SNe Ia: Observational Confidence, or Not?

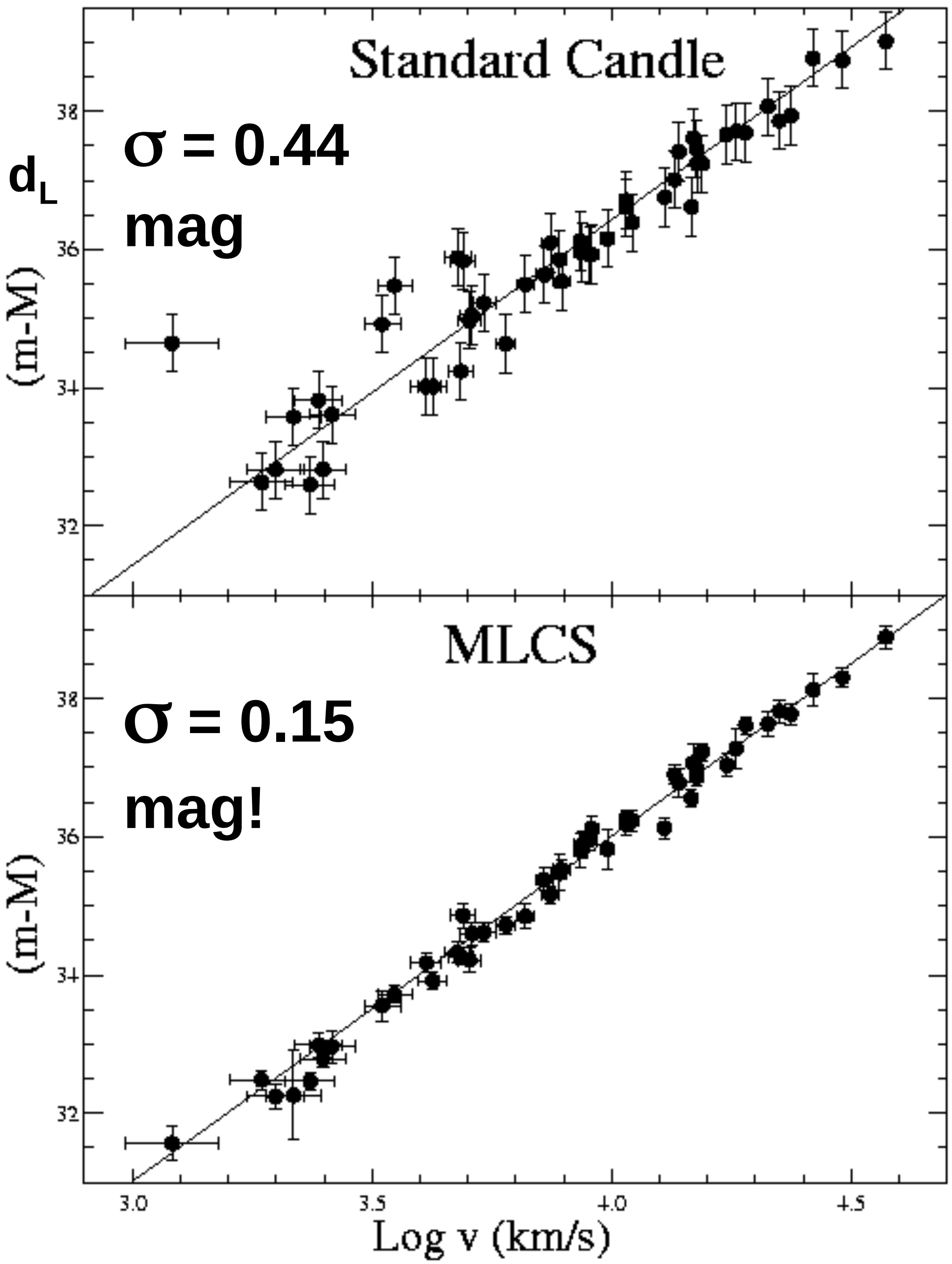
Alex Filippenko
Department of Astronomy
University of California, Berkeley

$\propto$ log d_L

σ = 0.44 mag

$\propto$ log d_L

σ = 0.15 mag!



(Riess et al. 1995, 1996, 1999)


Happy (belated) birthday, Ken!
Kavli Institute for Theoretical Physics
Ken Nomoto
Univ. of Tokyo

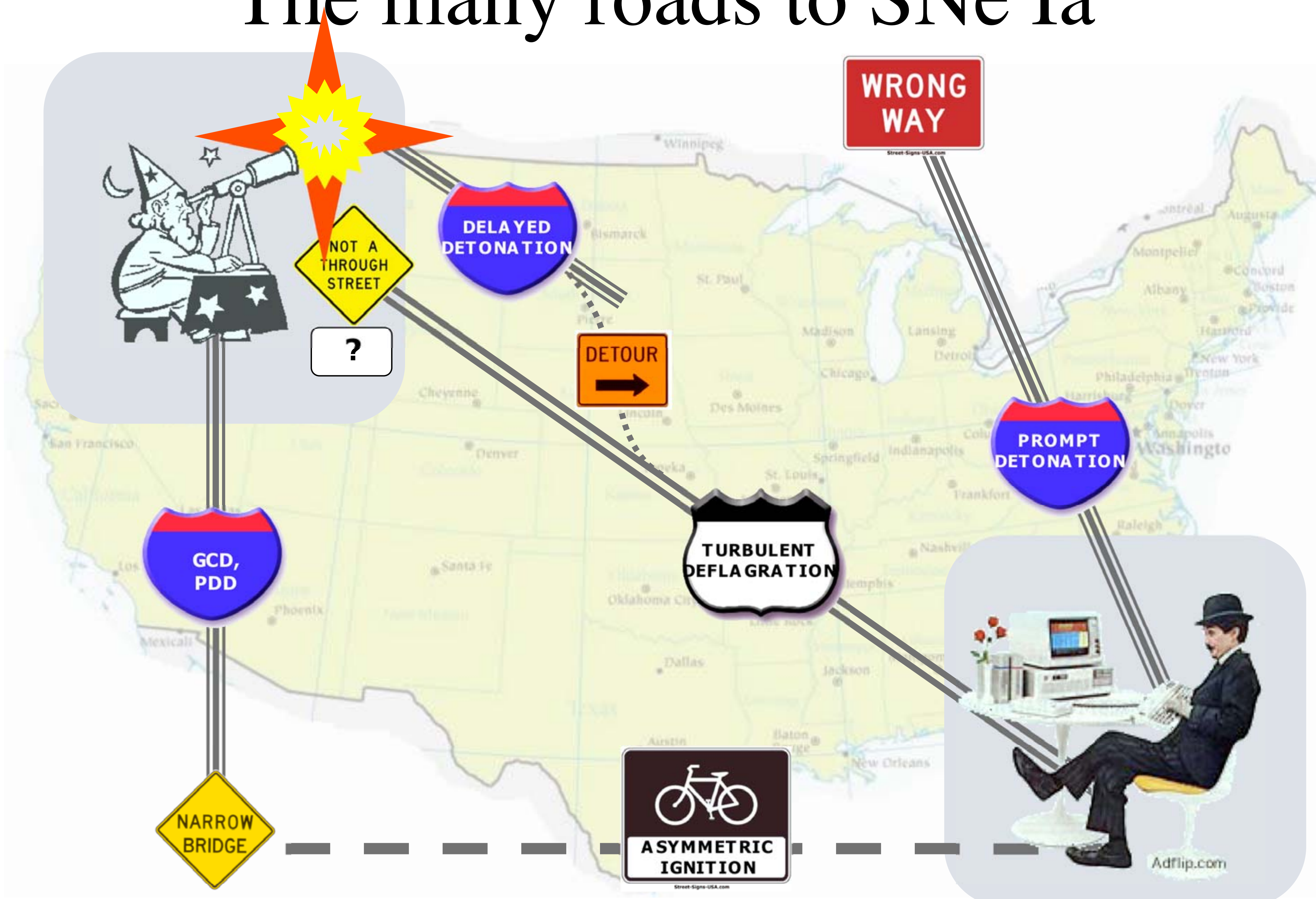
SN Ia: What do we really know?

- **White dwarf progenitors (no H, He; some SNe Ia from old stellar pops.)**
- **Thermonuclear runaway (spectra; no compact remnants found).**
- **Powered by Ni to Co to Fe decay (spectra, light curves).**
- **Binary systems (no other known way to trigger instability).**

SN Ia: What do we probably know?

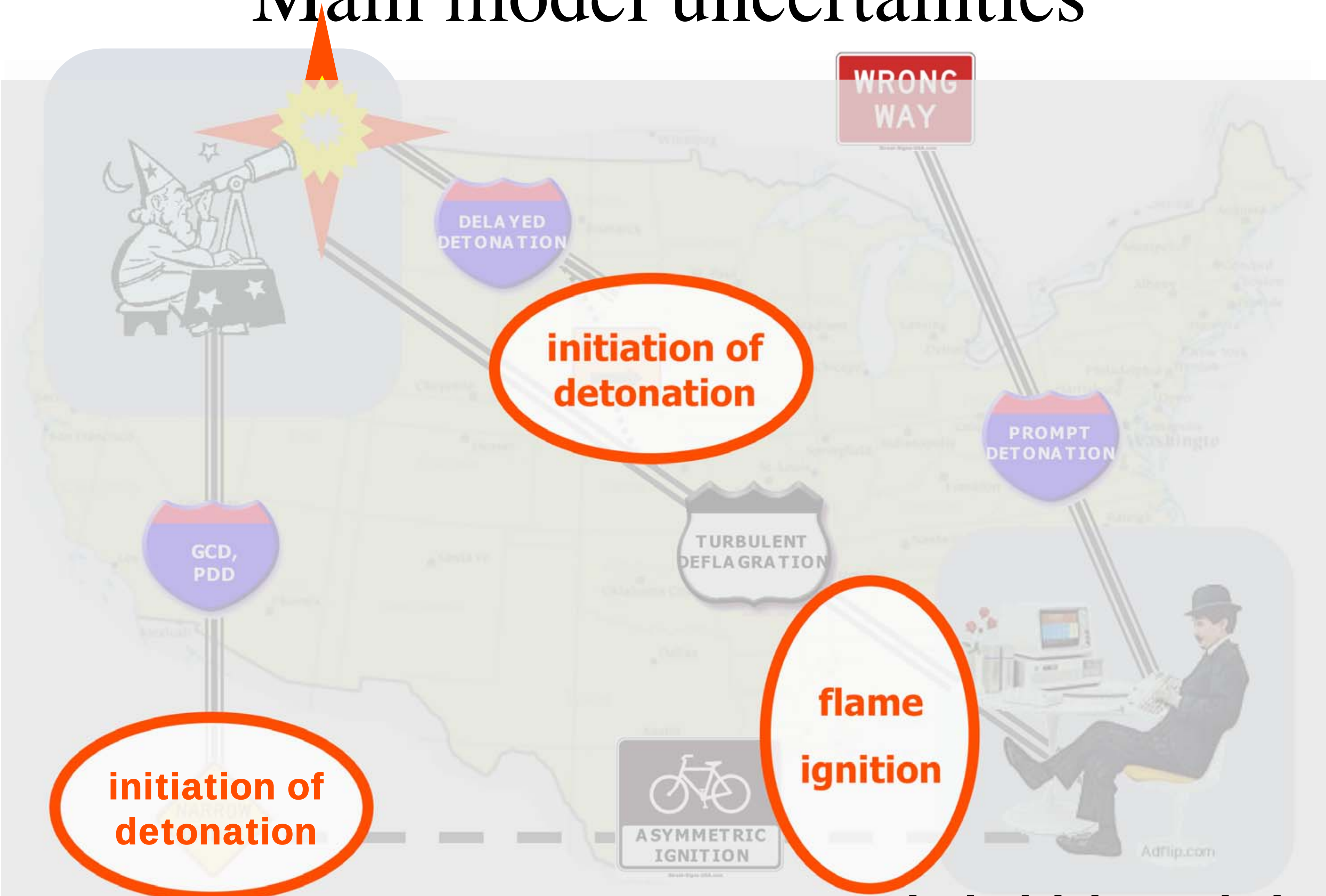
- **CO white dwarfs (ONeMg and He WDs don't work).**
- **Chandra mass, for many or most (uniformity of spectra, light curves)**
- **Explosion mechanism (some sort of combination of deflagration and detonation -- but details hotly debated)**

The many roads to SNe Ia



(Friedrich Röpke)

Main model uncertainties



(Friedrich Röpke)

SN Ia: What do we NOT know?

- **Explosion mechanism details; where does ignition occur; what governs transition to detonation; etc.?**
- **Super-Chandra, sub-Chandra WD for some or many? Rotation?**
- **Progenitors: single or double degenerates? Nature of donor?**
- **Dependence of L on stellar pop. (density? Z? mass?)**
- **"Weirdos."**

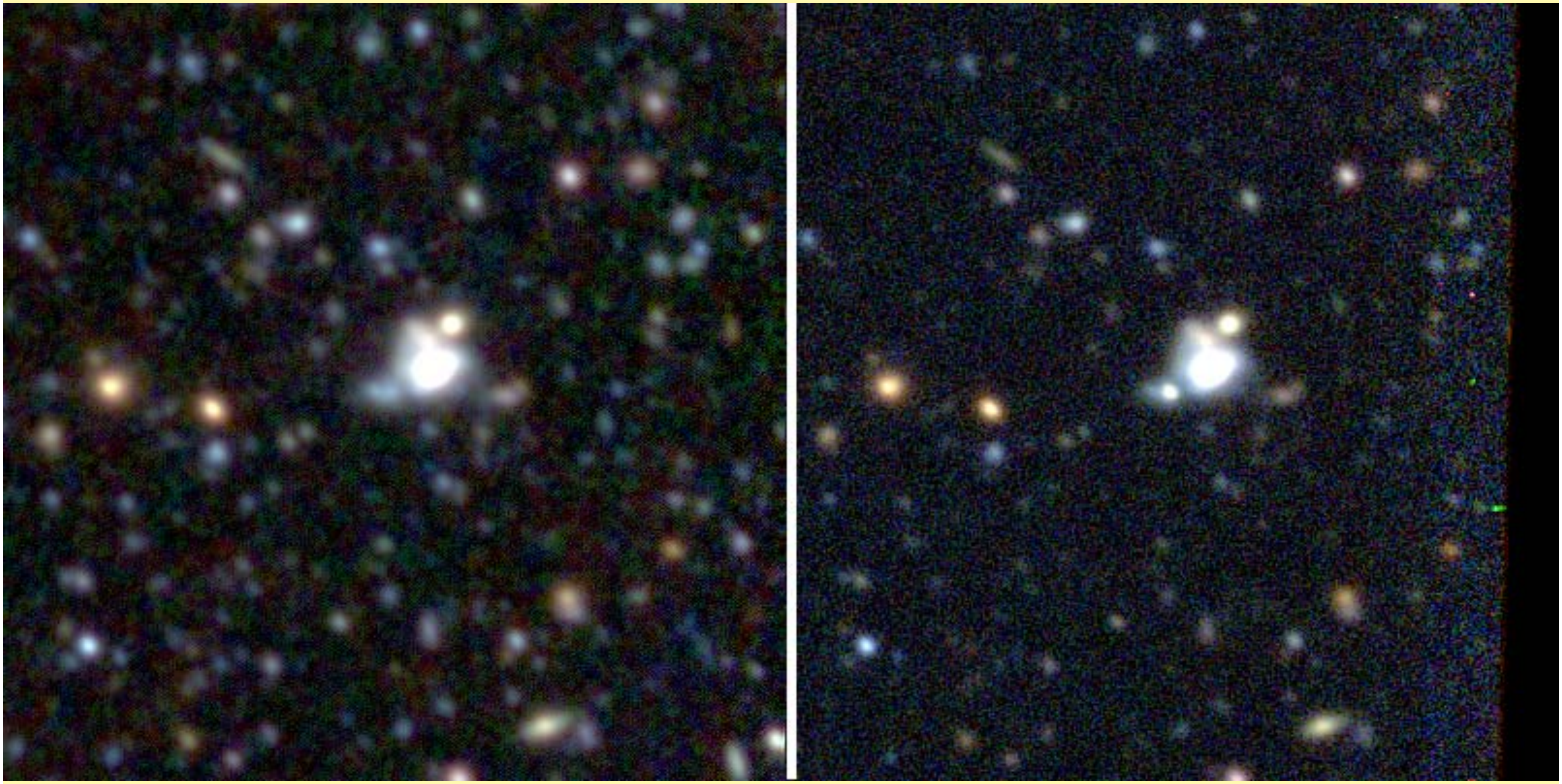
(1) Sub-Chandra masses?

- **Perhaps for the subluminous, SN 1991bg variety (and others?), as discussed by Bruno Leibundgut on Monday: not much Ni (0.1 M_sun,) not much total ejected mass (0.6).**
- **If Chandra mass, then perhaps a compact remnant left behind? (Edge-lit outward explosion?)**

Super-Chandra SN Ia?

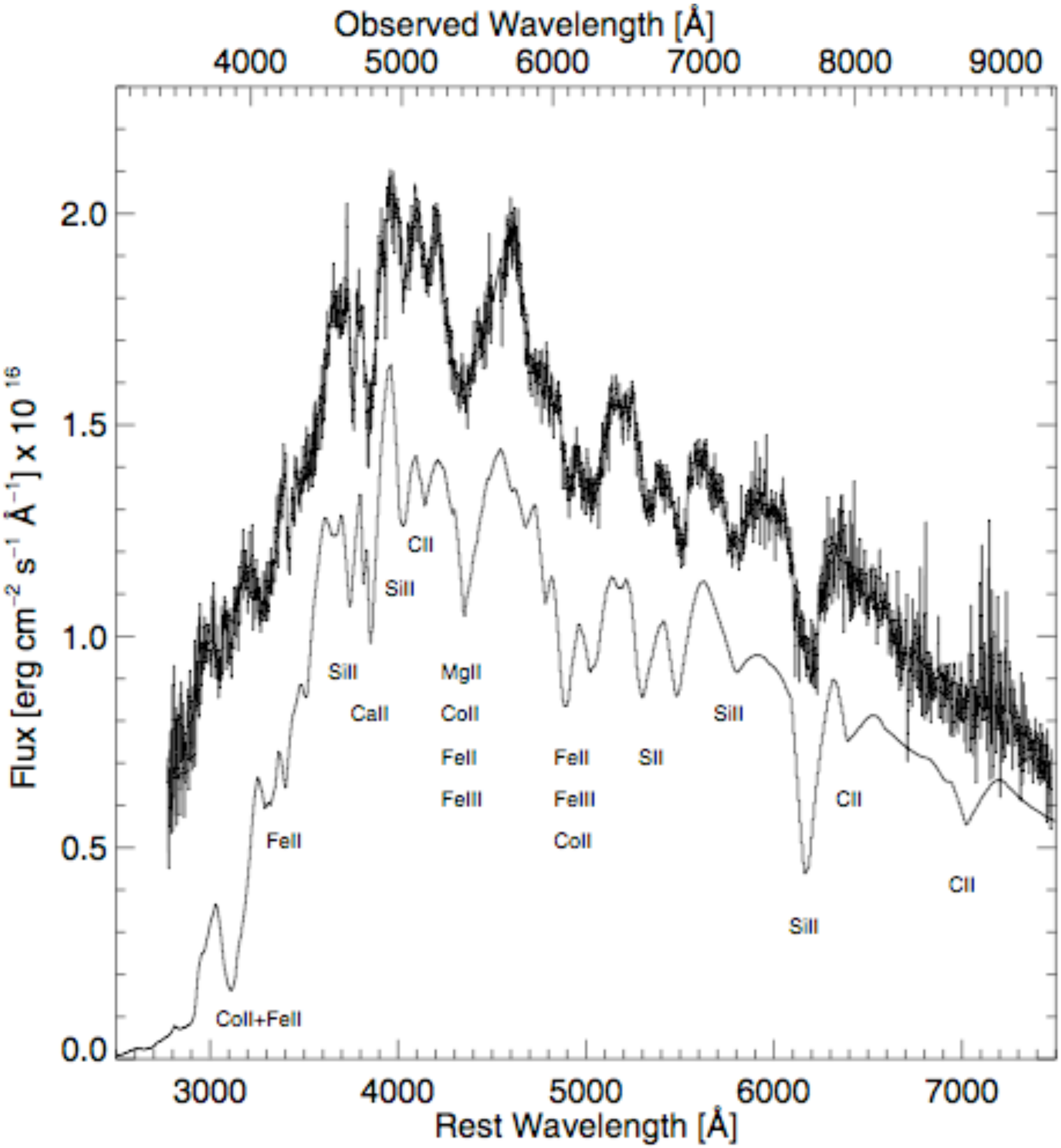
- SNLS 03D3bb: Howell et al. (2006)
- (Go to Andy Howell's talk on Thursday.)

SNLS 03D3bb (z = 0.2440)



Before **After**

(Courtesy Peter Nugent)

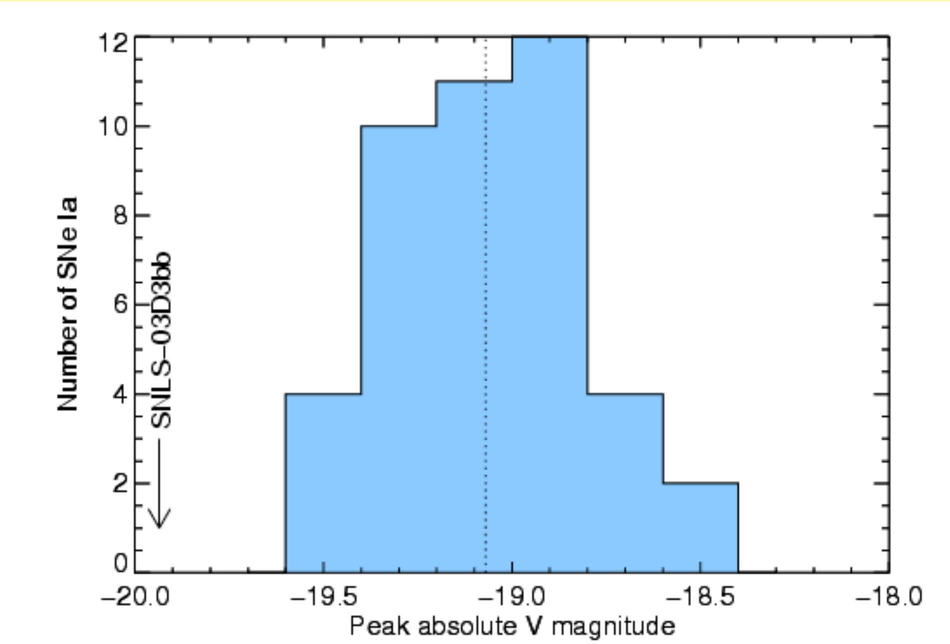


SNLS
03D3bb

Vphot ~ 8000 km/s 2 days after peak brightness

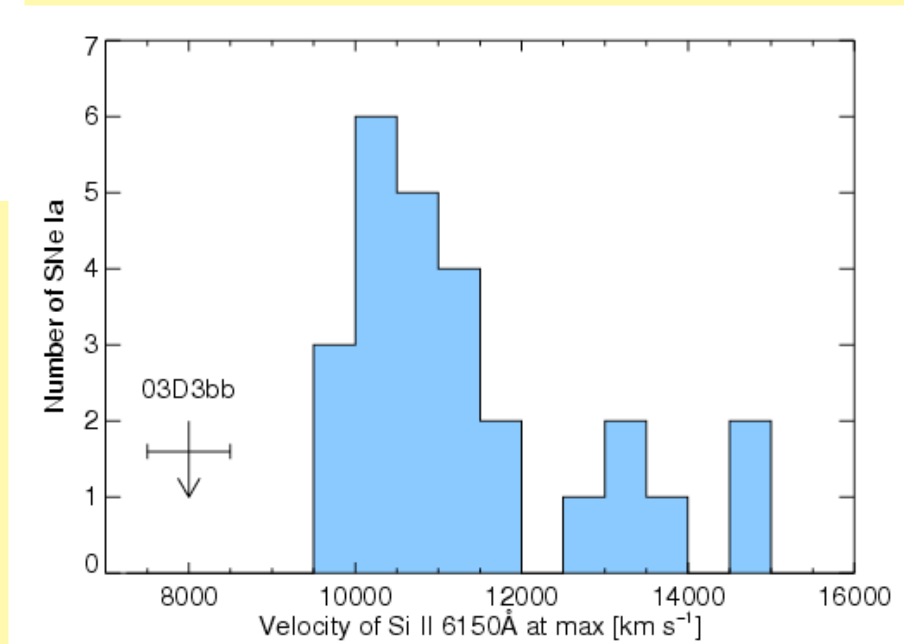
See the usual lines, and a CII line

SNLS 03D3bb



2.2 times more luminous

25% slower



Super-Chandra?

(1) A factor of 2.2 in L implies that the ^{56}Ni mass is about 1.3 M_sun. Peak spectrum typical, and see C (unburned). Thus there has to be some intermediate-mass elements and C/O there as well: $M > M_{Ch.}$

(2) Moreover, the velocity is 25% slower than that of a typical SN Ia; implies a KE 50% lower than average. Need to raise the binding energy considerably: $M > M_{Ch}$.

Conclude M ~ 2 M_sun.

Super-Chandra Mass?

- **Single degenerate with differential rotation (Yoon & Langer 2004) or magnetic fields?**
- **Double degenerate? (But how avoid formation and collapse of ONeMg WD?)**
- **Why don't we see more of them? Why not a continuum of high-L objects?**

A mystery object…

(2) No evidence for H

- No sign of H, neither at early nor late times.
- At early times, expect some ionization of CSM by free-free emission from reverse-shocked ejecta and by inverse-Compton scattered photospheric emission (Fransson et al. 1996).

SN 2001el

(From Peter Lundqvist's KITP talk, 2/15/07)

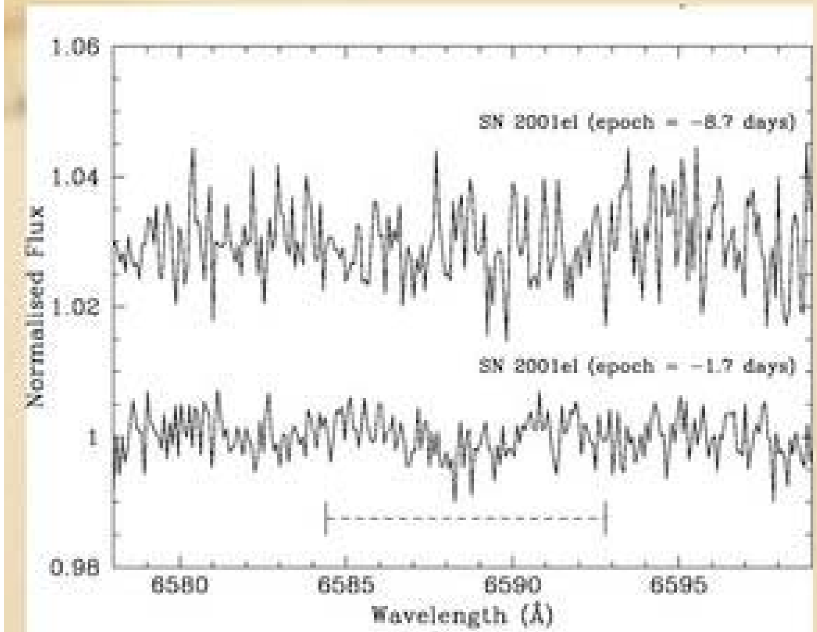


Fig. 3. Normalised and rebinned (~4 km s^{-1} pixel^{-1}) UVES spectra in the expected spectral region around Hα for SN 2001el on two epochs, September 21.3 and 28.3 (UT) 2001, i.e., 8.7 and 1.7 days before the SN maximum light, respectively. The expected wavelength range of Hα is marked with a horizontal dashed line, and the upper spectrum has been shifted vertically for clarity. No significant emission or absorption lines are visible.

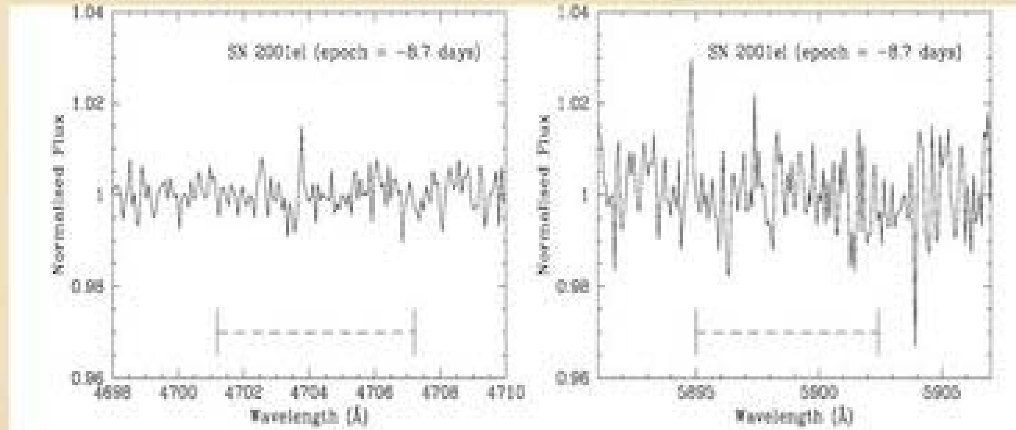


Fig. 4. Normalised and rebinned (~4 km s^{-1} pixel^{-1}) UVES spectra in the expected spectral regions around He II (4686 Å) and He I (5876 Å) for SN 2001el on September 21.3 (UT) 2001, i.e., 8.7 days before the maximum light. The expected wavelength range of the CSM lines is marked with a horizontal dashed line. No significant emission or absorption lines are visible.

Limit on mass loss rate: 9×10^{-6} M_o/yr (for a 10 km/s wind) (Mattila et al. 2005).

(See also Lundqvist et al. 2007) (Looking for H, He lines)

Results from the optical observations
(SN 2000cx)

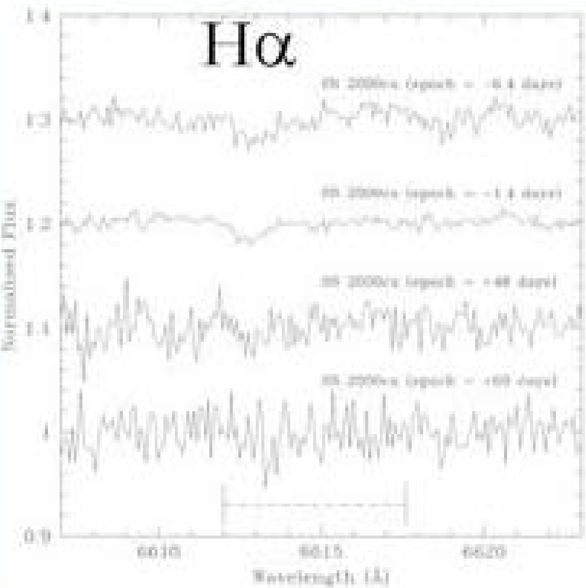


Fig. 1. Normalized UVES spectra in the expected spectral region around Hα for SN 2000cx on four epochs July 20.3, July 25.3, September 3.2, and October 12.3 (UT) 2000. The expected wavelength range of Hα is marked with a horizontal dashed line. No signs of CS Hα lines are visible either in emission or absorption (note that the feature at 6613 Å visible in the SN 2000cx spectra has been identified to be due to instrumental/atmospheric effects).

Table 2. 3σ upper limits on CS emission line fluxes of SN 2000cx. (Fluxes are not dereddened.)

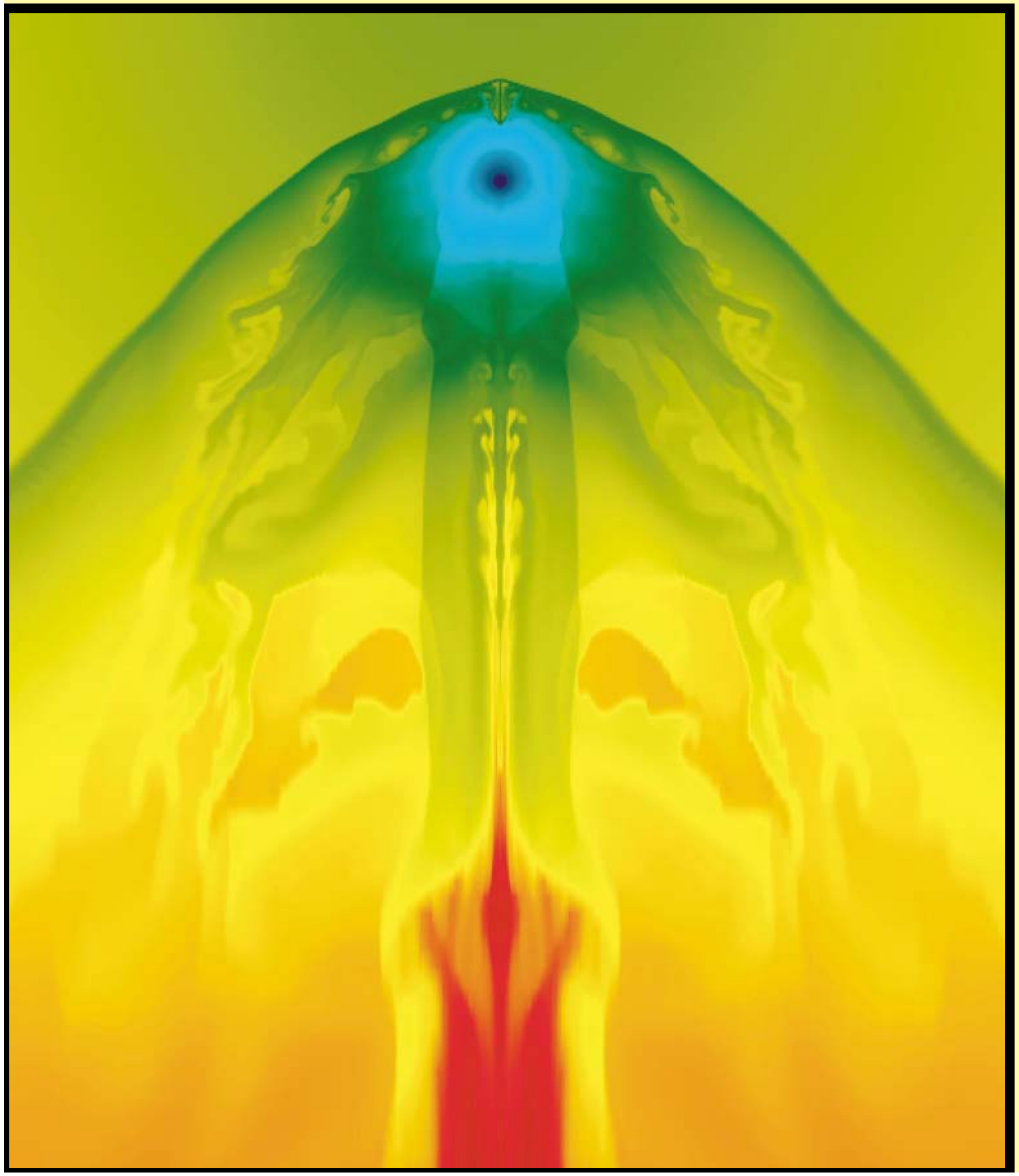
Julian day (24500+)	epoch[a] (days)	line	FWHM (km s^{-1})	flux (ergs s^{-1} cm^{-2})
1745.8	−6.4	Hα	37[b]	8.4(−17)[c]
		Hα	62[d]	1.3(−16)
		Hα	106[e]	1.5(−16)
		Hα	203[f]	2.3(−16)
		He I[g]	21[b]	7.2(−17)
		He I[g]	53[d]	1.1(−16)
		He II[h]	21[b]	4.7(−17)
		He II[h]	53[d]	7.9(−17)
1750.8	−1.4	Hα	37[b]	8.7(−17)
		Hα	62[d]	1.4(−16)
		He I[g]	21[b]	7.2(−17)
		He I[g]	53[d]	1.3(−16)
		He II[h]	21[b]	4.0(−17)
		He II[h]	53[d]	7.7(−17)
1799.7	+47.5	Hα	37[b]	3.1(−17)
		Hα	62[d]	4.8(−17)
1820.7	+68.5	Hα	37[b]	1.3(−17)
		Hα	62[d]	1.7(−17)
		Hα	106[e]	2.0(−17)
		Hα	203[f]	3.0(−17)

[a] Relative to B-band maximum (JD2451752.2, Li et al. 2001). To obtain the time since explosion used in, e.g., Figs. 11 and 12, a rise time of 16 days was assumed (as found for SN 1994D in Riess et al. 1999).
[b] Assuming $T = 2.8 \times 10^4$ K and $v = 10$ km s^{-1} for the wind.
[c] 9.2(−17) stands for 9.2×10^{-17}.
[d] Assuming $T = 2.8 \times 10^4$ K and $v = 50$ km s^{-1} for the wind.
[e] Assuming $T = 2.8 \times 10^4$ K and $v = 100$ km s^{-1} for the wind.
[f] Assuming $T = 2.8 \times 10^4$ K and $v = 200$ km s^{-1} for the wind.
[g] He I λ5876
[h] He II λ4686

(Lundqvist et al. 2007)

(From Peter Lundqvist's KITP talk, 2/15/07)

Constraining the Type Ia Supernova Progenitor: The Search for Hydrogen in Nebular Spectra



H should be entrained in the ejecta:

- Wheeler et al. (1975)
- Fryxell & Arnett (1981)
- Taam & Fryxell (1984)
- Chugai (1986)
- Livne et al. (1992)
- Marietta et al. (2000)

(Image: Marietta et al. 2000)

How Much Hydrogen?

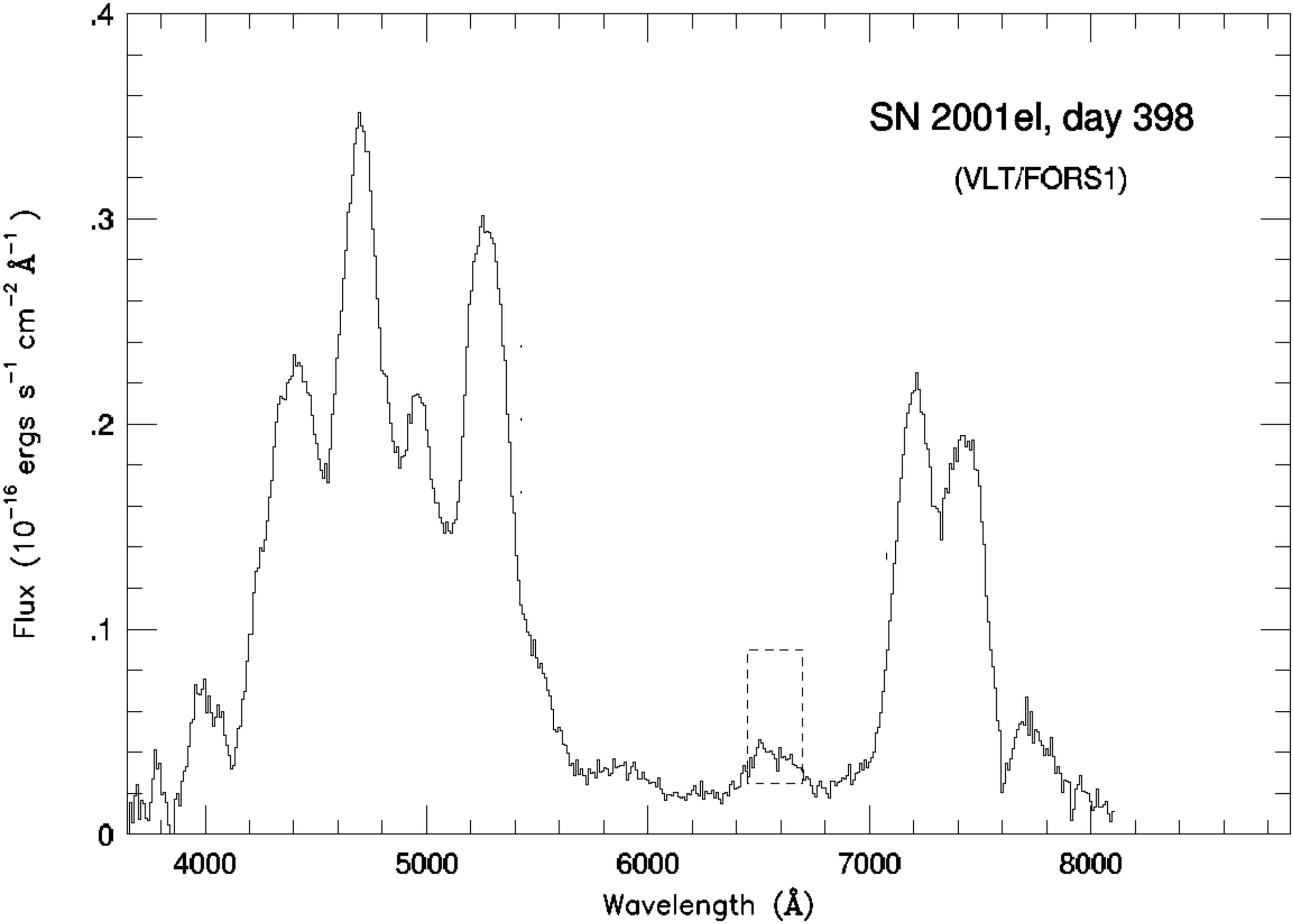
Progenitor System	Secondary Star	Mass Transfer	Separation (a/R)	Stripped Mass ($M_\odot$)
HCV	MS	RLOF	3.0	
HCVL	SG	RLOF	2.78	
HALGOL	RG	RLOF	2.52	
SYMB	RG	Wind	3.16	

(Marietta, Burrows & Fryxell 2000)

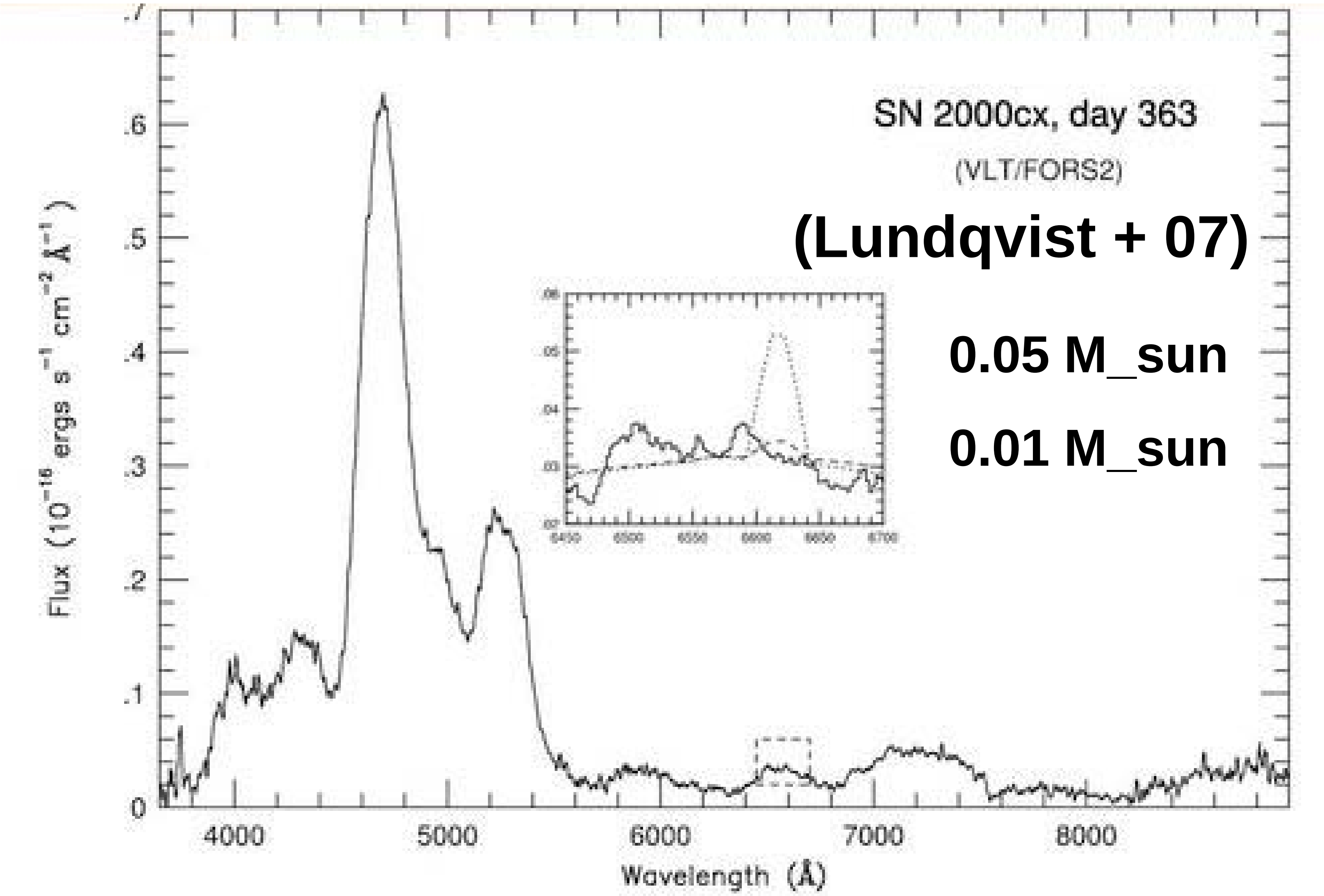
How Much Hydrogen?

Progenitor System	Secondary Star	Mass Transfer	Separation (a/R)	Stripped Mass ($M_\odot$)
HCV	MS	RLOF	3.0	0.15
HCVL	SG	RLOF	2.78	0.17
HALGOL	RG	RLOF	2.52	0.54
SYMB	RG	Wind	3.16	0.53

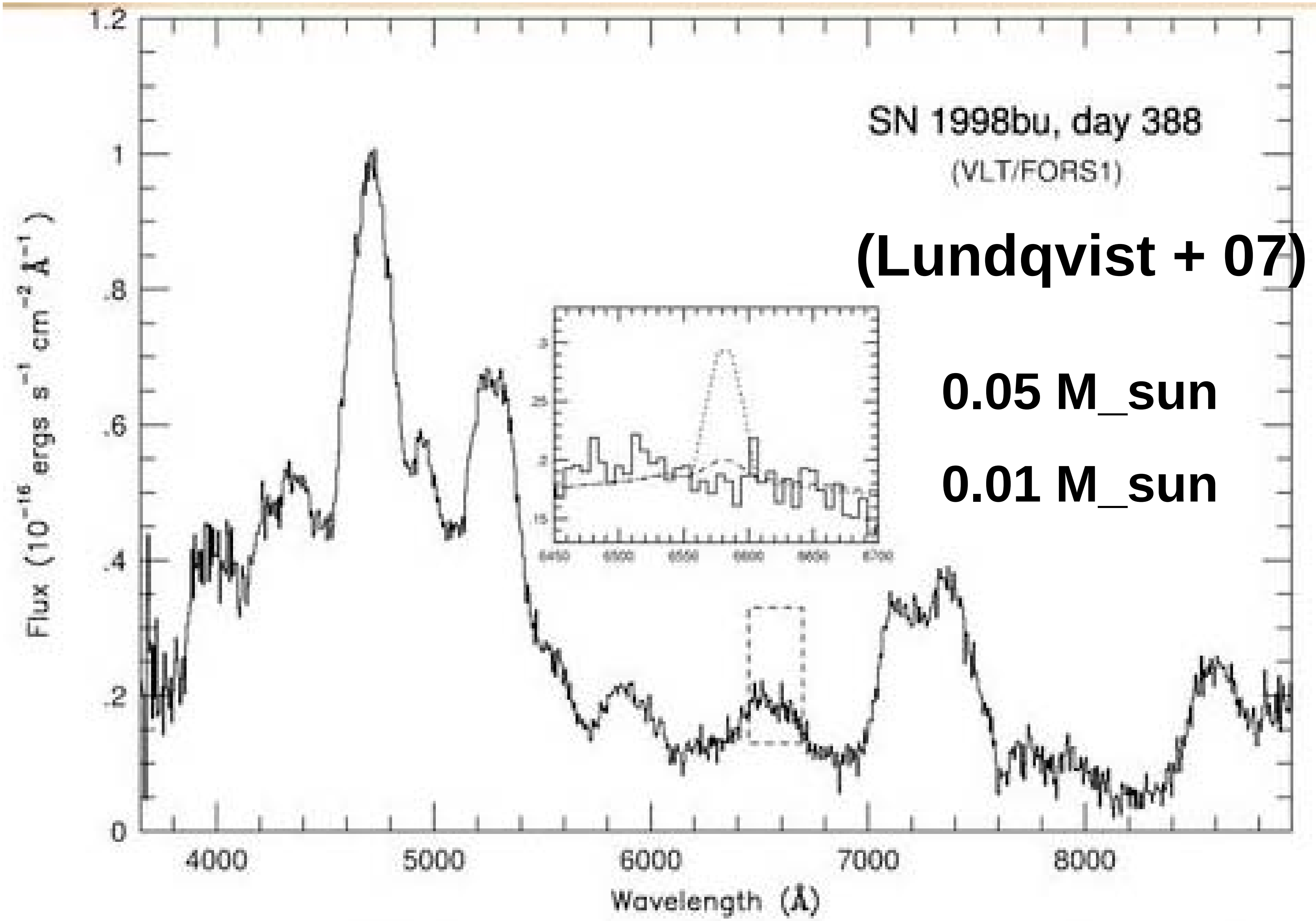
(Marietta, Burrows & Fryxell 2000)



(Mattila et al. 2005)



LT/FORS2 spectrum of SN 2000cx at 363 days after B maximum. The overall spectrum is de
et al. (2004). The inset is a blow-up of the region marked by dashed lines, concentrating on wa

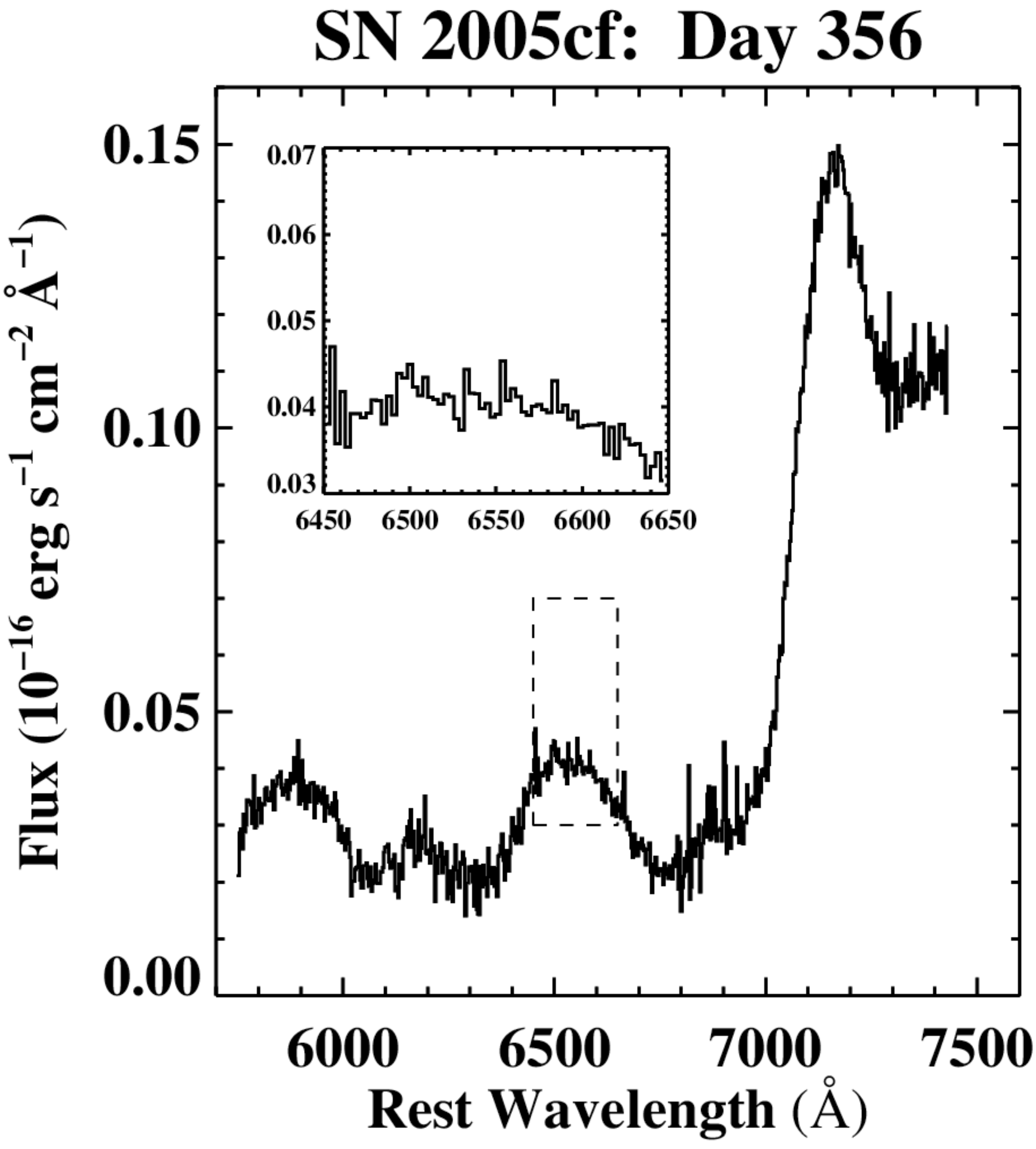


'/FORS1 spectrum of SN 1998bu at 388 days after *B* maximum. The overall spectrum is very

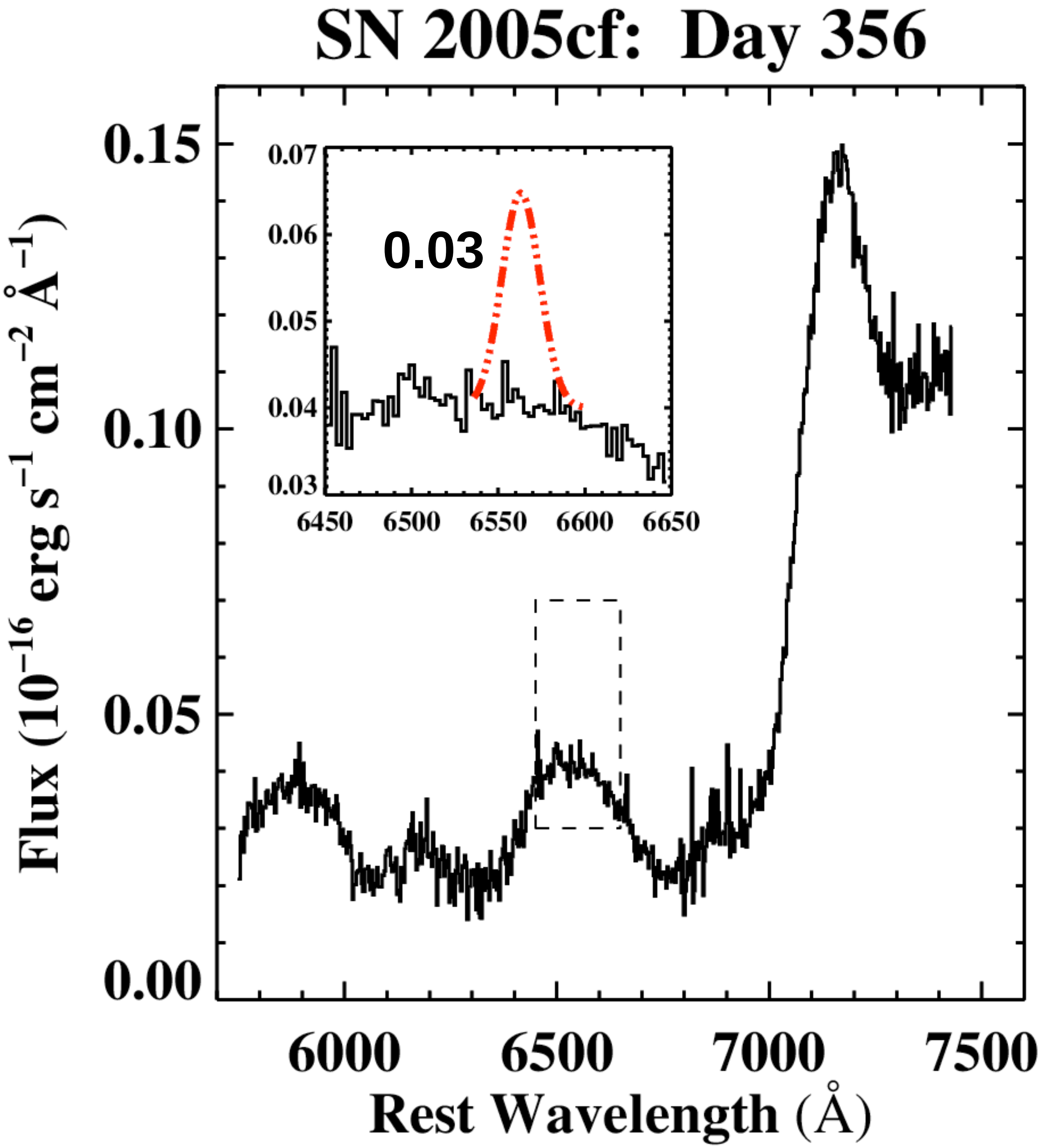
Nebular-Phase Spectroscopy of Normal SNe Ia

Supernova	Day	Telescope	Exposure (s)
SN 2005cf	269	Gemini N	10,800
	356	Keck I	11,100
	386	Keck I	6,600
SN 2005am	301	Keck I	7,200
	384	Gemini S	10,400

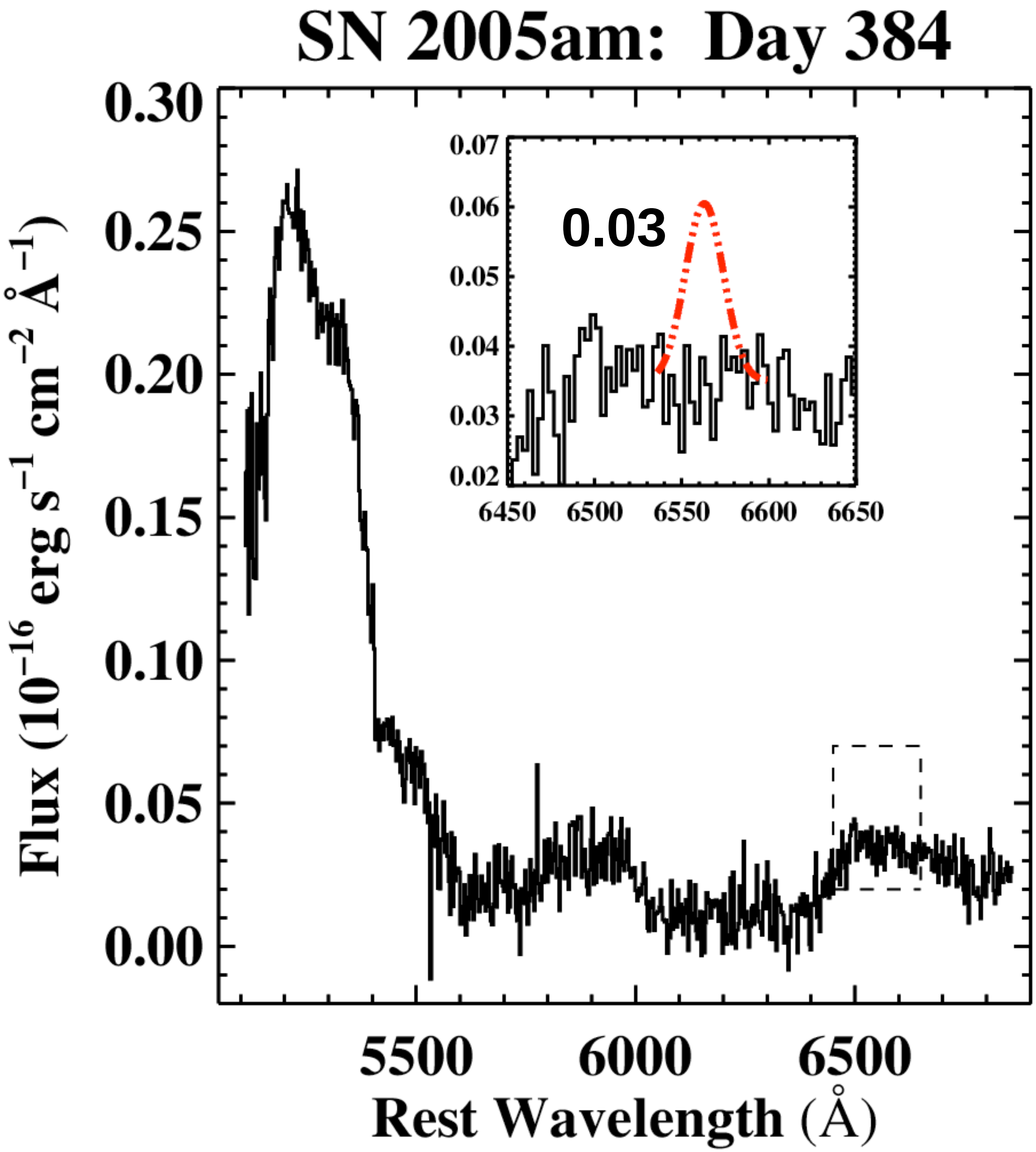
(Doug Leonard 2007, in prep.; Aspen, Feb. 2007 talk)



(Leonard 2007, in prep.)



(Leonard 2007, in prep.)



(Leonard 2007, in prep.)

Supernova	Day	Telescope	Exposure (s)	Solar Material ($M_\odot$)
SN 2005cf	269	Gemini N	10,800	< 0.01 (?)
	356	Keck I	11,100	< 0.01
	386	Keck I	6,600	< 0.02
SN 2005am	301	Keck I	7,200	< 0.03 (?)
	384	Gemini S	10,400	< 0.01

(Leonard 2007, in prep.)

How Much Hydrogen?

Progenitor System	Secondary Star	Mass Transfer	Separation (a/R)	Stripped Mass ($M_\odot$)
HCV	MS	RLOF	3.0	0.15
HCVL	SG	RLOF	2.78	0.17
HALGOL	RG	RLOF	2.52	0.54
SYMB	RG	Wind	3.16	0.53

(Marietta, Burrows & Fryxell 2000)

Conclusion

Wide symbiotics are the progenitors of most normal SNe Ia.

(Leonard 2007, in prep.; Aspen, Feb. 2007 talk)

Rebuttal

The lack of radio detections of SNe Ia STRONGLY argues against this conclusion! (In Aspen a few weeks ago, Nino Panagia mentioned that this is the ONLY model ruled out by the radio obs.)

Radio observations of SNe Ia

The Astrophysical Journal, 646:369–377, 2006 July 20

A SEARCH FOR RADIO EMISSION FROM TYPE Ia SUPERNOVAE

Nino Panacia,[1,2] Schuyler D. Van Dyk,[3] Kurt W. Weiler,[4] Richard A. Sramek,[5] Christopher J. Stockdale,[6] and Kimberly P. Murata[7]
Received 2006 February 21; accepted 2006 March 29

Using Chevalier's model From 1983 and adopting scaling of emission from SNe Ib and Ic, Panagia et al. (2006) obtain very low upper limits on the wind density.

TABLE 3
Lowest Upper Limits to SN Ia Progenitor Mass-Loss Rates

SN (1)	Distance (Mpc) (2)	Epoch (days) (3)	Wavelength (cm) (4)	Radio Luminosity[a] (ergs^{-1} Hz^{-1}) (5)	$\dot{M}$[b] ($M_\odot$ yr^{-1}) (6)
1980N	23.3	71	6	2.5×10^{26}	1.1×10^{-6}
1981B	16.6	17	6	6.5×10^{25}	1.3×10^{-7}
1982E	23.1	1416	20	2.3×10^{26}	7.3×10^{-6}
1983G	17.8	71	6	5.0×10^{25}	4.1×10^{-7}
1984A	17.4	74	6	7.1×10^{25}	5.3×10^{-7}
1985A	26.8	55	20	1.2×10^{26}	2.5×10^{-7}
1985B	28.0	69	20	3.1×10^{26}	6.1×10^{-7}
1986A	46.1	57	6	2.6×10^{26}	9.2×10^{-7}
1986G	5.5	28	6	5.0×10^{25}	1.7×10^{-7}
1986O	28	71	6	1.3×10^{26}	7.4×10^{-7}
1987D	30	83	6	1.3×10^{26}	8.4×10^{-7}
1987N	37.0	67	20	4.2×10^{26}	7.4×10^{-7}
1989B	11.1	15	3.6	8.1×10^{24}	3.3×10^{-8}
1989M	17.4	50	6	9.2×10^{25}	4.4×10^{-7}
1990M	39.4	32	3.6	1.5×10^{26}	5.4×10^{-7}
1991T	14.1	28	3.6	2.3×10^{25}	1.5×10^{-7}
1991bg	17.4	29	3.6	1.1×10^{26}	2.0×10^{-7}
1992A	24.0	29	6	4.1×10^{25}	1.6×10^{-7}
1994D	14	61	6	2.8×10^{25}	2.5×10^{-7}
1995al	30	17	20	1.7×10^{26}	1.2×10^{-7}
1996X	30	66	3.6	1.9×10^{26}	1.2×10^{-6}
1998bu	11.8	28	3.6	1.3×10^{25}	1.1×10^{-7}
1999by	11.3	15	3.6	2.1×10^{25}	8.0×10^{-8}
2002bo	22	95	20	6.8×10^{25}	3.0×10^{-7}
2002cv	22	41	20	6.8×10^{25}	3.0×10^{-7}
2003hv	23	61	3.6	6.2×10^{25}	5.8×10^{-7}
2003if	26.4	68	3.6	8.1×10^{25}	7.6×10^{-7}

[a] The spectral luminosity upper limit (2 σ), as estimated at the wavelength given in col. (4), which, when combined with the age of the SN at the time of observation, yielded the lowest mass-loss rate limit.

[b] The upper limit (2 σ) to the mass-loss rate, $\dot{M}$, is calculated from the spectral luminosity lowest upper limit given in col. (5), as measured at the wavelength given in col. (4) at an epoch after explosion given in col. (3). The mass-loss limits are calculated with the assumption that the SN Ia progenitor systems can be modeled by the known properties of SN Ib/c progenitor systems, and that the pre-SN wind velocity establishing the CSM is $w_{wind} = 10$ km s^{-1}.

(From Peter Lundqvist's KITP talk, 02/15/07)

Radiative transfer?

Maybe we don't see the H lines due to radiative transfer: iron curtain absorbs (scatters) the light. (Ejecta not sufficiently optically thin.) [Cecilia Kozma]

If so, we can't fully test single degenerate models with such observations… darn!

(3) Lots of H in some SNe Ia?

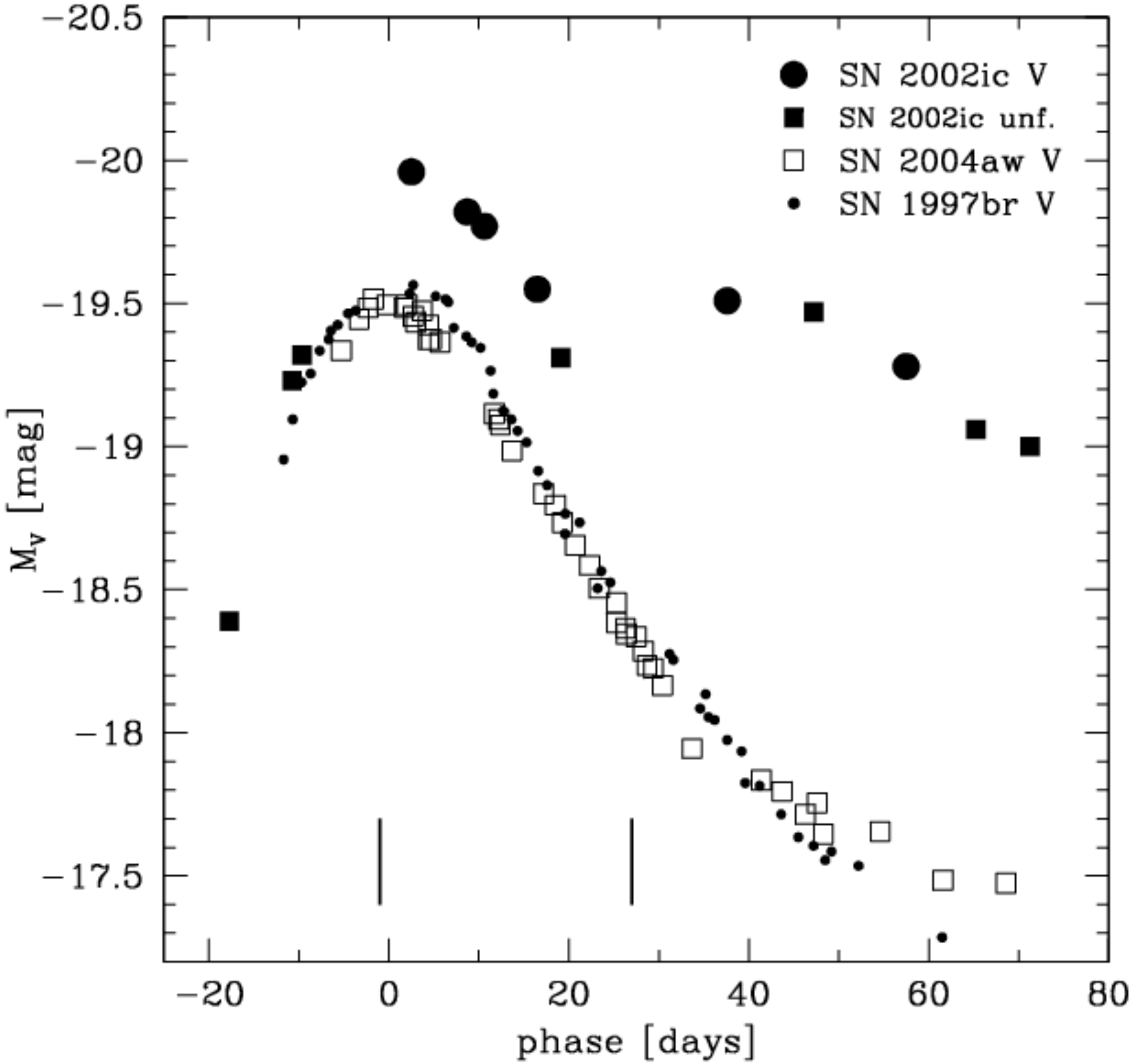
- SN 2002ic (Hamuy et al. 2003), SN 2005gj (Aldering et al. 2006).
- Maybe interacting with post-AGB companion? But then why do we see either no H, or lots of H?
- Livio & Riess (2003) argue that SN 2002ic-like objects might be explained just as well with double-degenerates: SN Ia inside common envelope.

But was SN 2002ic *actually* a SN Ic in CSM?

- The case is pretty good! (Benetti et al. 2006)
- Need to choose particular SNe Ic for comparison (SN 2004aw), just like the SN Ia interpretation requires SN 1991T-like object.

Figure 1

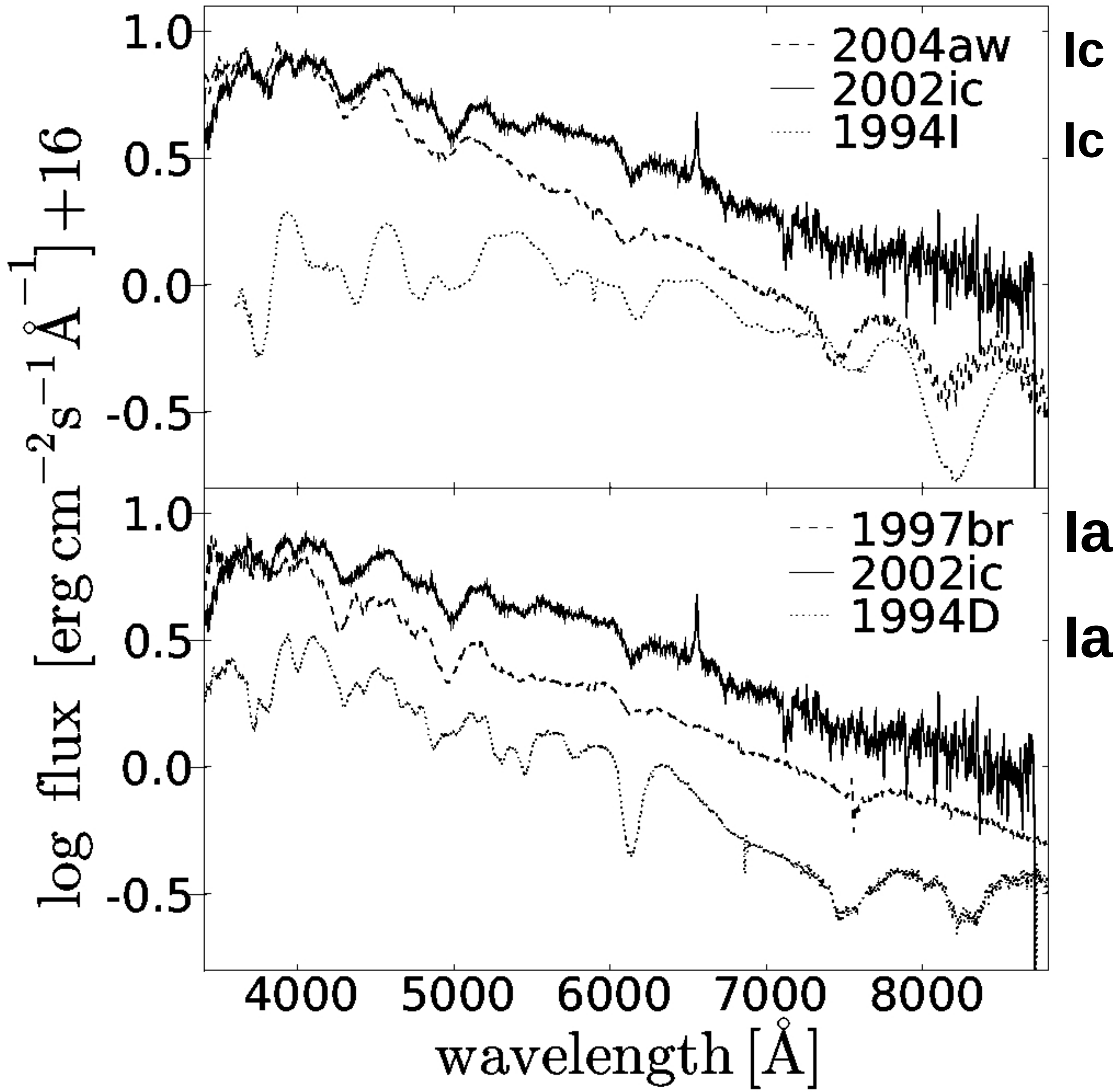
(Benetti et al. 2006)



(t ~ 0 d)

Figure 2

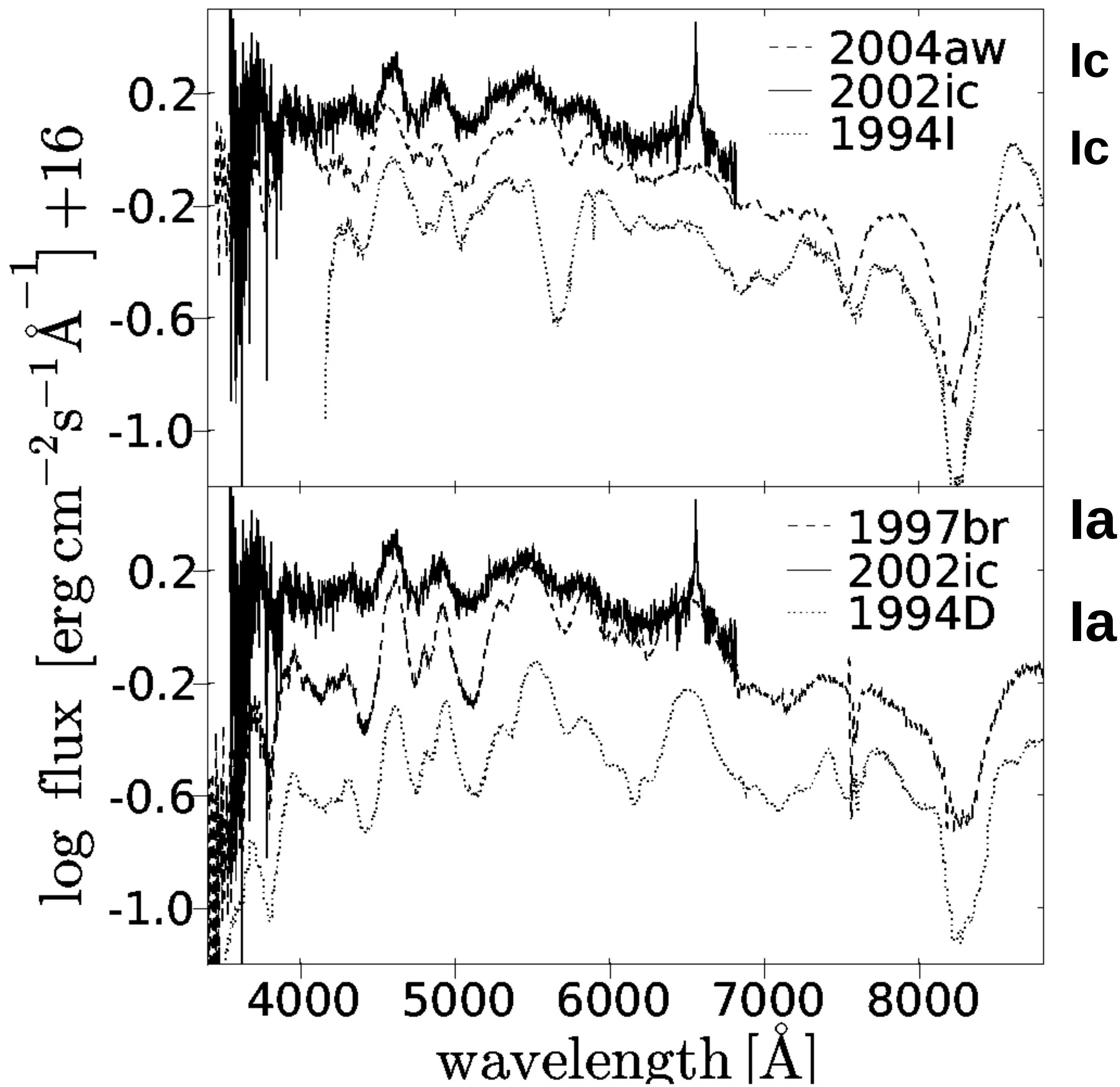
(Benetti
et al.
2006)



(t ~ 1 month)

Figure 3

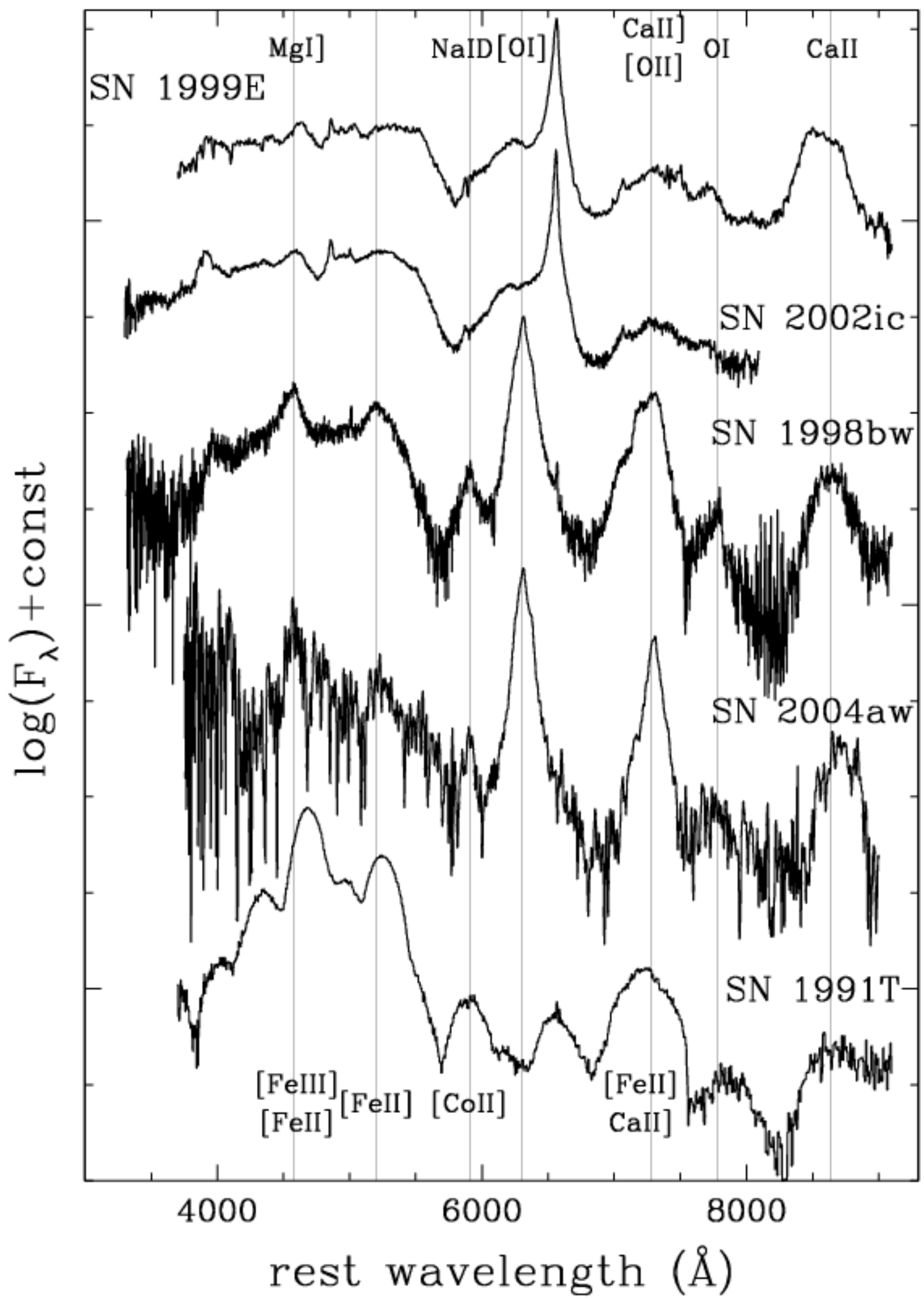
(Benetti et al. 2006)



t ~ 240 d

Figure 4

(Benetti et al. 2006)



“SNe IIa” -- NOT!?

- **Benetti et al. (2007, in prep.) have similar arguments for SN 2005gj.**
- **I think the odds are *higher* than 50/50 that these are core-collapse SNe whose ejecta are interacting with CSM. “SN Ia bandwagon”; should seriously consider alternatives!**
- **(See Soderberg talk on Friday.)**

Single Degenerates: Summary

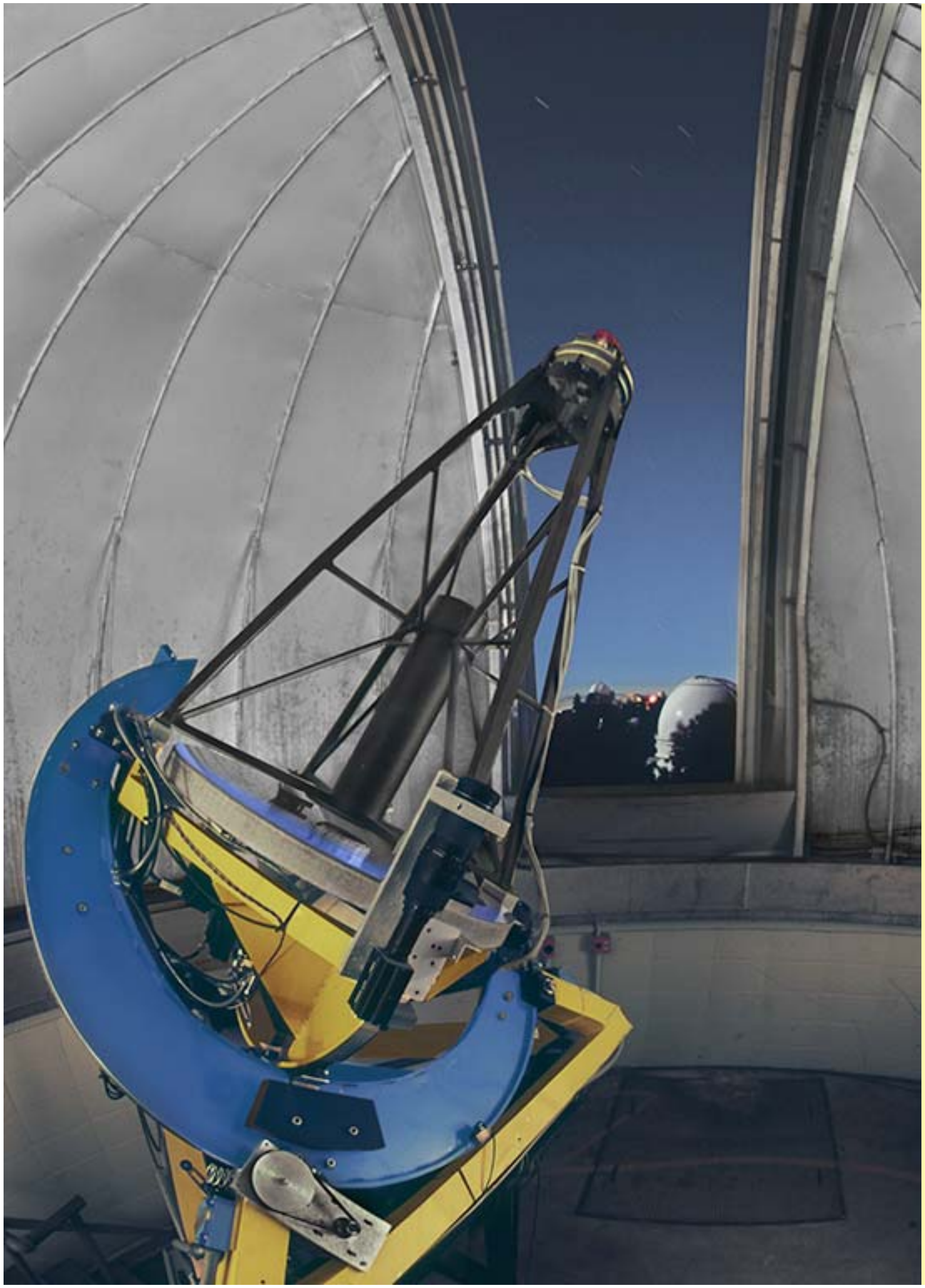
- **Several possible paths (super soft sources, etc.); could produce some or many SNe Ia (see Parthasarathy et al. 2007).**
- **But not enough SSSs (di Stefano talk), and not clear there are enough other candidates if require M(Chandra).**
- **If M < M(Chandra), looks more promising… but theorists don't like them.**
- **MISSING H! Big problem, in my opinion.**

(4) Double degenerates (DDs)?

- **The searches for binary WDs have been heroic (SPY: Napiwotzki talk); some interesting objects found.**
- **Small volume searched… not clearly inconsistent with existence.**
- **van den Heuvel talk: we certainly expect close double degenerates to exist; see binary neutron stars, for example.**

Two paths to SN Ia?

- Old stellar population (elliptical galaxies); long fuse.
- But also need a substantial population associated with relatively young stellar population. (Lots of SNe Ia in spiral galaxies.) [Go to Weidong Li’s talk on Friday.]



KAIT,

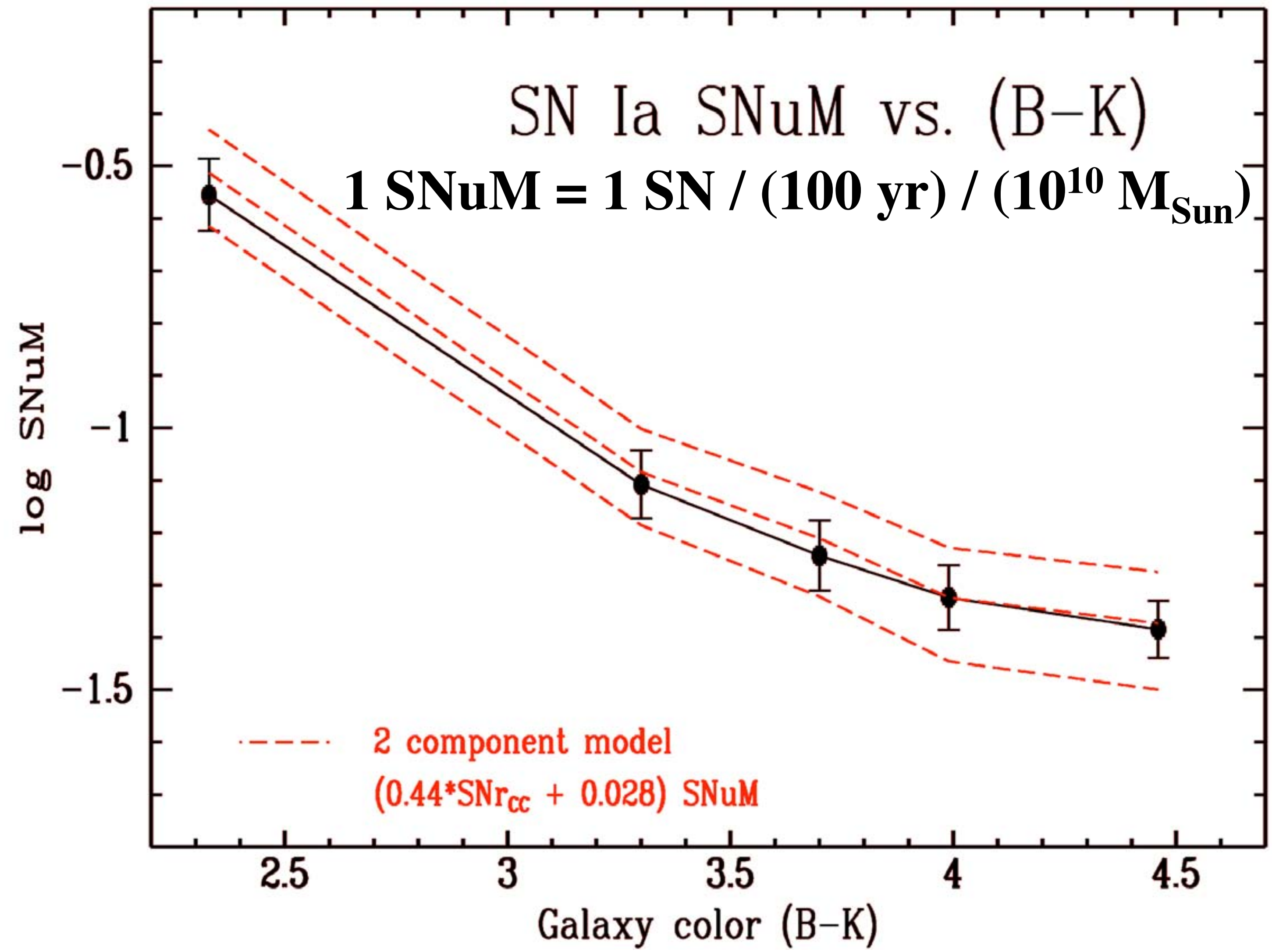
the Katzman Automatic Imaging Telescope; 0.76 m mirror.

Lick Observatory, near San Jose, CA

(AVF & Weidong Li)


Jesse
Leaman

SN Ia rate vs. galaxy color



SN Ia rate proportional to (1) SFR [prompt] and (2) galaxy mass [tardy] (confirms Mannucci et al. 2004, 2005, Scannapieco & Bildsten 2005, Niel et al. 2006, Sullivan et al. 2006)

(5) Diversity of SNe Ia, and correlations with environments

Families of Unusual SNe Ia

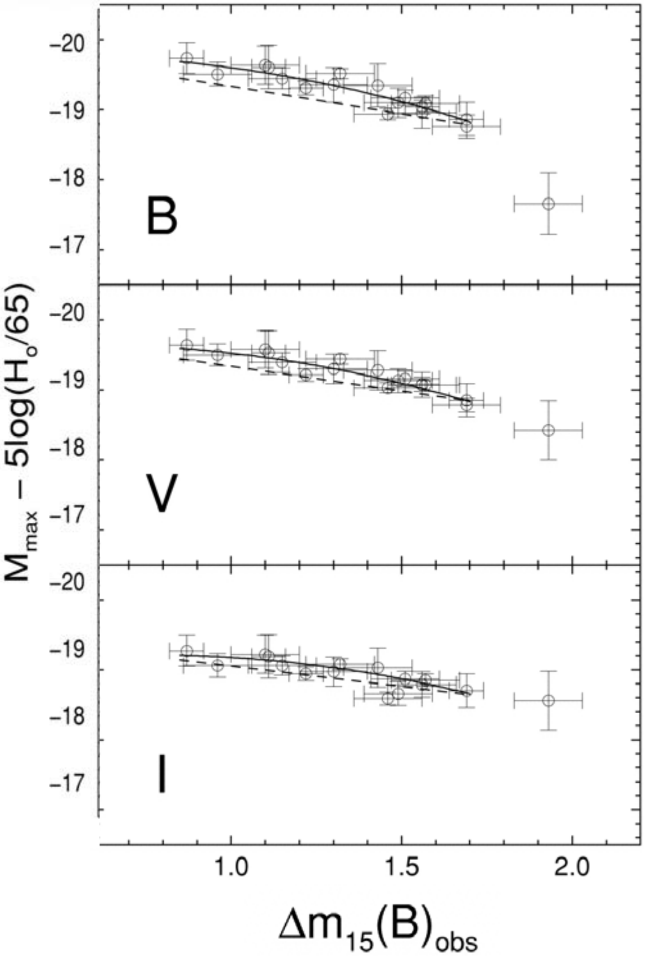
SN 1991T-like

- Luminous
- Slow decline
- Blue
- "Hot" spectra
- Late-type host galaxies

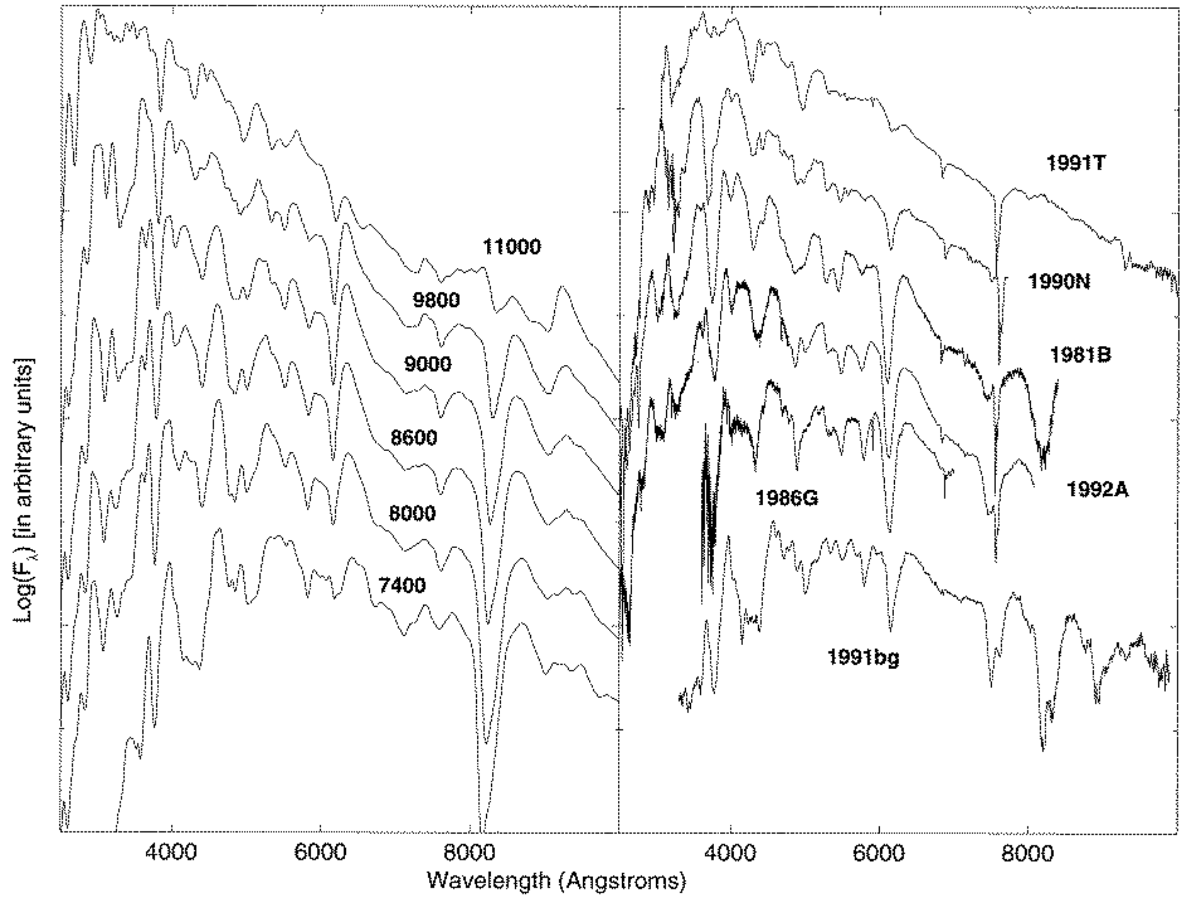
SN 1991bg-like

- Faint
- Fast decline
- Red
- "Cool" spectra
- Early-type host galaxies

Why are they found in different environments (young vs. old stellar populations)? How do the progenitors differ, if understand these SNe Ia as part of a well-defined sequence? [Density at the time of ignition (P. Lesaffre)? More massive progenitors (super-Ch?) in younger pops? Metallicity? Rotation?]



(Phillips et al. 1999)



(Nugent et al. 1995)

- **Light-curve shape correlates with luminosity (Phillips 1993, etc.)**
- **Photometric and spectroscopic variation are correlated**
- **Temperature sequence driven by ^{56}Ni production (Nugent et al. 1995, etc.)**

Families of Unusual SNe Ia

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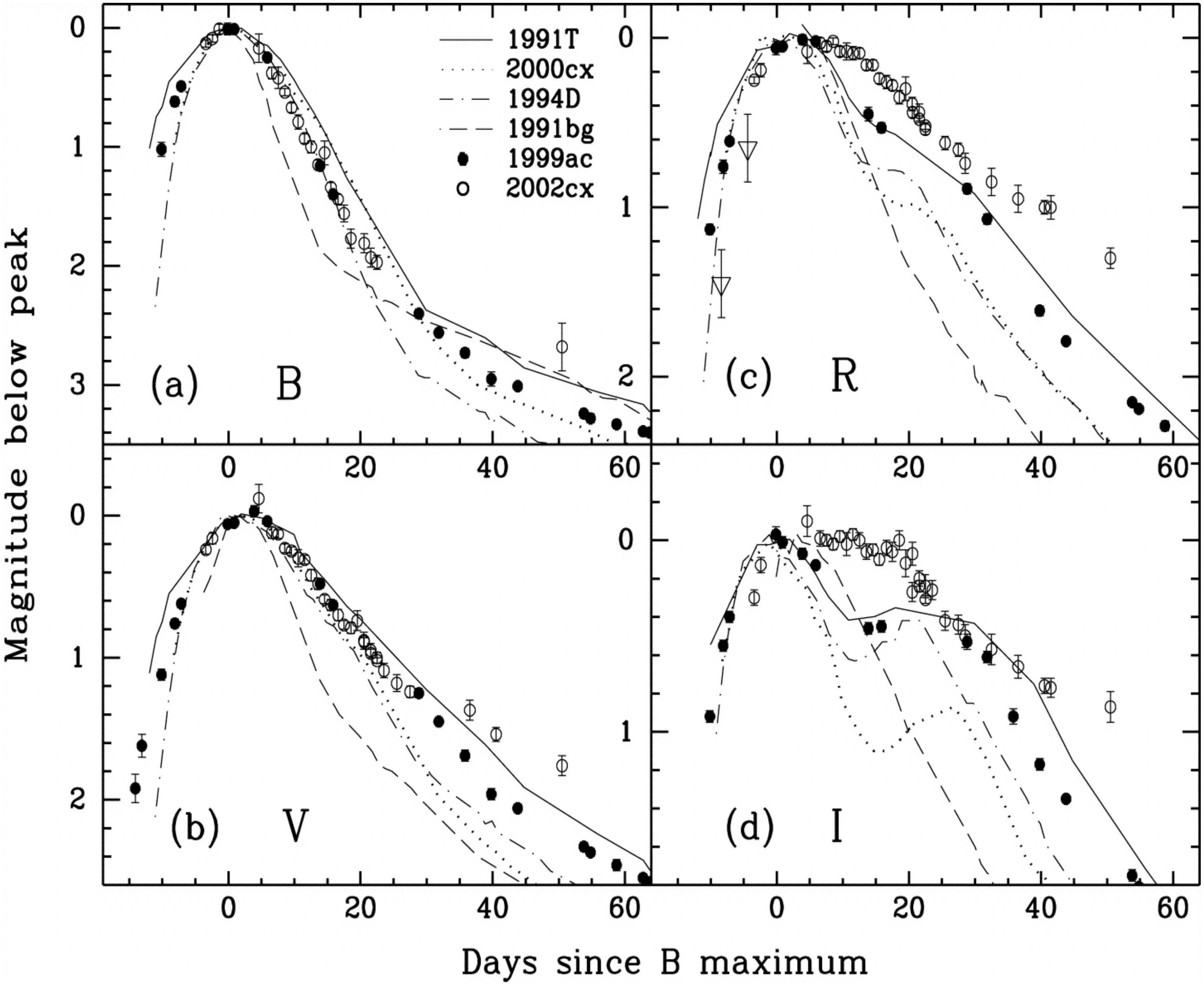
“Weirdos”

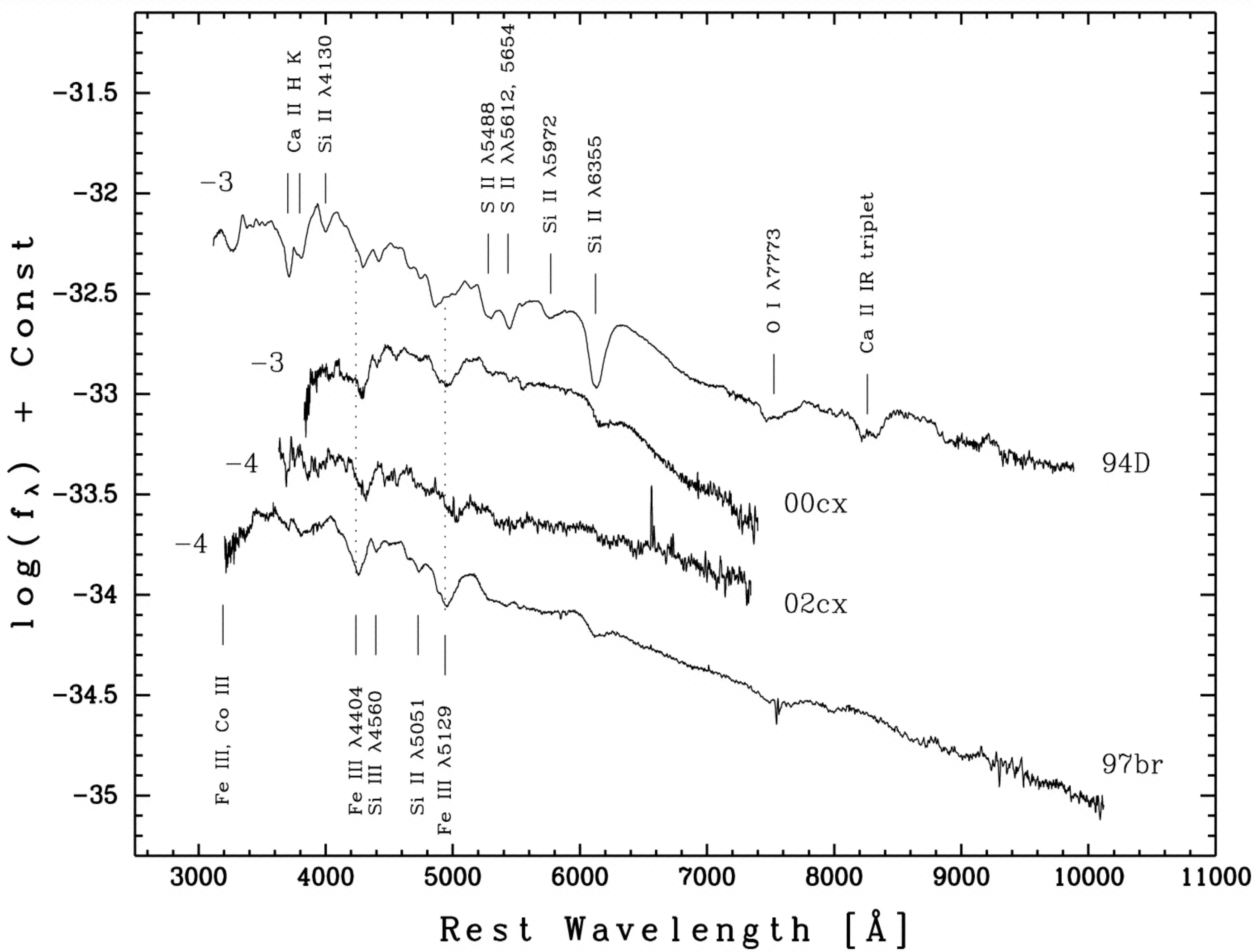
- SN 2002cx broke all the rules!
- Now there are more of them: a distinct subclass.

SN 2002cx: The Most Peculiar SN Ia (Li + 2003)



$\Delta m_{15}(B)$ ~ 1.56 mag; underluminous by ~1.6 mag in *B*

But spectrum has Fe III lines, like in SN 1991T



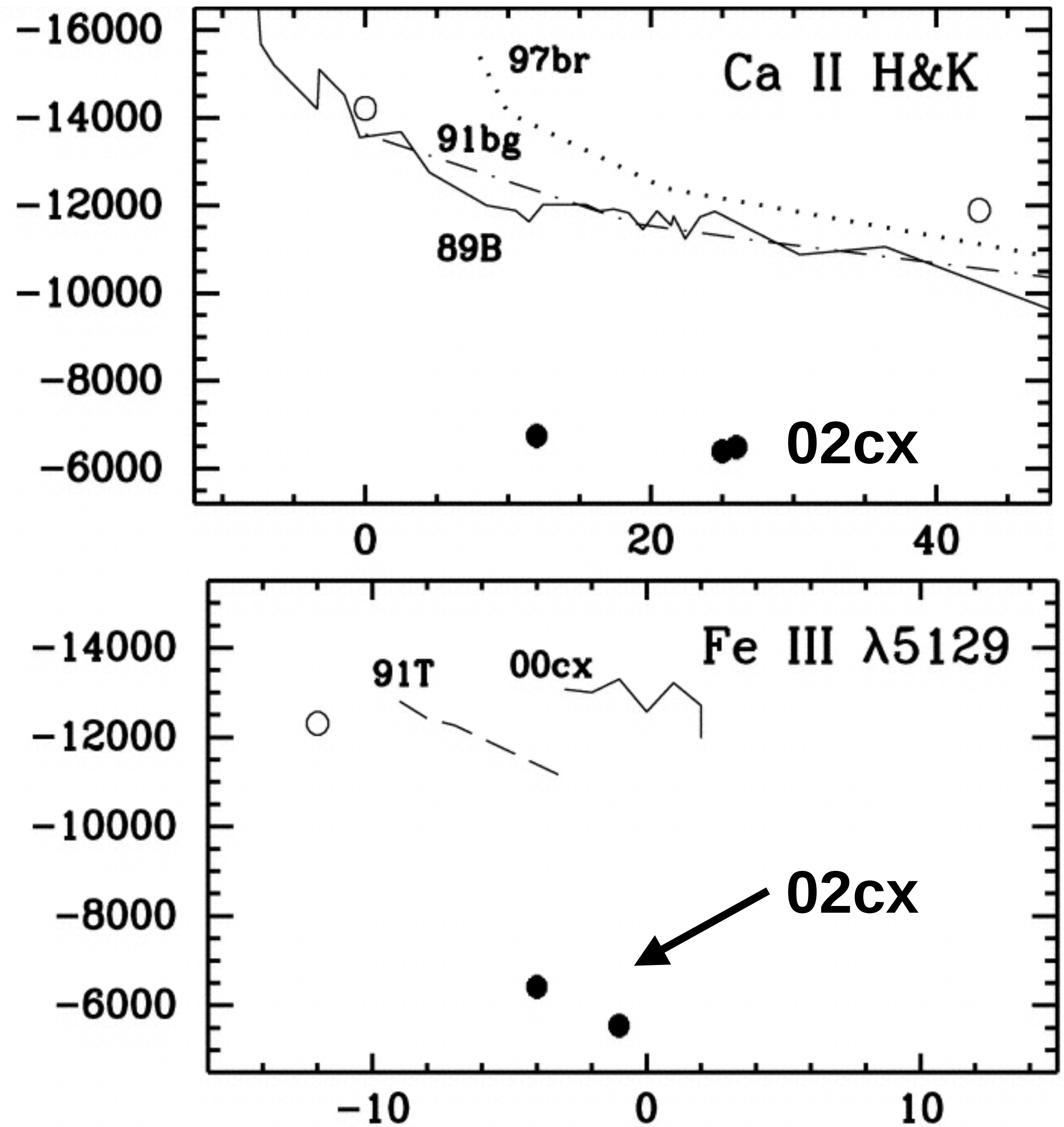
Very Low Expansion Velocities

v (km/s)

SN 2002cx had the lowest expansion velocities ever seen in a SN Ia.

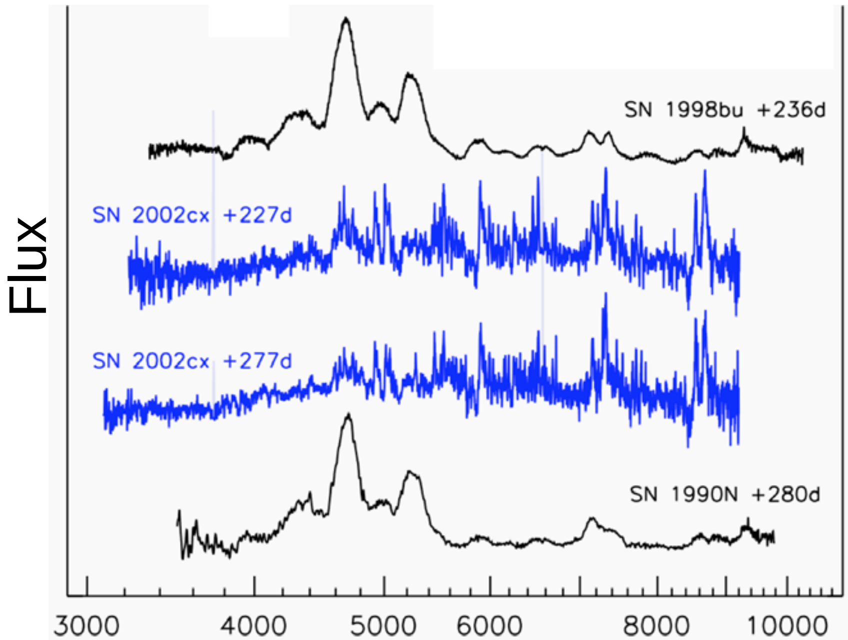
- **6000 km/sec (at max)**
- **2000 km/sec (day +56)**
- **700 km/sec (day +250)**

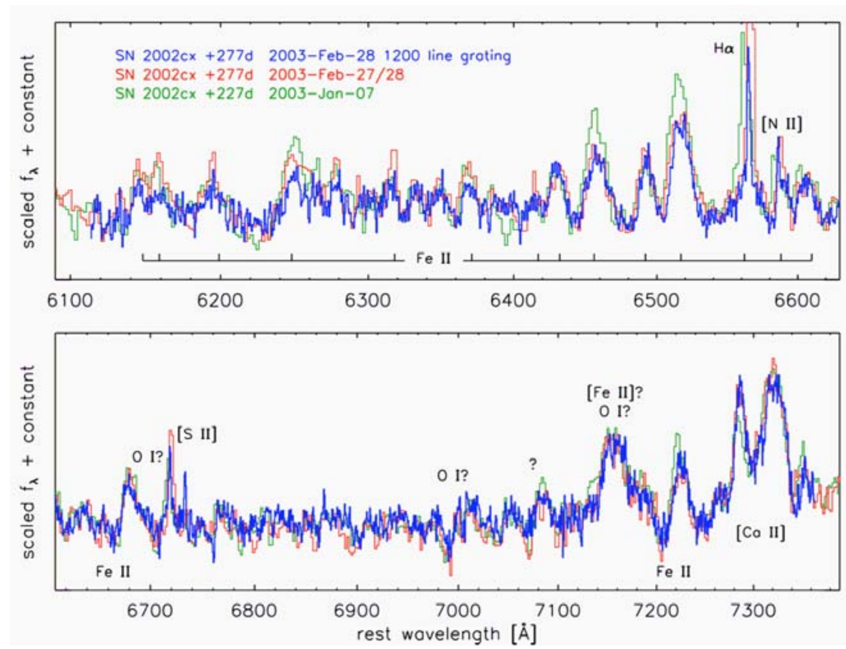
(Li + 03,
Branch + 04,
Jha + 06)



Days Relative to B maximum

Unusual at late times, too!



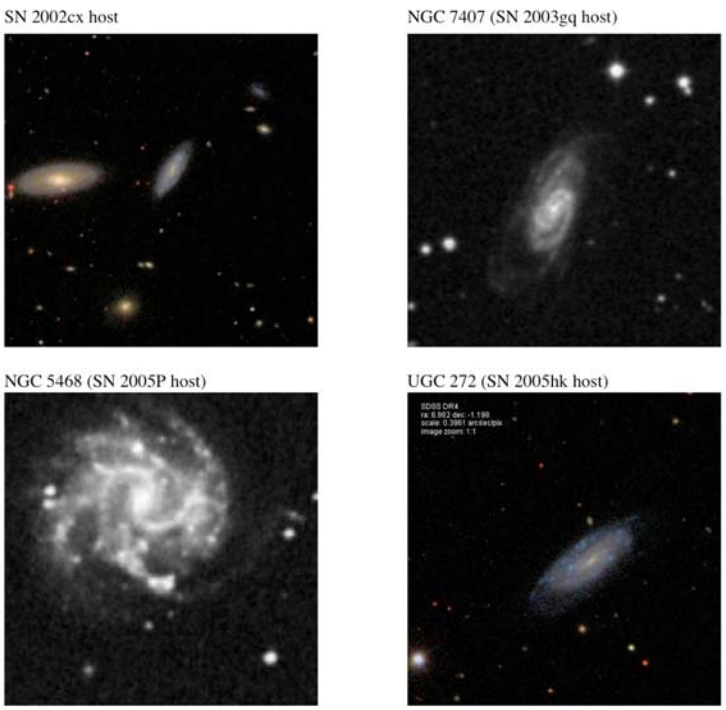


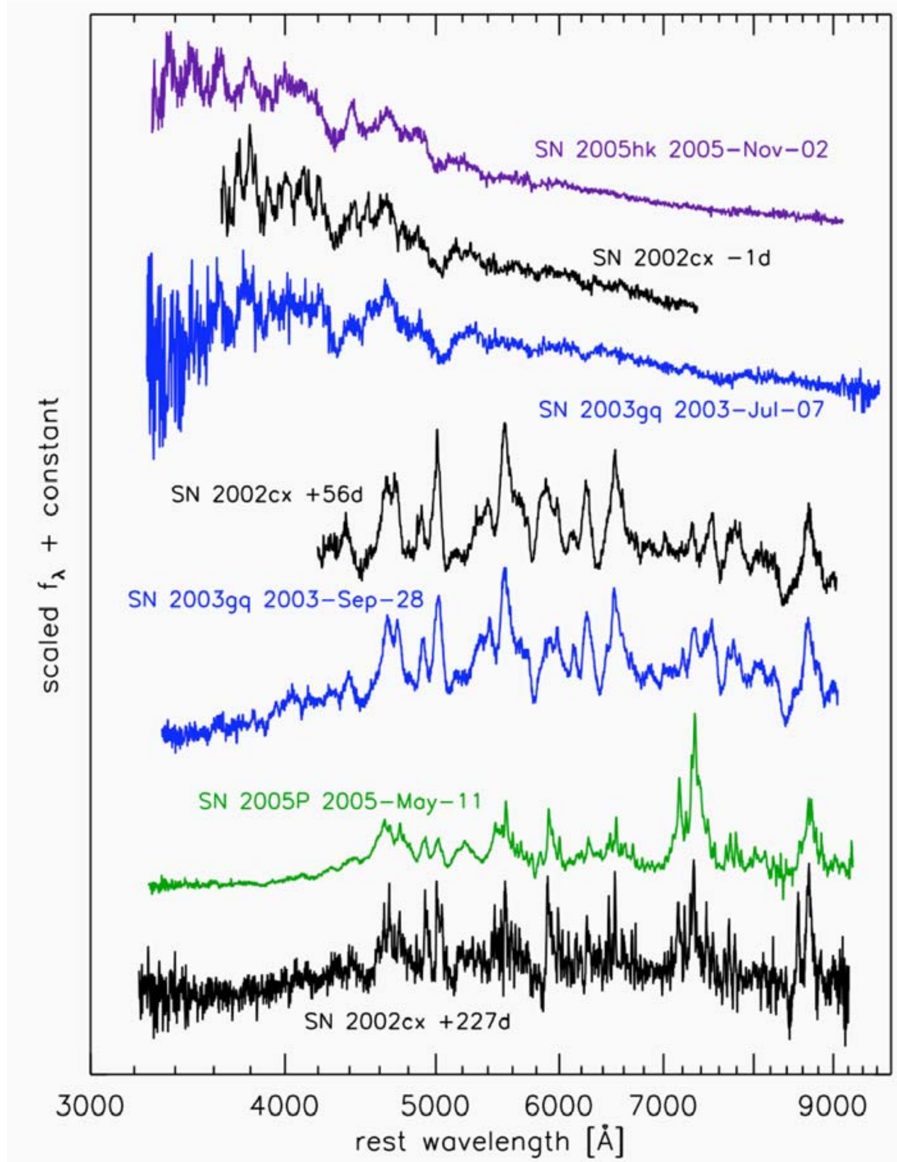
Jha et al. 2006 Wavelength

- **Spectra of SN 2002cx obtained at +227 and +277 days show *permitted* Fe II lines (and Ca II, Na I, maybe O I) with expansion velocities of ~700 km/sec. *High densities.***
- **Very slow late-time photometric decline (~3.5 mag below peak at day 277, versus 6 mag for a normal SN Ia)**

SN 2002cx is Not Unique

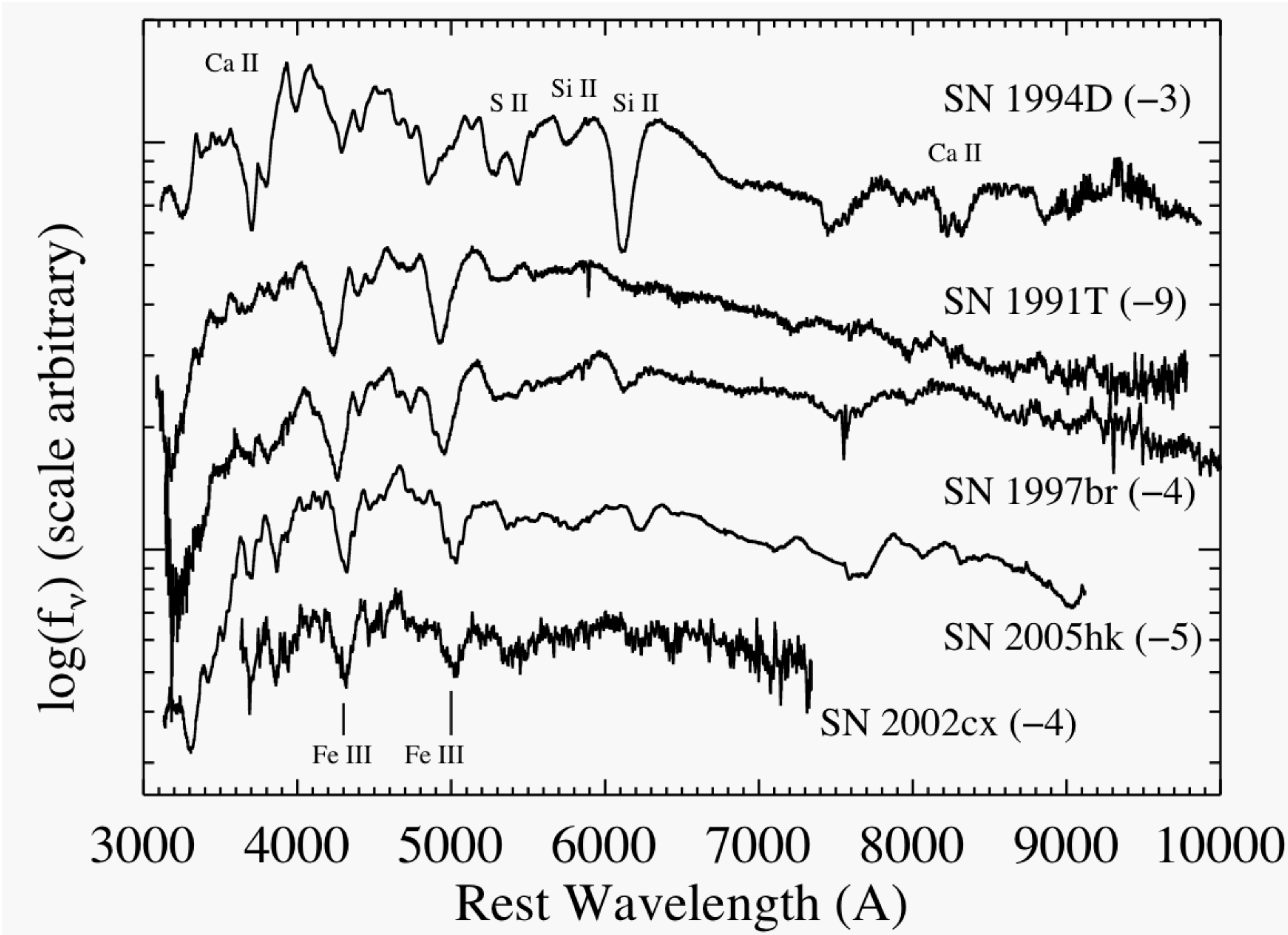
- **Spectroscopically similar Sne: 1991bj, 2003gq, 2005P, 2005cc, 2005hk**
- **So far all host galaxies are spirals**
- **About 5% of local SN Ia population (Phillips et al. 2007)**





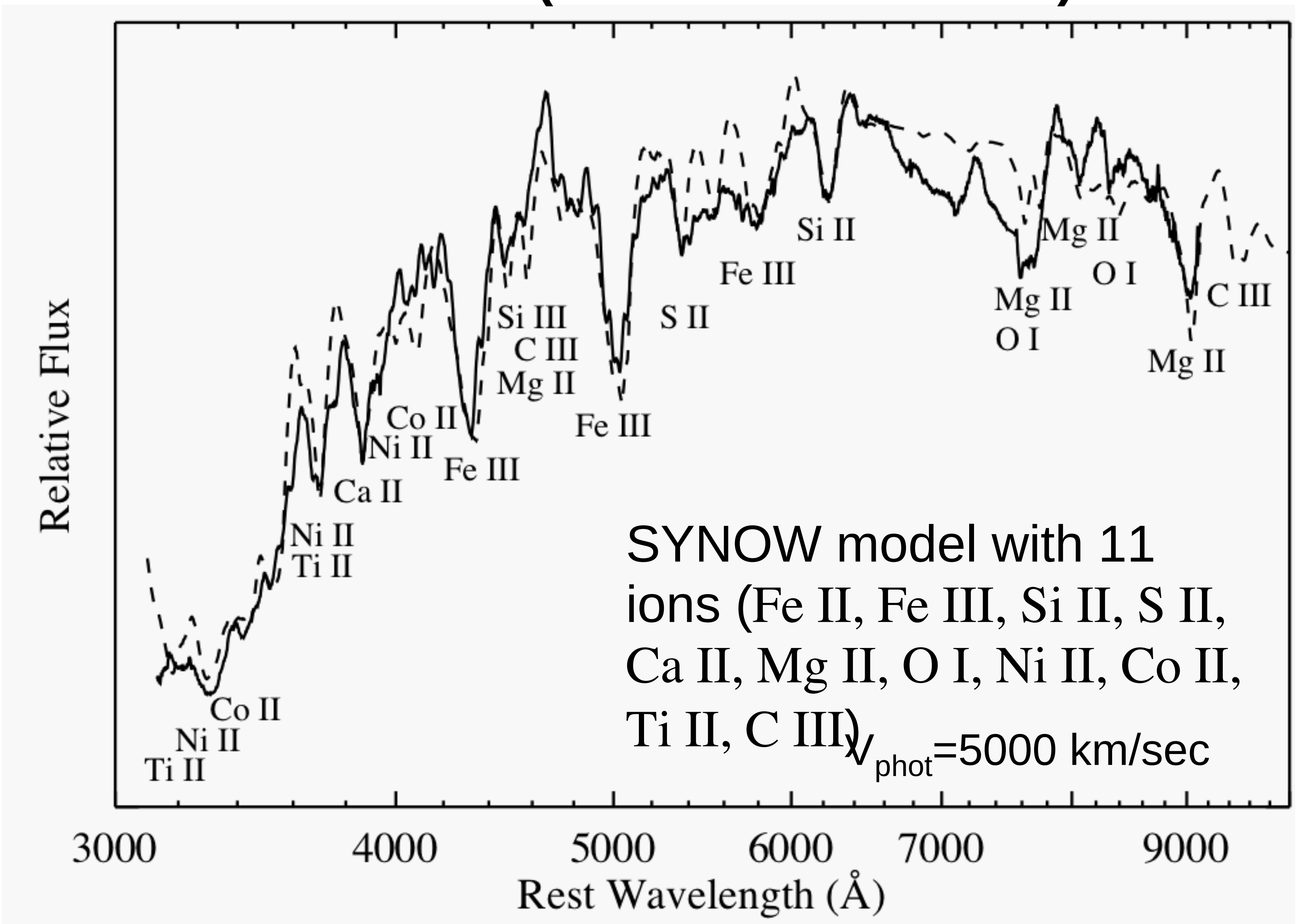
Jha et al. 2006

SN 2005hk - Twin of SN 2002cx



(See also Phillips talk; Stanishev et al. poster) **Chornock et al. 2006**

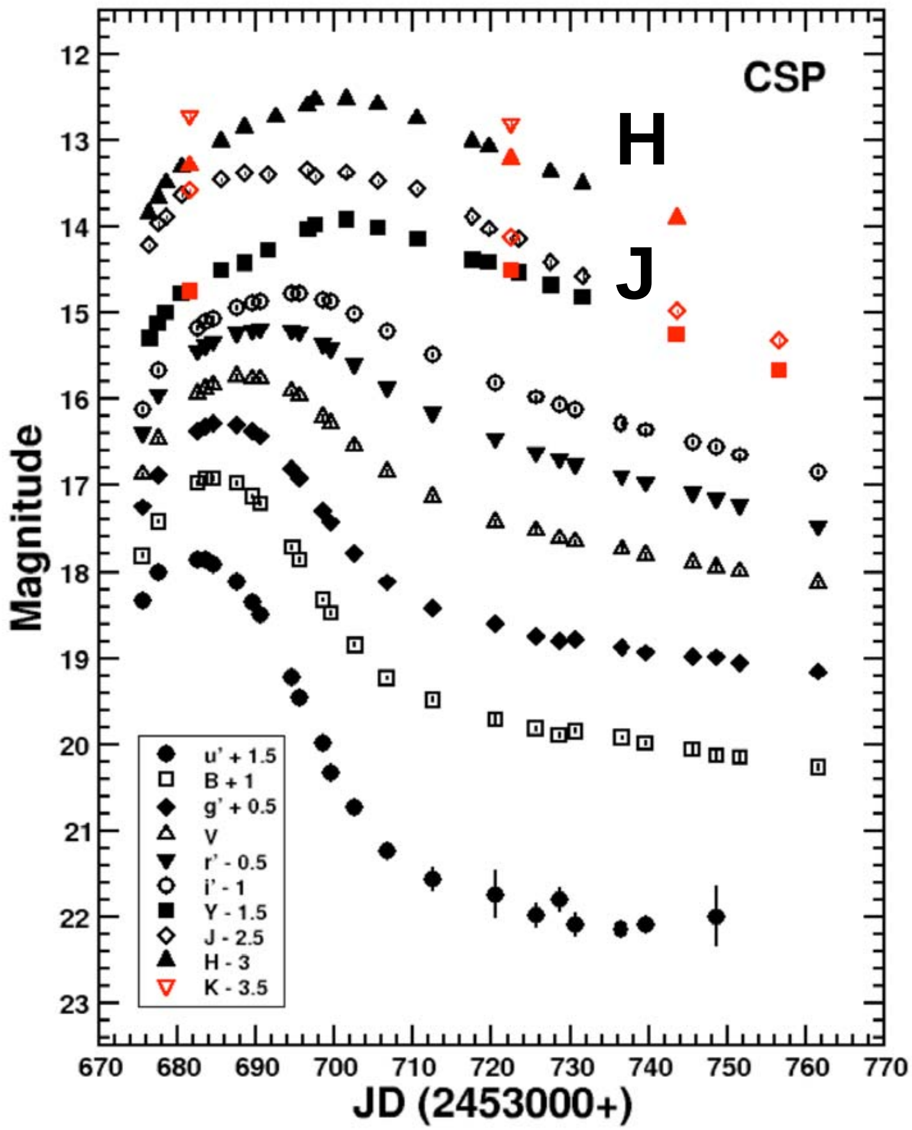
SN 2005hk (Chornock et al. 2006)



SYNOW model with 11 ions (Fe II, Fe III, Si II, S II, Ca II, Mg II, O I, Ni II, Co II, Ti II, C III)

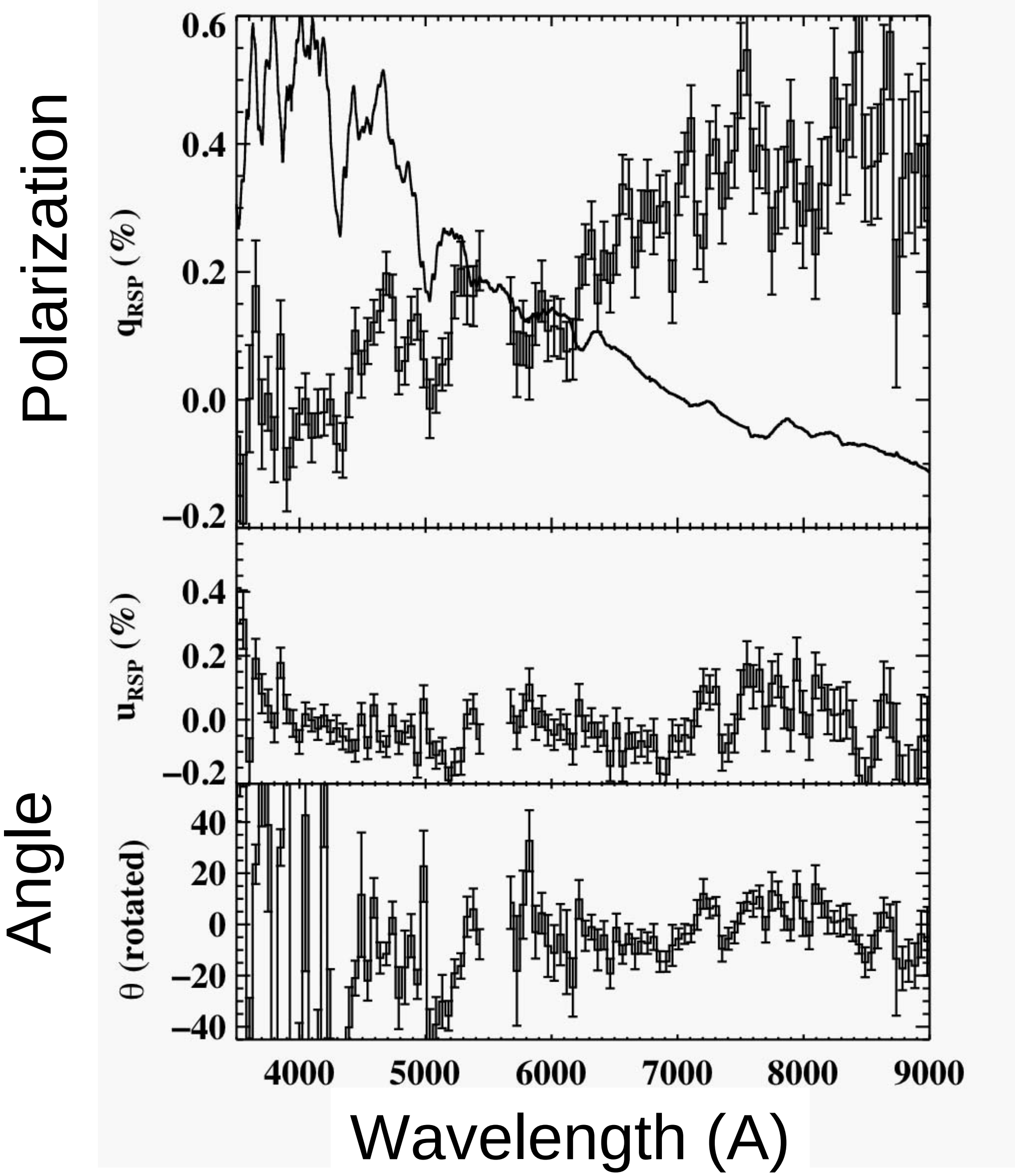
v_{phot}=5000 km/sec

CSP Observations of SN 2005hk (Phillips)



- No secondary maximum in IR.
- Strength of the secondary maximum correlated with the amount of mixing of ^{56}Ni in the ejecta (Kasen 2006).
- The absence of secondary maximum suggests complete mixing of

SN 2005hk Spectropolarimetry



- **Continuum polarization of 0.4% (normal for SNe Ia)**
- **Small (~0.2%) line feature at Fe III λ5129**
- **Models with strong asphericities are disfavored (e.g., Kasen et al. 2004)**

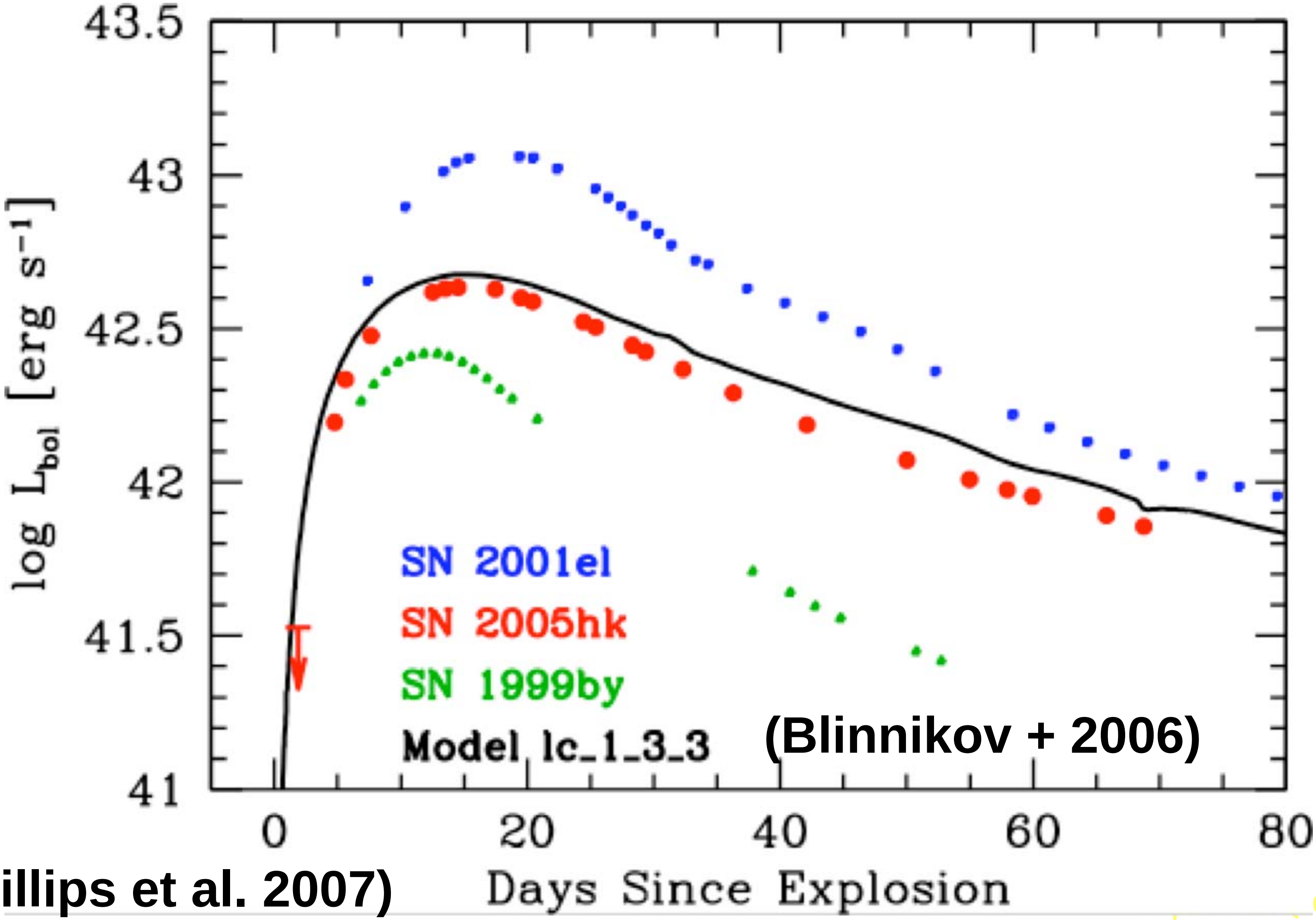
Chornock et al. 2006

So What Are They?

- **Dim, slow; well-mixed ejecta (lines of all species show roughly the same velocities; Na and Ca present at 600 km/s at late times; Ni mixed).**
- **Pure deflagrations??**
- **W. Hillebrandt: Rapidly spinning CO WDs (“mergers”) produce less Ni in the deflagration mode than non-rotating models; possibly the low-L SNe Ia.**

CSP Observations of SN 2005hk

A Pure Deflagration?



(Phillips et al. 2007)

Problems with deflagrations

- **Where is O hiding? Expect strong [O I] 6300 at late times (Kozma et al. 2005).**
- **Maybe hide [O I] because density high: [Ca II]/Ca II gives density ~ 10^9-10^{10} cm^{-3}, while [Fe II]/Fe II gives 10^8 cm^{-3} (above critical density of [O I]).**
- **But deflagration and DD models of SNe Ia give density 10^4-10^5 at this time. Why are 02cx-like objects so dense for a long time?**

Alternatives

- **Take note: all in spiral galaxies, near HII regions (but small numbers…)**
- **Perhaps deflagration of a CO layer on top of an ONeMg WD? (But gamma-rays not trapped enough…)**
- **Maybe new kind of core-collapse SN: but (a) why is [O I] 6300 absent at late times; (b) why are velocities low, instead of very high as in SNe Ic, especially if O layer stripped; and (c) why is polarization low?**

Conclusion

- **I don't have much observational confidence that we know the nature of the progenitors, the details of the explosion mechanisms, the reasons for an environmental dependence, the origin of very weird SNe Ia, and many other aspects of SNe Ia.**
- **There is MUCH work to be done!**