Axion streams are not bound to stay

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Axion minicluster (AMC) formation

1. AMCs formation

Axion miniclusters form in the early Universe as a result of $\mathcal{O}(1)$ nonlinear density fluctuations leading to a gravitational collapse. AMCs can typically have mass in the range $M_{\rm mc} \sim 10^{-16}$–$10^{-10}\, M_\odot$ with density many orders of magnitude higher than the cosmological mean C. Hogan, M. Rees, Phys. Lett. B (1988); E. Kolb, I. Tkachev, Phys. Rev. D (1994).

2. Dynamical evolution

Stellar encounters of AMCs result in the formation of cold stream of tidally disrupted matter. We model disruption with a Monte Carlo description of encounters, and track the stripped material as a superposition of phase-space packets.

This allows us to test if the debris remains bound or it rapidly dilutes.

3. Haloscope relevance

We are particularly interested in the possibility for detection in haloscopes.

However, their density evolves quickly, impacting detectability.

The main question: Do streams from disrupted axion miniclusters persist long enough, and dense enough, to be observable in a resonant cavity experiment?

Physical scales

Minicluster properties

$$\rho_{\rm mc} = 140(1+\delta)\delta^3\rho_{\rm eq} \tag{1}$$

$$R_{\rm mc} = \left(\frac{3M_{\rm mc}}{4\pi\rho_{\rm mc}}\right)^{1/3}, \qquad \sigma_{\rm mc} \sim \left(\frac{GM_{\rm mc}}{R_{\rm mc}}\right)^{1/2} \tag{2}$$

Stellar encounter impulse

$$\Delta E \sim \frac{G^2M_\star^2}{b^4 v_{\rm rel}^2} M_{\rm mc}\langle r^2\rangle. \tag{3}$$

Notation:

- $\rho_{\rm mc}$, $M_{\rm mc}$, $R_{\rm mc}$: density, mass and radius of the AMC.
- δ: primordial overdensity fluctuation.
- $\sigma_{\rm mc}$: internal velocity scale.
- b: impact parameter.
- $v_{\rm rel}$: relative velocity between the AMC and the star.
- $M_\star$: mass of the star.

Two velocity widths after stripping

$$\mathrm{Tangential}: \ \sigma_{\rm t} \sim \left(\frac{\mathrm{GM_{enc}}}{\mathrm{r_{strip}}}\right)^{1/2}; \qquad \mathrm{Longitudinal}: \ \sigma_{\rm l}^2 \simeq \frac{2\mathrm{E_i}}{\mathrm{M_i}}, \tag{4}$$

where $M_{\rm enc}$ is the enclosed mass at some radius, M_i and E_i is the stripped mass and the change in the energy, respectively.

Stream production

The evolution of the debris can be understood in terms of the phase-space distribution function $f(\mathrm{x}, \mathrm{v}, t)$ satisfying the collisionless Boltzmann equation,

$$\frac{\partial f}{\partial t} + \mathrm{v} \cdot \nabla_{\mathrm{x}} f - \nabla_{\mathrm{x}} \Phi \cdot \nabla_{\mathrm{v}} f = 0, \tag{5}$$

where Φ is the gravitational potential. The source term is set by AMC–star encounters the rate of diffusion is

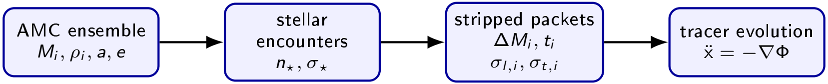
$$\Gamma_{\mathrm{diffuse}} = t_{\mathrm{vis}}^{-1}, \tag{6}$$

where t_{vis} is the visibility timescale. If the rates vary slowly, one obtains the steady-state abundance

$$\boxed{n_{\mathrm{stream}}(\mathrm{x}) \simeq \frac{n_{\mathrm{AMC}}(\mathrm{x})\, n_{\star}(\mathrm{x})\, \langle \sigma v \rangle(\mathrm{x})}{\Gamma_{\mathrm{diffuse}}(\mathrm{x})}} \tag{7}$$

Even though disruption is efficient, the large diffusion rate prevents the build-up of a significant stream population.

Numerical strategy



What is kept from each stripping event

Each encounter contributes a packet of debris with its own launch time, stripped mass, and anisotropic velocity width:

$$\{\Delta M_i,\ t_i,\ \sigma_{l,i},\ \sigma_{t,i}\}\,. \tag{8}$$

The stream is not treated as a single object, but as a superposition of phase-space packets.

What is computed after evolution

After evolving the tracers in the Galactic potential, we reconstruct

$$\rho(t), \qquad \gamma = \frac{d\log\rho}{d\log t}, \qquad \alpha = \frac{2E_{\rm kin}}{E_{\rm bind}}, \qquad t_{\rm vis}\,. \tag{9}$$

Coarse-grained estimator

The first estimate uses the principal axes of the tracer cloud:

$$\rho_{\mathrm{cg}}(t) \sim \frac{M_{\mathrm{stream}}}{V_{\mathrm{eff}}(t)}, \qquad V_{\mathrm{eff}} \sim \lambda_1\lambda_2\lambda_3. \tag{10}$$

It measures the global geometric dilution of the debris as the stream stretches and broadens.

Local estimator

The second estimate uses nearest-neighbor distances:

$$\rho_{\mathrm{loc}}(t) \sim \frac{m}{V_k}, \qquad V_k \sim r_k^3. \tag{11}$$

It is sensitive to local overdensities, residual clustering, and the density that a detector would sample when crossing the stream.

For ballistic expansion, $l_s \sim \sigma_l t, \qquad R_s \sim \sigma_t t, \qquad \rho(t) \sim \frac{M_{\mathrm{stream}}}{\pi R_s^2 l_s} \propto t^{-3}.$
Deviations from t^{-3} indicate ongoing perturbations, while convergence to this scaling identifies the free-streaming regime.

Bound or unbound?

Kinetic support versus self-gravity

$$E_{\mathrm{kin}} \sim \frac{1}{2}\left(\sigma_l^2 + 2\sigma_t^2\right), \qquad E_{\mathrm{bind}} \sim \frac{GM_{\mathrm{stream}}}{R_{\mathrm{char}}} \tag{12}$$

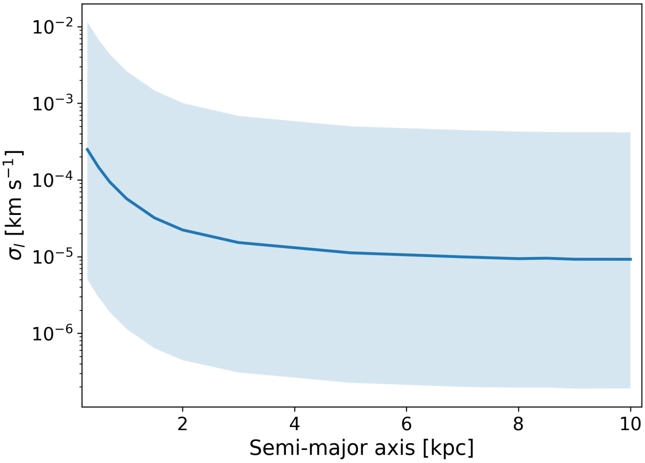
$$\boxed{\alpha \equiv \frac{2E_{\mathrm{kin}}}{E_{\mathrm{bind}}}} \tag{13}$$

- $\alpha \lesssim 1$: self-gravity can matter.
- $\alpha \gg 1$: debris is super-virial and expands.

Physical intuition

The velocity scale is inherited from the progenitor potential, while the self-gravity belongs only to the stripped fraction.

Result I: the debris is extremely cold



What the figure says

Inner-halo encounters generate the largest longitudinal dispersions, σ_l.

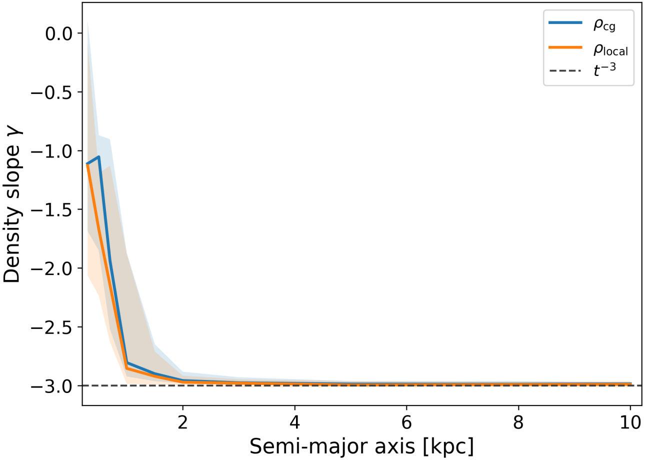
At larger radii, σ_l decreases and approaches $\sim 10^{-5}\,\mathrm{km\,s^{-1}}$.

The transverse scale remains $\sigma_t \sim 10^{-4}\,\mathrm{km\,s^{-1}}$, typically comparable to or larger than σ_l.

For a cavity

These velocity scales imply spectral line widths many orders of magnitude narrower than the expected standard halo signal.

Result II: dilution approaches free streaming outside the inner halo

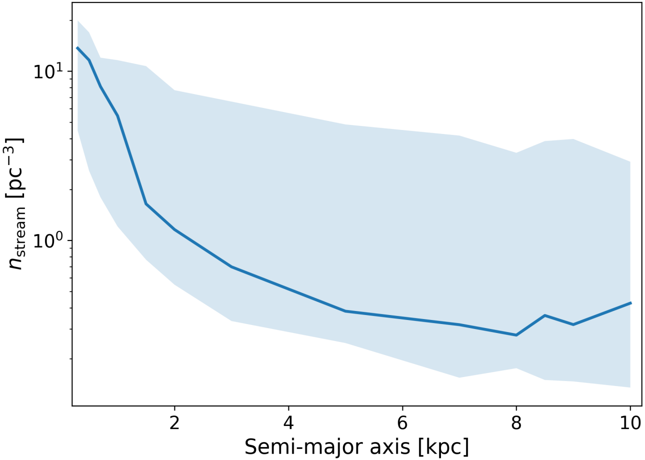


Measured slope

$$\gamma \equiv \frac{d \log \rho}{d \log t} \qquad (14)$$

- Inner halo: shallower than -3 because perturbations and orbital effects remain important.
- Beyond $a \sim 2\,\mathrm{kpc}$: $\gamma \simeq -3$ for both density estimators.
- The t^{-3} behavior is not imposed; it emerges dynamically.

Result III: steady-state stream abundance is suppressed



Effective population balance

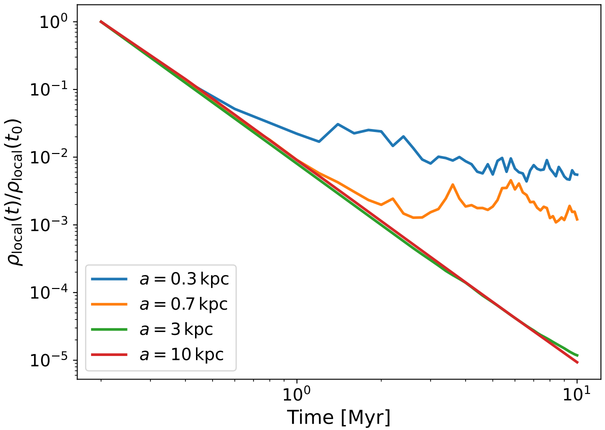
$$n_{\rm stream} \simeq \frac{S}{\Gamma_{\rm diffuse}}, \qquad \Gamma_{\rm diffuse} = t_{\rm vis}^{-1} \tag{15}$$

The production rate increases toward the inner halo, where stellar encounters are more frequent.

However, the visibility time is short because the stream density dilutes rapidly.

At the Solar radius, the resulting steady-state abundance is strongly suppressed.

Result IV: stream density evolution



Effective population balance

$$n_{\rm stream} \simeq \frac{S}{\Gamma_{\rm diffuse}}, \qquad \Gamma_{\rm diffuse} = t_{\rm vis}^{-1} \tag{16}$$

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Haloscope observables

Frequency mapping

$$\nu \simeq \nu_a \left(1 + \frac{v^2}{2c^2}\right), \qquad \frac{\Delta\nu}{\nu_a} \sim \frac{\sigma_v^2}{c^2} \tag{17}$$

The cavity directly maps the velocity distribution into frequency space.

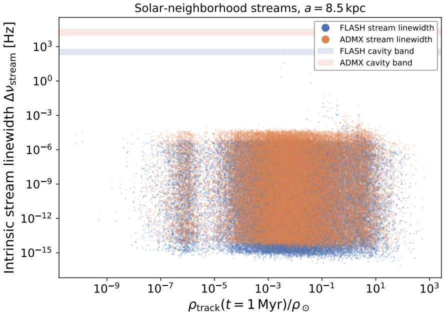
For the velocity scales of disrupted miniclusters,

$$\sigma_v \sim 10^{-5} - 10^{-3}\,\mathrm{km\,s^{-1}}, \tag{18}$$

one finds $\Delta\nu/\nu_a \sim 10^{-16} - 10^{-12}$.
At $\nu_a \sim 10\,\mathrm{GHz}$, this corresponds to

$$\Delta\nu \sim 10^{-6} - 10^{-2}\,\mathrm{Hz}, \tag{19}$$

far narrower than the standard halo signal.



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

Haloscope observables

Daily and annual frequency shifts

The bulk stream velocity is set by Galactic motion,

$$v_{\rm rel} \sim 10^2\,{\rm km\,s^{-1}}. \tag{20}$$

The observed frequency is modulated by the Earth's motion,

$$\frac{\delta\nu}{\nu_a} \sim \frac{v_\oplus v_{\rm rel}}{c^2}, \tag{21}$$

giving daily: $\sim 10^{-12}$, annual: $\sim 10^{-10}$. These shifts are comparable to those of the smooth halo component.

Frequency drift

A distinctive feature is the slow frequency drift induced by relative acceleration,

$$\dot{\nu} \sim \nu_a \frac{v_{\rm rel}}{c^2}\,\dot{v}. \tag{22}$$

For GHz-scale axion masses,

$$\dot{\nu} \sim 10^{-6} - 10^{-3}\,{\rm Hz\,day^{-1}}. \tag{23}$$

The drift is controlled by the detector–stream relative motion, not by the internal velocity dispersion.

Halscope observables

Signal amplitude

$$P_{\rm sig} \propto \rho_a \tag{24}$$

A stream line is useful only if

$$\rho_{\rm stream}/\rho_{\rm loc} \tag{25}$$

is large enough during the integration.

Encounter probability

$$P_{\rm encounter} \sim n_{\rm stream}\, \pi R_s^2\, v_{\rm rel}\, T_{\rm exp}, \qquad R_s \sim \sigma_t t_{\rm vis}. \tag{26}$$

Experimental message

Searches should not assume a stationary background of streams. The relevant target is a rare, high-coherence, time-localized feature.

- Narrow bins help.
- Drift tracking helps.
- Repeated confirmation in time is essential.

Emerging picture

Persistent-stream assumption

- Disrupted AMCs build a long-lived stream population.
- Streams can contribute significantly to local phase space.
- Detection searches can treat streams as quasi-static components.

This work

- Debris is cold but usually super-virial.
- Density dilution is fast, often close to t^{-3}.
- Detectable streams are rare transient features, not a generic background.

Production is continuous, but accumulation is inefficient.

Conclusions

1. Stellar encounters can strip axion miniclusters and produce very cold debris.
2. The debris is generically super-virial: $\alpha = 2E_{\mathrm{kin}}/E_{\mathrm{bind}} \gg 1$.
3. Stream densities dilute rapidly; $\rho \propto t^{-3}$ emerges outside the inner halo.
4. The steady-state contribution of streams to local dark matter is strongly suppressed.
5. For haloscopes: possible signatures are narrow, drifting, transient lines from rare nearby events.
6. At the Solar radius, only a fraction of order 10^{-4} of the realizations yields a nonzero encounter probability, with a nonzero-realization median $P_{\mathrm{enc}} \sim 10^{-11}$ and an upper tail reaching $P_{\mathrm{enc}} \sim 10^{-6}$.
7. Future research direction can be higher resolution N-body simulation, more realistic Galactic potential, as well as incorporating the wave nature of axions in the stream dynamics.

Axion streams are born cold, but they are not bound to stay.