Millisecond pulsars from accretion-induced collapse as the origin of the Galactic Centre gamma-ray excess signal

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Gamma-ray data from the Fermi Large Area Telescope reveal an unexplained, apparently diffuse, signal from the Galactic bulge that peaks near ~2 GeV with an approximately spherical intensity profile $\propto r^{-2.4}$ (refs. 3,5), where $r$ is the radial distance to the Galactic centre, that extends to angular radial scales of at least ~10° and possibly to ~20° (refs. 6–10). The origin of this ‘Galactic Centre excess’ (GCE) has been debated, with proposed sources prominently including self-annihilating dark matter11 and a hitherto undetected population of millisecond pulsars (MSPs). However, the conventional channel for the generation of MSPs has been found to predict too many low-mass X-ray binary (LMXB) systems and, because the canonical channel for the generation of MSPs has been found to predict too many low-mass X-ray binary (LMXB) systems, may not accommodate the large foreground model uncertainties (for example, ref. 18). This leaves a gap in the population of MSPs and also those of globular clusters whose MSPs and also those of globular clusters whose MSP disk population, since this predicts too many bright MSPs; however, note that this argument has been disputed19. Regardless, the bulge MSP population need not share the characteristics of the local Galactic disk MSP population: star formation ceased ~8–10 Gyr ago in the bulge20, while it is ongoing in the disk. Because MSPs spin down over time, thus becoming less $\gamma$-ray luminous (with those initially brightest evolving fastest), the systematic age difference between bulge and disk MSP populations should lead to a relative deficit of bright MSPs in the bulge.

So far, much of the discussion surrounding the tenability of the MSP explanation for the GCE has implicitly adopted the canonical ‘recycling’ formation scenario, whereby an old, slowly rotating neutron star (NS) formed in a core-collapse supernova accretes material from a companion during LMXB phases. This spins up the NS to millisecond periods, enabling it to emit $\gamma$ radiation. However, a recycling origin for the MSPs predicts that the bulge should host ~10° LMXBs, while observations by INTEGRAL have uncovered only 42 LMXBs with an additional 46 candidates within a 10° radius of the Galactic Centre.

This argument, however, neglects the existence of a separate mechanism that may produce ~50% of all observed MSPs21,22, namely, the AIC channel. AIC events occur when ultra-massive oxygen–neon (O–Ne) white dwarfs (WDs), accreting matter from their binary companions, approach the Chandrasekhar mass limit (~1.4 $M_\odot$), lose electron degeneracy pressure support due to electron capture on $^{24}$Mg and $^{24}$Na nuclei and collapse into neutron stars23. Conservation of angular momentum in AIC yields spin periods for the nascent NSs (with radii three orders of magnitude smaller than the parent WDs) of a few ms. Similarly, magnetic flux conservation during AIC means that progenitor O–Ne WD magnetic fields of ~10–100 G result in field strengths of ~10–100 G for the newly born NSs, directly matching observations. Furthermore, because little mass is lost in the collapse, the binary is not disrupted, nor does the system receive a large natal kick24–26. This means that NSs born via AIC have much smaller space velocities than those imparted to NSs during the generally asymmetrical explosion of a core-collapse supernova27. Thus, MSPs born via AIC are likely to remain trapped in the bulge gravitational potential, allowing for a large population to build up over its history and proffering an explanation of the detailed match between bulge stellar and GCE morphologies.
a match that is difficult to explain in the recycling channel in light of the large kicks typically delivered to core-collapse NSs (for example, ref. 13).

In this paper, we present a BPS forward model for the formation and evolution of the Galactic bulge AIC MSP population to ascertain whether its γ-ray phenomenology can explain the GCE (Methods). In this context, we note that template analyses11–13 have uncovered distinct contributions to the GCE signal from both the wider-scale ‘boxy’ bulge (BB) and the ‘nuclear bulge’ (NB), the latter constituting a stellar population with a distinct star formation history concentrated on physical scales ≲200 pc around the Galactic centre. Here in the main text, we concentrate on the former component, which makes up around 90% of the overall Galactic bulge mass. We show in the Supplementary Information that our model also successfully reproduces the measured γ-ray emission from the NB (Supplementary Section 14).

O–Ne WDs are generated when stars develop carbon–oxygen (CO) cores in the range of ~1.6–2.25 M⊙ that ignite carbon under semi-degenerate conditions. Crucial to the formation of compact binaries is common-envelope evolution, which occurs when a star (generally a giant) overfills its Roche lobe, engulfing both stars. A giant star with a convective envelope tends to further expand in response to mass loss, triggering unstable mass transfer at rates so high that the companion cannot capture all transferred matter. Instead, matter accumulates in a common envelope surrounding both giant core and companion star25. Since the envelope rotates more slowly than the stellar orbit, friction causes the stars to spiral together and transfer orbital energy to the envelope. This may release sufficient energy to shed the entire envelope, leaving either a close binary containing a WD and companion or a coalescence of the giant’s core with the companion (Supplementary Section 1).

In an AIC, while the rotational angular momentum of the collapsing O–Ne WD is largely retained, there is some angular momentum loss to gravitational wave radiation induced by the rapidly changing quadrupole moment. Despite the negligible kick, some baryonic mass is suddenly lost, lowering the effective gravitational mass, which expands the binary. Depending on system parameters, the stars may come into contact again and mass transfer may resume. We find that donor stars can transfer more than 0.1 M⊙ of material to the NS and thus post-AIC accretion is a very important determinant of the spin evolution of an AIC MSP population. Our BPS modelling includes all accretion torques acting on the NS (Supplementary Section 4). Extended Data Fig. 1 shows the evolution of the number of AIC-produced NSs and the number of AIC MSPs in the Galactic bulge according to our BPS. Extended Data Fig. 2 illustrates crucial evolutionary stages in the evolution of a typical AIC-producing binary system, and Extended Data Fig. 3 shows the type of the binary companion at the moment of AIC.)

Empirically, ~10% of an MSP’s rotational kinetic energy is lost to dipole radiation26, which emerges at γ-ray wavelengths due to ‘prompt’ emission by e−e+ pairs within the magnetosphere. A further, poorly determined fraction (1–90%; refs. 27,28), is carried away in relativistic pairs that escape the magnetosphere and, after possible re-acceleration at pulsar wind termination or intra-binary shocks, generates additional synchrotron and γ-ray inverse Compton (IC) signals on interstellar medium fields. Ultimately, both prompt and delayed signals are powered by the liberation, via magnetic dipole braking, of rotational kinetic energy. Figure 1 shows the evolution of this spin-down power according to our BPS model of the bulge AIC MSP population, which thus sets an upper limit on the total (that is, prompt + IC) γ-ray luminosity of the model MSP population, together with a datum indicating the measured11 GCE luminosity. There is sufficient power available to explain the signal at 13.8 Gyr cosmological (current) time.

We next determine the signal at Earth of γ-rays from the model bulge MSP population as described in Methods. Our initial estimate of the combined prompt spectrum detected from the bulge MSP population appears as the dot-dashed blue curve in Fig. 2. From this figure, it is evident that the predicted prompt spectrum at Earth is promisingly similar to that measured and, in particular, does a good job of reproducing the amplitude of the ~2 GeV bump. However, (1) the amplitude of the central value of the predicted signal is somewhat low and (2) the spectral shape is not a good fit to the high energy (Eγ ≥ 10 GeV) tail with an overall χ2 of 346 for 15 data points (and no tunable parameters), where we account for the errors in both the predicted prompt spectrum and the spectral measurements. But there is a potential further source of γ-ray emission powered by the MSP spin down that could contribute, in particular,
to this tail: IC off photons of the interstellar radiation field by $e^-$ that escape MSP magnetospheres (for example, ref. 37).

Now, while the total prompt emission is prescribed (up to statistical fluctuations) once we have the model MSPs' periods and period (temporal) derivatives from our BPS, this is not the case for the delayed IC signal, which is subject to a number of factors not determined within the model (Supplementary Section 7). On the other hand, we can exploit two important constraints: (1) that synchrotron radiation off the bulge magnetic field by the population of cosmic ray $e^-$ escaping MSPs (and supplying the IC signal) should not exceed the microwave frequency flux density measured within the inner Galaxy and (2) that the overall prompt + IC + synchrotron luminosity may not exceed the total power liberated by magnetic braking.

Using these constraints, we perform a simultaneous fitting of the IC and prompt signals to the GCE data points, allowing the amplitude of the prompt signal to float within the uncertainty range around the initial estimate; the fitted spectra and their uncertainty bands are shown in Fig. 2. Evidently, an old population of MSPs can well reproduce the GCE $\gamma$-ray signal. Figure 3 shows the broad-band, non-thermal emission from our fit. Here we saturate by construction the microwave data points that describe the spectrum of the 'microwave haze', an enduringly mysterious, non-thermal emission feature of the inner Galaxy for which some have considered an origin in inner-Galaxy pulsars or MSPs9,10. Our fit assumes that a dominant fraction, close to 100%, of the spin-down power liberated by magnetic braking ends up in relativistic pairs (compare with ref. 34).

We have evolved a model population of Galactic bulge binaries to the present day; these generate $1.1 \times 10^7$ AIC neutron stars that qualify as MSPs (rotational period $P < 40$ ms). Individually, these MSPs are indistinguishable from those from 'recycling'. At a population level, bulge MSPs are older and thus dimmer than typical local MSPs and characterized by a luminosity distribution of $10^{33} - 10^{36}$ erg s$^{-1}$, including both prompt and IC components (and taking the mean and standard deviation in the log). The model bulge AIC MSP population can fully explain both the spectrum and overall luminosity of the GCE and, as a bonus, the microwave haze from the inner Galaxy. Our model does not predict too many bright/resolvable MSPs (Supplementary Section 11), too many bright, individual X-ray sources, nor an excessive integrated X-ray luminosity (Supplementary Section 12).

The upcoming Cherenkov Telescope Array will look at the sky in photons of energies from 20 GeV to 300 TeV and is expected to spend at least 500 hours observing the inner Galaxy in each case, which we expect its point-source sensitivity at 0.1 TeV to approach few $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (ref. 38). Thus, the Cherenkov Telescope Array should resolve at least a handful of GCE MSPs, according to the best-fit spectral parameters reported above. In addition, we expect that point-source inference techniques directed at probing the flux distribution of the sub-threshold population in Fermi Large Area Telescope data (for example, ref. 39) will, as they become robust to systematics, start to test our MSP population predictions.

Methods

Binary-star evolution code. To evolve a model population of binaries up to AIC, we used the binary-star evolution (BSE) code9. The BSE algorithm presented by ref. 4, with updates as described by ref. 5, is a state-of-the-art rapid evolution algorithm that melds single star evolution9,10 with binary evolution. BSE takes as inputs stellar zero-age main-sequence (ZAMS) masses, $M_{1,ZAMS}$ and $M_{2,ZAMS}$ for the primary and secondary, respectively ($M_{3,ZAMS} \geq M_{1,ZAMS}$), and the initial binary separation, $a$. BSE evolves binary stellar components through detached, semidetached or contact phases of binary evolution. During the evolution of a binary system, eccentricity may evolve and, owing to tidal interactions (which are modelled in detail within BSE), synchronization of stellar rotation with the orbital motion may occur. BSE includes all orbital-angular-momentum loss mechanisms, including gravitational radiation and mass loss. Wind accretion (wherein the secondary accretes some of the material lost from the primary in a wind) and Roche lobe overflow (where mass transfer occurs if either star fills its Roche lobe) are modelled on nuclear, thermal or dynamical timescales, whichever is smallest. BSE dynamically adjusts orbital parameters while taking into consideration any mass variation in the two stars. Stars with deep surface-convection zones and degenerate cores are unstable to dynamical timescale mass loss unless the mass ratio of the system is less than some critical value. The outcome is a common-envelope event11. This results in either the merging of the two stars, probably accompanied by the generation of a very strong magnetic field12,13, or the formation of a close binary. Conversely, mass transfer on a nuclear or thermal timescale is assumed to be a steady process. Prescriptions to determine the type and rate of mass transfer, the response of the secondary to accretion and the outcome of any merger events are in place in BSE; details can be found in refs. 43,46,47.

Model binary population. Our synthetic population consists of $6.3 \times 10^6$ binary systems that, given parameter choices, would be hosted by a stellar population of $2.0 \times 10^{10} M_{\odot}$ total ZAMS mass. The binaries are numerically evolved up to 14 Gyr, generating a total of $9.1 \times 10^3$ AIC events, which start when the population is only $0.2$ Gyr old (compare with Extended Data Fig. 1). To construct our model binary population, we adopt empirically motivated, 'off-the-shelf' parameter choices (see next sub-section).

Choice of initial binary parameters. Before a detailed description of each characteristic or parameter choice we make, we provide a brief summary of our model binary population: (1) a binary star fraction of 70% is adopted12; (2) $M_{3,ZAMS}$ are drawn from the initial mass function of ref. 3; (3) $M_{1,ZAMS}$ are drawn from a flat mass-ratio distribution14,18; (4) initial eccentricities are set to zero; (5) orbital periods at zero age are drawn from a log-uniform distribution covering 10 to 10$^4$ days; (6) common-envelope efficiency factor (Supplementary Section 1) is set to $\zeta = 0.1$ (ref. 3); (7) the binding energy parameter $\Lambda$ is calculated using the Cambridge STARS code14,15; and (8) magnetic fields are assigned to each nascent NS via random sampling from the log-normal distribution of ref. 16.

It is standard practice in numerical BPS calculations and supported by observations of binary systems in the Galaxy10,28 that companion secondary masses be described by a flat distribution relative to primary masses: $0 < M_{2,ZAMS}/M_{1,ZAMS} < 1$.

Because the detailed calculations of ref. 3 have shown that orbits circularize before Roche lobe overflow occurs and that it is not necessary to include a distribution of eccentricities in population synthesis of interacting binaries, in our BPS we initialize all binaries with circular orbits (see also refs. 44,48,49).

A typical evolutionary pathway towards AIC. The reader is referred to Extended Data Fig. 2. The primary's ZAMS mass is $7.636 M_{\odot}$, and its radius at $t = 0$ is $3.364 R_{\odot}$. The secondary has a ZAMS mass of $5.702 M_{\odot}$ and a radius of $2.841 R_{\odot}$.
The next interaction does not occur until there is stable Roche lobe overflow (which begins at time \(t = 83\) Myr) between the Hertzsprung gap secondary (5.969 \(\text{M}_\odot\)) and the O–Ne WD (1.315 \(\text{M}_\odot\)) primary. The primary continues accreting mass for another \(-20\) Myr \((t = 103\) Myr\) until the secondary (now a Hertzsprung gap naked helium star) collapses into a CO WD (0.683 \(\text{M}_\odot\)). The system remains dormant till \(t = 108.4\) Myr, while spiralling closer \((a = 0.194\ R_\odot\) via gravitational radiation. The dormant phase is followed by the O–Ne WD accreting mass from the CO WD for \(-0.3\) Myr (an AM Canum Venaticorum system but an O–Ne WD). The early asymptotic-giant-branch and He giant-branch phases before becoming the Hertzsprung gap, first giant-branch, core-helium-burning star and then the main-sequence secondary accretes matter stably. At \(-54\) Myr from birth, the primary evolves through the Hertzsprung gap and then along the asymptotic-giant-branch giant branch, all the while donating mass to the main-sequence secondary. This is followed by a common-envelope phase between the late asymptotic-giant-branch primary (6.859 \(\text{M}_\odot\)) and the main-sequence companion (5.434 \(\text{M}_\odot\)). The common-envelope phase causes the binary orbit to shrink, and the primary moves from the early asymptotic giant branch to become a giant-branch naked helium star and soon evolves into an O–Ne WD.

Finally, after assigning the required distances and the spectral and other parameters (Supplementary Section 6), we can generate an initial estimate of the combined prompt emission from the bulge MSP population.

**Data availability**

The model MSP dataset created with our code has been posted to Zenodo at: https://doi.org/10.5281/zenodo.6342560.

**Code availability**

Our code is based on the BSE code available here: http://astronomy.swin.edu.au/~ hurley/bsedownload.html. We have made some refinements and modifications to BSE to account for the spin evolution of AIC-formed neutron stars post formation. These code extensions are presented in a GitHub repository here: https://github.com/gautam-404/Binary-Evolution/tree/master.

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**References**

1. Hooper, D. & Goodenough, L. Dark matter annihilation in the Galactic Center as seen by the Fermi Gamma Ray Space Telescope. Phys. Lett. B 697, 412–428 (2011).
2. Gordon, C. & Macias, O. Dark matter and pulsar model constraints from Galactic Center Fermi-LAT gamma-ray observations. Phys. Rev. D 88, 083521 (2013).
3. Abazajian, K. N., Canac, N., Horihuchi, S. & Kaplinghat, M. Astrophysical and dark matter interpretations of extended gamma-ray emission from the Galactic Center. Phys. Rev. D 90, 023526 (2014).
4. Daylan, T. et al. The characterization of the gamma-ray signal from the central Milky Way: a case for annihilating dark matter. Phys. Dark Universe 12, 1–23 (2016).
5. Calore, F., Cholis, I., McCabe, C. & Weiniger, C. A tale of taus: dark matter interpretations of the Fermi GeV excess in light of background model systematics. Phys. Rev. D 91, 063003 (2015).
6. Hooper, D. & Slater, T. R. Two emission mechanisms in the Fermi bubbles: a possible signal of annihilating dark matter. Phys. Dark Universe 2, 113–138 (2013).
7. Ackermann, M. et al. Observations of M31 and M33 with the Fermi Large Area Telescope: a galactic center excess in Andromeda. Astrophys. J. 836, 208 (2017).
8. Abazajian, K. N. The consistency of Fermi-LAT observations of the Galactic Center with a millisecond pulsar population in the central stellar cluster. J. Cosmol. Astropart. Phys. 2011, 010 (2011).
9. Haggard, D., Heinke, C., Hooper, D. & Linden, T. Low mass X-ray binaries in the inner Galaxy: implications for millisecond pulsars and the GeV excess. J. Cosmol. Astropart. Phys. 2017, 056 (2017).
10. Ploeg, H. & Gordon, C. The effect of kick velocities on the spatial distribution of millisecond pulsars and implications for the Galactic center excess. J. Cosmol. Astropart. Phys. 2021, 020 (2021).
11. Macias, O. et al. Galactic bulge preferred over dark matter for the Galactic Centre gamma-ray excess. Nat. Astron. 2, 387–392 (2018).
12. Bartels, R., Storm, E., Weniger, C. & Calore, F. The Fermi-LAT GeV excess as a tracer of stellar mass in the Galactic bulge. Nat. Astron. 2, 819–828 (2018).
13. Macias, O. et al. Strong evidence that the Galactic bulge is shining in gamma rays. J. Cosmol. Astropart. Phys. 2019, 042 (2019).
14. Plack Collaboration Planc Collaboration intermediate results. IX. Detection of the Galactic hase with Planc. Astron. Astrophys. 554, A139 (2013).
15. Chen, K. Gamma-ray emission from millisecond pulsars in globular clusters. Nature 352, 695–697 (1991).
16. Abd, A. A. et al. A population of gamma-ray emitting globular clusters seen with the Fermi Large Area Telescope. Astron. Astrophys. 524, A75 (2010).
17. Wang, W., Jiang, Z. J. & Cheng, K. S. Contribution to diffuse gamma-rays in the Galactic Centre region from unresolved millisecond pulsars. Mon. Not. R. Astron. Soc. 358, 263–269 (2005).
18. Buschmann, M. et al. Foreground mismodeling and the point source explanation of the Fermi Galactic Center excess. Phys. Rev. D 102, 023023 (2020).
19. Hooper, D. & Mohlabeng, G. The gamma-ray luminosity function of millisecond pulsars and implications for the GeV excess. J. Cosmol. Astropart. Phys. 2016, 049 (2016).
20. Ploeg, H., Gordon, C., Crocker, R. & Macias, O. Comparing the Galactic bulge and Galactic disk millisecond pulsars. J. Cosmol. Astropart. Phys. 2020, 035 (2020).
21. Natra, D. M. The controversial star-formation history and helium enrichment of the Milky Way Bulge. Publ. Astron. Soc. Austral. 33, e023 (2016).
22. Radhakrishnan, V. & Srinivasan, G. On the origin of the recently discovered ultra-rapid pulsar. Curr. Sci. 51, 1096–1099 (1982).
37. Zhang, J. et al. Discriminating different scenarios to account for the cosmic evolution models for \(Z=0.0001\) to 0.03. *Mon. Not. R. Astron. Soc.* **298**, 525–536 (1998).

38. Moe, M. & Di Stefano, R. The close binary properties of massive stars in the Milky Way and low-metallicity Magellanic Clouds. *Astrophys. J.* **778**, 95 (2013).

39. Mazeh, T., Simon, M., Prato, L., Markus, B. & Zucker, S. The mass ratio distribution in main-sequence spectroscopic binaries measured by infrared spectroscopy. *Astrophys. J.* **599**, 1344–1356 (2003).

40. Willems, B. & Kolb, U. Population synthesis of wide binary millisecond pulsars. *Mon. Not. R. Astron. Soc.* **337**, 1004–1016 (2002).

41. Moe, M. & Di Stefano, R. Mind your Ps and Qs: the interrelation between period (P) and mass-ratio (Q) distributions of binary stars. *Astrophys. J.* Suppl. **230**, 15 (2017).

42. Pompelj, J. L. et al. Whole Earth Telescope observations of the helium interacting binary PG 1346+082 (CR Rootis). *Astrophys. J.* **480**, 383–394 (1997).

43. Ivanova, N., Heinke, C. O., Rosio, F. A., Belczynski, K. & Freau, J. M. Formation and evolution of compact binaries in globular clusters. II. Binaries with neutron stars. *Mon. Not. R. Astron. Soc.* **386**, 553–576 (2008).

44. Lutikov, M. & Toonen, S. Fast-rising blue optical transients and AT2018cow following electron-capture collapse of merged white dwarfs. *Mon. Not. R. Astron. Soc.* **487**, 5618–5629 (2019).

45. Portail, M., Wegg, C., Gerhard, O. & Martinez-Valpaústa, I. Made-to-measure models of the Galactic box peanut bulge: stellar and total mass in the bulge region. *Mon. Not. R. Astron. Soc.* **448**, 713–731 (2015).

46. Maraston, C. Evolutionary synthesis of stellar populations: a modular tool. *Mon. Not. R. Astron. Soc.* **300**, 872–892 (1998).

47. Gontier, P. L. et al. Population syntheses of millisecond pulsars from the Galactic disk and bulge. *Astrophys. J.* **863**, 199 (2018).

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Author contributions

R.M.C. conceived the project in consultation with L.F. and A.J.R. A.G. performed the BPS under the supervision of L.F. A.J.R. and R.M.C. A.G. added new functionality to the existing BSE code to model neutron star period evolution under accretion torques. R.M.C. and H.P. analysed the BPS data to derive model \(\gamma\)-ray luminosities and spectra. C.G. consulted about data and statistical analysis. O.M. performed a number of novel \(\gamma\)-ray template analyses of the GCE in support of the project. An original draft of the paper was written by A.G. This was subsequently amended and extended by R.M.C. in consultation with all the other authors.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Fig. 1 | Cumulative AIC events and number of model bulge MSPs over cosmological time. MSP periods P are as labelled in the legend; we define any NS with P < 40 ms as an MSP. The ±1σ error band on the red curve for all AIC events reflects the uncertainties stemming from the bulge stellar mass determination and binarity fraction. (For clarity, equivalent error bands on the other curves are not shown.).
Extended Data Fig. 2 | The main evolutionary stages towards, and beyond, accretion induced collapse of a white dwarf. This schematic is for the model binary whose history is described in the Methods section 'A typical evolutionary pathway towards AIC'.

$t = 0 \text{ Myrs}$
$M_1 = 7.64 \, M_\odot$
$a = 2369 \, R_\odot$
$M_2 = 5.70 \, M_\odot$

$t = 40 \text{ Myrs}$
$M_1 = 6.86 \, M_\odot$
$a = 2129 \, R_\odot$
$M_2 = 5.43 \, M_\odot$

$t = 54 \text{ Myrs}$
$M_1 = 1.41 \, M_\odot$
$a = 84 \, R_\odot$
$M_2 = 5.97 \, M_\odot$

$t = 54 \text{ Myrs}$
$M_1 = 1.32 \, M_\odot$
$a = 2.87 \, R_\odot$
$M_2 = 1.03 \, M_\odot$

$t = 83 \text{ Myrs}$
$M_1 = 1.32 \, M_\odot$
$a = 2.86 \, R_\odot$
$M_2 = 1.03 \, M_\odot$

$t = 108 \text{ Myrs}$
$M_1 = 1.44 \, M_\odot$
$a = 0.194 \, R_\odot$
$M_2 = 0.683 \, M_\odot$

$t = 109 \text{ Myrs}$
$M_1 = 1.36 \, M_\odot$
$AIC$
$M_2 = 0.109 \, M_\odot$
Extended Data Fig. 3 | Cosmological time vs. donor star type at time of AIC for all AIC events in our simulated population. Given our empirically-motivated parameter choices, this model binary population is as expected for a host stellar population of total zero age main sequence mass of $2 \times 10^6 \, M_\odot$. For more details on stellar types, the reader is referred to S.I. sec. 2.