Dark Matter Searches with the Micro-X X-ray Sounding Rocket

Enectalí Figueroa-Feliciano[1], Antonia Hubbard[2], Kevork Abazaijan[3], Joseph Adams[4], Adam Anderson[5], Carlos Argüelles[6], Simon Bandler[4], Alexey Boyarsky[7], Joseph Bramante[8], Esra Bulbul[9], André de Gouvêa[1], W. Bertrand Doriese[10], Megan Eckart[2], Joshua Fuhrman[1], Gene Hilton[10], Daniel Jardin[1], Caroline Kilbourne[4], Ranjan Laha[11], Reneé Manzagol-Harwood[1], Maxim Markevitch[4], Dan McCammon[12], F. Scott Porter[4], Carl Reintsema[10], Oleg Ruchayskiy[13], Nicholas Rodd[14], Denys Savchenko[15], Chintan Shah[4], Stephen Smith[4], Joel Ullom[10], Aaron Vincent[8], Patrick Wikus[16]

[1] Department of Physics and Astronomy, Northwestern University, Evanston, IL, USA
[2] Lawrence Livermore National Laboratory, Livermore, CA, USA
[3] Department of Physics and Astronomy, University of California, Irvine, CA, USA
[4] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[5] Fermi National Accelerator Laboratory, Batavia, IL, USA
[6] Department of Physics, Harvard University, Cambridge, MA, USA
[7] Leiden University, Leiden, Netherlands
[8] Department of Physics, Engineering Physics and Astronomy, Queen's University, Kingston ON, Canada
[9] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
[10] National Institute for Standards and Technology, Boulder, CO, USA
[11] Theoretical Physics Department, CERN, Geneva, Switzerland
[12] Department of Physics, University of Wisconsin, Madison, WI, USA
[13] Niels Bohr Institute, Copenhagen University, Copenhagen, Denmark
[14] Berkeley Center for Theoretical Physics, University of California, Berkeley, CA, USA
[15] Bogolyubov Institute for Theoretical Physics of the NAS of Ukraine, Kyiv, Ukraine
[16] Bruker BioSpin AG, Fallanden, Switzerland

Contact Information:

Enectalí Figueroa-Feliciano: *enectali@northwestern.edu*
Antonia Hubbard: *hubbard8@llnl.gov*

Thematic Areas:

- ■ CF1: Dark Matter: Particle Like
- ■ NF2: Sterile Neutrinos
- ■ NF3: BSM
- ■ IF1: Quantum Sensors
- ■ IF2: Photon Sensors

Micro-X is a high-resolution X-ray spectroscopy sounding rocket mission. It flew for the first time in July 2018, becoming the first program to carry Transition-Edge Sensors and multiplexing SQUID readout electronics in space. The instrument's original configuration was optimized for Supernova Remnant imaging, and this same configuration is planned for the reflight in 2021. We propose to modify the payload for indirect galactic dark matter searches in the X-ray band. Micro-X can achieve world-leading dark matter sensitivity in the keV regime with a single 300 second flight. The modifications will widen the field of view and optimize the detector response at higher energies. If an X-ray excess is seen (as has been previously reported by the X-ray satellites), Micro-X will be able to differentiate an atomic line from a dark matter signature. The modifications required to optimize the instrument for dark matter searches are understood and attainable with current technologies.

1 X-ray dark matter detection

Galactic dark matter surrounds the plane of luminous matter in the Milky Way and should produce an all-sky signal as seen from the solar system. This signal may be in the X-ray band if dark matter is one of the candidates predicted to participate in X-ray-producing interactions[1]. A notable example is the keV-scale sterile neutrino, which could decay to an X-ray and an active neutrino, producing an X-ray at half the sterile neutrino mass[2]. If keV-scale sterile neutrinos make up galactic dark matter, they are therefore predicted to produce an all-sky, monoenergetic X-ray signal.

Dark matter detection in the X-ray band is particularly compelling because several satellites (*Chandra, XMM-Newton, Suzaku*, and *NuSTAR*) observe an excess at 3.5 keV that may be the product of a dark matter interaction[3–7]. Broadly, these instruments have resolutions of $\sim$100 eV at this energy, and the observations are Ms-long. This excess is reported from the Galactic Center, galaxies, and galaxy clusters. It may be of atomic origin, but this implies that flux predictions are off by an order of magnitude[3–5]; laboratory astrophysics efforts to explore the atomic interpretation cannot currently account for this excess[8–11]. Complicating this discussion are the analyses that report no excess, sometimes even using the same data[3;5]. These analyses are limited by the low signal-to-noise ratio and systematic uncertainties of the instruments[12–15]. The line remains unconfirmed after limited observations with calorimeteric resolution as well[16;17]. The nature of this excess requires a new, high-resolution detector to be resolved.

2 The Micro-X Sounding Rocket

Sounding rockets are suborbital missions that provide approximately 5 minutes of data in the upper atmosphere ($>$160 km altitude). keV-scale X-rays are attenuated by the atmosphere, so they can only be observed above this altitude. Sounding rockets are significantly less expensive than satellite missions, and the instrument can be recovered after flight and reflown.

A sounding rocket mission with high-resolution detectors and a large FOV is well-suited to an indirect galactic dark matter search[17;18]. Galactic dark matter is an all-sky signal, so a 33° half-angle FOV sounding rocket observes a dark matter flux that is 2700 times that of *XMM-Newton*, making up for the short exposure[17]. Microcalorimeters provide the resolution required to separate the monoenergetic signal from nearby atomic lines[16]. Modifying Micro-X for a large FOV makes it an excellent instrument for this observation[17;18].

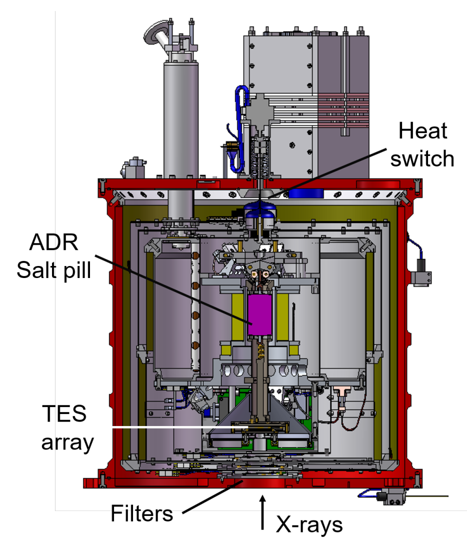

Figure 1: The Micro-X cryostat, which opens to space on the bottom side, and interfaces to electronics on the top side.

Micro-X launched in July 2018, marking the first operation of Transition Edge Sensor microcalorimeters (TES) and Time-Division Multiplexing (TDM) readout electronics in space. The instrument flew in its imaging configuration to observe the Cassiopeia A Supernova Remnant. While a rocket pointing error led to no time on-target, X-rays from the on-board calibration source were observed, and analysis of the system monitoring data made this a useful engineering flight[19]. The reflight is scheduled for 2021, and a modified version of the instrument for observing diffuse, all-sky signals is then proposed for dark matter searches.

The detector in both configurations is a 128-pixel TES array (Au/Bi absorber and Mo/Au TES[20;21]). The detectors are read out with a TDM Superconducting QUantum Interference Device (SQUID) system[22–24]. Temperature control for the cryogenic detectors uses a pumped LHe cryostat and an Adiabatic Demagnetization Refrigerator (ADR) (Figure 1), which maintained a temperature of 75 mK$\pm$6 μK during the science observation in the first flight[19]. Magnetic shielding minimizes the field from the ADR and the Earth at the detectors[19]. A vibration isolation system[25] kept any discernible heat from coupling onto the detectors during the first flight launch. With the largely successful demonstration of the instrument during the first flight, modifications are being implemented from the lessons learned in preparation for the SNR reflight [19]. The program will then be in a position to prepare modifications for a dark matter search.

To reach the dark matter instrument goals shown in Table 1, modifications are required for a larger FOV and a higher-energy bandpass, as described in [18]. The proposed detectors are a Mo/Au bilayer TES with a Au/Bi absorber (3 μm Bi, 0.7 μm Au). The expected signal rate is <10 Hz across the array (<1 Hz/pixel), which is well within the readout capabilities of the system.

Configuration	First flight	Dark Matter
Operating temperature	75 mK	75 mK
Energy resolution	4.5 - 10 eV	3 eV
Bandpass	0.2 – 4 keV	0.5 – 10 keV
Effective area	0.47 cm^2	1.1 cm^2
Field of view	11.8 arcmins	33 degrees
Observation time	300 s	300 s
Expected counts	13,000	2,400

Table 1: Micro-X instrument specifications

3 Dark Matter Sensitivity

The proposed first target is a region near the Galactic Center that is relatively quiet in the X-ray band. The background spectrum is a nearly flat continuum with 0.6 counts/flight/2.5 eV [17]. Using the flux derived from [26], 20.3±4.5 signal events are expected in a single flight, corresponding to $>5\sigma$ significance [18]. Micro-X will be sensitive to both the reported 3.5 keV excess and to any X-ray signature of dark matter in this energy band. In the case of sterile neutrinos, this sensitivity can be converted into the parameters shown in Figure 2. The Micro-X observations are statistics-limited, so additional flights will further increase the sensitivity. If a line is detected, Micro-X can discern between dark matter and an atomic origin by mapping the Doppler shift of the line across the Galaxy with multiple flights [27;28]. An atomic background will be co-moving with the Earth, while a dark matter signal will come from the stationary halo. This "velocity spectroscopy" drives the 3 eV resolution specification of the TES array.

The Micro-X observation is highly complementary with future *XRISM* satellite [29;30] observations. Micro-X is optimized for the all-sky galactic signal, and its short flight precludes it from observing fainter targets. *XRISM* will get excellent spectra from extragalactic sources like galaxy clusters and dwarf spheroidals. If it were to observe the Galactic Center, it would take 35 Ms of observation time to accumulate the same signal flux as one Micro-X flight. In a more realistic scenario of co-added observations, it would take >100 Ms of data to accumulate the same signal flux. Thus a combination of data from both experiments is an excellent way to enhance sensitivity to dark matter signals in the X-ray band.

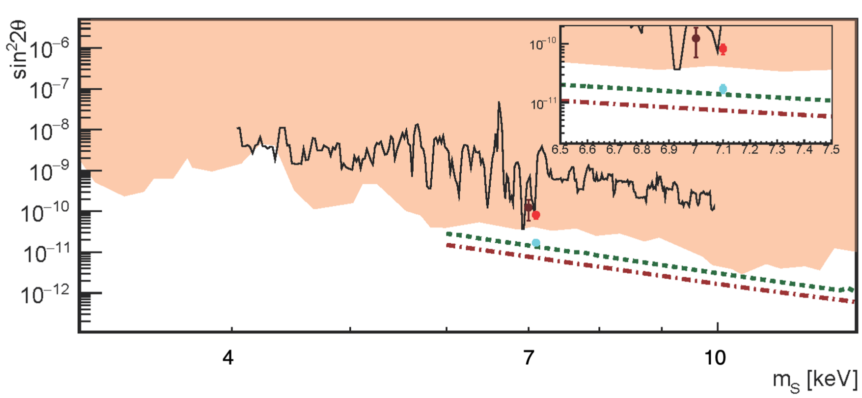

Figure 2: Projected sensitivity to sterile neutrino dark matter from first (green dotted) and second (red dash-dotted) proposed targets [18]. Previous claims from [26], [31], and [7] are shown in red, maroon, and blue dots, respectively. Previous exclusion limits from X-ray observations (shaded) and XQC (black line [17]) are shown.

References

[1] K. Abazajian, G. M. Fuller, and W. H. Tucker, "Direct detection of warm dark matter in the X-ray," *Astrophys. J.*, vol. 562, pp. 593–604, 2001.

[2] S. Dodelson and L. M. Widrow, "Sterile neutrinos as dark matter," *Phys. Rev. Lett.*, vol. 72, pp. 17–20, Jan 1994.

[3] M. Drewes *et al.*, "A White Paper on keV Sterile Neutrino Dark Matter," *JCAP*, vol. 01, p. 025, 2017.

[4] K. N. Abazajian, "Sterile neutrinos in cosmology," *Phys. Rept.*, vol. 711-712, pp. 1–28, 2017.

[5] A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens, and O. Ruchayskiy, "Sterile neutrino Dark Matter," *Progress in Particle and Nuclear Physics*, vol. 104, pp. 1–45, Jan. 2019.

[6] E. Bulbul, M. Markevitch, A. Foster, R. a. K. Smith, M. Loewenstein, and S. W. Randall, "Detection of an Unidentified Emission Line in the Stacked X-Ray Spectrum of Galaxy Clusters," *The Astrophysical Journal*, vol. 789, p. 13, July 2014.

[7] A. Boyarsky, D. Iakubovskyi, O. Ruchayskiy, and D. Savchenko, "Surface brightness profile of the 3.5 kev line in the milky way halo," 2018.

[8] C. Shah *et al.*, "Laboratory measurements compellingly support charge-exchange mechanism for the 'dark matter' $\sim$3.5 kev x-ray line," *The Astrophysical Journal*, vol. 833, 08 2016.

[9] N. Cappelluti, E. Bulbul, A. Foster, P. Natarajan, M. C. Urry, M. W. Bautz, F. Civano, E. Miller, and R. K. Smith, "Searching for the 3.5 kev line in the deep fields withchandra: The 10 ms observations," *The Astrophysical Journal*, vol. 854, p. 179, Feb 2018.

[10] E. Bulbul *et al.*, "Laboratory Measurements of X-Ray Emission from Highly Charged Argon Ions," *Astrophys. J.*, vol. 870, no. 1, p. 21, 2019.

[11] A. C. Gall *et al.*, "EBIT Observation of Ar Dielectronic Recombination Lines near the Unknown Faint X-Ray Feature Found in the Stacked Spectrum of Galaxy Clusters," *The Astrophysical Journal*, vol. 872, p. 194, Feb. 2019.

[12] 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," *arXiv e-prints*, p. arXiv:1812.06976, Dec. 2018.

[13] K. N. Abazajian, "Technical Comment on "The dark matter interpretation of the 3.5-keV line is inconsistent with blank-sky observations"," *arXiv e-prints*, p. arXiv:2004.06170, Apr. 2020.

[14] 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"," *arXiv e-prints*, p. arXiv:2004.06601, Apr. 2020.

[15] C. Dessert, N. L. Rodd, and B. R. Safdi, "Response to a comment on Dessert et al. "The dark matter interpretation of the 3.5 keV line is inconsistent with blank-sky observations"," *Physics of the Dark Universe*, vol. 30, p. 100656, Dec. 2020.

[16] F. A. Aharonian *et al.*, "Hitomi Constraints on the 3.5 keV Line in the Perseus Galaxy Cluster," *The Astrophysical Journall*, vol. 837, p. L15, Mar. 2017.

[17] E. Figueroa-Feliciano *et al.*, "Searching for keV Sterile Neutrino Dark Matter with X-Ray Microcalorimeter Sounding Rockets," *The Astrophysical Journal*, vol. 814, p. 82, Nov. 2015.

[18] J. Adams *et al.*, “Micro-X Sounding Rocket: Transitioning from First Flight to a Dark Matter Configuration,” *J. Low Temp. Phys.*, vol. 199, no. 3-4, pp. 1072–1081, 2020.

[19] The Micro-X collaboration, “First Flight Performance of the Micro-X Microcalorimeter X-Ray Sounding Rocket,” *in preparation*, 2020.

[20] M. E. Eckart *et al.*, “Large-Absorber TES X-ray Microcalorimeters and the Micro-X Detector Array,” in *American Institute of Physics Conference Series* (B. Young, B. Cabrera, and A. Miller, eds.), vol. 1185 of *American Institute of Physics Conference Series*, pp. 699–702, Dec. 2009.

[21] M. E. Eckart *et al.*, “Development of tes microcalorimeter arrays for the micro-x sounding rocket experiment,” *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, pp. 2101705–2101705, 2013.

[22] C. D. Reintsema *et al.*, “Electronics for a Next-Generation SQUID-Based Time-Domain Multiplexing System,” in *American Institute of Physics Conference Series* (B. Young, B. Cabrera, and A. Miller, eds.), vol. 1185 of *American Institute of Physics Conference Series*, pp. 237–240, Dec. 2009.

[23] J. A. Chervenak *et al.*, “Performance of multiplexed SQUID readout for Cryogenic Sensor Arrays,” *Nuclear Instruments and Methods in Physics Research A*, vol. 444, pp. 107–110, Apr. 2000.

[24] P. de Korte *et al.*, “Time-division superconducting quantum interference device multiplexer for transition-edge sensors,” *Review of Scientific Instruments*, vol. 74, pp. 3807–3815, Aug. 2003.

[25] M. E. Danowski *et al.*, “Vibration Isolation Design for the Micro-X Rocket Payload,” *Journal of Low Temperature Physics*, vol. 184, pp. 597–603, Aug. 2016.

[26] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, and J. Franse, “Unidentified Line in X-Ray Spectra of the Andromeda Galaxy and Perseus Galaxy Cluster,” *Physical Review Letters*, vol. 113, p. 251301, Dec. 2014.

[27] E. G. Speckhard, K. C. Y. Ng, J. F. Beacom, and R. Laha, “Dark Matter Velocity Spectroscopy,” *Physical Review Letters*, vol. 116, p. 031301, Jan. 2016.

[28] D. Powell, R. Laha, K. C. Y. Ng, and T. Abel, “Doppler effect on indirect detection of dark matter using dark matter only simulations,” *Physical Review D*, vol. 95, p. 063012, Mar. 2017.

[29] M. Tashiro *et al.*, “Concept of the X-ray Astronomy Recovery Mission,” in *Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray*, vol. 10699 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, p. 1069922, July 2018.

[30] Y. Ishisaki *et al.*, “Resolve Instrument on X-ray Astronomy Recovery Mission (XARM),” *Journal of Low Temperature Physics*, vol. 193, pp. 991–995, Dec. 2018.

[31] N. Cappelluti *et al.*, “Searching for the 3.5 keV Line in the Deep Fields with Chandra: The 10 Ms Observations,” *The Astrophysical Journal*, vol. 854, p. 179, Feb. 2018.

Part of this work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.