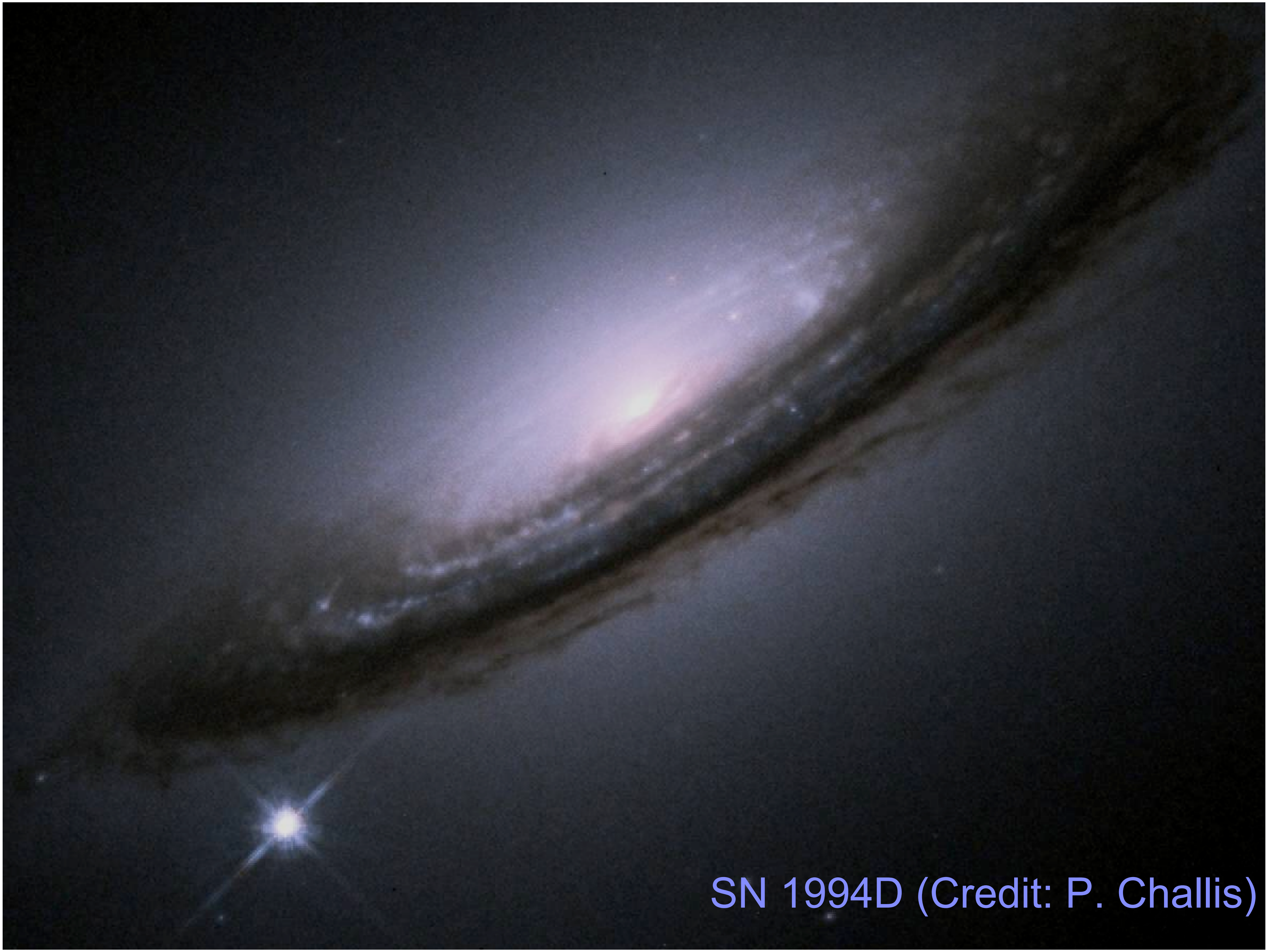
How to classify spectra of exploding stars (?)

Stéphane Blondin

Harvard-Smithsonian Center for Astrophysics

Astrostatistics Seminar
(03/13/2007)

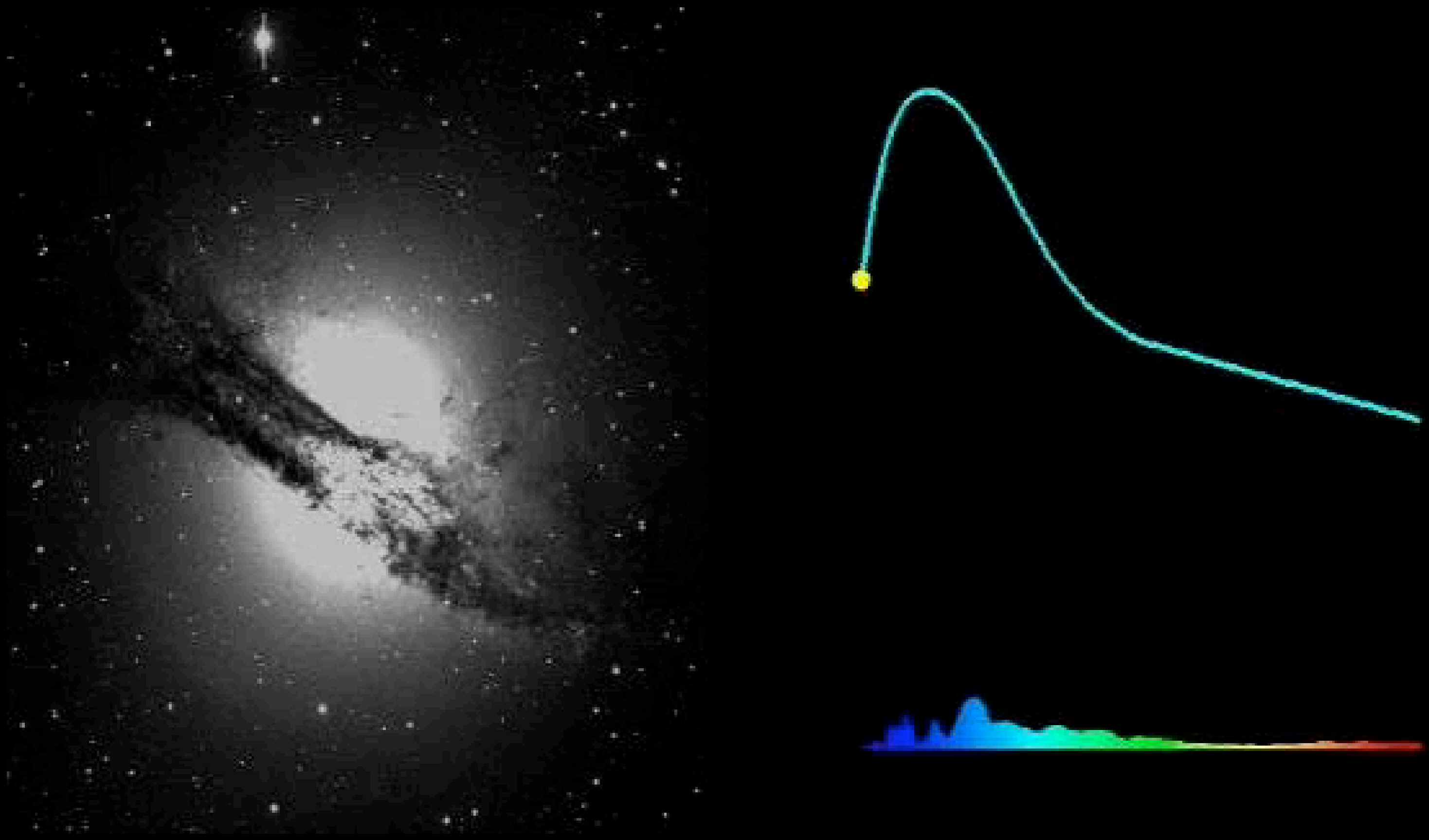


SN 1994D (Credit: P. Challis)

Layout

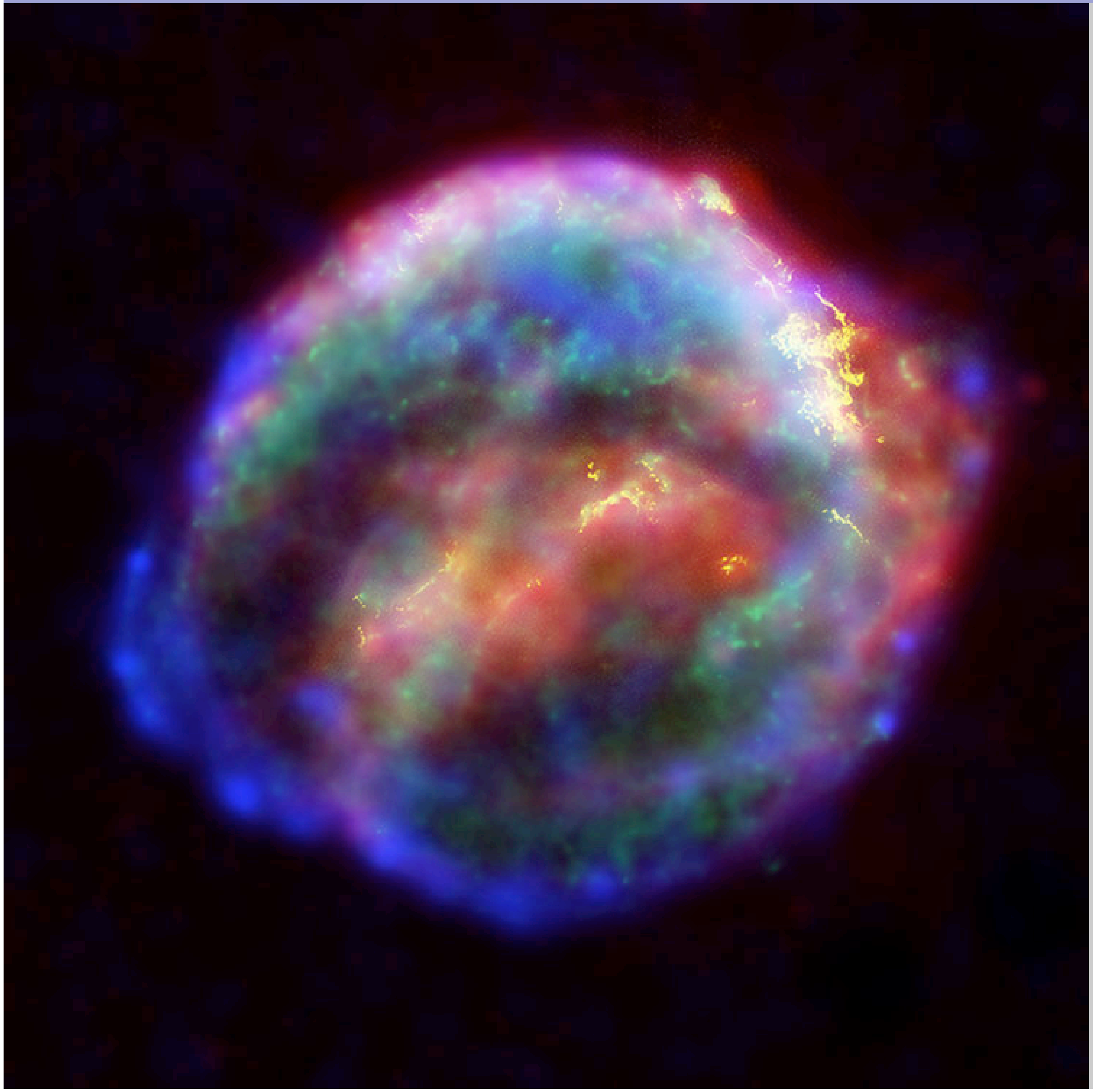
1. Introduction
    - What is a supernova?
    - Why study them?
    - Supernovae by the 1000s
2. Supernova Classification
3. Cross-correlation Technique
4. Other Techniques
5. An Optimal Classification?

SN 1986G in Centaurus A



Credits: Supernova Cosmology Project, LBNL, NERSC

Why Study Supernovae?



Synthesize and distribute heavy elements (e.g. ^{254}Cf)

SN 1604 (Kepler's SN)

Credit: Spitzer, HST, Chandra

Why Study Supernovae?

Trigger star formation

Orion Nebula

Credit: HST

Why Study Supernovae?

18 December 1998

Science

Vol. 282 No. 5397
Pages 2141–2336 $7

THE ACCELERATING UNIVERSE

Breakthrough of the Year

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

Embarrass physicists

Accelerating Universe

Credit: Science Magazine

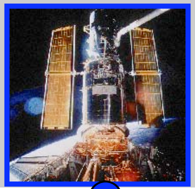
WWW Supernova Search

KAIT

APO 2.5m

CFHT

HST

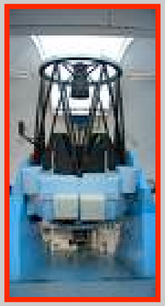


MDM 2.4m

FLWO 1.2m, 1.5m, and 1.3m

TNG

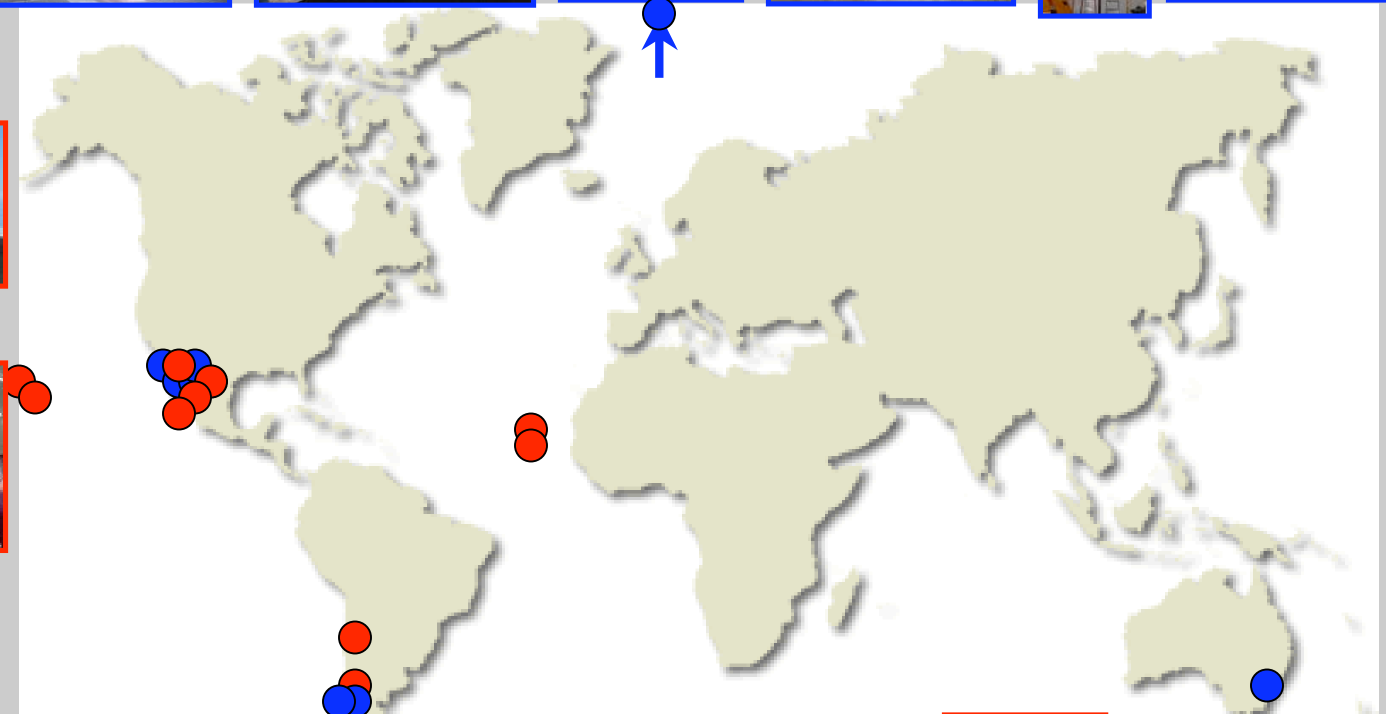
NOT



Keck

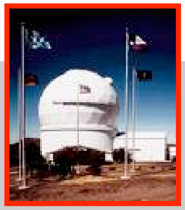
Gemini N&S

CTIO 4m



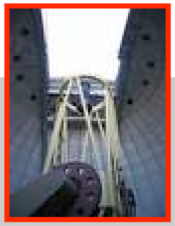
VLT

Magellan



HET

MMT

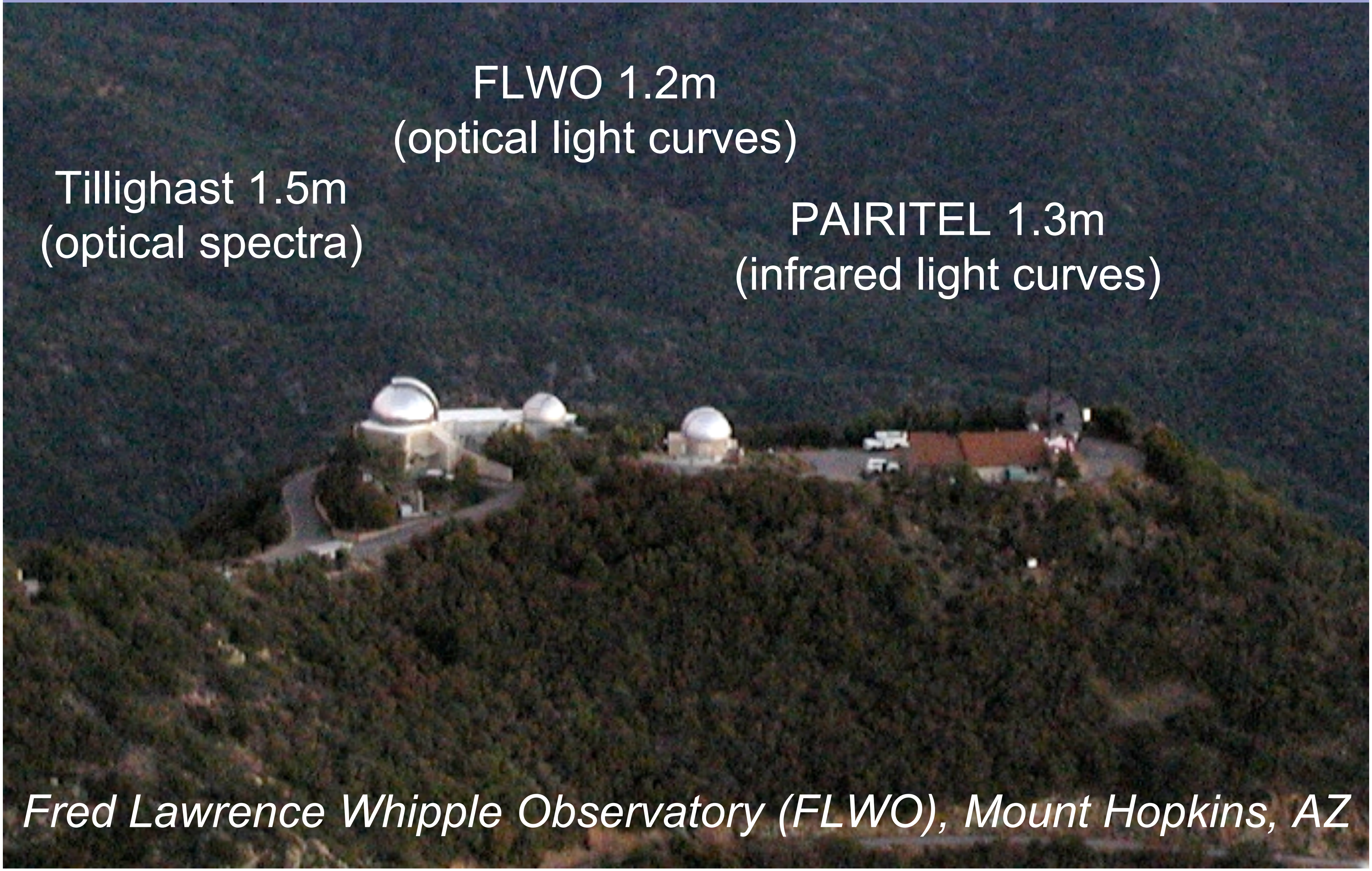


Lick 3m

Dupont 2.5m

MSSSO 2.3m

CfA Supernova Search



FLWO 1.2m
(optical light curves)

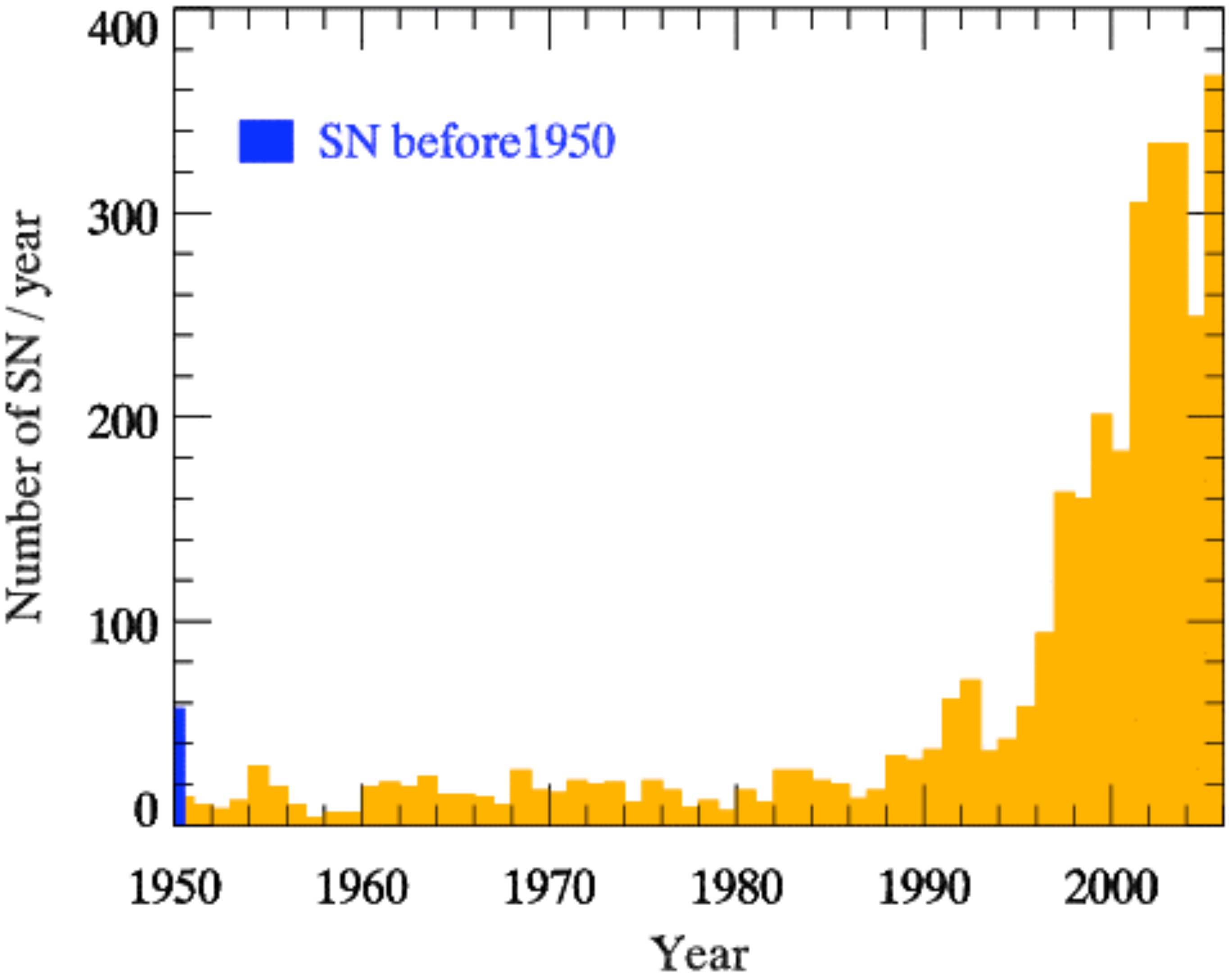
Tillighast 1.5m
(optical spectra)

PAIRITEL 1.3m
(infrared light curves)

Fred Lawrence Whipple Observatory (FLWO), Mount Hopkins, AZ

Supernovae by the 1000s

~3700 SNe since 1006 (50% since 2000)



~50% discovered by amateurs

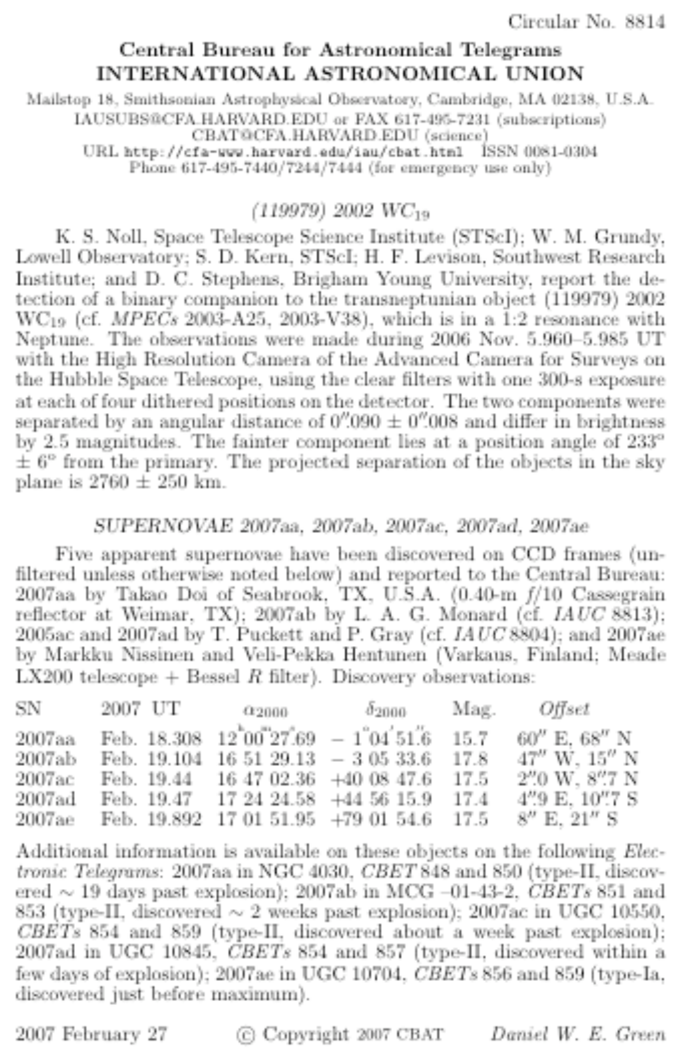
~300+ SNe/year (in IAU circulars)

>1/3 classifications by CfA astronomers

~40% non-secure classification

IAU Circulars (IAUC,CBET)

Discovery (19 Feb 2007)



Circular No. 8814

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)

(119979) 2002 WC$_{19}$

K. S. Noll, Space Telescope Science Institute (STScI); W. M. Grundy, Lowell Observatory; S. D. Kern, STScI; H. F. Levison, Southwest Research Institute; and D. C. Stephens, Brigham Young University, report the detection of a binary companion to the transneptunian object (119979) 2002 WC$_{19}$ (cf. *MPECs* 2003-A25, 2003-V38), which is in a 1:2 resonance with Neptune. The observations were made during 2006 Nov. 5.960–5.985 UT with the High Resolution Camera of the Advanced Camera for Surveys on the Hubble Space Telescope, using the clear filters with one 300-s exposure at each of four dithered positions on the detector. The two components were separated by an angular distance of $0''.090 \pm 0''.008$ and differ in brightness by 2.5 magnitudes. The fainter component lies at a position angle of 233° ± 6° from the primary. The projected separation of the objects in the sky plane is 2760 ± 250 km.

SUPERNOVAE 2007aa, 2007ab, 2007ac, 2007ad, 2007ae

Five apparent supernovae have been discovered on CCD frames (unfiltered unless otherwise noted below) and reported to the Central Bureau: 2007aa by Takao Doi of Seabrook, TX, U.S.A. (0.40-m *f*/10 Cassegrain reflector at Weimar, TX); 2007ab by L. A. G. Monard (cf. *IAUC* 8813); 2005ac and 2007ad by T. Puckett and P. Gray (cf. *IAUC* 8804); and 2007ae by Markku Nissinen and Veli-Pekka Hentunen (Varkaus, Finland; Meade LX200 telescope + Bessel *R* filter). Discovery observations:

SN	2007 UT	α_{2000}	δ_{2000}	Mag.	*Offset*
2007aa	Feb. 18.308	$12^h00^m27^s.69$	$-1°04'51''.6$	15.7	60″ E, 68″ N
2007ab	Feb. 19.104	16 51 29.13	− 3 05 33.6	17.8	47″ W, 15″ N
2007ac	Feb. 19.44	16 47 02.36	+40 08 47.6	17.5	2″.0 W, 8″.7 N
2007ad	Feb. 19.47	17 24 24.58	+44 56 15.9	17.4	4″.9 E, 10″.7 S
2007ae	Feb. 19.892	17 01 51.95	+79 01 54.6	17.5	8″ E, 21″ S

Additional information is available on these objects on the following *Electronic Telegrams*: 2007aa in NGC 4030, *CBET* 848 and 850 (type-II, discovered ~ 19 days past explosion); 2007ab in MCG –01-43-2, *CBETs* 851 and 853 (type-II, discovered ~ 2 weeks past explosion); 2007ac in UGC 10550, *CBETs* 854 and 859 (type-II, discovered about a week past explosion); 2007ad in UGC 10845, *CBETs* 854 and 857 (type-II, discovered within a few days of explosion); 2007ae in UGC 10704, *CBETs* 856 and 859 (type-Ia, discovered just before maximum).

2007 February 27 *Daniel W. E. Green*

Classification (25 Feb 2007)

Electronic Telegram No. 859
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

SUPERNOVAE 2007ac AND 2007ae

S. Blondin, M. Modjaz, R. Kirshner, and P. Challis, Harvard-Smithsonian Center for Astrophysics, report that a spectrogram (range 350-740 nm) of SN 2007ac (cf. CBET 854), obtained by A. Vaz on Feb. 25.54 UT with the F. L. Whipple Observatory 1.5-m telescope (+ FAST), shows it to be a type-II supernova roughly 1-2 weeks past explosion. The spectrum consists of a blue continuum and P-Cyg lines of the Balmer series, consistent with the plateau phase of a normal type-II supernova. The spectrum is similar to the type-II-plateau supernova 1999em at 10 days past explosion. Adopting a recession velocity of 9056 km/s for the host galaxy (Rines et al. 2002, A.J. 124, 1266), the maximum absorption in the H_beta line (rest 486.1 nm) is blueshifted by roughly 9500 km/s.

Blondin et al. add that a spectrum (range 350-740 nm) of SN 2007ae (cf. CBET 856), obtained on Feb. 25.54 by Vaz, shows it to be a type-Ia supernova around maximum light. Cross-correlation with a library of supernova spectra indicates that 2007ae is most similar to the type-Ia supernova 1999ee at maximum light. Adopting a recession velocity of 19303 km/s for the host galaxy (Berrington et al. 2002, A.J. 123, 2261), the maximum absorption in the Si II line (rest 635.5 nm) is blueshifted by roughly 11000 km/s.

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

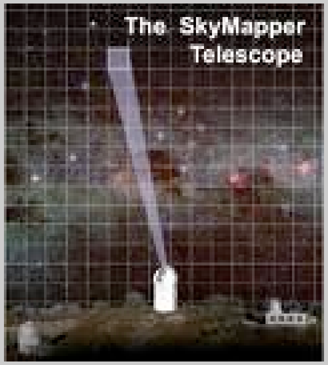
2007 February 25 (CBET 859) Daniel W. E. Green

Future Supernova Surveys

Ground-based (2007-2013):

DARK ENERGY
Survey

Pan-STARRS

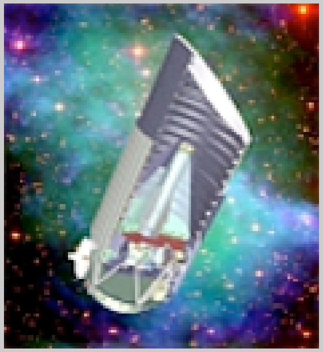


LSST
Large Synoptic Survey Telescope

Space-based (2015+):

ADEPT

Destiny



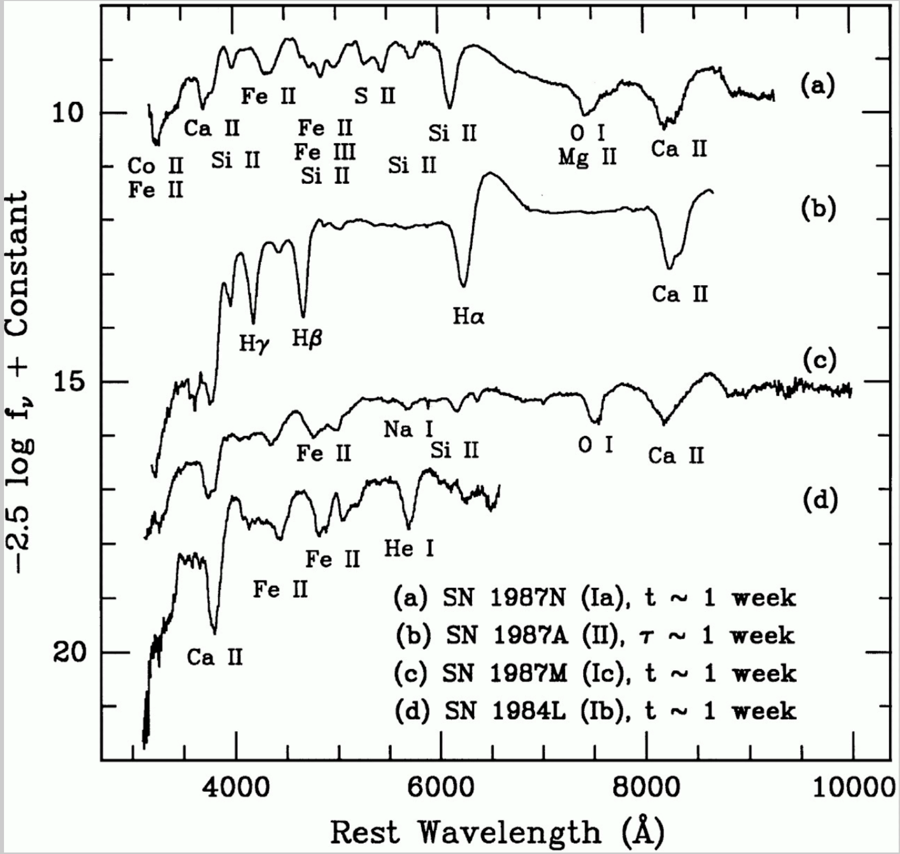
SNAP

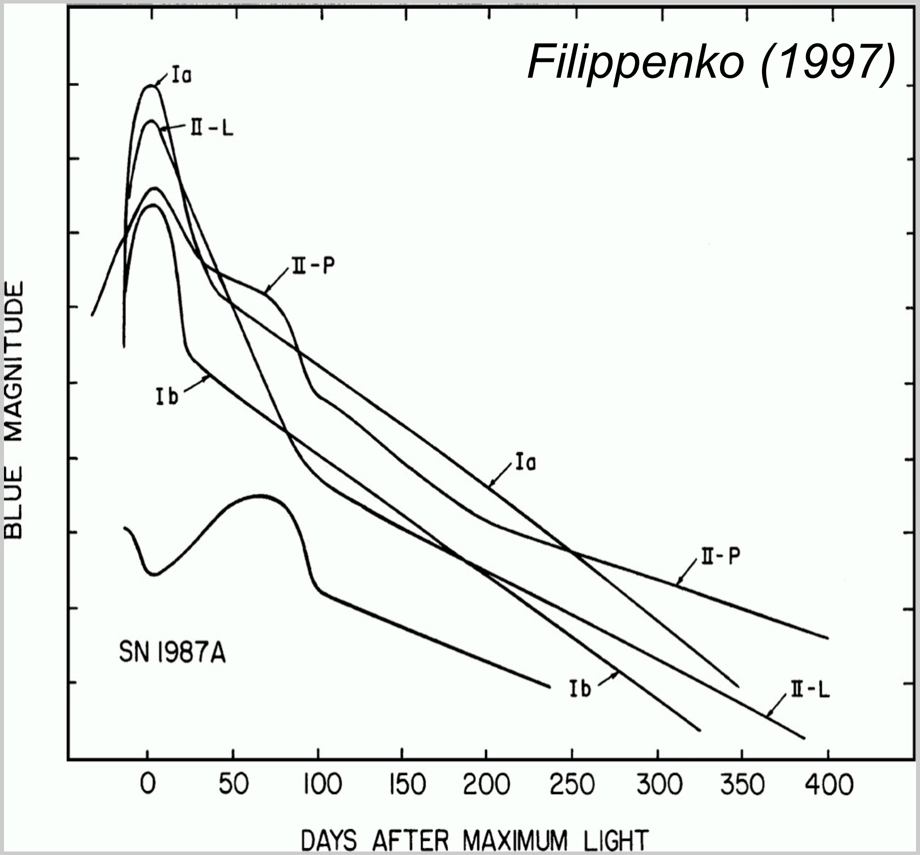
Layout

1. Introduction
2. Supernova Classification
    - Spectra and light curves
    - A brief history of supernova classification
    - Complications
3. Cross-correlation Technique
4. Other Techniques
5. An Optimal Classification?

Spectra and Light Curves

Classification based on **early-time optical spectra**

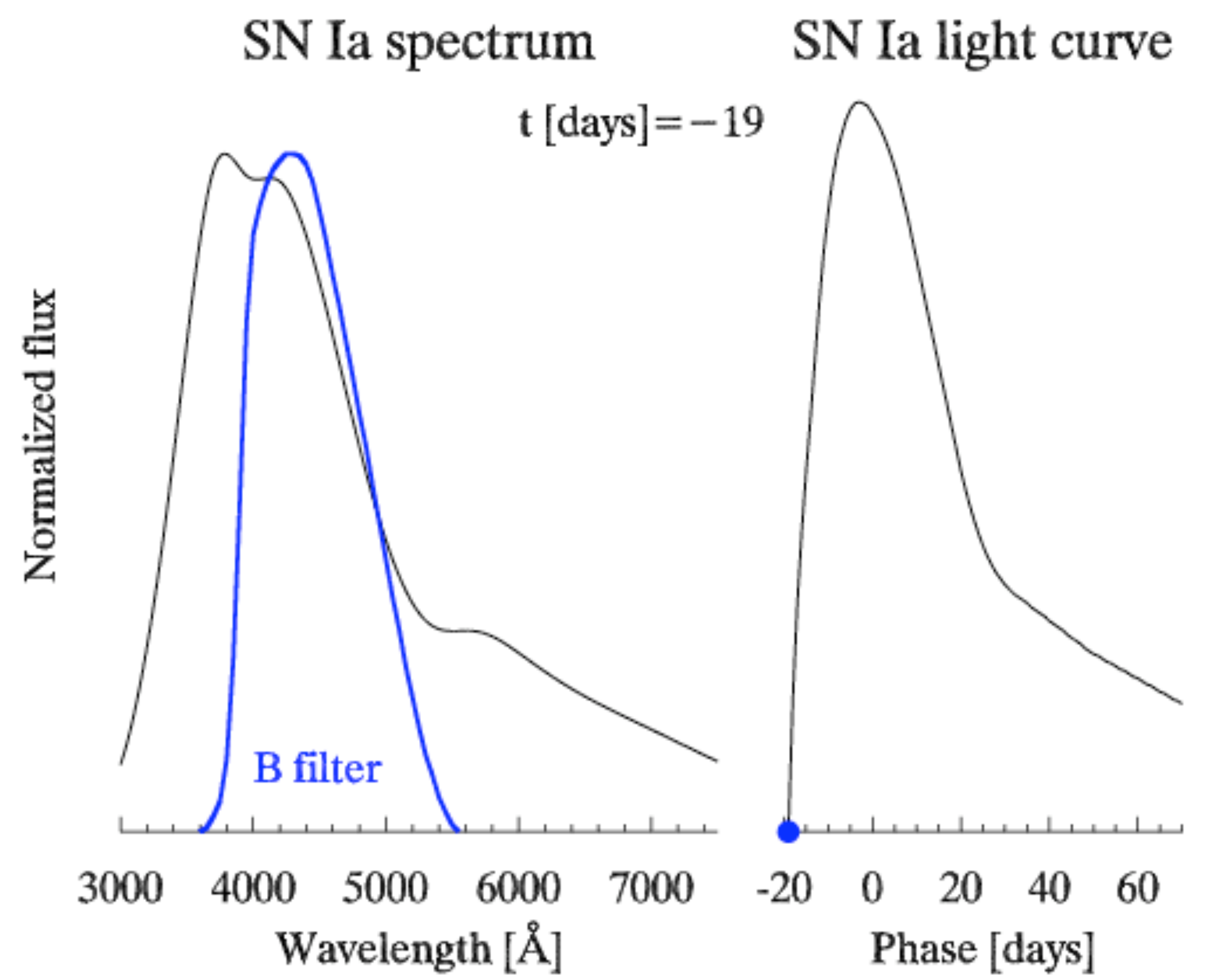



Filippenko (1997)

Spectrum: Flux (energy flow) per wavelength, $\boldsymbol{S(\lambda)}$

Phase: Age of supernova in days from maximum light, t_B

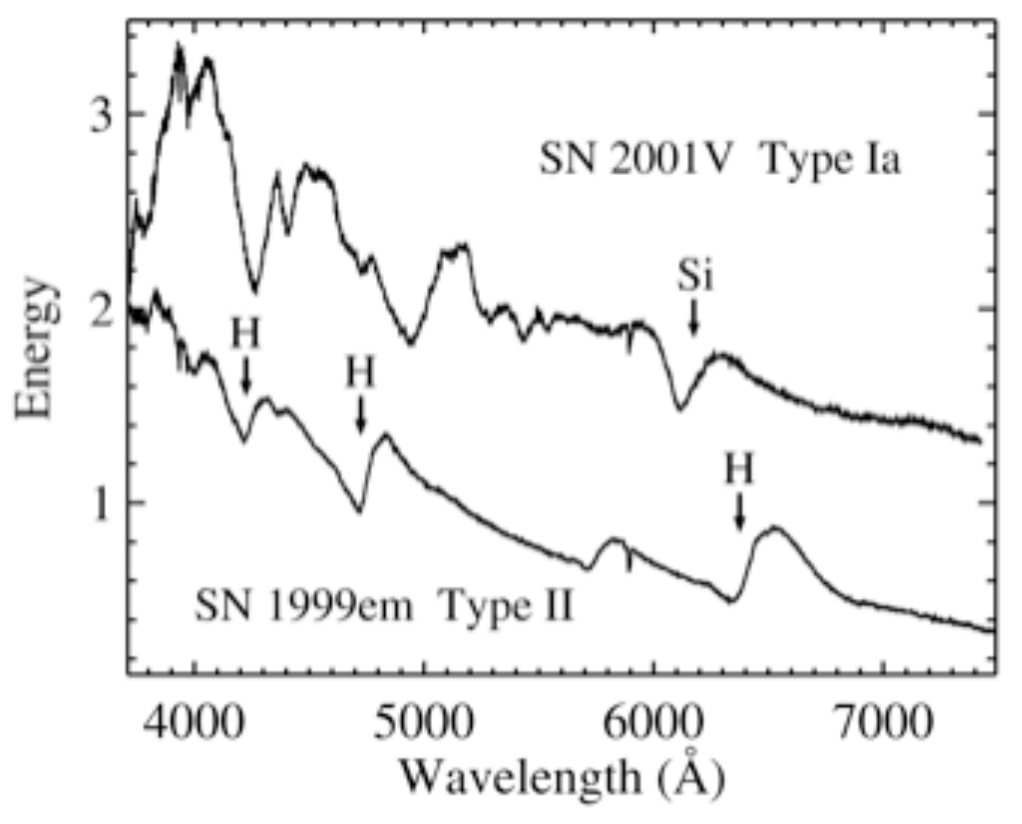
Spectra and Light Curves



A Brief History of Supernova Classification

1941: Rudolph Minkowski defines two supernova types based on elements in optical spectrum:

Type I (no hydrogen) and Type II (hydrogen)



A Brief History of Supernova Classification

1941: Rudolph Minkowski defines two supernova types based on elements in optical spectrum:

Type I (no hydrogen) and Type II (hydrogen)

1965: Fritz Zwicky tries to have the last word:

Type II extended to include Type III, Type IV, and Type V

A Brief History of Supernova Classification

1941: Rudolph Minkowski defines two supernova types based on elements in optical spectrum:

Type I (no hydrogen) and Type II (hydrogen)

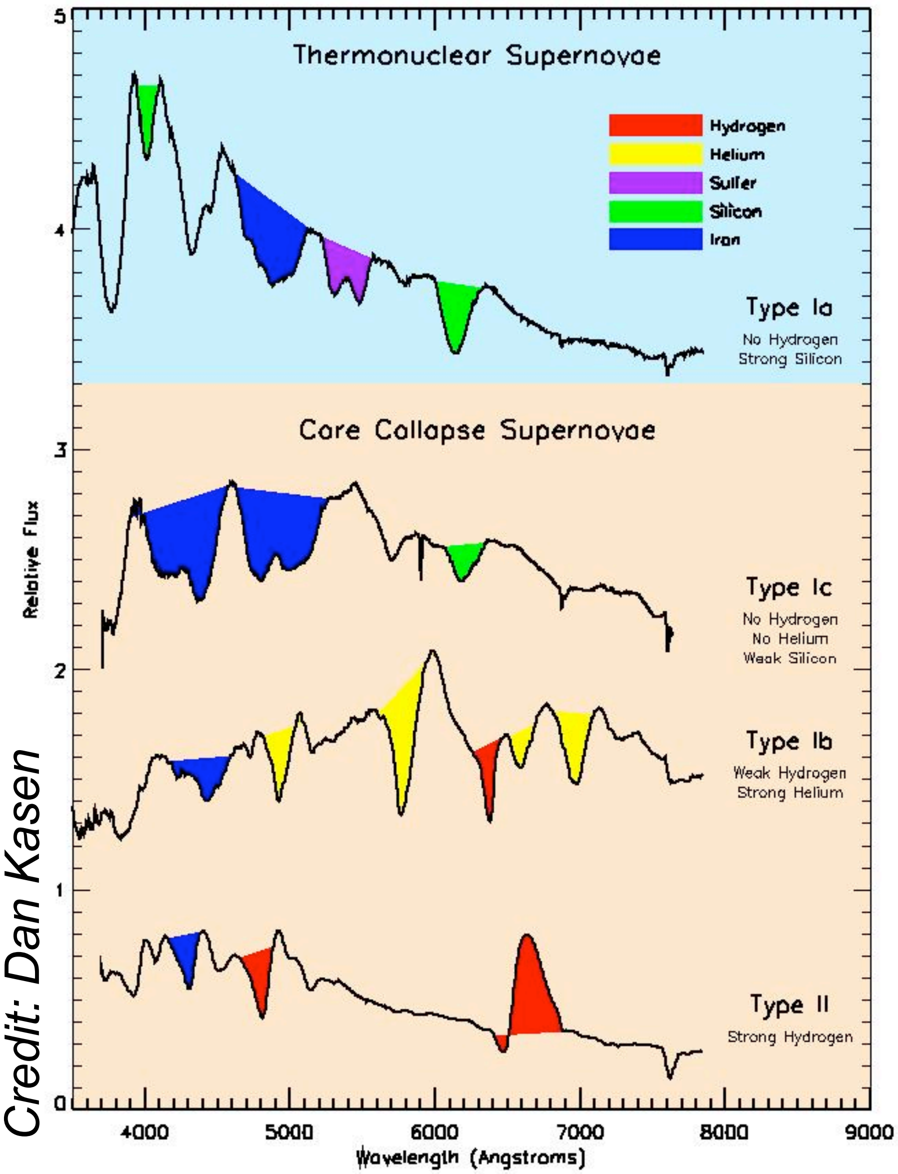
1965: Fritz Zwicky tries to have the last word:

Type II extended to include Type III, Type IV, and Type V

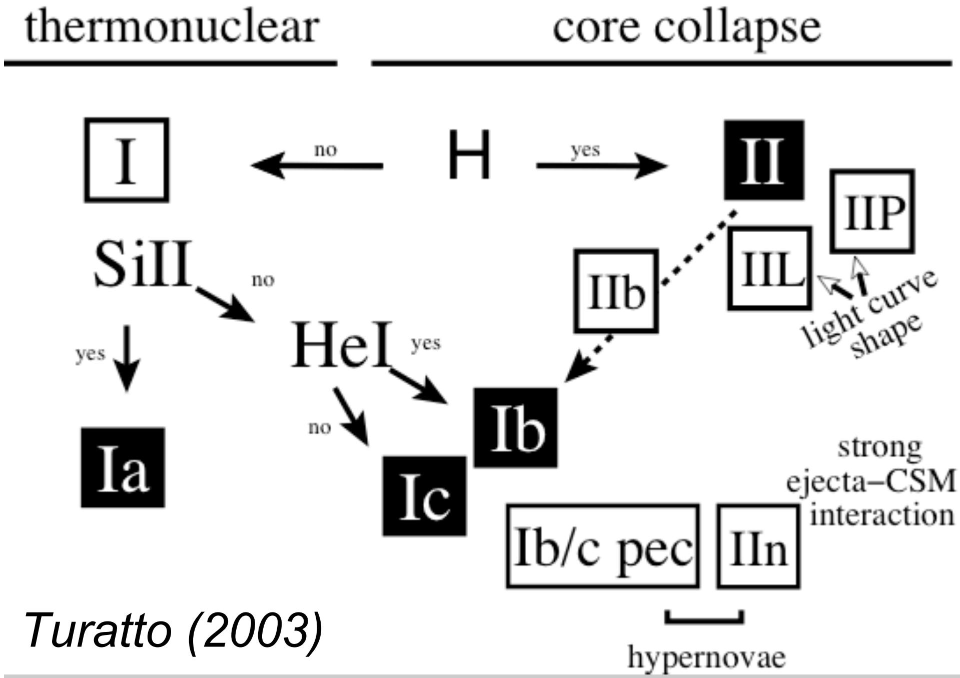
1980’s: Focus shifts to Type I supernovae:

Type Ia (silicon) and Type Ib/c (no silicon)

Present-day Supernova Classification

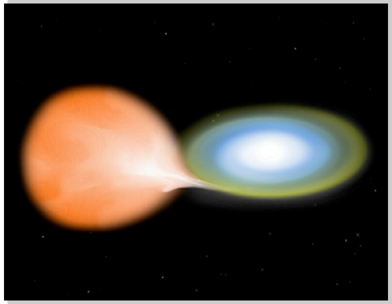


Credit: Dan Kasen

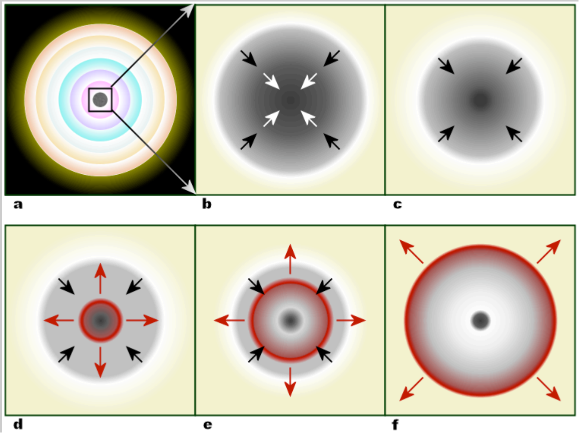


Turatto (2003)

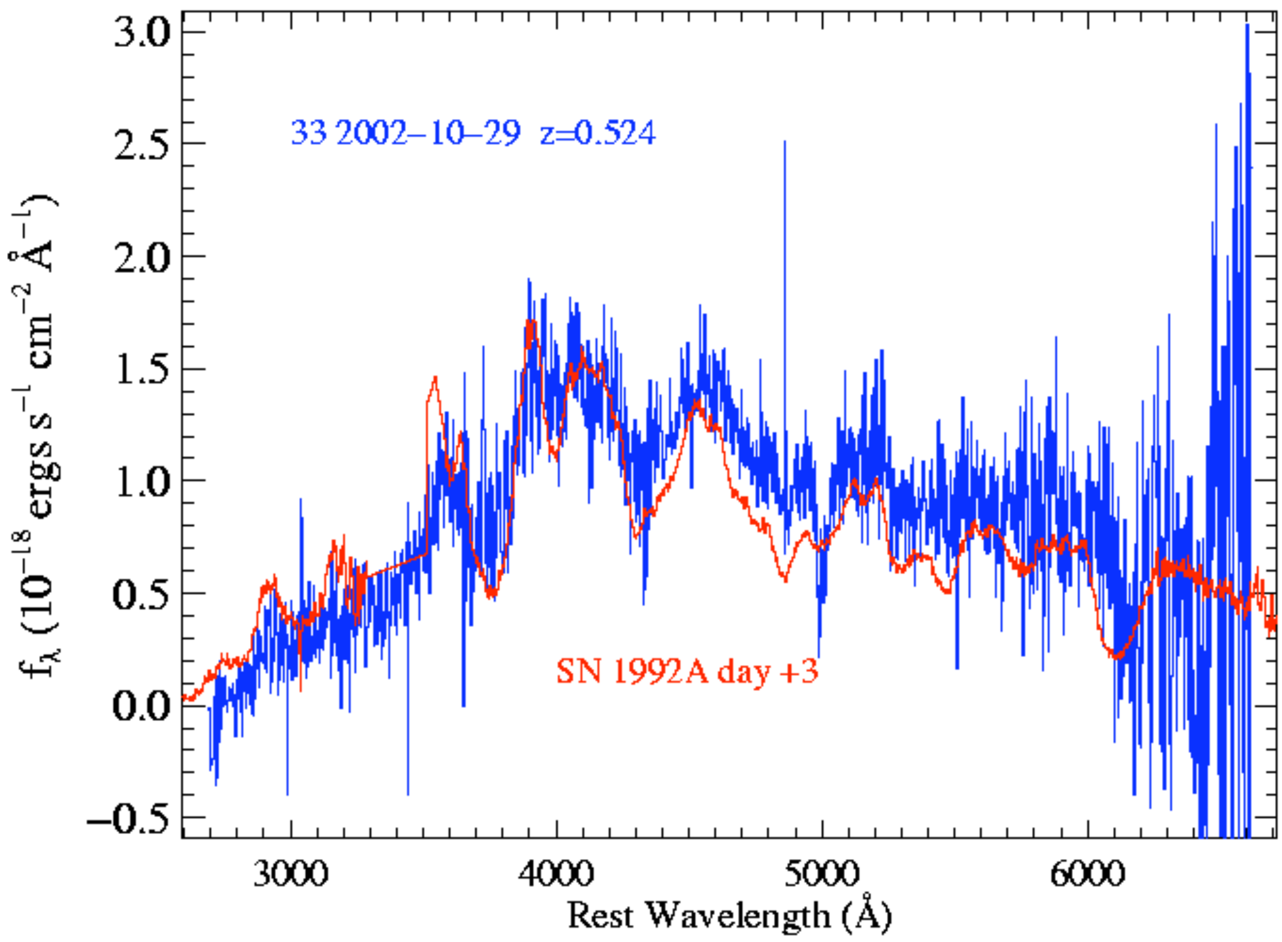
SN Ia



SN Ib/c & II

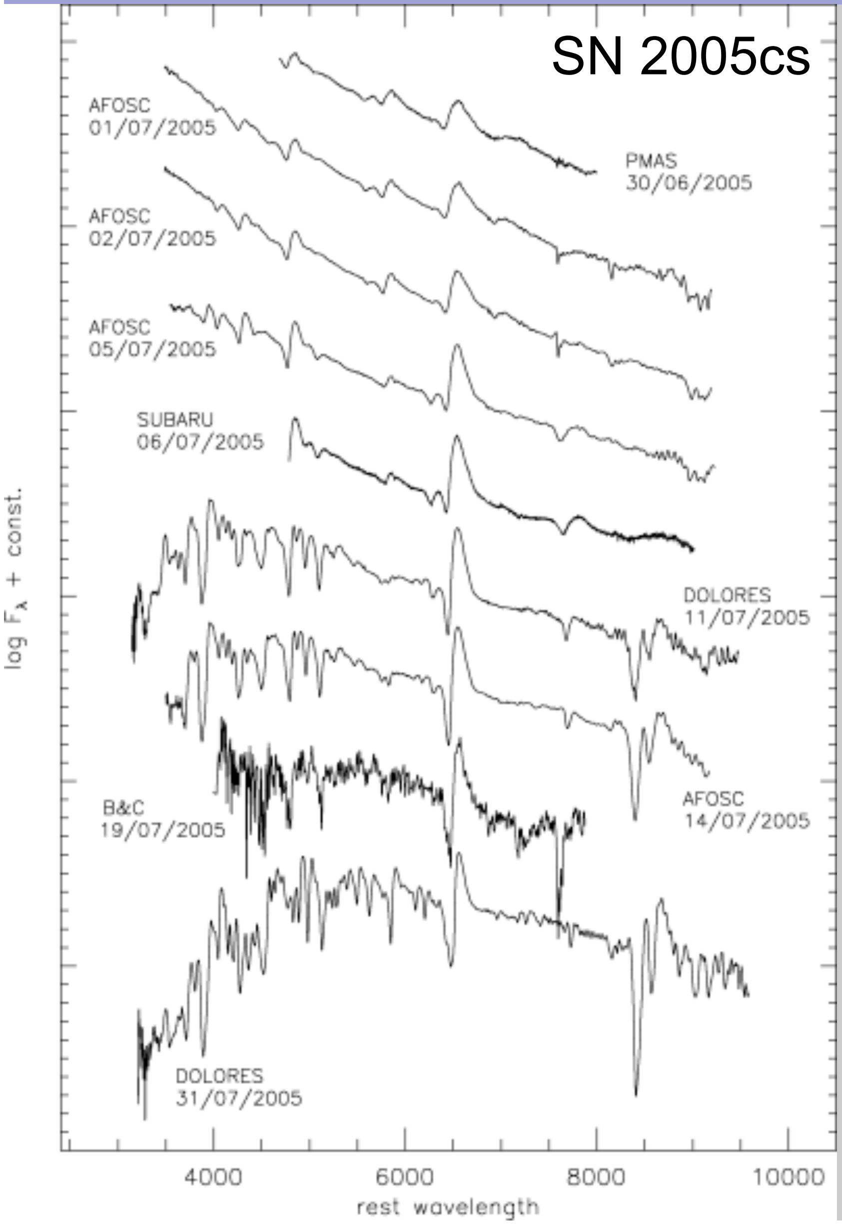


Spectral comparison



Credit: Tom Matheson

Complications – I. Inhomogeneous Data



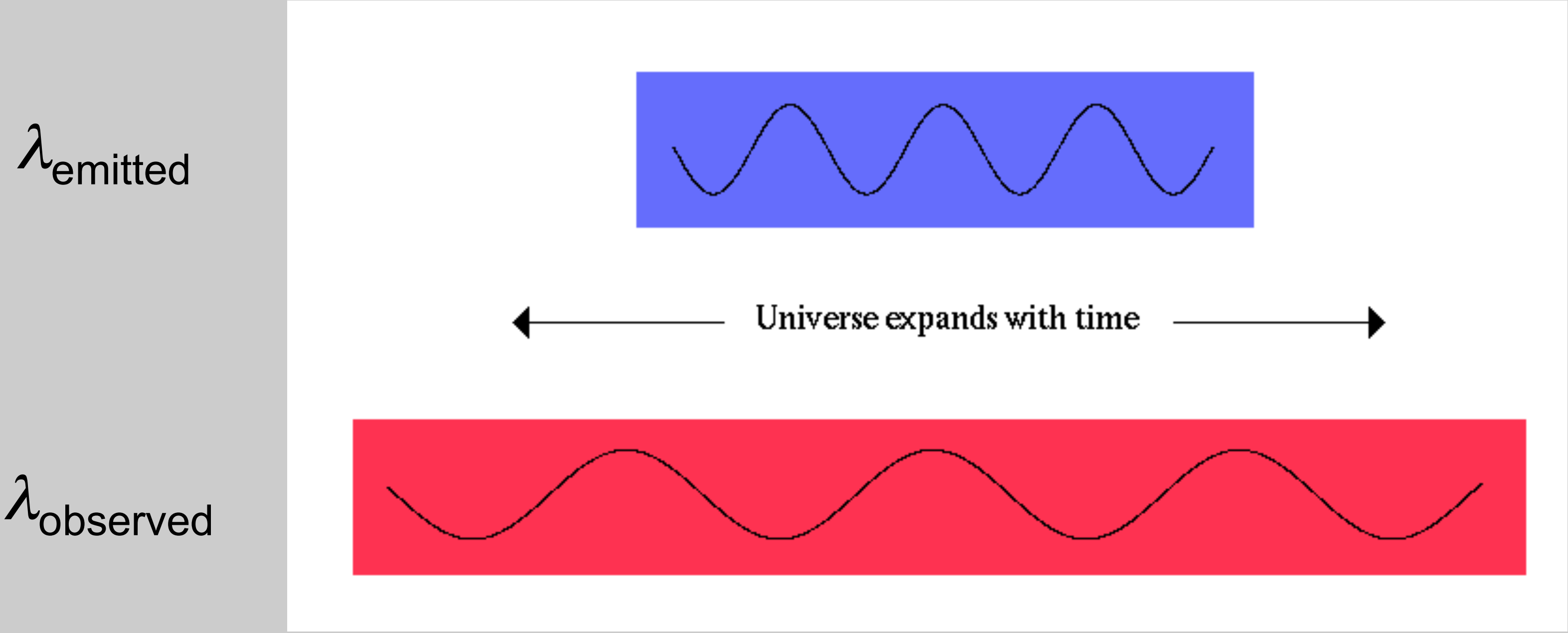
Different telescopes & instruments

⇒ different wavelength **range** & **resolution**

Pastorello et al. (2005)

Complications – I. Inhomogeneous Data

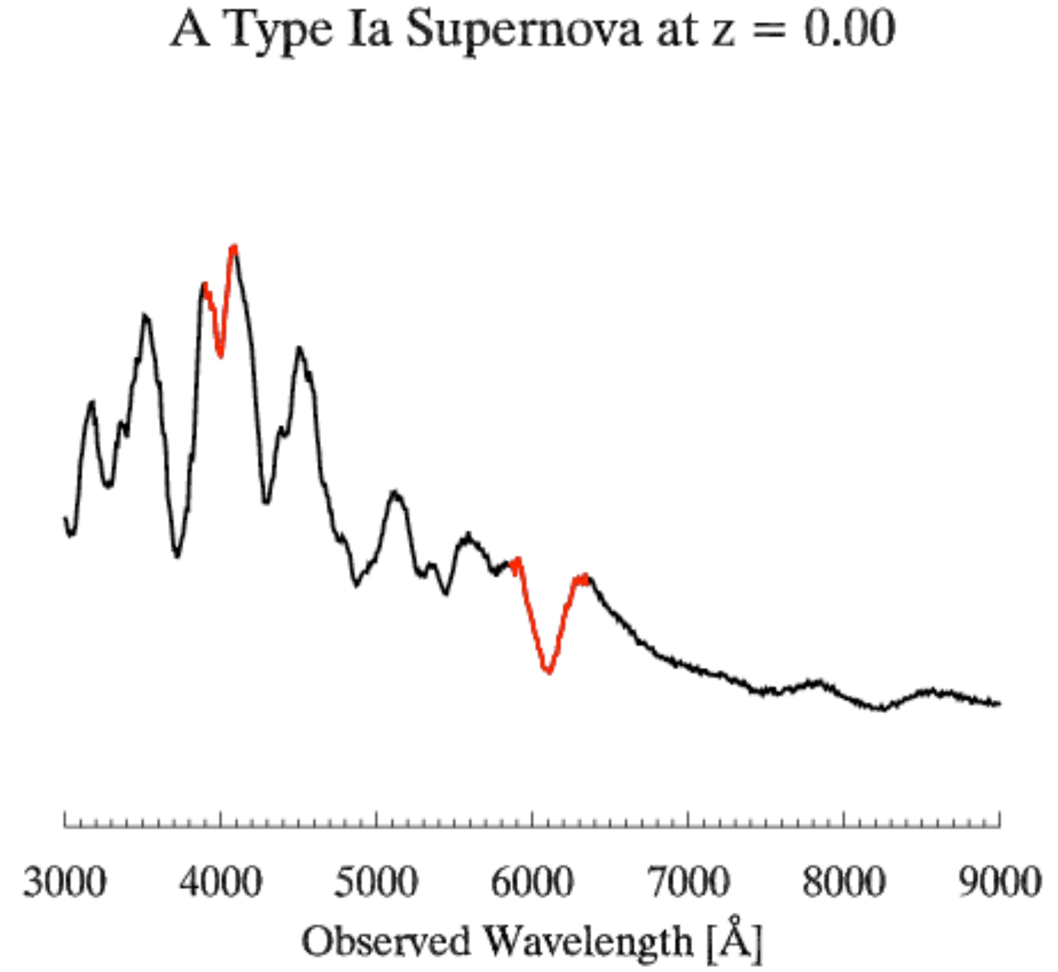
…not forgetting about ***redshift, z****:* (proxy for distance & time)



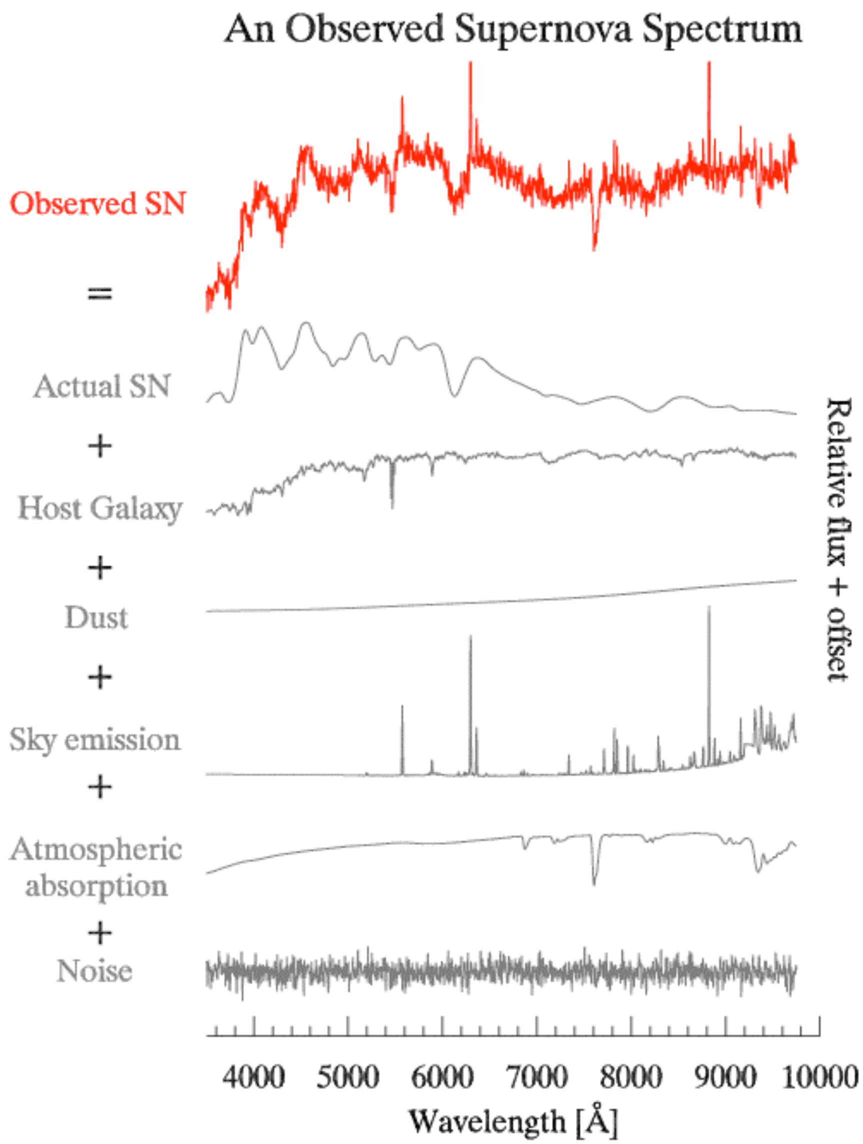
$$1 + z = \frac{\lambda_{observed}}{\lambda_{emitted}}$$

Complications – I. Inhomogeneous Data

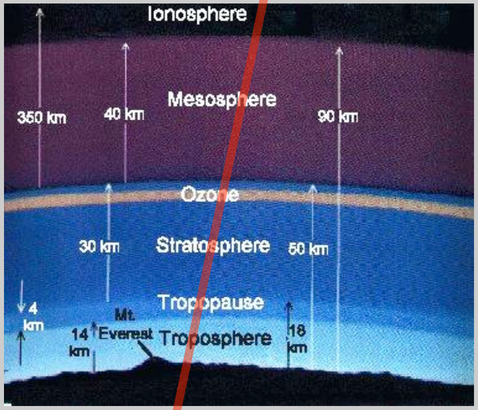
…not forgetting about ***redshift, z****:*



Complications – II. Relative Flux



SN,
host galaxy,
dust



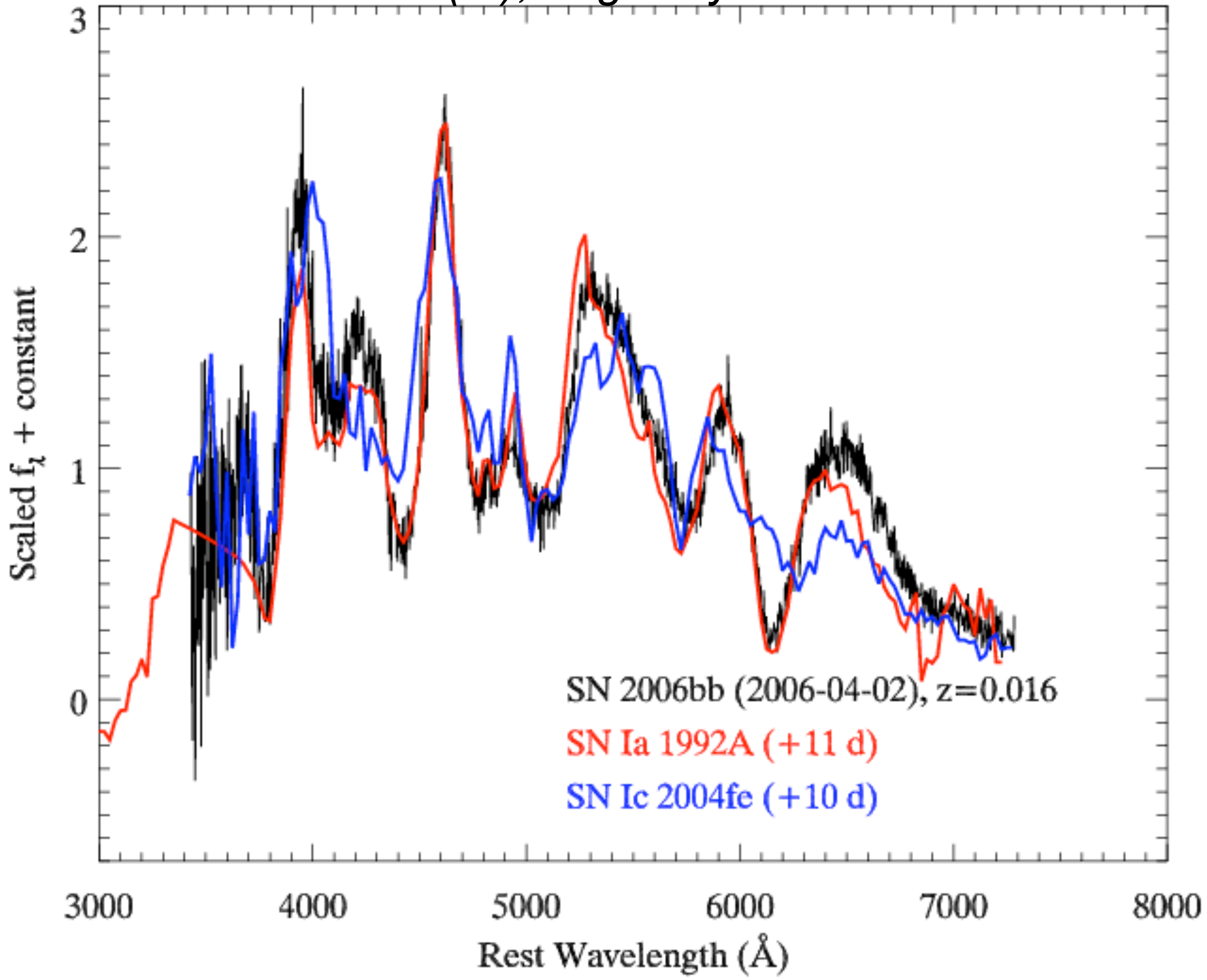
Atmospheric
absorption
&
Sky
emission

Telescope,
detector noise

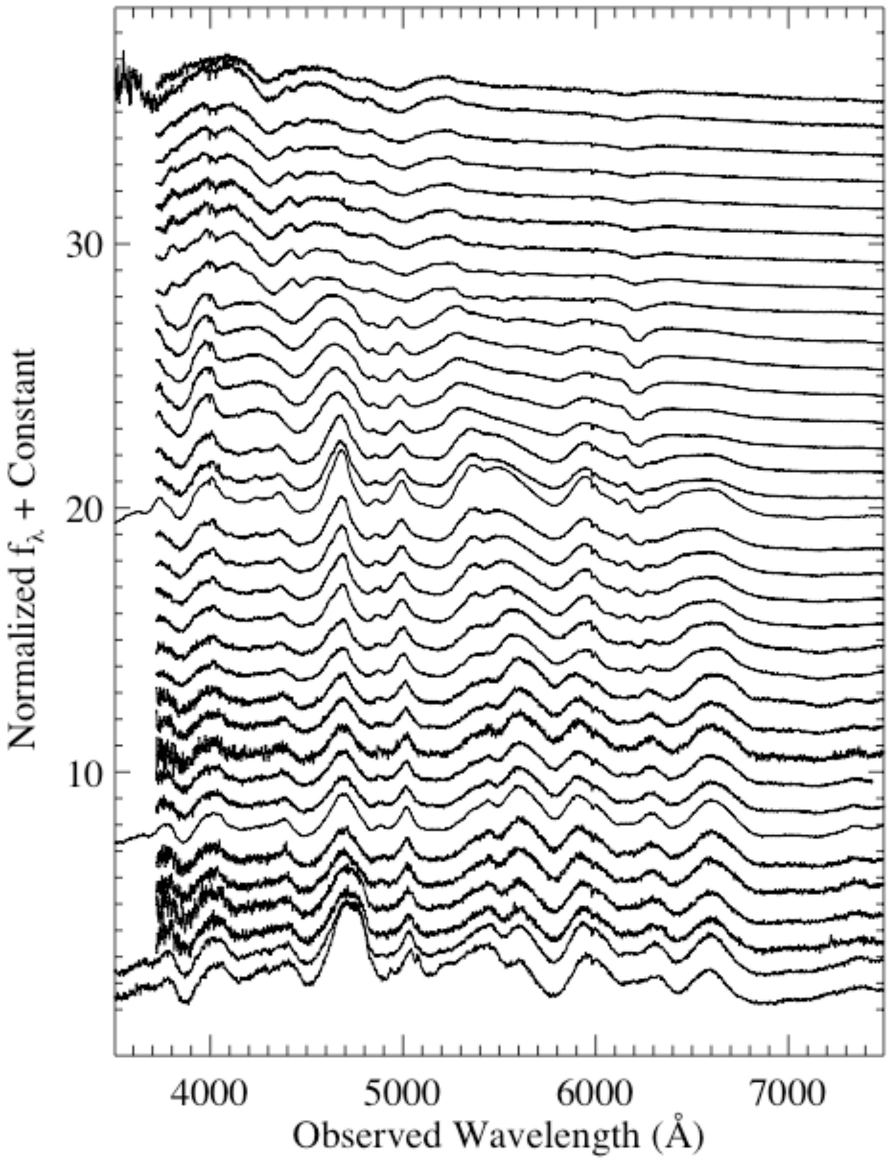
Complications – III. Supernova Types

Depending on the phase, supernovae of different types can have similar spectra…

SN 2006bb (Ia), originally classified as Ic



Complications – IV. Spectral Evolution



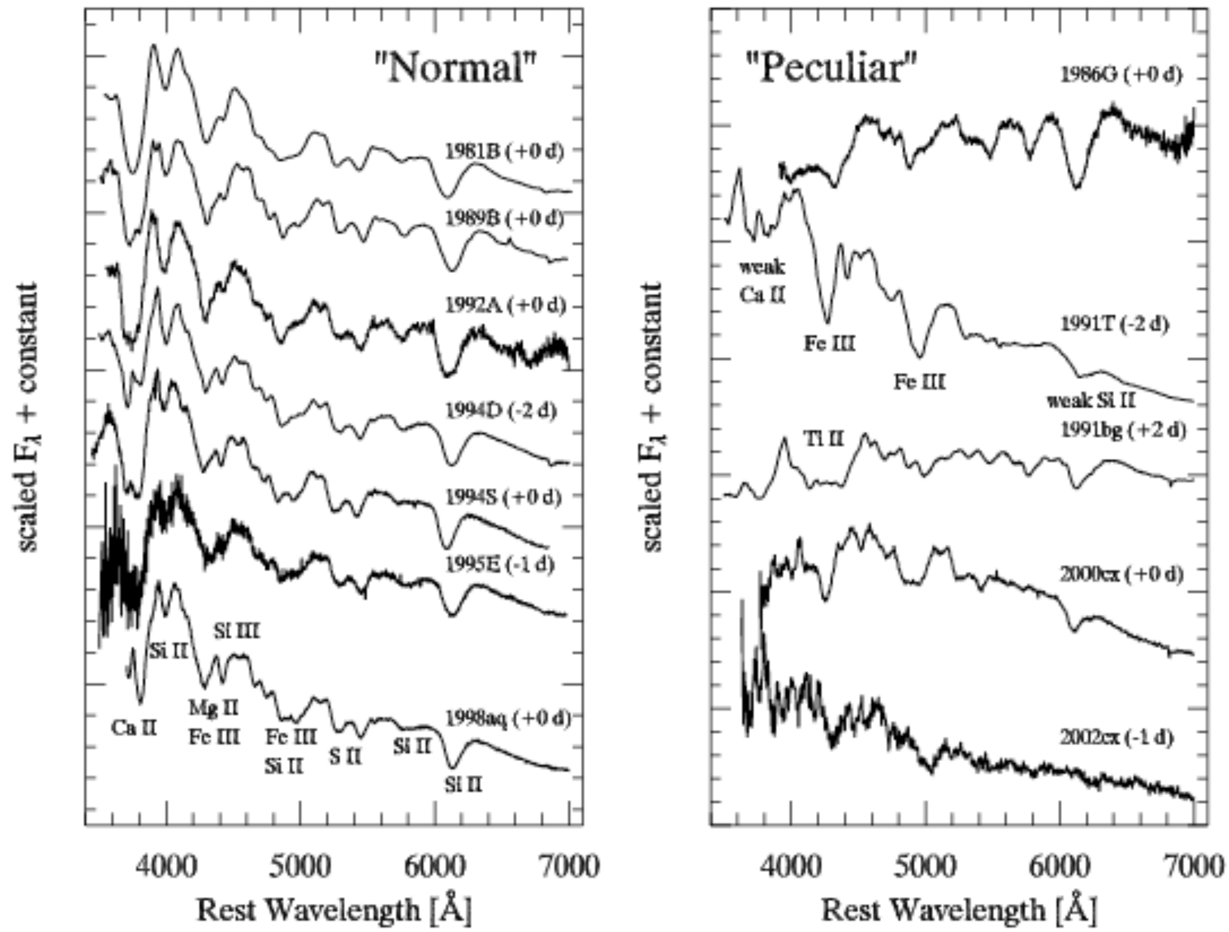
Type Ia supernova between
−14 to +106 days from maximum

time

SN 2001V (Matheson et al. 2007)

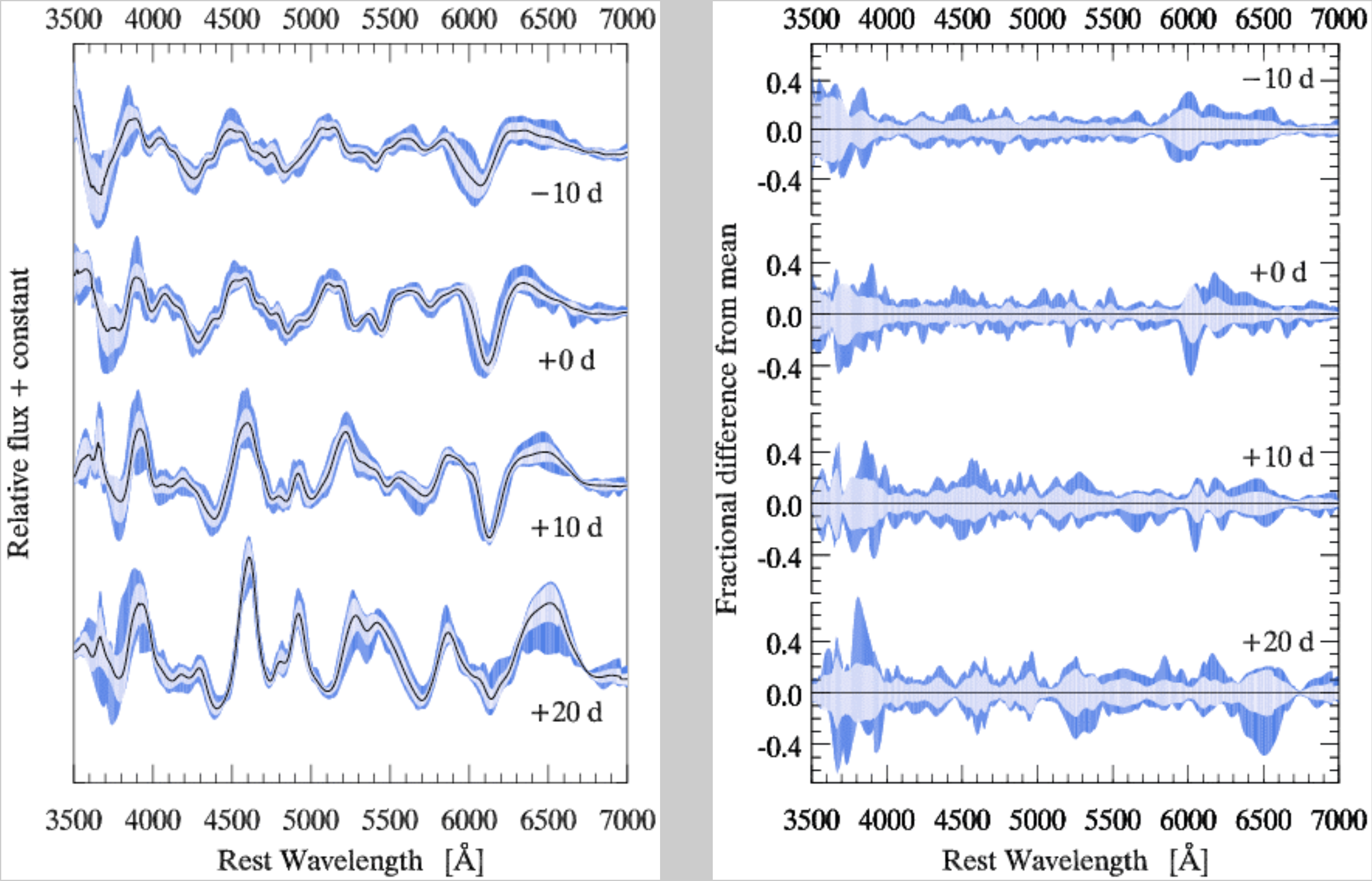
Complications – V. Supernova Subtypes

Ia	normal, 1991T-like, 1991bg-like, peculiar
Ib	normal, peculiar, IIb
Ic	normal, broad-line, peculiar
II	normal (IIP), IIL, IIn, IIb, peculiar



“normal” and “peculiar” SN Ia

Complications – VI. Intrinsic Variation

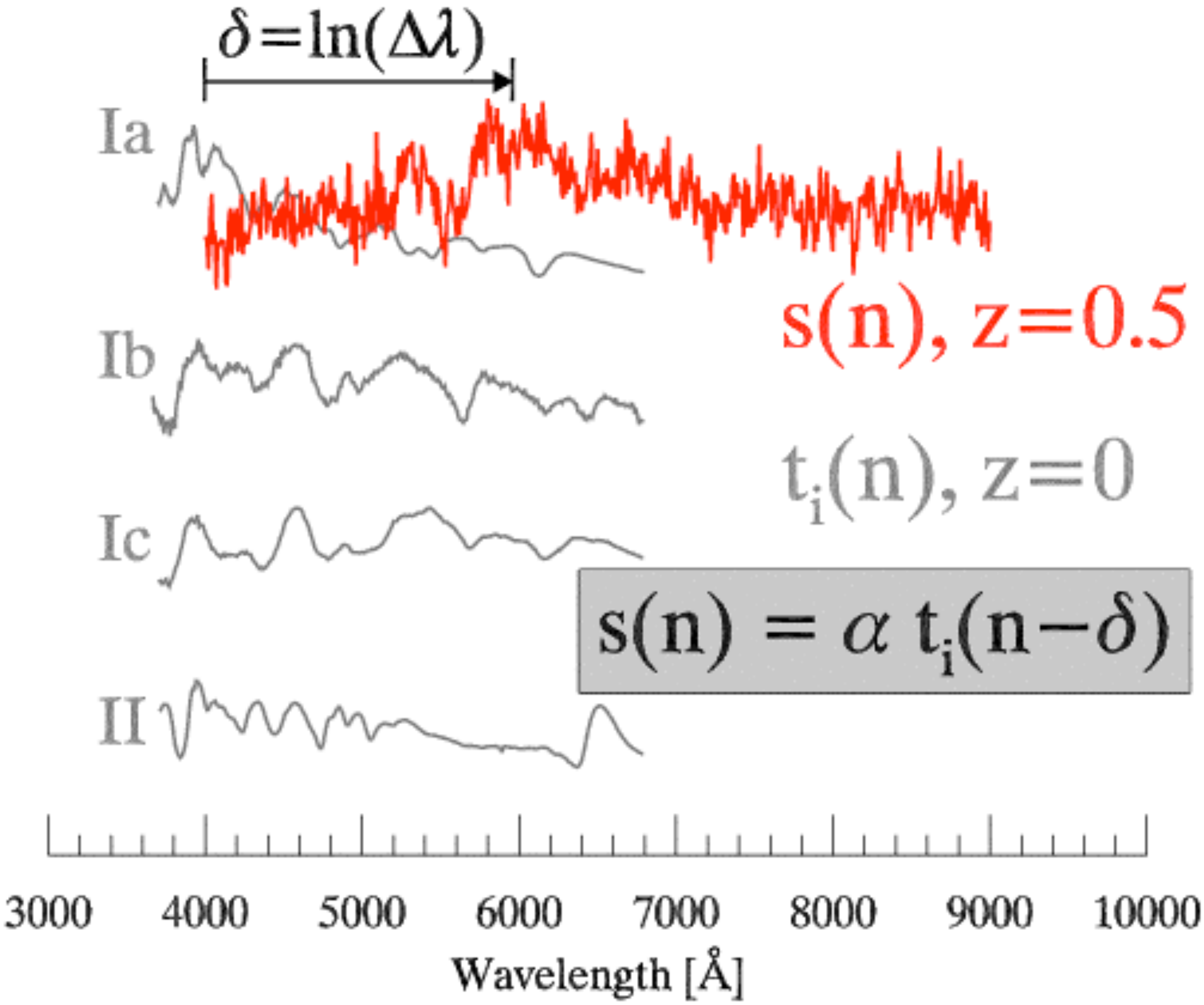


Intrinsic variation amongst SN Ia at a given phase (Blondin & Tonry 2007)

Layout

1. Introduction
2. Supernova Classification
3. Cross-correlation Technique
    - Correlation basics
    - Spectrum pre-processing
    - Correlation parameters (*r*, *lap*)
    - Results: redshift, phase, and type determination
4. Other Techniques
5. An Optimal Classification?

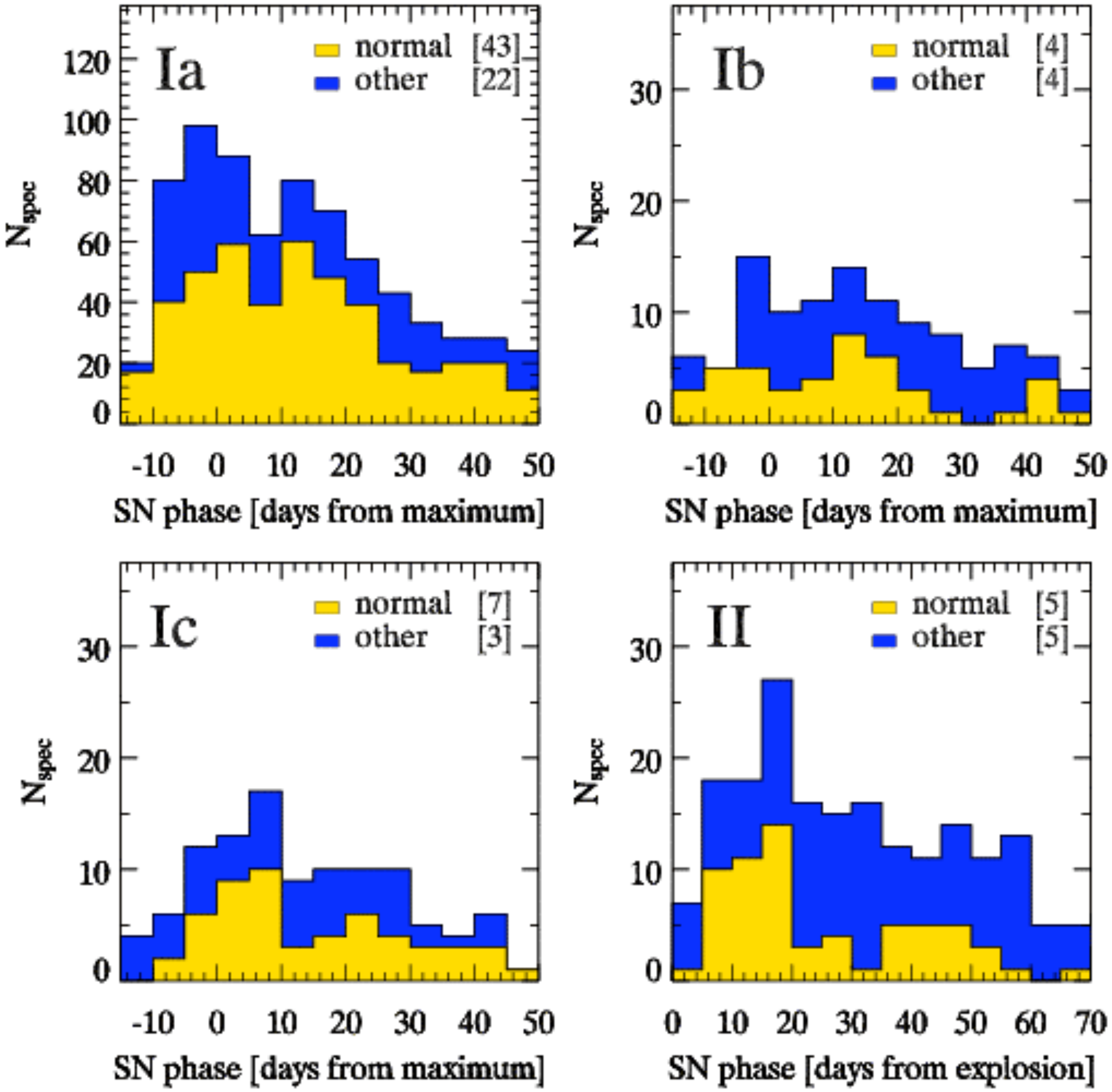
Cross-correlation basics



Input $\boldsymbol{s}(n)$

Templates $\boldsymbol{t}_i(n)$

SN spectral database



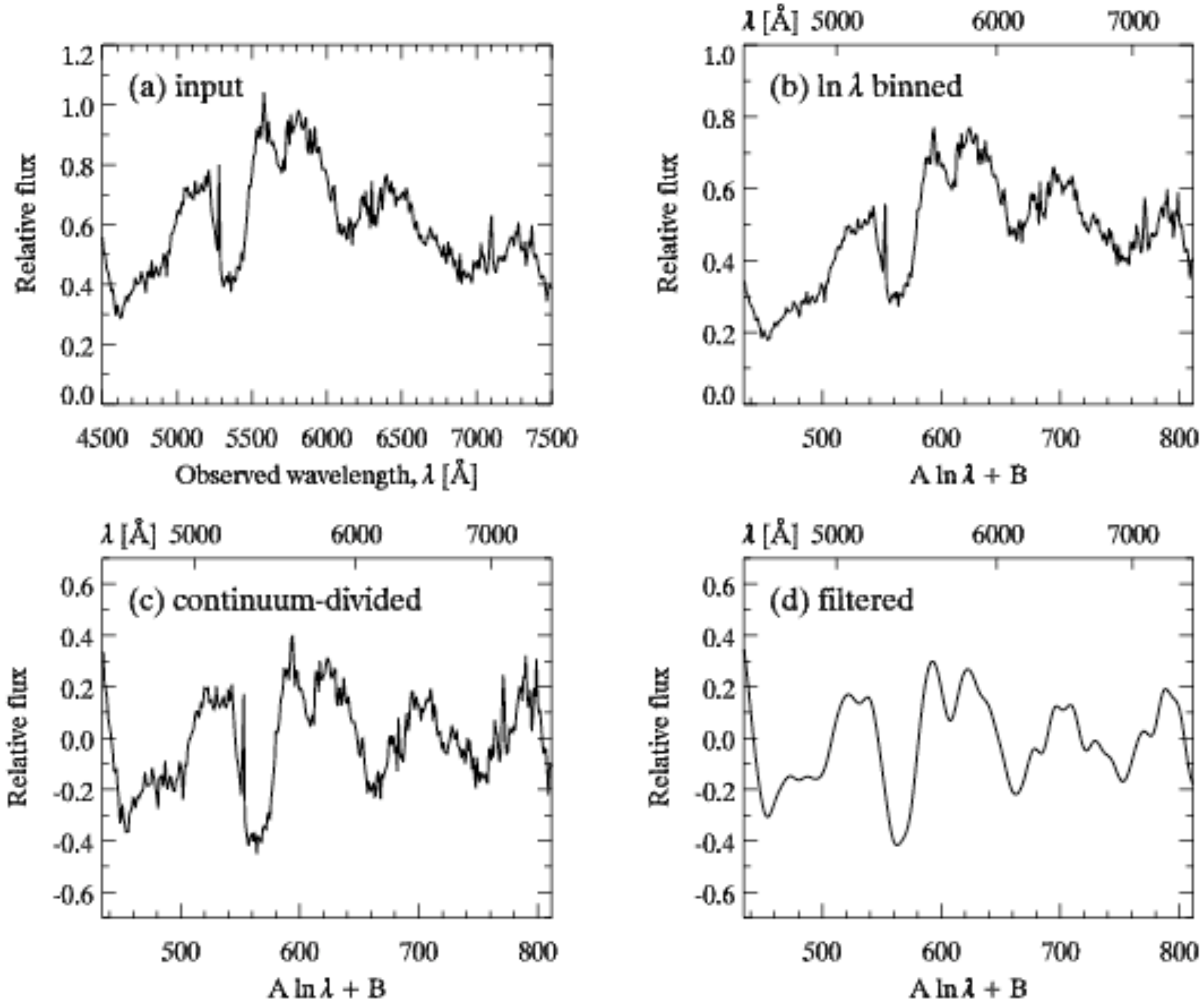
	N_{SN}	N_{spec}
Ia	64	796
Ib	8	172
Ic	9	116
II	10	353
Total	**91**	**1437**

[**65%** from **CfA**]

high S/N spectra

$\lambda_{min} \leq 4000$ Å, $\lambda_{max} \geq 6500$ Å

Spectrum pre-processing



Spectra are:

(b) binned,

(c) flattened, and

(d) filtered

✔

input F_λ, F_ν, ADU, $\Re$

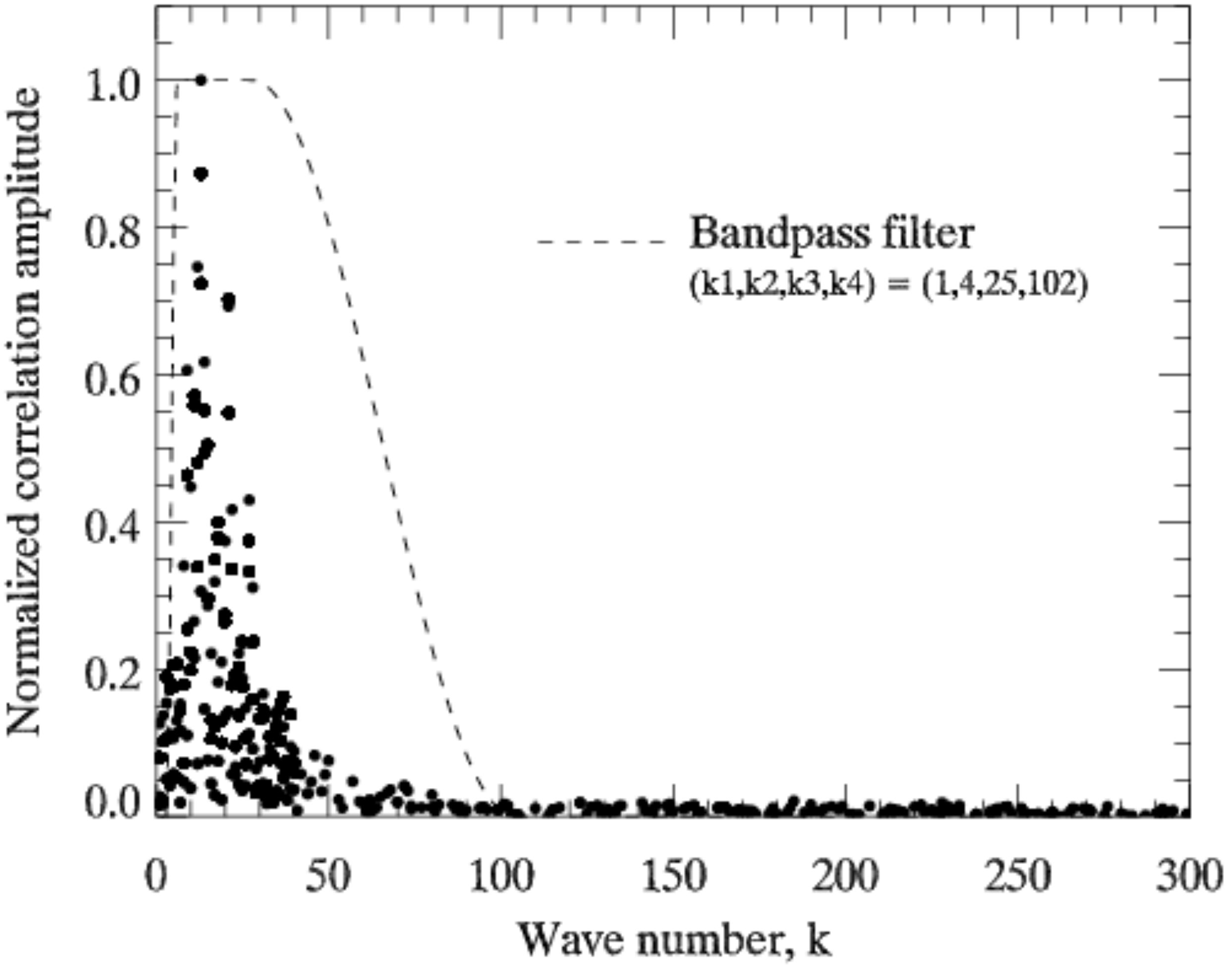
[*] insensitive to reddening

[*] less sensitive to galaxy contamination

✖

see [*]

Bandpass filtering



All correlation signal at **low *k*** (*k* ~ 25)

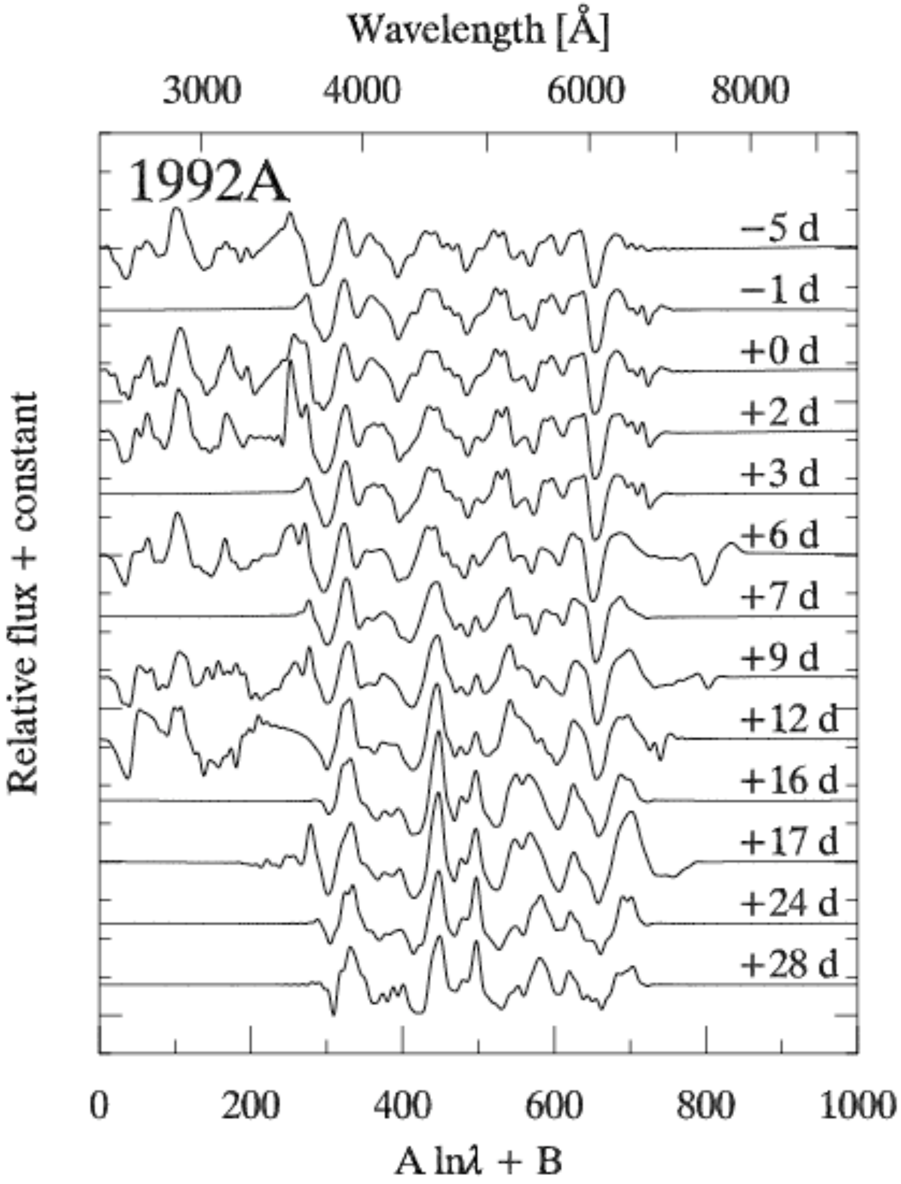
***k* > 100:**

high-freq. noise

***k* < 5:**

low-freq. residuals from continuum subtraction

A typical SN template

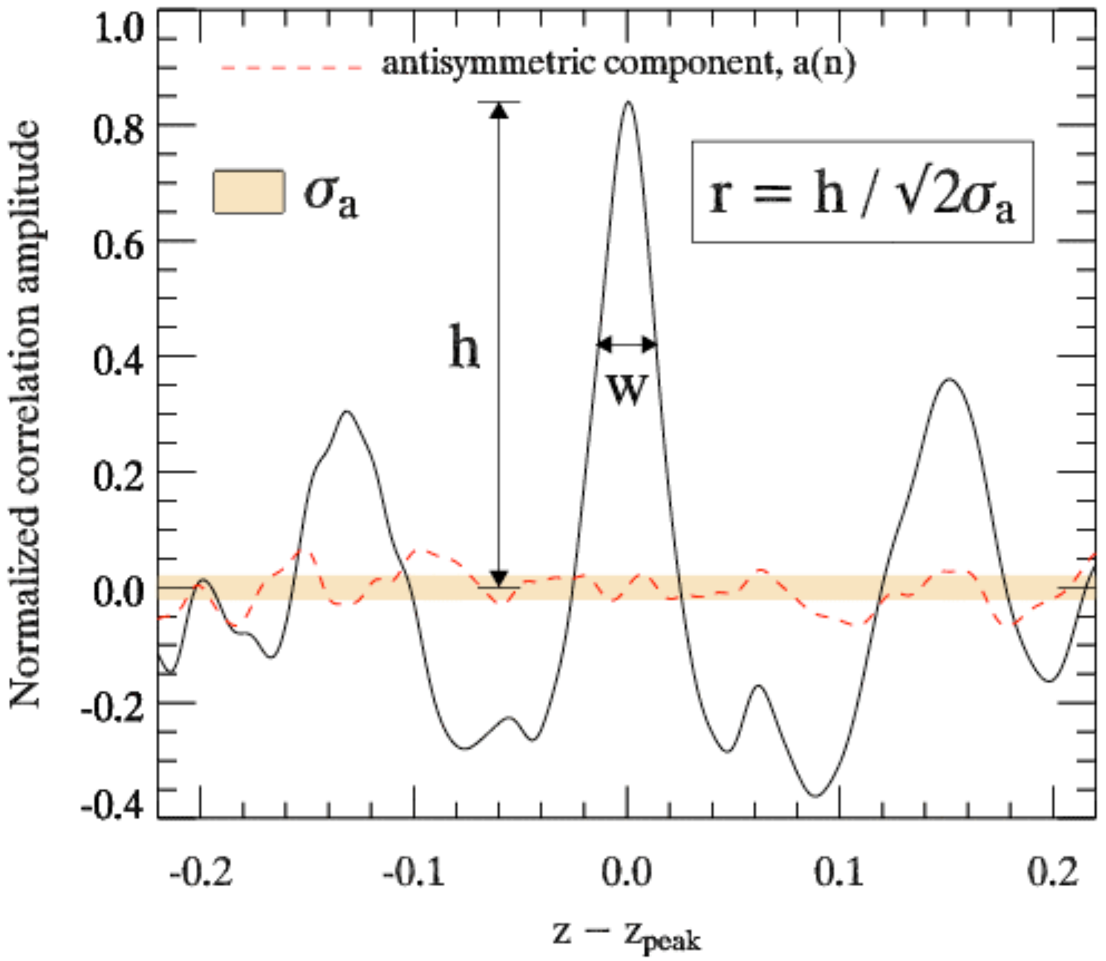


Type Ia SN 1992A

(*Kirshner et al*. 1993)

> “It looks as if
> Some pallid thing had squashed
> its features flat…”
>
> *Robert Frost*

Correlation *r*-value



Correlation parameters:

r ratio of height of correlation peak to RMS of antisymmetric component

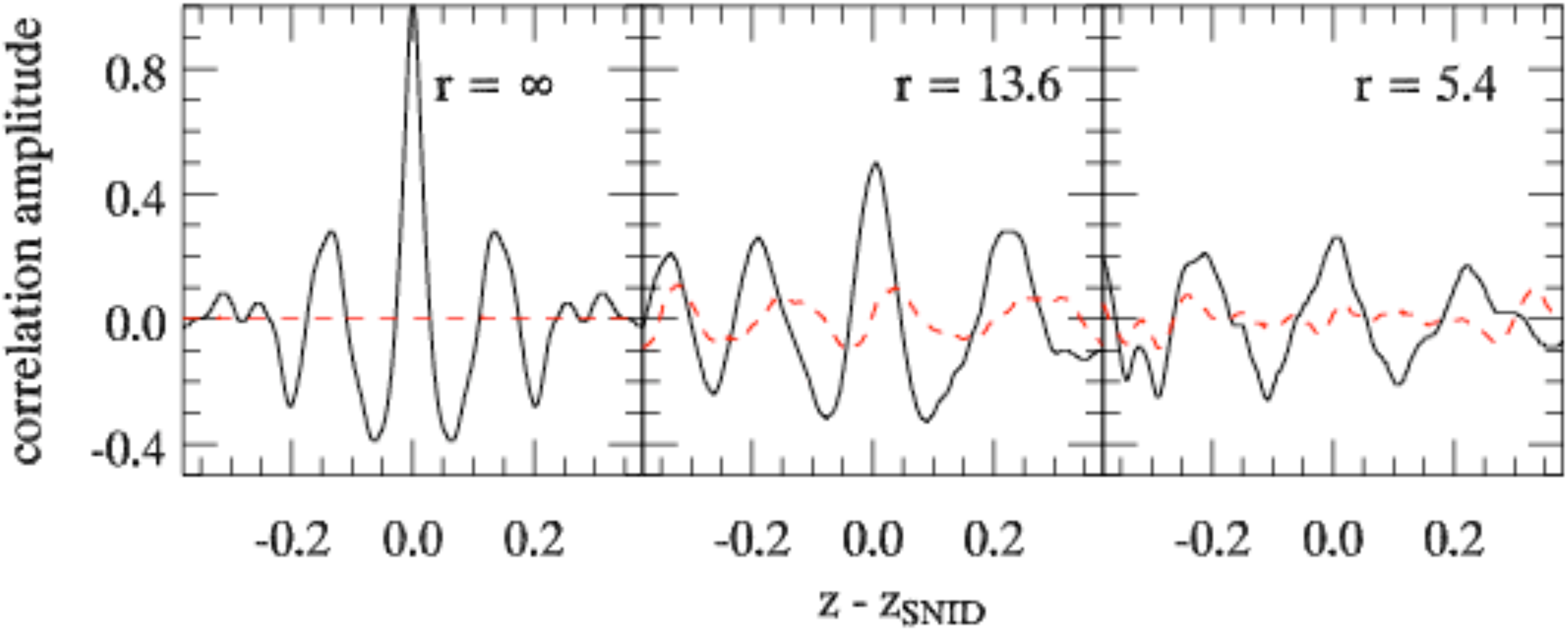
lap overlap in rest wavelength between input and template spectrum, trimmed at correlation redshift

rlap = *r* × *lap*

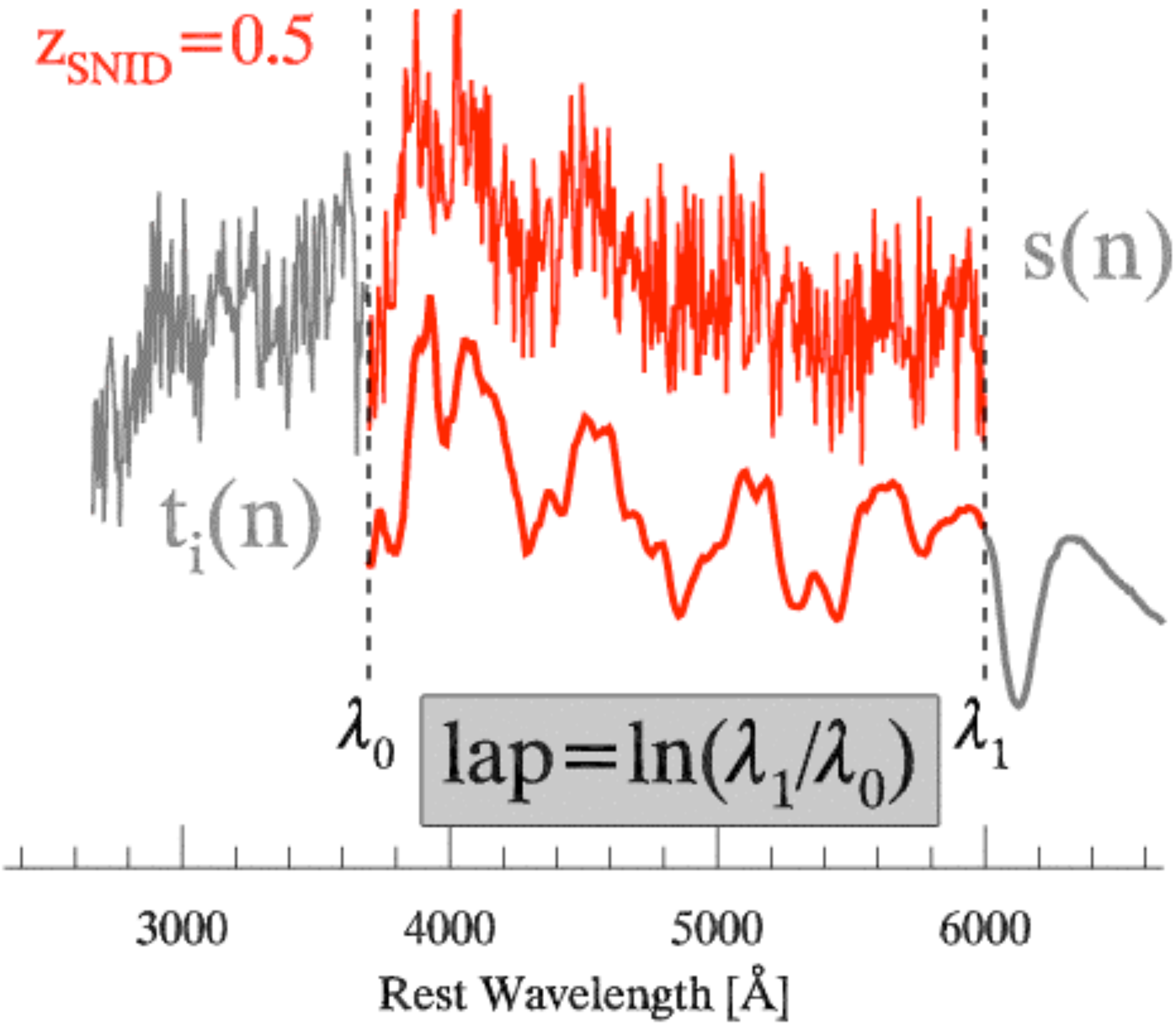
$$z_{err} \propto w / (1 + rlap)$$

Correlation functions

The ***perfect,*** the ***good,*** and the ***bad***



Spectrum over*lap*

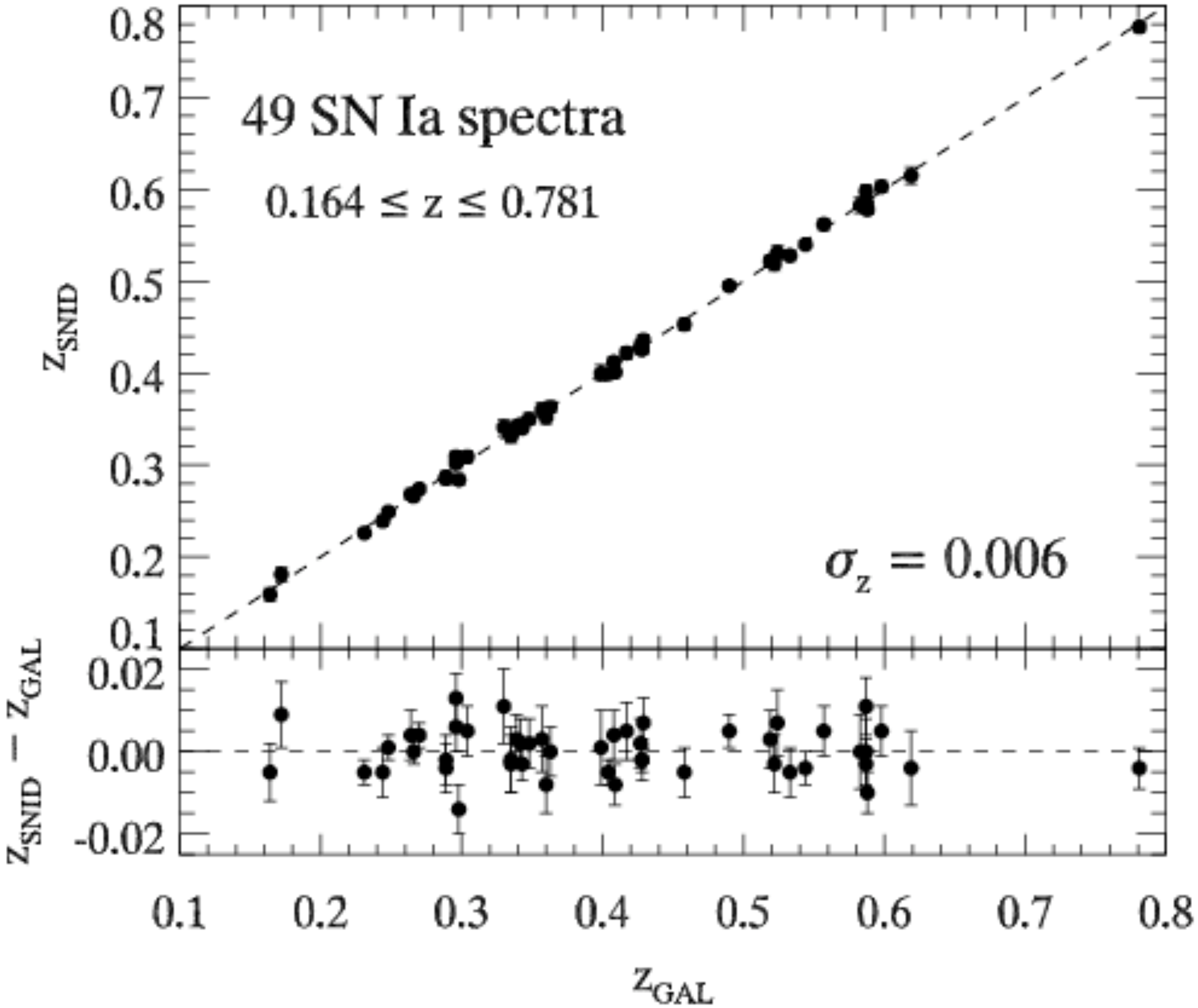


Typically:

rlap ≥ 5

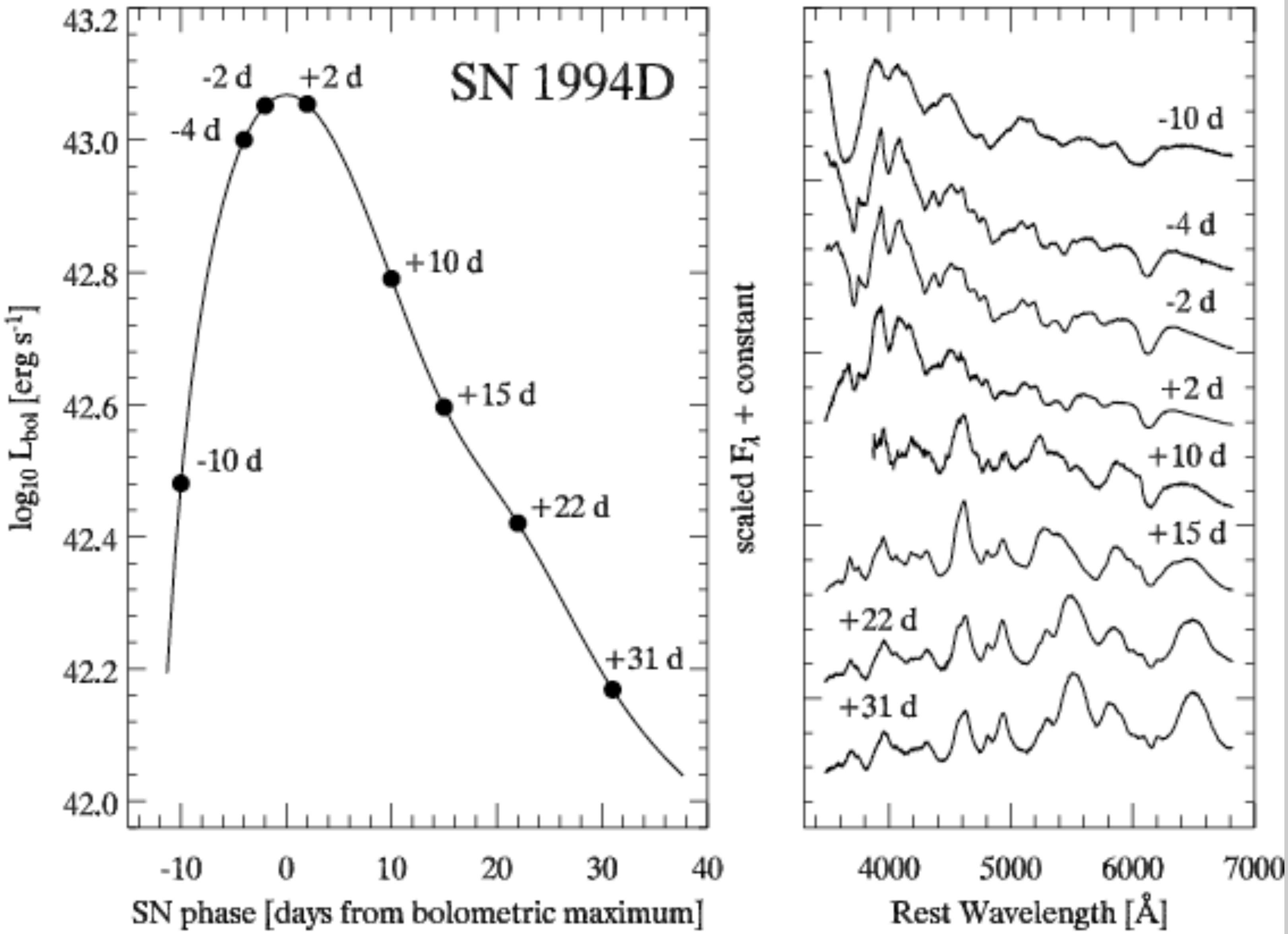
lap ≥ 0.40

SN *vs.* Galaxy redshifts

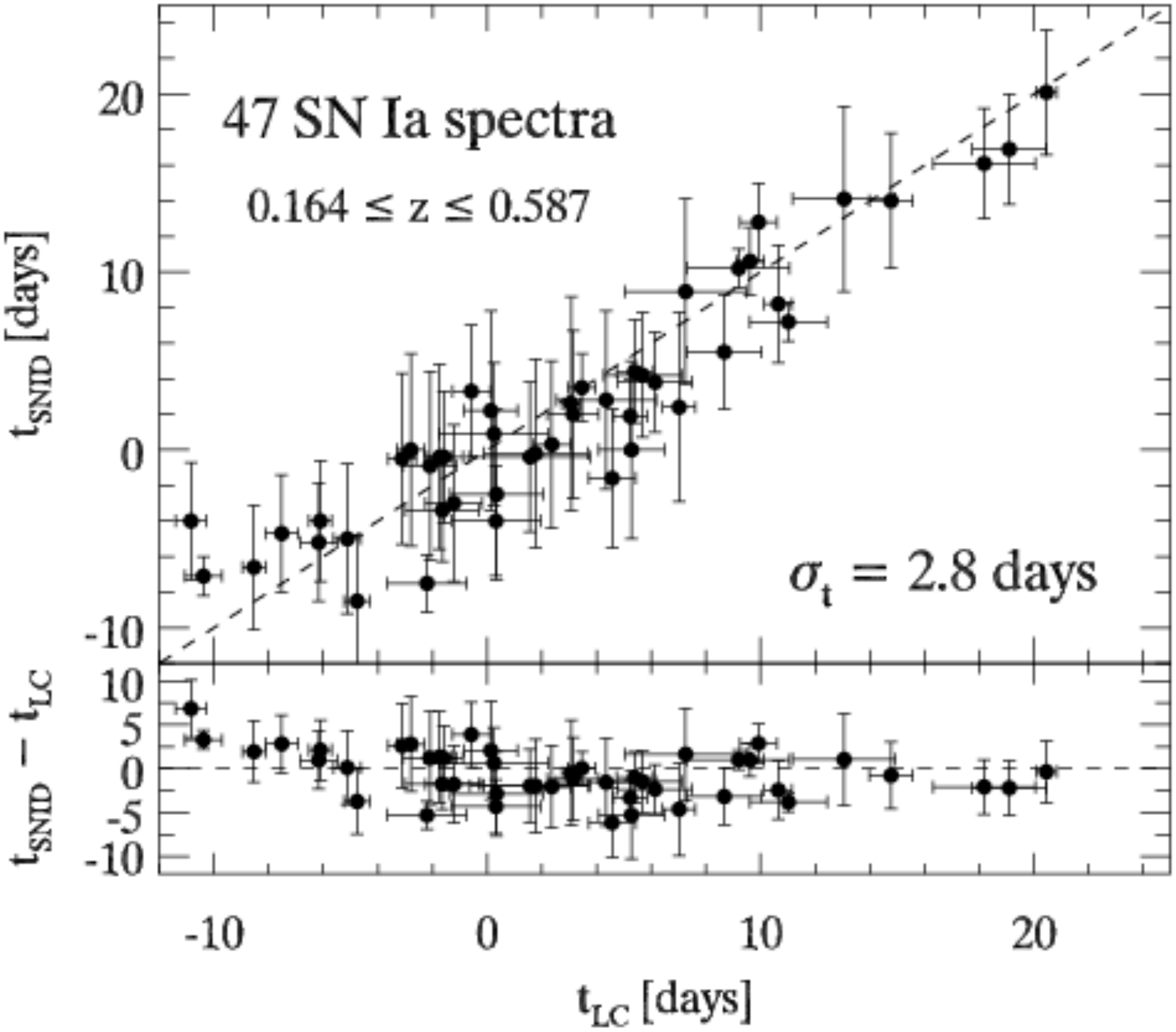


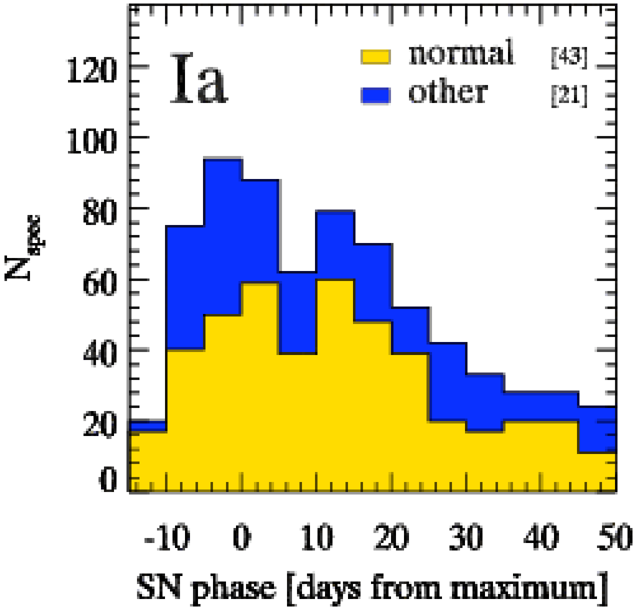
data from ***ESSENCE***
(Matheson et al. 2005;
Miknaitis et al. 2007;
Blondin & Tonry 2007)

Phase determination



Spectrum *vs.* lightcurve phase

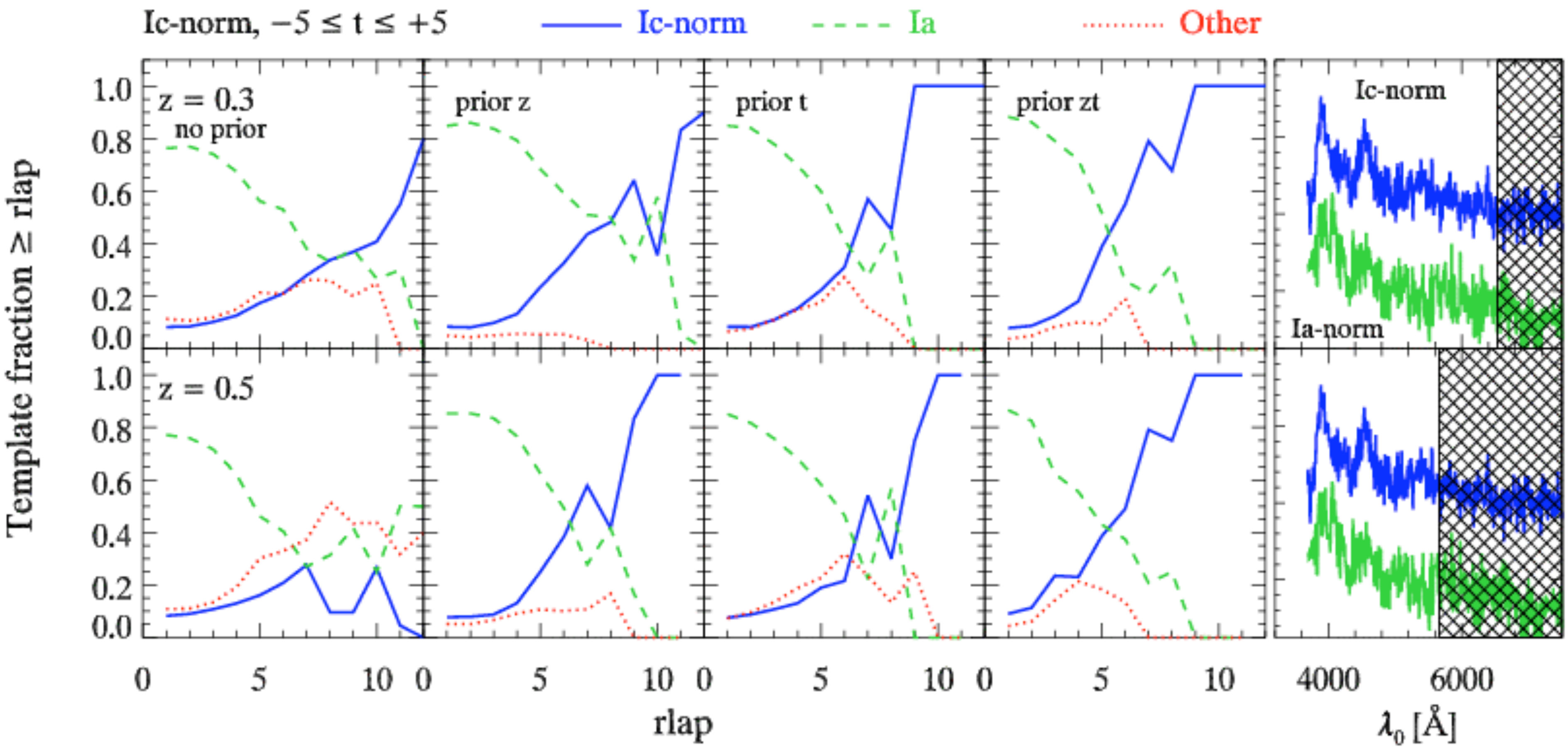




*data from **ESSENCE** (Matheson et al. 2005; Blondin & Tonry 2007; Foley et al. in prep)*

t_{LC} corrected for (1+z) time dilation

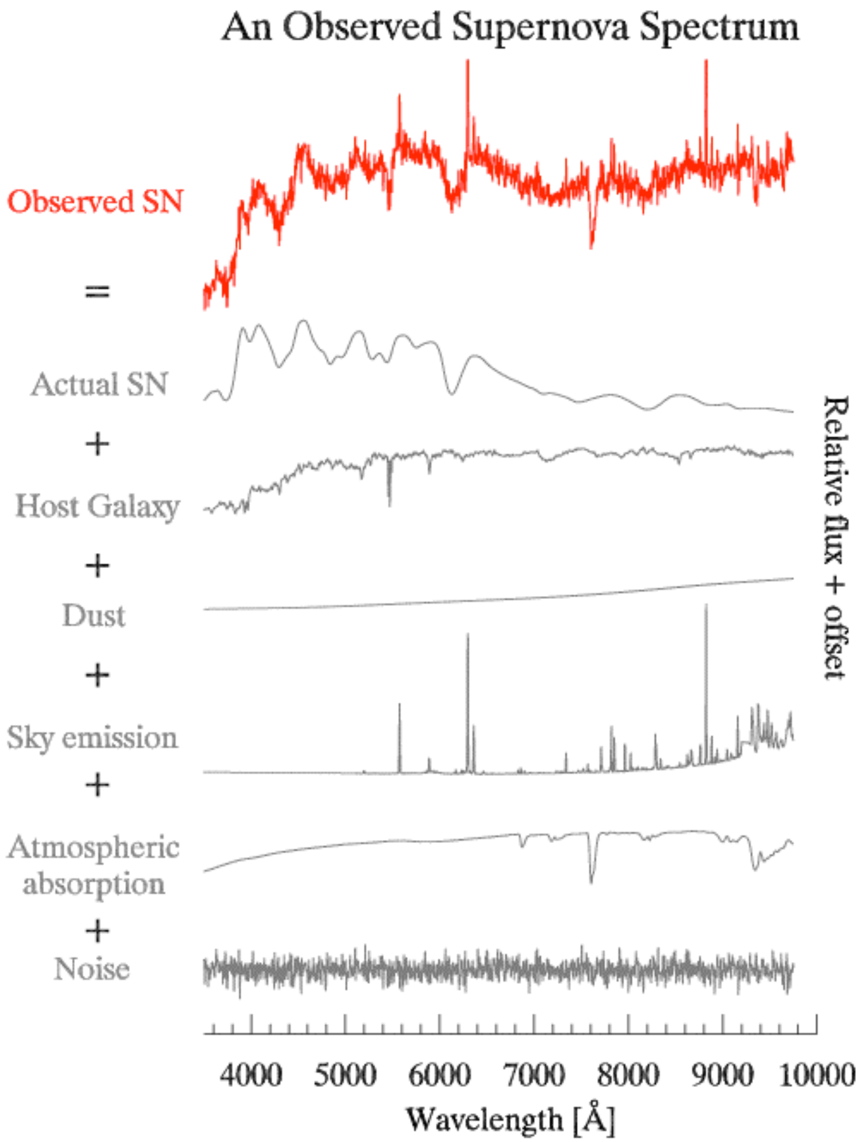
SN Ia *vs.* SN Ic


Ic-norm, −5 ≤ t ≤ +5
Ic-norm
Ia
Other
Template fraction ≥ rlap
z = 0.3
no prior
prior z
prior t
prior zt
z = 0.5
Ic-norm
Ia-norm
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
rlap
4000
6000
λ0 [Å]

Layout

1. Introduction
2. Supernova Classification
3. Cross-correlation Technique
4. Other Techniques
    - χ^2 minimization
    - Principal Component Analysis (PCA)
    - Artificial Neural Networks (ANN)
    - Bayesian approach
5. An Optimal Classification?

χ^2 minimization



(Howell et al. 2005)

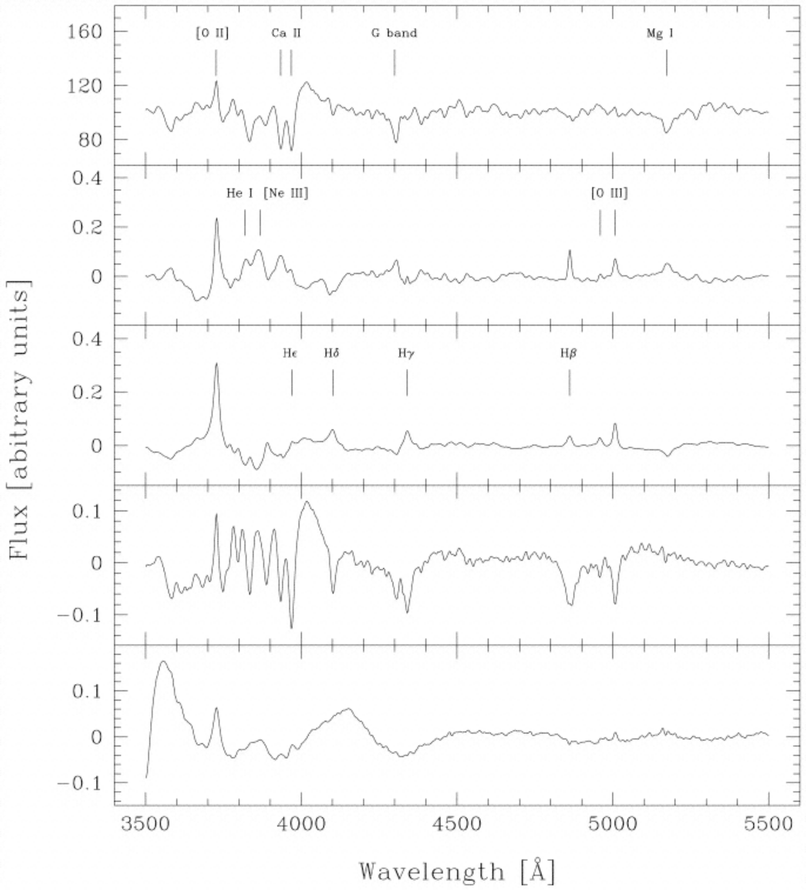
$$\chi^2(z) = \sum \frac{[O(\lambda) - aT(\lambda;z)10^{cA_\lambda} - bG(\lambda;z)]^2}{\sigma(\lambda)^2}$$

$O(\lambda)$	input spectrum
$T(\lambda;z)$	template spectrum at redshift z
$G(\lambda;z)$	galaxy template at redshift z
A_λ	reddening law
$\sigma(z)$	error associated with $O(z)$

- ✖ no better than cross-correlation method despite more free parameters
- ✖ computationally slow (though see Rybicki & Press 1995)

Principal Component Analysis

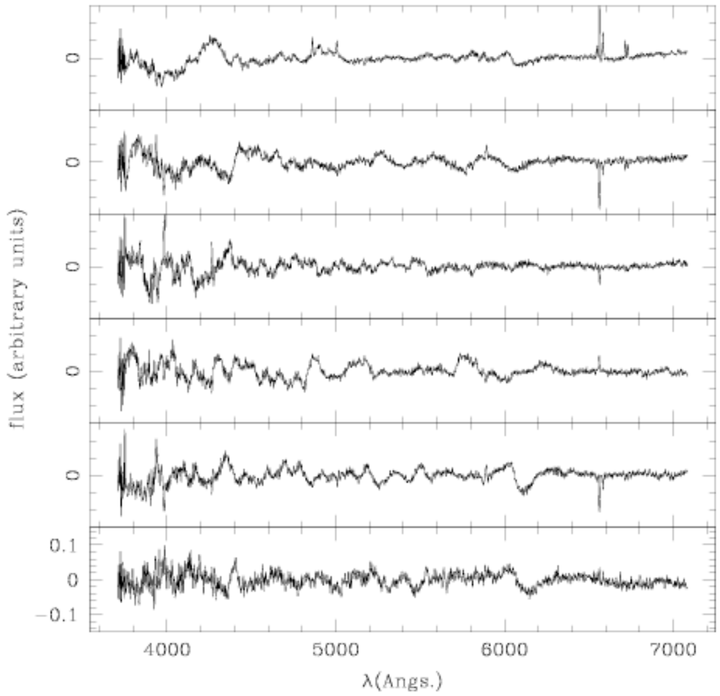
Principle: Highlight *differences* between spectra using eigenspectra
⇒ relate eigenspectra to *physical properties* in the input spectra



(Bromley et al. 1998)

Okay for galaxy spectra…

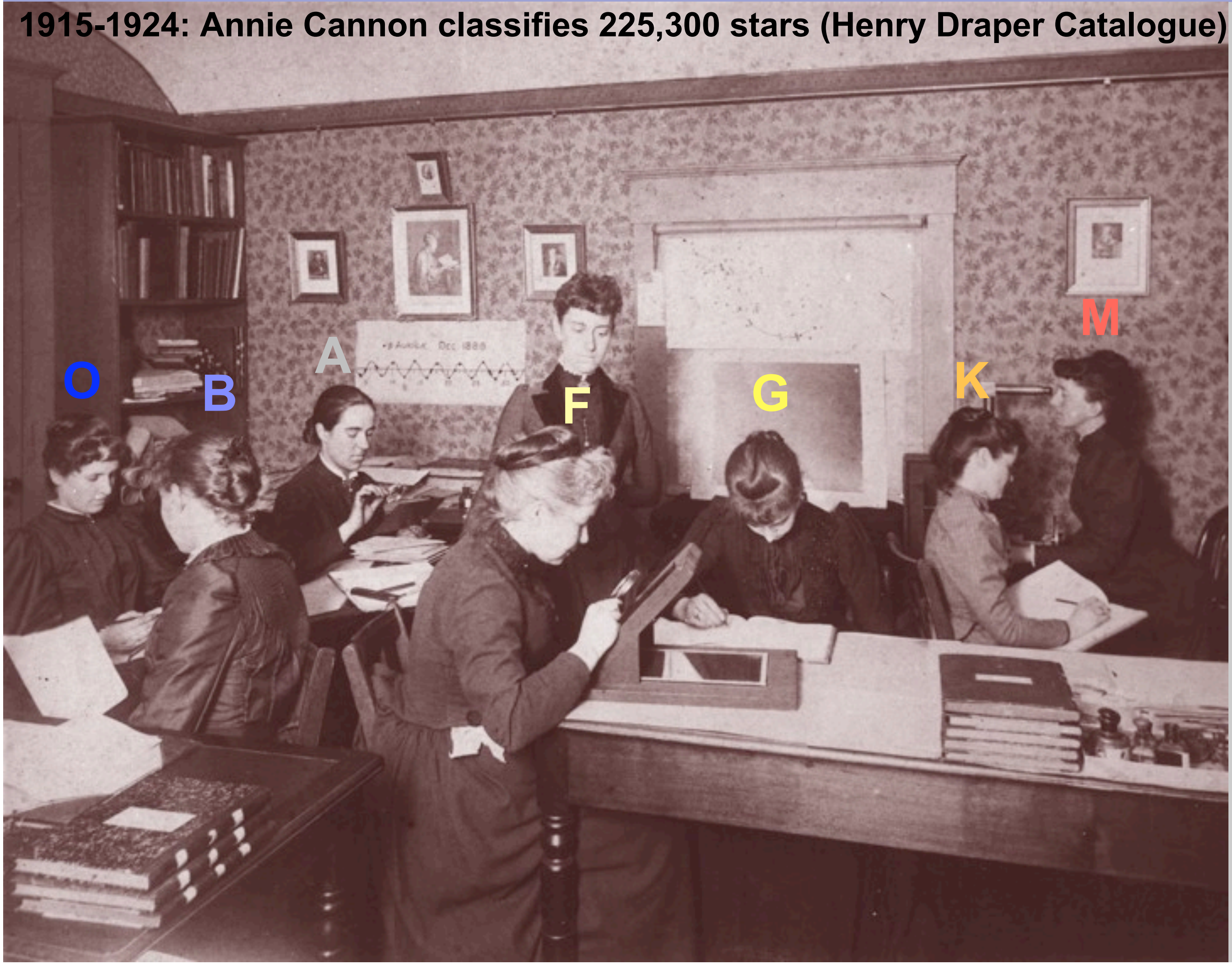
(Blondin & Bromley)

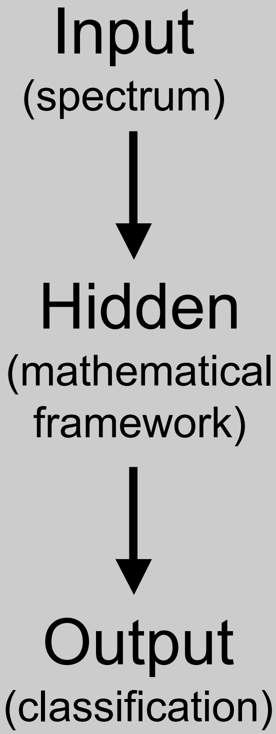


… but for supernova spectra?

Neural Networks

1915-1924: Annie Cannon classifies 225,300 stars (Henry Draper Catalogue)




Input
(spectrum)

Hidden
(mathematical framework)

Output
(classification)

Bayesian Approach

(*Kuznetsova & Connolly 2006*)

$$P(T_i | \{m_j\}) = \sum_k P(t_k | \{m_j\})$$

$$= \frac{\sum_k P(\{m_j\} | t_k, T_i) P(t_k, T_i)}{\sum_i \sum_k P(\{m_j\} | t_k, T_i) P(t_k, T_i)}$$

T_i	supernova type
$\{m_j\}$	measurements (e.g. light curve)
t_k	model (template) depending on *k* parameters

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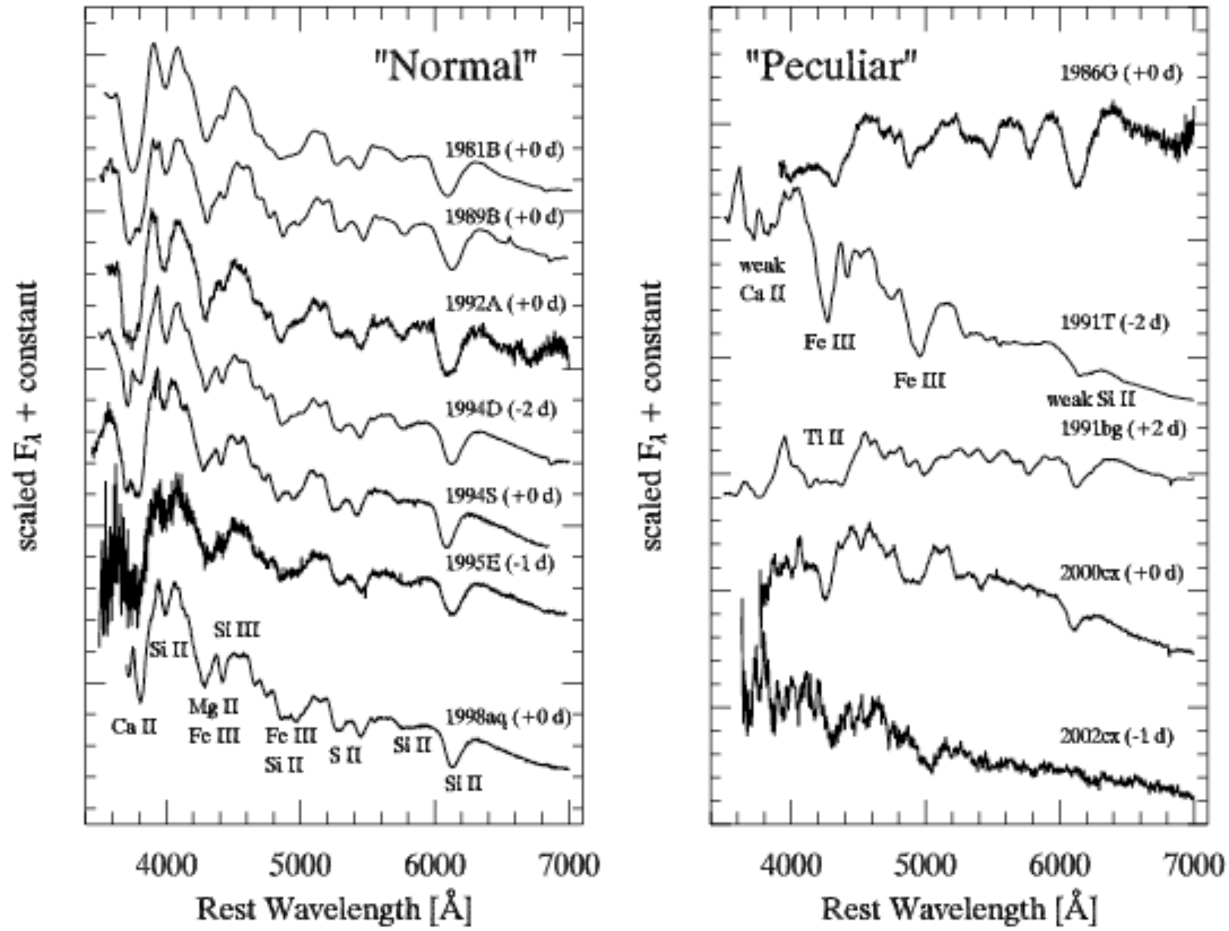
Requirements for an automated supernova classification

An automated classification of supernova spectra should…

1. determine the supernova type/subtype and assign a confidence

Supernova Subtypes

Ia	normal, 1991T-like, 1991bg-like, peculiar
Ib	normal, peculiar, IIb
Ic	normal, broad-line, peculiar
II	normal (IIP), IIL, IIn, IIb, peculiar

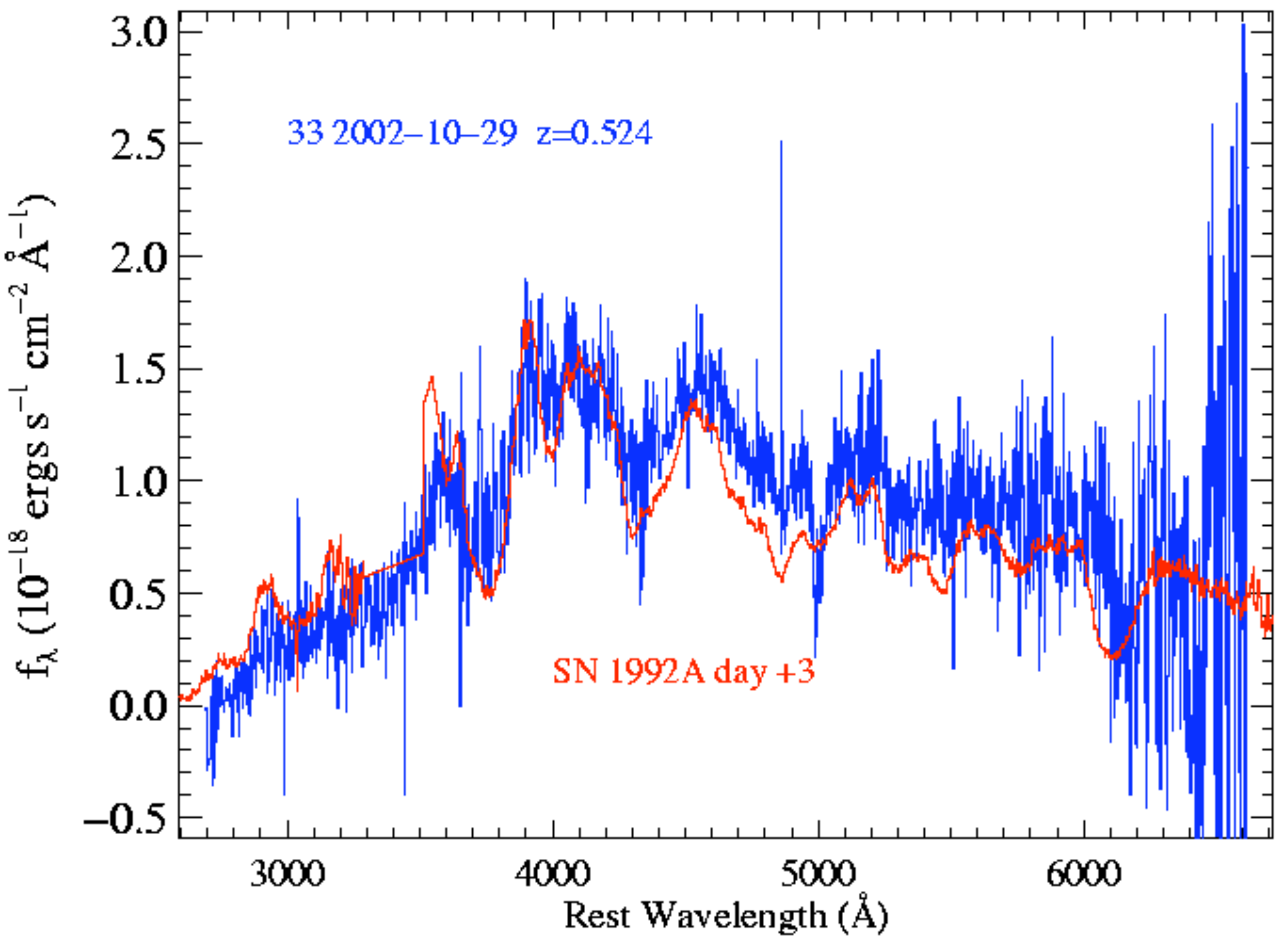


“normal” and “peculiar” SN Ia

An automated classification of supernova spectra should…

1. determine the supernova type/subtype and assign a confidence
2. work with inhomogeneous data sets (wavelength coverage, SNR)
    - possibly determine redshift

Spectral comparison

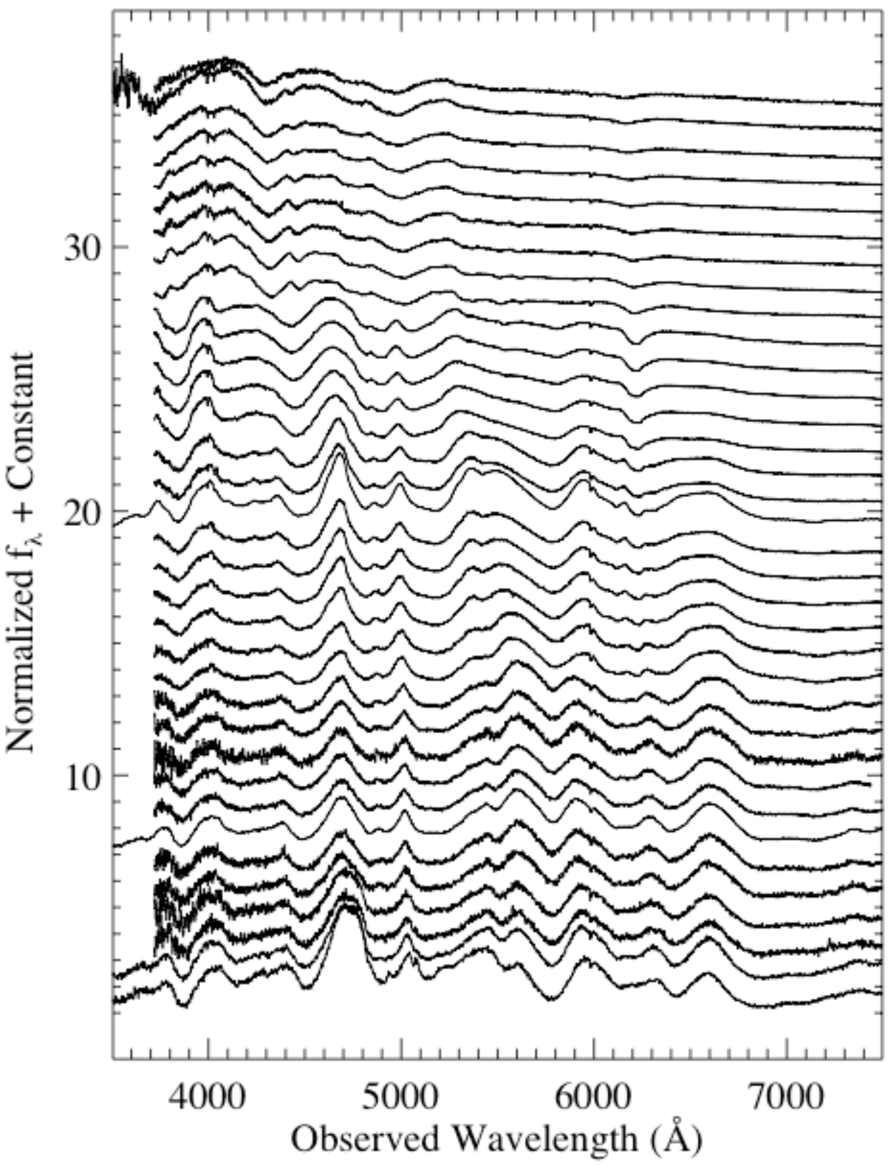


Credit: Tom Matheson

An automated classification of supernova spectra should…

1. determine the supernova type/subtype and assign a confidence
2. work with inhomogeneous data sets (wavelength coverage, SNR)
    - possibly determine redshift
3. take into account time-variation of spectra
    - i.e. determine phase

Spectral Evolution



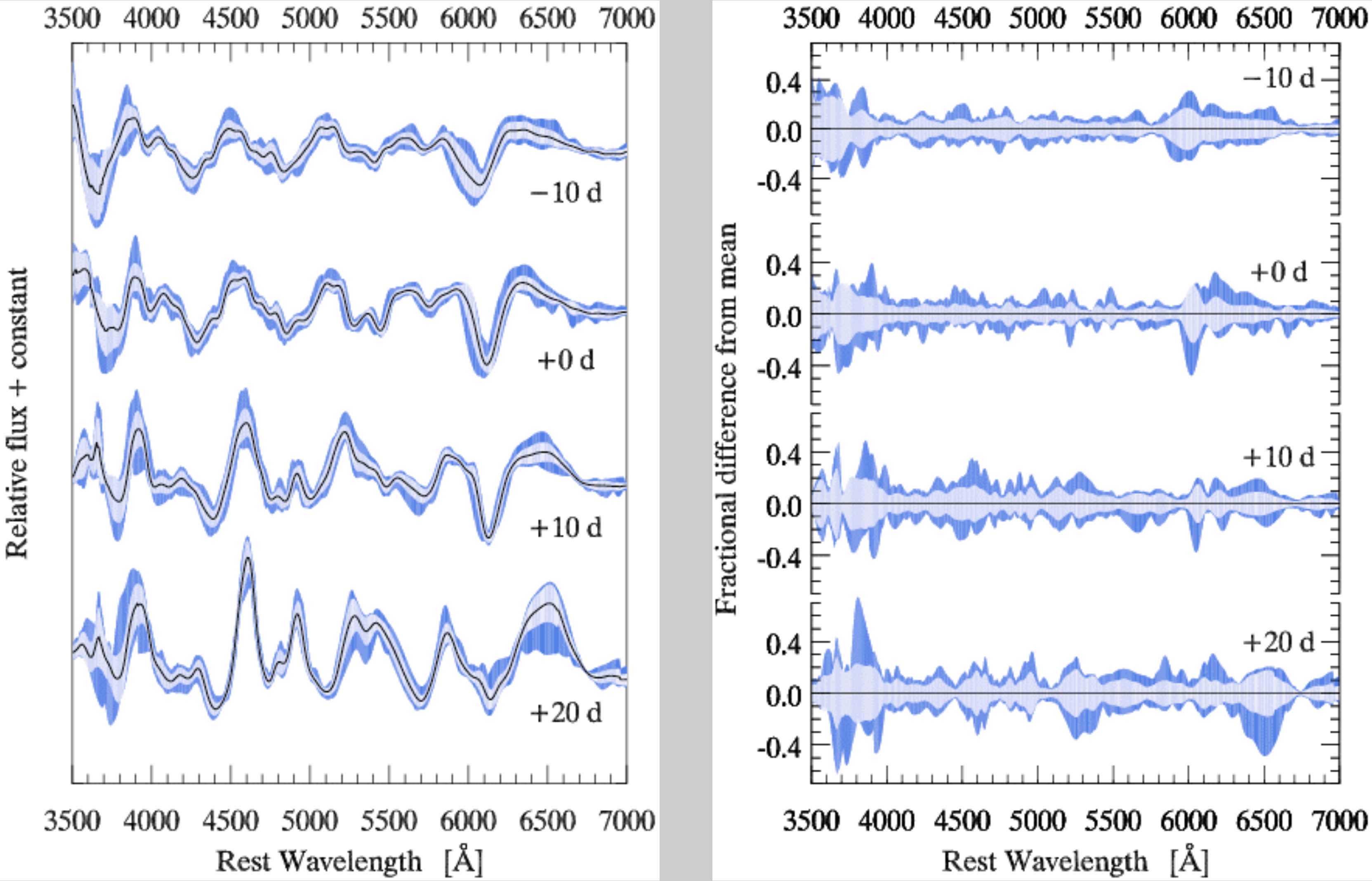
Type Ia supernova between
−14 to +106 days from maximum

SN 2001V (Matheson et al. 2007)

An automated classification of supernova spectra should…

1. determine the supernova type/subtype and assign a confidence
2. work with inhomogeneous data sets (wavelength coverage, SNR)
   - possibly determine redshift
3. take into account time-variation of spectra
   - i.e. determine phase
4. take into account spectral variance at a given phase

Intrinsic Variation

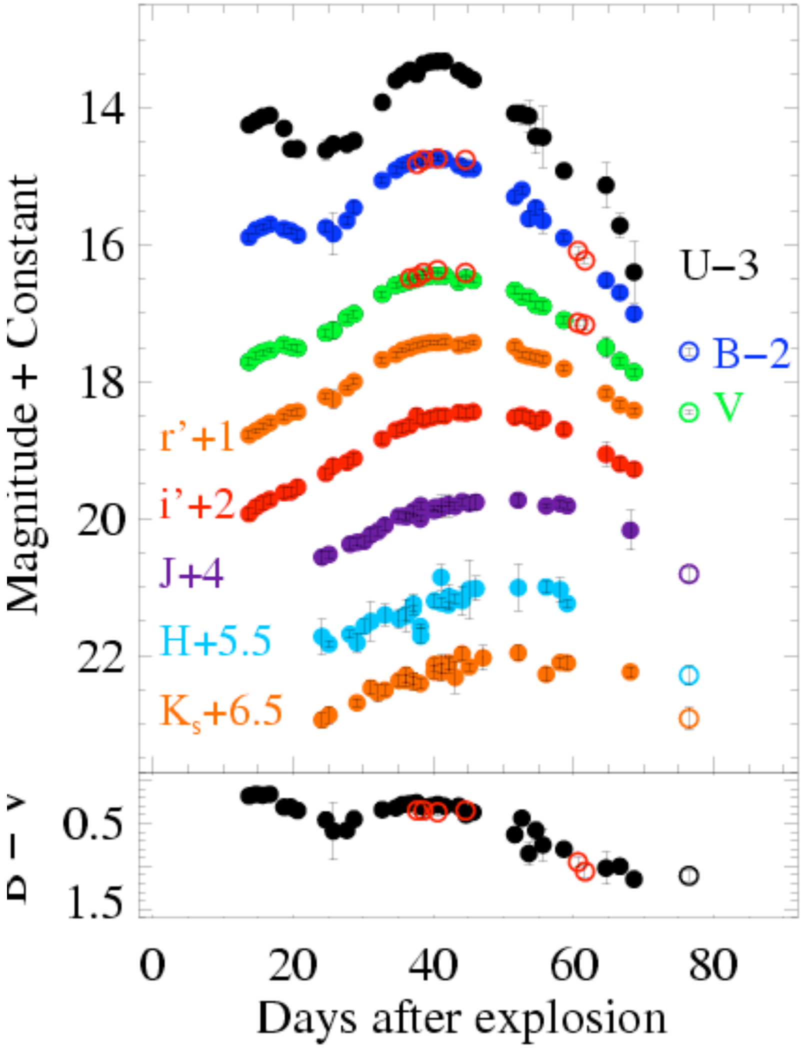


Intrinsic variation amongst SN Ia at a given phase (Blondin & Tonry 2007)

An automated classification of supernova spectra should…

1. determine the supernova type/subtype and assign a confidence
2. work with inhomogeneous data sets (wavelength coverage, SNR)
    - possibly determine redshift
3. take into account time-variation of spectra
    - i.e. determine phase
4. take into account spectral variance at a given phase
5. include external priors (light curve, survey parameters, SN rates, etc.)

Multicolor Light Curve of SN 2005bf (Ib)



(Tominaga et al. 2005)

An automated classification of supernova spectra should…

1. determine the supernova type/subtype and assign a confidence
2. work with inhomogeneous data sets (wavelength coverage, SNR)
    - possibly determine redshift
3. take into account time-variation of spectra
    - i.e. determine phase
4. take into account spectral variance at a given phase
5. include external priors (light curve, survey parameters, SN rates, etc.)
6. give the probability of the input spectrum *not* being a supernova

So…

…what’s the answer?