Early-time light curves of Type Ib/c supernovae from the SDSS-II Supernova Survey

(Taddia et al. 2014, A&A, resubmitted)

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Outline

1) The SDSS-II SN Ib/c sample

2) Early light-curve shape of SNe Ib/c (rise time, Δm_{15})

3) Bolometric properties (L, T_{BB}, R_{ph}) and explosion parameters (E_K, M_{ej}, ^{56}Ni mass, R)

4) ^{56}Ni mixing and early-time plateau

5) Future iPTF/ZTF observations of SNe Ib/c

SDSS-II sample of SNe Ib/c

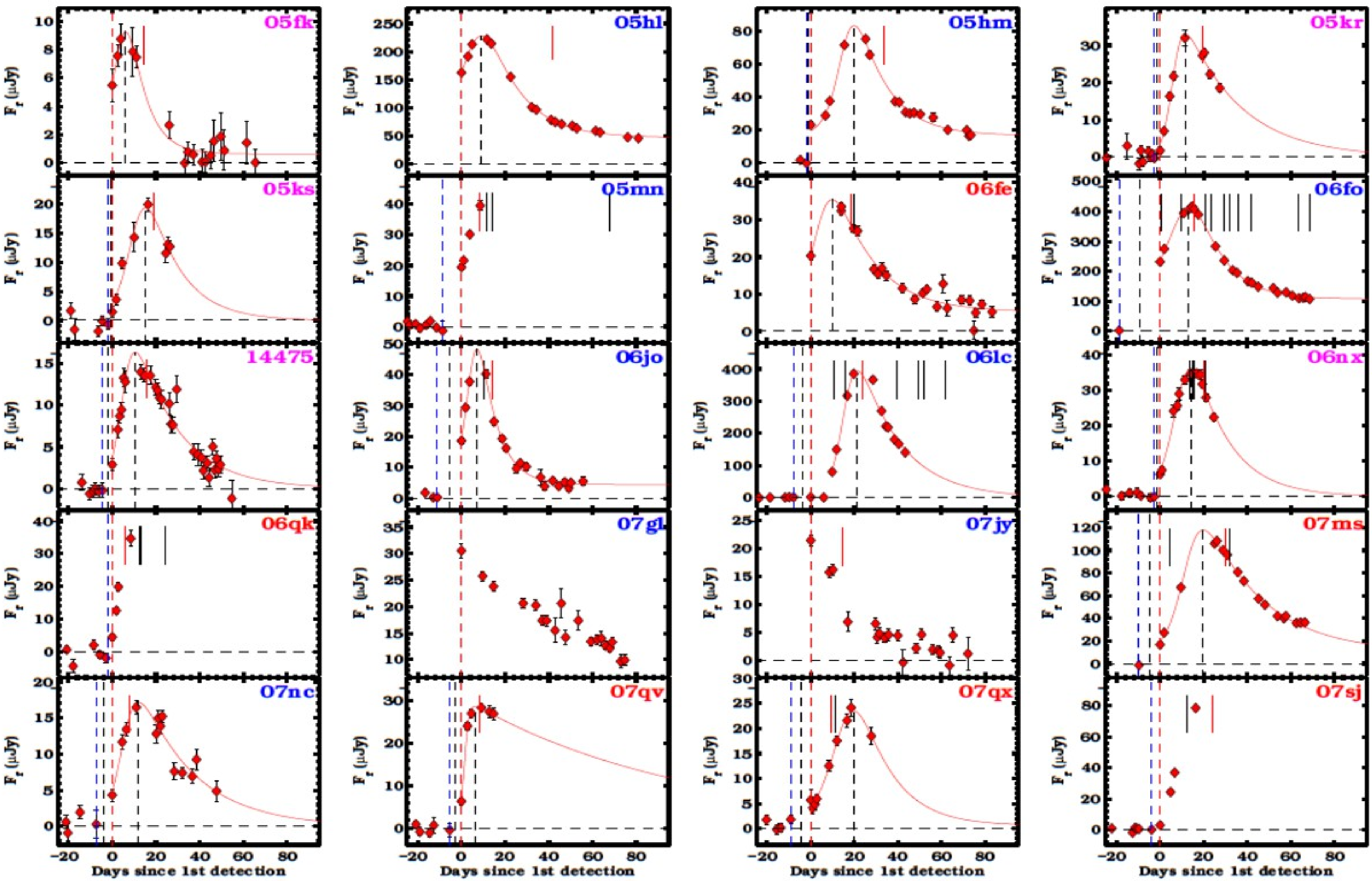
20 SNe: 9 SNe Ib, 6 SNe Ic, 5 SNe Ic-BL

Light curves and spectra released by **Sako et al. (2014)**

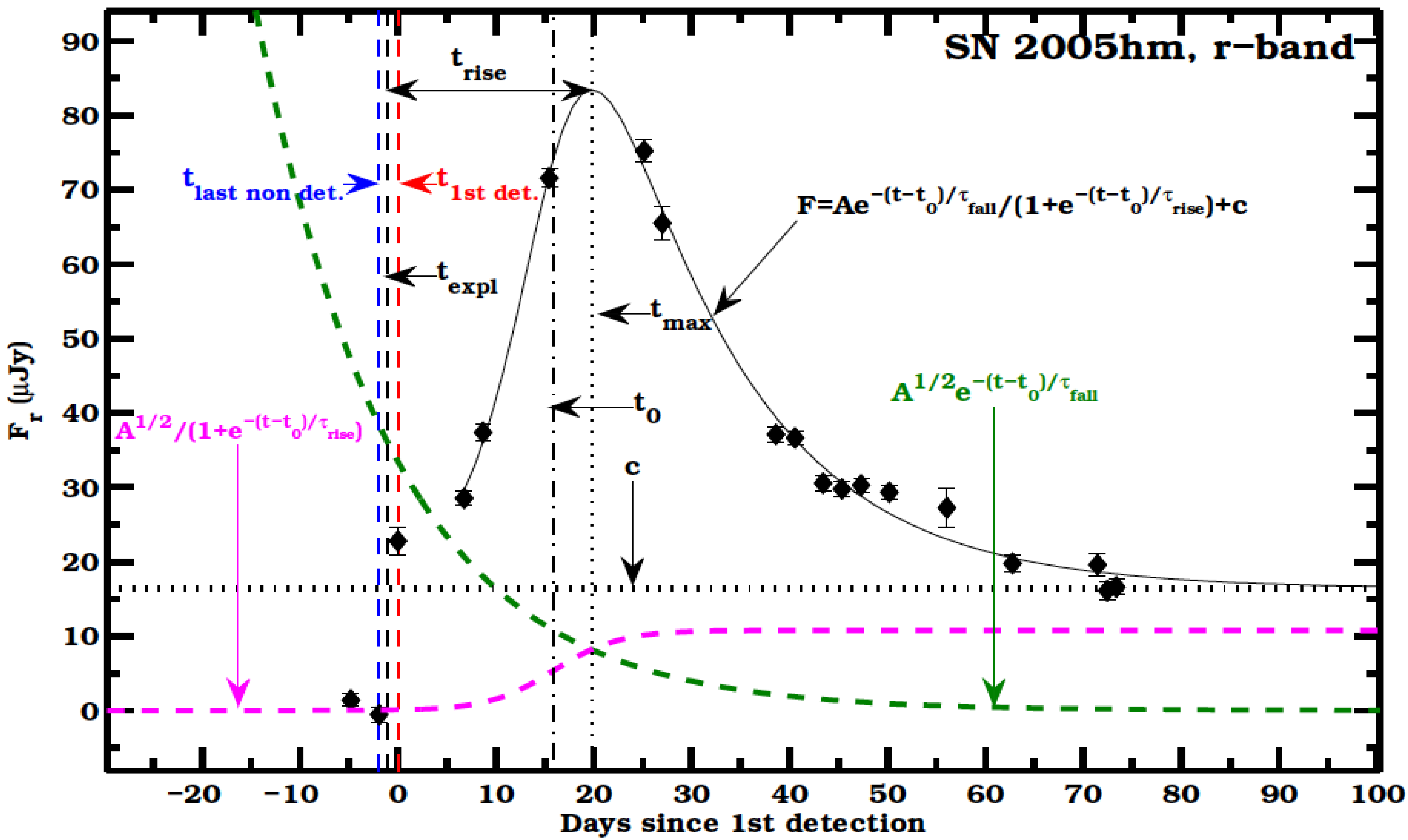
Data are well-suited to study the early phase of SNe Ib/c:

1) **multi-band** observations: *ugriz* filters
2) High **cadence**: ~4 days
3) Availability of **pre-explosion images**
4) Average **follow-up duration**: ~2 months

ugriz Light curves of SDSS-II SNe Ib/c



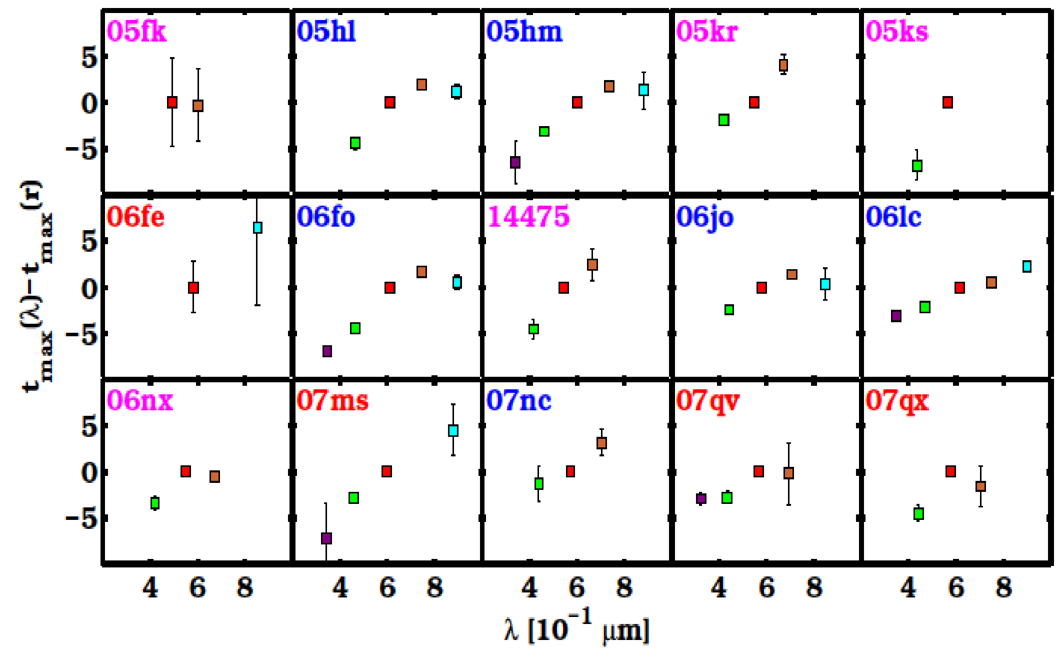
Light curve fit



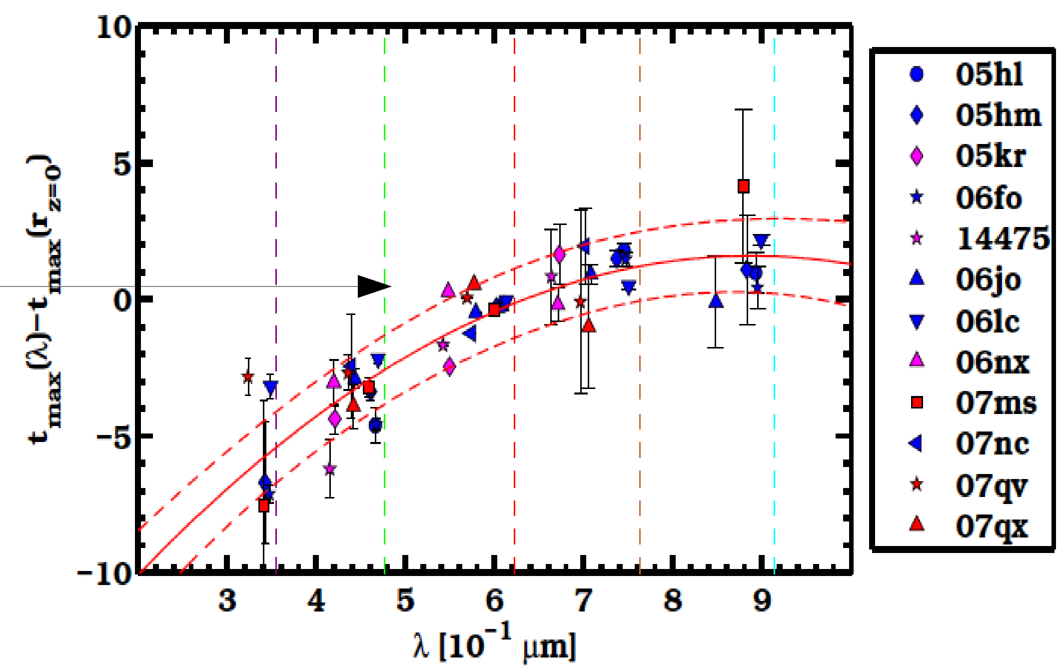
Light curve properties derived from fit: Epoch of maximum light, rise time, Δm_{-10}, Δm_{15}

Early light-curve shape of SNe Ib/c

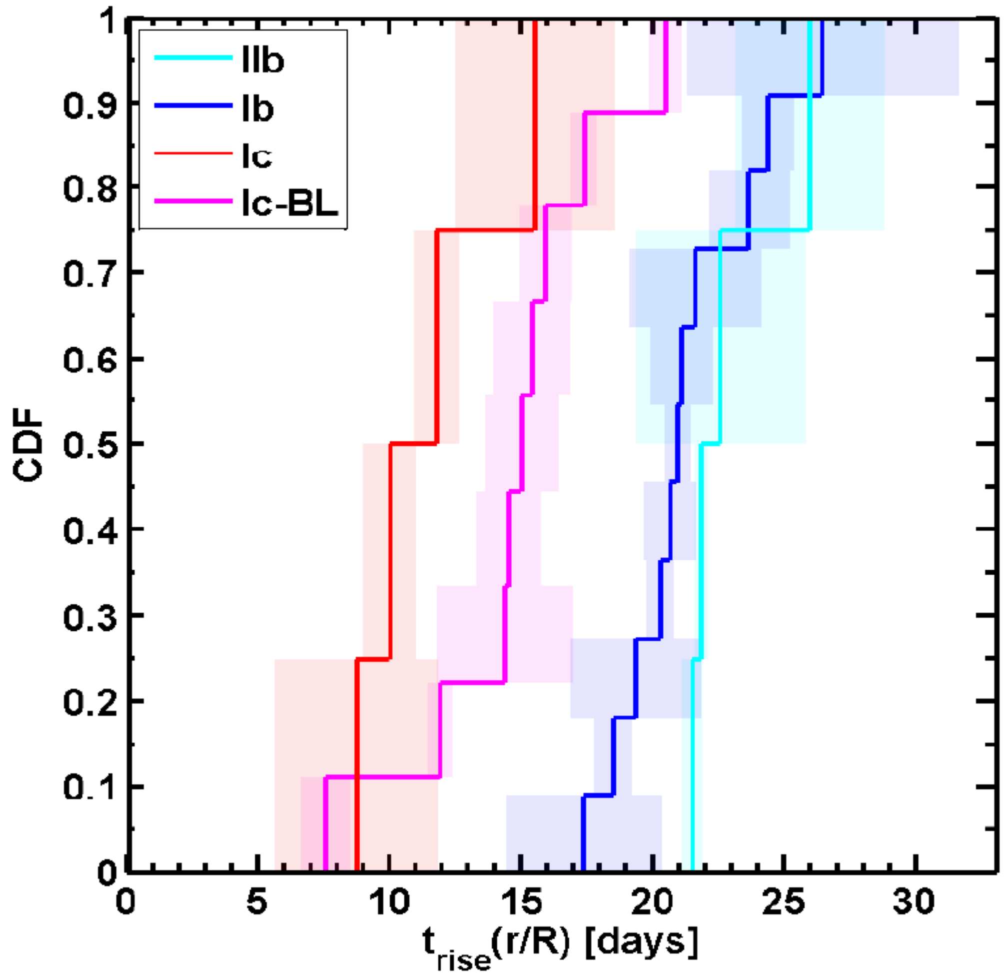
Peak epoch for different filters



Given the epoch of maximum light in one filter it is possible to establish the epoch of maximum of other filters with little uncertainty



Rise time

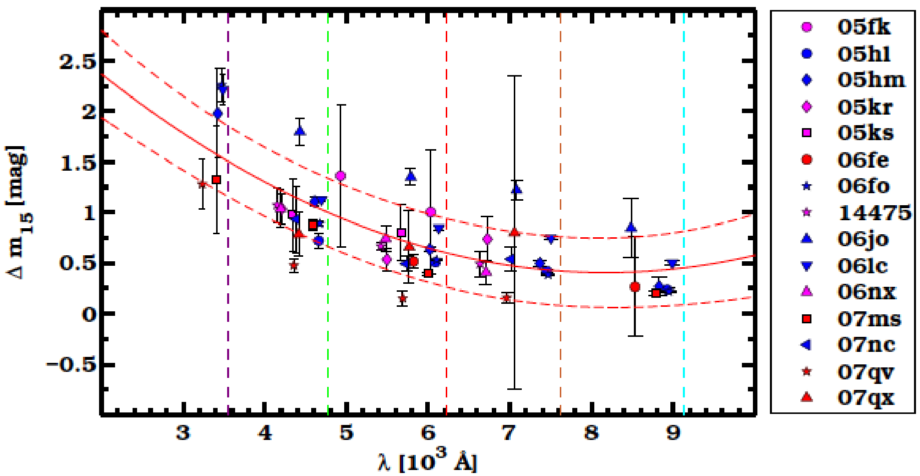


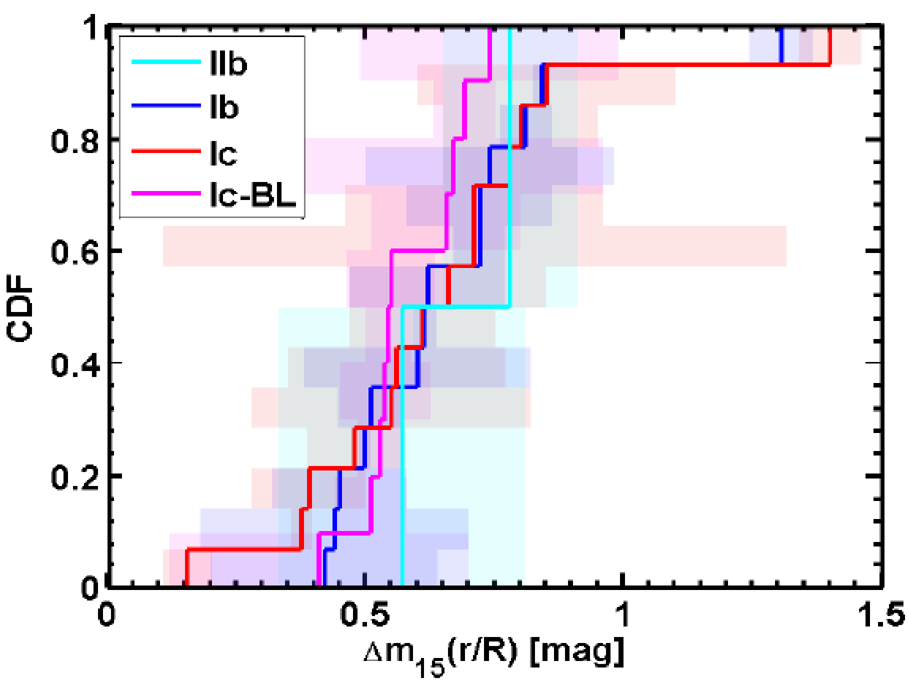
Well-constrained R/r band light-curve rise-times and Δm_{-10} for SNe IIb, Ib, Ic and Ic-BL in the literature.

SN	Type	t_{rise} (days)	Δm_{-10} (mag)	Ref.
1993J	IIb	22.53(3.24)	0.77(0.15)	Kumar et al. (2013); Richmond et al. (1994)
2008ax	IIb	21.50(0.40)	0.63(0.15)	Taubenberger et al. (2011)
2011dh	IIb	21.86(0.23)	0.61(0.10)	Ergon et al. (2014)
2011fu	IIb	26.40(2.90)	0.42(0.15)	Kumar et al. (2013)
1998dt	Ib	17.60(3.00)	1.00(0.10)	Matheson et al. (2001)
1999ex	Ib	20.49(0.52)	0.38(0.10)	Stritzinger et al. (2002);
2004dk	Ib	23.75(1.55)	0.50(0.10)	Drout et al. (2011)
2005hm	Ib	21.06(1.17)	0.76(0.03)	This paper
2006fo	Ib	…	0.38(0.01)	This paper
2006lc	Ib	26.41(5.18)	1.08(0.02)	This paper
2007Y	Ib	21.00(0.50)	0.67(0.10)	Stritzinger et al. (2009)
2007nc	Ib	…	0.80(0.15)	This paper
2007uy	Ib	21.72(2.50)	…	Roy et al. (2013), explosion date from modelling of radio data
2008D	Ib	20.75(1.00)	0.31(0.10)	Soderberg et al. (2008); Malesani et al. (2009)
2009jf	Ib	24.50(1.00)	0.34(0.10)	Valenti et al. (2011), good pre-explosion limit
2011ei	Ib	19.50(2.50)	0.69(0.20)	Milisavljevic et al. (2013)
iPTF 13bvn	Ib	18.55(0.70)	0.57(0.10)	(Fremling et al. 2014)
1994I	Ic	10.01(1.02)	2.50(0.50)	Richmond et al. (1996)
2004aw	Ic	…	0.27(0.05)	Taubenberger et al. (2006)
2004dn	Ic	…	0.60(0.15)	Drout et al. (2011)
2004fe	Ic	…	1.20(0.10)	Drout et al. (2011)
2007gr	Ic	15.50(3.02)	0.73(0.04)	Hunter et al. (2009)
2007ms	Ic	…	0.56(0.08)	This paper
2007qv	Ic	8.72(3.08)	…	This paper
2007qx	Ic	…	0.62(0.17)	This paper
PTF 10vgv	Ic	11.91(0.85)	2.63(0.50)	Corsi et al. (2012)
2013dk	Ic	…	1.33(0.20)	Elias-Rosa et al. (2013), Δm_{-10} scaled to r from V
1998bw	Ic-BL	17.50(0.50)	0.68(0.15)	Clocchiatti et al. (2011)
2003jd	Ic-BL	16.20(1.00)	…	Valenti et al. (2008), only error on max epoch
2005kr	Ic-BL	15.40(1.45)	1.18(0.16)	This paper
14475	Ic-BL	14.36(2.58)	1.15(0.31)	This paper
2006aj	Ic-BL	12.30(0.50)	2.40(0.50)	Ferrero et al. (2007), Δm_{-10} is extrapolated
2006nx	Ic-BL	14.99(1.41)	1.10(0.12)	This paper
2009bb	Ic-BL	14.65(1.25)	1.37(0.20)	Pignata et al. (2011)
2010bh	Ic-BL	8.00(1.00)	2.00(0.50)	Bufano et al. (2012), Δm_{-8}
PTF 12gzk	Ic-BL	20.74(0.62)	0.45(0.10)	Ben-Ami et al. (2012)

Helium-poor (Ic, Ic-BL) SNe rise faster than helium-rich (Ib, IIb) SNe

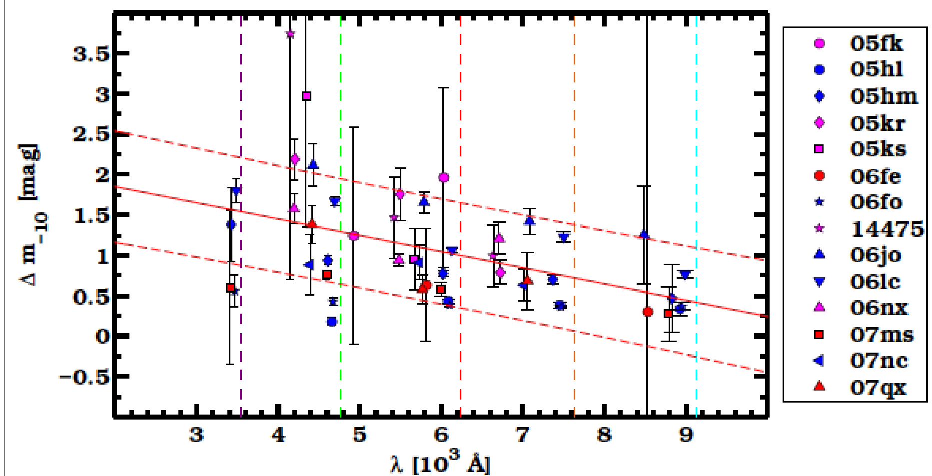
LC Width after peak (Δm_{15})

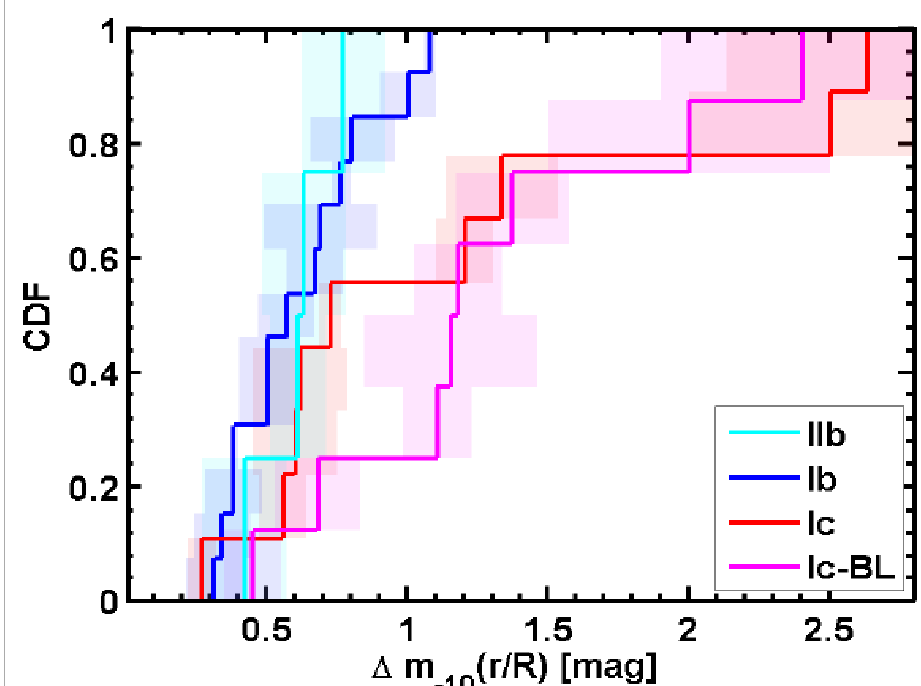




Δm_{15} has the same distribution for all the SN types

LC Width before peak (Δm_{-10})

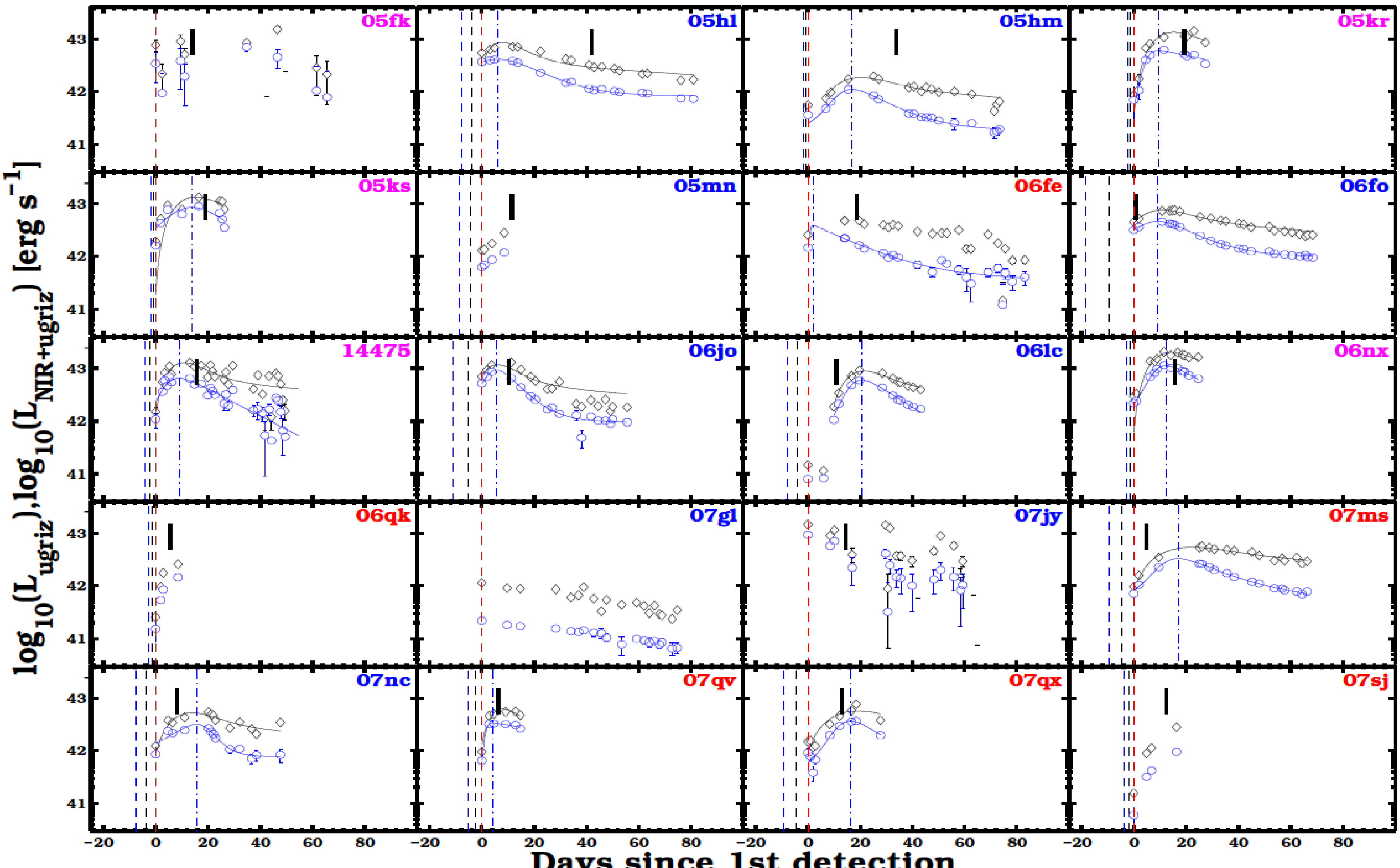




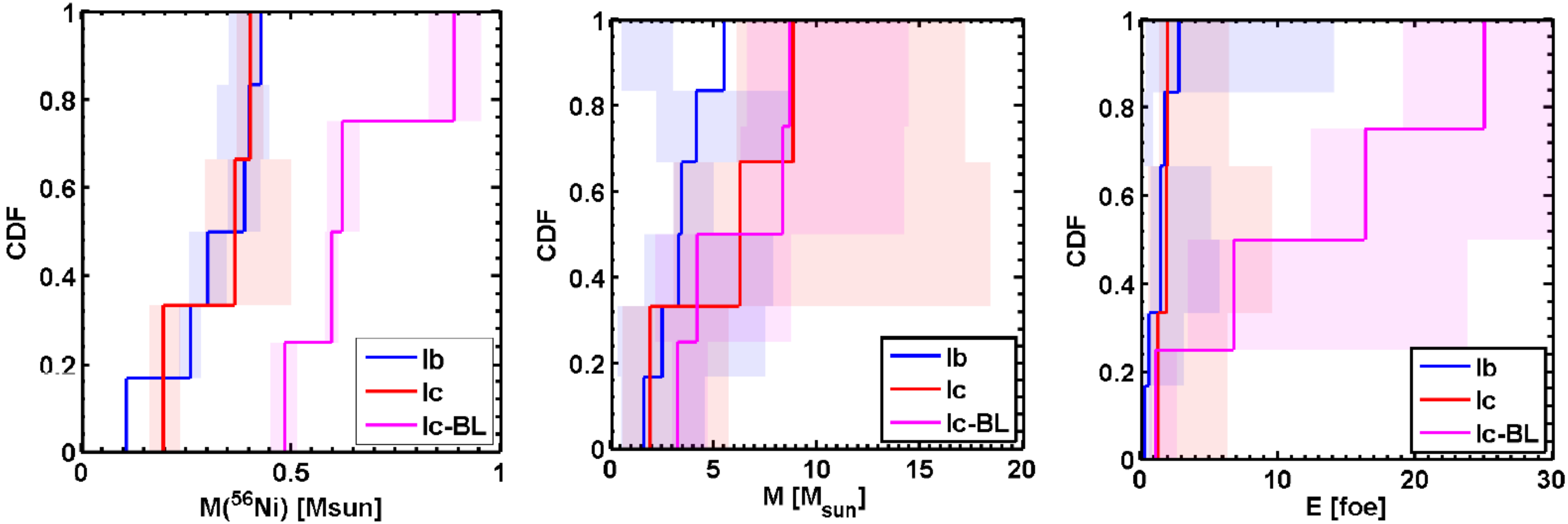
Δm_{-10} is larger for helium-poor SNe

Bolometric properties and explosion parameters

Bolometric light curves



Explosion parameters: E_K, M_{ej}, $M(^{56}Ni)$

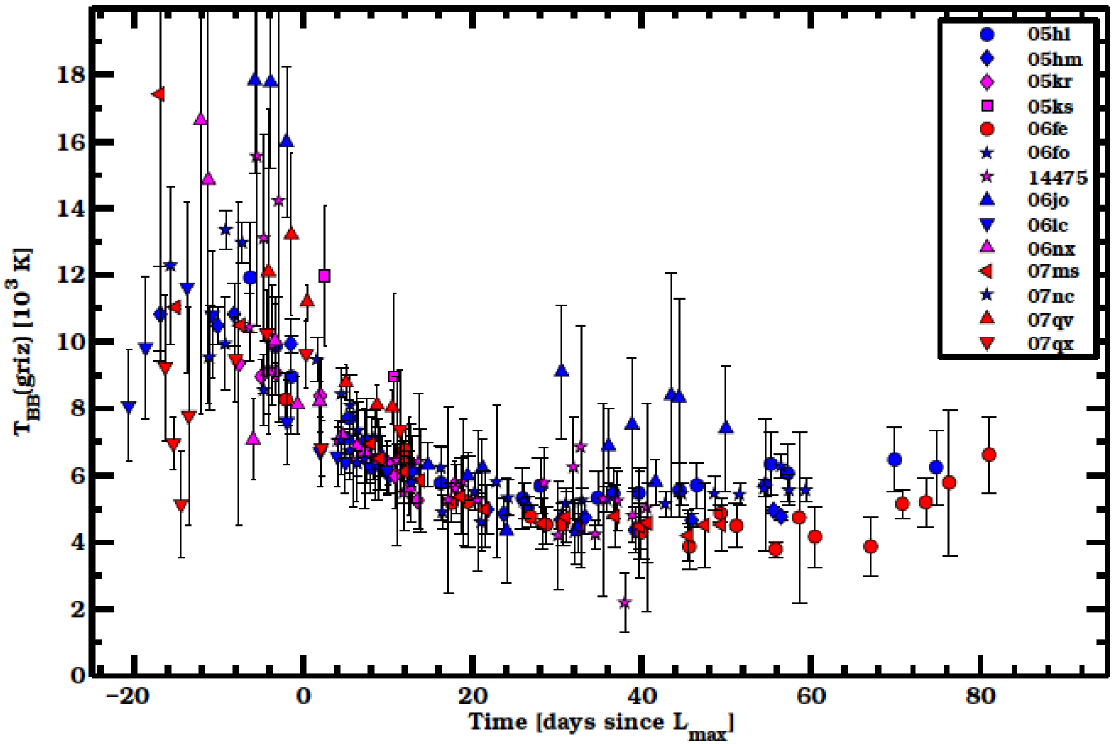


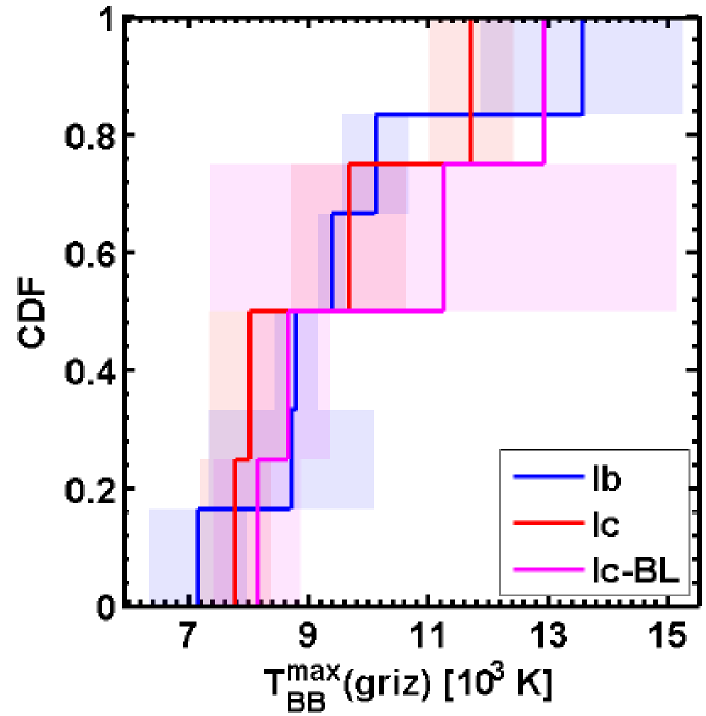
1) Arnett fit to the bolometric light curves to obtain E_K, M_{ej}, $M(^{56}Ni)$

2) SNe Ic-BL produce more ^{56}Ni and are more energetic than SNe Ib and Ic.

3) Average E_K, M_{ej}, $M(^{56}Ni)$ values are similar to those found by similar studies (Drout et al. 2011, Cano 2013)

Temperature

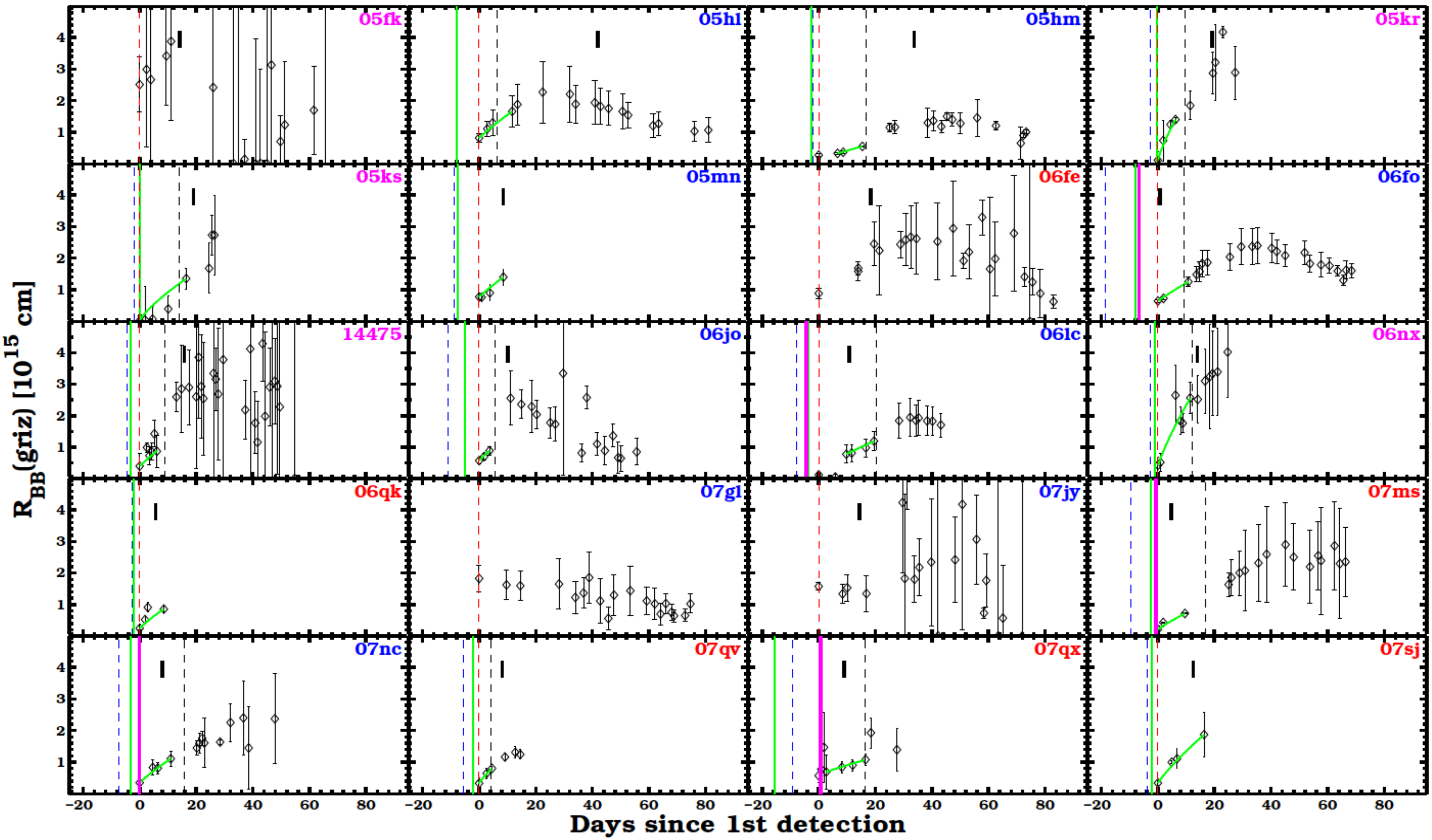




1) We obtain the temperature evolution from black-body fits on the spectral energy distributions.

2) Typical T=8000 K at maximum light.

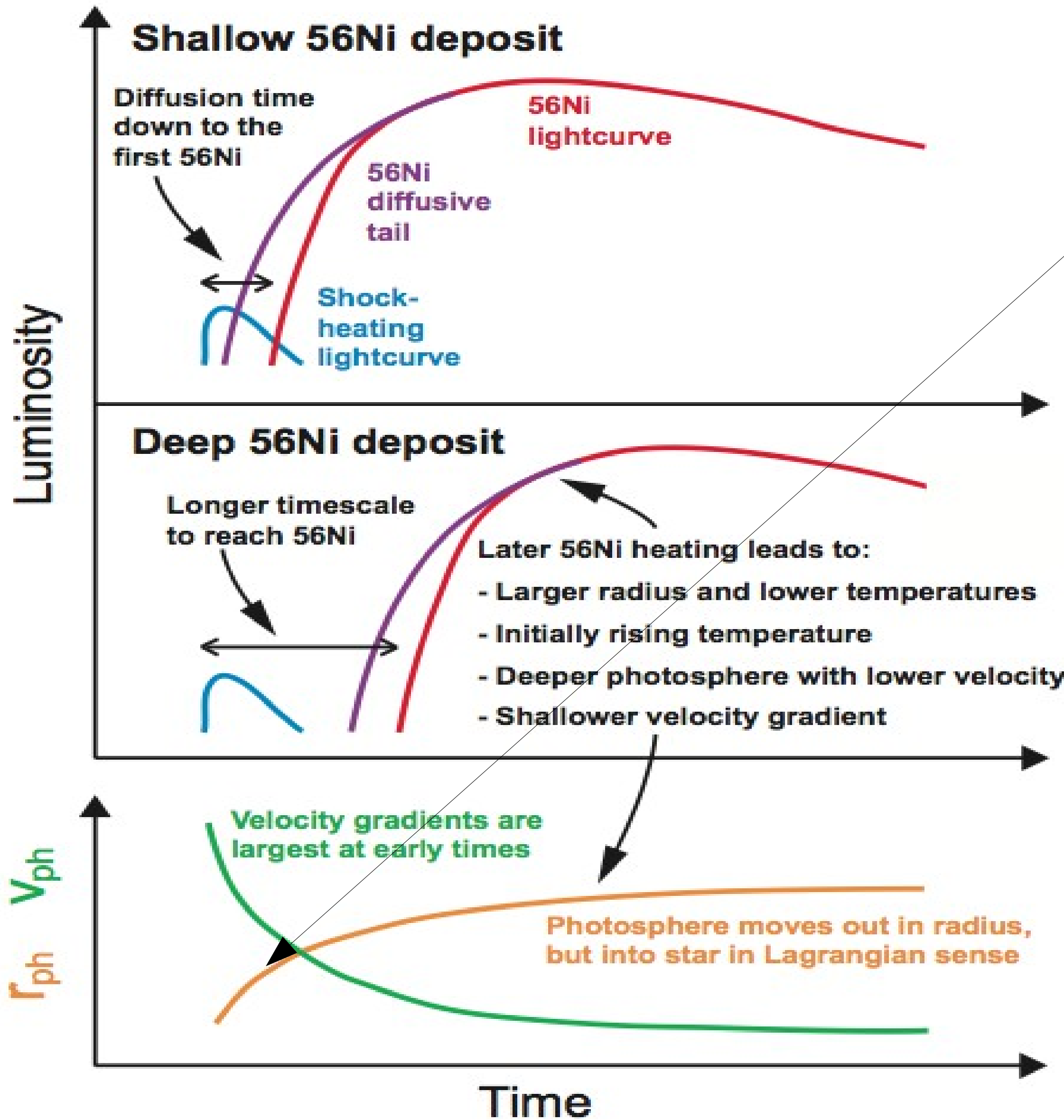
Photospheric radius



1) Typical $R_{ph} = 10^{15}$ cm at maximum light.

2) The evolution of R_{ph} is crucial to establish the explosion date.

Constraining the explosion date



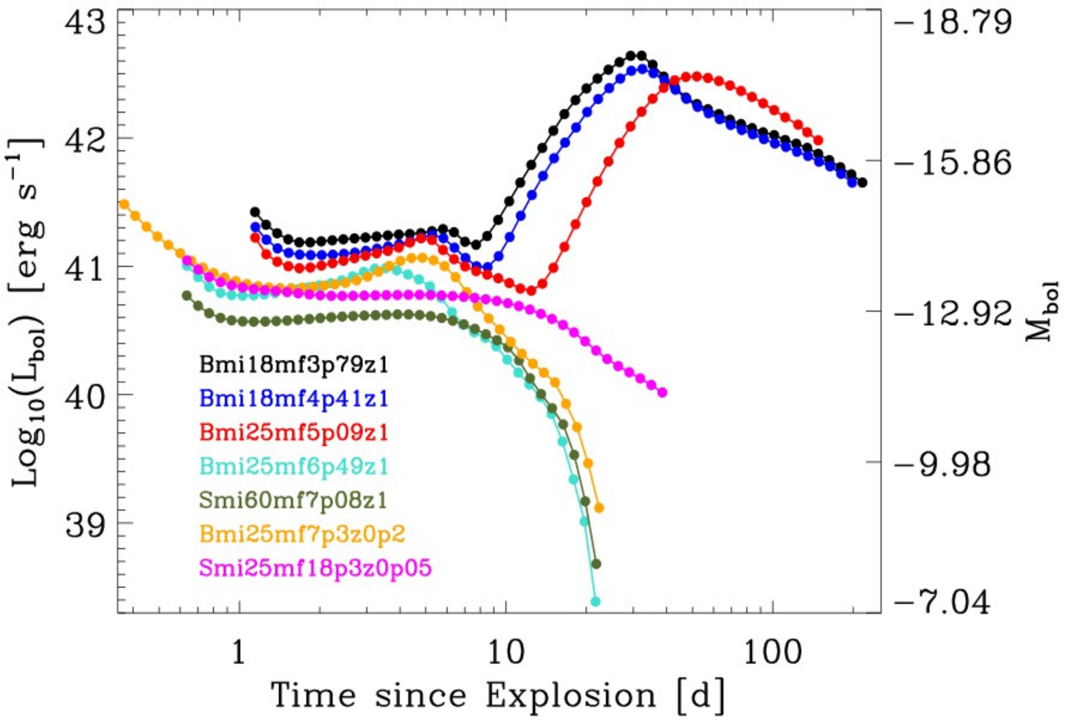
R_{ph} evolution shows that most of our targets were discovered soon after explosion

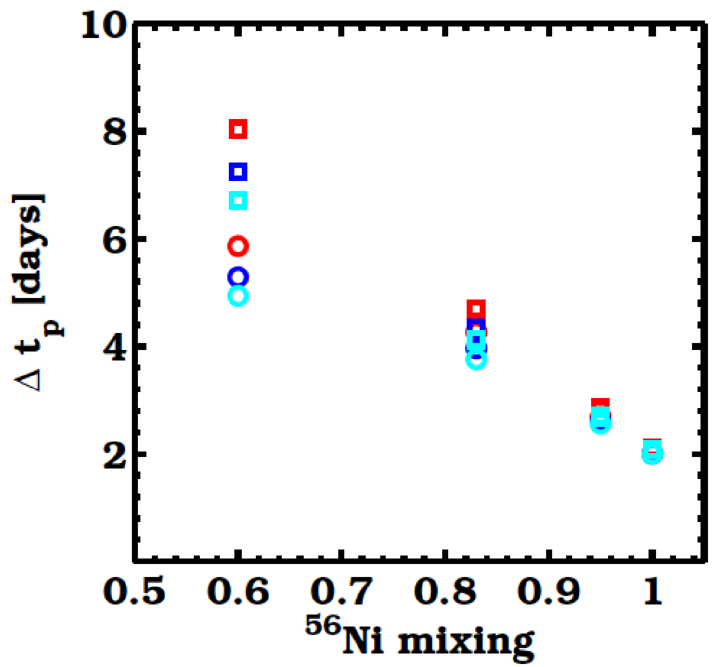
Piro & Nakar (2013)

Early-time plateau and ^{56}Ni mixing

1) **Dessart et al. (2011) predict a dark phase** of several days after explosion **if the ^{56}Ni is not mixed** to the outer layers

2) **Dessart et al. (2012):** "The lack of He I lines in SNe Ic may result from a variety of causes: A genuine helium deficiency; strongly-asymmetric mixing; **weak mixing**; or a more massive, perhaps single, progenitor characterized by a larger oxygen-rich core. **Helium deficiency is not a prerequisite for SNe Ic**."

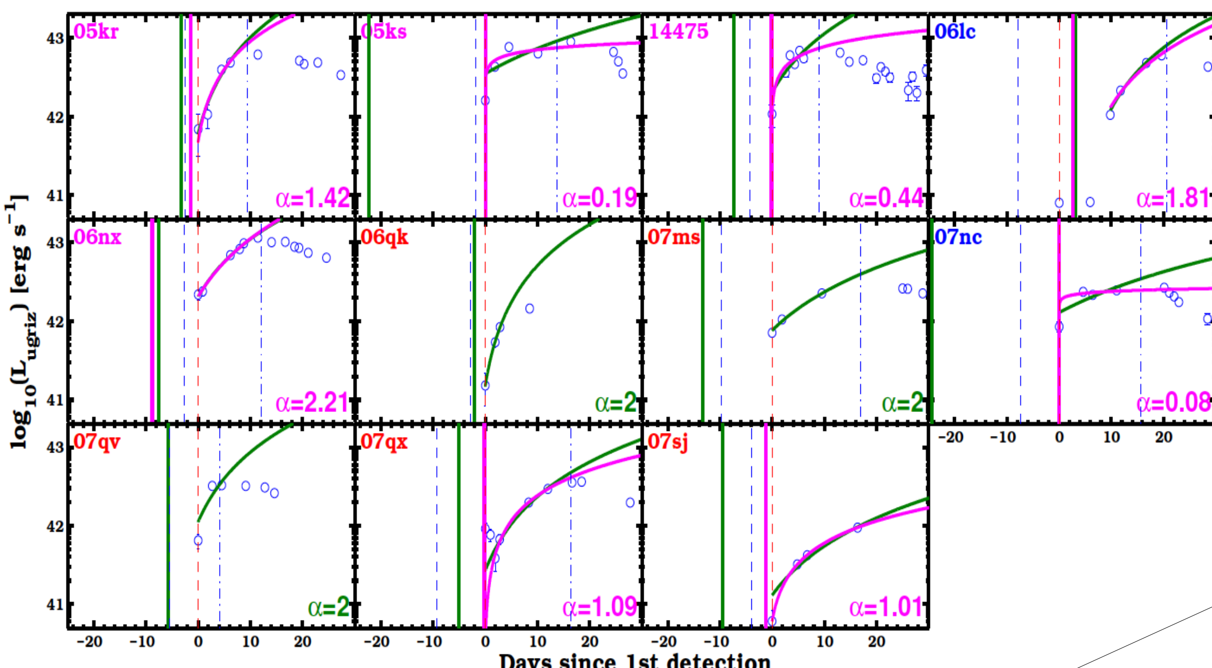


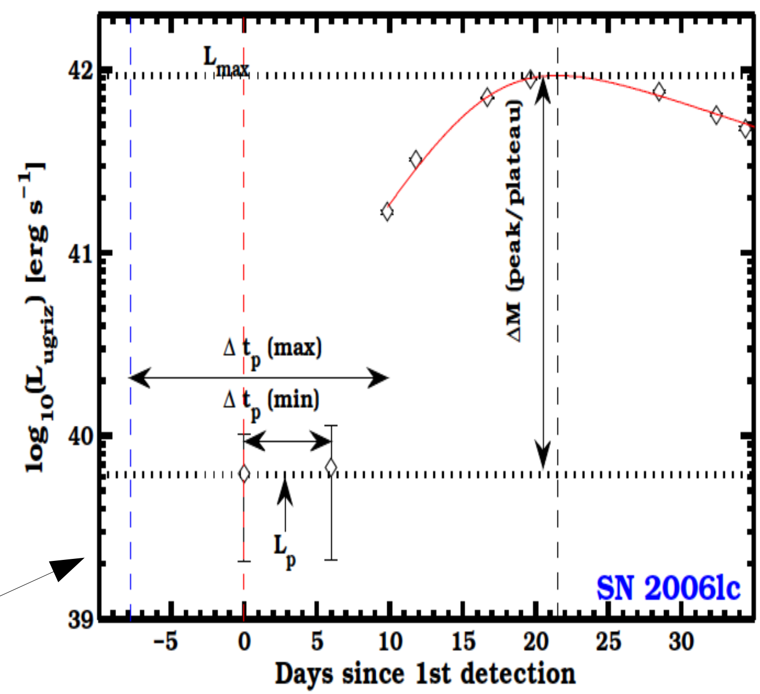


1) We **do NOT detect any plateau for SNe Ic** and Ic-BL

2) We infer **strong ^{56}Ni mixing for our helium-poor events**, based on the limits of the plateau duration. Therefore, the **spectral appearance of SNe Ic must be due to a real lack of their helium envelope**.

3) By fitting the rising part of the light curve with a power-law, we obtain **α<2** for the majority of the targets, again implying strong mixing (Piro & Nakar 2013).





4) For a single SN Ib (2006lc) we detect a faint plateau, suggesting that in this SN the ^{56}Ni is weakly mixed

Outlook for iPTF/ZTF

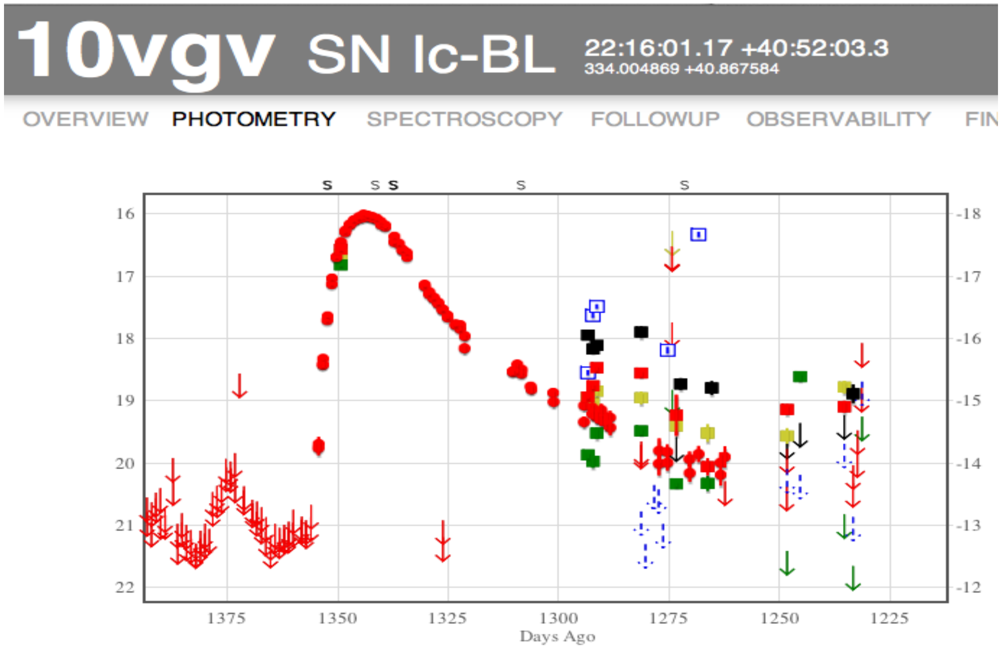
1) With **higher cadence** we will be able to detect the **shock break-out cooling tail**, crucial to determine the **progenitor radius** with good precision (see e.g., Bersten et al. 2011, 2013). In our work we have two possible detections of this phase for SNe 2005hm and 2007qx.

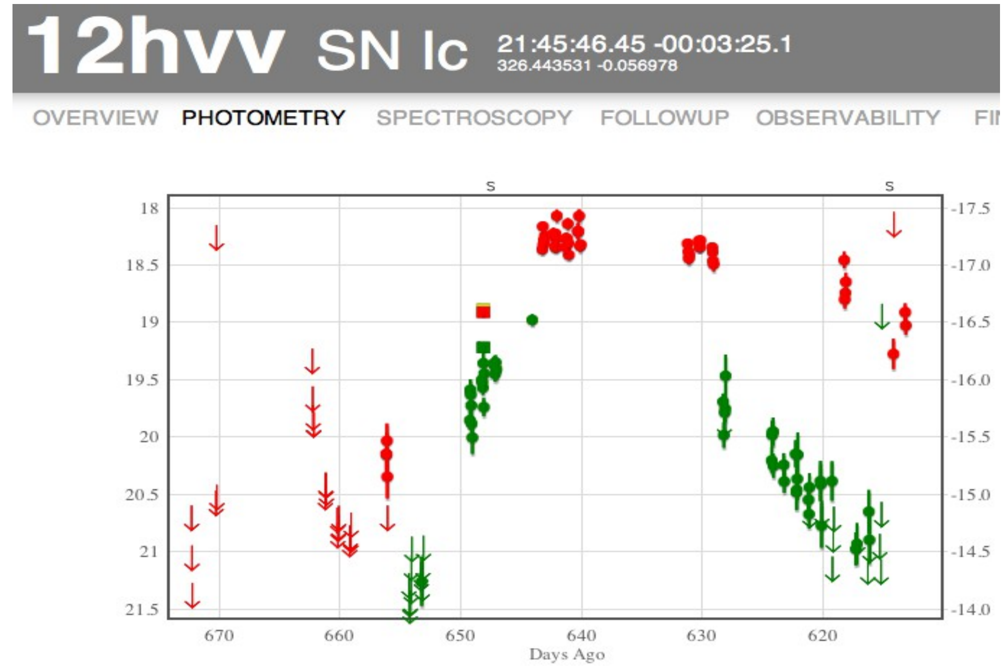
2) It is important to constrain the temperature to construct bolometric light curves that can be compared to theoretical models. This is why **multi-band** (at least *g* and *r*) observations and/or spectral observations at early times (SED machine) will be important to study the upcoming SE-SNe discovered by iPTF/ZTF.

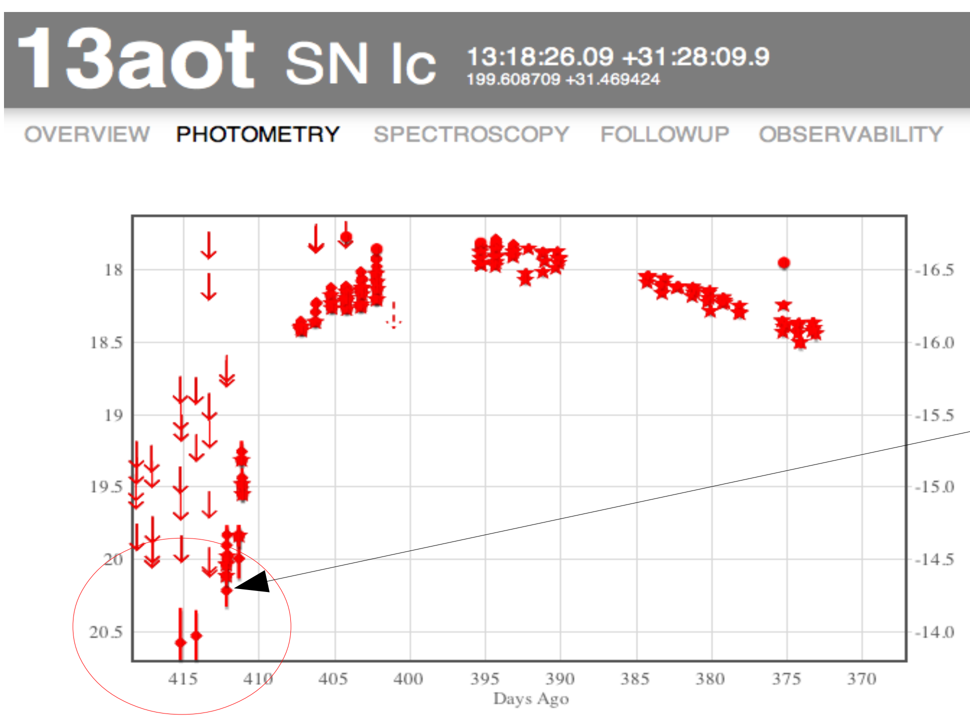
3) The **detection of a possible dark plateau phase** requires that the observations are deep enough to detect luminosities of 10^{41}erg s^{-1} (or M~-13 mag). This means limiting apparent magnitudes of ~22 mag for objects at distances of ~100 Mpc. For iPTF and ZTF the best strategy might be to **increase the cadence** rather than the individual exposure times **to reach a combined limiting magnitude of r~23 mag**, required to discover (or rule out) more dark plateaus of SNe Ib/c.

4) High-cadence spectral observations will be important to make a **proper sub-classification of SE-SNe**, e.g., to differentiate between Ib and IIb and to clarify the amount of He I in the spectra as a function of time.

A few examples in the PTF archive



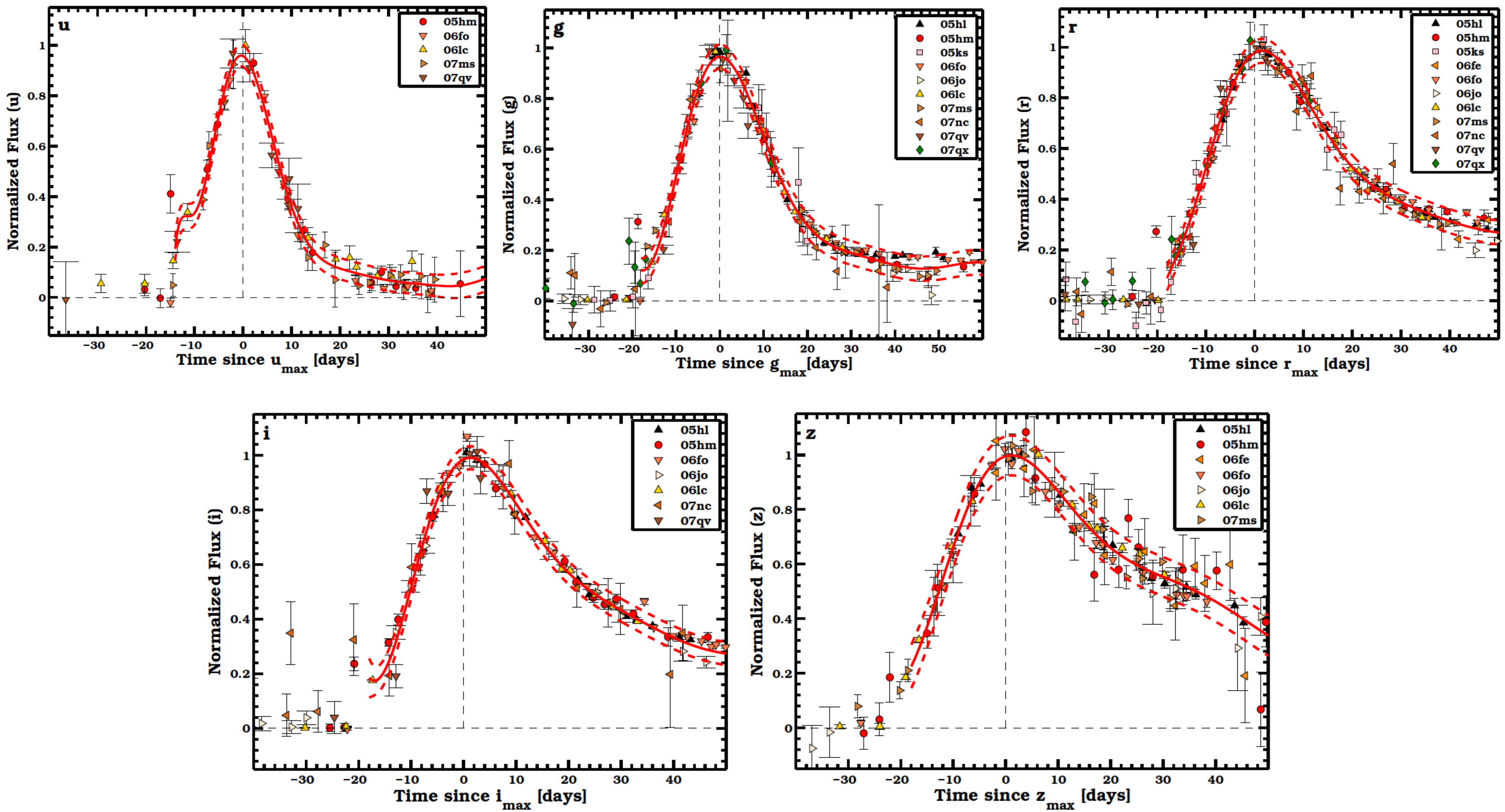




Early dark
phase?

Thanks!

Light-curve templates



Conclusions on the bolometric properties

1) ^{56}Ni mass estimates of SNe Ib/Ic/Ic-BL give typical values of 0.3, 0.3, 0.6 M_{sun}, respectively. Energies are on the order 1.4-1.7 foe for SNe Ib and Ic and about one order of magnitude larger for SNe Ic-BL. Typical ejecta masses for SNe Ib/Ic/Ic-BL are 3.4, 5.7, 6.1 M_{sun}).

2) Limits on the early-plateau duration, light curve shape onthe rise and early temperature evolution imply strong ^{56}Ni mixing for most SNe Ic and Ic-BL. Therefore, the cause of the spectral difference between SNe Ic and Ib sub-types is not well explained by nickel mixing, but is better understood in the context of a real lack of helium in SN Ic progenitors.

3) We detect an early plateau in the case of SN Ib 2006lc, and radiation from the shock cooling tail in the early light curves of SNe 2005hm and 2007qx.

4) The best limits from PN13 model on the progenitor radii suggest that SNe Ib/c arise from compact objects.

Summary of the light curve shape properties:

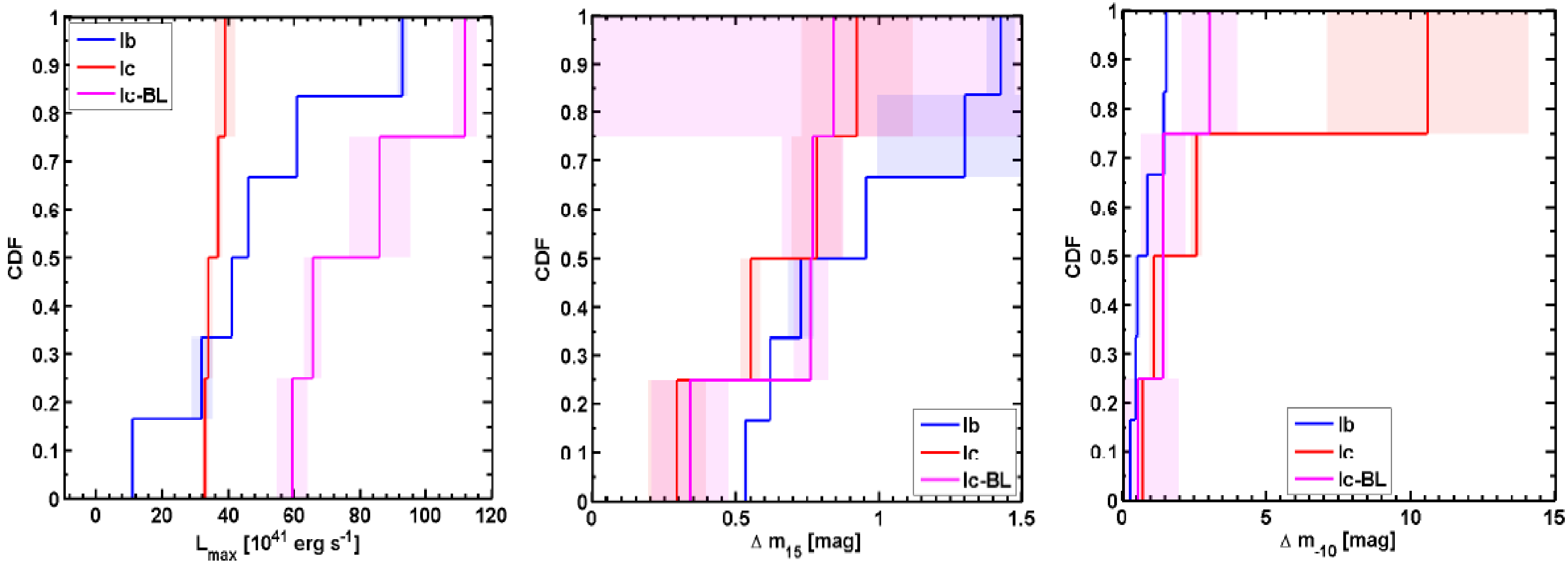
1) Both SNe Ib and SNe Ic/Ic-BL peak first in the bluer and then successively in the redder bands.

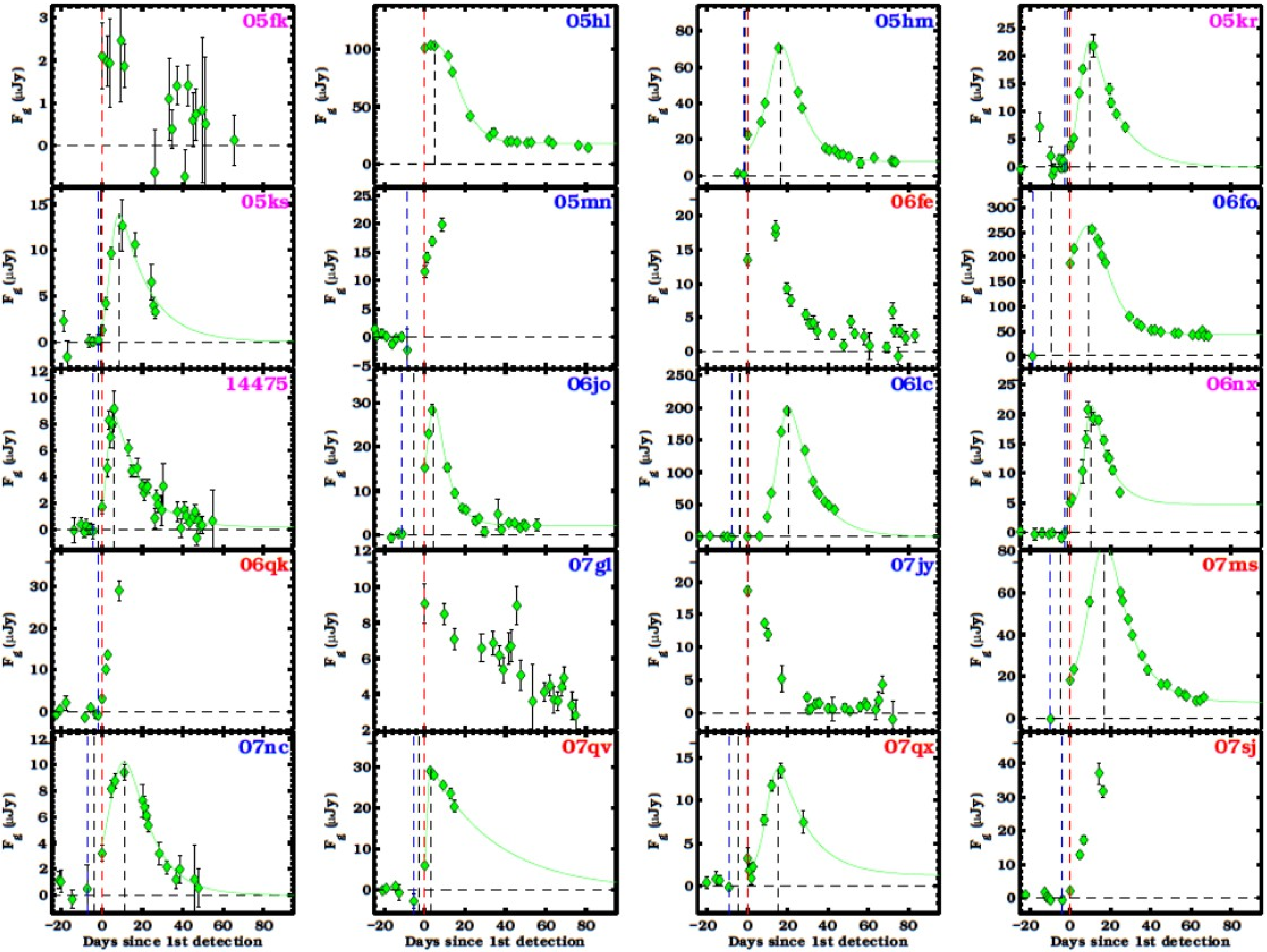
2) SNe Ic and Ic-BL rise to maximum in a shorter time than SNe Ib and IIb, a result that is statistically significant in the *r* band.

3) The steepness of the light curves after maximum (Δm_{15}) is similar for the different SE SN types.

4) The steepness of the light curves on the rise (Δm_{-10}) is larger for SNe Ic-BL and Ic than for SNe Ib and IIb.
Δm_{15} and Δm_{-10} are larger in the bluer bands.

Bolometric light curve shape




05fk
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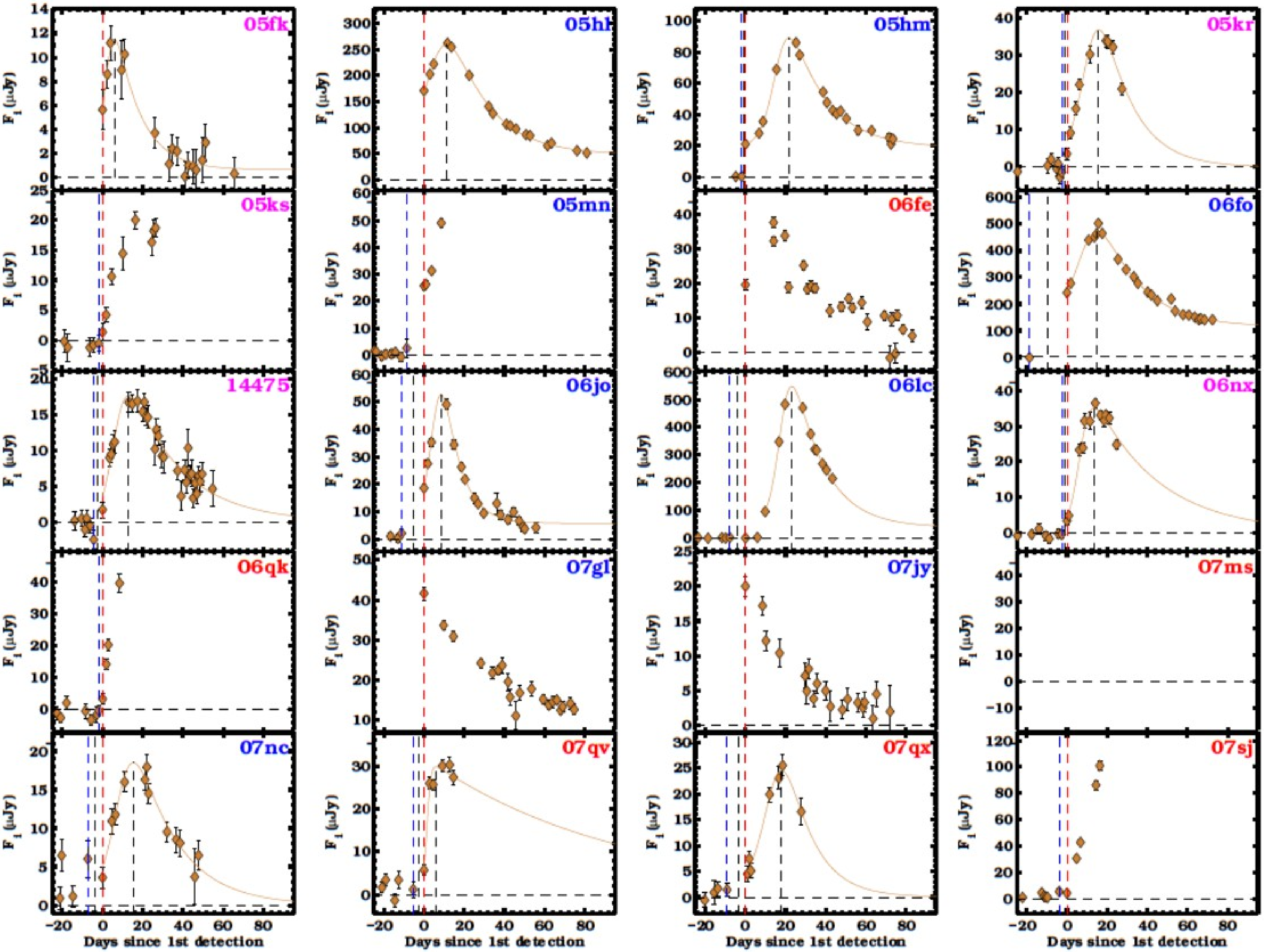
F_g (μJy)
Days since 1st detection



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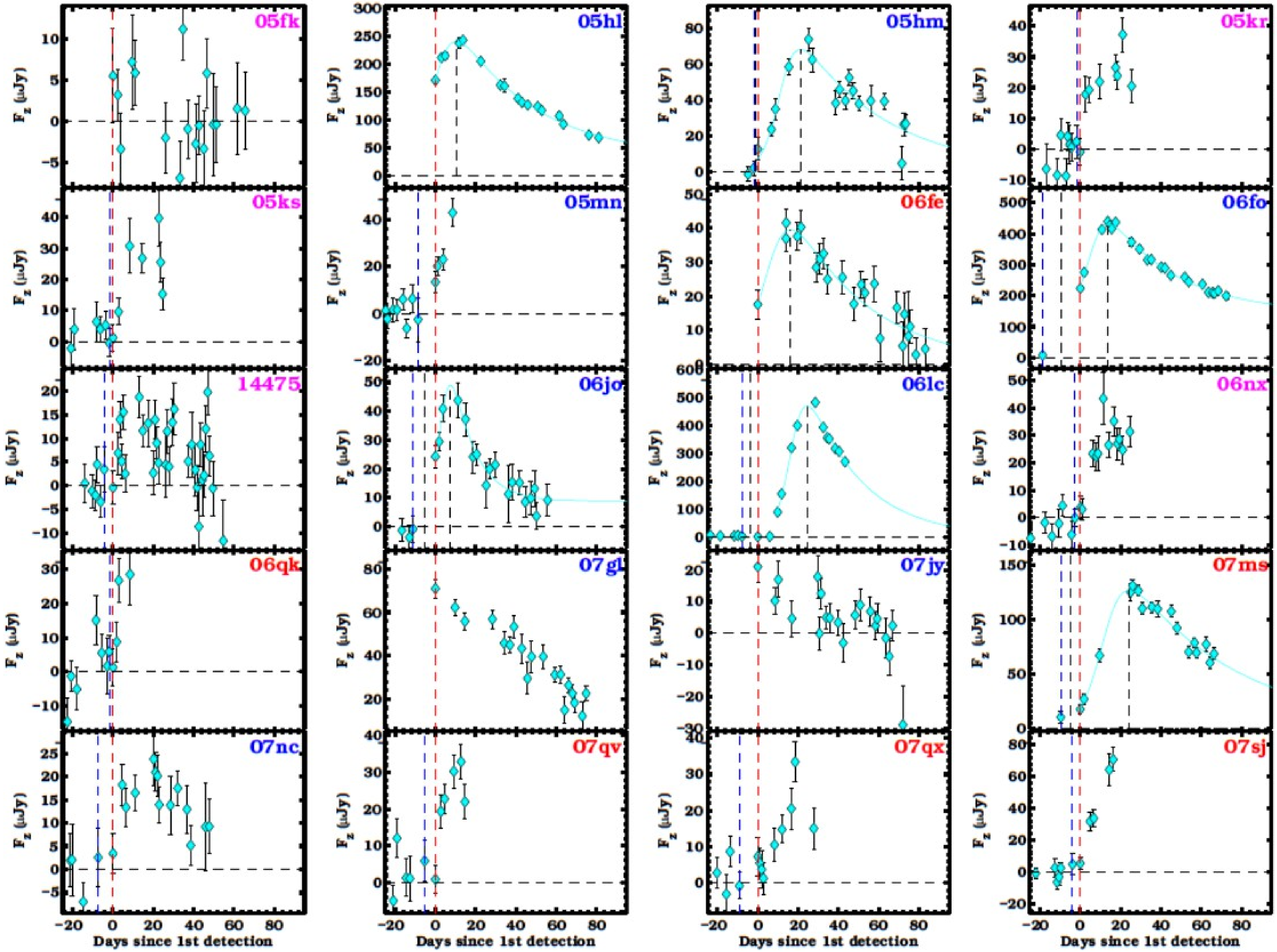
F_i (μJy)
Days since 1st detection



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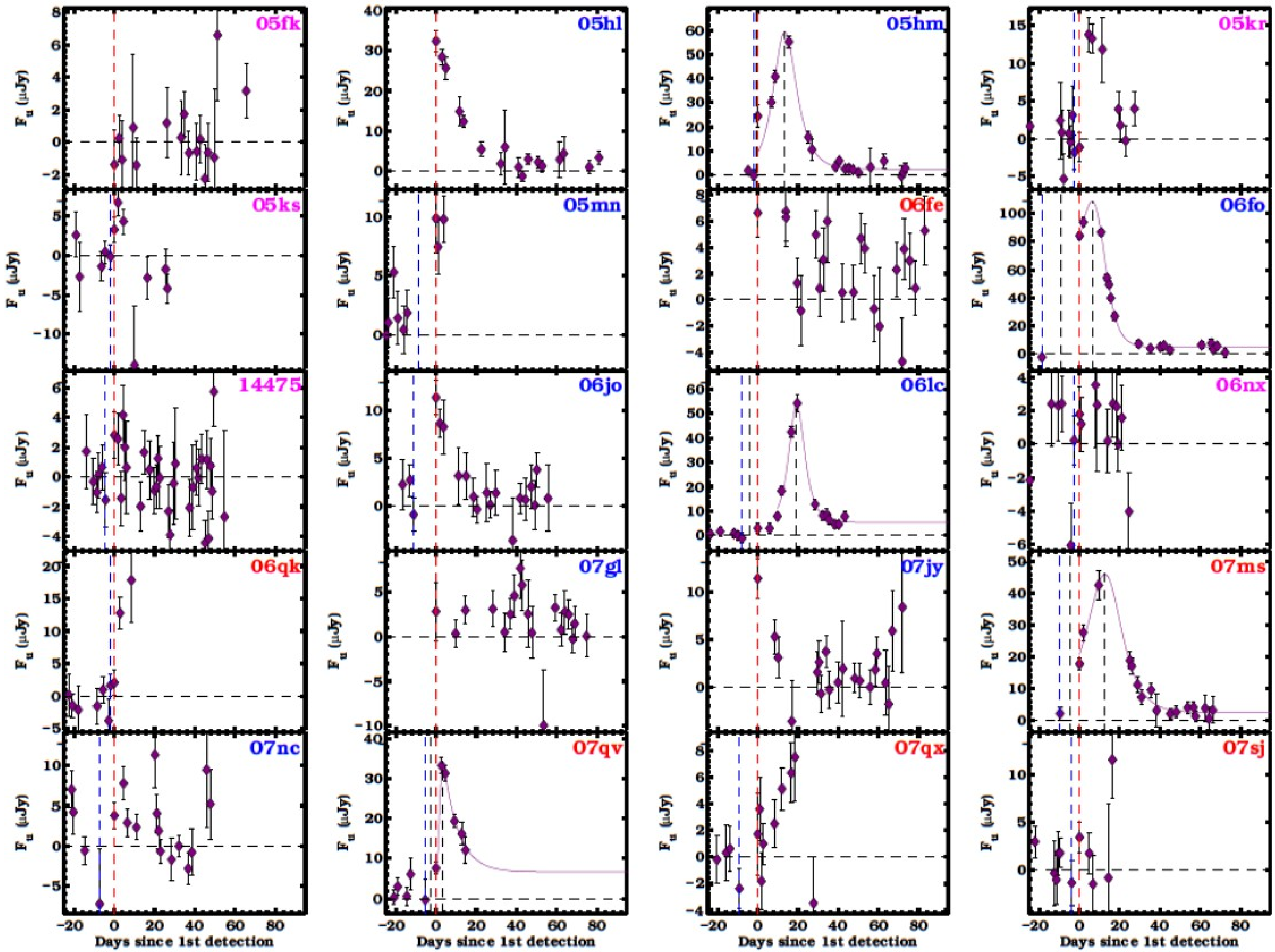
F_z (μJy)
Days since 1st detection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07qx
07sj
F_u (μJy)
Days since 1st detection

SDSS SN Ib/c spectra