Diffuse Galactic antimatter from faint thermonuclear supernovae in old stellar populations

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Our Galaxy hosts the annihilation of a few $10^{43}$ low-energy positrons every second. Radioactive isotopes capable of supplying such positrons are synthesized in stars, stellar remnants and supernovae. For decades, however, there has been no positive identification of a main stellar positron source, leading to suggestions that many positrons originate from exotic sources like the Galaxy’s central supermassive black hole or dark matter annihilation. Here we show that a single type of transient source, deriving from stellar populations of age 3–6 Gyr and yielding ~0.03 $M_\odot$ of the positron emitter $^{44}$Ti, can simultaneously explain the strength and morphology of the Galactic positron annihilation signal and the Solar System abundance of the $^{44}$Ti decay product $^{44}$Ca. This transient is likely the merger of two low-mass white dwarfs, observed in external galaxies as the sub-luminous, thermonuclear supernova known as SN 1991bg-like.

First detected more than 40 years ago, the Galactic positron annihilation signal poses two central, unresolved challenges: (1) the development of an understanding of the absolute positron production rate in the Galaxy; and (2) the finding of an explanation for the gross morphology of the positron annihilation distribution across the Galaxy. In particular, historical measurements have suggested a positron annihilation rate $\sim$1.4 times larger in the Galactic bulge than in the Galactic disk, despite the bulge hosting $\lesssim$50% of the stellar mass and much less (<10%) recent star formation than the disk (see Supplementary Information).

This apparent strong positron emission from the bulge spurred the development of models in which positrons are injected by exotic sources such as the annihilation of dark matter or by the central supermassive black hole. However, severe gamma ray continuum constraints at energies $\gtrsim$511 keV imply that most Galactic positrons are injected into the interstellar medium (ISM) with kinetic energies $\lesssim$3 MeV. This has ruled out many explanations for the origin of positrons involving dark matter and others invoking diffuse, hadronic cosmic rays or compact positron sources such as pulsars. The energy constraint also means that the positrons’ diffusive transport distance is less than or equal to a kiloparsec within their $10^5$–$10^7$ yr lifetime in the ISM. The positrons are therefore expected to annihilate relatively close to their injection sites, meaning that the Galaxy presents a thick target to the positrons on these spatial scales. Given that we also expect the annihilation of positrons in the Galaxy to be in a quasi-steady state (because the time between positron injection events is much less than the lifetimes of positrons in the ISM), then the Galactic production of positrons is in saturation. This implies that (1) the sky distribution of annihilation radiation broadly reflects the distribution of positron sources and (2) the current positron injection rate into the ISM is equal to the annihilation rate inferred from the annihilation radiation flux.

The empirical situation regarding positron annihilation has recently undergone two important updates after a novel analysis of a larger dataset generated by the SPI spectrometer2 on the European Space Agency’s INTEGRAL satellite: (1) the measured disk positron annihilation rate has been subject to a significant upwards revision after the detection of considerably more low surface brightness emission (implying a revised total Galactic positron annihilation rate of $5.0^{+1.5}_{-1.3} \times 10^{43}$ $s^{-1}$); and (2) the existence of a distinct, point-like Galactic centre source has been demonstrated with 5σ statistical significance10.

These new findings have important consequences for our understanding of Galactic positron production. Given the revision of the measured disk annihilation rate, the bulge ($B$) to disk ($D$) positron luminosity ratio is revised downwards to $B/D = 0.42 \pm 0.09$; this is equal, within error, to the ratio of the bulge to disk stellar mass $^1$:

$$M_{\text{bulge}} / M_{\text{disk}} = (1.6 \pm 0.2) \times 10^{10} M_\odot / (3.7 \pm 0.5) \times 10^{10} M_\odot = 0.4 \pm 0.1$$

(see Supplementary Material). The effective angular resolution of the SPI observations of 2.7” (ref. 19) means that the point-like Galactic centre positron source encompasses the entire nuclear bulge stellar population surrounding the supermassive black hole. The ratio of the positron luminosities of the nuclear bulge ($N$) to the bulge...
\[N/B = (8.3 \pm 2.1) \times 10^{-2} \text{ (ref. 4), again statistically equal to the ratio of the stellar masses of these structures:}\]

\[M_{SN}/M_{	ext{baryon}} = (1.4 \pm 0.6) \times 10^9 M_\odot / (1.6 \pm 0.2) \times 10^{10} M_\odot = 0.09 \pm 0.04\]

Together, these facts imply that a single type of positron source connected to old stellar populations is preferred. For instance, ordinary type Ia (thermonuclear) supernovae (SNe Ia) have been a theoretically favoured, putative source of Galactic positrons\(^{12}\). Alternatively, following older suggestions\(^3\), it was recently noted\(^1\) that flaring microquasars, also plausibly connected to old stars in some instances, seem capable of sustaining the Galactic positron annihilation rate.

However, the updated empirical situation now allows us to address the question of positron source age more quantitatively. To do this, we use the formalism of delay time distributions (DTDs; Fig. 1) and the known star formation histories of the bulge, disk and nucleus (Fig. 2) to find the positron source delay time \(t_d\) between star formation and the formation of a transient source that can reproduce the inferred \(B/D\) and \(N/B\) positron luminosity ratios. We adopt the parsimonious assumption (retrospectively justified by a global analysis of the data; see Supplementary Information) that the time-integrated efficiency for positron source creation per unit mass star formation is invariant throughout the Galaxy.

The blue and green bands in Fig. 3 show the modelled, current \(B/D\) and \(N/B\) ratios normalized to the observationally inferred positron injection ratios as a function of the positron source delay time \(t_d\). Given that both bands show agreement of the model and observations for \(t_d \approx 3–6\) Gyr, we conclude that a single type of positron source, arising in stellar objects of this characteristic age and older, can explain the gross distribution of positron annihilation in the Galaxy.

But what is this source? We have already seen that positron injection and energy constraints rule out many scenarios for positron creation. However, the required low injection energies are entirely compatible with a positron origin in the \(\beta^+\) decay of radionuclides synthesized in stars and/or stellar explosions\(^{12}\). Important positron-producing decay chains (with their markedly different total lifetimes shown in parentheses) are: \(^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca} (\sim 60\) years); and \(^{26}\text{Al} \rightarrow ^{26}\text{Mg} (\sim 717,000\) years).

We consider each of these isotopes in turn.

\[\text{Given the rates of SNe Ia and their prodigious yield of } ^{44}\text{Sc} (\sim 0.6M_\odot \text{ per event, if only a few per cent}^{19}\text{ of the positrons released in } ^{44}\text{Sc} \rightarrow ^{44}\text{Fe} \text{ decay chain could reach the ISM, then they could sustain the total diffuse Galactic positron production}^{12}\text{. However, this explanation fails for two reasons: (1) the typical delay time of an SN Ia is too short to reproduce the observed Galactic annihilation line distribution (see Fig. 3 and ref. 8); and (2) recent analyses based on pseudo-bolometric SN Ia light curves constructed with the inclusion of infrared data (missing in earlier studies) indicate complete positron trapping in SN Ia ejecta to late times of } \gtrsim 2800\text{ days}^{18}\text{, implying that very few positrons (<1\%) escape to the ISM.}\]

Similarly, the long decay time of \(^{26}\text{Al}\) (comparable to the \(10^{10}\) year positron ISM thermalization timescale)\(^{8,9}\) guarantees that the flux of the 1.809\,MeV gamma ray line associated with \(^{26}\text{Al}\) is in a steady state, whereas the total intensity of this line normalizes the total \(^{26}\text{Al}\) production in the Galaxy to only \(4 \times 10^{42}\ \text{s}^{-1}\) (ref. 4), \(\lesssim 10\%\) of the Galactic value. Moreover, the \(^{26}\text{Al}\) emission is distributed along the Galactic plane, correlated with massive stars\(^{19}\), and does not match the overall annihilation morphology.

This leaves \(^{44}\text{Ti}\) as the only viable radionuclide source of positrons. The fact that the \(^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca}\) decay chain has a 60 year decay time opens an interesting potentiality. On the one hand, such a decay time means that supernova ejecta have expanded to low densities before the daughter positrons are released and such positrons are extremely likely\(^9\) to reach the ISM. On the other hand, this decay time is considerably less than the positron ISM thermalization time, meaning that, depending on the recurrence time of Galactic \(^{44}\text{Ti}\) sources, the total mass of \(^{44}\text{Ti}\) in the Galaxy need not be in a steady state (even while the ISM daughter positrons of \(^{44}\text{Ti}\) are in a steady state).

However, any \(^{44}\text{Ti}\) scenario for Galactic positron production is also constrained by the following consideration. The observed abundance of \(^{44}\text{Ca}\) relative to \(^{56}\text{Fe}\) in Solar System material indicates that Galactic \(^{44}\text{Ti}\) production at a look-back time \(t\text{_{look-back}} > 4.55\) Gyr would have generated a positron luminosity of \((0.3–1.2) \times 10^{41} \text{e}^+\text{s}^{-1}\) (refs. \(^{8,12,15}\)), \(\lesssim 25\%\) of the current value. Thus if \(^{44}\text{Ti}\) is currently the source of most positrons, the Galactic \(^{44}\text{Ti}\) injection rate must be significantly larger now than between the Big Bang and the formation of the Solar System 4.55 Gyr ago. This requirement is naturally satisfied for \(^{44}\text{Ti}\) sources that occur at roughly the same few Gyr delay times required by the Galactic distribution of positron annihilation.

As a further consideration, it is conventionally assumed that core-collapse supernovae deliver most of the \(^{44}\text{Ti}\) in the Galaxy via alpha-rich freeze-out near the mass cut between the proto-neutron star and the ejecta. However, although evidence exists for the synthesis of a few \(\sim 10^{-4} M_\odot\) of \(^{44}\text{Ti}\) in three specific supernova remnants\(^{20}\), the number of remnants currently emitting in the \(^{44}\text{Ti}\) gamma ray and X-ray lines is too small to be a comfortable match to the number expected if such sources were responsible for most Galactic \(^{44}\text{Ca}\) (ref. \(^{21}\)). Core-collapse nucleosynthesis models do not yield sufficient \(^{44}\text{Ti}\) to explain the abundance of \(^{44}\text{Ca}\) in mainstream, pre-Solar System material\(^{22}\).
The origin of pre-solar $^{44}$Ca, which very likely derives from $^{44}$Ti, is an important, unresolved problem in nuclear astrophysics.

A possible resolution of all these anomalies is that there are events, rarer than core-collapse supernovae, that supply significantly larger masses of $^{44}$Ti than core-collapse supernovae seem capable of supplying\(^\text{22}\). To comfortably obey the observational constraints (see Supplementary Information), these events should currently occur in the Galaxy every $\geq 300$ yr (a few times longer than the decay time of the $^{44}$Ti decay chain so that, as presaged earlier, the mass of $^{44}$Ti in the Galaxy is not in a steady state so that neither is the $^{44}$Ti gamma ray and X-ray line flux from the Galaxy steady) and they should also feature a minimum mean $^{44}$Ti yield:

$$\left\langle M_{44n}\right\rangle \geq 0.013M_\odot \left(\frac{R}{300 \text{ year}}\right)^{1/2} \left(\frac{N_\odot}{5 \times 10^{43} \text{ s}^{-1}}\right)$$

Thus a universal, stellar positron source in the Galaxy that explains both the morphology and total amount of positron annihilation would: (1) occur at a characteristic delay time $\sim 3$–6 Gyr subsequent to star formation and would therefore be more frequent in today’s Galactic disk than at early times; (2) would have a rate evolving according to this characteristic delay and would currently synthesize $5.8^{+1.9}_{-1.5} \times 10^{-8} M_\odot \text{yr}^{-1}$ of $^{44}$Ti (saturating the total Galactic positron luminosity minus that due to $^{40}$Al decay); and (3) achieve this by yielding $\geq 0.013M_\odot$ of $^{44}$Ti per event and occurring with a mean repetition time $\geq 300$ yr. Such a source would simultaneously explain the origin of pre-solar $^{44}$Ca and naturally address the lack of strong $^{44}$Ti gamma ray and X-ray line sources in the current sky.

This large $^{44}$Ti yield can probably only be observed by astrophysical He detonations in which incomplete burning of He leads\(^\text{24,25}\) to nucleosynthesis products dominated by intermediate mass alpha nuclei such as $^{40}$Ca, $^{44}$Ti and $^{48}$Cr. Under optimum conditions, up to about one-third of the He can be burned to $^{44}$Ti for adiabatically compressed He white dwarf matter.

Our binary evolution population synthesis (BPS) models\(^\text{27}\) using StarTrack\(^\text{27}\) show an evolutionary channel that is expected to aggregate large masses of He at the high densities suitable for detonation at long timescales after star formation. This channel (channel 3 in ref. \(^\text{28}\)) involves low mass ($\sim 1.4$–$2.0 M_\odot$) interacting binary star systems that experience two mass transfer events (with only the second being a common envelope interaction), evolve into a carbon–oxygen (CO) white dwarf and a (pure) $0.31$–$0.37 M_\odot$ He white dwarf (with the progenitor of the latter never undergoing He core burning) and then subsequently merge (Fig. 4). These mergers occur at a characteristic timescale $t_\text{p} = 5.4^{0.8}_{0.6} \times 10^8 \text{ yr}$ (2$\sigma$). Non-trivially, this is an extremely good match to the empirical constraints on the characteristic delay time of a Galactic positron source (compare the vertical dashed lines on the right of Fig. 3).

It has previously been suggested\(^\text{24,27}\) that mergers of CO white dwarf–He white dwarf binaries may be the immediate progenitors of the class of sub-luminous thermonuclear supernova known as SN 1991bg-like (SN 91bg (ref. \(^\text{29}\))). The $^{44}$Ni yields we estimate for our channel 3 merger events (Fig. 4) are a good match to the empirically determined $^{44}$Ni yields of SNe 1991bg (but are too large to match SN 2005E-like supernovae, a class previously suggested\(^\text{31}\) to supply the Galactic positrons). The $^{44}$Ni yields are estimated by assuming that the merger product assumes a transient configuration of quasi-hydrostatic equilibrium with the He white dwarf secondarily accreted on to the CO white dwarf primary before (1) the helium shell detonates and (2) the CO core detonates.

Empirically, SNe 91bg immediately match a number of our requirements: they are fairly frequent today, representing $\sim 15%$ of all thermonuclear supernovae among the local galaxies sampled in the volume-limited Lick Observatory Supernova Search (LOSS)\(^\text{32}\) of 74 SNe Ia within 80 Mpc. They also occur in old stellar environments such as elliptical galaxies\(^\text{13,13}\). The cosmological rate of SNe 91bg is increasing\(^\text{34}\) (within large statistical uncertainties), suggesting that they are governed by delay times significantly larger than core-collapse SNe or SNe Ia (which are becoming less frequent in today’s universe) as required by our scenario. In addition, SNe 91bg do show evidence of Ti in their spectra, as revealed by a characteristic Ti absorption trough in their spectra around $-4.200 \text{ Å}$ (on this basis their potential importance for supply Galactic $^{44}$Ti decay positrons was previously noted\(^\text{22}\)).
Because SNe 91bg represent 10% of the 31 thermonuclear supernovae in early type galaxies in the LOSS sample and, spectrally, the bulge is an early type galaxy (of Hubble type E0), we set the current bulge SN 91bg to the all SN Ia relative rate at \( f_{\text{SN91bg,Ia}} = 0.32 \pm 0.16 \) (2σ). We determine (see Supplementary Information) the rate of ordinary bulge SN Ia (excluding SN 91bg) to be \( f_{\text{SN91bg,Ia}} = 9.8 \times 10^{-3} \) century from which \( R_{\text{SN91bg,Ia}} = 4.6 \times 10^{-3} \) century. Given our assumption (retrospectively justified by an analysis of the data; see Supplementary Information) of a universal efficiency per unit stellar mass formed for creating positron sources (here understood to be SNe 91bg), we can then also calculate the current SN 91bg Galactic recurrence time of \( t_{\text{SN91bg,Ia}} = 530 \) yr.

Integrating over disk supernova explosions up to 4.55 Gyr ago, we find that a mean 44Ti yield \( 0.029^{+0.032}_{-0.015} M_\odot f_{\text{SN91bg}} (0.32) \) is required to reproduce the observed abundance of 44Ca relative to 46Fe (from 44Ni synthesized in SNe Ia and core-collapse SNe) for a characteristic delay time consistent with the other constraints (Fig. 3, orange curve). Adopting \( M_{44\text{Ti}} = 0.029 M_\odot \) and the Galactic SN 91bg rate already determined, we predict the current positron injection rate shown as the red curve in Fig. 3. This saturates, within errors, the absolute positron luminosity of the Galaxy (minus the positron luminosity of \( 4 \times 10^{-5} \) s\(^{-1}\) due to 44Al decay) within a \( t_\infty \) range consistent with the other constraints.

The mean 44Ti yield per SN 91bg implied by this analysis, ~0.03 M_\odot, is close to the direct estimates we can make for CO white dwarf–He white dwarf mergers using our BPS model (Fig. 4), assuming a quasi-hydrostatic configuration, as seems to be warranted on the basis of our procedure for calculating the 56Ni yield of the same explosions. It is also well within the range found for CO white dwarf–He white dwarf mergers using our BPS data (Fig. 4), assuming a quasi-hydrostatic configuration, as seems to be warranted on the basis of our procedure for calculating the 56Ni yield of the same explosions. SN 91bg rate already determined, we predict the current positron injection rate shown as the red curve in Fig. 3. This saturates, within errors, the absolute positron luminosity of the Galaxy (minus the positron luminosity of 4 × 10^{-5} s^{-1} due to 44Al decay) within a \( t_\infty \) range consistent with the other constraints.

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simulations to the community. The considerations presented here do not constitute a logical proof that there is a single type of positron in the Galaxy. A $\sim$10% contribution from $^{26}$Al from massive stars is inescapable; other sources such as microquasars\(^{14,14}\) plausibly make a further contribution. We have shown here, however, that the Galactic annihilation morphology admits of a single dominant positron source type, which must then be connected to stellar populations 3–6 Gyr old. This is a general constraint that is difficult to evade given the extreme paucity of young stars in the Galactic bulge, together with the fact that all regions of the Galaxy have old stellar populations.

**Methods**

**Star formation rate parameterization.** For the disk and bulge star formation rates (SFRs), we use the form suggested by ref. \(^{17}\):

$$\log_{10}[SFR + D] = \max[Az^2 + Bz + Cz, 0]$$

The coefficients $A$, $B$, and $D$ for the disk are determined by fitting to the Milky Way disk star formation history data of ref. \(^{16}\) renormalized so that the integrated stellar mass of the disk (outside the VVV volume) is $(3.7 \pm 0.5) \times 10^{10} M_{\odot}$ (ref. \(^{16}\)). We find $[A = -4.06 \times 10^{-3}, B = 0.331, C = 0.388, D = 0.7071]$ (note that we account for a factor 0.26 of the SFR lost to stellar winds and stellar ejecta\(^{15}\)). This parameterization gives a present day SFR in the disk of $1.4 M_{\odot}$ yr\(^{-1}\), in tolerable agreement with previously published estimates (such as $1.65 \pm 0.19 M_{\odot}$ yr\(^{-1}\) for a Kroupa initial mass function\(^{16}\)). For the current bulge region mass we require that the SFR, with the form given by equation (2), integrates to $K_{\text{roupa}}$ initial mass function account for a factor 0.26 of the SFR lost to stellar winds and stellar ejecta\(^{15}\). The bulge star formation histories are plotted in Fig. 2.

**Delay time distribution.** Our adopted DTD increases in proportion to $t^r$ for times $t < t_0$ and asymptotes in proportion to $t^s$ for times $t > t_0$ with the characteristic timescale $t_0$ labeled as the delay time (and $r$ and $s$ parameters of the function describing the DTD). A population whose mergers are governed purely by gravitational radiation typically has $s = -1$ (ref. \(^{19}\)); if there are other processes hastening the process of inspiral, the DTDs is steepened, leading to $s < -1$. Following ref. \(^{17}\) we set $a = 4, s = -1$ and $t_0 = 0.3$ Gyr for SN Ia (for these $a$ and $s$ parameters, the maximum rate of SN Ia occurs at 1.32 $t_0$, subsequent to a star formation burst.)

For the SN 91bg DTD, we set fiducial values of $s = -1.6$ and $a = 3.7$ on the basis of fitting the data for CO white dwarf–He white dwarf mergers in our BPS (see Supplementary Fig. 1). Using a Markov chain Monte Carlo approach we fit (using the emcee package\(^{20}\)) the DTD functional form from ref. \(^{17}\) to the histogrammed BPS data. From this we obtain $t_0 = (5.4^{+0.8}_{-0.6}) \times 10^7$ yr, $s = -1.67^{+0.56}_{-0.75}$, and $a = 3.7^{+1.2}_{-0.7}$ (1$\sigma$ errors). Note that in Fig. 3 we set $s = -1.6$ and $a = 3.7$, but that $t_0$ is a free parameter we scan over; we have checked that we obtain similar constraints when setting $s = -1.0$ and $a = 4.0$.

**Estimated $^{44}$Ti and $^{56}$Ni yields of He white dwarf–CO white dwarf mergers.** Our estimates of the $^{44}$Ti and $^{56}$Ni yields of the He white dwarf–CO white dwarf mergers modelled within our BPS calculation are $\sim 0.03 M_{\odot}$ and $\sim 0.1 M_{\odot}$, respectively. To obtain these estimates we have assumed that the yields are insensitive to the propagation and annihilation of nucleosynthesis positrons in the Galaxy. The $\gamma$-ray emission from the Galactic Centre region observed by SPI/INTEGRAL revisited an annihilation in a cooling ISM? Mon. Not. R. Astron. Soc. 411, 1727–1743 (2011).

To estimate the initial density profile of He (and CO) before it detonates, we assume that the merger remnant temporarily assumes a configuration of quasi-hydrostatic equilibrium with a total mass given by the combined mass of the pre-merger primary and secondary white dwarfs, with the He of the disrupted secondary white dwarf accreted into a shell on top of the primary CO white dwarf. This sort of approach is consonant with the suggestion\(^{21}\) that relatively low-mass CO–CO white dwarf mergers first produce a merger remnant containing most of the aggregated mass of the binary before subsequently detonating. On the other hand, it is in tension with the pictures based on hydrodynamic merger simulations\(^{22,23}\). In particular, the prompt detonation scenario\(^{24}\) does not allow the assembly of $0.1 M_{\odot}$ mass of He in the correct density range for $^{44}$Ti synthesis because detonation is triggered via He ignition shortly after mass transfer begins. The possibility of explosions at a later phase, shortly after the dynamic merger is complete, has previously been investigated\(^{25}\) and a best match with SN 91bg explosions has been suggested from the simulated merger of a $0.45 M_{\odot}$ He white dwarf with a $0.9 M_{\odot}$ CO white dwarf. This system is significantly more massive than the population of mergers identified in our BPS calculations and this model would yield only $\sim 3 \times 10^{-6}$ of $^{44}$Ti, insufficient for our scenario. Thus we require that explosions occur in less massive mergers (and probably at later phases) than those explored previously\(^{20}\).

We gain some confidence for this picture by considering the $^{56}$Ni yields from the mergers, which we calculate in two ways. First, we produce an interpolation of the fractional $^{56}$Ni yield of CO burning as a function of the initial density as presented in Fig. A1 of ref. \(^{26}\). We then apply this parameterized yield to the CO–He merger remnant density profiles generated by assuming that the remnants reach hydrostatic equilibrium before detonating. Second, we use an existing interpolation\(^{27}\) of the modelled yield of $^{56}$Ni in detonations of single, sub-Chandrasekhar white dwarfs given purely as a function of the total mass of the white dwarf. We find excellent agreement between these two approaches (see Supplementary Fig. 5). We then observe that, for our modelled distribution of CO white dwarf–He white dwarf mergers, applying either of these approaches, we derive $^{56}$Ni yields that are very close to the observationally inferred $^{56}$Ni yields of the sample of SN 91bg assembled in ref.\(^{28}\); this is an independent consistency check of our model.

We calculate $^{44}$Ti yields from the He detonation in the merged He–CO remnants in a similar fashion to $^{56}$Ni: (1) the initial He density profile is obtained assuming that the merger remnant achieves hydrostatic equilibrium before detonation; and (2) this density distribution is convolved with the fractional yield of $^{44}$Ti from He detonation given as a function of density in ref.\(^{17}\) (using our own interpolation of their results and adopting a fixed temperature of $2 \times 10^8$ K (ref. \(^{17}\))).

**Data availability.** The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions
All the authors discussed the results and commented on the manuscript. R.M.C. wrote the paper. A.I.R. performed the BPS modelling and provided theoretical input. I.R.S. provided theoretical input, helped with calculating the yields of the helium detonations and contributed to the writing of the paper. F.H.P., A.M. and B.E.T. provided advice about the rates, prevalence and distribution of 91bg in supernova searches. H.B., L.F. and J.E. provided advice on the BPS modelling, A.M. and M.W. provided statistical analysis. D.M.N. provided advice about the star formation history of the Galactic bulge and other theoretical input. S.S. provided input on the phenomenology of SN explosions. F.A. provided input on the phenomenology of positron transport and annihilation radiation. All the authors commented on the draft text.

Additional information
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Competing interests
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