

SENSEI: A Search for Diurnal Modulation in Sub-GeV Dark Matter Scattering

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Dark matter particles with sufficiently large interactions with ordinary matter can scatter in the Earth's atmosphere and crust before reaching an underground detector. This Earth-shielding effect can induce a directional dependence in the dark matter flux, leading to a sidereal daily modulation in the signal rate. We perform a search for such a modulation using data from the SENSEI experiment, targeting MeV-scale dark matter. We achieve nearly an order-of-magnitude improvement in sensitivity over previous direct-detection bounds for dark-matter masses below ~ 1 MeV, assuming the standard halo model with a Maxwell-Boltzmann velocity distribution, and restrict the amplitude of a general daily modulation signal to be below 6.8 e/g/d.

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Introduction—There is substantial evidence that a large fraction of the matter in our Universe consists of a non-baryonic form of matter known as dark matter (DM). Despite direct-detection experiments searching for DM for the past four decades, no convincing evidence for DM

interactions in terrestrial detectors has been found. DM candidates with mass less than the proton (“sub-GeV DM”) are well-motivated and have been given much attention over the last decade [1,2]. DM particles in this mass range can scatter off electrons and deposit energies of $\mathcal{O}(\text{few eV})$ [3,4]. Consequently, semiconductor-based detectors with eV-scale ionization thresholds are well-suited for these searches [3,5,6], providing the sensitivity required to probe sub-GeV DM candidates.

Particle interactions in silicon can excite electrons from the valence band to the conduction band, leading to the creation of one or more electron-hole pairs (simply referred

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to as electrons, e^-). The Skipper-CCD is a silicon detector that can measure these signals [7]. The charge in each pixel of a Skipper-CCD is moved pixel by pixel to the readout stage, where it is measured repeatedly and nondestructively to achieve subelectron noise levels sufficient for single-electron resolution. However, in the lowest charge bins, the detector sensitivity is limited by backgrounds [8–11]. This makes it especially challenging to search for DM particles with masses near the MeV scale, as these would only populate the lowest charge bins. One method to substantially improve our sensitivity to such DM particles is to search for a time-varying signal over a time-independent background.

The DM scattering rate can modulate annually [12] or daily. Here, we will focus on the diurnal modulation induced by DM scattering in the Earth before interacting in the detector. One example is DM that couples to the visible sector via a dark photon that is kinetically mixed with the ordinary photon, which predicts that DM couples both to electrons and nucleons. For sufficiently large DM interactions, scattering in the Earth distorts the DM velocity distribution before the DM reaches underground detectors [13–16]. As a result, the observable DM flux depends on the detector’s location on Earth through its orientation relative to the incoming DM wind, leading either to an attenuation or an enhancement of the detectable flux due to this anisotropic scattering effect. The resulting daily modulation has been recently studied theoretically [17] and experimentally [18,19]. In this Letter we present the first results from a daily modulation search with the SENSEI experiment using data taken at the underground MINOS cavern at Fermi National Accelerator Laboratory (Fermilab). We perform both a model-independent and a model-dependent search, present a new modulation analysis tool, and demonstrate an improved limit for DM masses: $m_\chi < 2$ MeV. See Supplemental Materials for additional analysis details [20].

Data collection—The dataset used here—collected at the MINOS underground cavern at Fermilab between February 29 and May 16, 2024—was previously described in Ref. [23], where it was used to characterize the detector’s overall single-electron rate by comparison with that study’s primary SNOLAB dataset. Data were collected using two science-grade Skipper-CCDs designed at the Lawrence Berkeley National Laboratory and fabricated at Teledyne DALSA Semiconductor, each of which has a thickness of 665 μm and an active area of 6144×1024 pixels of size $15 \times 15 \mu\text{m}^2$, for an active mass of 2.19 g. Each CCD is read out through four amplifiers, each of which reads a “quadrant” of 512 rows by 3072 columns.

We refer to a single exposure and readout of both Skipper-CCDs, with a total of eight quadrants, as an “image.” To mitigate the effects of exposure-independent charge accumulation in the serial register, the data are binned during readout by summing 32 rows into the serial register at a time. As a result, each “superpixel” in the

image corresponds to a 1×32 block of physical pixels. With four amplifiers, each reading one CCD quadrant including 128×4 superpixels of overscan per quadrant, the total readout time per image is approximately 16 min.

While the data from MINOS described in [23] include cyclic exposures of 0, 2, and 6 h, our analysis is restricted to the 6-h exposures and to single-electron events. By refraining from any prior daily-modulation analysis of this dataset, we ensure our search remains unbiased. To ensure a hidden-data (“blind”) analysis, we develop and validate the analysis framework on two sets of three consecutive days, amounting to 12 images, which represent approximately 8% of the full dataset. We then perform the analysis on 141 6-h images (comprising the DM search dataset), collected over a period of 75 days, with a quadrant-dependent $1e^-$ density ranging from 1.09×10^{-5} to $2.46 \times 10^{-5} e^-/\text{pixel}$ and total exposure of 1.09×10^5 g/d.

Data reconstruction and selection—Data processing, calibration, and corrections are done using the exact same procedure as in [23]. The masks used are also identical to those described in [23] with the caveat that the hot image mask is not used as it could introduce or hide a modulation signal. The noisy-image mask is applied, although we find zero “noisy” images. The masks remove $\approx 23\%$ of the pixels across all images.

Signal modeling—

Model-independent rate: For a model-independent signal, we fit the number of events sourced by the DM to a constant that includes both the background and an average DM signal rate, together with a single sine function with a period of 1 d, defined as

$$S_{\text{ind}}(\mu) = \int_{t_{\text{exp}}} a_1 \cdot \sin(\omega t + \phi) dt. \quad (1)$$

Here, a_1 is the amplitude of the signal’s daily modulation rate, t_{exp} is the exposure duration, $\omega = (2\pi/T_{\text{sid}})$ is the angular frequency corresponding to a sidereal daily modulation rate, and ϕ is the modulation phase relative to the time of the first measurement. Consequently, we define the model-independent signal parameters as $\mu = (a_1, \phi)$. The overall rate is constrained to be higher than 0 at all times.

Model-dependent rate: Within specific models the scattering rate and modulation amplitude can be calculated as a function of the model parameters. For concreteness, we consider here the case of sub-GeV DM interacting with the visible sector through a dark photon that is kinetically mixed with the ordinary photon [2,3,5,24,25]. Such DM particles can scatter off both nuclei and electrons, with the former dominating the scattering in the atmosphere and the Earth, and the latter creating the observable signal in the detector [26].

The DM-electron scattering rate is given by [5]

$$\frac{dR}{d\ln E_e} = \frac{\rho_\chi}{m_\chi} \frac{\bar{\sigma}_e}{8m_{\chi e}^2} \int \frac{dq}{q^2} |F_{\text{DM}}(q)|^2 |f_{\text{res}}(E_e, q)|^2 \eta(v_{\text{min}}). \quad (2)$$

Here, E_e and q denote the energy transferred to the electron and the momentum lost by the DM, respectively. The DM mass is denoted by m_χ , and the local DM density is taken to be $\rho_\chi = 0.3 \text{ GeV/cm}^3$ recommended from [27] (see also Refs. [28–32]). The quantity $\mu_{\chi e}$ is the reduced mass of the DM-electron system, and $\bar{\sigma}_e$ is the reference DM-free electron scattering cross section, defined at a fixed momentum transfer $q_0 = \alpha m_e$, with m_e the electron mass. The function $F_{\text{DM}}(q) = (\alpha m_e/q)^n$ encapsulates the momentum dependence of the interaction. Specifically, $n = 0$ corresponds to the case of a heavy mediator ($m_{A'} \gg \alpha m_e$, where $m_{A'}$ is the dark-photon mass), while $n = 2$ describes the light mediator limit ($m_{A'} \ll \alpha m_e$). The material-specific, dimensionless response function $f_{\text{res}}(E_e, q)$ characterizes the probability of an electron excitation with energy E_e and momentum transfer q in the target [5].

Crucially for the present analysis, the dependence on the DM halo velocity distribution is encoded in

$$\eta(v_{\min}) = \int_{v_{\min}} \frac{f(\mathbf{v}, t)}{v} d^3\mathbf{v}. \quad (3)$$

The DM velocity distribution is typically modeled as an isotropic Maxwell-Boltzmann distribution in the Galactic frame [33]. In this Letter, we adopt the standard halo model with parameters $v_0 = 238 \text{ km/s}$ and $v_{\text{esc}} = 544 \text{ km/s}$, following [27]. The Earth’s velocity is computed as a function of time and evaluated on March 3, 2024, corresponding to the midpoint of the data-taking period. However, this distribution is subsequently modified as DM particles traverse the Earth. We define the isodetection angle (or isoangle) Θ as the angle between the local zenith and the direction of the mean DM flux, given by $\langle \vec{v}_\chi \rangle = -\vec{v}_{\text{lab}}$. Here, $\Theta = 0^\circ$ corresponds to a flux arriving from directly overhead, while $\Theta = 180^\circ$ corresponds to a flux arriving from directly beneath the detector. In most DM searches, the directionality of the flux is neglected. However, if the DM-nucleus scattering cross section is sufficiently large, DM particles may undergo scattering within the Earth’s interior—particularly in the mantle and core—before reaching the detector. This can significantly alter the incoming DM flux and the observable signal. Importantly, the isoangle Θ varies with time due to the Earth’s rotation. Over the course of a sidereal day, $\Theta(t)$ modulates at any fixed detector location. For our experimental setup at Fermilab (41.84°N), $\Theta(t)$ varies between 10° and 86° (for more details see Refs. [16,17,34]). Consequently, for models with sufficiently large DM-nucleus cross sections, a characteristic daily modulation of the signal is expected.

To quantify this effect, we employ the DaMaSCUS code [16], which performs a full 3D Monte Carlo simulation of DM propagation through the Earth, accounting for energy loss and deflection due to elastic scattering. The resulting distribution, $f(v, \Theta_i)$, can be integrated and convolved with

the relevant detector response to obtain the differential event rate as a function of isodetection angle. Since Θ_i is a deterministic function of time at a fixed location, it is straightforward to convert $\Theta_i \rightarrow t_i$, allowing one to express the event rate as a function of time. By implementing the ionization model from [35], and using a modified version of QCDark [36], which incorporates a charge-screening function based on the formalism in [37] (for details see also Ref. [17]), we compute the number of time-dependent single-electron events from the rate as

$$S_d(\mu) = \int_{t_{\text{exp}}} R_{1e^-}(m_\chi, \bar{\sigma}_e, t) dt, \quad (4)$$

where $\mu = (m_\chi, \bar{\sigma}_e, t)$, and t_{exp} is the exposure duration. In what follows, we use $S(\mu)$ as a generic notation for the signal model, covering both the model-independent signal $S_{\text{ind}}(\mu)$ and the model-dependent signal $S_d(\mu)$.

Statistical treatment—Using the number of unmasked pixels containing 1 e^- events, we perform a likelihood ratio analysis based on [38] to search for a potential DM signal. Our analysis framework is general and accommodates both model-independent [Eq. (1)] and model-dependent [Eq. (4)] signals.

To search for a DM signal, we compute the profile likelihood-ratio test statistic based on the background-only hypothesis, $\mu = 0$. We then compute a p value as the percentile of the observed test statistic within the distribution of toy Monte Carlo simulations under the background-only hypothesis. In case no evidence for a DM signal is found, we set a 90% CL upper limit on the signal strength μ . For each μ , we compute the statistic of the observed data, simulate its distribution under the signal-plus-background hypothesis with toy Monte Carlo, and identify the μ at which the observed test statistic reaches the 90th percentile. The full details of the likelihood analysis computations and the Monte Carlo simulation are provided in Supplemental Material [20].

In the single-image likelihood function used in this analysis, we assume Poisson statistics with a constant dark current across all quadrants throughout data collection. Upon inspecting the data, we observed deviations from a pure Poisson distribution. To ensure these deviations do not bias the results, we performed a dedicated validation test (see Supplemental Material [20]). Furthermore, we conducted an additional test to verify that the time-independent background component is consistent with Poisson statistics under the test statistic employed in our analysis. To evaluate this consistency, we applied the bootstrap method [39,40], which involves uniformly resampling the 1 e^- time-ordered dataset to produce new datasets with randomly shuffled time stamps. This procedure effectively removes any time-dependent structure, allowing us to isolate and test the time-independent background. It should be noted, however, that this method cannot detect small deviations

from Poisson statistics that arise from time-independent sources.

Any finite dataset will naturally exhibit statistical fluctuations around an ideal Poisson distribution. To quantify the expected range of such fluctuations under the null hypothesis, we generate an ensemble of Monte Carlo datasets with no injected signal assuming purely Poisson statistics. For each simulated dataset, we perform multiple bootstrap resamplings of the time stamps. For each resampled instance, we compute the p value. We then average the p values obtained from these bootstrap samples to assign a single mean p value to that dataset. Repeating this procedure over the full ensemble of simulated datasets yields a distribution of mean p values that is used to define a $\pm 2\sigma_p$ -wide band within which the data are consistent with Poisson fluctuations, which is referred to as the Poisson-consistency band. The method was further validated on simulated datasets containing both background and signal. We assess sensitivity to model-dependent (blue) and model-independent (red) signals by comparing results before bootstrapping (solid curves) and after bootstrapping (dashed curves). At low SNR, all curves converge to the Poisson consistency band, as expected: when the signal is negligible, the datasets are dominated by Poisson background and thus yield consistent results with the no-signal hypothesis. In the presence of a signal, the mean p value, $p\text{-value}(t_{\mu=0})$, decreases with SNR in the time-ordered simulated datasets, whereas it remains flat for the bootstrapped datasets up to SNR ratio of 0.7 (model-dependent) and 0.55 (model-independent). More details on the bootstrap simulation are provided in Supplemental Material [20].

We then apply the same bootstrap procedure to the observed dataset to compute its mean p value. If this value lies within the Poisson-consistency band, the data are statistically compatible with the Poisson assumption of a time-independent background within our statistical treatment method. If, however, the mean p value deviates significantly, i.e., by more than $2\sigma_p$, this would indicate a statistically significant departure from Poisson behavior. Such a deviation could correspond to a background fluctuation that mimics a signal-like effect large enough to substantially alter our exclusion limits. In that case, it is necessary to investigate the origin of the non-Poissonian background, whether due to unknown systematics or genuine time-dependent effects, before interpreting the result.

Results—For the signal models defined in Eqs. (1) and (2), the fits yield $p\text{-value} > 0.001$, indicating no statistically significant evidence for a DM signal at any mass. Results from the bootstrap test are presented in Fig. 1. The mean p value and statistical error of the observed data after performing the bootstrap procedure for a model-dependent signal [Eq. (4)] is 0.52 ± 0.02 (blue band in Fig. 1), while for a model-independent signal [Eq. (1)] the p value is 0.46 ± 0.01 (red band in Fig. 1). In both cases, the mean p values lie within the Poisson-consistency band. The figure also shows simulations using

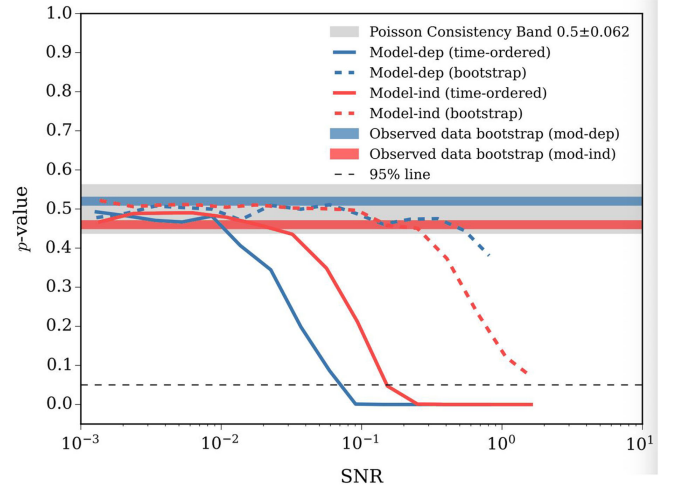


FIG. 1. Results of the bootstrap test validating the assumption of a Poisson-distributed, time-independent background of our observed data. The gray band shows the 2σ variance around a mean p value calculated from fitting background-only Poisson-based Monte Carlo datasets. The blue and red bands indicate the calculated variance of the p value obtained from bootstrapping the observed data multiple times. No statistical deviation of the background from the Poisson assumption is observed. All horizontal bands are signal-to-noise ratio (SNR) independent. The dashed gray line shows the 95% indication for a dark-matter signal. For the simulation bootstrap test the p value is shown as a function of the SNR. For each value of SNR, the mean p value from 500 simulated datasets was calculated, assuming a model-independent [Eq. (1), red] and model-dependent [Eq. (4), blue] signal. The solid lines indicate fits using time-ordered time stamps, while dashed lines indicate fits using bootstrap-resampled time stamps.

normal-ordered time stamps (solid lines) and bootstrap-resampled time stamps (dashed lines) for both signals, with each data point for the line obtained by calculating the mean of 500 p values computed for simulated datasets at a given signal-to-noise ratio.

Applying the procedure outlined in the “Statistical Treatment” section, we obtain a 90% CL upper limit on the model-independent modulation amplitude of

$$a_1 \leq 6.8 \, e^{-g^{-1} d^{-1}}. \quad (5)$$

For the model-dependent analysis, Fig. 2 compares the least noisy CCD quadrant of the data (shown in black), after subtraction of the best-fit background, with the expected DM signal from Eq. (2) (after subtracting the mean DM signal rate). We assume a DM particle mass of 1 MeV and a cross section $\bar{\sigma}_e = 5 \times 10^{-32} \text{ cm}^2$, interacting via a heavy dark-photon mediator. This quadrant dominates the resulting constraint on the model.

Figure 3 shows the 90% CL exclusion limits for light (left panel) and heavy (right panel) mediators, computed using DaMaSCUS and QCDark. The solid purple line and

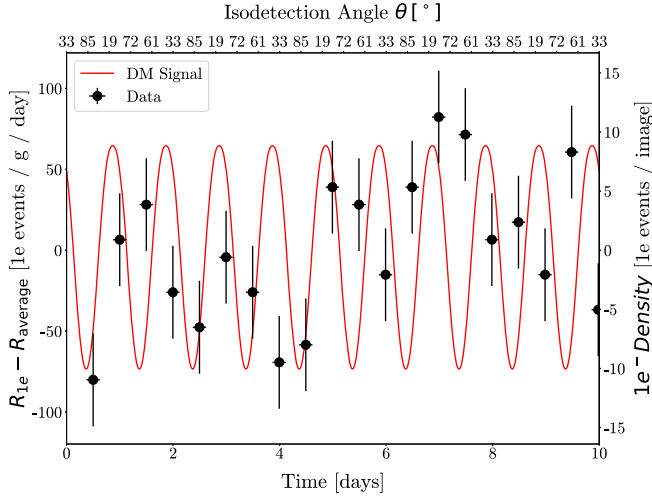


FIG. 2. Comparison of the fluctuation around the average of both the measured $1 e^-$ rate (black circles) with the rate predicted for a 1 MeV DM particle interacting with ordinary matter through a heavy dark-photon mediator with a cross section of $\sigma_e = 5 \times 10^{-32} \text{ cm}^2$ (solid red line), which represents the current most stringent bound at this mass. The measured rate is taken from the lowest-noise CCD quadrant, with an average value of $135 e^-/\text{g/d}$. The lower x axis shows the first 10 days of measurement, while the upper x axis indicates the corresponding isodetection angles. Vertical error bars denote the statistical uncertainty of each image, given by the square root of the counts in the image, while horizontal error bars indicate the estimated average rate over the associated 6-h exposure (note that the 6-h exposures were not taken sequentially).

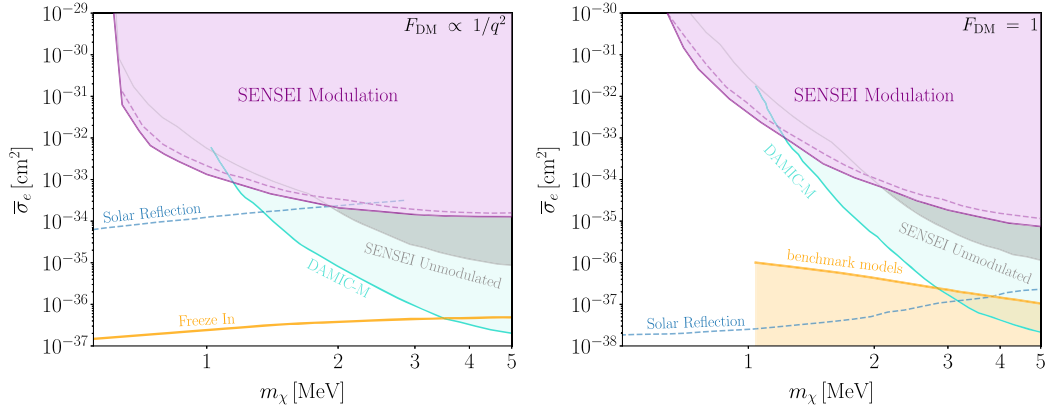


FIG. 3. 90% CL upper limits on the DM-electron scattering cross section for a light (left) and heavy (right) dark-photon mediator, calculated with DaMaSCUS and QEDark. Solid purple line and shaded region correspond to the constraints applied directly to the model referenced in Eq. (4), while the dashed line indicates the 90% CL upper limit obtained by recasting our constraint in Eq. (5) on the model-independent modulation amplitude a_1 of Eq. (1); the latter was calculated by fitting the mass and $\bar{\sigma}_e$ that generates the same daily modulation amplitude a_1 . The blue dashed curve shows the upper limit from solar-reflected halo DM, assuming a dark-photon mediator [44] using data from [45] (see also Ref. [46]). The orange solid curve indicates the canonical freeze-in benchmark target for the light-mediator model [3,5,47,48] and benchmark regions for a heavy mediator [3,5,47–55]. The solid gray line and shaded region denote the existing SENSEI limits [23,41]. The turquoise region shows the DAMIC-M limit from [43]; we show the DAMIC-M daily modulation constraint from [19] in Supplemental Material [20], as it is based on QEDark without screening.

shaded region represent the exclusion limits derived in this Letter. For comparison, previous constraints from SENSEI [41,42] and DAMIC-M [43] are also included. The daily-modulation search limit by DAMIC-M [19] is included only in Supplemental Material [20], since it was calculated with QEDark without screening, and can thus not be directly compared; nevertheless, Supplemental Material [20] performs the comparison under a consistent set of assumptions and demonstrate that our upper limit is more constraining. This analysis significantly improves upon previous direct-detection limits in the region dominated by the single-electron ($1 e^-$) channel, particularly for DM masses in the range of approximately 0.6–1 MeV. The dashed purple lines correspond to exclusion limits obtained by identifying the values of $\bar{\sigma}_e$ and m_χ that saturate the model-independent limit from Eq. (5). As expected, these recasted limits are slightly weaker than those obtained from the full model-dependent analysis, since the model-independent constraint does not incorporate the full spectral information encoded in the specific model from Eq. (4).

In summary, we have presented both model-independent and model-dependent searches for daily modulation in the single-electron event rate measured with Skipper-CCDs at Fermilab. This approach enabled a significant improvement—by approximately an order of magnitude—in the constraints on halo DM scattering for DM masses below 1 MeV, relative to previous results, although the bounds are still weaker than those obtained from solar reflected DM. The sensitivity can be enhanced further by considering datasets with larger exposures.

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Data availability—The data that support the findings of this article are openly available [56].

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