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# RECONCILING $^{56}$NI PRODUCTION IN TYPE IA SUPERNOVAE WITH DOUBLE DEGENERATE SCENARIOS

ANTHONY L. PIRO[1], TODD A. THOMPSON[2], AND CHRISTOPHER S. KOCHANEK[2]

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## ABSTRACT

Binary white dwarf (WD) coalescence driven by gravitational waves or collisions in triple systems are potential progenitors of Type Ia supernovae (SNe Ia). We combine the distribution of $^{56}$Ni inferred from observations of SNe Ia with the results of both sub-Chandrasekhar detonation models and direct collision calculations to estimate what mass WDs should be exploding in each scenario to reproduce the observations. These WD mass distributions are then compared with the observed Galactic WD mass distribution and Monte Carlo simulations of WD-WD binary populations. For collisions, we find that the average mass of the individual components of the WD-WD binary must be peaked at $\approx 0.75\,M_{\odot}$, significantly higher than the average WD mass in binaries or in the field of $\approx 0.55-0.60\,M_{\odot}$. Thus, if collisions indeed produce a large fraction of SNe Ia, then a mechanism must exist that favors large mass WDs. In particular, collisions between WDs of average mass must be highly suppressed. For sub-Chandrasekhar detonations, we find that the average mass of the exploding WDs must be peaked at $\approx 1.1\,M_{\odot}$, consistent with the average sum of the masses in WD-WD binaries. This interesting similarity should be tested by future calculations of the $^{56}$Ni yield from double degenerate mergers. These models may also explain why SNe Ia are on average dimmer in early-type hosts: in old environments binaries evolve too quickly to have mergers between two high mass WDs at current times. As future simulations explore the $^{56}$Ni yield over a wider range of parameters, the general framework discussed here will be an important tool for continuing to assess double degenerate scenarios.

*Subject headings:* nuclear reactions, nucleosynthesis, abundances — supernovae: general — white dwarfs

## 1. INTRODUCTION

The use of Type Ia supernovae (SNe Ia) as precision probes of cosmology (e.g., Riess et al. 1998; Perlmutter et al. 1999) will ultimately be limited by systematic uncertainties. Understanding and minimizing these uncertainties should be advanced by having a complete physical understanding of the underlying mechanism behind the explosion. Thus, one of the consequences of the focus on SNe Ia as cosmological distance indicators has been to emphasize the enormous theoretical uncertainties that remain about these events. It is generally accepted that they result from unstable thermonuclear ignition of degenerate matter (Hoyle & Fowler 1960) in a C/O white dwarf (WD), but frustratingly the specific progenitor systems have not yet been identified. The main three candidates are (1) stable accretion from a non-degenerate binary companion until the Chandrasekhar limit is reached (single degenerates, Whelan & Iben 1973), (2) the merger of two C/O WDs (double degenerates, Iben & Tutukov 1984; Webbink 1984), or (3) accretion and detonation of a helium shell on a C/O WD that leads to a prompt detonation of the core (double detonations, Woosley & Weaver 1994a; Livne & Arnett 1995). An important outstanding problem is to understand how these scenarios contribute to the SNe Ia we observe, and whether any one channel is dominant.

In recent years, the double degenerate mechanism has been increasingly at the center of attention. Observationally, there are arguments in favor of this scenario from the non-detection of a companion in pre-explosion imaging of nearby SNe Ia (Li et al. 2011a), the lack of radio emission from SNe Ia (Hancock et al. 2011; Horesh et al. 2012), the lack of hydrogen emission in nebular spectra of SNe Ia (Leonard 2007; Shappee et al. 2013a), the lack of X-ray emission in elliptical galaxies (Gilfanov & Bogdán 2010), a lack of a signature of ejecta interaction with a companion (Kasen 2010; Hayden et al. 2010; Bloom et al. 2012), and the missing companions in SNe Ia remnants (Schaefer & Pagnotta 2012) even though they should be super-luminous (Pan et al. 2012; Shappee et al. 2013b). Potential problems with matching the rate of SNe Ia with double degenerate mergers may be alleviated if the mergers are in sub-Chandrasekhar WD-WD binaries (van Kerkwijk et al. 2010; Badenes & Maoz 2012).

On the theoretical side, double degenerate scenarios have historically been disfavored because accretion after tidal disruption triggers burning that turns the C/O WD into a O/Ne WD (Nomoto & Iben 1985; Saio & Nomoto 1998), which then collapses to a neutron star due to electron captures (Nomoto & Kondo 1991). This problem remains even with more detailed treatments of the long-term evolution of the merger remnant (Shen et al. 2012). More recently though, the double degenerate scenario has been revitalized by new simulations which indicate that ignition may be triggered by a detonation in an accretion stream (Guillochon et al. 2010; Dan et al. 2012) or in "violent mergers" involving massive WDs (Pakmor et al. 2012). WDs may also explode in direct collisions (Rosswog et al. 2009), which would be another way for double degenerates to give rise to SNe Ia. While this scenario may have been viewed as unlikely only a few years ago, it is now reasonably clear that triples systems are more common (Raghavan et al. 2010) and that the Kozai mechanism both greatly accelerates binary mergers and drives direct collisions (Thompson 2011; Katz & Dong 2012) in such systems.

With this increased focus on double degenerate scenarios, the time is ripe to make better comparisons to observed and theoretical populations of WD binaries. The Lick Observatory Supernova Search (LOSS) finds a rate of $(3.01\pm0.062)\times$

[1] Theoretical Astrophysics, California Institute of Technology, 1200 E California Blvd., M/C 350-17, Pasadena, CA 91125; piro@caltech.edu
[2] Department of Astronomy and Center for Cosmology & Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA

$10^{-5}$ Ia Mpc$^{-3}$ yr$^{-1}$ (Li et al. 2011c), which corresponds to $(4.0-7.1)\times10^{-3}$ Ia yr$^{-1}$ for the Milky Way. For a Galactic star formation rate of $\approx 0.7-1.5\,M_\odot\,\mathrm{yr}^{-1}$ (Robitaille & Whitney 2010), a few percent of all WDs formed must end their lives as SNe Ia. This may be a small number, but it is not negligible and may be an important limitation on any SN Ia production scenario. *Namely, if a scenario requires a distributions of WD masses that is too different from the known distribution of WD masses, then it will be difficult for that scenario to explain the majority of SNe Ia.* In this work we investigate this problem using the following strategy. First, the luminosity distribution of SNe Ia implies a corresponding distribution of radioactive $^{56}$Ni synthesized, which we present in §2. Next in §3, we combine this $^{56}$Ni distribution with theoretical yields from sub-Chandrasekhar detonation models and collision calculations to find the implied mass distributions of WDs that must be exploding for each scenario. We compare this to what is known about field WDs and Monte Carlo calculations of WD-WD binaries to discuss how likely a given scenario is for explaining most SNe Ia. We conclude in §4 with a summary of our results and a discussion of future work in this area.

## 2. THE OBSERVED $^{56}$NI DISTRIBUTION

We begin by investigating the range of nickel masses, $M_{56}$, produced in SNe Ia. LOSS provides the peak $B$-band absolute magnitude, $M_{\rm max}(B)$, of 74 SNe Ia within 80 Mpc (Li et al. 2011b). The sample is estimated to be 98% complete due to the high peak luminosity of these SNe. There may be some bias because LOSS targets specific galaxies rather than broadly surveying the sky. For example, the sample is mostly composed of normal SNe Ia, without any super-Chandrasekhar events (e.g., SN 2003fg, Howell et al. 2006) possibly because these tend to be associated with low-metallicity dwarf galaxies (Khan et al. 2011) that are not a focus of the survey.

The standard peak luminosity-decline rate relation from Phillips (1993),

$$M_{\rm max}(B) = -21.726 + 2.698\Delta m_{15}(B), \tag{1}$$

where $\Delta m_{15}(B)$ is the change in the magnitude 15 days post peak, allows us to calculate $\Delta m_{15}(B)$ for each SN. This is substituted into the decline rate-nickel mass relation presented in Mazzali et al. (2007),

$$M_{56}/M_\odot = 1.34 - 0.67\Delta m_{15}(B), \tag{2}$$

which has an rms dispersion of $0.13\,M_\odot$, to calculate the distribution of $M_{56}$ from the LOSS catalog of SNe Ia. In Figure 1 we plot histograms summarizing this analysis. We compare all SNe Ia (solid line) with SNe Ia from early-type host galaxies (dashed line) and late-type host galaxies (dotted line). It has long been appreciated that SNe Ia are on average brighter in late-type galaxies in comparison to early-type galaxies (e.g., Howell et al. 2007), which corresponds to the average SNe Ia in a late-type galaxy producing $\approx 0.13\,M_\odot$ more $^{56}$Ni (Piro & Bildsten 2008). Although this difference is apparent in Figure 1, both distributions still show a clear peak at around $M_{56}\approx 0.65\,M_\odot$. For this reason, and because combining both types of hosts provides the best statistics on the $M_{56}$ distribution, we focus on the luminosity distribution of all SNe Ia together for the present study. In the future, similar analysis can and should be applied to SNe Ia with early- and late-type hosts separately.

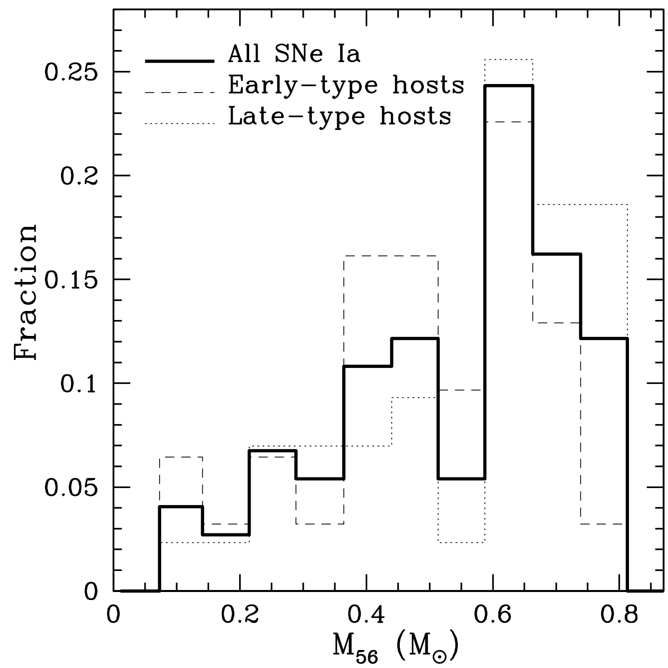


FIG. 1.— Histogram showing the fraction of SNe Ia that produce different amounts of $^{56}$Ni using the LOSS sample (Li et al. 2011b).

## 3. PROGENITOR WHITE DWARF MASS DISTRIBUTIONS

Different SNe Ia mechanisms imply different relations between the mass of the exploding WD and the amount of $^{56}$Ni synthesized. For the present work we focus on two different scenarios for double degenerate explosions as follows.

**sub-Chandrasekhar Detonations:** We use the work of Sim et al. (2010), which considers the detonation of sub-Chandrasekhar WDs. Although they do not study a specific mechanism for triggering these detonations, such an event could occur in a double detonation following helium accretion from a non-degenerate helium star or a helium WD (Fink et al. 2010) or in a WD-WD merger from a circular orbit (van Kerkwijk et al. 2010). We refer to this case as the "detonation scenario." Sim et al. (2010) find that they can reproduce the range of $M_{56}$ needed for the observed SNe Ia given a very narrow WD mass range of $M_{\rm WD}\approx 0.97-1.15\,M_\odot$. We fit their results with a third-order polynomial,

$$\log_{10}(M_{56}/M_\odot) = 56.47(M_{\rm WD}/M_\odot)^3 - 186.30(M_{\rm WD}/M_\odot)^2 + 206.56(M_{\rm WD}/M_\odot) - 77.13, \tag{3}$$

to estimate the $^{56}$Ni as a function of the detonating WD mass.

**Collisions:** We consider the collision calculations of Kushnir et al. (2013), which we refer to as the "collision scenario." They generally find that the $^{56}$Ni yield only depends on the average mass of the constituents in the collision,

$$M_{\rm avg} = 0.5(M_{\rm WD,1} + M_{\rm WD,2}), \tag{4}$$

where $M_{\rm WD,1}$ and $M_{\rm WD,2}$ are the primary and secondary masses of the WDs that are colliding, respectively. Again, we fit their $^{56}$Ni yield with a third-order polynomial,

$$\log_{10}(M_{56}/M_\odot) = 16.42(M_{\rm avg}/M_\odot)^3 - 40.49(M_{\rm avg}/M_\odot)^2 + 34.13(M_{\rm avg}/M_\odot) - 9.98. \tag{5}$$

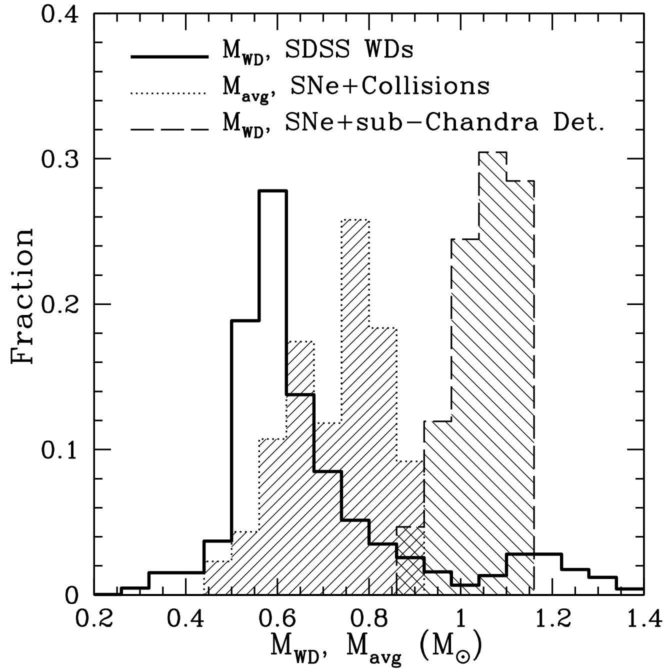


FIG. 2.— Histograms of the distribution of WD masses $M_{\rm WD}$ from the SDSS WD catalog (Kepler et al. 2007, thick, solid line) as compared to the WD masses needed for sub-Chandrasekhar detonations (Sim et al. 2010, dashed line, lightly shaded histogram) and average collision masses $M_{\rm avg}$ needed for head-on collisions (Kushnir et al. 2013, dotted line, darkly shaded histogram).

In the future, a more complete comparison with collision calculations should also include the mass ratio and impact parameter of the collision. For example, in the best-resolved smooth particle hydrodynamic 3D simulations of Raskin et al. (2010), they generally find $\sim 10\%$ more $^{56}$Ni production in equal mass head-on collisions in comparison to Kushnir et al. (2013), and a significant decrease in $^{56}$Ni for unequal mass head-on collisions. For the time being, we delay doing a comparison with this other set of calculations until there exists a more complete survey over the full range of parameters.

We combine the $^{56}$Ni distribution in Figure 1 with equation (3) and then equation (5) to derive the WD mass distribution needed to reproduce the observations in the detonation and collision scenarios, respectively. The results are shown in Figure 2 (dashed and dotted lines, respectively, shaded) together with the mass distribution of field WDs (solid line), which we discuss in the following section. Figure 2 shows that collisions must come from WD-WD binaries with component masses of $\approx 0.75\,M_\odot$ in order to reproduce the observed SNe Ia luminosity function, whereas sub-Chandrasekhar detonations must come from WDs with masses of $\approx 1.1\,M_\odot$.

### 3.1. *Comparisons to Field White Dwarfs*

We next compare these inferred mass distributions with that of field WDs. For this we use the volume-corrected mass distribution of spectroscopically confirmed WDs from Sloan Digital Sky Survey Data Release 4 (Kepler et al. 2007). Summing all DA and DB WDs, the total sample contains over 1,800 WDs. Plotting this distribution on Figure 2 (thick, solid line), the average mass of field WDs is $\approx 0.55-0.60\,M_\odot$, and it is clearly different than either the detonation or collision scenarios. In particular, this comparison shows that collisions between average-mass WDs of $\sim 0.6\,M_\odot$ produce too little Ni to power observed SNe Ia. Thus, if collisions are responsible for the SNe Ia we see, they must pick out high-mass progenitors and collisions must be suppressed in binaries with average-mass WD constituents.

Although the mass distribution inferred for sub-Chandrasekhar detonations is also inconsistent with the field WD population, as one would expect naively, its peak at $\approx 1.1\,M_\odot$ is not too dissimilar from the secondary high-mass peak in the field WD population at $\approx 1.2\,M_\odot$. It has been suggested that the high mass peak is due to mergers of lower mass WDs (Vennes 1999; Liebert et al. 2005), which may indicate a connection between mergers and sub-Chandrasekhar detonations. The implication may be that either (1) SN Ia progenitors are coming from the same binary mergers that would produce these massive WDs or that (2) the WDs merged first and then the explosion was triggered later, as in a double detonation. In the first case, it is unclear why some WDs would explode upon merger (producing SNe Ia) while other WDs would produce the massive field WDs. In the second case, it seems like a specialized set of circumstances would be needed to first produce massive WD via a merger and then have an event that subsequently triggered an explosion. On the other hand, it has also been argued that the kinematics of massive WDs are consistent with single star evolution (Wegg & Phinney 2012). The suggestion is then that perhaps SNe Ia come from more massive WDs that are simply the result of more massive main sequence stars. Whatever the conclusion is, the rough similarity of these peaks clearly requires more investigation, some of which we conduct in the next section.

### 3.2. *Comparisons to Binary Populations*

So far we have made comparisons to field WDs, but SN Ia progenitors are expected to be in binary (or perhaps triple) systems. To asses the impact of binarity we calculate a simple model for the binary mass distribution. This investigation has two main goals, namely (1) to test whether WD-WD binaries have a mass distribution that is significantly different from the field WD mass distribution that we used in the previous section, and (2) to estimate the average and total mass in binaries for additional comparisons with explosion scenarios.

Our analysis proceeds as follows. First, we consider a distribution of main sequence stars with mass $M_1$, which obeys a Salpeter initial mass function,

$$dN/dM_1 \propto M_1^{-2.35}. \tag{6}$$

Next we consider companion masses $M_2$, which are assigned a flat distribution in mass so that the probability $P(q)$ is constant, where $q = M_2/M_1 \leq 1$. For a given binary we can evaluate the final masses of each of the WDs that are created using the initial mass-final mass relation (Kalirai et al. 2008)

$$M_{{\rm WD},i}/M_\odot = 0.109 M_i + 0.394. \tag{7}$$

We assume a maximum mass of $7\,M_\odot$ for $M_1$ and $M_2$ to produce a C/O WD. The lower mass limit does not matter because stars with a sufficiently low mass to produce helium WDs are excluded by our model due to their long time on the main sequence. The timescale for formation of a double degenerate binary is

$$t_{\rm form} = t_{\rm birth} + 10\left(\frac{M_2}{M_\odot}\right)^{-2.5} {\rm Gyr}, \tag{8}$$

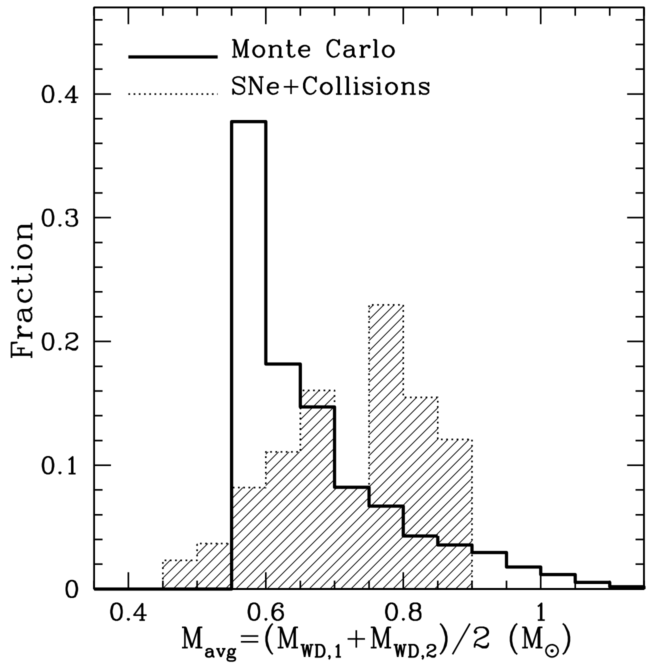


FIG. 3.— Histograms of the distribution of *average* WD masses $M_{\rm avg}$ from Monte Carlo binary estimates as described in the text (thick, solid line) in comparison to the average WD masses needed for head-on collisions (Kushnir et al. 2013, dotted line, darkly shaded histogram).

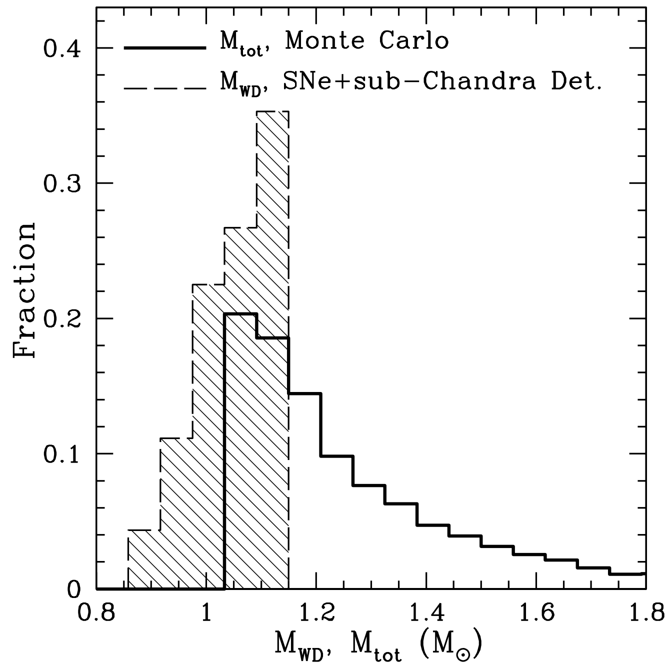


FIG. 4.— Histograms of the distribution of *tota*l WD masses $M_{\rm avg}$ from Monte Carlo binary estimates (thick, solid line) as compared to the average WD masses needed for sub-Chandrasekhar detonation (Sim et al. 2010, dashed line, lightly shaded histogram).

where $t_{\rm birth}$ is the time when the main-sequence binary was first created. Note that $t_{\rm form}$ is controlled by mass $M_2$, since the lower mass secondary will take longer to evolve off the main sequence. Finally, there is an explosion time given by the sum of the formation time and the timescale for ignition of a detonation or a collision,

$$t_{\rm exp} = t_{\rm form} + t_{\rm ign}. \quad (9)$$

Given this set of prescriptions, we can assemble a large number of WD binaries with a distribution of masses and associated timescales. We can then estimate the current distribution now at time $t_{\rm now} \approx 10\,{\rm Gyr}$ by asking which binaries have $t_{\rm now} > t_{\rm form}$ and $t_{\rm now} < t_{\rm exp}$, in other words, those binaries that have had enough time to produce double degenerates, but have not yet exploded as SN Ia. In this way we can estimate a WD-WD binary mass distribution for comparison with the detonation and collision scenarios.

For our first comparison we look at the distribution of average masses, $M_{\rm avg}$, from the Monte Carlo analysis and compare this to the same distribution needed for collisions to reproduce SNe Ia observations in Figure 3. For this specific case we use $t_{\rm ign} = 250\,{\rm Myr}$, although we find that the results do not depend sensitively on this assumption as long $t_{\rm ign} \lesssim t_{\rm form}$. We also use a constant star formation rate at all times, which corresponds to $t_{\rm birth}$ being distributed uniformly in time, although our analysis can be generalized to more complicated star formation star formation histories. We find that the Monte Carlo mass distribution is similar to the field distribution shown in Figure 2, with the exception that the Monte Carlo calculation does not give additional high mass peaks (perhaps because we are not accounting for mergers; see §3.1). We therefore again find that the mass distribution of WDs is strongly inconsistent with that needed for a collision scenario: WD masses are on average just too low to account for the brightness of observed SNe Ia given the calculated $^{56}$Ni yields of collision simulations.

For the sub-Chandrasekhar detonation scenario, we compare with the *total* mass in each of the binaries,

$$M_{\rm tot} = M_{\rm WD,1} + M_{\rm WD,2}. \quad (10)$$

The idea here is that a merger in a double degenerate could potentially be qualitatively similar to the mass budget of just combining the two WDs. One should be careful here because exploding two $0.6\,M_\odot$ WDs separately will yield much less $^{56}$Ni mass than exploding one $1.2\,M_\odot$ WD. Using $M_{\rm tot}$ corresponds to the assumption that following the merger the density reaches a configuration roughly like the larger mass object, which may require some time to adjust to the increase in mass (e.g., Shen et al. 2012). With these caveats in mind, we show the comparison between the detonation scenario and Monte Carlo analysis in Figure 4. In this case the peaks are basically consistent at $M_{\rm tot} \approx 1.1\,M_\odot$. We conclude from this comparison that it is at least plausible that *the average SNe Ia could be explained by sub-Chandrasekhar mergers as long as the total mass of the binary corresponds to the explosion mass.*

The main difference between the Monte Carlo analysis and the detonation scenario is that the SN Ia luminosity function implies a population of lower mass mergers with $M_{\rm tot} \lesssim 1.0\,M_\odot$, while the Monte Carlo analysis implies some much more massive mergers with $M_{\rm tot} \gtrsim 1.2\,M_\odot$. The more massive mergers could potentially correspond to super-Chandrasekhar SN Ia or perhaps lead to AIC. Taking the results from the model at face value, we find 53% of the binaries have $M_{\rm tot} \leq 1.2\,M_\odot$, 24% have $1.2\,M_\odot < M_{\rm tot} \leq 1.4\,M_\odot$, and 23% have $M_{\rm tot} > 1.4\,M_\odot$.

## 4. CONCLUSION AND DISCUSSION

We have conducted an initial investigation into the viability of the collision and sub-Chandrasekhar detonation scenarios for SNe Ia. We derive the WD mass distributions needed to explain the observed luminosity function of SNe Ia (Figure 1) using the latest estimates of $^{56}$Ni production in each scenario as a function of WD mass. We compare these with both observed field WD mass distributions and binary WD-WD masses from Monte Carlo population analysis.

### 4.1. *sub-Chandrasekhar Detonation Scenario*

Our main conclusion for the sub-Chandrasekhar detonation scenario (Sim et al. 2010) is that it requires the explosion of WDs with an average mass of $\approx 1.1 M_\odot$. This is clearly inconsistent with the general mass distribution of *single* field WDs, but may be similar to a population of more massive WDs which have a distribution peak at around $\approx 1.2 M_\odot$ (Figure 2). We then compared the detonation scenario with the total mass in double degenerate binaries and also found that they exhibited a similar peak (Figure 4). Although this connection is enticing, there are a number of problems that still need to be sorted out to understand its importance. First, if two WDs merge, the mass of the resulting WD that experiences the detonation need not be exactly the sum of the two constituents. This analysis would therefore benefit from some conversion factor, which would give a better estimate of how much material is at a sufficiently high density to produce $^{56}$Ni. Second, there are difficulties with explaining lower luminosity SNe Ia within this simple picture because they would require $M_{\rm tot} \approx 0.9 M_\odot$, which is difficult to produce with two C/O WDs. This may be related to the conversion problem mentioned just above, or it could indicate that a different progenitor (for example, double detonations where a lower mass helium WD is involved) is needed in this luminosity range.

### 4.2. *Collision Scenario*

For the collision scenario we find that the average mass of an exploding WD must be $\approx 0.75 M_\odot$. We show that this is difficult to reconcile with any natural population of WDs. The problem mainly stems from the finding of Kushnir et al. (2013) that the $^{56}$Ni yield depends most strongly on the average mass of the collision. We note that DB WDs and magnetic WDs are generally more massive than DA and non-magnetic WDs (Wickramasinghe & Ferrario 2000; Kepler et al. 2007), but there is not a clear reason why these populations should be expected to participate in collisions more often than regular WDs. Our conclusions do not rule out the collision mechanism for producing some SNe Ia, and in fact low luminosity SNe Ia with $M_{56} \lesssim 0.4 M_\odot$ may be naturally explained by collisions, but it makes it hard to see how collisions could produce a significant fraction of the normal SNe Ia that we observe. This inconsistency may be fixed if the $^{56}$Ni yields in hydrodynamic calculations are too low by $\approx 0.15 M_\odot$, the conversion from SN Ia peak luminosity to $M_{56}$ is too high by the same factor, or physics associated with glancing collisions that yield subsequent mergers produce much more $^{56}$Ni, making them more akin to the sub-Chandrasekhar mass detonations discussed here.

### 4.3. *Missing Details and Future Work*

The investigation presented here uses a simple analysis to compare WD populations and explosion scenarios. Additional details should be included in future, more comprehensive work. In the Monte Carlo analysis we used a constant star formation rate over all time. In cases were star formation is more strongly peaked at earlier times, this would favor lower mass progenitors at later times since they have longer to evolve. *This naturally predicts lower luminosity SNe Ia in older systems because the higher mass systems evolve more rapidly.* This may explain why late-type hosts have systematically brighter SNe Ia than early-type hosts, and why the brightest events also occur in these kinds of galaxies (e.g., Howell et al. 2007).

Another factor we have not completely accounted for is the timescale for detonation or collision in each scenario and as a function of the WD masses. As long as $t_{\rm ign}$ is less than $t_{\rm form}$ this is a relatively small correction, but this need not be the case for all mass ratios. In particular, higher mass primaries have a wider range of possible companion masses. The "eccentric Kozai mechanism" (EKM), which promotes very strong eccentricity maxima and collisions in the inner binary of triple systems (Ford et al. 2000; Naoz et al. 2011; Lithwick & Naoz 2011; Katz et al. 2011; Naoz et al. 2013), favors high mass ratio binaries and is suppressed over a wide range of tertiary inclination when the masses of the inner binary are approximately equal (see Naoz et al. 2013; Shappee & Thompson 2013). If EKM eccentricity maxima generically lead to collisions, then this would favor collisions in systems with higher $M_{\rm avg}$, which might help alleviate some of the inconsistencies seen in Figure 3. The EKM has also recently been shown to be enhanced over a broad range of parameter space in quadruple systems (Pejcha et al. 2013), potentially favoring WD-WD collisions in systems with initial mass distributions that might be different from normal binaries.

The machinery we have developed can be applied to new theoretical calculations of collisions and detonations, as well as test other novel double degenerate scenarios. Some of the questions that would be particularly important to work out include the following.

- In collision scenarios, what is the $^{56}$Ni production as a function of the impact parameter and mass ratio?
- In collision scenarios, how does the timescale for the collision ($t_{\rm ign}$ in our model) depend on the mass ratio?
- In sub-Chandrasekhar detonation scenarios, what is the expected $^{56}$Ni as a function of the $M_{\rm tot}$, and how does it depend on the mass ratio?
- As the rates of super-Chrandrasekhar SNe Ia are better characterized in comparison to regular SNe Ia, does this favor detonation or collision scenarios?
- Since we have not considered helium WDs in our binary population calculation, what role does the merger of a helium WD and a C/O WD play in any of these scenarios, including potentially producing a double detonation?

As these questions are better investigated, it should be more clear as to whether or not double degenerates produce the majority of the SNe Ia.

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