

A Dark-matter Origin of Little Red Dots: Early Seeding and Super-Bondi Accretion

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Abstract

The “Little red dots” (LRDs) are a population of accreting supermassive black holes (SMBHs) in the early Universe which often exhibit undermassive or even undetectable stellar hosts[1–3]. Their early emergence, high space density, and extremely large black-hole-to-stellar mass ratios pose a serious challenge to conventional seeding scenarios that rely on baryon for both the formation and growth of black holes. Here we demonstrate that the above anomalies can be naturally resolved if dark matter is self-interacting [4, 5]. We apply a fully relativistic, non-equilibrium halo-evolution model, first developed in our earlier work [6], to trace the complete gravothermal evolution of self-interacting dark matter (SIDM) halos, from the initial collapse into BH seeds to the subsequent accretion of dark matter. We find that in highly concentrated halos assembled before reionization, **gravothermal collapse efficiently produces stellar-mass black-hole seeds** within a few hundred million years. Remarkably, and contrary to standard expectations for dark-matter accretion, heat conduction in SIDM then sustains a **prolonged super-Bondi inflow** that drives these seeds to supermassive scale by the LRD epoch, **without baryonic assistance**. The halo conditions required for completing these processes, together with the probability of avoiding major mergers that disrupt gravothermal evolution, result in an SMBH population **consistent with the observed abundance and redshift distribution of LRDs**. Our findings establish a pathway in which SMBHs are **seeded and assembled primarily from dark matter**, well before substantial galaxies form around them, thereby offering both a compelling physical explanation for LRDs and a new observational probe of dark-matter microphysics.

1 Introduction

The “little red dots” (LRDs) are a population of compact, unresolved sources discovered by the James Webb Space Telescope in the early Universe that are widely interpreted as accreting supermassive black holes (SMBHs) [1, 7–9]. They are remarkably abundant at high redshift, with inferred comoving number densities of order $\sim 10^{-4} \text{ Mpc}^{-3}$ at $4 \lesssim z \lesssim 9$, which could account for up to 1–10 per cent of the galaxy population at that epoch [7, 8, 10]. Many LRDs show only marginal or undetectable stellar components, implying mass ratios between black holes (BHs) and stellar hosts much higher than nearby values [9], or even approaching unity in some systems [2, 3, 11]. Their early emergence, high abundance, and extreme BH-to-stellar mass ratios pose a challenge to conventional baryonic SMBH-seeding scenarios within the standard cosmological paradigm, including Population III remnants [12], very massive stars [13], and direct-collapse black holes [14, 15]. Population III remnants ($\sim 10\text{--}100 M_\odot$) require sustained Eddington accretion despite strong stellar and BH feedback, whereas the heavier seeds from runaway stellar mergers or direct gas collapse ($\sim 10^4\text{--}10^5 M_\odot$) form only under rare conditions, including extreme stellar densities, low metallicities, suppressed fragmentation, and rapid gas inflow [12, 16–21]. These physical conditions are difficult to satisfy given the rapid star formation and chemical enrichment inferred at the LRD epochs [22, 23]. The unusual demographics of LRDs therefore motivate SMBH-formation pathways that are less tightly coupled to stellar evolution and other baryonic processes.

Dark matter provides one such possibility. Among alternative dark-matter models, self-interacting dark matter (SIDM) has attracted broad interest across galaxy formation [4, 5,

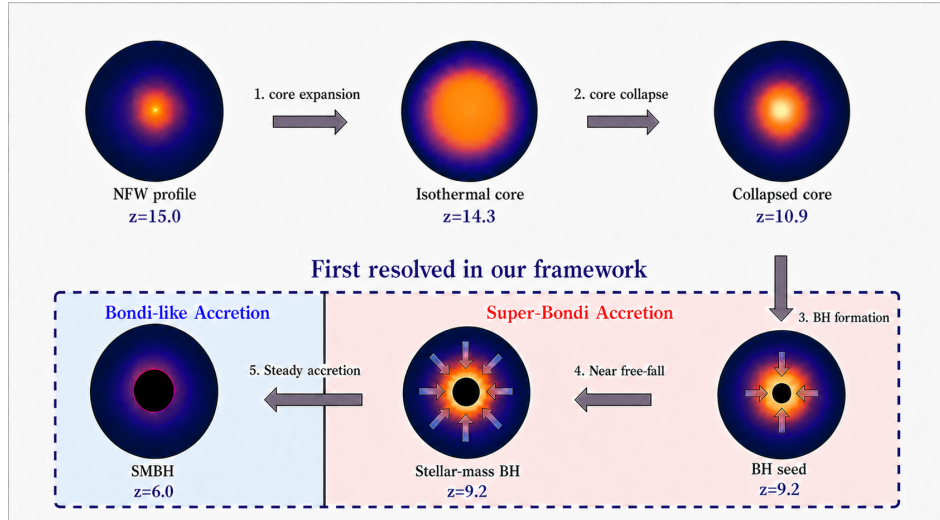


Fig. 1 Five stages to form an SMBH out of an isolated SIDM halo. Our fiducial case is a halo with mass $M_{\text{vir}} = 10^{7.5} M_\odot$, formed at a pre-reionization epoch ($z = 15$) with a Navarro–Frenk–White (NFW) profile of concentration $c = 10$. Self-scattering thermalizes the central part of the halo (Stage 1), which later collapses (Stage 2) and produces a seed BH by $z = 9.2$ (Stage 3). The seed BH subsequently grows by accreting the surrounding SIDM at a super-Bondi rate, due to the near-free-fall SIDM inflow (Stage 4) and heat conduction effects (early Stage 5) until the BH reaches the supermassive scale by $z \sim 6$. The late stages of gravothermal evolution (Stages 3–5) are physically resolved for the first time in this work.

24, 25], particle physics [26–28], and compact-object astrophysics [29, 30]. By introducing elastic self-scattering between dark-matter particles, SIDM, while preserving the large-scale successes of the cold dark-matter paradigm [25], can address a broad range of small-scale phenomena with only two additional parameters specifying a velocity-dependent self-scattering cross section [27, 28]. In dense halo centers, self-scattering enables heat transport and drives a multi-stage gravothermal evolution (Fig. 1). The inner halo first develops a nearly isothermal, low-density core, potentially accounting for the shallow central density profiles observed in many galaxies [31–33]. Continued outward heat conduction, together with the negative heat capacity of self-gravitating systems, can subsequently reverse this evolution and trigger runaway gravothermal core collapse [29, 34–37]. These different evolutionary stages allow SIDM to produce a diverse range of subgalactic structures within a unified framework, from cored, low-surface-brightness galaxies [33] to the highly concentrated halos inferred from gravitational lensing [38–42]. Taken to its extreme, gravothermal collapse can drive the central SIDM density sufficiently high for BH formation [6, 29, 34–36, 43], opening a pathway in which BH seeds originate directly from dark-matter halos.

Gravothermal core collapse of SIDM halos has therefore been proposed as a pathway to form high-redshift SMBHs associated with LRDs. Previous work showed that this scenario can reproduce the observationally inferred BH mass function of LRDs [44] using self-scattering cross sections consistent with independent constraints from nearby-galaxy rotation curves [45]. However, these predictions assumed that a fixed fraction ($\sim 1\%$) of the collapsing halo forms the BH seed [29, 43]. Determining the seed mass from first principles requires following gravothermal collapse into its highly nonlinear and relativistic regime, beyond the reach of quasi-equilibrium, non-relativistic fluid treatments [46–48] or current N -body simulations [49, 50]. Existing calculations therefore terminate during the early stages of gravothermal evolution (Stages 1 and 2 in Fig. 1), before the formation of an apparent horizon (Stage 3) and the subsequent dark-accretion phases (Stages 4–5). The mass of the resulting BH seed, and, equally importantly, the density and dynamical state of the SIDM remaining around it, has consequently remained uncertain.

An equally important open question is whether a BH seed formed through SIDM core collapse can subsequently grow to supermassive scales within the limited cosmic time available. Previous studies have considered dark-matter accretion onto BH seeds artificially embedded in SIDM halos [51–53], generally finding growth too slow to assemble SMBHs by $z \sim 6$ without additional baryonic effects [54–56]. However, a BH born from gravothermal collapse is not in an equilibrium halo: it emerges from a rapidly evolving, highly concentrated SIDM core whose thermodynamic and dynamical states are inherited directly from the collapse itself. Assessing its subsequent growth therefore requires following seed formation and dark-matter accretion as a single, continuous process. Furthermore, heat conduction in SIDM may significantly reduce central thermal support and facilitate accretion, an effect neglected in previous studies. To quantify this effect, we extend our relativistic, non-equilibrium Misner–Sharp framework [6] (Methods) to evolve SIDM halos continuously from gravothermal collapse through horizon formation and into the ensuing accretion phase (Fig. 1). We apply this method to pre-reionization halos over a range of masses, concentrations and self-interaction parameters, and combine these calculations with cosmological halo abundances and merger histories to investigate whether the resulting conductive enhancement can make dark-matter accretion alone sufficiently rapid to account for the SMBHs of LRDs.

2 Dark seeding and dark accretion

We first illustrate the SIDM pathway using a fiducial pre-reionization halo before exploring how SMBH formation depends on halo properties. This example follows the complete evolution from gravothermal collapse to BH seeding and subsequent dark-matter accretion, providing the physical basis for the parameter study presented in Section 3.

Our fiducial halo has a virial mass of $M_{\text{vir}} = 10^{7.5} M_{\odot}$ and forms at $z = 15$, when sufficiently massive halos already exist but baryonic effects remain relatively weak.¹ We initialize the halo with a Navarro–Frenk–White (NFW) density profile [59] and a concentration of $c = 10$ (corresponding to scale radius $R_s = 60$ pc), a relatively high but realistic value in cosmological simulations [44]. We adopt a velocity-dependent SIDM model with $\sigma_0 = 20 \text{ cm}^2 \text{ g}^{-1}$ and $w = 100 \text{ km/s}$, consistent with independent constraints from nearby galaxy rotation curves [45] (Methods). We later vary these parameters to determine the halo conditions required for timely SMBH formation (Section 3).

2.1 BH seed formation

Schematically illustrated in Fig. 1, heat conduction drives the fiducial SIDM halo through two well-known stages of gravothermal evolution: initial core expansion (Stage 1), followed by runaway core collapse (Stage 2) [6]. During the late stages of collapse, a dense central core develops within a lower-density envelope by $t \sim 150 \text{ Myr}$ ($z = 10.9$; Fig. 2).² The core then contracts while continuously losing mass until reaching the threshold for BH formation. Owing to the velocity-dependent self-interaction cross section, the late-stage evolution deviates from the standard self-similar gravothermal-collapse solution [34].

At $t = 258 \text{ Myr}$ ($z = 9.2$), the mass profile first satisfies the apparent-horizon condition $R = 2m$ in geometrized units ($G = c = 1$), where R is the areal radius and m the enclosed Misner–Sharp mass (Fig. 2, lower panel). This occurs at $m = 10^{-6} M_{\text{vir}}$, signaling the formation of a central BH seed with a mass of $\sim 30 M_{\odot}$. This rapid collapse is enabled by two factors: the high characteristic densities of early-Universe halos, which substantially shorten the SIDM relaxation timescale relative to their lower-redshift counterparts (e.g., see [6] for comparison), and the velocity-dependent self-interaction cross section, which accelerates the final collapse phase (Stage 2, see Methods; Fig. 6). Although the resulting seed is relatively light, SIDM offers an important demographic advantage: BH seeds arise naturally in sufficiently concentrated halos, circumventing the need for rare baryonic environments invoked by conventional seeding models.

2.2 Super-Bondi dark accretion

The newly formed BH seed is embedded in a dense residual SIDM core, providing ideal conditions for subsequent dark accretion. Immediately after formation, the BH seed is embedded within a dark-matter core with density $\rho \sim 10^{30} \rho_s$, surrounded by a much lower-density envelope with $\rho \sim 0.1 \rho_s$, where ρ_s denotes the scale density of the initial NFW halo (Fig. 2, upper panel). The BH first rapidly accretes the residual core (Stage 4), after which the outer envelope continuously replenishes the central region, sustaining a prolonged phase of steady accretion

¹At $z = 15$, the adopted halo mass corresponds to a $\sim 3\sigma$ density peak and lies below the atomic-cooling threshold [57, 58].

²Here t denotes the elapsed time since halo formation at $z = 15$.

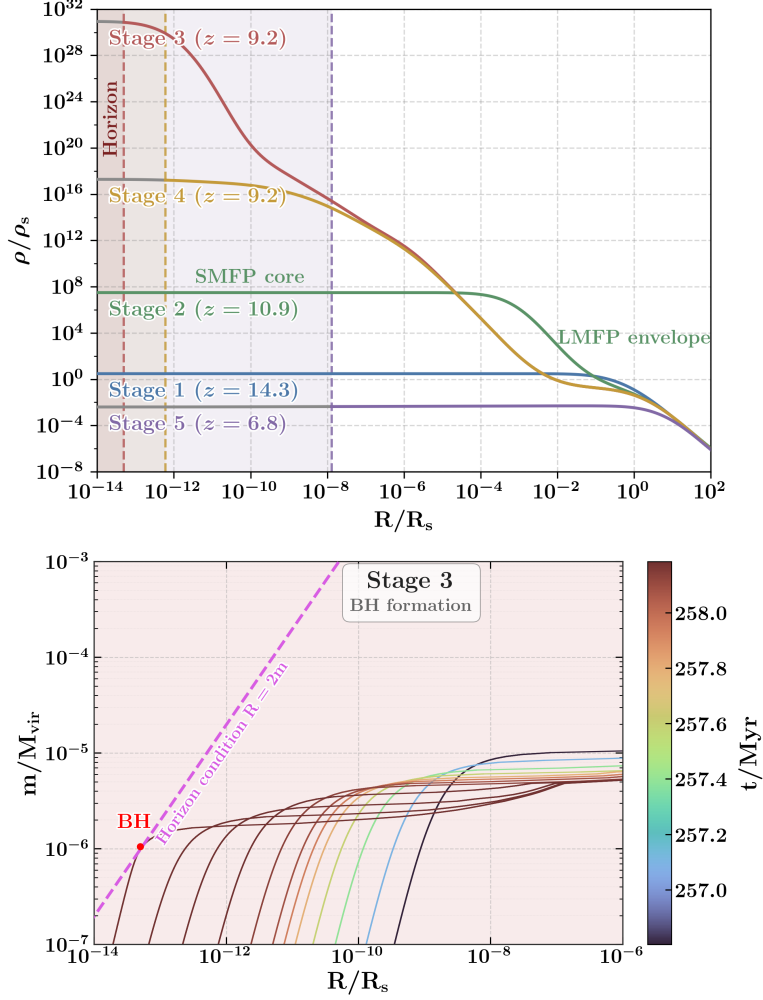


Fig. 2 Evolution of SIDM halo profile, illustrated by the fiducial experiment. *Upper:* Five representative density profiles corresponding to the evolutionary stages illustrated in Fig. 1. During gravothermal collapse (Stage 2), a dense central core develops and contracts until it forms a BH seed (Stage 3). The seed then grows by accreting the remaining core (Stage 4) and then as well as the surrounding envelope (Stage 5). The horizon radii in Stages 3–5 are indicated by the vertical dashed lines of corresponding colors. *Lower:* A zoomed-in view of the mass profiles immediately before the onset of BH formation (Stage 3), showing the first appearance of an apparent horizon and the emergence of a $\sim 30 M_\odot$ BH seed at $t = 258$ Myr. The color scale denotes the time elapsed since halo formation at $z = 15$.

(Stage 5). Fig. 3 compares the resulting accretion rate onto the central BH with the corresponding Bondi rate. The Bondi solution assumes a quasi-static ambient medium, in which the central BH gravity drives a perturbative inflow. At the onset of Stage 4 ($t = 258.2$ Myr), however, the residual core lies immediately outside the newly formed horizon. Here, strong general-relativistic effects can overcome thermal pressure support [6] to trigger a catastrophic inflow into the BH (Methods). The BH mass therefore rises rapidly from $\sim 30 M_\odot$

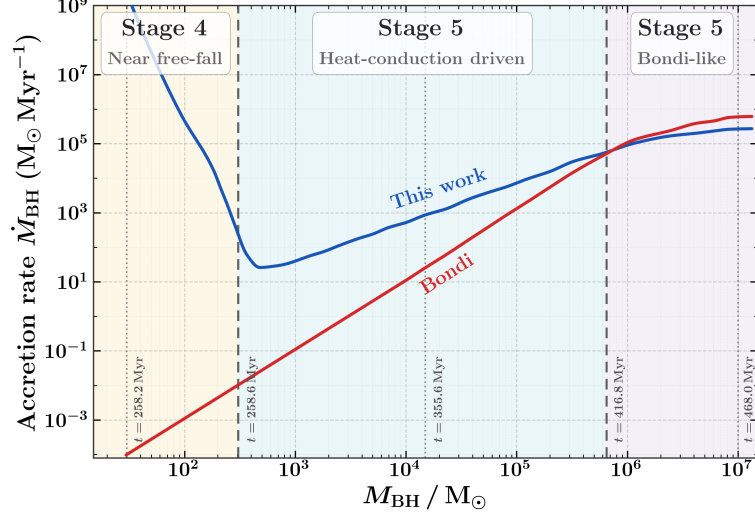


Fig. 3 Comparison of the accretion rate in our fiducial model (blue) and the Bondi prediction (red). The Bondi rate scales as $\dot{M}_B \propto M_{\text{BH}}^2$, whereas the dark accretion proceeds through three regimes: near-free-fall inflow during Stage 4, heat-conduction-driven super-Bondi accretion during most of Stage 5, and Bondi-like accretion at late times when BH gravity dominates the inflow.

to $\sim 300 M_\odot$ within only 0.4 Myr. This previously unexplored accretion phase is resolved self-consistently in our extended Misner–Sharp framework.

As the residual core is depleted, the BH accretion rate reaches a local minimum (Fig. 3) yet remains highly super-Bondi. The BH then begins to accrete the outer dark-matter envelope, marking the final stage of gravothermal evolution (Stage 5). Throughout most of this stage, the BH continues to accrete at a rate approximately two orders of magnitude above the Bondi rate, consistent with the independent findings of [52]. This enhancement is driven by SIDM heat conduction, which continuously transports energy outward, weakens central thermal pressure support, and sustains an inward mass flux. A quantitative interpretation of this super-Bondi phase is provided in Methods. As the BH grows toward supermassive scales, gravitational capture gradually overtakes gravothermal inflow, causing the accretion rate to asymptotically approach the Bondi rate, as shown in Fig. 3.

Fig. 4 shows the corresponding evolution of the BH mass. The growth track from our fiducial model (blue line) passes right through the region occupied by observed LRDs (red points), at $4 \lesssim z \lesssim 7$ and $10^{6.5} M_\odot \lesssim M_{\text{BH}} \lesssim 10^9 M_\odot$. Varying the initial halo properties within plausible ranges produces growth tracks that collectively span the observed LRD distribution in the $M_{\text{BH}}-z$ plane. Another interesting aspect is that halos with $M_{\text{vir}} \lesssim 10^6 M_\odot$ undergo frequent mergers at the LRD epochs (Methods; Fig. 7), interrupting gravothermal evolution and thereby suppressing the formation of lower-mass SMBHs through the SIDM channel (grey dashed line in Fig. 4). Intriguingly, the resulting characteristic BH mass coincides with the lower bound of observationally inferred LRD BH masses, although this bound remains uncertain [67]. In our fiducial isolated-halo calculations, BH growth ceases once the original SIDM halo is largely consumed (blue solid line in Fig. 4), reaching $M_{\text{BH}} \sim 10^{7.5} M_\odot$ by $t \approx 500 \text{ Myr}$ ($z \sim 6$). This result should be interpreted with caution and, in particular, does

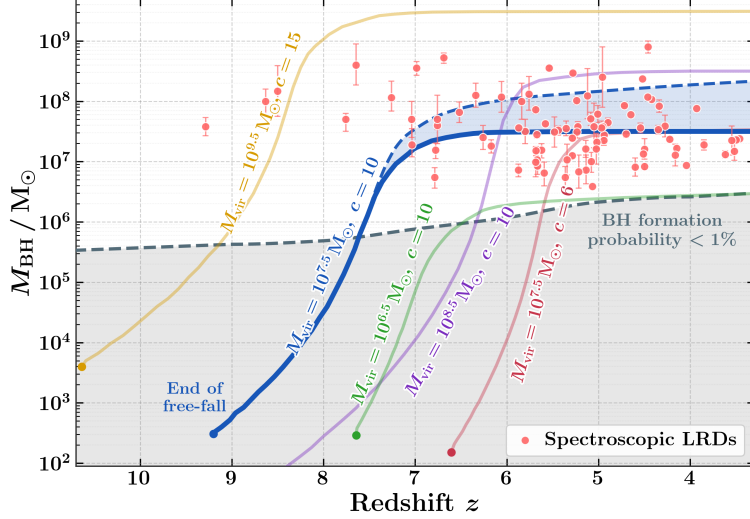


Fig. 4 Growth of the BHs seeded by core-collapsed SIDM halos, and a comparison with the observed LRDs. The blue solid curve is the predicted BH mass–redshift tracks our fiducial model, in which the BH seed forms at $z \sim 9$, subsequently accretes nearly the entire SIDM halo and reaches $M_{\text{BH}} \sim 10^{7.5} M_{\odot}$ by $z \sim 6$, characteristic of observed LRDs (red data points, from [3, 60–66] – only LRDs with spectroscopic BH-mass measurements are included). Varying the initial halo mass and concentration (but keeping halo formation at the pre-reionization epoch of $z = 15$) produces growth tracks spanning the observed LRD distribution (other solid lines). SIDM core collapse would be interrupted by major mergers (grey dashed line; see Methods and Fig. 7), naturally defining a redshift-dependent characteristic mass below which SMBH formation through this mechanism is unlikely. Intriguingly, this scale coincides with the uncertain observational lower bound on BH masses of $\sim 10^{5-6} M_{\odot}$ [67]. In a cosmological environment, smooth halo accretion can continuously replenish the SIDM reservoir, allowing further BH growth (blue dashed line). This smooth-accretion limit also sets a lower bound on the LRD host-halo mass by the LRD epoch.

not imply that the seed BH necessarily consumes the entire SIDM halo. The fluid approximation breaks down once the BH has consumed approximately 20 % of the halo, as the declining envelope density – and hence the SIDM scattering rate – becomes too low for the fluid treatment to remain valid (Methods). Moreover, in a cosmological setting, ongoing smooth halo accretion can replenish the SIDM reservoir as it is consumed by the central BH, allowing further growth (blue dashed line in Fig. 4). The SIDM pathway therefore naturally produces SMBHs with the masses and redshifts characteristics of the observed LRD population.

3 Cosmological SMBH demographics and observational predictions

3.1 Host-halo conditions and LRD abundance

We first identify the halo conditions required for SMBHs to form by the LRD epoch using a parameter survey shown in Fig. 5. For our fiducial SIDM model, halos initialized at $z = 15$ with $M_{\text{vir}} \gtrsim 10^7 M_{\odot}$ and concentrations $c \gtrsim 10$ generally complete both gravothermal collapse and the subsequent dark-accretion phase by $z \sim 6$. The detailed dependence of the formation timescale on halo mass and concentration is discussed in Methods. Here we adopt these criteria to predict the cosmological abundance of LRDs. The predicted abundance

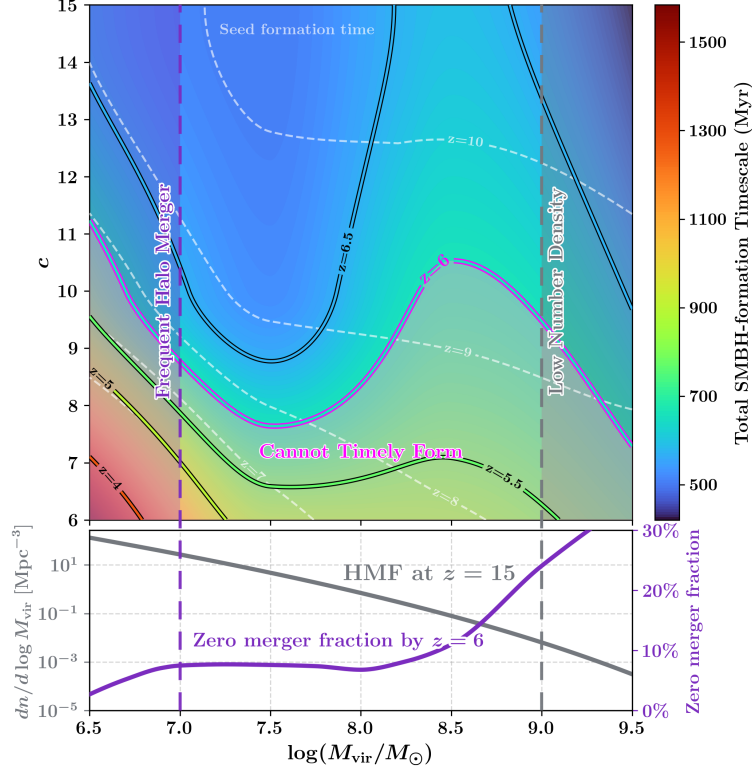


Fig. 5 Halo conditions for timely BH seeding and growth into SMBHs – dependence of SMBH formation time on halo virial mass, M_{vir} , and concentration, c , for a self-interaction cross section of $\sigma_0 = 20 \text{ cm}^2 \text{ g}^{-1}$ and $w = 100 \text{ km/s}$. *Upper*: Time elapsed from halo formation at $z = 15$ until the BH grows to supermassive scales by accreting half of the initial halo mass. In general, more massive and more concentrated halos evolve more rapidly. Halos with $M_{\text{vir}} \gtrsim 10^7 M_\odot$ and $c \gtrsim 10$ form SMBHs before $z = 6$ (magenta line). BH-seed formation time under different halo conditions is denoted by the white dashed contours. *Lower*: Two additional factors governing the abundance of viable SMBH halos: the fraction of halos that avoid major mergers by $z = 6$ (purple) and the halo mass function (HMF) at $z = 15$ (grey). That is, halos with $M_{\text{vir}} \lesssim 10^7 M_\odot$ are unlikely to produce SMBHs in time because gravothermal evolution is frequently interrupted by major mergers (purple dashed line), while very massive halos are intrinsically rare (grey dashed line). Together with the collapse and growth times shown above, these trends naturally define a preferred range of initial halo masses capable of hosting LRDs.

follows directly from three independently determined ingredients. The comoving number density of halos with $M_{\text{vir}} > 10^7 M_\odot$ at $z = 15$ is 7.7 Mpc^{-3} [68]. At these redshifts, halo concentrations are nearly independent of mass, and approximately 0.11% of halos satisfy $c > 10$ [44]. Together, these conditions imply a number density of $8 \times 10^{-3} \text{ Mpc}^{-3}$ for halos capable of producing SMBHs through SIDM core collapse.

However, not every such viable halo is expected to successfully form an SMBH and be detected as an LRD. Major mergers inject orbital kinetic energy into the halo center, resetting the gravothermal evolution and preventing core collapse [69]. Using cosmological merger trees (Methods; Fig. 7), we find that only $\gtrsim 8\%$ of viable halos avoid a major merger throughout their evolution, reducing the predicted SMBH number density to $6 \times 10^{-4} \text{ Mpc}^{-3}$.

Additionally, the duty cycle of high-redshift active galactic nuclei is expected to be 20-30 percent [70, 71]. The resulting abundance is therefore in good agreement with the observed LRD number density of $\sim 10^{-4} \text{ Mpc}^{-3}$ [10]. Integrating over the halo mass function further gives a total SIDM-seeded SMBH mass density of $\rho_{\text{BH}} \approx 8 \times 10^3 M_{\odot} \text{ Mpc}^{-3}$, about an order of magnitude below the local SMBH mass density [72], leaving ample room for subsequent baryonic growth. Together, these results show that the SIDM scenario quantitatively reproduces the observed abundance of LRDs while remaining consistent with local constraints.

3.2 The characteristic redshift and halo-mass scales of LRDs

Beyond the abundance comparison above, our model makes additional predictions for the redshift and mass distributions of SIDM-seeded BHs. Encouragingly, these trends are consistent with the properties of the current LRD sample. Before $z \gtrsim 9$, the cosmic time budget is simply too short for gravothermal collapse and subsequent dark accretion to assemble SMBHs. At lower redshifts, although suitable halos become increasingly common, uninterrupted gravothermal evolution becomes progressively rarer because hierarchical structure formation produces frequent major mergers. By $z \sim 4$, most halos have experienced at least one major merger (Fig. 7), resetting the gravothermal clock and suppressing new SMBH formation. The combination of these effects places the preferred epoch of SIDM-seeded SMBH formation at $4 \lesssim z \lesssim 9$, coincident with the redshift range occupied by the observed LRD population.

Merger statistics also select a characteristic halo-mass range for LRD hosts. Halos with $M_{\text{vir}} \lesssim 10^7 M_{\odot}$ rarely remain free of disruptive major mergers (Fig. 5; Fig. 7), which can interrupt gravothermal evolution and prevent SMBH formation even when the nominal collapse timescale is sufficiently short [69]. Combined with the gravothermal constraints shown in Fig. 5, formation of LRDs favors halos of $M_{\text{vir}} \sim 10^7\text{--}10^9 M_{\odot}$ during the pre-reionization epoch. By the time these systems are observed as LRDs, continued cosmological mass assembly can increase their masses by approximately 0.5–1 dex [73]. Their host halos nevertheless remain substantially less massive than those inferred for luminous quasars [74], providing a testable prediction through future measurements of LRD clustering and large-scale environments.

3.3 Observational signatures and tests of the SIDM scenario

Because the SIDM scenario explicitly links SMBH formation to the properties and assembly histories of dark-matter halos, it makes several distinctive predictions that can be tested with observations.

First, LRDs should preferentially inhabit early-forming, highly concentrated halos with quiescent assembly histories. Their host halos should therefore exhibit characteristic assembly bias and spatial clustering. Cosmological simulations that combine SIDM halo evolution with realistic merger histories will enable quantitative predictions for these signatures. Notably, LRD hosting halos grow into low-mass host halos of $M_{\text{vir}} \lesssim 10^{9.5} M_{\odot}$, which corresponds to a halo bias of $b \sim 2$; yet, the requirement of early formation and high concentration yields assembly bias that increases the clustering strength to $b \sim 3$ [75].

Second, the SIDM pathway allows for the possible existence of nearly “naked” SMBHs. In the absence of disruptive mergers, a BH formed through SIDM core collapse can consume

a substantial fraction of its original host halo (Fig. 4). Although such uninterrupted evolution is expected to be uncommon, it may already have observational support. A recent dynamical analysis of a gravitationally lensed LRD found gas motions consistent with an almost purely Keplerian potential, suggesting a system containing little stellar mass and possibly little remaining dark matter [11].

Finally, the demographics of LRDs offer a new probe of SIDM microphysics. The self-interaction cross section influences both gravothermal collapse and the subsequent dark-accretion phase in opposite ways: reducing the cross section delays BH seed formation but also weakens collisional pressure support, enhancing late-time accretion. Over the range explored here, these competing effects largely compensate, leaving the predicted SMBH abundance relatively insensitive to the cross section around the values we adopted (Methods). Extending the calculations across a broader SIDM parameter space should identify the regions where either timely seed formation or subsequent growth becomes impossible. Joint measurements of the LRD abundance, redshift evolution, clustering, and BH-mass distribution could therefore provide complementary constraints on the dark-matter physics that are inaccessible through any single observable or nearby-galaxy kinematics alone.

4 Methods

Extended Misner–Sharp formalism

The simulations in this study are based on the Misner–Sharp framework [76], which provides a general-relativistic, non-equilibrium description of fluid dynamics. In our previous work [6], we first adapted this framework to model SIDM halo evolution by incorporating heat conduction in SIDM. Unlike conventional fluid treatments of SIDM halos, this extension allows us to capture BH seed formation and follow the ensuing accretion within a single, unified framework.

More specifically, we adopt the time-dependent, spherically symmetric metric

$$ds^2 = -e^{2\phi(r,t)} dt^2 + e^{\lambda(r,t)} dr^2 + R(r,t)^2 d\Omega^2, \quad (1)$$

where r is the comoving radial coordinate, $R(r, t)$ is the circumferential radius, and $\phi(r, t)$ is the gravitational potential.

To model heat conduction in SIDM, we extend the perfect-fluid energy–momentum tensor to include the heat-flux four-vector q^μ

$$T^{\mu\nu} = [\rho(1 + \epsilon) + P]u^\mu u^\nu + P g^{\mu\nu} + q^\mu u^\nu + q^\nu u^\mu, \quad (2)$$

where ρ is the rest-mass density, ϵ is the specific internal energy, P is the pressure, and u^μ is the fluid four-velocity. Assuming sufficiently frequent SIDM collisions, we close the system with the ideal-gas equation of state $P = (\gamma - 1)\rho\epsilon$, where γ is the adiabatic index. Following Eckart’s relativistic thermodynamics [46, 77], we express the radial heat flux q^r as

$$q^r = -(\gamma - 1)\kappa e^{-\lambda} e^{-\phi} \frac{\partial}{\partial r} (\epsilon e^\phi), \quad (3)$$

where κ is the thermal conductivity.

To capture nonequilibrium collapse, the formalism tracks the bulk radial velocity $U \equiv e^{-\phi} \partial R / \partial t$ by solving the acceleration equation

$$e^{-\phi} \frac{\partial U}{\partial t} = \Gamma e^{-\lambda/2} \frac{\partial \phi}{\partial r} - \frac{m + 4\pi R^3 P}{R^2}, \quad (4)$$

where m is the enclosed mass and $\Gamma = \sqrt{1 - 2m/R + U^2}$ is the generalized Lorentz factor. Equation (4) explicitly couples general-relativistic gravity to the pressure gradient. As the apparent horizon is approached ($R \rightarrow 2m$), $\Gamma \rightarrow 0$. This relativistic effect strongly suppresses the outward pressure-gradient term $\partial \phi / \partial r$ (see [6]), reducing thermal support and triggering the rapid dynamical inflow during the initial accretion phase (Stage 4).

We resolve central BH formation by tracking outgoing radial null geodesics [78]. A trapped surface forms when $R = 2m$, marking the apparent horizon [79, 80]. This condition provides a self-consistent criterion for determining the initial BH seed mass without nonrelativistic approximations. A complete derivation of the coupled hydrodynamic equations is provided in [6].

Velocity-dependent cross section

Compared with [6], a key extension in this work is the adoption of a velocity-dependent cross section [81–83]

$$\sigma(v) = \frac{\sigma_0}{(1 + (v/w)^2)^2}, \quad (5)$$

where $v = \sqrt{P/\rho}$ is the SIDM velocity dispersion. For the fiducial model, we adopt the observationally favored values $\sigma_0 = 20 \text{ cm}^2 \text{ g}^{-1}$ and $w = 100 \text{ km/s}$ [45].

Fig. 6 shows the central-density evolution of an SIDM halo for different cross-section models. The distinct collapse trajectories are governed by the transition between heat-conduction regimes. In the low-density, long-mean-free-path (LMFP) regime, where the dark-matter collisional mean free path greatly exceeds the characteristic halo scale height, the conductivity scales as $\kappa \propto \sigma$. As the core enters the high-density, short-mean-free-path (SMFP) regime at late times, however, the scaling changes to $\kappa \propto \sigma^{-1}$ [34].

For constant-cross-section models, a larger cross section (red) suppresses SMFP heat conduction more strongly than a smaller one (green), delaying late-time collapse and preventing timely BH-seed formation. Incorporating a velocity-dependent cross section naturally circumvents this bottleneck. As the core velocity dispersion increases, the effective cross section decreases as v^{-4} in the SMFP regime. This reduction in σ increases the conductivity and accelerates the final collapse phase.

Among the velocity-dependent models, the one with larger σ_0 (black) collapses faster than that with smaller σ_0 (orange) because it maximizes the initial LMFP conductivity without suffering the late-time SMFP penalty. Under this optimal scenario, a seed BH forms within $\sim 250 \text{ Myr}$. Because astrophysical observations independently favor velocity-dependent cross sections [e.g., 5, 27], this accelerated collapse pathway is observationally motivated.

Super-Bondi accretion

After the BH seed forms, we follow its subsequent growth by introducing an inner boundary representing the horizon. This boundary acts as a strictly one-way membrane: mass and

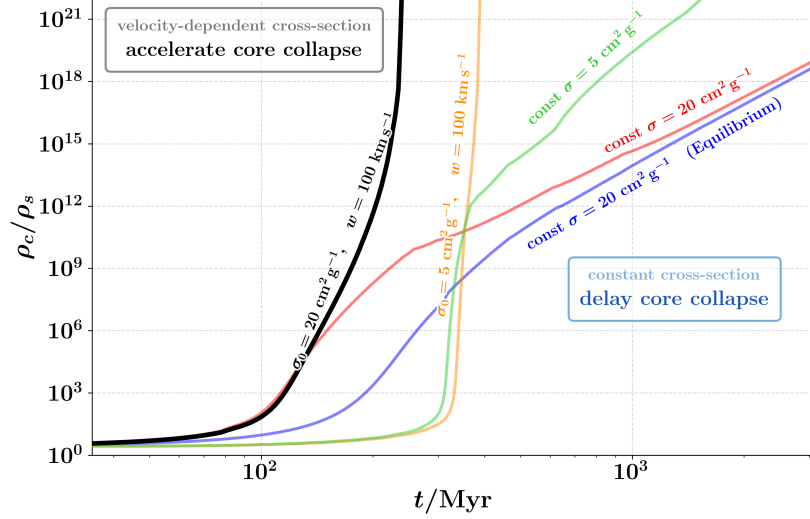


Fig. 6 Impact of the self-interaction cross section and numerical method on gravothermal evolution – Evolution of the central density of an SIDM halo with $M_{\text{vir}} = 10^8 M_{\odot}$ and $c = 10$, initialized at $z = 15$, for different self-interaction cross-section models. Models with velocity-dependent cross sections (black and orange) undergo accelerated late-stage gravothermal collapse, whereas models with constant cross sections (red and green) collapse more slowly at late times. The blue curve shows the conventional equilibrium treatment using the same cross-section parameters as the red curve.

energy can cross it only inward, while the horizon expands as it absorbs the inflowing material (Fig. 2, upper panel).

The standard Bondi accretion rate is

$$\dot{M}_{\text{B}} = 4\pi\lambda_s G^2 M_{\text{BH}}^2 \rho_{\infty} c_{\text{s},\infty}^{-3}, \quad (6)$$

which scales as $\dot{M}_{\text{B}} \propto M_{\text{BH}}^2$ and becomes significant only once the BH is sufficiently massive. During Stage 4, however, the inflow is nearly in free fall, with its velocity approaching the speed of light near the horizon, producing a mass flux far above the Bondi rate. Such super-Bondi accretion does not violate the Eddington constraint, since SIDM does not produce radiation and hence is not subject to the radiative Eddington limit [55].

During early Stage 5, the accretion rate can exceed the Bondi limit by two orders of magnitude for an extended period. This super-Bondi phase is governed by the ratio of two timescales: the LMFP relaxation time, which characterizes SIDM particle collisions,

$$t_{\text{r}} \sim (\rho_{\infty} c_{\text{s},\infty} \sigma_0)^{-1} \approx 7.5 \text{ Myr}, \quad (7)$$

and the Bondi accretion timescale,

$$t_{\text{B}} \sim \sqrt{\frac{R_{\text{s}}^3}{GM_{\text{BH}}}}. \quad (8)$$

At the onset of Stage 5, $M_{\text{BH}} = 300 M_{\odot}$ and $t_{\text{B}} \approx 440 \text{ Myr} \sim 60 t_{\text{r}}$, so gravothermal collapse outpaces BH capture by a factor of ~ 60 , explaining the nearly two-order-of-magnitude accretion enhancement. As the BH grows to $M_{\text{BH}} \approx 10^6 M_{\odot}$, t_{B} falls to $\approx 7.6 \text{ Myr} \sim t_{\text{r}}$; heat conduction no longer dominates, and the accretion rate approaches the Bondi limit (Fig. 3). This transition is consistent with the dark Bondi accretion picture of [55], in which baryons accelerate early growth while dark-matter accretion sets the final BH mass. Adding baryons to our pure-SIDM model may thus shorten the growth timescale without substantially changing the final mass, which is primarily determined by the available dark-matter reservoir and therefore closely tied to the halo mass.

Toward the end of Stage 5, BH accretion reduces the halo mass and envelope density, lowering both the Bondi-predicted and actual accretion rates (Fig. 3). After the BH consumes approximately 20% of the halo mass, the envelope density drops to $\sim 1\%$ of its initial value (Fig. 2, upper panel, purple line), elongating the relaxation time to $t_{\text{r}} \approx 750 \text{ Myr}$. SIDM collisions then become too infrequent on the evolutionary timescale to sustain the fluid approximation, placing subsequent evolution beyond the applicability of our fluid simulation. We therefore regard the final BH mass shown in Fig. 4 as an upper limit.

Parameter space scanning

We systematically scan $6.5 < \log(M_{\text{vir}}/M_{\odot}) < 9.5$ and $6 < c < 15$ to determine how the BH-seed formation and DM-accretion times depend on halo properties. The results are summarized in Fig. 5.

At the low-mass end, the BH-seed formation time (white dashed contours) increases sharply because of the longer SIDM relaxation time. At higher masses, however, the formation time becomes largely independent of mass and is governed primarily by concentration. For the subsequent evolution, the total SMBH-formation timescale—defined as the time at which the BH has consumed half of the isolated halo mass—depends nonmonotonically on halo mass. Although higher concentrations consistently accelerate accretion, a delay occurs near $M_{\text{vir}} \sim 10^{8.5} M_{\odot}$. This localized feature arises from an exceptionally low LMFP density produced by the velocity-dependent cross section³.

Our parameter scan shows that halos initialized at $z = 15$ with $c \gtrsim 10$ can generally produce SMBHs with $M_{\text{BH}} \gtrsim 10^6 M_{\odot}$ by $z \sim 6$ (magenta contour). At the low-mass end, halos with $M_{\text{vir}} \lesssim 10^7 M_{\odot}$ are disfavored by frequent halo mergers (grey dashed line, Fig. 7), whereas the halo abundance declines sharply at $M_{\text{vir}} \gtrsim 10^9 M_{\odot}$ (purple dashed lines). The viable parameter space is therefore approximately $10^7 M_{\odot} \lesssim M_{\text{vir}} \lesssim 10^9 M_{\odot}$ and $c \gtrsim 10$.

We also test the sensitivity of these results to the cross section. For $\sigma_0 = 5 \text{ cm}^2 \text{ g}^{-1}$ and $w = 100 \text{ km/s}$, the gravothermal phases (Stages 1 and 2) last longer (Fig. 6). This longer evolution, however, allows the LMFP envelope to reach a higher density⁴. Consequently, after the BH seed forms, its Stage 5 accretion rate is higher. The total evolution time (Stages 1–5) is close to that in the fiducial model ($\sigma_0 = 20 \text{ cm}^2 \text{ g}^{-1}$ and $w = 100 \text{ km/s}$). These results indicate that, over $\sigma_0 = 5\text{--}20 \text{ cm}^2 \text{ g}^{-1}$, the predicted high-redshift SMBH number density is insensitive to the cross section.

³The LMFP density is established during Stage 2, as the core enters the SMFP regime. If the core velocity dispersion approaches the scale velocity w at this transition, heat conduction becomes particularly efficient, producing a large density contrast between the inner SMFP core and the outer LMFP envelope. For $M_{\text{vir}} = 10^{8.5} M_{\odot}$, $v \sim 100 \text{ km/s}$ at the transition.

⁴Before the LMFP-to-SMFP transition, the LMFP density continues to increase. A smaller cross section delays this transition, after which the SMFP region continues to contract while the LMFP envelope remains nearly unchanged.

Merger tree analysis

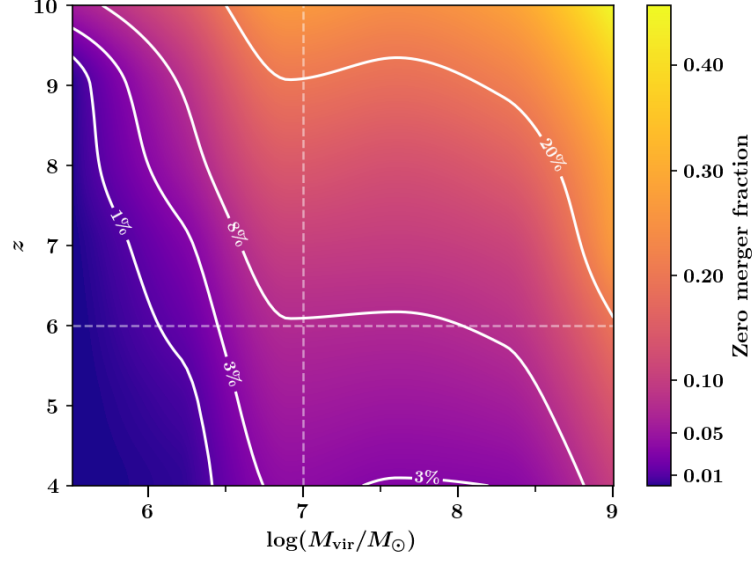


Fig. 7 Exploring the halo mass and redshift regime in which gravothermal evolution is unlikely to be interrupted by major mergers – fraction of halos that experience no major merger (mass ratio $> 1:3$) between $z = 15$ and redshift z , as a function of halo mass, M_{vir} , at $z = 15$. The fraction declines sharply below $M_{\text{vir}} \sim 10^7 M_{\odot}$, indicating that low-mass halos are unlikely to complete BH seeding before being disrupted by major mergers. Among the halos with $10^7 M_{\odot} \lesssim M_{\text{vir}} \lesssim 10^8 M_{\odot}$, approximately 8% remain free of major mergers until $z = 6$, allowing them to complete gravothermal evolution and form a supermassive BH by the LRD epoch.

Only a small fraction of viable halos ($M_{\text{vir}} \gtrsim 10^7 M_{\odot}$ and $c \gtrsim 10$ at $z = 15$) can form high-redshift SMBHs because strong external energy injection—primarily from major mergers—can interrupt their formation. To quantify the fraction of viable halos affected by major mergers during SMBH formation, we construct cosmological merger trees using the *SatGen* algorithm [73, 84, 85]. We adopt a final redshift $z = 4$ and generate 10000 merger trees for halos with final masses in the range $10^8 M_{\odot} < M_{\text{vir}} < 10^{11} M_{\odot}$. We then analyze the number of major mergers between redshifts z and 15 as a function of halo virial mass at $z = 15$. Specifically, we determine the fraction of halos that undergo no mergers with a mass ratio larger than 1:3 over this redshift interval. The results are shown in Fig. 7.

As shown by the contours, only $\gtrsim 8\%$ of halos have undergone no major merger by $z = 6$ and therefore successfully form a high-redshift SMBH. Within the viable mass range $M_{\text{vir}} \gtrsim 10^7 M_{\odot}$, this fraction is insensitive to halo mass. Below $M_{\text{vir}} \sim 10^7 M_{\odot}$, however, this fraction decreases sharply. Thus, even given sufficient time, low-mass halos cannot form SMBHs because frequent major mergers disrupt their formation. Moreover, by $z = 4$, most halos have undergone at least one major merger. Therefore, the SIDM scenario naturally suppresses low-redshift SMBH seeding, consistent with the observed LRD redshift range $4 \lesssim z \lesssim 9$.

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Contributions. H.P.G. developed and extended the Misner-Sharp framework, performed the calculations presented in this work, generated the figures, and prepared the first draft. F.J. co-conceived the project, advised on the cosmic-structure-formation aspects of this work, and developed the manuscript’s narrative and logical structure. X.C. proposed and conceived this project, advised on the development of the extended Misner-Sharp framework, and co-developed the narrative and logical structure of the manuscript. R.L. provided key input on the interpretations of the results and the figure comparing the model with observations. Z.X.J. constructed and analyzed halo merger trees used in this work. All authors contributed to the interpretation of the results, provided feedback on the analysis and manuscript, and approved the final version.

Code availability. The code used to model SIDM halo evolution in the Misner-Sharp framework is available in Ref. [86] and can be accessed at <https://github.com/Hua-Peng-G/SIDM>.

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