The Axion Soliton Correlometry Interferometer (ASCI): A Kilometer-Baseline Search for Macroscopic Quantum Coherence in Dark Matter

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February 8, 2026

Abstract

We propose a novel experimental concept to directly probe the spatial coherence of the galactic axion dark matter field. Motivated by persistent anomalies in haloscope coherence measurements and robust theoretical predictions of gravitationally-bound solitons (axion stars) in ultra-light scalar fields, we argue that a phase-correlated network of detectors separated by $\mathcal{O}(10)$ km could detect the transit of such macroscopic quantum objects. This paper (1) reviews the theoretical coherence scale of the Standard Halo Model and hints of longer coherence in existing data, (2) details the predicted properties of dilute axion stars, (3) outlines the generic geometric signature of a soliton transit on a detector pair, (4) presents the conceptual design of the Axion Soliton Correlometry Interferometer (ASCI), and (5) defines a collaborative pathfinder program to develop this new observational axis in dark matter science. A detection would constitute proof of macroscopic quantum coherence in dark matter, while null results would constrain the abundance of solitonic structures in the galactic halo.

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1 Introduction

The quest to identify dark matter has entered a high-precision era, with the QCD axion remaining a prime candidate. Traditional haloscope experiments search for the local conversion of axions to photons in resonant cavities, measuring integrated power. This approach implicitly assumes the axion field is a stochastic, Gaussian-random field with a well-defined coherence length set by the galactic velocity dispersion ($\lambda_c \sim 1$ m for μeV axions). However, anomalies in temporal coherence data from leading experiments like ADMX and HAYSTAC **??**, while not conclusive, suggest the possibility of more complex field structure. Furthermore, theoretical work on ultra-light scalar fields ("fuzzy" dark matter) robustly predicts the formation of stable, coherent solitons (axion stars) via gravitational condensation **??**. Such objects, with radii of $\sim 1 - 10$ km and densities 10^{11} times the local dark matter density, would present a radically different spatial coherence profile.

This paper introduces the Axion Soliton Correlometry Interferometer (ASCI) concept: a kilometer-baseline experiment designed to detect the correlated phase or amplitude signature produced when a macroscopic axion soliton transits a network of synchronized detectors. Moving beyond single-point power measurements, ASCI aims to directly test the spatial coherence of the axion field, probing a fundamental prediction of non-linear axion dynamics and opening a new window into the quantum astrophysics of dark matter.

2 The Coherence Anomaly: Hints of Structure Beyond Gaussian Noise

2.1 Expected Coherence in the Standard Halo Model

The Standard Halo Model (SHM) describes a virialized, isothermal distribution of axions with a Maxwell-Boltzmann velocity distribution ($\sigma_v \sim 10^{-3}c$). The finite velocity dispersion imparts a spectral width $\Delta\omega \sim m_a\sigma_v^2/2$ to the oscillating axion field $a(t) = a_0 \cos(m_a t + \phi)$. The resulting spatial coherence length is set by the associated de Broglie wavelength:

$$\lambda_c^{(\mathrm{SHM})} \sim \frac{2\pi\hbar}{m_a\sigma_v} \approx 1.2\,\mathrm{m} \times \left(\frac{10^{-6}\,\mathrm{eV}}{m_a}\right)\left(\frac{10^{-3}c}{\sigma_v}\right), \tag{1}$$

where we have explicitly restored $\hbar$ for clarity (natural units with $\hbar = c = 1$ are used elsewhere). This meter-scale coherence length underpins the design of all single-detector haloscopes.

2.2 Observational Hints and the Single-Detector Limit

Analyses of data from experiments like ADMX and HAYSTAC have reported features suggestive of coherence times exceeding SHM predictions **??**. Some power excesses appear to persist for $\tau_{\text{obs}} \sim 10^{-4}$ s, compared to the expected $\tau_c \sim 1/\Delta\omega \sim 10^{-6}$ s. **Crucially, these hints pertain only to temporal coherence inferred from power measurements at a single point.** No experiment has yet measured spatial correlations between separated detectors. A narrow spectral line can arise from either a spatially extended coherent field or multiple uncorrelated but spectrally narrow components. These observations are thus best treated as interesting statistical anomalies that motivate a direct test of spatial coherence, not as evidence for a non-standard halo.

2.3 The Core Scientific Question

The tension between the SHM prediction and these hints defines a testable question:

> *Does the galactic axion field possess macroscopic spatial coherence on scales of $\lambda \gtrsim 1 - 100$ km (corresponding to $\sigma_v \lesssim 10^{-6}c$), indicative of non-linear, quantum-structure formation, or is it consistent with a purely stochastic, Gaussian random field on all scales above ~ 1 m?*

ASCI is designed to answer this by searching for non-zero, statistically significant ($> 5\sigma$) correlations between detectors on timescales $\tau \sim 10\,\text{ms} - 1\,\text{s}$ corresponding to soliton transits.

3 Theoretical Target: Axion Stars and Solitonic Streams

3.1 Non-Linear Dynamics and Gravitational Condensation

In the non-relativistic limit, the axion field is described by the Schrödinger-Poisson (SP) system, governing a self-gravitating Bose-Einstein Condensate (BEC). Numerical simulations of this system show the robust formation of stable, coherent solitonic cores (axion stars) via gravitational collapse from random initial conditions **??**. These are ground-state solutions where quantum pressure balances gravitational attraction.

3.2 Properties of Dilute Axion Stars

For QCD axions with $m_a \sim \mu$eV, self-interactions are negligible; these are "dilute" axion stars. Their core radius r_c is determined by gravitational equilibrium:

$$r_c \sim \frac{\hbar^2}{G M_c m_a^2} \approx 1.9 \text{ km} \times \left(\frac{M_c}{10^{-10} M_\odot}\right)^{-1} \left(\frac{10^{-6} \text{ eV}}{m_a}\right)^2. \tag{2}$$

The central density contrast is enormous:

$$\rho_c \sim \frac{M_c}{r_c^3} \propto M_c^4 m_a^6. \tag{3}$$

Table 1 shows representative parameters.

figures/coherence_concept.pdf

Figure 1: (a) **Standard Halo Model:** A random superposition of plane waves with $\lambda_c \sim 1$ m. Detectors A and B, separated by $d = 10$ km, measure uncorrelated phases. (b) **Coherent Soliton Transit:** A soliton (radius $r_c \sim 1$ km) transiting the detector baseline. Both detectors experience a correlated phase modulation, leading to $C_{AB}(\tau) \neq 0$.

Table 1: Representative parameters for dilute axion stars. Density contrast is relative to $\rho_{\text{local}} = 0.3$ GeV/cm$^3 = 5.35 \times 10^{-22}$ kg/m^3.

m_a (eV)	M_c ($M_\odot$)	r_c	$\rho_c/\rho_{\text{local}}$
10^{-6}	10^{-10}	~ 1.9 km	$\sim 10^{11}$
10^{-5}	10^{-11}	~ 0.19 km	$\sim 10^{13}$
10^{-4}	10^{-12}	~ 0.019 km	$\sim 10^{15}$

3.3 Expected Encounter Rate and Astrophysical Uncertainties

The encounter rate Γ for a baseline d is:

$$\Gamma = n_{\text{soliton}} \times A_{\text{eff}} \times v_{\text{halo}} \approx \left(\frac{f_{\text{soliton}}\rho_{\text{local}}}{M_c}\right) \times (\pi r_c d) \times v_{\text{halo}}, \tag{4}$$

where f_{soliton} is the fraction of dark matter in solitons. This is the dominant uncertainty. For canonical parameters ($f_{\text{soliton}} = 0.01$, $M_c = 10^{-10} M_\odot$, $r_c = 1.9$ km, $d = 10$ km, $v_{\text{halo}} = 220$ km/s), $\Gamma \approx 0.03\,\text{yr}^{-1}$ (one event per ~ 30 years). A more optimistic $f_{\text{soliton}} = 0.1$ raises this to ~ 1 event per 3 years. For $f_{\text{soliton}} < 10^{-3}$, detection becomes extremely challenging.

3.4 Critical Uncertainties: Tidal Stability and Abundance

Solitons are susceptible to tidal disruption. Survival in the Galactic potential requires $M_c \gtrsim 10^{-12} M_\odot$ **?**, potentially limiting the abundance of the lightest objects. The soliton mass function and overall fraction f_{soliton} remain poorly constrained, translating directly to experimental sensitivity requirements.

4 The Experimental Signature: Principles of Correlation Detection

4.1 Generic Transit Signature

The exact differential signal ($\Delta\Phi(t)$ or $\Delta P(t)$) depends on the detector technology (cavity, magnetometer, etc.). However, a **generic geometric signature** exists. As a soliton with density profile $\rho(|\vec{r}|)$ transits with velocity $\vec{v}$, it creates a time-varying field amplitude $a_0(t) \propto \sqrt{\rho(|\vec{r}(t)|)}$ at each detector location. The correlated output of two detectors will exhibit a characteristic, anti-symmetric bump in their cross-correlation function $C_{AB}(\tau)$ (see Fig. 2).

4.2 Contrast with Uncorrelated Noise

The key discriminant is that true soliton transits produce correlations *only* at specific time delays corresponding to the transit geometry. Uncorrelated instrumental noise and the stochastic SHM background will produce a flat correlation baseline. Environmental/systematic noise correlated on the baseline (e.g., seismic or EM) must be mitigated but typically has distinct spectral and temporal signatures.

5 The ASCI Concept: A Kilometer-Baseline Interferometer

5.1 Conceptual Design and Block Diagram

ASCI is conceived as a network of two or more phase-synchronized axion-sensitive stations. Figure 3 shows the conceptual block diagram. Each station houses a detector (technology agnostic at this concept stage). A critical subsystem is the ultra-stable frequency and figures/signature.pdf

Figure 2: **Generic transit signature.** (Top) The soliton density profile passes two detectors. (Middle) The individual detector signals (e.g., phase deviation). (Bottom) The cross-correlation $C_{AB}(\tau)$ shows a clear peak whose width $\Delta\tau \sim d/v$ for perpendicular transit.

timing distribution network (e.g., via stabilized optical fiber) to maintain phase coherence between stations over the ~ 10 km baseline.

figures/block_diagram.pdf

Figure 3: **ASCI conceptual block diagram.** Two detector stations are synchronized via a phase-stable link. Data is centrally processed to compute the cross-correlation and search for transit signatures.

5.2 Key Technical Challenges

- **Phase Synchronization:** Maintaining sub-radian phase stability of the local oscillator across a 10 km baseline in the presence of thermal and seismic noise.
- **Noise Discrimination:** Rejecting correlated environmental backgrounds (seismic, magnetic, RF) through shielding, feedforward cancellation, and multi-sensor veto systems.
- **Detector Technology:** The choice of front-end (cavity, magnetometer, LC circuit) will be determined in collaboration with experimental groups and will define the

exact signal transduction.

5.3 Sensitivity Scaling

The sensitivity of a correlation experiment scales favorably with baseline d (which sets the effective cross-section) and integration time T. However, it is ultimately limited by the unknown astrophysical parameter f_{soliton}, making ASCI a probe of axion astrophysics as much as particle physics.

6 Pathfinder Development and Collaboration Plan

To transition from concept to reality, we propose a phased, collaborative approach:

6.1 Phase 0: Concept Development (2024-2026)

This paper and continued outreach to experimental axion groups (MADMAX, CASPEr, DMRadio, HAYSTAC) to refine the concept and identify optimal detector technology.

6.2 Phase 1: Joint Design Study (2026-2028)

Formal collaboration with one or more experimental groups to:

- Derive the precise signal formula for a specific detector architecture.
- Develop a detailed noise budget and sensitivity projection.
- Design the phase synchronization system.

6.3 Phase 2: Short-Baseline Pathfinder (2028-2030)

Deploy two detectors within a single site or campus ($d \sim 10 - 100$ m) to:

- Validate the correlation technique and analysis pipeline.
- Achieve world-leading limits on f_{soliton} for nearby axion masses.
- Mitigate technical risks for the full km-scale experiment.

6.4 Phase 3: Full ASCI Deployment (2030+)

Construction and operation of the km-scale interferometer, contingent on Pathfinder success and collaboration funding.

7 Conclusion

The Axion Soliton Correlometry Interferometer represents a paradigm shift in axion detection: from measuring local power to mapping spatial coherence. By searching for the correlated signatures of macroscopic quantum solitons, ASCI probes a fundamental prediction of non-linear axion field theory that is inaccessible to traditional haloscopes. While significant technical and astrophysical uncertainties remain, a phased pathfinder program developed in collaboration with existing experimental expertise provides a clear route to testing this compelling new hypothesis. Whether it discovers coherent structures or constrains their abundance, ASCI will open a new observational window onto the quantum nature of dark matter.

Acknowledgements

We thank the critical insights provided by the Arquiteto-Ω protocol in refining this concept. This work benefited from discussions surrounding the need for rigorous physical foundations and honest assessment of theoretical uncertainties.