Fermi and eROSITA bubbles as relics of the past activity of the Galaxy’s central black hole

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The newly launched X-ray satellite, eROSITA, has recently revealed two gigantic bubbles extending to ~80° above and below the Galactic Centre. The morphology of these ‘eROSITA bubbles’ bears a remarkable resemblance to the Fermi bubbles previously discovered by the Fermi Gamma-ray Space Telescope and its counterpart, the microwave haze. The physical origin of these striking structures has been intensely debated; however, because of their symmetry about the Galactic Centre, they probably originate from some energetic outbursts from the Galactic Centre in the past. Here we propose a theoretical model in which the eROSITA bubbles, Fermi bubbles and the microwave haze could be simultaneously explained by a single event of jet activity from the central supermassive black hole a few million years ago. Using numerical simulations, we show that this model could successfully reproduce the morphology and multi-wavelength spectra of the observed bubbles and haze, which allows us to derive critical constraints on the energetics and timescales of the outburst. This study serves as an important step forward in our understanding of the past Galactic Centre activity of our own Galaxy and may bring valuable insights into the broader picture of supermassive-black-hole–galaxy co-evolution in the context of galaxy formation.

Recent data taken by the eROSITA satellite have revealed striking images of two giant X-ray bubbles extending ~80° (which corresponds to ~15 kpc assuming a distance to the Galactic Centre (GC) of 8.5 kpc) above and below the GC. Despite the larger extent, the morphology of the ‘eROSITA bubbles’ is remarkably similar to the Fermi bubbles, the two γ-ray bubbles detected by the Fermi Gamma-ray Space Telescope in 2010 (ref. 1). It has also been shown previously that the γ-ray bubbles have counterparts in the microwave band, known as the microwave/Wilkinson Microwave Anisotropy Probe (WMAP)/Planck haze1,4, as well as polarized lobes in radio5. The edges of the Fermi bubbles at low latitudes also align with earlier detections of X-ray shells in the 1.5 keV band by ROSAT-6. Because of their morphological similarities, enormous physical sizes and symmetry about the GC, these fascinating structures most likely originate from the same event of powerful energy outburst from the GC sometime in the past. Understanding their physical origin would therefore provide valuable information about the history of our Milky Way Galaxy.

Before the detection of the eROSITA bubbles, the physical origin of the Fermi bubbles and microwave haze had been hotly debated8. Key questions to address include whether the γ-ray emission is hadronic or leptonic, and whether the triggering mechanism is associated with a nuclear starburst, or with activity of the central supermassive black hole (SMBH). Because of the proximity to the GC, the ample spatially resolved, multi-wavelength observational data provide very stringent constraints on the proposed theoretical models. One strong constraint comes from the hard spectrum of the γ-ray bubbles with spectral index of −2.1 (ref. 9), which means that the γ-ray emission has to be generated by cosmic-ray (CR) protons or nuclei. Previous studies have found that purely hadronic models with a power law extending to PeV energies10,11,14. Previous studies have found that purely hadronic models are disfavoured because the predicted microwave emission from secondary particles produced via pion decay is not enough to account for the observed haze emission7. In addition, the upper limits in TeV γ-rays obtained by HAWC have ruled out hadronic models with a power law extending to PeV energies16. On the other hand, both the leptonic jet models and in situ acceleration models remain promising mechanisms to explain the γ-ray bubbles and microwave haze17,18,19,20. In this Article, we show that the new eROSITA data provide crucial information that allows us to put additional constraints on these two scenarios, and that the combination of the γ-ray, X-ray and microwave images and spectra strongly suggest that past jet activity of the GC black hole is the likely culprit.

Simulations of past jet activity of Sagittarius A* We performed three-dimensional hydrodynamic simulations of energy release at the GC in the form of bipolar jets perpendicular to the Galactic plane. The simulations self-consistently model the evolution of cosmic rays (CRs) injected with the jets at the GC, including their dynamical interactions with the thermal gas within the Galactic halo, and energy losses of CR electrons due to synchrotron radiation and inverse-Compton (IC) scattering as they travel within the Galactic magnetic and radiation fields (see Methods for the simulation details). Modelling of the CRs together with the thermal gas allows us to compute the thermal radiation from the gas and the non-thermal emission generated by the CRs self-consistently. For the simulation results presented in this work, the jet activity of the central SMBH is assumed to start 2.6 Myr ago and last for 0.1 Myr (see Methods for discussion on the chosen parameters). Because of the large pressure contrast with respect to the ambient gas, the jet material expanded into a pair of ‘cocoons’ or ‘bubbles’ above and below the GC, similar to radio bubbles observed in galaxy clusters.

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ARTICLES
https://doi.org/10.1038/s41550-022-01618-x

NaturE AstronomY | Vol 6 | May 2022 | 584–591 | www.nature.com/natureastronomy

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the eROSITA bubbles and Fermi bubbles are successfully reproduced. The CR electrons within the cocoons that were transported from the GC interact with the interstellar radiation field (ISRF) and shine in the γ-ray band as the observed Fermi bubbles extending to Galactic latitudes of |b| ≈ 50°–55° (Fig. 2). The same energy injection from the black hole and subsequent cocoon expansion pushed the gas within the Galactic halo away from the GC with supersonic speeds, forming an outward propagating shock. At the shock front, the compression of gas caused an increase in the local gas density, producing enhanced thermal Bremsstrahlung emission in the X-ray band manifested as the magnetic draping effect in the northeast part of the eROSITA bubble. Despite the large scatter seen in the observed profile for the north X-ray bubble. The X-ray emission predicted by the leptonic jet model shows very good agreement with the observed eROSITA bubbles as well, not only in terms of the extension of the X-ray bubbles but also in terms of the X-ray surface brightness variations. Figure 4 shows the comparisons between the simulated and observed X-ray surface brightness profiles at three horizontal cuts, |l| = 40°, 50° and 60°, as well as the latitude-averaged profiles. Overall, the predicted amplitudes of the brightness variations and the locations of the X-ray bubble edges are largely consistent with the observational data. In our simulation, the forward shock compresses the gas into a thick shell with width of ~2.5 kpc (Fig. 1), consistent with estimates from simple geometrical models. Due to the projection of the compressed gas shell enclosing the γ-ray bubbles with low gas densities, the modelled X-ray profiles are limb-brightened at the Galactic longitude of |l| ≈ 50°, similar to the data. At lower latitudes (|b| = 40° and 50°), there is some emission at |l| ≈ 15°–20° due to gas that is ejected within the AGN jets being compressed near the contact discontinuity. This feature may be related to the two peaks at |l| ≈ 20° for |b| = 40° seen in the observed profile for the north X-ray bubble. Despite the large scatter seen in the data, the simulated latitude-averaged profile of the X-ray emission as a function of Galactic longitude approximately falls between the observed values corresponding to the emission from north and south bubbles. It is difficult to establish an exact match to the data because the observed X-ray sky in this region has many complex features. In particular, the northeast part of the eROSITA bubble is coincident with a prominent structure called North Polar Spur (NPS). The NPS was discovered several decades ago, but its origin remains elusive and...
is a subject of ongoing debate. Due to the spatial correlation with the Loop I feature in the radio band, some proposed that the NPS is associated with a local superbubble in the Solar neighbourhood; other evidence supports scenarios related to past GC activity. The discovery of the south eROSITA bubble has further strengthened the GC hypothesis. Regardless of its origin, the NPS generates a substantial degree of asymmetry in the X-ray sky, complicating the interpretations of the true emission from a GC event. While these considerations prohibit a firm conclusion, our simulated X-ray profiles suggest that an energy outburst from the GC could contribute to the NPS emission, at least partially (that is, the peak of emission at $l \approx -20^\circ$). This is in line with the conclusion drawn from a recent study of the radio/optical polarization data near the NPS, which suggests that the NPS could be a superposition of both local and GC structures (see Methods for more detailed discussion).

Additional constraints on the formation of these gigantic bubbles come from the broad-band spectra in the same region in the sky from microwaves by WMAP and Planck to GeV $\gamma$ rays by Fermi and TeV $\gamma$ rays by HAWC. We compiled the available observational constraints and our simulated spectra in Fig. 5. In agreement with previous studies, we find that the leptonic model can simultaneously reproduce the GeV $\gamma$-ray spectrum of the Fermi bubbles and the microwave spectrum of the WMAP/Planck haze. In the model, the primary CR electrons injected by the AGN jets are quickly heated to a few $10^7$ K, which are conditions comparable with those of dense CGs. In the shock downstream, the electron number density is enhanced to $n_e \approx 10^3$ cm$^{-3}$ and the gas temperature is $T \approx 10^8$ K. At the present day, the forward shock is moving at a speed of $\approx 2,000$ km s$^{-1}$ (Mach number $M \approx 10$) in the vertical direction and $\approx 1,300$ km s$^{-1}$ $(M \approx 6)$ in the lateral direction at a height of 5 kpc away from the Galactic plane. Inside the contact discontinuity, the electron number density is $n_e \approx 10^4$–$10^5$ cm$^{-3}$ and the gas temperature is $T \approx 10^9$–$10^10$ K (though the temperature distribution within the contact discontinuity is uncertain due to parameter degeneracies; Methods). According to our model, the central SMBH was active ~2.6 Myr ago, injecting a pair of bipolar jets in mostly kinetic forms for a duration of ~0.1–1 times the Eddington rate during the active phase, corresponding to a consumption of $\approx 10^9$–$10^10$ solar masses within ~0.1 Myr.

Our model of the Fermi/eROSITA bubbles makes a specific prediction that could be tested with future observations. The region between the contact discontinuity and the forward shock is compressed to electron number densities of a few $10^5$ cm$^{-3}$ and shock heated to a few $10^8$ K, which are conditions comparable with those typically observed in the intracluster medium of cool-core galaxy clusters. Unlike in most of the Milky Way halo, this region could produce iron $K\alpha$ emission from hydrogen-like ($6.7$ keV) or helium-like ($6.9$ keV) iron ions that have peak collisional ionization equilibrium fractions at a few $10^7$ K and $10^8$ K, respectively. We note that whether such a line is detectable depends on the fraction of the fast hot gas. Since the temperature of the gas is uncertain in our model, that fraction may be too small for existing instruments to detect. However, it may be detectable with Athena as its effective area is almost 2 orders of magnitude larger than Chandra’s at $6.9$ keV (ref. 23). Given the expected post-shock velocity of $\approx 2,000$ km s$^{-1}$ (Fig. 1d), the total Doppler line broadening is expected to be about 45 eV at 6.7 keV line energy, but the exact value will depend on the details of the velocity projection. A shift of this magnitude should be detectable with the Athena X-ray Integral Field Unit that has a planned spectral resolution of 2.5 eV up to line energies of 7 keV and more than sufficient spatial resolution to probe this region. Thus, a coherent outflow originating from the region between the shock and contact discontinuity could be a testable model prediction, especially if the data quality is sufficient to constrain not only the line width but also its skewness or profile.

**Discussion**

As mentioned above, both the leptonic jet model and the model of in situ acceleration by shocks or turbulence are promising mechanisms to explain the $\gamma$-ray emission of the Fermi bubbles, but new insights could be obtained by adding the constraints from the eROSITA data. One primary difference between the leptonic
jet model and the shock acceleration model is the location of the forward shock driven by the outburst. In the leptonic jet model, the surface of the eROSITA and Fermi bubbles corresponds to the forward shock and contact discontinuity, respectively. On the other hand, if the Fermi bubbles are produced by shock-accelerated CRs as proposed in some of the in situ acceleration models\textsuperscript{16}, the more extended eROSITA bubbles would be left unexplained. In this regard, the leptonic jet model may be favoured as both the eROSITA bubbles and the Fermi bubbles could be simultaneously accounted for by a single event. In situ acceleration models in which the Fermi bubbles are produced by CRs accelerated by turbulence generated within the bubbles\textsuperscript{19} remain a possibility. In this scenario, the forward shock driven by the outflow could account for the eROSITA bubbles, and the turbulence in the shock downstream could potentially stochastically accelerate CRs that are responsible for the $\gamma$-ray bubbles. However, note that the surface of the Fermi bubbles is very smooth, suggesting that hydrodynamic instabilities at the bubble surface are suppressed, and hence the amount of turbulence generated may be limited. Also, in this scenario the turbulence is expected to be volume-filling in the shock downstream and of increasing strength toward the shock front\textsuperscript{11}, and therefore the sharp edges of the Fermi bubbles cannot be naturally explained. More detailed simulations are needed to test whether the stochastic acceleration models could satisfy all the observational constraints.

Our simulation suggests that a single past jet activity $\sim$2.6 Myr ago from the GC black hole could be the common origin for the eROSITA bubbles, the Fermi bubbles and the microwave haze. The required Eddington ratio is estimated to be $\sim$0.1–1 during the brief active accretion phase of $\sim$0.1 Myr. Though such high activity for Sgr A* may appear somewhat surprising given its extreme quiescence at the present day, multiple lines of evidence have pointed to much elevated past activity from Sgr A* over the past $\sim$10 Myr (ref. \textsuperscript{31}). In particular, recent studies have found enhanced ionization levels in the Magellanic Stream, which could be explained if Sgr A* went through a phase of Seyfert-like flaring activity a few Myr ago\textsuperscript{9}. The energetics and timescales obtained by our simulations are in good agreement with such a Seyfert-flare scenario. The epoch of outburst predicted by our model is also in line with several independent constraints from kinematic studies of the halo gas using X-ray and ultraviolet (UV) absorption lines\textsuperscript{22–24}, which estimated that the outburst occurred $\sim$2–8 Myr ago (though there remain uncertainties in the interpretations; see Methods for detailed discussion).

![Fig. 3] Gamma-ray and microwave profiles. a, Intensity profiles of the microwave haze at 23 GHz ($I_\nu$) as a function of radius from the GC ($r$). The blue curve shows the predicted synchrotron emission from CR electrons (CRe) from the leptonic jet model and the blue shaded region shows the observed limits of the WMAP haze\textsuperscript{63}. b, Gamma-ray intensity profiles ($N$ is the number of gamma-ray photons per unit area per solid angle per unit time) as a function of Galactic longitudes averaged over the latitude region of $40\degree < |b| < 50\degree$. Curves show the predicted IC emission and shaded regions show the observed limits\textsuperscript{9}. Colours correspond to different energy bins (red: $E = 1–3$ GeV; green: $E = 3–10$ GeV; blue: $E = 10–500$ GeV).

![Fig. 4] X-ray surface brightness profiles. Profiles of X-ray surface brightness (in units of counts s$^{-1}$ deg$^{-2}$) as a function of Galactic longitudes in the 0.6–1.0 keV range comparing the model predictions (blue) and the observed profile of the eROSITA bubbles (north and south bubbles shown in orange and red colours, respectively). a–d, Horizontal cuts at Galactic latitudes of $|b| = 60\degree$ (a), $50\degree$ (b), $40\degree$ (c) and the latitude-averaged profiles (d). The overall amplitudes and locations of the X-ray shells are well reproduced by the model, though interpretation is complicated by the asymmetry in the data caused by the NPS observed in the northern X-ray sky.
The rich multi-wavelength observational data as well as detailed theoretical modelling have provided valuable information about the past GC activity. For example, our model suggests that the radiation and magnetic fields are probably suppressed in the inner-kpc region near the GC at the time when the jets were launched (Methods). Such suppression could perhaps be related to an earlier injection that produced the GC chimney\(^\text{15}\) and bipolar radio bubbles\(^\text{36}\) recently observed close to the Galactic plane. Alternatively, the suppression could be associated with the formation of the nuclear star cluster ~6 Myr ago\(^\text{37}\), where stellar winds or supernova explosions of the massive young stars could have helped to evacuate the gas and create a GC environment less hostile to the cooling CR electrons within the jets. Such a scenario is also broadly consistent with the emerging picture of SMBH–galaxy co-evolution in that AGN activity often accompanies star formation activity in the galaxy\(^\text{46}\). Some open questions remain to be addressed; for example, whether CRs accelerated at the forward shock could generate observable non-thermal emission in the leptonic jet scenario, whether the thermal structure of the Galactic halo probed by X-ray absorption line studies\(^\text{48}\) could be explained, how the jet-induced outflows entrain cold gas and how it may be related to the high velocity clouds observed in the Galactic halo\(^\text{49}\). Future investigations will further reveal the impact of this energetic feedback on the evolution history of our Milky Way Galaxy, and how this event fits in the broader picture of SMBH–galaxy co-evolution in the universe.

Methods
Simulation setup and parameters. We carried out three-dimensional hydrodynamic simulations of bipolar jets emanating from the GC and perpendicular to the Galactic plane including relevant CR physics using the FLASH code\(^\text{40}\). We utilized the CRSPS code to self-consistently model the evolution of CR spectrum due to synchrotron and IC cooling, while accounting for the dynamical interaction between the CRs and the thermal gas\(^\text{41}\). The modeling of the CR spectral evolution is crucial, as it allows us to simultaneously compute the non-thermal radiation from the CRs and the Bremsstrahlung emission from the thermal gas. The injected CR electrons are assumed to follow an initial power-law spectrum ranging from 10 GeV to 10 TeV, with a spectral index of $-2.1$. In our previous work\(^\text{41}\), we have demonstrated that the magnetic field within the Fermi bubbles needs to be amplified to values comparable with the ambient field at the present day to reproduce the microwave haze emission. Therefore, we do not simulate the magnetic field directly, but adopt the default magnetic field distribution in GALPROP\(^\text{42}\) for the computation of the microwave haze, that is, $|B| = B_0 \exp(-z_0/\zeta_c) \exp(-R>R_0)$, where $R$ is the projected radius to the Galaxy’s rotational axis, $B_0$ is the average field strength at the GC and $z_0$ and $R_0$ are the characteristic scales in the vertical and radial directions, respectively. We adopt $z_0=2$ kpc, $R_0=10$ kpc and $B_0=50$ G as motivated by observational constraints\(^\text{43}\). As will be discussed below, the high-energy cutoff in the observed $\gamma$-ray spectrum requires suppression of radiation and/or magnetic field strengths near the GC at the time of jet injection. Therefore, for computing the synchrotron losses in the simulations, we have used a factor-of-three lower normalization of magnetic field strength compared with the value adopted in our earlier work\(^\text{15}\). For IC scattering, we utilize the ISRF model in GALPROP and compute the CR electron energy losses and $\gamma$-ray emissivity including the Klein–Nishina effect. To generate the $\gamma$-ray radiation due to IC scattering and the microwave haze emission by synchrotron radiation while satisfying the HAWC constraint.

![Fig. 5 | Broad-band spectrum for the Fermi bubbles.](image)

Table 1 | Input and derived jet parameters

| Parameter | Description | Value | Unit |
|-----------|-------------|-------|------|
| $\eta$    | Density contrast | 0.05  | -    |
| $n_e$     | Energy density contrast | 0.81  | -    |
| $\varepsilon_{\gamma\nu}$ | CR energy density | $6.82 \times 10^{-7}$ | erg cm$^{-3}$ |
| $v_{jet}$ | Jet speed | 0.025 | c    |
| $R_{jet}$ | Radius of cross-section | 0.5  | kpc  |
| $\rho_j$  | Thermal gas density | $1.95 \times 10^{-25}$ | g cm$^{-3}$ |
| $\varepsilon_{\gamma}$ | Thermal energy density | $1.29 \times 10^{-9}$ | erg cm$^{-3}$ |
| $P_{ke}$  | Kinetic power | $3.08 \times 10^{44}$ | erg s$^{-1}$ |
| $P_{\gamma}$ | Thermal power | $7.21 \times 10^{42}$ | erg s$^{-1}$ |
| $P_{\nu}$ | CR power | $3.82 \times 10^{41}$ | erg s$^{-1}$ |
| $P_{\gamma}$ | Magnetic power | $3.31 \times 10^{41}$ | erg s$^{-1}$ |
| $P_{total}$ | Total power | $3.16 \times 10^{44}$ | erg s$^{-1}$ |
| $E_{\gamma}$ | Total injected energy | $1.00 \times 10^{57}$ | erg |

*The total injected energy by both bipolar jets is $2 \times 10^{59}$ erg. \({}\)The velocity of light.
and heated to $T \approx 10^9$ K, producing the X-ray bubbles as observed. Within the contact discontinuity, the underdense cavity filled with thermal gas and CRs, though their relative contributions are uncertain due to the parameter degeneracy discussed above. The CR distribution is edge-brightened, which reproduces the nearly flat intensity of the Fermi bubbles. Similar to our previous findings, we find that only a small fraction ($\eta$) of the simulated CRs needs to be CR electrons to match the observed $\gamma$-ray and microwave spectra. Note that the value of $\eta$ is larger than that found in our previous studies because of the reduced amount of CR energy injected in the current simulations.

For completeness, we show the comparisons between the predicted and observed profiles for the microwave haze and $\gamma$-ray bubbles in Fig. 2. As can be seen, the leptonic jet model can simultaneously reproduce not only the spectra of the $\gamma$-ray bubbles and the microwave haze (Fig. 3) but also the key features in their spatial distributions. The predicted synchrotron emission follows a centrally peaked profile primarily because of the Galactic magnetic field from the GC. For the $\gamma$-ray profiles, the nearly flat intensity profiles and sharp edges of the observed bubbles are reproduced, which requires very specific three-dimensional distributions of CRs as well as suppression of CR diffusion across the bubble surface (see discussion in the main text). Note, though, that due to large uncertainties in the predicted and observed $\gamma$-ray profiles, any deviations need to be related to the bending of the observed Fermi bubbles toward the west and that could be accounted for in the model by invoking a slight tilt as considered in our earlier work. As a side note, we point out that in our previous analysis based on magnetohydrodynamical simulations, the CRs needed to be replenished by a second jet injection to match the microwave profile. That was because the initial magnetic field strength inferred in our model is consistent with some of the observational studies, other studies have inferred more mild outflow velocities of $\sim 200$ km s$^{-1}$ (refs. (7,23)). The apparent discrepancies could be explained by taking into account a number of factors. (1) The predicted hot gas in the range of $T \approx 10^7$ K would not contribute substantial emission in the X-ray band probed by current data. In addition, for shocks, it is likely that CRs are preferentially heated to higher temperatures than the radiating electrons. Therefore, outflow velocities inferred by measuring the temperature contrast (where the temperature is obtained by fitting the X-ray spectrum emitted by the electrons) between the shocked gas and the ambient medium may underestimate the true velocities. Note also that given the typical conditions in the Galactic regions surrounding the Fermi Bubbles (electron density $n_e \sim 10^{-3}$ km$^{-3}$ temperature variances from $T \sim 2 \times 10^5$ K to $\sim 5 \times 10^6$ K) and the corresponding long cooling times $\sim n_b T_e (n_e/n_b) \sim 375$ Myr to 3.3 Gyr, the E0shock is unlikely to be strongly radiative or isothermal. (2) The UV absorption lines probe the kinematics of the cooler $T \approx 10^6$ K gas, and thus using them to infer the velocity of the hot gas (which depend on both $n_e$ and $T_e$) is likely incorrect. (3) The cooler gas is formed/entrained in the hot flow, which remains a major unresolved question itself. Furthermore, in an entrainment scenario, the velocities of the cold clouds are typically smaller than those of the hot gas due to imperfect momentum transfer.

The inferred velocities of $\sim 10^{-1} \times 300$ km s$^{-1}$ from UV absorption lines would thus imply even higher velocities for the hot flow. (3) There remain large uncertainties in the interpretations of the observational data, for example, assumptions about the geometry of the outflows and injection patterns (continuous versus instantaneous injections), the asymmetric emission measure of the Galactic halo and confusion due to foreground/background projections (for example, the NPS). Given all the above considerations, we leave the detailed comparisons with these observational data to dedicated future work.

**Initial GC environment and particle acceleration.** As discussed in our previous study, the latitude-independent high-energy cutoff in the observed $\gamma$-ray spectrum at $\sim 1100$ GeV implies a very uniform form factor for the maximum CR energy, $E_{\text{max}} \approx 300$ GeV. The maximum energy of CR electrons today is set by the fast synchrotron and IC cooling near the GC at early times, followed by adiabatic cooling due to the bubble expansion. These considerations allow us to infer conditions within $\sim$kpc from the GC in the early phase of the evolution. Because of the parameter modifications mentioned above, the expansion is somewhat slower, and the age of the bubbles becomes somewhat larger than our previous estimates, changing from 1.2 Myr to 2.6 Myr. This leads to longer times for the CR electrons to cool adiabatically, changing $E_{\text{max}}$ by a factor of 10 from the simulation time $t = 0.4$ Myr to $t = 2.6$ Myr. This implies that the maximum CR energy is $\sim 3$ TeV at the time when the jets leaves the inner kpc region. According to the constraints we obtained in the previous study (see their fig. 6), it implies that either the initial jet velocity needs to be larger or the initial radiation plus magnetic field energy density near the GC needs to be suppressed when the jets were first launched. Assuming that the initial jet velocity is unchanged (otherwise it would modify other properties such as bubble morphology), the radiation ($\eta_m$) plus magnetic field ($\eta_B$) energy densities inferred would need to be suppressed to $\eta_m \approx \eta_B \approx 1.9 \times 10^{-6}$ erg cm$^{-3}$. Assuming the energy density of the ISRF at the GC is $\eta_\nu \approx 1.5 \times 10^{-6}$ erg cm$^{-3}$, the same as the GALPROP model at the present day after taking into account the Klein–Nishina effect, then the magnetic field strength at the GC at the time of injection would need to be $\sim 3\eta_G$. Equivalently, if one would like to estimate characteristic CR cooling times, one could define an effective field strength such that $\eta_B = \eta_B (\gamma_{\text{cut}}/8\eta_G)$. Our constraints would imply that $\eta_B = 7\eta_G$. One could ask whether the inferred GC conditions are consistent with CR electrons being accelerated up to $\sim 3$ TeV by checking 2 criteria. First, assuming that the CRs within the jets are accelerated by diffuse shock acceleration (DSA), the maximum CR electron energy can be estimated by balancing the DSA acceleration rate and the IC plus synchrotron cooling rate $\dot{E}_{\text{cool}} = E_{\text{max}}^\gamma 

\frac{dE}{dt} = \frac{1}{6} \lambda \frac{\dot{E}_{\text{cool}}}{\dot{E}_{\text{max}}} \frac{B}{\rho G} \frac{G}{V^2} \approx 7 \text{ GeV s}^{-1}.

where $z = 0.1$ is the DSA acceleration efficiency. One can see that, given the suppressed radiation and magnetic field strengths, the acceleration of CR electrons is not strongly limited by the synchrotron and IC cooling. Of course, the magnetic field strength within the jets is uncertain and could be higher, especially close to the black hole. But the above estimate suggests that the condition of $E_{\text{max}} \approx 3$ TeV could be satisfied for a wide range of magnetic field strengths. The second criterion is the constraint on acceleration timescales. The maximum rate of particle acceleration by a strong parallel shock can be written in the following form:

$\frac{dE}{dt} = \frac{1}{6} \lambda \frac{\dot{E}_{\text{cool}}}{\dot{E}_{\text{max}}} \frac{B}{\rho G} \frac{G}{V^2} \approx 7 \text{ GeV s}^{-1}.

$ is the charge and $\rho_{\text{gas}}$ is the shock velocity in cm s$^{-1}$. For $V_{\text{shock}} = 0.05$ cm s$^{-1}$, $B \approx 2 \mu G$ and $\eta_\nu = 3\times 10^{-4}$ TeV$^{-1}$, one could then estimate the maximum acceleration timescale $t_{\text{acc}} \approx \dot{E}_{\text{max}}/\dot{E}_{\text{cool}}$ to accelerate CRs to $E_{\text{max}} \approx 3$ TeV, which is much less than the dynamical time of the jets $t_{\text{dyn}} \approx (1/kpc) / (0.13 \text{ Myr})$. Therefore, one could then estimate the maximum acceleration timescale $t_{\text{acc}} \approx \dot{E}_{\text{max}}/\dot{E}_{\text{cool}}$ to accelerate CRs to $E_{\text{max}} \approx 3$ TeV. Therefore, overall, we find that DSA is a plausible mechanism to accelerate CR electrons to the energy required in the model.

Relativistic magnetic reconnection is also a possible primary particle-acceleration mechanism. The properties of relativistic magnetic reconnection depend strongly on the magnetization parameter $\sigma = B/\rho V^2$. In the rest mass particle energy density, with the relativistic regime defined by $\sigma > 1$. One finds that as $\sigma$ increases, the energetic particle spectral index $p$ (assuming the particle energy spectrum is a power law distribution, $E^{-p}$) decreases, and can drop below $p = 2$. This raises the interesting possibility that the observed $E^\gamma$ spectrum is actually an aged spectrum, which would allow the jet to be older and/or the particle transport slower than what is inferred from DSA. However, the hardening of the spectrum is accompanied by a decrease in the maximum particle energy achievable (as it must be): $\tau_{\max} \approx (\sigma + 1) (2 - p)/(p - 1/2)^{1/2}$. Thus, to achieve $3\text{ TeV}$ ($\tau_{\max} \approx 6 \times 10^6$), $\sigma$ must be very large or $p$ must be very close to 2. For example, if $p = 1.5$, $\sigma > 2.4$ km s$^{-1}$ while if $p = 1.8$ in order $\sigma > 4.2$. But with $p$ so close to 2, the constraints on aging are essentially the same as for DSA. Thus, we regard the constraints on jet age and particle transport as robust.

**Uncertainties and limitations of the current model.** The power of the two jets obtained in our model is $6.32 \times 10^{54}$ erg s$^{-1}$, which is close to the Eddington luminosity for $\sigma G r^2 \approx 1$. Note, however, that the estimated jet power in our model is directly proportional to the unknown initial central gas density assumed in the simulations. Although we have used the observational constraints from X-ray absorption line studies to inform the gas profile of the Galactic halo, the true value near the GC at the time of injection remains highly uncertain. As discussed in the main text, if the gas near the GC were evacuated due to a prior energy injection or the formation of the nuclear star cluster, it is conceivable that the central density is lower than that assumed in our model. Therefore, the energetics of the SMBH accretion event obtained in our model should be considered as an overestimate, and the Eddington ratio is likely to be in the range of $0.1-1$ given the above considerations.
Our simulation setup of the Galactic halo is relatively simple and is strictly symmetric about the GC. In reality, the Galactic halo is much more complex. The most prominent structure is the NPS, which is very bright in the northeastern X-ray sky. As mentioned in the main text, it remains uncertain whether the NPS is associated with a local superbubble or a GC event. Generally speaking, studies based on stellar polarization and extinction tend to support the local superbubble scenario\(^{1,11,12}\), whereas analyses based on X-ray data tend to suggest a GC origin\(^{13-15}\). To reconcile the apparent discrepancies, it has been proposed that the X-ray emission of the NPS may be a superposition of both the local and GC structures\(^{16}\). Our simulation also supports this conclusion. It has also been reported that the emission measure of the Galactic halo is asymmetric about the Galactic plane\(^{16}\). If the outflow from the GC is expanding into this asymmetric Galactic medium, the brighter emission of the NPS could also be accounted for\(^{17}\). Another limitation of our simulation is that we have only modelled the hot component of the halo gas and neglected the colder, multiphase Galactic disk. Therefore, our simulation results cannot be directly compared with observed structures close to the Galactic plane, including the X-ray shells observed by ROSAT\(^{18}\), and the more recently discovered HI outflows\(^{19}\), X-ray chimney\(^{20}\) and bipolar radio bubbles\(^{21}\). Since all these structures may provide important clues to the formation of the gamma-ray bubbles, we will extend our model to include the Galactic disk component and investigate the detailed jet–disk interactions in future work.

To inflate the nearly symmetric eROSITA and Fermi bubbles, our model requires bipolar jets in the direction perpendicular to the Galactic plane. Generally speaking, the directions of SMBH jets are determined by the orientation of accretion disks and/or the black hole spins on much smaller scales and do not need to align with the rotational axis of the host galaxies. Future studies would be required to see whether this condition could be relaxed by considering tilted jets interacting with dense, multiphase interstellar medium within the Galactic disk\(^{22}\). Alternatively, such alignment may indeed be expected in low-mass, disk galaxies such as the Milky Way, as recent simulations have shown\(^{23}\). In this case, the rotational axis of the black hole accretion disk may align with that of the host galaxy as it is fed by gas with high angular momentum, and the black hole spin could efficiently align with the accretion disk due to the Bardeen–Petterson effect\(^{24}\) because of the relatively small mass of the black hole compared with its accretion disk.

Finally, we note that the computational costs of our three-dimensional, CR hydrodynamic simulations forbid us to do a full parameter scan of all the possible combinations of the six jet parameters. Therefore, the jet parameters we found in this study may not be unique, even though the parameter space should be very limited given the stringent constraints from all the available observational data\(^{15}\). Nevertheless, our current simulation serves as a proof of concept that the gigantic bubbles within our Galaxy could plausibly originate from past jet activity of the GC black hole.

**Data availability**

Source data are provided with this paper. Source data associated with Figs. 1 and 2 are available from the corresponding author upon reasonable request.

**Code availability**

The simulations were performed using the code FLASH, publicly available at https://flash.rochester.edu/site/flashcode/, with modifications described in ref. 11. The CR module is a proprietary software product funded by NASA and NSF and is not publicly available.

Received: 21 December 2021; Accepted: 26 January 2022; Published online: 7 March 2022

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Acknowledgements
H.-Y.K.Y. acknowledges support from the Yushan Scholar Program of the Ministry of Education of Taiwan and Ministry of Science and Technology of Taiwan (MOST 109-2112-M-007-037-MY3); M.R. acknowledges support from National Science Foundation Collaborative Research Grants AST-1715140 and AST-2009227 and National Aeronautics and Space Administration grants 80NSSC20K1541 and 80NSSC20K1583. E.G.Z. acknowledges support from National Science Foundation Collaborative Research Grant AST-2009323. The simulations are performed and analysed using computing facilities operated by the National Center for High-performance Computing and the Center for Informatics and Computation in Astronomy at National Tsing Hua University. FLASH was developed largely by the US Department of Energy-supported ASC/Alliances Center for Astrophysical Thermonuclear Flashes at University of Chicago. Data analysis presented in this paper was conducted with the publicly available yt visualization software®.

Author contributions
H.-Y.K.Y. carried out the simulations and analyses and prepared the manuscript. M.R. participated in the interpretation of the simulation results and assisted in the preparation of the manuscript. E.G.Z. contributed to the discussions of particle acceleration and assisted in the preparation of the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41550-022-01618-x.

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Peer review information Nature Astronomy thanks Jun Kataoka and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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