

Transient axion streams from disrupted miniclusters

Luca Visinelli^{1,2,*} and Momchil Naydenov^{3,4,†}

¹*Dipartimento di Fisica “E.R. Caianiello,” Università degli Studi di Salerno,
Via Giovanni Paolo II, 132–84084 Fisciano (SA), Italy*

²*Istituto Nazionale di Fisica Nucleare—Gruppo Collegato di Salerno—Sezione di Napoli,
Via Giovanni Paolo II, 132–84084 Fisciano (SA), Italy*

³*Faculty of Physics, Sofia University, 5 James Bourchier Boulevard, 1164 Sofia, Bulgaria*

⁴*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, C.P. 13, 00044 Frascati, Italy*



(Received 11 June 2026; accepted 14 September 2026; published 29 September 2026)

We investigate the formation and evolution of axion streams generated by the tidal disruption of axion miniclusters through stellar encounters in the Milky Way halo. Combining a large-scale Monte Carlo treatment of repeated stellar flybys with a tracer reconstruction of the stripped debris, we follow the phase-space evolution of the streams across a broad range of galactocentric radii and assess their contribution to the local dark matter distribution. We find that the kinetic energy of the stripped debris typically exceeds its residual self-gravitational binding energy at formation, so that the subsequent evolution is dominated by anisotropic free expansion and orbital shear. As a result, stream densities can decrease by factors as large as $\sim 10^{-9}$ over Galactic timescales, strongly suppressing the steady-state abundance of dense streams near the Solar circle. At the Solar radius, only a small fraction of realizations yields a nonzero encounter probability over a 10-year exposure, implying that observable streams are dominated by rare recent and nearby disruption events rather than by a persistent population of long-lived overdense substructure. Despite this rapid dilution, the streams remain dynamically cold and produce detector-frame linewidths many orders of magnitude narrower than the cavity bandwidths of current haloscope experiments. For representative haloscope configurations, we find characteristic stream linewidths in the range $\Delta\nu_{\text{stream}} \sim 10^{-7} - 10^1$ Hz, while the corresponding Doppler drift remains well below the cavity response width.

DOI: [10.1103/d559-xlbr](https://doi.org/10.1103/d559-xlbr)

I. INTRODUCTION

The QCD axion [1,2] is one of the most compelling candidates for the dark matter (DM) of the Universe, arising naturally from the Peccei-Quinn (PQ) solution to the strong CP problem [3,4]; see Refs. [5–7] for reviews. In post-inflationary PQ symmetry-breaking scenarios, spatial variations of the axion field generate $\mathcal{O}(1)$ density fluctuations at the onset of oscillations. These fluctuations can become nonlinear and gravitationally collapse into compact bound structures known as axion miniclusters (AMCs) [8–10]. Subsequent studies have explored the formation, survival, and phenomenology of AMCs, including their disruption in Galactic environments and their contribution to the Milky Way DM halo [11,12].

Over the past decade, significant progress has been made in understanding the formation and internal structure of AMCs. Simulations of axion string and domain wall networks have refined predictions for the axion relic abundance and the small-scale density fluctuations relevant for AMC formation [13–22], while dedicated studies of nonlinear structure formation have characterized the AMC mass function and internal density profiles [23–25]. These results indicate that AMCs span a broad mass range, typically $M_{\text{AMC}} \sim 10^{-16} - 10^{-10} M_{\odot}$, with densities far above the cosmological mean. Their internal structure is often approximated either by Navarro-Frenk-White profiles or by steep power-law profiles when the inner scale radius is unresolved [25–27]. Although the detailed properties of AMCs depend on the cosmological history and axion model parameters [28–30], their existence is a robust prediction of postinflationary axion cosmology. More generally, axion direct-detection experiments are sensitive to fine-grained features of the Galactic halo, including transient overdensities and departures from a smooth Maxwellian velocity distribution [31].

Once formed, AMCs evolve within the Galactic environment and are subject to a variety of disruptive processes.

*Contact author: lvisinelli@unisa.it

†Contact author: mnaydenov@phys.uni-sofia.bg

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

Tidal interactions with stars, passages through the Galactic disk, and encounters with other substructures can induce heating, mass loss, and eventual disruption [26,32,33]. Monte Carlo studies tracking repeated stellar encounters have shown that the survival probability of AMCs depends sensitively on their internal density profile and orbital parameters, with dense systems surviving preferentially while diffuse structures are efficiently stripped [26]. More recently, additional effects such as wave dynamics and cumulative perturbations have been shown to further enhance the efficiency of tidal stripping [34,35].

A natural consequence of these interactions is the formation of tidal debris streams. As AMCs lose mass, the stripped axions are released into the halo, forming elongated, kinematically cold structures analogous to the tidal streams observed in simulations of cold DM subhalos and other self-gravitating debris systems [36–39]. Such streams are of particular interest for direct detection [40,41], since they can generate highly non-Maxwellian velocity distributions and potentially observable spectral features in axion haloscope experiments and related searches for axion substructure [36,42–45]. Whether these structures can remain sufficiently overdense and dynamically coherent over astrophysical timescales is, however, not guaranteed. Despite recent progress, the subsequent evolution of the stripped material remains somewhat unexplored. Previous studies have focused on the disruption of AMCs and the production of tidal debris, while the long-term dynamics of the streams themselves has received less attention. In phenomenological applications, the resulting streams are often treated as coherent structures over astrophysically relevant timescales. However, this assumption is nontrivial: the stripped debris inherits both the internal velocity dispersion of the progenitor and the kinematic perturbations induced by stellar encounters, raising the question of whether such streams persist as overdense structures within the Galactic halo or disperse.

In this work, we revisit the formation and evolution of axion streams generated by stellar encounters with AMCs, focusing on their dynamical stability. We adopt the Monte Carlo framework for stellar disruption developed in Ref. [26], specialized here to an axion mass $m_a = 50 \mu\text{eV}$ and power-law AMC density profiles. For each realization, we track the stripped mass and reconstruct the kinematic properties of the debris, including both longitudinal and transverse velocity dispersions. We then model the subsequent evolution of the stream as a collisionless system to determine whether the resulting structures can survive as persistent overdensities within the Galactic halo. Our analysis indicates that axion streams produced by tidal stripping evolve predominantly through collisionless expansion and phase mixing. For typical stripped mass fractions and stream geometries, the velocity dispersion of the debris exceeds the escape velocity associated with its self-gravity. As a result, the streams undergo anisotropic

expansion, with longitudinal stretching driven by tidal kicks and transverse broadening inherited from the progenitor. The stream density dilutes as $\propto t^{-3}$, implying that these structures are generally transient on Galactic timescales.

These findings have important implications for the phenomenology of axion DM. In contrast to scenarios in which long-lived streams dominate the local phase-space distribution, we find that tidal debris is typically short lived and subdominant. Observable streams may still arise from recent and nearby disruption events, although such occurrences are expected to be rare. Our results place the detectability of axion streams within a more constrained dynamical framework, directly linking their observational prospects to the disruption history of miniclusters in the Milky Way. The original code used for the tidal stripping of AMCs was developed in Ref. [26] and is publicly available [46]. The extensions and analysis tools developed for the present work, including the stream evolution and tracer reconstruction modules, are available [47].

II. PHYSICS SETUP

We summarize the physical framework describing the formation and tidal disruption of AMCs in a galactic environment, following the Monte Carlo approach developed in Ref. [26]. In postinflation PQ scenarios, $\mathcal{O}(1)$ density fluctuations at the onset of axion oscillations lead to the formation of gravitationally bound structures shortly after matter-radiation equality [8,9]. These AMCs span a broad mass range and are characterized by internal densities determined by the primordial overdensity δ [9],

$$\rho_{\text{AMC}} = 140(1 + \delta)\delta^3 \rho_{\text{eq}}, \quad (1)$$

where ρ_{eq} is the cosmological matter density at equality. For a given mass and density, the characteristic radius and internal velocity dispersion are

$$R_{\text{AMC}} = \left(\frac{3M_{\text{AMC}}}{4\pi\rho_{\text{AMC}}} \right)^{1/3}, \quad \sigma_{\text{AMC}} \sim \left(\frac{GM_{\text{AMC}}}{R_{\text{AMC}}} \right)^{1/2}. \quad (2)$$

Alongside AMCs, denser gravitationally bound objects known as axion stars may also form, characterized by different equilibrium configurations and density profiles [48–51].

After their formation, AMCs evolve within the Galactic halo under the combined influence of the smooth gravitational potential and discrete encounters with stars. The stellar population is described by a spatially varying number density $n_\star(\mathbf{r})$ and velocity dispersion $\sigma_\star(\mathbf{r})$, which determine both the rate and strength of gravitational flybys. The characteristic relative velocity is

$$v_{\text{rel}} \sim \sqrt{2}\sigma_\star. \quad (3)$$

When the duration of an encounter is short compared to the internal dynamical time of the minicluster, the interaction can be treated within the impulse approximation. The corresponding energy injection is

$$\Delta E \sim \frac{G^2 M_\star^2}{b^4 v_{\text{rel}}^2} \langle r^2 \rangle M'_{\text{AMC}}, \quad (4)$$

where $M_\star$ is the stellar mass, b is the impact parameter, and $\langle r^2 \rangle$ is the mean-square radius of the minicluster. Here, M'_{AMC} is the instantaneous mass of the AMC. Repeated encounters lead to cumulative heating, tidal stripping, and progressive mass loss from the outer regions of the bound object.

Each realization is initialized by assigning an AMC with initial mass M_{ini} and density ρ_{ini} drawn from a prescribed mass function. The corresponding radius R_{ini} and velocity scale σ_{AMC} follow from the relations above. The minicluster is then placed on a bound Galactic orbit specified by its semimajor axis, eccentricity, and orbital phase, which determine the local stellar environment encountered along the trajectory.

The cumulative effect of stellar flybys is modeled as a sequence of discrete perturbations with encounter rate

$$\frac{dN}{dt} = n_\star(\mathbf{r}) \pi b_{\text{max}}^2 v_{\text{rel}}(t), \quad (5)$$

where $\mathbf{r} = \mathbf{r}(t)$ and b_{max} is an effective maximum impact parameter. Individual encounters are sampled from the corresponding local distributions of impact parameters and relative velocities. For each event, the injected energy is computed using Eq. (4), and the subsequent dynamical response is implemented through a semianalytic stripping operator that updates the bound mass and radius of the AMC after energy injection and structural readjustment. Iterating this procedure yields the full stripping history of each realization.

Relative to the original implementation of Ref. [26], the framework adopted here retains detailed information about the stripped material itself rather than focusing only on the surviving bound remnant. Each stripping event is recorded individually together with its associated orbital and kinematic properties, including the stripping time, local phase-space configuration, injected energy, stripped mass, and characteristic velocity scales inherited from the tidal encounter. This allows the debris to be reconstructed as a sequence of localized packets in phase space rather than as a single effective stream component. The framework also reconstructs the longitudinal and transverse velocity dispersions associated with each stripping event, which provide the initial conditions for the subsequent stream evolution developed below. The main output of the Monte Carlo stage is the event history of each realization, consisting of a sequence of stripping events indexed by i

and characterized by a stripping time t_i , stripped mass element ΔM_i , orbital position $\mathbf{x}_i$, velocity $\mathbf{v}_i$, and the corresponding effective velocity dispersions. These stripping histories provide the initial conditions for the stream reconstruction and phase-space evolution discussed in the following section.

III. STREAM RECONSTRUCTION

To follow the evolution of the stripped debris, we extend the Monte Carlo framework of Ref. [26] by retaining the full stripping history of each AMC realization. Rather than characterizing disruption only through the surviving bound fraction, we reconstruct the stripped component as a collisionless tracer ensemble evolving in the Galactic potential. This allows us to assess if the resulting axion streams can remain coherent and self-gravitating over Galactic timescales, or instead disperse through phase mixing and orbital shear.

The numerical framework consists of three stages. First, the Monte Carlo evolution follows AMCs undergoing repeated stellar encounters and records the stripping history of each realization. Second, the stripped material is reconstructed as a collection of localized phase-space packets. Third, tracer particles associated with these packets are evolved in a smooth Galactic potential and used to infer the stream morphology, density evolution, visibility time, and effective abundance. The tracer ensemble should be interpreted as an effective coarse-grained representation of the stripped debris rather than a fully self-consistent N -body realization. Unlike the original Monte Carlo framework of Ref. [26], which follows only the evolution of the bound AMC remnant, our implementation stores the full stripping history of each realization. Each stripping event with nonzero mass loss is characterized by the stripping time t_i , stripped mass ΔM_i , injected energy ΔE_i , and the local orbital configuration of the parent AMC. Since the Monte Carlo calculation does not explicitly evolve the stripped particles, we reconstruct their initial phase-space coordinates from the local orbital properties of the AMC at the stripping event. Each event is described by a localized packet with phase-space coordinates $(\mathbf{x}_i, \mathbf{v}_i)$ corresponding to the effective bulk motion of the debris immediately after stripping. The packet carries a total mass ΔM_i and seeds the subsequent tracer reconstruction.

The internal phase-space structure of the packet is modeled through an anisotropic Gaussian velocity distribution aligned with the local stream direction. The longitudinal velocity dispersion is estimated from the specific energy injected during the encounter,

$$\sigma_{l,i}^2 \simeq \frac{2\Delta E_i}{M_i}, \quad (6)$$

where M_i is the bound AMC mass immediately before stripping. The transverse velocity scale is identified with

the characteristic internal velocity dispersion of the progenitor AMC,

$$\sigma_{t,i} \simeq \left(\frac{GM_i}{R_i} \right)^{1/2}, \quad (7)$$

where R_i is the corresponding AMC radius. Physically, $\sigma_{l,i}$ parametrizes the velocity spread induced by the tidal encounter, while $\sigma_{t,i}$ is the initial thickness of the stream inherited from the internal dynamics of the parent AMC.

For computational simplicity, the packet centroid is reconstructed using a planar approximation to the local AMC orbit. The sampled orbital radius r_i , orbital phase ϕ_i , and AMC speed v_i determine the initial phase-space coordinates of the packet. A local orthonormal basis is then constructed from the packet velocity, defining one longitudinal direction parallel to the bulk motion and two transverse directions orthogonal to it. Tracer particles are sampled around the packet centroid using the dispersions $(\sigma_{l,i}, \sigma_{t,i})$ along these directions. The tracers are subsequently evolved in an external smooth Galactic mean field $\Phi(\mathbf{x})$, according to

$$\ddot{\mathbf{x}} = -\nabla\Phi(\mathbf{x}), \quad (8)$$

using a symplectic leapfrog integrator. The tracer particles are evolved in a static logarithmic Galactic potential,

$$\Phi(r) = \frac{1}{2} v_c^2 \ln(r^2 + r_{\text{soft}}^2), \quad (9)$$

with circular velocity $v_c = 220 \text{ km s}^{-1}$ and softening radius $r_{\text{soft}} = 0.05 \text{ pc}$, so that an approximately flat rotation curve is produced for $r \gg r_{\text{soft}}$. The purpose of this evolution is to capture the effects of orbital shear and phase mixing on the stripped debris. The self-gravity of both the debris and the surviving AMC remnant is neglected. This approximation is justified *a posteriori* by the fact that the kinetic energy of the reconstructed streams dominates over residual self-gravity, see Eq. (18) below, so that their subsequent evolution is governed primarily by collisionless expansion and phase mixing.

The tracer evolution naturally produces elongated filamentary structures through orbital shear and phase mixing. To quantify the dilution of the streams, we reconstruct the density using two complementary estimators. The first is a coarse-grained estimator based on the covariance matrix of the tracer distribution,

$$C_{ij}(t) = \langle (x_i - \langle x_i \rangle)(x_j - \langle x_j \rangle) \rangle, \quad (10)$$

from which we define the effective volume

$$V_{\text{eff}}(t) \equiv \frac{4\pi}{3} \sqrt{\lambda_1 \lambda_2 \lambda_3}, \quad (11)$$

where λ_i are the eigenvalues of C_{ij} , ordered such that $\lambda_1 \geq \lambda_2 \geq \lambda_3$. The corresponding coarse-grained density estimator is

$$\rho_{\text{cg}}(t) \sim \frac{M_{\text{stream}}}{V_{\text{eff}}(t)}. \quad (12)$$

We also construct a nearest-neighbor density estimator, ρ_{local} , based on the distance to the k th nearest tracer, which is more sensitive to localized overdensities within the filamentary stream structure. The final stream associated with a given AMC realization is obtained by superposing the tracer populations generated by all stripping events occurring during the disruption.

The density evolution is characterized through the logarithmic slope

$$\gamma(t) \equiv \frac{d \log \rho}{d \log t}, \quad (13)$$

where ρ denotes either ρ_{cg} or ρ_{local} . We compare the reconstructed evolution with the ballistic estimate

$$l_s(t) \sim \sigma_l t, \quad R_s(t) \sim \sigma_t t, \quad (14)$$

where σ_l and σ_t are characteristic longitudinal and transverse velocity scales representative of the tracer ensemble. This implies

$$\rho_{\text{stream}}(t) \sim \frac{M_{\text{stream}}}{\pi R_s^2(t) l_s(t)} \propto t^{-3}. \quad (15)$$

This scaling is not imposed in the simulations and serves only as a benchmark for interpreting the reconstructed stream evolution.

To assess whether the stripped component remains self-gravitating, we compare the characteristic specific kinetic energy,

$$E_{\text{kin}} \sim \frac{1}{2} (\sigma_l^2 + 2\sigma_t^2), \quad (16)$$

with the specific gravitational binding energy,

$$E_{\text{bind}} \sim \frac{GM_{\text{stream}}}{R_s(t)}. \quad (17)$$

We define the virial parameter

$$\alpha \equiv \frac{2E_{\text{kin}}}{E_{\text{bind}}}, \quad (18)$$

which quantifies the relative importance of kinetic support and residual self-gravity. For the representative stripping realizations reconstructed here we typically find $\alpha \gg 1$ already at early times, indicating that the subsequent

evolution is dominated by collisionless expansion and phase mixing rather than gravitational collapse. Residual self-gravity may nevertheless remain relevant for unusually dense or marginally bound streams in the high-density tail.

Finally, we define a visibility time t_{vis} as the time at which the reconstructed stream density falls below a threshold $10\rho_{\text{DM,loc}}$, where $\rho_{\text{DM,loc}}$ is the local Galactic DM density. The corresponding effective dilution rate is

$$\Gamma_{\text{diffuse}} = t_{\text{vis}}^{-1}, \quad (19)$$

which provides an estimate of the steady-state stream abundance,

$$n_{\text{stream}} \sim n_{\text{AMC}} \frac{t_{\text{vis}}}{T_{\text{age}}} \sim \frac{n_{\text{AMC}}}{T_{\text{age}} \Gamma_{\text{diffuse}}}. \quad (20)$$

This relation connects the production of tidal debris to its subsequent dilution through phase mixing and orbital shear.

IV. RESULTS

We now present the results obtained from the Monte Carlo evolution of tidally disrupted AMCs and from the tracer reconstruction of the resulting debris streams. All radial statistics shown below are derived from ensembles with $N_{\text{AMC}} = 10^6$ realizations at each orbital radius. The sample is sufficiently large to probe the rare-event tails associated with strong stellar encounters and highly disrupted systems. For each orbital configuration, the minicluster population is evolved under repeated stellar encounters while the stripped component is reconstructed through tracer particles. This procedure allows us to follow directly the morphology and density evolution of the debris without imposing an *a priori* analytic stream model. The orbital evolution is computed within the Milky Way model adopted in Ref. [26], which includes the dominant stellar populations responsible for tidal perturbations in the Galactic bulge and disk. The simulations probe orbital radii spanning the inner Galaxy, Solar neighborhood, and outer halo, with the semimajor axis ranging within $a = 0.3$ and 10 kpc.

We begin by considering the longitudinal velocity dispersion σ_l induced by tidal stripping and orbital-energy injection. Figure 1 shows the median value and statistical spread as functions of galactocentric semimajor axis. The longitudinal velocity dispersion decreases systematically with galactocentric radius. In the inner Galaxy, repeated stellar encounters generate characteristic values $\sigma_l \sim 10^{-4} \text{ km s}^{-1}$ while, beyond $a \gtrsim 5 \text{ kpc}$, the dispersion asymptotes to $\sigma_l \sim 10^{-5} \text{ km s}^{-1}$. The broad statistical spread reflects the stochastic nature of the encounter history, particularly for orbits crossing the dense stellar environment of the inner Galaxy.

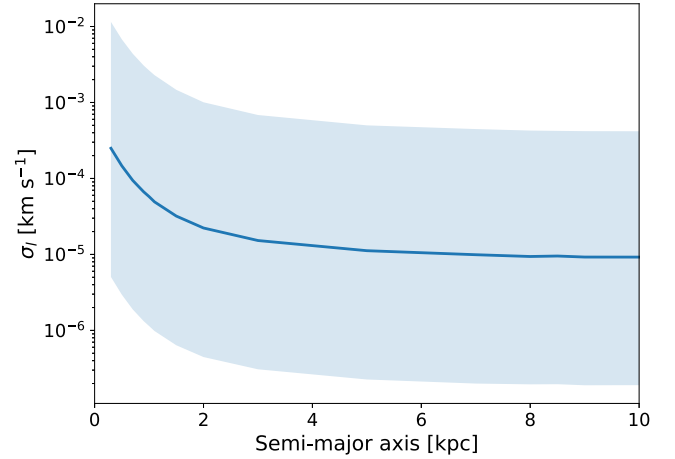


FIG. 1. Median longitudinal velocity dispersion σ_l of the stripped debris as a function of orbital semimajor axis a . The shaded band corresponds to the 1σ spread among Monte Carlo realizations.

The total stripped mass transferred into the stream,

$$M_{\text{stream}} = M_{\text{ini}} - M_{\text{fin}}, \quad (21)$$

also shows a pronounced radial dependence. As shown in Fig. 2, the characteristic stripped mass decreases by nearly four orders of magnitude between the inner and outer halo. Typical stream masses are $M_{\text{stream}} \sim 10^{-13} M_{\odot}$ at sub-kpc radii, while for $a \gtrsim 5 \text{ kpc}$ they decrease to $M_{\text{stream}} \sim 10^{-16} - 10^{-17} M_{\odot}$. Both M_{stream} and σ_l are controlled by the cumulative tidal energy injected through stellar encounters, as indicated by the similarity between their radial profiles. Orbital shear and repeated weak perturbations may broaden the velocity distribution without significantly increasing the stripped mass fraction.

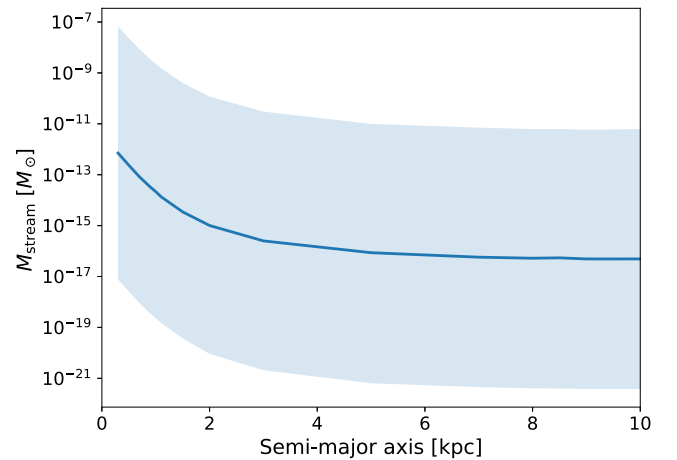


FIG. 2. Median stream mass M_{stream} as a function of orbital semi-major axis. The shaded band corresponds to the 1σ spread among Monte Carlo realizations.

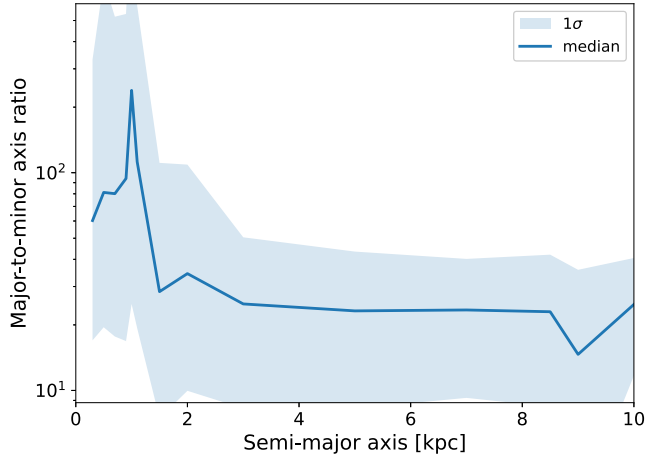


FIG. 3. Final major-to-minor axis ratio of the reconstructed stream distribution as a function of semimajor axis.

The tracer reconstruction reveals that the stripped debris evolves into highly anisotropic filamentary structures. We characterize the morphology through the ratio between the principal axes of the tracer covariance matrix, shown in Fig. 3. Streams formed in the inner Galaxy become extremely elongated, with axis ratios reaching $\mathcal{O}(10^2)$ because of strong tidal stretching and orbital shear. Outside the central kiloparsec the anisotropy decreases steadily with galactocentric radius, indicating that streams formed in the outer halo are less filamentary.

Figure 4 shows the time dependence of the major-to-minor axis ratio for representative streams at $a = 0.3$ kpc, $a = 0.7$ kpc, $a = 3$ kpc, and $a = 10$ kpc. Streams formed in the inner Galaxy rapidly develop highly elongated morphologies, reaching axis ratios $\mathcal{O}(10^2)$ within a few Myr. At sub-kpc radii the evolution is irregular because of repeated perturbations and orbital shear, while at larger radii it approaches a smoother ballistic regime.

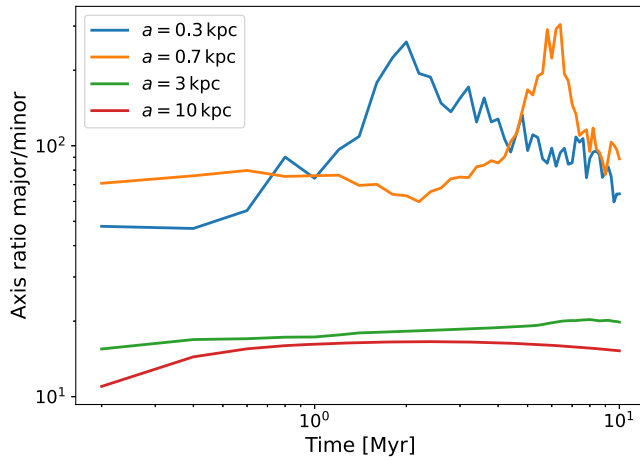


FIG. 4. Time evolution of the major-to-minor axis ratio for representative streams at $a = 0.3$ kpc, $a = 0.7$ kpc, $a = 3$ kpc, and $a = 10$ kpc.

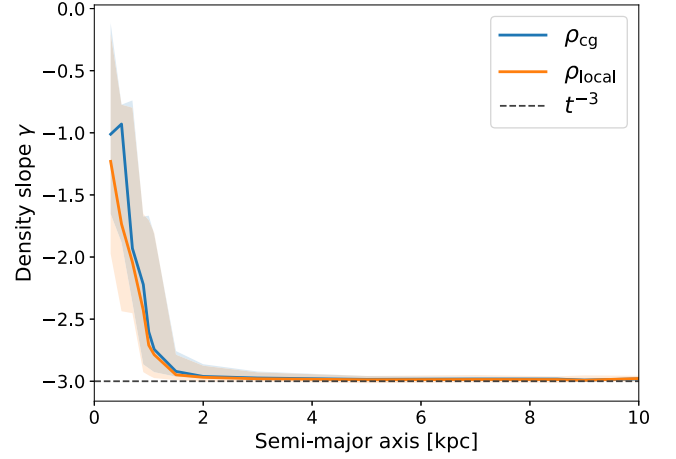


FIG. 5. Median logarithmic density slope γ as a function of semimajor axis for the coarse-grained density ρ_{cg} and the local-density estimator ρ_{local} . The dashed line corresponds to the ballistic scaling $\gamma = -3$. The shaded band corresponds to the 1σ spread among Monte Carlo realizations.

The radial dependence of the fitted density slope γ from Eq. (13) is shown in Fig. 5. Both the coarse-grained density ρ_{cg} and the local estimator ρ_{local} rapidly converge toward the ballistic scaling $\gamma \simeq -3$. The convergence is nearly complete beyond $a \sim 2$ kpc, where the two estimators become almost indistinguishable. Significant deviations appear only in the innermost Galactic region, where repeated perturbations and strong orbital shear slow the effective dilution. The reconstructed evolution is consistent with streams behaving as transient freely expanding debris rather than long-lived self-gravitating structures.

The strong dilution of the streams has direct implications for their steady-state abundance. Figure 6 shows the inferred number density of surviving streams, which decreases systematically with galactocentric radius. The broad uncertainty

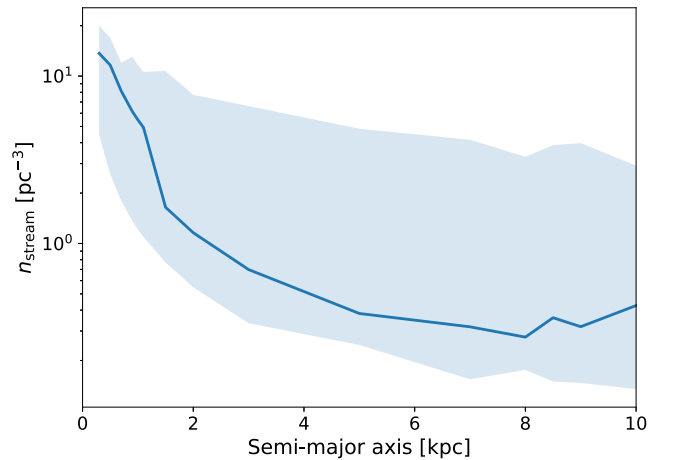


FIG. 6. Estimated stream number density as a function of semi-major axis. The shaded region indicates the statistical spread among realizations.

band reflects the sensitivity of the population to rare encounters and stochastic disruption histories.

V. DISCUSSION

The reconstructed stream evolution indicates that tidally stripped AMC debris evolves predominantly through collisionless expansion and phase mixing rather than through self-gravitating dynamics. Figure 7 shows the normalized evolution of the coarse-grained tracer-density estimator $\rho_{\text{cg}}(t)/\rho_{\text{cg}}(t_0)$ for representative streams formed at different galactocentric radii. The normalization removes the arbitrary absolute scale associated with the covariance-volume estimator and isolates the relative dilution rate of the reconstructed debris. Outer-halo realizations evolve approximately according to the ballistic scaling $\rho_{\text{cg}} \propto t^{-3}$ expected from Eq. (15), while streams formed in the inner Galaxy exhibit stronger temporal fluctuations because of repeated perturbations and orbital shear. The intermediate case at $a = 0.7$ kpc already shows substantial dilution, while still retaining visible fluctuations inherited from the denser stellar environment of the inner halo.

The coarse-grained estimator ρ_{cg} should not be interpreted as the microscopic density within individual stream filaments. Instead, it probes the large scale geometric dilution of the tracer ensemble reconstructed from the covariance volume of the stream. To investigate the survival of localized overdensities more directly, Fig. 8 shows the normalized evolution of the local tracer density estimator $\rho_{\text{local}}(t)/\rho_{\text{local}}(t_0)$ reconstructed from nearest-neighbor tracer distances. The outer halo realizations again evolve close to the ballistic scaling expected for approximately collisionless free expansion. By contrast, inner halo realizations retain larger local overdensities over longer time-scales and develop persistent fluctuations associated with the filamentary morphology of the streams. Localized

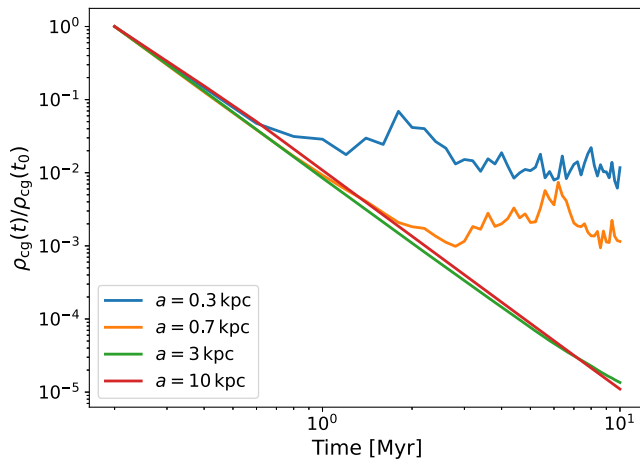


FIG. 7. Representative evolution of the normalized coarse-grained tracer-density estimator $\rho_{\text{cg}}(t)/\rho_{\text{cg}}(t_0)$ for streams formed at $a = 0.3$ kpc, $a = 0.7$ kpc, $a = 3$ kpc, and $a = 10$ kpc.

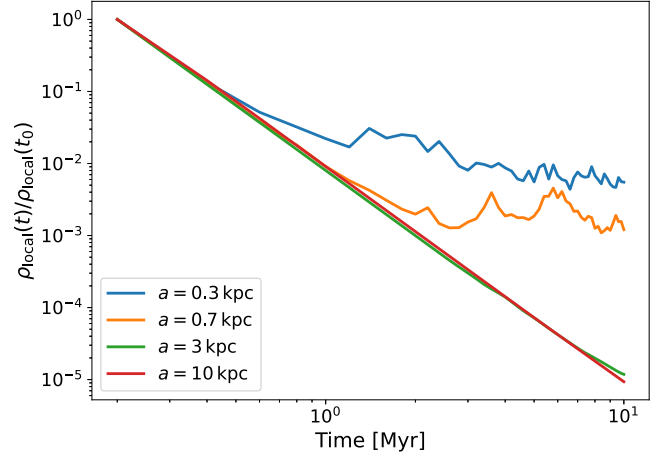


FIG. 8. Representative evolution of the normalized local tracer-density estimator $\rho_{\text{local}}(t)/\rho_{\text{local}}(t_0)$ for streams formed at $a = 0.3$ kpc, $a = 0.7$ kpc, $a = 3$ kpc, and $a = 10$ kpc.

overdensities can survive substantially longer than suggested by the covariance-volume estimator alone, even while the stream undergoes significant large scale dilution.

The effective steady-state estimate introduced above can be interpreted schematically in terms of a kinetic equation for the stream population,

$$\frac{dn_{\text{stream}}}{dt} = S - \Gamma_{\text{diffuse}} n_{\text{stream}}, \quad (22)$$

where S is the local source term associated with AMC disruption and Γ_{diffuse} is the effective dilution rate extracted from the reconstructed density evolution. The rapid decline of the reconstructed density estimators indicates that dilution efficiently suppresses the accumulation of a long-lived steady-state stream population throughout most of the Galactic halo.

This framework has direct implications for axion DM haloscope searches [40,41]. The interpretation of haloscope signals in terms of the underlying Galactic phase-space distribution has been developed extensively in Ref. [31], including the effects of velocity substructure and time-dependent modulation. In haloscope experiments the signal frequency is determined by the axion kinetic energy, so that the intrinsic rest-frame linewidth scales as

$$\frac{\Delta\nu}{\nu_a} \sim \frac{\sigma_v^2}{c^2}. \quad (23)$$

In the detector frame, the observable linewidth is set by the projection of the stream velocity dispersion along the Earth-stream relative motion,

$$\Delta\nu_{\text{lab}} \simeq \nu_a \frac{v_{\oplus} \sigma_{\text{avg}}}{c^2}, \quad (24)$$

where $v_{\oplus}$ denotes the Earth-stream relative speed, $\sigma_{\text{avg}} = \sqrt{(\sigma_l^2 + 2\sigma_t^2)/3}$, and the axion rest-mass frequency

is $\nu_a = m_a/(2\pi)$. The principal limitation for direct detection is not spectral broadening, but rather the rapid density dilution of the debris streams.

In the Monte Carlo implementation, a stream is considered visible while its reconstructed density satisfies

$$\rho_{\text{stream}} > \rho_{\text{thr}}, \quad (25)$$

where the threshold is defined relative to the local Galactic DM density $\rho_{\text{loc}} = 0.45 \text{ GeV cm}^{-3}$ as $\rho_{\text{thr}} = 10\rho_{\text{loc}}$. This criterion selects streams that are significantly overdense with respect to the smooth halo background. The corresponding visibility time is the last time at which the stream remains overdense relative to this threshold. The simulations indicate that the retained density fraction can decrease to values as small as $\sim 10^{-9}$, while the corresponding visibility timescale is typically

$$t_{\text{vis}} \sim 10^5 - 10^7 \text{ yr}, \quad (26)$$

depending on orbital radius and disruption history. Although streams are continuously produced throughout the Galactic halo, the resulting steady-state population is dominated by diffuse structures with small local density contrasts.

To investigate the implications for direct detection more quantitatively, we perform dedicated Solar-neighborhood simulations at $a = 8.5 \text{ kpc}$ with $N_{\text{AMC}} = 10^6$, including the Earth-relative velocity $v_{\oplus} = 232 \text{ km s}^{-1}$ and an experimental exposure time $T_{\text{exp}} = 10 \text{ yr}$. For the conservative prescription in which only fully disrupted AMCs are counted as stream sources, we obtain a disruption fraction $f_{\text{dis}} \simeq 10^{-4}$ together with characteristic stream masses

$$\langle M_{\text{stream}} \rangle \sim 5 \times 10^{-17} M_{\odot}. \quad (27)$$

The inferred stream abundance near the Solar circle remains small, $n_{\text{stream}} \lesssim \mathcal{O}(0.1 - 1) \text{ pc}^{-3}$, with a highly skewed distribution dominated by rare disruption events. The operational stream density entering the population-level visibility estimate is the analytic ballistic density track ρ_{track} introduced in Eq. (15). Figure 9 shows its evolution at the Solar radius. The solid curve corresponds to the median over realizations, while the dark and light shaded regions indicate the 1σ and 2σ spreads in log space, respectively. The comparison with the local Galactic DM density $\rho_{\odot}$ illustrates the rapid dilution of the stream population relative to the smooth halo background. While the median stream density rapidly falls below $\rho_{\odot}$, the broader 2σ region shows that a subset of realizations can temporarily retain substantially larger densities because of rare disruption histories.

The resulting encounter-probability distribution is similarly sparse. In the conservative prescription, the median encounter probability over a decade-long exposure is effectively zero. At the Solar radius, only a fraction of

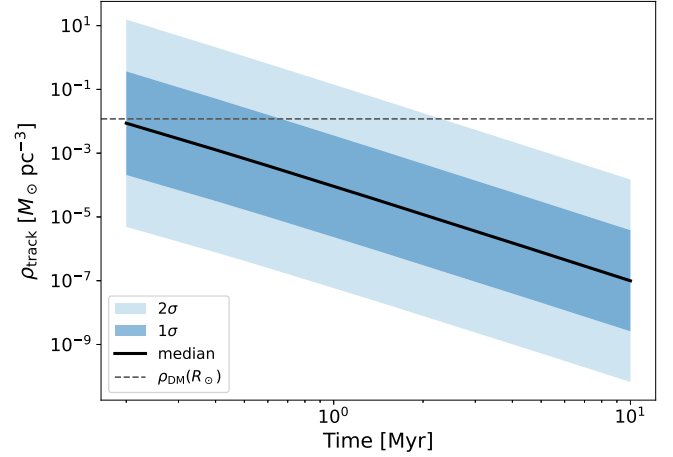


FIG. 9. Evolution of the analytic stream-density track ρ_{track} at the Solar radius, $a = 8.5 \text{ kpc}$. The solid black line shows the median over realizations, while the dark and light shaded regions correspond to the 1σ and 2σ spreads in log space, respectively. The horizontal dashed line indicates the local Galactic DM density $\rho_{\odot}$.

order 10^{-4} of the realizations yields a nonzero encounter probability, with a nonzero-realization median $P_{\text{enc}} \sim 10^{-11}$ and an upper tail reaching $P_{\text{enc}} \sim 10^{-6}$. Observable events are associated with rare realizations involving comparatively young and nearby streams rather than with a persistent background of long-lived overdense substructure. This picture is qualitatively consistent with the broader postinflationary scenario in which direct-detection experiments probe a highly intermittent axion density field containing both rare overdense structures and extended underdense minivoids [52].

The corresponding haloscope phenomenology is illustrated in Fig. 10, which shows the detector-frame stream

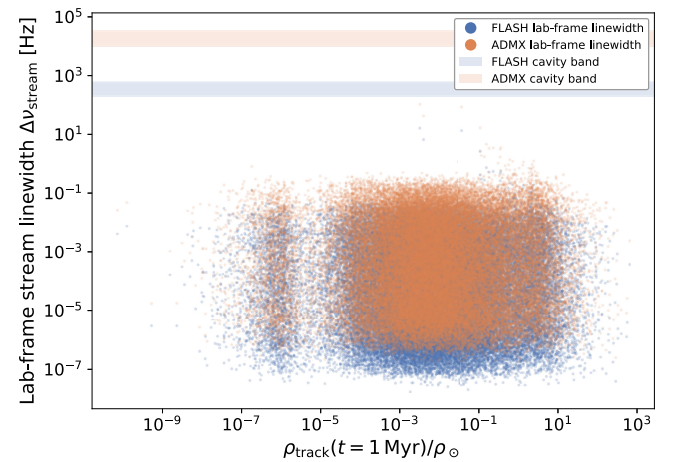


FIG. 10. Detector-frame stream linewidth as a function of the reconstructed density contrast at the Solar radius, $a = 8.5 \text{ kpc}$, evaluated at $t = 1 \text{ Myr}$. The shaded horizontal bands indicate the cavity bandwidth ranges for FLASH (blue) and ADMX (orange).

linewidth as a function of the reconstructed density contrast at the Solar radius. The linewidths estimated from Eq. (24) are compared with the cavity bandwidths of representative haloscope configurations, namely the FINUDA magnet for Light Axion Search (FLASH) [53], with frequency range $f = 100\text{--}300$ MHz and quality factor $Q_{\text{cavity}} = 5 \times 10^5$, and the Axion Dark Matter eXperiment (ADMX) [54], in the configuration probing $f = 0.6\text{--}2$ GHz and with $Q_{\text{cavity}} = 6 \times 10^4$ [55–57]. Although the detector-frame linewidths are substantially larger than the intrinsic rest-frame estimates, they remain many orders of magnitude smaller than the corresponding cavity bandwidths. The stream signal appears effectively monochromatic at the level of the cavity response.

Three distinct spectral scales enter the problem: the intrinsic stream linewidth determined by the velocity dispersion, the secular Doppler drift induced by the Earth-stream relative acceleration, and the instrumental cavity bandwidth. The secular drift of the signal frequency may be estimated as

$$\dot{\nu} \sim \nu_a \frac{v_{\oplus} a_{\oplus}}{c^2}, \quad (28)$$

where $a_{\oplus}$ denotes the characteristic acceleration of the Earth in the Galactic frame. This defines an effective drift quality factor,

$$Q_{\text{drift}} \equiv \frac{\nu_a^2}{\dot{\nu}} \sim \frac{\nu_a c^2}{v_{\oplus} a_{\oplus}} \gg Q_{\text{cavity}}, \quad (29)$$

showing that the secular Doppler drift remains far smaller than the instrumental response width of present haloscope cavities. The drift does not significantly broaden the signal at the cavity-response level, although it may become relevant for ultralong coherent integrations, narrow Fourier-bin analyses, and phase-sensitive signal reconstruction.

The linewidth estimates above also determine the characteristic coherence time of the signal,

$$t_{\text{coh}} \sim \frac{1}{\Delta\nu_{\text{lab}}}. \quad (30)$$

For the stream realizations reconstructed here, the narrow velocity dispersions imply coherence times ranging from fractions of a second up to $\sim 10^7$ s for the narrowest streams. In realistic searches, however, the effective coherence time relevant for matched filtering and phase-sensitive analyses is also affected by finite detector resolution and by the time-dependent Doppler modulation induced by the Earth-stream relative motion.

The approximately rectangular support of the Monte Carlo distribution in Fig. 10 reflects the weak correlation between the density contrast and the velocity width in the present framework. The linewidth is controlled primarily by the internal velocity dispersion projected

along the Earth-stream relative motion, while the density contrast depends mainly on the stripped mass fraction and on the subsequent geometric dilution during ballistic expansion. Density dilution and spectral narrowness are largely decoupled observables, so even strongly diluted streams can remain spectrally narrow in the laboratory frame. The bounded support of the distribution is also influenced by the finite AMC mass range and by the fixed Solar-radius benchmark adopted in the present analysis.

The direct-detection phenomenology proposed in Ref. [43] remains viable, but is restricted to the rare high-density tail of the stream population. In this regime the signal would appear as a transient and extremely narrow spectral feature with slowly varying Doppler modulation induced by the Earth-stream relative motion. The intrinsic evolution of the stream morphology occurs on Galactic dynamical timescales vastly longer than experimental integration windows, allowing the signal to be treated as effectively stationary during a typical observation.

Several limitations of the present analysis should nevertheless be emphasized. The Monte Carlo framework treats the stream evolution in an effective manner and neglects possible subsequent perturbations from Galactic substructure, giant molecular clouds, and time-dependent non-axisymmetric structures. In addition, the present treatment follows the debris in the collisionless approximation and does not attempt to resolve interference effects or fine-grained caustic structures associated with the wave nature of the axion field. The predicted linewidths should be interpreted as idealized collisionless estimates, since unresolved perturbations, wave interference effects, finite detector resolution, and experimental systematics may broaden the observable signal under realistic observational conditions.

Future work should extend the present framework in several directions. Higher-resolution tracer reconstructions and dedicated N -body simulations would allow a more precise characterization of the long-term stream morphology and dilution rates, while more realistic Galactic potentials could quantify the impact of disk crossings and time-dependent perturbations. A particularly important extension would be to incorporate the wave nature of the axion field directly into the stream evolution. Interference effects, coherent wave dynamics, and fine-grained caustic structures could modify the local phase-space distribution on scales inaccessible to the present collisionless treatment. It would also be interesting to couple the present framework directly to mock haloscope pipelines in order to quantify the detectability of transient stream signals in realistic experimental searches.

VI. CONCLUSIONS

In this work, we have investigated the formation and evolution of axion streams generated by the tidal disruption of axion miniclusters through stellar encounters in the

Galactic halo. Combining a large-scale Monte Carlo treatment of cumulative stellar flybys with a tracer reconstruction of the stripped debris, we have followed the subsequent evolution of the streams across a broad range of galactocentric radii and characterized their masses, morphology, kinematics, and density evolution. Our analysis identifies a simple dynamical picture for the fate of tidally stripped AMC debris. Although stellar encounters can efficiently remove material from miniclusters, the stripped component typically carries only a modest fraction of the progenitor mass while inheriting velocity scales associated with the deeper potential of the original bound configuration. The characteristic kinetic energy of the debris generally exceeds its residual self-gravitational binding energy, so that the subsequent evolution is governed primarily by collisionless expansion and orbital shear rather than by self-gravitating dynamics.

The simulations reveal a transition between two dynamical regimes. In the inner Galaxy, repeated stellar encounters continuously perturb the streams, producing strongly filamentary structures with large axis ratios and substantial temporal fluctuations in density and morphology. By contrast, streams formed at larger galactocentric radii evolve more smoothly and rapidly approach an approximately ballistic regime. In this limit, both the local and coarse-grained density estimators converge toward the asymptotic scaling expected from free phase-space dilution, while the surviving density fraction decreases to extremely small values at late times. The resulting steady-state abundance of dense streams near the Solar circle is strongly suppressed.

These results have direct implications for axion halo-scope searches. The reconstructed stream velocity dispersions imply extremely narrow spectral features compared to both the virialized Galactic halo and the instrumental bandwidths of current cavity experiments. For the FLASH and ADMX benchmark configurations considered here, the intrinsic stream linewidths is many orders of magnitude smaller than the corresponding cavity bandwidths, so that any surviving stream component behaves effectively as an ultranarrow monochromatic feature within the detector response. The dominant limitation for direct detection is not spectral resolution, but rather the small probability of encountering a sufficiently dense stream during the lifetime of an experiment. Our dedicated Solar-neighborhood realizations indicate that observable events are controlled by the rare high-density tail associated with comparatively recent and nearby disruption events rather than by a quasi-steady population of persistent overdense streams.

More broadly, our results show that the phenomenology of axion substructure is intrinsically dynamical. The observational relevance of streams depends not only on the formation of compact miniclusters, but also on the

subsequent competition between tidal stripping, orbital shear, and phase-space dilution. Within the collisionless framework developed here, the stripped debris evolves predominantly into diffuse filamentary structures whose detectability is strongly suppressed by rapid density dilution despite their extremely cold kinematics.

Several important extensions nevertheless remain to be explored. Higher-resolution N -body simulations and more realistic Galactic potentials could provide a more precise characterization of the long-term stream evolution and dilution rates. A particularly important direction will be to incorporate the wave nature of the axion field directly into the stream dynamics, including possible interference effects and fine-grained caustic structures inaccessible to the present collisionless treatment.

Overall, our results provide a unified dynamical picture of the interplay between tidal stripping and stream evolution in post-inflationary axion cosmology. While AMCs may survive as compact substructures throughout the Galactic halo, the debris generated by their disruption evolves predominantly into transient diffuse streams whose observational relevance is controlled by rare high-density realizations. Future high-resolution simulations and dedicated experimental searches will determine whether such transient axion streams can ultimately be observed.

ACKNOWLEDGMENTS

We thank Ciaran O’Hare and Giovanni Pierobon for stimulating conversations. L. V. acknowledges support by the National Natural Science Foundation of China (NSFC) through the Grant No. 12350610240 “Astrophysical Axion Laboratories.” This work is supported by the Istituto Nazionale di Fisica Nucleare (INFN) through the Commissione Scientifica Nazionale 4 (CSN4) Iniziativa Specifica “Quantum Universe” (QGSKY). This publication is based upon work from the COST Actions “COSMIC WISPerS” (CA21106) and “Addressing observational tensions in cosmology with systematics and fundamental physics (CosmoVerse)” (CA21136), both supported by COST (European Cooperation in Science and Technology). M. N. acknowledges the support of BNSF KP-06-N98/2 from December 1, 2025 “Nuclear spectra, isomers and symmetry: test of fundamental constants and dark matter” and BNSF/SU 80-10-180 from March 20, 2026 “Experimental detection of dark matter.”

DATA AVAILABILITY

The original code used for the tidal stripping of AMCs was developed in Ref. [26] and is publicly available [46]. The extensions and analysis tools developed for the present work, including the stream evolution and tracer reconstruction modules, are available [47].

- [1] S. Weinberg, *Phys. Rev. Lett.* **40**, 223 (1978).
- [2] F. Wilczek, *Phys. Rev. Lett.* **40**, 279 (1978).
- [3] R. D. Peccei and H. R. Quinn, *Phys. Rev. Lett.* **38**, 1440 (1977).
- [4] R. D. Peccei and H. R. Quinn, *Phys. Rev. D* **16**, 1791 (1977).
- [5] D. J. E. Marsh, *Phys. Rep.* **643**, 1 (2016).
- [6] L. Di Luzio, M. Giannotti, E. Nardi, and L. Visinelli, *Phys. Rep.* **870**, 1 (2020).
- [7] A. Arza *et al.*, [arXiv:2603.03433](#).
- [8] C. J. Hogan and M. J. Rees, *Phys. Lett. B* **205**, 228 (1988).
- [9] E. W. Kolb and I. I. Tkachev, *Phys. Rev. D* **49**, 5040 (1994).
- [10] E. W. Kolb and I. I. Tkachev, *Phys. Rev. Lett.* **71**, 3051 (1993).
- [11] I. I. Tkachev, *JETP Lett.* **101**, 1 (2015).
- [12] P. Tinyakov, I. Tkachev, and K. Zioutas, *J. Cosmol. Astropart. Phys.* **01** (2016) 035.
- [13] T. Hiramatsu, M. Kawasaki, K. Saikawa, and T. Sekiguchi, *J. Cosmol. Astropart. Phys.* **01** (2013) 001.
- [14] T. Hiramatsu, M. Kawasaki, K. Saikawa, and T. Sekiguchi, *Phys. Rev. D* **85**, 105020 (2012); **86**, 089902(E) (2012).
- [15] L. Fleury and G. D. Moore, *J. Cosmol. Astropart. Phys.* **01** (2016) 004.
- [16] V. B. Klaer and G. D. Moore, *J. Cosmol. Astropart. Phys.* **11** (2017) 049.
- [17] M. Gorghetto, E. Hardy, and G. Villadoro, *J. High Energy Phys.* **07** (2018) 151.
- [18] M. Buschmann, J. W. Foster, and B. R. Safdi, *Phys. Rev. Lett.* **124**, 161103 (2020).
- [19] M. Gorghetto, E. Hardy, and G. Villadoro, *SciPost Phys.* **10**, 050 (2021).
- [20] M. Buschmann, J. W. Foster, A. Hook, A. Peterson, D. E. Willcox, W. Zhang, and B. R. Safdi, *Nat. Commun.* **13**, 1049 (2022).
- [21] J. N. Benabou, M. Buschmann, J. W. Foster, and B. R. Safdi, *Phys. Rev. Lett.* **134**, 241003 (2025).
- [22] K. Saikawa, J. Redondo, A. Vaquero, and M. Kaltschmidt, *J. Cosmol. Astropart. Phys.* **10** (2024) 043.
- [23] M. Fairbairn, D. J. E. Marsh, J. Quevillon, and S. Rozier, *Phys. Rev. D* **97**, 083502 (2018).
- [24] J. Enander, A. Pargner, and T. Schwetz, *J. Cosmol. Astropart. Phys.* **12** (2017) 038.
- [25] A. Vaquero, J. Redondo, and J. Stadler, *J. Cosmol. Astropart. Phys.* **04** (2019) 012.
- [26] B. J. Kavanagh, T. D. P. Edwards, L. Visinelli, and C. Weniger, *Phys. Rev. D* **104**, 063038 (2021).
- [27] D. Ellis, D. J. E. Marsh, B. Eggemeier, J. Niemeyer, J. Redondo, and K. Dolag, *Phys. Rev. D* **106**, 103514 (2022).
- [28] N. Blinov, M. J. Dolan, and P. Draper, *Phys. Rev. D* **101**, 035002 (2020).
- [29] L. Visinelli and J. Redondo, *Phys. Rev. D* **101**, 023008 (2020).
- [30] E. Hardy, N. Sánchez González, H. Stubbs, and L. Tranchedone, *Phys. Rev. D* **113**, 115052 (2026).
- [31] J. W. Foster, N. L. Rodd, and B. R. Safdi, *Phys. Rev. D* **97**, 123006 (2018).
- [32] A. M. Green and S. P. Goodwin, *Mon. Not. R. Astron. Soc.* **375**, 1111 (2007).
- [33] T. D. P. Edwards, B. J. Kavanagh, L. Visinelli, and C. Weniger, *Phys. Rev. Lett.* **127**, 131103 (2021).
- [34] V. Dandoy, T. Schwetz, and E. Todarello, *J. Cosmol. Astropart. Phys.* **09** (2022) 081.
- [35] I. DSouza and C. Gordon, *Phys. Rev. D* **109**, 123035 (2024).
- [36] C. A. J. O'Hare and G. Pierobon, *J. Cosmol. Astropart. Phys.* **04** (2026) 039.
- [37] E. L. Sirks, K. A. Oman, A. Robertson, R. Massey, and C. Frenk, *Mon. Not. R. Astron. Soc.* **511**, 5927 (2022).
- [38] S. Collazo, M. F. Mestre, and C. R. Argüelles, *Astron. Astrophys.* **699**, A315 (2025).
- [39] A. Caputo and L. Teodori, *Phys. Rev. D* **114**, 063013 (2026).
- [40] P. Sikivie, *Phys. Rev. Lett.* **51**, 1415 (1983); **52**, 695(E) (1984).
- [41] P. Sikivie, *Phys. Rev. D* **32**, 2988 (1985); **36**, 974(E) (1987).
- [42] C. A. J. O'Hare and A. M. Green, *Phys. Rev. D* **95**, 063017 (2017).
- [43] C. A. J. O'Hare, G. Pierobon, and J. Redondo, *Phys. Rev. Lett.* **133**, 081001 (2024).
- [44] U. Bhura *et al.*, [arXiv:2603.13194](#).
- [45] M. Maroudas, T.-S. Cezar, A. Gardikiotis, and D. Horns, *J. Instrum.* **21**, P06036 (2026).
- [46] B. J. Kavanagh, [bradkav/axion-miniclusters: Pre-release version, Zenodo, 10.5281/zenodo.4006129](#) (2020).
- [47] L. Visinelli, AxionStreams: Numerical tools for transient axion streams from disrupted miniclusters, Zenodo, [10.5281/zenodo.22756132](#) (2026).
- [48] J. Barranco and A. Bernal, *Phys. Rev. D* **83**, 043525 (2011).
- [49] P. H. Chavanis and L. Delfini, *Phys. Rev. D* **84**, 043532 (2011).
- [50] L. Visinelli, S. Baum, J. Redondo, K. Freese, and F. Wilczek, *Phys. Lett. B* **777**, 64 (2018).
- [51] M. Gorghetto, E. Hardy, and G. Villadoro, *J. High Energy Phys.* **08** (2024) 126.
- [52] B. Eggemeier, C. A. J. O'Hare, G. Pierobon, J. Redondo, and Y. Y. Y. Wong, *Phys. Rev. D* **107**, 083510 (2023).
- [53] D. Alesini *et al.*, *Phys. Dark Universe* **42**, 101370 (2023).
- [54] S. J. Asztalos *et al.* (ADMX Collaboration), *Phys. Rev. D* **64**, 092003 (2001).
- [55] N. Du *et al.* (ADMX Collaboration), *Phys. Rev. Lett.* **120**, 151301 (2018).
- [56] C. Bartram *et al.* (ADMX Collaboration), *Rev. Sci. Instrum.* **94**, 044703 (2023).
- [57] A. T. Hipp *et al.* (ADMX Collaboration), *Phys. Rev. D* **112**, L101101 (2025).