Intermediate-mass black holes should help us to understand the evolutionary connection between stellar-mass and super-massive black holes. However, the existence of intermediate-mass black holes is still uncertain, and their formation process is therefore unknown. It has long been suspected that black holes with masses 100 to 10,000 times that of the Sun should form and reside in dense stellar systems. Therefore, dedicated observational campaigns have targeted globular clusters for many decades, searching for signatures of these elusive objects. All candidate signatures appear radio-dim and do not have the X-ray to radio flux ratios required for accreting black holes. Based on the lack of an electromagnetic counterpart, upper limits of 2,060 and 470 solar masses have been placed on the mass of a putative black hole in 47 Tucanae (NGC 104) from radio and X-ray observations, respectively. Here we show there is evidence for a central black hole in 47 Tucanae with a mass of $2 \pm 1.5_{-0.5}^{+0.8} \times 10^5$ solar masses when the dynamical state of the globular cluster is probed with pulsars. The existence of an intermediate-mass black hole in the centre of one of the densest clusters with no detectable electromagnetic counterpart suggests that the black hole is not accreting at a sufficient rate to make it electromagnetically bright and therefore, contrary to expectations, is gas-starved. This intermediate-mass black hole might be a member of an electromagnetically invisible population of black holes that grow into supermassive black holes in galaxies.

An intermediate-mass black hole (IMBH) strongly affects the spatial distribution of stars in globular clusters (GCs). Massive stars sink into the centre more efficiently because of relaxation in order to achieve energy equipartition. As a consequence, as stars sink closer to the centre they are scattered by the black hole, heating up the core. This process quenches mass segregation (Fig. 1). Over the lifetime of a cluster, dynamical processes such as energy equipartition and two-body relaxation therefore contribute to the outward propagation of an integrated dynamical effect beyond the black hole’s radius of direct influence. We find that this dynamical signature is efficiently propagated outward into the cluster. In relation to this effect, the distributions of pulsar accelerations for any projected distance from the centre show distinct features also sensitive to an IMBH. There are currently 25 pulsars with rotational periods in the range 1–10 ms (millisecond pulsars) detected within the cluster 47 Tuc. These, 19 have phase resolved timing solutions (Extended Data Table 1), which we use to infer spatial accelerations caused by the gravitational potential of the cluster. Pulsar acceleration measurements together with N-body simulations provide stringent constraints on the mass of the central black hole in one of the most massive clusters (globular cluster mass $M_{GC} \approx 0.7 \times 10^6 M_\odot$, where $M_\odot$ refers to solar mass) with a compact core.

IMBHs produce distinct imprints on how massive stars dynamically settle three-dimensionally after the cluster has relaxed. The upper limit of $1.500 M_\odot$ placed on the black hole mass ($M_\bullet$) in 47 Tuc in earlier kinematic studies appears inconclusive, because new kinematic data and N-body models imply that no clear distinction between globular cluster models can be made on the basis of available velocity dispersion measurements alone (Fig. 2). In order to constrain the dynamical effects of a black hole in a cluster, we take a fundamentally different approach. In addition to pulsar accelerations, we jointly use this spatial imprint that carries information about the black hole beyond the radius of influence. We quantify how likely it is that a range of observed pulsar accelerations are related to specific model distributions.

The dynamical N-body simulations of isolated star clusters evolve under the influence of stellar evolution and two-body relaxation. A grid of several hundred star clusters starting with different initial half-mass radii, density profiles and masses of their central black hole are run up to an age of $T = 11.75$ Gyr to match the age of 47 Tuc. We select those clusters that best match the surface density and velocity dispersion profiles of this globular cluster. The presence of primordial binaries does not play a notable role in the final segregation profile of heavy stars if clusters with the same surface density profile are compared (see Extended Data Fig. 1 and Methods). No other a priori assumptions are made that limit the dynamics of the cluster.

The best-fitting models for the no-IMBH case and for IMBHs with 0.5% and 1% of the cluster mass are selected as a subset of viable replicas of 47 Tuc. Models with black hole masses larger than 1% of the cluster mass lead to fits which significantly deviate from the observed density and velocity dispersion profile of 47 Tuc. Hence such massive black holes are ruled out, while models with smaller black hole masses or without a black hole lead to comparable fits.

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![Figure 1](https://example.com/figure1.png) *Figure 1 | Projected distribution of neutron stars in 47 Tuc. The blue line shows how the neutron stars in N-body simulations are segregated for models without an IMBH, whereas the red and green lines show the relative change in the presence of IMBHs with 0.5% and 1% of the total cluster mass, respectively. Mass segregation is quenched by the black hole (in IMBH models) and the density cusp is flattened. As a consequence, the number density of neutron stars in the innermost 1 pc becomes smaller when a black hole is present.*
In each simulated replica of 47 Tuc we have full spatial and kinematic information of all stars, including neutron stars. The majority of neutron stars (~90%) become unbound because of high kick velocities following the supernovae explosions during their formation\cite{17,18}. We extract accelerations of all simulated neutron stars with projected distances that match the observed pulsars in 47 Tuc. Integrated accelerations of these matched neutron stars form distinctly different distributions (Extended Data Fig. 2).

N-body models with an IMBH produce pulsar accelerations that are overall more consistent with observations than models without an IMBH. The relative likelihoods for models in Fig. 3 show that a central black hole is required to produce the observed pulsar accelerations (\(P\)) with the acceleration distributions produced in N-body simulations (\(\Lambda\)) with (red curve) and without (broken curve) an IMBH (see equation (1)). Each point on the curves represents a unique comparison for a slight variation in the N-body models. The peak likelihood gives an independent dynamical measure of the total cluster mass, \(M_{\text{GC}} \approx 0.76 \times 10^6 M_\odot\). The observed pulsar accelerations and distributions within the cluster are at least 10 times more likely to be produced in the presence of a black hole.

We employ bootstrapping in order to cross-check whether the black hole detection signature comes from pulsar observations, and we can rule out systematic effects. Any statistical distance approach can be employed to calculate differences for two distributions. The Kullback–Leibler (KL) divergence (\(D_{\text{KL}}\)) is particularly well suited and mathematically robust for cases where the information entropy is quantified as a likelihood (\(L\)) (see Methods section ‘Information theory and statistical learning‘). KL divergences are calculated for randomly selected pulsars to quantify relative likelihoods for all models. We trace how the inference for the black hole mass changes in Fig. 4a. We find that the inference flattens with decreasing numbers of randomly selected pulsars (Extended Data Fig. 3); this indicates that the black hole detection signal is produced by pulsar data. Such behaviour is expected only in systems where there is statistical learning, that is, the information driving the inference comes from data, and not from random errors or outliers. For the case of 47 Tuc, the dynamical information extracted from \(N < 10\) pulsars appears insufficient to conclusively infer a black hole mass, whereas the inference is sufficiently informative for \(N > 16\) pulsars.

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**Figure 2 | Kinematic data for 47 Tuc compared with theoretical models.** The blue, red, and green lines refer to the predicted velocity dispersion profiles for different N-body models (see key). Associated colour bars show the variation in the predicted range. Error bars are the 1σ dispersions from the Gaussian error distribution for each velocity measurement. Circle and triangle data points respectively denote radial velocity and proper motion observations\textsuperscript{16}. The kinematic distance to 47 Tuc is\textsuperscript{14,15} \(d = 4\text{ kpc}\).

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**Figure 3 | Comparison of N-body model likelihoods of 47 Tuc.** The likelihood (\(L\)) for each model is calculated by comparing the observed pulsar accelerations (\(P\)) with the acceleration distributions produced in N-body simulations (\(\Lambda\)) with (red curve) and without (broken curve) an IMBH (see equation (1)). Each point on the curves represents a unique comparison for a slight variation in the N-body models. The peak likelihood gives an independent dynamical measure of the total cluster mass, \(M_{\text{GC}} \approx 0.76 \times 10^6 M_\odot\). The observed pulsar accelerations and distributions within the cluster are at least 10 times more likely to be produced in the presence of a black hole.

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**Figure 4 | Inferred masses of the black hole and the globular cluster.**

**a.** The normalized probabilities of N-body models with different black hole masses. Pulsars in 47 Tuc imply a central black hole with mass \(M_* \approx 2,300 M_\odot \) (solid vertical line). The other vertical lines delineate the central 68%, 95% and 99% estimate limits for the mass of the central black hole (see key, numbers in parentheses in units of solar masses).

**b.** The joint inference for the total globular cluster mass and the central black hole mass in 47 Tuc. Relative probability is colour coded (colour bar at right). The black dot shows peak probability at \(M_* \approx 2,300 M_\odot\) and \(M_{\text{GC}} \approx 0.76 \times 10^6 M_\odot\).
Stars are expected to form a density cusp in power-law form \( \rho(r) \propto r^{-7/4} \) (\( \rho \) and \( r \) refer to density and radius, respectively) around the black hole because of short relaxation times in the centres of globular clusters\(^{24}\). However, such a sharp cusp is predicted only for idealized model clusters of stars with the same mass. The actual shape of the cusp is difficult to predict because of the unknowns in stellar evolution, such as the mass function and binary fraction. While the projected density profile is expected to be relatively sharp, this cannot be used as a direct indication of a similar cusp in luminosity because the mass-to-light ratio (M/L) is not constant. More realistic multi-mass cluster models find that giant stars should follow a shallower slope of about \(-0.25\) in a typical cluster in projection\(^{2}\). A segregated neutron star and massive white dwarf population lead to a sharp rise of the dark mass, making the luminosity cusp shallower. Moreover, the stochastic motion of an IMBH relative to the cluster centre will flatten the centrally rising cusp even further. Therefore, it is not surprising that an IMBH in 47 Tuc would produce an optically unresolved shallow cusp.

An inescapable conclusion from having an electromagnetically undetectable black hole in the cluster centre is that the core is devoid of gas within its radius of influence. Winds driven by main sequence stars\(^{30,20}\), novae\(^{21}\) and M-dwarfs\(^{22}\) contribute to clearing the gas. Additionally, the kinetic energy injected by the pulsars’ high energy emission into the intra-cluster environment alone may be sufficient to clear the ionized plasma from the central core\(^{27}\). In globular clusters, pulsars can provide the integrated ram pressure enhancement in the centre needed to create a gas-free cavity. The observed signature in the dispersion measures of pulsars in 47 Tuc\(^{24}\) is probably due to the bound plasma remaining present beyond the radius of influence of the black hole.

It is possible that such black holes sitting in the gas-deficient central cavities of primordial globular clusters constitute a subpopulation of progenitor seeds that formed the supermassive black holes in galaxy centres. For this, the black hole must form rapidly during the early evolutionary phases of the cluster and continue to grow exponentially after the cluster sinks to the core of a galaxy. Although massive and compact clusters are preferred environments where IMBHs can be found, mounting evidence suggests that the formation and retention of such black holes are stochastic\(^{25}\). For cases in which seed black holes are retained, it has been shown that they can grow rapidly through accretion at super-Eddington rates\(^{26}\). Stellar winds of massive stars can provide a gas reservoir with mass loss rates of \(\sim 10^{-6} (M_{\odot}/10^{4}M_{\odot})^{-1}\) to partially feed the black hole\(^{17}\). The gas present in the core can then be accreted as the IMBH stochastically moves in the core. It is likely that runaway collisions\(^{27}\) play at least a partial role in the growth of black holes, as well as the mergers of compact binaries\(^{32}\). In fact, binaries with formation black holes are expected to form in the early phases of the cluster evolution and may be retained\(^{28}\). Some of these massive binaries could eventually merge and drift towards thecentre, feeding the black hole, which would make these sources ideal for tidal disruption and gravitational wave detection. The rapid growth of a black hole in a primordial globular cluster that merges with the galactic bulge as it passes close to the centre of a galaxy may continue exponentially at super-Eddington rates\(^{29}\), producing the supermassive black holes in quasars\(^{30}\).

**Online Content** Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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1. Volonteri, M. The formation and evolution of massive black holes. Science 337, 544–547 (2012).
2. Baumgardt, H., Makino, J. & Hut, P. Which globular clusters contain intermediate-mass black holes? Astrophys. J. 620, 238–243 (2005).
3. Sigurdsson, S. & Hernquist, L. Primordial black holes in globular clusters. Nature 364, 423–425 (1993).
4. Ebisuzaki, T. et al. Missing link found? The “runaway” path to supermassive black holes. Astrophys. J. 562, L19–L22 (2001).
5. Miller, M. C. & Hamilton, D. P. Production of intermediate-mass black holes in globular clusters. Mon. Not. R. Astron. Soc. 330, 232–240 (2002).
6. Maccarone, T. J., Kundu, A., Zepl, S. E. & Rhode, K. L. A black hole in a globular cluster. Nature 445, 183–185 (2007).
7. Strader, J. et al. No evidence for intermediate-mass black holes in globular clusters: strong constraints from the JVLA. Astrophys. J. 750, L27 (2012).
8. De Rijcke, S., Buijze, P. & Dejonghe, H. Upper limits on the central black hole masses of 47 Tuc and NGC 6397 from radio continuum emission. Mon. Not. R. Astron. Soc. 368, L43–L46 (2006).
9. Grindlay, J. E., Heinke, C., Edmonds, P. D. & Murray, S. S. High-resolution X-ray imaging of a globular cluster core: compact binaries in 47Tuc. Science 292, 2390–2395 (2001).
10. Freire, P. C. et al. Further results from the timing of the millisecond pulsars in 47 Tucanae. Mon. Not. R. Astron. Soc. 340, 1359–1374 (2003).
11. Ridolfi, A. et al. Long-term observations of the pulsars in 47 Tucanae — I. A study of four elusory binary systems. Mon. Not. R. Astron. Soc. 462, 1819–1823 (2016).
12. Pan, Z. et al. Discovery of two new pulsars in 47 Tucanae (NGC 104). Mon. Not. R. Astron. Soc. 459, L26–L30 (2016).
13. Phinney, E. S. Pulsars as probes of Newtonian dynamical systems. Phil. Trans. R. Soc. Lond. A 341, 39–75 (1992).
14. Baumgardt, H. N-body modeling of globular clusters: masses, mass-to-light ratios and intermediate-mass black holes. Mon. Not. R. Astron. Soc. 464, 2174–2202 (2017).
15. McLaughlin, D. E. et al. Hubble Space Telescope proper motions and stellar dynamics in the core of the globular cluster 47 Tucanae. Astrophys. J. Suppl. Ser. 166, 249–297 (2006).
16. Watkins, L. L., van der Marel, R. P., Bellini, A. & Anderson, J. Hubble Space Telescope Proper Motion (HST-PMO) catalogs of galactic globular clusters. II. Kinematical profiles and maps. Astrophys. J. 803, 29 (2015).
17. Pfahl, E., Rappaport, S. & Podsiadlowski, P. A comprehensive study of neutron star retention in globular clusters. Astrophys. J. 573, 283–305 (2002).
18. Ivanova, N., Heinke, C. O., Rasio, F. A., Belczynski, K. & Fregeau, J. M. Formation and evolution of compact binaries in globular clusters. Mon. Not. R. Astron. Soc. 386, 553–576 (2008).
19. Bahcall, J. N. & Wolf, R. A. Star distribution around a massive black hole in a globular cluster. Astrophys. J. 209, 214–232 (1976).
20. Smith, G. H. Globular cluster winds driven by main-sequence stars. Publ. Astron. Soc. Pacif. 111, 980–985 (1999).
21. Scott, E. H. & Durisen, R. H. Nova-driven winds in globular clusters. Astrophys. J. 222, 612–620 (1978).
22. Coleman, G. D. & Woerden, S. P. Large-scale winds driven by flare-star mass loss. Astrophys. J. 218, 792–800 (1977).
23. Spitzer, R. R. Evolution of gas from globular clusters by winds from millisecond pulsars. Nature 352, 221–222 (1991).
24. Freire, P. C. et al. Detection of excited gas in the globular cluster 47 Tucanae. Astrophys. J. 557, L105–L110 (2001).
25. Giersz, M., Leigh, N., Hyjko, A., Lutzgendorf, N. & Askar, A. MOCCA code for star cluster simulations — IV. A new scenario for intermediate mass black hole formation in globular clusters. Mon. Not. R. Astron. Soc. 454, 3150–3165 (2015).
26. Soria, R. et al. Super-Eddington mechanical power of an accreting black hole in M83. Science 343, 1330–1333 (2014).
27. Portegies Zwart, S. F., Baumgardt, H., Hut, P., Makino, J. & McMillan, S. L. W. Formation of massive black holes through runaway collisions in dense young star clusters. Nature 428, 724–726 (2004).
28. Morscher, M., Pattabiraman, B., Rodriguez, C., Rasio, F. A. & Umbreit, S. The dynamical evolution of stellar black holes in globular clusters. Astrophys. J. 800, 9 (2015).
29. Alexander, T. & Natarajan, P. Rapid growth of seed black holes in the early universe by supra-exponential accretion. Science 345, 1330–1333 (2014).
30. Richstone, D. et al. Supermassive black holes and the evolution of galaxies. Nature 395, A14–A19 (1998).

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Bases the observed number of pulsars, the total predicted number of neutron stars in the cluster may change between 200 and 1,500 because of the integrated uncertainties in the luminosity distribution, beaming, flux densities and spectral indices of pulsars; and the initial mass function, binary fraction, encounter rate and scintillation properties of the cluster. Our N-body simulations with an ~10% retention fraction predict ~1,000 neutron stars in 47 Tuc.

**N-Body simulations.** A grid of several hundred N-body simulations of star clusters, varying the initial density profile of the cluster, its initial half-mass radius and the mass ratio of the black hole to the total cluster mass (MAMGC) were used for our study. All simulations were produced using the GPU-enabled version of the collisional N-body code NBODY6\(^6\), which includes two-body relaxation, tidal fields, and fitting formula for the modelling of stellar and binary evolution. The simulations were run up to \( T = 11.75 \) Gyr, the age of 47 Tuc\(^5\), and then scaled to have the same half-mass radius as 47 Tuc\(^26-38\). The best-fitting models to the surface density and velocity dispersion profiles of 47 Tuc were determined with a \( \chi^2 \) test.

All simulations were run with 100,000 particles except the simulations with 0.5% IMBHs, which used 200,000 particles\(^6\). The initial conditions are King models with initial concentrations of \( c = 0.2, 0.5, 1.0, 1.5, 2.0 \) and 2.5. These values cover the observed concentrations of galactic globular clusters\(^39,40\). Initial relaxation times of the N-body models range from 300 Myr to 12 Gyr with a half-mass radius \( R_{1/2} = 2 \) pc to \( R_{1/2} = 35 \) pc. It is unlikely that 47 Tuc has started with a half-mass relaxation time outside this range, since this would require that the cluster started with either a mass or half-mass radius very different from that of observed clusters. Also we find that the best-fitting N-body models are well inside the trial grid, away from the edges in the parameter space. All models were isolated. IMBHs influence mainly the core of a star cluster and the dynamics in the core are hardly influenced by tidal effects. Therefore, the use of isolated models is justified.

The black hole was treated as a massive star in the simulations, so the IMBH was not fixed in these simulations and was allowed to wander stochastically around in the core. All models became mass segregated, where the amount of segregation depends on the initial half-mass relaxation time and initial concentration of the model. The simulations, stellar-mass black holes form from stellar evolution, concentrate near the IMBH owing to mass segregation, and then kick each other out because of close encounters. Stellar-mass black holes have kicked each other out by \( T = 11.75 \) Gyr in all simulations, except those with the largest relaxation times where only a handful remain.

Models with black hole masses of 1% of the cluster mass deviate significantly from the observed density profile of 47 Tuc. The discrepancy is strongest for radii around 10\(^3\) where the observed density profile has a near constant density core. A near constant density core at this distance is in good agreement with theoretical predictions\(^2\). The 1% IMBH model also has a strong central rise in the density profile, which is not seen in observations. We expect that both problems would become even more pronounced for more massive black holes. Hence the presence of black holes with mass equal to or larger than ~1% of the cluster mass (~8,000 M\(_\odot\)) can already be excluded. The 0.5% IMBH model leads to a better fit of the observational data. At the core of the cluster within 5\(^\prime\), the surface density of the 0.5% IMBH model is compatible with the observed density profile. Only at distances beyond \( r \approx 10^3 \) the surface density of the model cluster <20% lower than the observed profile. Such differences could be attributed to the uncertainties in the mass function and binary fractions in 47 Tuc\(^31\).

**Primordial binaries.** Primordial binaries are expected to play an important role in the early evolution of the cluster core\(^2\). For 47 Tuc, it has been estimated that primordial binaries may have pushed the core radii up to an additional 20% during the early stages of the evolution\(^19\).

In order to comparatively study the possible effects of primordial binaries on the current mass segregation, we ran additional simulations for three different model clusters. The mass function, neutron star and black hole retention fractions were kept consistent with other runs. These simulations’ base code was the GPU enabled NBODY6 with a Hermite integration scheme for variable time steps\(^48\). This integration scheme applies chain regularization\(^18\) in order to have sufficient time resolution to follow the tight orbits of binaries and their close encounters with other stars over the cluster lifetime.

Our first cluster was evolved with 10% primordial binaries. We took a snapshot of that simulation at \( T = 11.75 \) Gyr, by which time almost half of all stars had left the cluster and the global binary fraction went down to 7%. The fraction of binaries within 50% of the projected half-light radius increased to 15% at this time, fully consistent with observations of 47 Tuc\(^6\). We compare this with snapshots of the other two simulations, one without primordial binaries and the other with a 0.5% IMBH model. All snapshots are taken at the same time of their evolution and scaled by their projected half-light radii to compare their stellar distributions.

**Information theory and statistical learning.** The Kullback–Leibler (KL) divergence (\( D_{KL} \)) provides a mathematically robust approach for a comprehensive treatment of the acceleration distributions\(^47,42\). \( D_{KL} \) quantifies the entropy between two distributions. Specifically, \( D_{KL} \) is proportional to \(- E[\log(L)]\), where \( E \) is the expectation value and \( L \) is the likelihood. This likelihood value has a trivial numeric relation to the measured \( \langle P \rangle \) and simulated \( \langle \chi \rangle \) pulsar accelerations, which then can be calculated given that the information entropy is

\[
D_{KL}(\langle P \rangle | \langle \chi \rangle) = \sum_i P_i (\log(P_i) - \log(\chi_i)) = - \log(\chi) = - \sum_i \log(P_i)
\]

The intrinsic spin-down contribution to measured pulsar accelerations. The measured spin-down rates (\( P_m \)) of galactic millisecond pulsars can be used as a proxy to disentangle the overall potential contribution of the intrinsic spin-down (\( P_i \)) to the measured apparent accelerations. For pulsars in globular clusters \( P_m = P_i \) because \( P_m \) is modified by the cluster potential. The acceleration due to the cluster potential is

\[
a_{\text{GC}} = - \frac{\langle P_m - P_i \rangle}{P_m}
\]

The variation in the pulsar magnetospheric geometry, formation channels and internal structure (that is, moment of inertia), which determine \( P_i \), are expected to be similar for pulsars in clusters and the galactic disk. Therefore, the \( P_i \) distribution of pulsars in clusters should be comparable to the \( P_m \) distribution of galactic pulsars. Hence, we use the two-dimensional observed period-spin down (\( P - P_m \)) distribution of galactic pulsars to infer the possible range for the intrinsic spin-down contribution to pulsar accelerations in 47 Tuc\(^46\). The level of uncertainty due to the unknown contribution of the intrinsic \( P_i \) to the measured pulsar accelerations are represented with different shades in Extended Data Fig. 2.

Because the intrinsic \( P \) s of pulsars are not individually known, we treat the observed range of \( P \) and \( P_m \) of galactic millisecond pulsars as a distribution of values to offset the intrinsic contribution to the measured acceleration. Instead of assuming a single acceleration term, we use the 68%, 95% and 99% probable intervals for the acceleration values corresponding to each pulsar in 47 Tuc.

**The globular cluster centre.** We use the kinematic centre (\( \alpha, \delta \)) = (0h 24 min 05.67 s, -72° 04' 52.62") of 47 Tuc\(^15\) for our calculations. The uncertainty in the centre is about ±0.25\(^\prime\) in each coordinate\(^49,50\). In order to study the potential contribution of an asymmetry to our calculations, we randomly shift the cluster centre within the error box and re-calculate the black hole mass with randomly selected pulsars for many bootstrap cycles. We find that the effect of uncertainty in the centre of the inferred black hole mass is less than 5%.

**Code availability.** The simulations\(^14\) were produced with the GPU-enabled version of the collisional N-body code NBODY6\(^5,15\) publicly available online at this URL: http://www.ast.cam.ac.uk/~swee/web/pages/nbody.htm (the authors can provide further details for reproducing the simulations).

**Data availability.** Data are available from the corresponding author upon reasonable request.

31. Camilo, F., Lorimer, D. R., Freire, P., Lyne, A. G. & Manchester, R. N. Observations of 20 millisecond pulsars in 47 Tucanae at 20 centimeters. Astrophys. J. 535, 975–990 (2000).
32. Freire, P. C. et al. Timing the millisecond pulsars in 47 Tucanae. Mon. Not. R. Astron. Soc. 326, 901–915 (2001).
33. Asarseth, J. S. From NBODY1 to NBODY6: The growth of an industry. Publ. Astron. Soc. Pacif. 111, 1333–1346 (1999).
34. Nitadori, K. & Asarseth, J. S. Accelerating NBODY6 with graphics processing units. Mon. Not. R. Astron. Soc. 424, 545–562 (2012).
35. Vandenbreg, D. A., Brogaard, K., Eaman, R. & Casandjian, L. The ages of 55 galactic clusters as determined using an improved \( \Delta W_{\text{heav}} \) method along with color-magnitude diagram constraints, and their implications for broader issues. Astrophys. J. 775, 134 (2013).
36. Baumgardt, H., Makino, J., Hut, P., McMillan, S. & Portegies Zwart, S. A dynamical model for the globular cluster G1. Astron. J. 589, L25–L28 (2003).
37. McNamara, B. J., Harrison, T. E., Baumgardt, H. & Khalaj, P. A search for an intermediate-mass black hole in the core of the globular cluster NGC 6266. Astrophys. J. 745, 175 (2012).
38. Jalali, B. et al. A dynamical N-body model for the central region of \( \omega \) Centauri. Astron. Astrophys. 538, A19 (2012).
39. Harris, W. E. A catalog of parameters for globular clusters in the Milky Way. *Astron. J.* **112**, 1487 (1996).
40. Harris, W. E. A new catalog of globular clusters in the Milky Way. Preprint at https://arxiv.org/abs/1012.3224 (2010).
41. Baumgardt, H., Makino, J. & Ebisuzaki, T. Massive black holes in star clusters. II. Realistic cluster models. *Astrophys. J.* **613**, 1143–1156 (2004).
42. Goodman, J. & Hut, P. Primordial binaries and globular cluster evolution. *Nature* **339**, 40–42 (1989).
43. Giersz, M. & Heggie, D. C. Monte Carlo simulations of star clusters — VII. The globular cluster 47 Tuc. *Mon. Not. R. Astron. Soc.* **410**, 2698–2713 (2011).
44. Lützgendorf, N., Baumgardt, H. & Kruijssen, J. M. D. N-body simulations of globular clusters in tidal fields: effects of intermediate-mass black holes. *Astron. Astrophys.* **558**, A117 (2013).
45. Hurley, J. R., Pols, O. R. & Tout, C. A. Comprehensive analytic formulae for stellar evolution as a function of mass and metallicity. *Mon. Not. R. Astron. Soc.* **315**, 543–569 (2000).
46. Albrow, M. D. et al. The frequency of binary stars in the core of 47 Tucanae. *Astrophys. J.* **559**, 1060–1081 (2001).
47. Kullback, S. & Leibler, R. A. On information and sufficiency. *Ann. Math. Stat.* **22**, 79–86 (1951).
48. Kiziltan, B. & Thorsett, S. E. Constraints on pulsar evolution: the joint period-spin-down distribution of millisecond pulsars. *Astrophys. J.* **693**, L109–L112 (2009).
49. Guhathakurta, P., Yanny, B., Schneider, D. P. & Bahcall, J. N. Globular cluster photometry with the Hubble Space Telescope. I — Description of the method and analysis of the core of 47 Tuc. *Astron. J.* **104**, 1790–1817 (1992).
50. Calzetti, D., de Marchi, G., Paresce, F. & Shara, M. The center of gravity and density profile of 47 Tucanae. *Astrophys. J.* **402**, L1–L4 (1993).
Extended Data Figure 1 | Cluster surface brightnesses and corresponding neutron star spatial distributions in N-body models for projected half-light radii. The solid, dashed and dotted lines represent N-body models with an IMBH, with and without primordial binaries, respectively. a, All models have roughly comparable surface brightnesses; in contrast, b, the distribution of neutron stars is notably different for the IMBH model. The neutron star spatial distributions for N-body simulations with and without primordial binaries are similar. Therefore, it is unlikely that primordial binaries play a considerable role in shaping the final segregation profile of clusters with an IMBH.
Extended Data Figure 2 | Comparison of the observed and predicted pulsar accelerations. The observed acceleration (shaded areas) for each pulsar (named at the top of each panel) in 47 Tuc is compared with the integrated acceleration distributions for pulsars with the same line-of-sight distance predicted from N-body simulations (solid line, models with IMBH; dashed line, model without IMBH). The KL divergence method is used to calculate the integrated information entropy between distributions (equation (1)). The shaded areas show the 68%, 95% and 99% range of possible accelerations experienced owing to the gravitational potential of the cluster. Darker shades represent higher probability. The ambiguity is largely due to the unknown intrinsic spin-down of individual pulsars.
Extended Data Figure 3 | Predictive power correlates with number of observed pulsars. Shown are the normalized probabilities of $N$-body models with different black hole masses, as in Fig. 4a, for different numbers of randomly selected pulsars. The converging inference with increasing number of pulsars is indicative of statistical learning and demonstrates that the information comes from observations. The line thickness scales with the level of ambiguity for each inference.
Extended Data Table 1 | Pulsars with timing solutions in 47 Tuc (NGC 104)

| Pulsar | α: RA(J2000) [hms] | δ: Dec(J2000) [dms] | Distance from the cluster center | Period (P) [ms] | dP/dt [10^{-20} s/s] | Ref. |
|--------|---------------------|---------------------|----------------------------------|----------------|----------------------|-----|
| 0024–7204AB | 00:24:08.1657(4) | −72:04:47.616(2) | 0′12.6″ | 3.7046395539391(2) | +0.9844(3) | 12 |
| 0023–7204C | 00:23:50.35311(9) | −72:04:31.4926(4) | 1′13.8″ | 5.7567799555132(2) | −4.9850(6) | 10 |
| 0024–7204D | 00:24:13.87934(7) | −72:04:43.8405(3) | 0′38.9″ | 5.3575732846827(2) | −0.3429(7) | 10 |
| 0024–7205E | 00:24:11.10361(1) | −72:05:20.1377(4) | 0′37.2″ | 3.5363291527603(2) | +9.8510(6) | 10 |
| 0024–7204F | 00:24:03.8539(1) | −72:04:42.8065(5) | 0′12.9″ | 2.6235793525110(1) | +6.4500(4) | 10 |
| 0024–7204G | 00:24:07.9587(3) | −72:04:39.6911(7) | 0′16.7″ | 4.0403791435630(4) | −4.215(2) | 10 |
| 0024–7204H | 00:24:06.7014(3) | −72:04:06.795(1) | 0′46.1″ | 3.210340793484(4) | −0.183(1) | 10 |
| 0024–7204I | 00:24:07.9330(3) | −72:04:39.669(1) | 0′16.6″ | 3.4839920616611(5) | −4.587(2) | 10 |
| 0023–7203J | 00:23:59.40735(3) | −72:03:58.7914(1) | 1′01.1″ | 2.10063354535247(3) | −0.97921(9) | 10 |
| 0024–7204L | 00:24:03.771(1) | −72:04:56.913(4) | 0′09.8″ | 4.346167999460(1) | −12.206(4) | 10 |
| 0023–7205M | 00:23:54.4877(8) | −72:05:30.741(3) | 1′04.2″ | 3.676643217598(1) | −3.844(3) | 10 |
| 0024–7204N | 00:24:09.1865(4) | −72:04:28.880(2) | 0′28.7″ | 3.0539543462594(4) | −2.1870(9) | 10 |
| 0024–7204O | 00:24:04.6512(1) | −72:04:53.7552(5) | 0′04.8″ | 2.6433425272417(2) | +3.6354(9) | 10 |
| 0024–7204Q | 00:24:16.4891(4) | −72:04:25.153(2) | 0′57.0″ | 4.0331811845699(5) | +3.402(2) | 10 |
| 0024–7204S | 00:24:03.9799(4) | −72:04:42.342(1) | 0′12.9″ | 2.8304059578772(4) | −12.054(2) | 10 |
| 0024–7204T | 00:24:08.548(2) | −72:04:38.926(7) | 0′19.1″ | 7.588479807363(4) | +29.37(1) | 10 |
| 0024–7203U | 00:24:09.8351(2) | −72:03:59.6760(9) | 0′56.3″ | 4.3428266963896(4) | +9.523(1) | 10 |
| 0024–7204W | 00:24:06.058(1) | −72:04:49.088(2) | 0′04.0″ | 2.3523445319370(3) | −8.6553(1) | 11 |
| 0024–7201X | 00:24:22.38565(9) | −72:01:17.4414(7) | 3′48.6″ | 4.77152291069355(5) | +1.83609(7) | 11 |

Numbers in parentheses correspond to uncertainties in the last digit. In columns 5 and 6, the period (P) and spin-down (dP/dt) of millisecond pulsars are very precisely measured. The uncertainties in the last digits quoted in these columns correspond to the 1σ errors of the weighted least squares fit to the timing residuals. α, Right ascension; δ, declination.
Corrigendum: An intermediate-mass black hole in the centre of the globular cluster 47 Tucanae

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After the completion of the initial work and submission of this Letter in 2015, some additional data shared with us in 2016 (that we were given to understand will be published shortly) were later incorporated into the analysis owing to an oversight and miscommunication. These data have now been removed from the paper and will be published elsewhere by their originators at a later time. We reran the core analysis on the reduced dataset. Although the main conclusions of the work remain unchanged by these revisions, there are minor changes in the values calculated. Specifically, the central black hole mass changes from $2.200 M_\odot$ to $2.300 M_\odot$, the total cluster mass changes from $0.75 \times 10^6 M_\odot$ to $0.76 \times 10^6 M_\odot$, and the number of pulsar timing solutions used in the analysis reduces from 23 to 19. The main text, Figure 4, Extended Data Figs 2 and 3, and Extended Data Table 1 have been updated to reflect these three changes. In addition, the original refs 10 and 32 have been swapped round. We apologize for any inconvenience caused by this miscommunication. The original Letter has been corrected online.