PROCEEDINGS OF SCIENCE

The DarkNESS mission: probing dark matter with a Skipper-CCD satellite observatory

Nathan Saffold,[a,*] **Phoenix M. Alpine,**[b] **Rouven Essig,**[c] **Juan Estrada,**[a,d] **Terry Kim,**[a] **Donna Kubik**[a] **and Michael F. Lembeck**[b]

[a] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[b] *Aerospace Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA*
[c] *C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, NY 11794, USA*
[d] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA*

E-mail: nsaffold@fnal.gov

The invention of Skipper-CCDs with sub-electron noise has paved the way for groundbreaking low-threshold dark matter (DM) experiments, such as SENSEI and DAMIC. Conventionally, these experiments are deployed underground to mitigate cosmogenic backgrounds; however, some DM signatures are inaccessible to underground experiments due to attenuation in the Earth's atmosphere and crust. The DarkNESS mission will deploy an array of Skipper-CCDs on a 6U CubeSat in Low Earth Orbit (LEO) to search for electron recoils from strongly-interacting sub-GeV DM as well as X-ray line signatures from sterile neutrino decay. Using a series of observations from LEO, the DarkNESS mission will set competitive upper limits on the DM-electron scattering cross section and help resolve the experimental conundrum associated with the purported observation of a 3.5 keV X-ray line, potentially produced from sterile neutrino decay. This work will describe the DarkNESS instrument, the technical challenges in operating Skipper-CCDs in the space environment, the scientific objectives of the DarkNESS mission, and the DM parameter space that DarkNESS will probe.

XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
28.08–01.09.2023
University of Vienna

[*] Speaker

https://pos.sissa.it/

1. Introduction

Despite overwhelming evidence that dark matter (DM) exists, and a vigorous experimental program aiming to detect DM, there have been no conclusive detections of DM. Although the nature of DM remains unknown, there are many well-motivated extensions to the Standard Model that naturally provide DM candidates. Two well-motivated DM candidates are sterile neutrino DM [1] and sub-GeV DM interacting via electron recoils [2], and both of these DM models will be probed by the upcoming DarkNESS mission.

Satellite-, balloon-, and rocket-borne observations are paramount to detect astronomical signals that do not penetrate the Earth's atmosphere. Since the birth of X-ray astronomy in the early 1960s, space-based observations of the X-ray sky have informed our understanding of the Universe. Similarly, the deployment of particle detectors in space has contributed to investigations of high-energy astrophysical processes, as well as the radiation environment in which these instruments operate. In recent decades, CubeSats have enabled opportunities to deploy compact instrumentation in the space environment with the potential to make a significant impact on focused scientific goals.

The Dark matter Nanosatellite Equipped with Skipper Sensors (DarkNESS) mission will deploy Skipper Charge-Coupled Devices (Skipper-CCDs) on a 6U CubeSat to search for diffuse X-rays from sterile neutrino decays and electron recoils from sub-GeV DM. While CCDs have been used in focal plane arrays for many space-based instruments, DarkNESS will be the first to deploy novel CCDs with a Skipper amplifier in space. The Skipper amplifier makes repetitive, nondestructive measurements of the charge in each pixel, reducing the noise from $\sim 2\,e^-$ in conventional CCDs to sub-electron levels in Skipper-CCDs [3]. Since their invention, Skipper-CCDs have been used for DM direct detection [4], coherent elastic neutrino-nucleus scattering searches [5], as well as ground-based astronomy [6]. By demonstrating the operation of Skipper-CCDs in space, DarkNESS will pave the way for future space-based instruments using Skipper-CCDs in X-ray spectrometers and single-photon counting arrays [7]. This work will provide an overview of the DarkNESS mission, including its science objectives and projected science reach.

2. Instrument design

The DarkNESS instrument consists of four 1.3-megapixel Skipper-CCDs housed in a 6U CubeSat. Each Skipper-CCD has an area of $1.9 \times 1.6\,\mathrm{cm}^2$ and a thickness of $250\,\mu$m. The CCDs and a flex cable are epoxied and wirebonded onto an aluminum nitride ceramic substrate, forming a multi-chip module (MCM). Each CCD is biased and read out using a small-format Low Threshold Acquisition readout electronics board, hereby referred to as a space-LTA (sLTA). The sLTA uses less power than the readout electronics previously designed for direct DM searches [8], and has a copper core engineered to facilitate thermal management during operations in space. The Skipper-CCDs are operated at a bias voltage of 80 V, and the sLTA is designed to read out the CCDs at a rate of 250 kpixels/s. Fermilab is in charge of the development of the Skipper instrument, the sLTA readout electronics, and the analysis tools used to process the instrument's data.

The Skipper-CCDs are actively chilled to an operating temperature of 170 K using a Ricor K508N compact cryocooler. The heat generated by the detector module and readout electronics is passively transported to two body-mounted radiator panels, which are designed to radiate the

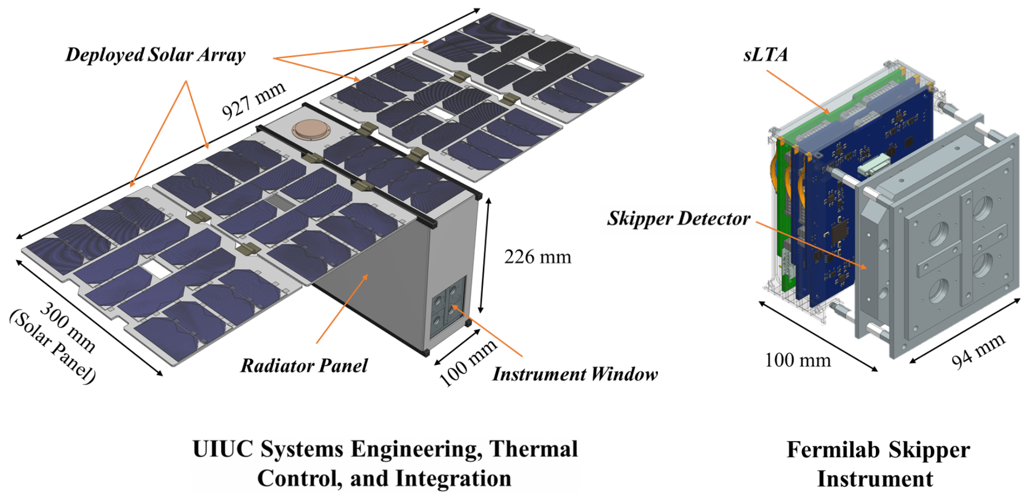

Figure 1: Overview of the DarkNESS preliminary design. Fermilab is responsible for the development of the Skipper-CCD instrument. The Laboratory for Advanced Space Systems at Illinois (LASSI) is responsible for designing and integrating the thermal control system as well as systems engineering for the project.

waste heat into dark space. The Skipper instrument and supporting thermal control hardware will be integrated into a 6U CubeSat bus. This bus encompasses key satellite subsystems including the flight computer, payload controller, attitude control system, electrical power system, and a dedicated S-band radio to downlink science and telemetry data. The bus supports a dual-deployable solar array configuration, which will provide up to 72 W of power in direct sunlight. The Laboratory for Advanced Space Systems at Illinois (LASSI) is responsible for the design and integration of the thermal control system. Figure 1 shows the preliminary design of DarkNESS, featuring the Skipper-CCD instrument and satellite configuration.

3. DarkNESS mission

DarkNESS will launch into a mid-inclination Low Earth Orbit (LEO) at an approximate altitude of ~400 km. Upon reaching orbit, it will undergo commissioning to establish control and confirm operational readiness. Once commissioning is complete, DarkNESS will enter its science phase, conducting observations of its primary science targets: the Galactic Center (GC) and Cygnus X-1 (Cyg X-1). The mission is anticipated to last for two years from deployment, concluding as the satellite naturally decays from its orbit.

The DarkNESS mission will map the diffuse X-ray background around the GC and search for unidentified X-ray lines that could be produced by DM. DM that decays into two-body final states including a photon will give rise to nearly monochromatic line signatures that can stand out above the X-ray background. The sterile neutrino is one such DM candidate that could decay, producing an active neutrino and a photon. This process produces the photon with an energy equal to half the mass of the sterile neutrino, providing a potential signature of new physics [1]. The decay of a ~7 keV sterile neutrino could explain an unidentified X-ray line at 3.5 keV that was detected with high significance using stacked observations of galaxy clusters from instruments on the XMM-Newton satellite [9]. This detection inspired a flurry of follow-up observations with mixed results.

The most recent results in this area disfavor the interpretation of the 3.5 keV line as a byproduct of DM decay (e.g. [10–13]). With dedicated observations of the GC diffuse emission, DarkNESS will help resolve the origin of the 3.5 keV line with competitive sensitivity, as shown in Fig. 2.

The second science objective of DarkNESS is to search for strongly-interacting sub-GeV DM. While underground experiments have set some of the most competitive DM limits, DM models with a higher cross section would not make it through the Earth's atmosphere and crust to reach underground detectors. These models are heavily constrained by CMB and other measurements, but are still allowed for a subdominant DM component [14–16]. DarkNESS will search for strongly-interacting sub-GeV DM by observing towards Cyg X-1, which is the motion direction of the Sun, and looking for modulations in the rate of low-energy events over the orbital period [17]. For strongly-interacting DM, the expected DM signal rate depends heavily on the position of the detector relative to the Earth, since the Earth would block a large fraction of the strongly-interacting DM flux coming from Cyg X-1. This shielding effect leads to a large modulation in the DM signal rate over the course of the orbital period, as discussed in Ref. [17].

As the first mission-operating Skipper-CCDs in space, DarkNESS will help advance the technology readiness level of Skipper-CCDs for space-based applications. The radiation environment in LEO will provide significant challenges for detector operations, as background cosmic rays will deposit energy in the CCDs, leaving ionization tracks in the images and potentially inducing radiation damage in the silicon lattice. While laboratory measurements have given promising results for the radiation tolerance of similar CCDs [18], these tests were done with CCDs without a Skipper amplifier, and work to understand the radiation tolerance of the Skipper-CCD amplifier is ongoing. The DarkNESS mission will study the effects of radiation on Skipper-CCDs using laboratory measurements, simulations, and finally with the first operation of Skipper-CCDs in space.

4. Sensitivity calculation

4.1 Decaying dark matter

The expected flux of photons from decaying DM is proportional to the decay rate Γ and the number of DM particles in the line-of-sight of the observation. The decay rate of a sterile neutrino ν_s into a photon and an active neutrino is given as [1]

$$\Gamma_{\nu_s \to \gamma \nu_a} = \frac{9\alpha G_F^2 m_\chi^5 \sin^2 2\theta}{1024\pi^4} = (1.38 \times 10^{-29}) \left(\frac{\sin^2 2\theta}{10^{-7}}\right) \left(\frac{m_\chi}{1 \text{ keV}}\right)^5 \text{ s}^{-1}. \quad (1)$$

Here, m_χ is the sterile neutrino mass, θ is the mixing angle between the active and sterile neutrino states, α is the fine-structure constant, and G_F is the Fermi constant. Due to the high density of DM in the GC, observations of the GC predict a large signal flux from DM decays, but also contain significant flux from conventional astrophysical sources including low-mass X-ray binaries and diffuse emission in the Galactic Ridge. Based on a detailed spectral model of the X-ray background for a 20° field of view (FOV) observation of the GC [19], we are able to set upper limits on the flux from unidentified lines that DarkNESS could measure above the modeled background using a sliding energy window. The flux limits are recast into units of $\sin^2 2\theta$ and shown in Fig. 2. These limits assume 25 hours of exposure time (300 images with five-minute exposure times)

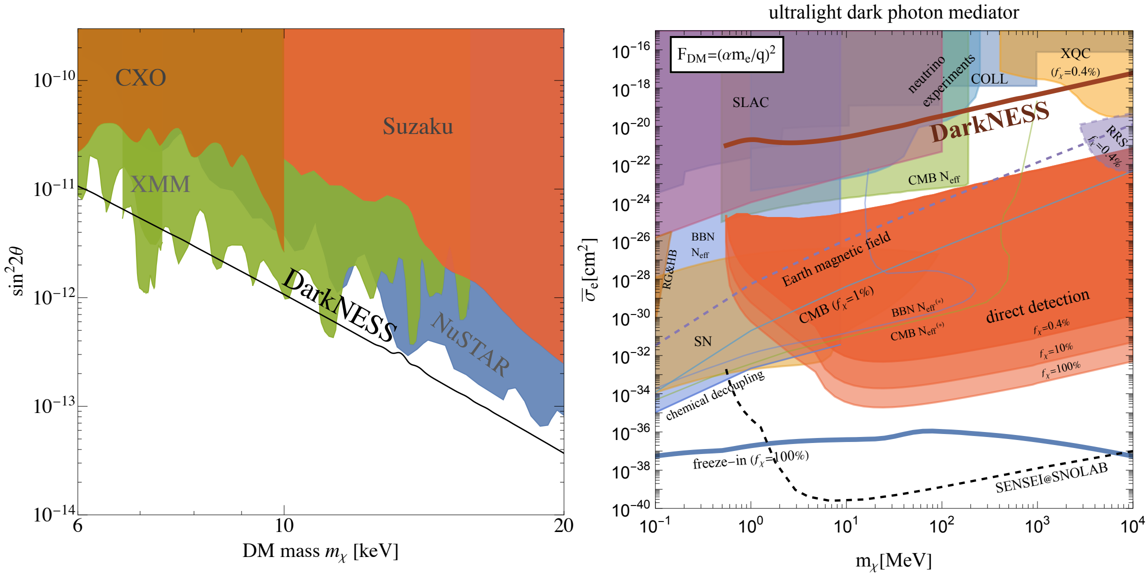

Figure 2: *Left:* DarkNESS sensitivity to probe X-rays from sterile neutrino decay using 25 hours of observation time of the Galactic Center. Using wide FOV observations with Skipper-CCDs provides competitive sensitivity to X-rays from decaying DM. *Right:* DarkNESS discovery reach to probe DM interacting strongly with via an ultralight dark photon, assuming an exposure of 0.1 gram-months and 10^9 background events (plot adapted from [17]).

pointing at Galactic Center with a 20° FOV, with the energy resolution of a typical CCD [20]. To be conservative, we assume only 15% of the CCD area survives analysis cuts due to cosmic ray bombardment. Using wide FOV observations of the GC, DarkNESS will provide competitive sensitivity to X-ray signatures of sterile neutrino decay.

4.2 Strongly-interacting sub-GeV dark matter

Strongly-interacting sub-GeV DM would result in a strong modulation in the rate of low-energy events in a space-borne detector pointed at Cyg X-1. Using low-threshold Skipper-CCDs in LEO to search for this modulation signature will expand the upper limits on the DM-electron scattering cross section into new parameter space, as shown in Fig. 2. The limits shown assume a 0.1 g-month exposure, which requires about 100 hours of observation time using the DarkNESS Skipper instrument, well within the expected DarkNESS mission lifetime.

5. Conclusions and future work

DarkNESS will be the first deployment of Skipper-CCDs in space and will probe unexplored DM parameter space. Using focused observations of the GC and Cyg X-1, DarkNESS will provide competitive sensitivity to X-ray signatures of sterile neutrino decay and strongly-interacting sub-GeV DM. DarkNESS is currently in the critical design phase and will complete a critical design review in mid-2024. After finalizing the design, the Skipper instrument will be built, calibrated, and integrated into the satellite bus. The satellite system will be subjected to environmental testing to demonstrate flight readiness prior to launch, which is planned for late 2025.

Acknowledgments

We are grateful for the support of the Heising-Simons Foundation. The author thanks Adam Anderson for useful discussions on sterile neutrino limit calculations, and Timon Emken for helpful consultations on computing and interpreting the strongly-interacting sub-GeV dark matter limits.

References

[1] R. Adhikari, M. Agostini, N.A. Ky, T. Araki, M. Archidiacono, M. Bahr et al., *A white paper on keV sterile neutrino dark matter*, *Journal of Cosmology and Astroparticle Physics* **2017** (2017) 025.

[2] R. Essig, J. Mardon and T. Volansky, *Direct detection of sub-GeV dark matter*, *Phys. Rev. D* **85** (2012) 076007.

[3] J. Tiffenberg, M. Sofo-Haro, A. Drlica-Wagner, R. Essig, Y. Guardincerri, S. Holland et al., *Single-electron and single-photon sensitivity with a silicon Skipper CCD*, *Phys. Rev. Lett.* **119** (2017) 131802 [1706.00028].

[4] L. Barak, I.M. Bloch, M. Cababie, G. Cancelo, L. Chaplinsky, F. Chierchie et al., *SENSEI: Direct-detection results on sub-GeV dark matter from a new skipper CCD*, *Physical Review Letters* **125** (2020) .

[5] and Alexis Aguilar-Arevalo, J. Bernal, X. Bertou, C. Bonifazi, G. Cancelo, V.G.P.B. de Carvalho et al., *Search for coherent elastic neutrino-nucleus scattering at a nuclear reactor with CONNIE 2019 data*, *Journal of High Energy Physics* **2022** (2022) .

[6] E.M. Villalpando, A. Drlica-Wagner, A.A.P. Malagón, A. Bakshi, M. Bonati, J. Campa et al., *Characterization and Optimization of Skipper CCDs for the SOAR Integral Field Spectrograph*, 2023.

[7] B.J. Rauscher, S.E. Holland, E. Kan, D. Kelly, L. Miko, D.B. Mott et al., *Radiation tolerant, photon counting, visible, and near-IR detectors for space coronagraphs*, in *Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave*, L.E. Coyle, S. Matsuura and M.D. Perrin, eds., vol. 12180, p. 1218065, International Society for Optics and Photonics, SPIE, 2022, DOI.

[8] G. Cancelo et al., *Low Threshold Acquisition controller for Skipper CCDs*, 2004.07599.

[9] E. Bulbul et al., *Detection of an Unidentified Emission Line in the Stacked X-Ray Spectrum of Galaxy Clusters*, *The Astrophysical Journal* **789** (2014) 13.

[10] C. Dessert, N.L. Rodd and B.R. Safdi, *The dark matter interpretation of the 3.5-keV line is inconsistent with blank-sky observations*, *Science* **367** (2020) 1465.

[11] A. Boyarsky, D. Malyshev, O. Ruchayskiy and D. Savchenko, *Technical comment on the paper of Dessert et al. "The dark matter interpretation of the 3.5 keV line is inconsistent with blank-sky observations"*, 2020. 10.48550/ARXIV.2004.06601.

[12] D. Sicilian, D. Lopez, M. Moscetti, E. Bulbul and N. Cappelluti, *Constraining Sterile Neutrino Dark Matter in the Milky Way Halo with Swift-XRT*, *The Astrophysical Journal* **941** (2022) 2 [2208.12271].

[13] C. Dessert, J.W. Foster, Y. Park and B.R. Safdi, *Was There a 3.5 keV Line?*, 2023.

[14] K.K. Boddy, V. Gluscevic, V. Poulin, E.D. Kovetz, M. Kamionkowski and R. Barkana, *Critical assessment of CMB limits on dark matter-baryon scattering: New treatment of the relative bulk velocity*, *Physical Review D* **98** (2018) .

[15] A. Prabhu and C. Blanco, *Constraints on dark matter-electron scattering from molecular cloud ionization*, *Physical Review D* **108** (2023) .

[16] C. Blanco, I. Harris, Y. Kahn and A. Prabhu, *Constraining dark matter-proton scattering from molecular cloud ionization*, 2023.

[17] T. Emken, R. Essig, C. Kouvaris and M. Sholapurkar, *Direct detection of strongly interacting sub-GeV dark matter via electron recoils*, *Journal of Cosmology and Astroparticle Physics* **2019** (2019) 070.

[18] K. Dawson, C. Bebek, J. Emes, S. Holland, S. Jelinsky, A. Karcher et al., *Radiation Tolerance of Fully-Depleted P-Channel CCDs Designed for the SNAP Satellite*, *IEEE Transactions on Nuclear Science* **55** (2008) 1725 [0711.2105].

[19] E. Figueroa-Feliciano, A.J. Anderson, D. Castro, D.C. Goldfinger, J. Rutherford, M.E. Eckart et al., *Searching for keV Sterile Neutrino Dark Matter with X-ray Microcalorimeter Sounding Rockets*, 2015.

[20] A. Aguilar-Arevalo, D. Amidei, X. Bertou, D. Bole, M. Butner, G. Cancelo et al., *The DAMIC dark matter experiment*, 2015.