Emission From Young Type Ia Supernovae

Last Update: January 22, 2017

1 Introduction

Observations of Type Ia supernovae (SNe Ia) within a few days of explosion is a promising avenue to further constrain the progenitor systems and explosion mechanisms of these SNe. This note summarizes theoretical and observational results in this field together with my thoughts towards future developement. The organization of this note is as follows: Section 1 discusses the SN shock breakout. Section 3 talks about the SN-companion collisioin. Section 4 talks about the diversity of radioactively powered light curves. Section 5 presents possible signatures from SN-CSM interaction. In addition, some of the thoughts are applicable to Type Ibc supernovae (SNe Ibc), which is discussed in Section 6.

2 SN Shock Breakout

A SN explosion begins with a SN shock breaking out of the surface of the exploding star. The shock breakout occurs when the opacity in front of the radiatively-driven SN shock drops to $\sim c/v_{sh}$, where c is the speed of light and v_{sh} is the speed of the shock wave. The shock breakout produces a bright flash in the X-ray on the light crossing timescale. Thanks to the small size of the progenitor star (a white dwarf), the timescale for shock breakout in a SN Ia is subsecond. Therefore, it is not feasible to catch this signal with any current X-ray instrument except for serendipitous discoveries.

Following the shock breakout, the heated and unbinded envelops in the exploding star (the ejecta) starts to expand rapidly, giving off thermal emissions. This adiabatic and free expanding phase has been approached by multiple theoretical models (e.g., Piro, Chang & Weinberg 2010; Rabinak & Waxman 2011). Despite subtle differences in assumptions on ejecta profiles and opacity, these models give similar predictions on the light curve. The successful application of these models to SN2011fe (Bloom et al. 2012) led to a strong constraint on the size of its progenitor star ($\lesssim 0.02R_\odot$; see Figure 1). A caveat here is that this result strongly depends on the assumption on the exact explosion time of the SN. Piro & Nakar (2014) argued that SN2011fe may have experienced a dark period of $\sim$ a day before the rise of its radioactively powered light curve.

According to Figure 1, the shock cooling light curve peaks at $g \simeq -10.5\,\mathrm{mag}$ within 0.1 day of the SN explosion. Hence, this cooling phase can only be caught by an extremely fast cadence transient survey (something like a two-hour cadence) of very nearby galaxies. For example, with a detection limit of $g = 21.5\,\mathrm{mag}$, this measurements can be undertaken for SNe in galaxies up to a distance modulus of $\mu = 32\,\mathrm{mag}$. The all-sky SN Ia rate within this distance is 0.07 per year, unfortunately.

3 SN-Companion Collision

If a SN is born in the single-degenerate channel, its companion may still be alive at the time of the SN explosion. Thus the inevitable collision bewteen the SN ejecta and the companion may produce visible signatures in the early light curve of the SN, which could serve as a “smoking gun” for the single-degenerate channel. In contrast, this SN-companion collision signature is not expected in the double-degenerate scenario.

On the theory side, Kasen (2010) provided the currently widely-accepted model that describes the expected signature from the SN-compaion collision (there are a few other papers debating the

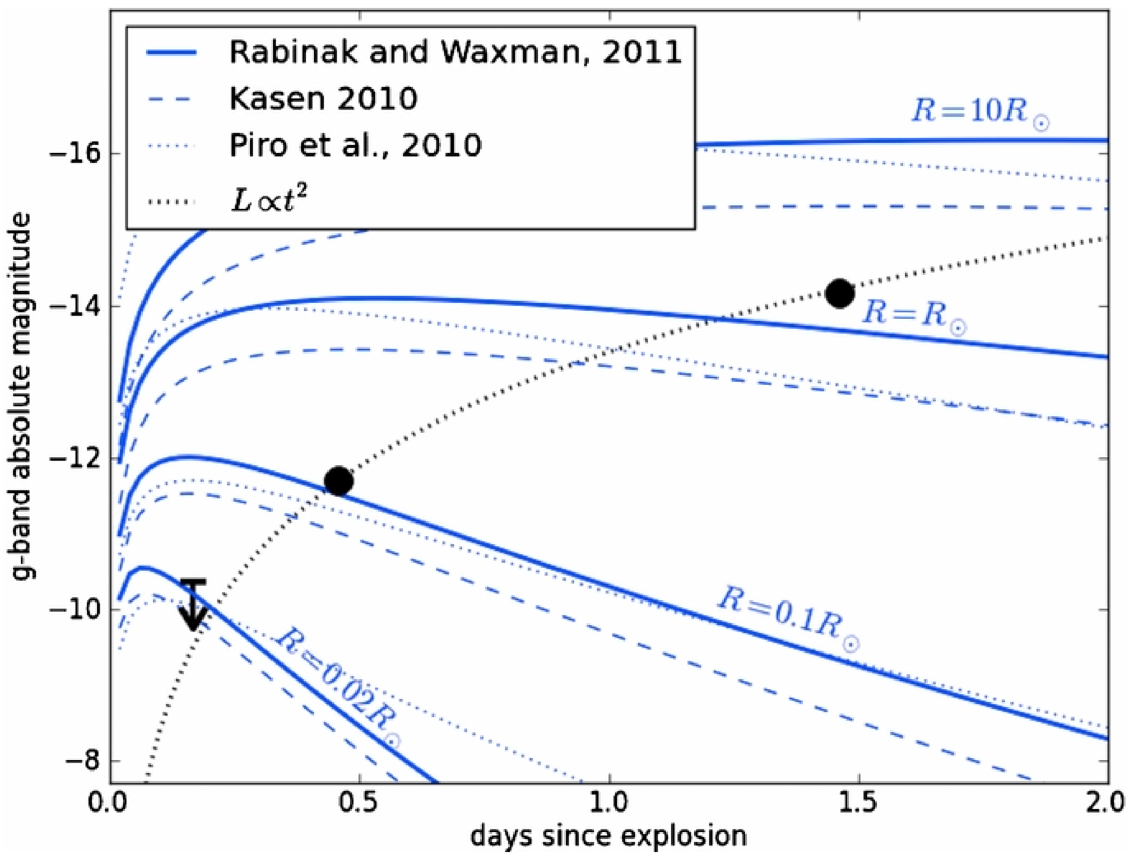

Figure 1: SN-Shock cooling models are compared to early observations of SN2011fe. [Figure 2 in Bloom et al. (2012)]

impact of the collision on the color of the SNe at peak). It also provided analytical equations for convenient comparison to observations. On the observation side, searching for the SN-companion collision signatures has been carried out in a few optical surveys (Hayden et al. 2010; Bianco et al. 2011), but their cadences and sensitivities were not ideal to catch this signature, so it is not surprising that these searches ended up with null detection. Brown et al. (2012a) also looked at archival Swift data of SNe Ia (very few of them were observed within five days of explosions) and reported non-detection in any of the observed SNe. Recent fast-cadence optical surveys, such as (i)PTF and ASAS-SN, have allowed researchers to rapidly trigger UV follow-up observations for individual nearby events in order to look for this signature. Brown et al. (2012b) reported non-detection of this signature in the early observation of SN2011fe. Cao et al. (2015) reported first detection of a strong and declining UV emission from a young low-velocity SN Ia iPTF14atg, which is consistent with expectation of SN-companion collision. Marion et al. (2016) reportedly attribute a possible excess in the early emission of SN2012cg to the SN-companion collision, but this result was strongly questioned recently (e.g., Shappee et al. 2016 arXiv: 161007601).

Assuming an ejecta mass of $1.4M_\odot$ and an expansion velocity of $10^9\,\mathrm{km\,s^{-1}}$, we use Kasen's model to calculate the expected light curves of SN-companion collision in different filters. The angular dependence of the light curves is approximated by the parameterized equation from Brown et al. (2012a). If we fix the binary separation at $a = 10^{13}$ cm, the expected light curves at different viewing angles in the UVOT *uvm2* (the UVOT *uvm2* bandpass is very similar to the bandpass of the proposed ULTRASAT), PTF g, and PTF R bands are shown in Figures 2, 3 and 4, respectively.

Figure 5 also shows the absolute magnitude range of SN-companion collision as a function of binary separation at one day after explosion.

We conclude from these figures that near-UV is a much more preferred waveband to detect the SN-companion collision signature than optical. First, the signature in the near-UV is brighter than that in the optical by a couple of magnitude. Second, the contrast between the SN-companion collision signature and the SN photospheric emission is much greater in the near-UV than in the optical. We may still detect a clear signal of SN-companion collision in the near-UV even 3 − 4 days after the explosion. The downside of the near-UV is much more sensitive to extinction.

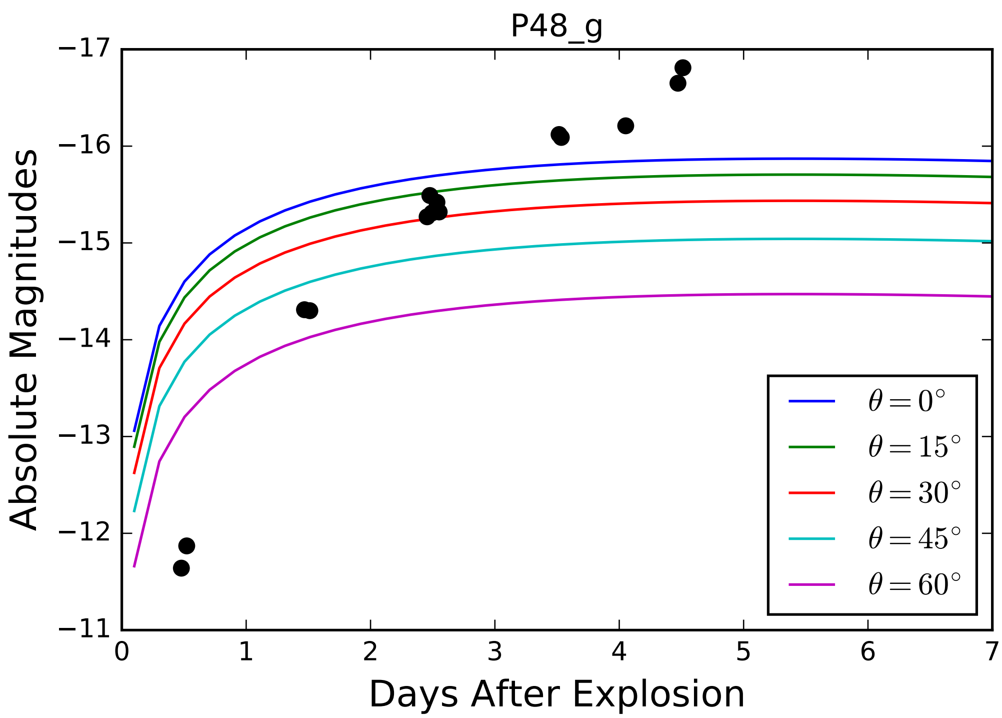

Figure 2: Theoretical g-band light curves of SN-companion collision in a binary separating by 10^{13} cm. The black circles show the observed light curve of SN2011fe.

4 Diversity Of Radioactively Powered Light Curves

The radioactively powered light curve does not rise until the energy of radioactive decay diffuses to the photosphere. Thus a SN may experience a dark period after the SN shock breakout. For example, Piro & Nakar (2014) claimed that SN2011fe had a period of one day, and consequently the tight constraint on the size of the progenitor derived in Bloom et al. (2012) does not hold. Constraining the dark period of a SN Ia not only improves estimates of its rise time and thus its ejecta and total ^{56}Ni masses, but also provides further constraints on the mixing of nucleosynthesis in the SN explosion.

Recently, Piro & Morozova (2016) presented theoretical early light curves for both weak and strong mixing in the ejecta. Figure 6 illustrates that the initial rise rate of the light curve is correlated with the degree of mixing in the ejecta: strong mixing leads to an early and fast-initial-rise light curve, while weak mixing leads to a delayed and slow-initial-rise light curve. Therefore

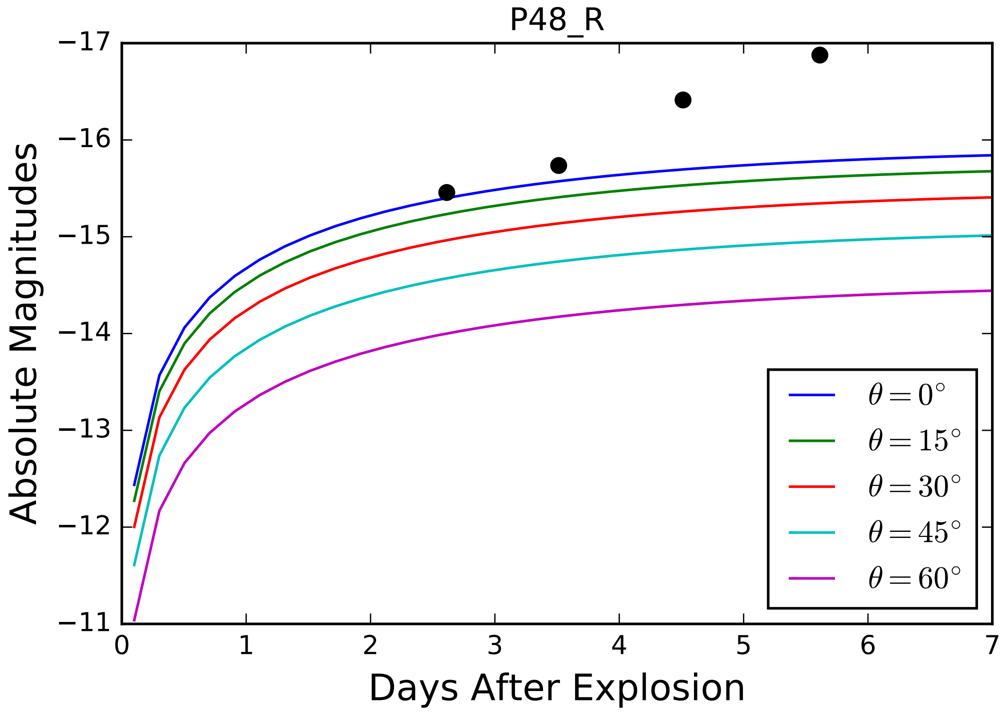

Figure 3: Same as Figure 2, but in the R band.

measuring the rise rate in the first day of the light curve provides a useful tool to estimate the length of the dark period.

I want to emphasize that the diversity of the early light curve arising from mixing of ^{56}Ni is distinguishable in observations from that of the SN-companion collision signature at various viewing angles. The former emission is generated by the photosphere heated up continuously by radioactive decay energy, while the latter emission follows the cooling of the SN-companion collision. Thus these two scenarios lead to distinct evolution of photospheric temperatures and can be distinguished by SN color evolution.

5 SN-CSM Interaction

Most progenitor scenarios of SNe Ia involve some sort of mass transfer process, which in principle should leave excess material around the exploding star. This circumstellar material may interact with the SN ejecta and produce signals on the SN light curve and spectra. For example, some SNe Ia show varying Na I D absorption (e.g., Sternberg et al. 2011). A special subtype of SNe Ia, called SNe Ia-CSM, have also been identified (e.g., Silverman et al. 2013). Observations of these SNe at very young age may provide diagnostics to the mass loss history of the progenitor systems. So far, to my knowledge, none of these events has very early data.

First, existence of an extended material around the SN progenitor will produce an extra peak in the very early light curve (Figure 7). This peak is due to the cooling of the material in the circumstellar medium after the SN shock heats it up. The duration and amplitude of this early peak can be used to estimate the mass and location of the circumstellar material (Piro & Morozova 2016).

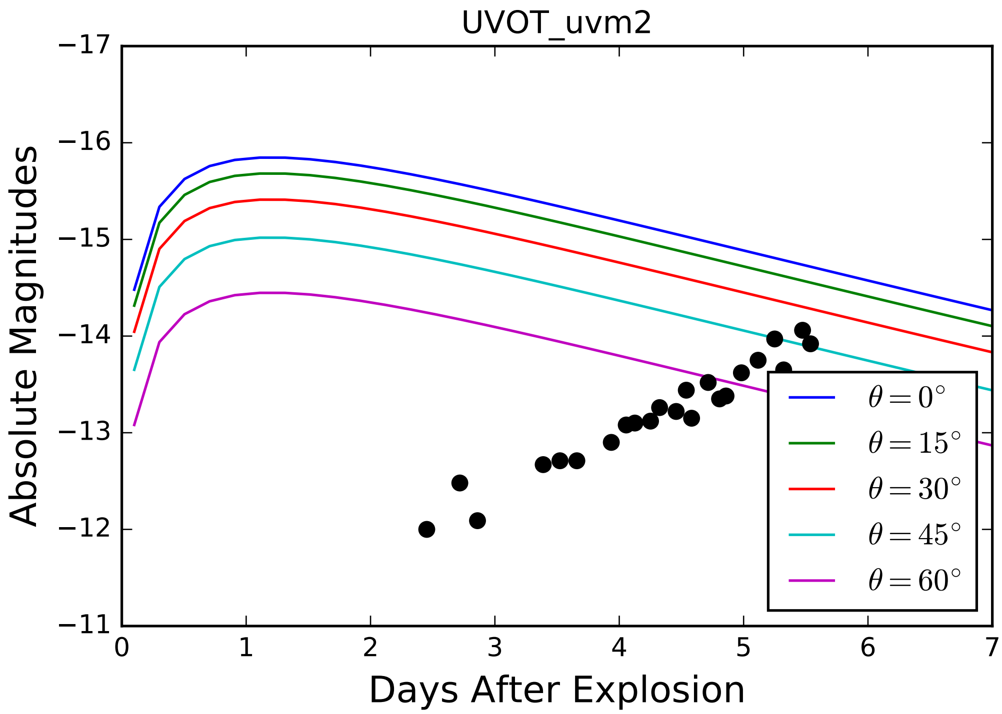

Figure 4: Same as Figure 2, but in the UVOT *uvm2* band.

Separately, analogous to flash signature in the earliest spectra of SNe II (Gal-Yam et al. 2014), high energy photons from the SN explosion may ionize the circumstellar medium. The consequent recombination emission lines may appear in the earliest spectra of a SN Ia-CSM. These recombination lines are very useful to probe the chemical abundance and density profile of the circumstellar medium.

6 Some Thoughts On Type Ibc SNe

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The ideas presented in Sections 3 and 4 may also be applicable to SNe Ibc, however, with very large uncertainties. Both observational and theoretical work is warranted to make progresses here.

Mass loss history plays an important role in the evolution of SN Ibc progenitors. There are two scenarios: a Wolf-Rayet star strips its hydrogen and (part of) helium layers through strong stellar winds; a less massive star removes its outer envelope by close binary interaction. Observations of the only identified progenitor system of a Type Ib SN iPTF13bvn (Folatelli et al. 2016; Eldridge & Maund 2016).

The SN-companion collision signature may also be used to distinguish these two scenarios. However, the opening angle of the companion star in the binary system is in general much smaller than that in the single-degenerate channel of SNe Ia, because the binary progenitors of SNe Ibc are not necessarily close enough to enable Roche lobe mass transfer. Therefore, the chance for us to see the SN-companion collision signature is very low.

If the material stripped from the progenitor star of a SN Ibc stays close at the time of explosion, we should also expect to see an extra peak in the light curve, which is generated by the cooling

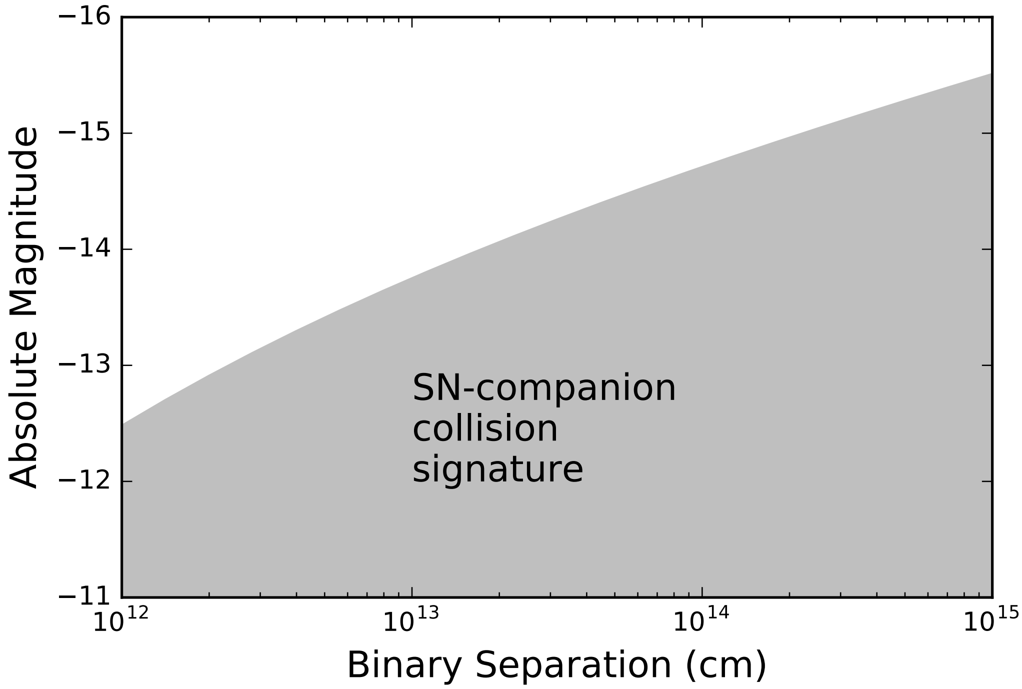

Figure 5: The absolute g-band magnitude range of SN-companion collision (gray region) at one day after explosion as a function of the binary separation

of the extended material, and recombination lines in the early spectra, which are produced by the extended material ionized by the high-energy photons from the SN. In fact, we have seen both signatures in a few cases in iPTF. For example, Type Ic SN iPTF15dtg showed a double-peaked light curve (Taddia et al. 2016). Although the exact type of iPTF14gqr is still in debate (Ca-rich vs Type Ibc), it shows a double-peaked light curve, with its first peak decaying within three days of explosion. The spectra taken during its first peak show He II 4686, C IV 4650 and C IV 5806, hallmark lines of flash spectroscopy.

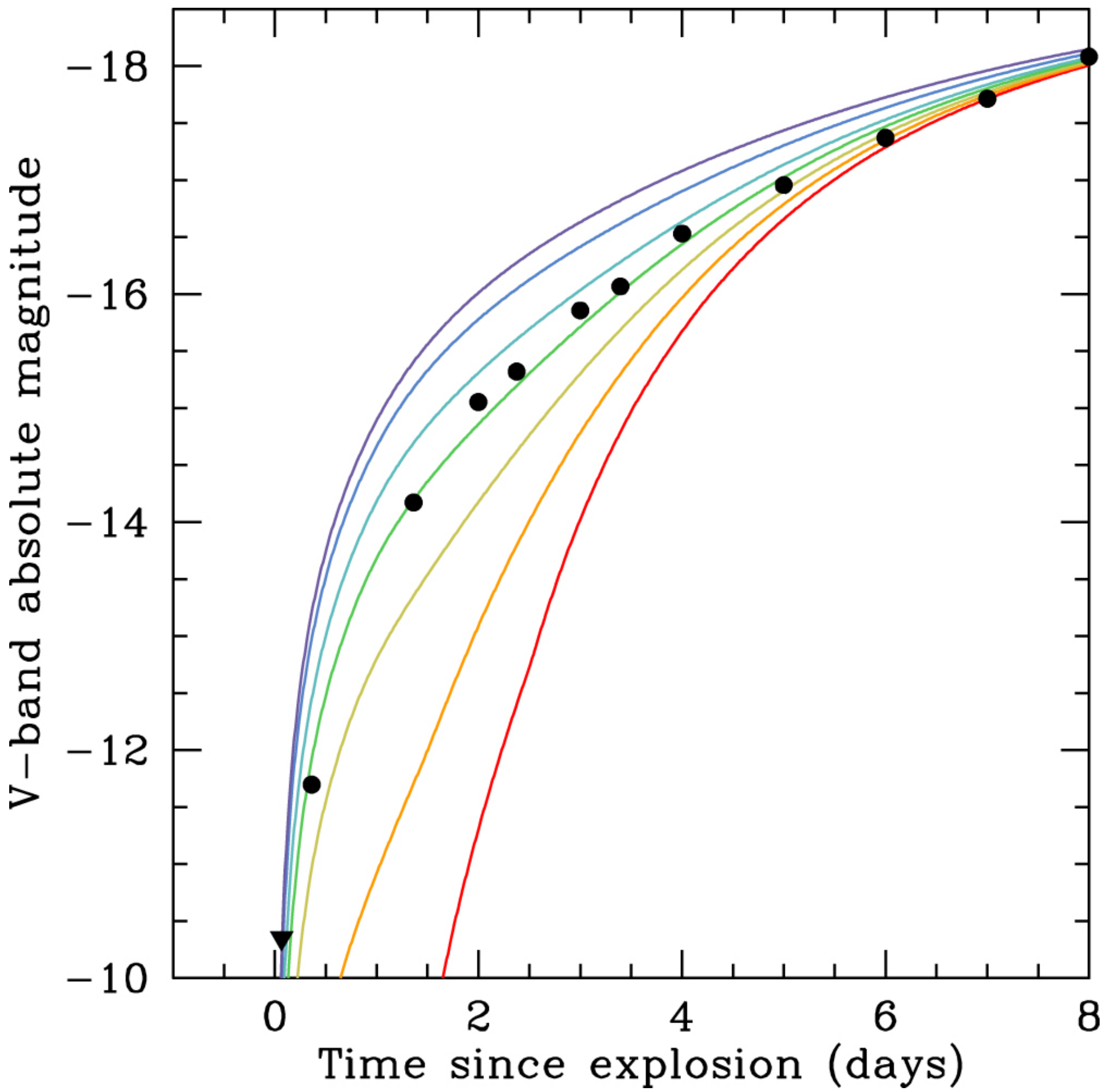

Figure 6: The radioactively powered light curves from the ejecta of weak (red) and strong (blue) mixing. The circles and triangle are the observed light curve of SN2011fe. [Figure 7 in Piro & Morozova (2016)]

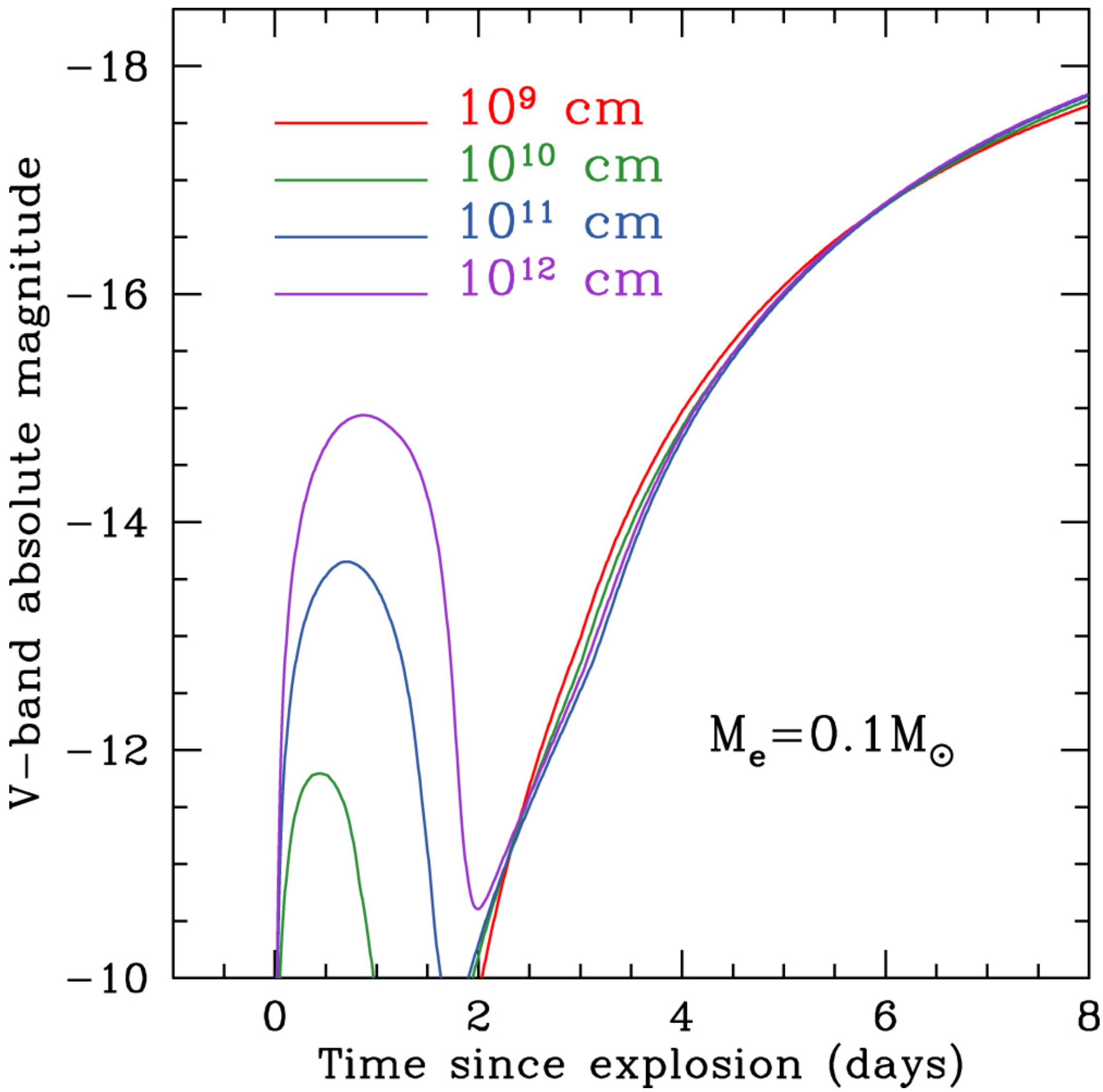

Figure 7: The early light curve peak produced by an extended material of $0.1M_\odot$ at different distances. [Figure 10 in Piro & Morozova (2016)]