Pair-instability supernovae via collision runaway in young dense star clusters

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters.

Citation
Pan, Tony, Abraham Loeb, and Daniel Kasen. 2012. “Pair-Instability Supernovae via Collision Runaway in Young Dense Star Clusters.” Monthly Notices of the Royal Astronomical Society 423 (3): 2203–8. https://doi.org/10.1111/j.1365-2966.2012.21030.x.

Citable link
http://nrs.harvard.edu/urn-3:HUL.InstRepos:41412108

Terms of Use
This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA
Pair-instability supernovae via collision runaway in young dense star clusters

Tony Pan,1⋆ Abraham Loeb1 and Daniel Kasen2,3

1Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
2Departments of Physics and Astronomy, University of California, 366 LeConte Hall, Berkeley, CA 94720, USA
3Nuclear Science Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94708, USA

ABSTRACT
Stars with helium cores between ~64 and 133 M⊙ are theoretically predicted to die as pair-instability supernovae. This requires very massive progenitors, which are theoretically prohibited for Pop II/I stars within the Galactic stellar mass limit due to mass-loss via line-driven winds. However, the runaway collision of stars in a dense, young star cluster could create a merged star with sufficient mass to end its life as a pair-instability supernova, even with enhanced mass-loss at non-zero metallicity. We show that the predicted rate from this mechanism is consistent with the inferred volumetric rate of roughly ~2 × 10^{-9} Mpc^{-3} yr^{-1} of the two observed pair-instability supernovae, SN 2007bi and PTF 10nnm, neither of which has metal-free host galaxies. Contrary to prior literature, only pair-instability supernovae at low redshifts z < 2 will be observable with the Large Synoptic Survey Telescope. We estimate that the telescope will observe ~10^2 such events per year that originate from the collisional runaway mergers in clusters.

Key words: supernovae: general – galaxies: star clusters: general.

1 INTRODUCTION
Pair-instability supernovae (PISNe) are thought to occur for stars with helium cores between ~64 and 133 M⊙ (Heger & Woosley 2002). At zero metallicity, this corresponds to initial stellar masses between ~140 and 260 M⊙. These enormous stellar masses may have been reached by Pop III stars, which are predicted to have a top-heavy mass distribution (Bromm & Larson 2004). However, at lower redshifts, as the universe was enriched, Pop III stars ceased to form once the local metallicity exceeded a critical threshold Z_{crit} ~ 10^{-3} Z⊙ (Bromm & Loeb 2003). Since it is almost impossible to raise the intergalactic medium metallicity in a homogeneous way (Furlanetto & Loeb 2003; Scannapieco, Schneider & Ferrara 2003), pristine metal-free stars will still be formed past the end of the reionization epoch z ∼ 6 (Trenti, Stiavelli & Michael Shull 2009), conceivably all the way down to z = 2.5 (Tornatore, Ferrara & Schneider 2007). Observations have confirmed the existence of extremely metal-poor star formation at moderate redshifts of z = 3.357 and 5.563 (Fosbury et al. 2003; Raiter, Fosbury & Teimoorinia 2010). The detectability of PISNe from Pop III stars at these moderate redshifts was investigated by Scannapieco et al. (2005).

Outside these surviving pristine regions, there is a wide range of observations that support an upper limit to stellar mass at ~150 M⊙ in our Galactic neighbourhood (Figer 2005; Weidner, Kroupa & Bonnell 2010), preventing the formation of PISNe from Pop II/I stars (but see Crowther et al. 2010 for stars determined to be above 150 M⊙ in the R136 cluster). Nevertheless, even if very massive stars can form in metal-rich regions, these radiatively supported stars are loosely bound and have strong winds driven mainly by radiation pressure through spectral lines, scaling as M ∝ Z^{0.5−0.7} (Vink et al. 2001; Kudritzki 2002). So even Pop II/I stars with initial masses between ~140 and 260 M⊙ will suffer copious mass-loss during both the hydrogen- and helium-burning stages, and may not end their lives with enough mass remaining to die as PISNe; this prediction could be contested, as there are still large uncertainties in mass-loss models from hot massive stars (Puls, Vink & Najarro 2008). Nevertheless, due to mass-loss the possibility of PISNe is usually not considered for solar composition stars, even though the pair instability arises irrespective of the progenitor’s metallicity.

Regardless, PISNe have very likely already been observed at low redshifts, most convincingly in the case of the very luminous and long-duration event SN 2007bi (Gal-Yam et al. 2009). More recently, the Palomar Transient Factory observed a new presumed PISN, PTF 10nnm (Gal-Yam 2012; Yaron et al., in preparation), and another PISN candidate was reported by the Pan-STARRS1 survey, PS1-11ap (Kotak et al., in preparation). Although it may be possible to explain bright events like SN 2007bi with alternative models (e.g. Woosley, Blinnikov & Heger 2007; Kasen & Bildsten 2010; Moriya et al. 2010) on the whole the observations seem to...
favour a scenario in which a large total mass and radioactive mass were ejected, as in a PISN explosion. The observations therefore suggest that very massive stars above the Galactic limit are formed in the local universe. The metallicities of the host galaxies of both supernovae (SNe) are low but well above the maximum metallicity required to form Pop III stars (Young et al. 2010). Either pockets of pristine gas survive in the dwarf host galaxy of SN 2007bi and PTF 10mm, or the initial mass function (IMF) of Pop II/I stars merely steepens at the very high end (instead of a hard upper limit), or there are other exotic ways to form a very massive star.

In theory, mergers of stars can form massive SN progenitors at any metallicity and circumvent the upper mass limit for Pop II/I stars at \( \sim 150 \, M_\odot \). The most likely environment for such mergers is a dense, young star cluster undergoing core collapse, in which a runaway collision product can become massive enough to die as an ultra-luminous SN. Portegies Zwart & van den Heuvel (2007) first investigated this scenario for a collapsar, and Yungelson et al. (2008), Glesbeek et al. (2009) and Vanbeveren et al. (2009) discussed the conditions under which the runaway collision product will end its life as a PISN.

In this paper, we calculate the number of collision runaway merger products within dense, young star clusters that lie in the PISN progenitor mass range, and show that the predicted event rate is roughly equal to the inferred rate of PISNe from the detection of SN 2007bi and PTF 10mm in existing surveys, without requiring the SN progenitor to be metal free. We further investigate the observability and rate of these events in the low-redshift universe with the Large Synoptic Survey Telescope (LSST).

## 2 Rates from Runaway Collisions

An appreciable fraction of stars are born in clusters; Bastian (2008) found the fraction of mass that forms in clusters > 100 \( M_\odot \) out of the total star formation rate to be \( \Gamma \sim 8 \pm 3 \) per cent. As soon as the cluster forms the massive stars start to sink to the cluster centre due to dynamic friction, driving the cluster into a state of core collapse on a time-scale of \( t_{\text{cc}} \approx 0.2 \, t_{\text{rh}} \), where \( t_{\text{rh}} \) is the relaxation time:

\[
t_{\text{rh}} \approx 2 \, \text{Myr} \left( \frac{r}{1 \, \text{pc}} \right)^{\frac{3}{2}} \left( \frac{m}{1 \, M_\odot} \right)^{-\frac{3}{2}} N \frac{\log \lambda}{\log \lambda - 1}
\]

\[
\approx 200 \, \text{Myr} \left( \frac{r}{1 \, \text{pc}} \right)^{\frac{3}{2}} \left( \frac{m}{10^6 \, M_\odot} \right)^{-\frac{3}{2}} \left( \frac{m}{M_\odot} \right).
\]

Here \( m \) is the cluster mass, \( r \) is its half-mass radius, \( N \) is the number of stars, \( \langle m \rangle = N/m \approx 0.5 \, M_\odot \) is the average stellar mass and \( \log \lambda \approx \log (0.1 N) \approx 10 \) (Portegies Zwart, McMillan & Gieles 2010). In sufficiently compact clusters, the formation of a dense central subsystem of massive stars may lead to a collision runaway, where multiple stellar mergers result in the formation of an unusually massive object (Gürkan, Freitag & Rasio 2004; Freitag, Gürkan & Rasio 2006). This prescription is often invoked to form intermediate-mass black holes via the photodisintegration instability that collapses a supermassive star directly into a black hole.

For a successful collision runaway to occur, the star cluster must experience core collapse before the most massive star explodes as an SN (\( \sim 3 \, \text{Myr} \)). For compact clusters (\( t_{\text{rh}} \lesssim 100 \, \text{Myr} \)), basically all massive stars sink to the core during the runaway and the final merged object’s mass scales with the cluster mass, \( m \approx 8 \times 10^{-4} m \log \lambda \) (Portegies Zwart & McMillan 2002). For clusters with longer relaxation times, only a portion of massive stars sink to the core in time and the merged object’s mass scales as \( m \approx m^{1/2} \) (McMillan & Portegies Zwart 2004). A fitting formula for combining these scalings is given by Portegies Zwart et al. (2006), calibrated by \( N \)-body simulations for Salpeter-like mass functions:

\[
m_t \sim 0.01 m \left( 1 + \frac{t_{\text{rh}}}{100 \, \text{Myr}} \right)^{-\frac{1}{2}}.
\]

To get statistics on the final runaway mass \( m_r \) from equations (1) and (2), we need to specify the number distribution of clusters as a function of their mass \( m \) and radius \( r \).

The functional form of the cluster IMF is well represented by a Schechter (1976) distribution,

\[
\Phi(m) = \frac{dN}{dm} = A m^{-\beta} e^{-m/m_*},
\]

where observationally \( \beta \sim 2 \) (Zhang & Fall 1999; McCrady & Graham 2007). For Milky Way-type spiral galaxies the break mass \( m_* \approx 2 \times 10^5 M_\odot \) (Gieles et al. 2006; Larsen 2009), whereas for interacting galaxies and luminous infrared (IR) galaxies \( m_* \gtrsim 10^6 M_\odot \) (Bastian 2008). Our results are not sensitive to the choice of \( m_* \).

Several studies have discussed the lack of any clear correlation between the size of a cluster and its mass or luminosity (Larsen 2004; Scheepmaker et al. 2007). Lacking a functional distribution of cluster radii, we use the empirical distribution of radii for each cluster mass bin, for observed clusters younger than 5 Myr, compiled in tables 2–4 of Portegies Zwart et al. (2010). The restriction on cluster age is important, as clusters expand considerably during the first 10 Myr of their evolution. Note that this empirical construction underestimates the number of supermassive collision runaway objects (\( > 10^5 M_\odot \)), as there happens to be no observed \( > 10^6 M_\odot \) clusters younger than 5 Myr in the current sample, but this does not drastically affect our PISN rate estimates. With the joint number distribution of clusters as a function of their mass and radius, we can find the number distribution of the final mass of the runaway collision merged object, see Fig. 1.

However, as we have not taken mass-loss into account in our estimate of the final runaway mass in equation (2), we artificially inflate the mass range for PISN progenitors required at the end of the last merger event, to compensate for the mass lost during the collision runaway merger sequence. For zero-metallicity Pop III stars, mass-loss via line-driven winds should be negligible, and Heger & Woosley (2002) found the progenitor mass range to be

\[\text{Figure 1.} \quad \text{Differential number distribution of the final runaway mass formed, per } 1 \, M_\odot \text{ of stellar mass formed in all clusters. The calculated distribution is not perfectly smooth owing to the finite number of samples in the observed radius distribution.}\]
140–260 M⊙; this should set the upper limit of the PISN rate from runaway collision products.

As for Pop II/I PISN progenitors, we caution that mass-loss via stellar winds for massive stars $M > 100$ M⊙ is not well understood. In fact, the observations of PISNe at low redshifts (Gal-Yam et al. 2009), and of Type II SNe whose progenitors are found to sometimes retain their hydrogen envelopes until shortly before their explosion (Smith et al. 2011), suggest that most commonly used stellar mass-loss models are inaccurate for very massive stars, and likely overestimate the total mass-loss, as the models do not allow such SNe to exist at the measured metallicities. Therefore, to account for this uncertainty, we present here various PISN progenitor mass range scenarios described in the literature dependent on the assumed metallicity and mass-loss prescription.

Yungelson et al. (2008) studied the evolution and fate of supermassive stars with solar metallicity from the zero-age main sequence using detailed stellar structure models. However, instead of extrapolating commonly used mass-loss models, e.g. de Jager, Nieuwenhuijzen & van der Hucht (1988), Vink et al. (2001) and Kudritzki (2002), they used an ad hoc mass-loss prescription consistent with existing models in their relevant regimes and more consistent with the observed Hertzsprung–Russell diagram location and mass-loss ranges found for young massive stars in clusters in the Milky Way and the Magellanic Clouds. Notably, their time-averaged Wolf–Rayet (WR) mass-loss rate $\dot{M}_{\text{WR}}$ hardly exceeds $10^{-4} \, M_\odot \, \text{yr}^{-1}$, which better fits the observations of hydrogen-rich WR stars that account for iron-line blanketing and clumping in determining $\dot{M}_{\text{WR}}$ (Hamann, Gräfener & Liermann 2006), and also agrees well with $\dot{M}_{\text{WR}}$ estimates based on radio observations (Cappa, Goss & van der Hucht 2004). On the contrary, the extrapolation of WR mass-loss formulas to high stellar masses given by Langer (1989), Nugis & Lamers (2000), Nelemans & van den Heuvel (2001) and De Donder & Vanbeveren (2003) overestimates the mass-loss rates compared with these observations. Therefore, we use the results of Yungelson et al. (2008) as our fiducial model. They allow the creation of PISN progenitors at $Z \sim Z_\odot$ in the initial mass range of $250–800$ M⊙; however, they do not account for the mass-loss from stellar collisions.

Alternatively, by extrapolating theoretical mass-loss rates for radiation-driven wind, Belkus et al. (2007) found that when the metallicity $Z$ is between 0.001 and 0.02 $Z_\odot$, one may expect PISN candidates for stars with masses from $\sim$300 to $1000$ M⊙; however, at $Z > 0.02 Z_\odot$ no PISNe are expected. Using the observed galaxy luminosity–metallicity relationship (Kirby et al. 2008; Guseva et al. 2009) and the galaxy luminosity function at low redshifts $z \sim 0.1$ (Blanton et al. 2003), we find that ~0.3 per cent of stellar mass is formed in $Z \lesssim 0.02 Z_\odot$ galaxies, and fold this factor into the predicted PISN rate for this scenario.

In addition, Glebbeek et al. (2009) followed the evolution of the collision product for a few merger sequences for an $m \sim 5 \times 10^3$ M⊙ cluster, including mass-loss along the course of the collision sequence by using the prescription of Vink et al. (2001), and found that above $Z = 0.001 Z_\odot$, the collision runaway product cannot die with sufficient mass to undergo a PISN. The main-sequence stellar wind mass-loss rates between this work and Yungelson et al. (2008) are similar; however, Glebbeek et al. (2009) also calculated the mass-loss from stellar collisions to be roughly ~20 per cent of the total merger product mass before mass-loss. Nevertheless, the main source of discrepancy between their conclusions was due to their very different WR mass-loss rates. Glebbeek et al. (2009) implemented a strong WR mass-loss rate from Nugis & Lamers (2000) (up to $3.6 \times 10^{-3} \, M_\odot \, \text{yr}^{-1}$ at $Z = 0.02$), bringing the collision product down to only $m_t \sim 10$ M⊙ by the end of core helium burning. Using a comparable mass-loss rate, Vanbeveren et al. (2009) reached the same conclusion that PISNe cannot occur above $Z = 0.001 Z_\odot$. Note that with these mass-loss rates, essentially no star in the low-redshift universe below $M \sim 1000 M_\odot$ will end its life as a PISN, irrespective of the collision runaway mechanism.

To account for the ~20 per cent mass-loss due to unbound ejecta from the stellar collision, we can further increase the required PISN progenitor mass range. The new adjusted mass range for PISN progenitors would be ~313–1000 M⊙ in the Yungelson et al. (2008) scenario and ~375–1250 M⊙ in the Belkus et al. (2007) scenario.

Combining the above, we can estimate the number of collision runaway products that have a final mass $m_t$ in the various PISN progenitor mass range scenarios. Using the global comoving star formation rate from Reddy & Steidel (2009), we estimate the PISN rate as a function of redshift in Figs 2 and 3. If the collision runaway mechanism is indeed responsible for creating PISN progenitors at Pop II/I environments in the local universe, we find that only the mass-loss prescription described by Yungelson et al. (2008) fits the current rate of PISNe inferred from observation.

### 3 Observability with LSST

The LSST is a planned wide-field survey telescope that should begin operations at the end of this decade. It has a very wide field of view of 9.6 deg², and six bands: $u$, $g$, $r$, $i$, $z$ and $y$, covering 320–1080 nm. For the most sensitive bands $g$, $r$ and $i$, a single visit will reach $M_{AB} = 25.0, 24.7$ and 24.0 (5σ) sensitivity, respectively. These bands will...
be visited 10, 23 and 23 times every year during the 10 years of operation, reaching a co-added depth of $M_{AB} = 26.3, 26.4$ and 25.7 per year by stacking multiple images. Note that for objects much dimmer than $\sim 22$ mag arcsec$^{-2}$ or $\sim 25.5$ mag pixel$^{-1}$ for the LSST, the signal will be dominated by the sky background (e.g. airglow and zodiacal light), so in this regime the limiting signal flux needed to reach a fixed signal-to-noise ratio is inversely proportional to the square root of the integration time.

We used simulated PISN light curves and spectra from Kasen, Woosley & Heger (2011), who improved radiative transfer calculations by using a multiwavelength Monte Carlo code which includes detailed line opacities. In particular, we use models He130, He100 and He80, which represent the pair-instability explosions of non-rotating bare helium cores with masses 130, 100 and 80 $M_\odot$, respectively, as non-pristine massive stars formed via runaway collisions. The brightest helium core model He130 peaks at around $M_{AB} \sim -22$ in the rest-frame $r$ band, and stays above $M_{AB} = -21$ for half a year and above $M_{AB} = -20$ for almost one year. Such an event in the local universe will be easily detectable; however, the rates for PISNe from both Pop III and Pop II/I progenitors are predicted to be very low at $z \sim 0$. These rates increase at higher redshifts, but since the higher wavelength $z, y$ LSST bands are much less sensitive, the best strategy to find PISNe is to continue using the $g, r$ and $i$ bands and observe at the rest frame ultraviolet (UV) and optical luminosity of the SNe.

Using the co-added depth sensitivities, we find that using the $r$ band is optimal for the helium core PISN models, and that we can observe the brightest He130 model out to a redshift of $z \sim 1.8$ by stacking $\sim 10$ images (see Fig. 4). Below $z < 2$, the PISN is visible in the $r$ band for over one year in the observer frame; however, at $z \geq 2$, the SN will be too dim in the rest-frame UV wavelengths being effectively probed, even though the $(1+z)$ time dilation allows more stacked images. Even if one combines data from the $g, r$ and $i$ bands over one year and reaches a co-added depth of $M_{AB} \sim 27$, the SN will still be too dim to be observable beyond $z = 3$. Alternative PISN models where the progenitors are red supergiants which retain their hydrogen envelopes have a longer plateau in their light curves and thus stay visible slightly longer than the helium core models. However, the conclusions are similar; in terms of instrument capability, redshifts $z < 2$ are most suitable for detecting PISNe in the normal operation mode of the LSST.

The smaller He100 model is only visible out to $z \sim 1.2$, while even smaller progenitors are too dim to be seen beyond $z < 0.4$. Combined with Fig. 3, we estimate that the LSST will see of the order of $\sim 10^3$ new PISNe per year that originated from the final collision runaway object in young, dense clusters.

These conclusions differ from those of Trenti et al. (2009) as well as the LSST Science Book (LSST Science Collaborations, 2009), which concluded that PISN at $z \sim 4$ will be within the capability of the LSST. The difference arises because Trenti et al. (2009) approximated the PISN with a blackbody spectrum with $T_{eff} = 1.5 \times 10^4$ K, which overestimates the rest-frame UV flux compared to the spectrum obtained by the radiation hydrodynamics simulations of Kasen et al. (2011). Also, in the LSST Science Book, when calculating that hundreds of $z = 2-4$ PISNe will be detected by the LSST (chapter 11.14), the authors used $z$- and $y$-band sensitivities of $\sim 26.2$. This is unrealistic as $M_{AB} \sim 26.2$ can only be reached in the $z$ band by stacking all images over the entire 10 yr lifetime of the survey, but no PISN will stay bright enough that long even with time dilation; the $y$ band is even less sensitive. Our findings suggest that, to find PISNe at $z > 2$, an instrument with better IR capabilities such as the James Webb Space Telescope$^1$ is required.

Although stacking multiple images averages out the time variation in the SN light curve, the LSST also allows a secondary survey over a smaller area of sky, going substantially deeper in a single epoch. However, due to the steep luminosity function of PISNe, we will preferentially see only the massive PISN events beyond the local universe, so narrow, deep exposures by the LSST are more useful for improving light-curve coverage, instead of SN discovery.

4 DISCUSSION

Runaway collisions were explored most seriously in massive, dense clusters, so equation (2) may not be accurate for $m < 10^3 M_\odot$.

---

$^1$ http://www.jwst.nasa.gov/
However, only more massive clusters can make runaway masses \( m_r \) in the PISN progenitor mass range, so this does not affect the predicted PISN rate. In addition, initial mass segregation of stars within young clusters observed by de Grijs et al. (2002) and Stolte et al. (2006) will shorten the time to runaway collisions and increase \( m_r \), but we do not take this into account.

For \( z \lesssim 6 \), the rate and detectability of PISN from Pop III progenitors born in surviving pockets of metal-free gas were investigated by Scannapieco et al. (2005). To model the PISN light curves, they used an implicit hydrodynamics code which only implements grey diffusive radiation transport; for spectra and colours they assumed a blackbody distribution. Depending on the intergalactic medium metal enrichment history, their predicted rates span two orders of magnitude, with their lower end roughly equal to our collision runaway rates at \( z = 1 - 2 \). However, a PISN with a pristine host galaxy has yet to be observed.

A pilot search done using the Spitzer/IRAC dark field found no candidates above the sensitivity limit of \( M_{AB}(3.6 \, \mu m) \approx 24 \), placing a 95 per cent confidence upper limit of 23 deg\(^{-2}\) yr\(^{-1}\) for >1 Jy sources with plateau scales less than \( 400/(1 + z) \) (Frost et al. 2009), which does not contradict the predicted rate of \(<0.1 \) PISN per deg\(^2\) per year for our collision runaway model.

More recently, observers have discovered a class of ultraluminous SN, with luminosities exceeding those of the brightest pair-instability events and rates of the order of \( \sim 10^{-8} \) Mpc\(^{-3}\) yr\(^{-1}\) at \( z \approx 0.3 \). These events do not appear to be standard radioactively powered PISNe, as their luminosities are too high and their light-curve durations too short (e.g., Chomiuk et al. 2011; Quimby et al. 2011). Comparing the rate of those events to that of the two putative observed PISNe, Gal-Yam found that PISNe are roughly approximately five times rarer than the Quimby et al. (2011) ultra-luminous SNe (Gal-Yam 2012). This gives a PISN rate of \( \sim 2 \times 10^{-9} \) Mpc\(^{-3}\) yr\(^{-1}\) in the local universe, roughly consistent with the collision runaway rates found in Fig. 2.

If the collision runaways of massive stars in young, massive stellar clusters give rise to PISNe at Pop II/I metallicities, we expect to see such a young, massive cluster at the same location after the light of the SN has faded away. However, even a 10\(^3\) M\(_\odot\) cluster only has an absolute magnitude of about \( -8.2 \) mag, so the PISN will have to occur close by (\( z < 0.05 \)) for its host cluster to be observed with current telescopes. Also, these PISNe should follow the distribution of clusters and appear in the luminous parts of their host galaxies, analogous to the position of long-duration gamma-ray bursts. Note that due to the steep distribution of collision runaway masses (see Fig. 1), the rates of PISNe from collision runaways will still be higher in environments with low metallicities, as long as the mass-loss for massive stars is proportional to metallicity.

Alternatively, if mass-loss models are wrong and the Galactic stellar mass limit is violated, we need not invoke stellar mergers to create the massive progenitors required for the observed non-pristine PISNe. Langer et al. (2007) found that hydrogen-rich PISNe could occur at metallicities as high as \( Z_\odot/3 \), resulting in a rate of about 1 PISN per 10\(^3\) SNe in the \( z \approx 0 \) universe. For a more conservative metallicity threshold of \( Z_\odot/10 \), the rate would be about 1 PISN per 10\(^4\) SNe. However, even the latter is a few times higher than the current inferred rate of PISNe.

5 CONCLUSION

We have shown that the runaway collision and merger of stars in a young, dense star cluster may form the massive progenitor of a PISN at non-zero metallicity. The volumetric rate of such events is a few times \( 10^{-9} \) Mpc\(^{-3}\) yr\(^{-1}\) in the local universe, roughly matching the inferred rate of PISN events SN 2007bi and PTF 10nmn, in ongoing surveys both of which have a metal-poor but not metal-free host galaxy. We expect that the primary survey of the LSST would see \( \sim 10^2 \) such events per year.

ACKNOWLEDGMENTS

We thank Charlie Conroy for helpful comments. TP was supported by the Hertz Foundation. This work was supported in part by NSF grant AST-0907890 and NASA grants NNX08AL43G and NNA09DB30A. DK was supported in part by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Divisions of Nuclear Physics, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231, and by an NSF Astronomy and Astrophysics grant NSF-AST-1109896. This research has been supported by the DOE SciDAC Program (DE-FC02-06ER41438). We are grateful for computer time provided by ORNL through an INCITE award and by NERSC.

REFERENCES

Bastian N., 2008, MNRAS, 390, 759
Belkus H., Van Bever J., Vanbeveren D., 2007, ApJ, 659, 1576
Blanton M. R. et al., 2003, ApJ, 592, 819
Bromm V., Larson R. B., 2004, ARA&A, 42, 79
Bromm V., Loeb A., 2003, Nat, 425, 812
Cappa C., Goss W. M., van der Hucht K. A., 2004, AJ, 127, 2885
Chomiuk L. et al., 2011, ApJ, 743, 144
Crowther P. A., Schnurr O., Hirschi R., Yusof N., Parker R. J., Goodwin S. P., Kassim H. A., 2010, MNRAS, 408, 731
De Donder E., Vanbeveren D., 2003, New Astron., 8, 415
de Grijs R., Gilmore G. F., Mackey A. D., Wilkinson M. I., Beaulieu S. F., Johnson R. A., Santiago B. X., 2002, MNRAS, 337, 597
de Jager C., Nieuwenhuijzen H., van der Hucht K. A., 1988, A&A, 72, 259
Figer D. F., 2005, Nat, 434, 192
Fosbury R. A. E. et al., 2003, ApJ, 596, 797
Freitag M., Gürtan M. A., Rasio F. A., 2006, MNRAS, 368, 141
Frost M. I., Surace J., Moustakas L. A., Krick J., 2009, ApJ, 698, L68
Furlanetto S. R., Loeb A., 2003, ApJ, 588, 18
Gal-Yam A. et al., 2009, Nat, 462, 624
Gal-Yam A., 2012, Sci, submitted
Gieles M., Larsen S. S., Scheepmaker R. A., Bastian N., Haas M. R., Lamers H. J. G. L. M., 2006, A&A, 446, L9
Glebbeek E., Gaburov E., de Mink S. E., Pols O. R., Portegies Zwart S. F., 2009, A&A, 497, 255
Gürkan M. A., Freitag M., Rasio F. A., 2004, ApJ, 604, 632
Guseva N. G., Papaderos P., Meyer H. T., Izotov Y. I., Fricke K. J., 2009, A&A, 505, 63
Hamann W.-R., Gratier G., Liermann A., 2006, A&A, 457, 1015
Heger A., Woosley S. E., 2002, ApJ, 567, 532
Kasen D., Bildsten L., 2010, ApJ, 717, 245
Kasen D., Woosley S. E., Heger A., 2011, ApJ, 734, 102
Kirby E. N., Simon J. D., Geha M., Guhathakurta P., Frebel A., 2008, ApJ, 685, L43
Kudritzki R. P., 2002, ApJ, 577, 389
Langer N., 1989, A&A, 220, 135
Langer N., Norman C. A., de Koter A., Vink J. S., Cantiello M., Yoon S., 2009, A&A, 475, L19
Larsen S. S., 2009, A&A, 461, 537
Larsen S. S., 2009, A&A, 494, 539
LSST Science Collaborations, 2009, preprint (arXiv:0912.0201)
McCready N., Graham J. R., 2007, ApJ, 663, 844
McMillan S., Portegies Zwart S., 2004, preprint (arXiv:astro-ph/0412622)
Moriya T., Tominga N., Tanaka M., Maeda K., Nomoto K., 2010, ApJ, 717, L83
Nelemans G., van den Heuvel E. P. J., 2001, A&A, 376, 950
Nugis T., Lamers H. J. G. L. M., 2000, A&A, 360, 227
Portegies Zwart S. F., McMillan S. L. W., 2002, ApJ, 576, 899
Portegies Zwart S. F., van den Heuvel E. P. J., 2007, Nat, 450, 388
Portegies Zwart S. F., Baumgardt H., McMillan S. L. W., Makino J., Hut P., Ebisuzaki T., 2006, ApJ, 641, 319
Portegies Zwart S. F., McMillan S. L. W., Gieles M., 2010, ARA&A, 48, 431
Puls J., Vink J. S., Najarro F., 2008, A&AR, 16, 209
Quimby R. M. et al., 2011, Nat, 474, 487
Raiter A., Fosbury R. A. E., Teimoorinia H., 2010, A&A, 510, A109
Reddy N. A., Steidel C. C., 2009, ApJ, 692, 778
Scannapieco E., Schneider R., Ferrara A., 2003, ApJ, 589, 35
Scannapieco E., Madau P., Woosley S., Heger A., Ferrara A., 2005, ApJ, 633, 1031
Schechter P., 1976, ApJ, 203, 297
Scheepmaker R. A., Haas M. R., Gieles M., Bastian N., Larsen S. S., Lamers H. J. G. L. M., 2007, A&A, 469, 925
Smith N. et al., 2011, ApJ, 732, 63
Stolte A., Brandner W., Brandl B., Zinnecker H., 2006, AJ, 132, 253
Tornatore L., Ferrara A., Schneider R., 2007, MNRAS, 382, 945
Trenti M., Stiavelli M., Michael Shull J., 2009, ApJ, 700, 1672
Vanbeveren D., Belkus H., van Bever J., Mennecens N., 2009, Ap&SS, 324, 271
Vink J. S., de Koter A., Lamers H. J. G. L. M., 2001, A&A, 369, 574
Weidner C., Kroupa P., Bonnell I. A. D., 2010, MNRAS, 401, 275
Woosley S. E., Blinnikov S., Heger A., 2007, Nat, 450, 390
Young D. R. et al., 2010, A&A, 512, A70
Youngson L. R., van den Heuvel E. P. J., Vink J. S., Portegies Zwart S. F., de Koter A., 2008, A&A, 477, 223
Zhang Q., Fall S. M., 1999, ApJ, 527, L81

This paper has been typeset from a TeX/LaTeX file prepared by the author.