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# 1. Imaging observations and data reduction

## 1.1 Pan-STARRS1 imaging for PTF12dam (= PS1-12arh) and PS1-11ap

The Pan-STARRS1 (PS1) system and its application to transients has been described in refs 21, 23, 24, 25, 32 and 33. We summarize the relevant system details here for completeness.

PS1 is a high-etendue wide-field imaging system designed for dedicated survey observations, on a 1.8 meter telescope on Haleakala with a 1.4 Gigapixel camera and a 7 deg$^2$ field of view. The PS1 observations are obtained through a set of five broadband filters, which are $g_{P1}$ ($\lambda_{eff}$ = 483 nm), $r_{P1}$ ($\lambda_{eff}$ = 619 nm), $i_{P1}$ ($\lambda_{eff}$ = 752 nm), $z_{P1}$ ($\lambda_{eff}$ = 866 nm), and $y_{P1}$ ($\lambda_{eff}$ = 971 nm). See ref. 33 for full details of the bandpasses.

This paper uses images and photometry from both the PS1 Medium Deep Field survey (MDS) and the wide 3π Survey. The goal of the 3π Survey is to observe the portion of the sky North of -30 deg declination, with a total of 20 exposures per year across all five filters for each field center. The 3π survey plan is to observe each position 4 times in each of $g_{P1}$, $r_{P1}$, $i_{P1}$, $z_{P1}$, and $y_{P1}$ during a 12 month period, although this can be interrupted by weather. The 4 epochs in a calendar year are typically split into two pairs called Transient Time Interval (TTI) pairs, which are single observations separated by 20-30 minutes to allow for the discovery of moving objects. The exposure times at each epoch (i.e. in each of the TTI exposures) are 43s, 40s, 45s, 30s and 30s in $g_{P1}$, $r_{P1}$, $i_{P1}$, $z_{P1}$ and $y_{P1}$, leading to 5σ depths of roughly 22.0, 21.6, 21.7, 21.4. and 19.3 (in the PS1 AB system described by ref. 32). The PS1 images are processed by the Pan-STARRS1 Image Processing Pipeline (IPP), on a computer cluster hosted in the Maui High Performance Computer Center. This performs automatic bias subtraction, flat fielding, a flux-conserving warping to a sky-based image plane, masking and artifact removal, object detection, photometry and astrometry[34,35]. The TTI pairs are not stacked together, but kept as individual frames. Full stacking of all data across the sky, over the three years is now underway but for the purposes of transient searches, the individual exposures are kept separate.

The PS1 MDS obtains deep multi-epoch images in the $g_{P1}$, $r_{P1}$, $i_{P1}$, $z_{P1}$ and $y_{P1}$ bands of 10 fields with a typical cycle of observations being $g_{P1}$ and $r_{P1}$ on one night, followed by $i_{P1}$ and $z_{P1}$ bands on the subsequent nights[23]. In some cases this cycle is broken to optimise for sky brightness. Observations in the $y_{P1}$ band are taken close to the full moon. The MDS Images are also processed through the Image Processing Pipeline, and are stacked to give a single nightly image containing eight exposures in a dithered sequence. The observing season for each field is 6 months per year. PS1-11ap was detected

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throughout the 2011 observing season for MD05.

### 1.2 Follow-up imaging for PTF12dam

Optical imaging in SDSS-like g, r, i and z filters was obtained with RATCam on the 2.0m Liverpool Telescope, and FS02 on the 2.0m Faulkes Telescope North. The data were automatically reduced by respective facility pipelines to produce detrended images (bias and flat field corrected). Optical images obtained using ACAM on the 4.2m William Herschel Telescope, OSIRIS on the 10.4m Gran Telescopio Canarias, LRS on the 3.58m Telescopio Nazionale Galileo, and ALFOSC on the 2.56m Nordic Optical Telescope (NOT) were reduced using standard tasks within the IRAF [i] package CCDRED, to debias, trim and flatfield the images. Multiple exposures from the same epochs and filters were median-combined with cosmic ray rejection using the IMALIGN and IMCOMBINE tasks.

Near infrared imaging was taken from three sources: NOTCam on the NOT, NICS on the TNG, and WFCAM on the UK infrared telescope. NOT and UKIRT data were reduced by facility pipelines, while we reduced TNG data using standard IRAF packages. Images were flat field corrected and sky subtracted. For each position in the mosaic making up the image, a sky frame was created by median combining exposures from all the other positions in the dithering pattern to get rid of stars. The sky-subtracted individual dithers were aligned and combined to produce the final images.

UV observations were obtained with UVOT on board the Swift satellite. The frames were reduced using tools within HEAsoft[ii]. UVOT data were obtained in uvw2, uvm2, uvw1 and u filters, with spatial resolution of about 2 arcsec (full width at half maximum, FWHM). Eight epochs, spread over a period of 50 days, are available. Individual images for each epoch were first co-added, before aperture magnitudes were measured following the prescription of ref. 36.

[i] Image Reduction and Analysis Facility (IRAF), a software system distributed by the National Optical Astronomy Observatories (NOAO).
[ii] Available from the NASA High Energy Astrophysics Science Archive Research Center

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# 2. Photometric measurements

## 2.1 PTF12dam in PS1 data and follow-up data

The host galaxy of PTF12dam is bright ($g$ = 19.30, or $M_g$ = −19) compared to most ultra-luminous supernova hosts[37] and we correct for galaxy flux as follows. For observations in g,r,i,z where PTF12dam+host is more than a magnitude brighter than the host alone, we subtract the contribution from the host flux in a given band simply using the magnitudes (model mags) from SDSS DR9 (ref. 38). The host is a compact source, such that essentially all of the flux falls within the SN PSF. When the brightness of the supernova and galaxy are comparable, we subtract an SDSS template image from our target image using the HOTPanTS[iii] code (ref. 39), which matches the seeing in the two images by computing a convolution kernel from the PSFs of point sources in the images. The resultant subtracted image contains only flux from the supernova. Extended Data Fig. 2 shows the image subtractions for the critical PS1 early detections, which constrain the rise time.

In both cases, photometric flux measurements were performed using the custom built SNOOPY package[40] (implemented in IRAF by E. Cappellaro). This suite of programs is based on the standard DAOPHOT PSF-fitting task, available within IRAF. The zero point for each observation was calibrated by comparing multiple point sources in the field with SDSS photometry. Colour corrections and extinction for each site were then used to refine the measured magnitudes.

As PTF12dam is at a redshift of $z$ = 0.107, a $k$-correction was applied to convert our measured magnitudes in each filter to the magnitudes that would be obtained in the restframe. To compute the $k$-corrections, we used SYNPHOT[iv], to calculate synthetic *gri* photometry at every epoch for which we obtained a spectrum. Magnitudes (in the SDSS AB system) were measured for the observed spectrum and after correcting it to restframe. The $k$-corrections (shown in 1) were thus the differences between these two, and were then applied to the measured photometry from the imaging. The corrections for other epochs were calculated using linear interpolation. The z band lies at the red edge of the optical spectra, and hence was not covered by both the observed and rest frame spectra simultaneously. For these magnitudes, colour-based $k$-corrections were used instead[v] (refs 41, 42).

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[iii] http://www.astro.washington.edu/users/becker/hotpants.html

[iv] SYNPHOT is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.
http://www.stsci.edu/institute/software_hardware/stsdas/synphot

[v] http://kcor.sai.msu.ru/

The errors were calculated in SNOOPY using an artificial star experiment. The fitted supernova PSF is placed at different locations on the image, and the magnitude is computed each time. The standard deviation of these measurements gives the error in fitting the background, which is the dominant source of error since the bright supernova has a well-defined PSF that can be fit at all times.

Table 1 lists the *griz* ground-based photometry after image subtraction (or host flux subtraction), and before the *k*-correction is applied. The absolute AB magnitudes in these filters are calculated using a flat ΛCDM cosmology with $H_0$ = 72 km $s^{-1}$ $Mpc^{-1}$, $\Omega_M$ = 0.27 and $\Omega_\Lambda$ = 0.73. The date of maximum light (MJD = 56088, corresponding to 10$^{th}$ June 2012) was determined from our bolometric light curve (Section 5); this coincides with the peak in *r*. Epochs are taken relative to this, and corrected for cosmological time dilation using the observed redshift $z = 0.107$.

Swift photometry was carried out using aperture photometry with the HEAsoft tools, and calibrated using the latest calibration database provided by HEASARC. A secondary calibration was carried out by calculating the mean shifts in brightness of close stars from their average magnitudes in each band. To transform the UVOT *u* magnitudes from the instrumental system into standard SDSS magnitudes (in order to maintain consistency with our optical imaging, and ease the creation of our bolometric light curve; see section 5), a shift of $\Delta u$ = -0.21 mag was applied. This shift was computed from the magnitudes of stars in the PTF12dam field listed in SDSS. Thus, Table 2 lists the SWIFT photometric measurements in the AB system. Host galaxy flux, inferred from our model host template (see section 3) was subtracted from all UVOT photometry. Due to the lack of UV spectral coverage, no *k*-correction has been applied to the SWIFT magnitudes.

Near infrared photometry was carried out using aperture photometry with the PHOT task in IRAF, and calibrated using the magnitudes of nearby sources in the 2MASS catalogue. Because only a few 2MASS sources were available in the field, a secondary calibration was carried out. In each band, we calculated the mean magnitudes of sources with flux similar to that of the supernova. The difference from their mean values (averaged over these sources) in each image was measured; this shift was then applied to the calculated supernova magnitude. No image subtraction was applied for the NIR photometry. There is no host detected in 2MASS, to limiting magnitudes of $J$ = 17, $H$ = 16, $K$ = 15.5. No *k*-correction was applied to the NIR data, as we lack sufficient NIR spectral coverage to reliably cover all epochs. Photometric measurements, in Vega magnitudes, are given in Table 2.

All PTF12dam photometry is plotted in Extended Data Figure 2.

## 2.2 PS1-11ap in the Pan-STARRS1 Medium Deep Survey

For the MDS, the 8 images taken during any one night are stacked to produce a “nightly stack”. This nightly data product is used in two image differencing pipelines that run simultaneously, but independently. The PS1 system is developing the Transient Science Server (PS1 TSS), which automatically takes the nightly stacks, creates image differences with manually created deep reference images, carries out PSF fitting photometry on the image differences, and returns catalogues of variables and transient candidates. Photometric and astrometric measurements are performed by the PS1 IPP system at the Maui High Performance Computing Centre and ingested into a MySQL database hosted at Queen’s University Belfast. Independent difference image analysis is also run with the *photpipe* pipeline[43] hosted at Harvard/CfA, and since this uses forced photometry and an accurate zeropoint calibration, we employ the *photpipe* measurements for PS1-11ap in this paper. This pipeline produces image differences from the IPP-created nightly stacks, with respect to a custom-built deep reference stack. Forced-centroid PSF-fitting photometry is applied on its image differences, with a PSF derived from reference stars in each nightly stack. The zeropoints were measured for the AB system from comparison with field stars in the SDSS catalog. The Poisson error is propagated through the resampling and image differencing. Since this does not take the covariance into account, *photpipe* also runs forced photometry in apertures at random positions and calculates the standard deviation of the ratio between the flux and the error. All errors are multiplied by the standard deviation to correct for the covariance. The difference imaging photometry in the observer frame $z_{P1}$ band is reported in AB magnitudes in Table 3. This was corrected to an absolute restframe AB mag at $\lambda_{eff}$ = 5680 Å using

$$M_{5680} = z_{P1} - 5\log\left(\frac{d_L}{10}\right) + 2.5\log(1+z)$$

where $z_{P1}$ is the apparent AB magnitude in the $z_{P1}$ filter, $d_L$ is the luminosity distance in parsecs, and $z$ is the redshift. This equation corrects for cosmological expansion, but is not a full *k*-correction. $M_{5680}$ should be close to the absolute r-band AB magnitude. We have earlier coverage in the PS1 $i_{P1}$ band, so to compare the rise we convert $i_{P1}$ to $z_{P1}$ using the observed colour at the earliest $z_{P1}$ point, $i_{P1} - z_{P1} = -0.18$. The full dataset of $g_{P1}$, $r_{P1}$, $i_{P1}$, $z_{P1}$ and $y_{P1}$, with full *k*-corrections, supplementary data, and spectral series, will be presented in a companion paper[31]. These absolute *r* magnitudes are plotted in Figure 1.

### 2.3 SN2007bi photometry

The published photometry for SN2007bi[1,10] has until now been in the Johnson-Cousins *UBVRI* system. For ease of comparison, we converted the existing R band photometry to SDSS *r* magnitudes. This was done using colour transformations in *V–R* (ref. 44) between SDSS and Johnson-Cousins filter systems. Multicolour photometry of SN2007bi was used where available[10] although most photometric data for SN2007bi is in *R* only[1]. We considered linear interpolation of the required correction between these epochs, but found that the conversion factor varied negligibly with time, and so were able to apply a constant shift of +0.15 magnitudes to the *R* data, to bring it into the AB *r* system, and estimated the additional error due to the uncertainty in *V* magnitudes and the coefficients in the transformation. While a detailed S-correction would have been preferable, the lack of SN2007bi spectra earlier than 54d post-peak meant that such a correction would necessarily have been based on the spectra of PTF12dam. We felt that the additional uncertainty this would introduce (to what is only a small correction) meant that it was not worthwhile.

## 3 Spectroscopic data and analysis of PTF12dam and PS1-11ap

Optical spectra of PTF12dam were taken with the Gran Telescopio Canarias (GTC) with the OSIRIS instrument; the William Herschel Telescope plus ISIS spectrograph; the Nordic Optical Telescope plus ALFOSC; the Asiago Copernico Telescope plus AFOSC; and the Gemini North telescope with GMOS-N. Spectra of PS1-11ap were taken with the William Herschel Telescope plus ISIS and the Gemini North telescope with GMOS-N. The details of the wavelength coverage and resolution are listed in Table 4.

Standard procedures within IRAF were used to detrend the CCD data, and extraction of spectra was carried out using variance-weighted cleaning with the IRAF task APALL. When this was insufficient to remove cosmic rays, the 2D frames were first cleaned using LACosmic[vi] (ref. 45). Spectra were wavelength-calibrated using spectra of arc lamps for comparison, and flux-calibrated using sensitivity functions derived from the spectra of standard stars obtained on the same nights as our spectra.

Observed spectra were adjusted to restframe by applying a redshift correction, and were also corrected for extinction. Prominent host galaxy lines (in particular Hα, Hβ and the [O III] 4959 & 5007 Å doublet) gave $z$ = 0.107. We measured the flux ratio of Hα/Hβ as 2.99 in the observed frame in the NOT spectrum from 2012 August 9th. This compares to an expected intrinsic

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[vi] http://www.astro.yale.edu/dokkum/lacosmic/

line ratio of 2.86 for case B recombination[46]. We assumed that $R_V$ for this host galaxy is similar to that observed in the LMC ($R_V$ = 3.16; ref. 47), and hence we estimated a host galaxy extinction in the V band of $A_V^{host}$ = 0.1 mag from the Balmer decrement. Within the uncertainties, we find similar results if we were to apply $R_V$ = 2.93, which has been proposed for an SMC-like environment[47]. We used a Milky Way extinction in the direction of PTF12dam of $A_V^{MW}$ = 0.037 mag from the NASA/IPAC IRSA dust maps[vii] (ref. 48). These were applied separately to the spectra and to all filters with the appropriate redshift corrections. Host reddening was assumed to be negligible for PS1-11ap and SN2007bi, and only a galactic extinction correction was applied.

Near infrared spectra were obtained using NICS on the TNG on 26$^{th}$ May and 9$^{th}$ July 2012. As for the optical, the spectra were calibrated in wavelength through spectra of comparison lamps acquired with the same configuration of the PTF12dam observation. First order flux calibrations were obtained using A0 standard stars taken in the same night with the same set-up used for PTF12dam. Solar analogues at a similar airmass were observed either before or after PTF12dam, to facilitate the removal of the strong telluric absorptions between 1 and 2 µm. The spectra show no broad hydrogen or helium (consistent with the optical spectra). The early (-13d) spectrum is nearly featureless with two narrow host galaxy lines from [S III] (9500 Å) and He I (10580 Å), while the later one, at 27 days after peak, shows broad absorption due to the Ca II NIR triplet, which is also seen in the optical spectra with the longest wavelength coverage.

The two latest optical spectra of PTF12dam, at 171d and 221d after peak, have significant contamination from the host galaxy in the continuum, as judged from the pre-discovery SDSS flux of the host and our photometric measurements. The host is not resolved from the SN hence no host subtraction is possible in the 2D spectroscopic reductions. At the present time, we do not have a spectrum of the host hence we constructed a galaxy template to subtract. We used *starburst99*[viii] (ref. 49) to calculate series of spectra for both continuous star-formation and an initial burst, settling on a 30 Myr old stellar population with a continuous star-formation history (at a metallicity of 0.05 solar, and a Salpeter initial mass function). This does not include nebular emission lines, hence we added narrow emission lines with fluxes as measured from the spectra of PTF12dam at 221d (after continuum subtraction). This provided a galaxy template spectrum, which we scaled and reddened until synthetic photometry (with the IRAF task SYNPHOT) through SDSS ugriz and GALEX FUV and NUV filters matched pre-discovery measurements[38]. Thus we have a model galaxy spectrum that reproduces the observed flux. The continuum from this model spectrum was then subtracted from the PTF12dam spectra and NUV photometry in Figs 2 and 3. With this subtraction, the nebular features are more prominent, as one would expect. In fact, at this phase, the +171d pseudo-nebular spectrum looks almost identical

[vii] http://irsa.ipac.caltech.edu/applications/DUST/
[viii] http://www.stsci.edu/science/starburst99/docs/default.htm

to SN2007bi after +134d. A similar fit was made for the host of PS1-11ap, and subtracted accordingly.

All spectra of PTF12dam are shown in Extended Data Fig. 3.

At the epochs after peak luminosity, while PTF12dam and PS-11ap are still in the photospheric phase, the spectral lines are assumed to be those identified for SN2007bi[1], as the spectra are closely matched. However the early spectra we have of these two super-luminous SNe before and around maximum light explore new epochs, particularly in the near-UV. We determine the main features of our spectra before maximum light using SYN++, a C++ version of the commonly used synthetic spectrum tool SYNOW[ix] (refs 50, 51). Single-ion spectra were generated for common ions in ejecta with temperatures and velocities appropriate to our spectra ($T \sim 15000$ K and $v \sim 11000$ km s$^{-1}$). We find that all of the main features can be accounted for with O II, Ca II, Fe III, Mg II and Si II.

## 4 Nebular phase modelling

Nebular phase modelling[1] of the SN2007bi spectrum was a key component in the argument for a large ejecta mass and PISN explanation. The model achieved a good fit to most of the lines, but crucially the strong [Fe II] 7155 Å line predicted in the model does not appear in the observed spectrum. The only strong iron line identified was an [Fe II] 5200 Å blend. It was the strength of this line that possibly suggested[1] a high mass of $^{56}$Ni, in combination with an ejecta mass of 60-80M$_\odot$, was required. While this is a self-consistent argument in favour of the PISN scenario, the aim of this section is to explore if it is the only plausible solution.

Using the NLTE solver[19], we investigated whether the ejecta parameters of our proposed core-collapse and magnetar-heating scenario are consistent with the nebular spectra of SN2007bi. PTF12dam appears to be evolving to a similar spectrum, although our last spectrum is still only quasi-nebular. Full spectral modelling requires the calculation of heating, ionization, and excitation by gamma-rays, X-rays, and diffuse UV/optical radiation in a multi-zone supernova ejecta structure taken from stellar evolution/explosion models, including NLTE solutions for the important atoms and a detailed radiative transfer treatment[19]. Such an analysis is beyond the scope here, and we instead aim to explore the range of densities and temperatures that can roughly reproduce the luminosities of the most prominent lines in the SN2007bi spectrum at 367d after peak. We compute NLTE solutions for oxygen, magnesium and iron, as functions of density and temperature, taking

[ix] https://c3.lbl.gov/es/

thermal processes and recombination into account. In these models, the variable parameters are:

$n_{\{OI,\ MgI,\ FeII\}}$ - Number density of the element (O I, Mg I, and Fe II, respectively);
$n_e$ - Number density of electrons;
$T$ - Temperature.

The fixed parameters are:

Velocity gradient (we assume homologous expansion: dv/dr=1/$t$);
$n_{OII} = 0.9\ n_e$ ;
$n_{MgII} = 0.1\ n_e$ ;
$n_{FeIII} = 0$,

where we assume that oxygen and magnesium dominate the composition of the ejecta in the region where oxygen/magnesium lines are produced. The 0.9:0.1 partition roughly reflects the relative abundances of oxygen and magnesium in stellar evolution models, where the ratio is close to the solar ratio of $n_O/n_{Mg} \sim 13$ (refs 52, 53), and that iron is singly ionized (recombinations are usually not important for the [Fe II] lines anyway).

We explored solutions in the range $10^0 < \{n_e,\ n_i\} < 10^{10}$ cm$^{-3}$ and for three temperatures: $T = 2000$, 5000 and 8000 K.

It can be seen from Extended Data Fig. 5 that the electron density must be close to $n_e = 10^7$ cm$^{-3}$ in order to reproduce the O I 7774 Å luminosity, which is a density-sensitive recombination line. At a temperature of 5000 K, the O I and Mg I densities needed to reproduce [O I] 6300, 6364 Å and Mg I] 4571 Å are $n_{OI} \sim 10^6$ and $n_{MgI} \sim 10^3$ cm$^{-3}$, respectively. That magnesium is more strongly ionized than oxygen is consistent with its much lower ionization potential.

This electron density can be checked for consistency against the mass we derive from the light curve (see Main Text and Section 5 below). If we assume single ionization ($n_{ion} \sim n_e$) then the total number of ions is $N_{ion} \sim n_e V$, where $V$ is the volume. The volume comes simply from spherical expansion at 10000 km s$^{-1}$ for 400 days, where these numbers are the FWHM of the Mg I] 4571 Å line and the approximate time since explosion (367d + rise time). Assuming oxygen dominated ejecta ($\bar{A} \sim 16$), we estimate an approximate mass:

$$M_{ejecta} \sim N_{ion}\ \bar{A}\ m_{proton} \sim 22\ M_{\odot}$$

Thus it is consistent with the mass derived from the light curve.

We then investigated what conditions are required to produce a strong [Fe II] 5200 Å line. We find that for $T < 3000$ K, the strongest [Fe II] line is 7155 Å (in agreement with previous models[1]), which is not observed. For temperatures

$T$ > 6000 K, [Fe II] 4330 Å will be the strongest visible line, which is not observed either. Between 3000-6000 K, the 5200 Å line (which is observed) should be the dominant feature. We therefore find that the temperature is likely to be in this intermediate regime. However, even in this regime the other [Fe II] lines remain at levels of 60-90% of the flux of the feature at 5200 Å, much higher than their observational limits. We therefore also conclude that Fe II can at most contribute only part of the 5200 Å feature.

Given the strong Mg I] 4571 Å line in the spectrum, one good candidate for contributing to emission around 5200 A is Mg I 5183 Å, which is the second strongest recombination line after Mg I] 4571 Å. This line is an allowed triplet (5167.32, 5172.68 and 5183.60 Å), with the latter two transitions dominating. As Extended Data Fig. 5 shows, the flux in this line can become a significant fraction of the Mg I] 4571 Å flux. In the regime where it is strong, the electron density is constrained to the same value as that from the O I 7774 Å recombination line, $n_e \sim 10^7$ cm$^{-3}$.

For a given electron density, we can use the temperature constraints on the iron-emitting zone to put an upper limit to the Fe II density. Using the range 3000 K < $T$ < 6000 K, and assuming a similar electron density to that derived for the oxygen/magnesium zones ($n_e \sim 10^6$-$10^8$ cm$^{-3}$), we find $n_{\mathrm{FeII}} < 10^6$ cm$^{-3}$, and an Fe II mass of 0.001-1 $M_\odot$ (at 6000 and 3000 K, respectively). While a lower electron density in this zone would allow for a larger iron mass, this calculation shows that there are density regimes where small iron masses (and therefore small/moderate amounts of $^{56}$Ni) can reproduce the 5200 Å feature.

We conclude that a 10-20 $M_\odot$ core-collapse ejecta, dominated by oxygen/magnesium and <<1 $M_\odot$ of $^{56}$Ni, can reproduce the main lines observed in SN2007bi, given that some power source keeps the ejecta ionized ($1-x_e \ll 1$) and hot ($T \gtrsim 5000$ K) for several hundred days. Energy input by an energetic (fast-spinning) and medium-fast decaying magnetar (spin-down time scale of months/years) is an excellent candidate for providing such physical conditions.

In summary, previous nebular modelling[1] of SN2007bi can explain the observed lines if the heating of a large ejecta mass is caused by radioactive $^{56}$Ni. However our calculations indicate that this is not the only physical scenario that can reproduce the nebular spectrum. Moreover, we find that the lack of an observed [Fe II] 7155 Å line, which should be detectable at the low temperatures and high iron mass in a PISN (and was also predicted by previous nebular models[1]), is problematic for a pair-instability interpretation of SN2007bi. We have shown here that the strong line at 5200 Å, previously interpreted as a ‘smoking gun’ signature of a very high-nickel-mass event, can be reproduced with small-to-moderate amounts of nickel under certain physical conditions (higher temperature, and some Mg I blending).

# 5 Bolometric light curve and alternative model fits

We derived a bolometric light curve for PTF12dam by converting magnitudes in near-UV, optical and NIR filters into physical fluxes, correcting for the extinction described in Section 3. We derive an SED at each epoch by linearly interpolating the flux between the effective filter wavelengths. The total flux was then converted to a luminosity using the distance derived from the redshift and our assumed cosmology (Section 2.1). This was done at every epoch with an *r* band observation, and magnitudes in other filters were interpolated to these epochs using low-order polynomials. Zero flux was assumed outside of the observed wavelength range (1700-23000 Å). Between epochs -11d and +21d, we have full restframe flux coverage from the UV to the NIR. Outside of this period, we make simple extrapolations to account for missing UV and NIR data. To correct the early epochs (i.e. more than 11d before peak) for missing UV and NIR data, we extrapolated the flux contribution by assuming a linear gradient in colour evolution in each filter with respect to *r*. This is reasonable, since the colour evolution is very close to linear over the epochs where we have full coverage. To correct the late epochs for missing UV data, we simply extrapolated the UV light curves linearly. This is because the rapid fall off in the near-UV after maximum light means that it contributes little to the total luminosity beyond ~ 40d post-peak, so the lack of coverage does not have a significant effect.

To determine the errors due to the missing near-UV coverage at early and late times, we make two bolometric light curves. Method 1 is the one described above. For method 2, we integrate only the observed bands at each epoch, and assume the fraction of flux in the UV at all epochs when it is no longer observed is the same as the fraction at -20d (early times) or +25d (late times). At these later epochs, the integrated luminosity is converted to a total luminosity by adding this missing fraction. The additional error in log($L$) due to missing UV points is taken to be the difference in log($L$) given by these two methods, and is included on Figure 4.

## 5.1 Light curve models powered by radioactive $^{56}$Ni

We modelled the total luminosity of PTF12dam using a semi-analytic treatment based on the Arnett diffusion solution for a specified power source in a radiation-dominated, homologously expanding ejecta[21,22]. The treatment is identical to our magnetar fit (see Main Text and Supplementary Information section 5.2), but with the magnetar power source replaced by $^{56}$Ni and $^{56}$Co decay. For the $^{56}$Ni-powered models, we initially adopted an explosion energy of $10^{51}$ erg and computed the ejecta mass and $^{56}$Ni mass that produced the best fit to the bolometric light curve. The best fit was formally determined through a $\chi^2$ minimization. We use $\chi^2$ per degree of freedom, with 16 degrees of freedom (19 data points minus 3 free parameters: ejecta mass, $^{56}$Ni mass, and time). We were unable to produce a satisfactory fit (see Extended Data Fig. 6) to the shape of the light curve, particularly around peak, and found ejecta masses of ~15 $M_\odot$ with quite unphysical $^{56}$Ni masses of greater than 14 $M_\odot$. The parameters for this best fitting model are given in Extended Data Fig. 6. Formally, better fits can be obtained with higher explosion energies of $10^{52}$ and $10^{53}$ erg, but again very high $^{56}$Ni masses of 14 $M_\odot$ and 17 $M_\odot$ are required. While this results in $M_{Ni}/M_{ej}$ ratios that are unphysically high for an iron core-collapse supernova, for the most energetic explosions we find ratios that could be produced in thermonuclear events. However, the associated total ejecta mass is not compatible with any proposed progenitor of such an explosion. $M_{ej} \lesssim 50$ $M_\odot$ is much too high for a SN Ia-like model. As for pair-instability models: producing more than 10 $M_\odot$ of $^{56}$Ni seems to require[7] helium cores of more than 110 $M_\odot$, so we would expect much more massive ejecta compared to the 50 $M_\odot$ in our fit. Thus, we are in a region of parameter space that does not correspond to any quantitative physical model. The same problem occurs in fitting similar models to a more typical SLSN, PS1-10bzj[54], with fits giving ejecta compositions that are >75% $^{56}$Ni. It should be noted that a good fit was found for PS1-10bzj with a magnetar-powered model similar to ours.

The core-collapse of a massive star (43 $M_\odot$ carbon-oxygen core from a 100 $M_\odot$ main-sequence progenitor) has also previously been proposed[10,20] to explain the SN2007bi light curve. A model[20] with an explosion energy (a free parameter) of $3.6\times10^{52}$ erg and $M_{ej}$ = 40 $M_\odot$ reproduces the light curve with a $^{56}$Ni mass of $M_{Ni}$ = 6.1 $M_\odot$. However this was based on the SN2007bi peak luminosity of $5.8\times10^{43}$ erg s$^{-1}$. PTF12dam is intrinsically brighter, and a full bolometric luminosity calculated from our UV to NIR coverage provides a measured peak luminosity of $1.2\times10^{44}$ erg s$^{-1}$. This difference, a factor of 2.1, explains why we require a much larger $^{56}$Ni to total ejecta mass ratio than that proposed[20] for SN2007bi. The measured luminosity of PTF12dam effectively makes core-collapse models unphysical due to the large $^{56}$Ni mass required. Even extreme massive-core-collapse models[20] produce only 4 $M_\odot$ of $^{56}$Ni, and none has $M_{Ni}/M_{ej} > 0.2$. Additionally, such models are only likely to be possible in extremely low metallicity environments of $Z \sim Z_\odot/200$. We therefore cannot find a physically reasonable fit to our light curve from this radioactive diffusion model.

### 5.2 Unexplored parameters in PISN models

The long rise times of existing PISN models[7,8] are central to our conclusion that the objects we observe are not pair-instability explosions, so it is important to establish how fundamental the slow rise is. Could more sophisticated models (taking into account rotation, magnetic fields, mixing and higher dimensions) have substantially shorter rise times?

Simple arguments show that they cannot. The rise time of a supernova is set by the diffusion timescale, given by[22]

$$t_{\mathrm{diff}} = 440\mathrm{d}\left(\frac{E}{10^{51}\mathrm{erg}}\right)^{-1/4}\left(\frac{M_{\mathrm{ej}}}{100\,M_{\odot}}\right)^{3/4}\left(\frac{\kappa}{0.2\ \mathrm{cm}^2\mathrm{g}^{-1}}\right)^{1/2},$$

where $E$ is the kinetic energy of the explosion, $M_{\mathrm{ej}}$ the ejected mass and $\kappa$ the opacity. In the rising phase, the gas will be highly ionized, so $\kappa$ must be close to 0.2 $\mathrm{cm}^2\,\mathrm{g}^{-1}$. For a 100 $M_{\odot}$ sphere, this gives diffusion times of 246d or 140d for an explosion of energy $10^{52}$ or $10^{53}$ erg respectively. If the ejected mass of $^{56}$Ni is 5 $M_{\odot}$, a self-consistent set of parameters[7,8] is $E \sim 4\times10^{52}$ erg and $M_{\mathrm{ej}} \sim$ 100 $M_{\odot}$. The diffusion time is then 175d.

Testing this calculation against our light curve fits (Extended Data Fig. 6), we find that $t_{\mathrm{rise}} \sim 1.1\ t_{\mathrm{diff}}$, confirming the validity of this approximation. The timescales calculated in this way are independent of more complicated effects like rotation or magnetic fields, as this is just radiative diffusion (in the particularly simple regime where electron scattering dominates the opacity). Even if we conservatively set the rise time as half of the diffusion time, a super-luminous pair-instability event like that proposed for SN2007bi should have $t_{\mathrm{rise}} \gtrsim$ 100d.

Multi-dimensional simulations of PISN explosions[55] have suggested that mixing in the ejecta is negligible. However, consequences of mixing have been studied for $^{56}$Ni-powered SNe Ia[56] and Ibc[57,58]. In fact, mixing serves to flatten the early parts of model light curves, since photons begin diffusing out earlier, without significantly decreasing the time to reach maximum light, as the bulk of the nickel still resides in the inner ejecta. Such models also display redder spectra[57]. These two effects mean that the one-dimensional models we find to be incompatible with PTF12dam and PS1-11ap are likely better fits than PISN models with detailed mixing would be.

### 5.3 Pulsational pair-instability supernovae

Another mechanism proposed to explain super-luminous supernovae, closely related to the PISN scenario, is the so-called ‘pulsational pair-instability’. Stars with zero-age main sequence masses of 90-130 $M_{\odot}$ are expected to eject shells of material in a series of pair-instability-powered eruptions; collisions between successive shells can produce a bright display[59]. However, these interaction-driven events involve large amounts of hydrogen and/or helium[59,60] at relatively low velocities ($\sim10^3$ km $\mathrm{s}^{-1}$) and are therefore expected to display narrow H/He lines. Furthermore, to reach the luminosities of SLSNe ($L\sim10^{44}$ erg $\mathrm{s}^{-1}$), the first shell must have reached a significant radius before the second shell collides with it (in order to avoid adiabatic losses), and at typical radii of $10^{15}$-$10^{16}$ cm, the spectra produced are faint in the U and B bands[59]. The spectra of pulsational-PISNe must therefore be very different, exhibiting a low continuum temperature and narrow H/He lines, from those observed in our objects.

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### 5.4 Details of the magnetar powered model

Our magnetar[16,17,61] model[14,21,22] assumes a SN explosion energy of $10^{51}$ erg and derives a magnetar luminosity from magnetic field and spin period; these are free parameters to fit. Assuming a 45° angle between spin axis and magnetic field (this can be fixed, as it simply serves to change the effective *B*-field), we feed the time-averaged magnetar luminosity into the Arnett diffusion solution[21,22], in the same way as for the radioactive model of section 5.1. The resultant luminosity of the SN is calculated, and the excess input energy goes into kinetic energy of the explosion. These models have been tested against more detailed simulations (via private communication with Dan Kasen, based on published models[14]) and found to yield good agreement[21]. The magnetar model can generate a wide range of light curves because the ejecta mass and power source are decoupled, such that we can find an ejecta mass to fit the observed diffusion timescale (along with explosion energy and opacity[22]), and an energy input to power the observed luminosity. We found that this model could fit the data with physically reasonable parameters for the explosion, ejecta and magnetar. The power source in a SLSN (be it a magnetar or something else) keeps the ejecta ionized for much longer than in a typical supernova, such that electron scattering provides a high continuum opacity. The opacity for a highly ionized, hydrogen-free gas is $\kappa \sim 0.1\text{-}0.2$ cm$^2$ g$^{-1}$. Within these limits, we find ejecta masses in the range 10-16 $M_\odot$.

This suggests a fairly massive progenitor, in which case we might expect black hole formation to be a more likely outcome. A central-engine model could still apply in such a scenario; however, the engine would then be accretion onto the black hole. Fallback models[62] predict an energy input similar to the magnetar, but with an asymptotic time dependence of $L \propto t^{-5/3}$ rather than $t^{-2}$.

We can check for consistency between our light curve fitting and observed spectral evolution by estimating the time taken for the ejecta to become nebular. We set the continuum optical depth, $\tau_c$, to unity in the expression

$$\tau_c = \kappa \rho v t$$

where $\kappa$ is the opacity, $\rho$ the density and $v$ the velocity of the ejecta, and $t$ is the time since explosion. For electron scattering, $\kappa = 0.2$ cm$^2$ g$^{-1}$, giving

$$t_{\rm neb} \approx 360\,{\rm d} \left(\frac{M}{10\,M_\odot}\right)^{1/2} \left(\frac{v}{10^4\ {\rm km\ s^{-1}}}\right)^{-1}.$$

Thus, we would expect the transition to the nebular phase to occur at approximately a year after explosion. PTF12dam is not yet fully nebular at ~280 d after explosion (221d post-peak spectrum, with 50-60d rise), while the transition in SN2007bi occurred somewhere between 134 and 367d after peak (all in respective rest frames).

We treat the magnetar input as remaining fully trapped for the 200 post-peak days of light curve data. Models predict[63] that most of the magnetar emission is initially transformed to kinetic energy of relativistic particles; the opacity to these is much higher than the optical opacity, and this wind will remain fully trapped at the base of the ejecta for a long time. However, much of the wind energy is converted to X-rays and gamma rays at the interface between the wind and the ejecta, so opacity at these wavelengths becomes important. Calculations of the emission and reabsorption of this radiation is hampered by several uncertain physical processes operating at the interface, and how partitioning between magnetic, thermal and non-thermal electron and ion pools occur[63]. For a 3 ms pulsar (with a magnetic field of $10^{13}$ G) in 5 $M_{\odot}$ of hydrogen- and helium-dominated ejecta, gamma rays start to escape at a significant rate after ~100 d (ref. 63). For PTF12dam, we expect a longer timescale, as the higher ejecta mass (15 $M_{\odot}$ rather than 5 $M_{\odot}$) and a greater opacity (metal- rather than hydrogen-dominated) both serve to increase gamma ray trapping. Thus, our assumption of full trapping over the observed period is a reasonable one.

### 5.5 Temperature evolution

Spectral models[13] show that one of the key observables to distinguish between magnetar-powered super-luminous supernovae and PISNe is the colour of the spectra: the extremely massive progenitors of PISNe result in low energy-to-ejecta-mass ratios and therefore their spectra should be much cooler. We estimated effective temperatures for PTF12dam and SN2007bi using two methods. We fitted blackbody curves to the optical photometric flux, and then to the continuum in the spectra. The two methods gave similar temperature estimates. Our magnetar light curve model also provides the photospheric temperature evolution. The radius of the ejecta is derived from the input kinetic energy and elapsed time; the effective temperature can then be estimated from the luminosity and radius using the Stefan-Boltzmann law.

We calculate an effective temperature for the PISN models[7] by fitting a blackbody curve to synthetic photometry derived from these model spectra. The results are shown in Extended Data Fig. 4. We can see that the magnetar model better matches the observed evolution: with high early temperatures followed by a steep decline before flattening, though our observed rise seems to be slower than the simple model predicts. We note, however, that the early temperatures are not so well constrained, as we have only photometry and no spectra at these epochs. The PISN models show a relatively constant temperature phase of ~100d before declining just after maximum light, as expected from the increase in IGE line blanketing, and do not reach temperatures above $10^4$ K, in contrast to our observations.

## 6 Do PISNe exist?

### 6.1 PISN rate within $z < 0.6$

Our Monte-Carlo simulation[25] generates a random array of redshifts (within the range $0 < z < 1$) and explosion epochs within the survey year for 50000 objects based on PISN models[7], and computes observer frame light curves including $k$-corrections, time dilation and average extinction. The rate of occurrence as a function of redshift is computed from the change in volume and cosmic star-formation history, assuming that a fixed fraction (0.007) of the star formation leads to core-collapse, and that the PISN rate is itself a fixed fraction of the core-collapse rate. The models are then subjected to a simulated survey with the depth and cadence of the PS1 Medium Deep Survey in order to calculate the number we should expect to see.

As a sanity check, we also carry out a rough manual calculation of the approximate rate limit we would expect to recover. The PS1 Medium Deep survey fields cover 70 square degrees[23], which corresponds to a volume within redshift $z < 0.6$ of 0.07 Gpc$^3$. The brightest models have absolute peak magnitudes in the NUV of $M_U \sim -22$ (AB magnitude; refs 12,24), giving apparent peak magnitudes $r_{P1}$, $i_{P1} \lesssim 20$-21. The typical PS1 nightly detection limit in these filters is 23.5 (refs 21, 23, 24), which would allow them to be detected 2-3 magnitudes before and after maximum light (130-200d in observer frame). The observing window for each Medium Deep field during a single year is 150d. We assume that the survey is sensitive to about 50% of all the $z < 0.6$ PISNe reaching these magnitudes at maximum light during this window. They would be readily identifiable by their high luminosity and slow rise and decline over the season, but we may miss the detection of a peak in around 50% (such events would have incomplete lightcurves). In 3 years of the Medium Deep Survey, we have detected no supernova-like transients with these peak magnitudes exhibiting a PISN-like rise time (within $z < 0.6$), and only PS1-11ap has shown a slow decline (e.g. refs 2, 24, 64). We thus conclude that the super-luminous PISN rate must be less than 10 Gpc$^{-3}$ yr$^{-1}$, or, using the core-collapse SN rate at $0.5 < z < 0.9$, (ref. 26; $4\times10^{-4}$ SNe Mpc$^{-3}$ yr$^{-1}$), this corresponds to less than $\sim10^{-5}$ of the core collapse rate, in agreement with the results of our simulation. These bright PISN candidates thus appear to be a factor of a few (perhaps up to 10) less common than the general population of SLSNe of type I and type Ic[1,12].

### 6.2 PISN candidates at higher redshift

Two SLSN, at redshifts 2.05 and 3.90, were recently presented[4], and suggested to be possible pair instability supernovae. These objects display rise times similar to PTF12dam, though not so well constrained, and are shown to fit PISN model light curves[7] quite well (the same models that PTF12dam clearly does not match; see Figs 1 and 4). This apparent contradiction results from their high redshifts. The observed optical photometry actually probes restframe UV. The PISN models quickly fade in the UV relative to the optical, due to line blocking[7,8]. Integrating the SEDs of these models between 1500 and 2500 Å, the approximate wavelength range sampled by these observations[4], we confirm the fit: the resultant light curves do indeed reach peak in ~50 days, before fading to negligible brightness in a further ~150 days. Thus, we cannot exclude the possibility that these high-redshift SLSNe are the first observed examples of PISNe. However, the lack of spectra and restframe optical data preclude a firm classification.

PISNe were originally expected only at high redshift, as the required massive cores are difficult to form except at low metallicities. While we still expect very massive stars and PISNe to be more common in the early Universe, it should be noted that recent simulations[65] show that stars of initial mass 100-290 $M_\odot$ may end their lives in hydrogen-free PISNe at SMC metallicity.

## References


32. Gezari, S. *et al.* An ultraviolet-optical flare from the tidal disruption of a helium-rich stellar core. *Nature* **485**, 217-220 (2012).

33. Tonry J. L. *et al*. The Pan-STARRS1 photometric system. *Astrophys. J.* **750**, 99 (2012).

34. Magnier, E., Kaiser, N. & Chambers, K. C. The Pan-STARRS PS1 Image Processing Pipeline. *AMOS Conference Proceedings,* Sept. 10-14, 455-461, (2006).

35. Magnier, E., Liu, M., Monet, D. G. & Chambers, K. C. The extended solar neighborhood: precision astrometry from the Pan-STARRS 1 3-pi Survey, A Giant Step: from Milli- to Micro-arcsecond Astrometry. *Proceedings IAU Symposium*, **248**, 553-559, (2008).

36. Poole, T. S. *et al*. Photometric calibration of the Swift ultraviolet/optical telescope. *Mon. Not. R. Astron. Soc.* **383**, 627-645 (2007).

37. Neill, J. D. *et al*. The extreme hosts of extreme supernovae. *Astrophys. J.* **727**, 15 (2011).

38. Ahn, C. P. *et al*. The ninth data release of the Sloan Digital Sky Survey: first spectroscopic data from the SDSS-III Baryon Oscillation Spectroscopic Survey. *Astrophys. J. Suppl. Ser.* **203,** 21 (2012).

39. Alard, C. & Lupton, R. H. A method for optimal image subtraction. *Astrophys. J.* **503**, 325-331 (1998).

40. Patat, F. PhD thesis, Univ. Padova (1996).

41. Chilingarian, I., Melchior, A.-L. & Zolotukhin, I. Analytical approximations of *K*-corrections in optical and near-infrared bands. *Mon. Not. R. Astron. Soc.* **405**, 1409-1420 (2010).

42. Chilingarian, I. & Zolotukhin, I. A universal ultraviolet-optical colour-colour-magnitude relation of galaxies. *Mon. Not. R. Astron. Soc.* **419**, 1727-1739 (2012).

43. Rest, A. *et al*. Testing LMC microlensing scenarios: the discrimination power of the SuperMACHO microlensing survey. *Astrophys. J.* **634**, 1103-1115 (2008).

44. Jordi, K., Grebel, E. K. & Ammon, K. Empirical color transformations between SDSS photometry and other photometric systems. *Astron. & Astrophys.* **460**, 339-347 (2006).

45. van Dokkum, P. G. Cosmic-ray rejection by Laplacian edge detection. *Proc. Astron. Soc. Pacific.* **113**, 1420-1427 (2001).

46. Osterbrock, D. E. Astrophysics of gaseous nebulae and active galactic nuclei. *Mill Valley, CA: University Science Books* (1989).

47. Pei, Y. Interstellar dust from the Milky Way to the Magellanic Clouds. *Astrophys. J.* **395**, 130-139 (1992).

48. Schlegel, D. J., Finkbeiner, D. P. & Davis, M. Maps of dust infrared emission for use in estimation of reddening and Cosmic Microwave Background radiation foregrounds. *Astrophys. J.* **500**, 525-553 (1998).

49. Leitherer, C. *et al*. Starburst99: Synthesis models for galaxies with active star formation. *Astrophys. J. Suppl. Ser.* **123**, 3-40 (1999).

50. Fisher, A., Branch, D., Nugent, P. & Baron, E. Evidence for a high-velocity carbon-rich layer in the type Ia SN 1990N. *Astrophys. J. Lett.* **481**, L89-L92 (1998).

51. Branch, D. *et al*. Direct analysis of spectra of type Ib supernovae. *Astrophys. J.* **566**, 1005-1017 (2002).

52. Lodders, K. Solar system abundances and condensation temperatures of the elements. *Astrophys. J.* **591**(2), 1220-1247 (2008).

53. Asplund, M., Grevesse, N., Sauval, A. J. & Scott, P. The chemical composition of the Sun. *Annu. Rev. Astron. Astrophys.* **47**, 481-522 (2009).

54. Lunnan, R. *et al.* PS1-10bzj: A Fast, Hydrogen-Poor Superluminous Supernova in a Metal Poor Host Galaxy. *Submitted to Astrophys. J.* Preprint at <http://arxiv.org/abs/1303.1531> (2013).

55. Joggerst, C. C., & Whalen, D. J. The Early Evolution of Primordial Pair-instability Supernovae. *Astrophys. J.* **728**, 129 (2011).

56. Piro, A. L. & Nakar, E. Constraints on Shallow 56Ni from the Early Lightcurves of Type Ia Supernovae. *Submitted to Astrophys. J.* Preprint at <http://arxiv.org/abs/1211.6438> (2012).

57. Dessart, L., Hillier, D. J., Li, C., & Woosley, S. On the nature of supernovae Ib and Ic. *Monthly Notices of the Royal Astronomical Society*, **424**(3), 2139-2159 (2012).

58. Bersten, M. C. *et* al. The Type IIb Supernova 2011dh from a Supergiant Progenitor. *Astrophys. J.* **757**, 31 (2012).

59. Woosley, S. E., Blinnikov, S., & Heger, A. Pulsational pair instability as an explanation for the most luminous supernovae. *Nature*, **450**(7168), 390-392 (2007).

60. Chatzopoulos, E. & Wheeler, J. C. Effects of Rotation on the Minimum Mass of Primordial Progenitors of Pair-instability Supernovae. *Astrophys. J.* **748**, 42 (2012).

61. Ostriker, J. P., & Gunn, J. E. Do pulsars make supernovae? *Astrophys. J.* **164**, L95-L104 (1971).

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

63. Kotera, K., Phinney, E. S. & Olinto, A. V. Signatures of pulsars in the light curves of newly formed supernova remnants. *Mon. Not. R. Astron. Soc.* (accepted). Preprint at <http://arxiv.org/abs/1304.5326> (2013).

64. Chornock, R. *et al*. PS1-10afx at z=1.388: Pan-STARRS1 discovery of a new type of super-luminous supernova. *Astrophys. J. Lett.* (in press). <http://arxiv.org/abs/1302.0009> (2013).

65. Yusof, N. *et al*. Evolution and fate of very massive stars. *Mon. Not. R. Astron. Soc.* (accepted). Preprint at <http://arxiv.org/abs/1305.2099> (2013).