

**Fig. 1.** Examples of 9 SNe from the sample and their classification through the SNID package.

the sample<sup>3</sup>. In order to identify these SNe, the SE SN template presented by Taddia et al. (2015) was used as a reference. The template was shifted and stretched to fit the SN light curve at maximum. The SNe that presented a stretch factor higher than 1.5 were considered as having a broad light curve. The method used and these SNe will be discussed in detail in a forthcom-

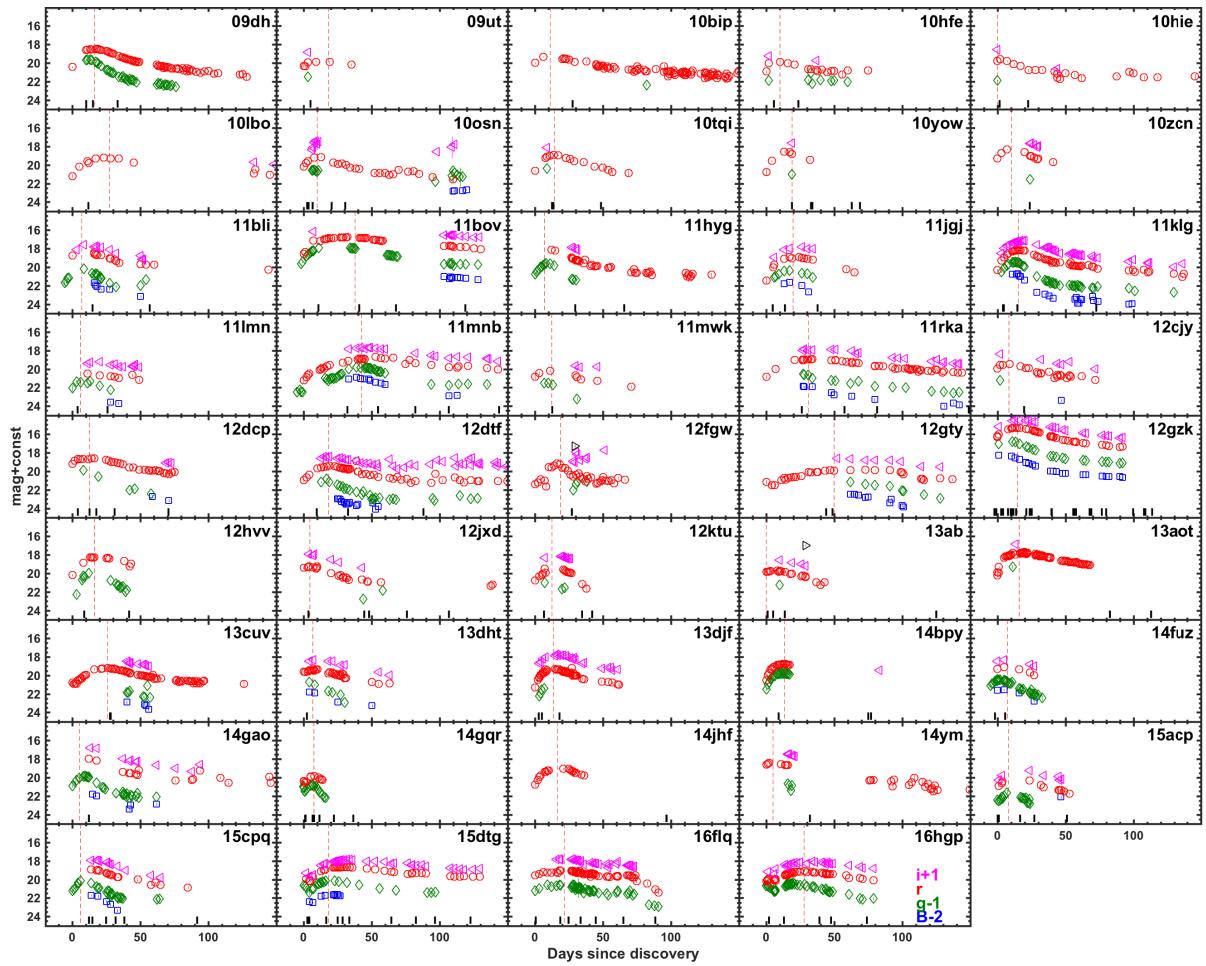
ing paper (Karamehmetoglu et al. in prep). Our sample also includes an object with a very narrow light curve<sup>4</sup>. The presence of a wider variety of objects is likely due to large sample and the untargeted nature of the survey.

<sup>3</sup> PTF11mnb, PTF11rka, PTF12gtv, iPTF15dtg, iPTF16flq and iPTF16hgp.

<sup>4</sup> iPTF14gqr.







**Fig. 4.** Light curves in  $B, g, r, i$  of the 44 SNe Ic for which we have pre-maximum observations. We plot the apparent magnitude as a function of days since discovery. Shifts have been applied for clarity, as indicated in the legend in the bottom row. The peak epoch is shown as a dashed red line. The black dashed lines at the bottom represent epochs of spectral observations.

enough signal-to-noise (S/N) close to the Na I D line to properly detect it. On the other hand, the  $g - r$  method relies on an intrinsic colour curve template and on assuming homogeneity of the colour evolution for these SNe. In this work we will adopt the extinction estimated from the Na I D, unless otherwise specified. The main reason is that we want to compare our results with those published in the literature, which most often have used this method. However, throughout the analysis we will discuss how some values will be affected if we instead chose the extinction estimated from the second method.

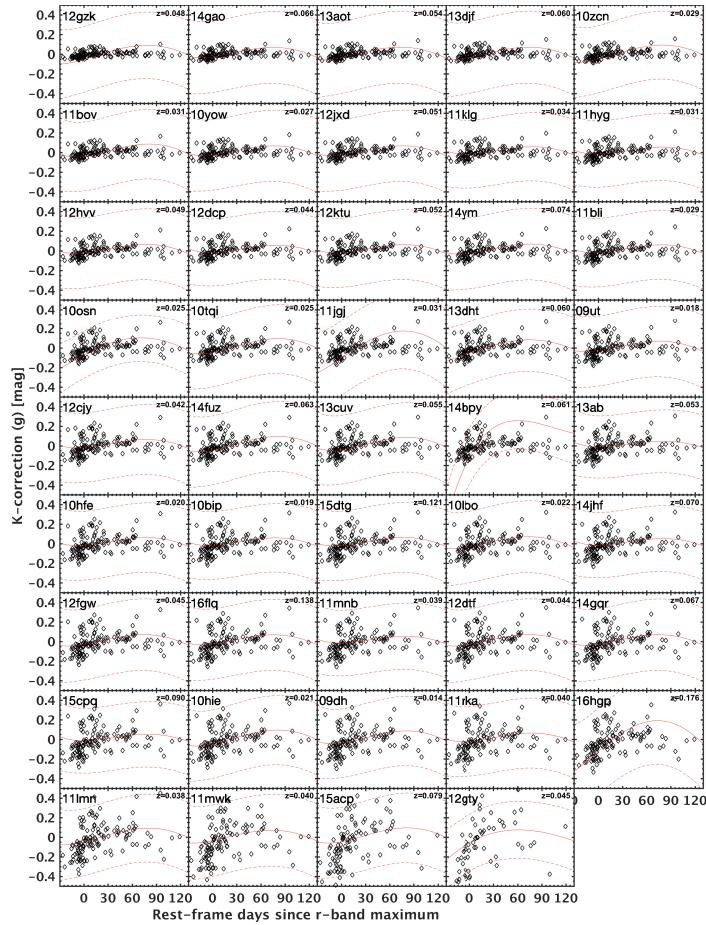
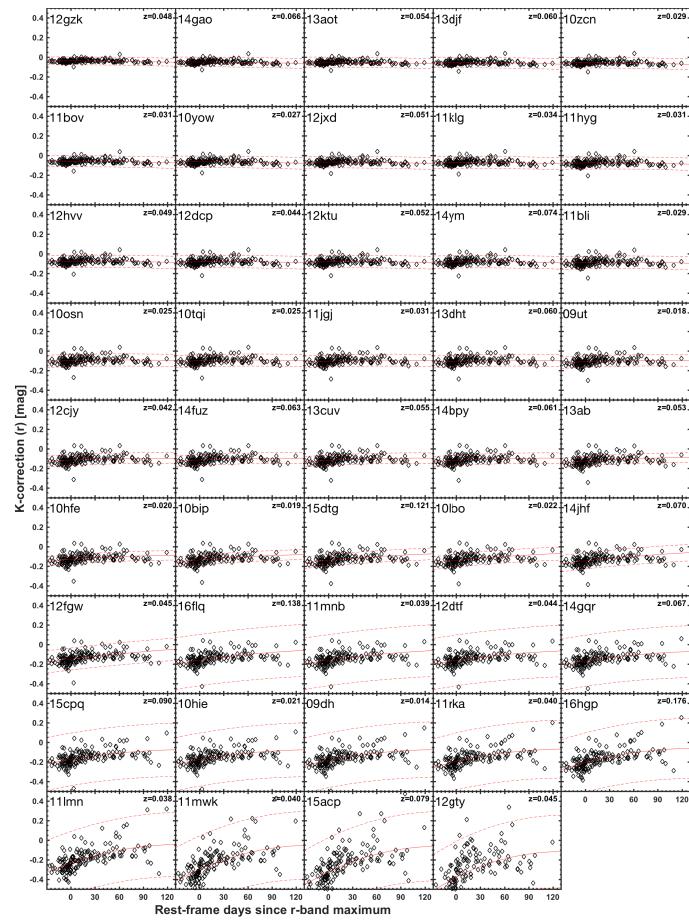
#### 4.4. Absolute magnitudes

We applied the presented corrections; Milky Way and host extinctions, distances and K-corrections, to the light curves to obtain the absolute magnitudes, see Fig. 11.

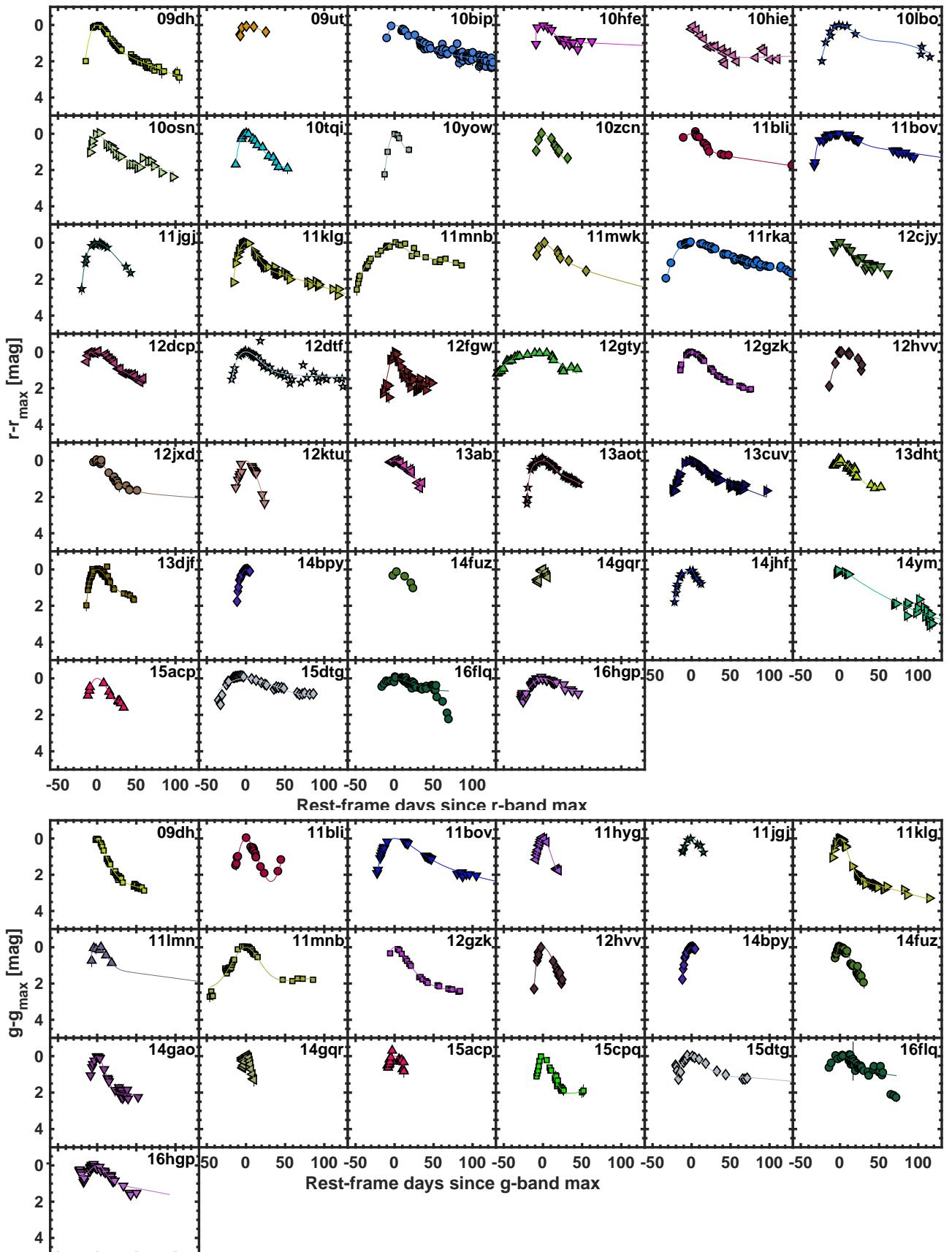
The uncertainty on the absolute magnitudes takes into account the uncertainties due to the host extinction estimates and the photometric errors. In addition, the uncertainty on the distance adds a systematic error of  $\pm 0.15$  mag which has not been included in the figure. This systematic is for an adopted uncertainty on  $H_0$  of  $\pm 5$  km s $^{-1}$ , which dominates uncertainties from the peculiar velocities at the redshifts of our sample SNe. The

distribution of the  $r$ -band absolute magnitudes at peak is shown in Fig. 12.

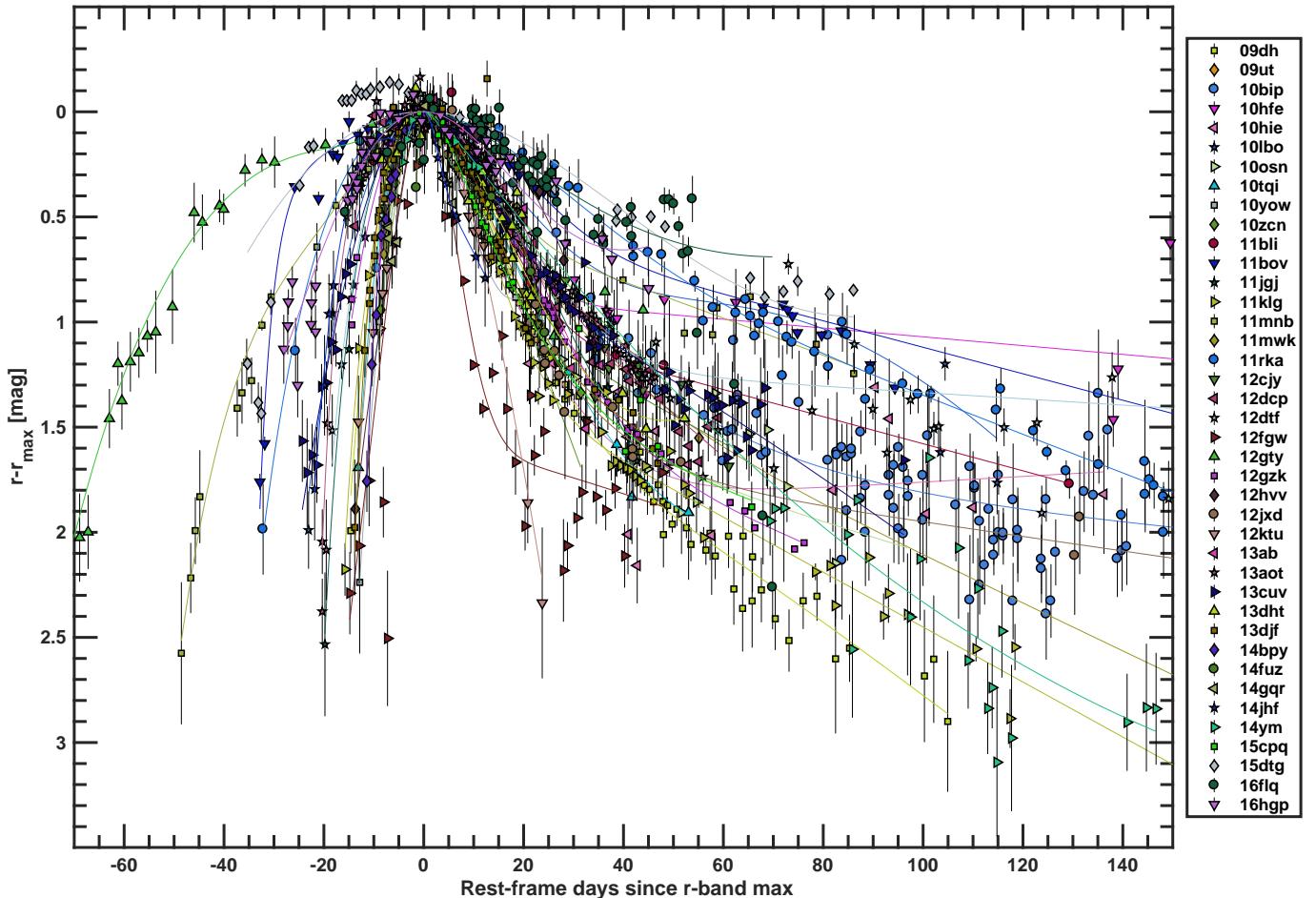
Our  $r$ -band magnitudes span the interval  $-15.45$  to  $-19.73$  mag when the host extinction has not been accounted for, giving an average of  $\langle M_r^{\text{peak}} \rangle = -17.50 \pm 0.82$  mag. It ranges from  $-15.54$  to  $-19.81$  mag when the host extinction from Na I D is included, with an average of  $\langle M_r^{\text{peak}} \rangle = -17.71 \pm 0.85$  mag. If we instead consider the extinction estimates from  $g - r$ , the interval is  $-16.91$  to  $-19.84$  mag and an average of  $\langle M_r^{\text{peak}} \rangle = -18.07 \pm 0.84$  mag. All values for each SN in the sample are reported in Table 3. We notice how PTF12gyt is the brightest SN in the sample with an absolute peak magnitude of  $-19.81$ . The absolute magnitude ranges available in the literature are  $M_r^{\text{peak}} = -18.26 \pm 0.21$  mag (Taddia et al. 2015);  $M_r^{\text{peak}} = -17.64 \pm 0.26$  mag (Taddia et al. 2018b) and  $M_R^{\text{peak}} = -18.3 \pm 0.6$  mag (Drout et al. 2011). The average peak magnitude in the  $r$  band estimated for our sample is thus in agreement with the ones from the literature. We compared these values also with the (i)PTF sample of SNe Ic-BL (Taddia et al. 2019) where the average peak magnitude is  $-18.7 \pm 0.7$  mag. Our SNe Ic are on average fainter than the SNe Ic-BL. We investigated the absolute  $r$ -band magnitude peak versus  $\Delta m_{15}(r)$  behaviour, to test if there



**Fig. 5.** K-corrections in the  $r$  band for our SN sample. The solid red line represents the second order polynomial fit, whereas the red dashed lines show the  $1\sigma$  uncertainties. The SNe have been ordered according to increasing redshift.



**Fig. 6.** Upper panel: Individual 40 SNe and their Contardo fits in the *r* band. Lower panel: Individual 19 SNe and their Contardo fits in the *g* band.



**Fig. 7.** These are the  $r$ /band light curves for our 40 SNe Ic plotted together. The best Contardo fits are included as full lines. In this and following plots the individual SNe are represented with symbols and colors as provided in the legend to the right. The light curves are normalised at peak in order to illustrate their diversity.

is a Phillips-like relation as for SNe Ia (Phillips 1993). We found that SNe Ic do not show any clear correlation (see Fig. 13).

This is in agreement with previous studies on SE SNe (Prentice et al. 2016; Lyman et al. 2016; Drout et al. 2011). Also a dedicated study on SNe Ic-BL has shown that there is no evidence for such a correlation (Taddia et al. 2019).

For SNe having data more than 70 days past peak, we also measured the slope at late epochs. We investigated the  $\Delta m_{15}(r)$  versus the slope and we did not see any clear correlation. This is not in agreement with what Taddia et al. (2018b) found in their work. Our  $g$ -band peak magnitudes for 19 SNe span the interval  $-15.86$  to  $-18.91$  mag when the host extinction is not taken into account and it ranges from  $-17.10$  to  $-19.51$  mag when included, with an average value of  $-17.99 \pm 0.69$  mag. Finally, if we consider the extinction we get from the  $g - r$  method the interval is  $-17.04$  to  $-19.44$  mag. In this case the average is  $-18.39 \pm 0.65$  mag. The average value for the peak magnitude in the  $g$ -band is in agreement with the  $-17.28 \pm 0.24$  found by Taddia et al. (2018b).

#### 4.5. Explosion epochs and rise times

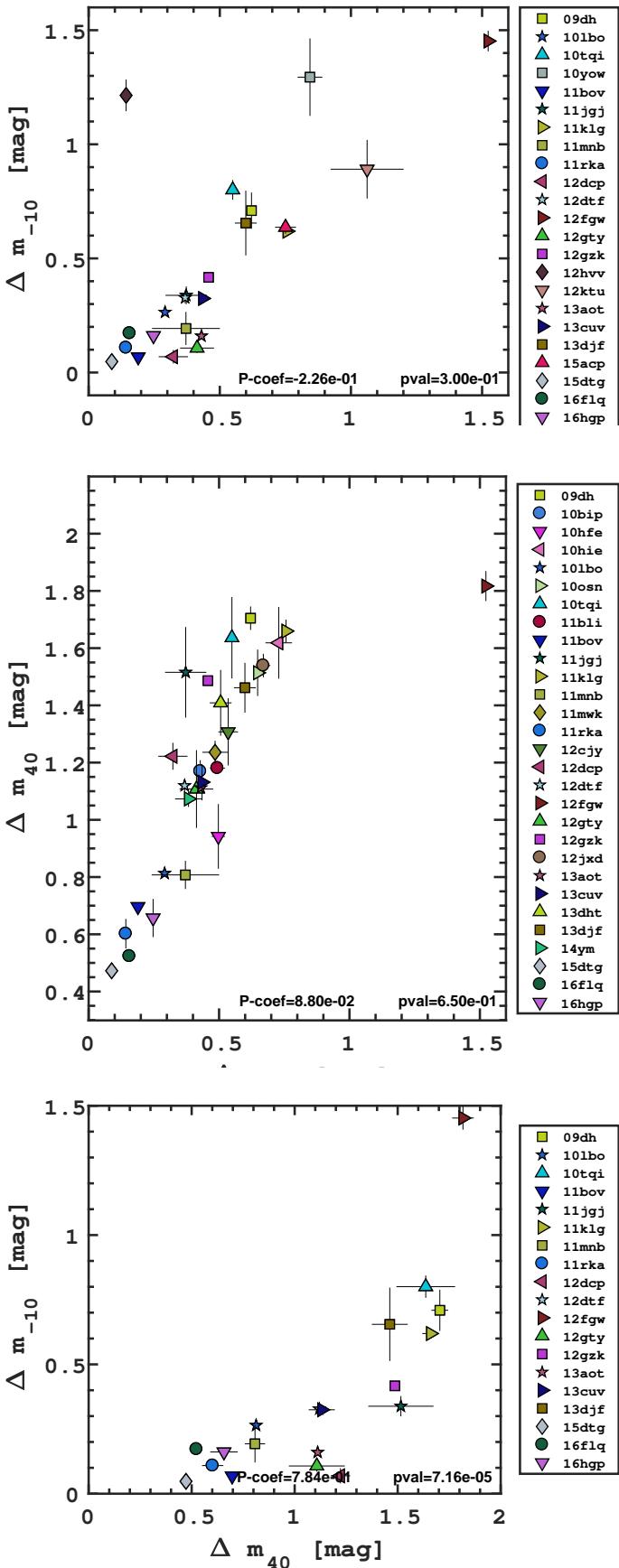
The separation between last non-detection and first detection for all the SNe of the sample varies in the interval 1 – 30 days, with

the exception of six SNe<sup>8</sup> that do not have last non-detection within 50 days prior the first detection. In order to estimate the explosion epochs for each SN, we compare their  $r$ -band light curves with the  $r$ -band light curve of iPTF13djf. This supernova has a good photometric coverage and well determined explosion epoch, with a limit on the discovery date of only  $\pm 1$  day. Since the explosion epoch of iPTF13djf is well constrained, as is the peak epoch in the  $r$  band, we use it as a template and the stretch of the best fit allows us to infer the explosion epoch for all other SNe in the sample. The light curve of iPTF13djf is stretched in time and shifted in magnitude to fit our SN light curves until +30 days post peak. The estimated explosion epochs were checked against the pre-explosion limits for consistency. We adopted  $\pm 2$  days as a conservative estimate of the uncertainties on the explosion epochs.

In a few cases when this method did not give results consistent with the pre-explosion limits, we assume the last non-detection as the explosion epoch.<sup>9</sup> We note that in these cases the values we will estimate for the rise time will have to be considered as an upper limit. When an estimate for the SN explosion epoch was available from literature, we adopted the latter as our explosion epoch. This was the case for PTF11mnb (Taddia et al. 2018a),

<sup>8</sup> PTF10hie, PTF11klg, iPTF12cjy, iPTF14jhf, iPTF14ym and iPTF16flq.

<sup>9</sup> We assumed the last non detection as explosion epoch for PTF09dh, PTF10hfe, PTF10tqi, PTF10zcn and PTF12gzk.



**Fig. 8.** Correlations between rise and decay in the  $r$  band. Upper panel: The plot shows  $\Delta m_{15}$  against  $\Delta m_{-10}$ . Mid panel:  $\Delta m_{15}$  versus  $\Delta m_{40}$ . Lower panel: The plot shows  $\Delta m_{40}$  against  $\Delta m_{-10}$ . Plots show a correlation among parameters and their p-values, along with the Pearson son coefficients

are also reported.  
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iPTF14gqr (De et al. 2018) and iPTF15dtg (Taddia et al. 2016). The best fits and the obtained explosion epochs are shown in Fig. 14.

The inferred explosion epochs are reported in Table 4. The explosion epochs and the epochs of the maximum in  $r$  band allow us to compute the rest-frame  $r$ -band rise time, these are provided in Table 4. The average rise time we get is 25.3 days which is somewhat higher than the 16.8 days found by Lyman et al. (2016) and the 13.3 days found by Taddia et al. (2018b). This is most likely due to the fact we have more slow rising SNe than in their samples.

## 5. Construction of the Bolometric Light curves

Modeling of the bolometric light curves can help derive parameters on the supernova progenitors and on the explosion physics. To accomplish this, we need to estimate the explosion epochs and construct the bolometric light curves.

### 5.1. Bolometric lightcurves

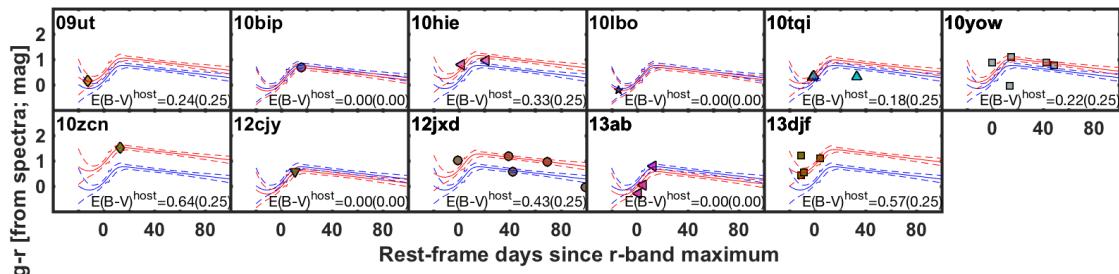
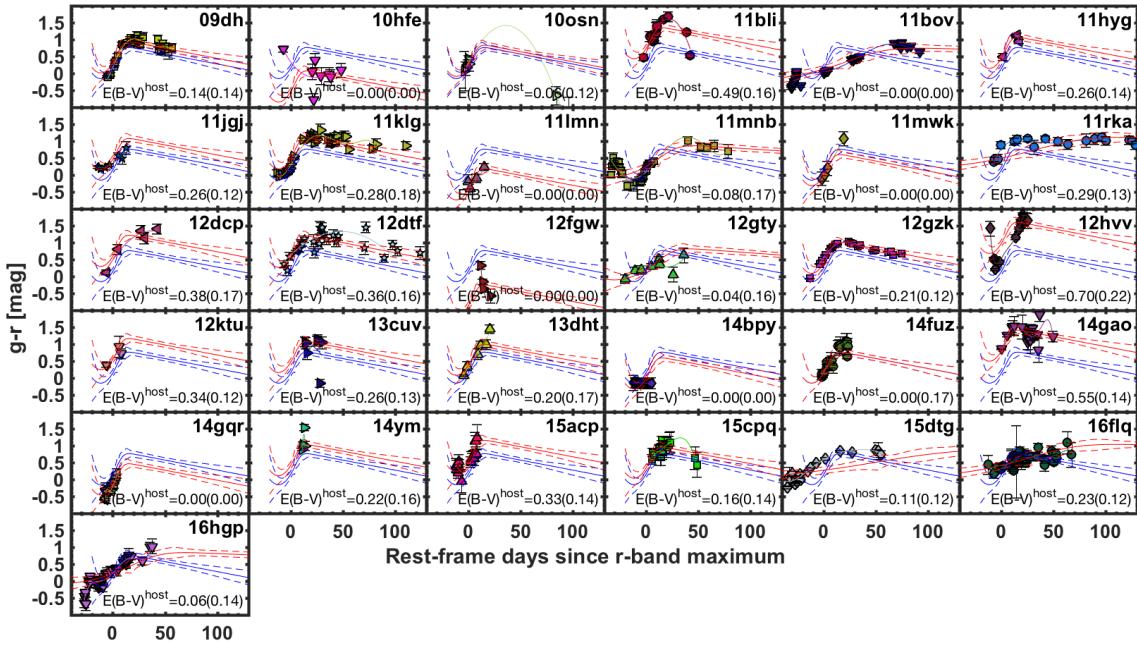
Due to the lack of a complete multiband coverage, in particular at early epochs, we used the absolute  $r$ -band light curves and the fit of the  $g - r$  colour evolution to compute the bolometric light curves, making use of the bolometric corrections for SE SNe presented by Lyman et al. (2014). In this way we are able to create bolometric light curves covering all the phases. The bolometric light curves of 12 SNe<sup>10</sup> were built by applying the bolometric correction directly to the  $g$  band, which is what is needed for the method of Lyman et al. (2014). For the other 30 SNe, we interpolate the  $g$  band from the  $r$  band and then applied the bolometric correction. Only for iPTF13aot and iPTF14jhf were we unable to build a bolometric light curve due to a lack of  $g - r$  evolution and these are therefore excluded from the analysis. The final bolometric light curves as a function of days since explosion are shown in Fig. 15.

The systematic uncertainties due to the bolometric correction (0.076 mag) and on the distance (0.15 mag) are not included in the errors of each bolometric light curve.

### 5.2. Analysis of the bolometric light curve shape

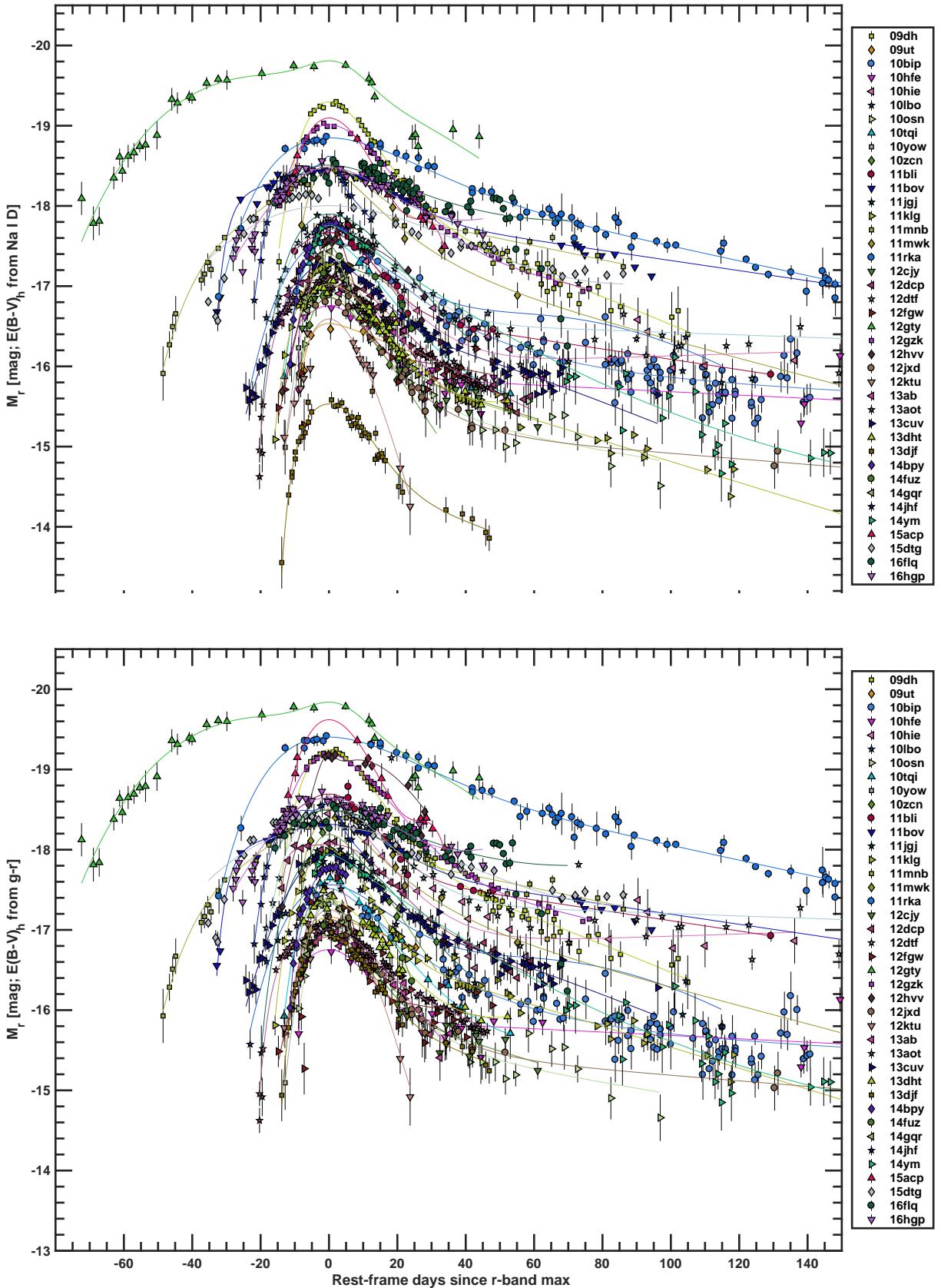
We fit the bolometric light curves with the Contardo function also used in Sect. 4.2. The best fits are shown in the plot as solid lines in Fig. 15. Following the same analysis as for the  $r$  band, this allows us to measure some properties of the shape of the bolometric light curves, such as the peak magnitude, the peak epoch,  $\Delta m_{-10}$ ,  $\Delta m_{15}$  as well as the linear decline slope. We present all these parameters in Table 2. Our sample peak magnitudes span the interval  $-16.10$  to  $-19.78$  mag giving an average of  $< M_{bol}^{peak} > = -17.62 \pm 0.94$  mag. These values are in agreement with the ones available in literature (Drout et al. 2011; Prentice et al. 2016; Lyman et al. 2016; Taddia et al. 2018b). We investigated the same correlations as for the  $r$ -band, they are presented in Fig. 16. We find the same correlations as for the  $r$ -band. We notice that the similarity of relations found among rise and decline parameters in  $r$ -band and bolometric light curve is likely due to the fact that the flux in  $r$  gives a close representation of the bolometric flux at most epochs. We also estimated

<sup>10</sup> PTF11bli, PTF11bov, PTF11hyg, PTF11lmn, PTF11mnb, iPTF14fuz, iPTF14gao, iPTF14gqr, iPTF15acp, iPTF15cpq, iPTF15dtg and iPTF16hgp.

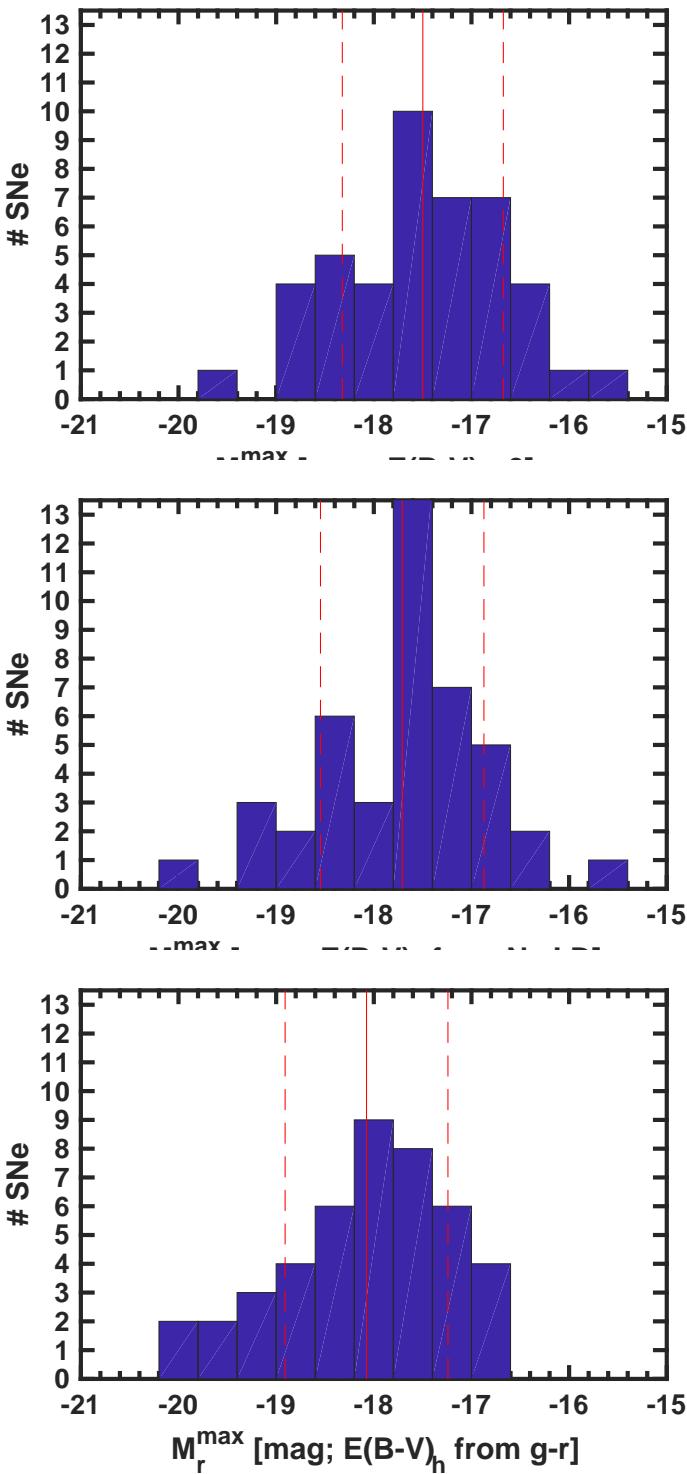


**Fig. 9.** Upper panel: Individual (MW corrected)  $g - r$  colour evolution for 31 SNe from photometry with the polynomial fits represented as solid lines. The red lines represent the fit of the data with the  $g - r$  template. The blue line is the template for a Type Ic with no extinction from Stritzinger et al. (2018), and each panel shows the reddening in  $E(B - V)$  required to shift the colour curve to the data. This represents the estimated host extinction measured in magnitudes. Bottom panel: Same as above for the 11 SNe where the colours are calculated from spectroscopy.



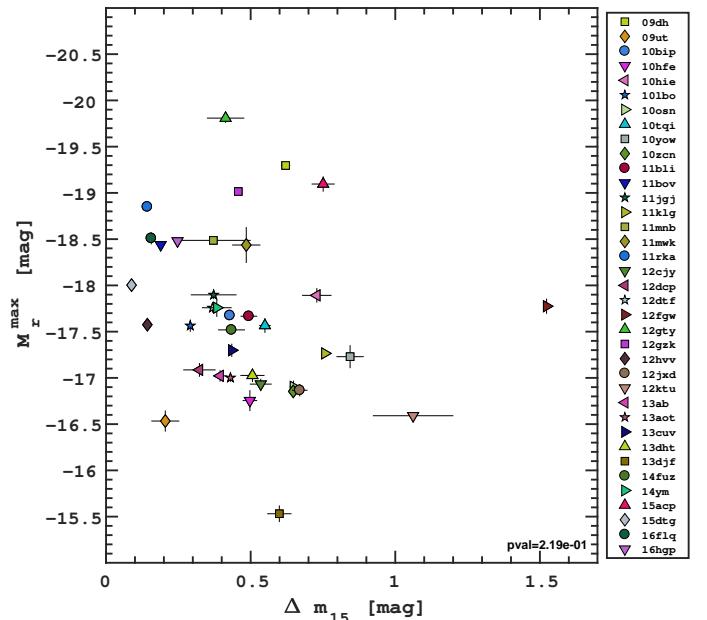


**Fig. 11.** Upper panel: Absolute magnitude in  $r$  band of the 40 SNe of the sample when extinction is estimated from the Na I D absorption. Bottom panel: Absolute magnitude in  $r$  band of the 40 SNe of the sample when extinction is estimated from  $g - r$  colour evolution. For SNe iPTF13aot and iPTF14jhf we assumed the extinction from the Na I D in both cases, since there is no estimate from  $g - r$ .



**Fig. 12.** Histogram representation of the absolute magnitudes at peak in the  $r$ -band distribution of the sample. Upper panel Distribution obtained correcting for the distance and the MW extinction. Middle panel Distribution obtained including also the extinction from the host galaxy, estimated through the Na I D absorption. Bottom panel Distribution obtained instead the host extinction from the colours.

In Fig. 19 we plot each estimated parameter against the others. We identify a correlation between  $M_{ej}$  and  $E_K$  (see bottom panel). We also notice a correlation between the  $M_{ej}$  and  $M_{56\text{Ni}}$ , and between  $M_{56\text{Ni}}$  and  $E_K$ . Note that the small variation of the velocity's range is possibly driving the correlation between



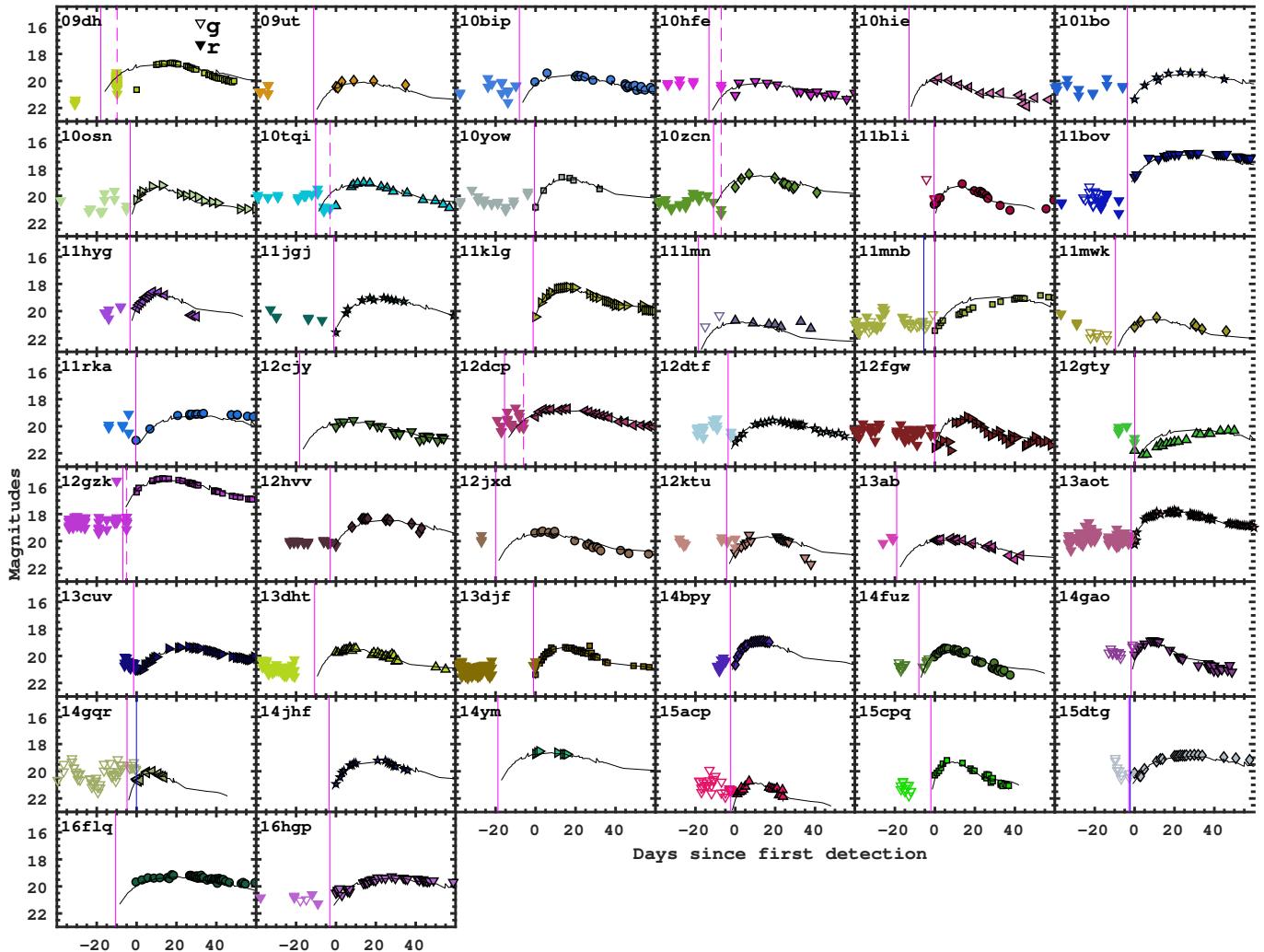
**Fig. 13.** Peak absolute  $r$ -band magnitude vs  $\Delta m_{15}$ . The plot shows no correlation.

the energy and the ejecta mass. The probability density function (PDF) of the three explosion parameters are shown in Fig. 20.

It shows, for all parameters, that most of the SNe are distributed around a common peak, but there are also evidence for distributions towards higher values in all three parameters. In Table 1 we present 8 SNe with a type Ibc classification<sup>12</sup>. We could not build the bolometric light curve for iPTF14jhf, which leaves us with 7 SNe Ibc. If we exclude these from our sample, we obtained average values of  $\langle M_{ej} \rangle = 4.65 \pm 0.93 M_\odot$ ,  $\langle E_K \rangle = 1.88 \pm 0.34 \text{ foe}$ , and  $\langle M_{56\text{Ni}} \rangle = 0.19 \pm 0.03 M_\odot$  where the errors are the weighted errors. In Sect. 2, we mentioned that 6 SNe show broader light curves compared to the rest of the sample, which will be discussed separately (Karamehmetoglu et al., in prep). Among these 6 SNe we already excluded PTF12gty as it is most likely a SLSN, leaving us with 5 SNe Ic showing a broad light curve. If we exclude these SNe<sup>13</sup> we obtain averages  $\langle M_{ej} \rangle = 3.57 \pm 0.40 M_\odot$ ,  $\langle E_K \rangle = 1.74 \pm 0.33 \text{ foe}$ , and  $\langle M_{56\text{Ni}} \rangle = 0.16 \pm 0.02 M_\odot$  where again the errors represent the weighted errors. Excluding the 5 SNe with broad light curves clearly gives lower average values for  $M_{ej}$  and  $M_{56\text{Ni}}$ . If we furthermore exclude from the average the peculiar fast ultrastripped iPTF14gqr (De et al. 2018) we get  $\langle M_{ej} \rangle = 3.67 \pm 0.39 M_\odot$ ,  $\langle E_K \rangle = 1.78 \pm 0.32 \text{ foe}$  and  $\langle M_{56\text{Ni}} \rangle = 0.16 \pm 0.02 M_\odot$ . These average values, now based on 34 normal SNe Ic, are still consistent with the previous ones within the uncertainties. We estimated the explosion parameters also in the case when the bolometric light curves were built considering the host extinction estimated from the  $g - r$  colour evolution. In this case we got  $\langle M_{ej} \rangle = 3.17 \pm 0.99$ ,  $\langle E_K \rangle = 1.12 \pm 0.23$ , and  $\langle M_{56\text{Ni}} \rangle = 0.77 \pm 0.25$  where again the errors are weighted sigma. The average  $\langle M_{ej} \rangle$ , as well as the  $\langle E_K \rangle$ , are lower but still consistent with the previous measurements within the uncertainties but  $\langle M_{56\text{Ni}} \rangle$  is higher. This is not surprising since we got systematically higher values of the extinction with this method and the  $M_{56\text{Ni}}$  depends mainly from the peak luminosity.

<sup>12</sup> PTF09ut, PTF11bli, PTF11lmn, PTF11mwk, iPTF14fuz, iPTF14jhf, iPTF15cpq and iPTF16flq.

<sup>13</sup> PTF11mnb, PTF11rka, iPTF15dtg, iPTF16flq and iPTF16hgp.



**Fig. 14.** The plot shows the fit of the light curve of iPTF13djf to the other SNe of the sample to estimate the explosion epoch. The open symbols represents the pre-explosion limits. Solid magenta lines represent the explosion epochs estimated from the fit. Dashed magenta lines represent the last non-detection assumed as explosion epoch. Blue solid lines represent explosion epochs available from literature.

## 8. Discussion and Conclusions

PTF and iPTF allowed for a larger, untargeted, and more homogeneous data set as compared with other SN Ic samples, and for this sample we also have good constraints on the explosion epochs.

We investigated two different methods to estimate the host extinction. First we inspected the spectra to look for Na I D absorption and using Taubenberger et al. (2006) we calculated the  $E(B-V)$ . This method is dependent on the S/N and resolution of the spectrum. The second method is based on the  $g-r$  colour evolution and is described in Stritzinger et al. (2018). This method assumes that SE SNe show an intrinsically homogeneous colour evolution in the range 0–20 days past peak. We compare the results of these methods in Fig. 10, which shows that the extinction estimated through the colour evolution is generally higher.

We adopted the extinction estimated from the Na I D for the overall analysis, but also compared how the peak magnitudes would change if we had adapted the other method. The average absolute peak magnitude is  $\langle M_r^{\text{peak}} \rangle = -17.71 \pm 0.85$  mag. In case we adopt the extinction from the  $g-r$  evolution we get  $\langle M_r^{\text{peak}} \rangle = -18.03 \pm 0.79$  mag. The effect on the overall peak magnitude distribution are shown in Fig. 12, where accounting

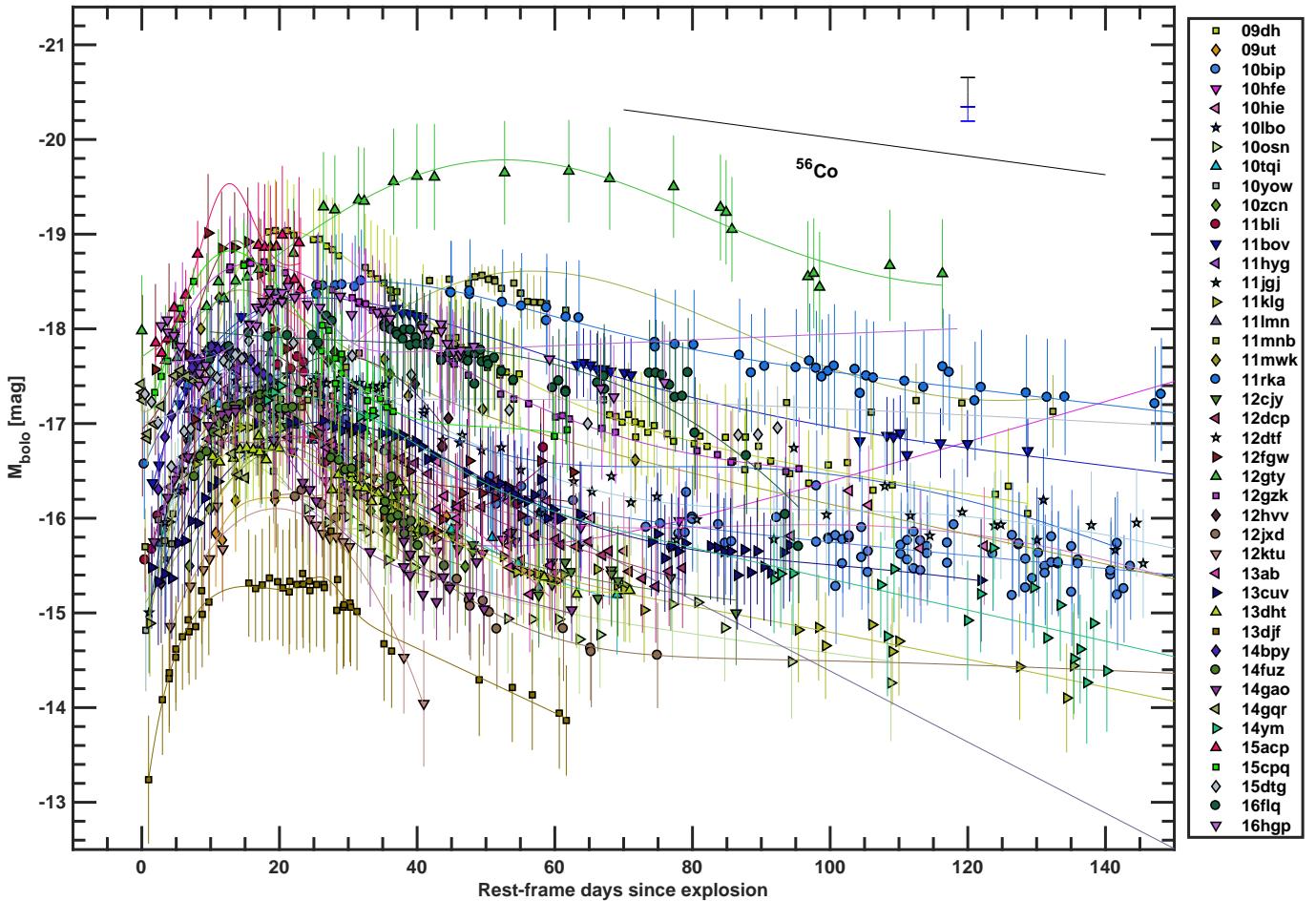
for higher extinction as suggested by the Stritzinger et al. (2018) method shifts the overall sample towards brighter magnitudes.

We investigated the light curve shape in both the  $r$  band and for the bolometric light curves. We looked for correlations among the main parameters: magnitude at peak,  $\Delta m_{-10}$ ,  $\Delta m_{15}$ ,  $\Delta m_{40}$  and slope. In both cases, we found a correlation between  $\Delta m_{15}$  and  $\Delta m_{-10}$ , implying that slow-rising SNe are also slow decliners. We see a correlation also among  $\Delta m_{40}$  vs  $\Delta m_{15}$  and among  $\Delta m_{40}$  vs  $\Delta m_{-10}$ .

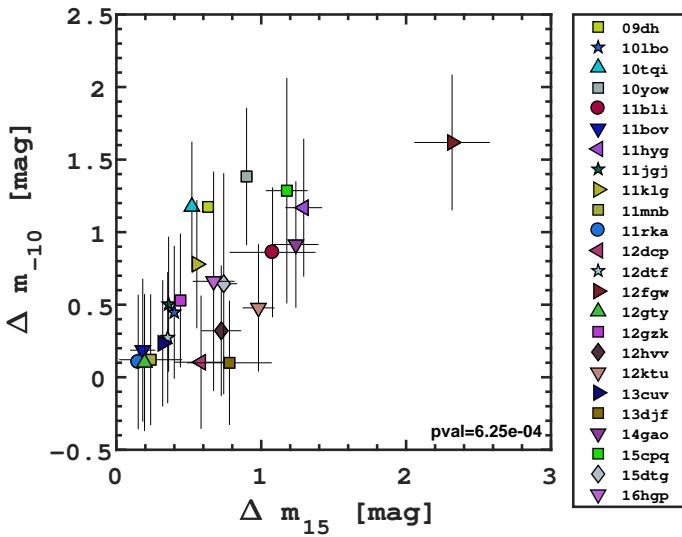
We fitted the bolometric light curves with an Arnett model (Arnett 1982) to estimate the explosion parameters. We obtained average values of  $\langle M_{ej} \rangle = 4.39 \pm 0.31 M_\odot$ ,  $\langle E_K \rangle = 1.71 \pm 0.16$  foe, and  $\langle M_{56\text{Ni}} \rangle = 0.19 \pm 0.05 M_\odot$ , when including all the 41 SNe Ic for which we could estimate these parameters. We searched for correlations among the explosion parameters and identify a correlation between  $M_{ej}$  and  $E_K$ . We also notice a correlation between the  $M_{ej}$  and  $M_{56\text{Ni}}$ , and between  $M_{56\text{Ni}}$  and  $E_K$ .

### 8.1. Comparison with the literature

Some of the SNe in this sample have already been discussed in the literature, and we will here compare our results with



**Fig. 15.** Bolometric light curves of 42 Type Ic SNe. The solid lines represent the Contardo fits performed on every individual light curve. The slope of the radioactive cobalt decay, 0.098 mag per day is illustrated in the upper right corner. There we also include a representative error bar that includes the uncertainty in distance, and extinction, respectively, which are not included in the errors on the data points.

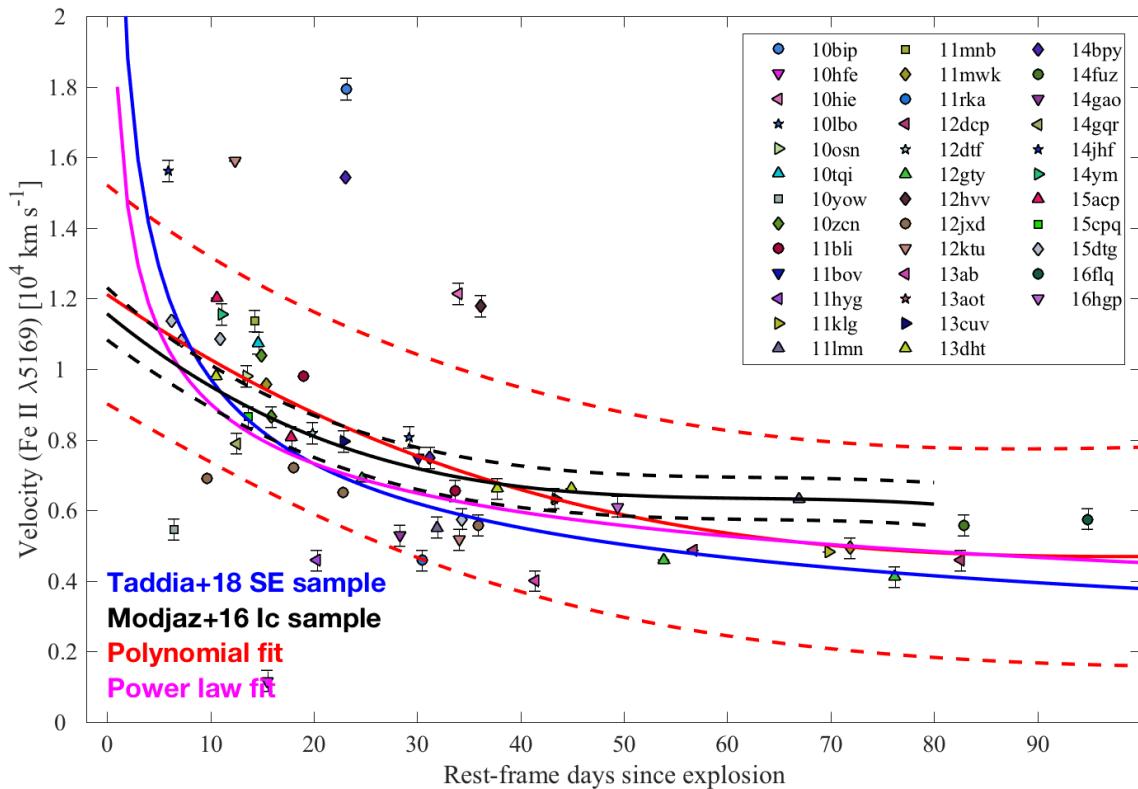


**Fig. 16.** Bolometric light curve shape:  $\Delta m_{15}$  vs  $\Delta m_{-10}$ . The plot does show a correlation, as also found in the r-band.

those available in these publications. SNe PTF09dh, PTF11bli, PTF11jgj, PTF11kdg, PTF11rka and PTF12gzk were presented in Prentice et al. (2016). Our estimated  $M_{56\text{Ni}}$  values for these SNe are in agreement with the ones provided in their work.

PTF12gzk is discussed in Ben-Ami et al. (2012), in which they noted that this SN showed some aspects in-between SNe Ic and SNe Ic-BL. They conclude that the mass of the progenitor star is  $25 - 35 M_\odot$ . We get quite high values for the ejecta mass which might point towards a massive progenitor star as found by Ben-Ami et al. (2012). PTF11bov is also known as SN 2011bm and was presented in Valenti et al. (2012) where they infer an initial mass for the progenitor of  $30 - 50 M_\odot$ . The ejecta mass we derive is close to the lower end of the interval they present in their work. iPTF15dtg was first introduced in Taddia et al. (2016) and investigated further in Taddia et al. (2019). In their first work they concluded that the peculiar long rise of this SN was most likely due to an extended envelope around the progenitor star, which they claim was a massive ( $> 35 M_\odot$ ) Wolf-Rayet star. The overall explosion parameters we estimated using the Arnett model are somewhat consistent with their lower values. In the subsequent paper, they accounted for additional peculiar behaviour of the SN at late times, which was explained by a combination of radioactive and magnetar powering which leads to a lower estimate of  $M_{ej}$  when compared with our estimate.

iPTF14gqr was presented in De et al. (2018) where they concluded that the best interpretation for this fast event is an ultra-stripped SN. We also obtained low values for the ejecta mass and kinetic energy, in agreement with the scenario presented in De et al. (2018). iPTF11mbn was presented in a separate paper as a SN Ic from a massive progenitor ( $85 M_\odot$ ; Taddia et al. 2018a). Our estimates also show high values for the explo-



**Fig. 17.** Fe II  $\lambda 5169$  velocity evolution for 37 SNe Ic from the sample (see Sect. 6.1 for the selection criteria). The magenta solid line represents the power law that fits the evolution with time. The blue solid line represents the trend found by Taddia et al. (2018b) and is similar to the one found in this work. The black lines represent the polynomial fit found by Modjaz et al. (2016). As a comparison, we fitted the data also with a polynomial fit, here shown in red.

sion parameters pointing towards a massive progenitor star. iPTF12gty was classified as a SLSN by Quimby et al. (2018) and further investigated by De Cia et al. (2017). Our spectral classification was pointing towards a SN Ic classification but this SN is a clear outlier in the sample in many ways. In particular, when applying the Arnett fit to estimate the explosion parameters we get a very high value of the  $^{56}\text{Ni}$  mass. We therefore conclude that iPTF12gty is most likely a super-luminous SN.

Our  $r$ -band absolute magnitudes span the interval  $-15.54$  to  $-19.81$  mag, with an average of  $\langle M_r \rangle = -17.71 \pm 0.85$  mag. The ranges available in the literature are  $M_r^{\text{peak}} = -18.26 \pm 0.21$  mag (Taddia et al. 2015);  $M_r^{\text{peak}} = -17.64 \pm 0.26$  mag (Taddia et al. 2018b) and  $M_R^{\text{peak}} = -18.3 \pm 0.6$  mag (Drout et al. 2011). The average peak magnitude in the  $r$  band estimated for our sample is in agreement with the ones from literature. We compared our values also with the (i)PTF sample of SNe Ic-BL (Taddia et al. 2019) where the peak magnitudes show a brighter average of  $-18.7 \pm 0.7$  mag.

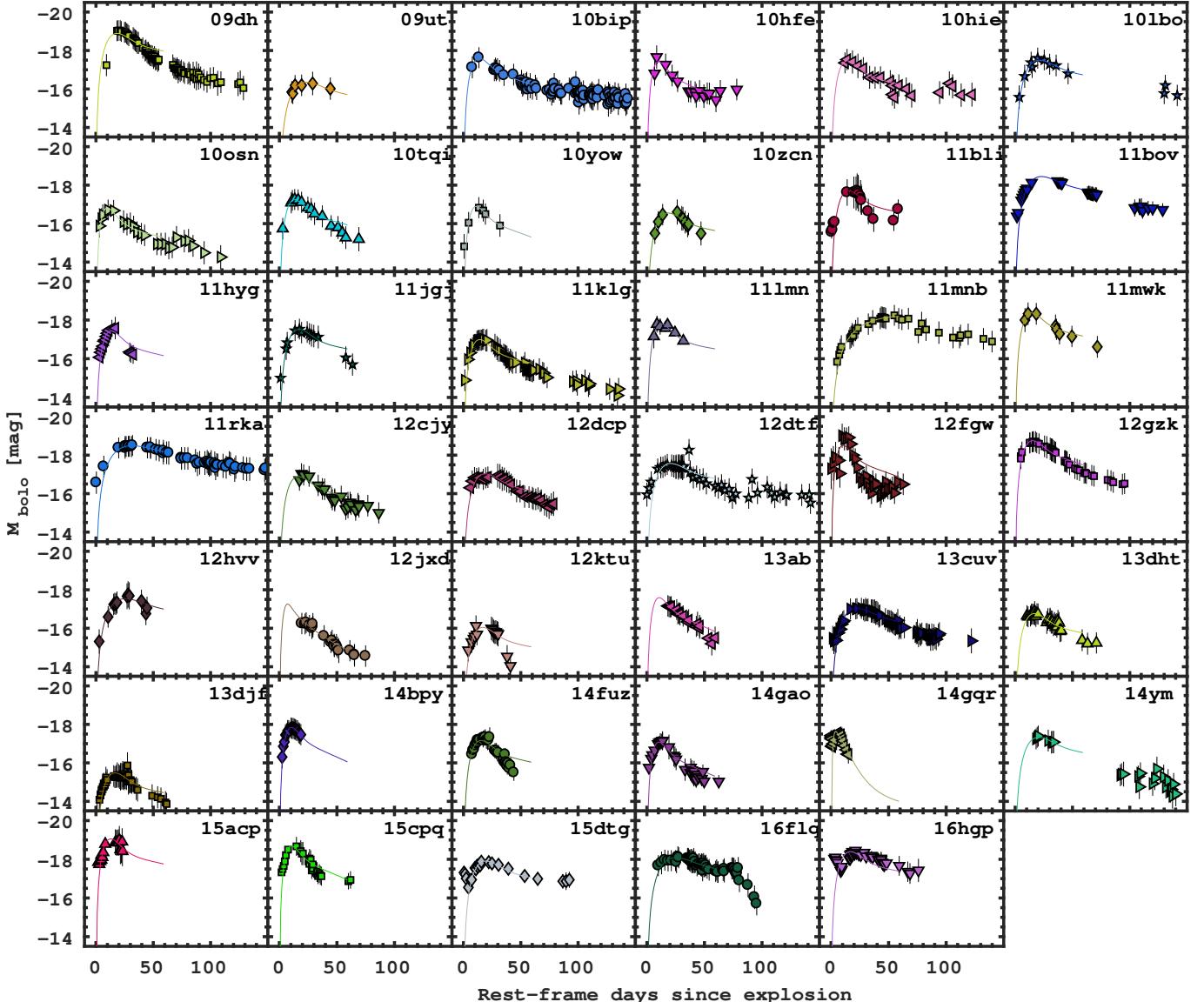
We analysed the shapes of the  $r$ -band light curves and of the bolometric light curves, searching for correlations among the different parameters. We identified a correlation in the  $r$  band between  $\Delta m_{15}$  and  $\Delta m_{-10}$  which is in agreement with the results from Taddia et al. (2019); Drout et al. (2011). We note that the fact that the fast risers are also the fast decliners is not trivially true. There could well be different physical circumstances determining the rise and the decline from peak, for example the mixing out of radioactive nickel will affect the steepness of the rising light curve whereas the time scale for the decline may be

more determined by the ejecta mass and composition. We did not find any Phillips-like relation and this is in agreement with previous works (Taddia et al. 2019; Lyman et al. 2016; Drout et al. 2011).

We compared the estimated average values for the explosion parameters of the 41 (i)PTF SNe Ic with the ones available in the literature. Drout et al. (2011) presented  $M_{^{56}\text{Ni}}$  values for 9 SNe Ic. In Cano et al. (2013) the explosion parameters for 13 SNe Ic are presented. Taddia et al. (2015) analysed three events, while the Lyman et al. (2016) sample contains 8 SNe Ic. A total number of 13 SNe Ic was presented in Prentice et al. (2016). Taddia et al. (2018b) presented 11 SNe Ic and in Prentice et al. (2019) three SNe Ic are included. Our (i)PTF sample with 41 SNe Ic therefore by far represents the largest sample of SNe Ic available where the explosion parameters have been estimated. We estimated the cumulative distribution functions (CDF) of the explosions parameters, and compared it to the available studies in the literature. The results of these comparisons are shown in Fig. 21.

We also report the average values and their standard deviations for the estimated explosion parameters from the different samples in Table 7. We also compared the  $M_{^{56}\text{Ni}}$  estimated by Meza & Anderson (2020) for 6 SNe Ic using Arnett model, and they get an average value lower than the one found in this work.

We searched for correlations among the explosions parameters (see Fig. 19), and identify a correlation between  $M_{ej}$  and  $E_K$ . We also notice correlations between  $M_{ej}$  and  $M_{^{56}\text{Ni}}$ , and between  $M_{^{56}\text{Ni}}$  and  $E_K$ . These correlations were also observed in other



**Fig. 18.** The plot shows the bolometric light curve computed and fitted with Arnett model for the 41 SNe of the sample.

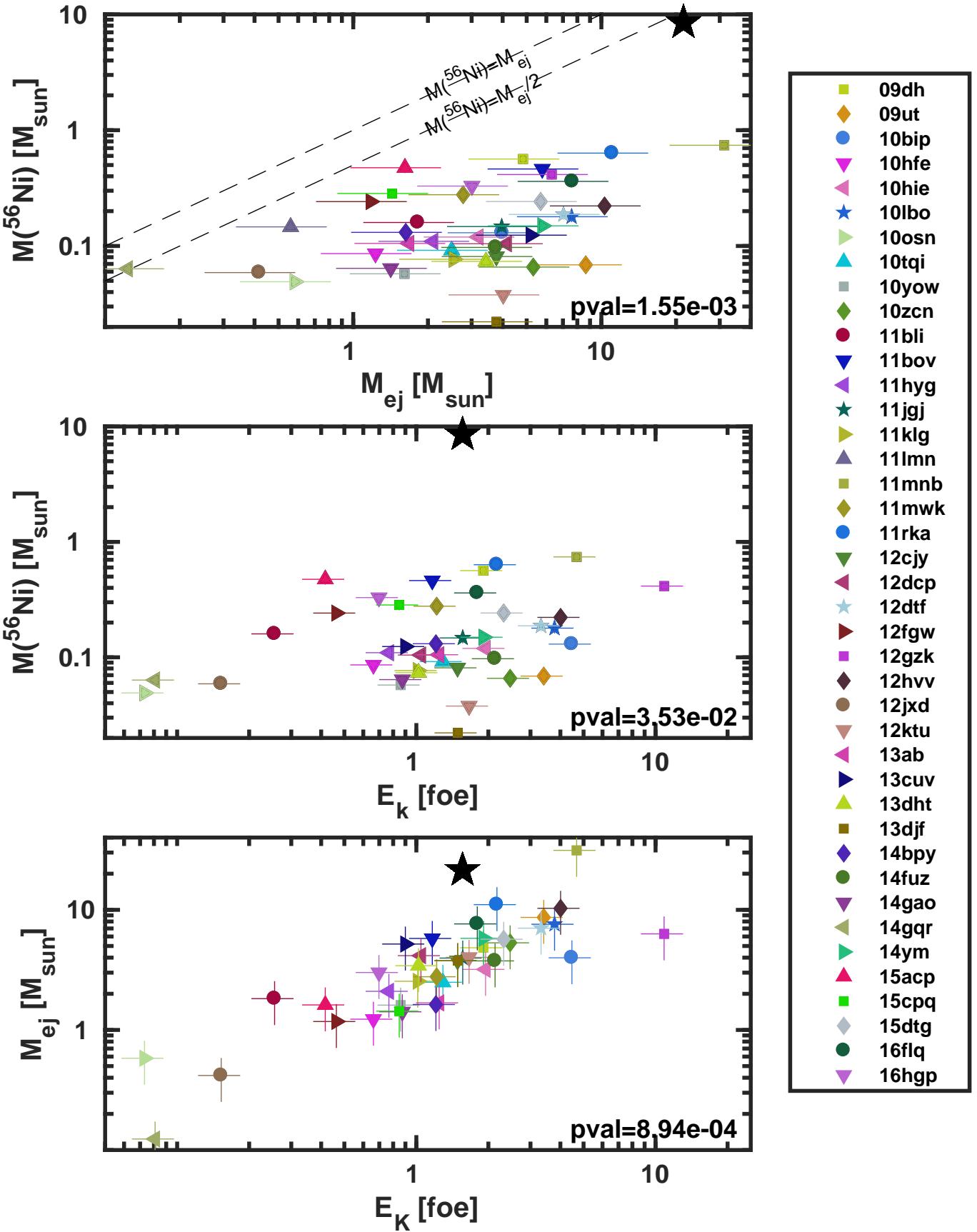
SE SN studies (Taddia et al. 2019, 2018a; Lyman et al. 2016). The strong correlation between ejecta mass and kinetic energy is, just as noted by Lyman et al. (2016), in fact mainly driven by the ejecta mass. The range in ejecta mass is much larger than the variation in velocity, and this is driving the relation. There is no correlation between ejecta mass and photospheric velocity.

### 8.2. Implications for progenitors

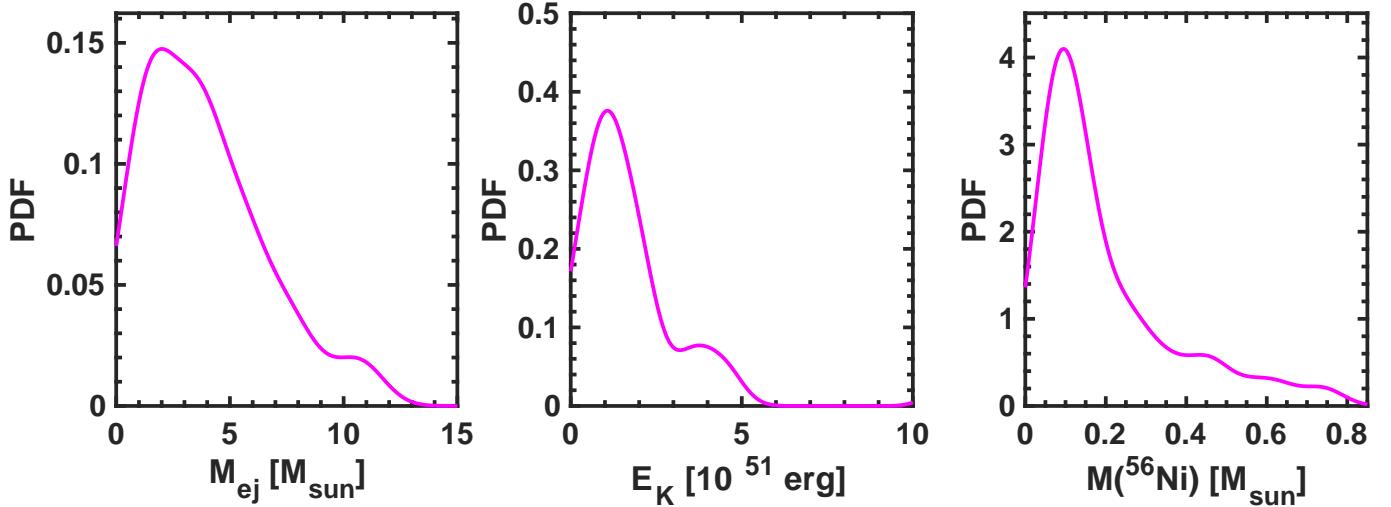
The PDF of the different explosion parameters are shown in Fig. 20. The  $E_K$  shows a first strong peak for energies lower than 3 foe and the  $M_{^{56}\text{Ni}}$  distribution shows a clear peak at values lower than  $0.3 M_\odot$ . The PDF of the  $M_{ej}$  shows a first peak for values lower than  $5 M_\odot$  and shows indication for additional peak(s) towards higher mass. A similar analysis for  $M_{ej}$  was presented in Lyman et al. (2016) and from a comparison with expectations from models they concluded that since the peak of ejecta masses is rather low, this indicates that the majority of SE SNe originate from not too massive stars, assuming the remnant is a neutron star. Moreover, since such stars are unable to get rid of all of their outer hydrogen and helium layers solely

from mass-loss from winds, they must likely have been born and stripped in a binary system. The trend we see here for our larger sample would lead to a similar conclusion. We notice that the PDF presented in Lyman et al. (2016) did not show a very pronounced secondary peak. This is due to the presence of SNe with broad light curves in our sample, which could arise from more massive star progenitors. We note that the apparent secondary peak in the PDF at  $\sim 10 M_\odot$  of ejected mass seems to be compatible with single, massive WR progenitors. These SNe will be discussed into more detail by Karamemehtoglu et al., (in prep.).

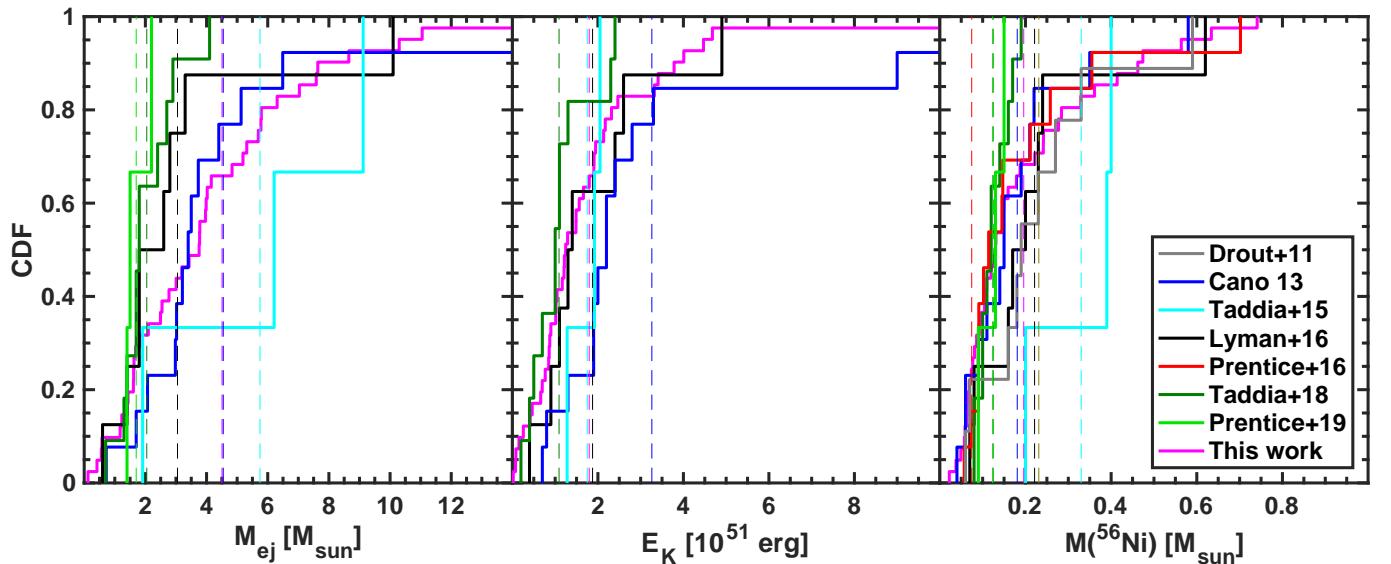
We have presented the sample of Type Ic supernovae collected by (i)PTF over a period of  $\sim 7$  years. The final sample of SNe that also have pre-peak photometry is made up of 44 objects, which we analyse in terms of light-curve and explosion parameters. This is the largest such sample to date. Our main results confirm trends seen in previous articles based on smaller and less homogeneous samples. Although our data are not always fantastic for individual SNe, the bulk sample provides a



**Fig. 19.** Explosions parameters for 41 SNe Ic plotted against each other. We see clear correlations between the parameters, as quantified by the p-values in the panels. SN PTF12gty has also been represented for completeness with a black star.



**Fig. 20.** Probability density functions for explosion parameters for our sample of SNe Ic



**Fig. 21.** Cumulative distribution functions for the explosion parameters compared to those of other samples in the literature. Dashed lines represent the average values for each sample from literature.

good picture of the overall properties of this class of extremely stripped supernovae.

The moderate ejecta masses remain a challenge for scenarios involving single very massive stars, as already proposed by Lyman et al. (2016), and corroborate discussions on the need for binary star evolution to produce most of the Type Ic SNe. Indications for a population of more massive progenitors are also seen. The ejected masses of radioactive nickel are  $\sim 0.2M_{\odot}$ , which is more than current neutrino driven explosion models (Ertl, et al. 2020) can easily accomplish. As mentioned, the correlation between ejecta mass and energy is largely spurious - but the correlation between ejecta mass and mass of radioactive nickel appears to be robust. It is statistically significant even if we exclude the most massive object that drives the correlation, and is something that a generic explosion model would have to explain.

There is hope for better understanding of these explosions from the observational perspective. The Zwicky Transient Facility (Bellm, et al. 2019) that has taken over on the P48 telescope after (i)PTF enable superior light curves also of Type Ic SNe. Over the first years, this survey has already observed almost 100 Type Ic SNe, and a fair fraction of these have better sampled

LC:s than the sample we have presented here. We look forward to analysing these new data.

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**Table 3.** Absolute magnitudes for 40 SNe in the  $r$  band (corrected for distance modulus and MW extinction), compared with the absolute magnitudes in the  $r$  band obtained when including the contribution from the host extinction with both methods, from the Na I D absorption and the  $g - r$  method.

SN	$M_r^{\text{peak}}$ no EBV <sub>host</sub> (mag)	$M_r^{\text{peak}}$ EBV <sub>host</sub> from Na I D (mag)	$M_r^{\text{peak}}$ EBV <sub>host</sub> from $g - r$ (mag)
09dh	-18.88	-19.30	-19.25
09ut	-16.53	-16.53	-17.16
10bip	-17.52	-17.67	-17.52
10hfe	-16.75	-16.75	-16.75
10hie	-17.84	-17.89	-18.68
10lbo	-17.56	-17.56	-17.56
10osn	-16.90	-16.90	-17.05
10tqi	-17.15	-17.57	-17.62
10yow	-16.78	-17.23	-17.33
10zcn	-16.55	-16.85	-18.19
11bli	-17.42	-17.67	-18.69
11bov	-18.32	-18.44	-18.32
11jgj	-17.32	-17.90	-18.00
11klg	-17.26	-17.26	-17.99
11mnb	-18.29	-18.49	-18.50
11mwk	-18.39	-18.44	-18.39
11rka	-18.64	-18.85	-19.40
12cjy	-16.93	-16.93	-16.93
12dcp	-17.09	-17.09	-18.07
12dtf	-17.67	-17.78	-18.56
12fgw	-17.77	-17.77	-17.77
12gty	-19.73	-19.81	-19.84
12gzk	-18.65	-19.01	-19.19
12hv	-17.37	-17.57	-19.18
12jxd	-16.04	-16.87	-17.14
12ktu	-16.38	-16.59	-17.25
13ab	-16.91	-17.02	-16.91
13aot	-16.90	-17.00	—
13cuv	-17.26	-17.30	-17.94
13dht	-16.87	-17.03	-17.38
13djf	-15.45	-15.53	-16.92
14bpv	-17.78	-17.78	-17.78
14fuz	-17.40	-17.52	-17.41
14gqr	-17.41	-17.41	-17.41
14jhf	-17.82	-18.62	—
14ym	-17.37	-17.76	-17.94
15acp	-18.77	-19.10	-19.62
15dtg	-18.00	-18.00	-18.28
16flq	-17.90	-18.51	-18.49
16hgp	-18.48	-18.48	-18.65



**Table 5.** Estimated Fe II  $\lambda 5169$  velocities at peak for 44 SNe of the sample

SN	$v_{max}$ (km s $^{-1}$ )
09dh	8125.6
09ut	8125.6
10bip	13706.70
10hfe	9497.55
10hie	10108.39
10lbo	9140.21
10osn	4589.67
10tqi	9315.55
10yow	9464.53
10zcn	8819.06
11bli	4847.10
11bov	5815.18
11hyg	7832.18
11klg	8172.07
11jgj	8125.6
11lmn	2437.49
11mnb	5005.96
11mwk	8573.56
11rka	5739.87
12cjy	8125.6
12dcp	6493.21
12dtf	8894.58
12fgw	8125.6
12gty	3492.84
12gzk	16984.08
12hvv	8076.82
12jxd	7831.30
12ktu	8319.47
13ab	11149.58
13aot	7728.21
13cuv	5389.32
13dht	7065.56
14djf	8125.6
14bpv	11148.79
14fuz	9754.77
14gao	10171.24
14gqr	10472.35
14jhf	7989.49
14ym	7436.66
15acp	6570.15
15cpq	9960.42
15dtg	8261.14
16flq	6281.47
16hgp	6235.76



**Table 7.** Comparison of the average estimates of the explosions parameters with estimates from the literature.

	$M_{ej}$ ( $M_{\odot}$ )	$E_K$ ( $10^{51}$ erg)	$M_{56Ni}$ ( $M_{\odot}$ )
Drout+11	$1.7^{+1.4}_{-0.9}$	$1.0^{+0.9}_{-0.5}$	0.24 (0.15)
Taddia+15	5.7 (3.6)	1.7 (0.4)	0.33 (0.11)
Lyman+16	3.0 (2.8)	1.9 (1.3)	0.22 (0.16)
Prentice+16	...	...	$0.16^{+0.03}_{-0.10}$
Taddia+18	2.1 (1.0)	1.2 (0.7)	0.13 (0.04)
Prentice+19	3.0 (0.7)	...	0.11 (0.09)
This work <sup>a</sup>	4.50 (0.79)	1.79 (0.29)	0.19 (0.03)
This work <sup>b</sup>	3.57 (0.40)	1.74 (0.33)	0.16 (0.02)
This work <sup>c</sup>	3.67 (0.39)	1.78 (0.32)	0.16 (0.02)
This work <sup>d</sup>	4.65 (0.92)	1.88 (0.34)	0.19 (0.03)

<sup>a</sup> Avarage values for the overall sample of 41 SNe

<sup>b</sup> Average values when the 5 SNe with broad light curve are excluded

<sup>c</sup> Average values when the 5 SNe with broad light curve and the 1 fast SN are excluded

<sup>d</sup> Average values when the 7 SNe with Ibc classification are excluded