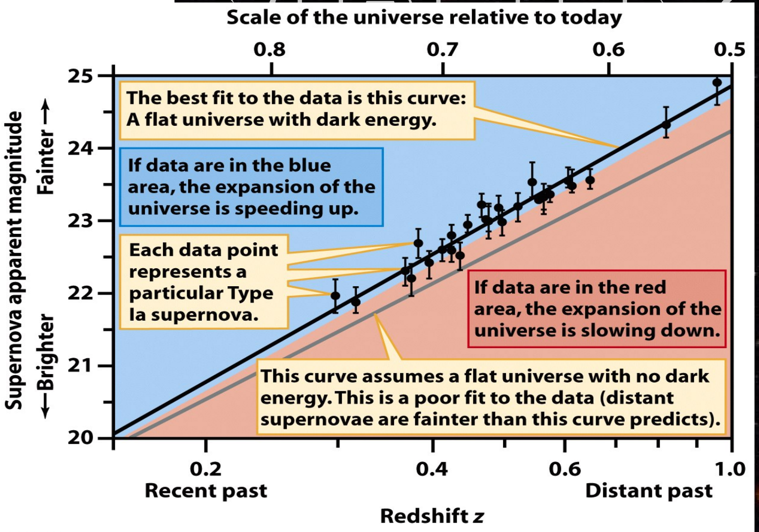


Figure 26-18
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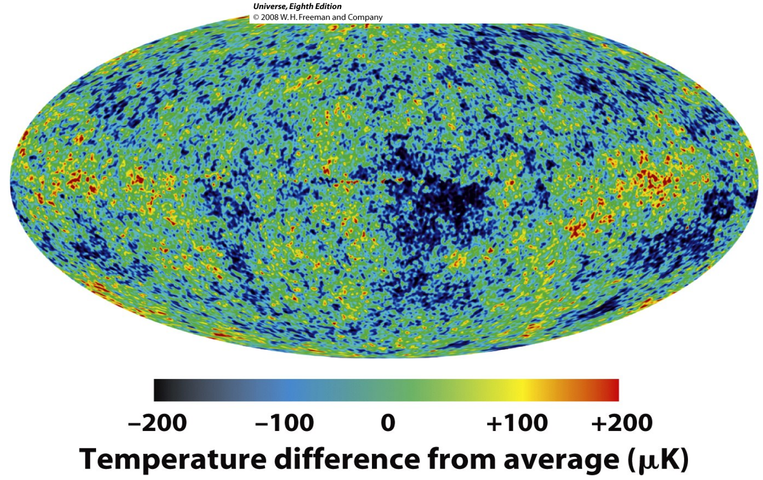


Figure 26-14
Universe, Eighth Edition

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

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

ADAM G. RIESS, ALEXEI V. FILIPPENKO, PETER CHALLIS, ALEJANDRO CLOCCHIATTI, ALAN DIERCKS, PETER M. GARNAVICH, RON L. GILLILAND, CRAIG J. HOGAN, SAURABH JHA, ROBERT P. KIRSHNER, B. LEIBUNDGUT, M. M. PHILLIPS, DAVID REISS, BRIAN P. SCHMIDT, ROBERT A. SCHOMMER, R. CHRIS SMITH, J. SPYROMILIO, CHRISTOPHER STUBBS, NICHOLAS B. SUNTZEFF, AND JOHN TONRY

Article Contents

1929 The Expansion of the Universe $v = H * d$

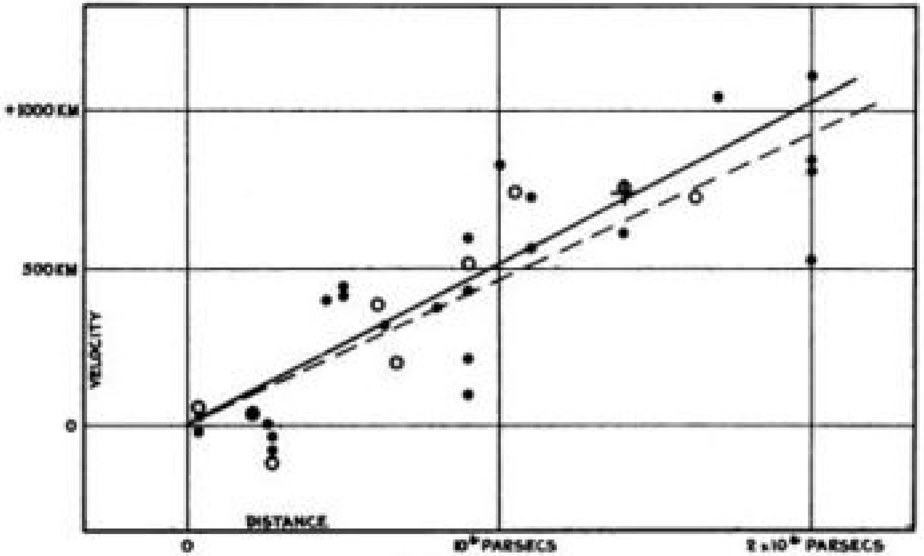
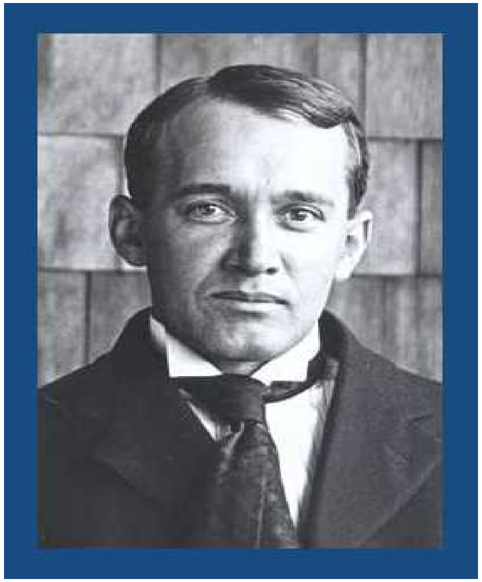


FIGURE 1

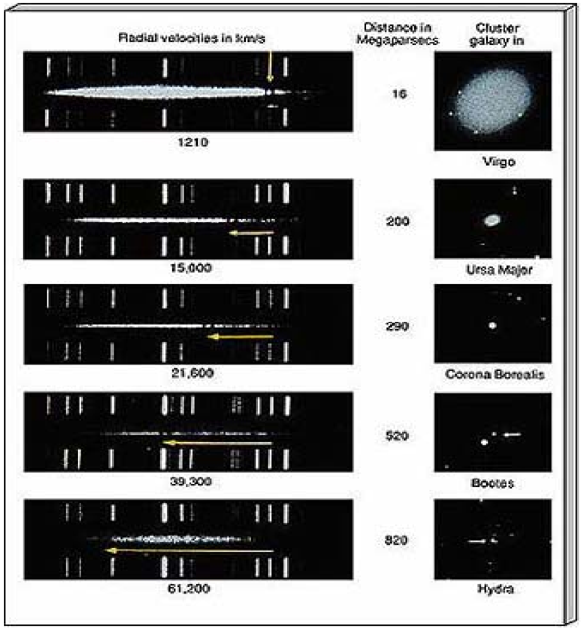
Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.



Slipher

Humason



Carl Wirtz
Knut Lundmark
George Lemaitre

http://arxiv.org/ftp/arxiv/papers/1106/1106.1195.pdf
http://hubblesite.org/pubinfo/pdf/2011/36/pdf.pdf

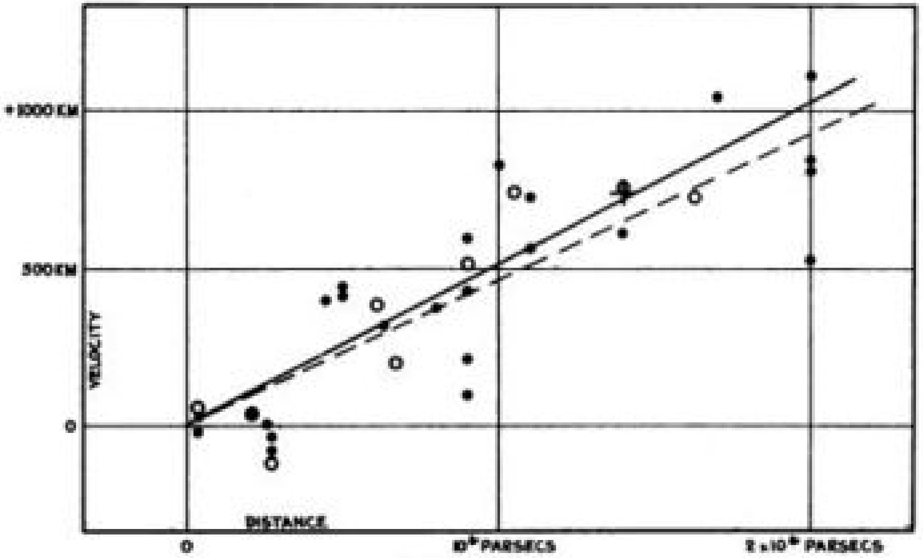


FIGURE 1

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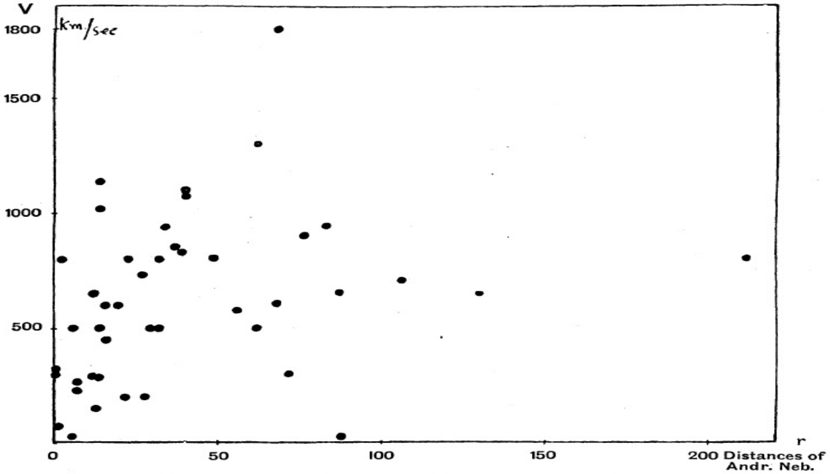
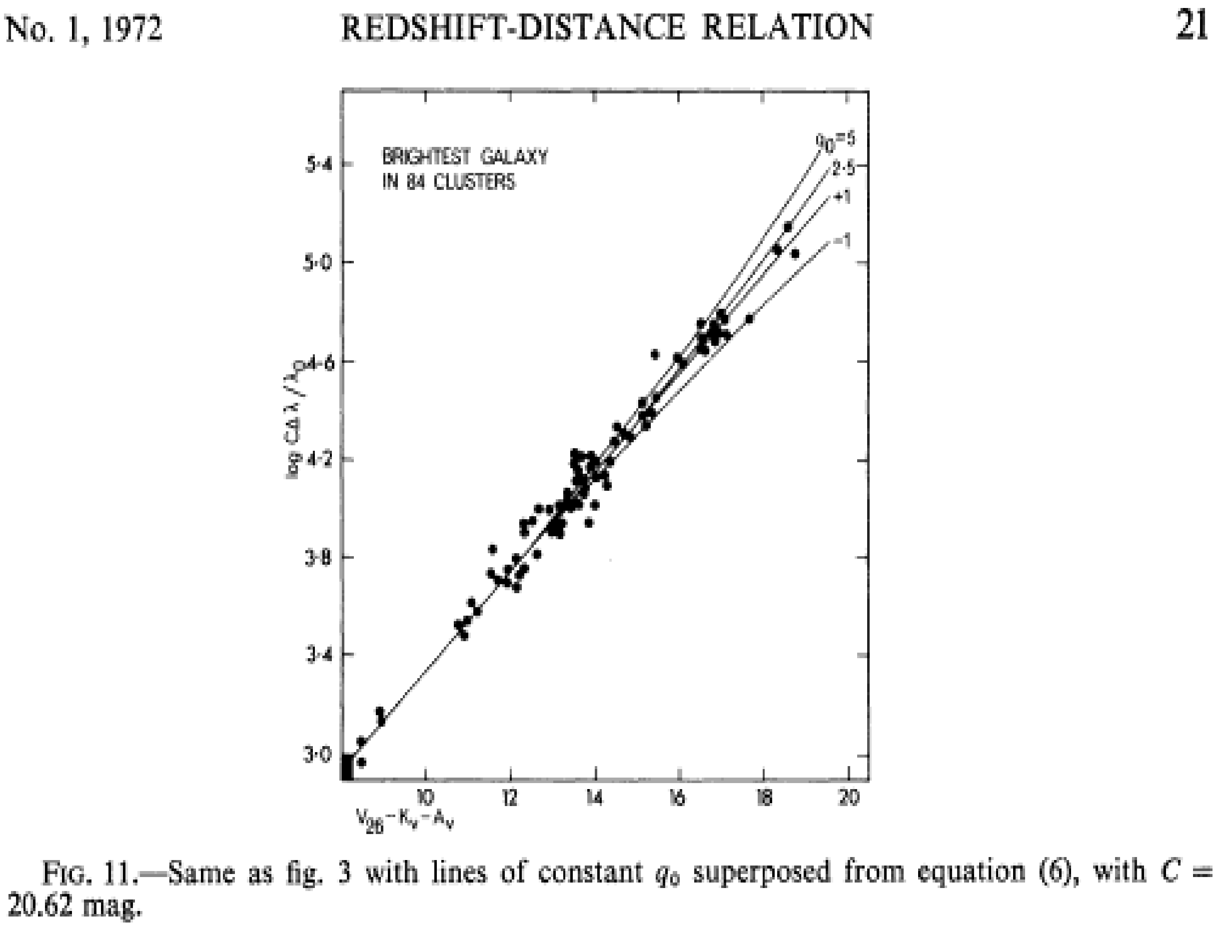


FIG. 5.—Relation between the relative distances (the unit is the distance of the Andromeda nebula) and the measured radial velocities of spiral nebulæ.

Lundmark 1924



No. 1, 1972 REDSHIFT-DISTANCE RELATION 21

FIG. 11.—Same as fig. 3 with lines of constant q_0 superposed from equation (6), with $C =$ 20.62 mag.

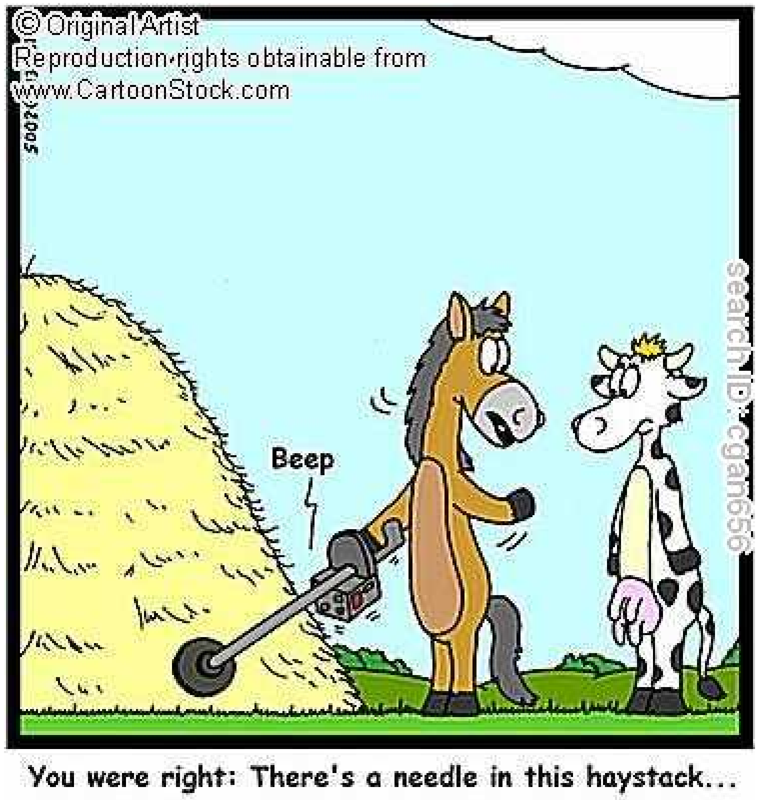
q > ½ → collapse
q < ½ → expansion
q < 0 → acceleration

Allan Sandage 1972,

q0=0.96

Kowal 1968, SNe I → H_0
Colgate 1979, SNe I → q_0

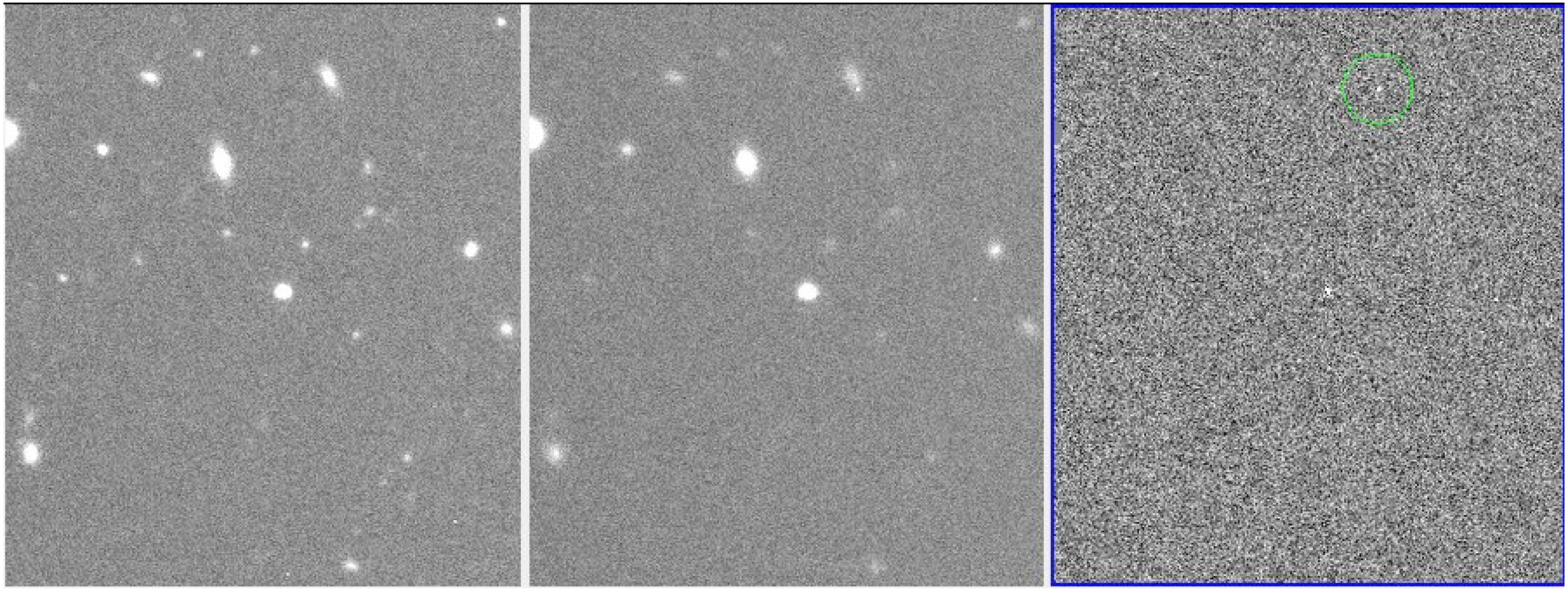
How to find supernovae?



You were right: There's a needle in this haystack...

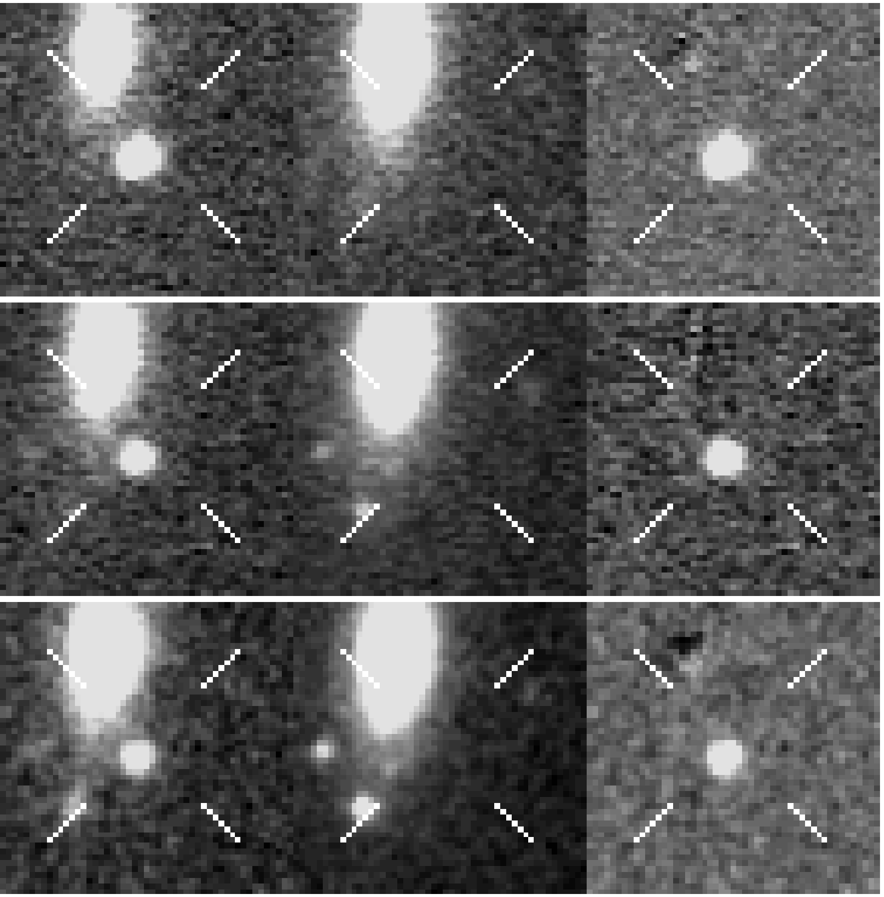
Time

~1990

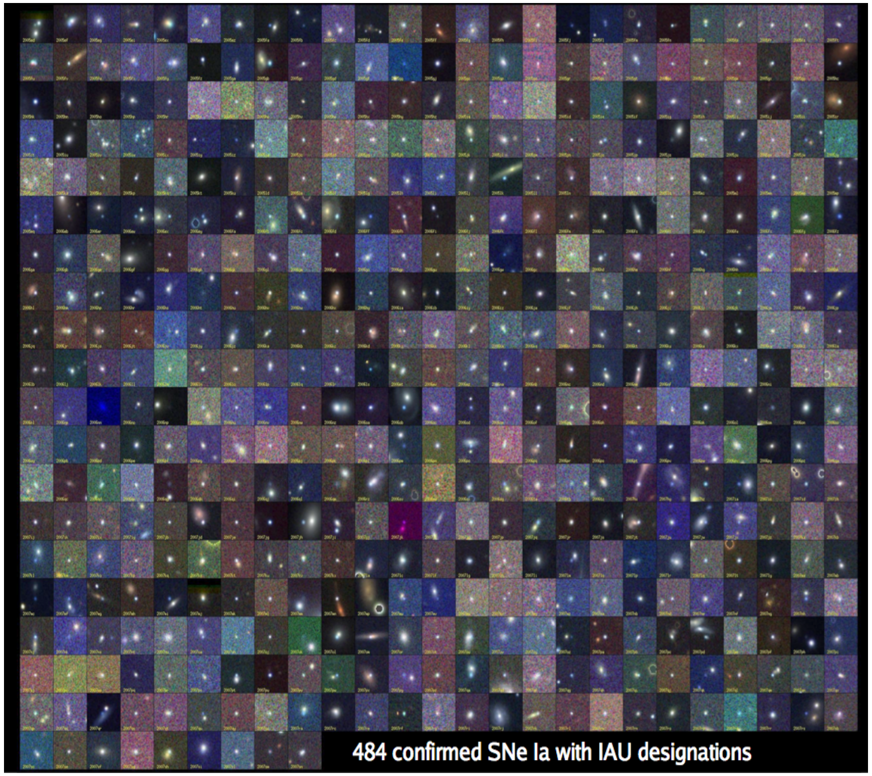


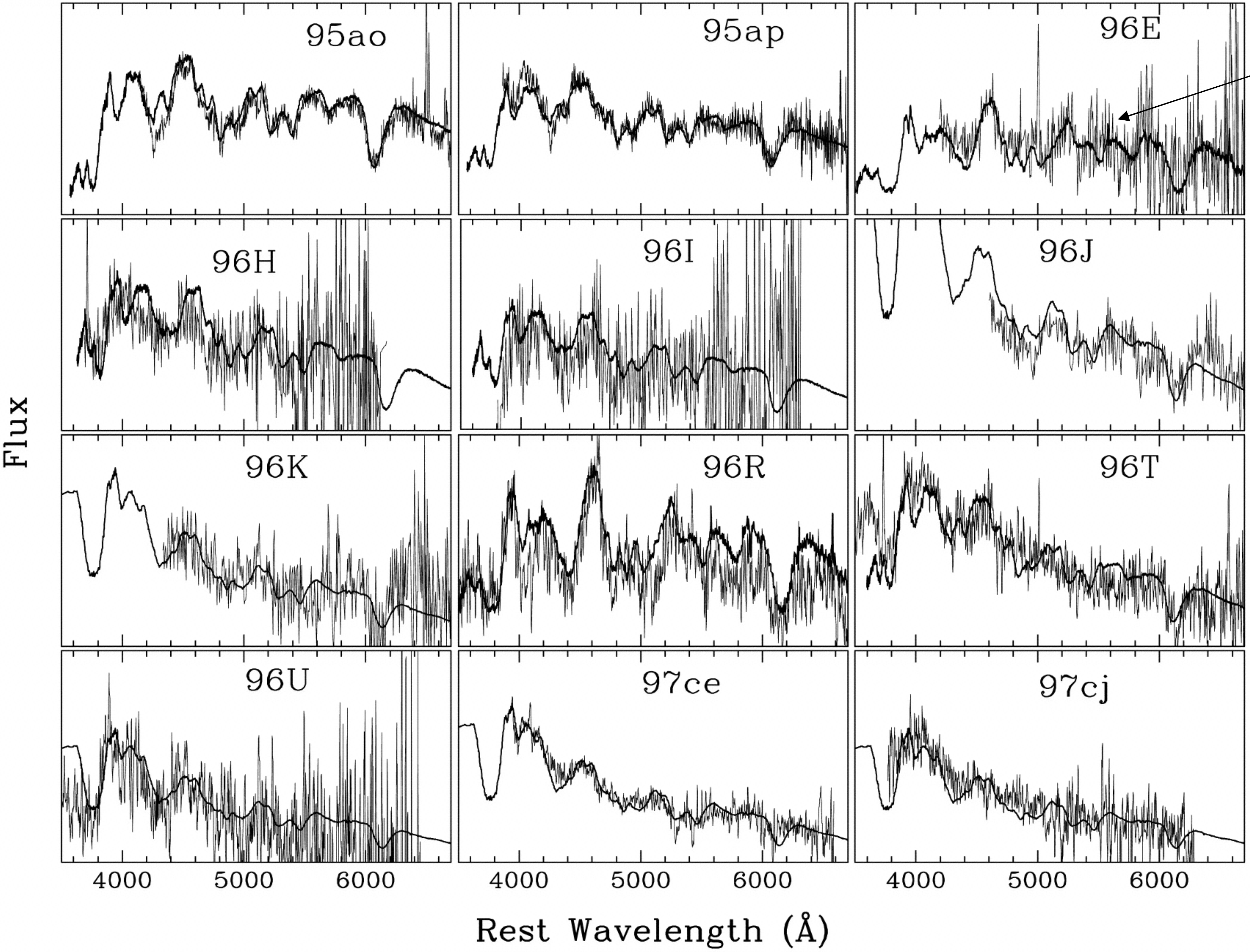
Danes found SN 1988U @ z=0.31 in 2 years search

Blanco 4m Telescope Cerro Tololo Inter-American Observatory



SDSS





ESO
3.6m

Getting the spectra → SNe Ia + redshift.

Riess et al. 1998, Figure 1

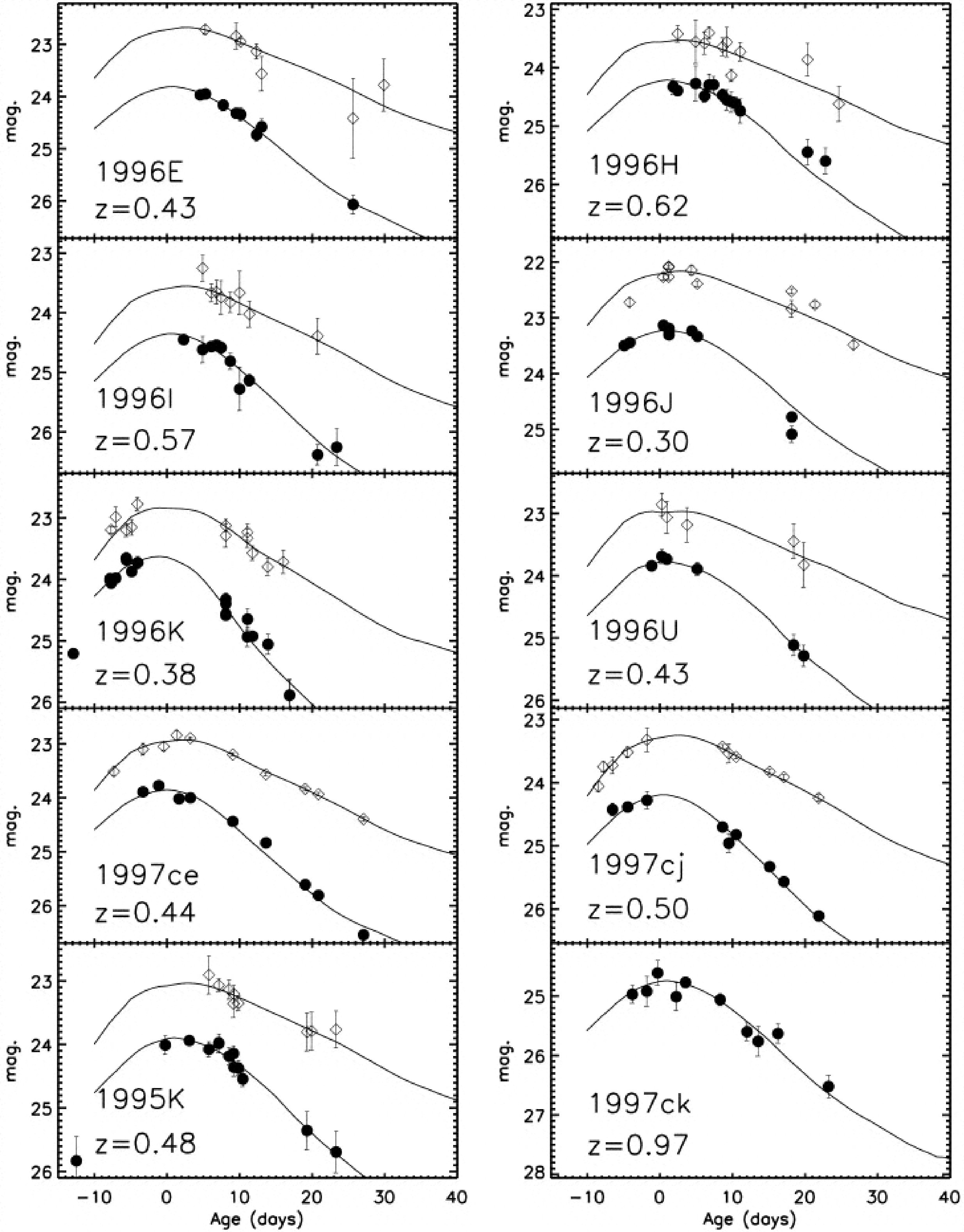
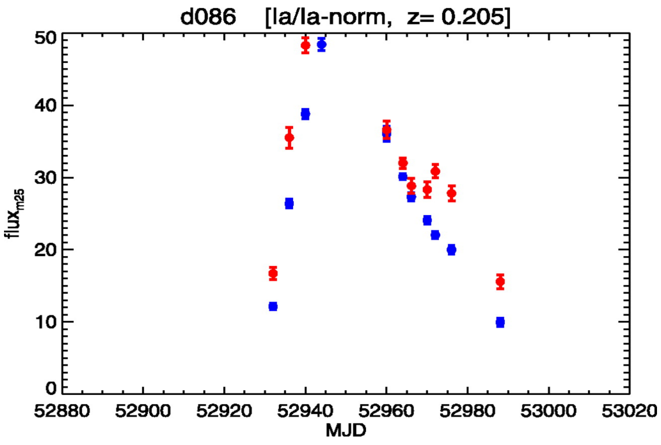


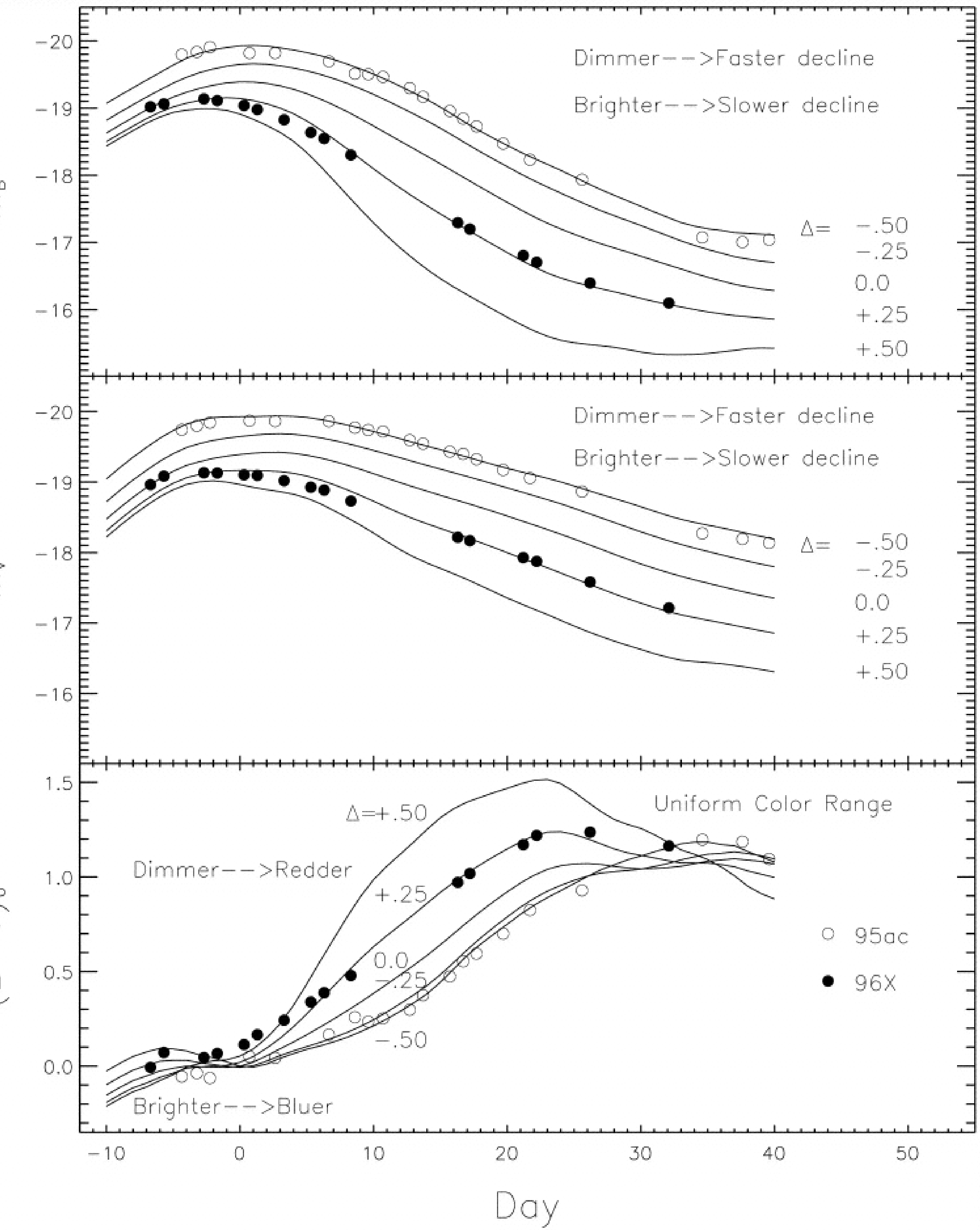
Fig. 2 Riess et al. 1998

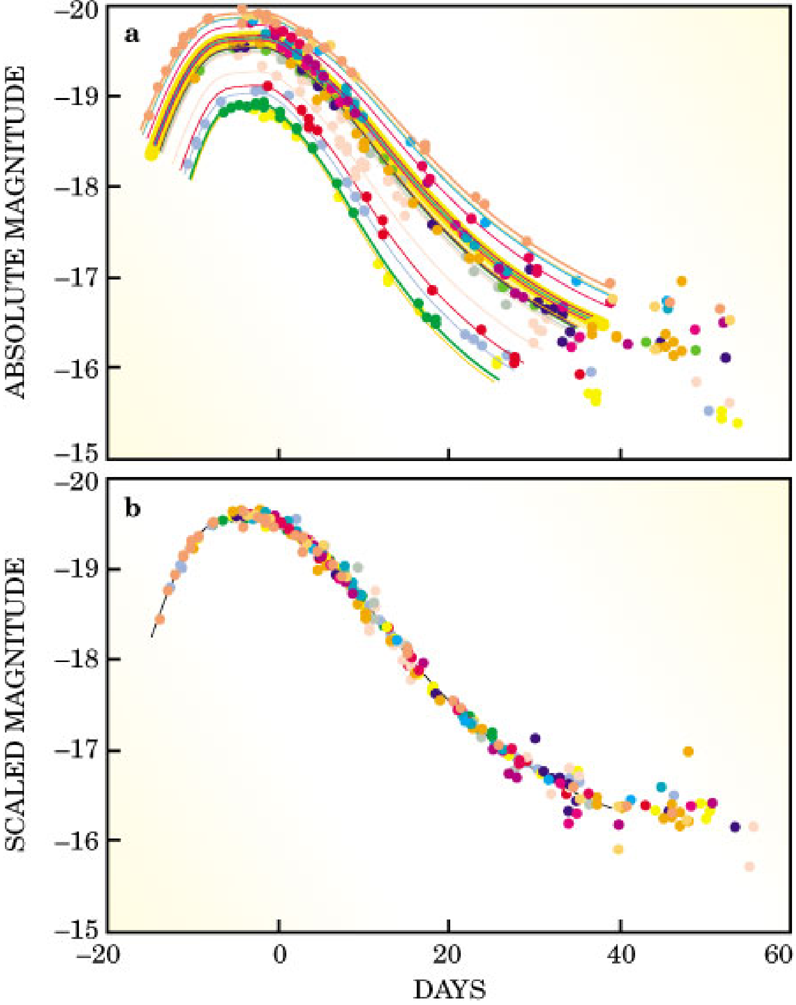
The lightcurves

With a variety of 1-4m class telescopes, B (35,45) and V (35,45) filters



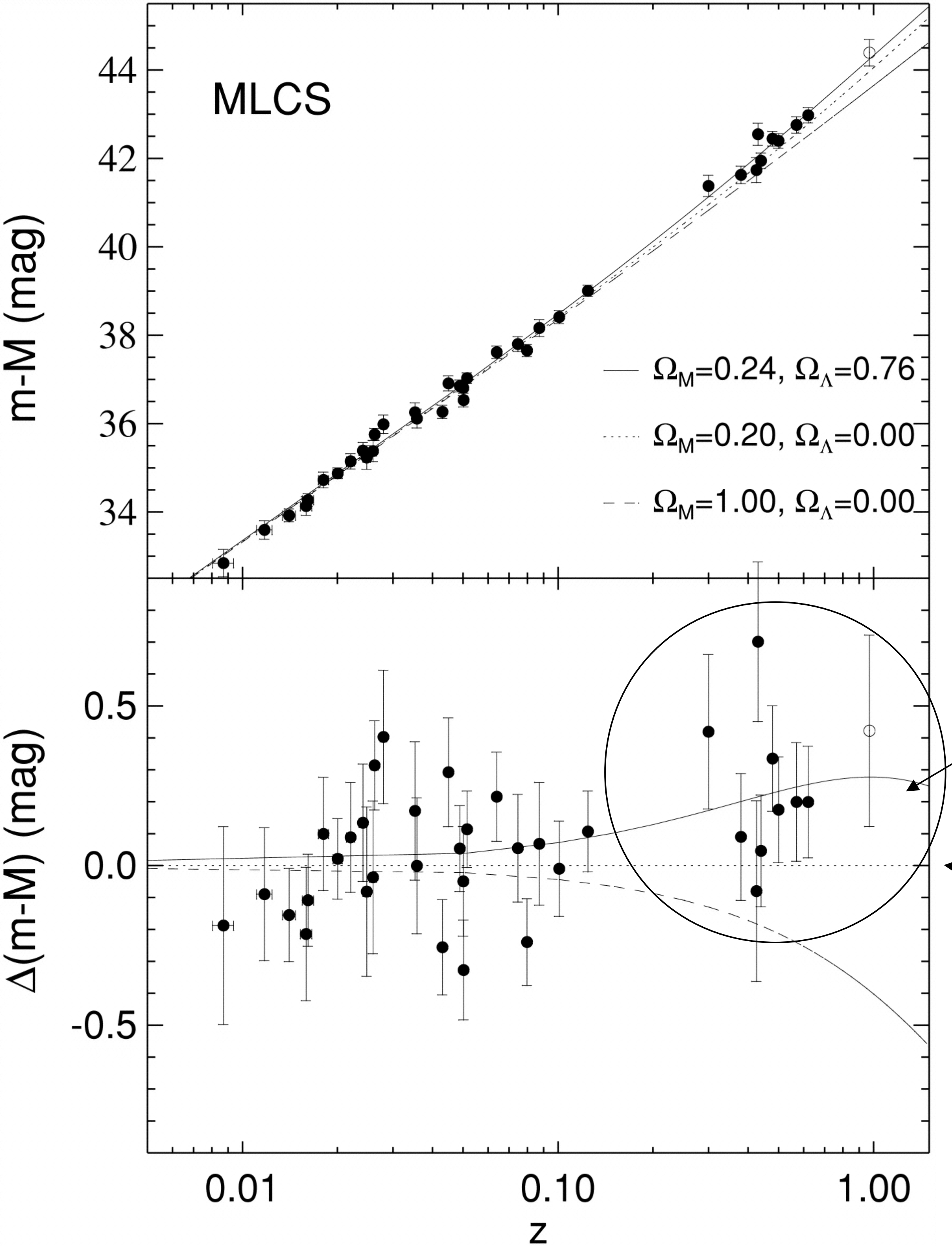
Miknaitis et al. 2007; ESSENCE; CTIO





Riess et al. Figure. 13.
—MLCS
Multi LightCurve Shape Fitter

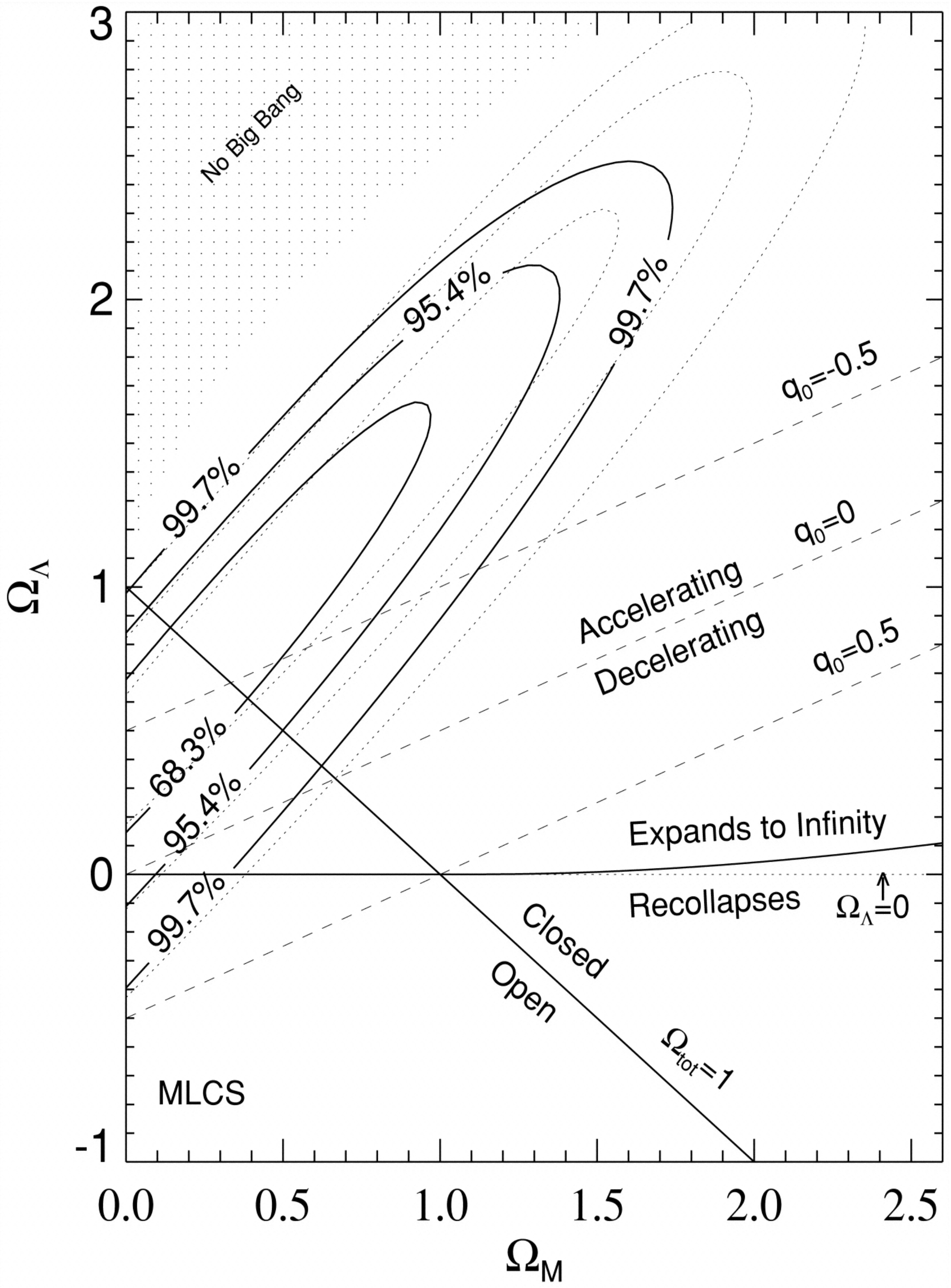
Riess et al. 1998



MLCS SNe Ia Hubble diagram. The upper panel shows the Hubble diagram for the low-redshift and high-redshift SNe Ia samples with distances measured from the MLCS method. Overplotted are 3 cosmologies: "low" and "high" ΩM with $\Omega\Lambda = 0$ and the best fit for a flat cosmology, $\Omega M = 0.24$, $\Omega\Lambda = 0.76$.

The bottom panel shows the difference between data and models with $\Omega M = 0.20$, $\Omega\Lambda = 0$.

The open symbol is SN 1997ck (z = 0.97), which lacks spectroscopic classification. The average difference between the data and the $\Omega M = 0.20$, $\Omega\Lambda = 0$ prediction is 0.25 mag.



Riess et a. 1998;
FIG. 6.—Joint confidence intervals for (ΩM, ΩΛ) from SNe Ia.

The solid contours are results from the MLCS method applied to well-observed SNe Ia light curves together with the snapshot method applied to incomplete SNe Ia light curves. The dotted contours are for the same objects excluding the unclassified SN 1997ck (z = 0.97). Regions representing specific cosmological scenarios are illustrated. Contours are closed by their intersection with the line ΩM = 0.

Article Contents

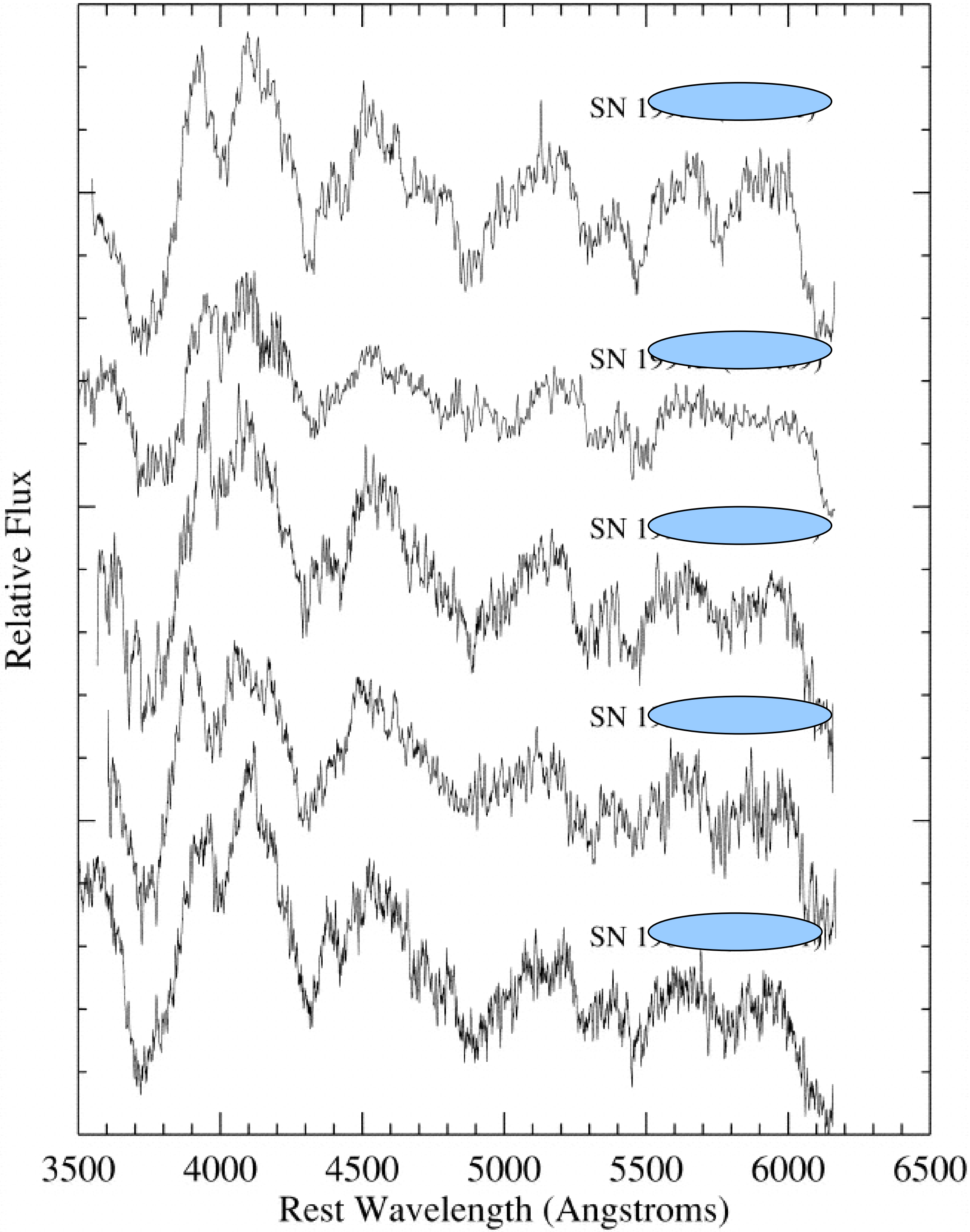


FIG. 11.— Riess et al.

Spectral comparison (in fλ) of SN. The spectra of the low-redshift SNe Ia were resampled and convolved with Gaussian noise.

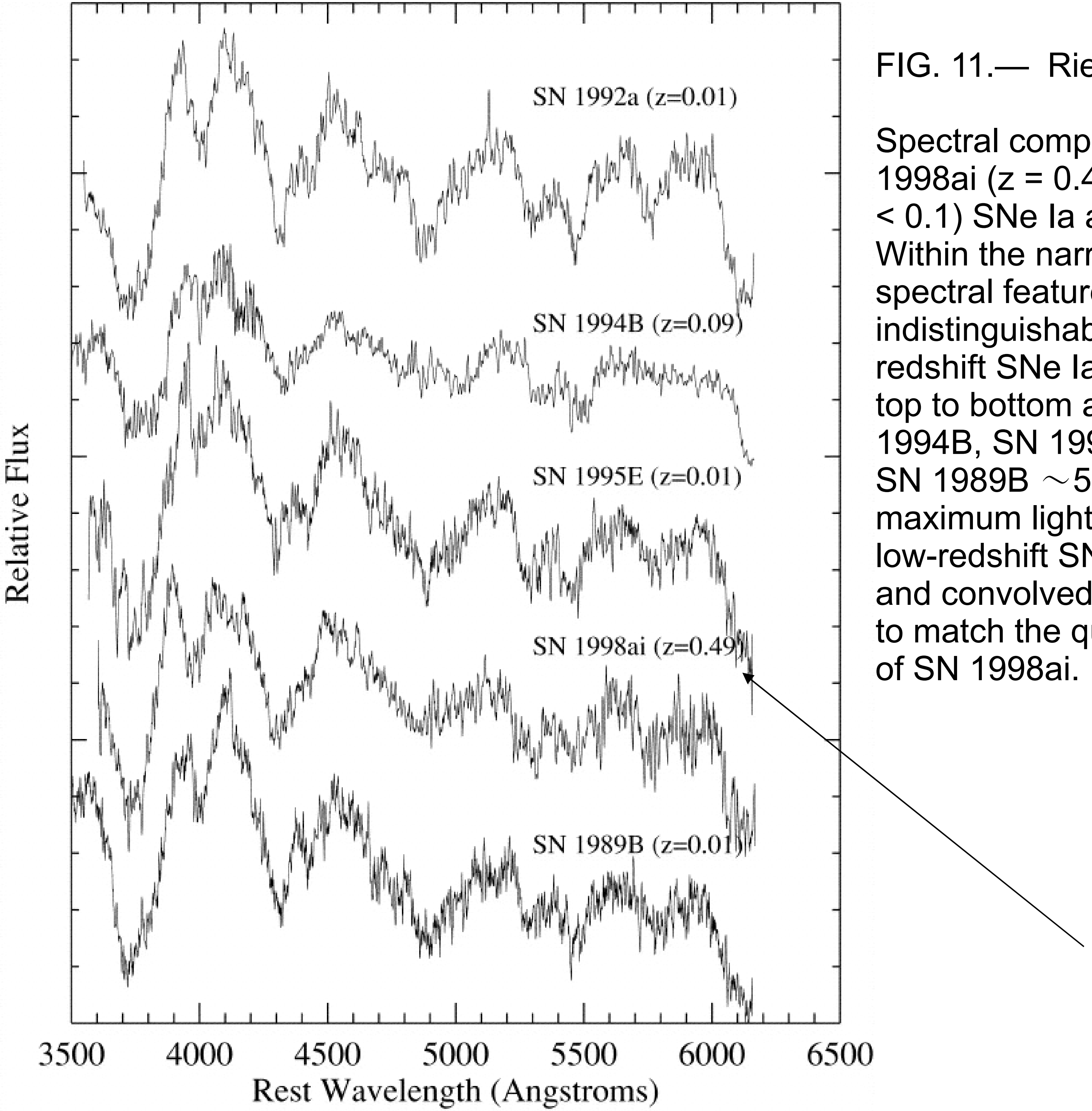
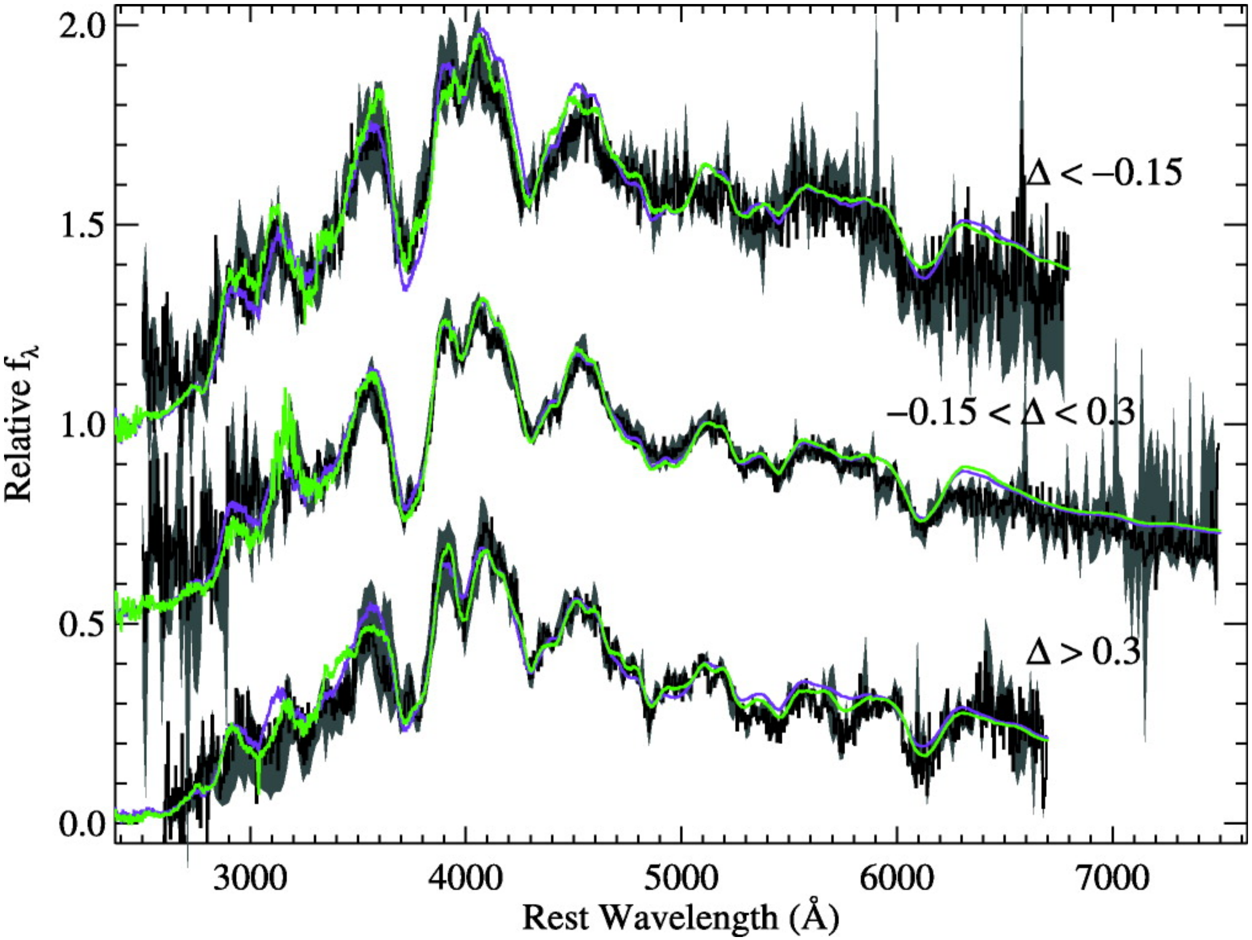


FIG. 11.— Riess et al.

Spectral comparison (in fλ) of SN 1998ai (z = 0.49) with low-redshift (z < 0.1) SNe Ia at a similar age. Within the narrow range of SN Ia spectral features, SN 1998ai is indistinguishable from the low-redshift SNe Ia. The spectra from top to bottom are SN 1992A, SN 1994B, SN 1995E, SN 1998ai, and SN 1989B ∼5 days before maximum light. The spectra of the low-redshift SNe Ia were resampled and convolved with Gaussian noise to match the quality of the spectrum of SN 1998ai.

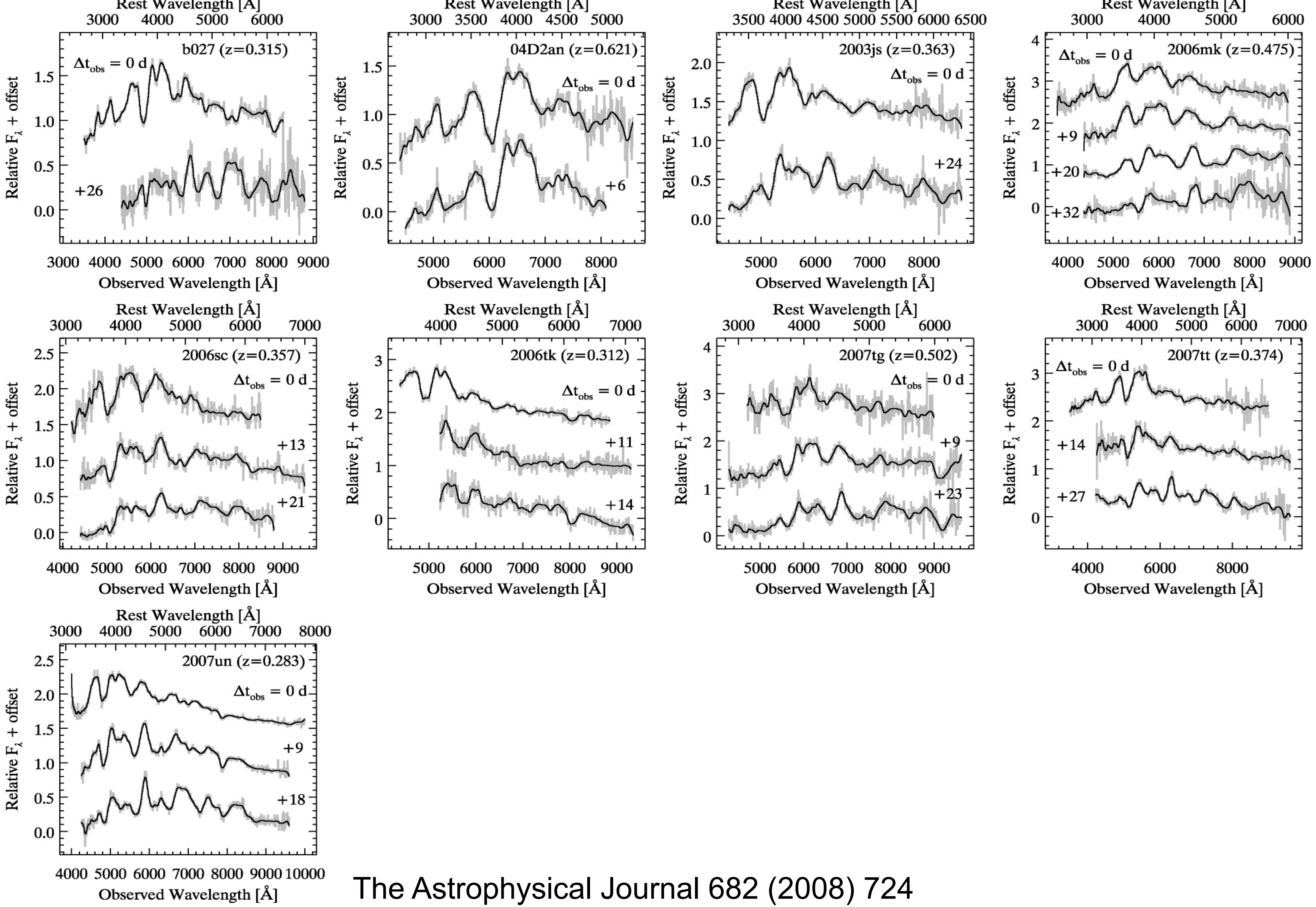


ESSENCE maximum light composite SN Ia spectra for different Δ bins.

The composite spectra consist of 3 (10), 14 (18), and 15 (9) individual spectra with average Δ of 0.33, (0.43), 0.01 (–0.05), and –0.32 (–0.28) for the underluminous, normal, and overluminous subsamples defined by Jha et al. (2006) for the ESSENCE (Lick) sample, respectively. All have average redshifts of ~0.3. The gray regions are the 1 σ bootstrap variation. The green lines are the Lick composite comparison spectra. The purple lines are the total Lick composite spectrum.

Foley et al. (ESSENCE) The Astrophysical Journal 684 (2008) 68

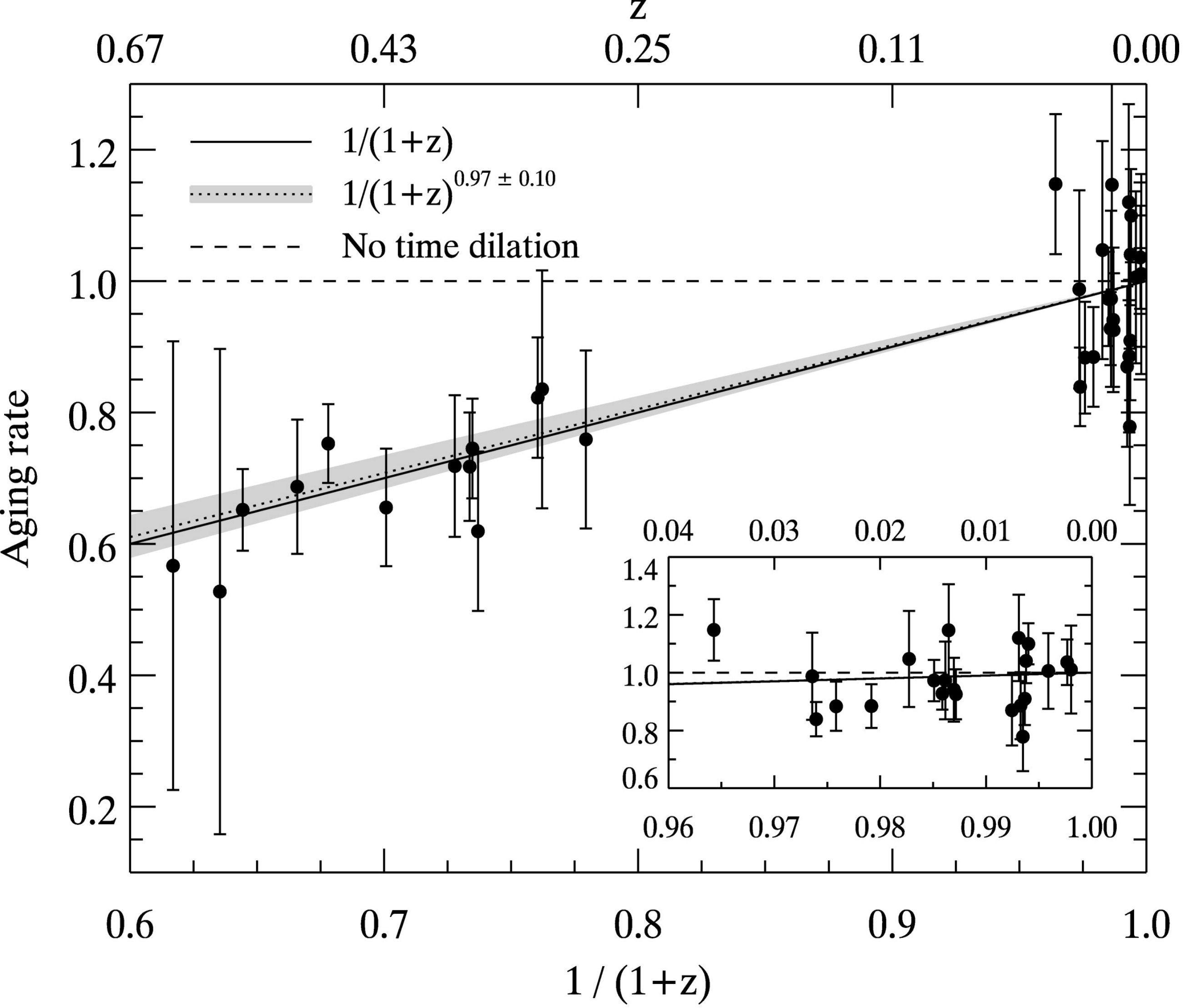
Constraining Cosmic Evolution of Type Ia Supernovae

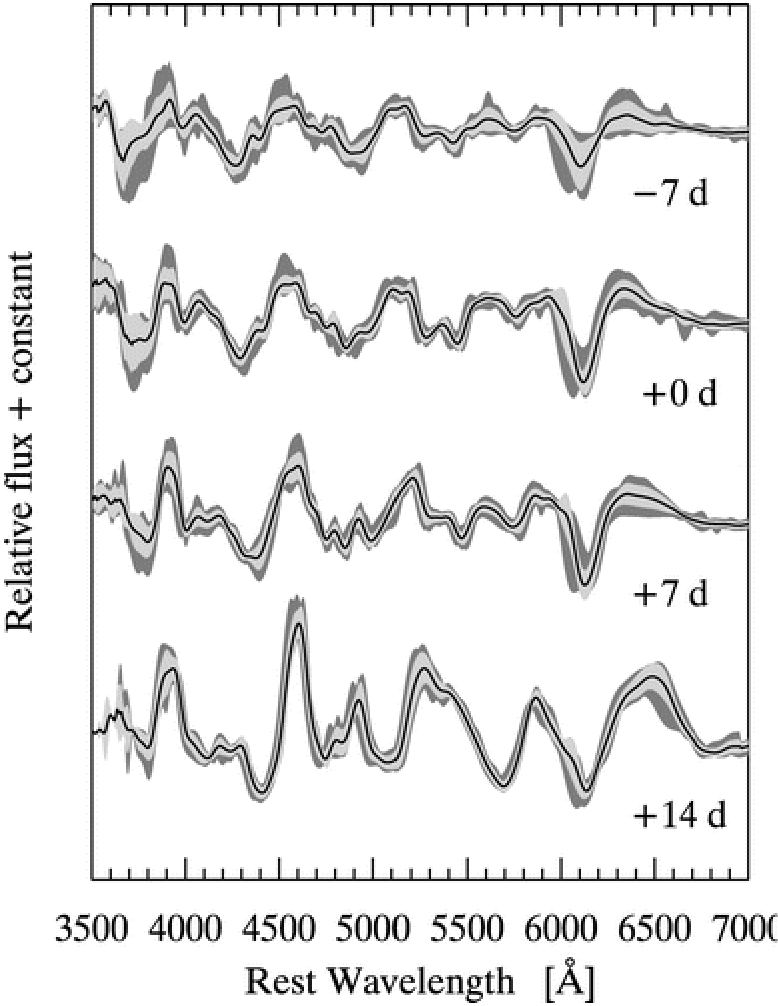


The Astrophysical Journal 682 (2008) 724

Time Dilation in Type Ia Supernova Spectra at High Redshift

S. Blondin, T. M. Davis, K. Krisciunas, B. P. Schmidt, J. Sollerman et al.





The Astrophysical Journal 682 (2008) 724

Time Dilation in Type Ia Supernova Spectra at High Redshift

S. Blondin, T. M. Davis, K. Krisciunas, B. P. Schmidt, J. Sollerman et al.

Article Contents

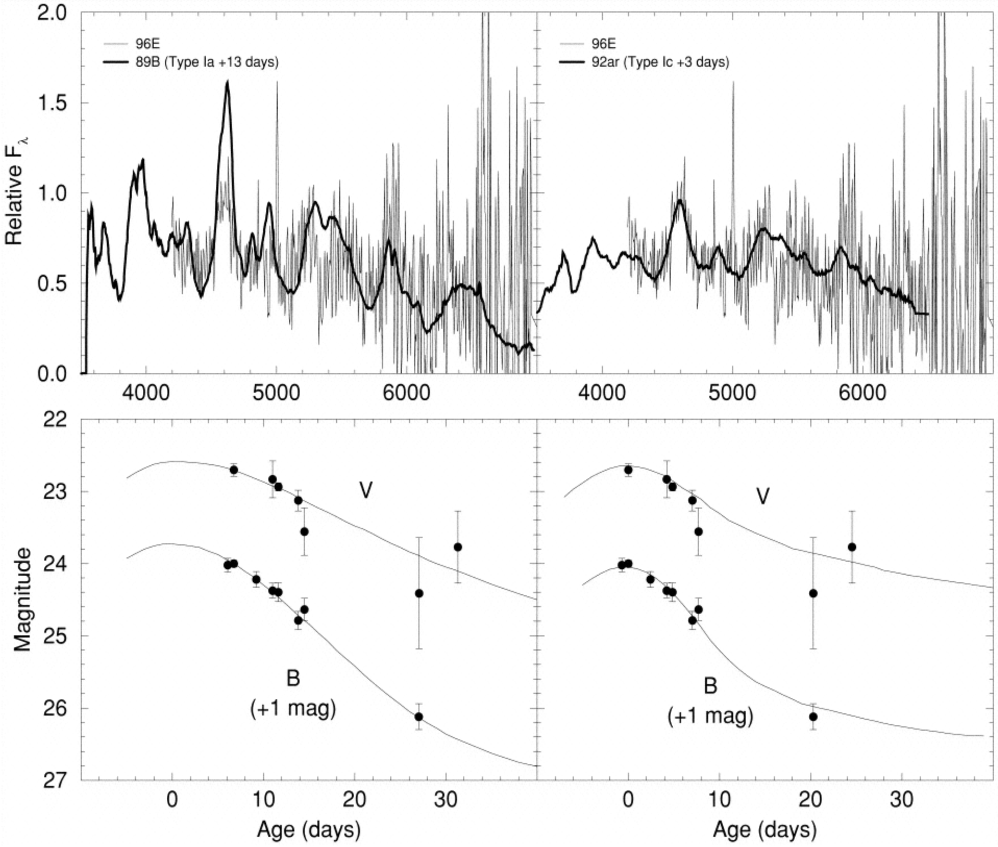
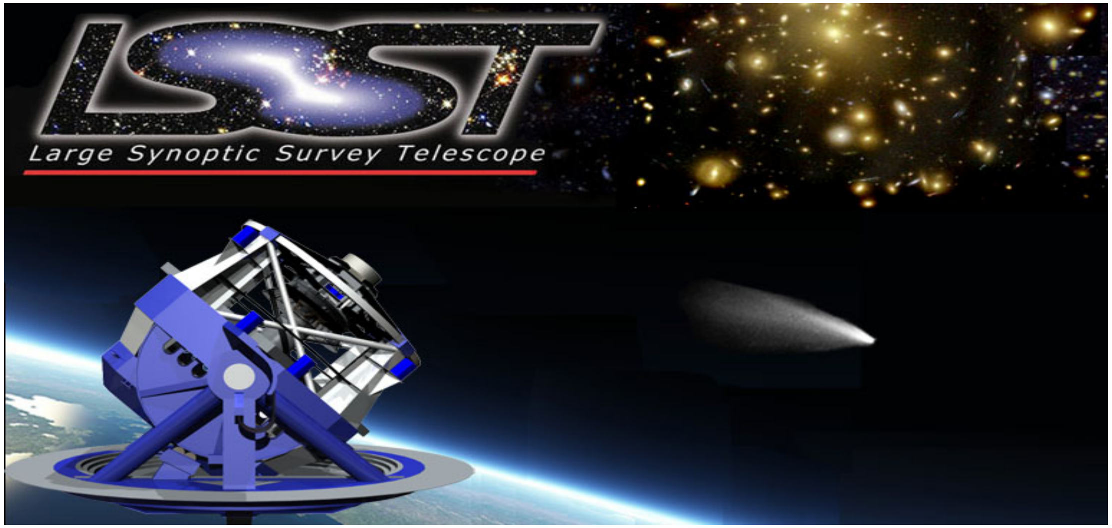
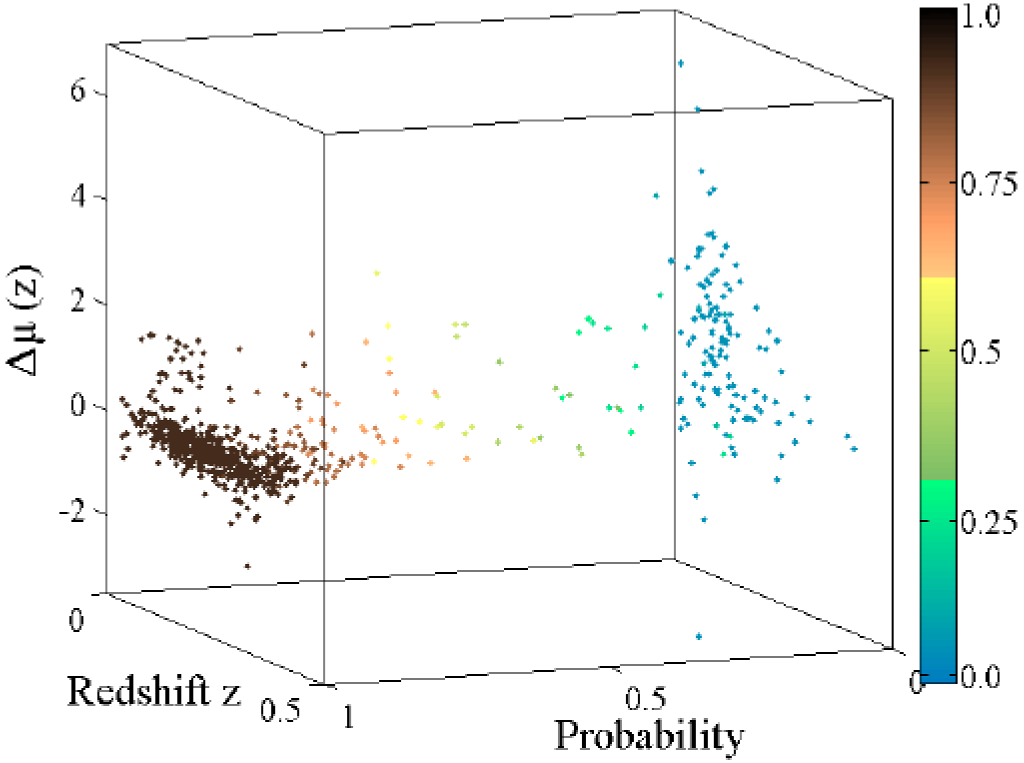


FIG. 12.— Riess et al. 1998

Comparison of the spectral and photometric observations of SN 1996E to those of Type Ia and **Type Ic** supernovae. The low signal-to-noise ratio of the spectrum of SN 1996E and the absence of data blueward of 4500 Å makes it difficult to distinguish between a Type Ia and Ic classification. The light and color curves of SN 1996E are also consistent with either supernova type. The spectrum was taken 6 days (rest frame) after the first photometric observation.





Hzolek et al. 2012, BEAMS & SDSS-II, arXiv 22 november 2011

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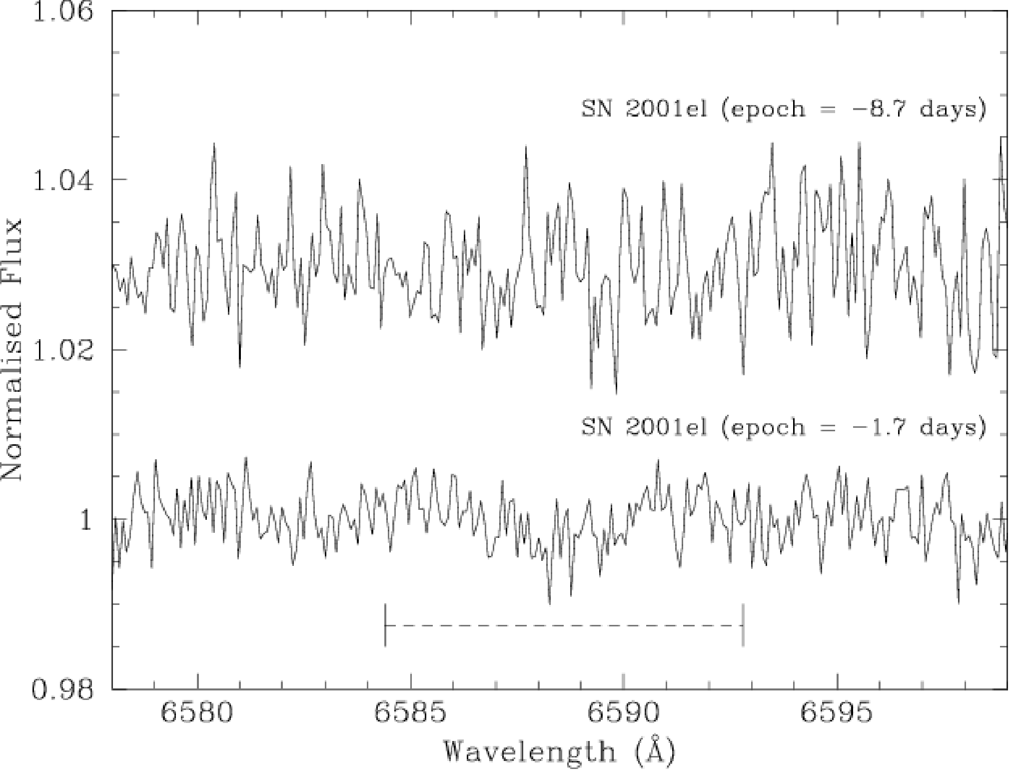
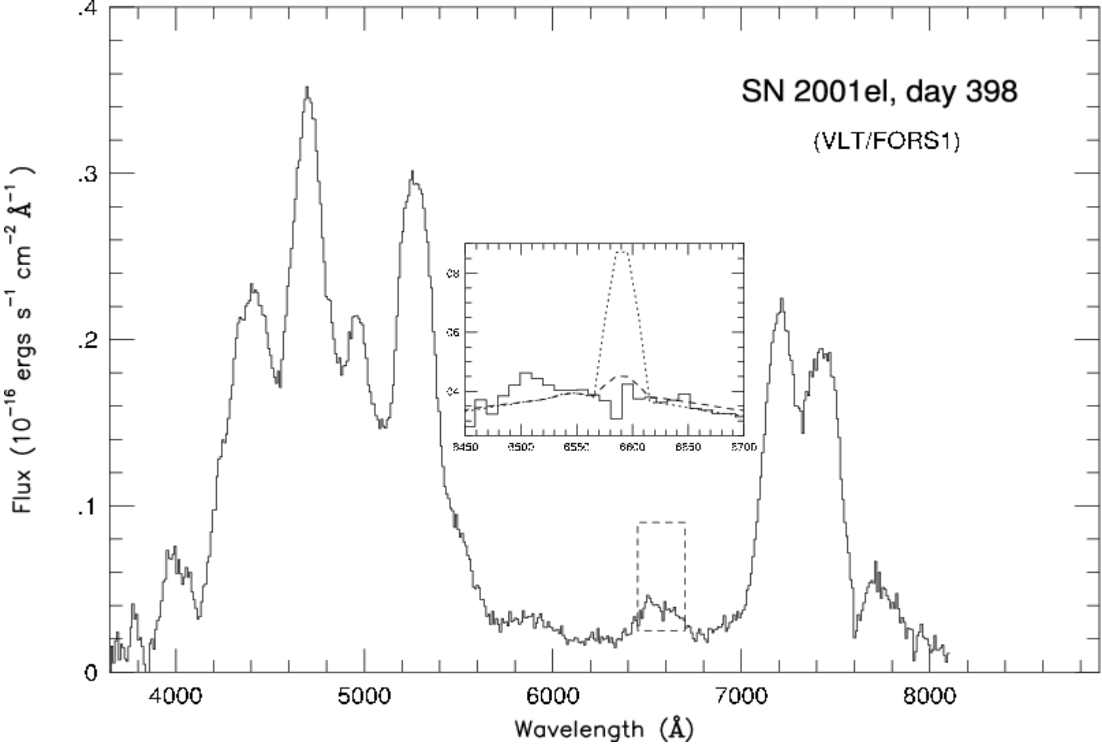
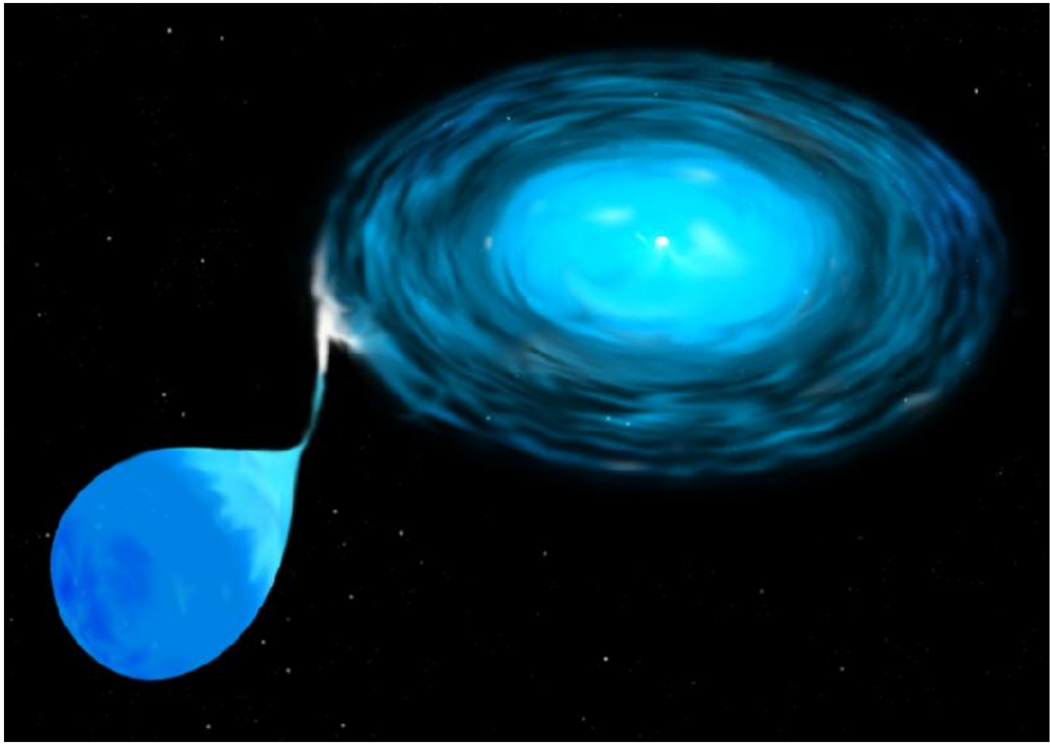
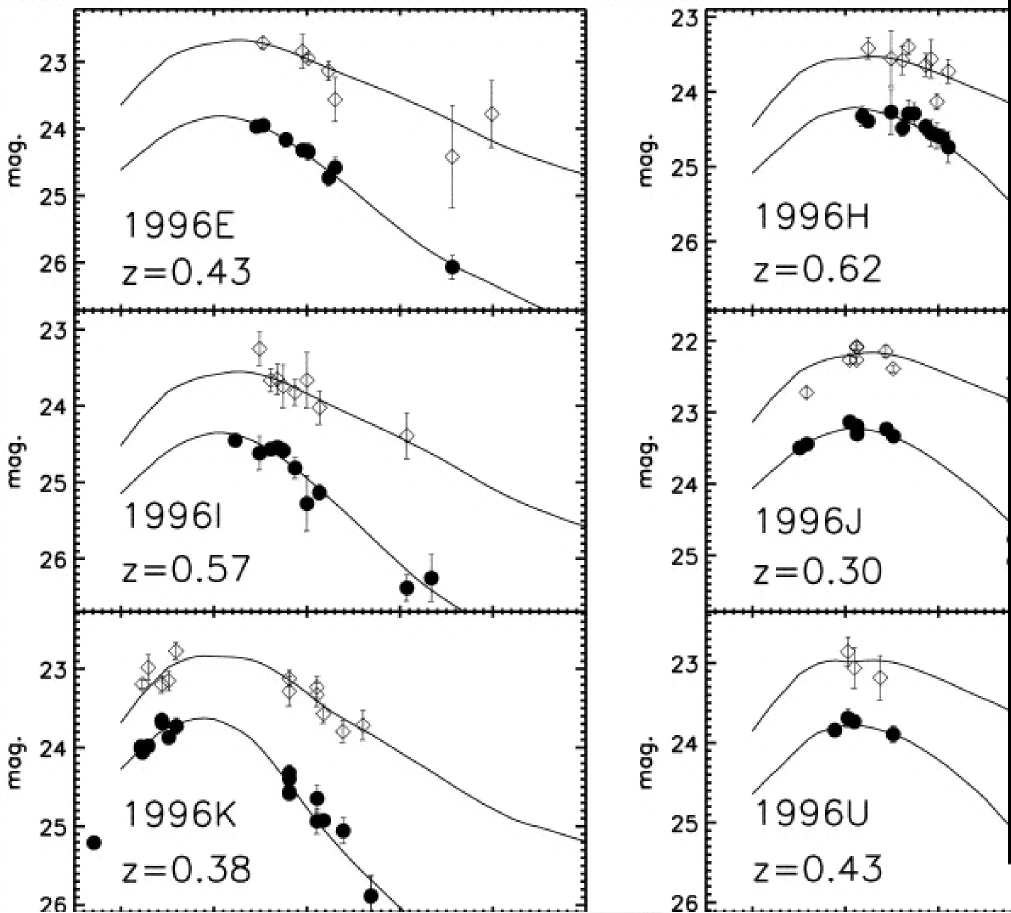
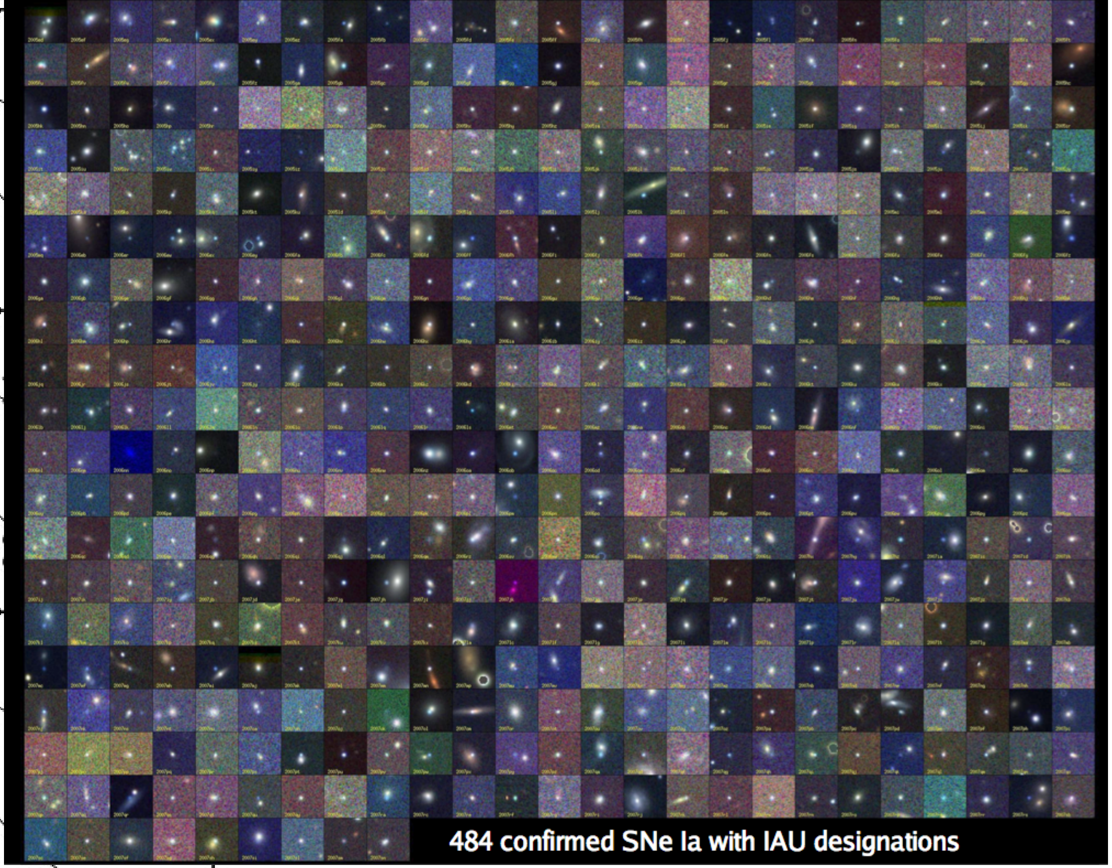


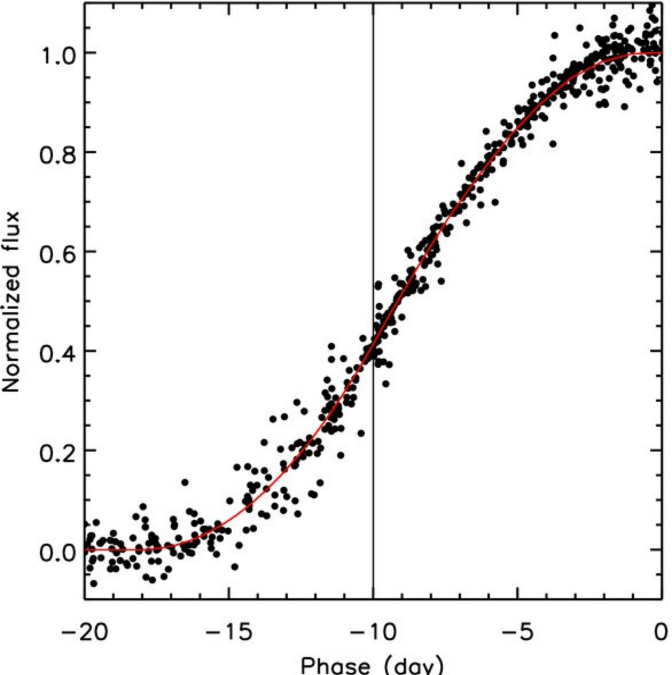


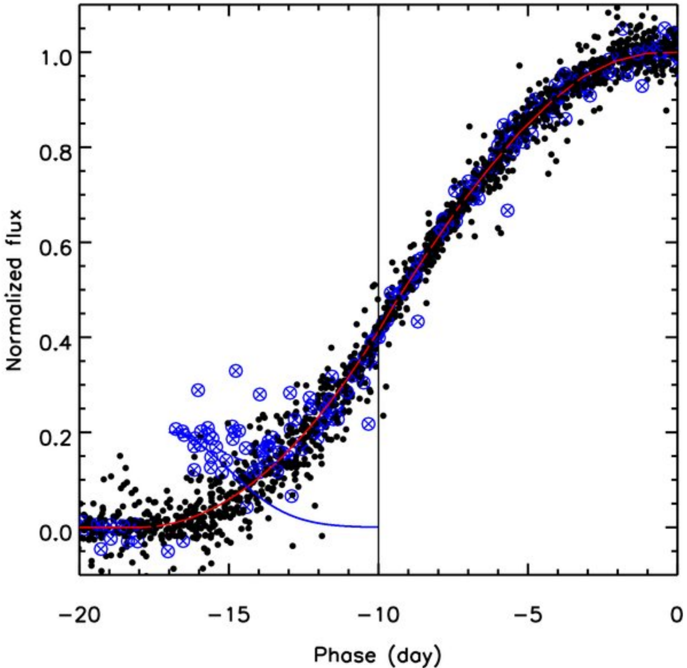
Mattila, Lundqvist, Sollerman, et al.
2005, A&A, 443, 649



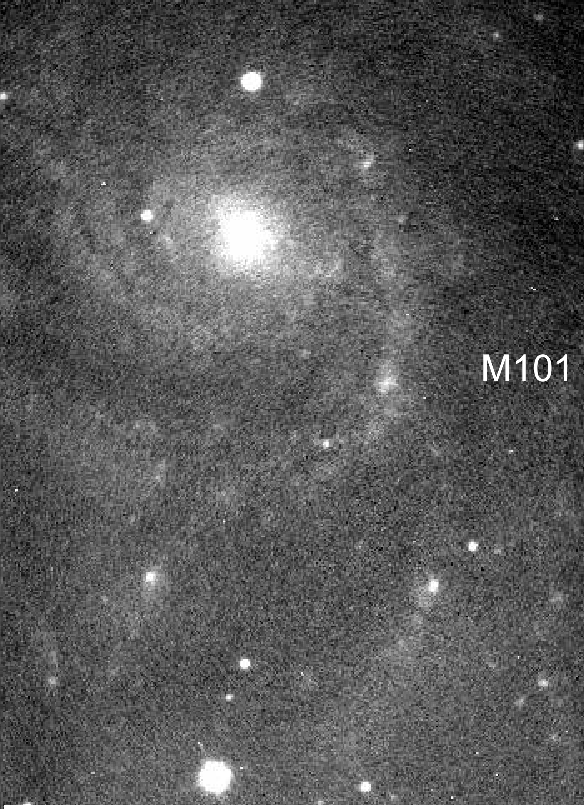






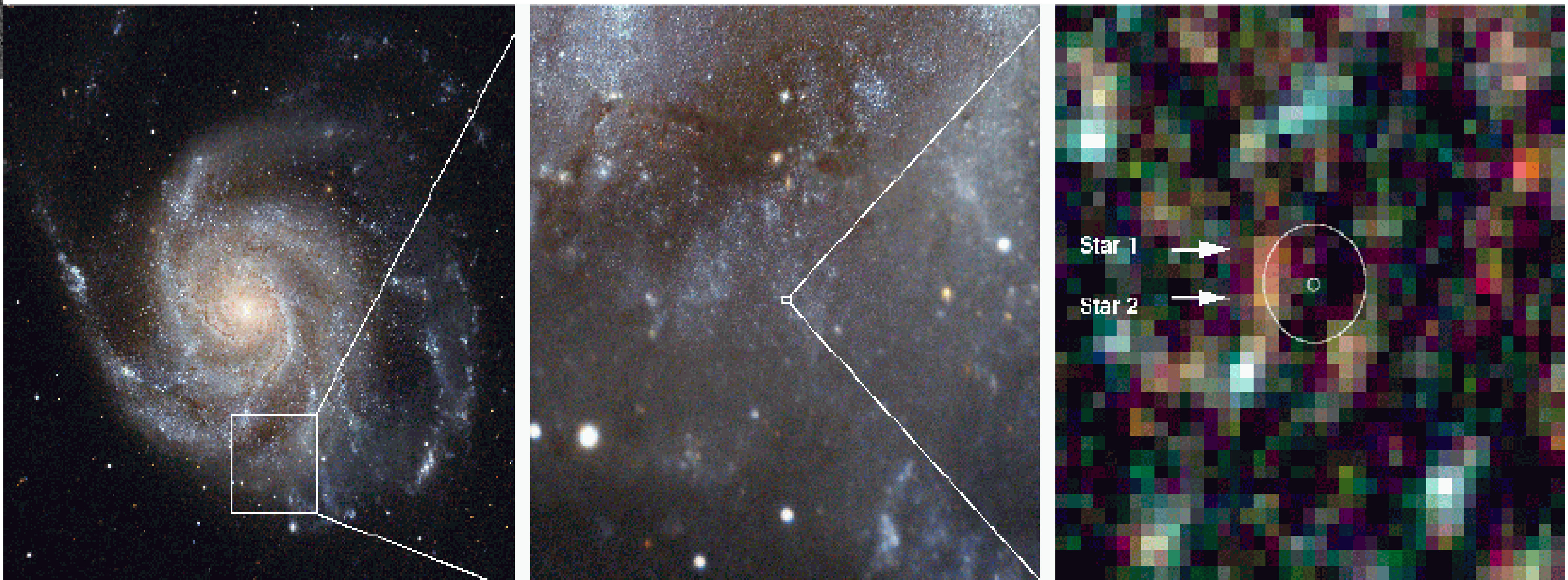


Hayden et al. 2010; SDSS-II



Li et al. Nature

Upper limits → M < 3.5Msun for companion



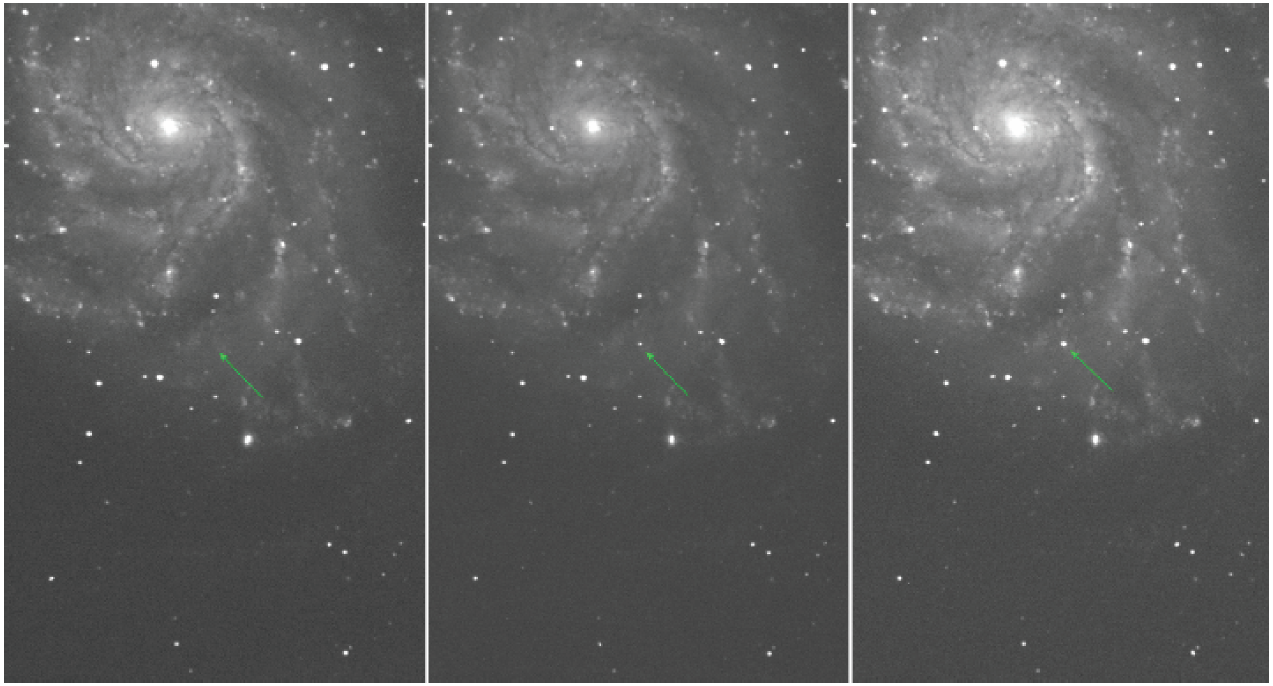
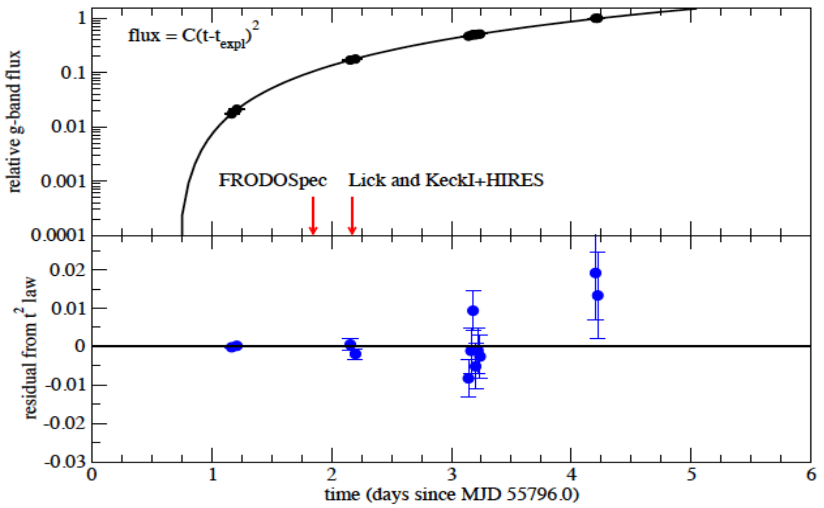


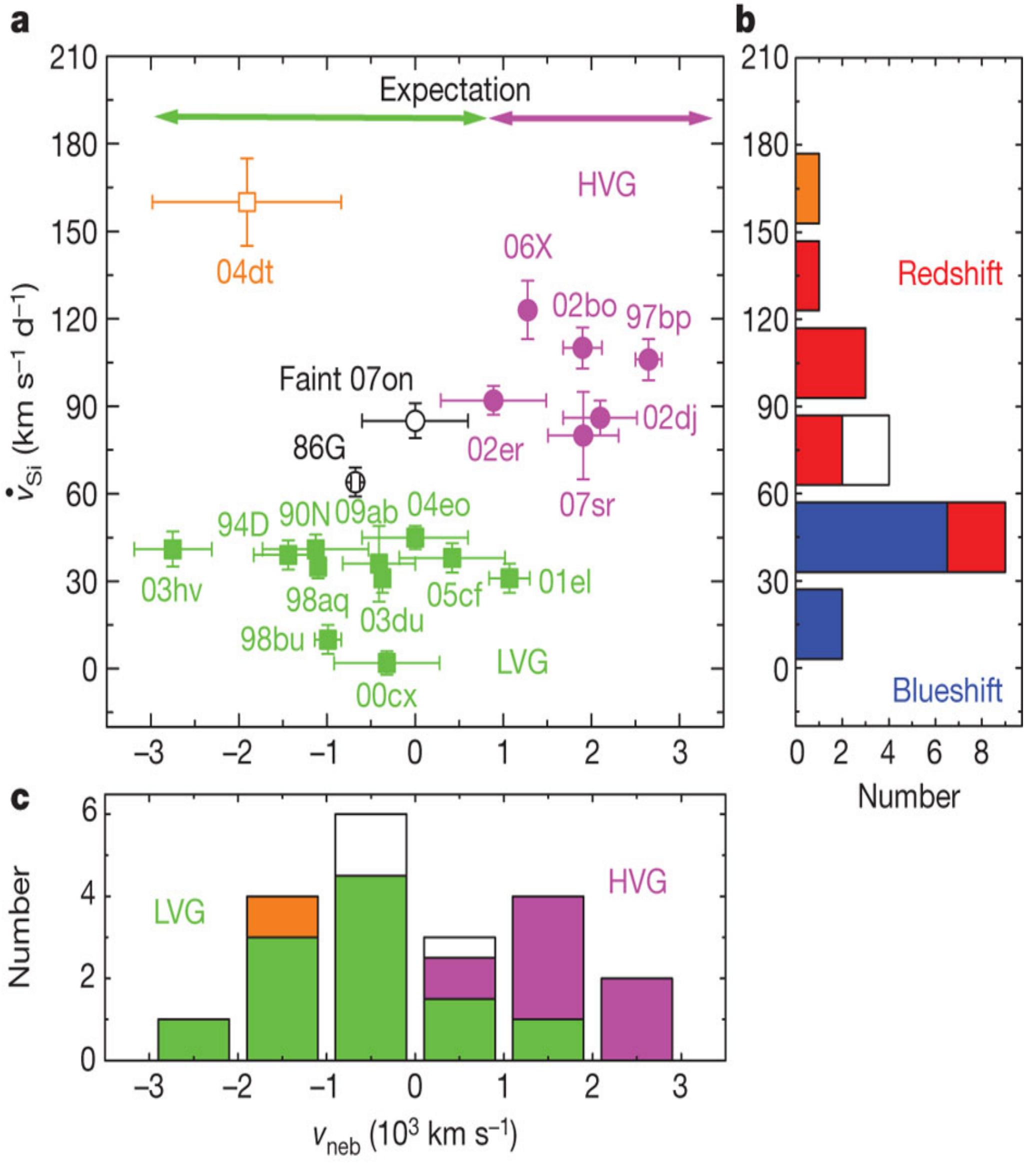
Figure 1: PTF *g*-band image sequence of the field of Messier 101 showing the appearance of SN 2011fe. From left to right, images are from August 23.22, 24.17, and 25.16 UT. The supernova

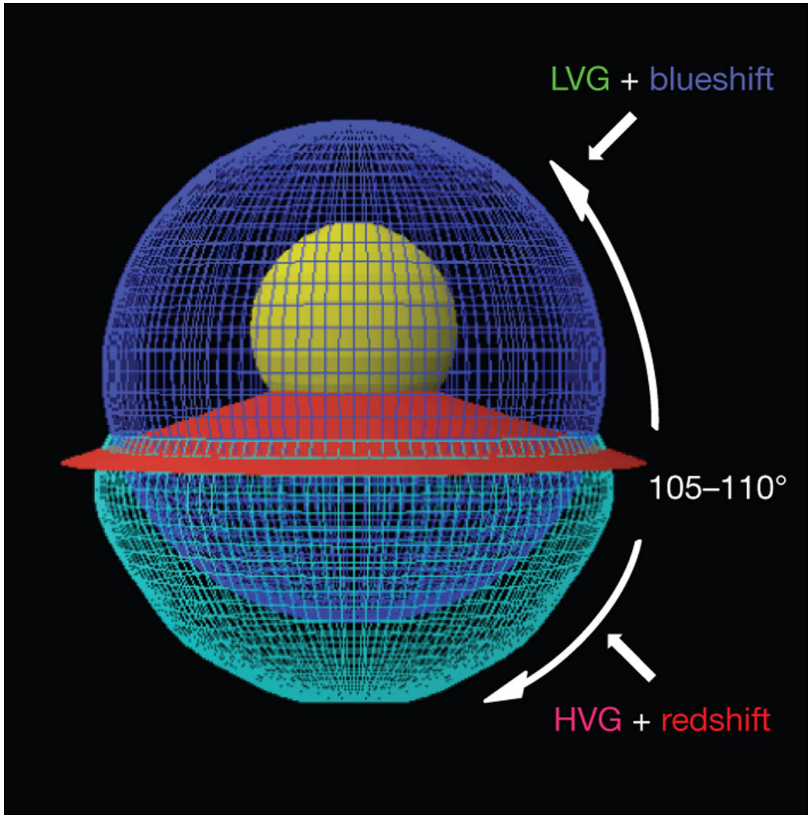
Nugent et al. 2011



m=17.35 → 10e40 erg/s → R < 0.1 Rsun
(11h past explosion, +- 20 min)

m(peak) = 9.9





K Maeda *et al. Nature* **466**, 82-85 (2010) doi:10.1038/nature09122

Asymmetric explosions?

nature

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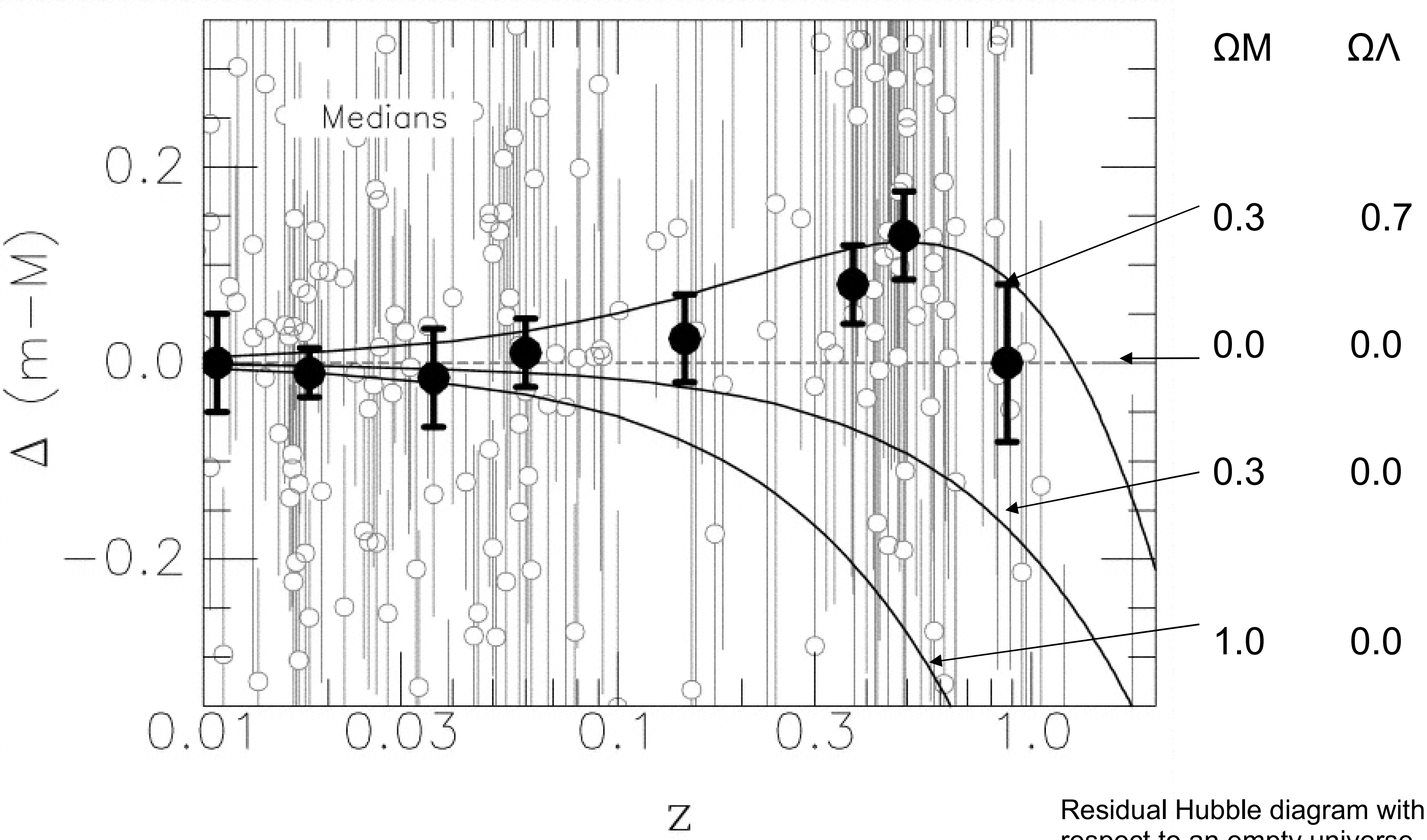
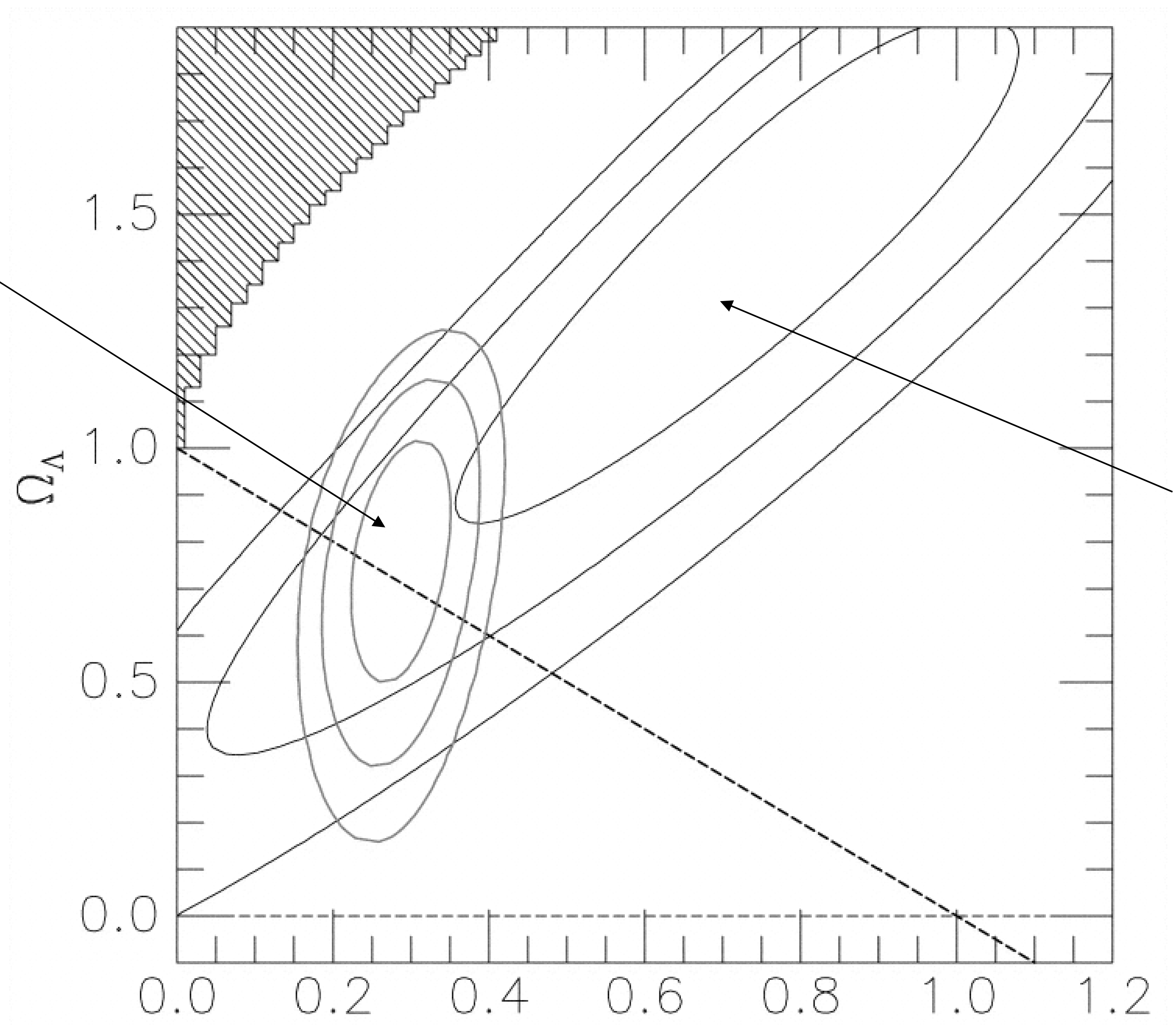


Residual Hubble diagram with respect to an empty universe. In this plot the highlighted points correspond to median values in eight redshift bins.

Tonry et al. **2003**, HZT, compilation of 230 SNe, high-z turnover hint



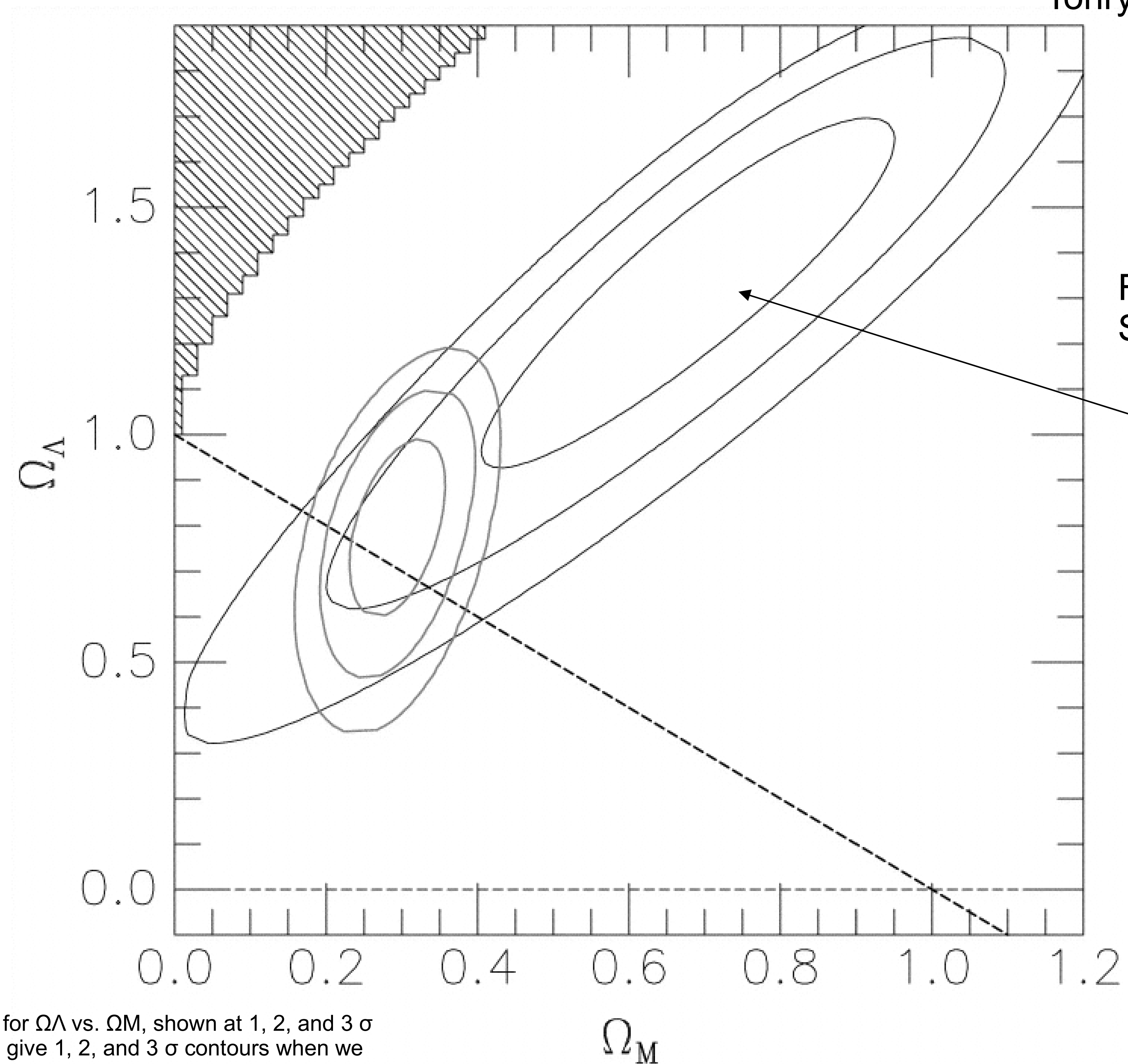
Including 2DF

26 new high-z SNe Ia only

Probability contours for ΩΛ vs. ΩM, shown at 1, 2, and 3 σ with w = -1. We also give 1, 2, and 3 σ contours when we adopt a prior of ΩMh = 0.20 ± 0.03 {Ho=72} from the 2dF survey (Percival et al. 2001). These constraints use only the 26 new SNe Ia at z > 0.3 (which are completely independent of any which have been used before for cosmological constraints).

If we assume a flat universe as well as w = -1, the SN Ia data require ΩM = 0.28 ± 0.05, independent of large-scale structure estimates.

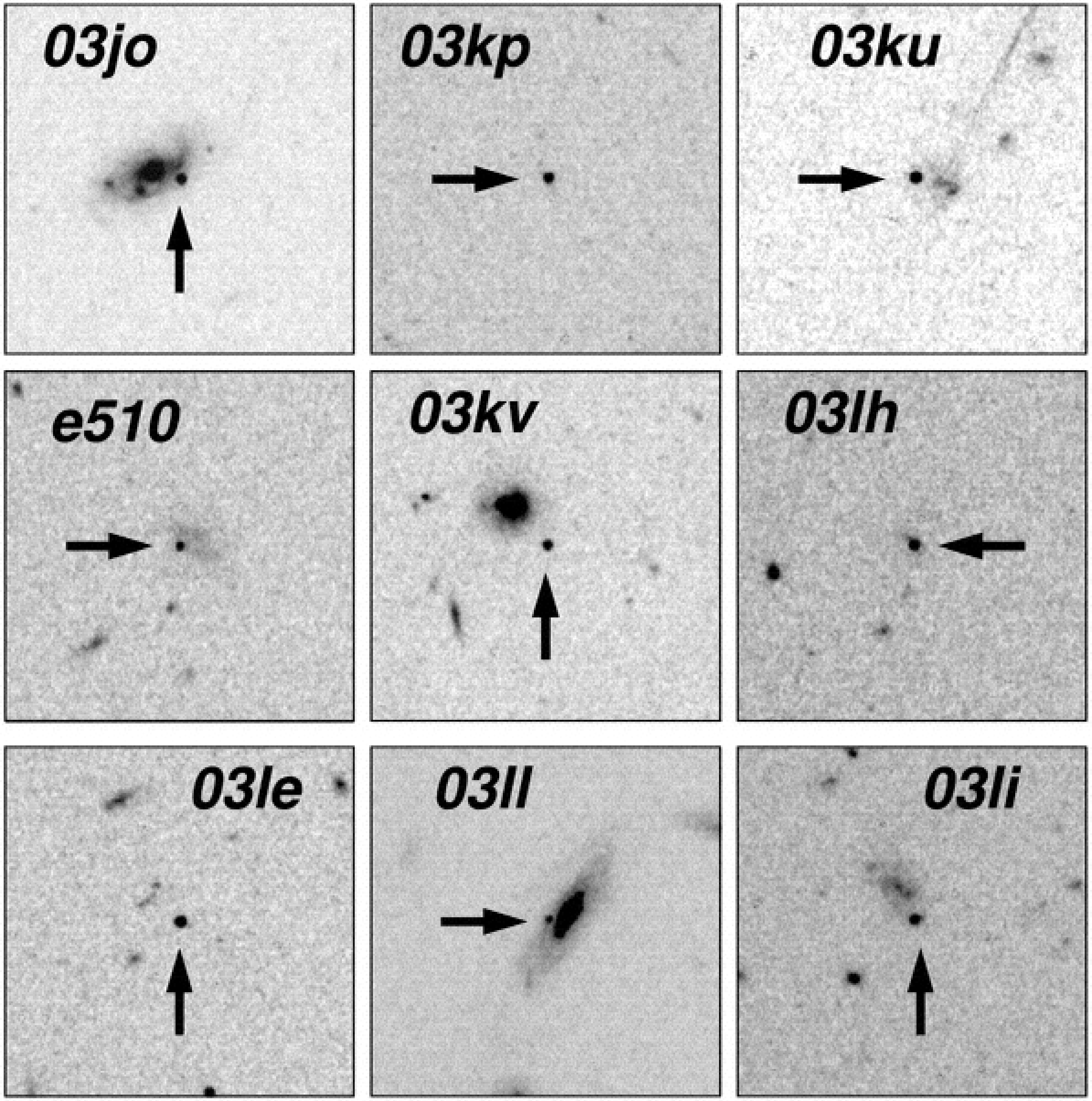
Tonry et al.

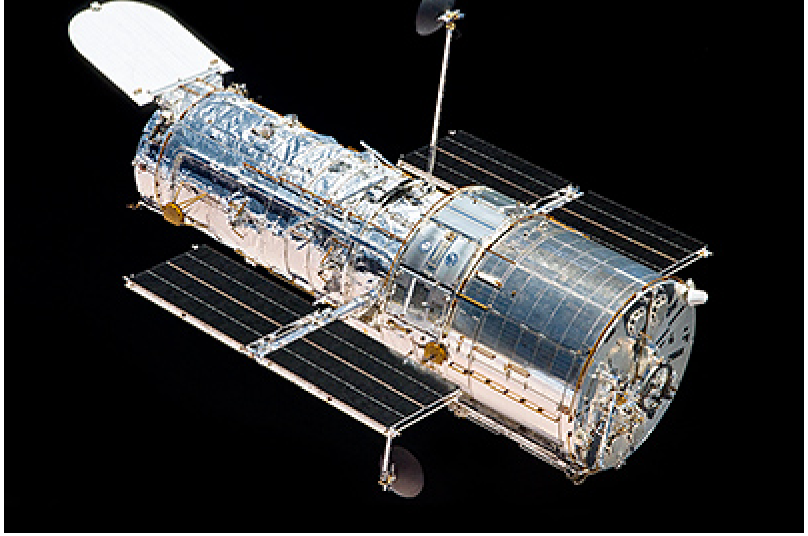


Full 2003
SN sample

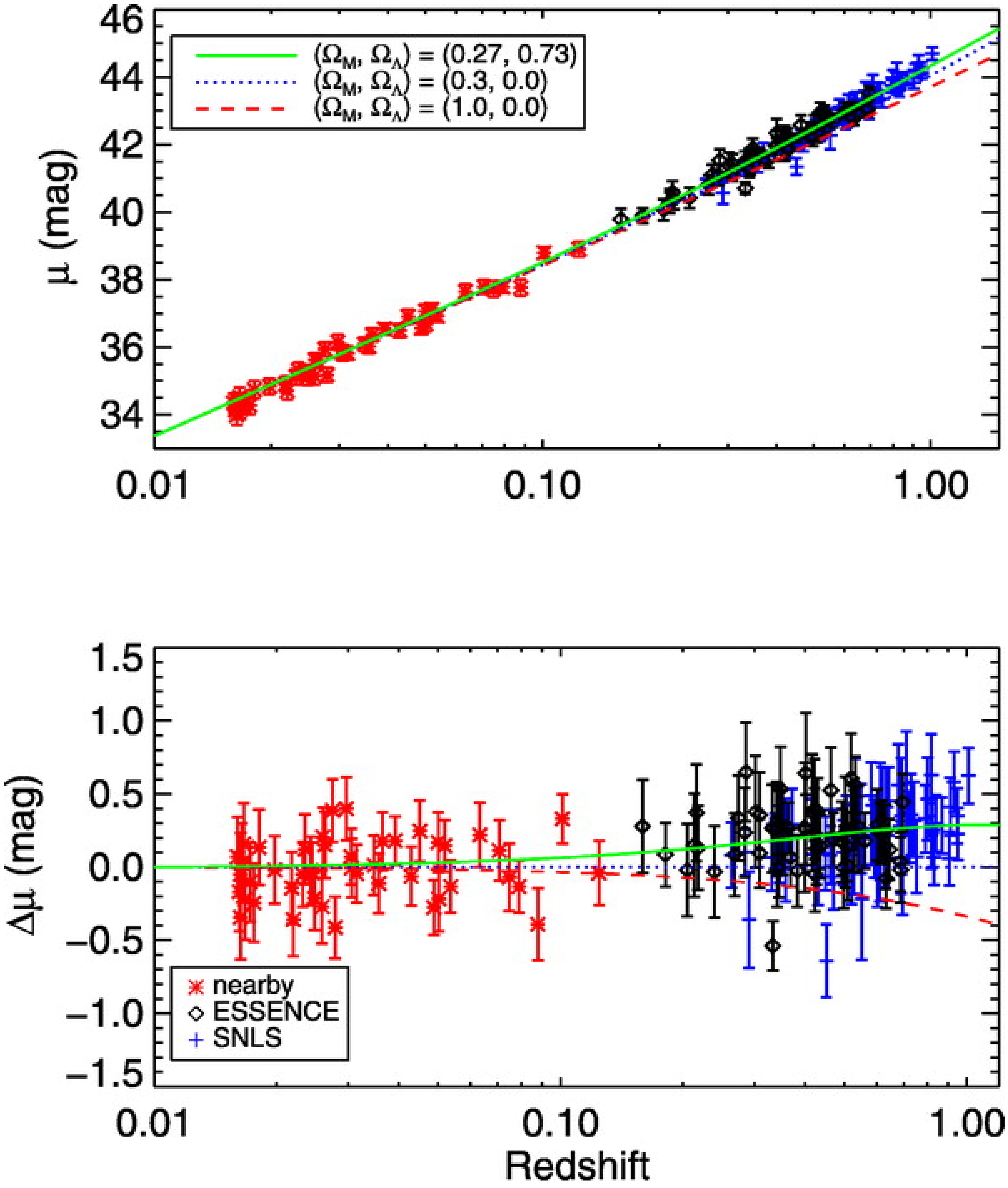
Probability contours for ΩΛ vs. ΩM, shown at 1, 2, and 3 σ with w = -1. We also give 1, 2, and 3 σ contours when we adopt a prior of ΩMh = 0.20 ± 0.03 from the 2dF survey (Percival et al. 2001). These constraints use the full sample of 172 SNe Ia with z > 0.01 and AV < 0.5 mag.

ESSENCE 2002-2007





Krisciunas et al. 2005,
ESSENCE

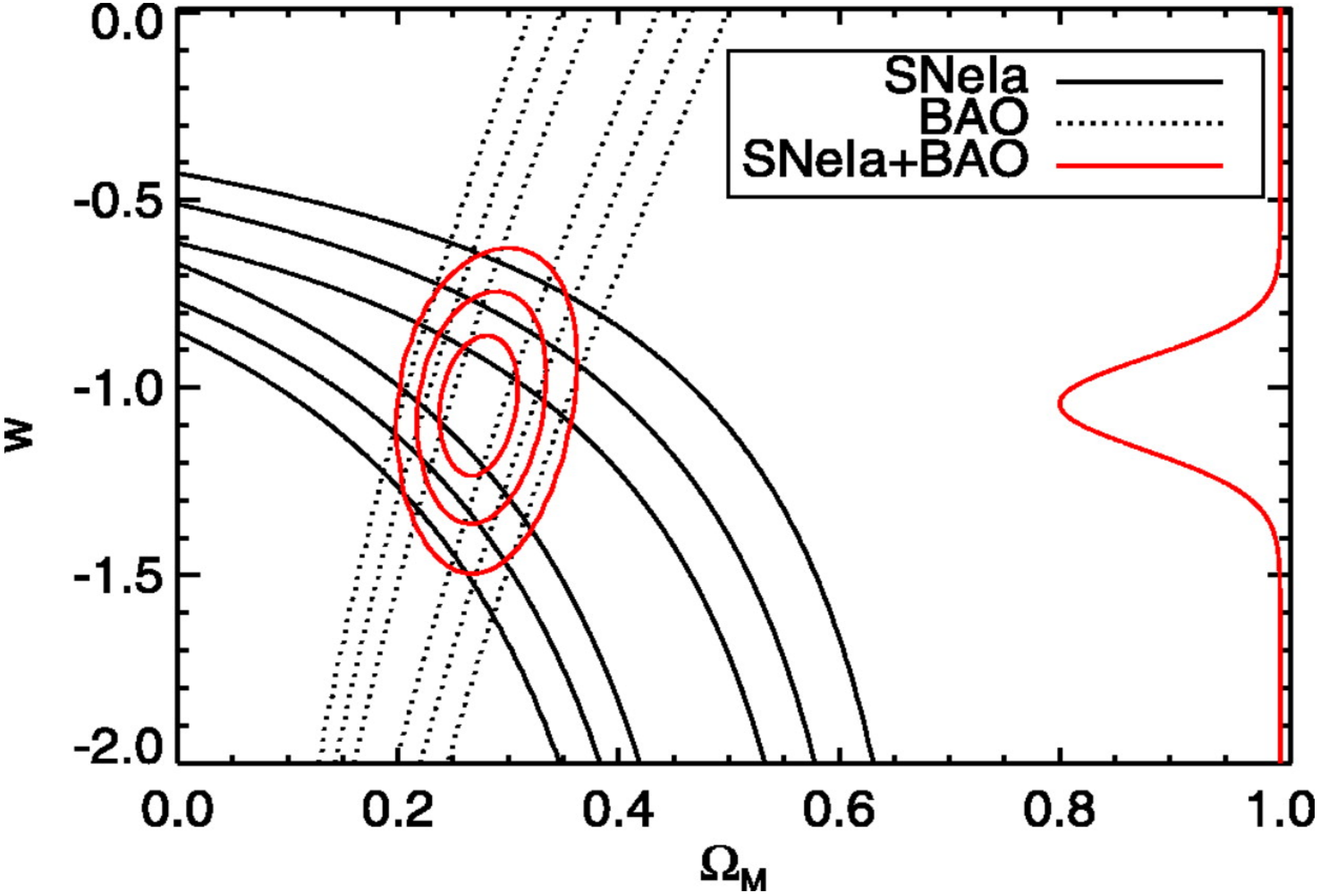


Relative luminosity distance modulus vs. redshift for the ESSENCE, SNLS, and nearby SNe Ia for MLCS2k2 with the glosz AV prior.
For comparison, the overplotted solid line and residuals are for a ΛCDM (w, ΩM, ΩΛ) = (-1, 0.27, 0.73) universe.

Wood-Vasey et al. 2007, first 3 years of ESSENCE data

Is it the cosmological constant?

Wood-Vasey et al. 2007; ESSENCE (first 3 years...)

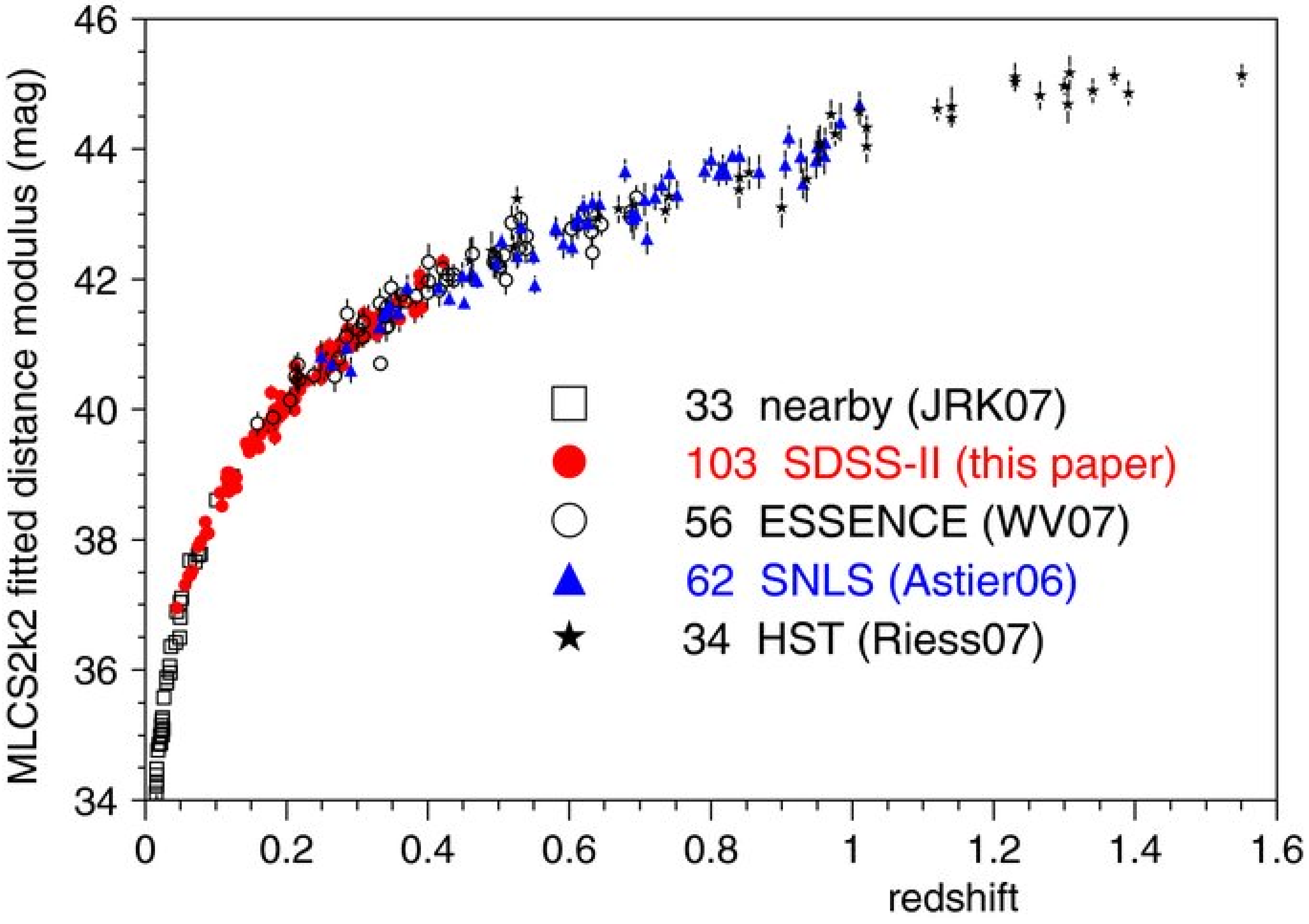


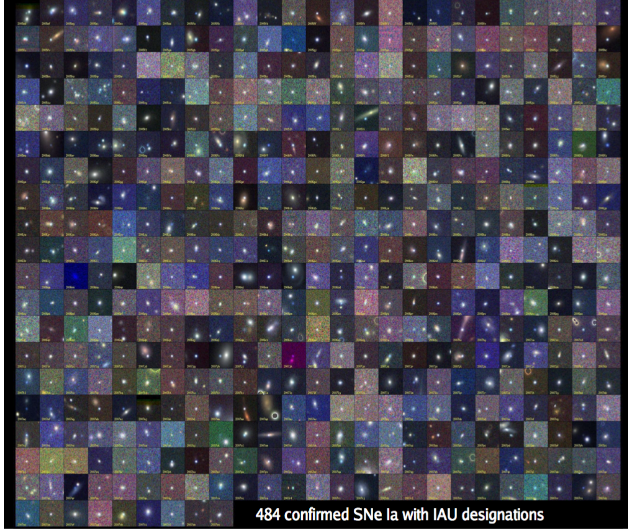
The ΩM - w 1, 2, and 3 σ contours from the ESSENCE+nearby sample for MLCS2k2 with the glosz AV prior. The BAO constraints are from Eisenstein et al. (2005).

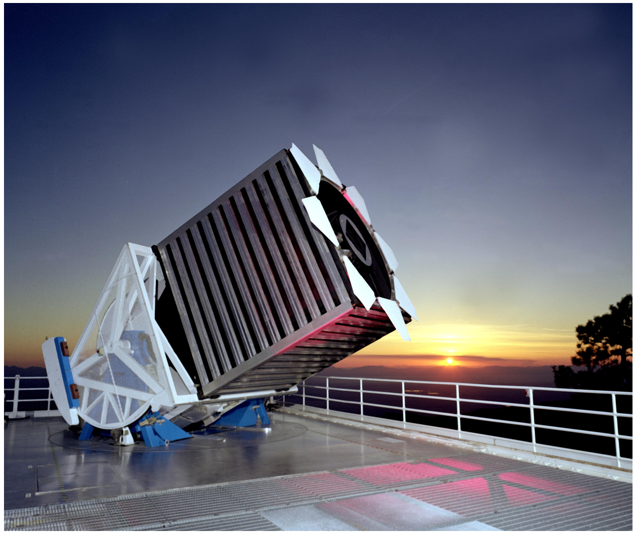
$\omega = \Pi\!\!/$

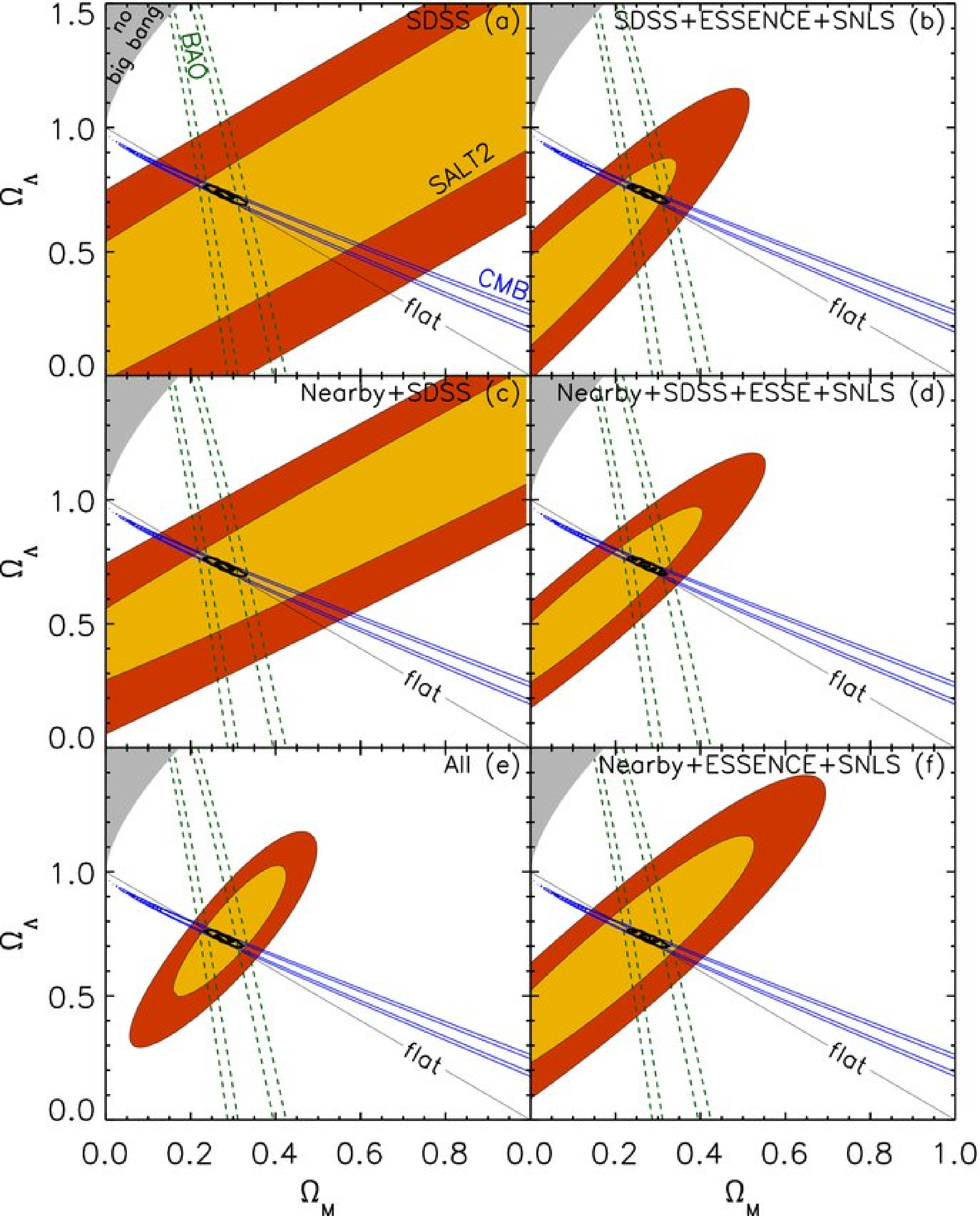
$$E(z) = \frac{H(z)}{H_0} = \left[\Omega_{k,0}(1+z)^2+\Omega_{R,0}(1+z)^4+\Omega_{M,0}(1+z)^3+\Omega_{DE}\exp\{\int_0^z \frac{-3[1+w(z')]dz'}{1+z'}\}\right]^{1/2}$$

Sloan Digital Sky Survey Supernova Survey (2005-2007)









For the ΛCDM model,SALTII statistical-uncertainty contours in the ΩM-ΩΛ plane for each of the six SN sample combinations indicated on the plots.
Long, black contours: 68%, 95%, and 99% confidence level regions for the SN data alone; green contours: corresponding CL regions for SDSS BAO (Eisenstein et al. 2005); blue contours: CL regions for WMAP-5 CMB (Komatsu et al. 2009); closed, red contours: combined constraints from SN+BAO+CMB.

Kessler et al. 2099, SDSS (FIRST YEARS DATA, 2 more years to publish)

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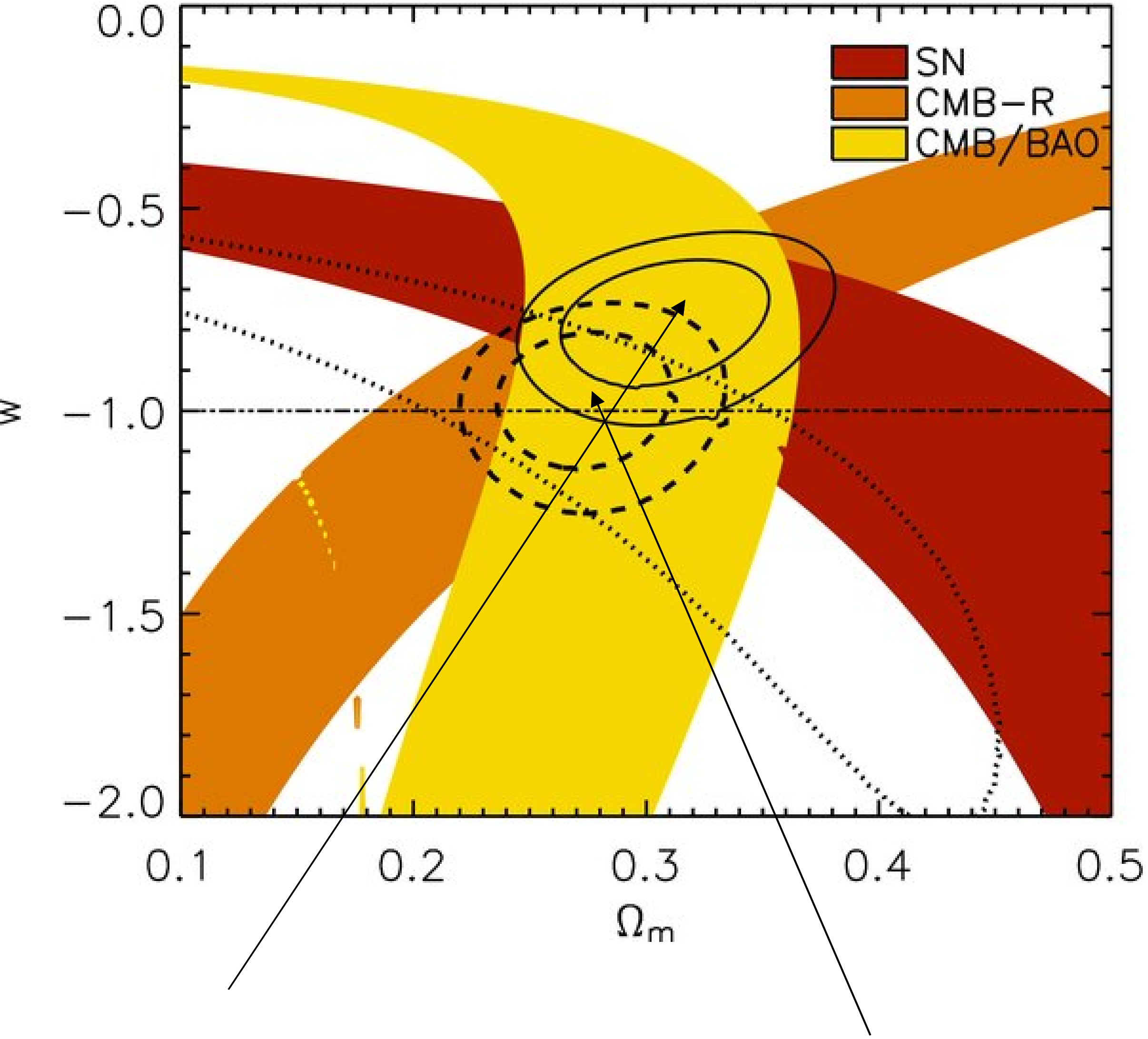


MLCS

SALT-II

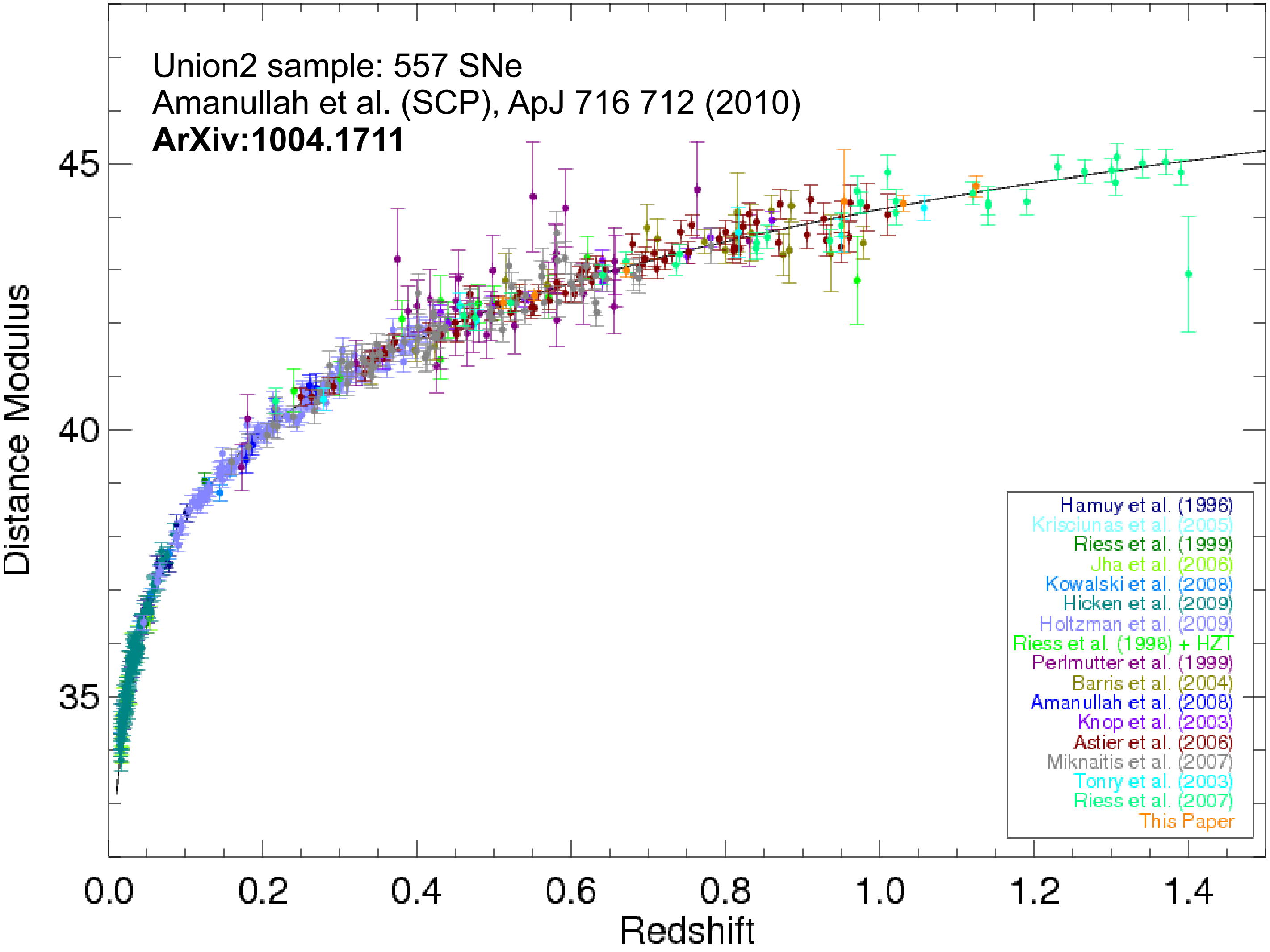
Flat dark-energy model (Fw): a flat universe with constant w. The constraint from each of the observational probes is shown by shaded contours. These are all 95% confidence intervals for two parameters. Overlaid with black lines (95% and 99.9% confidence intervals) are contours from combining CMB/BAO-ℓA, CMB-R, and SN constraints. The shaded contour labeled SN is for the analysis using the MLCS light-curve fitter. In this plot we have also added the CMB-R constraints, although these are not included in the model selection. The dotted supernova contours are using the SALT-II fits. For the SALT-II data set the combined contours are given by the dashed contours, and are clearly in better agreement with the cosmological-constant value, w = –1, shown by the dashed-dotted line.

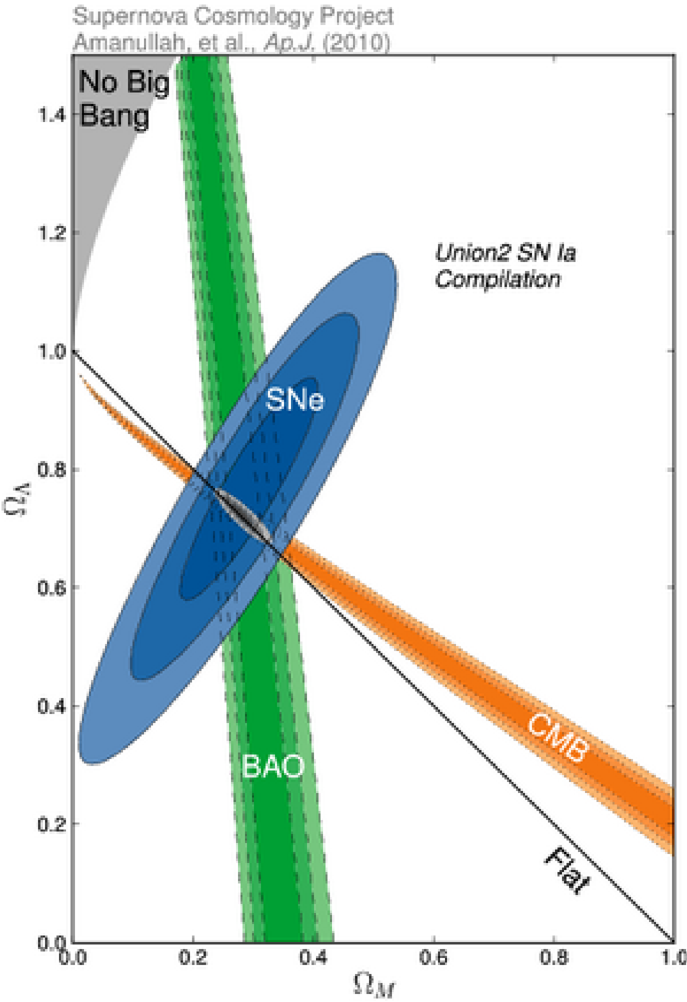
Makes a difference!

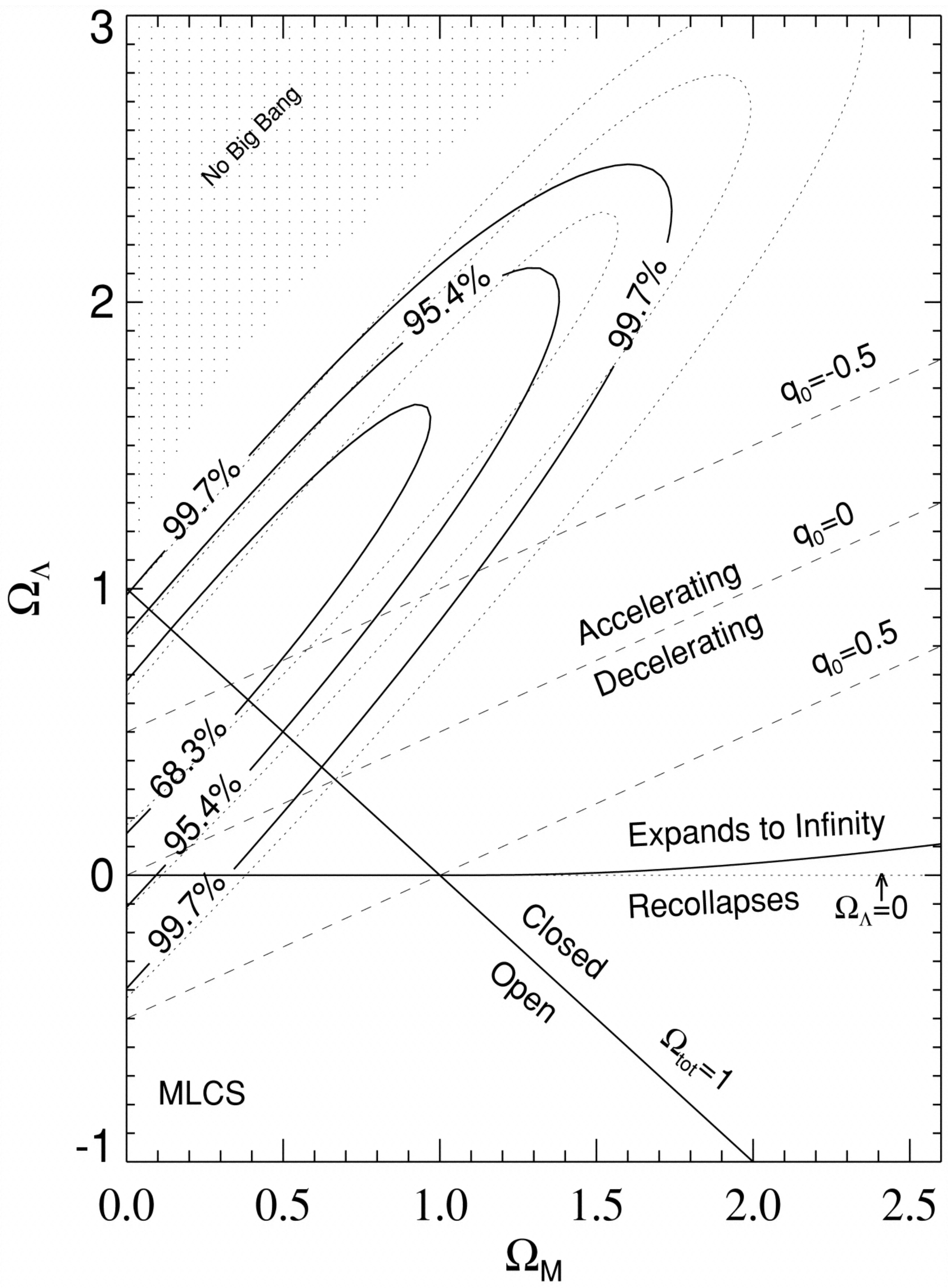
J. Sollerman et al. 2009 ApJ 703 1374

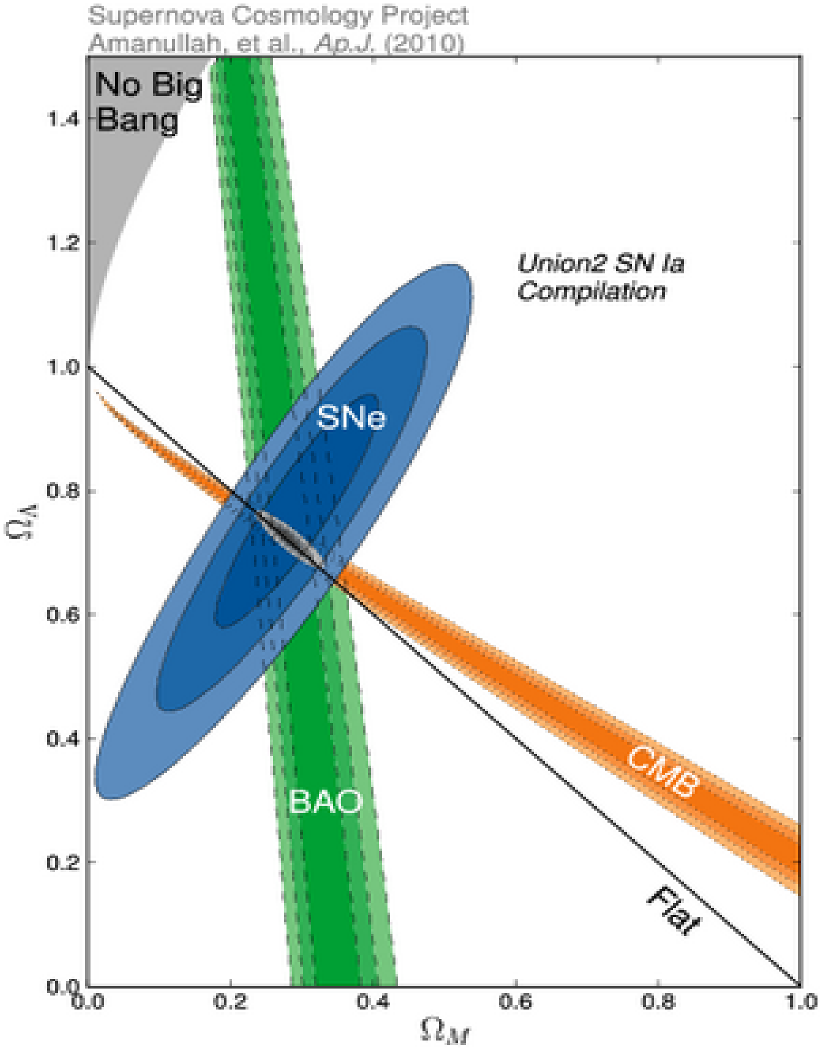
FIRST-YEAR SLOAN DIGITAL SKY SURVEY-II (SDSS-II) SUPERNOVA RESULTS: CONSTRAINTS ON NONSTANDARD COSMOLOGICAL MODELS

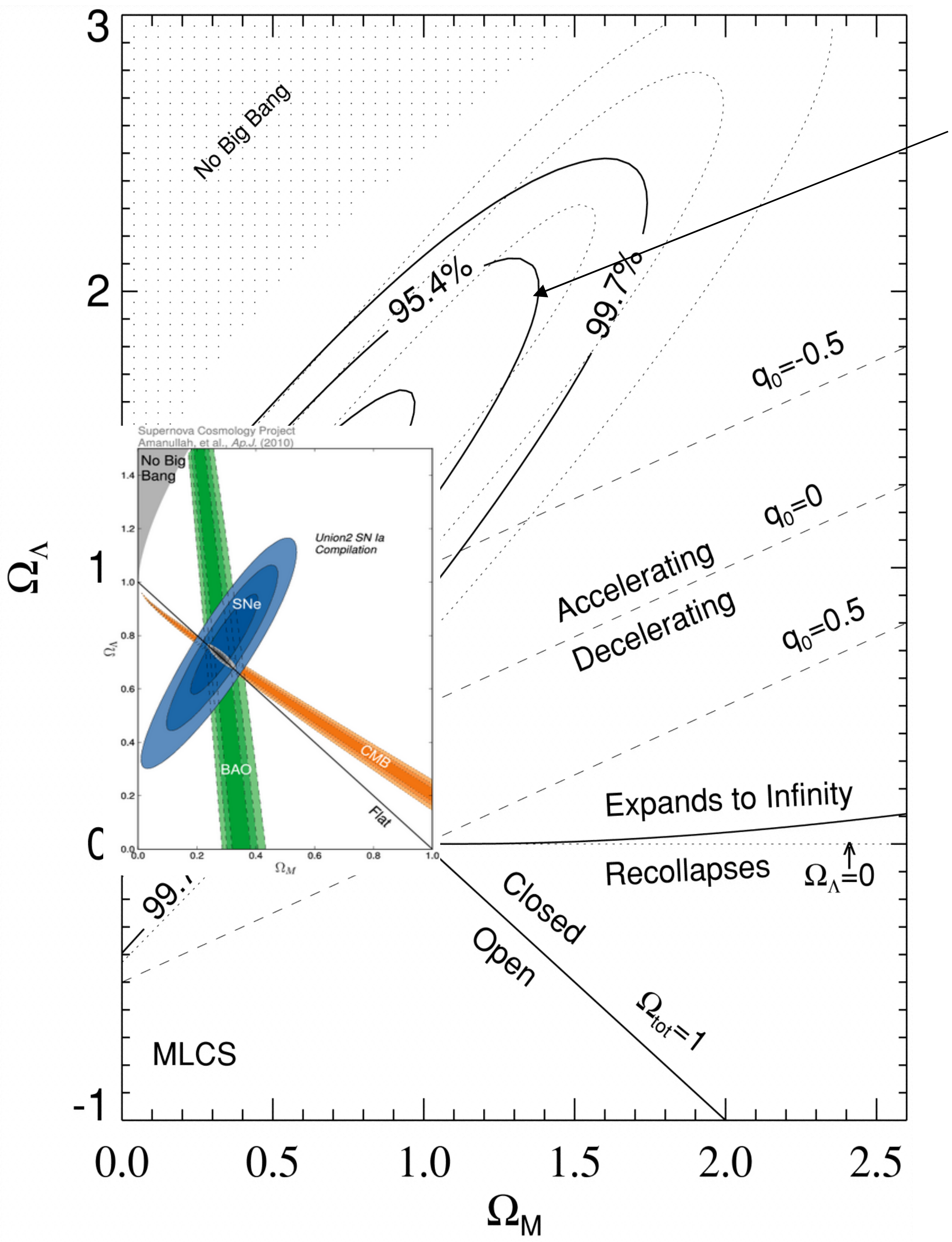
Supernova Cosmology Today!



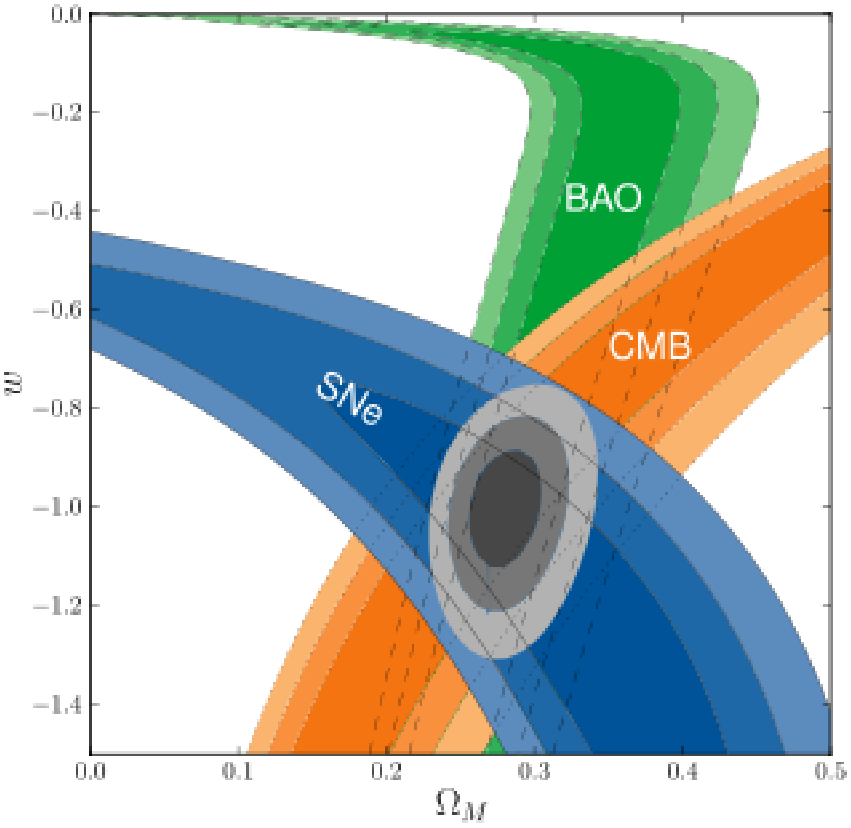


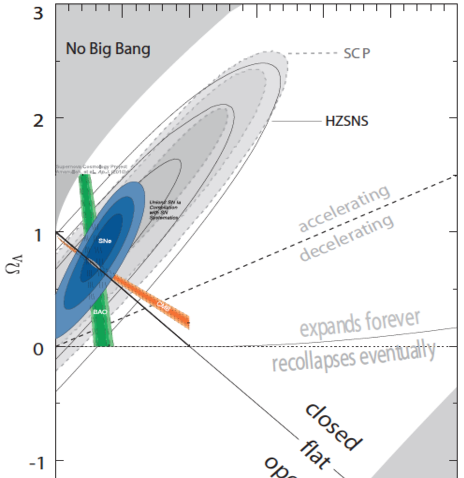


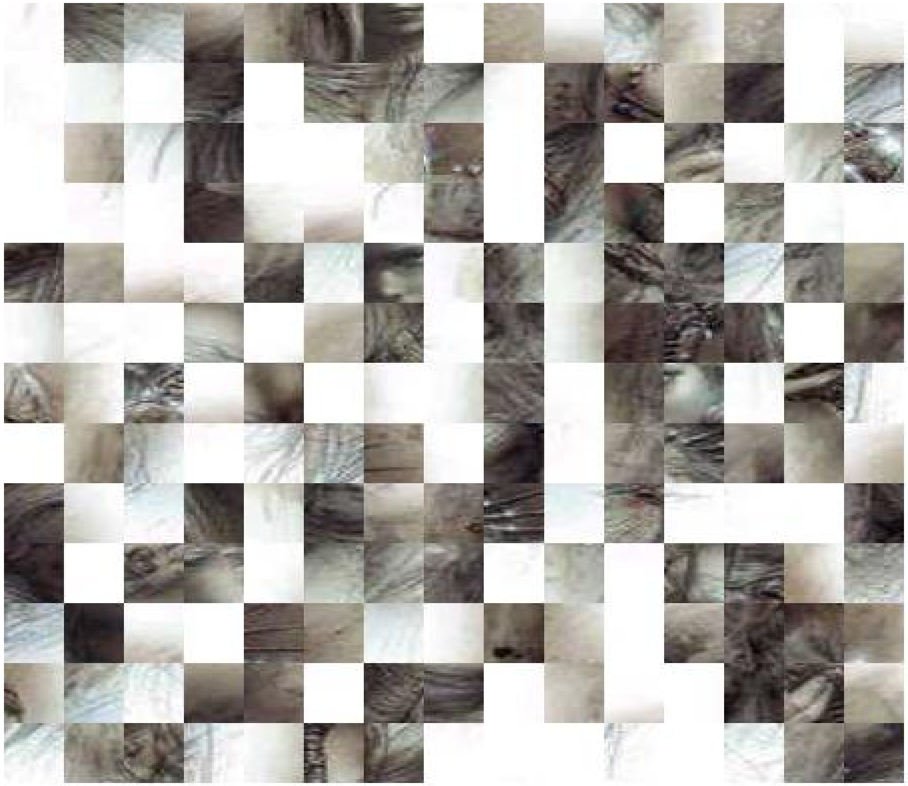

Supernova Cosmology Project
Amanullah, et al., *Ap.J.* (2010)


3
2
1
0
-1
0.0
0.5
1.0
1.5
2.0
2.5
Ω_Λ
Ω_M
No Big Bang
95.4%
99.7%
99.7
q_0=-0.5
q_0=0
q_0=0.5
Accelerating
Decelerating
Expands to Infinity
Recollapses
Ω_Λ=0
Closed
Open
Ω_{tot}=1
MLCS
Supernova Cosmology Project
Amanullah, et al., Ap.J. (2010)
No Big Bang
Union2 SN Ia Compilation
SNe
BAO
CMB
Flat
Ω_Λ
Ω_M
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0

Riess et al.


0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
w
0.0
0.1
0.2
0.3
0.4
0.5
Ω_M
BAO
CMB
SNe

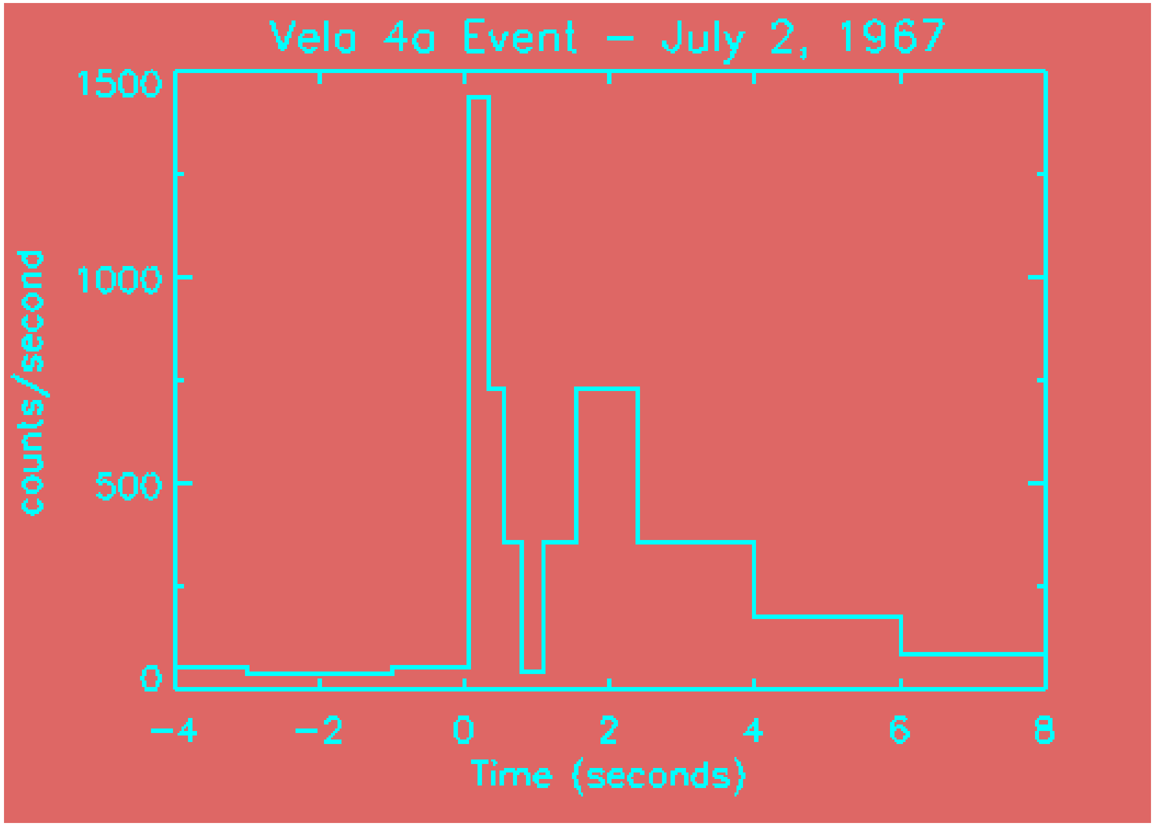

3
2
1
0
-1
No Big Bang
SCP
HZSNS
accelerating
decelerating
expands forever
recollapses eventually
closed
flat
Ω_Λ
SNe
BAO



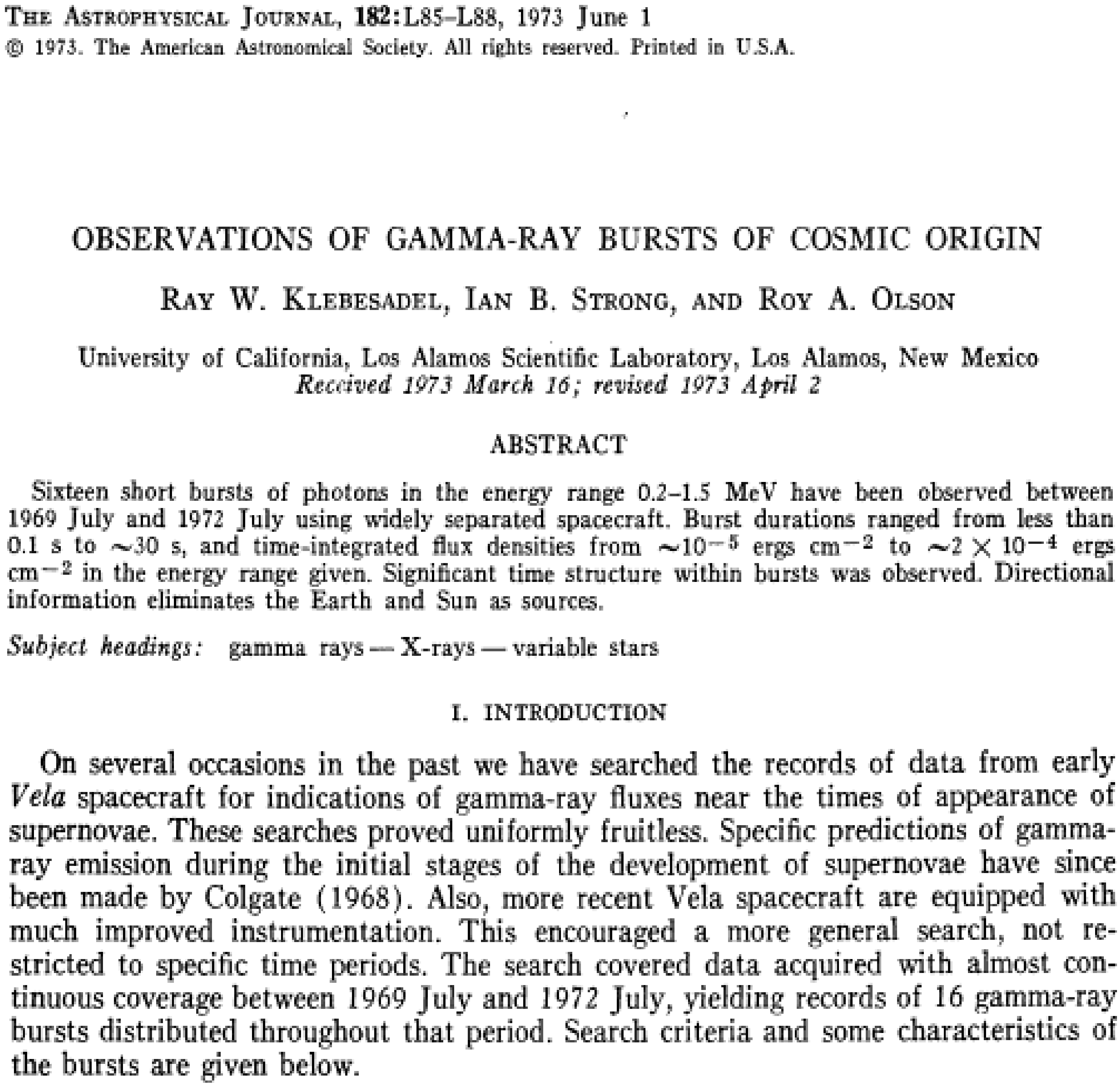
Gamma-Ray Bursts

(The Supernova Connection...)

Vela



Supernova-
connection
from the start



THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

I. INTRODUCTION

On several occasions in the past we have searched the records of data from early *Vela* spacecraft for indications of gamma-ray fluxes near the times of appearance of supernovae. These searches proved uniformly fruitless. Specific predictions of gamma-ray emission during the initial stages of the development of supernovae have since been made by Colgate (1968). Also, more recent Vela spacecraft are equipped with much improved instrumentation. This encouraged a more general search, not restricted to specific time periods. The search covered data acquired with almost continuous coverage between 1969 July and 1972 July, yielding records of 16 gamma-ray bursts distributed throughout that period. Search criteria and some characteristics of the bursts are given below.

Theories.....

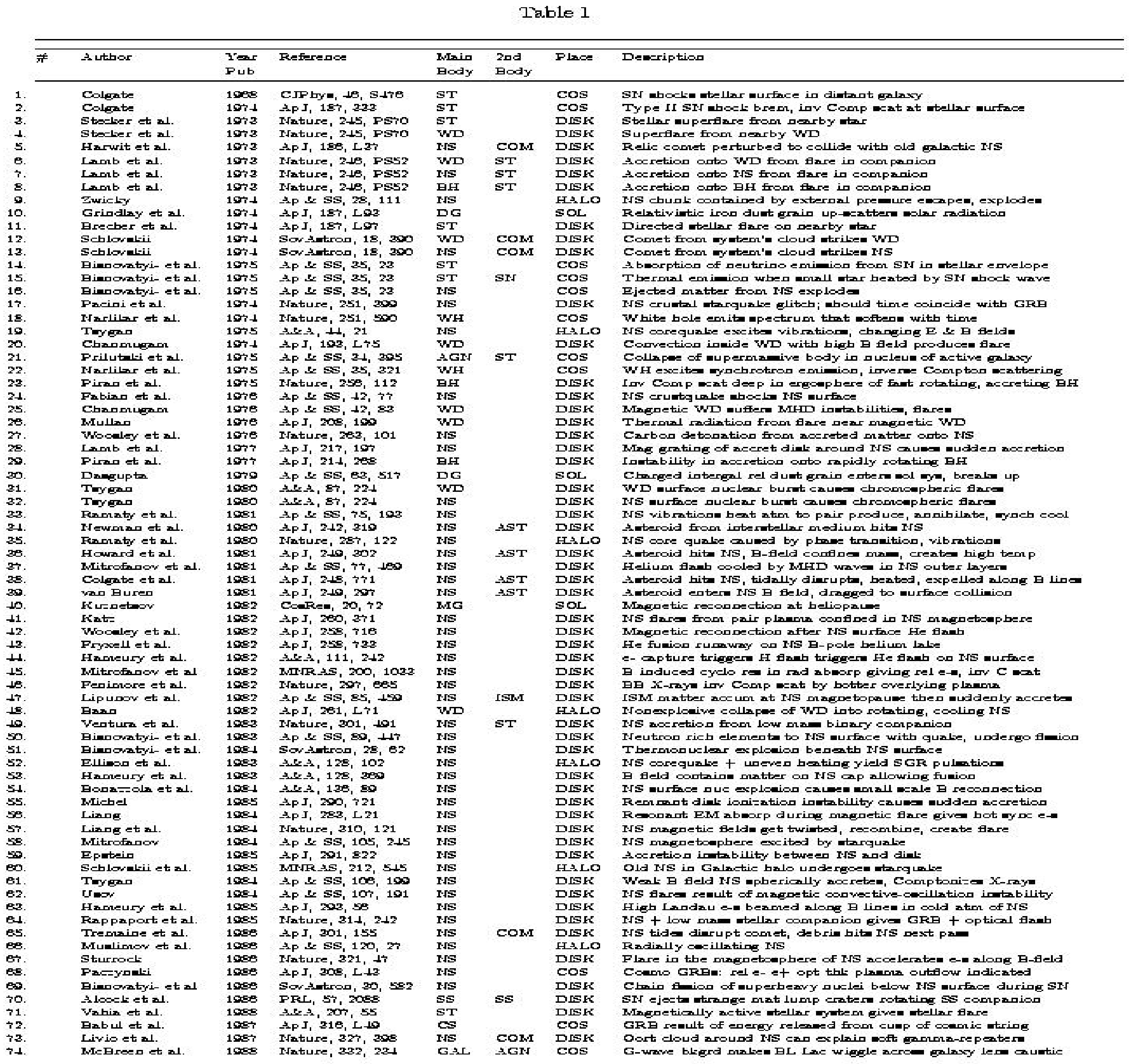


Table 1

#	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap & SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flare on nearby star
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
14.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
15.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
16.	Bisnovatyi- et al.	1975	Ap & SS, 35, 23	NS		COS	Ejected matter from NS explodes
17.	Pacini et al.	1974	Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
18.	Narlikar et al.	1974	Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
19.	Tsygan	1975	A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
20.	Chanmugam	1974	ApJ, 193, L75	WD		DISK	Convection inside WD with high B field produces flare
21.	Prilutski et al.	1975	Ap & SS, 34, 395	AGN	ST	COS	Collapse of supermassive body in nucleus of active galaxy
22.	Narlikar et al.	1975	Ap & SS, 35, 321	WH		COS	WH excites synchrotron emission, inverse Compton scattering
23.	Piran et al.	1975	Nature, 258, 113	BH		DISK	Inv Comp scat deep in ergosphere of fast rotating, accreting BH
24.	Fabian et al.	1976	Ap & SS, 42, 77	NS		DISK	NS crustquake shocks NS surface
25.	Chanmugam	1976	Ap & SS, 42, 83	WD		DISK	Magnetic WD suffers MHD instabilities, flares
26.	Mullan	1976	ApJ, 208, 199	WD		DISK	Thermal radiation from flare near magnetic WD
27.	Woosley et al.	1976	Nature, 263, 101	NS		DISK	Carbon detonation from accreted matter onto NS
28.	Lamb et al.	1977	ApJ, 217, 197	NS		DISK	Mag grating of accret disk around NS causes sudden accretion
29.	Piran et al.	1977	ApJ, 214, 268	BH		DISK	Instability in accretion onto rapidly rotating BH
30.	Dasgupta	1979	Ap & SS, 63, 517	DG		SOL	Charged intergal rel dust grain enters sol sys, breaks up
31.	Tsygan	1980	A&A, 87, 224	WD		DISK	WD surface nuclear burst causes chromospheric flares
32.	Tsygan	1980	A&A, 87, 224	NS		DISK	NS surface nuclear burst causes chromospheric flares
33.	Ramaty et al.	1981	Ap & SS, 75, 193	NS		DISK	NS vibrations heat atm to pair produce, annihilate, synch cool
34.	Newman et al.	1980	ApJ, 242, 319	NS	AST	DISK	Asteroid from interstellar medium hits NS
35.	Ramaty et al.	1980	Nature, 287, 122	NS		HALO	NS core quake caused by phase transition, vibrations
36.	Howard et al.	1981	ApJ, 249, 302	NS	AST	DISK	Asteroid hits NS, B-field confines mass, creates high temp
37.	Mitrofanov et al.	1981	Ap & SS, 77, 469	NS		DISK	Helium flash cooled by MHD waves in NS outer layers
38.	Colgate et al.	1981	ApJ, 248, 771	NS	AST	DISK	Asteroid hits NS, tidally disrupts, heated, expelled along B lines
39.	van Buren	1981	ApJ, 249, 297	NS	AST	DISK	Asteroid enters NS B field, dragged to surface collision
40.	Kuznetsov	1982	CosRes, 20, 72	MG		SOL	Magnetic reconnection at heliopause
41.	Katz	1982	ApJ, 260, 371	NS		DISK	NS flares from pair plasma confined in NS magnetosphere
42.	Woosley et al.	1982	ApJ, 258, 716	NS		DISK	Magnetic reconnection after NS surface He flash
43.	Fryxell et al.	1982	ApJ, 258, 733	NS		DISK	He fusion runaway on NS B-pole helium lake
44.	Hameury et al.	1982	A&A, 111, 242	NS		DISK	e- capture triggers H flash triggers He flash on NS surface
45.	Mitrofanov et al	1982	MNRAS, 200, 1033	NS		DISK	B induced cyclo res in rad absorp giving rel e-s, inv C scat
46.	Fenimore et al.	1982	Nature, 297, 665	NS		DISK	BB X-rays inv Comp scat by hotter overlying plasma
47.	Lipunov et al.	1982	Ap & SS, 85, 459	NS	ISM	DISK	ISM matter accum at NS magnetopause then suddenly accretes
48.	Baan	1982	ApJ, 261, L71	WD		HALO	Nonexplosive collapse of WD into rotating, cooling NS
49.	Ventura et al.	1983	Nature, 301, 491	NS	ST	DISK	NS accretion from low mass binary companion
50.	Bisnovatyi- et al.	1983	Ap & SS, 89, 447	NS		DISK	Neutron rich elements to NS surface with quake, undergo fission
51.	Bisnovatyi- et al.	1984	SovAstron, 28, 62	NS		DISK	Thermonuclear explosion beneath NS surface
52.	Ellison et al.	1983	A&A, 128, 102	NS		HALO	NS corequake + uneven heating yield SGR pulsations
53.	Hameury et al.	1983	A&A, 128, 369	NS		DISK	B field contains matter on NS cap allowing fusion
54.	Bonazzola et al.	1984	A&A, 136, 89	NS		DISK	NS surface nuc explosion causes small scale B reconnection
55.	Michel	1985	ApJ, 290, 721	NS		DISK	Remnant disk ionization instability causes sudden accretion
56.	Liang	1984	ApJ, 283, L21	NS		DISK	Resonant EM absorp during magnetic flare gives hot sync e-s
57.	Liang et al.	1984	Nature, 310, 121	NS		DISK	NS magnetic fields get twisted, recombine, create flare
58.	Mitrofanov	1984	Ap & SS, 105, 245	NS		DISK	NS magnetosphere excited by starquake
59.	Epstein	1985	ApJ, 291, 822	NS		DISK	Accretion instability between NS and disk
60.	Schlovskii et al.	1985	MNRAS, 212, 545	NS		HALO	Old NS in Galactic halo undergoes starquake
61.	Tsygan	1984	Ap & SS, 106, 199	NS		DISK	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Usov	1984	Ap & SS, 107, 191	NS		DISK	NS flares result of magnetic convective-oscillation instability
63.	Hameury et al.	1985	ApJ, 293, 56	NS		DISK	High Landau e-s beamed along B lines in cold atm of NS
64.	Rappaport et al.	1985	Nature, 314, 242	NS		DISK	NS + low mass stellar companion gives GRB + optical flash
65.	Tremaine et al.	1986	ApJ, 301, 155	NS	COM	DISK	NS tides disrupt comet, debris hits NS next pass
66.	Muslimov et al.	1986	Ap & SS, 120, 27	NS		HALO	Radially oscillating NS
67.	Sturrock	1986	Nature, 321, 47	NS		DISK	Flare in the magnetosphere of NS accelerates e-s along B-field
68.	Paczynski	1986	ApJ, 308, L43	NS		COS	Cosmo GRBs: rel e- e+ opt thk plasma outflow indicated
69.	Bisnovatyi- et al	1986	SovAstron, 30, 582	NS		DISK	Chain fission of superheavy nuclei below NS surface during SN
70.	Alcock et al.	1986	PRL, 57, 2088	SS	SS	DISK	SN ejects strange mat lump craters rotating SS companion
71.	Vahia et al.	1988	A&A, 207, 55	ST		DISK	Magnetically active stellar system gives stellar flare
72.	Babul et al.	1987	ApJ, 316, L49	CS		COS	GRB result of energy released from cusp of cosmic string
73.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters
74.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic

Nemiroff 1994

Theories.....

Several may be correct!

Table 1

#	Author	Year Pub	Reference	Main Body	2nd Body	Place	Description
1.	Colgate	1968	CJPhys, 46, S476	ST		COS	SN shocks stellar surface in distant galaxy
2.	Colgate	1974	ApJ, 187, 333	ST		COS	Type II SN shock brem, inv Comp scat at stellar surface
3.	Stecker et al.	1973	Nature, 245, PS70	ST		DISK	Stellar superflare from nearby star
4.	Stecker et al.	1973	Nature, 245, PS70	WD		DISK	Superflare from nearby WD
5.	Harwit et al.	1973	ApJ, 186, L37	NS	COM	DISK	Relic comet perturbed to collide with old galactic NS
6.	Lamb et al.	1973	Nature, 246, PS52	WD	ST	DISK	Accretion onto WD from flare in companion
7.	Lamb et al.	1973	Nature, 246, PS52	NS	ST	DISK	Accretion onto NS from flare in companion
8.	Lamb et al.	1973	Nature, 246, PS52	BH	ST	DISK	Accretion onto BH from flare in companion
9.	Zwicky	1974	Ap & SS, 28, 111	NS		HALO	NS chunk contained by external pressure escapes, explodes
10.	Grindlay et al.	1974	ApJ, 187, L93	DG		SOL	Relativistic iron dust grain up-scatters solar radiation
11.	Brecher et al.	1974	ApJ, 187, L97	ST		DISK	Directed stellar flare on nearby star
12.	Schlovskii	1974	SovAstron, 18, 390	WD	COM	DISK	Comet from system's cloud strikes WD
13.	Schlovskii	1974	SovAstron, 18, 390	NS	COM	DISK	Comet from system's cloud strikes NS
			Ap & SS, 35, 23	ST		COS	Absorption of neutrino emission from SN in stellar envelope
			Ap & SS, 35, 23	ST	SN	COS	Thermal emission when small star heated by SN shock wave
			Ap & SS, 35, 23	NS		COS	Ejected matter from NS explodes
			Nature, 251, 399	NS		DISK	NS crustal starquake glitch; should time coincide with GRB
			Nature, 251, 590	WH		COS	White hole emits spectrum that softens with time
			A&A, 44, 21	NS		HALO	NS corequake excites vibrations, changing E & B fields
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59.	Epstein	1985	ApJ, 291, 822	NS		DISK	Accretion instability between NS and disk
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61.	Tsygan	1984	Ap & SS, 106, 199	NS		DISK	Weak B field NS spherically accretes, Comptonizes X-rays
62.	Usov	1984	Ap & SS, 107, 191	NS		DISK	NS flares result of magnetic convective-oscillation instability
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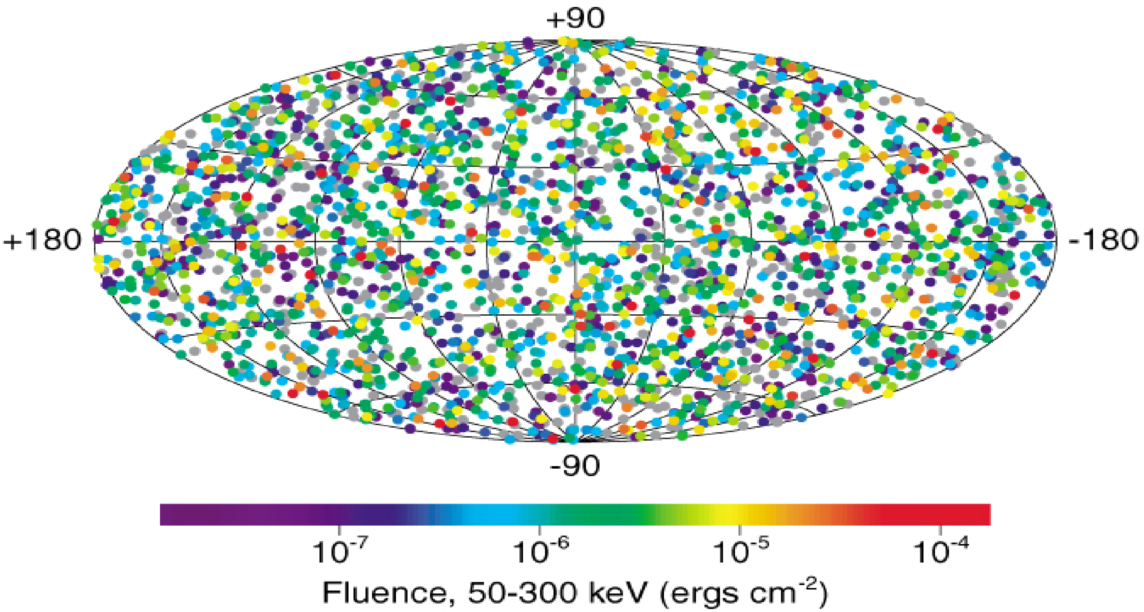
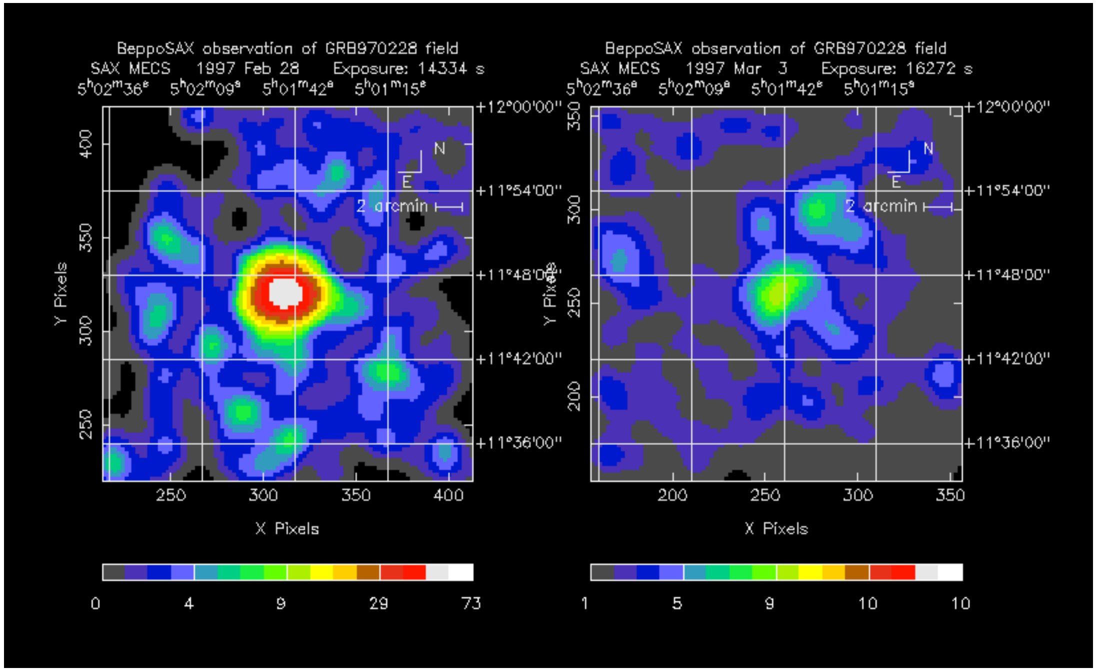
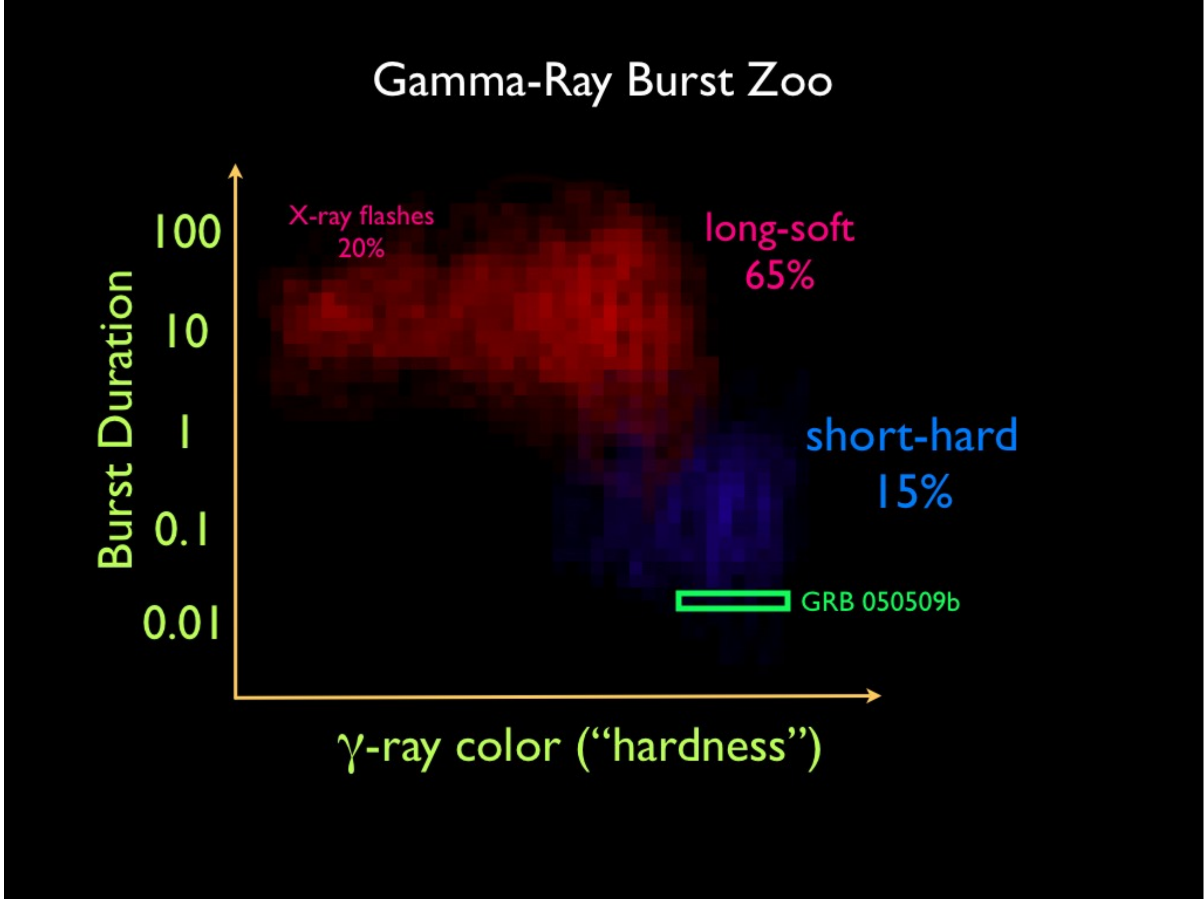
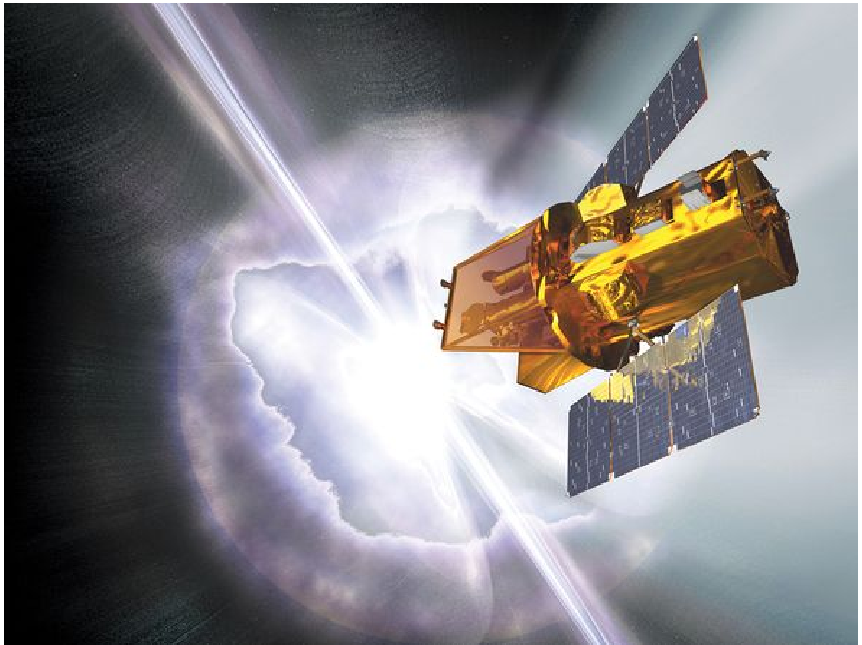
73.	Livio et al.	1987	Nature, 327, 398	NS	COM	DISK	Oort cloud around NS can explain soft gamma-repeaters
74.	McBreen et al.	1988	Nature, 332, 234	GAL	AGN	COS	G-wave bkgrd makes BL Lac wiggle across galaxy lens caustic

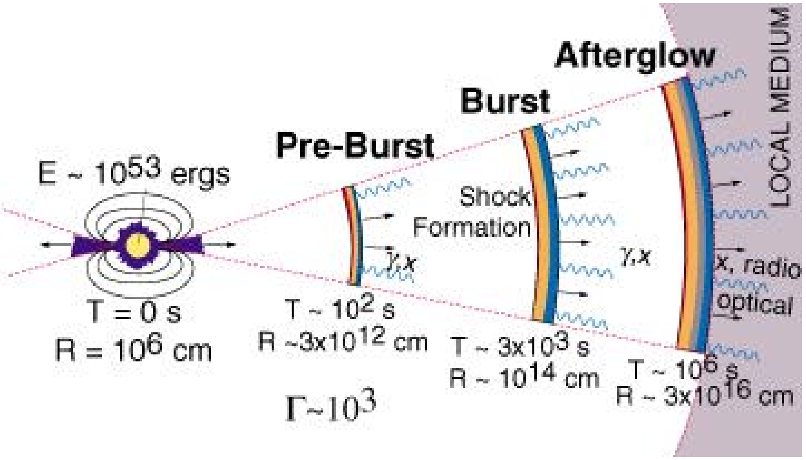
2704 BATSE Gamma-Ray Bursts



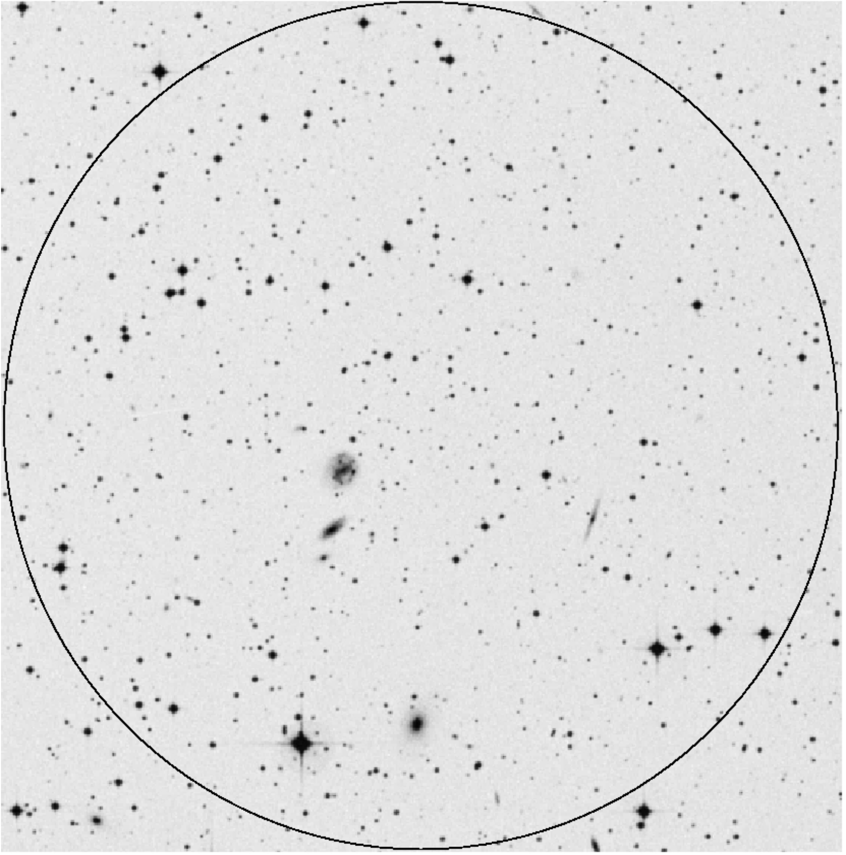


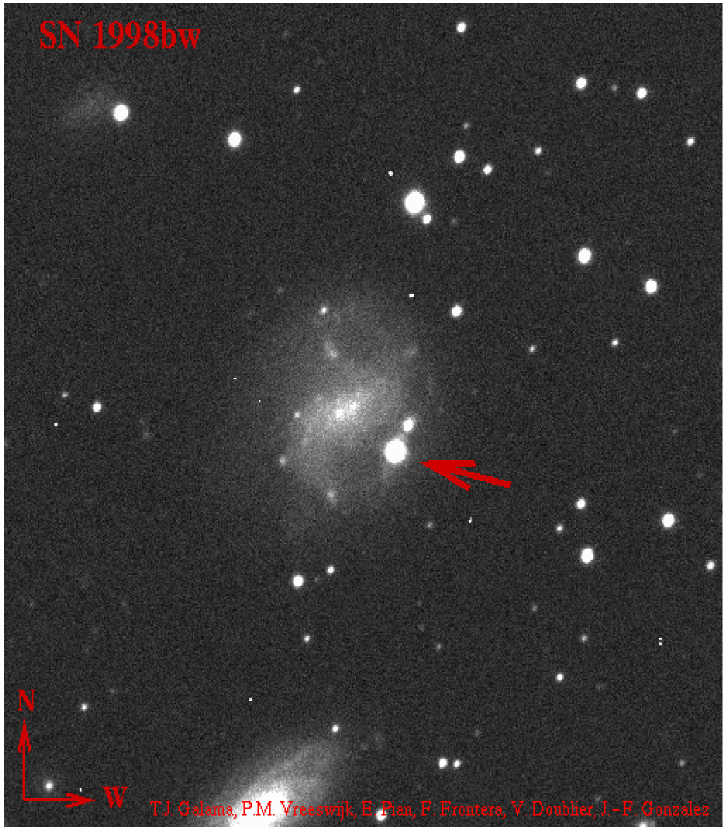

Gamma-Ray Burst Zoo
Burst Duration
100
10
1
0.1
0.01
X-ray flashes 20%
long-soft 65%
short-hard 15%
GRB 050509b
γ-ray color (“hardness”)



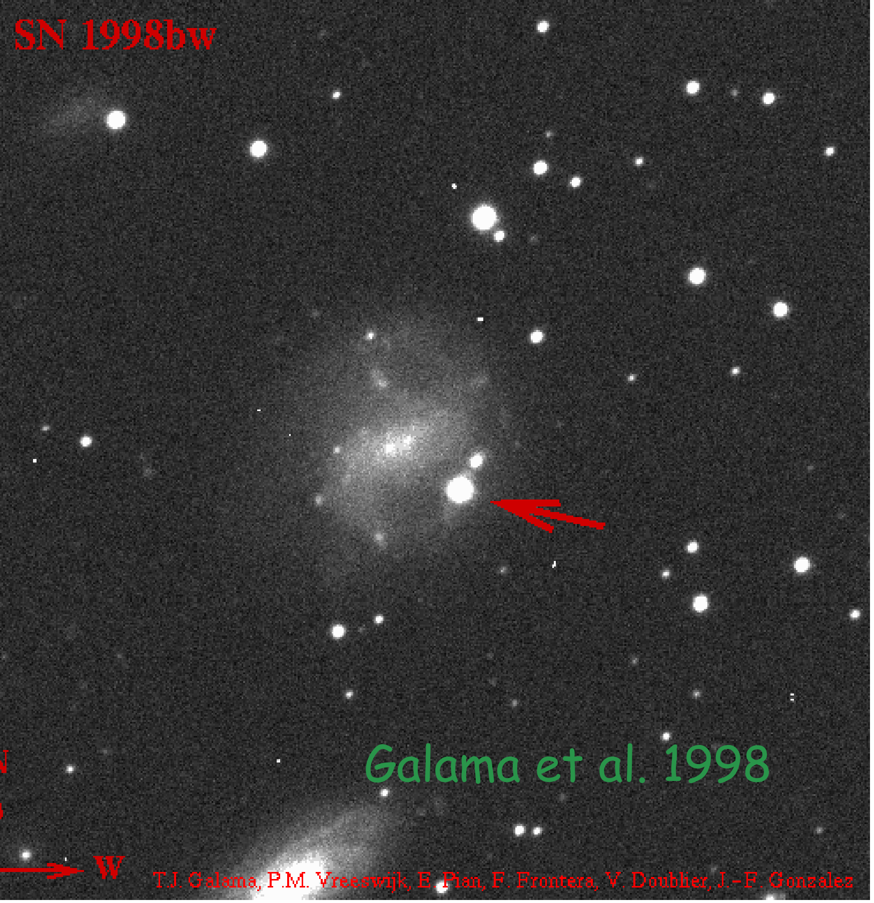

E ~ 10^53 ergs
T = 0 s
R = 10^6 cm
Pre-Burst
T ~ 10^2 s
R ~3x10^12 cm
Γ~10^3
Burst
Shock Formation
γ,x
T ~ 3x10^3 s
R ~ 10^14 cm
Afterglow
γ,x
x, radio
optical
T ~ 10^6 s
R ~ 3x10^16 cm
LOCAL MEDIUM

The first hint ..

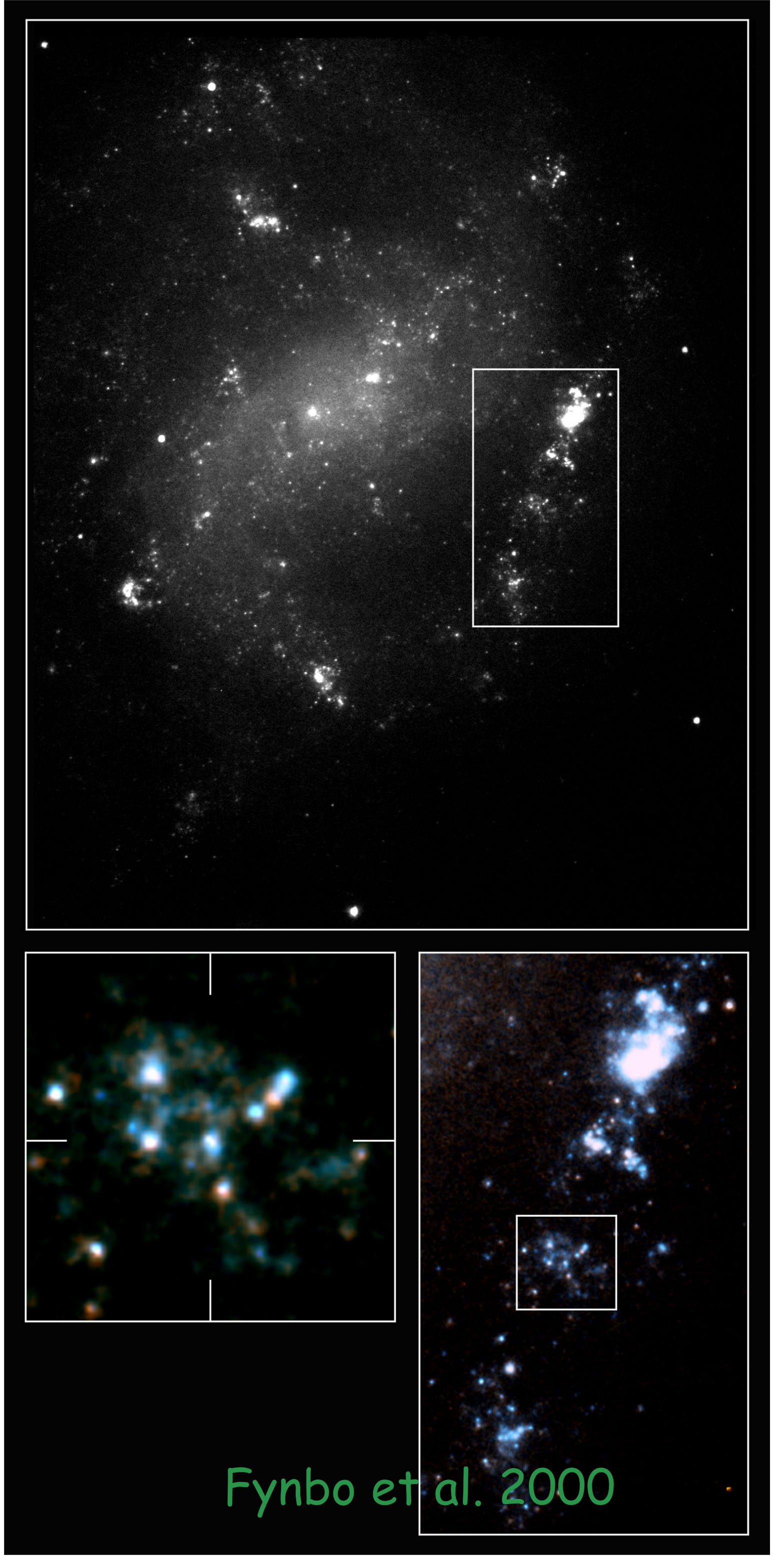




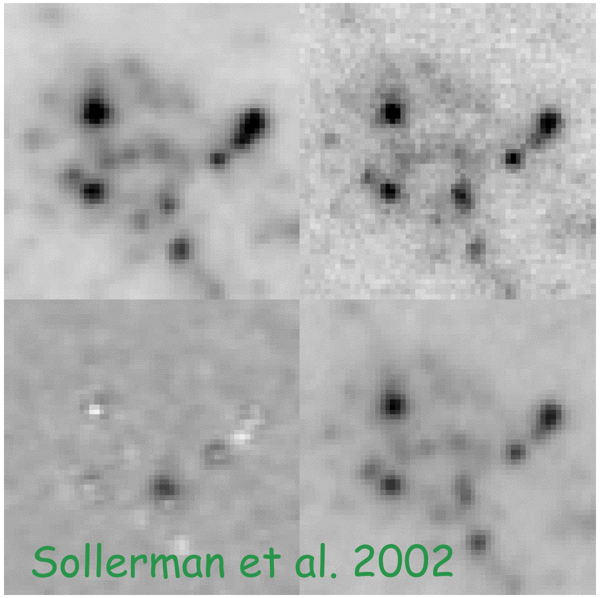
SN 1998bw



Galama et al. 1998

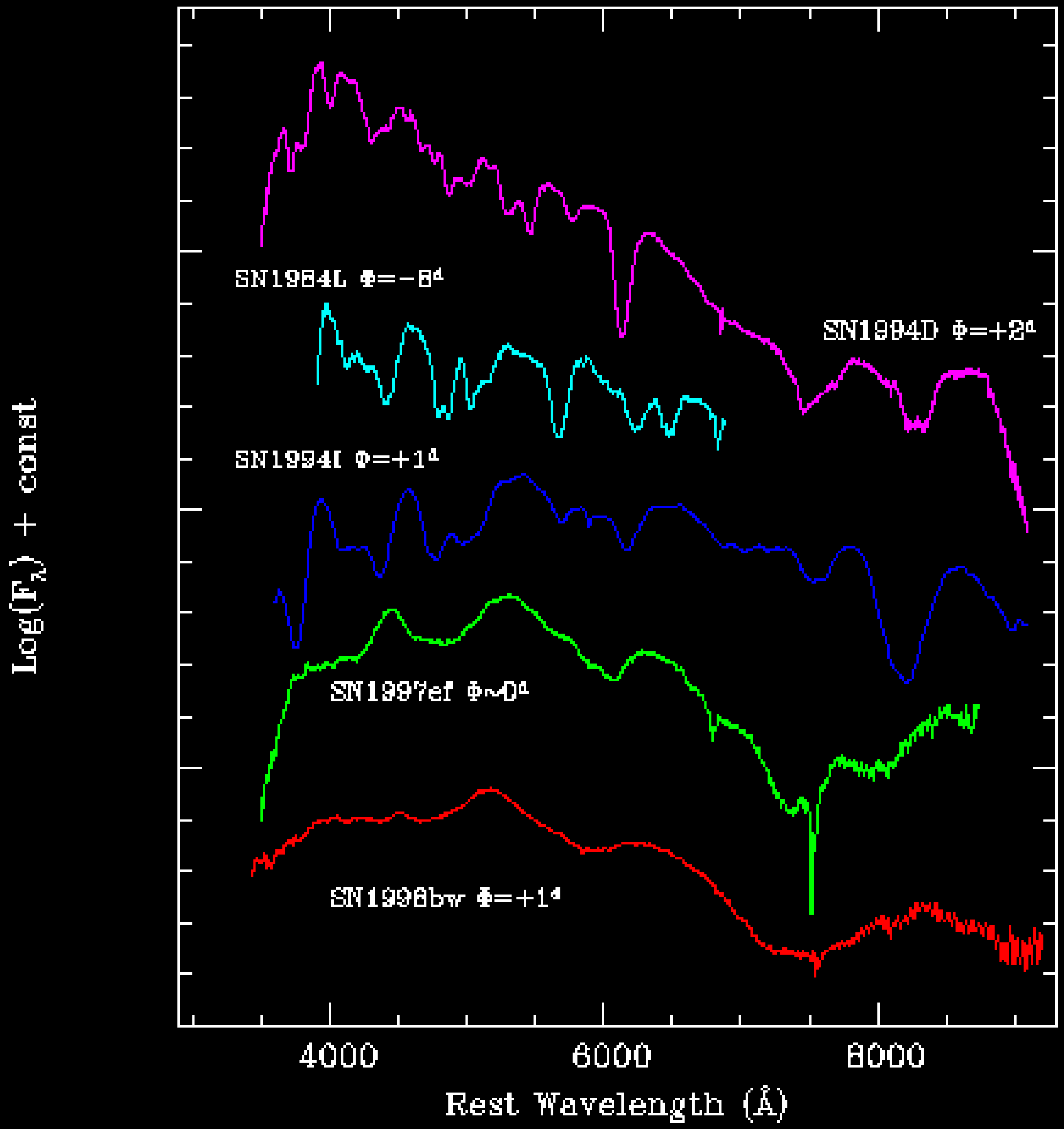


Fynbo et al. 2000

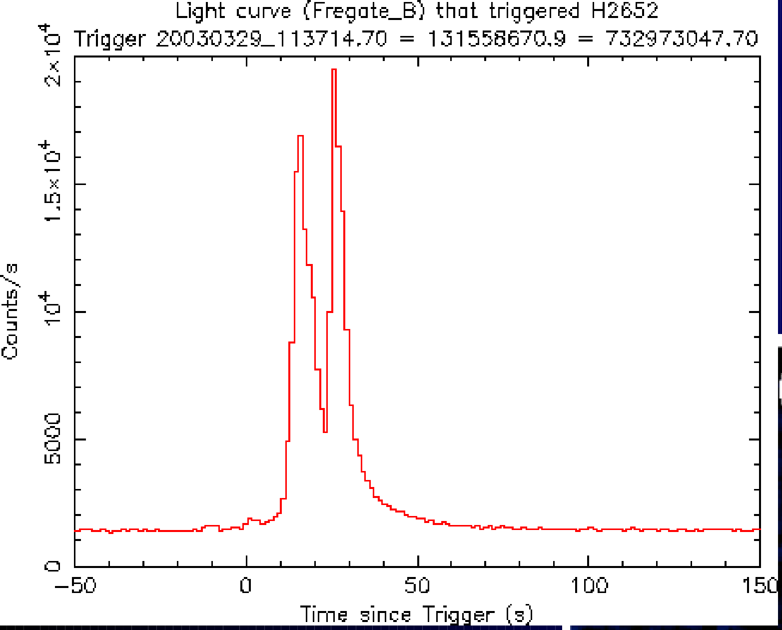


Sollerman et al. 2002

Maximum Light Spectra



GRB 030329



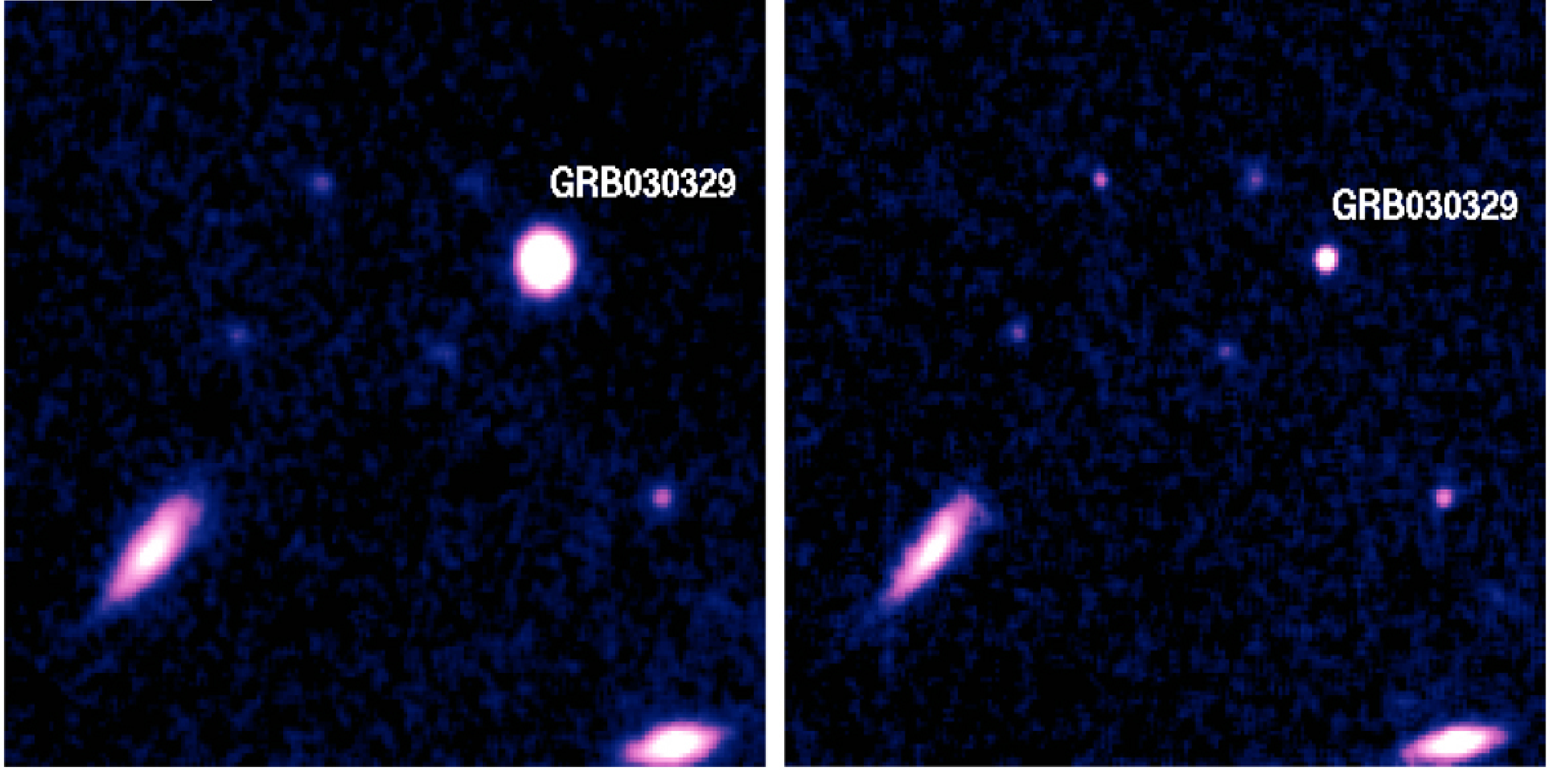
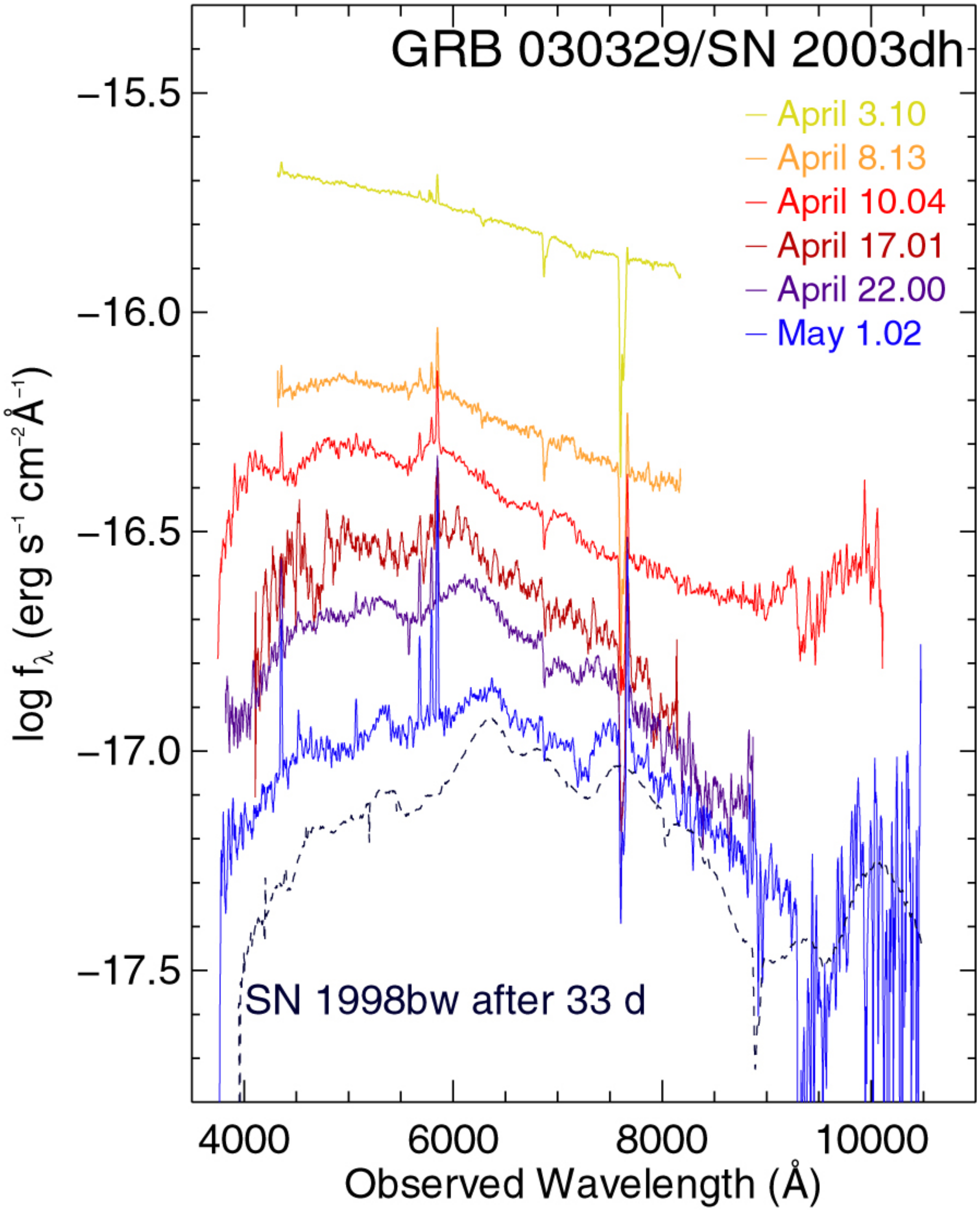


Image of Afterglow of GRB 030329
(VLT + FORS)

ESO PR Photo 17a/03 (18 June 2003)

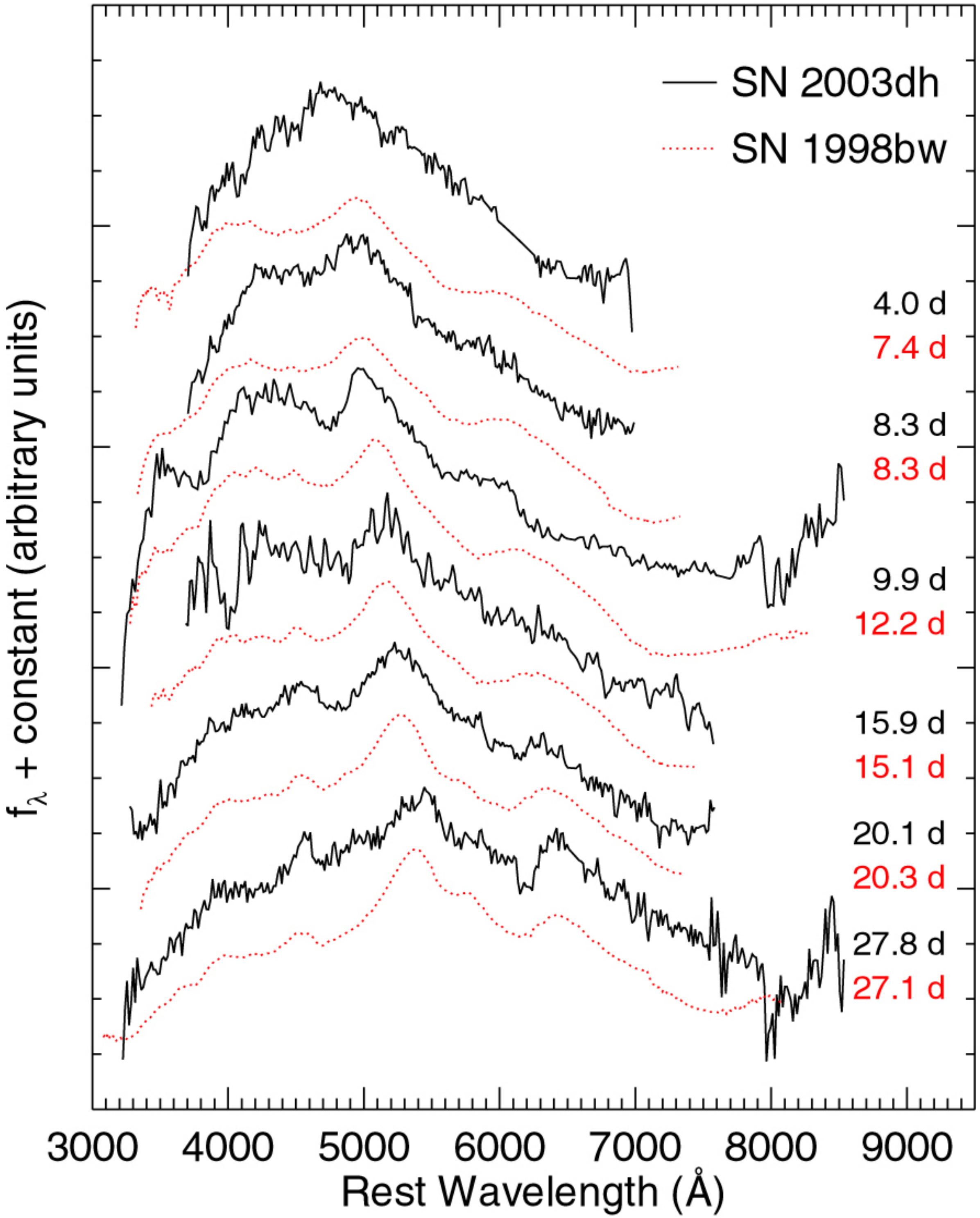
©European Southern Observatory

z=0.168526

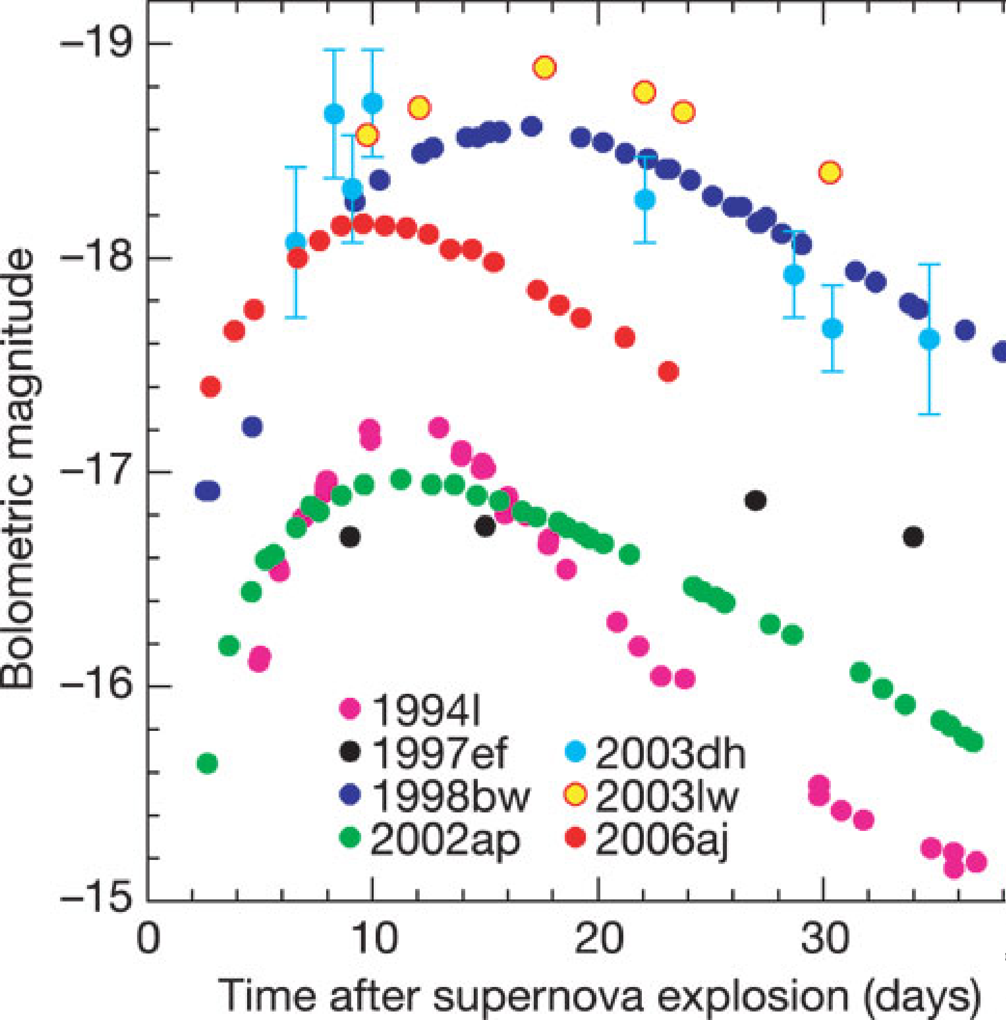


Hjorth, Sollerman, Moller, et al. 2003

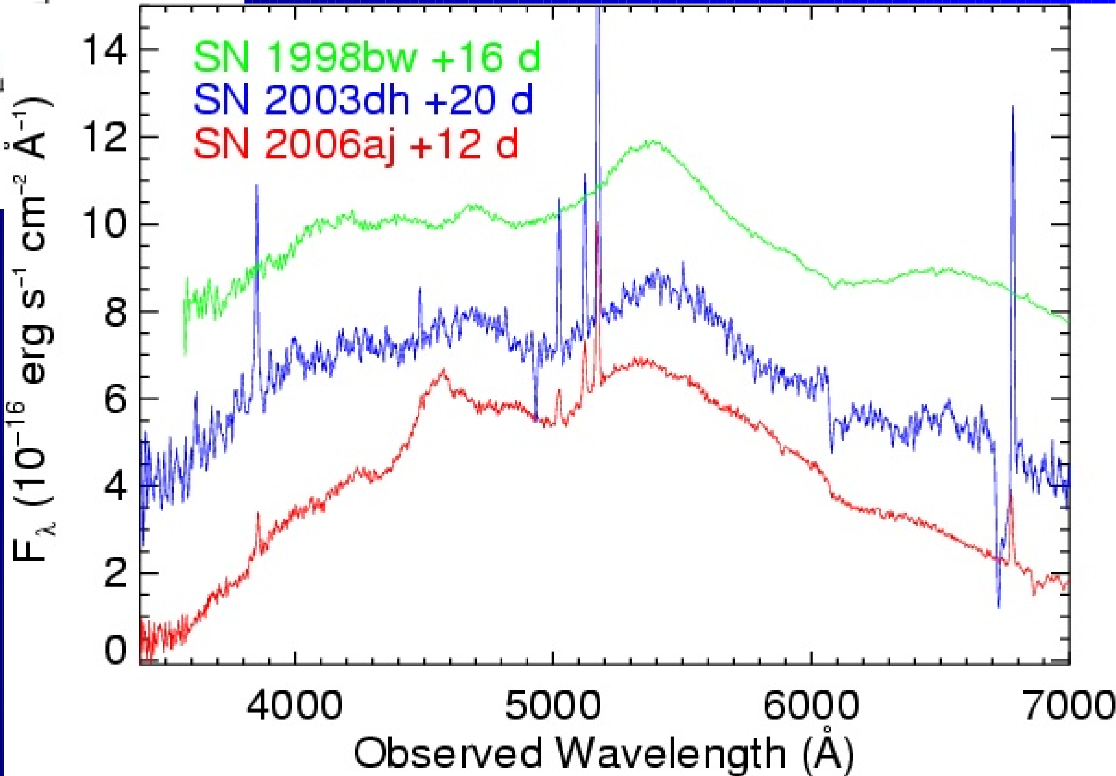
SN 2003dh



Amazingly similar..



Sollerman et al. 2006



XRF 060218 = SN 2006aj

Pian et al. 2006

fainter, faster.. diversity..

GRB 101219B
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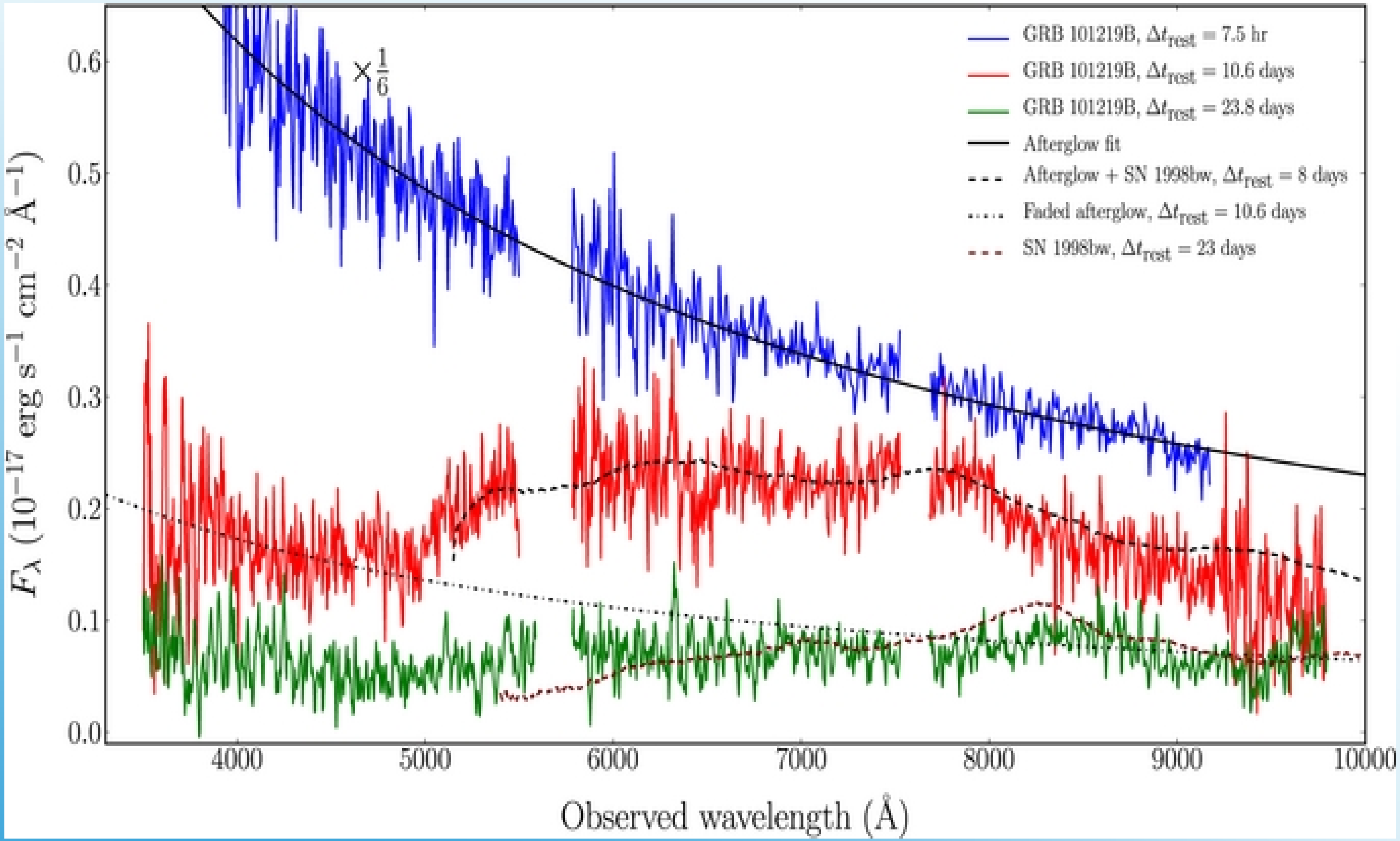
SN 2010ma



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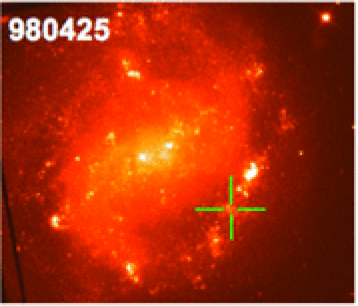
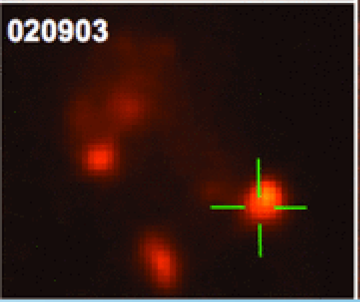
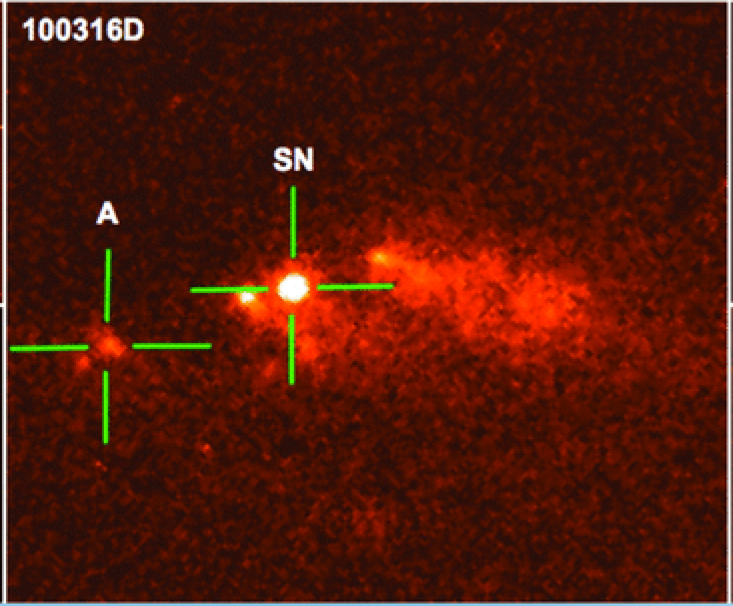
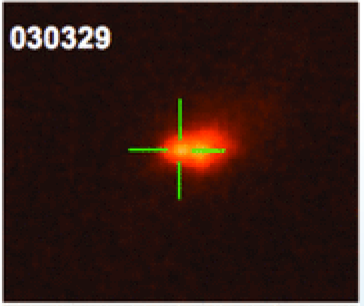
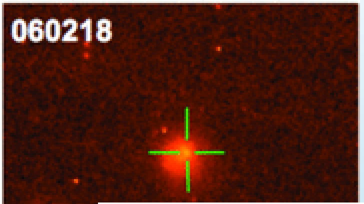
Sparre, Sollerman, Fynbo et al. 2011, ApJ





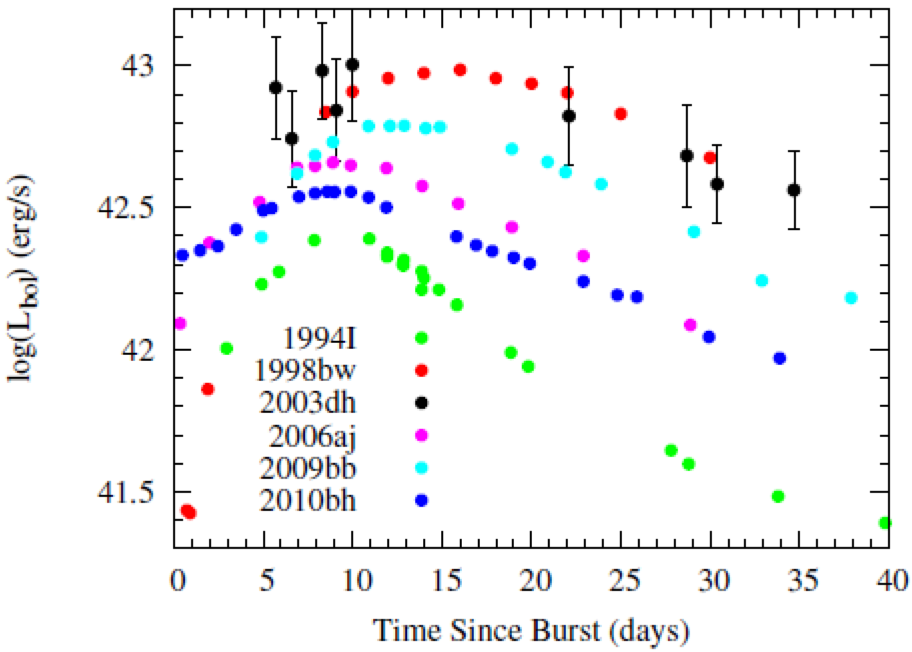




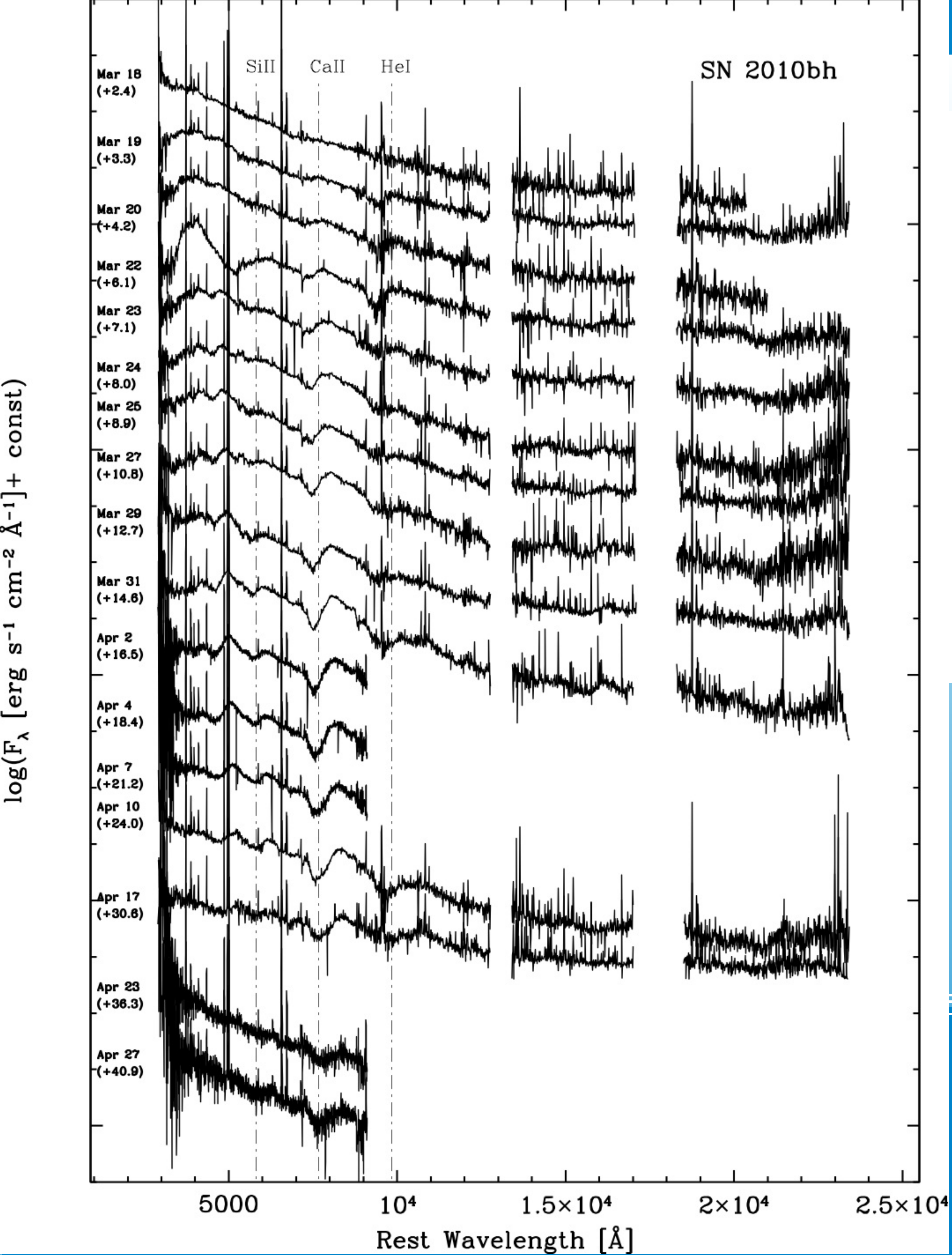


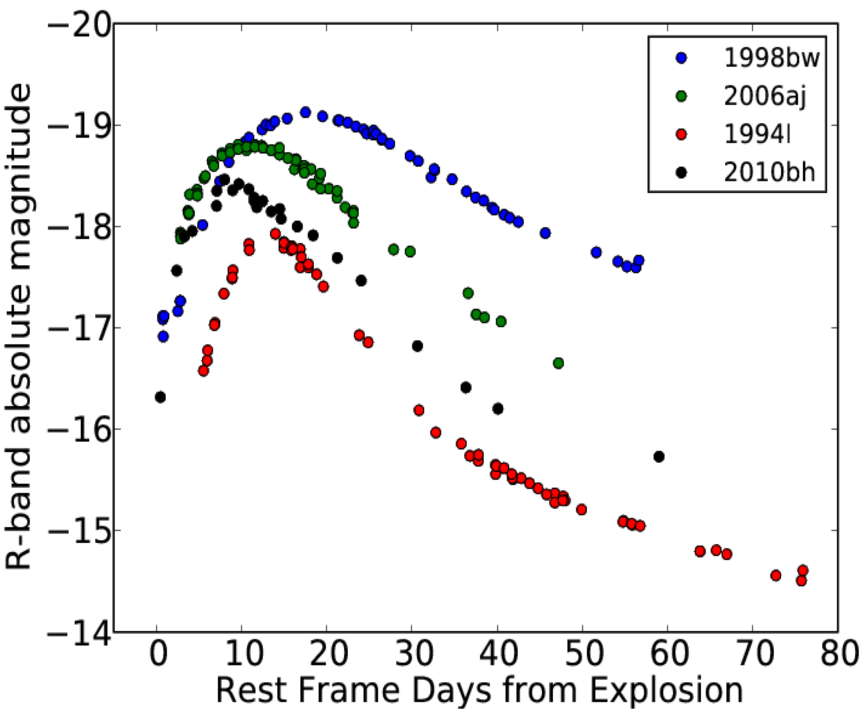
Starling, Wiersema, Levan, et al. 2011, MNRAS

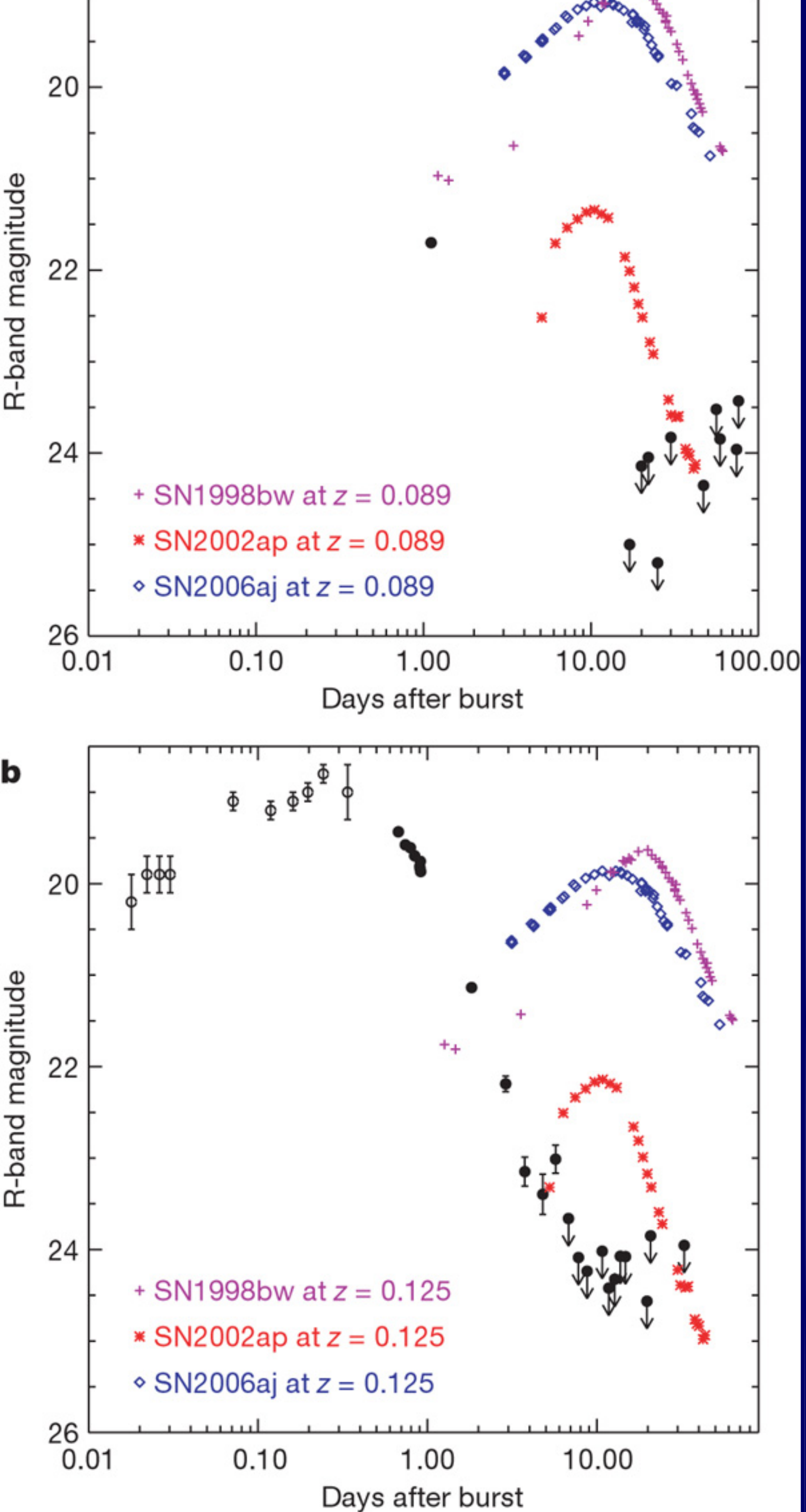
GRB 100316D = SN 2010bh



Bufano, Pian, Sollerman, et al. 2012



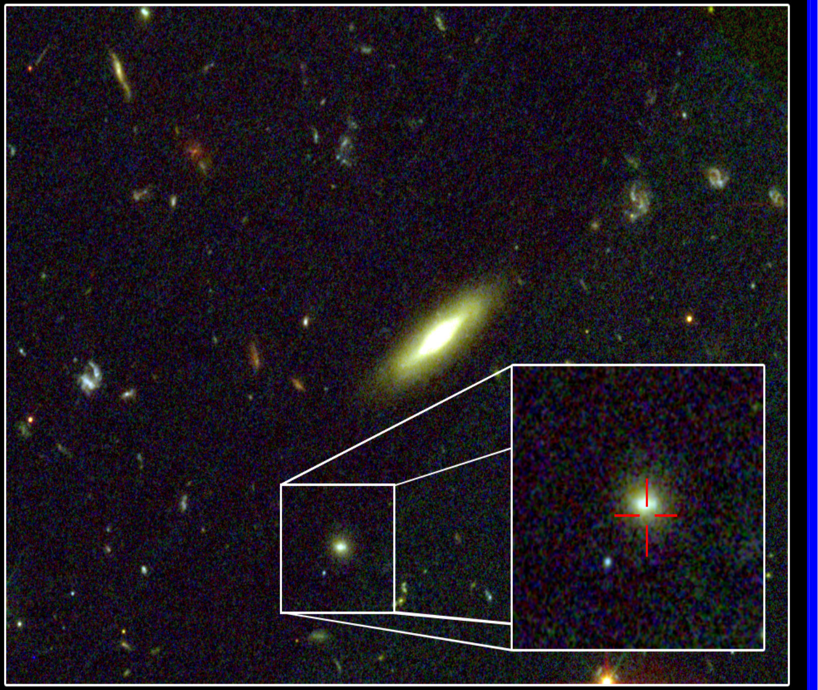




But not all GRBs have luminous supernova associated!

GRB 060614 and 060505

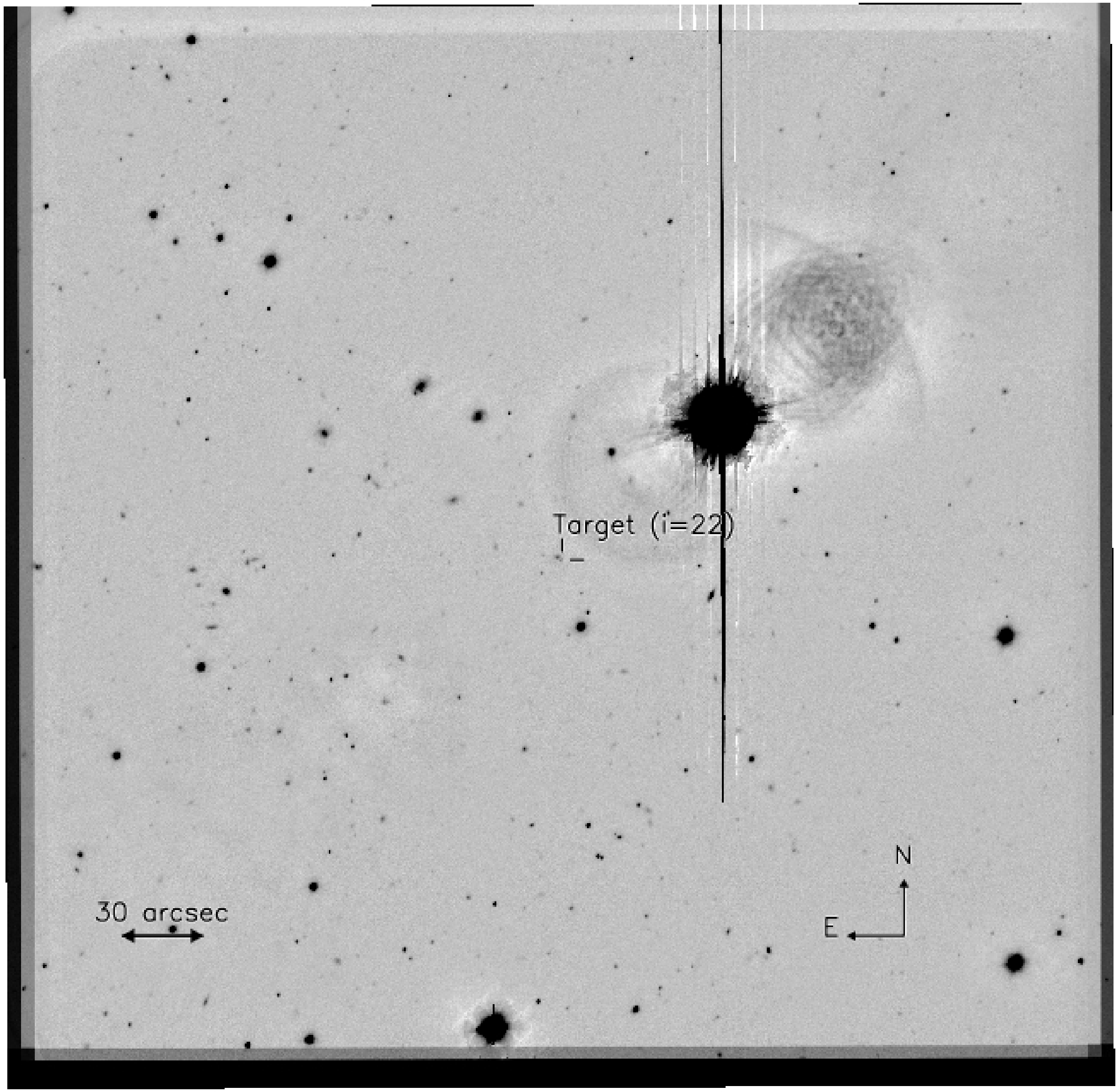
Fynbo et al. 2006



GRB 060614 HST • ACS K. Sharon, A. Gal-Yam

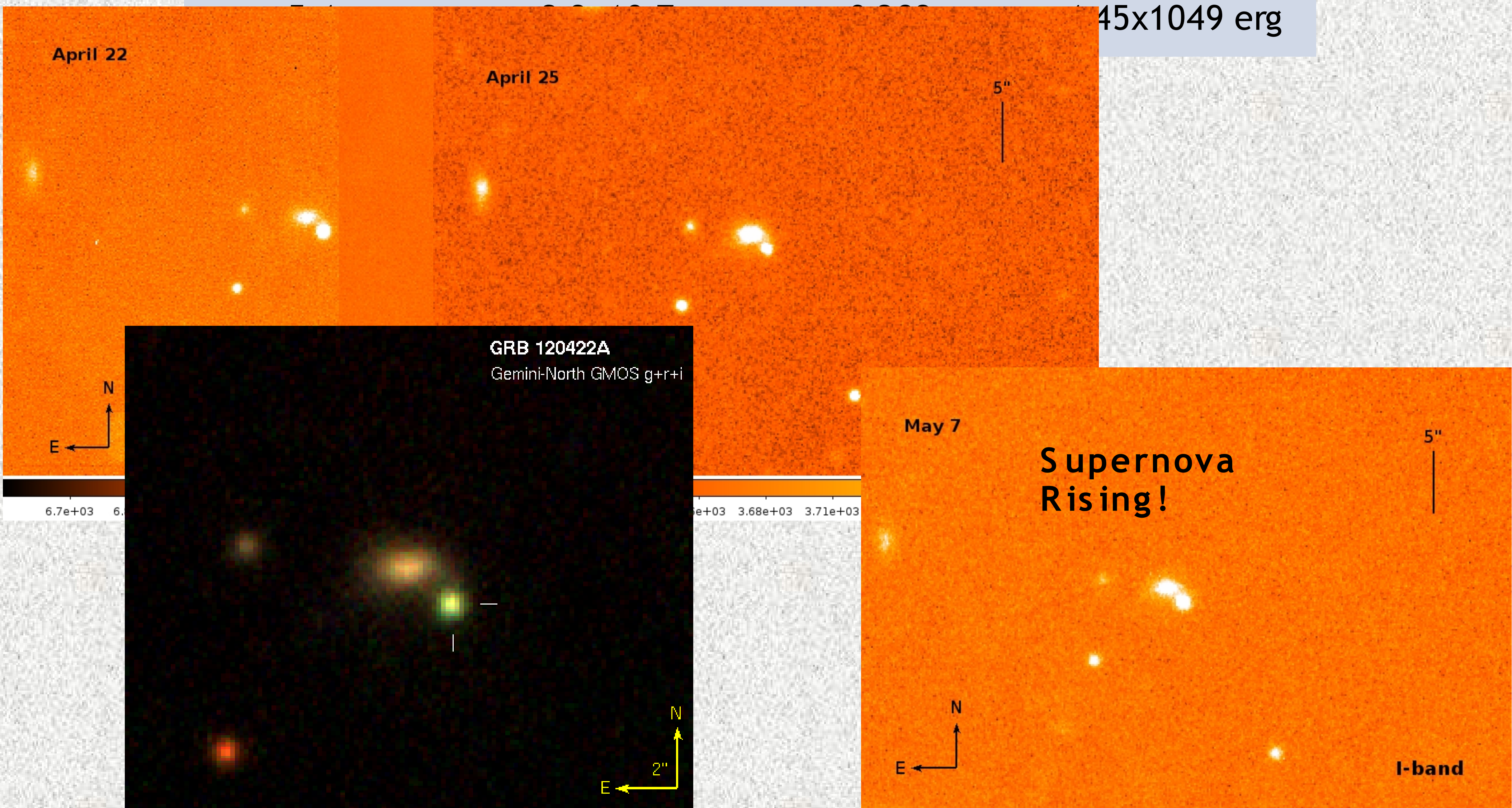
Program ID: P45
PI name: P. Jakobsson
Finding chart size: 7.0'x7.0'
Chart wavelength: ALFOSC i'

Target: GRB120422A
RA(J2000): 09:07:38.400
Dec(J2000): +14:01:07.60



GRB 120422A "Another" GRB with Associated Supernova

T90	Fluence	Redshift	Eiso
			45x1049 erg



Supernova Rising!