Origin of the Galactic 511 keV emission from positrons produced inirregular supernovae

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Gamma ray emission of 511 keV lines arising from electron-positron annihilation has been detected from the Galaxy since the 70s[1]. Spatially resolved observations using the INTEGRAL satellite have shown its full sky distribution to be strongly concentrated in the Galactic bulge, with a smaller contribution from the disk, unlike the situation in any other wavelength[2–4]. The puzzling distribution of the positrons gave rise to various suggestions, including stellar nucleosynthesis in core-collapse (CC) and type Ia thermonuclear supernovae (SNe), accreting compact objects, and more “exotic” explanations of annihilation of dark-matter particles. However, such models encounter difficulties in reproducing the total Galactic 511 keV flux as well as its peculiar bulge-centered distribution[4]. Theoretical models of SNe from thermonuclear Helium detonations on white dwarfs (WDs) were suggested as potential additional sources of positrons, contributing to the Galactic Gamma-ray emission[5].

Here, we show that the recently discovered class of faint, calcium-rich type Ib SNe (with the prototype SN 2005E)[6], thought to arise from such explosions, also called “Ia” SNe[5, 7], can explain both the 511 keV flux and its distribution, and can eliminate the need for non-astrophysical (e.g., dark matter annihilation) sources. Such SNe comprise a fraction of only ~ 2% of all SNe[6, 8], but they currently inject hundreds of times more positrons (from $^{44}$Ti decay) to the ISM than injected by CC SNe[9], enough to reproduce the total Galactic 511 keV line emission. They exclusively explode in old environments[6, 10–13], and their contribution to the 511 keV emission therefore follows the old (> 10 Gyrs) Galactic stellar population, dominated by the bulge, thereby reproducing the observed large bulge-to-disk ratio.

Best fit models of the observed full-sky distribution of 511 keV line emission find a total Galactic flux of $17.1^{+2.1}_{-1.2} \times 10^{-4}$ cm$^{-2}$s$^{-1}$ corresponding to a positron production rate of $\dot{N}_{e^+} = 19.6^{+2.3}_{-2} \times 10^{42}$s$^{-1}$, in a “bulge+thick disk” model[3, 14] (following the Galactic structure...
The contribution from the extended bulge is $\dot{N}_{\text{bulge}}^{e} = 11.5^{+1.8}_{-1.44} \times 10^{42} \text{ s}^{-1}$ and the disk contribution amounts to $\dot{N}_{\text{disk}}^{e} = 8.1^{+1.5}_{-1.0} \times 10^{42} \text{ s}^{-1}$, giving a bulge-to-disk ratio $B/D$ of $\sim 1.4$. The inferred injected positron energy (or, equivalently, the mass of decaying and/or annihilating dark matter particles in such models) from observations is constrained to be to up to a few MeV [4]. Any consistent model for the origin of the 511 keV line emission is required to reproduce the main observations of Galactic emission, including the total positron production rate, the bulge-to-disk production rate ratio, and the injected positron energy. These constraints exclude or require fine-tuned/extreme conditions for any of the suggested astrophysical and/or dark matter annihilation origins of the Galactic 511 keV emission, and the origin of the 511 keV $\gamma$-ray line has therefore remained a mystery (see ref. [4] for a detailed review).

Previous detailed radioactive models for positron production in SNe have considered only CC SNe or regular type Ia thermonuclear explosions. The former are expected to occur only in star forming regions, such as the Galactic disk, while the latter are expected to occur in both old and young stellar environments. However, studies of the delay time distribution of type Ia SNe found it to be consistent with a $t^{-1}$ behavior with the earliest SNe exploding only a few tens of Myrs after the formation of their stellar progenitors; such SNe are dominated by younger ($< 1 \text{ Gyr}$) stellar population [16]. Therefore, these potential positron production sources cannot explain the 511 keV distribution dominated by the old ($> 10 \text{ Gyrs}$) stellar population of the bulge. Here, we show that accounting for the recently discovered class of peculiar type Ib SNe, and their prototype SN 2005E, can explain both the total positron production rate, as well as its distribution.

SN-2005E like SNe [6] are faint (typical $M_b \sim (-15) - (-16)$ absolute B magnitude), type Ib SNe, showing very strong calcium lines and very little, if any, iron at late nebular phases. The ejecta mass of such SNe is inferred to be small, likely a few $0.1 \text{ M}_\odot$, with very little mass of radioactive Nickel and Iron elements but excessive amounts of Calcium (up to $\sim 0.1 \text{ M}_\odot$ of Calcium inferred). Although type Ib SNe are typically observed only in star-forming regions/galaxies, the majority of 2005E-like SNe are observed in very old, possibly metal-poor, environments, such as elliptical galaxies or galactic halos [6, 10–13], with a typical stellar population older than 10 Gyrs. The SN properties and environments suggest these are not CC SNe, but rather arise from thermonuclear Helium detonations in/on WDs, which are not limited to young environments [6]. Based on observations and irrespective
of the specific model for these SNe, their distribution appears to be most consistent with a very old stellar population\cite{6,10,13}, which is therefore adopted in the following. The inferred rate of these SNe from volume-limited surveys is found to be $\sim 10 \pm 5\%$ of the total rate of type Ia SNe\cite{6,8}. These are based on a small sample, hence the large uncertainty. However, these rates are likely to be systematically and significantly underestimated, due to detection bias against the discovery and follow-up observations of SNe in galaxy bulges\cite{17}.

In the following we therefore adopt $f_{\text{05E}} = 10\%$ as the typical fractional rate, which serves as a lower limit, to be better determined in future surveys. These issues are discussed in more detail in the appendix. Current theoretical models of such explosions, sometimes termed Ia SNe\cite{7}, can reproduce the general properties of these SNe, such as their faint luminosities, early light curve (though the faster rise of the modeled light curve compared to observations is still not understood), and the excessive amount of intermediate elements in their composition\cite{9,18}.

It has also been suggested that the large production of intermediate elements in such SNe explains the excessive amount of Calcium observed in Galaxy clusters\cite{6,19}, providing further support for these models. Overproduction of such intermediate elements is typical to these explosions, due to nucleosynthetic freeze-out\cite{5}. In particular, Helium detonations on WDs lead to the large production of radioactive Titanium isotopes\cite{5}, $^{44}$Ti, with as much as $M_{\text{\footnotesize$^{44}$Ti}}(\text{Ia}) = 3.3 \times 10^{-2} M_{\odot}$ of $^{44}$Ti produced in a single 2005E-like SN\cite{9} (based on theoretical models; the systematic uncertainties arising from different models and their implications on the production rate are discussed in the appendix). The eventual decay chain of these isotopes, $^{44}$Ti $\rightarrow^{44}$ Sc $\rightarrow^{44}$ Ca ($\tau = 85$ years), gives rise to the injection of positrons to the interstellar medium (ISM), which would annihilate non-locally in the Galactic ISM after diffusing in the ISM for typical timescales of $\sim 10^{5}$ yrs\cite{4}. Thereby, these can provide an additional positron source for 511 keV line annihilation emission. As we show in the following, accounting for these positron production channels (which potential importance was first pointed out in Ref.\cite{5}) from such SNe in the Milky-Way galaxy shows that they could serve as the dominant source of positrons producing the Galactic 511 keV line emission.

The total positron production rate from 2005E-like SNe per $10^{10}$ Solar mass, $\dot{N}_{e^+,\text{SN05E}}$, is

$$\dot{N}_{e^+,\text{SN05E}} = n_{e^+}(\text{SN05E}) \times R_{\text{SN05E}} = M_{\text{\footnotesize$^{44}$Ti}}(\text{Ia}) / (44 \times M_{\text{atom}}) \times R_{\text{Ia}} \times f_{\text{05E}},$$
Production rate of $^{44}$Ti and frequencies of Ia and Core-collapse supernovae.

|                  | $M_{44Ti}(M_\odot)$ | Fraction of Ia | $R_{SN}(\text{SNeM} ; \text{in Sbc galaxies})$ |
|------------------|---------------------|----------------|-----------------------------------------------|
| Ia/2005E-like SNe| $3.3 \times 10^{-2}$| $f_{SN05E} = 0.1$ | $R_{SN05E} = R_{Ia} \times f_{SN05E} = 0.017 \pm 0.06$ |
| Core-collapse    | $2 \times 10^{-4}$  | -              | $R_{CC} = 0.86$                               |

Table I: Production rates of $^{44}$Ti production in Ia SNe are based on theoretical models in Ref. [9] (see discussion on their uncertainties in the appendix), and production rates in CC SNe are based on observations of the Cas-A and SN 1987A SNRs. The 2005E-like SNe fraction of Ia SNe is based on refs. [6] and [8], and considered as a lower limit (see appendix for further discussion); the overall SN rates are based on ref. [22].

Galaxy model of stellar components and star formation (SFR) history

| Galaxy Model | Bulge ($M_\odot$) | Thin Disk ($M_\odot$) | Thick Disk ($M_\odot$) | Total Disk |
|--------------|-------------------|-----------------------|------------------------|------------|
| Mass         | $2.03 \pm 0.26 \times 10^{10}$ | $2.15 \pm 0.28 \times 10^{10}$ | $3.19 \pm 0.41 \times 10^9$ | $2.54 \pm 0.38 \times 10^{10}$ |
| SFR history  | 10-11 Gyrs        | 0-11 Gyrs             | 10-11 Gyrs             |            |

Table II: Galaxy structure is based on ref. [20], which only provided error bars for the bulge mass. The same level of uncertainty, $\sim 13\%$, is assumed for the disk components. SFR history is assumed to be continuous in the given range; based on ref. [21], and consistent with the Galaxy population SFR modeling used in ref. [20].

where $n_{e+}(SN05E)$ is the typical number of positrons injected by a 2005E-like SN, $M_{atom}$ is the atomic mass, $R_{05E} = R_{Ia} \times f_{05E}$, and $R_{Ia}$ are the rates of 2005E-like and type Ia SNe (SNeM, i.e. the rate per $10^{10}$ $M_\odot$ per century), respectively; $f_{05E}$ is the fractional rate of 2005E-like SNe out of regular type Ia SNe. For the calculations, we adopt the frequently used Galaxy structure model in ref. [20], which is also used for the best-fit modeling of the 511 keV line distribution, i.e., the bulge and disks are similarly defined. Note that in these models the bulge is defined differently then in some of the typical denotations; it is defined to be the spherical inner region the Galaxy, including any older parts of the stellar disk possibly extending to the inner regions. The disk is then defined accordingly to have a hole in its center. These definitions are adopted in all of the following. As prescribed in this model, most of the stars in the Galaxy reside in the Galactic disk (total mass of $2.54 \times 10^{10}$ $M_\odot$, with $2.15 \times 10^{10}M_\odot$ in the thin disk and $3.19 \times 10^9$ $M_\odot$ in the thick disk (error bars were not given for these Galaxy component masses in ref. [20] and we therefore adopt the
same ∼ 13 % uncertainty level as estimated for the bulge mass determination in the same ref.), with a smaller fraction in the bulge (2.03 ± 0.26 × 10^{10}), and a much smaller, negligible fraction in the Galactic halo (2.6 × 10^8 M⊙). The typical age of the bulge, thick disk, and halo stellar population is > 10 Gyrs, and they are thought to have formed over a period of ∼ 1 Gyr (see ref. [21] and references therein for an overview). The thin disk stellar population is thought to have formed continuously throughout the Galaxy evolution[21]. All of the bulge stellar population (beside the negligible younger population in the Galactic center) therefore contributes to the 2005E-like SN rate in the central parts of the Galaxy. Outside the bulge, both the thick-disk population and the oldest stellar population in the thin disk (where the latter is ∼ 10% of the thin disk population, i.e., only stellar population formed in the first Gyr, over the ∼ 10 Gyrs of evolution) contributes to the 2005E-like SN rate. The old progenitors of the 2005E-like SNe are therefore the main reason behind the dominant contribution of the bulge to the 511 keV emission, rather than the more massive thin disk. Since the 2005E-like SN rate is given in terms of the total type Ia SN rate, we follow ref. [4] and adopt a rate of R_{Ia} = 0.17 ± 0.06 SNeM, for Sbc galaxies like the Milky-way[22].

We find \( \dot{N}_{e+,SN05E}^{\text{bulge}} = 9.74 \pm 3.66 \times 10^{42}\text{s}^{-1} \), \( \dot{N}_{e+,SN05E}^{\text{thin-disk}} = 1.05 \pm 0.39 \times 10^{42}\text{s}^{-1} \), \( \dot{N}_{e+,SN05E}^{\text{thick-disk}} = 1.95 \pm 0.73 \times 10^{42}\text{s}^{-1} \), for a total of \( \dot{N}_{e+,SN05E}^{MW} = \dot{N}_{e+,SN05E}^{\text{bulge}} + \dot{N}_{e+,SN05E}^{\text{thin-disk}} + \dot{N}_{e+,SN05E}^{\text{thick-disk}} = 1.27 \pm 0.37 \times 10^{43}\text{s}^{-1} \). The observed emission of \(^{26}\text{Al}\) produced in CC SNe (and seen only in the Galactic disk, not the bulge) also provides us with an estimate of the expected contribution of positrons from such sources for a total of \( \dot{N}_{e+,CC-SN}^{\text{disk}} = 3.5 \pm 0.26 \times 10^{42} \). Taken together, we get \( \dot{N}_{e+,CC-SN}^{MW} = 12.7 \pm 3.7 \times 10^{42}\text{s}^{-1} \), which is consistent with the total observed Galactic positron production. The bulge-to-disk ratio is then \( B/D = 1.5 \pm 0.6 \), also consistent with the observed \( B/D = 1.42^{+0.34}_{-0.30} \). The relevant parameters of the model and observations are summarized in Tables 1-3.

The above calculation does not include positron production from \(^{44}\text{Ti}\) produced in CC SNe. \(^{44}\text{Ti}\) decay was observed in the supernovae remnants (SNRs) Cas-A and 1987A (a total up to a few\times 10^{-4} M⊙ in \(^{44}\text{Ti}\) per SN)[24, 25]. However, no gamma rays from \(^{44}\text{Ti}\) decay arising from the expected (but optically obscured) SNe that should have gone off during the past few 100 years in the galaxy have been detected. Detailed models suggest these are atypical events[26, 28], and therefore the total contribution from such sources is likely to be small. Nevertheless, if these production rates are used as an upper bound, i.e., taking the observed rates in Cas-A/1987A for all CC SNe, the positron production rate from such
Positron production rate in the Galaxy: comparison of the model with observations

| Source                  | bulge | thin disk | thick disk | total disk | total | bulge/disk |
|-------------------------|-------|-----------|------------|------------|-------|------------|
| 2005E-like/Ia           | 9.74 ± 3.66 | 1.05 ± 0.39 | 1.95 ± 0.73 | 3.0 ± 0.83 | 12.7 ± 3.7 |          |
| Contribution of $^{26}$Al | –     | 3.5 ± 0.26 | –          | 3.5 ± 0.26 | 3.5 ± 0.26 |          |
| Model (total)           | 9.74 ± 3.66 | 4.55 ± 0.47 | 1.95 ± 0.73 | 6.5 ± 0.87 | 16.2 ± 3.7 | 1.5 ± 0.6 |
| Observed 511 keV        | 11.5$^{+1.8}_{-1.4}$ | –      | –          | 8.1$^{+1.5}_{-1.4}$ | 19.6$^{+2.3}_{-2}$ | 1.42$^{+0.34}_{-0.30}$ |

Table III: Comparison of the production rate inferred from observed 511 keV emission and model prediction from 2005E-like SNe and and inferred contribution from $^{26}$Al decay.

sources is $\sim 3 \times 10^{42}$s$^{-1}$, which should be distributed mostly in the thin disk where current star formation occurs (with 10%, $\sim 0.3 \times 10^{42}$s$^{-1}$ contribution to the production rate from young stellar population in the Galactic center). Together with the positron production from the other sources discussed above, this can give rise to a total $\dot{N}_{e^+} = 19 \times 10^{42}$s$^{-1}$ and $B/D = 1.1$, still consistent with observations within the error-bars. The uncertainty in the numbers given in Table 3 account for the known uncertainties in the mass and distribution of the old and young stellar population in the Galaxy, as well as the uncertainties in the type Ia SNe rates. Additional discussions of other possible uncertainties can be found in the appendix, most important is the uncertainty in in rate of 05E-like SNe, and its likely underestimate.

Positron production from $^{44}$Ti decay in 2005E-like SNe can provide a robust mechanism for the origin and distribution of the Galactic 511 keV line emission in the Galaxy and can eliminate the need for non-astrophysical (e.g., dark matter annihilation) or fine-tuned astrophysical sources. This process also gives rise to additional specific observable predictions. In particular, 2005E-like SNe follow the oldest stellar population, and we therefore expect the 511 keV emission to similarly be correlated with the old stellar population in the Galaxy. In particular, beyond the expectation of a large B/D, consistent with the observations, we expect a significant fraction (30%; see Table 2) of the disk 511 keV emission to originate from the thick disk, rather than the more massive thin disk (i.e., a thick disk-to-thin disk positron production ratio of 0.3), which would not be expected from typical sources originating in the Galactic center, such as the central massive black hole, or dark matter concentration. In addition, given the observed delay-time distribution of standard type Ia SNe ($\propto t^{-1}$), their
expected current rate is only $\sim 5\%$ of the total type Ia rate, comparable with the current rate of 2005E-like SNe ($\sim 10\%$ of the total Ia rate). We therefore expect a large fraction of any detected SNRs in the bulge (excluding the younger Galactic center population in the $\sim 100 – 200$ pcs central environment) to be strong point sources of $^{44}\text{Ti}$ decay emission in 68/78 keV emission lines, potentially detectable with the current NuSTAR mission. These might even be observable in the bulge of M31, and specifically in the SNR of SN 1885A, possibly related to Ia SNe\cite{2010MNRAS.403.2161P} (although it is not a 2005E-like SN); such observations are strongly encouraged.

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The calculated rates for Galactic positron production depend on various SN characteristics and rates, as well as the Galaxy structure. Here we discuss these uncertainties in more
A. Bulge mass

The best fit modeling of the observed distribution of the 511 keV line emission made, makes use of the Galactic structure constructed in ref. [20]. Later modeling of the Galaxy structure [30] suggest a bulge mass of $2.4 \pm 0.6 \times 10^{10} \, M_\odot$, which is also consistent with more recent models [31]. These latter models are consistent with the most frequently used model for the Galaxy in ref. [20], which was adopted throughout this paper. Note that the larger estimates allow the bulge mass to be as much as 1.5 larger than the adopted model (in which $M_{\text{bulge}} = 2 \times 10^{10} \, M_\odot$), and would therefore correspond to a larger positron production from 2005E-like SNe (still consistent with observations), and possibly leading to an even larger B/D ratio, even if the disk mass is similarly up-scaled (since the total contribution from $^{26}$Al is known from observations independently of the disk mass, it would not be similarly up-scaled, and would therefore contribute a smaller fraction of the disk positrons in this case).

B. SN rate estimates and distribution

SN rate are notoriously difficult to measure, since they require an accurate and detailed knowledge of surveys used and their control time [16]. As can be inferred from our calculations in the main text, uncertainties in SN rate estimates dominate the overall uncertainties in the positron production rates we derive. Here we adopted the same type Ia SN rate as in Ref. [4], following ref. [22], for type Ia SN. These are generally consistent with the recent rate estimates based on a larger local SN sample in ref. [33]. The formal inferred rate of 2005E-like SNe is $10 \pm 5\%$ of the type Ia SN; it is based on the same [33] SN sample. This rate is also consistent with the suggestions that 2005E-like SNe produce most of the Calcium in the intra-cluster medium [6], in which case the best estimate for their rate can be as high as 16$\%$ of the type Ia SN rate [19]. However, most of the old stellar populations in galaxies (such as the stellar populations of elliptical galaxies and stellar halos in which such SNe were observed) is expected to reside in galaxy bulges, thick disks, galactic halos (external to the bulge) and the intergalactic medium in galaxy clusters, depending on the
detail.
Host and spatial location of 2005E-like SNe

| SN         | Closest galaxy | Galaxy type | Location¹ | Offset² |
|------------|----------------|-------------|-----------|---------|
| PTF09dav   | Anon           | disturbed Sb| IGM       | 40      |
| 2010et/PTF 10iuv | CGCG 170-011   | E           | IGM       | 37      |
| PTF11bij   | IC 3956        | E           | halo/IGM  | 33      |
| 2000ds     | NGC 2768       | E/S0        | halo/X-bulge |       |
| 2005cz     | NGC 4589       | E           | halo/X-bulge |       |
| 2007ke     | NGC 1129       | E           | halo/X-bulge |       |
| 2012hn     | NGC 2272       | E/S0        | halo/X-bulge |       |
| 2005E      | NGC 1032       | S0/a        | halo/X-bulge |       |
| 2001co     | NGC 5559       | SBb         | disk      |         |
| 2003H      | NGC 2207+IC 2163 | Interacting spirals | interacting disks |   |
| 2003dg     | UGC 6934       | Scd         | disk      |         |
| 2003dr     | NGC 5714       | Scd         | disk      |         |

¹Offset from center of nearest galaxy (kpc) for IGM SNe
²Location: central bulge (<3 kpc from center), disk (<1 kpc from disk), halo/X-bulge, IGM
galaxy type.

The detection efficiency in the inner bulges of galaxies is very poor, and significantly limits or even completely prohibits the discovery of SNe in these regions[17]. Galactic halos contain a few up-to 25% of the stellar mass of galaxies in late type galaxies (Sb and later, such as the Milky-way), and between 30-70% of the stellar mass in early type galaxies (E/S0/Sa)[32]. Together, and given the bias against detection of SNe in galaxy bulges/inner regions, one would expect to locate SNe from old stellar populations in either the thick disk of late type galaxies, the halo of early type galaxies, or in the intergalactic medium of galaxy clusters. Table 4 show that the distribution of 2005E-like SNe locations in galaxies, as well as the type of galaxies are consistent with these expectations, i.e. they originate in very old stellar populations. Given the thick-disk to bulge ratio in late type galaxies, as well as the relative stellar mass in halos, compared with the stellar mass in the inner regions of early type galaxies, we expect between 1/2 to 2/3 of 2005E-like SNe to be missed due to the bias against bulge SNe. The rate inferred from the detected SNe is therefore highly likely to be systematically underestimated by a factor of 2-3 and the formal uncertainty in
their rates can not be taken at face value. Instead, we adopt the overall rate of 10% of the type Ia SNe, which is the formally inferred from the detected 2005E-like SNe, but caution that it should be considered as a lower limit. This is also consistent with the study in ref. [13] showing that the distribution of these SNe is consistent with an old (> 10 Gyr), likely metal poor, stellar population as typically observed in galaxy bulges and stellar halos, once (simplistically) accounting for the detection bias against observations of the SNe in the inner regions of galaxies.

C. $^{44}$Ti production rate in thermonuclear Helium-detonations on WDs

The production rate of $^{44}$Ti in 05E-like SNe can not be directly constrained by current observations; though, as suggested in the main text, SNRs of such SNe, once discovered, should show strong emission from $^{44}$Ti decay, which would enable an observational calibration of the positron yield from these SNe.

As discussed in detail in ref. [6], the various properties of 05E-like SNe (old environment, excessive production of Calcium, low ejecta-masses and low luminosity/low production of $^{56}$Ni), all point out to an origin from a Helium-detonation on a WD. In such explosions explosive-nucleosynthesis occurs through the alpha-chain process, in which heavier elements are produced through consecutive fusion of alpha nuclei with progressively heavier atoms. In particular, $^{44}$Ti is directly produced from the fusion of an alpha nuclei with $^{40}$Ca atoms (i.e. they are neighboring isotopes in the alpha-chain), and therefore it would require a highly fine-tuned conditions in order to produce large abundances of one of these isotopes without producing significant abundances of the other. Indeed, the fractional ratio of $^{44}$Ti to stable Calcium, $^{40}$Ca is found to be large in all studied cases of Helium-detonations. Calcium is known observationally to be produced excessively (hence these SNe are sometimes called Calcium-rich SNe), with an estimated mass of $\sim 0.1 \, M_\odot$ of Calcium in the case of SN 2005E[6]. By taking the range of $^{44}$Ti to $^{40}$Ca ratios found in theoretical models and the estimated Calcium mass in SN-2005E one can infer that large $^{44}$Ti abundances should be produced.

Though the exact model for 05E-like SNe is still debated, the above discussion suggests a robust production of $^{44}$Ti in these SNe, and we therefore make use of the theoretical models for Helium-detonations in refs. [6, 9, 18] as proxies to infer the rate of $^{44}$Ti production. In
we ran a grid of 1-zone helium detonations, with various conditions for temperatures, densities and masses, independent of a specific spatial model (e.g. Helium-shell detonation, Helium WD merger with CO-WD etc.). The models in ref. [9, 18] include a detonation of a helium shell of varying mass between 0.15-0.3 M⊙ on a CO-WD with masses ranging between 0.45- 1.2 M⊙. All the models predict the production of very large abundance of ⁴⁴Ti typically in the range of $5 \times 10^{-3} - 3.3 \times 10^{-2}$M⊙. Later studies suggest that more massive CO WDs are likely to detonate and explode due to the Helium-shell ignition[34], and are not likely to produce 2005E-like SNe, where as lower mass WD may only have the helium-shell detonation, thereby producing .Ia events. Of the latter, the more likely models for 2005E-like SNe are therefore those with the lowest mass CO WDs; most of which produce $> 3 \times 10^{-2}$M⊙ of ⁴⁴Ti. In particular, the best-fit model compared with the observations of SN 2005E light curve is the model with 0.45 M⊙ CO WD and a Helium shell of 0.2 M⊙ in ref. [9], which we therefore adopt for our calculations. Though most of the low mass WD models ($M_{CO-WD} \leq 0.55M_\odot$) produce $> 2 \times 10^{-2}$M⊙ ⁴⁴Ti (most produce $> 3 \times 10^{-2}$ M⊙), consistent with the overall production rate we use, we do caution that some produce a few times smaller abundance, which could lead to lower positron production rates. Models producing as little as $1.5 \times 10^{-2}$ M⊙ of ⁴⁴Ti, could still produce the distribution of the 511 keV emission consistent with observations given the larger estimates for the bulge mass discussed above (up to $M_{bulge} = 3 \times 10^{10}$M⊙), with even smaller rates still consistent, if the 2005E-like SN rate are even larger, as expected, given the detection bias discussed earlier (see section B. above for discussion). Those models producing significantly less ⁴⁴Ti of only a few time $10^{-3}$ M⊙ can explain a significant fraction of the 511 keV bulge contribution, but can not, by themselves, explain the total Galactic positron production and the large bulge to disk ratio.

D. Production of positrons in type Ia SNe

As discussed in depth in refs. [4, 35], standard type Ia SN suggested to provide a significant source of Galactic positrons if a non-negligible fraction of the positrons produced in ⁵⁶Ni decay escapes the ejecta. However, as already mentioned in the main text and in refs. [4, 35], the delay time distribution (and bulge to disk ratio) of regular type Ia SN suggest the vast majority of these SNe explode in the thin disk and only a very small fraction of type
Ia SNe are expected to currently explode in the old stellar population of the Galactic bulge. The bulge-concentrated 511 keV line emission excludes a significant contribution from such sources, and we therefore do not include such a component in our model.

We should note that in principle fast decaying radioactive elements such as $^{56}$Ni considered in standard type Ia SNe can also contribute to positron production in Ia SNe; again, if significant fraction of positrons can escape the SN ejecta. Note that the small amount and lower density of material ejected in such SNe compared to regular type Ia SNe may give rise to a larger fraction of positron escape (note that these SNe achieve nebular phase very early, at times much shorter than the $^{56}$Ni chain decay), and could eventually contribute to the 511 keV emission. It is therefore possible that a non-negligible positron production in 05E-like SNe may also arise from such processes, allowing for smaller positron production from $^{44}$Ti, but these require further study in detailed explosion models; we do not include any such hypothetical contribution in the current model discussed here. In that regard it is also interesting to point out that for Ia SNe significant abundance of $^{48}$Cr and $^{52}$Fe, which are typically unimportant in regular Ia’s can be produced, and can therefore play a similar role as $^{56}$Ni in providing additional positron sources, if significant fraction of the positrons can escape the ejecta.