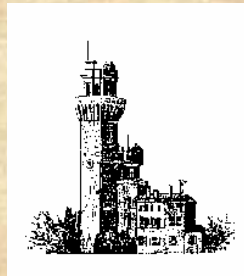


Interacting SNIa

Massimo Turatto



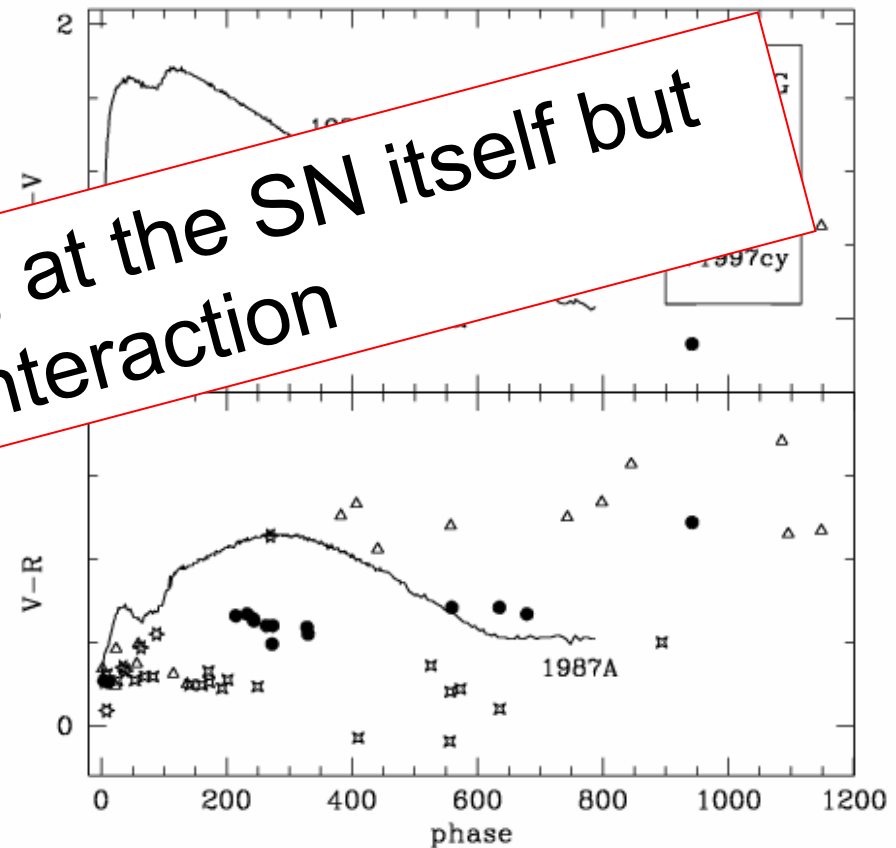
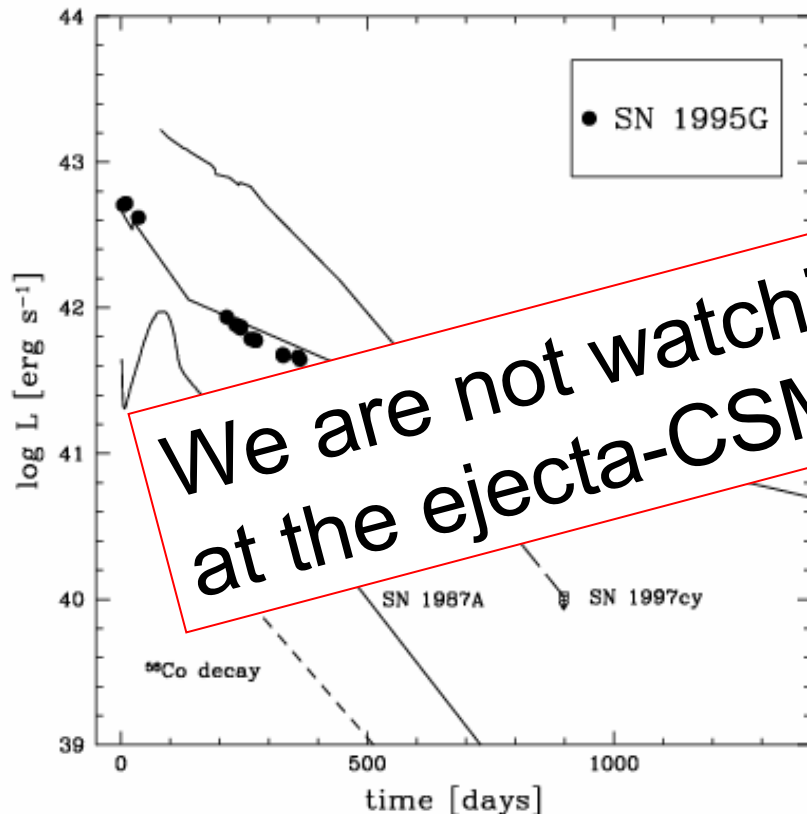
KITP - 2007

Strongly CSM interacting SNe

- CC-SNe
- Additional source of energy ($\gg E_r(\text{SN})$)
- Evolution depends on E_{exp} , M_{CSM} , ρ_{CSM} , ..
→ preSN history
- Resulting spectrum completely reshaped
→ SNIIn

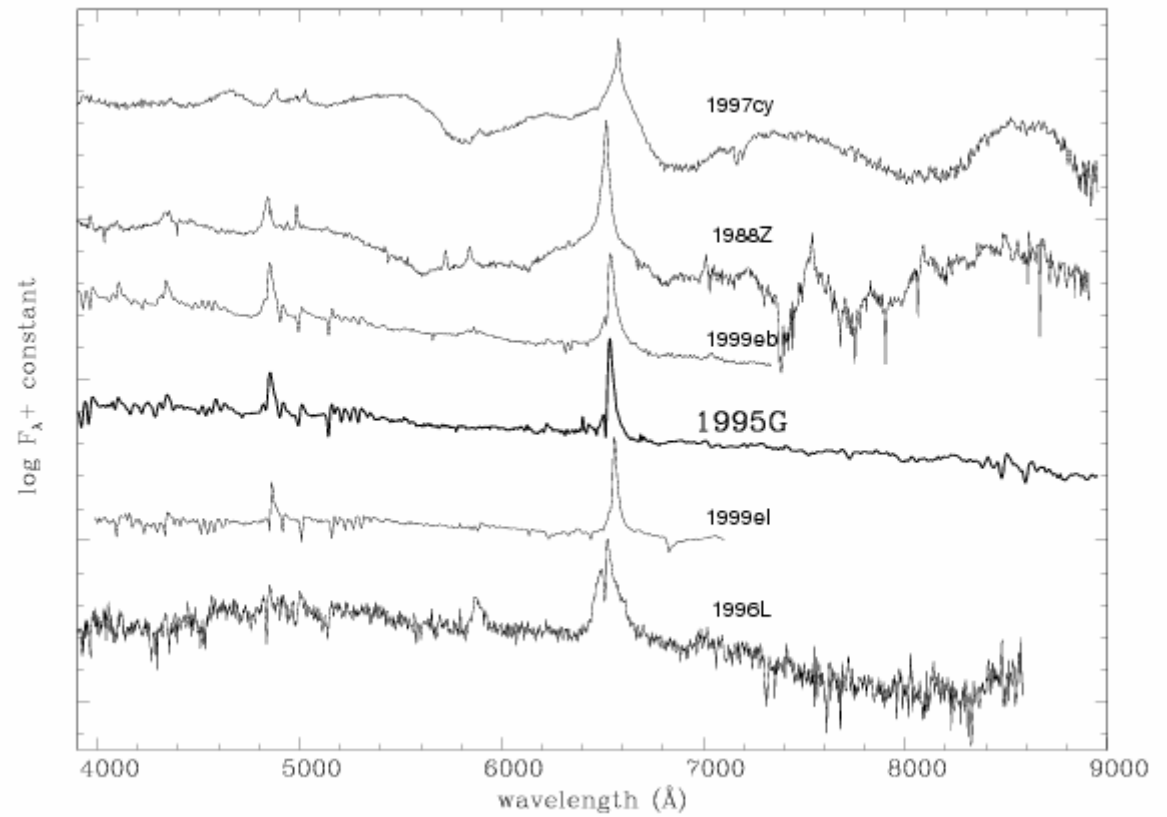
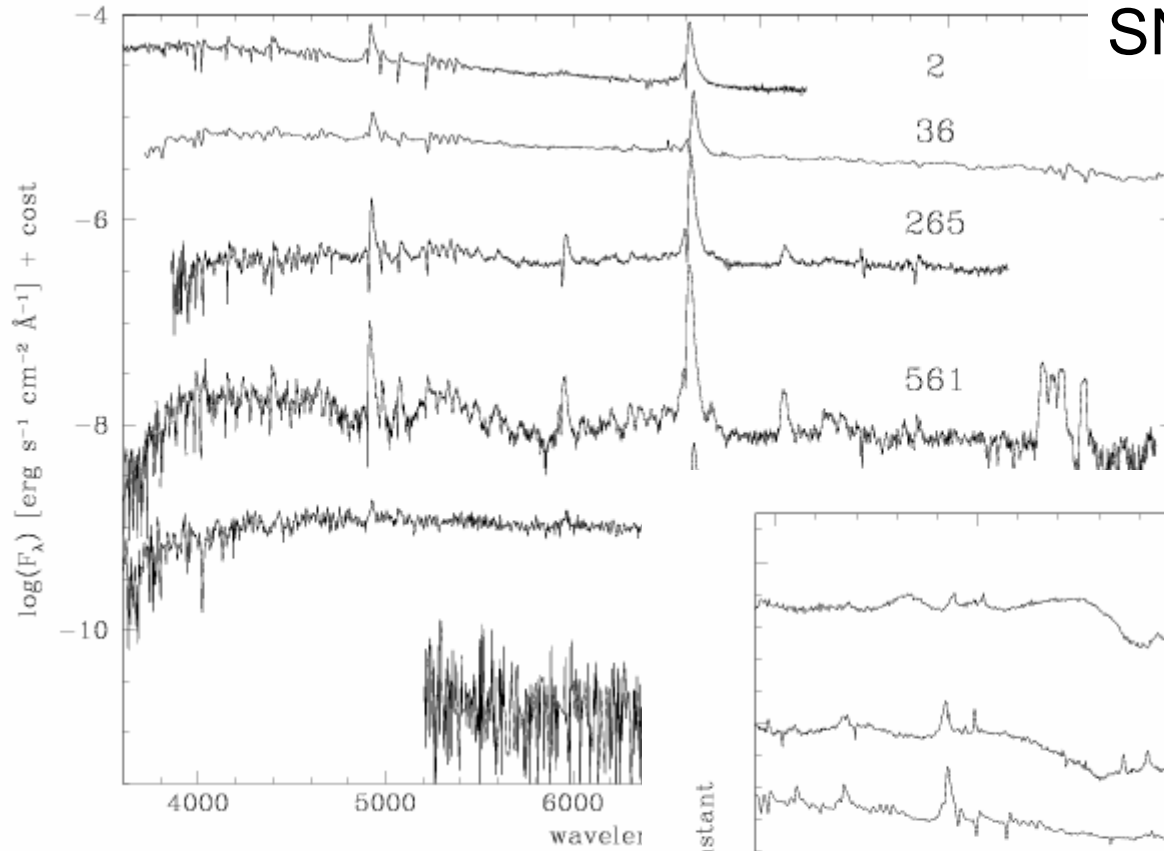
general characteristics of strongly CSM-interacting SNe:

- Slow evolution (i.c. \rightarrow not governed by radioactive decays)
- Strong radio and X-ray
- Balmer lines with multiple components \rightarrow complex kinematics
- High ionization lines \rightarrow shocks



We are not watching at the SN itself but at the ejecta-CSM interaction

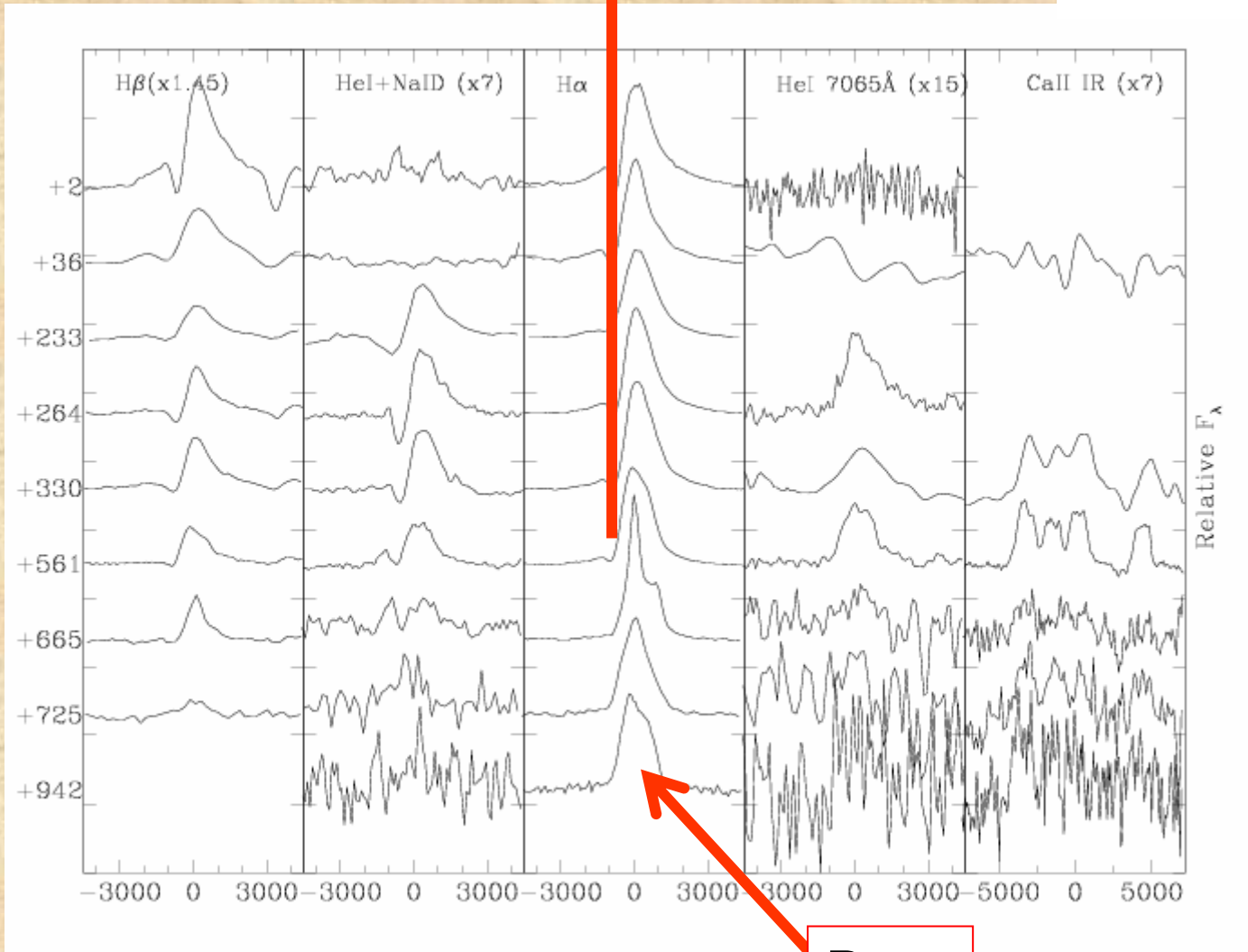
SN 1995G



Constant λ

→ No receding photosphere

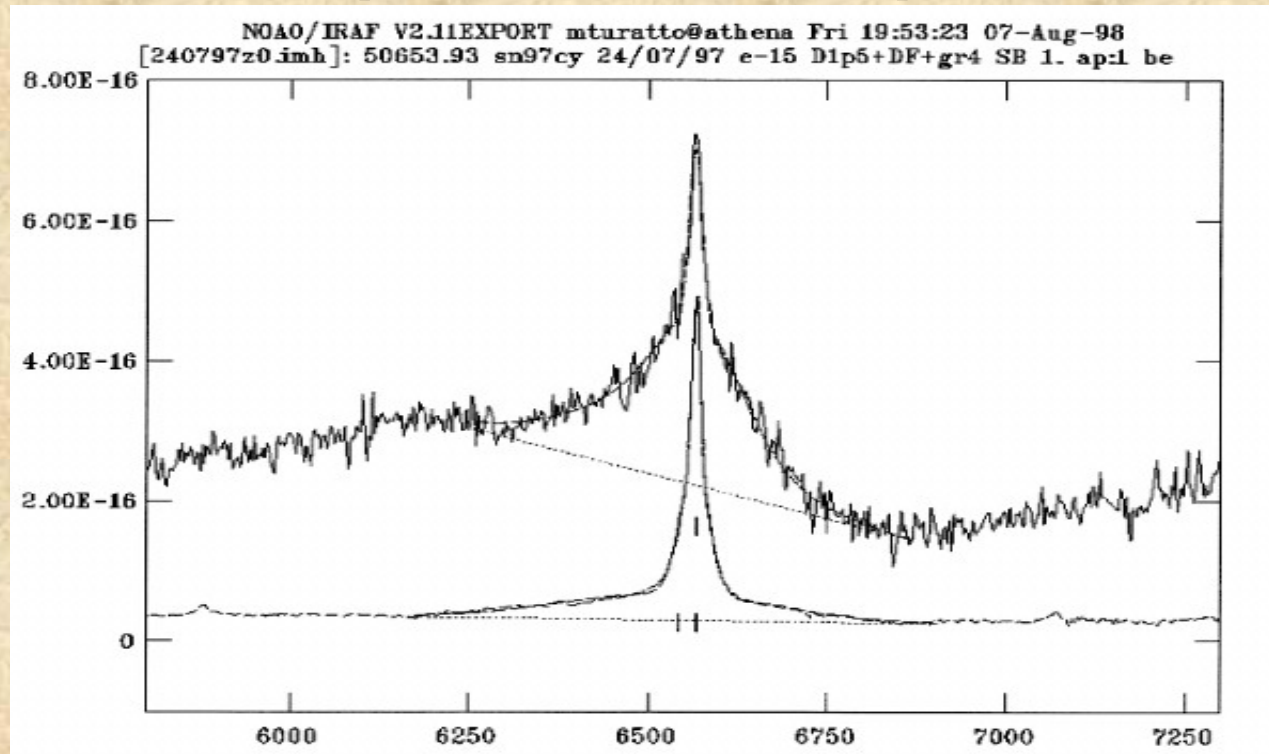
SN 1995G



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Boxy

composite H α profiles

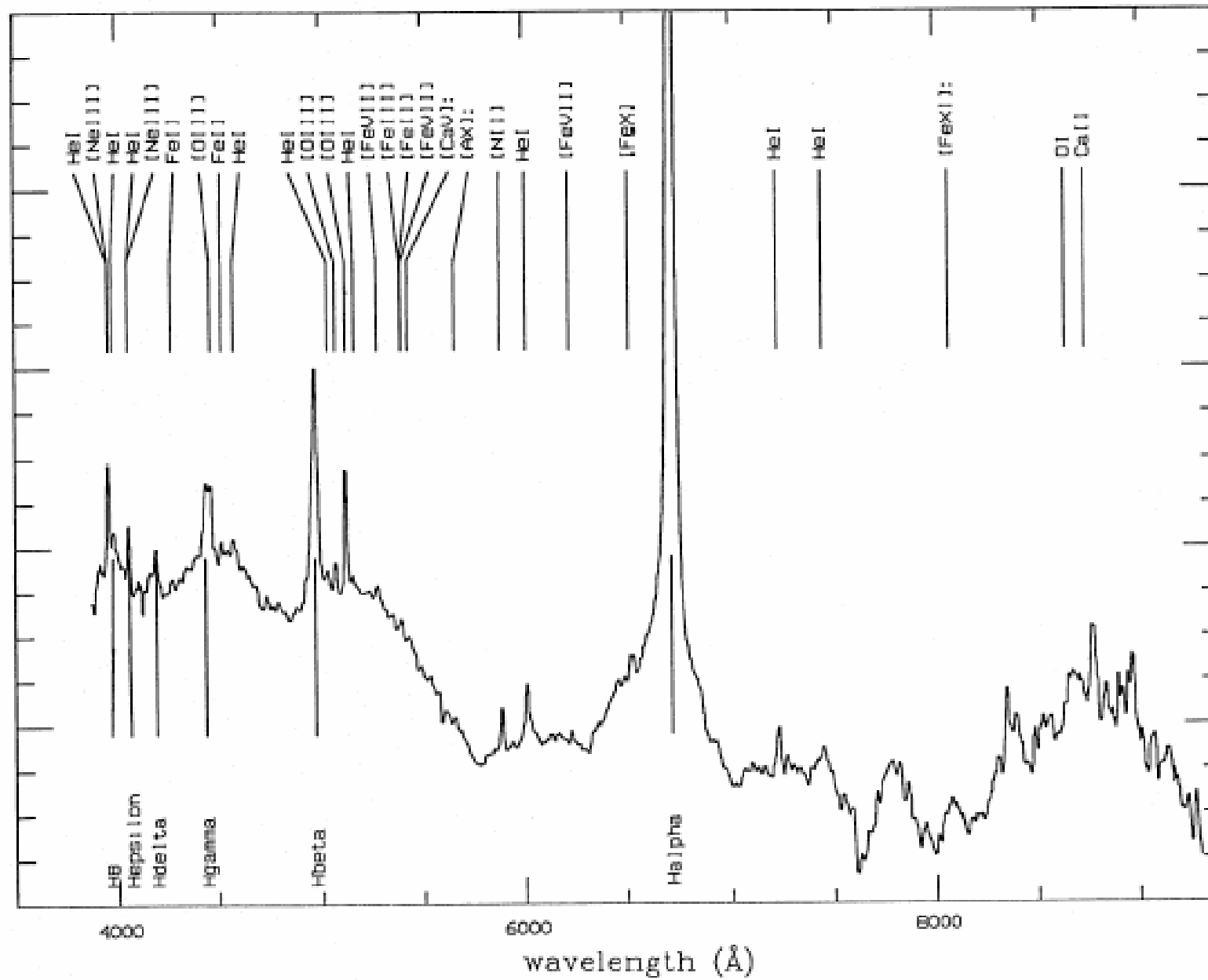


SN 1997cy

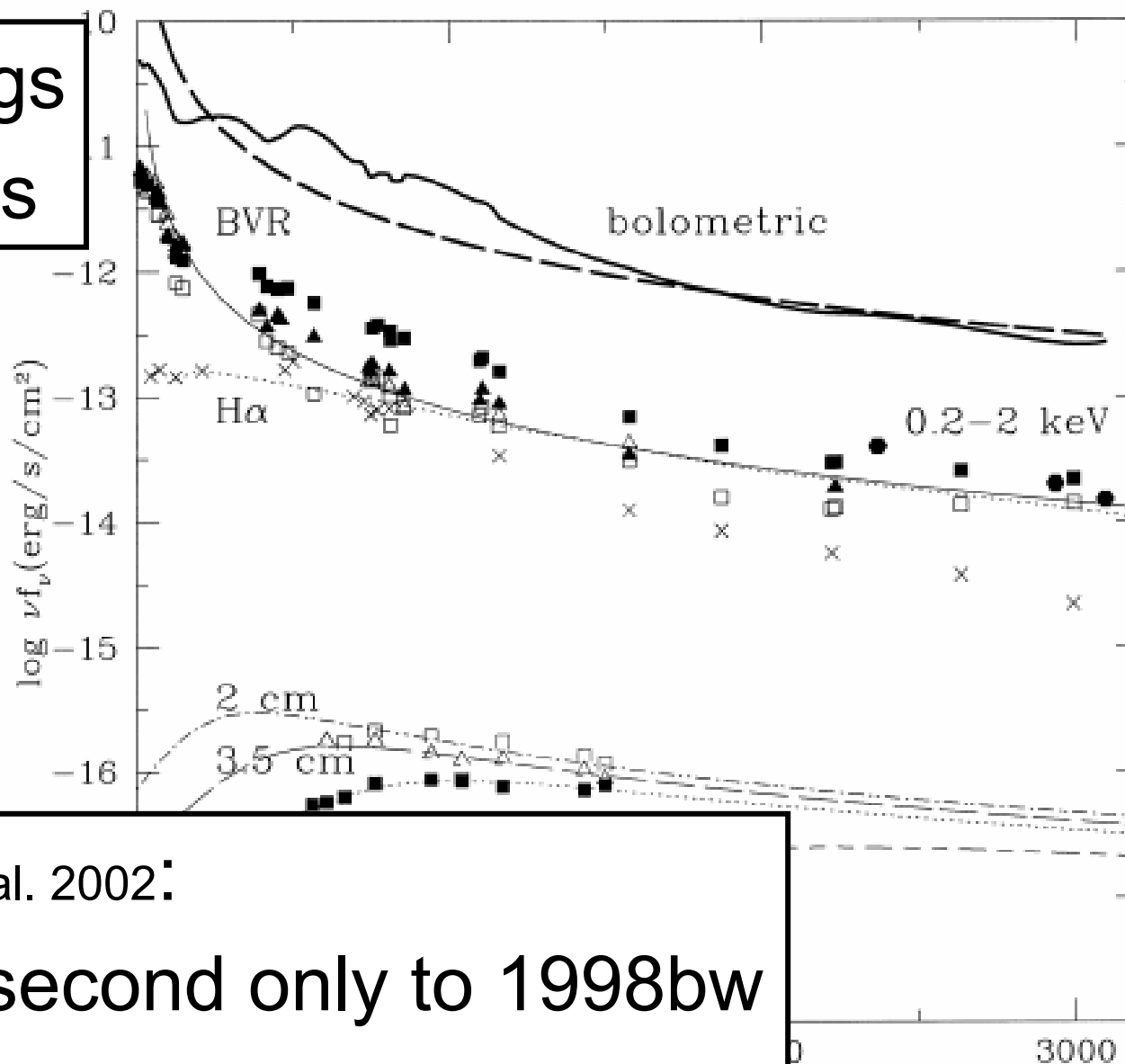
FWHM (km/s)	12800	4300	800
Flux (erg s ⁻¹ cm ⁻²)	4.6×10^{-14}	1.4×10^{-14}	4.4×10^{-15}

SN 1988Z

FWHM (km/s)	15000	2200	<700
Flux (erg s ⁻¹ cm ⁻²)	4.6×10^{-14}	1.4×10^{-14}	4.4×10^{-15}



$E_{\text{rad}} > 2 \times 10^{51}$ ergs
 $\sim 10^{52}$ ergs



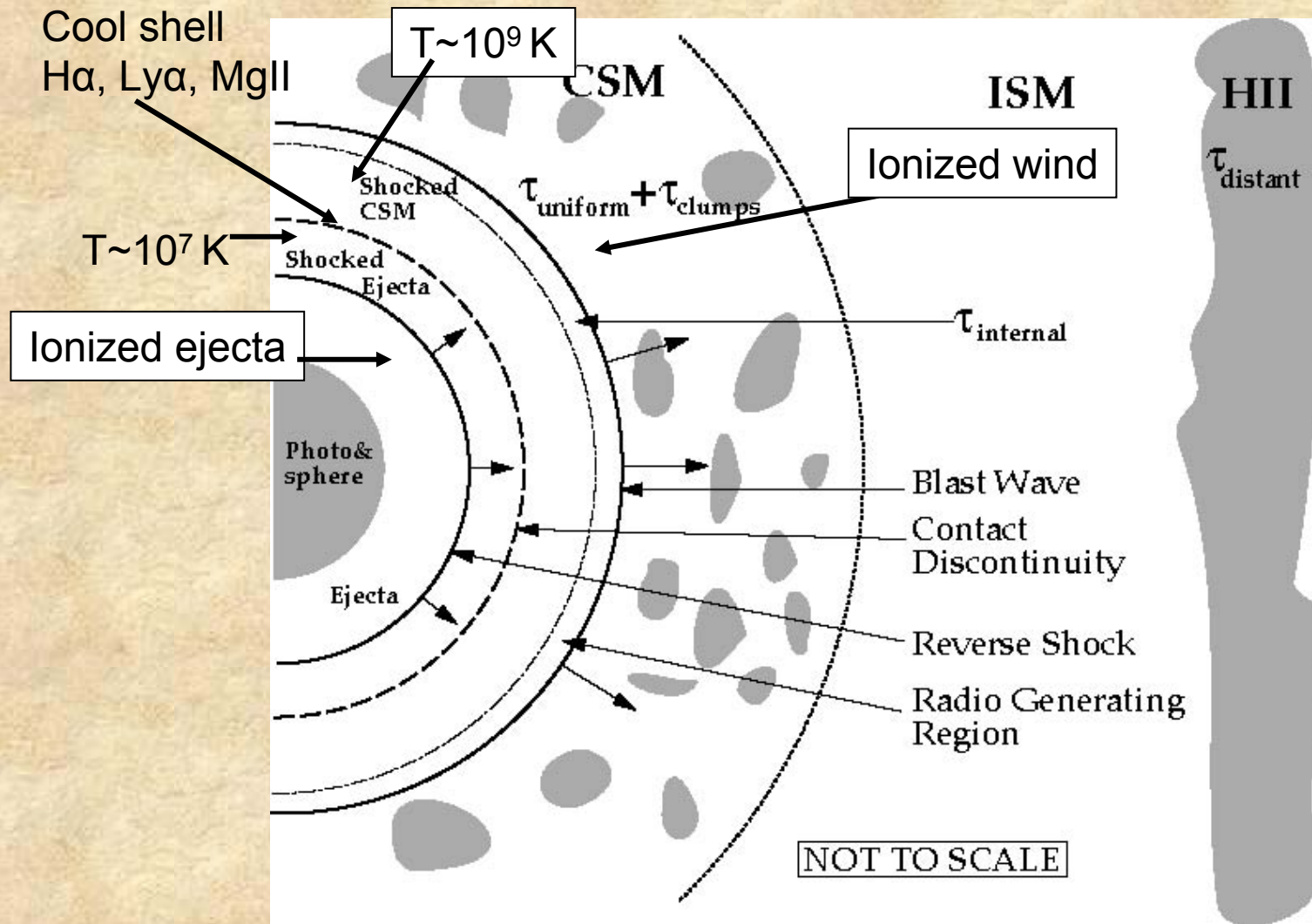
Radio Williams et al. 2002:

Bright RSN is second only to 1998bw
 Filamentary CSM

$M_{\text{dot}} = 10^{-4} M_{\odot}/\text{yr} \rightarrow M = 20-30 M_{\odot}$

Aretxaga et al. 1999

SN-CSM Interaction

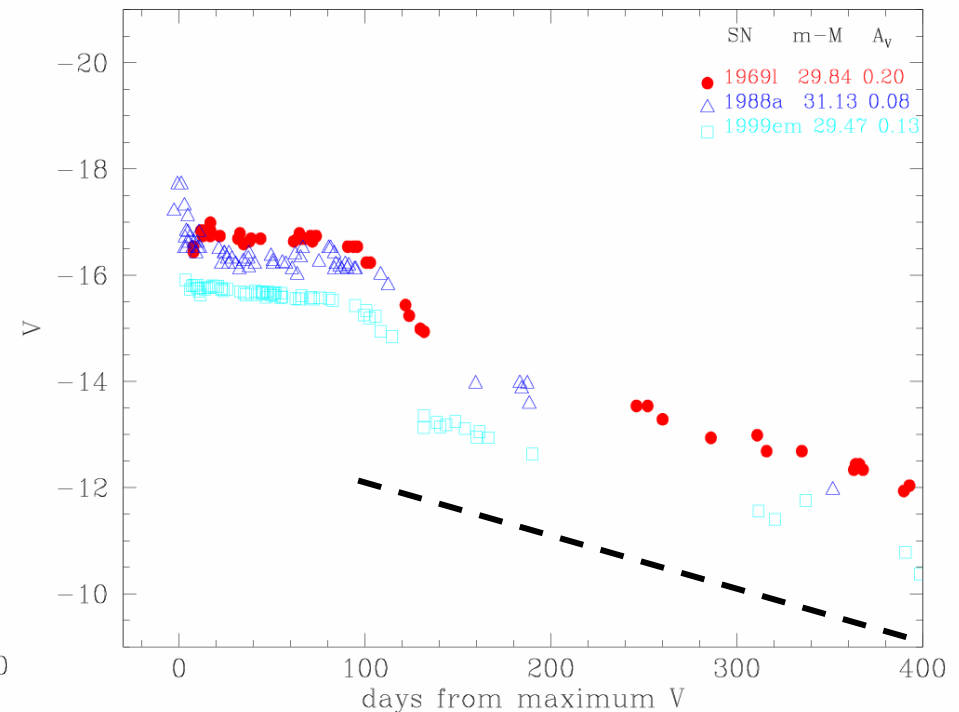
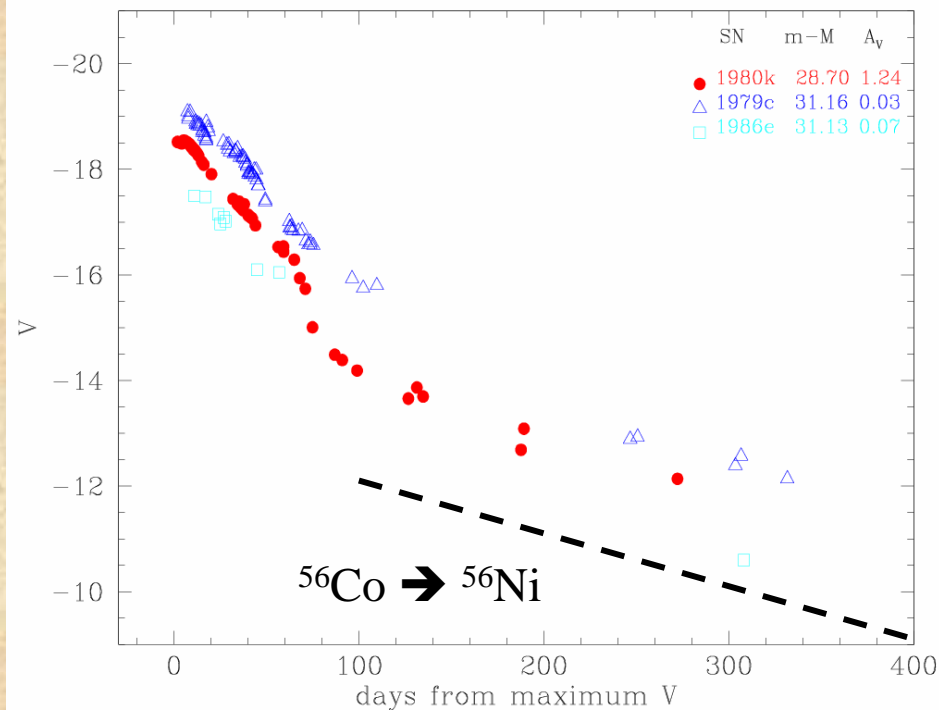


Chevalier & Fransson 1994 +
Terlevich et al. 1992 +
Chugai 1994 +

KITP 2007

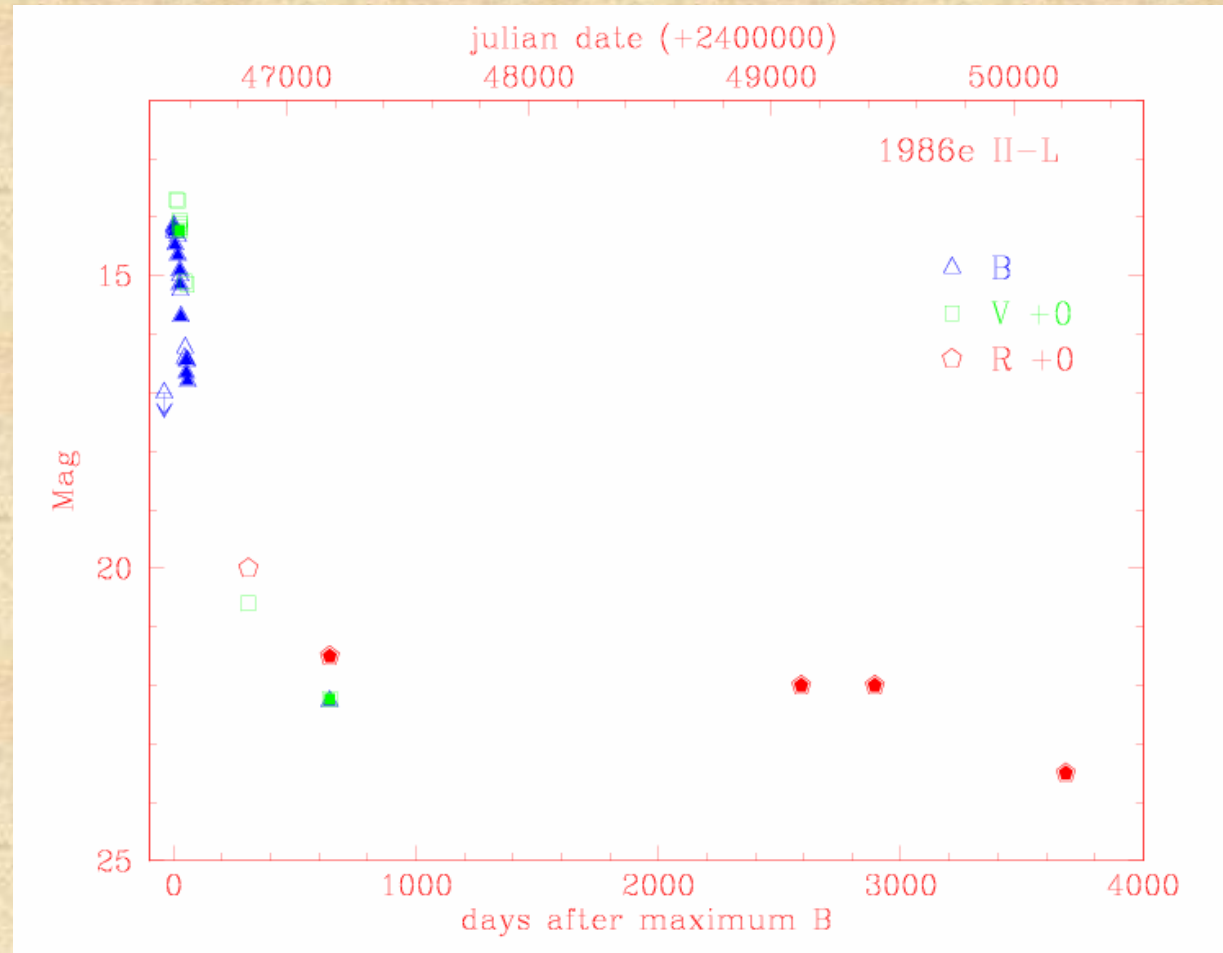
SNIIP & IIL

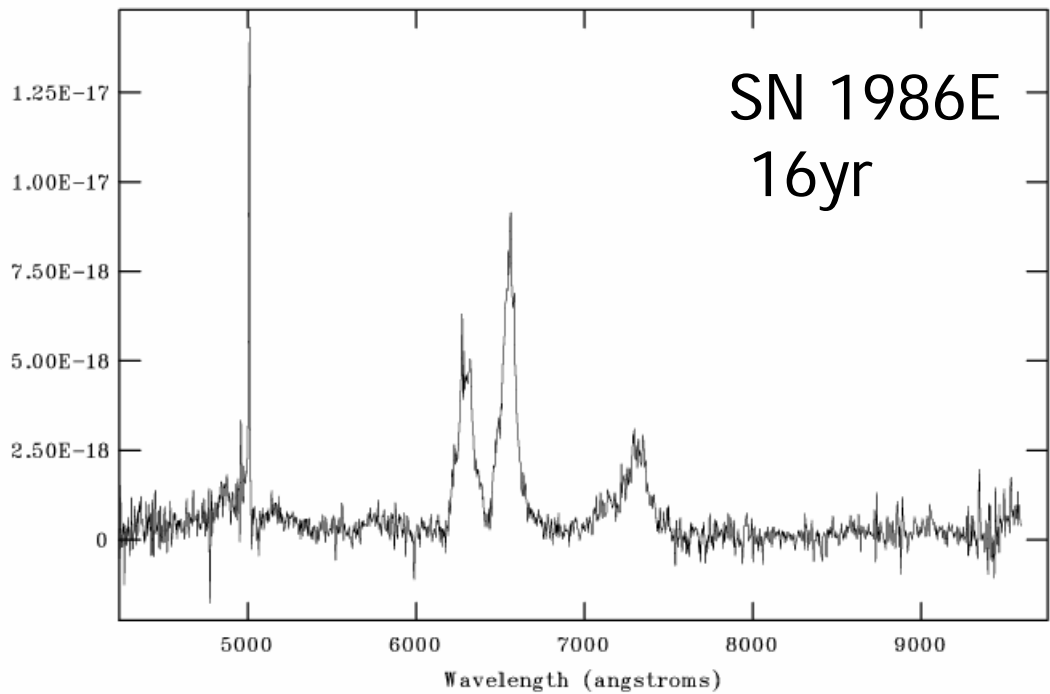
- Bulk of SNIIP
- Early phases dominated by configuration and envelope mass of the progenitor
- Late time powered by $^{56}\text{Co} \rightarrow ^{56}\text{Ni}$



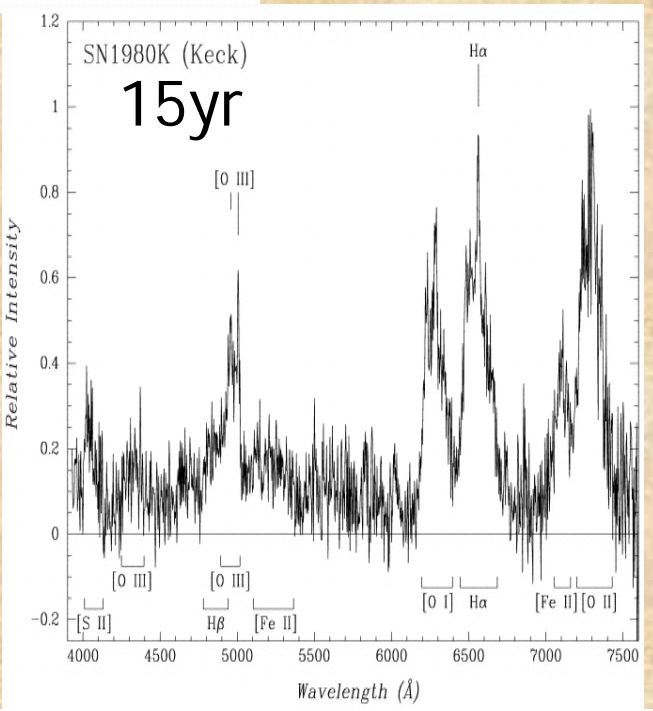
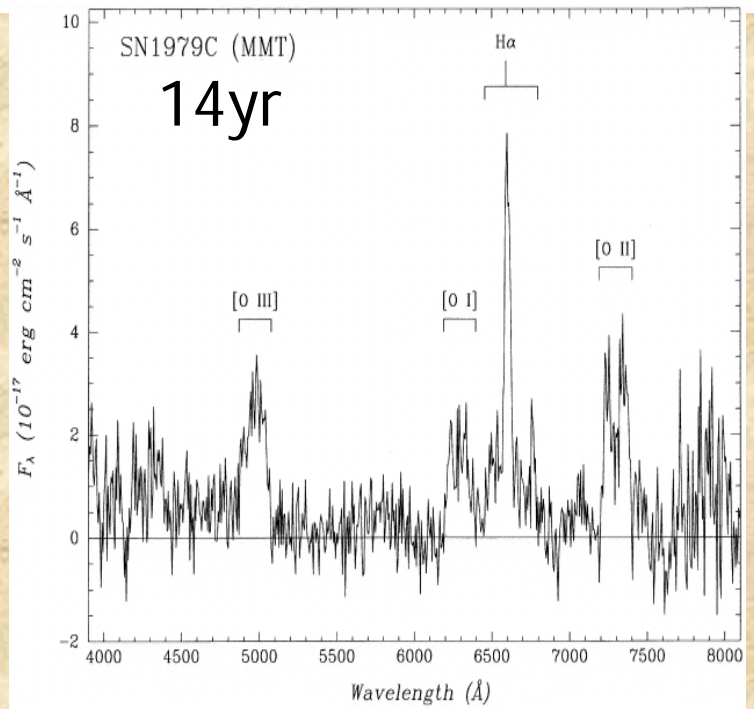
late SNIIL

- (all??) flatten at late times
- strong radio emission
- boxy sp.lines





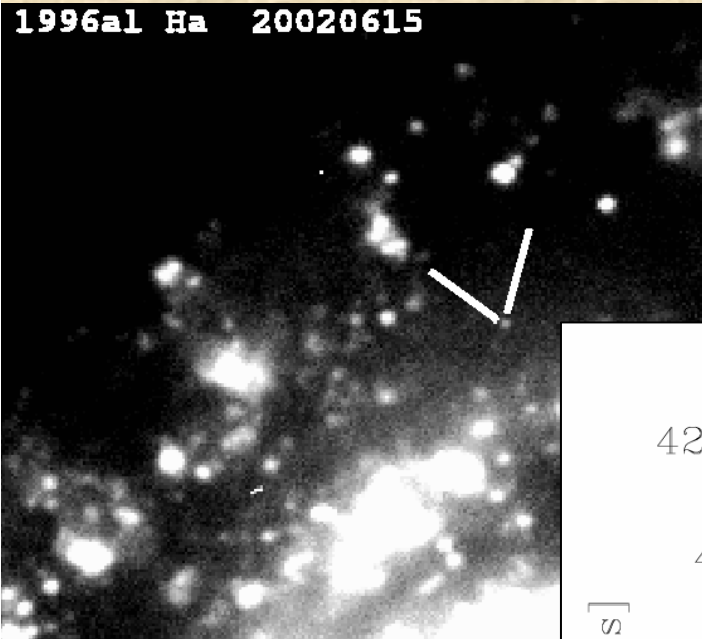
VLT



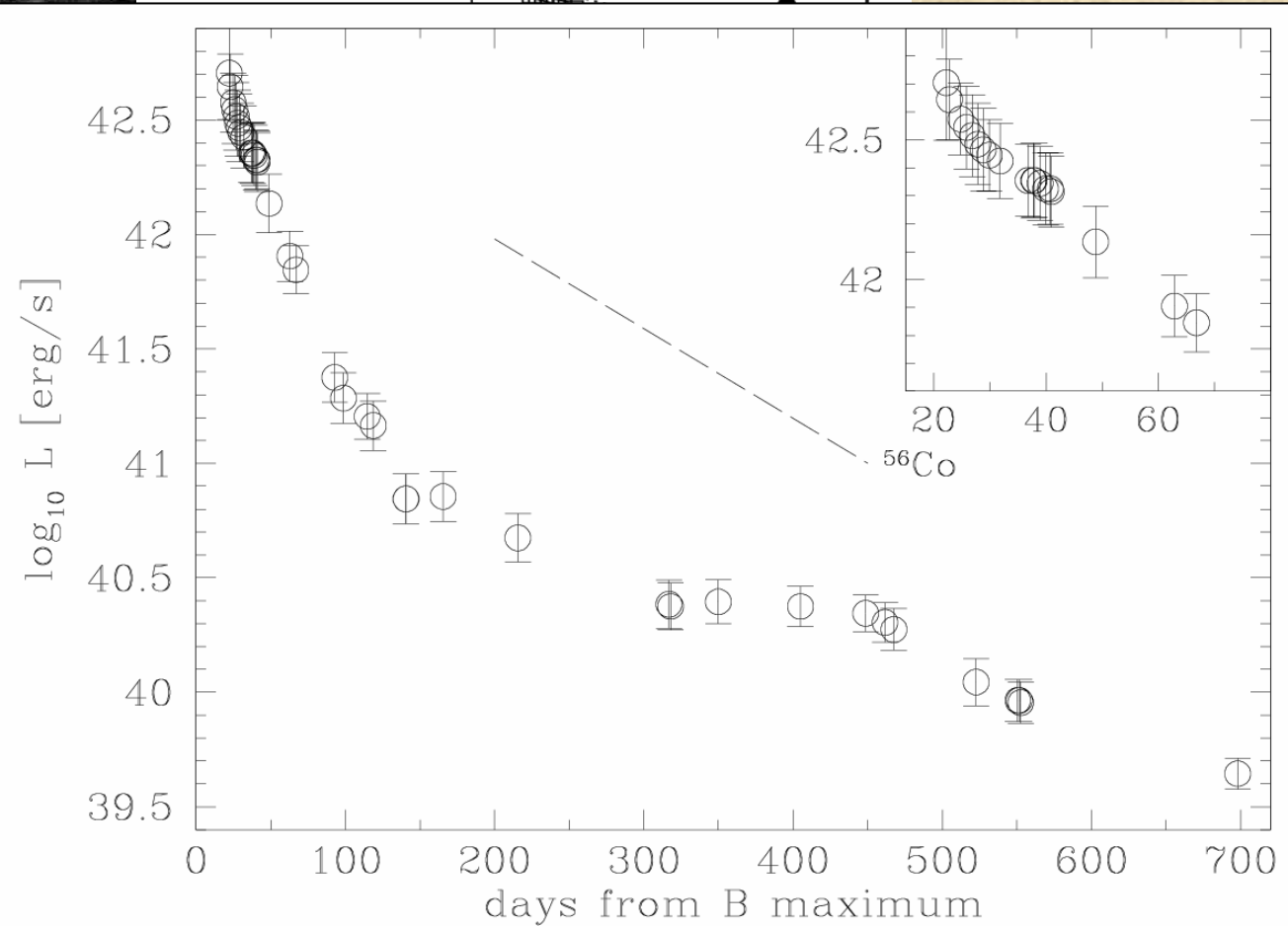
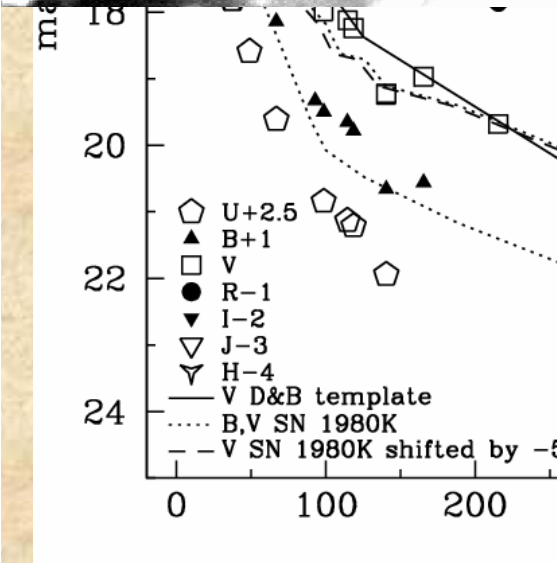
Fesen et al . 1999

SN1996al: a well studied SNIIL

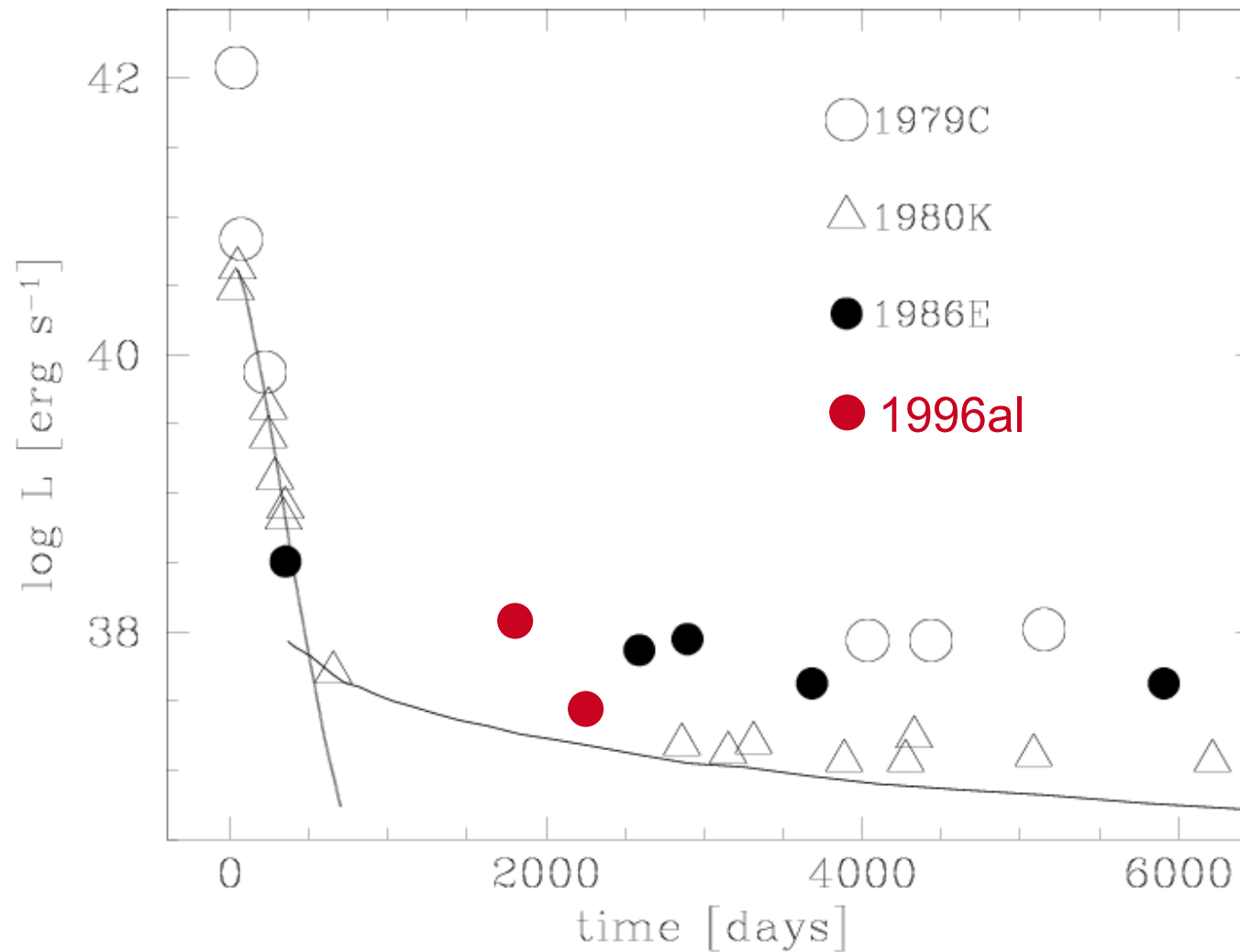
1996al Ha 20020615



SN1996al (Benetti et al. 1998 in preparation)

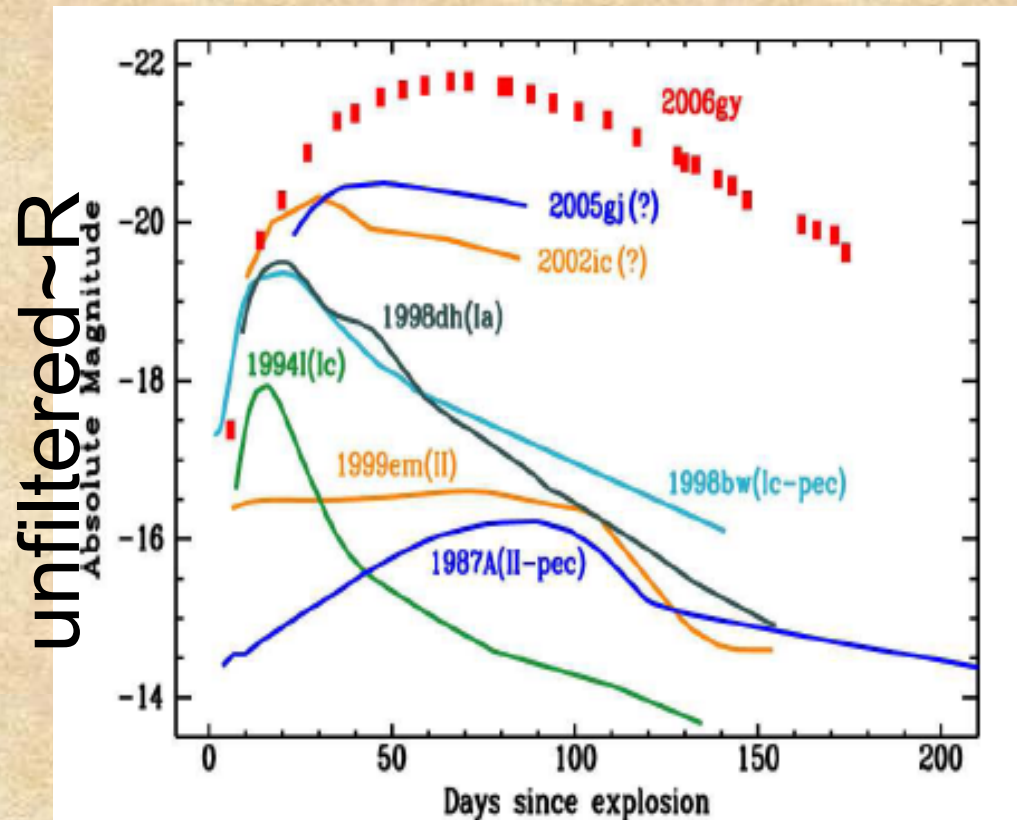


H α evolution for SNIIL



SN2006gy Ofek et al. 2007, Smith et al. 2007

- $M_V \sim -22$, the brightest SN ever
- Slow rise (70d) & broooad light curve
- $E_{\text{rad}} > 10^{51}$ ergs



Interpretation Smith et al. (2007)

- Interaction powered I.c. $\rightarrow M_{\text{dot}} = 0.5 M_{\odot}/\text{yr}$
comparable η Car
?? $L_x = 1.65 \times 10^{39} \text{ erg s}^{-1}$ (Smith 2007, Ofek 2007)
- Radioactively powered I.c. $\rightarrow M(\text{Ni}) = 22 M_{\odot}$
(PPSN)

$\rightarrow M_{\text{pr}} > 40 M_{\odot}$ (not interacting SNIa)

CSM Interacting SNIa

Echelle spectroscopy $< 10^{-6} M_{\odot}/\text{yr}$

Radio (VLA, ATCA) $< 10^{-7} - 10^{-8} M_{\odot}/\text{yr}$

Late-time observations (no H, O, CaII)

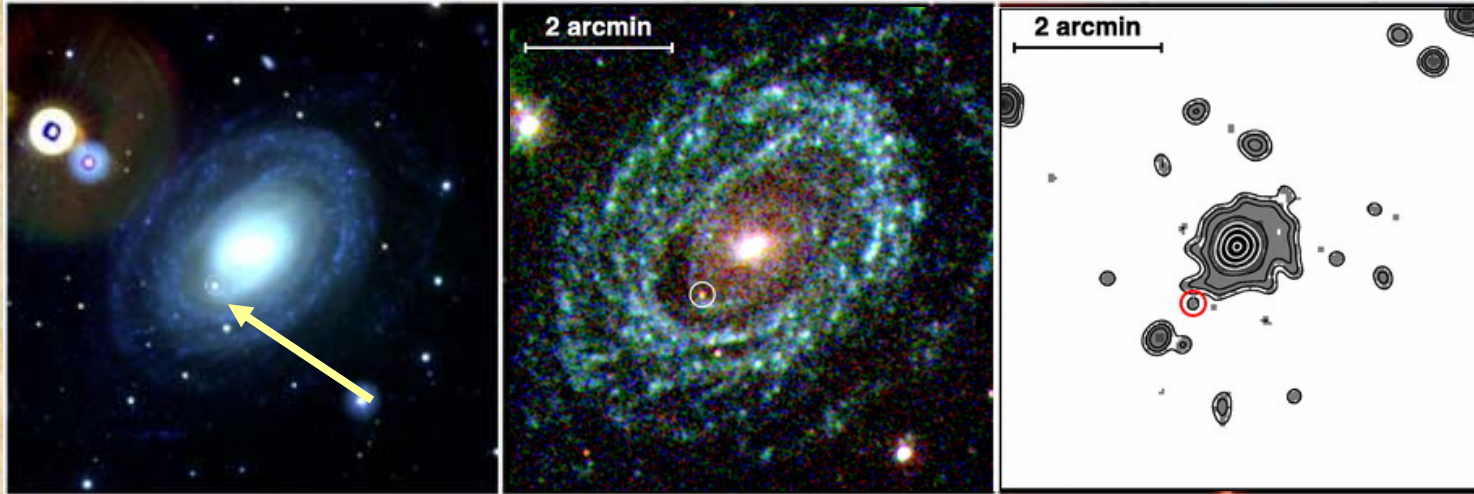
$M(\text{H}) \ll$ than expected (Marietta et al. 2000)

No clear X-Ray detection

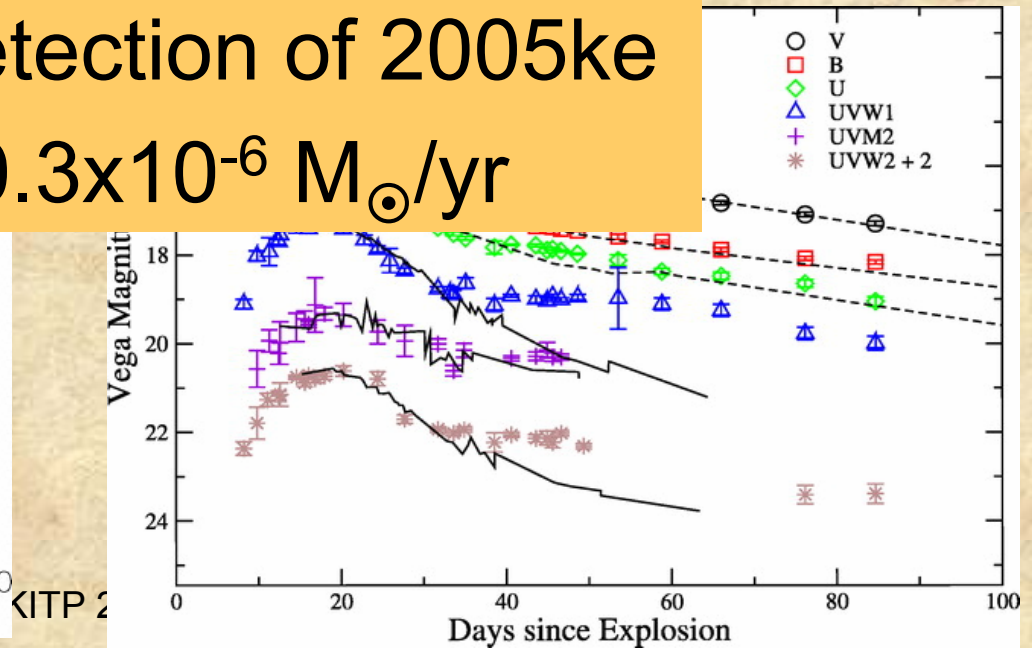
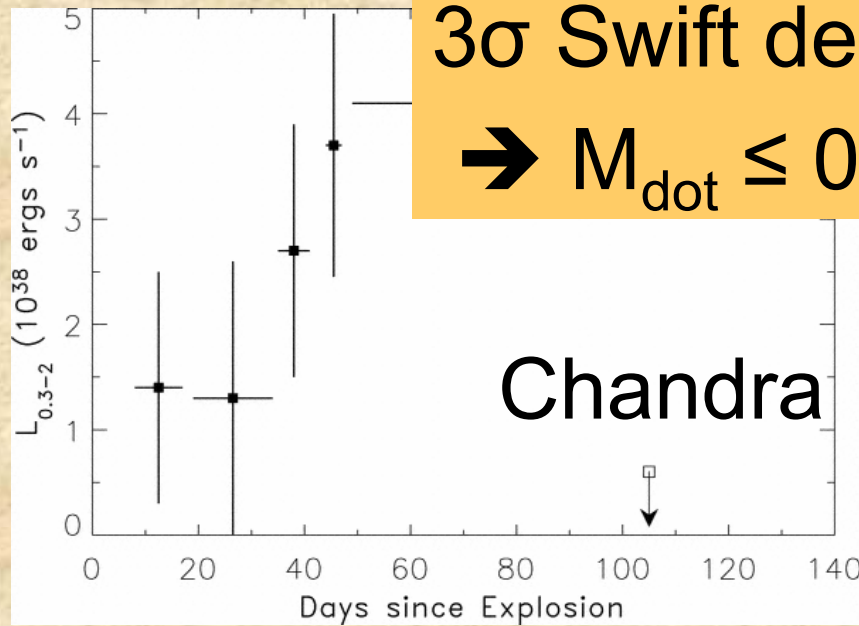
... but for the 3σ detection of 2005ke

SN2005ke

Immler et al. 2006



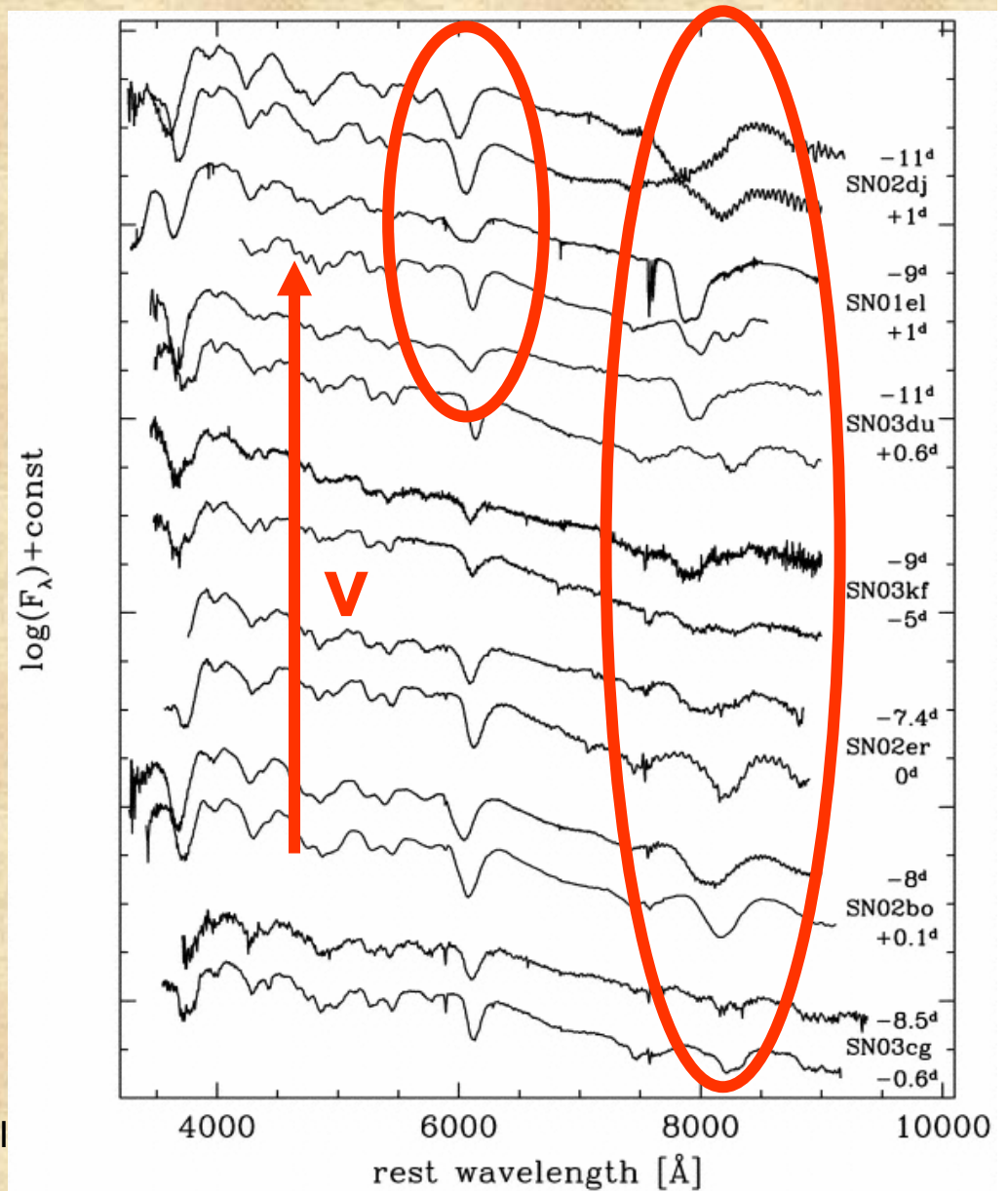
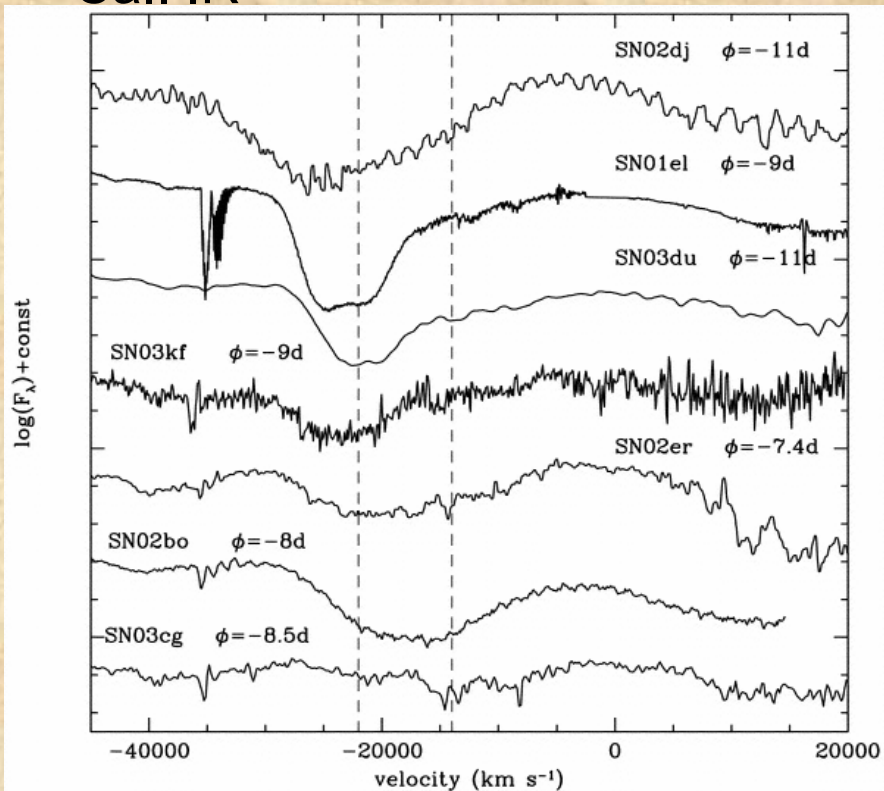
3 σ Swift detection of 2005ke
 $\rightarrow M_{\text{dot}} \leq 0.3 \times 10^{-6} M_{\odot}/\text{yr}$



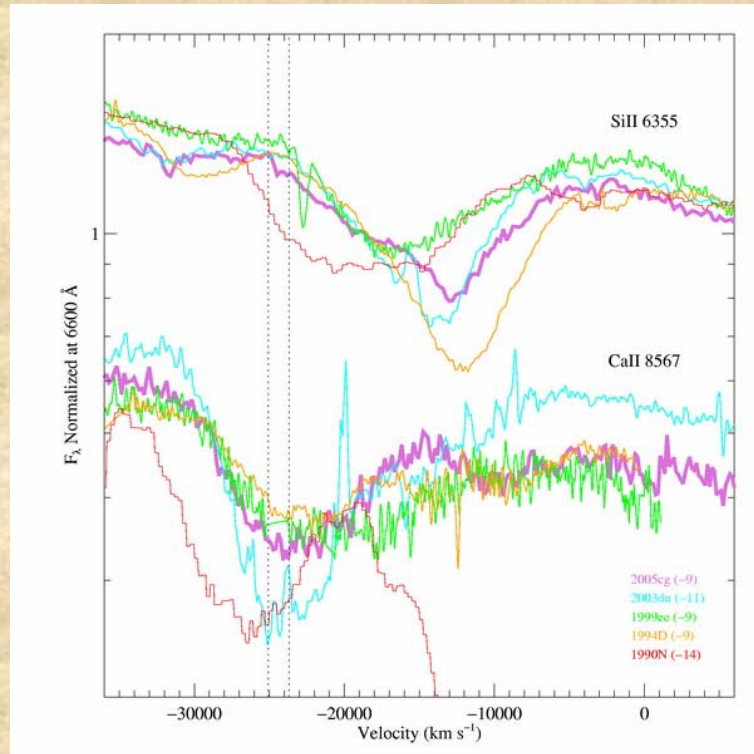
HV features in SNIa Mazzali et al. 2005

- Ca II **ubiquitous** (if early on ($t_{\max}-7d$))
- Si II sometimes

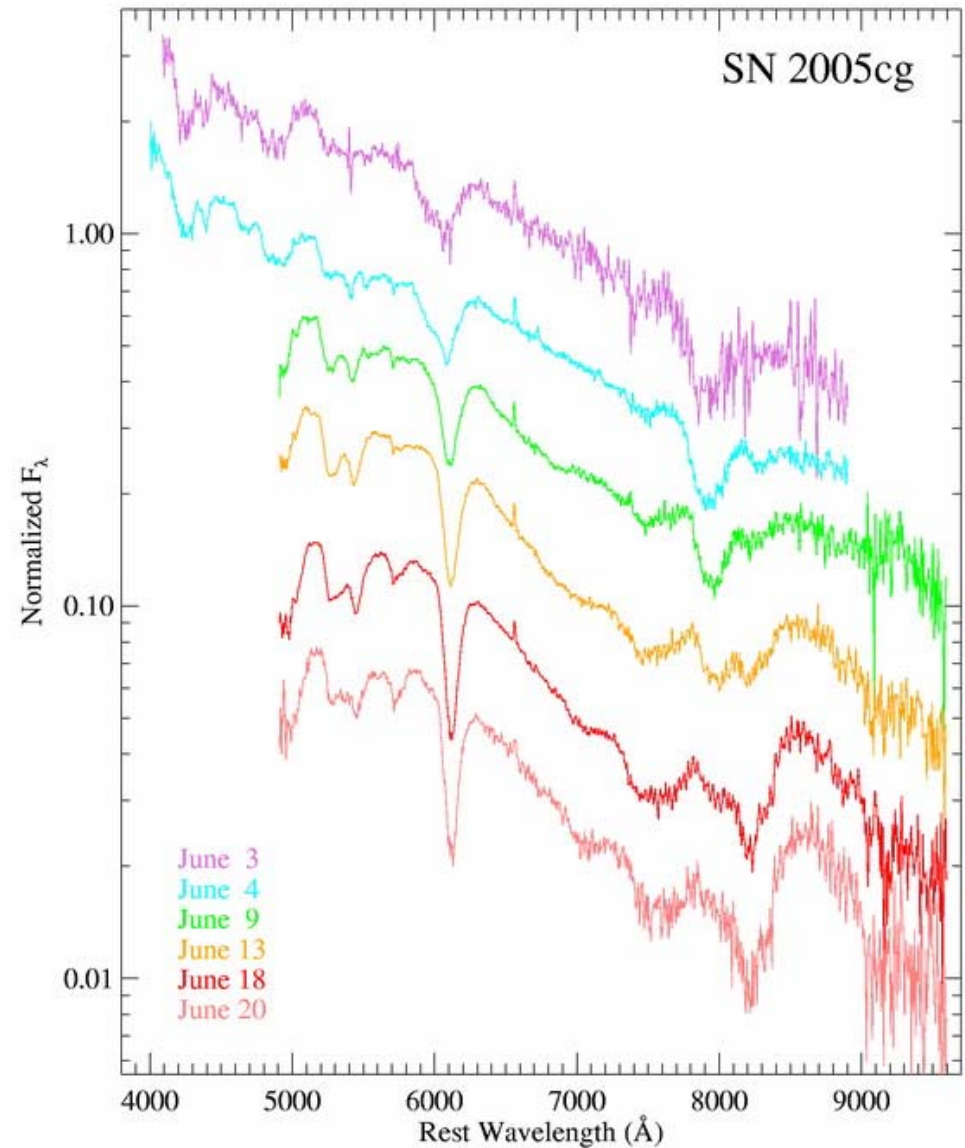
Ca II IR



SN 2005cg Quimby et al. 2005



$$HV_{\text{CaII}} = HV_{\text{cutoff}}_{\text{SiII}}$$



Physical interpretation

- CaIII recombination (long lived?) Höflich et al. 1998
- 3D abundance enhancements (ubiquity ?, polarization !) Mazzali et al. 2005b
- CSM interaction Gerardy et al. 2004
 $M_{\text{CSM}} \leq 5 \div 40 \times 10^{-3} M_{\odot}$ Quimby et al. 2005
 $M_{\text{CSM}} = 4 \times 10^{-3} M_{\odot}$ Mazzali et al. 2005a

SN 2002ic

(Hamuy et al. 2003)

- SiII & SII lines
- H α
- ➔ first SNIa for which H has been unequivocally detected

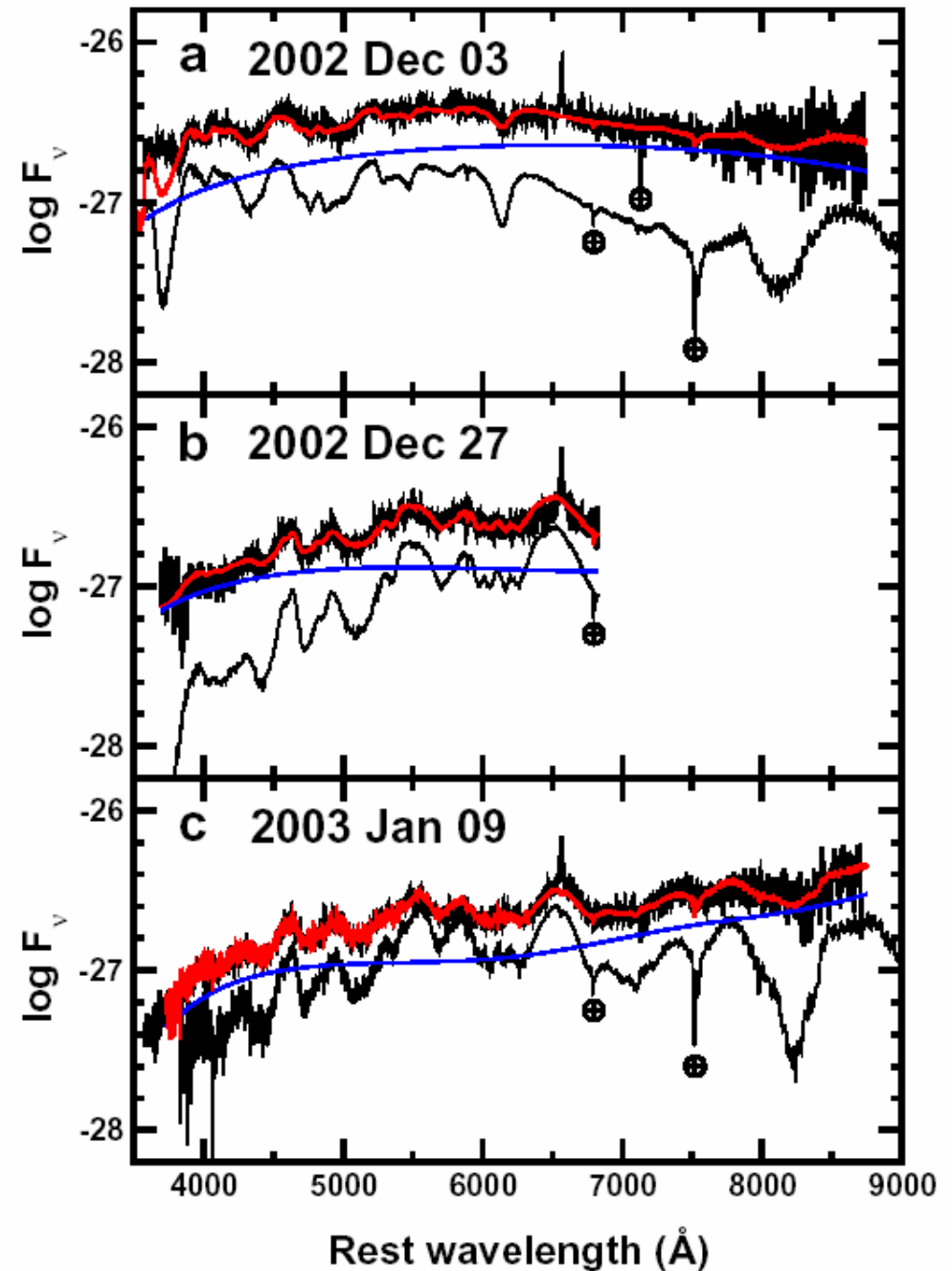
Need a strong, varying continuum at all epochs to:

- increase the flux
- reduce the contrast
- change the SED

➔ satisfactory fit

➔ CSM interacting SNIa

K

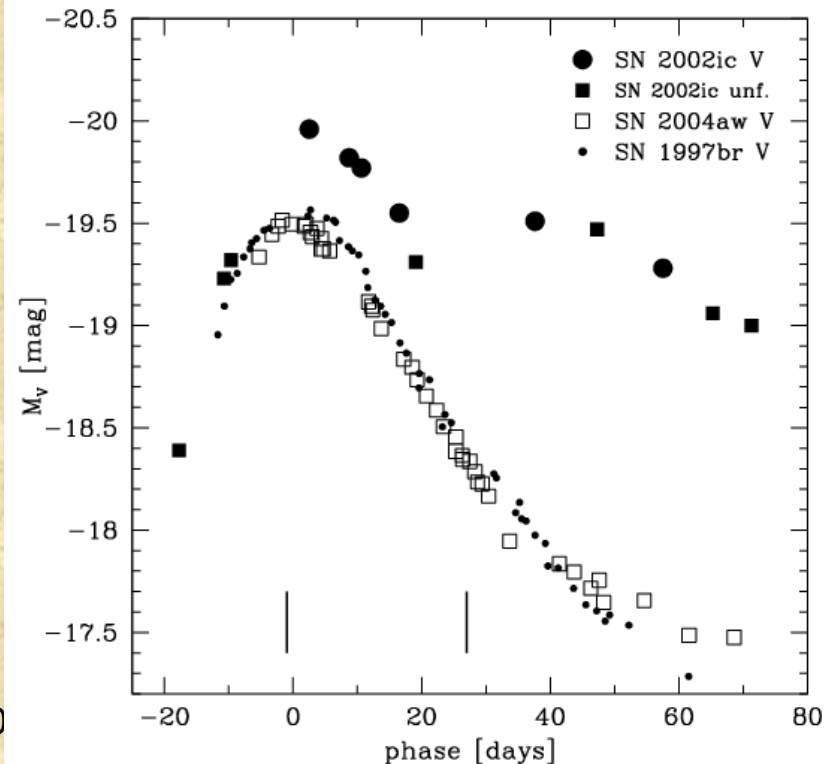


Light curve

Bright maximum, similar to SNIa peak
+ rebrightening@1m
(cavity, Wood-Vasey et al. 2004)

Slow late decline

2004aw(lc) \equiv 1999br(la)
[$E(B-V)_{aw}=0.85$ $E(B-V)_{br}=0.35$]



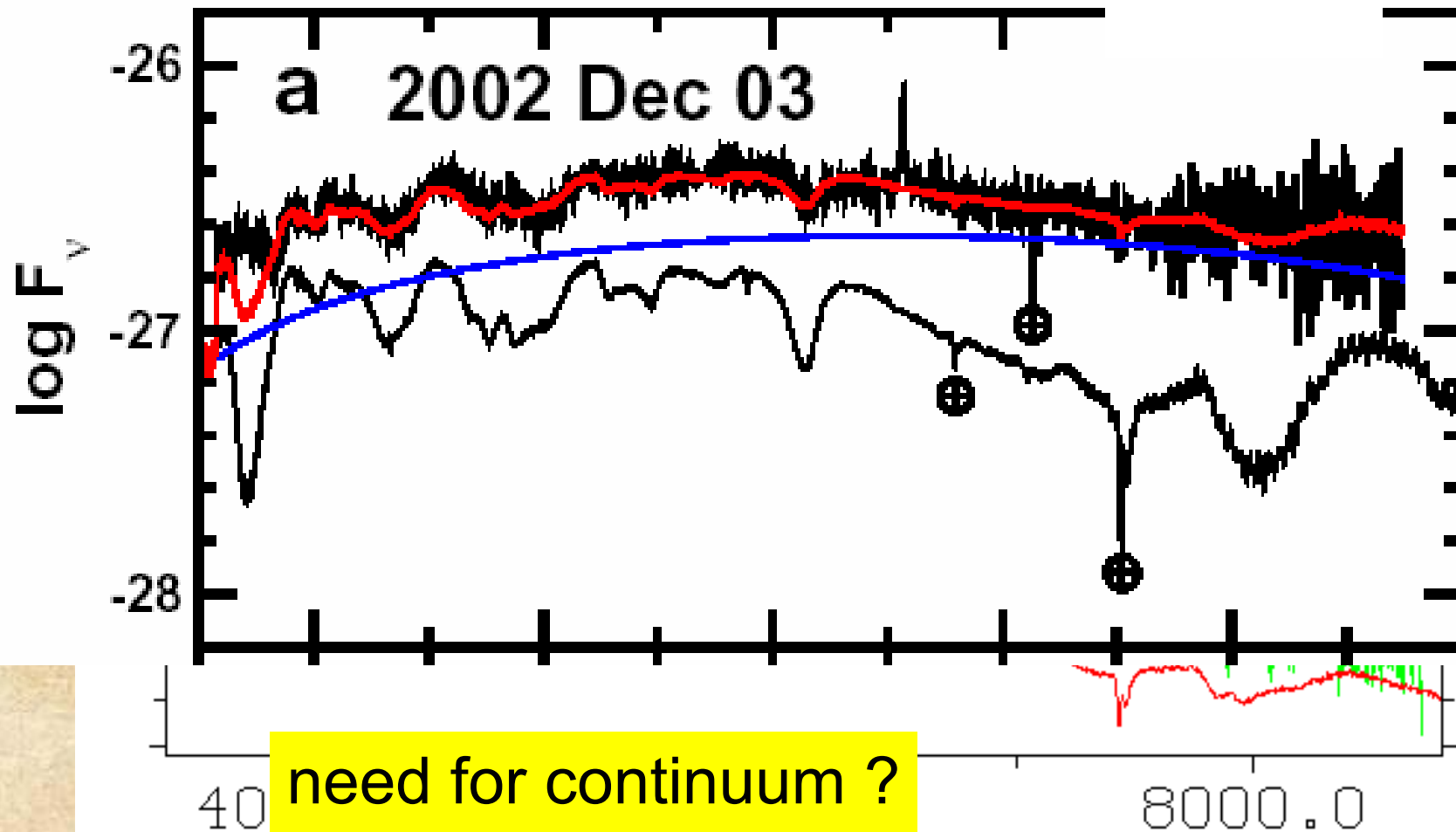
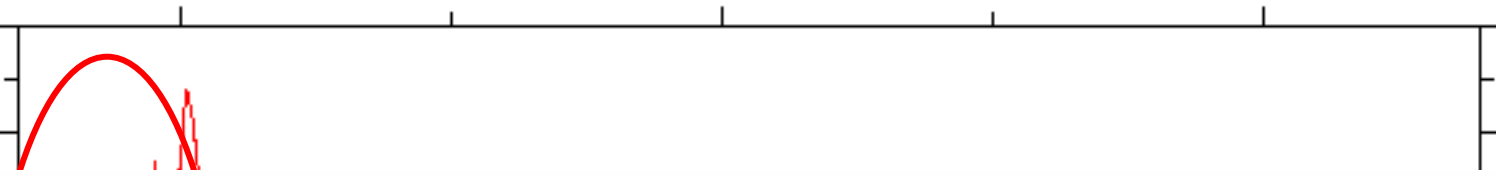
Observations →

- $M(H) = 1\text{--}6 \text{ Mo}$ (Hamuy et al. 2003; Chugai & Yungelson 2004; Wang et al. 2004) near the site of a thermonuclear explosion
- Cavity $r=1.7 \times 10^{15} \text{ cm}$ CSM-free region immediately surrounding the explosion (Wood-Vasey et al. 2004) → recurrent Nova 15yr before explosion (WV+ 2006)
- Asymmetry of H emitting gas ($p > 1\%$, Wang et al. 2004)

Possible interpretations:

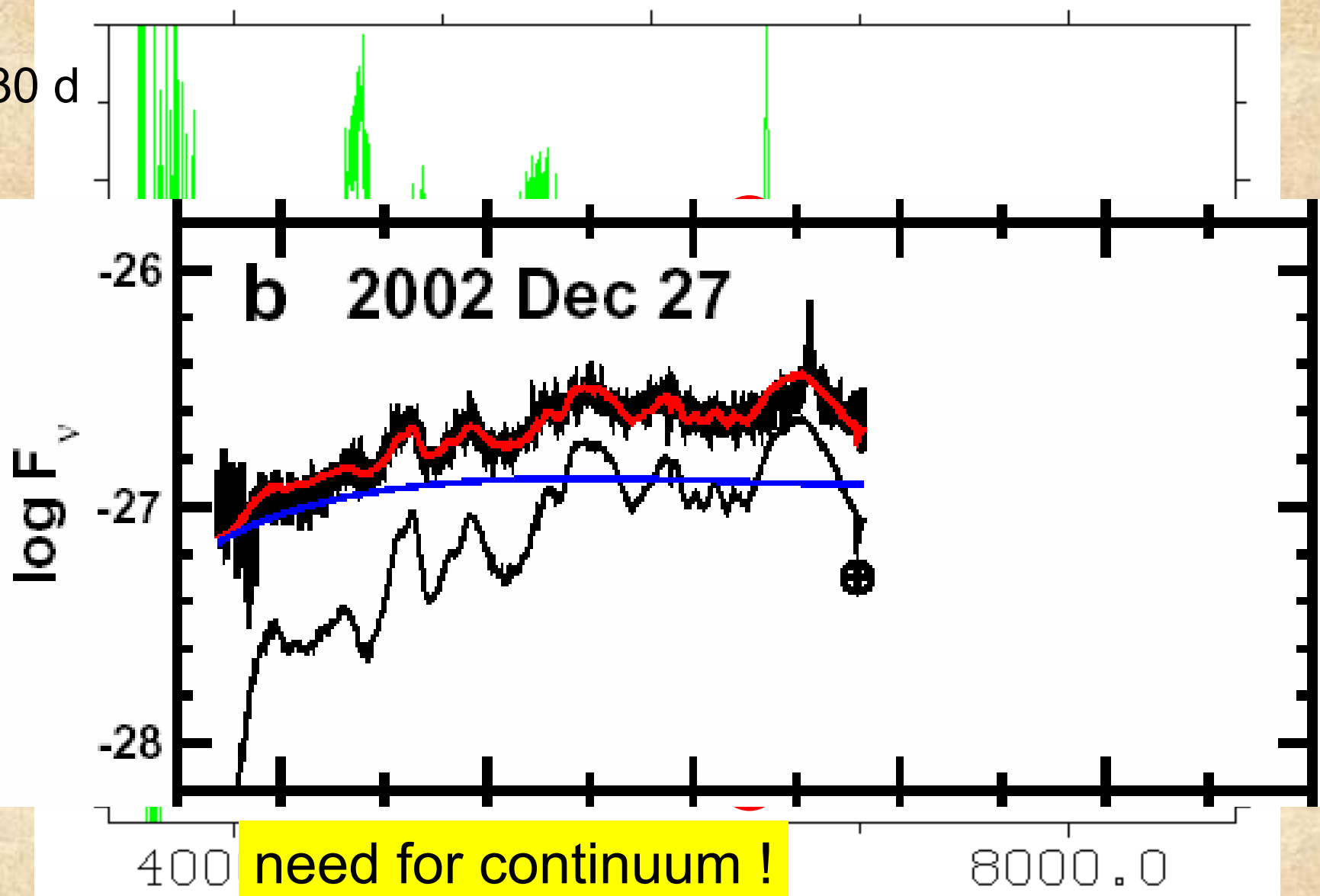
- the explosion of a WD in a binary system with a post-AGB companion (Hamuy et al. 2003)
- the explosion of the C/O core of a 25 Mo star (SN 1.5 Iben & Renzini 1983; Hamuy et al. 2003; Imshennik & Dunina-Barkovskaya 2005)
- the merger of a WD with the C/O core of an AGB star during a common-envelope phase (Livio & Riess 2003)
- the explosion of a WD in a SS X-ray system with delayed dynamical instability-triggered mass loss (Han & Podsiadlowski 2006).

max



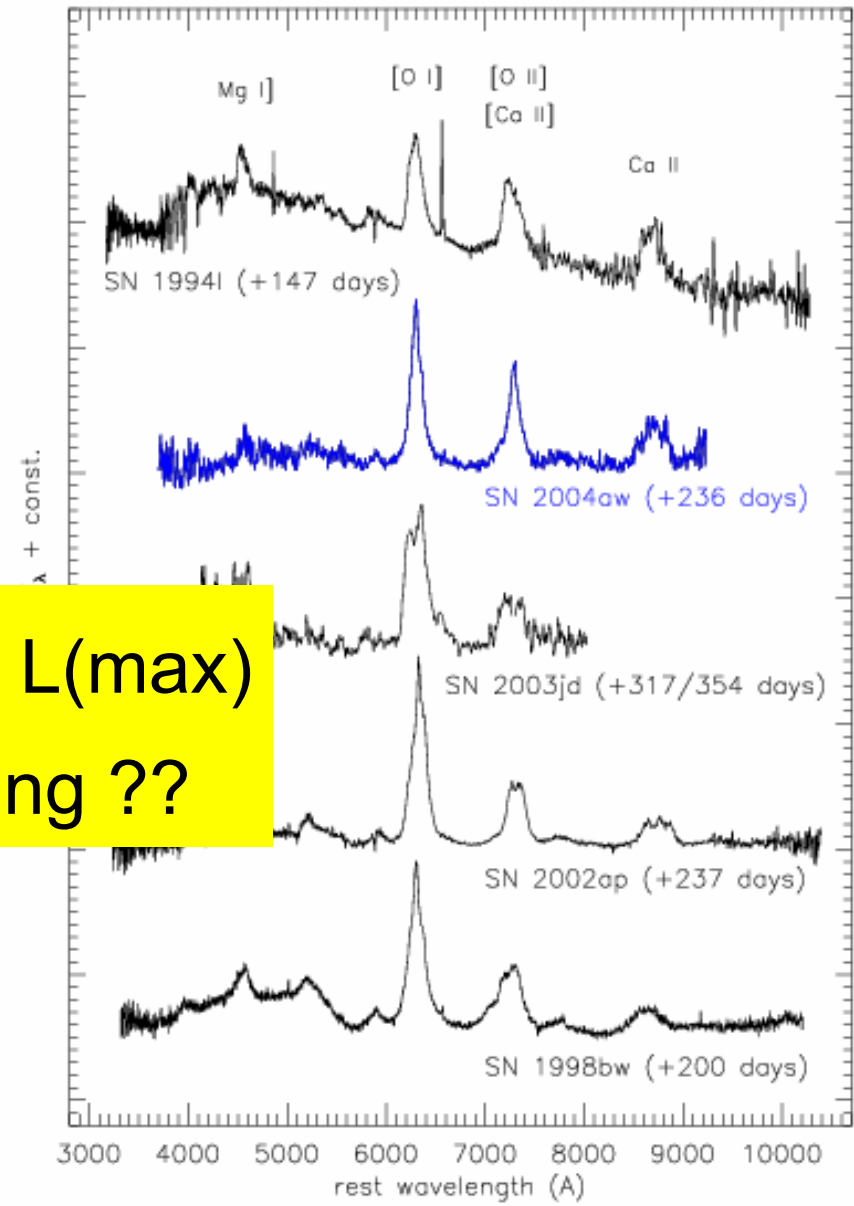
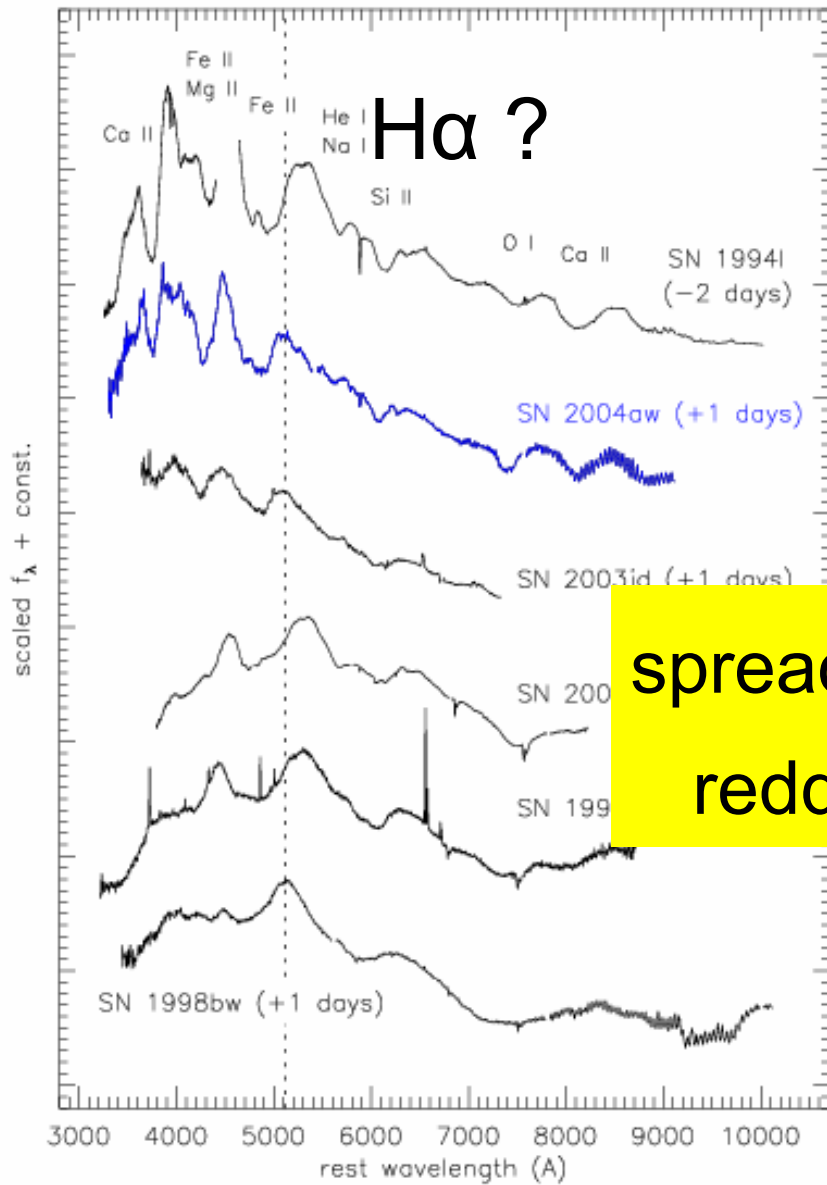
need for continuum ?
Ca H&K ?

+30 d



need for continuum !
Sill ? H α ?

SN Ic



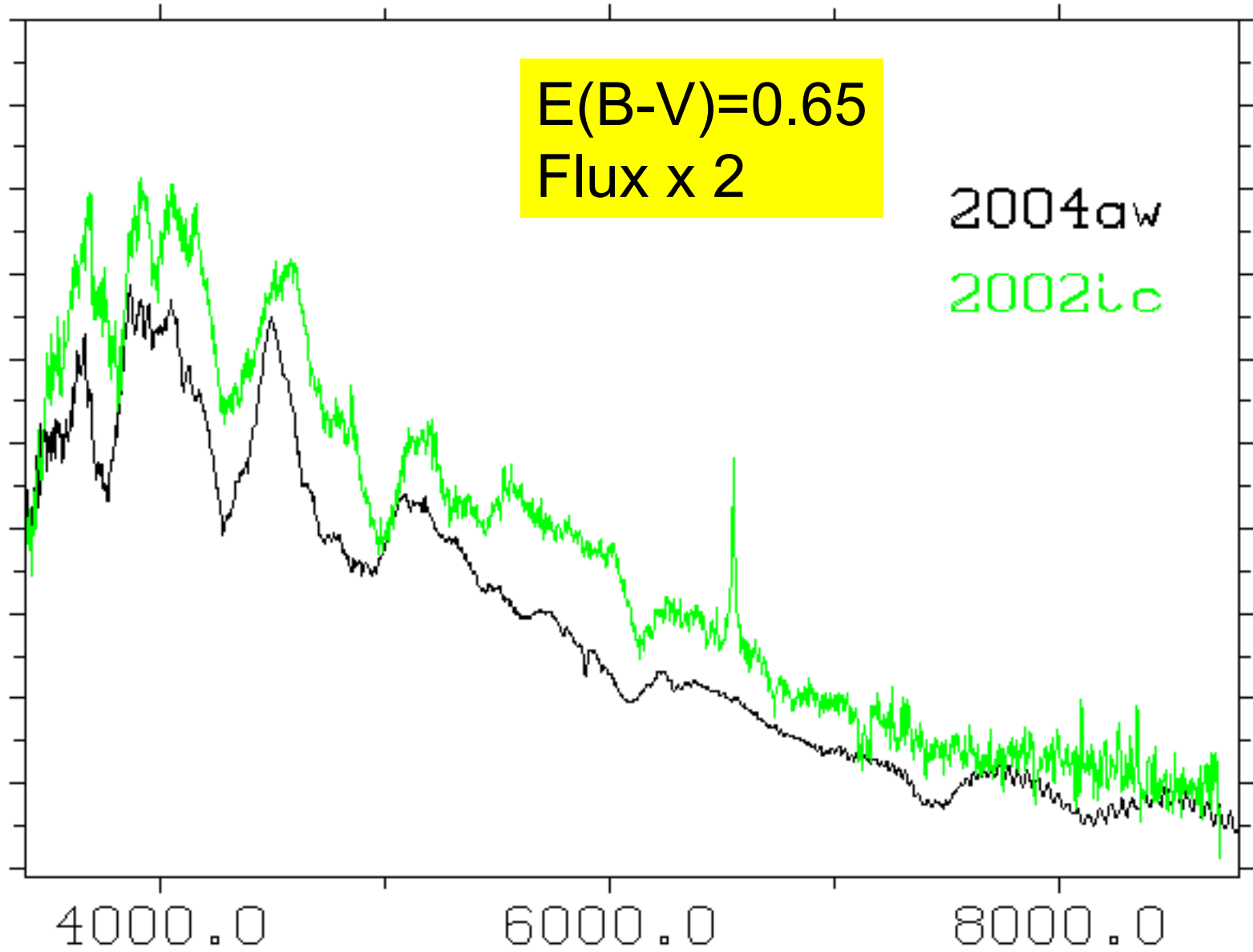
spread in L(max)
reddening ??

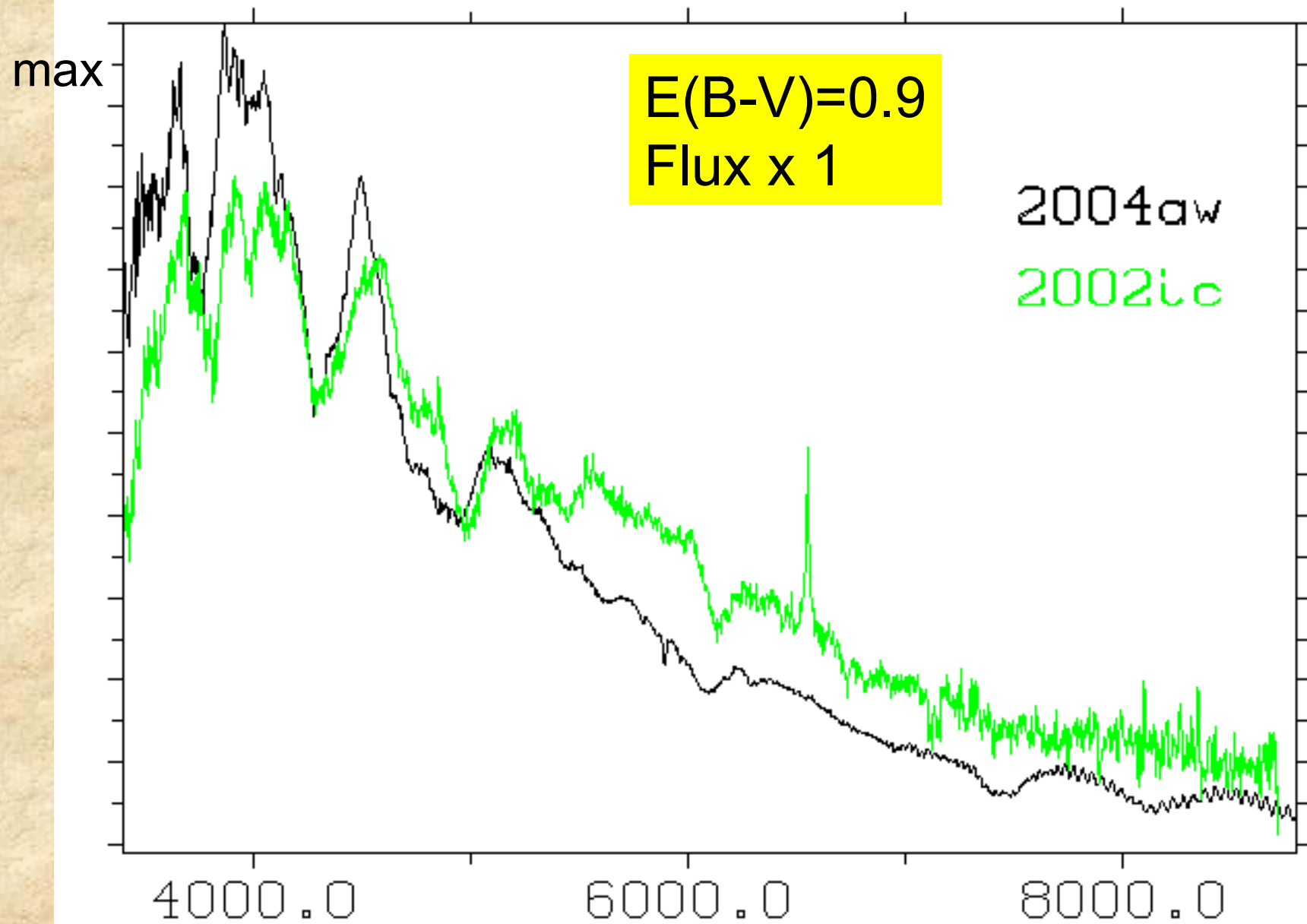
max

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200d

max

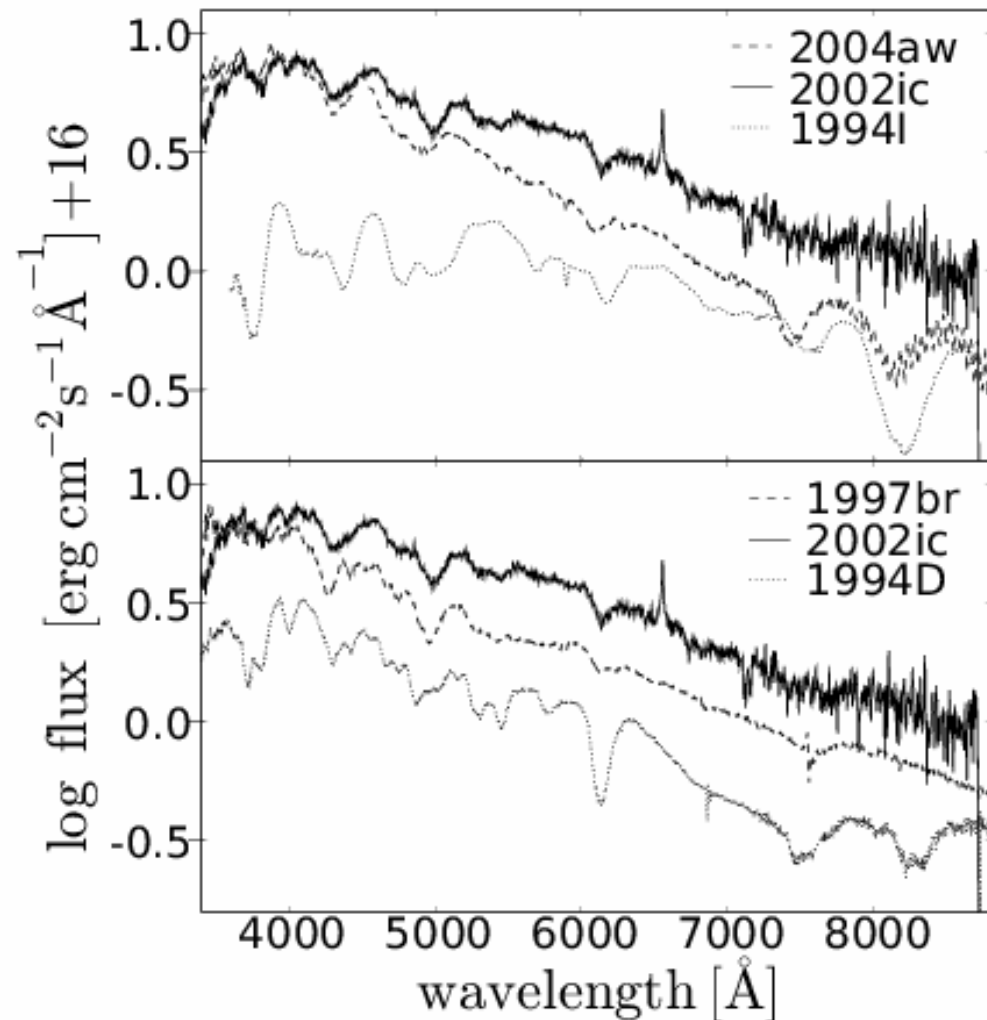




Early spectra

- 2004aw:
 1. Sill(?) ok
 2. Blue side ok
- SNIa:
 1. Sill, SII ok
 2. Red side ok

Benetti et al. (2006)



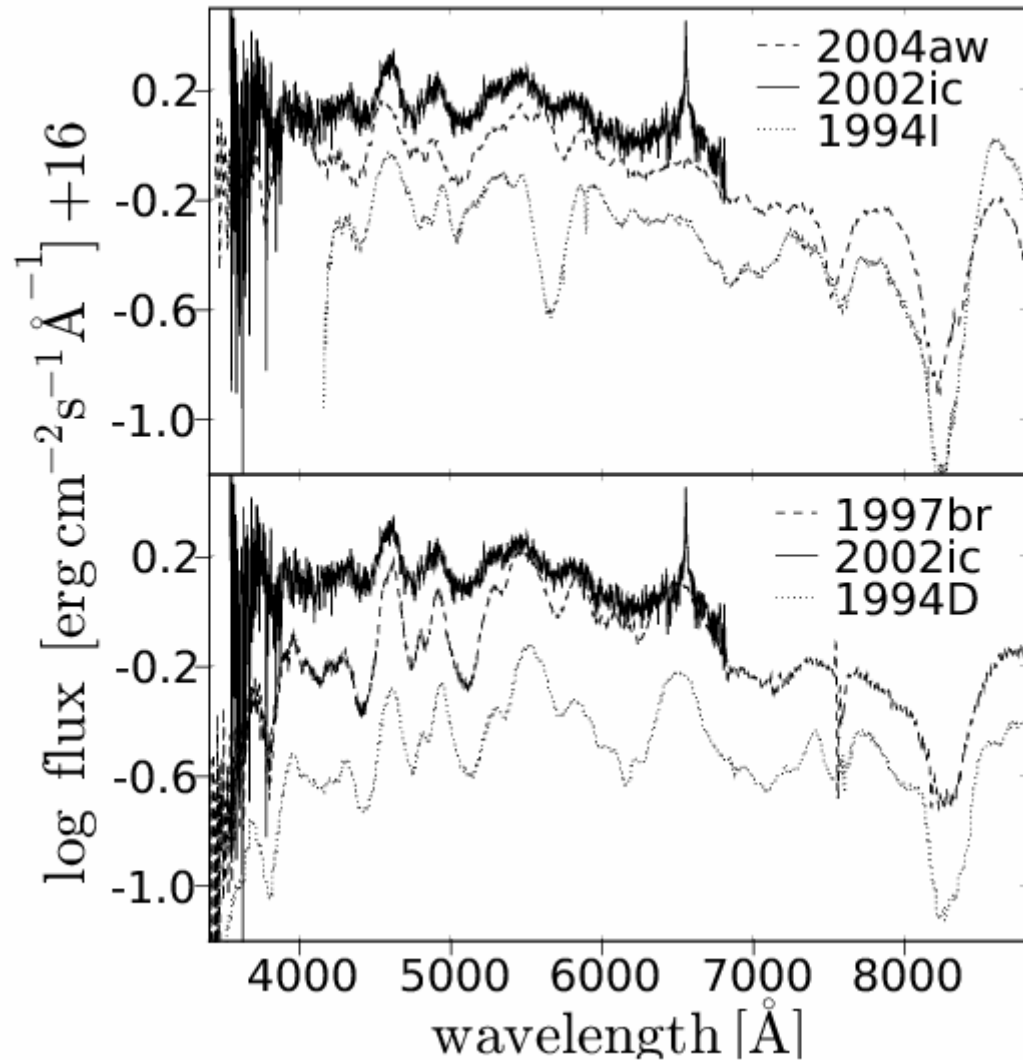
Surprising?

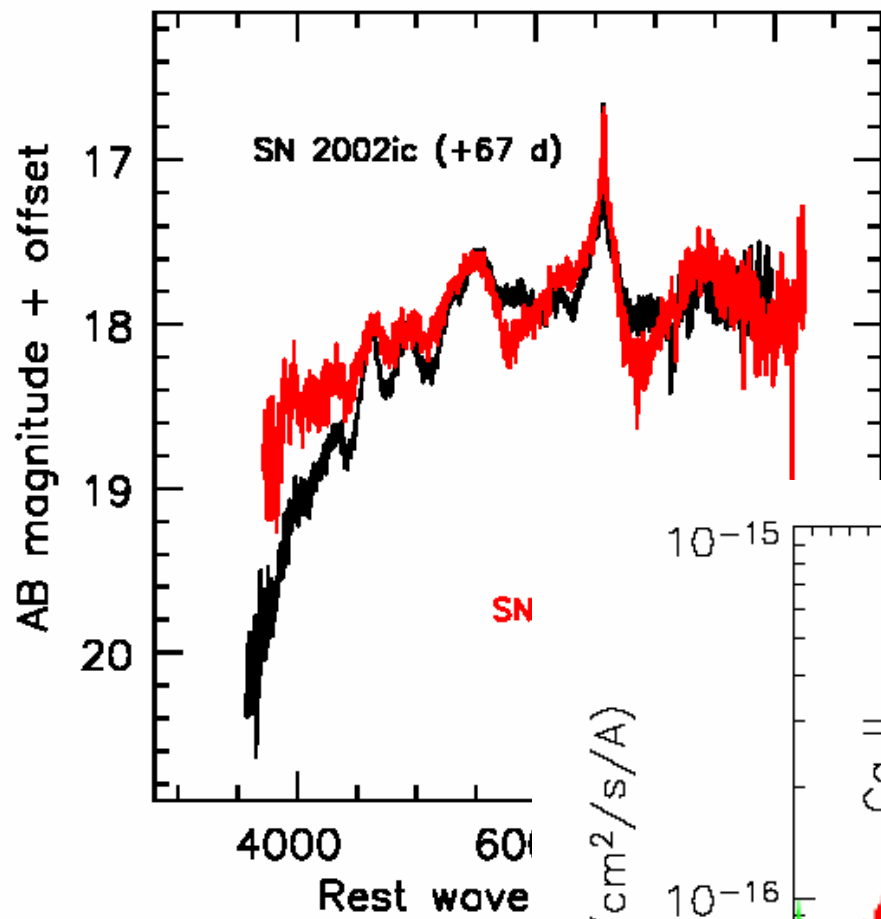
2004aw misclassified as SNIa

1 month later

Benetti et al. (2006)

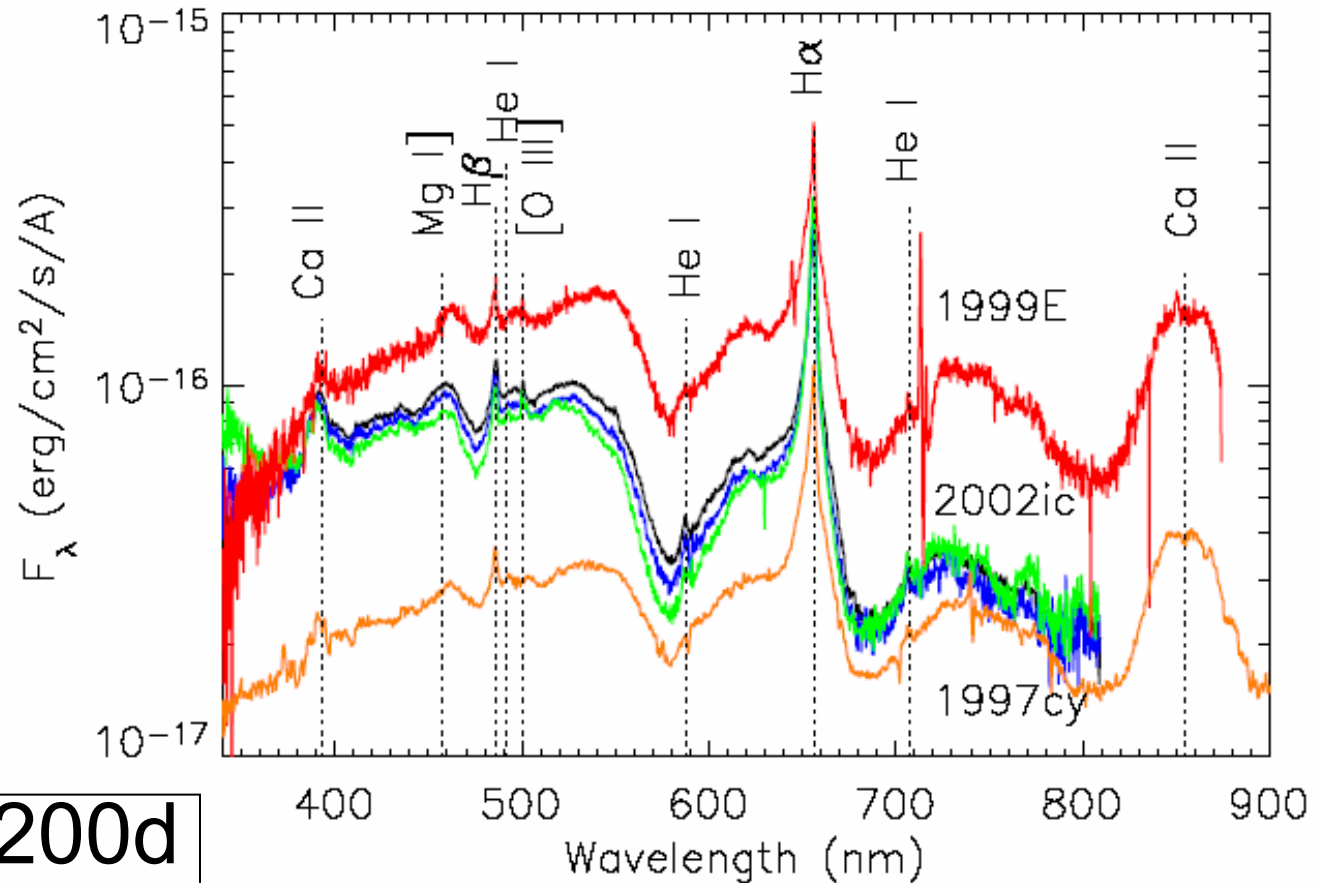
- 2004aw:
 1. SED ok
 2. Flux ok
 3. Broad H α base ok
- SNIa:
 1. Overall ok
 2. Broad H α base off by 50Å





Late time
 CSM interaction dominated

Deng et al. 2004



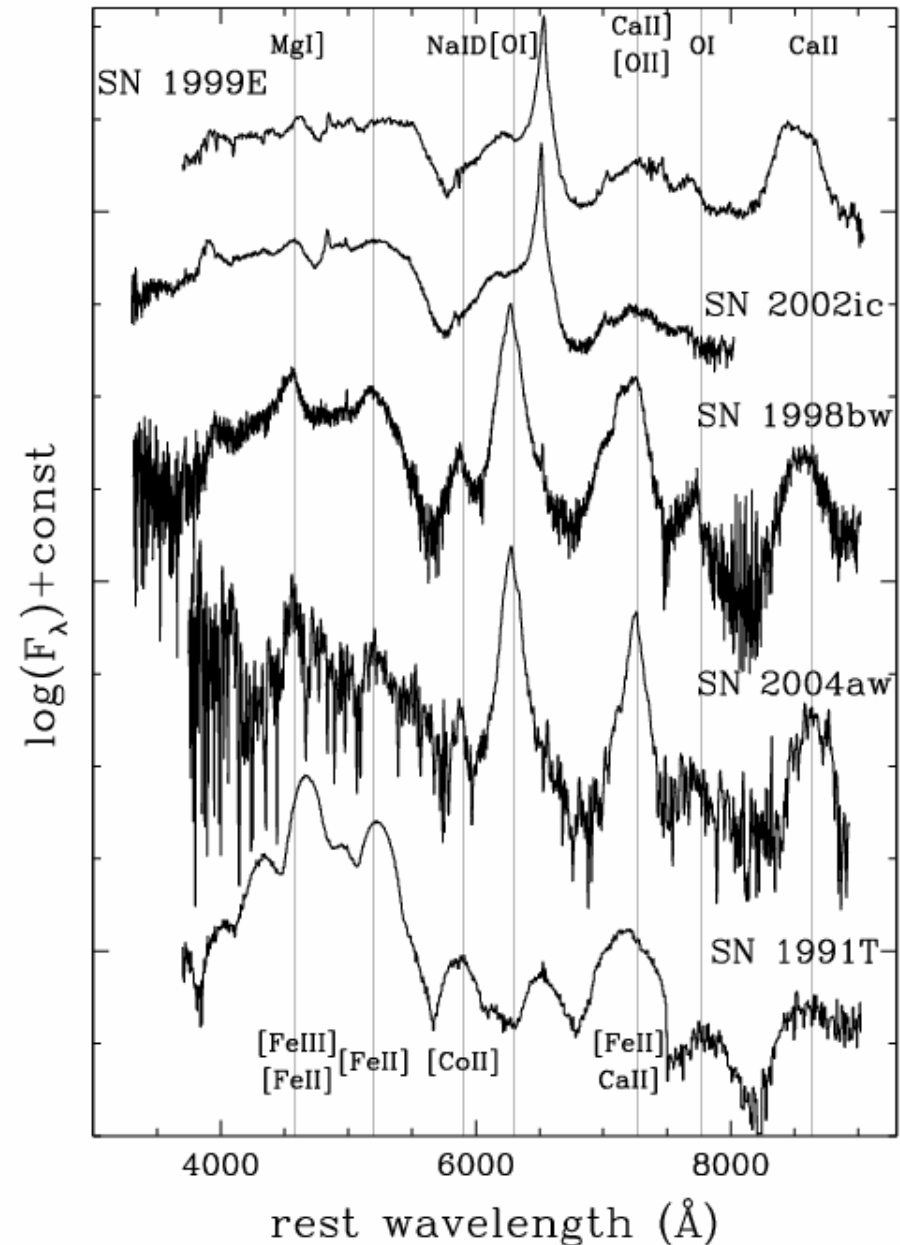
200d

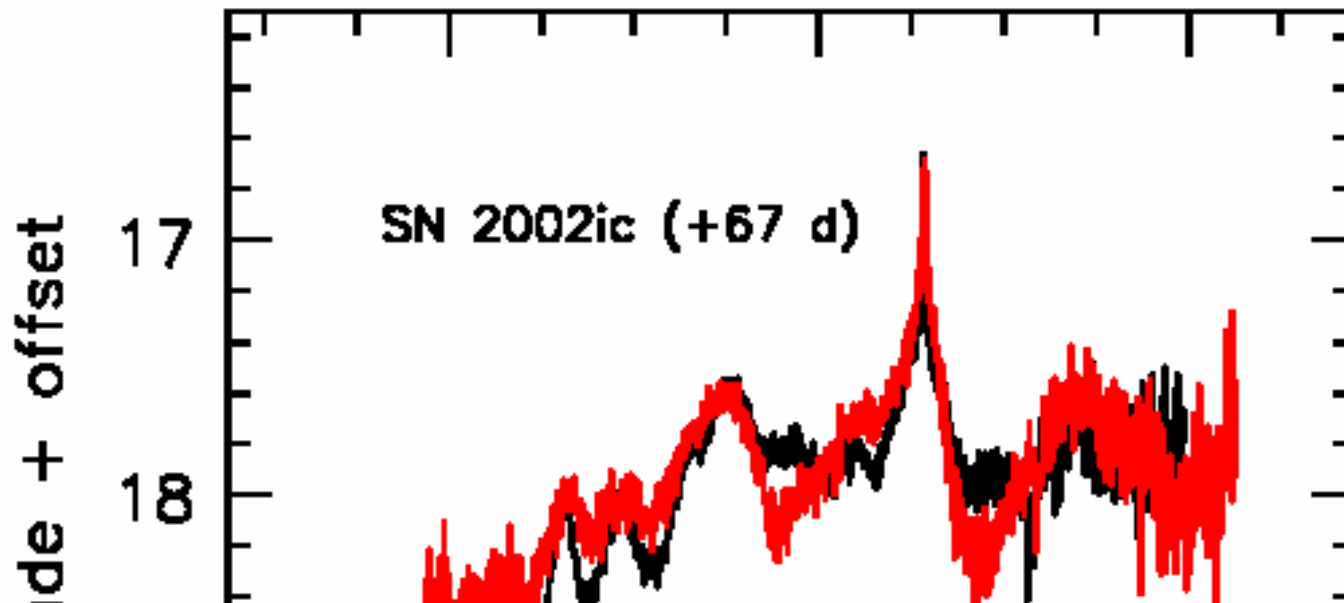


Late time

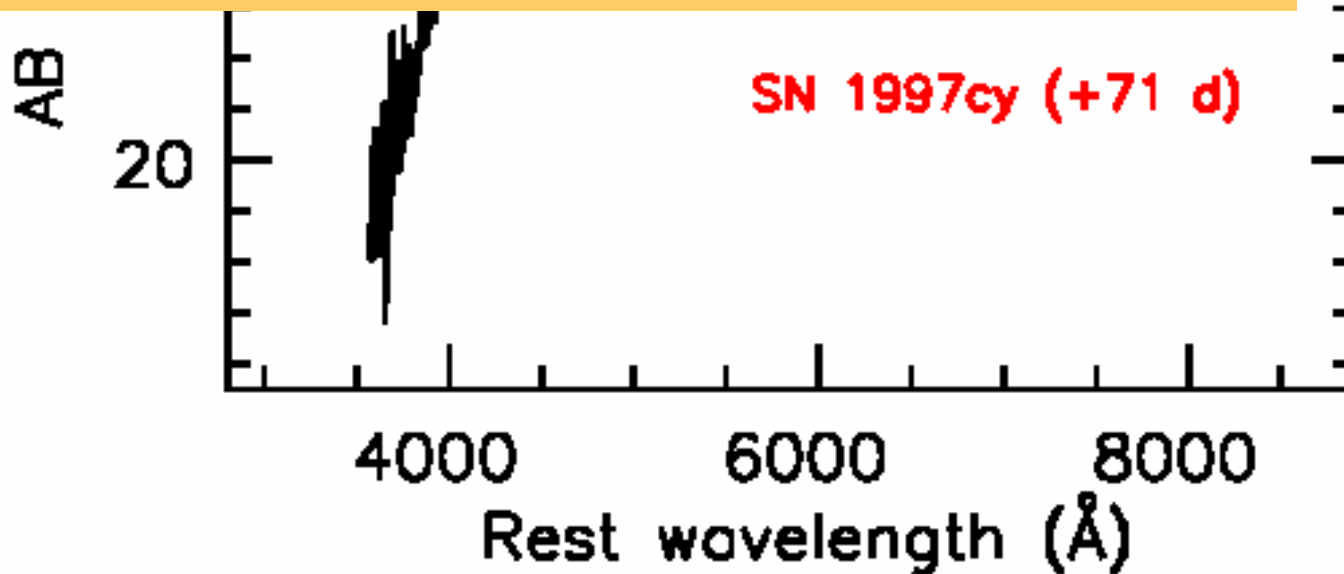
CSM interaction dominated

- O, Mg typical of CCSNe
- $\text{FWHM}(\text{OI}) = 7200 \text{ km/s}$
(Deng et al. 2004)
comparable to 1998bw
and 2004aw
- Models fail to
reproduce MgI (e.g.
Chugai et al. 2006)



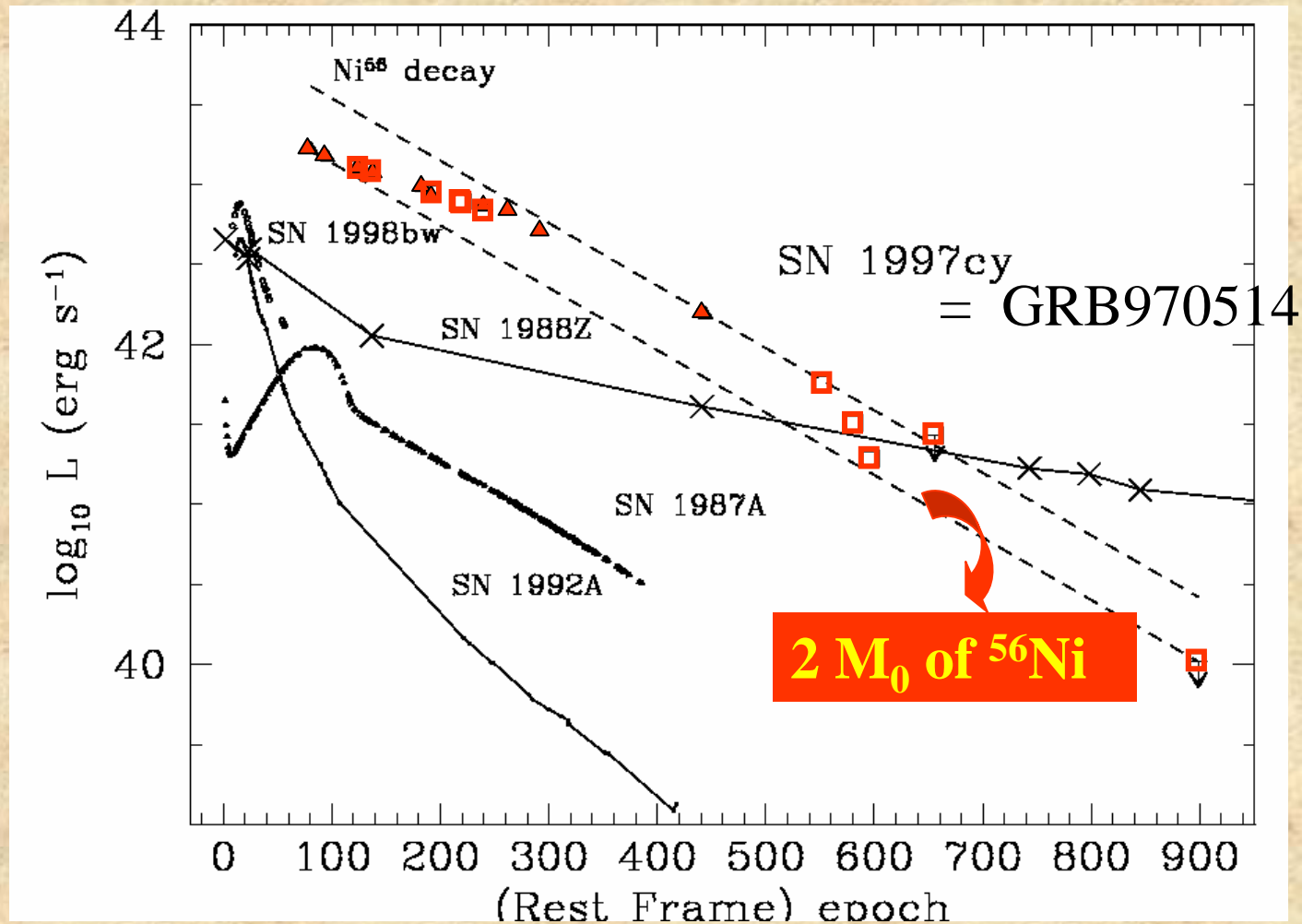


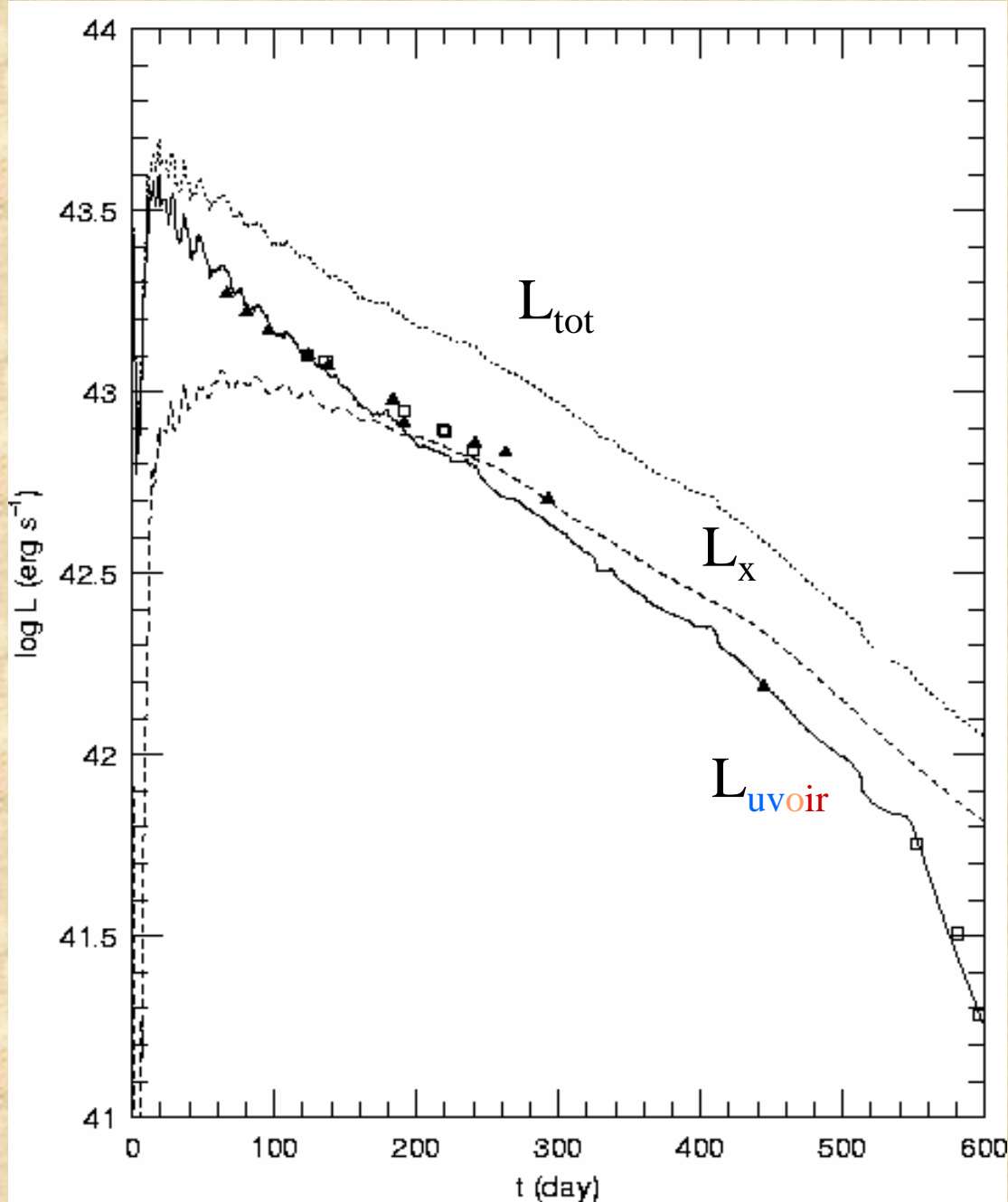
Correspondence is remarkable if explosion date is:
-20d before max for 2002ic
-coinciding with GRB for 1997cy (and 1999E)



1997cy bolometric

- among the **brightest** SN (all types) ever !!
- total radiated energy = 2×10^{50} ergs (3200Å to 1μ)





model parameters :

$$E=5 \times 10^{52} \text{ ergs}$$

$$r_{\text{st}}=1 \times 10^{15} \text{ cm}$$

$$\rho \propto r^{-n}, \quad n = -1.6 \text{ (not steady wind)}$$

$$\rho_{\text{st}}(\text{CSM})=4 \times 10^{-14} \text{ g cm}^{-3}$$

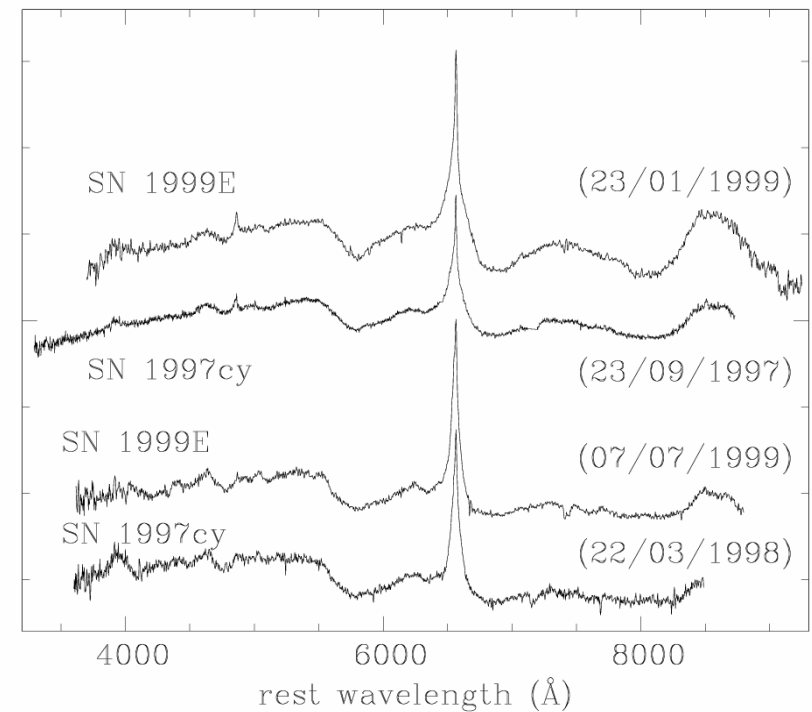
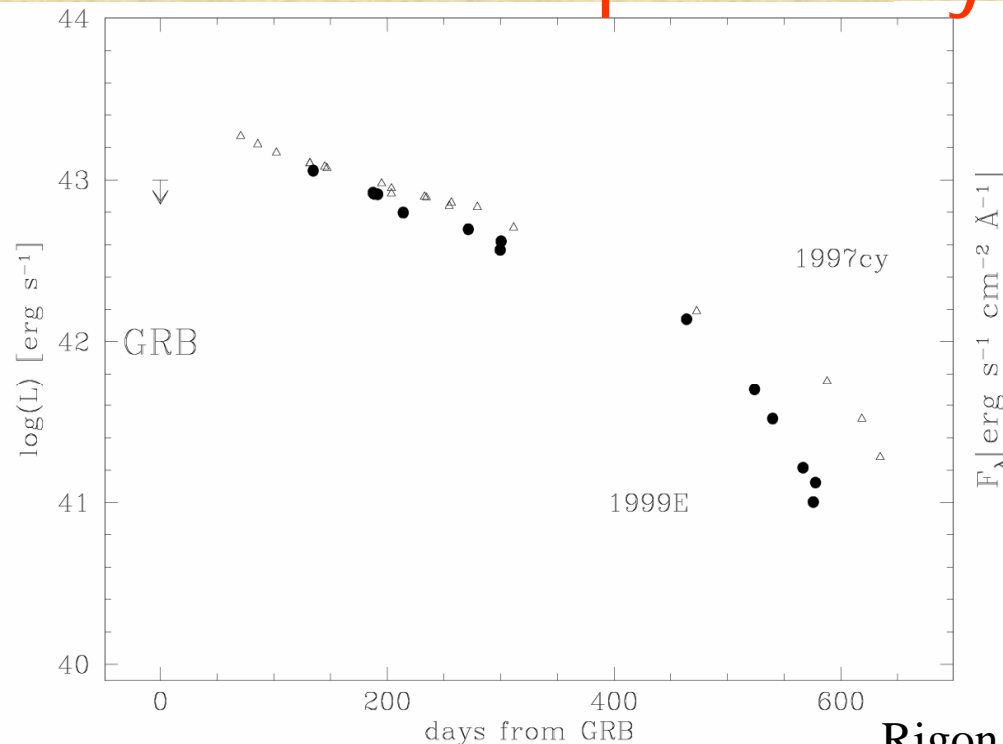
$$M=30M_0$$

Turatto et al. 2000

.... and SN 1999E

- the only 2 objects with such features (before 2002ic)
- both associated to BATSE GRB

combined probability $\Rightarrow 0.1\%$

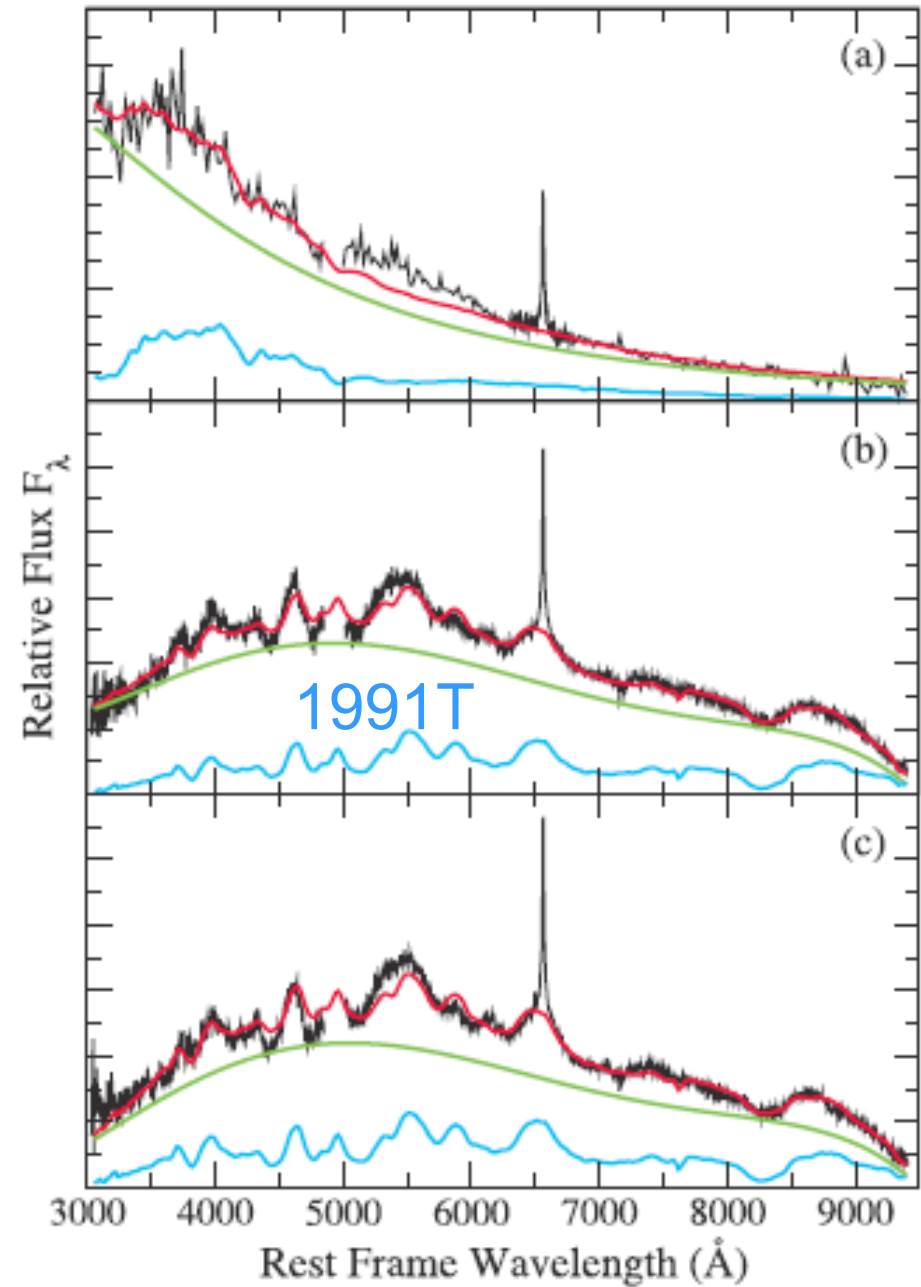


Rigon et al. 2002

Another one

SN 2005gj
(Aldering et al. 2006)

Best fit with another
SNIc !!!



Conclusions

- SN 2002ic & 2005gj → CSM interacting SNIc
- natural explanation for the presence of dense, structured CSM
- 1997cy and 1999E are hidden type Ic and possible GRB connection is revived
- Type Ia explanation still viable but need special WD configurations
- if present, CSM interaction in SNIa is only very strong