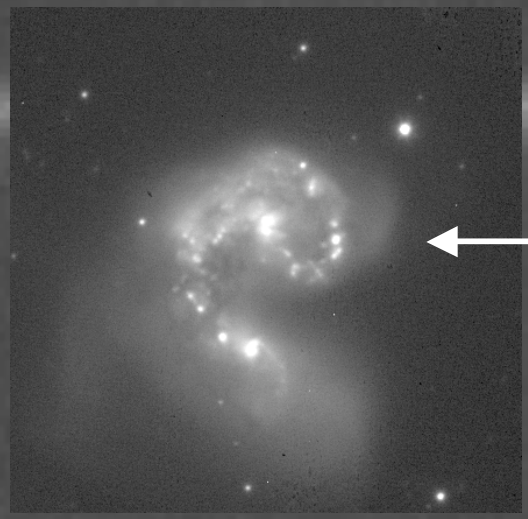


Varied Deaths of Massive Stars: Optical & NIR Properties of SN Ib/c

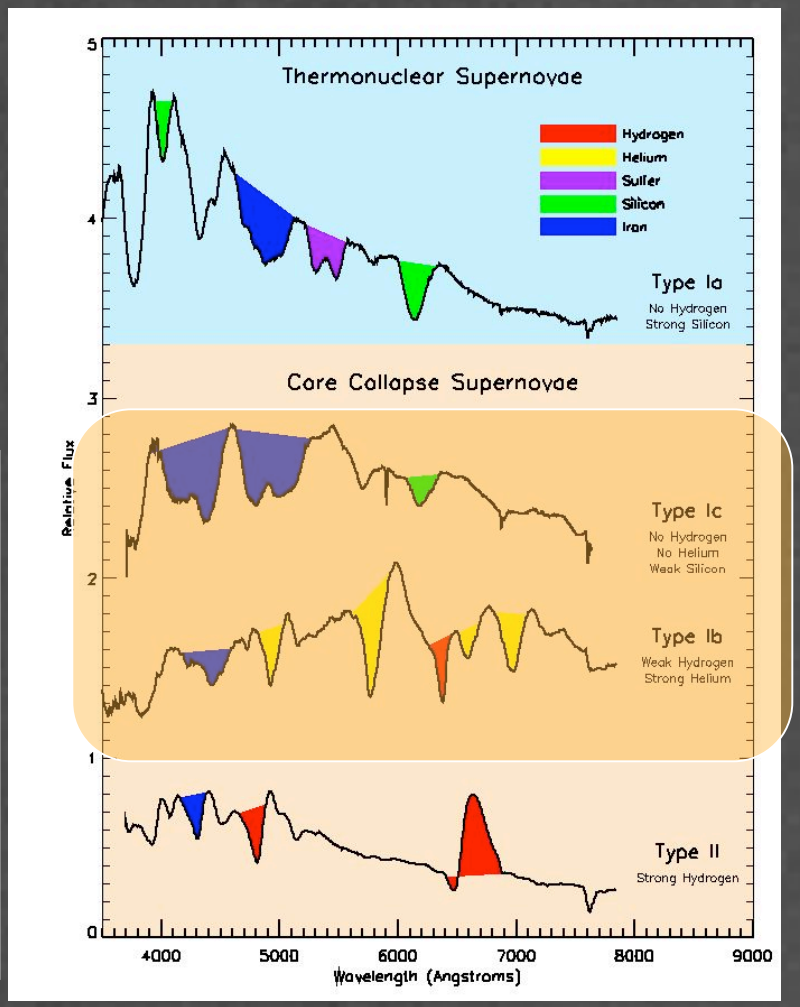
Maryam Modjaz (Harvard/CfA)

Fellow Stellar Death Detectives

- Bob Kirshner (Advisor, CfA)
- M. Hicken, S. Blondin, P. Challis, M. Wood-Vasey, A. Friedman (CfA)
- K. Z. Stanek, J. L. Prieto (Ohio State)
- T. Matheson (NOAO)
- L. Kewley (Hawaii), P. Garnavich (Notre-Dame), J. Greene (Princeton)
- J. Bloom, D. Kocevski (UC Berkeley)

SN Classification

- Spectra:

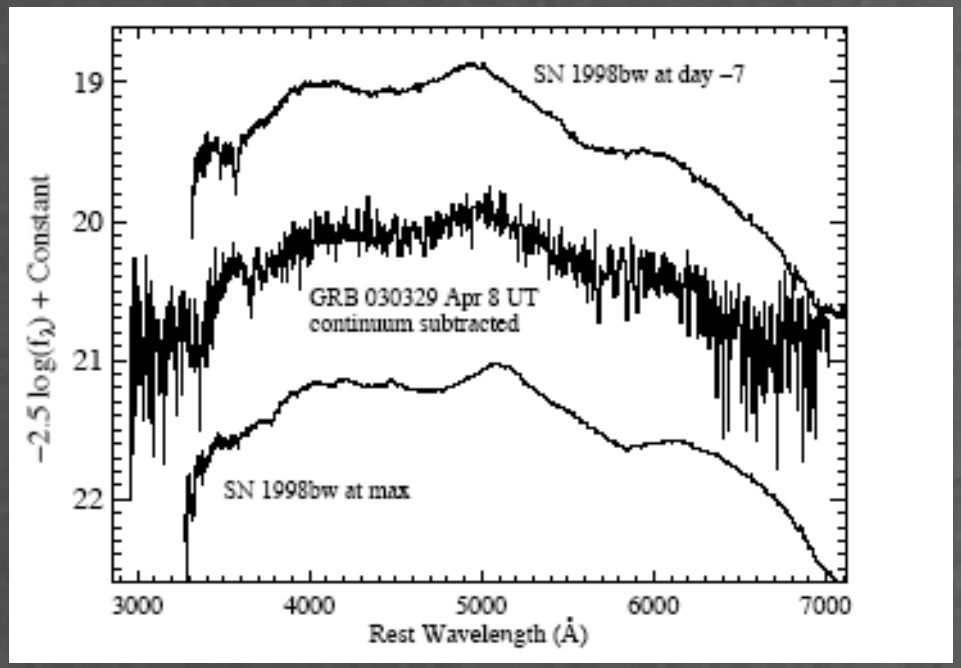


Credit: Dan Kasen

- SN Ib/c Progenitor Models
  - Massive (> 25 $M_{\odot}$) Wolf-Rayet Stars (e.g., Maeder & Conti 2004; Woosely et al. 1995)
  - He stars in binaries (e.g., Podsiadlowski et al. 2004)

SN-LGRB Connection

- Spectroscopic IDs
  - GRB980428/SN98bw (Galama et al. 1998) z=0.0085
  - GRB060218/SN06aj (e.g., Modjaz et al. 2006), z = 0.0335
  - **GRB030329/SN03dh z=0.1685**
  - GRB031201/SN03lw (Malesani et al. 2004), z=0.1005
  - GRB050525/SN05nc: della Valle et al 2006, z=0.6



Stanek et al. (2003), Matheson et al. (2003)

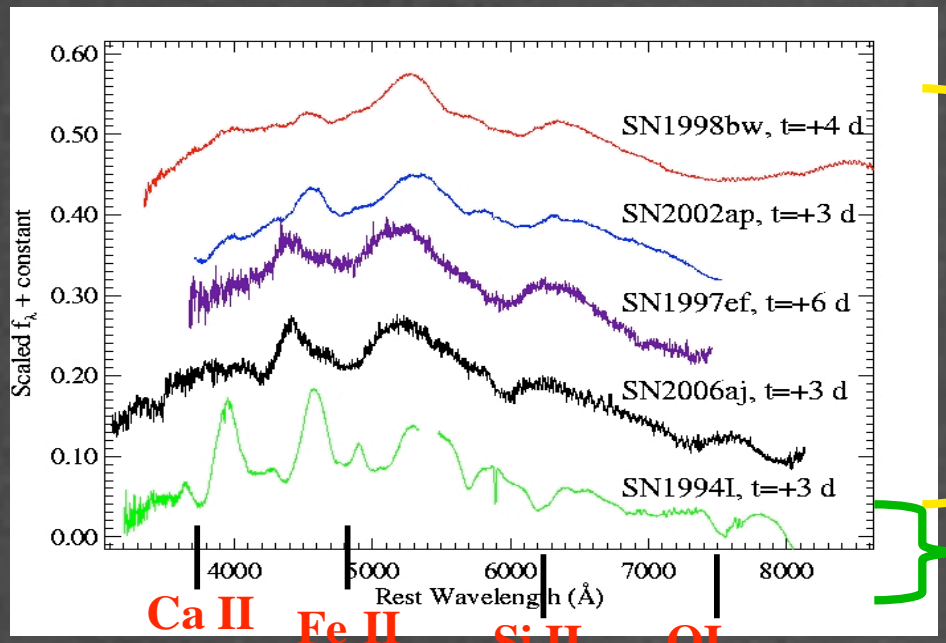
[see also Review (Woosely & Bloom 2006)]

SN-LGRB Connection

Broad Lines (> 30,000 km/s):

KE > 10^{52} erg ~10xKE of normal CC SN

Aka "Hypernovae"



Better:

"Broad-lined" SN Ic (bl SN Ic)

Normal SN Ic

- What fraction?
  - Not all (~15) broad-lined SN Ic have observed GRB viewing angle effects?
  - Soderberg et al (2006): <10% of all SNIb/c are off-axis GRBs

Relevance

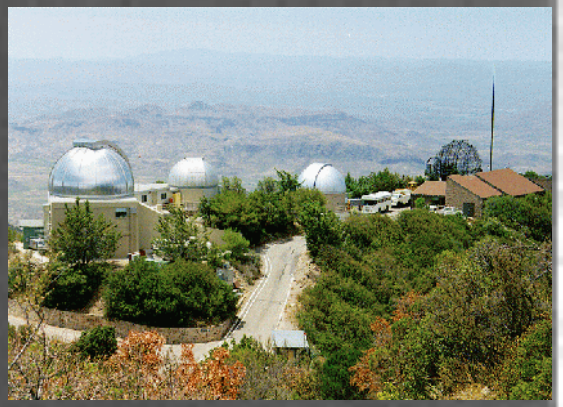
- Deaths of Massive stars
  - Constrain explosion energetics and element synthesis, progenitors and remnants
- Connection of bl SN Ic to GRBs
  - What is the range of SN Ic properties?
  - How aspherical are (normal) SN Ib/c explosions?
- Contamination of high-z SN Ia searches by SN Ic (Homeier 2005)

However, only a handful of well-studied objects

- E.g.,94I, 93J, 99ex, 04aw, bl SN Ic: 98bw, 02ap
- Matheson et al 2001 (mostly spectra)
- Richardson et al. 2006 (pre-CCD SNe)

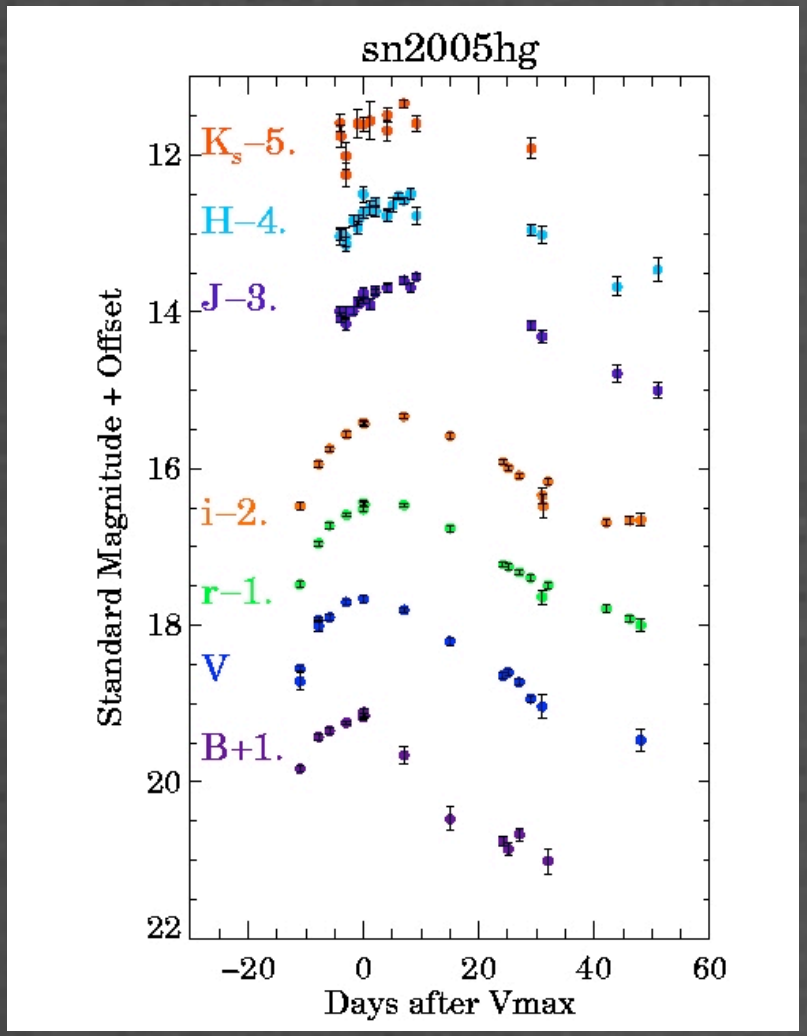
→ NEXT STEP: homogenous & densely covered data set

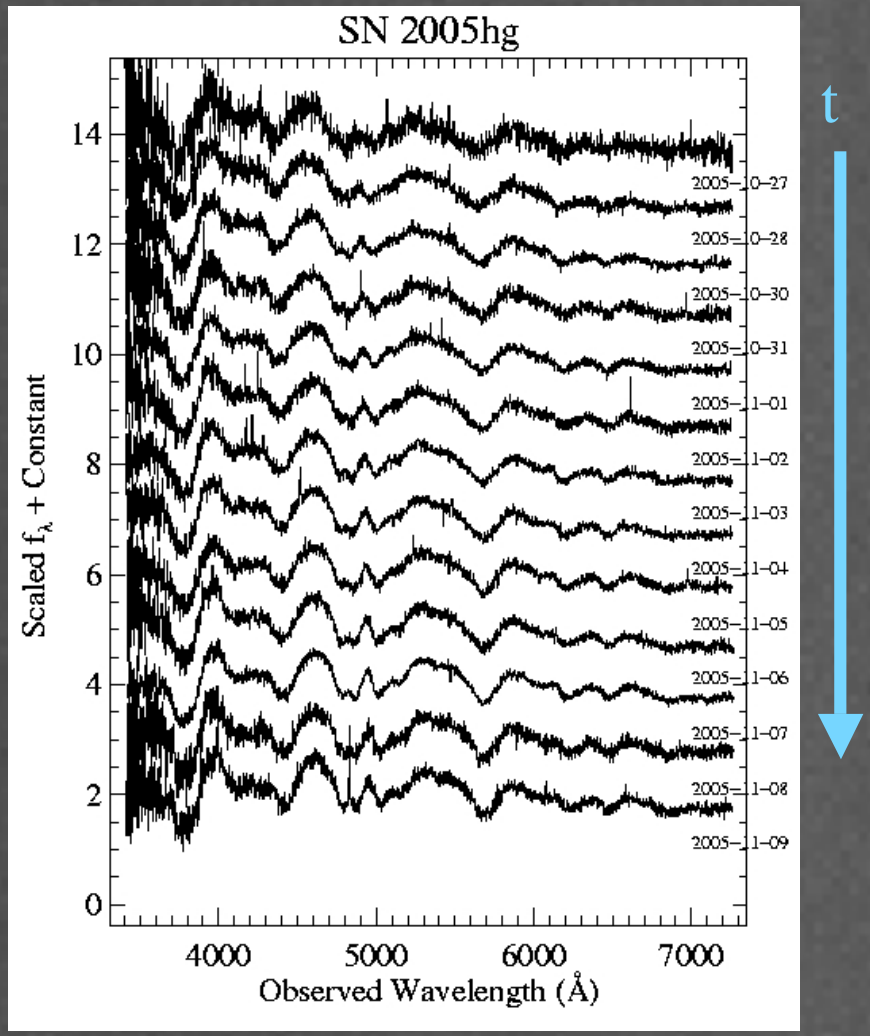
CfA Nearby SN Follow-Up



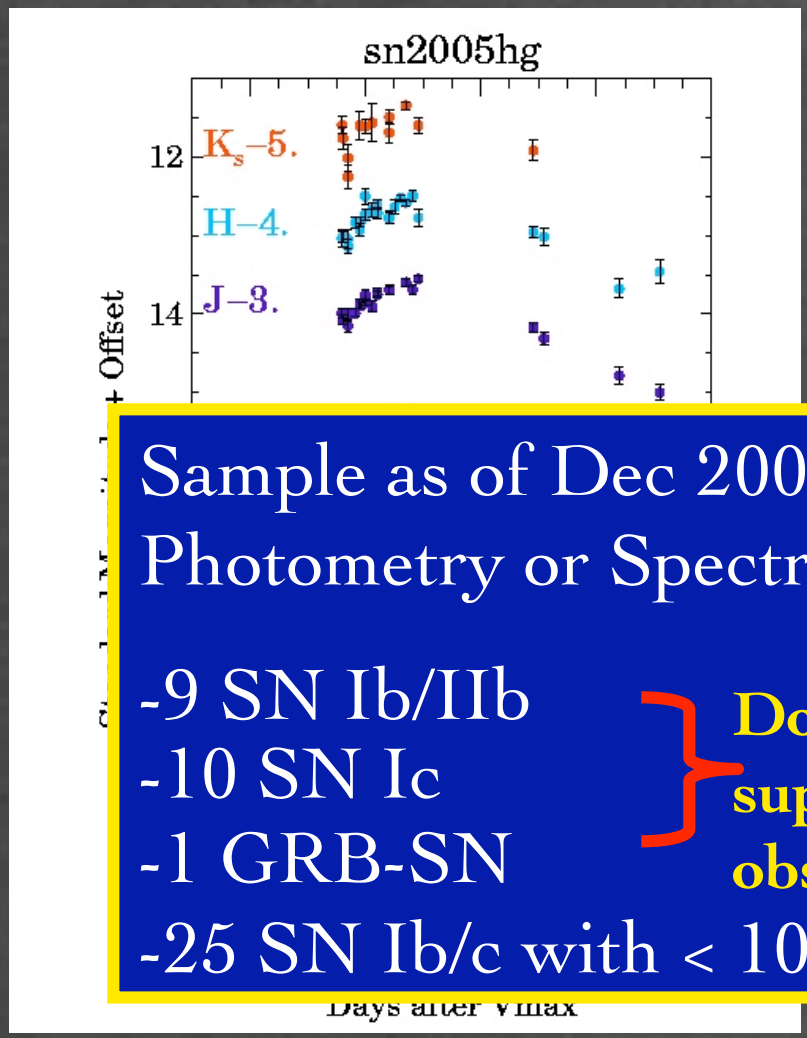
- Spectroscopy: FAST on FLWO 1.5m
  - Effective to m_V ~18.5, 3500 – 7300 Å
  - 3–4 spectra/night, ~300 spectra/year
  - Reduced in the same manner
- Optical Photometry (*UBVr'i'*): FLWO 1.2m
  - 3-4 SN/night, templates, standard star obs
- NIR Photometry (JHK_s): PAIRITEL 1.3m
  - 3-4 SN/night
- Late-time (>3 months) Spectra:
  - MMT (AZ), Magellan (Chile),
  - Gemini-North (Hawaii, GN-2005B/2006A,PI: M.Modjaz)

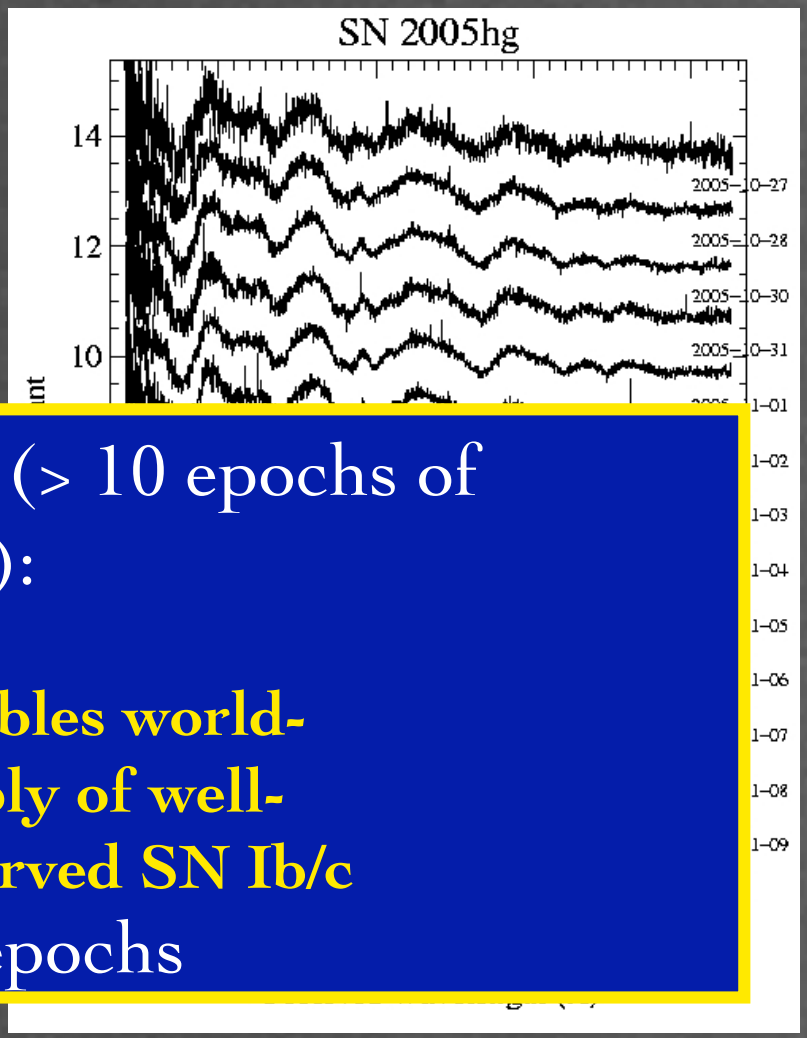
Representative Data





Representative Data





t

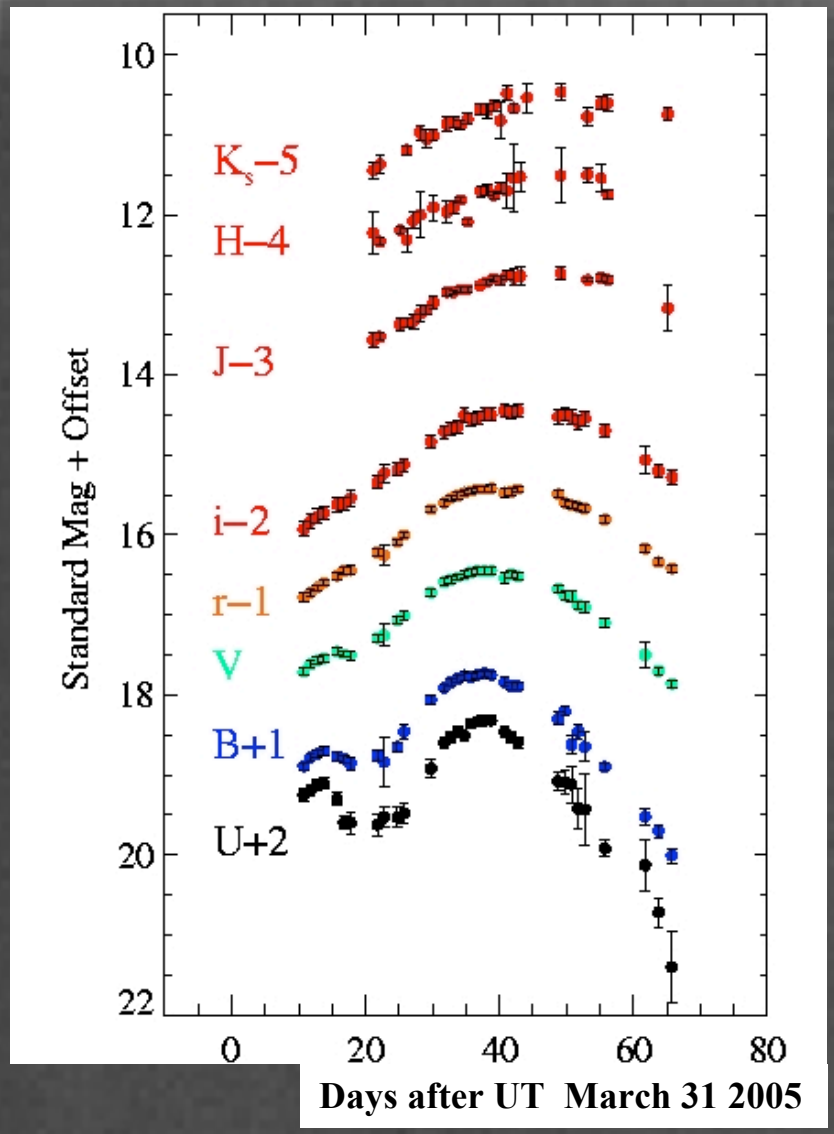
Sample as of Dec 2006 (> 10 epochs of Photometry or Spectra):

-9 SN Ib/IIb
-10 SN Ic
-1 GRB-SN

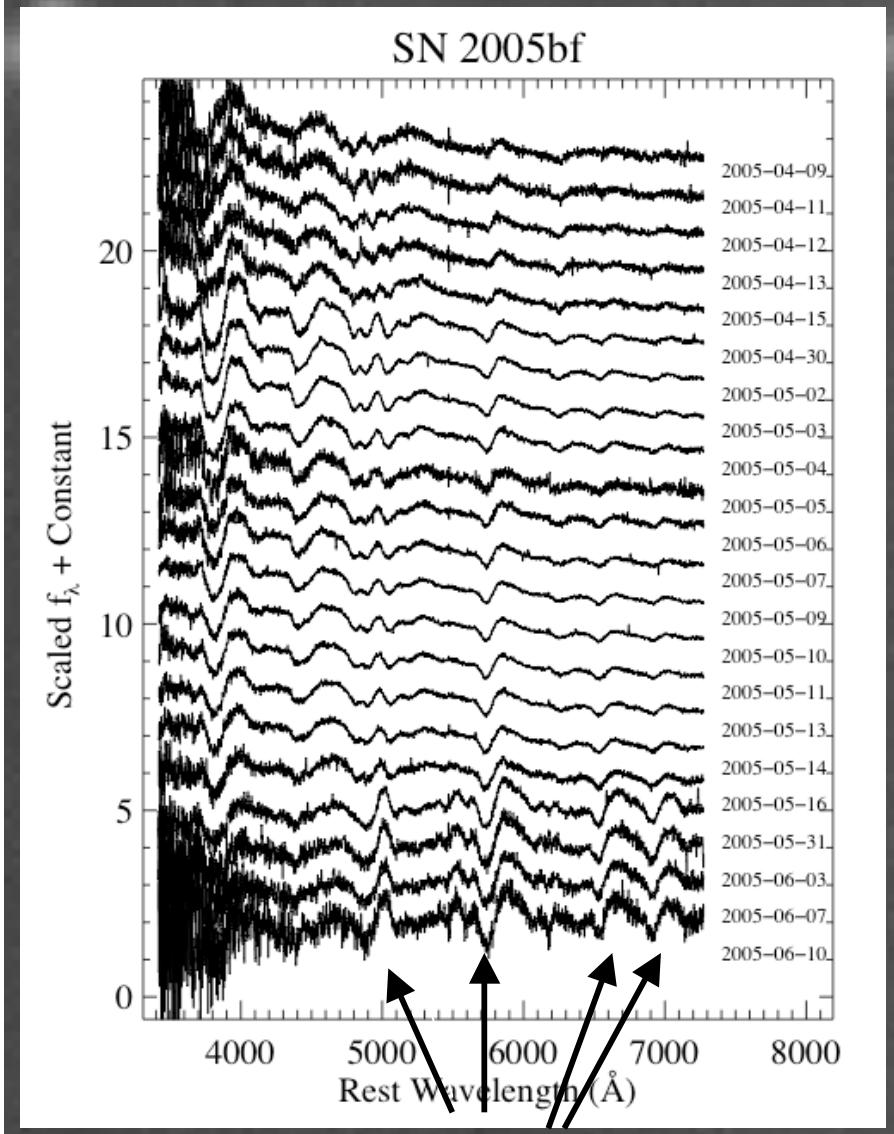
} **Doubles world-supply of well-observed SN Ib/c**

-25 SN Ib/c with < 10 epochs

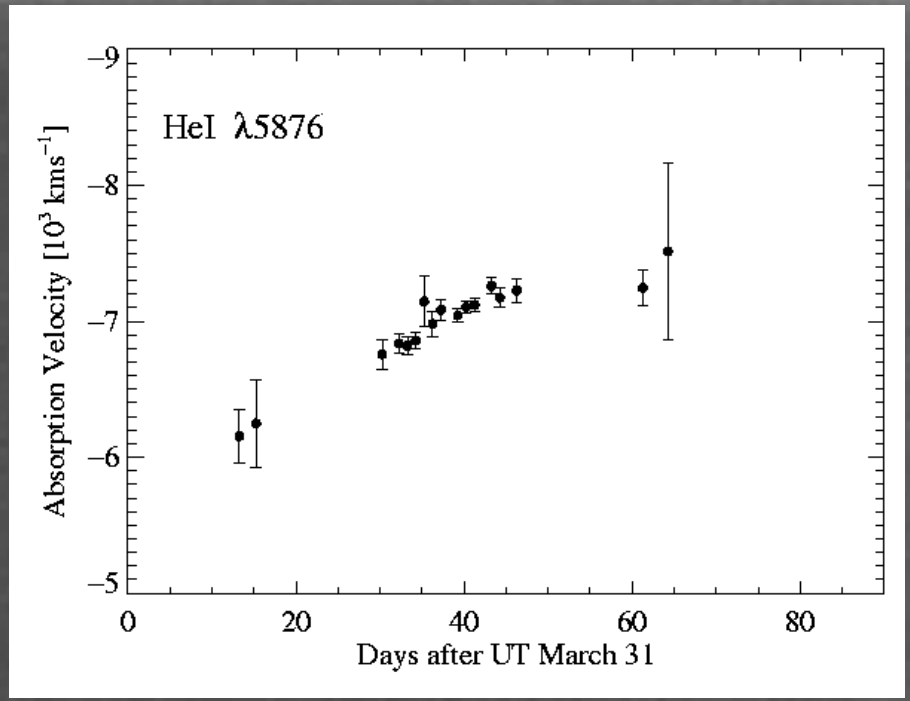
"Maverick": SN 2005bf (Ib-pec)



Tominaga et al (2005)



He lines

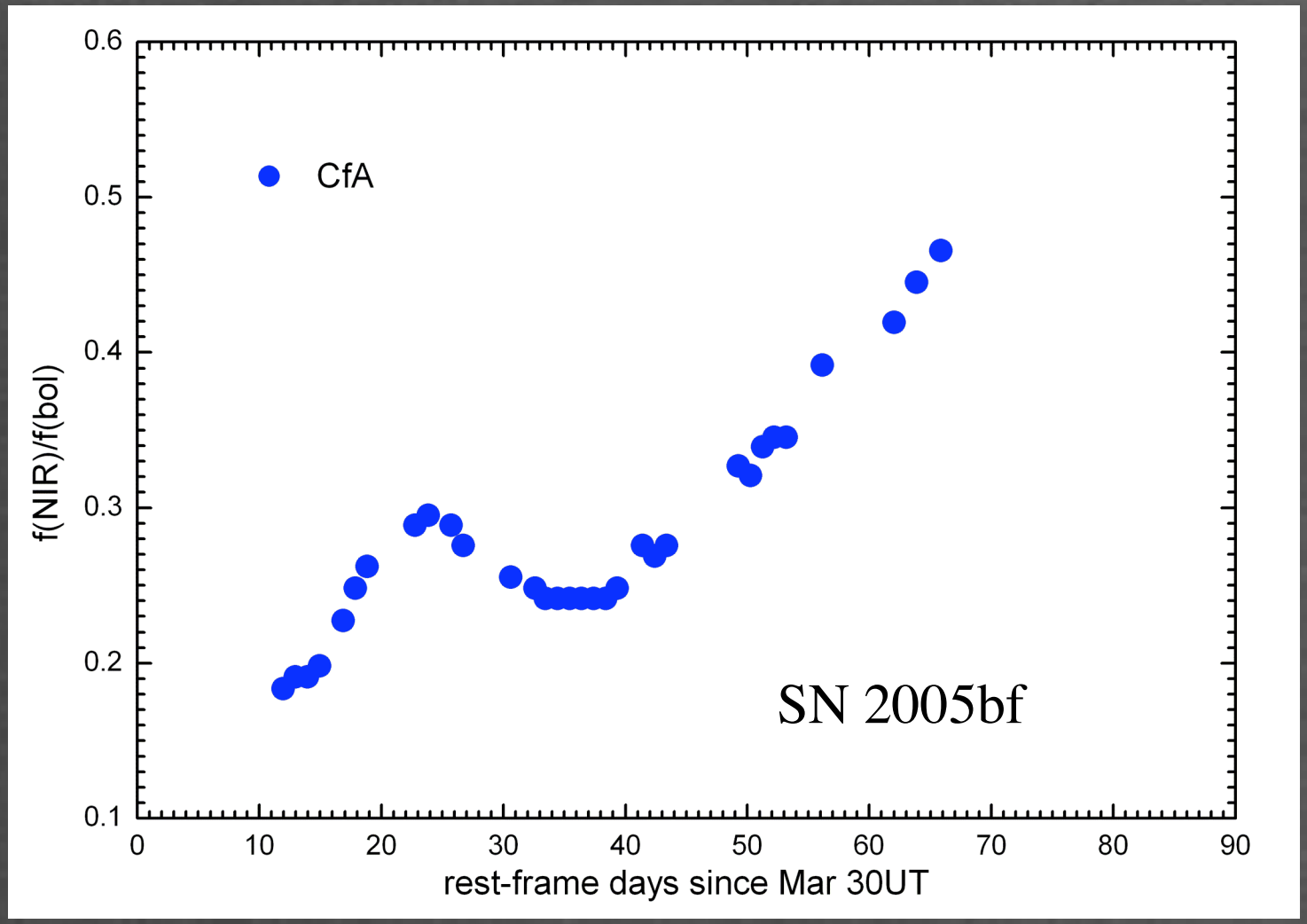


M. Modjaz

Tominaga et al (2005):

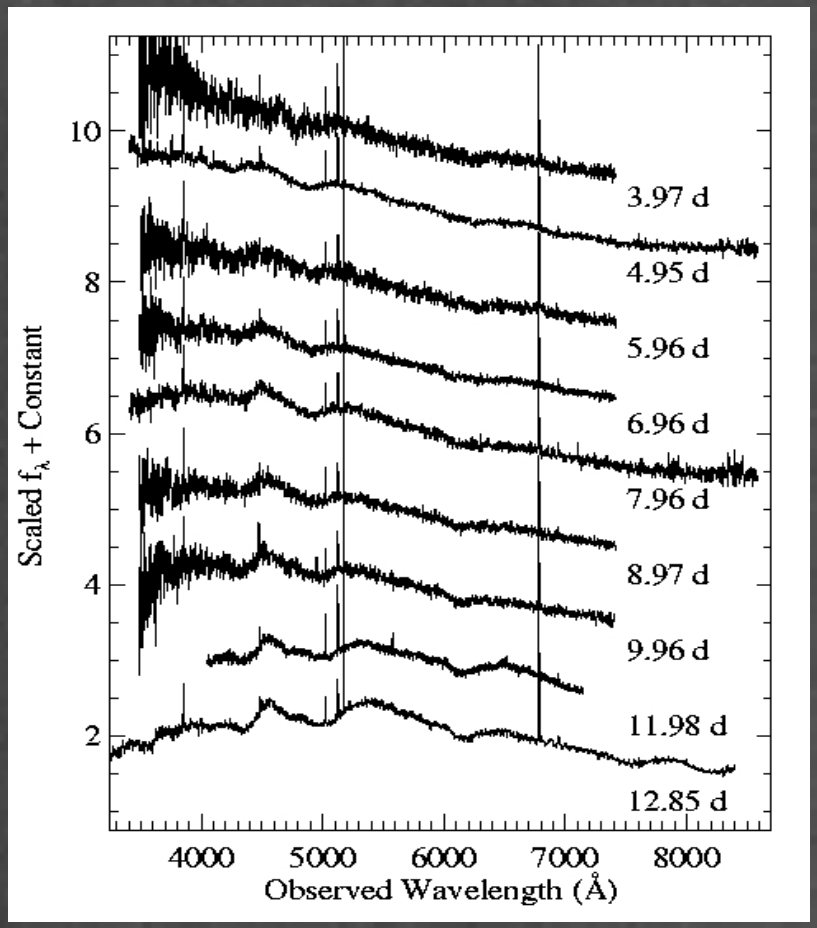
^{56}Ni ~ 0.3 $M_\odot$ M_{ej}~6-7 $M_\odot$, M_{prog}~25-30 $M_\odot$, NS remnant

Importance of NIR contribution



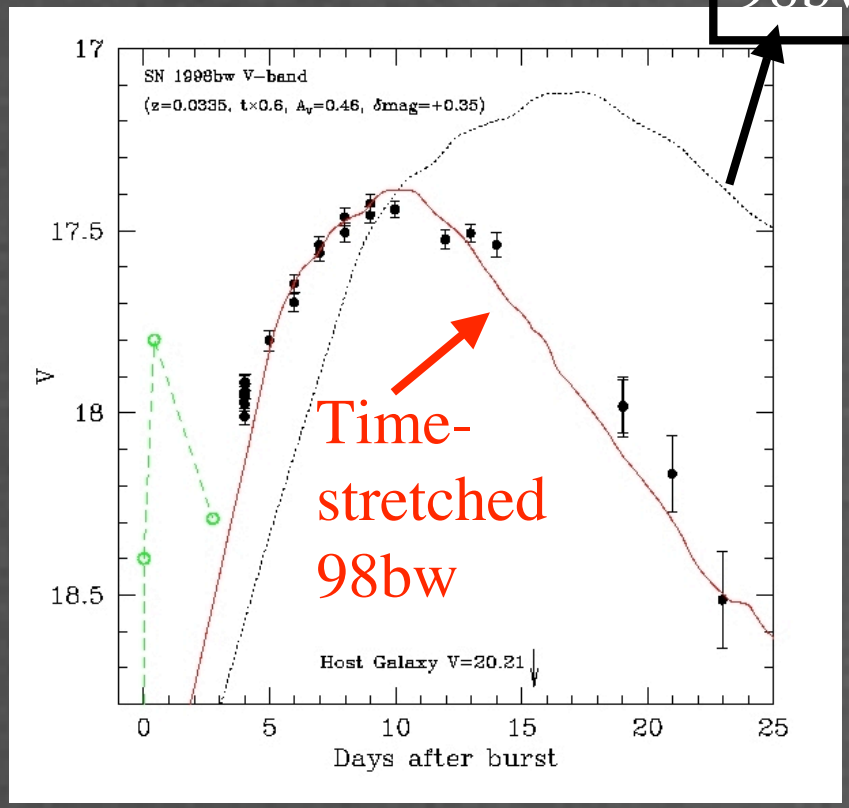
J. Deng, M. Modjaz

GRB060218/SN2006aj



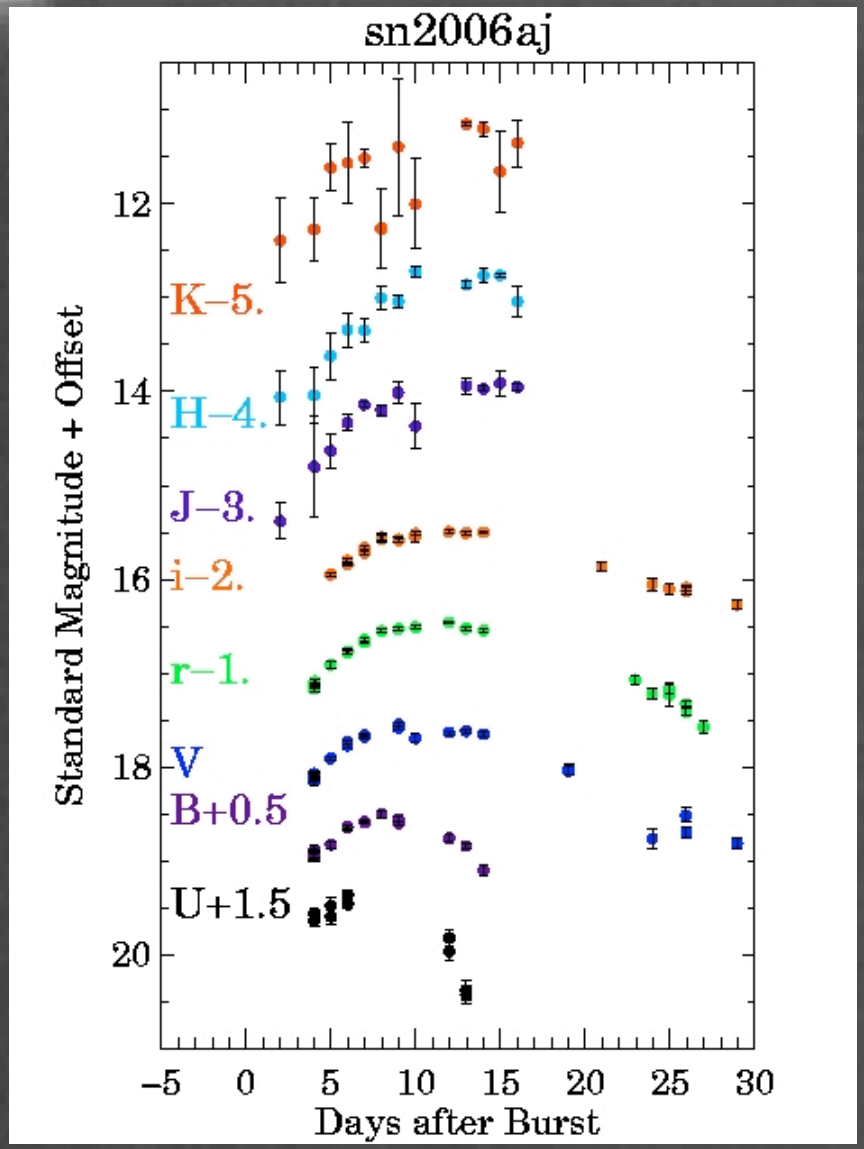
Diversity in SN-GRBs

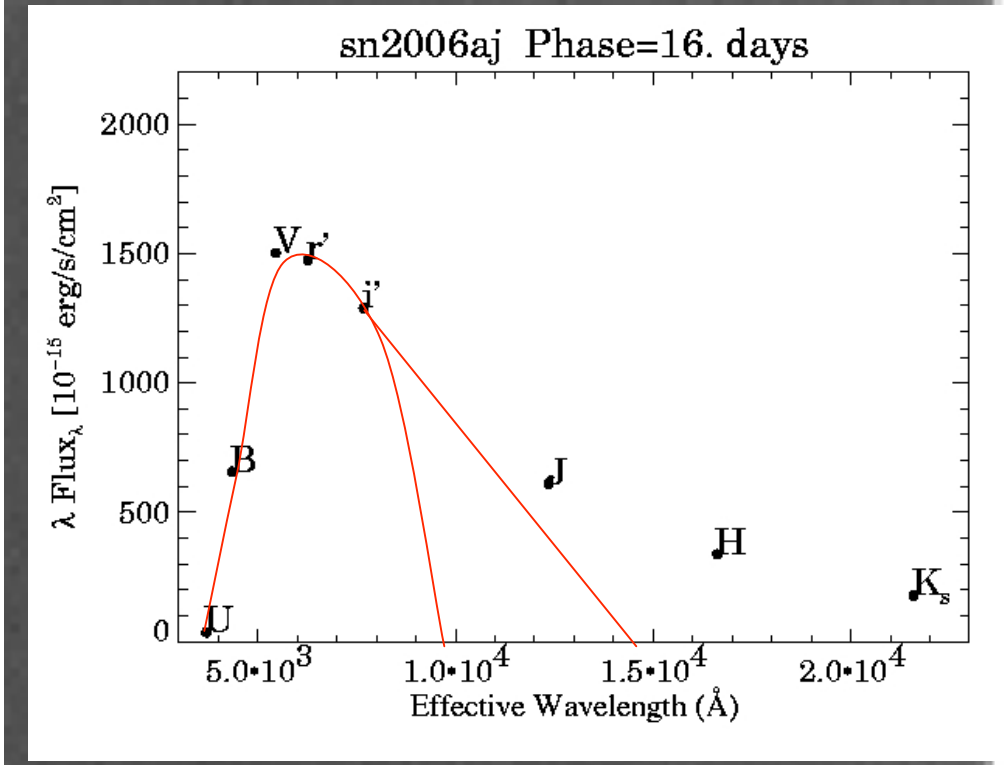
- z = 0.0335, Weak GRB Afterglow
- short risetime (10 days)



Modjaz et al. 2006

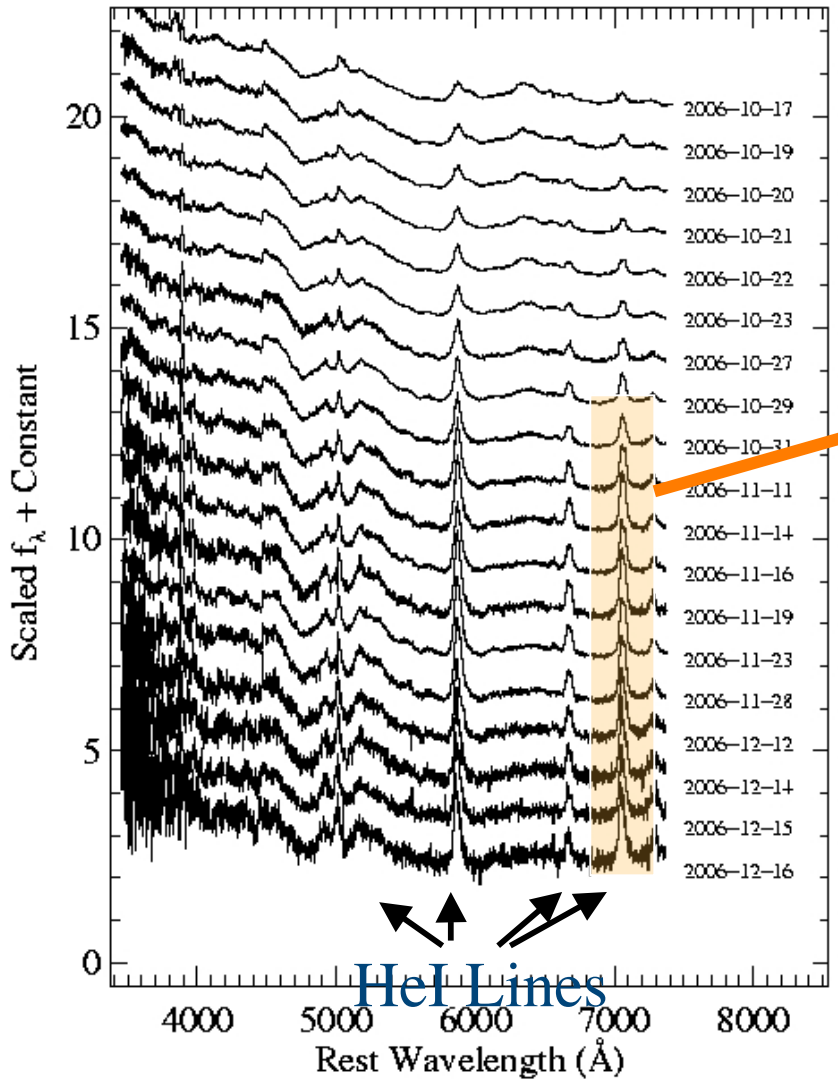
GRB060218/SN2006aj



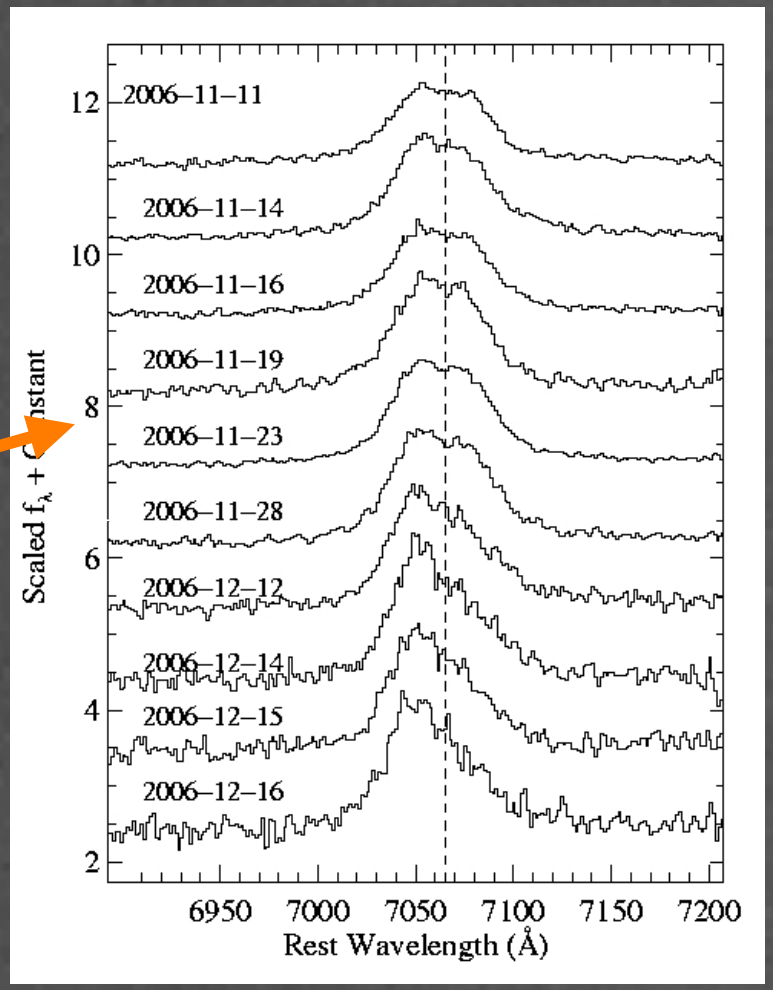


Kocevski, Modjaz et al (ApJ, submitted), Modjaz et al in prep

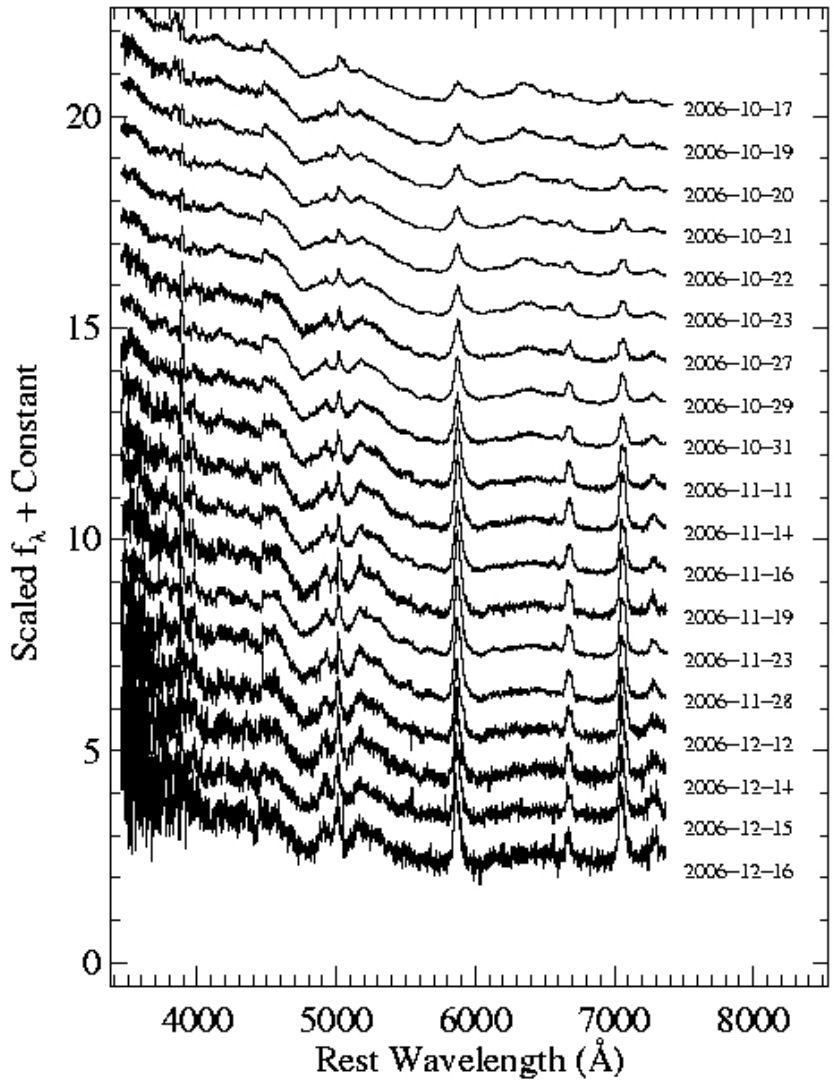
SN2006jc (Ib)

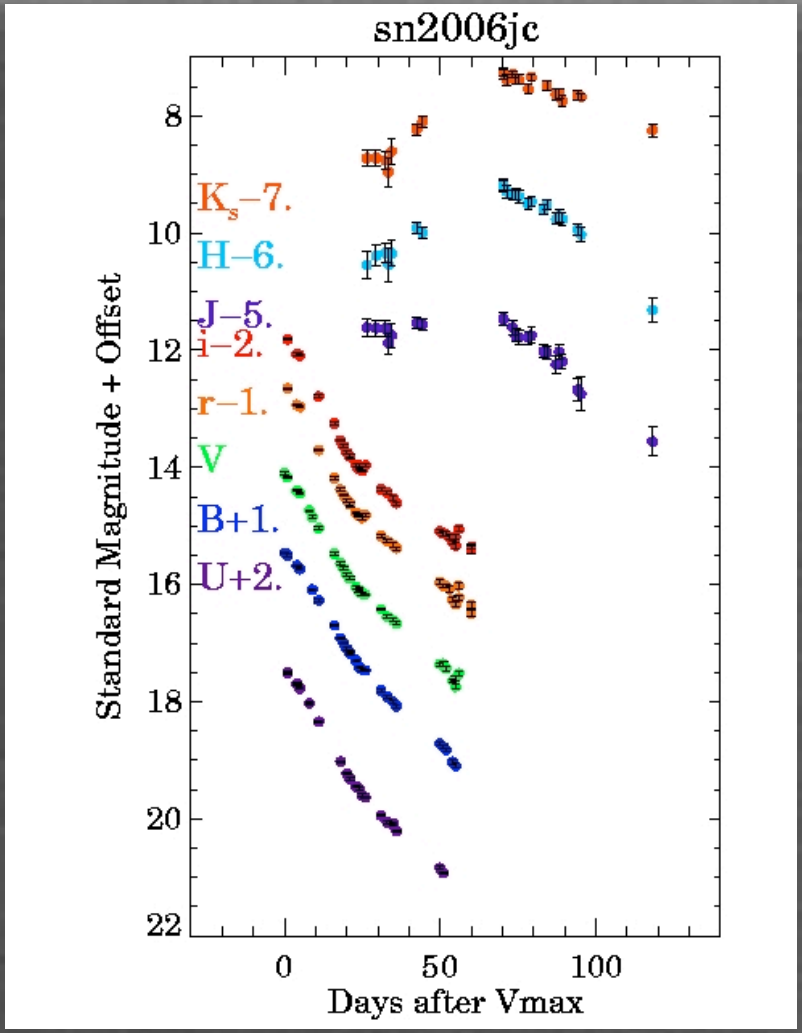


He I 7065

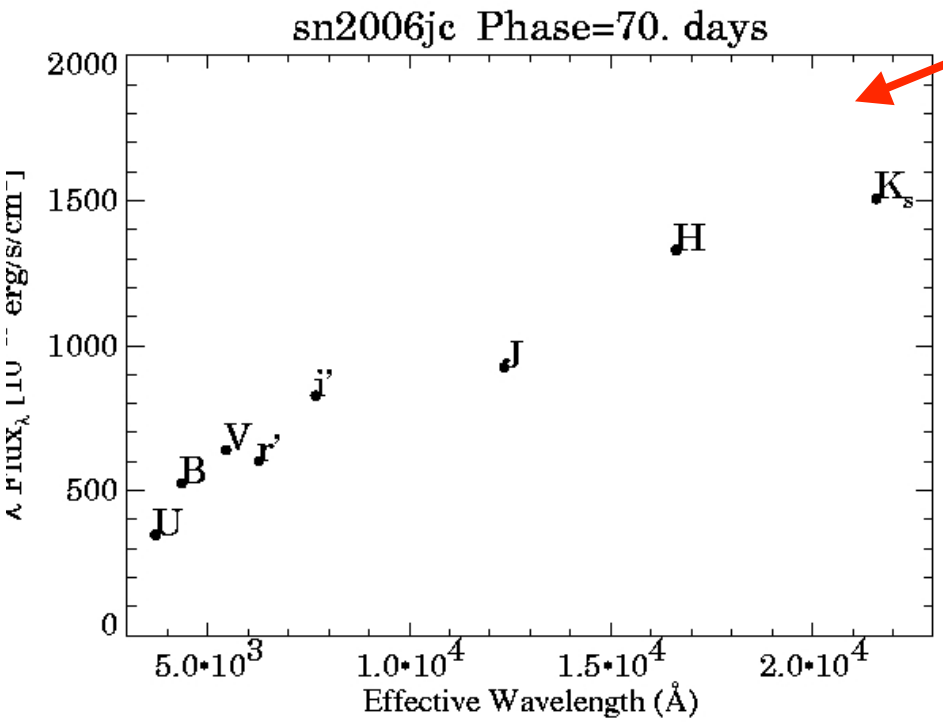


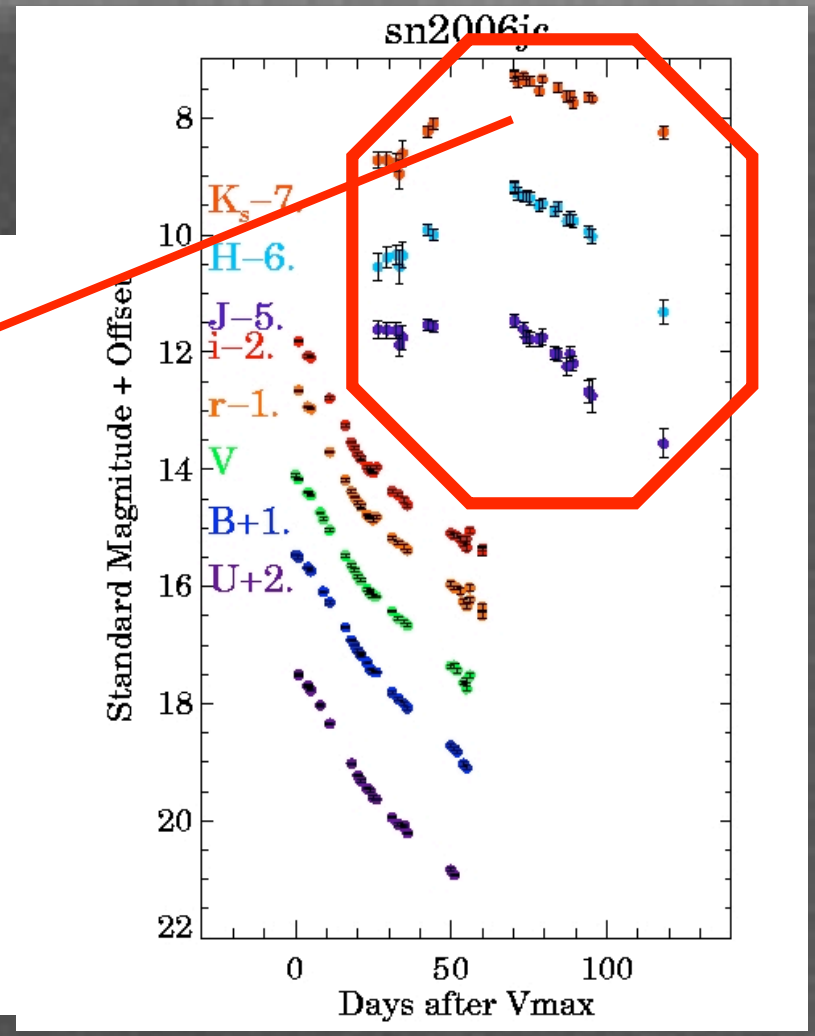
SN2006jc (Ib)


Scaled f_λ + Constant
Rest Wavelength (Å)
0
5
10
15
20
4000
5000
6000
7000
8000
2006–10–17
2006–10–19
2006–10–20
2006–10–21
2006–10–22
2006–10–23
2006–10–27
2006–10–29
2006–10–31
2006–11–11
2006–11–14
2006–11–16
2006–11–19
2006–11–23
2006–11–28
2006–12–12
2006–12–14
2006–12–15
2006–12–16


sn2006jc
Standard Magnitude + Offset
Days after Vmax
K_s–7.
H–6.
J–5.
i–2.
r–1.
V
B+1.
U+2.
8
10
12
14
16
18
20
22
0
50
100

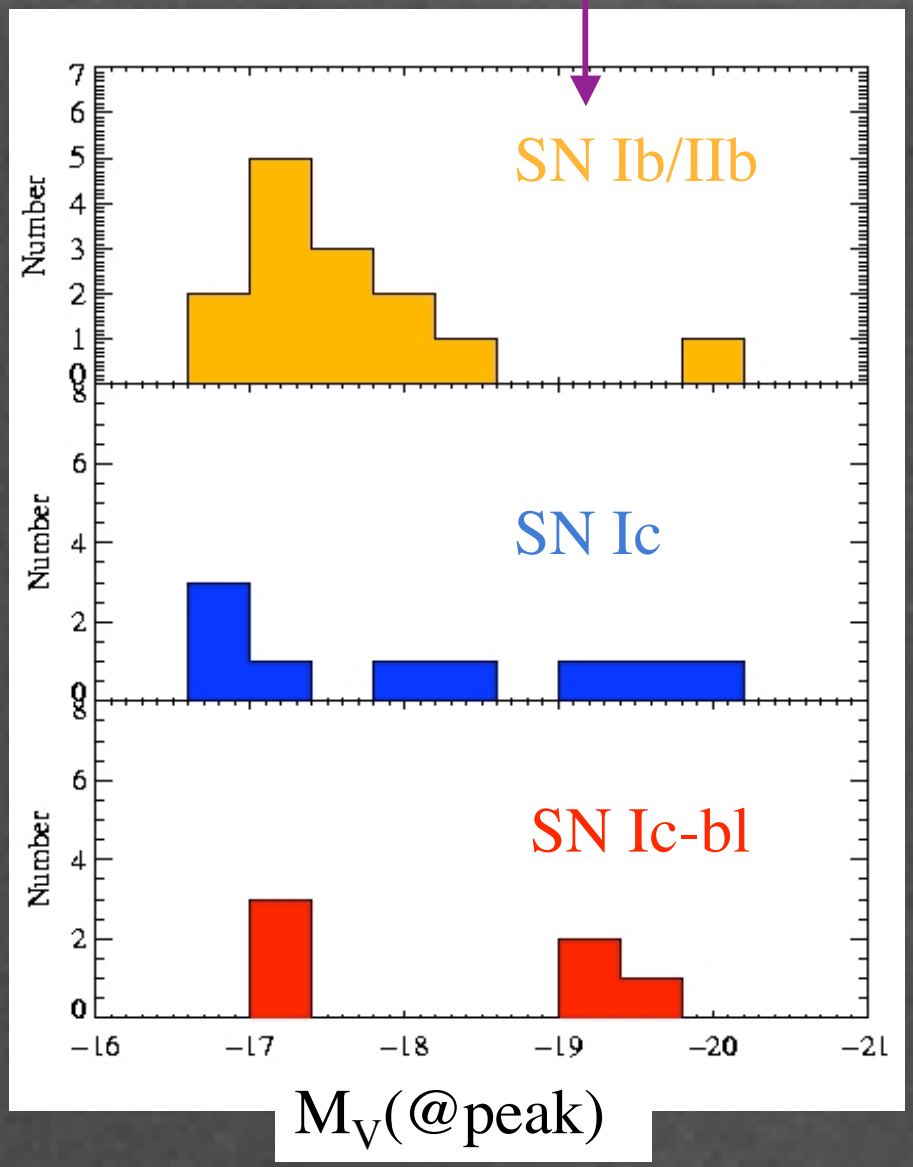
SN2006jc (Ib)





NIR Excess -> Dust emission

Analysis: a) Distribution of M_V



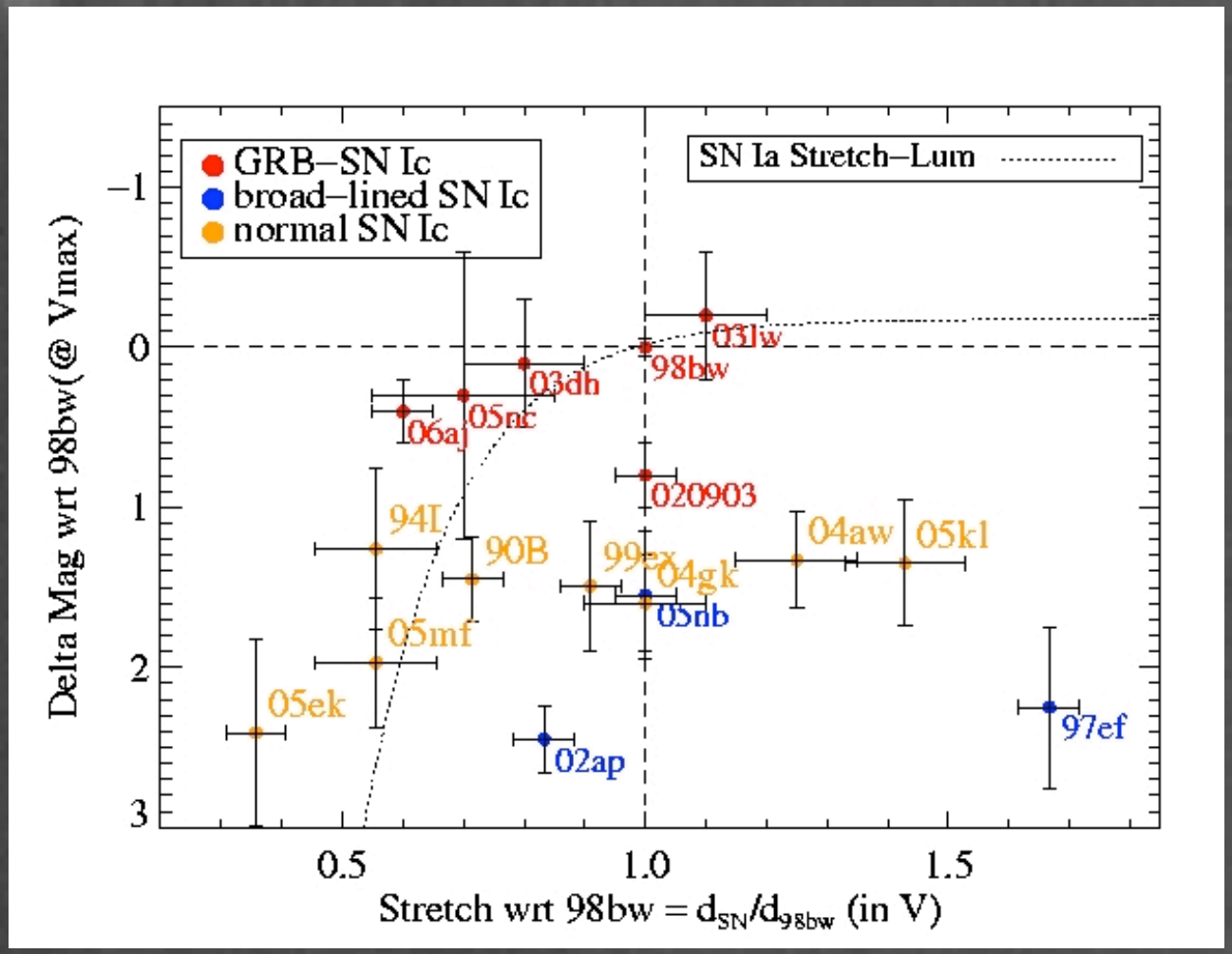
1) **Large range of mags (~4 mags)**

2) **SN Ib/IIb on average fainter than SN Ic**

3) **Broad-lined SN Ic not necessarily more luminous than normal SN Ib/c**

Richardson et al. (2006) & my sample

b) Luminosity & LC shape

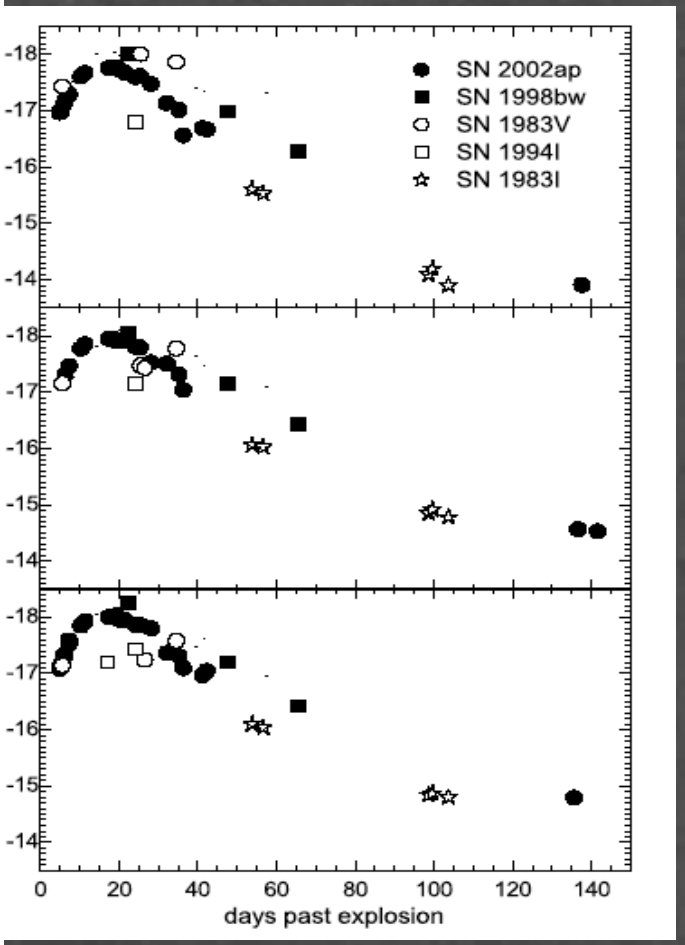


Modjaz et al. in prep

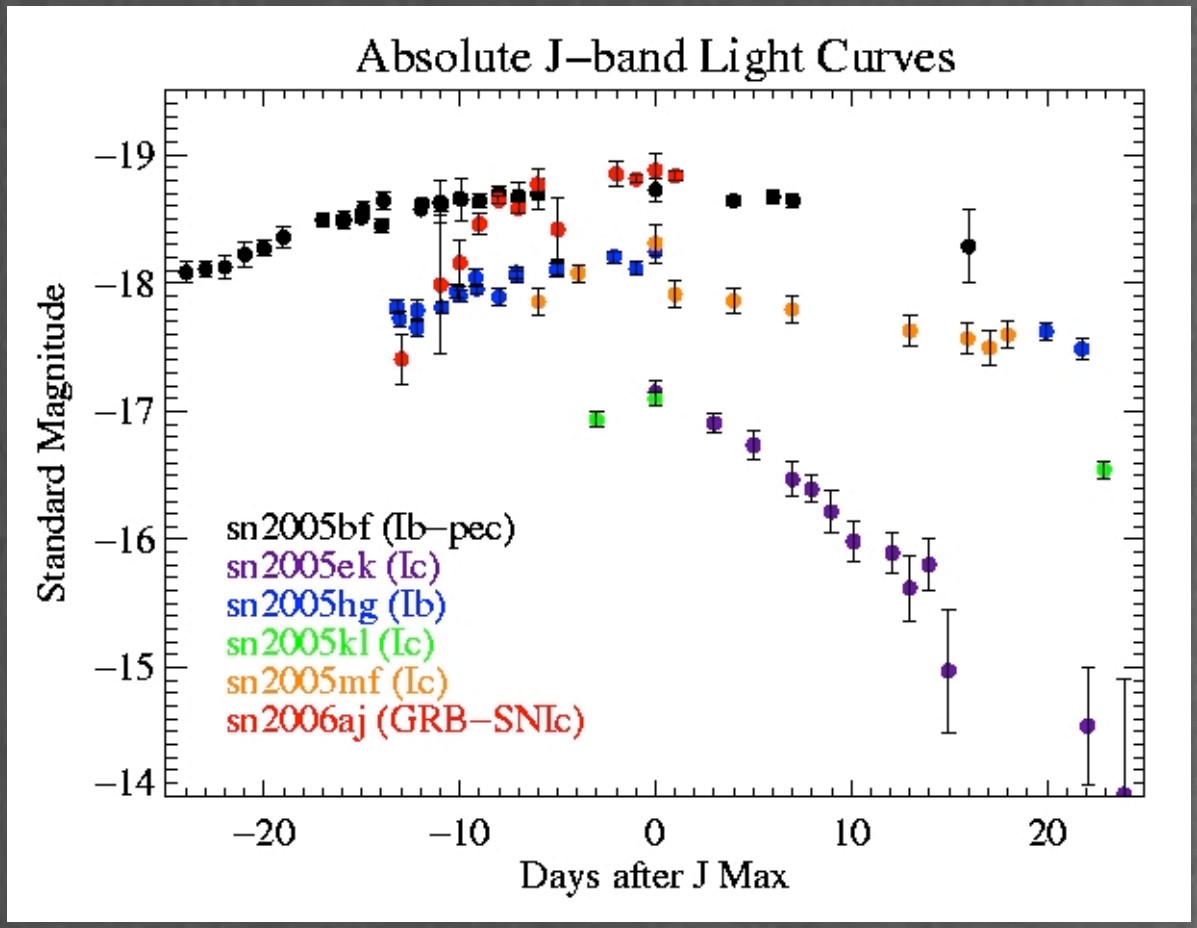
1) No Lum-LC shape relationship for SN Ic

2) GRB-SN & broad-lined SN have similar spectra but GRB-SN are more luminous (~2mag)

IR photometry



Yoshii et al (2004)



Modjaz et al in prep.

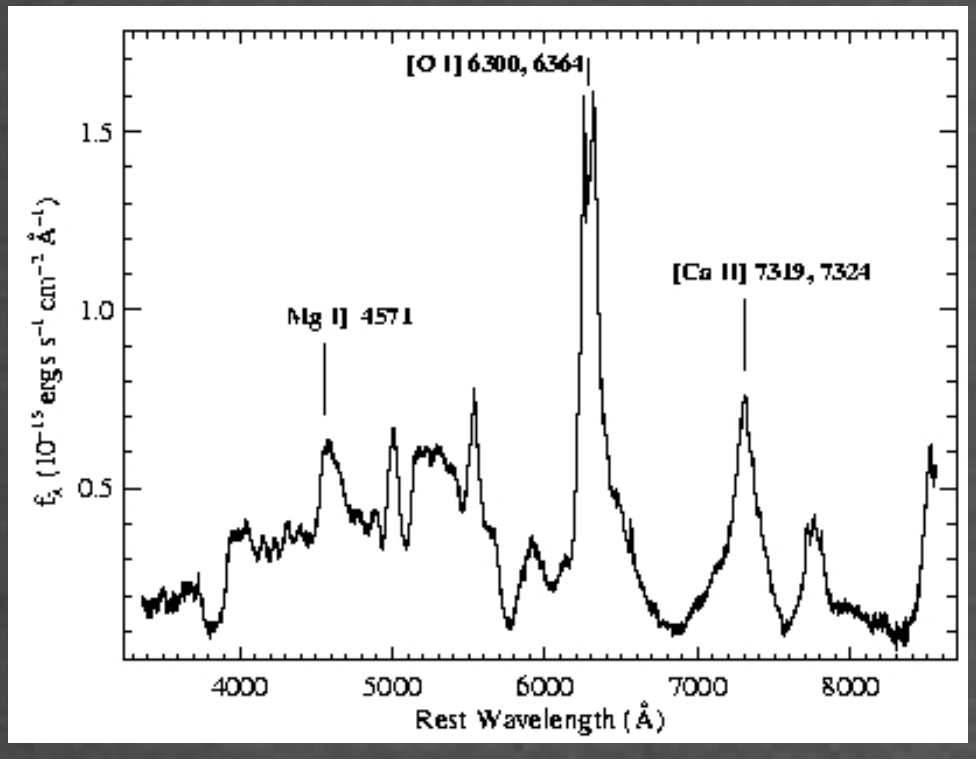
Late-time Line Diagnostics

Probe deeper than early-time spectra:

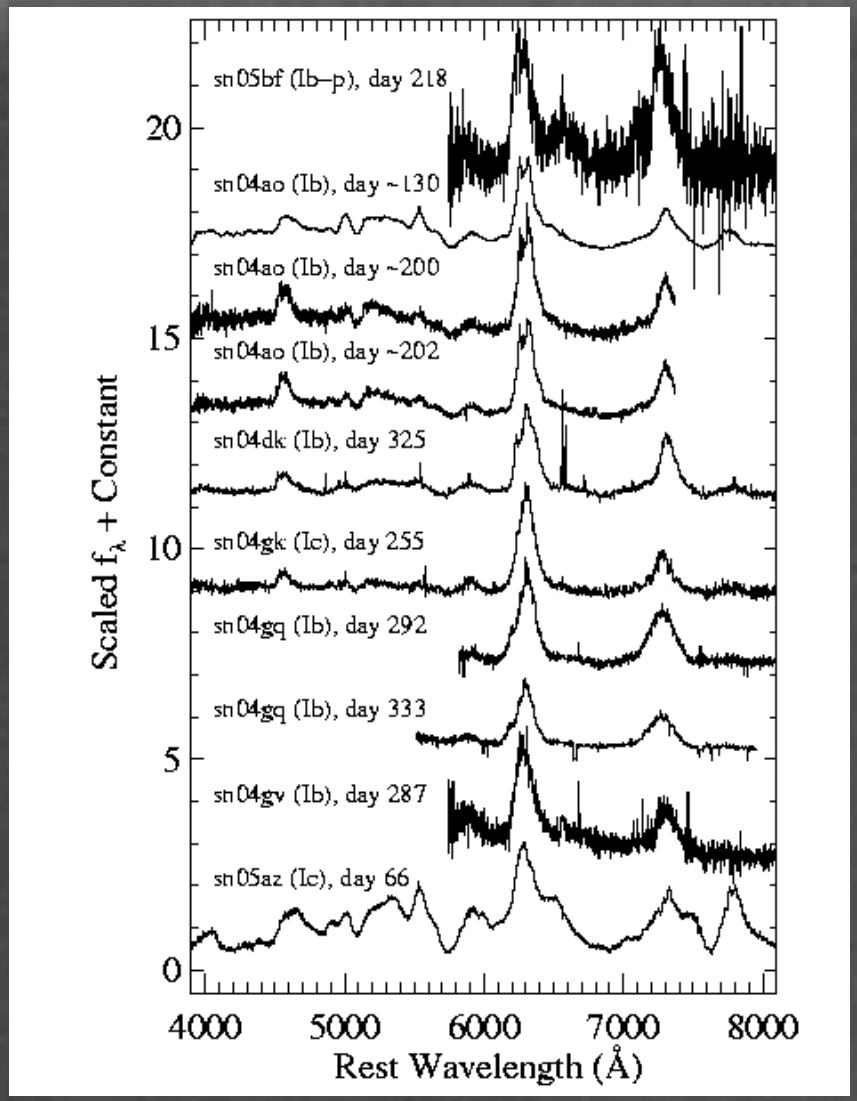
1) Line Ratios: state of core before explosion
(Foley et al. 2003, Maeda et al. 2005)

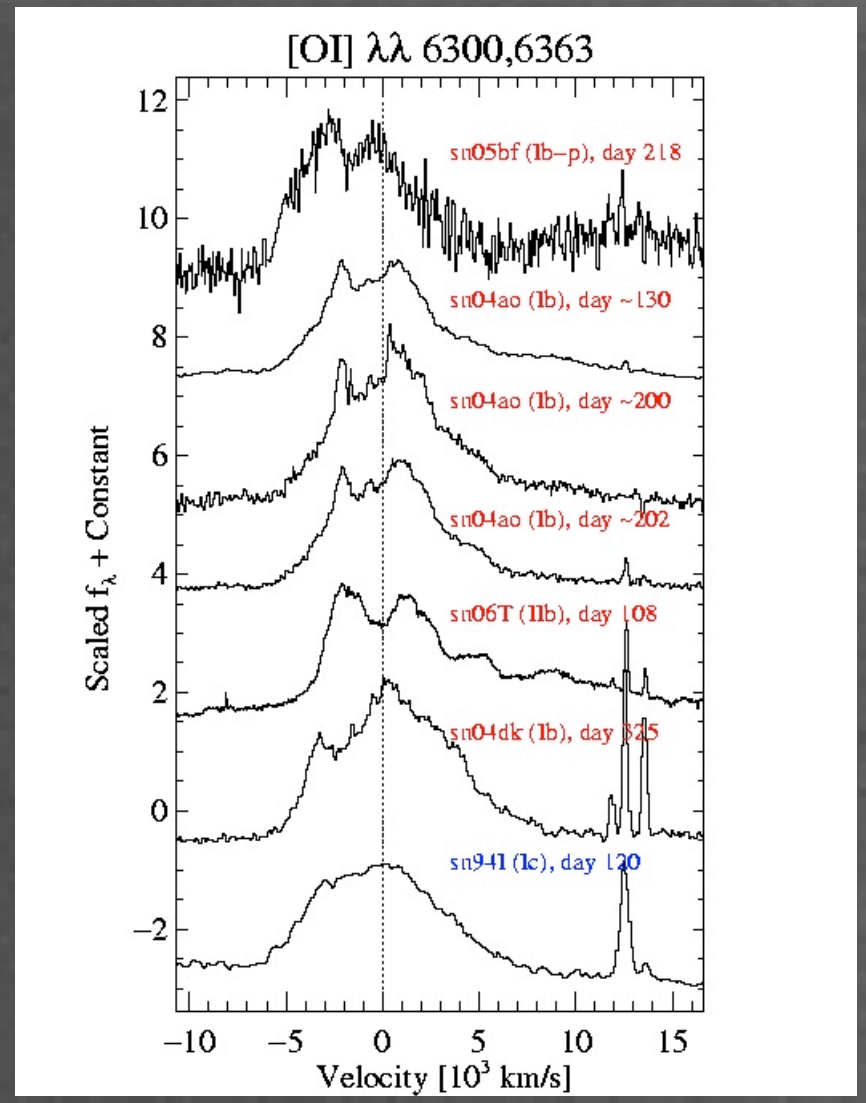
2) Line shape: geometry of explosion
(Mazzali et al. 2005, Maeda et al. 2006)

SN 2004ao
(SN Ib)



Late-time Spectra (~10 SN Ib/c)

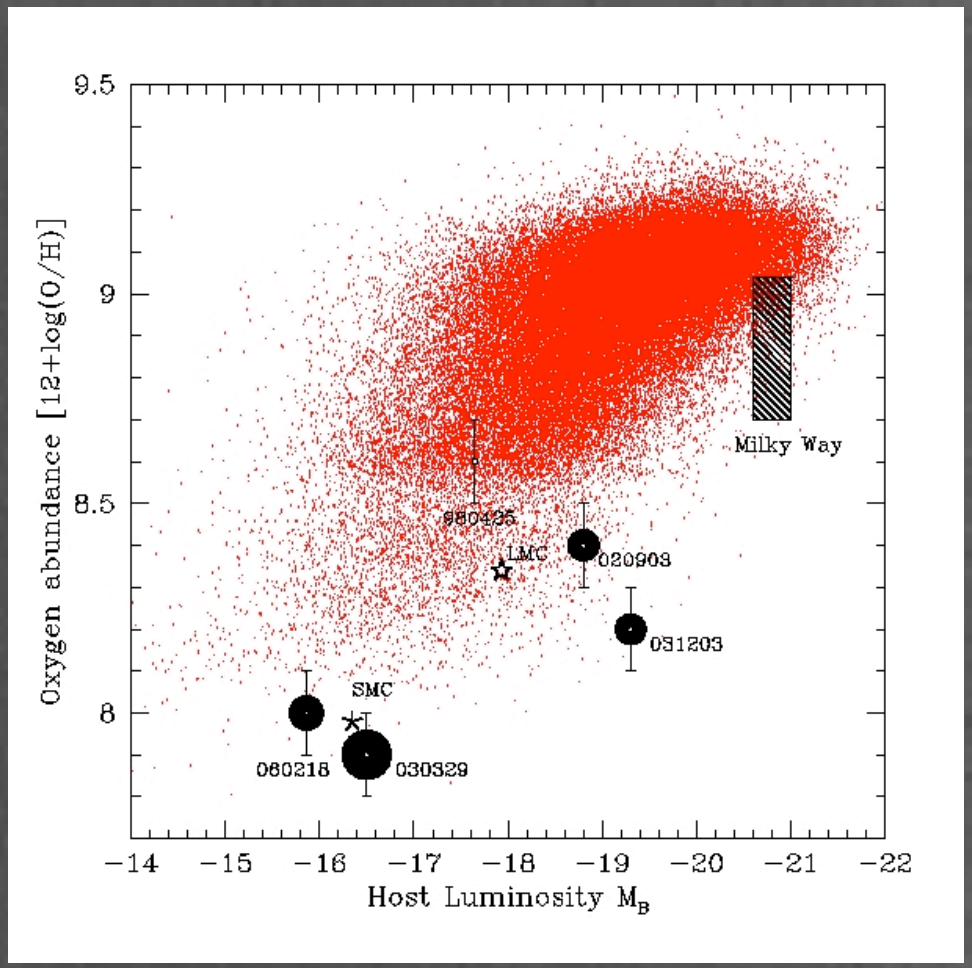




Modjaz et al. in prep

Host galaxies of LGRBs

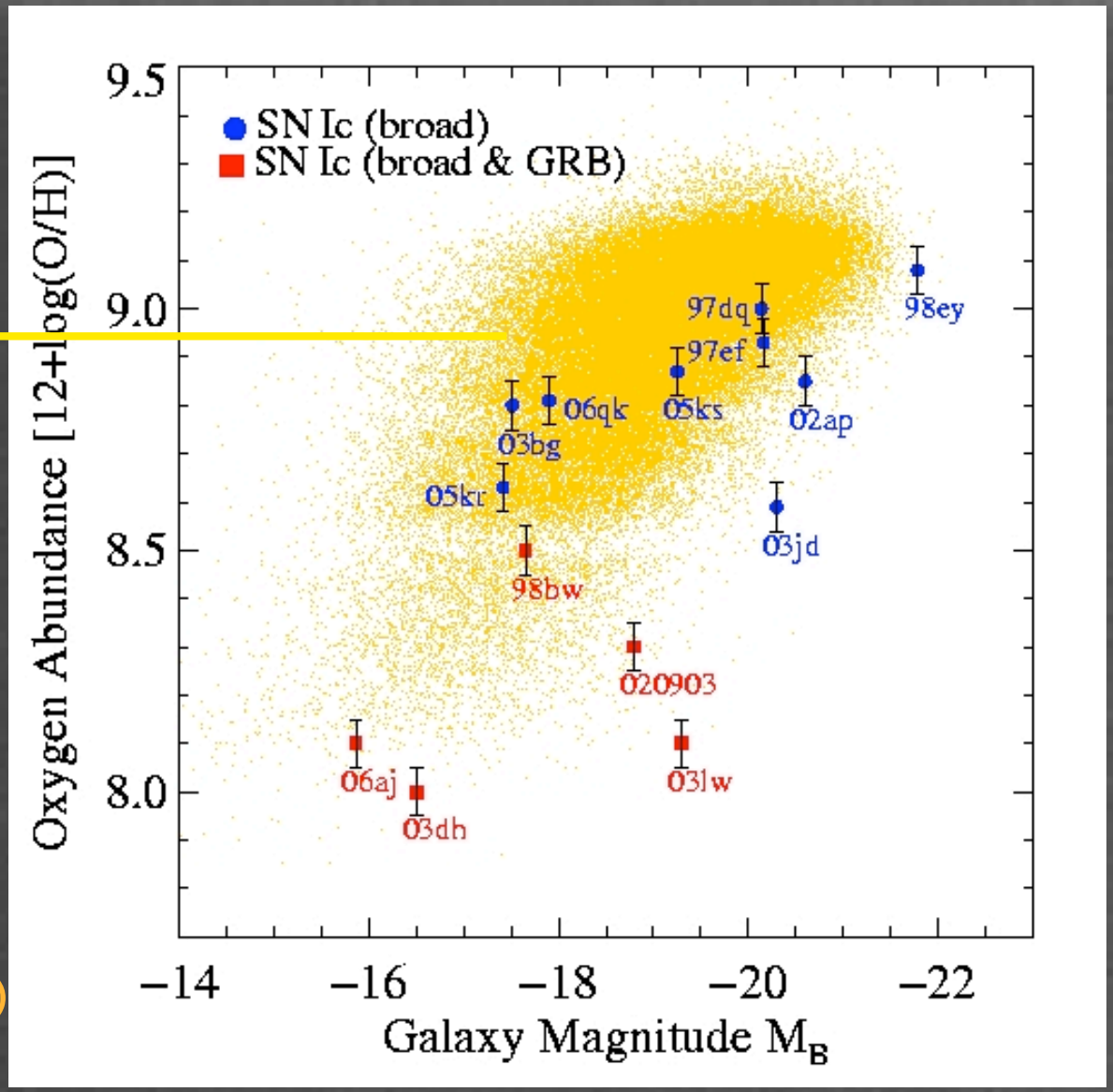
- Low-metallicity, sublum., irregular:
  - @ low-z (Sollerman et al. 2005, Gorosabel et al 2005, Modjaz et al. 2006)
  - @ high-z (Fruchter et al. 2006, Le Floc'h et al 2003)
  - GRB mechanism: Hirshi et al. (2005), Langer & Norman (2006), Woosley & Heger (2006)



Stanek et al (2007)

Host galaxies of GRB/SN and broad-lined SN Ic

Local SDSS galaxies



Modjaz et al.

(AJ submitted, astro-ph/ 0701246)

Conclusions

- Spectroscopic & photometric dataset for SN Ib and Ic is comprehensive, extensive & well time-sampled (Note: SN2005bf, SN2006aj, SN2006jc)
- NIR is important:
  - Contribution to SED
  - Dust signature
- Asphericity in even normal SN Ib/c [consistent with polarization studies & theory]
- Environs of broad-lined SN Ic have higher Z than those of SN-GRB): low Z key factor for GRB-jet