Radioactive decay of GRB-SNe at late-times

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The GRB-Supernova Association

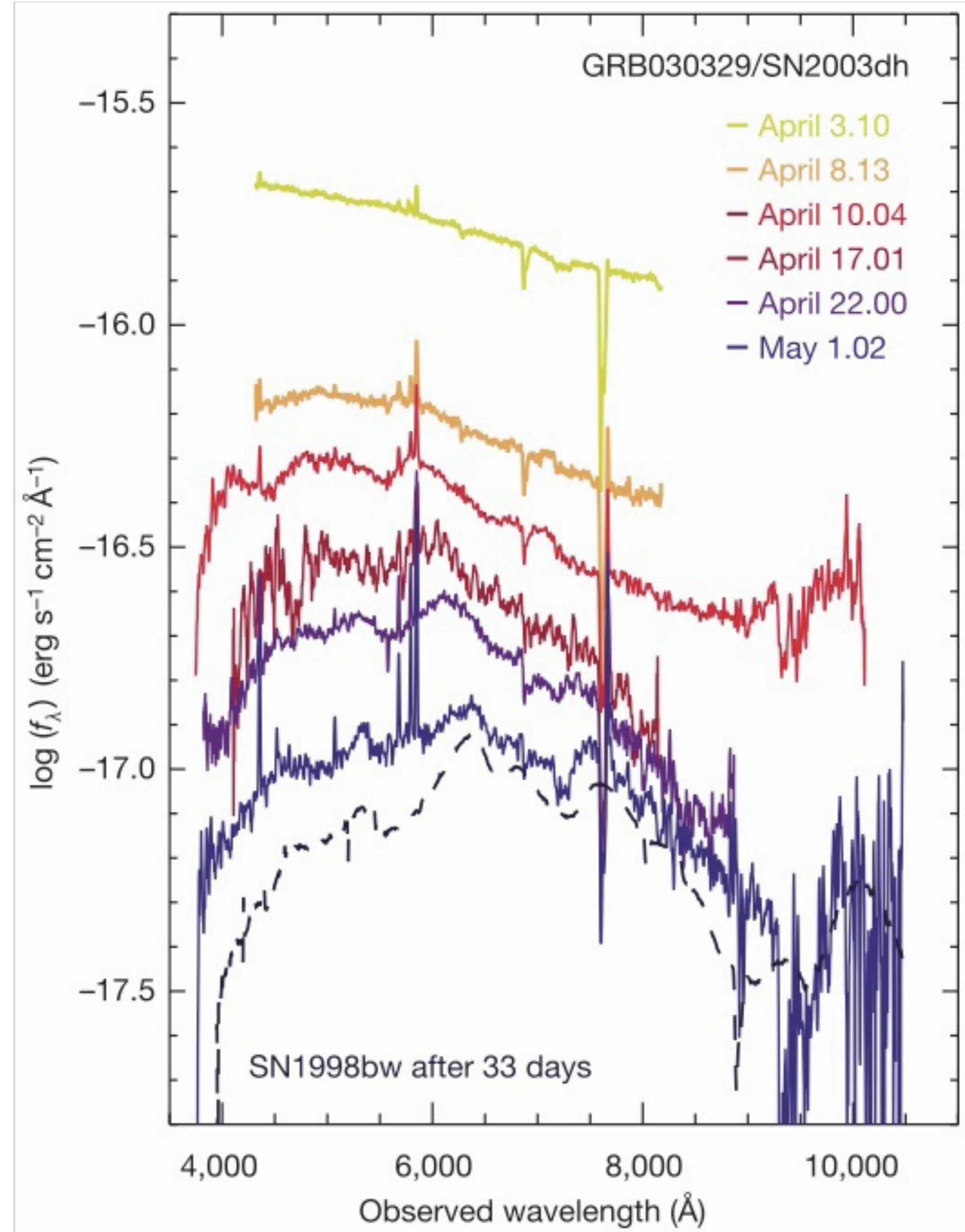
★ Long duration GRBs and stripped core collapse supernovae (SNe) are nature's most powerful explosions from massive stars

★ Stripped core collapse SNe (type IIb, Ib, Ic and Ic-bl) arise from massive stars stripped of their outer envelopes

★ Broad lined type Ic SNe are a sub-class of core collapse SNe Ic that reveal broad spectral features, indicative of higher ejecta velocities (~30, 000 km/s) that are much higher than those seen in typical type Ic SNe

★ Type Ic and broad lined type Ic SNe have spectra devoid of H and He

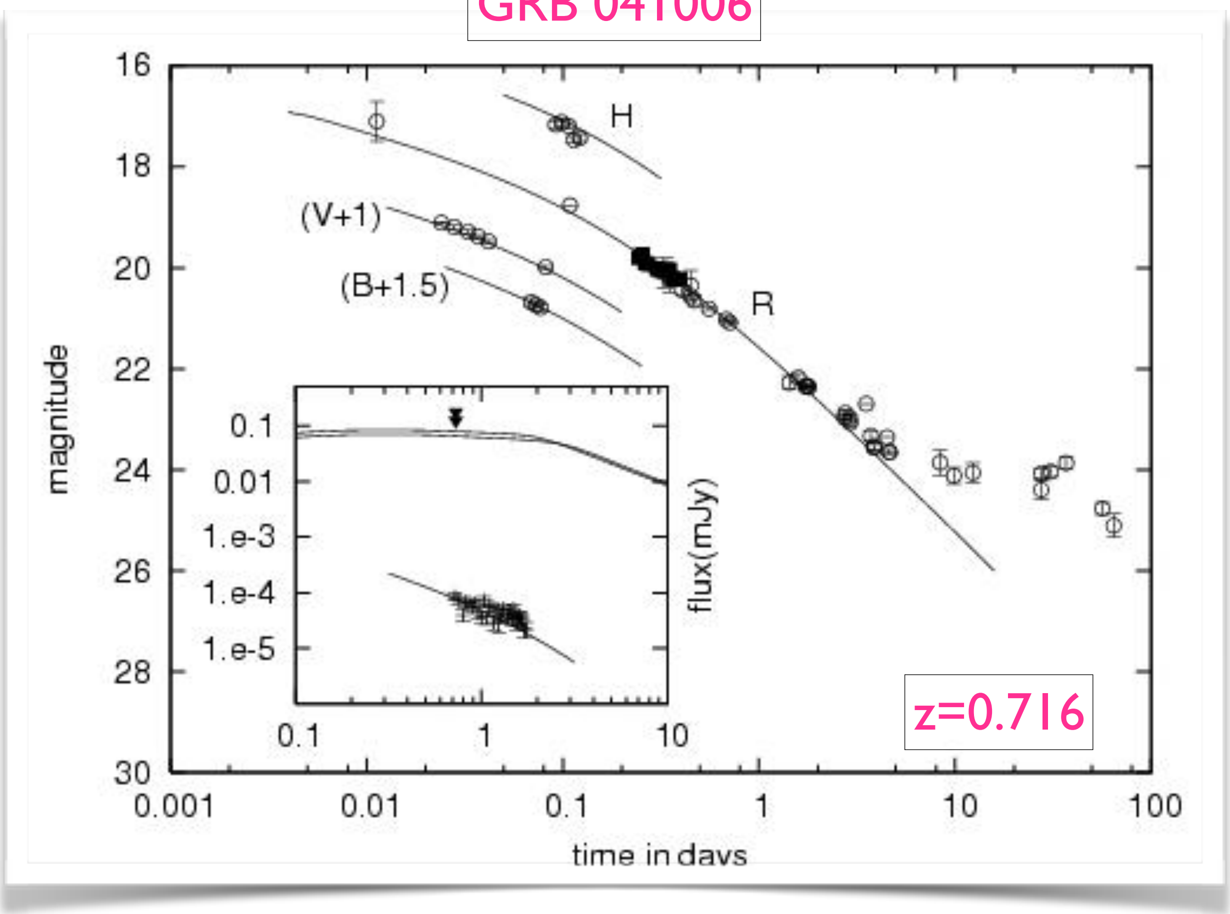
★ Interestingly, all SNe associated with long duration GRBs (till date) are typed as SNe Ic-bl and where measured have kinetic energy in excess of 10^{52} ergs which is about 10 times higher than the kinetic energy of normal core collapse SNe



Stanek et al. 2003

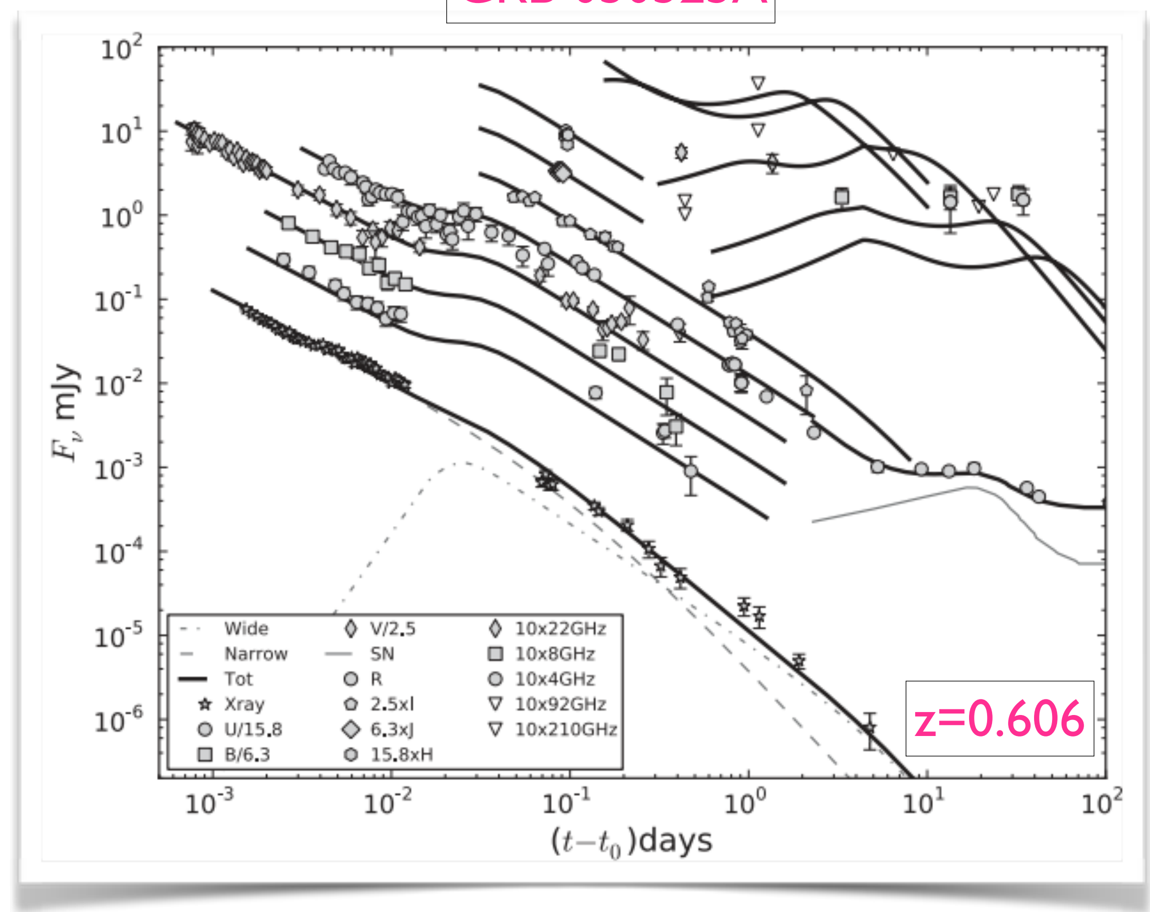
SNe signature in the light curve

GRB 041006



Misra, Resmi et al. 2005

GRB 050525A



Resmi, Misra et al. 2012

Sub-classes of GRB-SNe based on $L_{\gamma,iso}$

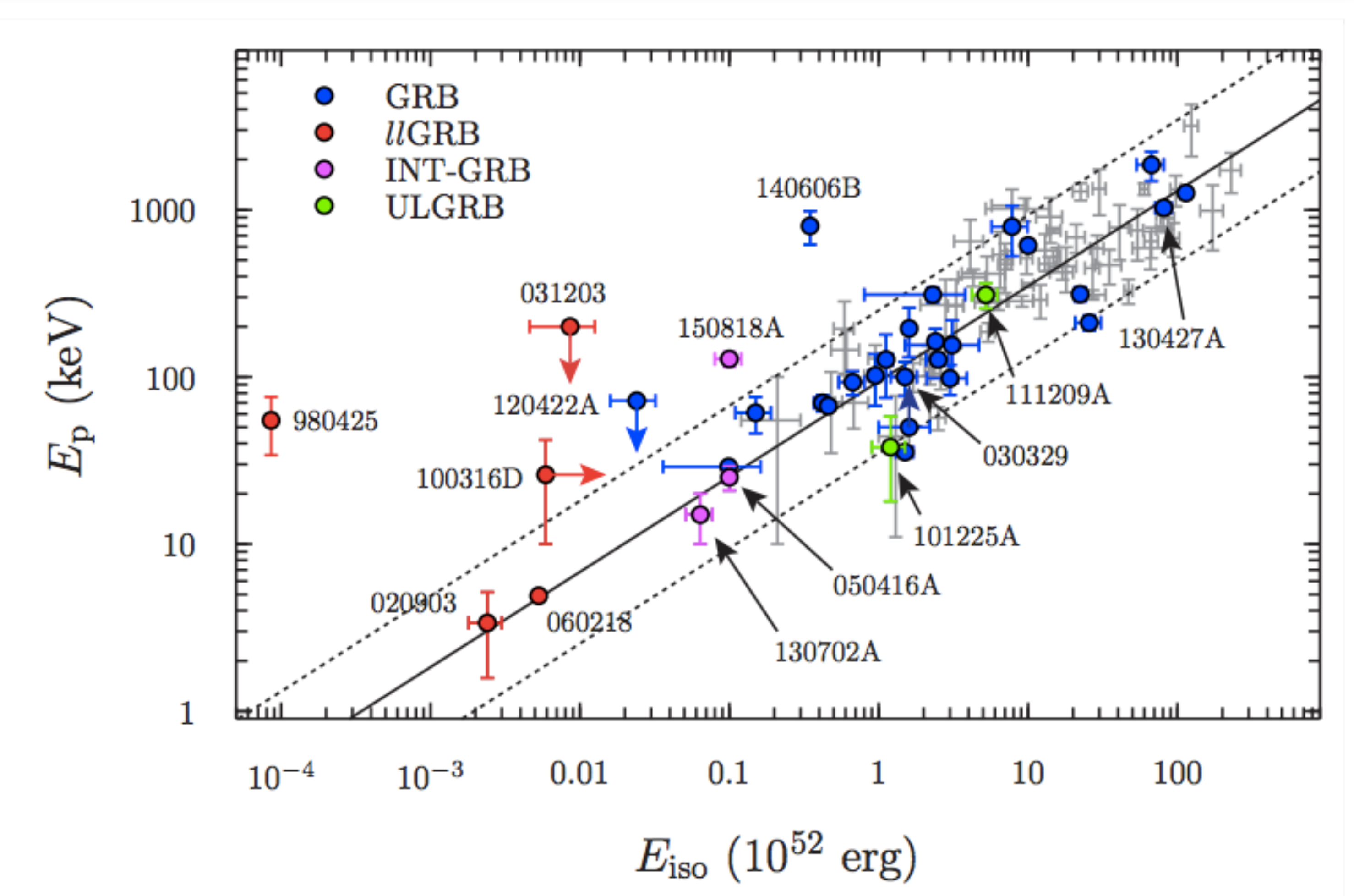
★ *ll*GRB-SNe: GRB-SNe associated with low luminosity GRBs ($L_{\gamma,iso} < 10^{48.5}$ *erg/s*)

★ INT-GRB-SNe: GRB-SNe associated with intermediate luminosity GRBs ($10^{48.5}$ *erg/s* $< L_{\gamma,iso} < 10^{49.5}$ *erg/s*)

★ GRB-SNe: GRB-SNe associated with high luminosity GRBs ($L_{\gamma,iso} > 10^{49.5}$ *erg/s*)

★ ULGRB-SNe: ultra-long duration GRB-SNe (exceptionally long duration of their **γ**-ray emission ~ 10^4 sec rather than their **γ**-ray luminosities)

Cano et al. 2016



*ll*GRB-SNe

★ Typically low redshift
GRBs 980425 (z=0.0085); 031203 (z=0.105);
060218 (z=0.033); 100316D (z=0.059)

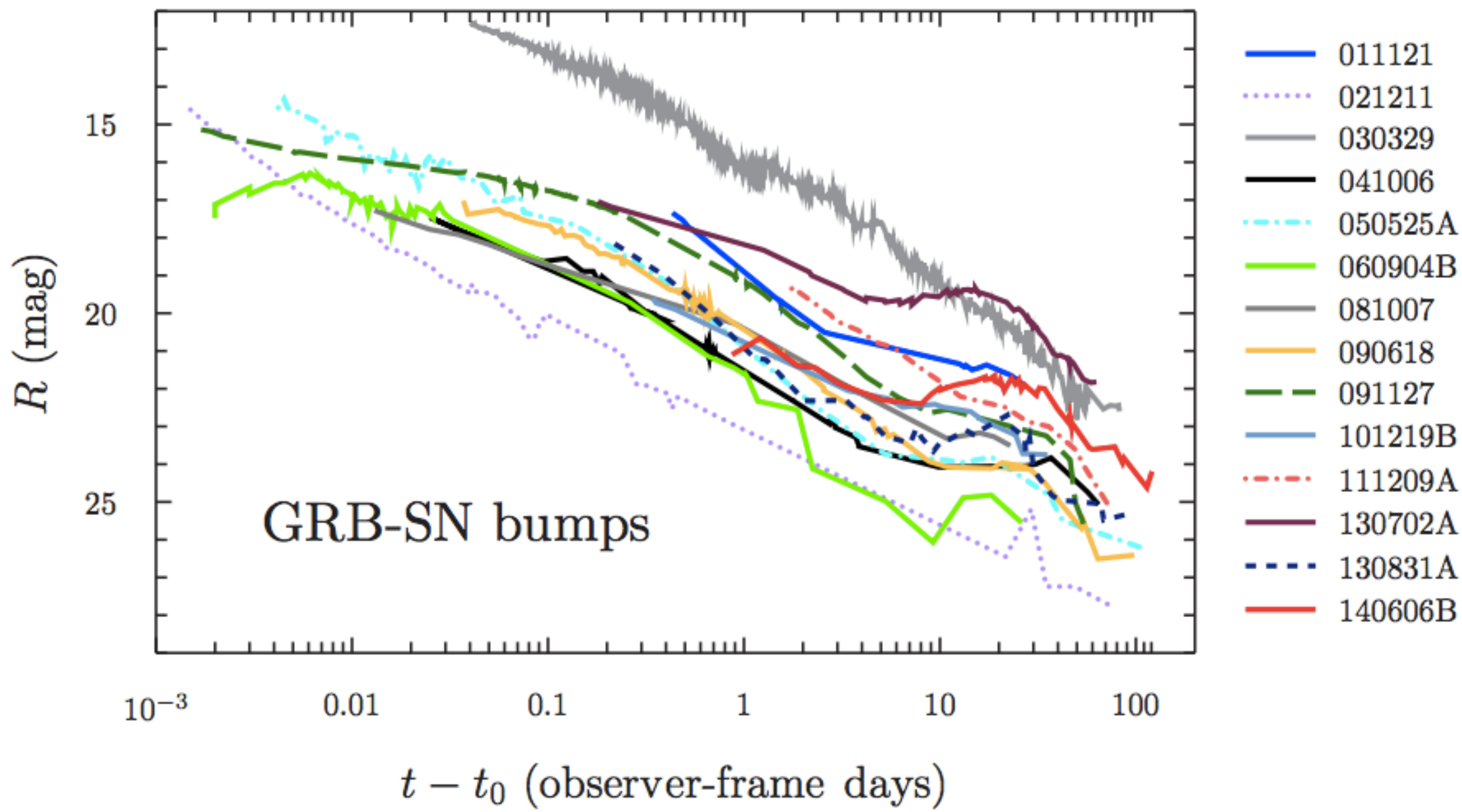
★ Follow E_{peak} - E_{iso} correlation; occasionally divergent

★ Faint undetected optical afterglows

- Do these represent a different population?
- Are all lGRBs associated with SNe?

Additional GRB-SN examples required

A mosaic of GRB-SNe (AG + SN)

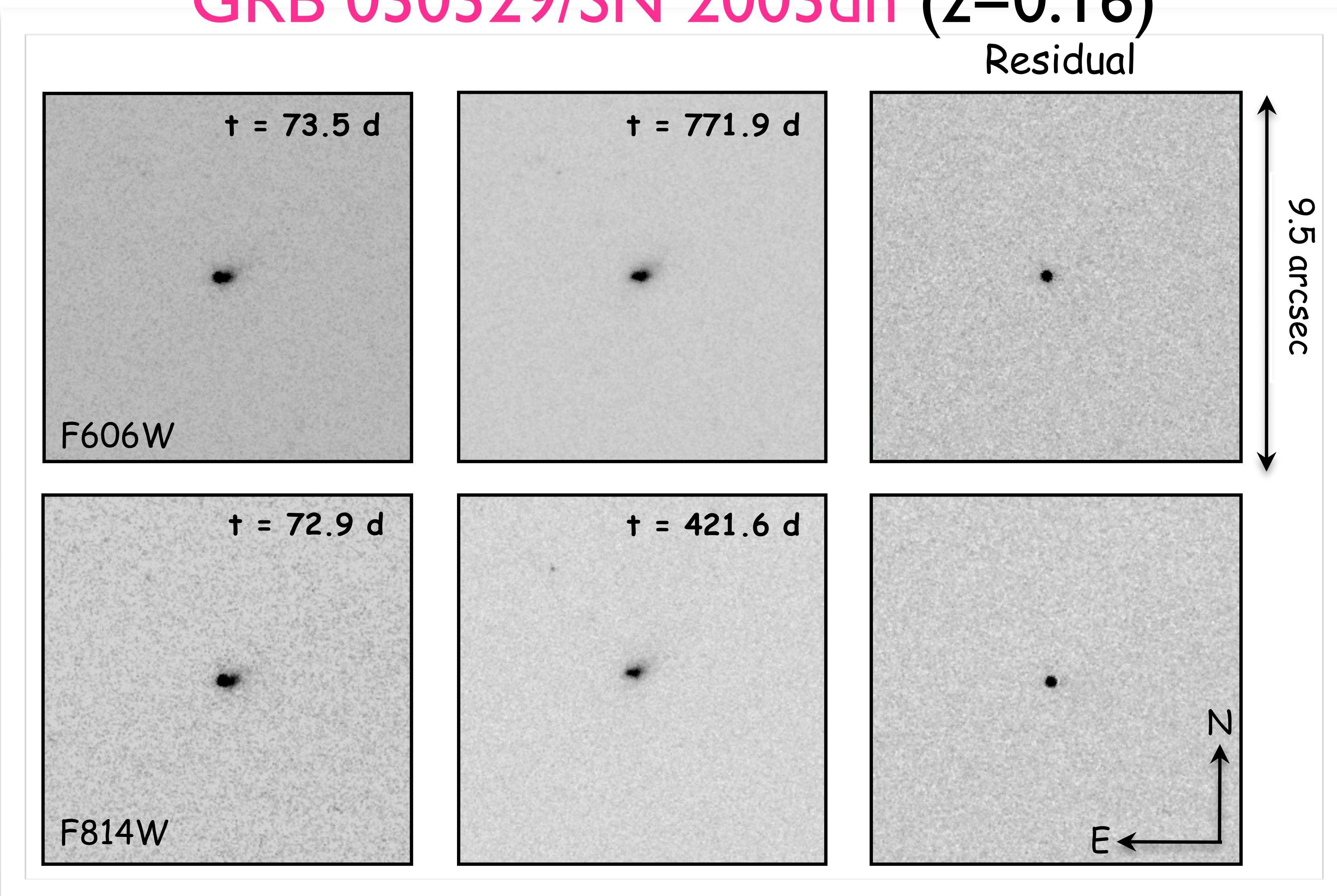


Cano et al. 2016

SN 2003dh & SN 2006aj are rare examples of SNe associated with GRBs/XRFs. GRBs are typically distant objects and hence lack detailed study at late-times due to unavailability of data. The *HST* data sets of two broad lined type Ic SNe - SN 2003dh & SN 2006aj offers a unique opportunity to study the late-time (~320 days) behaviour of the light curves and to constrain the decay nature in the nebular phase.

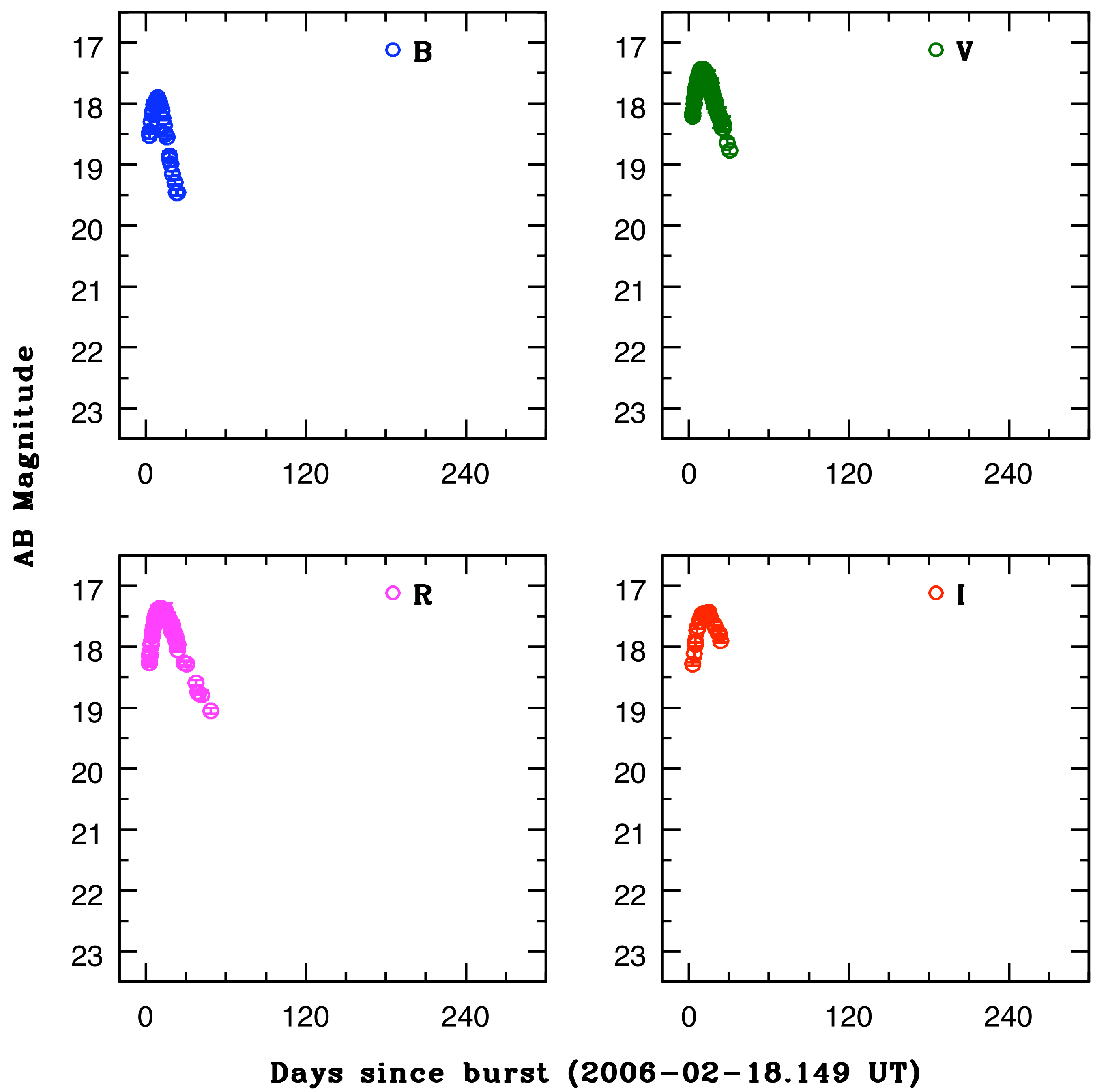
SN 1998bw, XRF 020903/SN, SN 2010bh are others for which late-time observations exist.

GRB 030329/SN 2003dh (z=0.16)

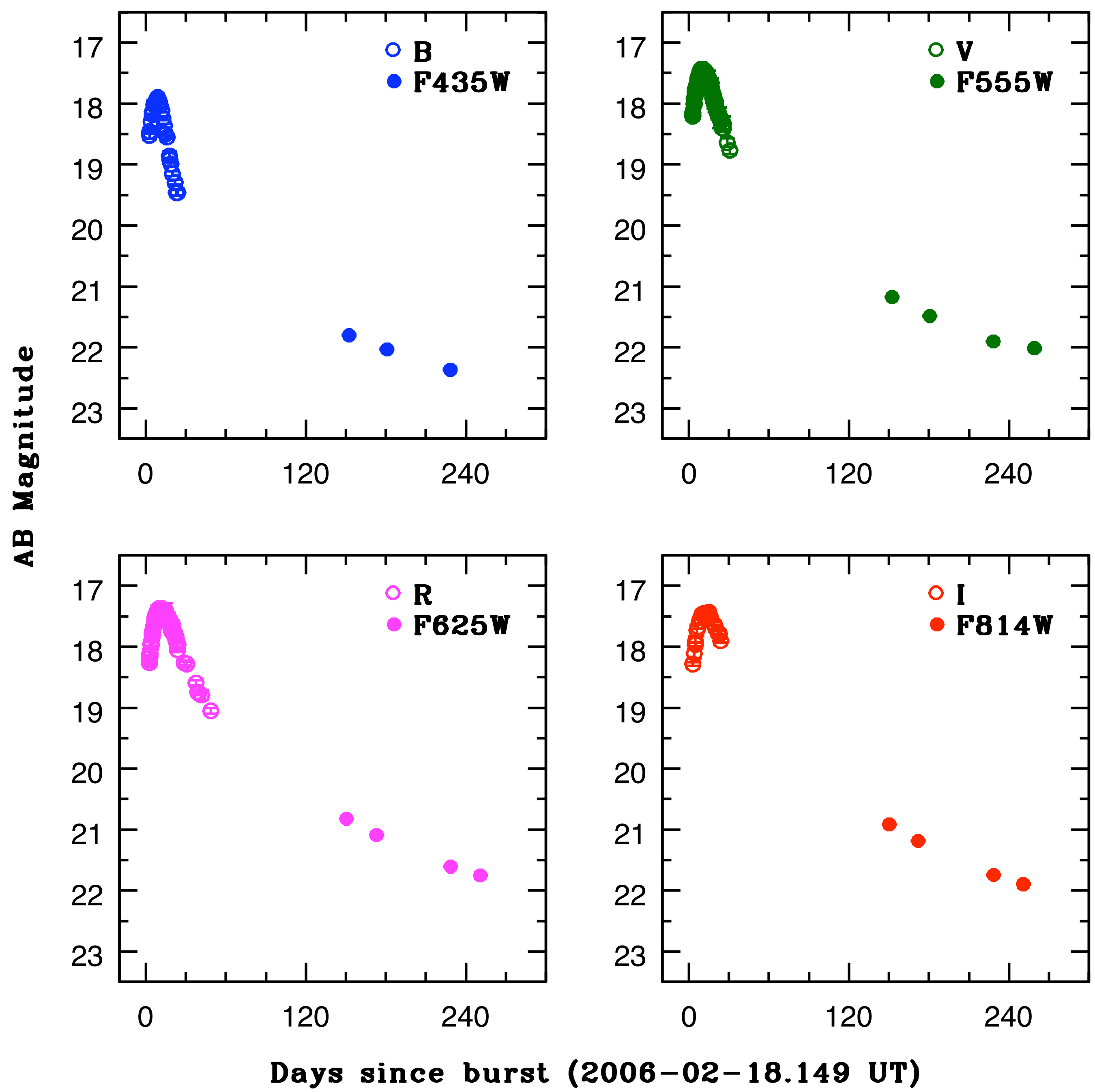


XRF 060218/SN 2006aj (z=0.033)

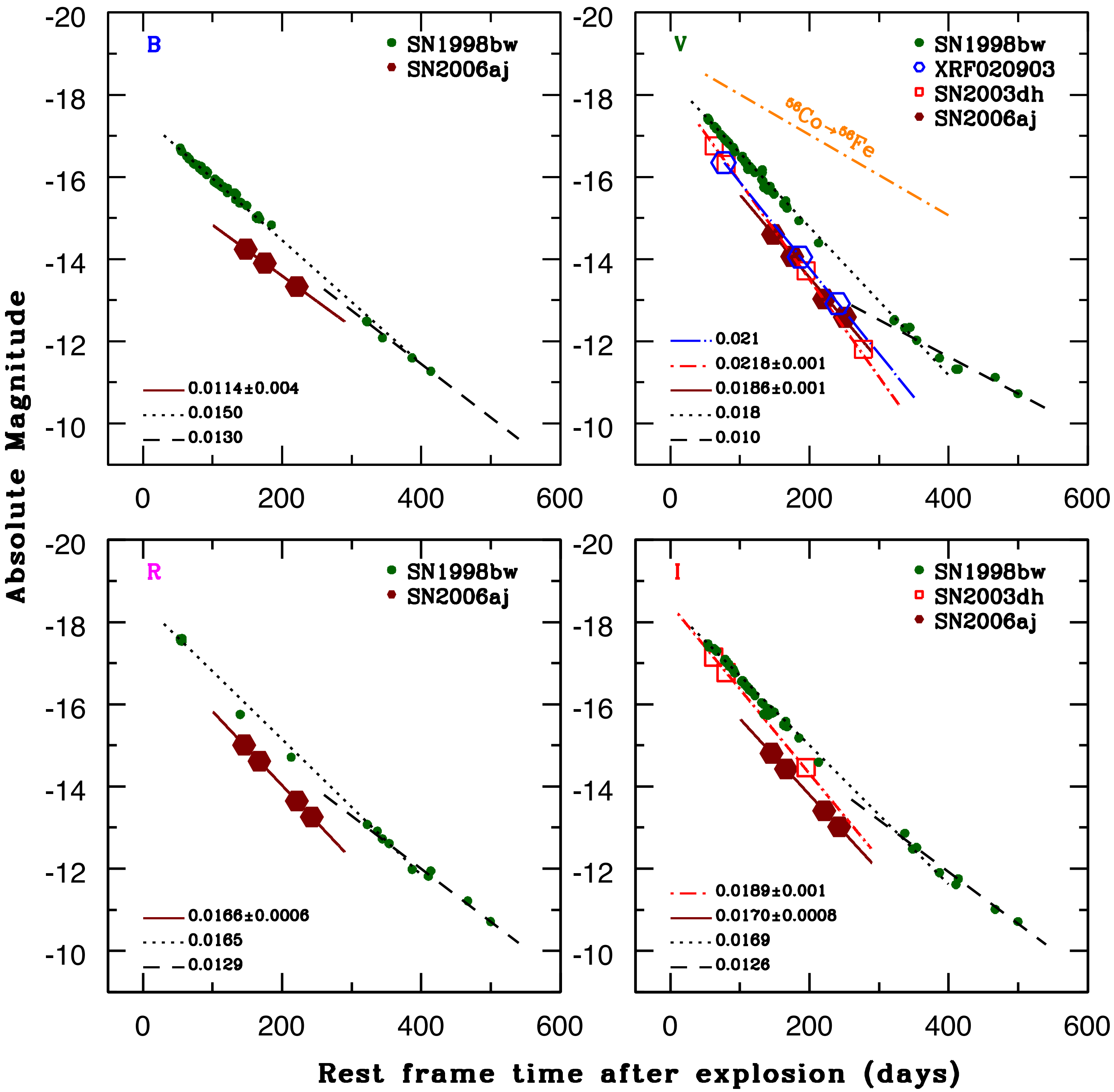
Light curve evolution of SN 2006aj



Light curve evolution of SN 2006aj



Comparing Supernovae Associated with GRBs/XRFs



Misra & Fruchter 2011

★The late-time data constrains the decay of SN 2003dh and SN 2006aj. The decay rates are very similar to that of SN 1998bw.

★We find that the slopes are steeper than the $^{56}Co \rightarrow ^{56}Fe$ decay rate (0.0098 mag/day) indicating that there is some leakage of γ-rays.

★The late-time luminosity in SN 2006aj is a factor of two less than that of SN 1998bw which suggests a factor of two less in the ejected mass of ^{56}Ni.

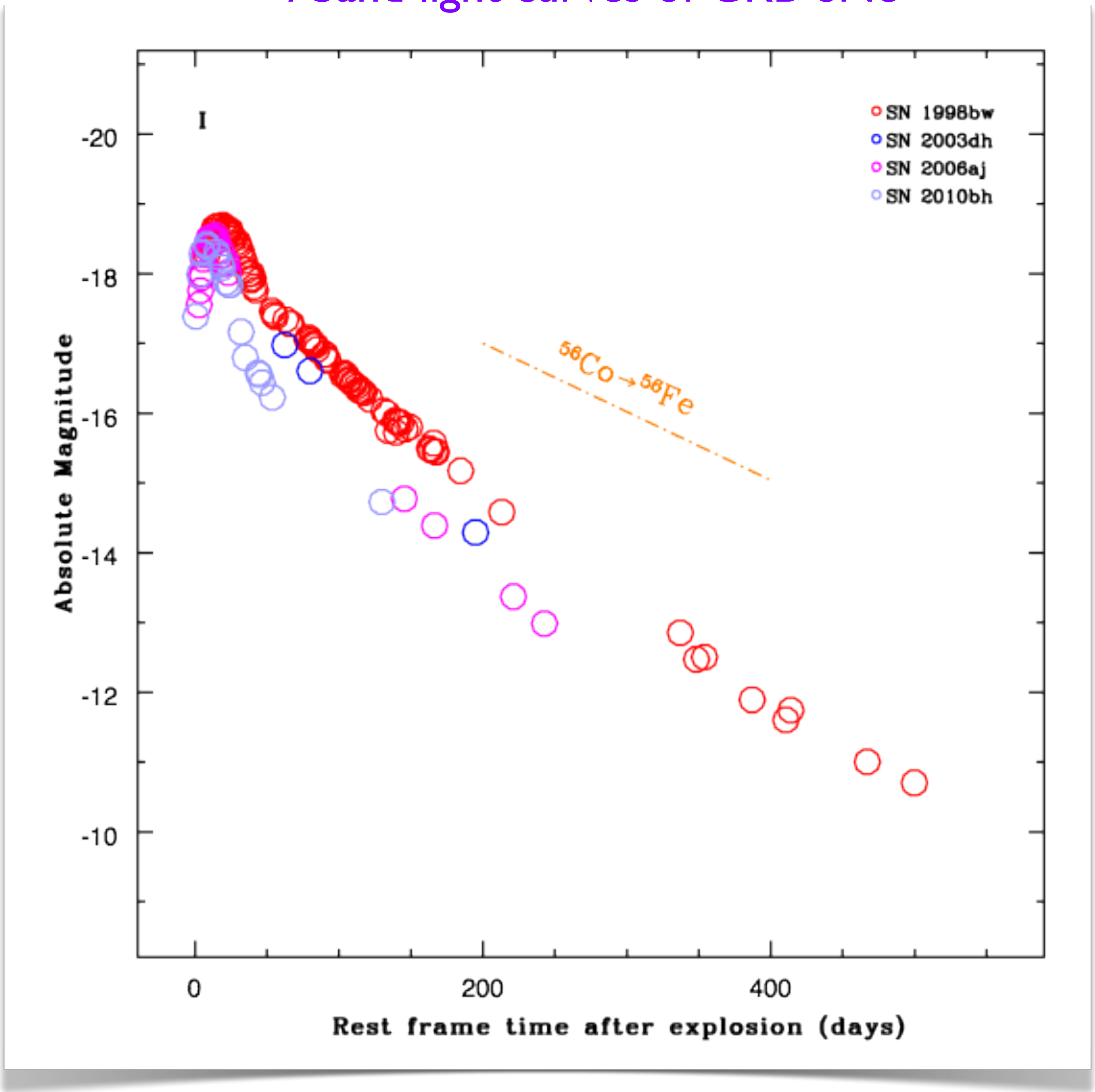
^{56}Ni mass estimates* of Type Ic SNe

SN	Redshift	$M(^{56}Ni)$ M_{sun}	M_{ej} M_{sun}	E_k (10^{51}) erg	References
980425/1998bw	0.0085	0.38 – 0.48	10±1	50±5	Iwamoto et al. 1998, Galama et al. 1998, Nakamura et al. 2001, Maeda et al. 2003
030329/2003dh	0.1685	0.25 – 0.45	8±2	40±10	Mazzali et al. 2003, Deng et al. 2005
060218/2006aj	0.0334	0.20 – 0.25	2	2	Mazzali et al. 2006, Ferraro et al. 2006
100316D/2010bh	0.0591	0.10 – 0.12	1.9-2.2	12-14	Cano et al. 2011
1997ef	0.0012	0.15	10	8	Iwamoto et al. 2000
2002ap	0.0022	0.08	3	4	Foley et al. 2003, Pandey et al. 2003, Mazzali et al. 2002, Tomita et al. 2006
2003jd	0.0188	0.36	3±0.05	7±2.5	Valenti et al. 2008a
2007bg	0.0346	0.12	1.5±0.5	4±1	Young et al. 2010
2007ru	0.0154	0.4	1.3±1	5±4	Sahu et al. 2009
1994I	0.002	0.07	0.9	1	Nomoto et al. 1994, Richmond et al.1996, Clocchiatti et al. 2008
2004aw	0.0163	0.25-0.35	3.5-8	3.5-9.0	Taubenberger et al. 2006
2007gr	0.0017	0.076	2-3.5	1-4	Valenti et al. 2008b, Hunter et al. 2009

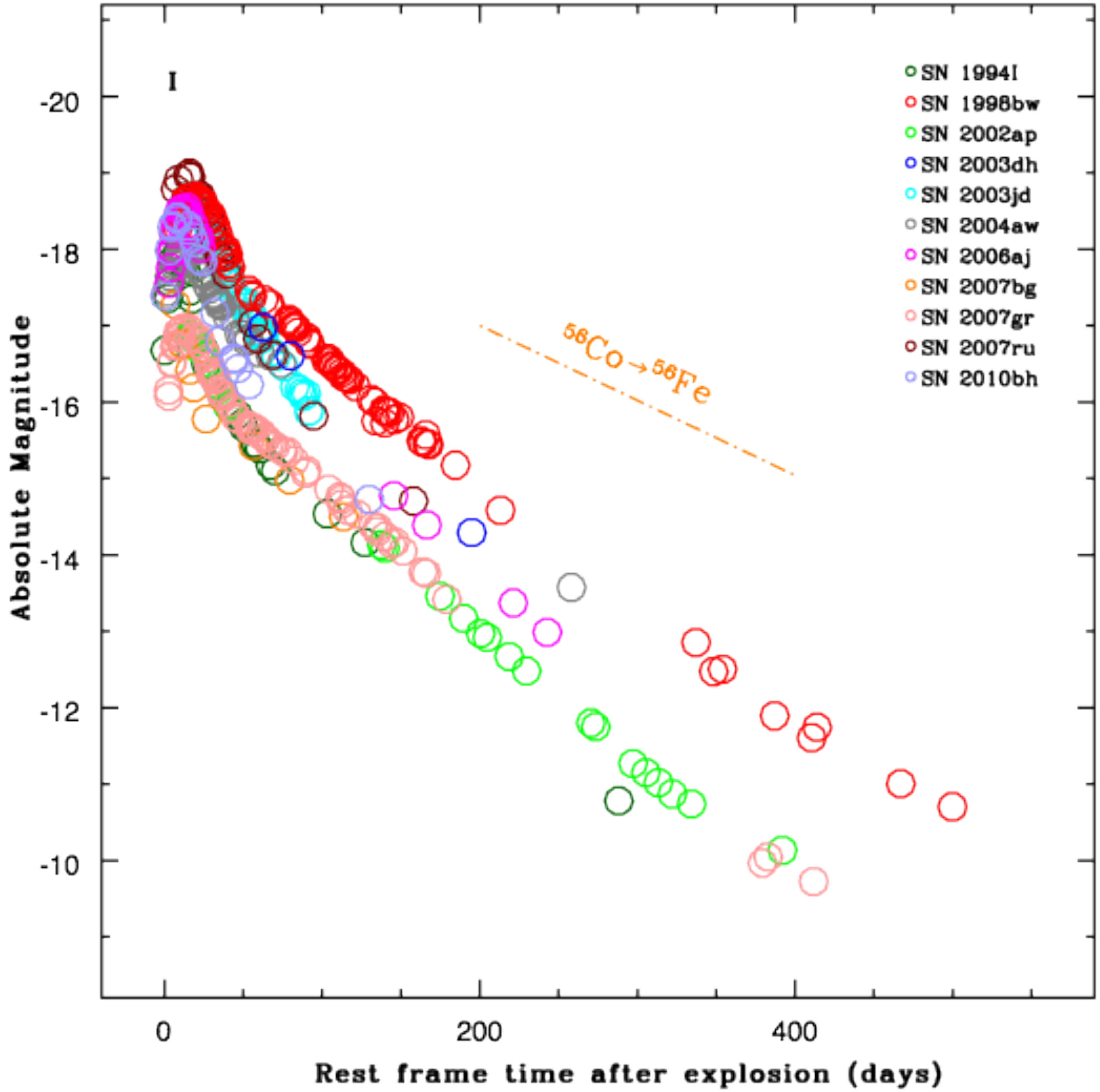
*From peak bolometric luminosity

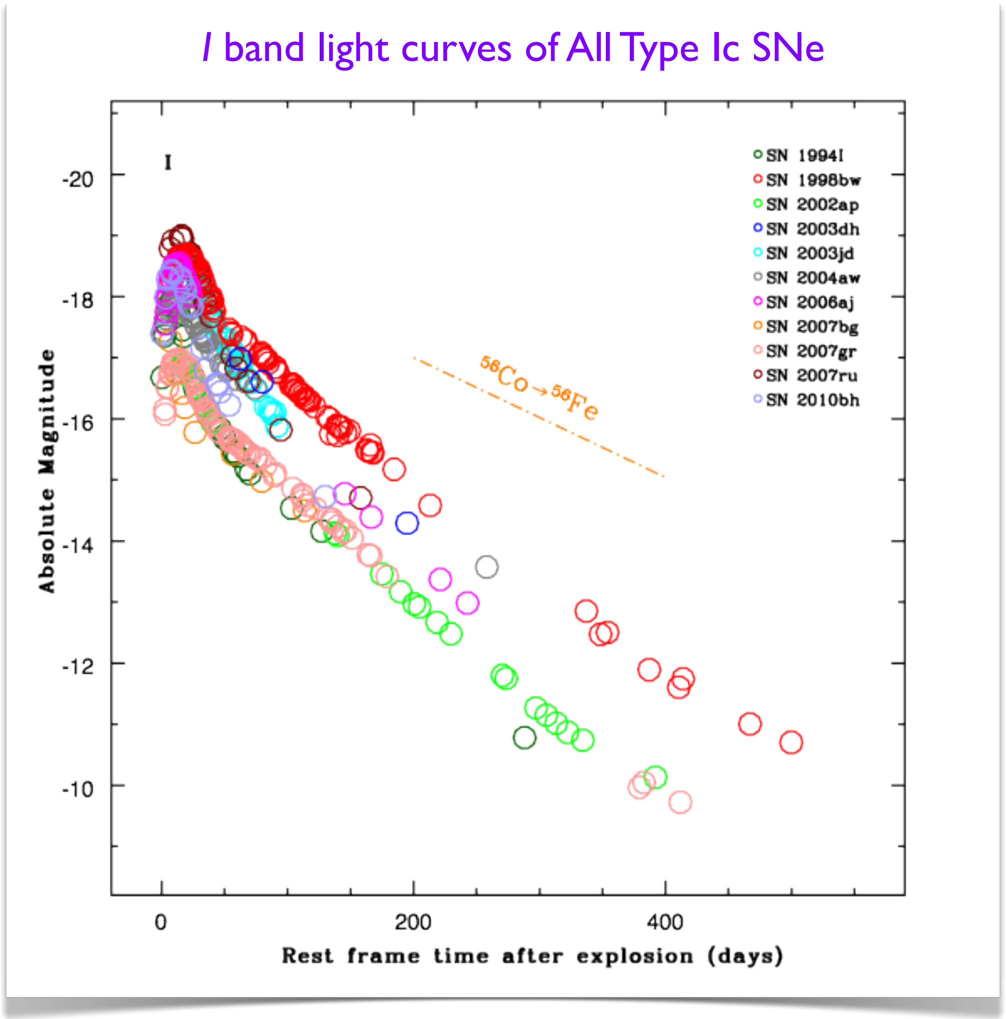
Type Ic's form a very heterogeneous class spanning a wide range in luminosities and ejected mass

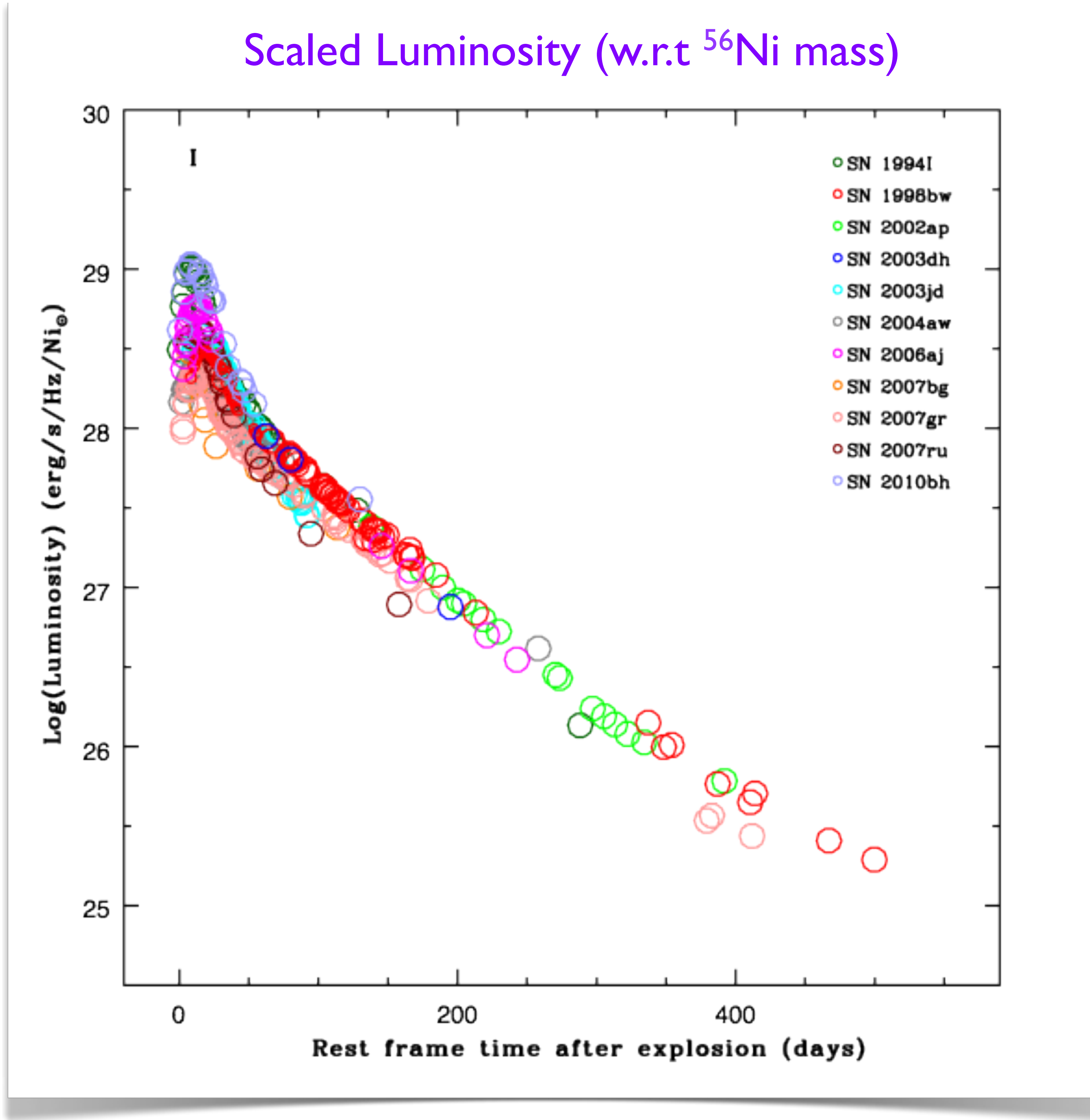
I band light curves of GRB-SNe



I band light curves of All Type Ic SNe

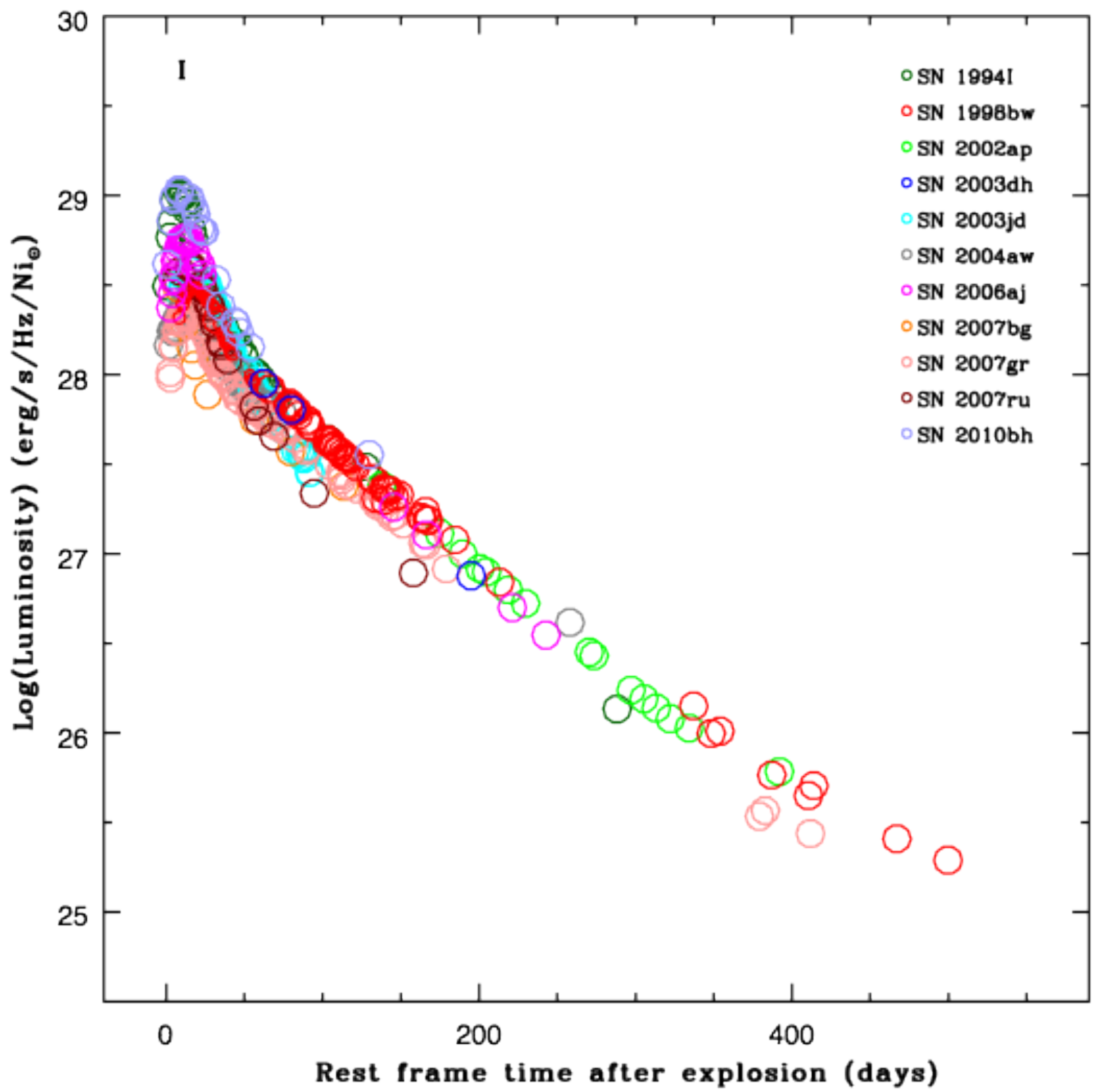



I band light curves of All Type Ic SNe
I
SN 1994I
SN 1998bw
SN 2002ap
SN 2003dh
SN 2003jd
SN 2004aw
SN 2006aj
SN 2007bg
SN 2007gr
SN 2007ru
SN 2010bh
56Co→56Fe
Absolute Magnitude
Rest frame time after explosion (days)

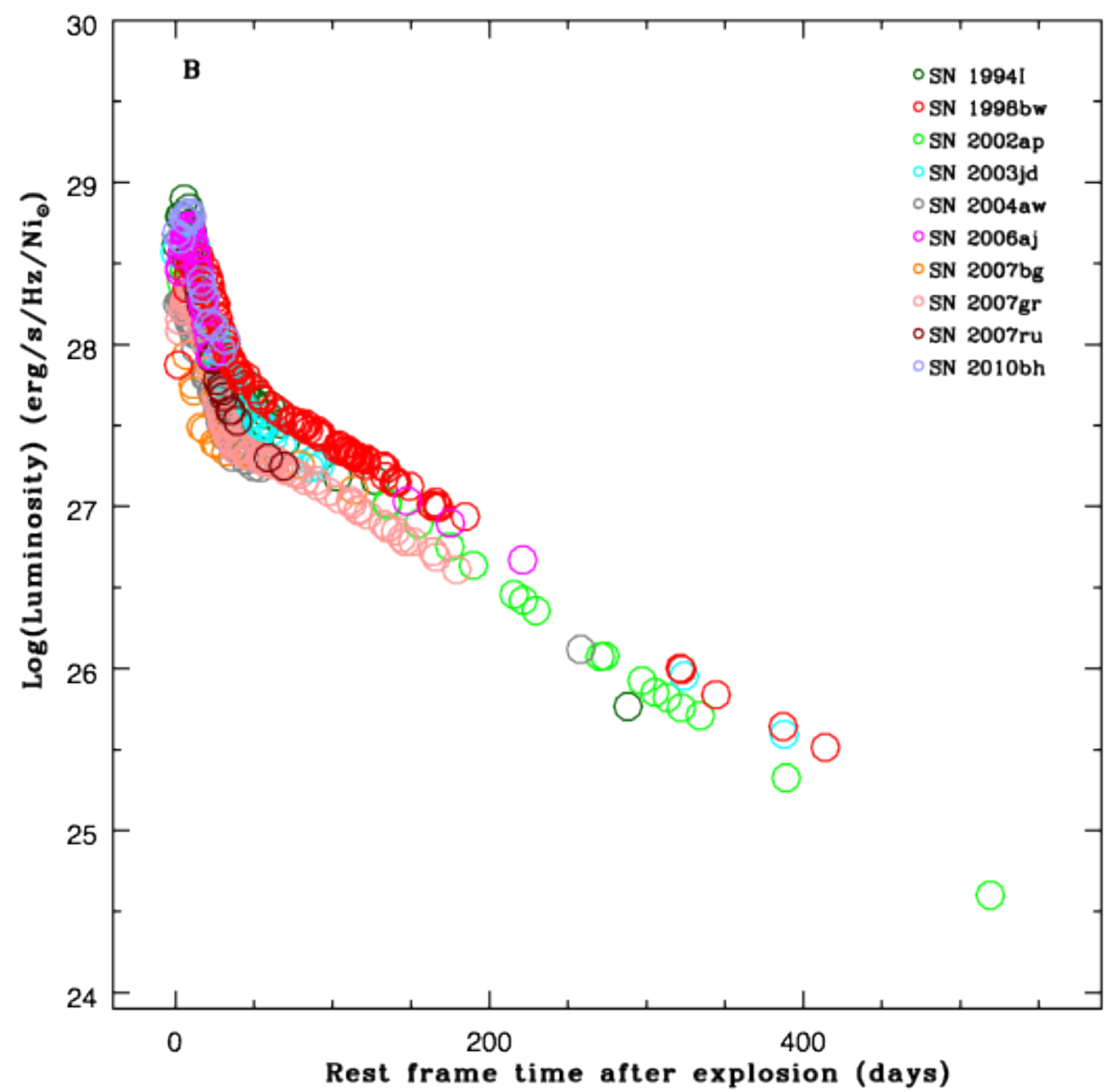

Scaled Luminosity (w.r.t 56Ni mass)
I
SN 1994I
SN 1998bw
SN 2002ap
SN 2003dh
SN 2003jd
SN 2004aw
SN 2006aj
SN 2007bg
SN 2007gr
SN 2007ru
SN 2010bh
Log(Luminosity) (erg/s/Hz/Ni⊙)
Rest frame time after explosion (days)

Scaled luminosity (w.r.t ^{56}Ni mass)

I-band



B-band



Concluding Remarks

- ★Recent observations and detections of GRB-SNe have significantly added to the GRB-SNe population. Associated supernova signature seen in both local and cosmological GRBs.

- ★SN 2006aj is one of the few GRB/XRF associated supernova which has been observed at such late times. GRB 980425/SN 1998bw, the SN associated with XRF 020903, GRB 030329/SN 2003dh and GRB 100316D/SN 2010bh are others for which late-time observations exist.

- ★Using the late-time data we constrain the decay nature of SN 2003dh and SN 2006aj. We find that the decay rates are steeper than the $^{56}Co \rightarrow ^{56}Fe$ (0.0098 mag/day) decay rates indicating that there is some leakage of γ-rays.

- ★The late-time light curves of a heterogeneous sample of type Ic supernovae, when scaled by the estimated ^{56}Ni mass, cluster together with a particularly low dispersion in the I-band.

- ★The excellent scaling between the late light curves implies that inspite of the great energy of their relativistic jets and high kinetic energies, the light curves of GRB associated supernovae are powered throughout by the radioactive decay of ^{56}Ni.

- ★Additional late-time observations of “true” cosmological GRBs to constrain the late-time behavior.