# A Fast-Evolving, Luminous Transient Discovered by K2/Kepler

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**For decades optical time-domain searches have been tuned to find ordinary supernovae,**

**which rise and fall in brightness over a period of weeks. Recently, supernova searches have improved their cadences and a handful of fast-evolving luminous transients (FELTs) have been identified[1–5]. FELTs have peak luminosities comparable to Type Ia supernovae, but rise to maximum in $< 10$ days and fade from view in <month. Here we present the most extreme example of this class thus far, KSN2015K, with a rise time of only 2.2 days and a time above half-maximum ($t_{1/2}$) of only 6.8 days. We show that, unlike Type Ia supernovae, the light curve of KSN2015K was not powered by the decay of radioactive elements. We furthermore argue that it is unlikely that it was powered by continuing energy deposition from a central remnant (a magnetar or black hole). Using numerical radiation hydrodynamical models, we show that the light curve of KSN2015K is well fit by a model where the supernova runs into external material presumably expelled in a presupernova mass loss episode. The rapid rise of KSN2015K therefore probes the venting of photons when a hypersonic shock wave breaks out of a dense extended medium.**

We identified KSN2015K as an unusual transient in the K2 Campaign 6 data from the extended Kepler mission [6]. While we have several ground-based optical programs to find supernovae during a K2 Campaign, KSN2015K was identified in February 2016 after the Campaign 6 data was publicly released. Re-analysis of images taken by DECam and Skymapper clearly show the transient, but it was not flagged because it only appeared on one epoch. We therefore could not obtain a spectrum of the transient itself. The host has a redshift of 0.090 implying a luminosity distance of 410 Mpc (assuming a flat cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$).

The K2 light curve of KSN2015K seems to have four phases (see Figure 1 and 2). The rise is well fit by a quadratic function starting 1.6 days before maximum. Before that, the light rises like $t^2$ and suggest the explosion occurred $2.2 \pm 0.1$ days before peak brightness. After maximum, KSN2015K shows a decline followed by a plateau and finally a power-law decay. Additional, ground-based photometry from DECam and SkyMapper show the color to be quite blue (see supplemental material). At peak, KSN2015K's color is $r - i = -0.15 \pm 0.05$, and $\sim 8$ days after peak its color remains quite blue at $g - r = -0.17 \pm 0.20$ even after fading to half its peak brightness.

The host galaxy is a star-forming spiral galaxy and the transient is seen projected on a spiral arm (see Figure 1 and the supplemental material). If the transient is associated with the arm, the environment suggests a relatively short time between birth and the transient outburst, but both thermonuclear and core-collapse supernovae are found in young, star-forming populations.

The progenitors of FELTs and the energy source that powers the light curve have been debated. Members of the class could originate from more than one type of progenitor. The high-cadence time-sampling of KSN2015K allows us to make strong constraints on the origin of this particular event.

If FELT light curves are powered by an internal energy source, such as the decay of radioactive isotopes or a central engine, then the light curve rise time is set by the photon diffusion timescale through the remnant, $t_{\rm diff} \propto (M\kappa/v)^{1/2}$ where $M$ is the remnant mass, $v$ the expansion velocity, and $\kappa$ the opacity. The rise time of KSN2015k was $\sim 8$ times shorter than that of Type Ia supernovas (which have mass $\approx 1\ M_{\odot}$), implying an ejected mass of only a few times $\sim 10^{-2}\ M_{\odot}$.

Differences in the velocity and opacity of the ejecta are unlikely to change this estimate by more than a factor of several. This mass constraint, however, does not apply to mechanisms that directly deposit thermal energy near the ejecta surface, such as the blast wave from the explosion or shocks from circumstellar interaction.

There are several explosive scenarios that may lead to the ejection of such a small ($10^{-4} - 10^{-1}\ M_{\odot}$) radioactive mass, such as the thermonuclear explosion of a shell of accreted helium on the surface of a white dwarf (a so-called ".1a" event[7]), the accretion induced collapse of a white dwarf to a neutron star[8,9], and the merger of two neutron stars[10,11] (or a neutron star and a black hole). The core collapse of massive stars (initial masses $\gtrsim 8\ M_{\odot}$) could also produce little ejecta if significant mass loss occurred prior to collapse via binary interactions [12], or if the explosion is weak and most of the star remains bound ("fallback supernova" models, e.g., [13].

While radioactive models can reproduce the timescales observed for the KSN2015K light curve, they fail to reproduce its peak brightness [7,9,14–16] on rather general physical grounds. The peak luminosity of a radioactive supernova is approximately (to within a factor of $\sim 2$) given by the instantaneous rate of heating by decay.

The heating rate for radioactive isotopes with half-lives in excess of a few days (such as $^{56}$Ni at $\sim 3 \times 10^{10}$ ergs s$^{-1}$ g$^{-1}$) requires a radioactive mass of $\sim 0.1\ M_{\odot}$ to power the peak of KSN2015K. This conflicts with the $\sim 10^{-2}\ M_{\odot}$ limit on the *total* ejecta mass inferred from the light curve risetime. This tension cannot be resolved by arguing for an anomalously low opacity in KSN2015K, since the luminosity and hence thermal state are similar to that of ordinary SN.

Figure 4 quantifies the allowed range of radioactive powered light curves and shows that such a source can be ruled out for KSN2015K.

An alternative possible power source for supernova light curves is energy deposition from a central engine, such as a rotating magnetized neutron star[17,18] (a magnetar) or an accreting black hole[19]. Such compact objects may be formed in the core collapse of a rotating massive star, and have been suggested to power the most luminous supernovae. The ejecta mass constraints above apply to central engine heating, but the peak luminosity can be substantially greater than is possible with radioactivity. However, explaining KSN2015K with a central engine implies unphysical or fine-tuned parameters. A magnetar with rotational energy $E_m$ and spindown time $t_m$ produces a peak light curve luminosity of approximately[20] $L \sim \; E_m \; t_m/t_{\rm diff}^2$. For magnetic spindown the quantity $E_m \; t_m$ depends only on the magnetic field $E_m \; t_m \propto \; B^{-2}$ and is independent on the spin period. The peak brightness of KSN2015K ($L \approx 10^{43}$ ergs s$^{-1}$ and $t_{\rm diff} \approx 2$ days) then implies an extreme dipole field of order $10^{16}$ Gauss, or ten times that of typical strong magnetars.

For a a black hole model, the small ejecta mass of KSN2015K would require a nearly failed supernova where all but $\lesssim 1\%$ of the star remained bound to the black hole. The power from fallback accretion can be estimated[21] as $P = \epsilon \; M_{\rm fb}/t_{\rm fb} \; (t/t_{\rm fb})^{-5/3}$, where $M_{\rm fb}$ is the fallback mass, $t_{\rm fb}$ the fallback time, and $\epsilon$ the accretion efficiency. For $M_{\rm fb} \approx M_\odot$ and adopting a relatively short fallback time $t_{\rm fb} \sim 1$ hour (characteristic of compact stripped star with $R \sim \; R_\odot$) the accretion power will far exceed the luminosity of KSN2015K at $t = 2$ days unless the efficiency is $\epsilon \sim 10^{-5}$, which is much less than the characteristic value $\epsilon \sim 0.1$. To reconcile the difference would require fine tuning the fallback dynamics and/or accretion disk formation such that only a tiny fraction of the infalling material was tapped to power the light curve.

Long gamma-ray bursts (GRB) result from the core-collapse of very massive stars[22] that drive collimated relativistic jets. When a jet is viewed off axis, no gamma-rays are seen, but the shocked circumstellar gas may be visible as an "orphan afterglow". The light curve of KSN2015K is a good match to orphan afterglow models (see the Supporting Material). However, GRBs are very rare compared to SNe, so the chance of having found a GRB afterglow during the K2 mission is exceedingly small.

A final class of models for KSN2015K suggests that the transient is powered by energy deposited by a hydrodynamical shock, either the shock of the supernova explosion itself or one occurring post-explosion due to the interaction of the stellar ejecta with the circumstellar medium (CSM) [23–27]. An explosion shock carries energy to the outer layers of the star and eventually vents in a shock breakout event at a radius $R$ where the optical depth $\tau$ is low enough that the radiative diffusion timescale, $t_d \approx \tau\ R/c$, becomes comparable to the dynamical time, $R/v_s$, where $v_s$ is the shock velocity. This occurs at an optical depth $\tau \approx\ c/v_s \approx 30$ for a shock velocity $v_s = 10^4$ km s$^{-1}$.

To explain the rapid rise of KSN2015K as a shock breakout event requires that the diffusion time from the shock $t_d \approx 30\ R/c$ be of order 2 days, which implies $R \approx 2 \times 10^{14}$ cm. This is larger than typical radii of red supergiant supernova progenitor stars[28]. The effective radii of red supergiants could be increased just prior to explosion by envelope inflation or enhanced mass loss through winds. However, if the progenitor had been a supergiant with a wind, the explosion would have resulted in a long lasting light curve similar to a Type IIP at later times[29] (i.e., $L \approx 10^{42}$ ergs s$^{-1}$ at $t \approx 50$ days), which is inconsistent with the rapid dimming of KSN2015K. We therefore conclude that the progenitor was more compact (e.g., stripped envelope star) with radius $\approx 10^{11}$ cm, that interacted with a dense and extended CSM at radius of several times $10^{14}$ cm. Shock breakout thus occurs in the extended CSM shell[23].

Assuming constant density, the CSM mass required to produce $\tau \approx c/v$ is $M \approx 4\pi R^2 c \kappa v_s \approx 10^{-2} M_\odot$ for $\kappa = 0.34\,\mathrm{cm}^2\,\mathrm{g}^{-1}$. This CSM must have been lost within a time $t_{\rm csm} \approx R/v_{\rm csm}$ before explosion, where $v_{\rm csm}$ is the CSM velocity. For $v_{\rm csm} = 10$ km s$^{-1}$ (typical of a red-giant wind) we have $t_{\rm csm} \approx 6$ years and an effective mass loss rate of $\dot{M} \approx 2 \times 10^{-3}\, M_\odot\, \mathrm{yr}^{-1}$. For the more likely case of a stripped envelope progenitor, the characteristic escape velocity is $v_{\rm csm} = 1000$ km s$^{-1}$ which implies a mass loss episode with $\dot{M} \approx 2 \times 10^{-1}\, M_\odot\, \mathrm{yr}^{-1}$ occurring $t_{\rm csm} \approx 20$ days before the explosion. Such mass loss rates are much greater than typical winds from massive stars, but could be produced in episodic mass loss outbursts.

To test whether the shock breakout in CSM can explain the light curve of KSN2015K, we ran numerical radiation-hydrodynamical simulations of a supernova running into a circumstellar shell (see SI). Figure 1 shows that for a model with CSM masses and radii roughly in the range estimated above, the venting of the post-shock energy at breakout can explain KSN2015K's very rapid rise to a luminous peak. The post maximum luminosity is due to the diffusion of shock deposited energy from deeper layers. At later times ($t \gtrsim 10$ days) the decline of the KSN2015k light curve becomes shallower and it is possible that radioactive $^{56}$Ni decay contributes to the luminosity. As the shape and brightness of the model light curves are sensitive to the CSM and ejecta parameters (Figure 1 of the SI) the full coverage high sampling of the KSN2015K light curve provides strong constraints on the conditions of shock breakout in a dense circumstellar medium.

Fast transients are difficult to discover and follow-up, and sufficient numbers have been discovered only in recent years due to surveys with improved cadence and depth like Pan-STARRS1 (PS1) and Palomar Transient Factory (PTF). One of the earliest fast-transients identified was SN2002bj, which was initially postulated to be a ".1a" [1] event, but its high luminosity makes this unlikely. The spectrum of SN2002bj was similar to a SNIa except for a prominent helium line suggesting that it might be a stripped core-collapse event with a helium envelope. The very bright SN2015U rose in less than 10 days and its time above half maximum was $t_{1/2} = 12$ days. It showed narrow helium features [4], implying that interaction with a hydrogen-poor CSM does occur in rapidly evolving events. Similarly, SN2010X had a rise of less than 10 days and $t_{1/2} = 15$ days, but was four times fainter than SN2002bj [2]. The rapid evolution and lower luminosity means SN2010X could be powered by radioactive decay of thermonuclear products. Figure 3 compares the light curve of KSN2015K with SN2002bj and SN2015U.

The largest sample of fast transients[3], discovered in the PS1 survey, has rise time upper-limits of 3 to 5 days and peak luminosities similar to KSN2015K (see Figure 4 for a comparison of rise times and absolute magnitudes). These PS1 transients also show very blue colors with typical $g - r = -0.2$ mag near maximum light and only a slow reddening afterwards. Thus, the PS1 transients are very similar to KSN2015K in all their photometric properties. **We also can expect to find a small number of FELTS in the K2 campaigns, using the FELT rate[3] determined from the PS1 sample (see Supporting Material). Other samples of fast transients from the Supernova Legacy Survey[5], the Palomar Transient Factory[5], and the Subaru telescope[30], are brighter, have significantly longer rise times and/or longer event durations, and are therefore unlikely to be in the same group than FELTS.**

Except for KSN2015K, most FELTS have poorly defined rise times, but their decays are well-documented. Most show steep power law decays with $\alpha \leq -0.6$ and KSN2015K itself had a decline from maximum of $\alpha \approx -1$. It has been argued that these steep declines disfavor a shock breakout in an extended wind model[5], since theoretical models [31] predict that the decline of the light curve following a wind breakout peak is a power law with index of $\alpha = -0.3$, if in thermal equilibrium. However, a luminosity decline with $\alpha = -0.6$ can be achieved by assuming the shock interacts with a wind, producing an outer ejecta profile with a density index of $n = 7$ rather than the typical $n = 10 - 12$ [23].

We find that KSN2015K and the fast transients from the PS1 sample are most consistent with the shock-breakout into a dense circumstellar shell. It reproduces the significant characteristics of FELTs (fast, bright, blue) without much fine tuning. Even though models with a central engine can fit the light curve of KSN2015K and other FELTS, it requires an unlikely confluence of rare occurrences, and therefore is less likely. All of the other models of the power source of these events cannot explain at least one of their main properties.

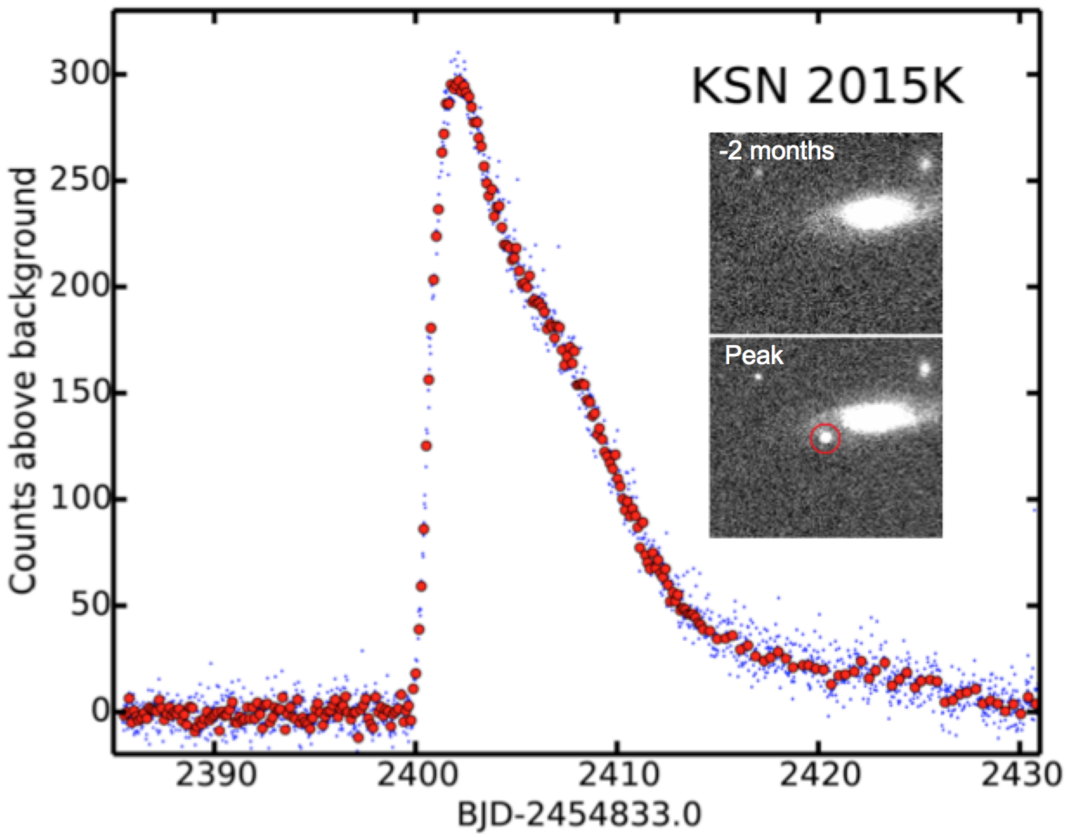


Figure 1: **The K2 light curve of KSN2015K.** Blue dots are individual 30-minute cadence observations while the red points are median values made from 3-hour bins. The image cutouts in the inlet show DECam images from UT July 7th 2015 (2 month before peak) and August 1st 2015 (around peak) in the top and bottom panels, respectively. KSN 2015K is marked with a red circle in the bottom panel.

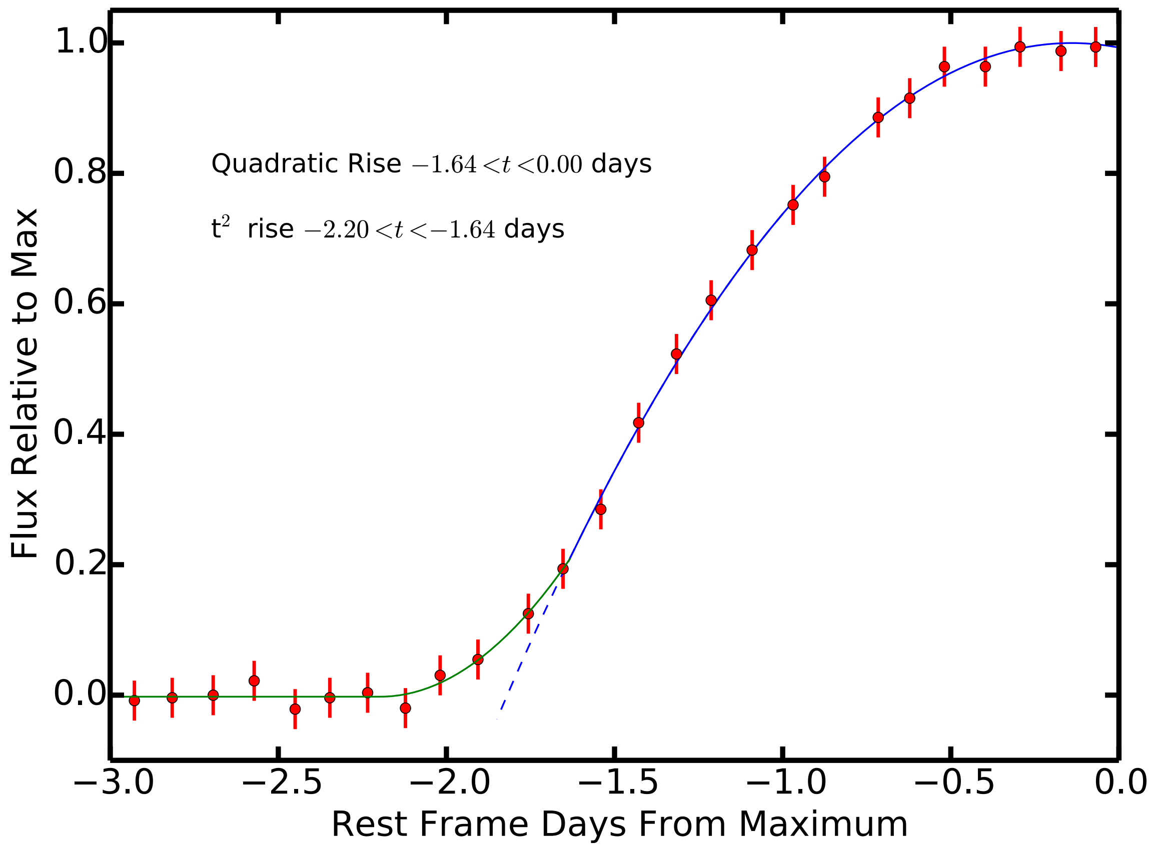


Figure 2: **KSN2015K's rise to maximum light.** Red points are 3 hour median bins of the K2 long cadence data. Error bars are $3\sigma$ uncertainties on the binned photometry points. Blue line is a quadratic fit to the points between $-1.7 < t < 0.0$ days. The green line is a $(t - t_0)^2$ fit to data between $-3.0 < t < -1.6$ days.

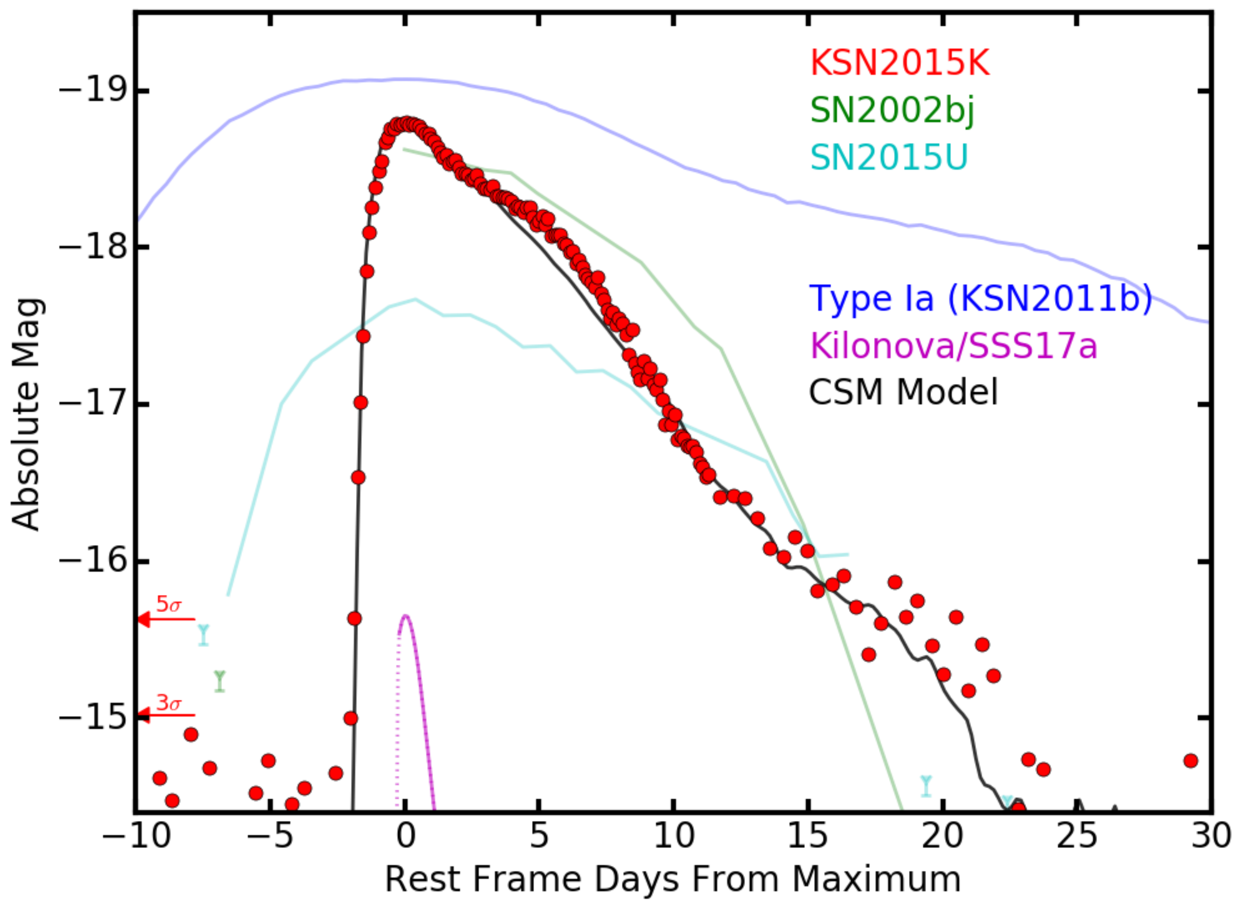


Figure 3: **Light curve comparison.** The KSN2015K light curve assuming $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and a Milky Way extinction of $A_V = 0.10$ mag. The light curve of a type Ia supernova (blue line) is shown for comparison. Also shown are light curves of the fast transients SN2002bj and SN2015U, and the kilonova SSS17a. The black line shows the best fit shock breakout in circumstellar material model.

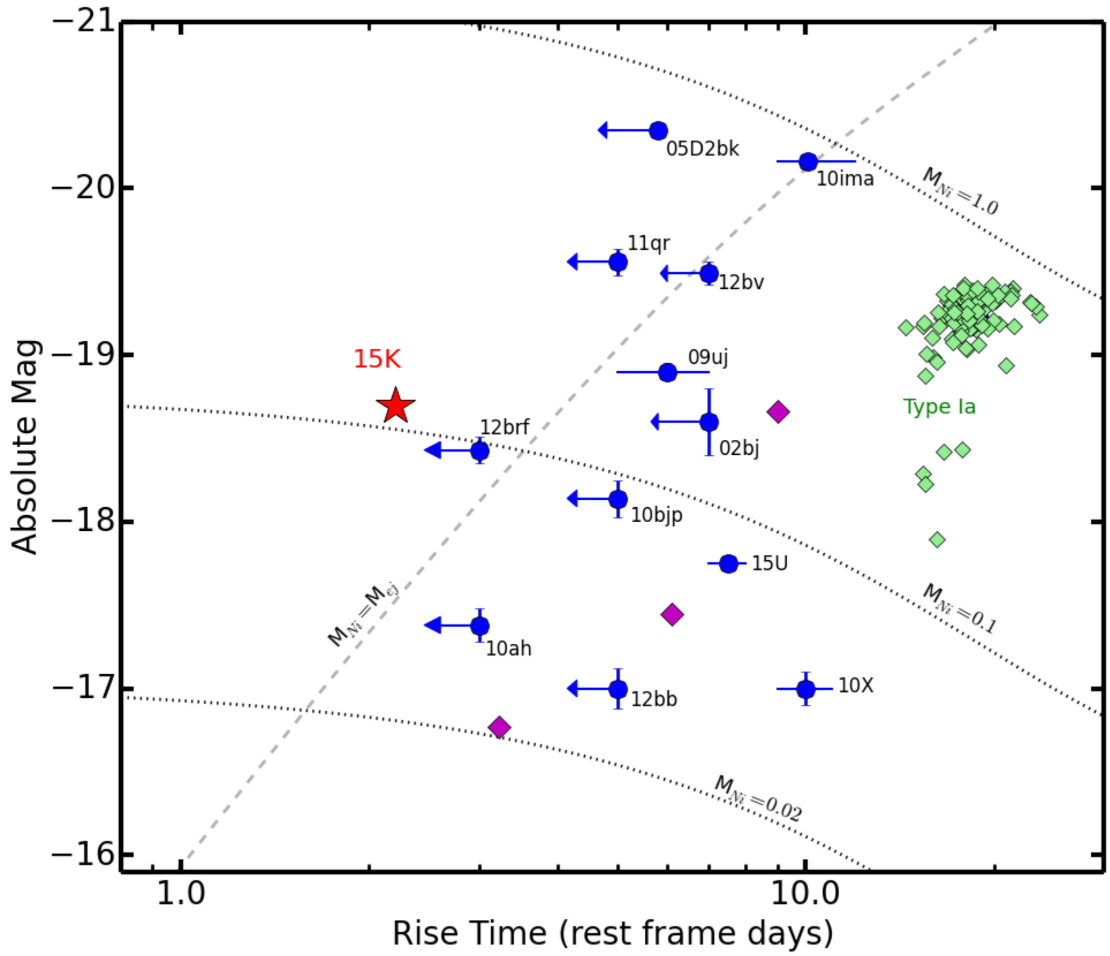


Figure 4: **Peak luminosity versus rise time:** The peak luminosity versus rise time at optical wavelengths for fast transients (blue) and type Ia supernovae (green) from SDSS-II. The red star shows the position of KSN2015K and the errors are smaller than the size of the symbol. Purple diamonds show ".1a" models [7]. Dotted lines show Arnett's rule for a range of synthesized $^{56}$Ni masses. The dashed line is a thermonuclear scenario where a pure $^{56}$Ni envelope is ejected at 10000 km s$^{-1}$. Events to the left of the dashed line cannot be fully powered with radioactive decay.

1. Poznanski, D. *et al.* An Unusually Fast-Evolving Supernova. *Science* **327**, 58 (2010). 0911.2699.

2. Kasliwal, M. M. *et al.* Rapidly Decaying Supernova 2010X: A Candidate ".Ia" Explosion. ApJ **723**, L98–L102 (2010). 1009.0960.

3. Drout, M. R. *et al.* Rapidly Evolving and Luminous Transients from Pan-STARRS1. ApJ **794**, 23 (2014). 1405.3668.

4. Shivvers, I. *et al.* SN 2015U: a rapidly evolving and luminous Type Ibn supernova. MNRAS **461**, 3057–3074 (2016). 1603.04866.

5. Arcavi, I. *et al.* Rapidly Rising Transients in the Supernova Superluminous Supernova Gap. ApJ **819**, 35 (2016). 1511.00704.

6. Howell, S. B. *et al.* The K2 Mission: Characterization and Early Results. PASP **126**, 398 (2014). 1402.5163.

7. Shen, K. J., Kasen, D., Weinberg, N. N., Bildsten, L. & Scannapieco, E. Thermonuclear .Ia Supernovae from Helium Shell Detonations: Explosion Models and Observables. ApJ **715**, 767–774 (2010). 1002.2258.

8. Dessart, L. *et al.* Multidimensional Simulations of the Accretion-induced Collapse of White Dwarfs to Neutron Stars. ApJ **644**, 1063–1084 (2006). astro-ph/0601603.

9. Darbha, S. *et al.* Nickel-rich outflows produced by the accretion-induced collapse of white dwarfs: light curves and spectra. MNRAS **409**, 846–854 (2010). 1005.1081.

10. Metzger, B. D. Kilonovae. *Living Reviews in Relativity* **20**, 3 (2017). 1610.09381.

11. Abbott, B. P. *et al.* Multi-messenger Observations of a Binary Neutron Star Merger. ApJ **848**, L12 (2017). 1710.05833.

12. Tauris, T. M., Langer, N. & Podsiadlowski, P. Ultra-stripped supernovae: progenitors and fate. MNRAS **451**, 2123–2144 (2015). 1505.00270.

13. Moriya, T. *et al.* Fallback Supernovae: A Possible Origin of Peculiar Supernovae with Extremely Low Explosion Energies. ApJ **719**, 1445–1453 (2010). 1006.5336.

14. Kasen, D., Fernández, R. & Metzger, B. D. Kilonova light curves from the disc wind outflows of compact object mergers. MNRAS **450**, 1777–1786 (2015). 1411.3726.

15. Moriya, T. J. *et al.* Light-curve and spectral properties of ultrastripped core-collapse supernovae leading to binary neutron stars. MNRAS **466**, 2085–2098 (2017). 1612.02882.

16. Piro, A. L. & Thompson, T. A. The Signature of Single-degenerate Accretion-induced Collapse. ApJ **794**, 28 (2014). 1406.4128.

17. Maeda, K. *et al.* The Unique Type Ib Supernova 2005bf at Nebular Phases: A Possible Birth Event of a Strongly Magnetized Neutron Star. ApJ **666**, 1069–1082 (2007). 0705.2713.

18. Kasen, D. & Bildsten, L. Supernova Light Curves Powered by Young Magnetars. ApJ **717**, 245–249 (2010). 0911.0680.

19. Dexter, J. & Kasen, D. Supernova Light Curves Powered by Fallback Accretion. ApJ **772**, 30 (2013). 1210.7240.

20. Kasen, D. & Bildsten, L. Supernova Light Curves Powered by Young Magnetars. ApJ **717**, 245–249 (2010). 0911.0680.

21. Chevalier, R. A. Neutron star accretion in a supernova. ApJ **346**, 847–859 (1989).

22. Stanek, K. Z. *et al.* Spectroscopic Discovery of the Supernova 2003dh Associated with GRB 030329. ApJ **591**, L17–L20 (2003). astro-ph/0304173.

23. Chevalier, R. A. & Irwin, C. M. Shock Breakout in Dense Mass Loss: Luminous Supernovae. ApJ **729**, L6 (2011). 1101.1111.

24. Balberg, S. & Loeb, A. Supernova shock breakout through a wind. MNRAS **414**, 1715–1720 (2011). 1101.1489.

25. Ofek, E. O. *et al.* Supernova PTF 09UJ: A Possible Shock Breakout from a Dense Circumstellar Wind. ApJ **724**, 1396–1401 (2010). 1009.5378.

26. Ginzburg, S. & Balberg, S. Light Curves from Supernova Shock Breakout through an Extended Wind. ApJ **780**, 18 (2014). 1308.6434.

27. Kleiser, I. K. W. & Kasen, D. Rapidly fading supernovae from massive star explosions. MNRAS **438**, 318–328 (2014). 1309.4088.

28. Dessart, L., Hillier, D. J., Waldman, R. & Livne, E. Type II-Plateau supernova radiation: dependences on progenitor and explosion properties. MNRAS **433**, 1745–1763 (2013). 1305.3386.

29. Moriya, T. J., Yoon, S.-C., Gräfener, G. & Blinnikov, S. I. Immediate dense circumstellar environment of supernova progenitors caused by wind acceleration: its effect on supernova light curves. MNRAS **469**, L108–L112 (2017). 1703.03084.

30. Tanaka, M. *et al.* Rapidly Rising Transients from the Subaru Hyper Suprime-Cam Transient Survey. ApJ **819**, 5 (2016). 1601.03261.

31. Svirski, G., Nakar, E. & Sari, R. Optical to X-Ray Supernova Light Curves Following Shock Breakout through a Thick Wind. ApJ **759**, 108 (2012). 1202.3437.

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