

Inference on inner galaxy structure via gravitational waves from supermassive binaries

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The detection of a stochastic gravitational wave background by pulsar-timing arrays indicates the presence of a population of supermassive black hole binaries. Although the observed spectrum generally matches predictions for orbital evolution driven by gravitational-wave emission in circular orbits, there is a preference for a spectral turnover at the lowest observed frequencies, which may point to substantial hardening during a transition from early environmental influences to later stages dominated by emission. In the vicinity of these binaries, the ejection of stars or dark matter particles through gravitational three-body slingshots efficiently extracts orbital energy, leading to a low-frequency turnover in the spectrum. Here we model how the gravitational-wave spectrum depends on the initial inner galactic profile before scouring by binary ejections while accounting for a range of initial binary eccentricities. By analysing the NANOGrav 15-year data, we find that a parsec-scale galactic-centre density of around $10^6 M_{\odot} \text{pc}^{-3}$ is favoured across most of the parameter space, thus shedding light on the environmental effects that shape black hole evolution and the combined matter density near galaxy centres.

Recent advances of pulsar-timing arrays (PTAs), which can leverage precise measurements of timing residuals within a galactic-scale detector, have ushered in a new era of stochastic gravitational wave background (SGWB) detection. The SGWB, defined by a superposition of incoherent gravitational waves (GWs), initially emerged as a common-spectrum process¹. Subsequent data provided evidence of a quadrupolar correlation function^{2–5}, famously known as the Hellings–Downs curve⁶, which affirmed the presence and characteristics of the SGWB.

The observed spectrum of the SGWB is consistent with expectations for a population of supermassive black hole binaries (SMBHBs)

that is dominated by binaries with comparable mass ratios, total masses in the range $10^{9.2–10.4} M_{\odot}$ and redshifts from 0.15 to 0.9 (refs. 7,8), where M_{\odot} represents the solar mass. Although the spectrum is consistent with a steady slope due to GW emission by circular binaries, the NANOGrav 15-year data⁷ exhibit a mild preference for a low-frequency turnover, a feature also indicated by data from the Parkes Pulsar Timing Array⁴ and European Pulsar Timing Array⁸, which have over 10 years of observations. This feature implies an acceleration in the rate of orbital hardening, which would be a potential solution to the final parsec problem^{9,10}.

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A natural and simple explanation involves environmental interactions with stars and cold dark matter, which are noted for their potentially high density in galactic centres^{11–13}. Both stars and dark matter can be expelled from a system through gravitational slingshots during encounters with binary components, thereby extracting orbital energy¹⁴. This process involves three-body scattering, for which the energy extraction efficiency is substantially higher than that of two-body dynamical friction¹⁵, especially when the binary components have comparable masses and are sufficiently close. Such three-body slingshot interactions can substantially alter the density profile of the galactic centre, particularly flattening the inner distribution^{16,17}. This underscores the importance of considering the co-evolution of the density profile and the binary orbit. A pivotal study by Sesana and Khan¹⁸ demonstrates that the orbital hardening rate observed in N -body simulations can be effectively approximated by results from scattering simulations¹⁴ within environments characterized by the distribution at the SMBHB influence radius¹⁹ before scouring. In this study, we use the NANOGrav 15-year dataset to investigate how the SGWB is shaped by initial galactic-centre density profiles and binary orbital eccentricities. By jointly modelling the co-evolution of eccentricity and environmental hardening through three-body scattering, we demonstrate that current PTA data, despite their marginal sensitivity, already encode measurable information about parsec-scale matter distributions in galactic centres.

Binary hardening by three-body scattering

The SGWB emanating from SMBHBs is an incoherent superposition of signals from individual sources. Its spectrum is characterized by the characteristic strain $h_c(f)$ obtained by integrating the single-binary GW emission over redshift z , total mass M and mass ratio $q \leq 1$ and weighted by the co-moving population distribution $d^3\eta/(dz dM dq)$, where η is the co-moving volumetric number density of binaries. The emitted GW frequency in the source frame f_s is related to the observed frequency by the usual redshift relation $f = f_s/(1+z)$.

The single-binary GW emission spectrum is inversely proportional to the orbital hardening rate da/dt , as binaries that spend longer at a given orbital separation contribute more strongly to the SGWB. The semimajor axis a satisfies Kepler's law, $a^3 = GM/(2\pi f_{\text{orb}})^2$, where G is Newton's constant and the orbital frequency $f_{\text{orb}} = f_s/2$ for circular binaries. The total hardening rate is $da/dt \equiv \sum_j (da/dt)_j$, with the index j accounting for all relevant mechanisms driving orbital decay.

For circular binaries evolving purely under GW emission, the evolution of the semimajor axis is

$$\left. \frac{da}{dt} \right|_{\text{GW}}^{e=0} = -\frac{64}{5} \frac{G^3 M^3}{c^5 a^3} \frac{q}{(1+q)^2}, \quad (1)$$

where c is the speed of light and e is the eccentricity. This scaling leads directly to the well-known power-law spectrum of the SGWB, $h_c \propto f^{-2/3}$, for a population of circular, GW-driven binaries. Eccentric orbits enhance GW emission over a range of frequencies, as discussed in Methods. Consequently, a turnover in the spectrum at lower frequencies is possible before the orbit undergoes circularization through GW emission²⁰.

In galactic centres, SMBHBs form within a background of stars and particle dark matter, once their separation falls below the influence radius r_i . This radius is defined as the distance at which the total enclosed mass of stars and dark matter is twice the mass of the SMBHB¹⁹. Given the extreme mass ratio between the SMBHB and the stars and dark matter, both act effectively as test particles. Each may undergo several gravitational encounters with one of the black holes (BHs) until it gains sufficient kinetic energy to be ejected. This three-body slingshot process becomes efficient as the semimajor axis a approaches the hardening radius, defined as $a_h \equiv r_i q/(4(1+q)^2)$ (ref. 14). The rate of orbital hardening due to three-body scattering, averaged over a

background of particles with matter density ρ and velocity dispersion σ , is given by¹⁴:

$$\left. \frac{da}{dt} \right|_{\text{3BS}} = -HG \frac{\rho}{\sigma} a^2, \quad (2)$$

where H is a dimensionless coefficient typically ranging from 15 to 20, as observed in scattering simulations¹⁴. It is important to note that three-body scattering is fundamentally distinct from two-body dynamical friction¹⁵ and becomes more dominant within the hardening radius. Assuming a constant ρ/σ ratio over time, the spectral evolution for circular orbits follows $h_c \propto f$. Note that three-body scatterings tend to increase the eccentricity on average¹⁴, in contrast to the effects of GW emission.

Historically, the three-body slingshot process was thought to stall orbital evolution by ejecting background stars and depleting the loss cone, a region of phase space consisting of low-angular-momentum orbits in which stars are close enough for strong interactions with the binary. This led to what is known as the final parsec problem⁹. However, N -body simulations^{21–23} have shown that merger-induced triaxiality can efficiently repopulate the loss cone²⁴.

These simulations also reveal that two initially cuspy profiles, each centred on a BH with peak densities, will merge and flatten into a single core profile following the merger^{16,17}. This underscores the need for comprehensive simulations that simultaneously address the co-evolution of the SMBHB orbit and the density profile. Further analysis comparing results from scattering simulations¹⁴ with N -body simulation outcomes²³ demonstrates that predictions of orbital evolution can closely align with equation (2), assuming that ρ/σ remains constant, as determined by the initial profile at the influence radius r_i of the SMBHB¹⁸. This statement is supported by observations that the total mass ejected during SMBHB evolution is approximately of the order of M (refs. 14,16,25–28) and is primarily distributed within the influence radius at the onset. During simulations, the loss cone at this radius remains fully populated as it is driven by the efficient diffusion of particles in triaxial potentials.

By comparing equation (1) with equation (2), one sees that the GW spectrum naturally separates into two regimes: a low-frequency phase dominated by three-body scattering and a high-frequency phase governed primarily by GW emission. The transition between these phases is marked by a turnover frequency in the source frame²⁹:

$$f_t = \pi^{-1} \left(\frac{5c^5}{64} \frac{(1+q)^2}{q} \frac{\rho_i}{\sigma_i} H \right)^{3/10} G^{-1/10} M^{-2/5} \\ \approx 2.8 \text{ nHz} \left(\frac{(1+q)^2}{q} \frac{\rho_i/\bar{\rho}_{\text{ref}}}{\sigma_i/\bar{\sigma}_{\text{ref}}} \frac{H}{18} \right)^{3/10} \left(\frac{M}{10^{10} M_\odot} \right)^{-2/5}. \quad (3)$$

Here we introduce ρ_i and σ_i as the values of ρ and σ evaluated at r_i , and define $\bar{\rho}_{\text{ref}} \equiv 10^5 M_\odot/\text{pc}^3 \approx 3.8 \times 10^6 \text{ c}^{-2} \text{ GeV cm}^{-3}$ and $\bar{\sigma}_{\text{ref}} \equiv 10^{-3} \text{ c}$. Figure 1 presents examples of the GW spectra from an individual SMBHB across various parameter settings, demonstrating how the magnitude of three-body scattering and the initial binary eccentricity influence the spectral shape.

Inference of galactic-centre matter distributions

The NANOGrav 15-year data indicate a slight preference for a turnover at low frequencies, particularly around 4 nHz (ref. 7), suggesting deviations from the expected behaviour of purely circular binaries driven by GW emission. Given that both eccentricity and star- and dark matter-induced three-body scatterings can contribute to this turnover, we conduct a comprehensive survey of their joint parameter space.

We adopt a straightforward power-law distribution for the galactic-centre density profile before scouring, parameterized as follows:

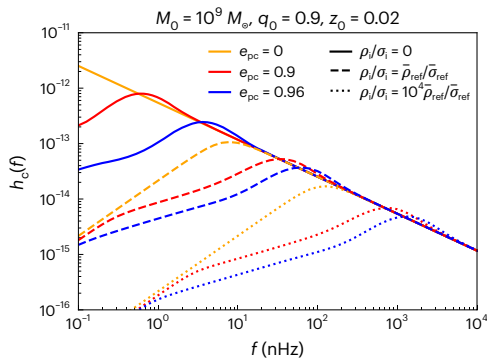


Fig. 1 | Illustrative SGWB spectra from a simplified SMBHB population. Examples of the SGWB spectra derived from an SMBHB population modelled as delta functions in the space (M, q, z) , specifically $d^3\eta/(dz dM dq) = \delta(M - M_0)\delta(z - z_0)\delta(q - q_0) \text{ Mpc}^{-3}$. The values of the constants (M_0, z_0, q_0) are indicated at the top. In all scenarios, the evolution of the semimajor axis begins at 1 pc, with the eccentricity e_{pc} defined at that separation. Colours indicate different e_{pc} values, and line styles denote variations in ρ/σ_i for three-body scattering, using $\bar{\rho}_{\text{ref}} \equiv 10^5 M_\odot \text{ pc}^{-3}$ and $\bar{\sigma}_{\text{ref}} \equiv 10^{-3} c$.

$$\rho(r) = \rho_{\text{pc}} \left(\frac{r}{1 \text{ pc}} \right)^{-\gamma}, \quad (4)$$

where r is the radial distance, the reference radius 1 pc is set for our analysis, ρ_{pc} denotes the matter density normalization to be constrained and γ represents the radial slope of the profile. We explore values of γ ranging from 0 to 2.4, consistent with the inner region of the Dehnen density-profile family³⁰. For each scenario, we first determine the influence radius r_i by satisfying the condition $\int_0^{r_i} \rho 4\pi r^2 dr = 2M$ (ref. 19) and then calculate $\rho_i \equiv \rho(r_i)$ using equation (4) and $\sigma_i \equiv \sigma(r_i) = \sqrt{GM/r_i}$ via the virial theorem.

Our analysis targets include the initial eccentricity e_0 , defined as occurring when the binary is formed at $a = r_i$, and the density-profile parameters ρ_{pc} and γ . The distribution of SMBHB parameters, namely total mass M , mass ratio q and redshift z , follows the fiducial population model derived from astrophysical interpretations of NANOGrav data (the fiducial ‘Phenom+Astro’ model without phenomenological environmental parameters) using `holodeck7`, as detailed in Supplementary Information. The dominant contributions to the SGWB are expected from binaries with $\log_{10}(M/M_\odot) \in (9.2, 10.4)$, $q \in (0.5, 0.8)$ and $z \in (0.15, 0.9)$ (ref. 7).

For each parameter combination of $(e_0, \rho_{\text{pc}}, \gamma)$ and (M, q, z) , we compute the orbital and eccentricity evolution of the SMBHB, taking into account both GW emission and three-body scattering, as detailed in Methods. We then derive the total SGWB spectrum by integrating over (M, q, z) . Finally, we assess the likelihood that the SGWB spectrum produced by each parameter set $(e_0, \rho_{\text{pc}}, \gamma)$ matches the observed spectrum in the lowest five frequency bins (2–10 nHz) of the NANOGrav 15-year data, which exhibit robust signal-to-noise ratios². We treat the overall normalization of the SMBHB distribution as a nuisance parameter, assigning it astrophysical priors consistent with how the fiducial population model was derived⁷, as detailed in Supplementary Information.

In Fig. 2, we present the posterior distribution of the parameters $(e_0, \log_{10}(\rho_{\text{pc}}[M_\odot \text{ pc}^{-3}]/10^5), \gamma)$. The results reveal that the 1σ regions (dark blue) indicate the presence of three-body scatterings, with $\log_{10}(\rho_{\text{pc}}[M_\odot \text{ pc}^{-3}]/10^5)$ estimated to be $0.8^{+1.6}_{-2.4}$. There is an expected degeneracy between e_0 and ρ_{pc} (refs. 8, 31–33), where a higher e_0 corresponds to a lower required density. However, the 1σ region indicates that when ρ_{pc} drops below $10 M_\odot \text{ pc}^{-3}$, GW emission requires an extremely high initial eccentricity, $e_0 > 0.999$, to account for the turnover. This is because lower densities result in a larger r_i , and GW emission tends to circularize the orbit before it reaches the observed frequency

range. The light blue regions represent the 2σ confidence interval. The white region is excluded at the 95% confidence level, thereby setting an upper limit on ρ_{pc} , as higher values would result in a turnover frequency inconsistent with the observational data.

In the left-hand panel of Fig. 3, we present the posterior distribution for the density-profile parameters $(\rho_{\text{pc}}, \gamma)$ for specific initial eccentricities $e_0 = 0, 0.5$ and 0.9 . The contours generally follow approximately constant values of ρ_i/σ_i , as indicated by equation (3). The right-hand panel of Fig. 3 presents the best-fitting spectra for various values of e_0 . Distributions with smaller γ values are preferred over steeper ones because a larger γ leads to a broader range of ρ_i/σ_i across the SMBHB population parameters (M, q) , which in turn results in a wider distribution of the turnover frequency f_t as defined in equation (3). This causes the spectrum to have a broader intermediate region, requiring a normalization factor higher than the fiducial value, making high- γ cases less favoured. A conservative upper limit on $\rho_{\text{pc}}(\gamma)$ is established based on the 95% exclusion for $e_0 = 0$, as higher e_0 values lead to more stringent constraints.

As a comparison, we examine various benchmark star and dark matter profiles: the modelled stellar distribution in the nearby galaxy M87 with $\gamma = 4/3$ and $\rho_{\text{pc}} \approx 0.7 \times 10^5 M_\odot \text{ pc}^{-3}$ (ref. 34) (black star); the Milky Way’s modelled core star distribution with $\gamma = 1/2$ and $\rho_{\text{pc}} \approx 1.8 \times 10^5 M_\odot \text{ pc}^{-3}$ (ref. 35) (brown star); a hypothetical dark matter spike in M87 with $\gamma = 7/3$ and $\rho_{\text{pc}} \approx 2.6 \times 10^6 M_\odot \text{ pc}^{-3}$ (ref. 12), which was formed by an adiabatically growing central SMBH from an initial Navarro–Frenk–White distribution¹¹ (grey dot); and a hypothetical flattened dark matter spike in the Milky Way with $\gamma = 1/2$ and $\rho_{\text{pc}} \approx 10^4 M_\odot \text{ pc}^{-3}$, which formed as the BH grew from a low-mass seed³⁶ (green dot). Interestingly, dark matter spikes are not favoured in the hardening process because higher γ values result in larger r_i above 1 pc, leading to lower ρ_i . Conversely, core-like stellar or dark matter profiles with $\gamma = 1/2$ in the Milky Way, as well as the stellar distribution in M87, fall naturally within the best-fitting region of our analysis. Lower γ values are expected due to flattening by previous SMBHB mergers or reformation after a galaxy merger³⁶.

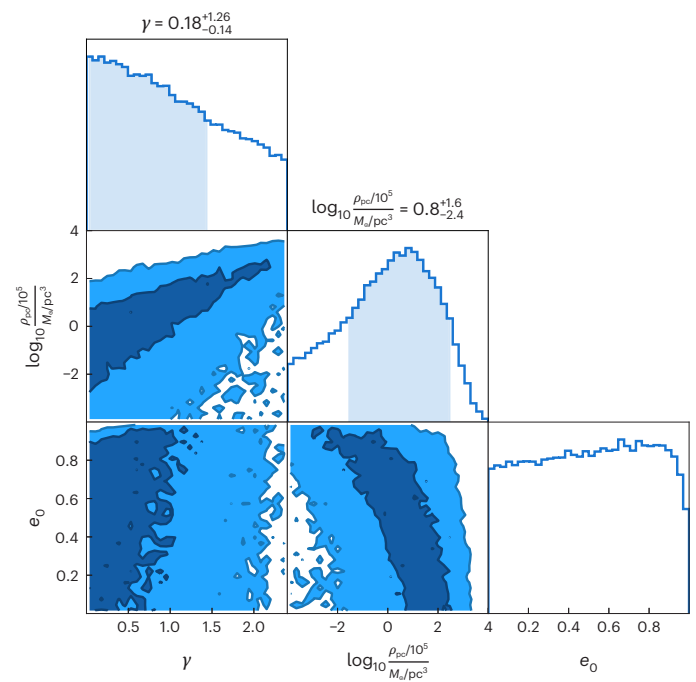


Fig. 2 | Posterior constraints on eccentricity and environmental parameters. Posterior distribution of the parameters $(e_0, \log_{10}(\rho_{\text{pc}}[M_\odot \text{ pc}^{-3}]/10^5), \gamma)$, which are the initial eccentricity and the pre-scouring density profile, inferred from the lowest five frequency bins of the NANOGrav 15-year dataset. The 1σ and 2σ confidence regions are shown in dark blue and light blue, respectively.

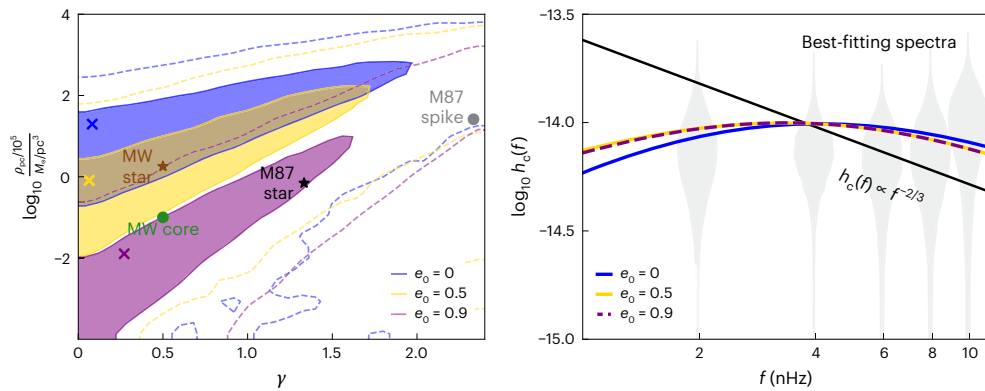


Fig. 3 | Constraints and corresponding SGWB spectra for fixed initial eccentricities. Left: posterior distribution of the density-profile parameters ($\log_{10}(\rho_{\text{pc}}[M_{\odot} \text{pc}^{-3}]/10^5), \gamma$) for three representative initial eccentricities, $e_0 = 0$ (blue), 0.5 (yellow) and 0.9 (purple). The 1σ and 2σ confidence regions are shown in darker shades and with dashed contours, respectively. Benchmark matter-density profiles, namely the stellar distribution in M87 (black star), the stellar core of the Milky Way (brown star), a dark matter spike in M87 (grey dot) and a

flattened dark matter core in the Milky Way (green dot), are included for comparison, with parameters detailed in the text. Right: best-fitting SGWB spectra corresponding to parameter choices ($\log_{10}(\rho_{\text{pc}}[M_{\odot} \text{pc}^{-3}]/10^5), \gamma$) = (1.3, 0.08), (-0.09, 0.06) and (-1.9, 0.27) for $e_0 = 0, 0.5$ and 0.9, respectively, as indicated by the crosses in the left-hand panel. The spectra are compared against the lowest five frequency bins of the NANOGrav 15-year dataset². MW, Milky Way.

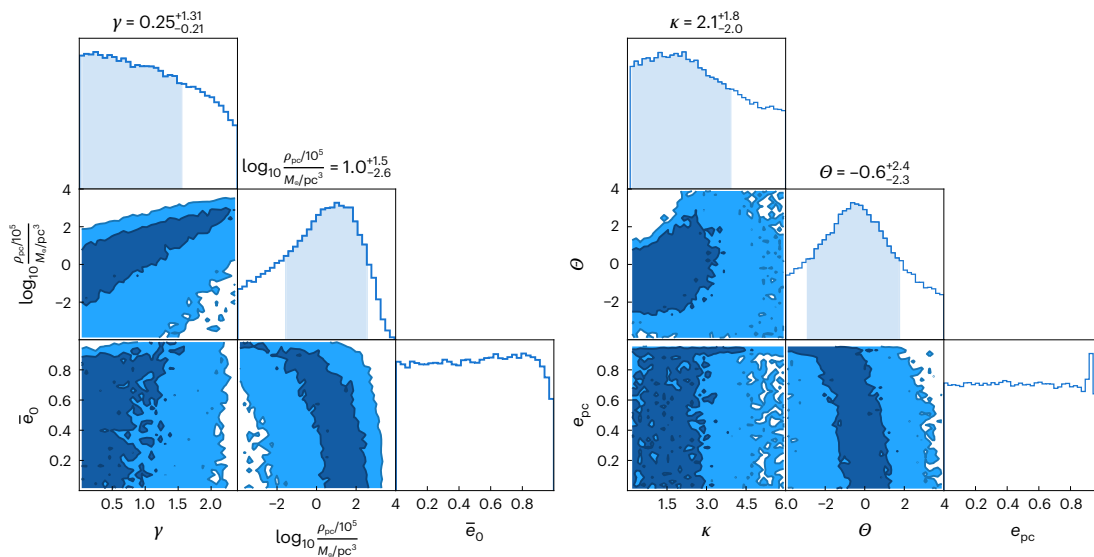


Fig. 4 | Posterior constraints from alternative eccentricity and density-profile parameterizations. Left: the universal initial eccentricity e_0 is replaced by the average eccentricity \bar{e}_0 of a power-law distribution. Right: the universal

density-profile parameters (ρ_{pc}, γ) are replaced by a Gaussian distribution of $\log_{10}[(\rho_i/\bar{\rho}_{\text{ref}})/(\sigma_i/\bar{\sigma}_{\text{ref}})]$, characterized by a mean θ and width κ , together with the eccentricity at $a = 1 \text{ pc}$, denoted e_{pc} .

We present in Methods analyses that show that each SMBHB can deviate from a universal $(e_0, \rho_{\text{pc}}, \gamma)$, including a power-law distribution of initial eccentricities and a variance in the initial density. The corresponding posterior constraints are shown in Fig. 4. These alternative parameterizations do not alter the conclusion that the posterior distribution favours $\rho_{\text{pc}} \approx 10^6 M_{\odot} \text{pc}^{-3}$. Furthermore, variations in the SMBHB population distribution merely shift the best-fitting region in accordance with the scaling relations from equation (3).

Discussions

In the vicinity of a binary BH, a test particle can extract orbital energy through several scatterings with each BH component. Within the PTA observation band, three-body ejections are substantially more efficient than two-body dynamical friction, especially for comparable-mass binaries, resulting in pronounced scouring of the surrounding matter distribution. In this study, we explore the potential imprints that stars or particle dark matter surrounding SMBHBs could leave on the

spectrum of the SGWB. Using the NANOGrav 15-year observational data, we constrain the relevant parameter space. Our results support the occurrence of three-body scatterings with a reasonable density distribution before scouring, primarily inferred from the low-frequency turnover in the SGWB spectrum, assuming no other dominant environmental influences are present. Continued monitoring with existing PTAs will lead to improved constraints on the low-frequency turnover. Future observations by FAST⁵, DSA-2000³⁷, the Square Kilometre Array³⁸ and next-generation astrometry missions³⁹ are expected to deliver substantially more precise spectral measurements⁴⁰, promising to shed light on the physical origin of the turnover.

Resolving the degeneracy with the initial eccentricity is essential if we are to precisely determine the density profile. Potential strategies for determining the SMBHB eccentricity include resolving individual binaries through either GW or electromagnetic observations^{41,42} and examining correlations among different frequency bins. This latter method is based on the observation that a high eccentricity contributes

to several integer multiples of frequency bins simultaneously⁴³. Nevertheless, setting a stringent upper limit on the galactic-centre density distribution is feasible, as both other environmental influences and non-zero orbital eccentricity tend to further elevate the turnover frequency.

The three-body slingshot mechanism considered in this study assumes that the test particles interact purely gravitationally. It, thus, applies to both stars and cold, collisionless dark matter. For a star-dominant distribution, such findings could reveal the star formation and relaxation rates near SMBHs in the galactic centre and may indicate a density higher than previously expected^{29,44}. If dark matter is the dominant density, the findings here could provide crucial insights into two long-standing questions: the identification of the particle nature of dark matter and the measurement of its density at galactic centres. Further studies are needed to evaluate how specific dark matter models, especially those that depart from the cold dark matter scenario, influence the applicability of three-body ejection. In Supplementary Information, we also discuss possible non-cold dark matter effects and other environmental mechanisms that may contribute to the observed turnover.

Methods

Evolution of eccentric orbits

We investigate the orbital evolution of SMBHBs driven by both three-body ejection of stars¹⁴ and cold dark matter¹⁶ and by GW emission. Our analysis incorporates eccentric orbits with an evolving eccentricity^{20,29,43}. Other possible environmental effects^{45–65} are discussed in Supplementary Information.

The coupled equations that govern the semimajor axis a and eccentricity e are as follows:

$$\begin{aligned} \frac{da(e,a)}{dt} &= -\frac{64}{5} \frac{G^3 M^3}{c^5 a^3} \frac{q}{(1+q)^2} \frac{(1+\frac{73}{24}e^2+\frac{37}{96}e^4)}{(1-e^2)^{7/2}} - HG \frac{\rho_i}{\sigma_i} a^2, \\ \frac{de(e,a)}{dt} &= -\frac{304}{15} \frac{G^3 M^3}{c^5 a^4} \frac{q}{(1+q)^2} \frac{e(1+\frac{121}{304}e^2)}{(1-e^2)^{5/2}} + HK(e,a)G \frac{\rho_i}{\sigma_i} a. \end{aligned} \quad (5)$$

The first terms on the right-hand side of these equations correspond to GW emission⁶⁶, and the second terms describe the effects of three-body ejections¹⁴. The dimensionless parameters H and K represent the hardening and eccentricity growth rates, respectively, as derived from scattering simulations. For hard binaries, H values typically range from 15 to 20 (ref. 14); in this study, we fixed H at 18. The function for K is approximated by^{14,67–69}:

$$K(e,a) \approx 0.3 e(1-e^2)^{0.6} \left(1 + \frac{a}{0.2a_h}\right)^{-1}, \quad (6)$$

which becomes most effective when a is within the hardening radius $a_h \equiv r_i q / (4(1+q)^2)$.

Each evolutionary case begins at the influence radius r_i , which is determined by solving the relation $\int_0^{r_i} \rho 4\pi r^2 dr = 2M$ (ref. 19) for a power-law distribution $\rho(r) = \rho_{pc}(r/1 \text{ pc})^{-\gamma}$ before scouring. Consequently, $\rho_i \equiv \rho(r_i)$ and $\sigma_i \equiv \sigma(r_i) = \sqrt{GM/r_i}$ are calculated. The initial eccentricity e_0 , defined at r_i , serves as a fitting parameter to be constrained.

We vary both the initial eccentricity e_0 and the density-profile parameters (ρ_{pc}, γ) . We then calculate the orbital evolution for the SMBHB with parameters (M, q) from the determined r_i . The SGWB spectrum is subsequently calculated by integrating over the SMBHB population parameters (M, q, z) , considering the density distribution $d^3\eta/(dz dM dq)$, as referenced in^{20,70,71}:

$$h_c^2(f) = \frac{4G}{c^2 4\pi f} \int dz dM dq \frac{d^3\eta}{dz dM dq} \frac{dE_{GW}}{df_s} \Big|_{f_s=(1+z)f}. \quad (7)$$

In this calculation, we neglect Poisson fluctuations in the SMBHB distribution, as these have a minor impact on the lowest frequency bins of the NANOGrav 15-year dataset^{72–76}.

The GW emission spectrum, $dE_{GW}/d \ln f_s$, calculated at the source frame frequency f_s , includes contributions from various orbital frequencies $f_{orb}^n = f_s/n$ for integer $n > 0$. It is expressed as⁶⁶:

$$\frac{dE_{GW}}{df_s} \Big|_{f_s=(1+z)f} = \sum_{n=1}^{+\infty} \frac{dE_{GW}^n/dt}{n df_{orb}^n/dt} \Big|_{f_{orb}^n=(1+z)f/n}, \quad (8)$$

where

$$\begin{aligned} \frac{dE_{GW}^n}{dt} &= \frac{32G^4 M^5}{5c^5 a^5} \frac{q^2}{(1+q)^4} g(n, e), \\ \frac{df_{orb}^n}{dt} &= -\frac{3\sqrt{GM}}{4\pi a^{5/2}} \frac{da}{dt}. \end{aligned} \quad (9)$$

The orbital frequency is related to a via Kepler's law $a^3 = GM/(2\pi f_{orb}^n)^2$. The function $g(n, e)$, defined as

$$\begin{aligned} g(n, e) &= \frac{n^4}{32} \left[\left\{ J_{n-2}(ne) - 2eJ_{n-1}(ne) + \frac{2}{n} J_n(ne) + 2eJ_{n+1}(ne) - J_{n+2}(ne) \right\}^2 \right. \\ &\quad \left. + (1-e^2) \left\{ J_{n-2}(ne) - 2J_n(ne) + J_{n+2}(ne) \right\}^2 + \frac{4}{3n^2} J_n^2(ne) \right], \end{aligned} \quad (10)$$

converges to $g(2, 0) = 1$ for circular orbits. Here J_n denotes the Bessel function of the first kind of order n .

In practice, we employ several methods to enhance the efficiency of numerical computation. In equation (8), we apply a cutoff to the summation over n , neglecting all contributions for $n > n_{max}$, with $n_{max} = 3n_{peak}(e_{max})$. The value of $n_{peak}(e)$ is given by⁷⁷:

$$n_{peak}(e) \approx 2 \left(1 + \sum_{k=1}^4 c_k e^k \right) (1-e^2)^{-3/2}, \quad (11)$$

where $c_1 = -1.01678$, $c_2 = 5.57372$, $c_3 = -4.9271$ and $c_4 = 1.68506$, and e_{max} represents the maximum eccentricity throughout the orbital evolution. Additionally, when n_{max} exceeds 100, we sum the contributions for $n > 101$ using logarithmic steps ($n = 101, 102, 104, 108, \dots$) and implement numerical integration over n using `numpy.trapz`.

Statistics

In our data analysis, we estimate the posterior distribution of $\log_{10} \rho_{pc}$, γ , e_0 and $\log_{10} N$. This can be separated into two components:

$$\begin{aligned} &P\left(\log_{10} \frac{\rho_{pc}/10^5}{M_\odot \text{ pc}^{-3}}, \gamma, e_0, \log_{10} N | \delta t\right) \\ &= \int \prod_k d \log_{10} h_c^2(f_k) P\left(\log_{10} \frac{\rho_{pc}/10^5}{M_\odot \text{ pc}^{-3}}, \gamma, e_0, \right. \\ &\quad \left. \log_{10} N | \{\log_{10} h_c^2(f_k)\}\right) \times P(\{\log_{10} h_c^2(f_k)\} | \delta t), \end{aligned} \quad (12)$$

where δt represents the residual timing data from the NANOGrav 15-year dataset², and $f_k = k/T_{obs}$ denotes the frequencies indexed by $k = 1, 2, 3, 4$ and 5 corresponding to the five lowest frequency bins, with $T_{obs} \approx 16$ years as the observation time.

The second term in equation (12) represents the posterior distributions of the free spectrum derived by the NANOGrav collaboration⁷. The first term is calculated using Bayes' theorem:

$$\begin{aligned} &P\left(\log_{10} \frac{\rho_{pc}/10^5}{M_\odot \text{ pc}^{-3}}, \gamma, e_0, \log_{10} N | \{\log_{10} h_c^2(f_k)\}\right) \\ &\propto P(\{\log_{10} h_c^2(f_k)\} | \log_{10} \frac{\rho_{pc}/10^5}{M_\odot \text{ pc}^{-3}}, \gamma, e_0, \log_{10} N) \\ &P\left(\log_{10} \frac{\rho_{pc}/10^5}{M_\odot \text{ pc}^{-3}}\right) P(\gamma) P(e_0) P(\log_{10} N). \end{aligned} \quad (13)$$

The first term is computed in section 'Evolution of eccentric orbits', where Poisson fluctuations are neglected. The remaining terms are the priors for each parameter:

$$\begin{aligned}
 P\left(\log_{10} \frac{\rho_{\text{pc}}/10^5}{M_{\odot} \text{pc}^{-3}}\right) &= U[-4, 4], \\
 P(\gamma) &= U[0, 2.4], \\
 P(e_0) &= U[0, 0.999], \\
 P(\log_{10} N) &= \mathcal{N}(-1.46, 1.09),
 \end{aligned}
 \tag{14}$$

where U denotes a uniform distribution, \mathcal{N} denotes a normal distribution and the prior for N is calculated in Supplementary Information.

For practical implementation, we use `PTArcade`⁷⁸, which is based on `ceffy1`⁷⁹, to model the prior distributions and fit the results to the free spectrum data.

Alternative parameterization

In the main text, we employed a universal parameterization for the initial eccentricity and density profile before scouring, $(e_0, \rho_{\text{pc}}, \gamma)$, for each SMBHB. In reality, each of these parameters can have its own distribution. In this section, we consider alternative parameterizations that allow for a distribution of initial eccentricities e_0 and a variance in ρ_i/σ_i across the SMBHB population. We show that these alternative choices have only a minor impact on our conclusion that the parsec-scale density is approximately $10^6 M_{\odot} \text{pc}^{-3}$.

First, we consider a power-law eccentricity distribution⁸⁰:

$$f(e_0) = \xi e_0^{\xi-1}, \tag{15}$$

where $\xi > 0$ is an exponent controlling the form of the distribution, and the distribution is normalized to unity. For example, $\xi = 2$ corresponds to the thermal distribution⁸¹, $\xi = 1$ yields a uniform distribution and $\xi > 0$ strongly suppresses high eccentricities. In the left panel of Fig. 4, we show the posterior distribution obtained by replacing the universal e_0 in Fig. 2 with the average value from this power-law distribution, $\bar{e}_0 = \xi/(\xi + 1)$, while leaving the other parameters unchanged. We find that the resulting posterior distribution differs only slightly from the universal parameterization case shown in Fig. 2.

We next consider alternatives to the density-profile parameters. We employ a Gaussian distribution for

$$\log_{10} [\bar{\rho}_i/\bar{\sigma}_i] \in \mathcal{N}(\theta, \kappa), \tag{16}$$

with mean value θ and Gaussian width κ , where $\bar{\rho}_i \equiv \rho_i/(10^5 M_{\odot} \text{pc}^{-3})$ and $\bar{\sigma}_i \equiv \sigma_i/(10^{-3} c)$. Accordingly, the initial eccentricity is replaced by the eccentricity defined at $a = 1 \text{ pc}$, e_{pc} . The corresponding posterior distribution is shown in the right-hand panel of Fig. 4.

Note that this distribution can exhibit high eccentricities e_{pc} within the 1σ region even in the absence of surrounding matter for three-body ejection. This arises from the difference in definition between e_{pc} and e_0 in the main text: e_0 is defined at the influence radius r_i , which is typically much larger than 1 pc for low-density environments. As a result, e_{pc} corresponds to a more extreme value of e_0 at low densities.

Data availability

The NANOGrav 15-year dataset is described in and available through ref. 7.

Code availability

All methods required to evaluate the conclusions in this paper are provided in the main text, Methods and Supplementary Information. The `holodeck` and `PTArcade` codes used in this work are publicly available via GitHub at <https://github.com/nanograv/holodeck> and <https://github.com/andrea-mitridate/PTArcade>, respectively. The code supporting the findings of this study is available via GitHub at https://github.com/XueXiao-Physics/NG15_Galactic_Tomography.

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Author contributions

This paper uses a decade's worth of pulsar-timing observations and is the product of the work of many people. Y.C., L.S. and X.X. initiated the project and developed the core idea, with D.J.D. contributing to its development. Y.C., M.D., D.J.D., X.F., A. Mitridate, L.S., and X.X. participated in discussions, provided critical feedback, and shaped

the research and analysis. Y.C. coordinated the project and wrote the paper. M.D., X.F. and X.X. developed the analysis code, created the figures and edited the text. X.F. performed the analysis using alternative parameterizations, under the guidance of Y.C. and X.X. D.J.D. offered guidance on the SMBHB population model and the `holodeck` code, wrote the discussion on the environmental effects from gas and edited the text. A. Mitridate provided guidance on the `PTArcade` code and the presentation of NANOGrav 15-year data. G.A., A.A., A.M.A., Z.A., P.T.B., P.R.B., H.T.C., K.C., M.E.D., P.B.D., T.D., E.C.F., W.F., E.F., G.E.F., N.G.-D., D.C.G., P.A.G., J.G., R.J.J., M.L.J., D.L.K., M.K., M.T.L., D.R.L., J.L., R.S.L., A. McEwen, M.A.M., N.M., B.W.M., C.N., D.J.N., B.B.P.P., N.S.P., H.A.R., S.M.R., P.S.R., A.S., C.S., B.J.S.-A., I.H.S., K.S., A.S., J.K.S. and H.M.W. developed timing models and ran observations for the NANOGrav 15-year dataset. Development of the `holodeck` population modelling framework was led by L.Z.K., with contributions from J.A.C.-C., D.W., E.C.G., K.G., M.S.S. and S.C. `PTArcade`, which was used in this analysis, was mainly developed by A. Mitridate, with help from D.W., K.D.O. G.A., A.A., A.M.A., Z.A., J.G.B., P.T.B., B.B., L.B., A.B., P.R.B., S.B.-S., R.B., J.A.C.-C., M.C., S.C., T.C., J.M.C., N.J.C., F.C., H.T.C., K.C., M.E.D., P.B.D., H.D., L.D., T.D., E.C.F., W.F., E.F., G.E.F., N.G.-D., P.A.G., K.A.G., J.G., D.C.G., K.G., J.S.H., R.J.J., A.D.J., M.L.J., L.Z.K., M.K., J.S.K., N. Laal, M.T.L., W.G.L., B.L., T.J.W.L., N. Lewandowska, T.L., D.R.L., J.L., R.S.L., C.-P.M., D.R.M., A. McEwen, J.W.M., M.A.M., N.M., B.W.M., P.M.M., C.M.F.M., A. Mitridate, C.N., D.J.N., S.K.O., K.D.O., T.T.P., B.B.P.P., P.P., N.S.P., H.A.R., S.M.R., P.S.R., J.D.R., J.C.R., A. Saffer, S.C.S., A. Schmiedekamp, C.S., K. Schmitz, B.J.S.-A., X.S., J.S., M.S.S., S.V.S.F., I.H.S., D.R.S., K. Stovall, A. Susobhanan, J.K.S., J.T., S.R.T., J.E.T., C.U., M.V., R.V.H., S.J.V., H.M.W., C.A.W., D.W. and O.Y. developed and validated the NANOGrav 15-year data.

Competing interests

The authors declare no competing interests.

Additional information

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