Searching for Dark Matter with Paleo-Detectors

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A large experimental program is underway to extend the sensitivity of direct detection experiments, searching for interaction of Dark Matter with nuclei, down to the neutrino floor. However, such experiments are becoming increasingly difficult and costly due to the large target masses and exquisite background rejection needed for the necessary improvements in sensitivity. We investigate an alternative approach to the detection of Dark Matter–nucleon interactions: Searching for the persistent traces left by Dark Matter scattering in ancient minerals obtained from much deeper than current underground laboratories. For such a search, it is crucial to understand the details of the nuclear recoils induced by Dark Matter, in particular, the range of the recoiling nuclei in the material. We estimate the sensitivity of paleo-detectors, which extends down to the neutrino floor for a wide range of Dark Matter masses. With readily available O(500) Myr old minerals, paleo-detectors can probe spin-independent WIMP-nucleon cross sections 2–3 orders of magnitude lower than current direct detection limits for most of the WIMP mass range.

Introduction The gravitational effects of Dark Matter (DM) are evident at length scales ranging from the smallest galaxies to the largest observable scales of our Universe. However, despite much experimental effort, the nature of DM is as yet unknown.

Weakly Interacting Massive Particles (WIMPs) are well motivated DM candidates. A large ongoing experimental program exists to search for WIMP induced nuclear recoil events in Direct Detection (DD) experiments [1–2]. Signatures include annual [3–5] and diurnal modulation [6]. The only experiment with positive results is DAMA, which reports a 9σ measurement of an annually modulated signal compatible with WIMP DM [7–9]. However, this result is in tension with null results of other DD experiments which have set stringent limits on the WIMP-nucleus interacting strength [10–17], especially for WIMP masses between 15 and 500 GeV. Hence, searches for unequivocal DM discovery continue.

In the next decades, DD experiments are expected to push into two different directions: Large scale detectors using e.g. liquid noble gas targets, sensitive to WIMPs with masses $m_\chi \gtrsim 5$ GeV, aim to obtain exposures (defined as the product of target mass and integration time) of $\varepsilon = \mathcal{O}(100)$ t yr [18–22]. For WIMPs with $m_\chi \lesssim 15$ GeV, the challenge is achieving low recoil energy thresholds rather than large detector masses; solid state detectors are envisaged to collect $\varepsilon = \mathcal{O}(10)$ kg yr with recoil energy thresholds of $\mathcal{O}(100)$ eV [23–24]. Recently, nm-scale detectors [25, 26] and concepts using molecular biology [27, 28] have been proposed to search for low-mass DM. Directional detectors [4] are being developed with the capability of determining the direction of the incoming WIMPs [29–36].

In order to suppress backgrounds, any DD apparatus must be built from radiopure material. To avoid cosmic ray backgrounds, DD experiments are typically located in deep underground laboratories. The deepest current laboratory is CJPL, China, with an overburden of $\sim 2.4$ km rock, corresponding to $\sim 6.7$ km w.e. (km water equivalent) shielding. Furthermore, DD experiments typically use multiple read-out modes to differentiate nuclear from electronic recoils, e.g. the scintillation and the ionization signal in the case of Xenon or Argon dual-phase time projection chambers.

In this letter and a series of papers in preparation, we investigate an alternative approach to search for WIMP-nucleus scattering. Instead of building a dedicated target instrumented to search for nuclear recoils in real time, we propose to search for the traces of WIMP interactions in a variety of ancient minerals. Many years ago in a similar approach, [37–40] looked at using ancient Mica as a dark matter detector. We use a variety of new materials and analysis techniques. Whereas in conventional DD experiments the observable is the prompt energy deposition of nuclear recoil in the target material read out via e.g. scintillation, ionization, or phonons, here the observable is the persistent chemical or structural change caused in the material by the recoiling nucleus. It is thus crucial to understand the behavior of the nuclear recoil and the length of the tracks. Conventional DD experiments require high quantum efficiency of the detector to read out the $\mathcal{O}(1)$ number of e.g. phonons, photons, or electrons produced by the nuclear recoil. In our case one needs to detect tracks with lengths of $1 - 1000$ nm.

One may use different technologies to measure the tracks. The best track length resolutions can be achieved by cleaving and chemically etching the minerals. Scanning the surfaces with Electron Microscopy (EM) or Atomic Force Microscopy (AFM) allows for length resolutions of $\mathcal{O}(1)$ nm or $\mathcal{O}(5)$ nm, respectively. A different...
We propose to use minerals obtained from deep underground; e.g. from ultra-deep boreholes used for geological R&D and oil exploration. This would offer an overburden of up to \( \mathcal{O}(12) \) km rock, corresponding to \( \mathcal{O}(30) \) km.w.e., making backgrounds induced by cosmic rays negligible. The most relevant background will be coherent scattering of neutrinos (\( \nu \)'s) off nuclei in the mineral, giving rise to the so-called neutrino floor (\( \nu \)-floor) in DD experiments. 

There are a large number of possible minerals one may use for such a search. Which of these should be used, depends on a number of factors: The mineral must 1) be readily available in cores from ultra-deep boreholes; 2) preserve the tracks caused by the recoiling nuclei for geological timescales; 3) have low molecular number density yielding long tracks and, in turn, good energy resolution; 4) consist of target nuclei which yield good separation of WIMP recoils from \( \nu \)-induced recoils; and 5) be suitable for the chosen read-out method, e.g. for EM and AFM the minerals must show perfect cleavage such that the target can be cleaved and etched. We investigate the mineral optimization problem for different ranges of WIMP masses in greater detail in forthcoming papers.

For definiteness we use Zabuyelite (Li\(_2\)CO\(_3\)), Halite (NaCl), Iltisite (Hg\(_2\)AgCl\(_2\)), and Sylvanite (Au\(_{0.75}\)Ag\(_{0.25}\)Te\(_2\)) in this work. These minerals balance all of the above criteria reasonably well. We focus on canonical spin-independent (SI) WIMP-nucleon interactions. We expect the sensitivity of paleo-detectors to other types of interactions to be comparable and will investigate in future work.

In the remainder of this letter, we estimate the sensitivity of paleo-detectors. We find, that with readily available \( \mathcal{O}(500) \) Myr old minerals, SI WIMP-nucleon scattering cross sections 2-3 orders of magnitude lower than current DD limits can be probed for most of the WIMP mass range. Reading out a few grams of target material with EM, AFM, or hXRM, paleo-detectors can be sensitive to SI WIMP-nucleon cross sections one order of magnitude away from the \( \nu \)-floor for Xe detectors for WIMPs with \( m_\chi \lesssim 10 \) GeV. For heavier WIMPs, scattering cross sections down to the Xe \( \nu \)-floor can also be probed by reading out \( \mathcal{O}(100) \) g of target mass with sXRM.

The sensitivity of our proposal far exceeds that of Refs. [37–40] using ancient Mica. This is due to improved read-out technology allowing for much larger exposure, improved shielding from backgrounds due to using minerals from ultra-deep boreholes instead of from close to the surface, and to using minerals different from Mica.

**Dark Matter Signal** The differential recoil rate per unit target mass for a WIMP with mass \( m_\chi \) scattering off a target nucleus with mass \( m_T \) is given by

\[
\frac{dR}{dE_R} = 2\rho_\chi\int d^3v v f(v,t) \frac{d\sigma_T}{dq^2}(q^2,v),
\]

where \( E_R \) is the recoil energy, \( \rho_\chi \) is the local WIMP mass density, \( f(v,t) \) the WIMP velocity distribution, and \( d\sigma_T/dq^2 \) the differential WIMP-nucleus scattering cross section with the (squared) momentum transfer \( q^2 = 2m_T E_R \). For canonical SI WIMP-nucleon couplings, the differential WIMP-nucleus cross section is well approximated by

\[
\frac{d\sigma_T}{dq^2}(q^2,v) = \frac{A^2 \sigma_n^\text{SI}}{4\mu_{(\chi\nu)}^2} F^2(q) \theta(q_{\text{max}} - q),
\]

where \( A_T \) is the number of nucleons in the target nucleus, \( \sigma_n^\text{SI} \) the SI WIMP-nucleon scattering cross section at zero momentum transfer, and \( \mu_{(\chi\nu)} \) the reduced mass of the WIMP-nucleon system. The form factor \( F(q) \) accounts for the finite size of the nucleus; we use the Helm form factor [22,41]. The Heaviside step function \( \theta(q_{\text{max}} - q) \) accounts for the maximal momentum transfer \( q_{\text{max}} = 2\mu_{(\chi\nu)} v \) given by the scattering kinematics. For the velocity distribution we use a Maxwell-Boltzmann distribution truncated at the galactic escape velocity and boosted to the Earth’s rest frame as in the Standard Halo Model [5].

From the differential recoil rate for given target nuclei we compute the associated spectrum of ionization track lengths. The stopping power for a recoiling nucleus incident on an amorphous target, \( dE/dx_T \), is obtained from the SRIM code [45] and the ionization track length for a recoiling nucleus with energy \( E_R \) is

\[
x_T(E_R) = \int_0^{E_R} dE \left( \frac{dE}{dx_T(E)} \right)^{-1}.
\]

Together with the recoil spectra obtained from Eq. [1] and summing over the contributions from the different target nuclei in the mineral weighted by the respective mass fraction in the target, we obtain the track...
length spectra for nuclear recoils induced by WIMPs. In Fig. 1 we plot track length spectra induced by WIMPs incident on Zabuyelite (black) and Sylvanite (red) for $m_\chi = 5$ GeV (solid) and $m_\chi = 500$ GeV (dashed), assuming $\sigma^{SI} = 10^{-45}$ cm$^2$.

**Backgrounds** There are a number of possible background sources which must be mitigated in order to be sensitive to WIMP induced signals. Background from intrinsic radioactivity can be suppressed by choosing target minerals with low levels of contamination by highly radioactive elements such as U or Th, e.g. by using marine evaporites. Out of the contaminants, $\beta$ and $\gamma$ emitters do not give rise to relevant background as they predominantly interact with electrons, which do not produce persistent tracks in the minerals. $\alpha$ emitters are a more serious problem, however, they can be rejected based on track length given by their particular energies and track patterns [37]. Due to the $O(500)$ Myr integration time, the entire decay chains of heavy highly radioactive elements such as U or Th are recorded in the mineral, leading to characteristic star-like patterns of more than 5 $\alpha$-tracks. Spontaneous fission of heavy nuclei would lead to even richer signatures.

Fast neutrons, which can scatter off the target nuclei and induce nuclear recoils with energies similar to WIMP-nucleon interactions, can be induced by cosmic rays. Such background is greatly suppressed by using minerals from ultra-deep boreholes with depths up to $\sim 10$ km. While the muon induced neutron flux is $O(10)$ cm$^{-2}$ Myr$^{-1}$ for the deepest current laboratories, with $O(2)$ km rock overburden, we expect a neutron flux of $\sim 10^{-4}$ (10$^{-5}$) cm$^{-2}$ Myr$^{-1}$ by using minerals obtained from a depth of 5 (10) km [50].

The most relevant background will be coherent scattering of neutrinos ($\nu$'s) off nuclei in the mineral, where the $\nu$'s come from the Sun, supernovae, and atmospheric cosmic ray interactions [31]. We use $\nu$-fluxes from Ref. [31]. The nuclear recoil spectrum due to the $\nu$-background is converted to an ionization track length spectrum analogously to the WIMPs. In Fig. 1 we plot track length spectra induced by background $\nu$'s (dotted) incident on Zabuyelite (black) and Sylvanite (red).

**Sensitivity Projection** From the track length spectra of the signal and the background, we estimate the sensitivity of the proposed search using a simple cut-and-count analysis. First, we account for the finite track length resolution by using a Monte Carlo sampling of the track length spectrum, where we smear the track length of each event

$$x_T^{\text{obs}} = x_T^{\text{true}} + \Delta_x(\sigma_x),$$

with the smeared (true) track length $x_T^{\text{true}}$ and where $\Delta_x$ is a random number drawn from a normal distribution with standard deviation $\sigma_x$ given by the track length resolution. We use $\sigma_x = \{1, 5, 15, 150\}$ nm as benchmark values for {EM, AFM/hXRM, sXRM, UVM}, respectively.

We then optimize the lower cutoff on the track length for each WIMP mass hypothesis by computing the minimal WIMP-nucleon cross section for which the signal-to-noise ratio satisfies

$$\frac{S}{\sqrt{B + \Sigma^2 B^2}} \geq 3,$$

as a function of the track length cutoff, with the smallest allowed cutoff given by $\sigma_x/2$. Here, $S/B$ is the number of signal (background) events and $\Sigma$ the systematic error of the background. We also demand the number of signal events above the cutoff to be $S \geq 5$.

Ref. [51] suggests that the uncertainties on the current $\nu$-fluxes are $O(5\%)$ for solar $\nu$'s, $O(50\%)$ for supernova $\nu$'s, and $O(20\%)$ for atmospheric $\nu$'s. In our case the background is instead given by an integration over the time of exposure for the target mineral, which is up to $t_{\text{int}} = O(1)$ Gyr. Extrapolating the $\nu$-fluxes over such geological timescales entails significant systematic uncertainties, for example from a varying supernova rate [52] or varying cosmic ray fluxes, which we account for by choosing $\Sigma = 100\%$.

**Results** In Fig. 2 we show the projected sensitivity for the example minerals Zabuyelite, Halite, Iltisite, and Sylvanite using either EM (left panel) or sXRM (right panel) as read-out methods. This figure demonstrates the potential of the proposed search as well as the trade-offs between different targets and read-out methods. Comparing to current DD limits, we find that, for nearly the entire WIMP mass range considered, the sensitivity of paleo-detectors is 2-3 orders of magnitude better than current limits. For WIMPs with masses $10$ GeV $\lesssim m_\chi \lesssim 20$ GeV, bounds from liquid Xe experiments are comparable to paleo-detectors.
The example minerals were selected as representatives of different classes of target materials. Zabuyelite (Li₂CO₃) and Halite (NaCl) contain only low-mass target nuclei and are extremely clean from α-emitters. Iltisite is an example of a mineral containing both lighter (S, Cl) and heavier (Br, Ag, Hg) target nuclei. Sylvanite contains only heavy targets (Au, Ag, Te).

The kinematics of elastic WIMP-nucleus scattering suggest that the target mass should approximately match the WIMP mass in order to yield the highest recoil energy and correspondingly largest track length. However, since ν’s tend to induce longer tracks on lighter target nuclei, heavier targets can be advantageous in differentiating WIMPS from ν’s in the cut-and-count analysis.

For Zabuyelite, the mineral with the lightest target nuclei considered, the track spectrum due to ν’s shown in Fig. 1 is dominated by solar ν’s for all track lengths. DM induced tracks are always shorter than the longest tracks induced by solar ν’s, such that the sensitivity is limited by the uncertainty on the number of events induced by solar ν’s for the entire WIMP mass range. On the other hand, the WIMP-induced tracks in Zabuyelite are comparatively long. Even when using read-outs with comparatively bad track length resolution such as sXRM, SI WIMP-nucleon cross sections σ_{SI}^{x=1 nm; ε=1 kg Myr} can be probed for WIMPs as light as 0.5 GeV, cf. Fig. 2.

For the minerals with heavier target nuclei considered, track length spectra are shorter for WIMPs as well as for ν-induced events. While this allows for sensitivity to light WIMPs similar to Zabuyelite when using read-out with excellent track length resolution such as EM, the sensitivity to light WIMPs deprecates with worsening track length resolutions since DM induced events do not yield sufficiently long tracks. This is reflected in the sensitivity curves for Halite, Iltisite, and Sylvanite terminating at some target-dependent lower value of the WIMP mass for sXRM read-out, cf. the right panel of Fig. 2.

However, the tracks induced by solar ν’s are shortened more than tracks induced by heavier WIMPs. In the case of Sylvanite, solar ν’s give rise to tracks shorter than x_T ≈ 10 nm. The ν-induced tracks for x_T ≥ 10 nm in Fig. 1 are due to supernova and atmospheric ν’s. Hence, for WIMPs with masses large enough to give rise to tracks longer than x_T ≈ 10 nm, the search can be decoupled from the solar ν background by using a lower cutoff in the analysis. Such decoupling is possible for WIMPs with m_χ ≥ 10 GeV in all targets considered except Zabuyelite, allowing to probe much smaller WIMP-nucleon cross sections for m_χ ≥ 10 GeV than for lighter WIMPs, cf. the left panel of Fig. 2.

With worsening track length resolution, the decoupling of heavier WIMPs from the background induced by solar ν’s shifts to larger WIMP masses. Comparing the two panels of Fig. 2, we see that for EM read-out WIMPs with masses m_χ ≥ 10 GeV decouple from solar ν’s, while for sXRM read-out such decoupling occurs only for m_χ ≥ 50 GeV in Sylvanite.

Note, that apart from the finite track length resolution we assumed perfect track reconstruction. Global corrections to the efficiency of the reconstruction would have virtually no influence on our sensitivity projections because, although the sensitivity is systematics limited, much larger exposures can account for significant decreases in efficiency. Corrections depending on the length of the tracks or the recoiling nucleus may affect our projections. We expect such effects on the sensitivity to
WIMPs with \( m_\chi \gtrsim 10 \text{ GeV} \) to be minor given the availability of target minerals with light constituent nuclei, which can provide for longer tracks. To the best of our knowledge, no reliable estimate of such corrections exists. We will investigate such corrections in future work.

**Discussion** In this letter, we have discussed a method for DM searches radically different from the usual Direct Detection approach. Instead of searching for WIMP-nucleus scattering in a real-time detector in underground laboratories, the approach is to examine ancient minerals for traces of the permanent changes caused by the damage of WIMP induced nuclear recoils. Such a search integrates over geological time scales of order 1 Gyr, yielding enormous exposure allowing for sensitivities down to the conventional \( \nu \)-floor even for a simple cut-and-count analysis.

While we only studied the sensitivity for canonical spin-independent WIMP-nucleus scattering in this letter, the proposed method is also sensitive to other types of WIMP-nucleus interactions, such as canonical spin-dependent interactions or more general interactions, e.g. those found in the non-relativistic effective field theory approach to WIMP-nucleon scattering [54]. Qualitatively, we expect the increase of sensitivity with respect to current bounds to be of the same order of magnitude as for the spin-independent case. Further, since multiple target nuclei would be present within a single mineral, one could search for \( A_T^2 \) or other dependence, and thus determine the type of WIMP/nucleon interaction.

Beyond the simple cut-and-count analysis used here to estimate the sensitivity, one may use more sophisticated analysis techniques. For appropriate combinations of target material and read-out method, recoils induced by background neutrinos can possibly be detected with sufficient statistics to reduce the uncertainty of the integrated \( \nu \)-flux. Thus, spectral information could help disentangle WIMP signals from the \( \nu \)-induced background. Such an approach promises to significantly extend the sensitivity of the search.

There are a number of interesting possibilities arising from this approach we leave for future work. For example, one could use a series of crystals of different ages. The age of the oldest available crystals is larger than the period of the Sun’s rotation around the galactic center \( T_\odot \sim 230 \text{ Myr} \). Using standard mineral dating methods, the age of the crystals can be determined with an accuracy of a few \% [55] [56]. If the DM in the Milky Way is not smoothly distributed but instead has significant substructure such as e.g. ultra-compact mini-halos [57] [58] or tidal streams [59] [61], the Earth may well have crossed such denser DM regions during this time span. Hence, while substructure usually renders typical DD experiments less sensitive due to a decrease in the local DM density, the signal one expects in ancient minerals may well increase by orders of magnitude.

Another possibility is the use of paleo-detectors as neutrino detectors. The large exposure would allow to study the \( \nu \)-flux from e.g. the Sun, supernovae, or cosmic rays more precisely.

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2 The particular case of track reconstruction by cleaving and etching Muscovite Mica has been discussed in Ref. [40].
[19] B. J. Mount et al., (2017), arXiv:1703.09144 [physics.ins-det]
[20] J. Aalbers et al. (DARWIN), JCAP 1611, 017 (2016), arXiv:1606.07001 [astro-ph.IM]
[21] C. E. Aalseth et al., Eur. Phys. J. Plus 133, 131 (2018), arXiv:1707.08145 [physics.ins-det]
[22] P. A. Amaudruz et al. (DEAP-3600), Submitted to: Astropart. Phys. (2017), arXiv:1712.01982 [astro-ph.IM]
[23] G. Angloher et al. (CRESST), (2015), arXiv:1503.08065 [astro-ph.IM]
[24] R. Agnese et al. (SuperCDMS), Phys. Rev. D95, 082002 (2017), arXiv:1610.00006 [physics.ins-det]
[25] A. Drukier, K. Freese, A. Lopez, D. Spergel, C. Cantor, G. Church, and T. Sano, (2012), arXiv:1206.6809 [astro-ph.IM]
[26] A. K. Drukier, A. Abramowicz, P. Bermuta, D. Q. Adams, S. Rydstrom, M. Gorski, P. Karlowicz, A. Nowicki, J. Piwowsarki, and J. Topinski, in Proceedings, 14th Marcel Grossmann Meeting on Recent Developments in Theoretical and Experimental General Relativity, Astrophysics, and Relativistic Field Theories (MG14) (In 4 Volumes): Rome, Italy, July 12-18, 2015; Vol. 1 (2017) pp. 667–680.
[27] A. Lopez, A. Drukier, K. Freese, C. Kurdak, and G. Tarle, (2014), arXiv:1403.8115 [astro-ph.IM]
[28] A. K. Drukier, C. Cantor, M. Chonosky, G. M. Church, R. L. Fagaly, K. Freese, A. Lopez, T. Sano, C. Savage, and W. P. Wong, Int. J. Mod. Phys. A29, 143007 (2014) arXiv:1403.8154 [astro-ph.IM]
[29] E. Daw et al., Proceedings, 3rd Workshop on Directional Detection of Dark Matter (CYGNUS 2011): Aussois, France, June 8-10, 2011, EAS Publ. Ser. 53, 11 (2012) arXiv:1110.0222 [physics.ins-det]
[30] J. B. R. Battat et al. (DRIFT), Phys. Dark Univ. 9-10, 1 (2015) arXiv:1410.7821 [hep-ex]
[31] Q. Riffard et al., in Proceedings, 48th Rencontres de Moriond on Very High Energy Phenomena in the Universe: La Thuile, Italy, March 9-16, 2013 (2013) pp. 227–230, arXiv:1306.4173 [astro-ph.IM]
[32] D. Santos et al., Proceedings, 4th Workshop on Directional Detection of Dark Matter (CYGNUS 2013): Toyama, Japan, June 10-12, 2013, J. Phys. Conf. Ser. 469, 012002 (2013) arXiv:1311.0616 [physics.ins-det]
[33] J. Monroe (DMTPC), Proceedings, 3rd Workshop on Directional Detection of Dark Matter (CYGNUS 2011): Aussois, France, June 8-10, 2011, EAS Publ. Ser. 53, 19 (2012)
[34] M. Leyton (DMTPC), Proceedings, 14th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2015): Torino, Italy, September 7-11, 2015, J. Phys. Conf. Ser. 718, 042035 (2016)
[35] K. Miuchi et al., Phys. Lett. B686, 11 (2010) arXiv:1002.1794 [astro-ph.CO]
[36] K. Nakamura et al., PTEP 2015, 043F01 (2015)
[37] D. P. Snowden-Ifft, E. S. Freeman, and P. B. Price, Phys. Rev. Lett. 74, 4133 (1995)
[38] J. Engel, M. T. Jessell, I. S. Towner, and W. E. Ormand, Phys. Rev. C52, 2216 (1995) arXiv:hep-ph/9504322
[39] D. P. Snowden-Ifft and A. J. Westphal, Phys. Rev. Lett. 78, 1628 (1997) arXiv:astro-ph/9701215 [astro-ph]
[40] J. I. Collar and F. T. Avignone, III, Nucl. Instrum. Meth. B95, 349 (1995) arXiv:astro-ph/9505055 [astro-ph]
[41] J. Billard, L. Strigari, and E. Figueroa-Feliciano, Phys. Rev. D89, 023524 (2014), arXiv:1307.5458 [hep-ph]
[42] R. H. Helm, Phys. Rev. 104, 1466 (1956)
[43] J. D. Lewis and P. F. Smith, Astropart. Phys. 6, 87 (1996)
[44] G. Duda, A. Kemper, and P. Gondolo, JCAP 0704, 012 (2007) arXiv:hep-ph/0608035 [hep-ph]
[45] J. F. Ziegler, J. P. Biersack, and U. Littmark, Pergamon Press, (1985).
[46] J. F. Ziegler, M. D. Ziegler, and J. P. Biersack, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 268, 1818 (2010) 19th International Conference on Ion Beam Analysis.
[47] W. D. Wilson, L. G. Haggmark, and J. P. Biersack, Phys. Rev. B15, 2458 (1977)
[48] J. Lindhard, M. Scharff, and H. E. Schiøtt, Mat. Fys. Medd. Dan. Vis. Selsk. 33, no. 14 (1963).
[49] J. Lindhard, , V. Nielsen, M. Scharff, and P. V. Thomsen, Mat. Fys. Medd. Dan. Vis. Selsk. 33, no. 10 (1963).
[50] D. Mei and A. Hime, Phys. Rev. D73, 053004 (2006) arXiv:astro-ph/0512125 [astro-ph]
[51] C. A. O’Hare, Phys. Rev. D94, 063527 (2016) arXiv:1604.03858 [astro-ph.CO]
[52] P. Cushman et al., in Proceedings, 2013 Community Summer Study on the Future of U.S. Particle Physics: Snowmass on the Mississippi (CSS2013): Minneapolis, MN, USA, July 29-August 6, 2013 (2013) arXiv:1310.8327 [hep-ex]
[53] M. Sorensen, H. Svensmark, and U. Gråe Jørgensen, (2017), arXiv:1708.08248 [astro-ph.SR]
[54] A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers, and Y. Xu, JCAP 1302, 004 (2013) arXiv:1203.3542 [hep-ph]
[55] P. R. Renne, W. D. Sharp, I. P. Montaæz, T. A. Becker, and R. A. Zierenberg, Earth and Planetary Science Letters 193, 539 (2001)
[56] A. Wójtowicz, S. P. Hryniv, T. M. Peryt, A. Bubniak, I. Bubniak, and P. M. Bilonizhka, Geologica Carpathica 54, 4, 243 (2003).
[57] V. Berezinsky, V. Dokuchaev, and Y. Eroshenko, Phys. Rev. D77, 083519 (2008), arXiv:0712.3499 [astro-ph]
[58] M. Ricotti and A. Gould, Astrophys. J. 707, 979 (2009), arXiv:0908.0735 [astro-ph.CO]
[59] D. Stiff, L. M. Widrow, and J. Frieman, Phys. Rev. D64, 083516 (2001), arXiv:astro-ph/0106048 [astro-ph]
[60] K. Freese, P. Gondolo, and H. J. Newberg, Phys. Rev. D71, 043516 (2005) arXiv:astro-ph/0309279 [astro-ph]
[61] M. Zemp, J. Diemand, M. Kuhlen, P. Madau, B. Moore, D. Potter, J. Stadel, and L. Widrow, Mon. Not. Roy. Astron. Soc. 394, 641 (2009) arXiv:0812.2033 [astro-ph]