

# Direct detection of cosmic walls with paleodetectors

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Paleo detectors are emerging dark matter detection technology that exploits ancient minerals as passive, time-integrated detectors. Unlike conventional real-time experiments, they search for permanent damage tracks—typically tens of nanometers to micrometers long—left in crystal lattices by rare particle interactions, most notably dark matter induced nuclear recoils accumulated over millions to billions of years. In this paper I propose a direct detection strategy for cosmic walls—either bubble walls produced by a late-time first-order phase transition or domain walls in a scaling regime—using paleo detectors as the target medium. Because the cosmic wall is expected to traverse Earth at most  $\mathcal{O}(1)$  time(s) in cosmic history, an ancient, continuously exposed detector is the only feasible way to observe it directly. By calculating the target recoils, I find that the smoking-gun signature would be parallel damage tracks found worldwide in minerals older than the wall-crossing epoch. I derive the limit on the wall-target coupling by assuming that a wall passed through the Earth within the last 0.5 Gyr. I also mention a novel indirect detection of ultrarelativistic cosmic walls by noting the induced cosmic rays.

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## I. INTRODUCTION

Recent years have seen growing interest in the use of paleo detectors [1–5], ancient natural minerals that serve as passive, long-duration solid state nuclear track detectors, offering a novel approach complementary to conventional real-time experiments for dark matter or neutrinos. Nuclear recoils induced by them leave damage tracks in the crystal lattice of insulating minerals, which can survive over geological timescales of hundreds of millions to billions of years. These tracks, typically nanometer- to micrometer-scale in length, can now be imaged with techniques such as small angle x-ray scattering, helium ion microscopy, or atomic force microscopy.

Because of their extremely long integration times and the directional information encoded in track morphology, paleo detectors are sensitive to rare interactions involving sub-GeV to multi-TeV dark matter and other nonstandard scenarios. Their natural shielding from cosmic rays and very low intrinsic radioactivity also make them ideal for ultralow-background searches. Feasibility studies with minerals such as muscovite, olivine, halite, and apatite have been reported and discussed in Refs. [4,6–8]. Although challenges remain—chiefly high-resolution, high-throughput read-out,

track-energy calibration, and radiogenic-background modeling—ongoing research and development indicates that paleo detectors could substantially extend our reach for elusive dark matter signals and other cosmological relics.

Bubble walls and domain walls, on the other hand, may survive into the late-time Universe. A first-order phase transition (FOPT) occurs in extensions of the Standard Model: bubbles nucleate by quantum tunneling, their walls expand, and eventually collide to complete the transition. Domain walls arise as topological defects in scenarios with degenerate vacua; once produced, the walls enter a scaling regime with  $\mathcal{O}(1)$  wall per Hubble horizon at each epoch. I refer to both kinds of defects collectively as cosmic walls.

Several ideas motivate such walls in the late-time Universe. For example, modest variations in the electron mass or the fine-structure constant, possibly generated by a late FOPT, can improve fits to cosmological data and alleviate existing tensions [9,10]. Axionlike-particle domain walls provide a natural explanation for the  $\sim 4\sigma$  cosmic birefringence signal [11,12].

Because a wall is expected to cross Earth at most  $\mathcal{O}(1)$  time over cosmic history, searches usually focus on indirect signatures, i.e., indirect detection in the dark matter terminology,—cosmic birefringence [11–15], gravitational waves from wall collapse (see, e.g., the recent nanoGrav explanation [16–25]), or gravitational effects on the cosmic microwave background [26–28]. Direct detections are rarer to be studied; the GNOME magnetometer network [29–32], for instance, targets models with domain wall densities much larger than the scaling prediction [33–35].

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In this paper, I propose using paleo detectors to perform a direct detection search for cosmic walls. I compute the recoils induced when a wall passes through a mineral in the weak-coupling limit and show that even very feebly interacting scenarios can already be constrained. Since a wall crossing would occur at most once in the entire cosmic history, an ancient, continuously exposed detector provides the only realistic means of observing it directly. As a direct detection method for cosmic walls, this proposal offers one of the widest and most general detection reaches among existing approaches.

## II. RECOILS FROM COSMIC WALLS

Before discussing specific wall-formation scenarios, I first outline how a cosmic wall interacts with scatterers inside a paleo detector. For concreteness, assume that the wall field  $\phi$  couples to a Dirac fermion  $N$ —which can be a nucleon, a fermionic atomic nucleus, or an electron—through

$$\mathcal{L}_{\text{int}} = -f(\phi)\bar{N}N, \quad (1)$$

where  $f$  is a generic function to be specified later. Such a coupling can be UV-completed, for example, if  $\phi$  mixes with the Standard-Model Higgs via a portal interaction [36]. Assuming  $\phi$  couples to the fundamental nucleon universally with  $f_n(\phi)\bar{n}n$ , I expect  $f(\phi) \simeq Af_n$  with  $A$  being the mass number of the nucleus because of the mass scaling. From the similar reason, when the nucleus is a boson, mass also scales with  $A$ , and we get a similar coupling. When the recoil nuclei is nonrelativistic, the result does not change as shown in the Appendix A.

Expand the field around its vacuum value  $\langle\phi\rangle = v$  by writing  $\phi = v + s/\sqrt{2}$ , the fluctuation  $s$  acquires a Yukawa interaction  $y = f'(v)$ ; existing constraints require  $y \ll 1$  (see, e.g., [37]). Here  $f'$  denotes the derivative of  $f(\phi)$  with respect to  $s$ . From this reason and to simplify the discussion, I consider the mass shift of  $N$  is negligible and I ignore it throughout the paper (see the Appendix B for a justification of this point, as well as for constraints from astrophysical and cosmological considerations).

I assume that the wall at rest has a characteristic width  $1/m_\phi$ , where  $m_\phi$  is the scalar mass. A convenient smooth profile is  $\phi(z) = v \frac{1 - \tanh(m_\phi z)}{2}$ , which I assume throughout the paper, but any smooth choice gives the same qualitative behavior. I orient the  $z$ -axis along the wall's motion through Earth and denote the wall velocity in the Earth frame by  $\beta_w$ , (the Lorentz factor is  $\gamma_w \equiv (1 - \beta_w^2)^{-1/2}$ ) which I take to be comparable to or larger than the typical velocity of  $N$ . Over the detector scale the wall is treated as perfectly planar, so its curvature is neglected.

For a wall to survive well after recombination epoch of the thermal history I impose the condition that solves the “domain wall problem”  $\gamma_w v^2 m_\phi \lesssim \text{MeV}^3$ , as in

Refs. [26,27], i.e., the wall's gravitational field does not spoil astrophysical and cosmological observations (see also the Appendix B).

A perturbative bound follows from the self-coupling of the scalar:  $m_\phi \lesssim v$ . One needs a potential barrier in the interval  $(0, v)$ , and the curvature of the potential must change by  $\mathcal{O}(m_\phi^2)$  within this interval. If  $m_\phi$  exceeds  $v$ , the higher derivatives of the potential, and hence the self-couplings, are forced to exceed unity in units of  $m_\phi$ . Combining the two bounds gives<sup>1</sup>

$$m_\phi \lesssim 1 \text{ MeV}. \quad (2)$$

In the wall frame,  $N$ , which is at rest in Earth, moves with velocity  $-\beta_w$ , giving a longitudinal momentum

$$|p_z^w| \simeq \gamma_w \beta_w m_N. \quad (3)$$

Because  $|p_z^w| \gtrsim \text{MeV}$ , for electron, nucleon, or nuclei, and the wall width is  $1/m_\phi > 1 \text{ MeV}^{-1}$ , the system is in the thick-wall limit  $2\pi/|p_z| \ll 1/m_\phi$ . In this limit the wall can be treated as a background field following a WKB approximation and reaction rates can be estimated from perturbation theory, following well-established techniques developed for expanding bubble walls in the early Universe, such as the study of wall friction [38–42], dark matter productions, [42–47], and particle production for baryogenesis [46,48–50]. In particular, particle production via the higher dimensional term from the interaction with the wall was studied in [42].

The elastic process  $N \rightarrow N$  produces practically no recoil in  $N$ . This is because the system, with the wall background in the wall frame, respects energy conservation and momentum conservation in the  $x$ - and  $y$ -directions. Although the momentum conservation in the  $z$ -direction is violated, since the tiny mass shift induced by Eq. (1) is negligible, the three conserved quantities together with the dispersion relation constrain the final state momentum—including its  $z$ -component—to coincide with that of the initial state. Thus, the net change in  $p_z$  vanishes.<sup>2</sup>

<sup>1</sup>If this limit is relaxed in specific model constructions, the thin-wall regime,  $2\pi/|p_z| \gg 1/m_\phi$  may be allowed. Then the wall can reflect  $N$  with probability  $\simeq \frac{1}{4} |\Delta m_N m_N / (p_z^w)^2|^2$ , giving reflected momentum  $2p_z^w$  from the simple discussions on the boundary conditions. Here  $\Delta m_N$  is the tiny mass difference of  $N$  before and after the wall passage. For  $p_z^w \sim 100 \text{ MeV}$  one needs  $\Delta m_N \gtrsim 7 \times 10^{-14} \text{ GeV}$  to obtain more than  $\mathcal{O}(10)$  tracks for  $N = 10^{24}$  targets.

<sup>2</sup>If one evades the scalar constraints, a large shift in  $m_N$  could in principle reflect the low-momentum mode of  $N$  in the wall frame. For instance, a domain wall whose interior gives  $N$  a much larger mass allows passage via tunneling; the reflected component would then impact the detector in the region where tunneling dominates. Such a scenario might be relevant to certain cosmic tensions and to models of cosmic birefringence, but its detailed study is left for future work.

The leading inelastic channel is therefore

$$N(p_i) \rightarrow N(p_f)s(p_\phi), \quad (4)$$

where, in the wall frame,  $p_i = \{p_i^0, 0, 0, p_i^z\}$ ,  $p_f = \{p_i^0(1-x), p_\perp, 0, p_f^z\}$ ,  $p_\phi = \{p_i^0x, -p_\perp, 0, p_\phi^z\}$ . Without loss of generality the transverse momentum  $p_\perp$  is chosen along the  $x$ -axis. Defining  $\Delta p_z = p_f^z + p_\phi^z - p_i^z = \sqrt{p_0^2(1-x)^2 - p_\perp^2 - m_N^2} + \sqrt{p_0^2x^2 - p_\perp^2 - m_\phi^2} - \sqrt{p_0^2 - m_N^2}$ , the transition probability is [42]

$$\begin{aligned} P_{N \rightarrow N\phi} &= \frac{1}{2} \sum_{\text{spins}} \int \frac{d^3 p_f d^3 p_\phi}{(2\pi)^3 2p_f^0 2p_\phi^0 2p_i^0} \\ &\quad \times \delta^{(3)}(p_f + p_\phi - p_i) |F|^2 \frac{|\mathcal{M}|^2}{|\Delta p_z|^2} \\ &= \frac{1}{2} \sum_{\text{spins}} \int \frac{dx}{8p_f^z p_\phi^z} \int \frac{dp_\perp^2}{8\pi^2} \frac{|\mathcal{M}|^2}{(\Delta p_z)^2} |F|^2, \end{aligned} \quad (5)$$

where the squared matrix element from the  $s\bar{N}N$  vertex is  $\sum_{\text{spins}} |\mathcal{M}|^2 = 4(p_f \cdot p_i + m_N^2)$ . The filtering function

$$F = \int dz e^{i\Delta p_z z} \partial_z f'(\langle \phi(z) \rangle) \quad (6)$$

controls the allowed violation of  $p_z$  conservation. There are two useful limits irrelevant to the detail form of  $F$  and wall profile,

$$F \longrightarrow \begin{cases} 0, & \text{if } |\Delta p_z| \gg m_\phi, \\ f'(v) - f'(0), & \text{if } |\Delta p_z| \ll m_\phi. \end{cases} \quad (7)$$

### A. Bubble walls from late-time FOPT

The first class of cosmic walls of interest is *bubble walls*. Consider a FOPT that completes after the minerals acting as paleo detectors were formed. Bubbles nucleate in the false vacuum; their boundaries are energetic walls, which accelerate until they reach a terminal Lorentz factor  $\gamma_w$  set by balance between the driving force from the difference of vacuum energy and friction due to ambient particles. Subsequent bubble collisions fill the Universe with the true vacuum.

With probability  $\mathcal{O}(1)$  a wall intersects a given mineral sample at speed  $\gamma_w$ . Because the wall size is macroscopic compared with the sample, curvature can be neglected and the formalism of the previous section applies. Momentum transfer to nucleons, nuclei or electrons then leaves charged tracks in the mineral. For this scenario I adopt

$$f(\phi) = \frac{|\phi|^2}{M}, \quad (8)$$

assuming that  $\phi$  carries a charge under a symmetry not shared by  $N$ . This yields a position-dependent effective Yukawa coupling  $f'(\phi) \propto \phi/M$ .

$F \simeq \sqrt{2}v/M$  in the  $|\Delta p_z| \ll m_\phi$  limit of Eq. (7). Substituting this constant and integrating over  $x$  and  $p_\perp^2$  in the region  $|\Delta p_z| < m_\phi$  give the production probability shown in the top panel of Fig. 1. The curves correspond to  $m_\phi = (10^{-8} - 10^{-2})m_N$  (top to bottom) and  $P_{N \rightarrow N\phi}$  is  $(0.1 - 1)(\frac{v}{M})^2$  in most of parameter region, while it is suppressed with  $\beta_w \ll 1$ .

Although we may have some relevant constraint, e.g., from fifth-force, on the Yukawa interaction  $f'(v)$ , this can be easily evaded, see Ref. [51] for a concrete symmetry-restoring model, where  $f'(v) - f'(0) \neq 0$ ,  $f'(v) = 0$ , and the associated bubble velocities. Also multifield models with almost degenerate vacua can achieve an enhanced bubble nucleation even for heavy  $m_\phi$ , e.g., [52].

### B. Scaling domain walls

A second class of cosmic walls consists of *domain walls*. They appear after a  $Z_2$  phase transition—first-order, second-order or cross-over—in which different Hubble patches settle into degenerate vacua separated by a potential barrier [27,53,54]; see also [55] for variants without explicit symmetry restoration. Analogous walls also arise for axion fields without a  $Z_2$  symmetry when large inflationary fluctuations drive neighboring patches to field values that differ by  $v$ , the periodicity scale [56,57]. In both cases, the

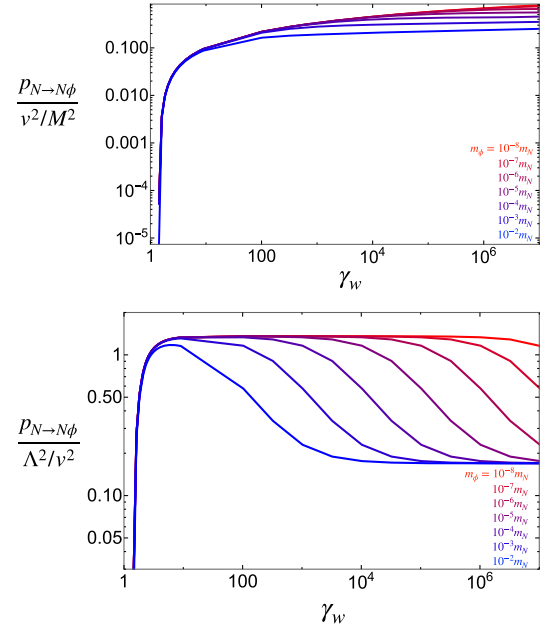


FIG. 1. The transition probability for  $N \rightarrow N\phi$  by varying the wall Lorentz factor. The top (bottom) panel is for the bubble wall (domain wall) scenario. Here I choose  $m_\phi = \{10^{-8} \dots 10^{-2}\}m_N$  from top to bottom.

field evolves toward the vacua in the early Universe and forms the walls.

After formation, the network approaches a scaling solution with  $\mathcal{O}(1)$  wall per Hubble volume at all times. Thus, the fraction of the Universe scanned by domain walls at any given time after formation is  $\frac{C d\beta_w H^{-2}}{H^{-3}}$ , where  $C$  is an  $\mathcal{O}(1)$  numerical factor, which can be determined by numerical simulations after fixing the model and formation mechanism. This expression also gives the probability that a given spatial coordinate is scanned by a domain wall. The probability that the coordinate is not scanned by the domain wall is then  $P = \exp[-\int dt C \beta_w H] = (1/(1+z_i))^{\beta_w C}$ , where  $z_i$  is the initial redshift relevant to the problem (e.g., the time of the mineral's formation). Therefore, if the mineral is formed about a Gyr ago (i.e.,  $z_i \sim 0.1$ ), the probability that the domain wall passes through it is approximately  $\sim \frac{\beta_w C z_i}{1+\beta_w C z_i}$ . Given that typical wall velocities are semirelativistic, with Lorentz factor  $\gamma_w \sim 1$ , it follows that the domain wall passes through the mineral on Earth  $\mathcal{O}(0.1-1)$  times for  $C = \mathcal{O}(1-10)$ .

Because the two vacua separated by the wall are equivalent, for an axion wall, which is my focus for concreteness, the wall- $N$  coupling must share that periodicity. I take

$$f(\phi) = \Lambda \cos(2\pi\phi/v + \theta), \quad (9)$$

so the interaction respects  $\phi \rightarrow \phi + v$ . The special choice  $\theta = 0$  preserves  $CP$  and automatically evades various limits such as fifth-force.  $F$  vanishes both for  $|\Delta p_z| \ll m_\phi$  and  $|\Delta p_z| \gg m_\phi$  in Eq. (7).

Numerical results for the recoil probability obtained by integrating over  $|\Delta k_z| < m_\phi$  and using the evaluated  $|F|$  is shown in the bottom panel of Fig. 1. The  $\gamma_w \gg 1$  behavior differs from the FOPT curves, but the overall magnitudes remain comparable.

The unchanged qualitative discussion holds for two reasons: (i) the filtering factor is nonzero for  $\Delta p_z \sim m_\phi$ , (ii) the phase-space integral over  $x$  and  $p_\perp^2$  with  $|\Delta p_z| \sim m_\phi$  where  $|F| \sim (2\pi)\Lambda/v$  gives a dominant contribution as large as the one in the FOPT case with the replacement of  $v/M \rightarrow (2\pi)\Lambda/v$ .<sup>3</sup>

That said, the precise recoil spectra are significantly different, as discussed in the next section, and in principle we can discriminate the two scenarios.

### III. RECOIL SPECTRA

Here I present numerical results for the momentum distribution of  $N$  produced by the wall passing through the mineral. This will be important for future precision

studies that search for signals by analyzing the damage tracks.

To this end, I perform a change of variables from the previous discussion to obtain the differential transition probability:

$$\partial_X^2 P = \frac{1}{\det|\partial_X Y|} \frac{1}{2} \sum_{\text{spins}} \frac{1}{8 p_f^z p_\phi^z} \cdot \frac{1}{8\pi^2} \frac{|\mathcal{M}|^2}{(\Delta p_z)^2} |F|^2, \quad (10)$$

where  $X$  denotes the variables of interest, and  $Y = \{x, p_\perp^2\}$  are the variables used in the previous section.

Specifically, I take

$$X = \{p_f^{\text{Earth}}, \sin[\theta_{\text{Earth}}](\equiv k_\perp/p_f^{\text{Earth}})\}. \quad (11)$$

Here, the superscript “Earth” indicates that the quantity is measured in the Earth frame. The first variable,  $p_f^{\text{Earth}}$ , represents the total recoil momentum in the Earth frame, while the second variable,  $\theta_{\text{Earth}}$ , denotes the polar angle of the momentum with respect to the direction of  $\vec{\beta}_w$ .

These distributions provide information about the typical patterns of the resulting damage tracks.

We can also estimate averaged recoil observables via

$$\langle Z \rangle \approx P_{N \rightarrow N\phi}^{-1} \cdot \left( \frac{1}{2} \sum_{\text{spins}} \int \frac{dx}{8 p_f^z p_\phi^z} \int \frac{dp_\perp^2}{8\pi^2} \frac{|\mathcal{M}|^2}{(\Delta p_z)^2} |F|^2 Z \right), \quad (12)$$

with

$$Z = p_{f,z}^{\text{Earth}}, \quad (p_{f,z}^{\text{Earth}} - \langle p_{f,z}^{\text{Earth}} \rangle)^2, \quad p_\perp^2, \quad \text{etc.}$$

#### A. Bubble walls from late-time FOPT

I obtain the recoil momentum distribution, shown in Fig. 2. Figure 3 (upper panel) displays the typical recoil momenta parallel ( $\sqrt{\langle p_{z,f}^{\text{Earth}} \rangle^2 + \langle (\Delta p_{z,f}^{\text{Earth}})^2 \rangle}$ ) and

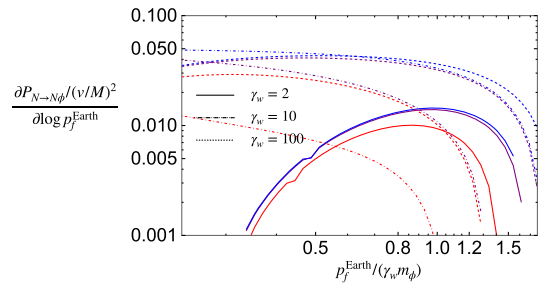


FIG. 2. The spectrum with respect to  $p_f^{\text{Earth}}$ . The solid, dot-dashed, dashed lines denote  $\gamma_w = 2, 10, 100$ , respectively. The red, purple blue lines denote  $m_\phi = \{0.1, 0.01, 0.001\} \times m_N$ , respectively.

<sup>3</sup>For other reactions, e.g., soft-photon emission, the infrared phase space may dominate. In such cases, condition (ii) is not satisfied.

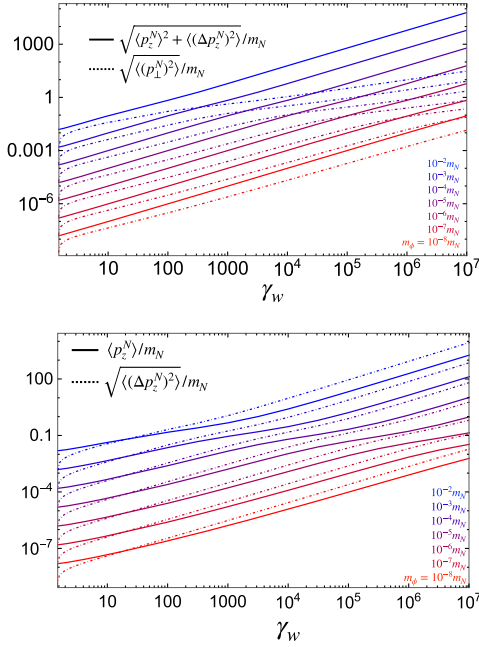


FIG. 3. The typical recoil momentum for  $N \rightarrow N\phi$  by varying the wall Lorentz factor.  $m_\phi = \{10^{-8}, \dots, 10^{-2}\}m_N$  from bottom to top. Solid (dashed) lines are for  $\langle p_{f,z}^{\text{Earth}} \rangle$  ( $\sqrt{\langle p_\perp^2 \rangle}$ ) in the top panel. In the bottom panels, solid (dashed) lines are  $\langle p_{f,z}^{\text{Earth}} \rangle$  ( $\sqrt{\langle (\Delta p_{f,z}^{\text{Earth}})^2 \rangle}$ ).

transverse ( $\sqrt{\langle p_\perp^2 \rangle}$ ) to the wall. The lower panel shows the mean and variance of the  $z$ -component.

The dependence on  $m_\phi$  and  $\gamma_w$  indicates that the recoil spectrum retains direct information about the wall width and its velocity. In the region where  $\gamma_w m_\phi \gtrsim m_N$ , the typical momentum in the  $z$ -direction dominates. However, this region is only physically justified for elementary particles. In the case of nuclei or nucleons, we require that  $\gamma_w m_\phi m_N \lesssim \text{GeV}^2$ , where the former quantity corresponds to the “center-of-mass energy” of the  $N$ – $\phi$  system within the wall, and the latter represents the QCD scale.

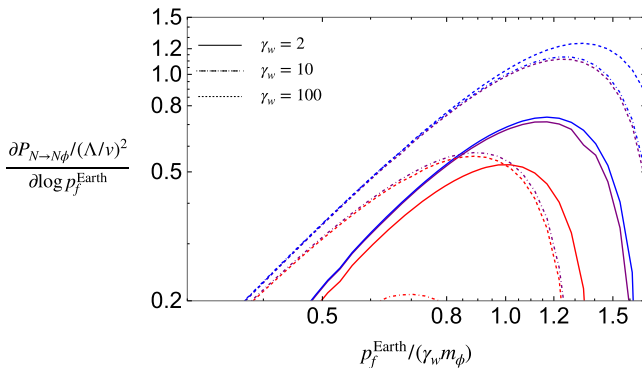


FIG. 4. As Fig. 2 but for the axion wall.

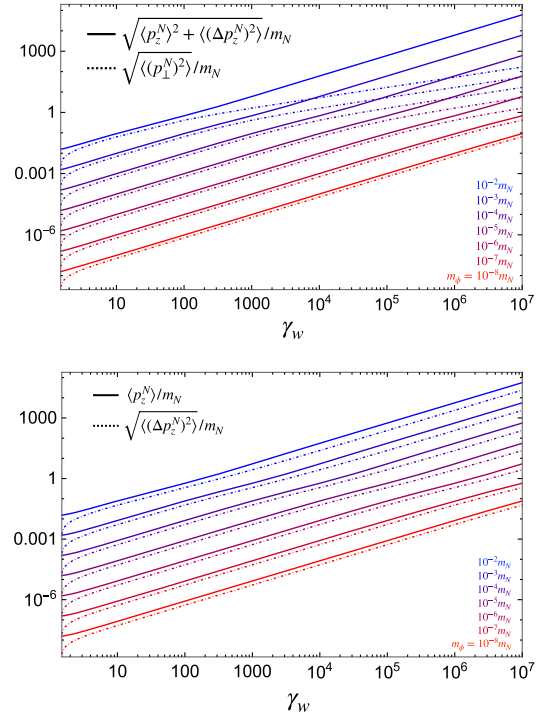


FIG. 5. As Fig. 3 but for the axion wall with  $\theta = 0$ .

## B. Scaling domain walls

The spectrum with respect to  $p_f^{\text{Earth}}$  are shown in Fig. 4. Also shown in Fig. 5 are the  $\gamma_w$  dependence of  $\langle Z \rangle$ .

The difference from the bubble wall case originates from the more restricted phase space at  $\Delta p_z \sim m_\phi$ : in the bubble wall case the additional region  $\Delta p_z \ll m_\phi$  is allowed, enlarging the phase space for  $p_z^z$ . Consequently the variance  $\langle (\Delta p_{f,z}^{\text{Earth}})^2 \rangle$  is modestly larger for the FOPT wall than for the scaling domain wall. Compared with the bubble wall case, where the dominant mode is wide in  $p_f^{\text{Earth}}$  at large  $\gamma_w \gtrsim 2$ , the dominant mode are narrower, which is due to the behavior of  $|F|$ .

## IV. FIRST LIMITS AND FUTURE PROSPECTS FOR COSMIC WALLS WITH PALEO DETECTORS

A rough rule of thumb is

$$P_{N \rightarrow N\phi} \sim |f'_{\text{typ}}|^2, \quad (13)$$

with  $f'_{\text{typ}} = \sqrt{2}v/M$  for late FOPT walls and  $f'_{\text{typ}} = \sqrt{2}\pi\Lambda/v$  for scaling walls. This is good approximation when  $\beta_w$  is close to 1 as seen in Fig. 1. The typical injected momentum is

$$p_N^{\text{Earth}} \sim \gamma_w m_\phi, \quad (14)$$

i.e. the inverse wall width in the Earth frame, which is the typical violation of the momentum conservation.

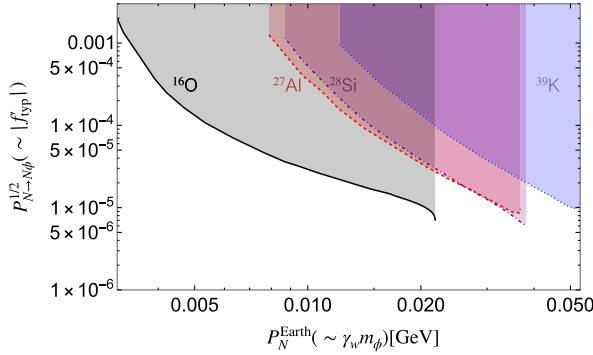


FIG. 6. Direct detection limit on cosmic walls derived from the data of the muscovite mica of Ref. [4]. The limit applies to a wall passage occurring within the last 0.5 Gyr.

Based on the absence of events in the 40–60 Å etched-depth range of tracks measured in  $\sim$ nanogram samples of 0.5 Gyr-old muscovite mica reported in Ref. [4], I reinterpret this null result as a bound on the passage rate of cosmic walls within the past 0.5 Gyr (see also Refs. [5,58] for the near one-to-one correspondence between recoil energy and etched depth). The resulting 90% CL limit on the interaction is shown in Fig. 6; the four lines correspond to  $N = {}^{16}\text{O}$ ,  ${}^{27}\text{Al}$ ,  ${}^{28}\text{Si}$ , and  ${}^{39}\text{K}$ , respectively, from left to right. To translate the recoil spectrum, I adopt the approximated formulas derived in this subsection and assume a dark matter velocity  $v_{\text{DM}} = 220 \text{ km s}^{-1}$ . Namely, I match the expected number of events via

$$N_{\text{target}} P_{N \rightarrow N\phi}^{\text{limit}} = N_{\text{target}} \frac{\rho_{\text{DM}}}{m_{\text{DM}}} v_{\text{DM}} \times (0.5 \text{ Gyr}) \times \sigma_{\text{limit}}, \quad (15)$$

where  $\sigma_{\text{limit}}$  is obtained from Ref. [58], and I use the same local dark matter density  $\rho_{\text{DM}} = 0.3 \text{ GeV cm}^3$  adopted there.

The relation between the recoil momentum and the dark matter mass is inferred from kinetic energy conservation,

$$\frac{1}{2} m_{\text{DM}} v_{\text{DM}}^2 = \frac{(p_N^{\text{Earth}})^2}{2m_N} + \frac{1}{2} m_{\text{DM}} v'^2, \quad (16)$$

and momentum conservation,

$$m_{\text{DM}} v_{\text{DM}} = p_N^{\text{Earth}} + m_{\text{DM}} v', \quad (17)$$

which together give  $p_N^{\text{Earth}}(m_{\text{DM}}, m_N)$ . Thus, for a given nuclear mass  $m_N$ , the recoil momentum can be mapped to an effective dark matter mass.

The limit at small  $p_N^{\text{Earth}}$  is weakened because low-momentum recoils produce damage tracks inefficiently in the detector. The limit does not reach to arbitrary large  $p_N^{\text{Earth}}$ , because the largest  $p_N^{\text{Earth}}$  is obtained from the kinematic limit  $m_{\text{DM}} \rightarrow \infty$  in the above mapping.

This bound can be significantly tightened—possibly even turned into a detection—by a dedicated reanalysis with (i) the full model-dependent recoil distribution and (ii) newer high-resolution track data with more minerals, should it become available. Track geometry itself is also informative. For nonrelativistic walls ( $\beta_w \ll 1$ ) and the relativistic  $N$  in the wall frame the transverse kick dominates (see Sec. III); event tracks all across the Earth would then appear nearly parallel,<sup>4</sup> providing a smoking-gun signature beyond the simple rate estimate. For  $\gamma_w \gtrsim 1$  and nonrelativistic  $N$  the distribution slightly broadens, but precise mapping of track orientations can still reveal the wall's velocity and direction.

For a target containing  $N_{\text{target}}$  scatterers (e.g., 100g muscovite), the expected number of events is given by

$$N_{\text{event}} = P_{N \rightarrow N\phi} \cdot N_{\text{target}} \sim 100 \left( \frac{|f'_{\text{typ}}|}{10^{-11}} \right)^2 \frac{N_{\text{target}}}{10^{24}}. \quad (18)$$

Since  $\frac{1}{\sqrt{2}} |f'(v)| \lesssim \frac{1}{\sqrt{2}} |f'_{\text{typ}}|$ , where the left-hand side represents the Yukawa coupling of  $\phi$  in the vacuum, one can see that this scenario is testable even with extremely small Yukawa couplings. It is sensitive even to cases where  $f'(v)$  is vanishingly small in the vacuum. The main potential backgrounds, such as radiogenic recoils, cosmic-ray-induced tracks, and geological or processing artifacts, could mimic a wall-crossing signal if the number of wall events is small. The mica track data used for our limit already demonstrate that such backgrounds can be suppressed in the relevant etched-depth ranges corresponding to recoil momenta of  $\mathcal{O}(1\text{--}10) \text{ MeV}$  and thus  $\gamma_w m_\phi = \mathcal{O}(1\text{--}10) \text{ MeV}$ .

I note that the sensitivity is lost if the wall passage occurs before the formation of most accessible minerals on Earth. In such a case, a similar approach could still be pursued by searching for suitable minerals in space, for example in comets.<sup>5</sup> Alternatively, assuming a flat probability distribution for the wall-passing epoch, the probability of intersecting a given mineral is  $\text{Gyr}/H_0^{-1} \sim 0.1$  with  $1/H_0$  being the present horizon given that in the relevant period the expansion of the Universe is negligible. In this situation, one can recast the limit/sensitivity derived here by replacing  $f'_{\text{typ}} \rightarrow f'_{\text{typ}}^{\text{ave}} = \sqrt{1/0.1} f'_{\text{typ}}$  to obtain a statistically averaged, generic result.

## V. CONCLUSIONS AND DISCUSSION

Cosmic walls intersect Earth at most  $\mathcal{O}(1)$  time over the age of the Universe. If the wall-matter coupling generates recoil energies above the paleo detector threshold, every

<sup>4</sup>The wall transit time is so short for  $m_\phi \gg 10^{-18} \text{ eV}$ , that Earth's rotation and revolution can be neglected.

<sup>5</sup>I thank T. Naka for informing me about his project on this topic.

mineral that already existed at the time of passage acquires damage tracks. In this work I showed that paleo detectors enable a truly direct search for cosmic walls and derived the first limit by recasting the existing ancient mica data. A dedicated reanalysis with modern, high-resolution read-out, or new data, could improve the limit or discover a signal.

A wall-induced signal arises from a characteristic recoil distribution and exhibits a distinctive global signature, since the wall motion is identical at every point on Earth at the same time. This gives a clear signature: minerals older than the wall event should contain tracks, whereas younger samples should be free of them. The three-dimensional orientation of the tracks further encodes the wall's Lorentz factor, trajectory, and the wall profile. Certain minerals, such as mica, olivine,<sup>6</sup> and diamond, are known or expected to have intrinsic directional sensitivity due to anisotropic crystal structures or etching behavior [6–8]. This implies that multisite paleo-detector comparisons (e.g., samples from both hemispheres), similar to the GNOME concept [29–32], may provide strong signal discrimination, provided the mineral orientation is preserved. A more detailed study targeting the detection of walls will be presented elsewhere.

Note that the derived limit can be readily recast for more specific scenarios, such as the frustrated domain wall scenario [33–35], in which domain walls pass through the Earth very frequently and behave as dark matter or dark energy. For instance, assuming an encounter rate of  $\mathcal{O}(1) \text{ yr}^{-1}$ , the limit/prospective sensitivity would simply be enhanced by a factor  $f'_{\text{typ}} \propto (\text{Gyr/yr})^{-1/2} \sim 10^{-5} - 10^{-4}$ , as the number of encounters scales with Gyr/yr. Therefore, my proposal, which uses ancient samples to directly detect cosmic walls, provides coverage of a wide and generic range of scenarios.

Ultrarelativistic walls also provide an indirect handle. Their large momentum transfer can boost Standard Model or hidden particles throughout cosmic space, effectively making the walls a source of cosmic rays. For a typical injected momentum  $p_X \sim m_\phi \gamma_w$  the flux is estimated as flux  $\simeq P_{N \rightarrow X\phi} n \simeq 10 \text{ km}^{-2} \text{ yr}^{-1} (\frac{P_{N \rightarrow X\phi}}{10^{-20}}) (\frac{n}{10^{-7} \text{ cm}^{-3}})$ , where  $n$  is the average baryon number density. Here  $X$  denotes a collection of the particles since the reaction is far beyond the QCD or even weak scale.  $N$  may be also neutrinos. Such a flux could be sought in large-area or large-volume observatories such as Telescope Array [59], Pierre Auger [60], IceCube [61], or KM3NeT [62], depending on the particle species  $X$ .

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## DATA AVAILABILITY

The data are not publicly available. The data are available from the authors upon reasonable request.

## APPENDIX A: ESTIMATION FOR BOSONIC NUCLEI

I now consider the possibility that a nucleus itself behaves as a boson. For simplicity I treat it as a complex scalar field and denote it by  $N$ . Its free Lagrangian contains the usual mass term

$$\mathcal{L} \supset -m_N^2 |N|^2, \quad (\text{A1})$$

where  $m_N \simeq A m_n$  with  $A$  the mass number and  $m_n$  the nucleon mass.

Assume that the wall field couples universally to individual nucleons through  $f_n(\phi) \bar{n} n$ . Then, to leading order in  $A$ , the induced coupling to the composite scalar  $N$  is

$$\mathcal{L}_{\text{int}} \supset 2m_N A f_n(\phi) |N|^2 \simeq 2m_N f(\phi) |N|^2, \quad (\text{A2})$$

where I have defined  $f(\phi) = A f_n(\phi)$  which is the same for the fermionic case. The squared matrix element is

$$|\mathcal{M}|^2 \simeq (2m_N)^2. \quad (\text{A3})$$

Repeating the analysis of the FOPT wall with this replacement yields the results shown in Figs. 7 and 8. For comparison the fermionic curves are overlaid (lighter color). The only significant deviation appears when the typical momentum approaches  $m_N$ , where the effective

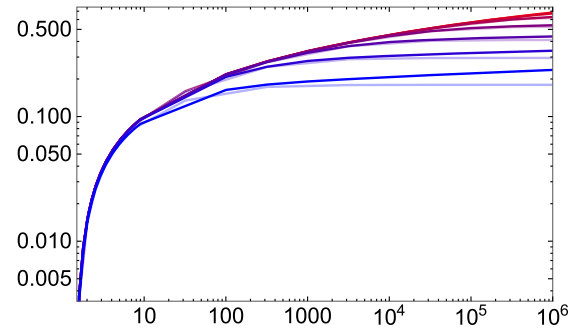


FIG. 7. Production probability for bosonic nuclei (darker curves) compared with the fermionic case discussed in the main part (lighter curves). Same as the top panel of Fig. 1 in the main part.

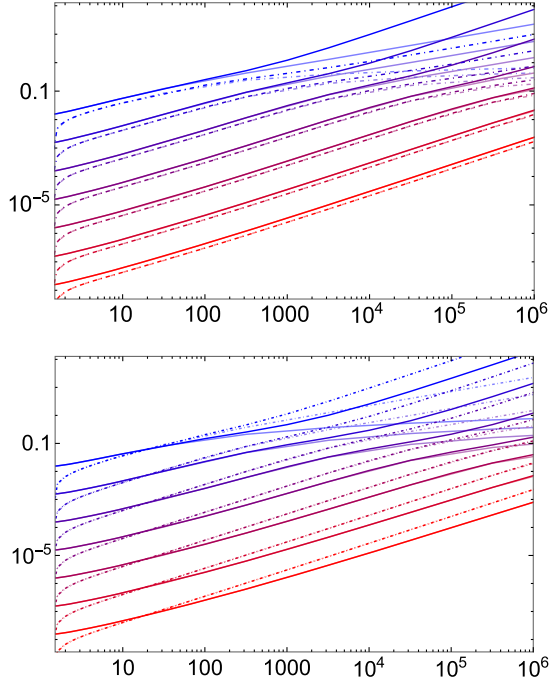


FIG. 8. Typical recoil momenta for bosonic nuclei (darker curves) versus the fermionic results of Fig. 3 (lighter curves).

field treatment breaks down and a microscopic description would be required.

## APPENDIX B: SUPPRESSED ASTROPHYSICAL AND COSMOLOGICAL EFFECTS FOR THE COSMIC WALLS

Here I show that I am studying cosmic walls whose astrophysical and cosmological effects are highly suppressed, given that the wall has a tension  $\sigma \ll \text{MeV}^3$  as discussed in the context of the domain wall problem.

### 1. Gravitational effects

First of all,<sup>7</sup>

$$\sigma \ll \text{MeV}^3 \sim 5 \times 10^{-5} \text{ kg/m}^2, \quad (\text{B1})$$

which induces a repulsive gravitational acceleration of

$$g_{\text{eff}} \lesssim 6 \times 10^{-23} c/s, \quad (\text{B2})$$

where  $c \sim 3 \times 10^8 \text{ m/s}$  is the speed of light. This provides an acceleration of any object away from the wall, but its magnitude is extremely small. Only when the integration time is extremely large, e.g.,  $13.8 \text{ Gyr} \sim 4 \times 10^{17} \text{ s}$ , can one obtain a visible effect, such as an impact on the precisely measured anisotropy of the cosmic microwave background.

<sup>7</sup>If one considers the boosted wall with  $\gamma_w > 1$ , one can replace  $\sigma$  by  $\sigma\gamma_w$  in the following discussions.

A domain wall that just satisfies the above requirement would alter the light by an angle of  $6 \times 10^{-23} c/s \times 13.8 \text{ Gyr} \sim 10^{-5}$  over the history of the Universe. This should be compared to the precisely measured temperature fluctuation,  $\sim 10^{-5} T_{\text{CMB}}$ , which immediately leads to the well-known condition relevant to the domain wall problem.

Now, one can see that the impact on other astrophysical objects is highly suppressed due to the short integration time and weak gravitational acceleration. When the wall is either before or after crossing an astrophysical object, the object is in free fall with the tiny acceleration and thus experiences no significant effect. Any impact can occur only during the actual passage of the wall, which might slightly alter the object's relative position or shape. Since the wall moves at nearly the speed of light, the crossing time is extremely short for any small object. Given the gravitational acceleration suppression in Eq. (B2), the effect is entirely negligible. For example, when the wall passes through a planet such as the Earth, the crossing lasts less than a second and produces a velocity change  $\ll 10^{-23} c$ , which is unobservable unless one could measure velocities with extraordinary precision in the ancient era.

The impact when it passes through a galaxy is also highly suppressed. For instance, when it passes through the Milky Way galaxy disk, with a radius of  $\sim 50 \text{ kpc}$ , the time to cross is  $5 \times 10^{12} \text{ s}$ , which causes a change in the velocity dispersion of the visible stars by  $\lesssim 3 \times 10^{-10} c$ . This is much smaller than the typical velocity dispersion of  $10^{-3} c$ , and the impact is completely negligible.

### 2. The interaction to $N$

Given the interaction introduced to study the recoil momentum of  $N$ , there may also be constraints on the cosmic wall from astrophysical and cosmological objects.

As I have mentioned in the main part, the change in the mass of  $N$  is very small. For the limit I derived (see Fig. 2 of the main text), the bound can be as small as  $f'_{\text{typ}} \sim 10^{-5}$ . For the bubble wall case with  $v \lesssim \text{MeV}$ , the change in the mass of  $N$  is  $\lesssim 10^{-5} \text{ MeV}$ . For the nuclei of interest, the mass shifts by a fraction up to  $\delta m_N/m_N \lesssim 10^{-7}$ . From the nonconservation of the transverse momentum, we obtain a momentum shift in the wall frame,  $\delta p_z^{\text{wall}} \sim \delta m_N m_N / p_z^{\text{wall}}$ . Assuming  $N$  is nonrelativistic in the cosmic frame,  $p_z^{\text{wall}} \sim \gamma_w \beta_w m_N$  for a (semi)relativistic wall. Then one finds  $\delta p_z^{\text{cosmic}} \sim \delta m_N$ , meaning that the velocity shift is  $< 10^{-7} \times c$ , which is totally negligible compared to the typical motion of matter in the Universe or any galaxies. It is also not important for producing a sizable recoil in the paleo detector. For the domain wall scenario, the mass shift is zero thanks to the symmetry stabilizing the domain wall network, and thus there is no limit from this reaction.

Let us consider the impact from the reaction  $N \rightarrow N\phi$ , which is the one mainly considered in the main part. This will induce a recoil of the nuclei. Satisfying the limit set in

the main part, the probability of inducing such a recoil is very small,  $\sim |f'_{\text{typ}}|^2 < 10^{-10}$ . Therefore, the impact on cosmological or astrophysical observations is not significant. For the recoil of sub-GeV charged  $N$ , one may have constraints from CMB data. However, the impact is suppressed by both the small probability and the small number density of baryons. The injected energy density averaged over the Universe should be  $\ll 10^{-10} \times n_B \times \text{GeV}$ , with  $n_B$  being the baryon number density. I used  $\ll$  because the kinetic energy of baryons is much smaller than GeV, and not all of the kinetic energy will be transferred to CMB photons. This is much safer than the typical limit from the CMB, e.g., [63].

Lastly, I note that friction can act on the wall. Locally, the friction may be significant compared to the wall kinetic energy depending on the interaction, and a dense object can in principle distort the wall shape. However, since the wall

extends across the entire Universe, the total tension energy far exceeds the frictional effect from any localized region. The friction is simply the transverse momentum transfer across the wall per unit area per unit time [38–42], and its averaged value can be estimated as friction  $\ll 10^{-10} \times n_B \times \text{GeV}$ , as in the previous paragraph. For friction to be irrelevant, we require friction  $\ll \sigma H_0$ , with  $H_0$  the present Hubble parameter. This condition implies

$$\sigma > (5 \text{ keV})^3 \frac{\text{friction}}{10^{-10} n_B \text{ GeV}}. \quad (\text{B3})$$

When this is satisfied, the wall tension is sufficient to restore any locally slowed segment after passing through a dense object. Therefore, the estimate that a cosmic wall crosses the Earth  $\mathcal{O}(0.1)$  times over the age of the Universe remains valid unless the tension is extremely small.

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