Nearby supernova rates from the Lick Observatory Supernova Search – IV. A recovery method for the delay-time distribution

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Abstract
Recovery of the supernova (SN) delay-time distribution (DTD) – the SN rate versus time that would follow a hypothetical brief burst of star formation – can shed light on SN progenitors and physics, as well as on the time-scales of chemical enrichment. Previous attempts to reconstruct the DTD have been based either on comparison of mean SN rates versus redshift to cosmic star-formation history (SFH), or on the comparison of SN rates among galaxies with different mean ages. Here, we present an approach to recover the SN DTD that avoids the averaging and loss of information of other schemes. We compare the SFHs of individual galaxies to the numbers of SNe discovered by a survey in each galaxy (generally zero, sometimes one SN, rarely a few). We apply the method to a subsample of 3505 galaxies, hosting 82 type-Ia SNe (SNe Ia) and 119 core-collapse supernovae (CC SNe), from the Lick Observatory Supernova Search (LOSS), that have SFHs reconstructed from Sloan Digital Sky Survey (SDSS) spectra. We find a $>2\sigma$ SN Ia DTD signal in our shortest-delay, ‘prompt’ bin at $<420$ Myr. We identify and study a systematic error, due to the limited aperture of the SDSS spectroscopic fibres, that causes some of the prompt signal to leak to the later bins of the DTD. After accounting for this systematic error, we demonstrate that a prompt SN Ia contribution is required by the data at the $>99$ per cent confidence level. We further find a $4\sigma$ indication of SNe Ia that are ‘delayed’ by $>2.4$ Gyr. Thus, the data support the existence of both prompt and delayed SNe Ia. We measure the time integral over the SN DTD. For CC SNe we find a total yield of $0.010 \pm 0.002$ SNe per $M_\odot$ formed, in excellent agreement with expectations, if all stars more massive than $8 M_\odot$ lead to visible SN explosions. This argues against scenarios in which the minimum mass for core-collapse SNe is $\gtrsim 10 M_\odot$, or in which a significant fraction of massive stars collapse without an accompanying explosion. For SNe Ia, the time-integrated yield is $0.0023 \pm 0.0006$ SNe per $M_\odot$ formed, most of them with delays $<2.4$ Gyr. Finally, we show the robust performance of the method on simulated samples, and demonstrate that its application to already existing SN samples, such as the full LOSS sample, but with complete and unbiased SFH estimates for the survey galaxies, could provide an accurate and detailed measurement of the SN Ia DTD.

Key words: methods: data analysis – supernovae: general – galaxies: star formation.

1 Introduction
Supernovae (SNe) figure prominently in many fields, whether in their roles as calibratable candles for cosmology, as the major sources of intermediate-mass and heavy elements, as heaters of the interstellar medium, as accelerators of cosmic rays, and more.
Physically, they are separated mainly into core-collapse SNe (CC SNe), which occur when the iron core of a massive star collapses to form a neutron star or a black hole, and type-Ia SNe (SNe Ia), which explode when a degenerate carbon–oxygen stellar core, probably a white dwarf (WD), approaches (or, rarely, exceeds) the Chandrasekhar mass, igniting the carbon and triggering a thermonuclear runaway. The two paths most often hypothesized for this mass growth in SNe Ia are the single-degenerate (SD) scenario, whereby a WD in a semidetached binary accretes matter from a main-sequence or evolved normal companion star (Whelan & Iben 1973), and the double-degenerate (DD) scenario, in which two WDs merge (Iben & Tutukov 1984; Webbink 1984). Additional, less conventional, paths have also been considered (e.g. Tout 2005; Maoz & Mannucci 2008; Raskin et al. 2009a; Rosswog et al. 2009).

For CC SNe, while many questions remain regarding the progenitors and the physics of particular subtypes, massive progenitor stars have by now been identified in pre-explosion images in a growing number of cases (see Smartt 2009, for a recent summary). This contrasts with the situation for SNe Ia, where only one or two very ambiguous progenitor identifications exist (Roelofs et al. 2008; Voss & Nelemans 2008; González Hernández et al. 2009; Kerzendorf et al. 2009). We thus do not quite know what is exploding in an SN Ia, an unsatisfactory situation given the ubiquity and importance of these events.

Driven by these problems, a major objective of SN studies has been the recovery of the SN delay-time distribution (DTD). The DTD is the SN rate as a function of time that would be observed following a δ-function burst of star formation. (In other contexts, the DTD would be called the delay function, the transfer function or the Green’s function.) Knowledge of the DTD would be useful for understanding the route along which cosmic metal enrichment and energy input by SNe proceed, but no less important, for obtaining clues about the SN progenitor systems. Different progenitor stars, binary systems and binary-evolution scenarios predict different DTDs.

The lifetime of a star with the minimum initial mass that is thought to lead to a CC SN explosion, \( \gtrsim 8 \, M_\odot \), sets a time division between CC SNe and SNe Ia in the DTD, at \( \sim 40 \) Myr. The precise mass border between core collapse and WD formation also depends on metallicity. Furthermore, initially lower-mass stars in tight binaries can become ‘rejuvenated’ by mass transfer and explode as CC SNe somewhat later than this.

For SNe Ia, the situation is much less clear. In both of the currently popular progenitor scenarios, SD and DD, calculations of the DTD depend on a series of assumptions regarding initial conditions (initial mass function, binary fraction, mass-ratio distribution, separation distribution), and complex physics (mass-loss, mass transfer, common-envelope evolution, accretion) that is sometimes computationally intractable except in the most rudimentary, parametrized forms (e.g. Yungelson & Livio 2000; Hurley, Tout & Pols 2002; Han & Podsiadlowski 2004; Nelemans et al. 2005; Bogomazov & Tutukov 2009; Ruiter, Belczynski & Fryer 2009; Meng & Yang 2010; Mennekens et al. 2010). In principle, observational estimates of the DTD could rule out particular theoretical models. Given the theoretical uncertainties, it is probably more realistic that the observations simply provide a ground truth that successful models will need to reproduce.

Previous attempts to recover the DTD have used SN rates measured in surveys of galaxies at different redshifts (i.e. different cosmic times), compared to cosmic star-formation histories (SFHs). This has been attempted for field surveys (Gal-Yam & Maoz 2004; Strolger et al. 2004; Poznanski et al. 2007; Dahlen, Strolger & Riess 2008) and galaxy-cluster surveys (Maoz & Gal-Yam 2004; Maoz et al., in preparation). An alternative approach has been to look at the SN rates per unit stellar mass in galaxies of particular types (star formation, quiescent, etc.), and to attempt to assign to each type a ‘formation age’, or some generic, simple, SFH (e.g. Mannucci et al. 2005; Mannucci, Della Valle & Panagia 2006; Sullivan et al. 2006; Pritchet, Howell & Sullivan 2008; Totani et al. 2008; Raskin et al. 2009b).

Results have been controversial and often contradictory. For example, Dahlen et al. (2004, 2008) have argued for an SN Ia DTD that is peaked at a delay of \( \sim 5 \) Gyr, with few SNe Ia at delays that are much shorter or longer. In contrast, Mannucci et al. (2005, 2006), Scannapieco & Bildsten (2005) and Sullivan et al. (2006) have found evidence for the existence of comparable numbers of both ‘prompt’ and ‘delayed’ SNe Ia: the former explode within \( \sim 500 \) Myr (or perhaps even within 100 Myr) of star formation, while the latter may have delays as long as 10 Gyr. The SN Ia rate has been described as the sum of two components, one proportional to stellar mass and the other proportional to the CC SN rate (Mannucci et al. 2005). In the similar ‘\( \Lambda + B \)’ parametrization introduced by Scannapieco & Bildsten (2005), the prompt-component rate is proportional to the star formation rate (SFR). The two SN Ia components need not represent two distinct physical populations. Instead, they could constitute the SNe included in two coarsely sampled time bins of what is in reality a continuous DTD. For example, Pritchet et al. (2008) have argued that a \( t^{-0.5 \pm 0.2} \) power-law DTD provides an improved fit, compared to the \( A + B \) model, to the dependence of SN rates on galaxy SFR, as measured in the Supernova Legacy Survey. We also note that a truly bimodal DTD, if it exists, could arise either from two different coexisting progenitor paths (e.g. DD and SD), or from bimodality in some secondary parameter, such as the binary separation distribution, of a single explosion mechanism. Regardless, there is currently an unclear picture on the form of the DTD, even at the most coarse resolution level.

A shortcoming of the approaches described above for recovering the DTD is that they involve averaging over the galaxy population (i.e. all the SNe are assumed to come from the entire host population considered), or averaging over time (i.e. the detailed SFH of a galaxy is represented by a single ‘age’ or simplified history for all galaxies of a certain type). Consequently, these approaches involve loss of information, and potential systematic errors (e.g. due to unrepresentative simplified histories).

In this paper, the fourth in a series analysing SN rates from the Lick Observatory SN Search (LOSS), we introduce a new approach to recover the DTD, by posing DTD inversion as a discretized linear problem. In this process, we use all of the available information on the SFHs of individual galaxies, rather than averaging rates over many types of galaxies in some redshift interval, or assigning a mean star-formation-weighted age to each galaxy. In Section 2 below, we present the method, and in Section 3, we apply the method to a subsample of LOSS galaxies and their SNe. We test the method’s performance on simulated SN surveys in Section 4. Our results are summarized and we discuss some future prospects in Section 5.

We note that diverse delay ranges have been associated in the literature with the term ‘prompt’ – e.g. \(< 100 \) Myr (Mannucci et al. 2006); \(< 180 \) Myr (Aubourg et al. 2008); 200–500 Myr (Raskin et al. 2009b); \(< 350, \sim 700 \) Myr, or <1 Gyr (Scannapieco & Bildsten 2005). The term therefore generally labels delays of roughly a few hundred million years. In our analysis of the Lick Observatory SN Search herein, we will define prompt SNe Ia as those with delays <420 Myr.
2 RECONSTRUCTION OF THE SN DTD – METHOD

Consider a sample of $N$ galaxies. The SN rate in the $i$th galaxy observed at cosmic time $t$ is given by the convolution

$$r_i(t) = \int_0^t S_i(t - \tau) \Psi(\tau) \, d\tau,$$

(1)

where $S_i(t)$ is the SFR versus cosmic time of the $i$th galaxy (stellar mass formed per unit time), $\Psi(\tau)$ is the DTD (SNe per unit time per stellar mass formed), and the integration is from the Big Bang ($t = 0$) to the time of observation. For the purpose of this paper, we assume that the DTD is a universal function: it is the same in all galaxies, independent of environment, metallicity and cosmic time – a simplifying assumption that may be invalid at some level. For example, a dependence of SN delay time on metallicity is expected in some models (e.g. Kobayashi, Tsujimoto & Nomoto 2000). Similarly, variations in the initial mass function (IMF) with cosmic times or environment would also lead to a variable DTD, but we will again ignore this possibility in the present context.

In contrast to the averaging approaches followed in the past (see Section 1), we will attempt to recover the DTD by directly inverting a linear, discretized version of equation (1), where the detailed history of every individual galaxy or galaxy subunit is taken into account. Suppose the SFHs of the $i = 1, 2, \ldots, N$ galaxies monitored as part of an SN survey are known (e.g. based on reconstruction of their stellar populations), with a temporal resolution that permits binning the stellar mass formed in each galaxy into $j = 1, 2, \ldots, K$ discrete time bins, where increasing $j$ corresponds to increasing lookback time. The time bins need not necessarily be equal, and generally will not be, since the temporal resolution of the SFH reconstruction degrades with increasing lookback time. For the $i$th galaxy in the survey, the stellar mass formed in the $j$th time bin is $m_{ij}$. The mean of the DTD over the $j$th bin (corresponding to a delay range equal to the lookback-time range of the $j$th bin in the SFH) is $\psi_j$. Then the integration in equation (1) can be approximated as a sum,

$$r_i \approx \sum_{j=1}^K m_{ij} \psi_j,$$

(2)

where $r_i$, the SN rate in a given galaxy, is measured at a particular cosmic time (e.g. corresponding to the redshift of the particular SN survey). Given a survey of $N$ galaxies, each with an observed SN rate, $r_i$, and a known binned SFH, $m_{ij}$, one could, in principle, algebraically invert this set of linear equations and recover the best-fitting parameters describing the binned DTD: $\Psi = (\psi_1, \psi_2, \ldots, \psi_K)$.

In practice, on human time-scales SNe in a given galaxy are rare events ($r_i < 1 \text{ yr}^{-1}$). Supernova surveys therefore monitor many galaxies, and record the number of SNe discovered in every galaxy. For a given model DTD, $\Psi$, the $i$th galaxy will have an expected number of SNe:

$$\lambda_i = r_i t_i,$$

(3)

where $t_i$ is the effective visibility time (often called the ‘control time’) during which an SN of a particular type would have been visible (given the actual on-target monitoring time, the distance to the galaxy, the flux limits of the survey and the detection efficiency). Since $\lambda_i \ll 1$, the number of SNe observed in the $i$th galaxy, $n_i$, obeys a Poisson probability distribution with expectation value $\lambda_i$,

$$P(n_i|\lambda_i) = (e^{-\lambda_i} \lambda_i^{n_i})/n_i!,$$

(4)

where $n_i$ is 0 for most of the galaxies, 1 for some of the galaxies and more than 1 for very few galaxies.

2.1 Maximum-likelihood DTD recovery

We now introduce a non-parametric, maximum-likelihood method to recover the DTD and its uncertainties. Considering a set of model DTDs, the likelihood of a particular DTD, given the set of measurements $n_1, n_2, \ldots, n_N$, is

$$L = \prod_{i=1}^N P(n_i|\lambda_i).$$

(5)

More conveniently, the log of the likelihood is

$$\ln L = \sum_{i=1}^N \ln P(n_i|\lambda_i) = -N \bar{\lambda}_i + \sum_{i=1}^N \ln \left(\frac{\lambda_i^{n_i}}{n_i!}\right),$$

(6)

where obviously only galaxies hosting SNe contribute to the second term. The best-fitting model can be found by scanning the parameter space of the vector $\Psi$ for the value that maximizes the log-likelihood. This procedure naturally allows restricting the DTD to have only positive values, as physically required (a negative SN rate is meaningless).

The covariance matrix $C_{ij}$ of the uncertainties in the best-fitting parameters can be found (e.g. Press et al. 1992) by calculating the curvature matrix,

$$\sigma_{ij} = \frac{1}{2} \frac{\partial^2 \ln L}{\partial \psi_j \partial \psi_i} = \sum_{i=1}^N \frac{\partial \ln P(n_i|\lambda_i)}{\partial \psi_j} \frac{\partial \ln P(n_i|\lambda_i)}{\partial \psi_i} = \sum_{i=1}^N I_{ij}^N (\lambda_i/n_i - 1)^2 m_{ij} m_{ik},$$

(7)

and inverting it,

$$[C] = [\sigma]^{-1}.$$

(8)

Because the values of the DTD are constrained to be positive, if the maximum-likelihood value of a DTD component, $\psi_j$, is close to zero, the square root of its variance, $\sqrt{C_{jj}}$, will not represent well its 1σ uncertainty range. An alternative, more reliable, procedure is to perform a Monte Carlo simulation in which many mock surveys are produced, each having the same galaxies, SFHs, and visibility times as the real survey, and having expectation values $\lambda_i$ based on the best-fitting DTD, but with the number of SNe in every galaxy, $n_i$, drawn from a Poisson distribution according to $\lambda_i$. The maximum-likelihood DTD, $\Psi$, is found for every realization. From the distribution of the values of every component, $\psi_j$, over all the realizations, one can estimate the range encompassing, say, ±34 per cent of the cases.

The above approach for recovering the DTD has several advantages over previous methods. First, all of the known information in the survey is included in the analysis in a statistically rigorous way, including the fact that many (usually most) of the galaxies did not host any SNe. Furthermore, the calculation is easily generalized to cases where the galaxies are not all at the same distances (e.g. combinations of surveys done at different redshifts) – one simply needs to use the appropriate SFH bins and visibility times for every galaxy. In fact, assuming that the DTD is a universal function, it is straightforward to include in a single analysis the data from completely disparate SN surveys. For example, one could combine the results of normal SN surveys with unconventional SN ‘surveys’, in which the SN rate is measured based on SN remnants in small subunits of a few nearby galaxies (Maoz & Badenes 2010).
The number and resolution of the time bins used in the analysis will naturally depend on the quality of the data. Larger numbers of observed SNe, \( N_\text{obs} \), as well as better data on the parent stellar populations (integrated colours and/or spectra), will permit a larger number of independent SFH and DTD time bins, and will thus improve the time resolution of the recovered DTD. We quantify this in Section 4 below.

## 3 APPLICATION TO THE LOSS–SDSS SAMPLE

We now apply our method to the SN survey data obtained by considering all LOSS galaxies with SFHs based on spectroscopy from the Sloan Digital Sky Survey (SDSS). First, we summarize briefly the essentials of each of these surveys and of the sample resulting from their intersection.

### 3.1 The Lick Observatory Supernova Search

The LOSS is an ongoing survey for SNe in a sample of \( \sim 15,000 \) nearby (redshift \( z < 0.05 \)) galaxies, conducted with the Katzman Automatic Imaging Telescope (KAIT) at Lick Observatory (Li et al. 2000; Filippenko et al. 2001, and in preparation). KAIT is a fully robotic telescope whose control system checks the weather and performs observations with a dedicated CCD camera without human intervention. The data are automatically processed through an image-subtraction pipeline, and candidate SNe are flagged and visually inspected. The promising SN candidates are re-observed and the confirmed SNe are reported to the Central Bureau of Astronomical Telegrams.

A series of papers (Leaman et al. 2011; Li et al. 2011a,b; Filippenko et al., in preparation) present the details and first results on the rates of SNe in the local Universe based on LOSS, using a sample of 1036 SNe discovered in more than 2 million observations between March 1998 through the end of 2008. This is the largest and most homogeneous set of SN statistics ever assembled for the determination of local SN rates. Filippenko et al. (in preparation) describe the instrumentation and the details of the SN survey. Leaman et al. (2011, Paper I in this series) present the control-time calculation for the galaxies in the sample, for SNe of different types and their luminosity functions (LFs), and details of the galaxy and SN samples used in the rate calculations. Monte Carlo simulations are used to determine the limiting magnitude and the SN detection efficiency in each LOSS search image.

Li et al. (2011a, Paper II in the series) discuss the observed SN LF using a volume-limited sample (\( D < 60 \) Mpc for CC SNe and \( D < 80 \) Mpc for SNe Ia) of 177 SNe, each with detailed spectroscopic classification and peak magnitude from dedicated photometric follow-up images or unfiltered survey images. These observed LFs solve two issues that have plagued historical SN-rate calculations – the intrinsic luminosity distribution of SNe and the host galaxy extinction. Finally, Li et al. (2011b, Paper III) combine all of the above ingredients, obtaining control times for different types of SNe and for each galaxy, based on its monitoring history, the observed LFs, and the limiting magnitudes and detection efficiencies of the search images. These are used to derive SN rates for SNe of different types, as a function of various galaxy properties.

### 3.2 VESPA star formation histories of SDSS galaxies

The SDSS (York et al. 2000) is a survey of \( \sim 10^4 \mathrm{deg}^2 \) of the North Galactic cap, consisting of imaging in five photometric bands (\( u, g, r, i, z \)), and 3-arcsec aperture fibre spectroscopy of \( \sim 10^6 \) targets, mostly galaxies, with \( r \lesssim 18 \) mag. Tojeiro et al. (2009) performed spectral synthesis modelling of all galaxy spectra in the SDSS using their VESPA code (Tojeiro et al. 2007). VESPA uses all of the available absorption features, as well as the shape of the continuum, to deconvolve the observed spectra and obtain an estimate of the SFH.

In order to recover the maximum amount of reliable information, the number of time bins used is variable, and depends on the quality of the data on each galaxy. At the highest resolution, VESPA uses 16 age bins, logarithmically spaced between 0.002 Gyr and \( t_0 = 13.7 \) Gyr, the age of the Universe. When data do not have sufficiently high signal-to-noise ratio for a fully resolved reconstruction, pairs of adjacent time bins are averaged. This process may be repeated down to the last two remaining bins. In the end, the SFH of every galaxy is computed using a different set of time bins.

VESPA masses are calculated assuming a Kroupa (2007) IMF; all of our results will therefore include this assumption implicitly. Bell et al. (2003) have shown that the Kroupa IMF gives a similar total stellar mass to that of a ‘diet Salpeter’ IMF, obtained by multiplying by 0.7 the total mass of the original Salpeter (1955) IMF, to account for the reduced number of low-mass stars. Thus, our results will be comparable to other SN rate studies, such as Mannucci et al. (2005, 2006), that have assumed the diet Salpeter IMF.

### 3.3 The LOSS–SDSS–VESPA sample

With the kind assistance of R. Tojeiro, we have derived VESPA SFHs for all of the LOSS galaxies that have SDSS spectroscopy. Our main sample of LOSS galaxies with VESPA SFHs consists of 3505 galaxies that hosted 201 SNe, among them 82 SNe Ia, 93 SNe II and 26 SNe Ibc (see Filippenko 1997 for a review of SN types; here we classify SNe Ibc and Ic as ‘Ibc’). An alternative sample, using a different VESPA dust model (see below), has slightly different numbers: 3508 galaxies hosting 202 SNe, among them 81 SNe Ia, 94 SNe II and 27 SNe Ibc. These numbers of SNe are consistent with those expected based on the fraction of the total LOSS visibility time that is in the VESPA galaxies. Other than the increase in Poisson errors due to the smaller number of SNe, the limitation of the calculation to VESPA galaxies should have no effect on our DTD reconstruction.

For the majority of these galaxies, it is practical to separate the SFHs into no more than four time bins: 0–70 Myr, 70–420 Myr, 420 Myr–2.4 Gyr and \( >2.4 \) Gyr. These correspond to the bins labelled 24, 25, 26 and 27 in Tojeiro et al. (2009). However, for each galaxy, the distribution of mass between the first two bins depends strongly on the particular dust model that is assumed, as well as on the spectral synthesis code that is used – Bruzual & Charlot (2003) or Maraston (2005) (R. Tojeiro, private communication). In fact, for some models, only a small fraction of the galaxies have any mass formed in the second time bin, a problem that persists at some level in other models as well. Due to this degeneracy, we have chosen to combine the first two time bins into a single bin, of 0–420 Myr. As the choice of stellar population model parameters affects the results in other time bins as well, we have used two alternative VESPA SFH reconstructions. One assumes a single dust component for each galaxy, while the other allows separate dust components for the young and the old stellar populations, effectively introducing an additional free parameter to the modelling (see Tojeiro et al. 2009 for details). Both reconstructions use the Maraston (2005) spectral synthesis models. Using these different SFH reconstructions gives some idea of the systematic errors in the DTD reconstruction arising from the uncertainty in the SFH (until now, we have treated the SFH values, \( m_{\|} \), as error-free independent variables).
3.4 The core-collapse SN DTD

We begin by deriving the DTD of the CC SNe in the LOSS–SDSS sample. Core-collapse SNe explode within $\lesssim 40$ Myr of star formation, and therefore their DTD should have zero amplitude on time-scales much longer than this. This can provide a first test of our sample and of the DTD recovery method.

3.4.1 Full-sample core-collapse SN DTD

Fig. 1 shows the reconstructed CC SN DTD, and its uncertainties from the Monte Carlo simulations described above, for the full sample of 3505 LOSS galaxies with VESPA SFHs using a single dust parameter. The SNe in this sample consist of 93 SNe II and 26 SNe Ib and Ic. Since SNe II and SNe Ibc have different visibility times, we have derived the DTD for each subsample separately, added the resulting DTD amplitudes in the corresponding bins and added the uncertainties in quadrature. Like the SFHs, the DTD in Fig. 1 has three time bins, corresponding to <420 Myr (‘prompt’ SNe), 420 Myr–2.4 Gyr (‘medium delay’ SNe) and $>2.4$ Gyr (‘delayed’ SNe). The best-fitting values and the uncertainties for these DTDs, as well as additional ones discussed below, are listed in Table 1.

The prompt, <420-Myr bin, in which all CC SNe should reside, indeed has a clear, $>7\sigma$ signal. However, there is also a strong 3.5$\sigma$-level DTD signal in the 420 Myr–2.4 Gyr bin, where no CC explosions are expected. As we will demonstrate and quantify in Section 3.4.2 below, this result is due to the following systematic error. The SDSS spectra of many of the LOSS galaxies (which are relatively nearby, and hence large in angle) are dominated by the old populations at the centre of each galaxy, due to the limited 3 arcsec aperture size of the SDSS fibres. However, many of the CC SNe explode in the outer regions, where there is ongoing star formation that is invisible to the SDSS spectroscopy. As a result, our DTD solution mistakenly associates these CC SNe with an old population, and hence a large delay. We also note that the integrals over these two bins of the best-fitting DTD are comparable: $\Psi_1$ for the first/second bin, the smaller SN numbers in the reduced sample lead to larger statistical errors. We have experimented with additional sample culling methods. For example, the SDSS data base gives, for each galaxy, the magnitude in each photometric band in an aperture of the size of the spectrograph fibre, and various measures of the size of the spectrograph fibre, and various measures of the SDSS data base gives, for each galaxy, the magnitude in each photometric band in an aperture of the size of the spectrograph fibre, and various measures of the size of the spectrograph fibre, and various measures of the size of the spectrograph fibre.
total magnitude of the galaxy. One can thus select to include in the DTD analysis only galaxies with no or weak radial colour gradients. Additional or alternative cuts can be made based on galaxy size, distance or fraction of total light within the fibre aperture (i.e. degree of concentration). We find that, as with the case of the selection (above) according to Hubble type, the more stringent the selection, the lower the leak out of the first bin in the CC SN DTD. At the same time, the lowered sample size increases the statistical errors.

3.5 The SN Ia DTD

Keeping in mind the systematics evidenced in the case of the CC SNe, we now proceed to derive the DTD for the SNe Ia in the sample. Figs 3–5 show the reconstructed SN Ia DTDs, and their uncertainties, for the LOSS–SDSS sample, using the two different VESPA SFH reconstructions. As for the CC SNe, the best-fitting values and uncertainties for these DTDs are listed in Table 1.

3.5.1 Full-sample SN Ia DTD, one-parameter dust model

In the DTD based on the SFHs with a one-parameter dust model, we obtain, in the ‘prompt’ (<420 Myr) bin, a best-fitting value of \(\Psi_1 = 0.0084^{+0.0054}_{-0.0039} \) SNe yr\(^{-1}\) (10\(^{10}\) M\(_\odot\))\(^{-1}\). (In other words, following a \(\delta\)-function starburst that forms a stellar mass of 10\(^{10}\) M\(_\odot\), the mean SN Ia rate in this stellar population over the first 420 Myr will be 0.0084\(^{+0.0054}_{-0.0039}\) SNe yr\(^{-1}\).) This result implies a \(>2\sigma\) detection of a prompt SN Ia component. As before, the uncertainties we quote are the statistical errors, as derived from the most probable ±34 per cent range in Monte Carlo simulations, using the best-fitting values as input. A model with the above best-fitting value of \(\Psi_1\) as input yields a recovered \(\Psi_1\) of 0 in fewer than 3 per cent of the Monte Carlo realizations. Conversely, a model with an input value of \(\Psi_1 = 0\) yields a recovered \(\Psi_1 \geq 0.0084\) (in the same units as before) in <0.2 per cent of the realizations. Models with an input value of \(\Psi_1 \leq 0.0031\) yield a recovered \(\Psi_1 \geq 0.0084\) in <5 per cent of Monte Carlo realizations. Thus \(\Psi_1 = 0.0031\) can be considered a 95 per cent confidence lower limit on the level of a prompt SN Ia component.

As another test of the presence of a prompt SN Ia component, we have forced \(\Psi_1 = 0\) in the DTD reconstruction. Compared to the previous result, the log of the likelihood of the best-fitting model decreases by 3.0. Since 2\(\Delta\ln L = \Delta \chi^2\), this indicates that a prompt

### Table 1. Summary of DTD reconstructions.

| Sample          | \(N_{\text{gal}}\) | \(N_{\text{SN}}\) | \(\Psi_1\) 0.04–0.42 Gyr | \(\Psi_2\) 0.42–2.4 Gyr | \(\Psi_3\) 2.4–14 Gyr | \(N_{\text{SN}}/M\) |
|-----------------|---------------------|-------------------|--------------------------|-------------------------|------------------------|-------------------|
| (1)             | (2)                 | (3)               | (4)                      | (5)                     | (6)                    | (7)               |
| CC SNe          |                     |                   |                          |                         |                        |                   |
| Full CC         | 3505                | 119               | 770 ± 100                | 127 ± 35                | 8.6 ± 8.5              | 0.00585 ± 0.00085 |
| No Sa–Sbc       | 1900                | 50                | 1320 ± 230               | 101 ± 66                | <5.3                   | 0.00750 ± 0.00150 |
| \(D < 100 \text{ Mpc}\) | 1951                | 92                | 1037 ± 146               | 192 ± 62                | <4.3                   | 0.00920 ± 0.00130 |
| \(D > 65 \text{ Mpc}\) | 1951                | 92                | 1430 ± 340               | 223 ± 165               | <13.4                  | 0.01040 ± 0.00360 |
| SNe Ia          |                     |                   |                          |                         |                        |                   |
| Full, 1-dust    | 3505                | 82                | 84\(^{+54}_{-39}\)       | 37\(^{+22}_{-14}\)      | 2.6\(^{+0.8}_{-0.6}\)   | 0.00137 ± 0.00032  |
| Full, 2-dust    | 3508                | 81                | 26\(^{+16}_{-12}\)       | 20\(^{+12}_{-5}\)       | 3.3\(^{+0.8}_{-0.5}\)   | 0.00086 ± 0.00024  |
| No Sa–Sbc       | 1900                | 49                | 136\(^{+110}_{-58}\)     | 55\(^{+40}_{-28}\)      | 3.6\(^{+1.5}_{-0.6}\)   | 0.00200 ± 0.00060  |

Column header explanations:

(1) Sample used to derive DTD. *Full CC*, full core-collapse (types II and Ibc) SN sample with VESPA SFH reconstructions using a single-parameter dust model; *No Sa–Sbc*, sample excluding all galaxies of Hubble type Sa through Sbc, to avoid small-fibre aperture effects; *\(D < 100 \text{ Mpc}\)*, core-collapse SN sample in galaxies within 100 Mpc; *\(D > 65 \text{ Mpc}\)*, core-collapse SN sample in galaxies within 65 Mpc; *Full*, full SN Ia sample, with VESPA SFH reconstructions using a single-parameter dust model; *Full, 1-dust*, full SN Ia sample, with VESPA SFH reconstructions using a two-parameter dust model.

(2) Number of galaxies in sample.

(3) Number of SNe in sample.

(4)–(6) DTD rates and 68 per cent uncertainty ranges, in units of 10\(^{-4}\) SNe yr\(^{-1}\) (10\(^{10}\) M\(_\odot\))\(^{-1}\). Upper limits, where given, correspond to a best fit of 0, and to the 95 per cent confidence limit.

(7) Time-integrated DTD, in units of SNe M\(_\odot\)^\(-1\).
component in the model improves the fit to the data at the 2.5σ level. Thus, this test supports, at the ~99 per cent confidence level, the existence of SNe Ia that explode within 420 Myr after star formation.

Since the uncertainties here are larger than was the case with the CC SN DTD, we can use this case to compare the adequacy of the errors calculated directly using the covariance-matrix formalism to those from the Monte Carlo simulations. From Figs 3–4, we see that the analytic 1σ errors generally match well the errors estimated from the simulations. From these simulations, we also find that the likelihood of the best-fitting model is attained in at least 10 per cent of simulated trials, indicating that the best-fitting model is acceptable in an absolute sense as well.

The mean rate found above in the first bin, Ψ₁, can be translated into an equivalent value of the ‘B’ parameter (Scannapieco & Bildsten 2005), the constant of proportionality between the SFR and the ‘prompt’ SN Ia rate (i.e. B is the number of prompt SNe per unit stellar mass formed). Multiplying Ψ₁ by 420 Myr to integrate over the bin, and dividing by 10^{10} to express the result per solar mass, the best-fitting DTD value in the prompt bin implies B ≈ (3.5 ± 1.7) × 10^{-4} M_{⊙}^{-1} (or B < 8 × 10^{-4} M_{⊙}^{-1} for the 2σ upper limit). This is several times lower than the values of B estimated by studies that compare the SN Ia rate per unit mass and the SFR in blue, vigorously star-forming galaxies (see recent summary and intercomparison in Maoz 2008; observables that are quoted there per unit stellar mass formed need to be divided by 0.7 to convert from the pure Salpeter IMF assumption to the low-mass-truncated or ‘diet’ IMFs considered here – Kroupa (2007) or, equivalently in terms of integrated mass, diet Salpeter (Bell et al. 2003); see Section 3.2). Such studies have usually found values of B = (1 – 3) × 10^{-4} M_{⊙}^{-1} (an exception is the value B = (3.9 ± 0.7) × 10^{-4} M_{⊙}^{-1} found by Sullivan et al. 2006).

As we showed in Section 3.4.2 above, at least part of this discrepancy must be due to the limited 3 arcsec aperture size of the SDSS fibres. Just as our CC SN DTD solution mistakenly associated CC SNe with an old population, and hence a large delay, it will do so for prompt SNe Ia that are associated with star-forming regions in the outer parts of a galaxy, outside the bulge-light-dominated fibre aperture. In fact, the leak should be comparable to the 40 per cent effect we saw for CC SNe. Thus, the true Ψ₁ level in Fig. 3 is likely about double the derived, ‘leaky’ one, and thus coincident, within the uncertainties, with the B-parameter values found by other studies, above. By the same token, our > 2σ significance on the detection of a prompt component is a lower limit.

Another contribution to the difference between the time-integrated Ψ₁ value and published B values may be that the B parameter found from SN rate measurements in galaxies with the highest SFRs are tracing an SN Ia population with an even smaller delay time, of < 100 Myr (Mannucci et al. 2005, 2006; Aubourg et al. 2008). The fact that our first time bin goes up to 420 Myr could then lead to a dilution of Ψ₁, due to its being averaged over the lower rates at these larger delays.

Turning to the later bins in the recovered SN Ia DTD, the intermediate-delay bin of 420 Myr to 2.4 Gyr has a signal of Ψ₂ = 0.0037 ± 0.0022 SNe yr^{-1} (10^{10} M_{⊙}^{-1})^{-1}. Although the uncertainty is still relatively large, there is a ~2.5σ DTD signal above zero in this bin. Naturally, some or all of this signal could be due to the ‘leak’ from the prompt bin, discussed above. Based on the observed 40 per cent leak in the CC SN DTD, ~20 per cent of the Ψ₂ signal could be leaked from Ψ₁.

Finally, the last DTD bin, > 2.4 Gyr, has the clearest signal, Ψ₃ = (2.55^{+0.55}_{-0.60}) × 10^{-4} SNe yr^{-1} (10^{10} M_{⊙}^{-1})^{-1}. At face value, this implies a ~4 σ detection of a population of SNe Ia with large delays. The ‘A’ parameter defined by Scannapieco & Bildsten (2005) was meant to measure the SN Ia rate per unit mass in an old population that has no ongoing star formation. Actually, SN Ia rates are expected to vary significantly among quiescent stellar populations of different ages, and therefore like the B parameter, A will depend on the ages of the stellar populations probed by an SN survey. Indeed, the typical values found for the A parameter have been in the range A ≈ (2 – 10) × 10^{-4} SNe yr^{-1} (10^{10} M_{⊙}^{-1})^{-1} (see compilation in Maoz 2008). However, Ψ₃ is the rate per unit mass formed. The published rates in old populations are per unit of existing stellar mass (i.e. in stars and stellar remnants). The difference is given by the stellar mass returned to the interstellar medium via SN explosions and mass-loss during stellar evolution. The fraction of returned material is an increasing function of time, and

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corresponds to \( \sim 25 \) per cent after 0.1 Gyr and \( \sim 50 \) per cent after 12 Gyr (Bruzual & Charlot 2003). Thus, for comparison to the \( A \) parameter, \( \Psi_1 \) needs to be doubled, giving a rate of \( (5.1^{+1.2}_{-1.0}) \times 10^{-4} \text{SNe yr}^{-1} \) \((10^{10} \msun)^{-1}\), in excellent agreement with other measurements of SN Ia rates in old populations. In principle, some or all of the \( \Psi_1 \) signal could again be the result of a leak from the prompt bin, due to the limited spatial coverage of the SDSS fibres. In practice, the time integral over the \( \Psi_1 \) rate, \( \Psi_1 \Delta t_1 \), is seen to be comparable to \( \Psi_1 \Delta t_1 \), as opposed to the few per cent leak into the \( \Psi_3 \) bin that we found in the CC SN case in Section 3.4.2. This suggests that our \( \Psi_1 \) value is real and largely uncontaminated. Furthermore, examining the time integrals over the best-fitting DTD in each of the bins, and attempting to correct for the leak from bin 1 to bin 2, suggests a relative contribution to the total SN Ia numbers of (prompt:medium:delayed) \( \approx 2:2:1 \). However, this is subject to large statistical and systematic uncertainties.

It has been known for a long time that SNe Ia can occur in early-type galaxies with little or no star formation, and hence our measurement of a significant delayed component is hardly revolutionary. However, an SN Ia in a particular early-type galaxy can always be attributed to some residual low-level star formation combined with a short SN Ia delay time. Our measurement, on the other hand, provides a statistically robust determination of the delayed component, and its level relative to the prompt components, in a population with detailed measured SFHs.

### 3.5.2 Full-sample SN Ia DTD, two-parameter dust model

Using the second VESPA SFH reconstruction that utilizes a two-parameter dust model, the best-fitting DTD values (Fig. 4 and Table 1) for the prompt, medium and delayed components are somewhat different from those obtained with the one-parameter dust model. However, these systematic differences are smaller than the statistical uncertainties of the results quoted above. For larger SN samples with smaller statistical uncertainties, the systematic uncertainties due to SF modelling may, however, become dominant. In what follows, we will use only the VESPA SFHs based on the first, one-parameter dust model.

### 3.5.3 Culled-sample SN Ia DTD

As in Section 3.4.2, we have repeated the DTD derivation for SNe Ia from the subsample of 1900 galaxies that excludes Hubble types Sa to Sbc. This sample hosts 49 SNe Ia. Fig. 5 shows the SN Ia DTD obtained for this culled sample. As was the case for the CC SNe in the culled sample, the prompt-bin amplitude is enhanced compared to the full-sample DTD, and the medium-delay bin rate is lowered. The rate in the third bin, in contrast, is hardly changed compared to Fig. 3, reconfirming the reality of that signal.

### 3.5.4 Comparison to DTD models

It is beyond the scope of this paper to attempt a detailed comparison of our recovered DTD to the many models that have been proposed, and to address the progenitor issue. None the less, we have superimposed in Fig. 5, which is our most reliable SN Ia DTD (in so far as the leakage problems are partly mitigated in it), a selection of DTDs that have appeared in the literature. Some are empirically motivated, in the sense that they were used to relate SN-rate data with star formation measurements, using one of the methods outlined in Section 1. Others are more theoretically motivated, based on a progenitor scenario.

The Scannapieco & Bildsten (2005) ‘\( A + B \)’ model has been discussed several times above. It is not exactly a DTD, but rather a prescription for relating an SN rate to a galaxy of a given current mass and SFR. Nevertheless, we have overplotted this model in Fig. 5, using the median literature values of the \( A \) and \( B \) parameters compiled by Maoz (2008). We have associated the prompt \( B \) component with the same 420 Myr bin of our DTD reconstructions, and the level to be plotted is then just the median level, \( B = 2 \times 10^{-3} \) \((10^{10} \msun)^{-1}\) divided by this time interval. The median value for the \( A \) parameter is \( A = 6 \times 10^{-4} \text{SNe yr}^{-1} \) \((10^{10} \msun)^{-1}\), which we plot as a constant rate at times \( > 420 \) Myr, but halved to account for stellar mass-loss (see above). As already noted, ‘\( A + B \)’ is an oversimplification, but its measured values are seen to be consistent with our DTD.

Strolger et al. (2004) and Dahlen et al. (2004) have deduced a Gaussian DTD centred at 4 Gyr with half-width 0.8 Gyr, as a best fit to their comparison of SN rates to cosmic SFH, out to \( z = 1.6 \). As seen in Fig. 5, such a DTD is strongly at odds with our local, directly derived, DTD.

Pritchet et al. (2008) have argued for a power-law DTD form, \( r^{-0.5 \pm 0.2} \), based on analysis of the Supernova Legacy Survey data. A dependence of roughly \( r^{-0.5} \) is also expected simply from the formation rate of WDs, when considering the IMF and main-sequence stellar lifetimes. In Fig. 5, we have plotted a \( r^{-0.5} \) curve, normalized to pass through the \( \Psi_1 \) rate, which is the most robust and stable rate in our DTD reconstruction. It appears that a \( r^{-0.5} \) dependence is too shallow to match our derived DTD, especially considering that \( \Psi_1 \) is likely underestimated by us, given the possibility of remaining leakage from \( \Psi_1 \) to \( \Psi_3 \), even in our culled sample (as evidenced from the CC SN sample).

Finally, we have overplotted in Fig. 5 two of the analytical models of Greggio (2005), as presented by Greggio et al. (2008), based on stellar-evolution arguments and on various parameterizations of the possible results of the complex common-envelope phases through which SN Ia progenitor systems must pass. For each of several SN Ia channels, Greggio (2005) calculates the DTDs that emerge when varying the values for the parameters describing the initial conditions, and the mass and separation distributions and limits of the systems that eventually explode. We show here one SD model and one DD model, again normalized to pass through our best-fitting \( \Psi_1 \) rate.

The ‘DD-Close-3’ label of the DD model refers to one of two possible parametric schemes used by Greggio (2005) to describe the WD separation distribution after the common-envelope phase, and to a minimum assumed initial mass of the secondary star in the binary, of \( 3 \msun \). This DD model appears to match well our recovered DTD, especially considering that we have residual leakage problems from \( \Psi_1 \) to \( \Psi_3 \), and hence \( \Psi_1 \) is underestimated. It is easy to see from Fig. 5 that this model, after its initial rise to maximum, is essentially a broken power law. At \( t \lesssim 400 \) Myr, the slope is \( \sim -0.5 \), just like the Pritchet et al. (2008) model slope. This slope is the result of stellar-evolution lifetimes and IMF (see above). At \( t > 400 \) Myr, the slope is \( \sim 1.3 \). A slope of roughly \( -1 \) is generic to models in which the merger rate is determined by energy loss to gravitational waves (e.g. Greggio 2005; Totani et al. 2008).

The Greggio (2005) SD model also matches our recovered LOSS–SDSS DTD in Fig. 5 remarkably well. It should be remembered, however, that in a full physical model, the normalization is not a free parameter, and is dictated by the efficiency...
of SN Ia production from the potential progenitor population. As emphasized by Maoz (2008), and further discussed in Section 3.6.2 below, the efficiencies found by binary population synthesis models are at least a factor of a few, and likely an order of magnitude, lower than indicated by observed SN rates (see also Mennekens et al. 2010). Furthermore, the SD model, whose shape matches our derived DTD so nicely, has been found to be even less efficient, by yet another order of magnitude, in some studies (e.g. Tutukov & Yungelson 2002).

From this brief comparison of our recovered DTD to previous work, we conclude the following. (1) The monotonically decreasing nature of the DTD that we have found is in agreement with most previous empirical determinations and theoretical expectations, except for that of Strolger et al. (2004). (2) The decline with time of our DTD is steeper than in the Pritchet et al. (2008) model. Two of the Greggio (2005) models, SD and DD-Close-3, fit well the shape of the recovered LOSS–SDSS DTD. (3) The normalization of full physical models to the observations has not been considered here, but it is another point at which models are challenged by these and other observations of SN rates.

3.6 The time-integrated DTD

Another interesting observable is the integral of the DTD over the age of the universe ($t_0$),

$$N_{SN}/M = \int_0^{t_0} \Psi(t) \, dt,$$

which gives the total number of SNe that eventually explode, per unit stellar mass formed in a short burst of star formation. We can approximate the integral in equation (9) with a sum over the binned DTD,

$$N_{SN}/M \approx \sum_{j=1,K} \Psi_j \Delta t_j.$$

The adequacy of this approximation will depend on the true form of $\Psi(t)$ and on the number of bins. From the simulations described in the next section, we find that, for declining power-law DTDs represented with three time bins, equation (10) typically underestimates $N_{SN}/M$ systematically by ~10–20 per cent.

3.6.1 Core-collapse SN yield per stellar mass

If all stars with mass $>8 \, M_\odot$ explode as CC SNe, then for CC SNe, $N_{SN}/M$ is just the ratio of the number of stars formed above this mass limit to the total stellar mass formed, and is easily calculated to be $N_{CC}/M = 0.010 \, SN/M$ for the ‘diet’ Salpeter IMF [as well as for the Kroupa (2007) IMF assumed by the the VESPA SFH reconstruction]. In contrast, the integral over our reconstructed DTD of the CC SNe is $(0.00585 \pm 0.00085) \, SN/M$, a factor of ~2 lower than expected. However, we can show that this deficit of CC SNe largely disappears in various subsamples of the LOSS–SDSS sample, and is therefore not a real effect.

For example, we have reduced the LOSS–SDSS galaxy sample by limiting the maximum galaxy distance to progressively smaller values. For each distance-limited sample, we recover the DTD. Fig. 6 shows the values of $N_{CC}/M$ we obtain by integrating over the reconstructed CC SN DTDs, for each distance limit. Several of these values are also listed in Table 1. Clearly, $N_{CC}/M$ rises with decreasing distance, and reaches close to the theoretically expected value when the sample is limited to galaxies closer than $D \approx 65 \, Mpc$. From this plot we estimate the observed limiting value to be $N_{CC}/M = 0.010 \pm 0.002$.

Although a potential explanation for the dependence of $N_{CC}/M$ on sample volume would be an increasing fraction of missing CC SNe with distance, perhaps due to mild obscuration of such SNe by dust, this is unlikely to be the correct explanation. $N_{CC}/M$ is derived from the DTD, which takes into account the visibility time of each type of CC SN at the distance of each galaxy in the sample. The visibility time, in turn, was calculated, as described in Paper II, using the observed LF of 87 nearby CC SNe, in which the effects of extinction are automatically included.

More likely, the decrease of $N_{CC}/M$ with distance is another manifestation of the SDSS fibre aperture problem. At larger distances, there are fewer low-mass galaxies and late-type spirals in the LOSS sample, and more high-mass intermediate and early types. In the earlier-type galaxies, VESPA in more likely to overestimate the total galaxy mass, based on the spectrum of the bulge population probed by the SDSS aperture. Indeed, if we rederive the CC SN DTD and $N_{CC}/M$, but exclude the earlier Hubble types (as in Section 3.4.2), or exclude massive galaxies, the values of $N_{CC}/M$ for the samples limited to $D < 125 \, Mpc$, $D < 150 \, Mpc$ and $D < 200 \, Mpc$ rise significantly, and approach their theoretically expected value.

Fig. 6. The time-integrated DTD, i.e. the total number of SNe produced over a Hubble time, per unit stellar mass formed, for different distance-limited galaxy subsamples. Top full symbols are for CC SNe (SN II plus SNe Ibc), bottom full symbols are for SNe Ia. Top empty symbols are for CC SNe in a subsample of galaxies with masses $<3 \times 10^{10} \, M_\odot$. Bottom empty symbols are for SNe Ia in a subsample of galaxies with masses $<7 \times 10^{10} \, M_\odot$. The rise in $N_{CC}/M$ toward its theoretically expected value with decreasing maximum sample distance or with sample culling is another manifestation of the SDSS small-fibre-aperture problem. The value of $N_{CC}/M$ at $\leq 65 \, Mpc$ indicates that most stars above $8 \, M_\odot$ produce CC SNe. The constant value of $N_{BB}/M$, on the other hand, shows that the systematics affecting SNe Ia are less dependent on distance. Nevertheless, culling the higher-mass galaxies from the sample increases $N_{BB}/M$ at all distances. The time-integrated ratio of CC SNe to SNe Ia is seen to be roughly 4:1.

3.6.2 ORI CODDL SN yield per stellar mass

The constant value of $N_{BB}/M$ at $\geq 65 \, Mpc$ indicates that most stars above $8 \, M_\odot$ produce CC SNe. The constant value of $N_{BB}/M$, on the other hand, shows that the systematics affecting SNe Ia are less dependent on distance. Nevertheless, culling the higher-mass galaxies from the sample increases $N_{BB}/M$ at all distances. The time-integrated ratio of CC SNe to SNe Ia is seen to be roughly 4:1.

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leak from the first to the second bin, decreases for the CC SNe as $D$ is reduced.

The fact that a galaxy sample can be defined (the $D \lesssim 65$ Mpc sample in the above example), for which $N_{\text{CC}}/M$ actually reaches its expected value, is important. It confirms that, indeed, the majority of stars with $>8$ M$_\odot$ produce CC SNe. This cannot be taken for granted. Given current observational and theoretical limits, the low-mass limit for core collapse could be as high as 10 or even 11 M$_\odot$ (see Smartt 2009, and references therein). Moving the limit from 8 to 10 M$_\odot$ would decrease the expected $N_{\text{CC}}/M$ by about 30 per cent (i.e. to our 2σ observed lower limit on $N_{\text{CC}}/M$). Raskin et al. (2008) have recently obtained a similar estimate of the lower mass limit for core collapse by matching, on the one hand, the differences in the spatial distributions of stars and SNe in spiral galaxies to, on the other hand, the predictions of simple stellar-population aging models.

Furthermore, in principle, a sizable fraction of high-mass stars could collapse directly to a black hole, with only a weak or null SN explosion accompanying the collapse (Kochanek et al. 2008). Our measurements of $N_{\text{CC}}/M$ also argue against this scenario, unless the minimum mass for CC SNe is even lower than 8 M$_\odot$. We note that these conclusions are reinforced by the fact that the discrete sum in equation (10) underestimates the true integral over $\Psi$.

### 3.6.2 The SN Ia yield per stellar mass

Fig. 6 also shows the results of a similar analysis for the SNe Ia: the integral $N_{\text{Ia}}/M$ over the best-fitting SN Ia DTD (shown in Fig. 3 for the full sample), again as a function of the sample distance limit. We see (lower filled symbols) that there is no obvious dependence on distance, with $N_{\text{Ia}}/M$ apparently constant at $\sim 0.00140 \pm 0.00033$ SNe M$^{-1}_\odot$. However, if we again limit the sample in mass, for example to $<7 \times 10^{10}$ M$_\odot$, we obtain (lower empty symbols in Fig. 6) higher values, $N_{\text{Ia}}/M \approx 0.00230 \pm 0.00060$ M$^{-1}_\odot$. The systematics of the masses of the SN Ia host galaxies, while present, are apparently less dependent on distance than those of the CC SN hosts.

These values of $N_{\text{Ia}}/M$ are also of interest. As already noted above, previous studies have found, just for the prompt SN Ia component embodied in the $B$ parameter, values of $B = (1 - 3) \times 10^{-3}$ M$^{-1}_\odot$. We note that the $B$ parameter, like $N_{\text{Ia}}/M$, relates to the stellar mass $M_{\odot}$ and $M_{\odot}$ formed. Mannucci et al. (2006) obtained an empirical DTD based on the observations described by Mannucci et al. (2005) and Della Valle et al. (2005). Their time-integrated SN rate is 0.0013 SNe M$^{-1}_\odot$. However, this rate is per unit of existing stellar mass, after assuming a fraction of recycled gas of 0.30 as an average among populations of different ages (Bruijne & Charlot 2003). Accounting for this factor, the Mannucci et al. (2006) result corresponds to $\sim 0.0010$ SNe M$^{-1}_\odot$ of formed stars, similar to the values measured here.

As discussed at length by Maoz (2008), $N_{\text{Ia}}/M$ is one of several observables that can be related directly to the fraction $\eta$ of stars in some initial mass range $[m_1, m_2]$ that eventually explode as SNe Ia:

$$\eta = \frac{N_{\text{Ia}} \int_{m_1}^{m_2} m(dN/dm) dm}{M \int_{m_1}^{m_2} (dN/dm) dm},$$

where $dN/dm$ is the IMF. For the ‘diet Salpeter’ IMF (which, again, gives results similar to the Kroupa IMF assumed by the VESPA SFH reconstruction), and an initial mass range of 3–8 M$_\odot$, often considered for the primary stars of SN Ia progenitor systems, the ratio of the two integrals equals 33. Adopting the higher value of $N_{\text{Ia}}/M$ that we have found in the culated sample, under the assumption that it is more robust against the fibre-aperture effect, we obtain $\eta = 7.6 \pm 2.0$ per cent. This is in agreement with the results of Mannucci et al. (2006), who found $\eta = 4.3$ per cent for these parameters. As noted by Maoz (2008), the consistently high values of the exploding fraction, $\eta$, derived from several different observables, may constitute a problem for current progenitor models.

Interestingly, in galaxy clusters, Maoz et al. (in preparation) estimate a time-integrated number of SNe Ia per present-day stellar mass of 0.011 SNe M$^{-1}_\odot$. This estimate is based on the observed ratio of total mass of iron (both in stars and in the intracluster medium) and the mass in stars. For an IMF with a standard high-mass end, the present-day mass observed in stars is related to the number of CC SNe, whose contribution to the iron mass has been estimated and subtracted. The remaining iron mass is then due to the SNe Ia. Multiplying by 0.5 to convert to formed mass, rather than present mass, this gives $N_{\text{Ia}}/M = 0.006$ SNe M$^{-1}_\odot$. Maoz et al. (in preparation) show that, given the uncertainties in observed cluster properties, this number could decrease by perhaps a factor of 0.6 at most, to $N_{\text{Ia}}/M = 0.0035$ SNe M$^{-1}_\odot$. This is still at least a factor of 1.5 greater than, but marginally consistent with, the $N_{\text{Ia}}/M = 0.0023 \pm 0.0006$ SNe M$^{-1}_\odot$ that we have found here based on LOSS.

The cluster-based value of $N_{\text{Ia}}/M$ may be evidence for early enrichment of clusters by CC SNe from a top-heavy IMF. These CC SNe from massive stars, which left no traces in the form of low-mass relatives, would have then produced the bulk of the iron mass in clusters. Alternatively, the large iron mass in clusters could have indeed come from SNe Ia, but this would imply a more efficient production of SNe Ia in cluster environments. Intriguingly, Sharon et al. (2007), Mannucci et al. (2008) and Graham et al. (2008) have all found evidence for SN Ia rates enhanced by factors of a few in cluster galaxies, compared to field early-type galaxies.

### 3.6.3 The ratio of CC SNe to SNe Ia

From the ratio of the time-integrated DTDs, $N_{\text{CC}}/M$ and $N_{\text{Ia}}/M$ (using the value of $N_{\text{CC}}/M$ at $D \lesssim 70$ Mpc for which the CC SN counts are fairly complete, but for which the errors are not excessively large because of the limited sample size, and $N_{\text{Ia}}/M$ from the low-mass sample; see above), the time-integrated ratio of CC SNe to SNe Ia is $N_{\text{CC}}/N_{\text{Ia}} = 4^{+4}_{-2.5}$. If we force the value of $N_{\text{CC}}/M = 0.01$ expected from a diet Salpeter IMF with a low-mass CC limit of 8 M$_\odot$, the allowed range in the ratio shrinks to $N_{\text{CC}}/N_{\text{Ia}} = 4^{+2}_{-1.7}$. We note that the ratio of time-integrated DTDs is distinct from the observed ratio of current rates, which is measured to be about 3:1 in local surveys (Mannucci et al. 2005; Paper II). The ratio of current rates depends on the summed SFH of the galaxies in the volume. It can be arbitrarily high for very young, star-forming populations (in which few SNe Ia have had time to form yet) to zero for old, inactive populations (with no CC SNe). In contrast, the ratio of the time-integrated DTDs, like the DTDs themselves, is independent of SFH, and intrinsic to the stellar-evolution processes that lead to SNe.

The ratio $N_{\text{CC}}/N_{\text{Ia}}$ of course equals $0.01$ M$^{-1}_\odot$)/(0.01 M$^{-1}_\odot$), for the diet Salpeter IMF and the said lower limit for CC SNe, and thus the cluster-based lower limit of $N_{\text{CC}}/N_{\text{Ia}} > 0.0035$ SNe M$^{-1}_\odot$ (Maoz et al., in preparation), discussed above, implies $N_{\text{CC}}/N_{\text{Ia}} < 2.9$, and possibly even 1:1. de Plaa et al. (2007), comparing cluster element abundances to theoretical SN element yields, have deduced an integrated CC SN to SN Ia ratio of 1:1. On the other hand, the observational uncertainties are such that a time-integrated CC SN
to SN Ia ratio of roughly 3:1, despite some tension, is consistent both with cluster measurements and with the LOSS data we have analysed here.

4 TESTS ON SIMULATED SAMPLES

To test our DTD recovery procedure and examine its performance on different kinds of input data sets, we have repeated the Monte Carlo mock survey generation described in Section 2, above, using the LOSS–SDSS galaxy sample and its VESPA-based SFHs (with one dust parameter). However, rather than inputting the best-fitting DTD from the inversion of the real data, we can choose other model DTDs and convolve those DTDs with $m_i$ according to equations (2)–(3), or we can change the sample properties in additional ways, as described below. Using the actual LOSS galaxy SFHs and visibility times (as opposed to, for example, random SFHs and visibility times) makes for a more realistic simulation. As before, the number of SNe found in each galaxy is assumed to be a Poisson distribution with expectation value $\lambda_i$. The different-shaped DTDs which can be input and recovered can also be scaled up or down to produce a larger or smaller total number of SNe in the mock survey (or, equivalently, the visibility times, $\tau_j$, can be scaled up or down). In these simulations, the SFHs are assumed to be error-free independent variables, and are used both for creating the mock samples and deriving their DTD. Therefore, these simulations will not display the ‘leakage’ between bins that we have encountered with the LOSS–SDSS sample, nor other problems due to systematic or random errors in the SFHs of the galaxies.

From our simulations, we find that the distribution of output DTD amplitudes is centred on the input DTD values, meaning that the method reliably recovers the input DTD with little bias. None the less, for low DTD amplitudes combined with large uncertainties (due to small SN numbers; see below), there can be some ‘pile-up’ in the distribution at zero amplitude, as a result of the positivity constraint of the DTD. Thus, obtaining a zero amplitude for a bin in the DTD reconstruction can happen, even when in reality the amplitude is non-zero but low, and the number of SNe in the survey is small.

We find that the relative uncertainty in the DTD amplitude in the $j$th bin scales roughly as one would expect from Poisson statistics, considering the number of SNe that contribute to every bin in the DTD. For example, with three time bins, the relative error in the first bin of the DTD is

$$\frac{\Delta \Psi_1}{\Psi_1} \approx \left( \frac{N_{\text{tot}}}{\sum m_{i,1} \Psi_1 + \sum m_{i,2} \Psi_2 + \sum m_{i,3} \Psi_3} \right)^{-1/2}. \quad (12)$$

For a survey with a fixed total number of SNe, $N_{\text{tot}}$, there will thus be a trade-off in the analysis between DTD accuracy and resolution. The uncertainties do not depend on the number of galaxies monitored, and thus a brief-duration survey of many galaxies and a long-duration survey of few galaxies are equivalent, as long as they produce the same total number of SNe.

Fig. 7 examines the quality of the reconstruction as the number of time bins is varied between three and five. Here, we have assumed a survey with 15 000 galaxies and $\sim 370$ SNe, similar to the full LOSS SN Ia sample, if all galaxies in it had SFH reconstructions available. To produce this large mock sample, we simply clone several times the 3505 SFHs and visibility times of the LOSS–SDSS sample, with its three time bins. To obtain a sample with five time bins in each galaxy’s SFH, we have split, in this example, the first SFH bin into two bins: a 0–100 Myr bin and a 100–420 Myr bin. The stellar mass in each sub-bin was randomized by $\pm 50$ per cent around the mass value corresponding to the relative time fractions. (Such randomization is essential, as otherwise the $m_i$ are no longer independent variables.) Similarly, we further split the last bin into two bins, corresponding to 2.4–6.5 Gyr and 6.5–13.5 Gyr. For the DTD in these simulations, we have taken a $\Psi(t) \propto t^{-1}$ dependence (which is roughly generic to DD models; see Section 3.5.4), scaled so as to give the desired total number of SNe using the LOSS visibility times. The simulations show that surveys with several hundred SNe enable reasonably good DTD recovery in terms of both accuracy and temporal resolution. Specifically, Fig. 7 demonstrates that already existing SN surveys, and LOSS in particular, have the power to measure reliably the SN Ia DTD, if the SFHs could be estimated in a comprehensive and unbiased way for the full sample of $\sim 15$ 000 galaxies. We briefly discuss the prospects for this in the concluding section below.

We have gauged the effect of the time binning on the time integral over the DTD, $N_{\text{SN}}/M$, as approximated in equation (10). To do this, we create mock samples using large numbers of bins in the SFH and the DTD. The mock samples also have a large number of SNe in order to minimize the statistical error and isolate the systematic effects due to the binning. We then rebin the SFHs of the sample into the same three coarse time bins we have used for the LOSS–SDSS analysis, and we recover the DTD binned into those same three time intervals. Finally, we compare the integrals $N_{\text{SN}}/M$ over the input DTD and the recovered DTD. We find that the $N_{\text{SN}}/M$ of the recovered DTD systematically underestimates...
the input $N_{SN}/M$ by 10–20 per cent, with the larger values for input DTDs that rise more steeply at small delays. This systematic error is comparable to the statistical errors in $N_{SN}/M$ we have found for the LOSS-DTD sample. Larger SN samples will naturally allow finer temporal binning of the DTD, reducing this systematic effect.

5 CONCLUSIONS AND OUTLOOK

We have presented a method to recover the SN DTD by jointly analysing SN survey data and reconstructed SFHs of the individual galaxies in a survey, while accounting for the small-number, Poisson-statistical nature of SN events in those individual galaxies. Our method is an improvement over previous ones in that it uses the full information contained in the data and avoids unnecessary averaging. The method is based on casting the expected SN numbers in each galaxy in the survey as a set of linear equations, in which the parameters to be constrained by the data are the values of the DTD in binned time intervals. We have shown a maximum-likelihood method by which to invert those equations to recover the DTD, and demonstrated the method’s performance using simulated mock samples. We have applied the method to a sample consisting of those galaxies in the LOSS SN survey that have SDSS–VESPASFH reconstructions, along with the SNe that these galaxies have hosted during the LOSS.

The recovered DTDs for CC SNe and SNe Ia are limited by Poisson statistics, because of the small numbers of SNe in this restricted subset of LOSS, and by systematic errors, because for many galaxies the light within the SDSS fibre aperture does not reliably represent the full stellar population of the galaxy and its SFH. Despite these shortcomings, we are able to make the following statements based on the analysis of these data.

(1) A ‘prompt’ SN Ia population, defined here as one that explodes within 420 Myr of star formation, exists at >99 per cent confidence. This confirms the growing number of reports of such a population, at levels similar to those found here.

(2) We clearly detect, at the 4σ level, a ‘delayed’ SN Ia population with delays in the range 2.4–13 Gyr, and a mean rate over this interval of $\Psi_{Ia} = (2.6 \pm 0.7) \times 10^{-3}$ SNe yr$^{-1}$ per 10$^{10}$ M$_\odot$ formed, or $A = (5.1 \pm 1.4) \times 10^{-3}$ SNe yr$^{-1}$ per remaining 10$^{10}$ M$_\odot$ in an old population. These first two conclusions together indicate that the SN Ia DTD peaks at short delays, but extends over a broad range of delay times, out to at least several Gyr. Progenitor models, a few of which we have briefly compared to our recovered DTD, will need to reproduce the observed numbers.

(3) The time-integrated SN Ia yield is $N_{Ia}/M = (2.3 \pm 0.6) \times 10^{-3}$ SNe per unit solar mass formed, or $(4.6 \pm 1.2) \times 10^{-3}$ SNe Ia per remaining unit solar mass in an old population. The best-fitting value is a factor of $1.5–3$ lower than the corresponding number in galaxy clusters, as deduced from their measured iron to stellar mass ratios. Although the current uncertainties can still accommodate this difference, it may indicate that clusters underwent additional enrichment by CC SNe from an early stellar population with a top-heavy IMF, or that SN Ia production is more efficient in galaxy clusters than in the field. The latter possibility has support both from direct cluster SN rate measurements and from cluster element abundance analysis. The measured time-integrated SN Ia yield also implies $\eta \approx 8$ per cent for the exploding fraction among the parent population of SN Ia primaries, if assumed to come from the 3–8 M$_\odot$ initial mass range.

(4) The time-integrated CC SN yield is $N_{CC}/M = (1.0 \pm 0.2) \times 10^{-2}$ SNe per unit solar mass formed. This rules out low-mass limits for CC explosions that are much above 8 M$_\odot$. Conversely, scenarios in which a significant fraction of high-mass stars end their evolution without SN explosions are excluded, unless the low-mass limit for core collapse is significantly below 8 M$_\odot$.

(5) The ratio of CC SN to SN Ia numbers from a brief burst of star formation, integrated over a Hubble time, is $(4_{-1}^{+3})$.

Our work points to the kinds of data that would improve upon these results. First, a larger sample of survey galaxies with spectroscopy, and hence SFHs, would obviously reduce the Poisson errors and permit better temporal resolution. As there are 14 882 galaxies monitored by LOSS, obtaining spectra for most or all of them would be a large, but not impossible, task. A dedicated or partly dedicated 2–4-m-class telescope could achieve this on a few-year time-scale. Long-slit spectra, drifted across the galaxy perpendicular to the slit length, would be more representative of the entire stellar population of each galaxy, largely avoiding the small-fibre-aperture problem we have encountered. Ideally, instead of long-slit spectra of the LOSS galaxies, one would obtain integral-field spectroscopy of each of these galaxies (using, e.g. an instrument such as SAURON on the William Herschel 4.2-m telescope: Bacon et al. 2001). In addition to including the full SFH of each galaxy without any aperture losses, such data, in the context of our method, would easily allow breaking up each galaxy into independent subunits, and considering the SFH of each subunit in relation to the SNe that it hosted (or, for almost all subunits, the SNe that it did not host).

It might be objected at this point, that because of the random stellar velocities in each galaxy, SN progenitor stars diﬀuse away from the regions where they were formed, and that this would invalidate our approach; by the time an SN Ia exploded, it would reside within a region that is completely different from the one in which its progenitor was formed. While this is true, and it would in fact invalidate a traditional ‘SN delay time’ analysis in which a single characteristic stellar population age is assigned to a region, it is inconsequential to our current method, in which the entire SFH of the region is considered. The reason is that the same spatial diﬀusion affects both the progenitor population and those stars among it that eventually explode. To see this, consider, as a toy example, a grid of $3 \times 3$ adjacent ‘cells’ in a particular galaxy. Suppose, for example, that 500 Myr ago there was a short burst of star formation in the central cell, forming a stellar mass $M$, and no activity in the other cells. Suppose, further, that the SN DTD is such that the stellar population formed in the burst leads, 500 Myr later, to nine SNe over the course of a decade, which are therefore detected in this galaxy by an SN survey such as LOSS (this is admittedly a somewhat unrealistically large number of SNe, but is used here just for the sake of illustration). The galaxy has thus produced a ratio of $9/M$ SNe over unit stellar mass formed 500 Myr ago. Finally, suppose that the stellar diﬀusion time-scale in the galaxy is such that, over the 500 Myr, the progenitors of the nine SNe, before exploding, have drifted out of the central cell in which they were formed, and there is now, on average, one SN in each cell. However, the entire stellar population of the burst will have diffused in the same way, and therefore each cell will have 1/9 of the 500-Myr-old population that was originally in the central cell. When we compare SN numbers to the 500-Myr-old stellar mass present today in each cell, we will see 1 SN per $M/9$ of stellar mass formed. In the DTD we derive, we will therefore still deduce the correct ratio of $9/M$ SNe per unit stellar mass formed 500 Myr earlier.
This argument holds, no matter what are the lookback times or the diffusion time-scales. It also holds for arbitrarily complex SFHs, which can be viewed as linear superpositions in space and in time of toy models of the type above. If a past starburst at a certain place and time in a galaxy produces SNe that are observed in the course of a survey, the stellar population of the burst and the SNe that it produces will both diffuse in the same way. If, on the other hand, a specific burst does not produce SNe detected by the survey (because the DTD has a low amplitude at the corresponding delay), then there will be no correlation between the number of SNe per cell and the mass of stars of that age per cell. An individual cell hosting SNe may, of course, include unrelated stellar populations that did not produce those SNe, but whose stars none the less drifted into the cell. However, over the entire galaxy, there will be no correlation between SNe and stars of that particular age, and it is such correlations that drive the results of our DTD recovery method.

We note that for the integral-field spectroscopy approach to work, the signal-to-noise ratio of the spectra of each individual galaxy cell needs to be sufficiently high for a reliable SFH reconstruction to be obtained. In particular, the presence of old stellar populations that are superimposed on younger and more luminous stars must be detectable. Naturally, spatially resolved, medium-spectral-resolution data of such a large sample of nearby galaxies would find many additional applications, and hence such data are worth the large effort required.

Shortly before submission of this work, Brandt et al. (2010) presented a DTD reconstruction analysis of a different SN sample. Their methodology shares several elements with ours. Brandt et al. (2010) study 107 SNe Ia from SDSS-II. Like us, they use VESPA to derive SFHs for a sample of SDSS galaxies, binned into three time bins, identical to those we have chosen. Like us, they treat the DTD amplitudes in the three discrete bins as free parameters, which are determined by a maximum-likelihood procedure. However, rather than comparing directly the presence or absence of SNe in each galaxy to the predictions of the DTD model (as we have), they use the DTD to create mock SN-host samples, and compare the mean spectrum of the mock host samples to the mean spectrum of the real host galaxies. Brandt et al. (2010) reach similar conclusions to ours, namely, significant detections of both prompt (<420 Myr) and delayed (>2.4 Gyr) SN Ia DTD components.

ACKNOWLEDGMENTS

We thank Rita Tojeiro for her assistance and patience with obtaining and explaining the VESPA SFHs, Jesse Leaman for his contribution to the determination of LOSS SN rates and Keren Sharon for her help with the comparison to models. DM acknowledges support by a grant from the Israel Science Foundation. LOSS, conducted by AVF’s group at the University of California, Berkeley, has been supported by many grants from the National Science Foundation, USA (most recently AST-0607485 and AST-0908886), the TABASGO Foundation, US Department of Energy SciDAC grant DE-FC02-06ER41453 and US Department of Energy grant DE-FG02-08ER41653. KAIT and its ongoing operation were made possible by donations from Sun Microsystems, Inc., the Hewlett-Packard Company, AutoScope Corporation, Lick Observatory, the National Science Foundation, the University of California, the Sylvia & Jim Katzman Foundation and the TABASGO Foundation.

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