NuSTAR Tests of Sterile-Neutrino Dark Matter: New Galactic Bulge Observations and Combined Impact

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We analyze two dedicated NuSTAR observations with exposure \( \sim 190 \) ks located \( \sim 10^\circ \) from the Galactic plane, one above and the other below, to search for x-ray lines from the radiative decay of sterile-neutrino dark matter. These fields were chosen to minimize astrophysical x-ray backgrounds while remaining near the densest region of the dark matter halo. We find no evidence of anomalous x-ray lines in the energy range 5–20 keV, corresponding to sterile neutrino masses 10–40 keV. Interpreted in the context of sterile neutrinos produced via neutrino mixing, these observations provide the leading constraints in the mass range 10–12 keV, improving upon previous constraints in this range by a factor \( \sim 2 \). We also compare our results to Monte Carlo simulations, showing that the fluctuations in our derived limit are not dominated by systematic effects. An updated model of the instrumental background, which is currently under development, will improve NuSTAR’s sensitivity to anomalous x-ray lines, particularly for energies 3–5 keV.

I. INTRODUCTION

Multiple lines of cosmological evidence indicate that \( \sim 80\% \) of the matter density of the Universe, and \( \sim 25\% \) of its energy density, is non-baryonic and non-luminous, hence its name, dark matter (DM) [1]. At present, the effects of DM are only measurable via its gravitational effects on astronomical scales, ranging from the motions of galaxies and galaxy clusters to the power spectrum of the Cosmic Microwave Background [2–7]. The lack of a viable Standard Model candidate for particle DM (hereafter symbolized \( \chi \)) has led to a plethora of theoretical models, many of which are also motivated by a desire to account for other phenomena not explained by the Standard Model (e.g., baryogenesis, neutrino masses, the hierarchy problem, etc).

The techniques of indirect detection use astronomical observations to search for the decay and/or annihilation of DM into Standard Model particles such as electrons/positrons, (anti)protons/nuclei, neutrinos, and photons [12]. Because photons are not deflected by astrophysical magnetic fields, it is possible to determine their arrival direction within the angular resolution of the detector, allowing for a rejection of photons from known astrophysical sources. Final states with mono-
energetic photons are particularly valuable for indirect DM searches, as they result in line-like signals atop a (usually) smooth continuum background.

A popular DM candidate with $m_\chi \sim$ keV is the sterile neutrino, with models such as the $\nu$MSM providing explanations for the particle nature of DM, neutrino masses, and baryogenesis [13–16]. The radiative decay of sterile neutrinos via $\chi \rightarrow \nu + \gamma$ would produce a mono-energetic x-ray photon and an active neutrino, each with $E = m_\chi/2$ [11, 17–23]. Sterile neutrinos may be produced in the early Universe via mixing with active neutrinos [24], and this production may be resonantly enhanced by primordial lepton asymmetry [25]. Considerations from Big Bang nucleosynthesis (BBN) [26–28] provide a lower limit on the mixing angle $\sin^2 2\theta$, with additional constraints from the observed number of Milky Way satellite galaxies [29] bounding the parameter space from the left (see Fig. 1).

Space-based x-ray observatories such as HEAO-1 [30], Chandra [31, 32], XMM-Newton [30, 33], Suzaku [34], Fermi-GBM [35], and INTEGRAL [36, 37] have provided stronger constraints on the $\chi \rightarrow \nu + \gamma$ decay rate for $m_\chi$ between $\sim$1–100 keV. The observation of an unknown x-ray line at $E \simeq$ 3.5 keV (“the 3.5-keV line”) in several analyses [8–10] has led to much interest, as well as many follow-up analyses using different instruments and astrophysical targets [38–59]. Some suggest that the 3.5-keV line may be a signature of sterile-neutrino DM [60] or other DM candidates [61–65]; alternatively, modeling systematics [40, 43] or novel astrophysical processes [66, 67] may play a role. Future high-spectral-resolution x-ray instruments may also be able to investigate the DM hypothesis for the origin of the 3.5-keV signal via velocity spectroscopy [68, 69].

Since its launch in 2012, the NuSTAR observatory, due to its unique large-angle aperture for unfocused x-rays, has provided the leading constraints on sterile-neutrino DM across the mass range 10–50 keV, leveraging observations of the Bullet Cluster [47], blank-sky fields [70], the Galactic center [71], and the M31 galaxy [72]. In each of these cases, the NuSTAR observations were originally performed to study non-DM phenomena; therefore, DM searches using these data had to contend with large astrophysical backgrounds and/or reduced effective areas from masking bright point sources in the field of view (FOV). Improving upon these constraints, and extending them to the NuSTAR limit of $E \simeq$ 3 keV (e.g., to test the tentative 3.5-keV signal), will therefore require observations with lower astrophysical backgrounds, as well as an improved model of the low-energy NuSTAR instrumental background.

In this paper, we present new constraints on the decay rate of sterile-neutrino DM particles using two NuSTAR observations, one $\sim$10° above and the other $\sim$10° below the Galactic plane, chosen to minimize astrophysical x-ray emission while still remaining near the center of the Galactic DM halo. These are the first NuSTAR observations dedicated to DM searches.

In Sec. II, we describe the data reduction and spectral modeling of the NuSTAR data, consistently incorporating the flux from the focused and unfocused FOVs. In Sec. III, we combine the line flux limits from these new observations to constrain the $\chi \rightarrow \nu + \gamma$ decay rate for sterile neutrinos in the mass range 10–40 keV, obtaining the strongest constraints to date in the 10–12 keV mass range. We conclude in Sec. IV.

II. NUSTAR DATA ANALYSIS

In this section, we outline the aspects of the NuSTAR instrument that are relevant to our DM search, and describe NuSTAR’s unique wide-angle aperture for unfocused x-rays (Sec. II A). After describing the recent NuSTAR off-plane observations (Sec. II B) and our treatment of the NuSTAR instrument response (Sec. II C), we conclude with a discussion of the spectral model we use to analyze the data (Sec. II D).

A. The NuSTAR Instrument

The NuSTAR instrument is more fully described in Refs. [76–78], with the aspects of the instrument relevant for our search technique described in our previous papers [71, 72]. Here, we summarize several key aspects.

The NuSTAR instrument contains two identical, independent, and co-aligned telescopes, each consisting of a grazing-incidence Pt/C-coated x-ray optics module and a Focal Plane Module (FPM). The FPMs (labeled A and B) contain an aperture stop, a $\sim$100-µm beryllium x-ray window with energy-dependent transmission efficiency $\xi_{Be}(E)$, and a solid-state CdZnTe detector array with energy resolution $\sim$0.4 keV for x-rays with energies $E \lesssim$ 20 keV. Within the telescopes, properly-focused incoming x-rays reflect twice off the mirror segments, leading to their alternative name of 2-bounce (2b) photons. Both telescopes share essentially-overlapping $13' \times 13'$ FOVs for focused x-rays with energies between 3–79 keV. The lower limit is primarily set by inactive material on the surface of the detector and $\xi_{Be}(E)$ (see Secs. II C and II D), whereas the upper limit is set by the Pt K-edge of the mirror materials. The maximum x-ray energy recorded by the detectors is $\sim$160 keV.

Unlike previous focusing x-ray telescopes such as Chandra or XMM-Newton, the 10-m gap between the NuSTAR optics bench and the focal plane is open to the sky, allowing stray photons to strike the detector array without interacting with the mirror elements or being blocked by the aperture stops. For this reason, these unfocused x-rays are called 0-bounce (0b) photons. Although the 0-bounce effective area $A_{0b}$ is limited by the physical $\sim$13 cm$^2$ area of each detector array, the 0-bounce FOV $\Delta \Omega_{0b}$ subtended by each array is $\sim$4.5 deg$^2$, nearly two orders of magnitude larger than the 2-bounce
TABLE I. NuSTAR Galactic Bulge observations used in this analysis, with 0-bounce effective areas after data cleaning.

| NuSTAR obsID | Pointing (J2000) RA, Dec (deg) | Effective Exposure$^a$ FPMA / B (ks) | Detector Area $A_{0b}$$^b$ FPMA / B (cm$^2$) | Solid Angle $\Delta \Omega_{0b}$$^c$ FPMA / B (deg$^2$) |
|--------------|--------------------------------|-------------------------------------|---------------------------------------------|---------------------------------------------|
| 40410001002  | 253.2508, -26.6472             | 50.0 / 49.8                        | 11.97 / 11.88                               | 4.36 / 4.62                                 |
| 40410002002  | 280.3521, -27.6344             | 44.7 / 44.6                        | 12.71 / 12.60                               | 4.53 / 4.56                                 |

$^a$ After OPTIMIZED SAA filtering and manual data screening.
$^b$ After bad pixel removal (both obsIDs) and point-source masking (40410001002 only).
$^c$ Average solid angle of sky for detecting 0-bounce photons, after correcting for bad pixel removal and vignetting efficiency.

**FIG. 2.** Sky map of the Galactic bulge region. The base color map shows the 17–60 keV flux measured by INTEGRAL [73], with many x-ray point sources clearly visible. The 0-bounce FOVs for the observations analyzed in this paper are indicated by the solid red (FPMA) and green (FPMB) “Pac-Man”-shaped curves, and avoid known bright x-ray sources. The dashed black contours indicate the predicted GRXE flux using the Galactic stellar mass model from Ref. [74] and the GRXE emissivity model from Ref. [75] (see Sec. IID). The contour values are symmetric about $b = 0^\circ$, decrease as $|b|$ increases, and are evenly spaced in $\log_{10}(\text{flux})$ between $10^{-12.5}–10^{-11}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$, inclusive.

FOV $\Delta \Omega_{2b}$, and more than counterbalancing the factor of $\sim 20$ reduction in effective area between the 2-bounce and 0-bounce apertures. This approach provides a large increase in sensitivity to diffuse x-ray emission such as that expected from decaying DM in galactic halos, and thus the 0-bounce technique has been the dominant contribution to recent NuSTAR sterile-neutrino constraints [70–72].

**B. NuSTAR Faint-Sky Off-Plane Observations**

The previous NuSTAR sterile-neutrino search in the Galactic center region [71] was hampered by the presence of bright x-ray point sources in both the 0-bounce and 2-bounce FOVs, whose removal from the data greatly reduced the effective area, as well as a large continuum background from the Galactic Ridge x-ray Emission (GRXE, see Sec. IID) which was the dominant background component for $E \lesssim 20$ keV. To combat both of these issues, we designed two dedicated NuSTAR observations (see Table I), one $\sim 10^\circ$ above the Galactic plane (obsID 40410001002), and the other $\sim 10^\circ$ below...
The high Galactic latitude of these fields was chosen to minimize the GRXE continuum background while still remaining near the center of the Galactic DM halo, as well as avoiding known bright x-ray sources near the Galactic plane (see Fig. 2).

The NuSTAR observations described above were carried out in August and October 2018, with an initial unfiltered exposure time of ~200 ks (summed over both obsIDs and FPMs). Data reduction and analysis are performed using the NuSTAR Data Analysis Software pipeline, NuSTARDAS v1.5.1. The flags SAAMODE=OPTIMIZED and TENTACLE=YES are used to remove events coincident with NuSTAR passages through the South Atlantic Anomaly (SAA), and “bad pixels” (defined in the NuSTAR calibration database) are removed. We observe a faint x-ray point source near the edge of the 2-bounce FOV in obsID 40410001002, whose position is consistent with the chromospherically-active stellar binary HD 152178 [79, 80]. This system has also been detected in x-rays by RXTE [81] and Suzaku [82]. To eliminate systematic uncertainties associated with modeling this source’s spectrum, we remove from our analysis all x-ray events in a circular region of radius 75′′ around the nominal position of the source in both FPMs, excluding ≥80% of the source photons [83]. The position of the x-ray source 1RXS J165306.1-263434 also lies within the 2-bounce FOV of this obsID [81]; however, it is sufficiently faint that its NuSTAR spectrum is consistent with background, so we do not exclude it from the analysis. There are no x-ray point sources visible in obsID 40410002002.) Finally, we inspect the 3–10 keV light-curves of each observation to check for transient fluctuations due to solar activity or unfiltered SAA events, and remove any time intervals with a count rate >2.5σ from the quiescent average. After all cuts, the total cleaned exposure time used in this analysis, summed over both obsIDs and telescopes, is ~190 ks.

We extract spectra from the full detector planes as extended sources using the nuproducts routine in NuSTARDAS, and bin each spectrum with equal logarithmic separations Δlog₁₀(E) = 0.01 (i.e., 100 bins per decade) in the energy ranges 5–20 keV and 95–110 keV. This provides a statistical uncertainty that is everywhere ~10% per bin while also being narrower than the ~0.4-keV NuSTAR energy resolution across the energy range 5–20 keV. As described in Ref. [72], we exclude the energy range 3–5 keV, as the behavior of the low-energy NuSTAR background—particularly the origin of the 3.5- and 4.5-keV lines in the default background model—is the subject of active investigation. (Additionally, including the 3–5 keV region can bias the determination of the internal power-law parameters discussed in Sec. II D; see Ref. [72] for details.) We also exclude the energy range 20–95 keV, as this region is dominated by a forest of instrumental lines. DM constraints in this energy range are therefore weakened and prone to systematic effects, as discussed in Refs. [70–72]. Excluding this energy range also speeds up our analysis, and we verify that it does not affect our results in the 5–20 keV energy range. Finally, we note that the 20–95 keV energy range has already been largely excluded by previous sterile-neutrino searches using data from Fermi-GBM [35], INTEGRAL [37], and NuSTAR [70–72].

C. NuSTAR Response Files

To describe the effects of the detector effective area and solid angle for the CXB, GRXE, and DM line components described in Sec. II D, we define custom response files that relate the measured event rate d²N/dEdt to the astrophysical flux. For 0-bounce components, the response is $E_{\text{Be}}(E)A_{0b}\Delta\Omega_{0b}$, where the grasp $A_{0b}\Delta\Omega_{0b}$ is calculated using the nuskybgd code [77] and $E_{\text{Be}}(E)$ is the Be window transmission efficiency. For 2-bounce components, the response is $E_{\text{Be}}(E)A_{2b}(E)\Delta\Omega_{2b}$, where $E_{\text{Be}}(E)$ and $A_{2b}(E)$ are calculated by NuSTARDAS, extracting the entire FOV as an extended source using nuproducts. Here, $\Delta\Omega_{2b}$ is simply the geometric area of the 2-bounce FOV, and is ~0.046 deg² for obsID 40410001002 and ~0.047 deg² for obsID 40410002002, the former being slightly less than the latter due to the exclusion of the 75′′-radius circle around the point source. The responses for internal detector components—the internal continuum, power-law, and lines—are calculated by nuproducts, and do not depend on area or solid angle.

D. NuSTAR Spectral Modeling

Our spectral model contains six components, which may be broadly classified as having instrumental or astrophysical origins (see Table II). The instrumental background consists of a low-energy internal power-law dominant at energies $E \lesssim 10$ keV, the internal detector continuum, and a series of phenomenologically-motivated lines. The astrophysical components include the Cosmic x-ray Background (CXB), with an event rate similar to the instrumental components’ over the energy range of this analysis; and the GRXE, whose flux is a factor ~10 lower than the CXB. The treatment of each of these model components is described in this section.

To describe the internal continuum and line backgrounds, we adopt the default NuSTAR spectral model of Ref. [77]. The internal continuum is parameterized by a broken power-law with $E_{\text{break}} = 124$ keV, and the line energies and widths are frozen to the values in the default model, with only the line normalizations free to fit. (The line normalizations are also allowed to vary between each of the spectra, accounting for differences in the instrumental background conditions between the FPMs.) We retain the 95–110 keV data as the event rate in this range is dominated by the internal continuum, and is necessary to constrain the overall continuum normalization. We explore alternative high-energy intervals with endpoints...
TABLE II. The NuSTAR spectral model used in this paper. Parameters with numerical values are frozen to those values.

| Model component | XSPEC model<sup>a</sup> | Parameter | Value |
|-----------------|--------------------------|-----------|-------|
| CXB             | powerlaw<highecut        | 3–20 keV flux | $2.6 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ deg}^{-2}$ [84] |
|                 |                          | Spectral index $\Gamma$ | 1.29 [84] |
|                 |                          | $E_{\text{cut}}$ | $10^{-4}$ keV |
|                 |                          | $E_{\text{fold}}$ | $\sim40$ keV [84] |
| GRXE            | apec                     | 3–20 keV flux | Free |
|                 |                          | Plasma $kT$ | 8 keV [85–87] |
|                 |                          | Abundance ratio | See Sec. II D |
| Internal continuum | bknpower              | $E_{\text{break}}$ | 124 keV [77] |
|                 |                          | $\Gamma(E < E_{\text{break}})$ | $-0.05$ [77] |
|                 |                          | $\Gamma(E > E_{\text{break}})$ | $-0.85$ [77] |
|                 |                          | Normalization | Free |
| Internal power-law | powerlaw              | Spectral index $\Gamma$ | See Sec. II D |
|                 |                          | Relative norm. | See Sec. II D |
| Internal lines | lorentz                  | Line energies | 10.2, 19.7, 104.5 keV [77] |
|                 |                          | Line widths | 0.6, 0.2, 0.5 keV [77] |
|                 |                          | Line norms. | Free |
| DM line | gaussian                 | Line energy | See Sec. II D |
|                 |                          | Line width | See Sec. II D |
|                 |                          | Line flux | See Sec. II D |

<sup>a</sup> The CXB, GRXE, and DM line models also include absorption from the interstellar medium through the tbabs model with fixed column density $N_H$, as well as absorption from the beryllium x-ray shield. All model components except the internal continuum include the absorption effects of detector surface material. See Sec. II D for details.

around 95 keV and 120 keV, and find that the fit quality is not sensitive to the precise values of the endpoints, provided the interval is sufficiently wide to constrain the internal continuum.

The default NuSTAR instrumental background model includes a $\sim1$-keV collisionally-ionized plasma component (the apec model in XSPEC [88]) which is strongest for energies $E < 5$ keV and is believed to result from reflected solar x-rays. Unfortunately, this model provides a poor fit ($\chi^2$/d.o.f. $\gtrsim 1.7$) to the observed spectrum, with the residuals indicating a clear excess in the energy range 5–10 keV. As we exclude the $E < 5$ keV data, we adopt the procedure described in Refs. [72, 87] and replace the apec model with a power-law. For each FPM, we use the data collected when the telescope aperture is occulted by the Earth to constrain the power-law spectral index and normalization with respect to the internal continuum. (As the Earth completely fills the 0-bounce and 2-bounce apertures during occultation mode, we assume that the astrophysical components contribute negligible flux, and include only the internal detector components when modeling the occulted data.) The spectral index and relative normalization of the internal power-law are frozen to their best-fit occultation-mode values during fits to the science data, shown in Figs. 3 and 4. This procedure provides a much better fit ($\chi^2$/d.o.f. $\lesssim 1.3$) to the observed science-mode spectra over the energy range of our analysis; however, there are still noticeable deviations, which will be discussed later in this section, and in Sec. III B.

The Cosmic X-ray Background (CXB) arises from unresolved extragalactic sources, and constitutes one of the dominant irreducible NuSTAR backgrounds in both the 0-bounce and 2-bounce FOVs. The CXB is largely isotropic, with degree-scale flux variations of $\sim5\%$ consistent with the expected Poisson fluctuations of the number of sources in the FOV [89]. As specified in the default NuSTAR background model, we parameterize the CXB spectrum with a cut-off power-law whose flux, spectral index, and $e$-folding energy are fixed to their INTEGRAL-measured values [84]; i.e., there are no free parameters in the CXB model. The highecut term brings a factor $\exp\left(\frac{E_{\text{cut}} - E}{E_{\text{fold}}}\right)$ for $E \geq E_{\text{cut}}$ and is constant for $E \leq E_{\text{cut}}$, so we choose $E_{\text{cut}} = 10^{-4}$ keV to ensure that the exponential is applied over the full energy range of our analysis. As shown in Figs. 3 and 4, the CXB is the dominant astrophysical background in these off-plane observations.

The GRXE is believed to result from unresolved point sources in the Galactic ridge [90], and its emissivity is
FIG. 3. Data and model spectra for obsID 40410001002, with FPMA (left) and FPMB (right), including contributions from the CXB, instrumental background, and the GRXE. The error bars correspond to ±1σ statistical uncertainties, and the CXB and GRXE curves incorporate both 0-bounce and 2-bounce emission. We exclude the energy range 20–95 keV as it is dominated by internal detector lines (in previous analyses [71, 72], we have already probed this range well), though we include the energy range 95–110 keV to constrain the internal detector continuum. See Sec. IID for details.

FIG. 4. Same as Fig. 3, but for obsID 40410002002.

observed to trace the near-infrared surface brightness (and hence stellar density) of the Galaxy [75, 86, 89, 91]. Broadband studies of the GRXE indicate that it is likely a multi-temperature plasma, with $kT_1 \lesssim 1$ keV and $kT_2 \sim 8$ keV [85–87]. We model the GRXE, which appears in both the 0-bounce and 2-bounce FOVs, as a single-temperature collisionally-ionized plasma (the apec model described previously) with a fixed temperature of 8 keV [87]. Particularly strong emission lines between 6–7 keV arise from Kα transitions in neutral and highly-ionized Fe, and it was these lines which limited the sensitivity of the previous sterile-neutrino search near the
Galactic center [71].

It is important to note that the “GRXE” component in our spectral model includes flux from the GRXE, unmodeled point sources, and any low-energy instrumental backgrounds not described by our default spectral model, as the GRXE component includes the only free normalization parameter in the low-energy part of our spectral model. Therefore, we leave both the GRXE elemental abundance (as a ratio to solar) and flux as free parameters, where the flux is unconstrained and the abundance ratio is constrained to the range 0.0–1.2. The lower bound arises from the requirement that elemental abundances be strictly positive, and the upper bound is set by previous measurements of the GRXE [86]. Additionally, freezing the abundance ratio to a nonzero value can force the GRXE flux to unreasonable extremes as the model attempts to fit the GRXE by way of its emission lines, thereby biasing the rest of the 5–20 keV fit. Finally, the 0-bounce and 2-bounce GRXE components are constrained to have the same flux and abundance ratio. (As shown by the slight bump in Figs. 3 and 4, the fits to the FPMB spectra of both obsIDs prefer a slightly higher GRXE abundance ratio than the FPMA spectra, though this difference is within the uncertainty on the value of the abundance parameter.)

We parameterize our DM line signal in XSPEC with a vanishingly-narrow Gaussian—i.e., a δ-function in $E$—as the intrinsic width of any DM line is expected to be much less than the $\sim$0.4 keV detector energy resolution with which it is convolved. Our treatment of the DM line during the line-search procedure is described further in Sec. III A.

The fluxes of the astrophysical components in our spectral model—CXB, GRXE, and DM line—are attenuated by absorption and scattering in the interstellar medium (ISM). This attenuation is parameterized in terms of the equivalent column density of neutral hydrogen, $N_{\text{H}}$, via the $tbabs$ model in XSPEC [92]. We adopt fixed values of $7.0 \times 10^{20} \text{cm}^{-2}$ for obsID 40410001020 and $1.1 \times 10^{20} \text{cm}^{-2}$ for obsID 40410002002 [93, 94]. (Both FPMS share the same $N_{\text{H}}$ value, which is assumed to be constant across the 0-bounce and 2-bounce FOVs despite the somewhat different sky coverage and values of $\Delta \Omega_{\text{0b}}$ from A/B.) This corresponds to an optical depth $\tau \lesssim 10^{-2}$ at $E = 5$ keV, falling steeply with increasing energy. Although the flux attenuation from the ISM is a $\lesssim 1\%$ effect across the energy range of this analysis, we include it for consistency.

Finally, we consider the absorption of x-rays within the NuSTAR instrument itself. Before incoming astrophysical x-rays (from the CXB, GRXE, or DM) strike the detectors, they must pass through a $\sim$100-μm beryllium shield with transmission efficiency $E_{\text{Be}}(E)$, rising from $\sim$0.67 at $E = 3$ keV to $\sim$0.92 at $E = 5$ keV. (The treatment of $E_{\text{Be}}$ is discussed further in Sec. II C.) An additional absorption effect arises in the detectors themselves. The CdZnTe detectors have a $\sim$0.11-μm platinum contact coating, as well as a $\sim$0.27-μm layer of inactive CdZnTe (both varying somewhat between individual detector crystals), through which incoming x-rays must pass [78]. At $E = 5$ keV, these detector components result in a flux attenuation of $\sim$25%, though this decreases quickly with increasing $E$ [72]. These detector absorption effects (often called $nuabs$ or $detabs$) are included in every spectral component except the internal continuum.

As shown in Figs. 3 and 4, the model described in Sec. II D provides an acceptable fit to the NuSTAR spectra ($\chi^2$/d.o.f. $< 1.35$ for all datasets), but there are several deviations from the model that may affect our derived line flux limits, and thus require further consideration. In Sec. III B, we perform Monte Carlo simulations to investigate whether these deviations are statistical or systematic in nature; here, we simply note that the spectral model described above is able to reproduce the data across most of the 5–20 keV energy range.

III. NUSTAR DM ANALYSIS

In this section, we describe the procedure used to search for DM line signals and set upper limits on the decay rate of DM to final states including a single monoenergetic photon (Sec. III A), and compare to sensitivity estimates from simulations (Sec. III B). Finally, we discuss the implications for sterile-neutrino dark matter (Sec. III C).

A. DM Line Search

Equipped with the spectral model described in Sec. II D, we search for DM line signals in the two observations. Our search procedure follows closely that from Refs. [71, 72], and is briefly described here.

We divide the 10–40 keV mass band into bins with equal logarithmic separations $\Delta \log m_{\chi}$ = 0.01 (i.e., 100 bins per decade in $m_{\chi}$). At each mass bin, we add a DM line with photon energy $E = m_{\chi}/2$ to the model. The number of DM photons in the line for each module and observation is

$$N_{\text{DM}} = \frac{\Gamma}{4\pi m_{\chi}} T A_{\text{0b}} \Delta \Omega_{\text{0b}} J (1 + f_{\text{2b}}),$$

where $\Gamma$ is the decay rate, $m_{\chi}$ is the DM mass, $T$ is the observation time, $A_{\text{0b}}$ and $\Delta \Omega_{\text{0b}}$ are the 0-bounce effective area and effective FOV defined in Sec. II C, $J$ is the FOV-averaged line-of-sight integral of the DM density (J-factor), and $f_{\text{2b}}$ is the energy-dependent contribution from the 2-bounce component (see Fig. 3 in Ref. [72] for the distribution of the 2-bounce contribution). Using the conservative sNFW as our default choice, we find $J \approx 20 \text{GeV cm}^{-3}\text{kpc sr}^{-1}$. If we use the NFW or coreNFW profiles instead, the J-factor is larger by $\sim$20%. The small deviations show that our results are robust with respect to density-profile choices, one of
the advantages of looking at high-latitude Galactic halos. (See Ref. [71] for additional details on the NFW, sNFW, and coreNFW profiles.) For the 2-bounce contribution, $f_{2\text{b}}$, we find a modest $\sim 20\%$ enhancement peaked at $E = 10\text{ keV}$ (see Fig. 3 of Ref. [72]).

At each DM mass, the only free parameter for the DM line is the decay rate. We find the best-fit $\chi^2(\Gamma)$ distribution for each module and observation by scanning through a range of $\Gamma$, conservatively refitting the entire spectral model to find the minimum $\chi^2$ value for each $\Gamma$. The sensitivity of the two observations (four separate fits including both modules) at each $m_\chi$ are combined by adding the respective $\chi^2$ distributions:

$$X^2(\Gamma) = \sum_{\text{obs}} \chi^2(\Gamma). \quad (2)$$

We note that for each module, the background parameters are allowed to be independent (see Sec. II D for exceptions). Compared with simply stacking the spectra, this combining procedure is used to avoid potential systematic errors due to combining observations with different instrumental and/or astrophysical backgrounds.

The minimum in $X^2(\Gamma)$ for each mass bin corresponds to the best-fit decay rate $\Gamma_{\text{min}}$, with a $5\sigma$ line detection requiring $X^2(\Gamma_{\text{min}}) - X^2(\Gamma = 0) < -25$. We find no signals consistent with decaying DM in the mass range $10$–$40\text{ keV}$, and instead set upper limits on the DM decay rate. The 95% one-sided upper limit, $\Gamma_{95}$, occurs at $X^2(\Gamma_{95}) = X^2(\Gamma_{\text{min}}) + 2.71$, and is shown in both frames of Fig. 5. In the $10$–$40\text{ keV}$ mass range, our results are comparable to previous NuSTAR limits from blank-sky [70], Galactic center [71], and M31 observations [72]. In particular, we are able to improve upon previous constraints in the $10$–$12\text{ keV}$ mass range by a factor of $\sim 2$. Finally, we note that with only $\sim 190 \text{ ks}$ exposure, our dedicated Galactic bulge observations are able to achieve sensitivity comparable with searches using several Ms combined exposure. This is due to the low astrophysical background, as well as the large J-factors in the chosen FOVs.

**B. Sensitivity Estimation with Simulations**

To validate our results, we perform line searches in mock spectra to find the expected upper limits when the spectra are purely statistically limited. This exercise also allows us to further study the deviations discussed in Sec. II D.

Instead of fully mimicking the actual analysis, where we analyze each module separately and then combine the constraints, we simplify the procedure by considering a single spectrum (rather than all four) per mock analysis to speed up the computation. We generate 100 Monte Carlo (MC) spectra with no DM line, using the fakeit tool in XSPEC. Each spectrum has 200 ks exposure, and is generated using the best-fit spectral model of FPMA, obsID 40410001002. This simplification is motivated by the fact that the spectrum for each module has similar best-fit model parameters, and hence statistics. We also test the results obtained with 10 of these simplified simulations against 10 full realizations (i.e., including both
obsIDs and both FPMs) and find good agreement. We then pass these mock spectra through the same fitting and line-search procedure as the data. At each mass bin, we thus have 100 simulated upper limits. We interpolate the cumulative distribution of these upper limits and find the corresponding 68% and 95% intervals. The upper limits can then obtained directly from the line-search procedure (see Sec. IIIA) without needing to combine different FPMs.

The right panel of Fig. 5 shows the expected upper limit bands obtained with the mock spectra. Our upper limits obtained from real data are consistent with the MC expectation across most of the 10–40 keV mass range at the 2σ level; however, there are several features that warrant closer attention. First, the limit worsens at the edges of the mass range (10 keV and 40 keV), expected to be caused by parts of the DM line leaving the 5–20 keV energy range of this analysis. (We note that the NuSTAR energy resolution is \( \sim 0.4 \) keV across this energy range.) Second, the upward fluctuation in the MC prediction at \( m_\chi \simeq 20 \) keV is caused by a weak line near \( E \simeq 10 \) keV in the background model, with the downward fluctuation in the observed limit arising from a downward fluctuation of the residuals near that energy in 40410001002B. This effect does not appear to be correlated with the other spectra, suggesting that it is either a statistical fluctuation or some transient fluctuation in the internal background or instrumental response, though we cannot definitively rule out the systematic hypothesis.

Similarly, the upward fluctuation in the observed limit near \( m_\chi \simeq 16 \) keV is driven mainly by upward fluctuations in the data from 40410002002B, which are also not correlated with other modules. Additionally, the feature near \( m_\chi \simeq 30 \) keV is caused by upward fluctuations in the data from two or more modules. Similar behaviors are also seen in other analyses (left panel of Fig. 5), and ongoing studies of the NuSTAR instrumental background have identified an edge in the spectrum near energies 15–17 keV that is not captured by the current background model. Therefore, our DM limits near \( m_\chi \simeq 30 \) keV are systematics-limited, and will likely improve an adjusted model of the instrumental background before the remaining \( \nu \)MSM parameter space near \( m_\chi \simeq 30 \) keV can be closed (see Fig. 1.)

Finally, we turn to the region near \( m_\chi \simeq 10–12 \) keV, where our results improve the most compared to previous analyses and the observed limit also touches the lower end of the MC band. A closer inspection shows that this is driven by several downward-fluctuating data points from 40410001002A and 40410002002A/B. These negative residuals appears at different energies in three different modules, and the bin widths are a factor \( \sim 4 \) narrower than the detector energy resolution. This lends support to the strong limit being caused by statistical downward fluctuations. Improved background modeling (ongoing) or more exposures in the future will be able to clarify the nature of the these features.

C. Sterile-Neutrino DM Constraints

For sterile neutrino DM, we convert the decay rate constraints to mixing angle constraints using \([20, 21]\)

\[
\Gamma = 1.38 \times 10^{-32} \text{s}^{-1} \left( \frac{\sin^2 2\theta}{10^{-10}} \right) \left( \frac{m_\chi}{\text{keV}} \right)^5. \tag{3}
\]

The aggregate constraints in the mass-mixing-angle plane from x-ray searches (including NuSTAR) are shown in Fig. 1. As described previously, our high-latitude Galactic bulge constraints are a factor \( \sim 2 \) stronger than the previous leading limits \([70]\) in the mass range 10–12 keV while requiring a factor \( \sim 50 \) less exposure time, and are comparable with previous NuSTAR constraints over the rest of the 10–40 keV mass range. This supports the use of observation regions with low astrophysical background and large J-factors.

In the context of the \( \nu \)MSM, the parameter space is also bounded by production and structure formation constraints \([29, 95]\) (see also Ref. [72] for discussion). As discussed in Sec. IIIB, the DM line analysis in this paper is limited mostly by statistics, except for the known feature near \( E \sim 15 \) keV. To cover the \( \nu \)MSM window for \( m_\chi > 10 \) keV, a factor \( \sim 4 \) improvement in sensitivity is needed, corresponding to \( \sim 4 \) Ms exposure of regions with large J-factors and minimal astrophysical backgrounds (similar to the present paper). Though a survey of this depth is feasible, we caution that systematic deviations from the default NuSTAR background model will likely prevent long exposures from reaching their design sensitivity until an improved model of the NuSTAR instrumental background can be developed. Ongoing work for improving the NuSTAR instrumental background model, especially in the 3–5 keV energy range, will be essential for further testing of the \( \nu \)MSM down to \( m_\chi = 6 \) keV, including the tentative signal at \( E \sim 3.5 \) keV.

IV. CONCLUSIONS AND OUTLOOK

The NuSTAR observatory’s large FOV for unfocused x-rays has been pivotal in constraining the properties of sterile-neutrino DM with \( m_\chi \sim \) keV, such as that predicted by the \( \nu \)MSM. NuSTAR observations of the Galactic center, blank-sky extragalactic fields, and M31 have provided world-leading constraints on the \( \chi \rightarrow \nu + \gamma \) decay rate in the mass range 10–50 keV, practically closing the “window” in the \( \nu \)MSM parameter space for masses 20–50 keV. Closing the window for masses 6–20 keV, however, has proved difficult, due to large astrophysical x-ray backgrounds in the observation regions.

In this paper, we analyze a combined \( \sim 190 \) ks of NuSTAR observations to search for x-rays originating from the radiative decay of sterile-neutrino DM in the Galactic halo. The observation regions were optimized to reduce astrophysical x-ray backgrounds from Galactic x-ray sources and from the Galactic ridge x-ray emission...
while remaining near the center of the Galactic halo, where the DM decay signal is expected to be strongest. We consistently model the flux from both the focused (2-bounce) and unfocused (0-bounce) NuSTAR apertures, though our sensitivity to decaying DM is dominated by the large unfocused FOV. To avoid the systematic effects of stacking spectra with different instrumental and astrophysical backgrounds, we model the spectra individually and combine the sensitivity of each.

Finding no evidence of sterile-neutrino DM decays, we instead set upper limits on the sterile neutrino decay rate in the mass range 10–40 keV. In the mass range ∼10–12 keV, our limits are a factor ∼2 stronger than the previous leading limits while requiring a factor ∼50 less exposure time. This is due in part to the low astrophysical background and large J-factor in these optimized observation regions, as well as downward statistical fluctuations. We also perform Monte Carlo simulations to determine our expected DM sensitivity, and find that our derived limits are consistent with expectations across most of the 10–40 keV mass range.

As the astrophysical background (now dominated by the irreducible CXB flux) in these observations is comparable to the instrumental background, we observe deviations of the spectra from the default NuSTAR background model. In particular, we find that the sterile neutrino limits in the mass range ∼25–40 keV are largely independent of exposure time and the choice of astrophysical target, likely indicating a systematic effect from the instrumental background. Detailed characterization of the instrumental background is ongoing, and additional NuSTAR searches, particularly with an improved model of the instrumental background, will be uniquely suited to probing the remaining νMSM parameter space, as well as investigating the nature of the 3.5-keV line.

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[1] M. Tanabashi et al. (Particle Data Group), “Review of Particle Physics,” Phys. Rev. D 98, 030001 (2018).
[2] G. Bertone, D. Hooper, and J. Silk, “Particle Dark Matter: Evidence, Candidates and Constraints,” Phys. Rept. 405, 279–390 (2005), arXiv:hep-ph/0404175 [hep-ph].
[3] L. E. Strigari, “Galactic Searches for Dark Matter,” Phys. Rept. 531, 1–88 (2013), arXiv:1211.7090 [astro-ph.CO].
[4] M. S. Seigar, Dark Matter in the Universe (Morgan & Claypool Publishers, 2015).
[5] M. R. Buckley and A. H. G. Peter, “Gravitational Probes of Dark Matter Physics,” Phys. Rept. 761, 1–60 (2018), arXiv:1712.06615 [astro-ph.CO].
[6] N. Aghanim et al. (Planck Collaboration), “Planck 2018 Results. VI. Cosmological Parameters,” (2018), arXiv:1807.06209 [astro-ph.CO].
[7] R. H. Wechsler and J. L. Tinker, “The Connection Between Galaxies and Their Dark Matter Halos,” Ann. Rev. Astron. Astrophys. 56, 435–487 (2018), arXiv:1804.03097 [astro-ph.GA].
[8] E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, and S. W. Randall, “Detection of an Unidentified Emission Line in the Stacked X-Ray Spectrum of Galaxy Clusters,” Astrophys. J. 789, 13 (2014), arXiv:1402.2301 [astro-ph.CO].
[9] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, and J. Franse, “Unidentified Line in X-ray Spectra of the Andromeda Galaxy and Perseus Galaxy Cluster,” Phys. Rev. Lett. 113, 251301 (2014), arXiv:1402.4119 [astro-ph.CO].
[10] A. Boyarsky, J. Franse, D. Iakubovskyi, and O. Ruchayskiy, “Checking the Dark Matter Origin of a 3.53 keV Line with the Milky Way Center,” Phys. Rev. Lett. 115, 161301 (2015), arXiv:1408.2503 [astro-ph.CO].
[11] K. N. Abazajian, “Sterile Neutrinos in Cosmology,” Phys. Rept. 711-712, 1–28 (2017), arXiv:1705.01837 [hep-ph].
[12] J. M. Gaskins, “A Review of Indirect Searches for Particle Dark Matter,” Contemp. Phys. 57, 496–525 (2016), arXiv:1604.00014 [astro-ph.HE].
[13] T. Asaka, S. Blanchet, and M. Shaposhnikov, “The νMSM, Dark Matter and Neutrino Masses,” Phys. Lett. B631, 151–156 (2005), arXiv:hep-ph/0503065 [hep-ph].
[14] T. Asaka, M. Laine, and M. Shaposhnikov, “Lightest Sterile Neutrino Abundance within the νMSM,” J. High Energy Phys. 01, 091 (2007), [Erratum: JHEP02,028(2015)], arXiv:hep-ph/0612182 [hep-ph].

[15] L. Canetti, M. Drewes, T. Frossard, and M. Shaposhnikov, “Dark Matter, Baryogenesis and Neutrino Oscillations from Right Handed Neutrinos,” Phys. Rev. D87, 093006 (2013), arXiv:1208.4607 [hep-ph].

[16] L. Canetti, M. Drewes, and M. Shaposhnikov, “Sterile Neutrinos as the Origin of Dark and Baryonic Matter,” Phys. Rev. Lett. 110, 061801 (2013), arXiv:1204.3902 [hep-ph].

[17] A. Kusenko, “Sterile Neutrinos: The Dark Side of the Light Fermions,” Phys. Rept. 481, 1–28 (2009), arXiv:0906.2968 [hep-ph].

[18] M. Drewes et al., “A White Paper on keV Sterile Neutrino Dark Matter,” J. Cosmology Astroparticle Phys. 1701, 025 (2017), arXiv:1602.04816 [hep-ph].

[19] A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens, and O. Ruchayskiy, “Sterile Neutrino Dark Matter,” Prog. Part. Nucl. Phys. 104, 1–45 (2019).

[20] R. Shrock, “Decay $\nu^l \rightarrow \nu^l \gamma$ in Gauge Theories of Weak and Electromagnetic Interactions,” Phys. Rev. D90, 743–748 (1974).

[21] P. B. Pal and L. Wolfenstein, “Radiative Decays of Massive Neutrinos,” Phys. Rev. D25, 766 (1982).

[22] A. D. Dolgov and S. H. Hansen, “Massive Sterile Neutrinos as Warm Dark Matter,” Astroparticle Phys. 16, 339–344 (2002), arXiv:hep-ph/0009083 [hep-ph].

[23] K. Abazajian, G. M. Fuller, and W. H. Tucker, “Direct Detection of Warm Dark Matter in the X-ray,” Astrop. J. 562, 593–604 (2001), arXiv:astro-ph/0106002 [astro-ph].

[24] S. Dodelson and L. M. Widrow, “Sterile-Neutrinos as Dark Matter,” Phys. Rev. Lett. 72, 17–20 (1994), arXiv:hep-ph/9303287 [hep-ph].

[25] X.-D. Shi and G. M. Fuller, “A New Dark Matter Candidate: Nonthermal Sterile Neutrinos,” Phys. Rev. Lett. 82, 2832–2835 (1999), arXiv:astro-ph/9810076 [astro-ph].

[26] A. D. Dolgov, S. H. Hansen, S. Pastor, S. T. Petcov, G. G. Raffelt, and D. V. Semikoz, “Cosmological Bounds on Neutrino Degeneracy Improved by Flavor Oscillations,” Nucl. Phys. B632, 363–382 (2002), arXiv:hep-ph/0201287 [hep-ph].

[27] P. D. Serpico and G. G. Raffelt, “Lepton Asymmetry and Primordial Nucleosynthesis in the Era of Precision Cosmology,” Phys. Rev. D71, 127301 (2005), arXiv:astro-ph/0506162 [astro-ph].

[28] A. Boyarsky, O. Ruchayskiy, and M. Shaposhnikov, “The Role of Sterile Neutrinos in Cosmology and Astrophysics,” Ann. Rev. Nucl. Part. Sci. 59, 191–214 (2009), arXiv:0901.0011 [hep-ph].

[29] J. F. Cherry and S. Horiuchi, “Closing in on Resonantly Produced Sterile Neutrino Dark Matter,” Phys. Rev. D95, 083015 (2017), arXiv:1701.07874 [hep-ph].

[30] A. Boyarsky, A. Neronov, O. Ruchayskiy, and M. Shaposhnikov, “Constraints on Sterile Neutrino as a Dark Matter Candidate from the Diffuse X-ray Background,” Mon. Not. Roy. Astron. Soc. 370, 213–218 (2006), arXiv:astro-ph/0512509 [astro-ph].

[31] S. Riemer-Sørensen and S. H. Hansen, “Decaying Dark Matter in Draco,” Astron. Astrophys. 500, L37–L40 (2009), arXiv:0901.2509 [astro-ph.CO].

[32] S. Horiuchi, P. J. Humphrey, J. Onorbe, K. N. Abazajian, M. Kaplinghat, and S. Garrison-Kimmel, “Sterile Neutrino Dark Matter Bounds from Galaxies of the Local Group,” Phys. Rev. D89, 025017 (2014), arXiv:1311.0282 [astro-ph.CO].

[33] C. R. Watson, J. F. Beacom, H. Yuksel, and T. P. Walker, “Direct X-ray Constraints on Sterile Neutrino Warm Dark Matter,” Phys. Rev. D 74, 033009 (2006), arXiv:astro-ph/0605424 [astro-ph].

[34] M. Loewenstein, A. Kusenko, and P. L. Biermann, “New Limits on Sterile Neutrinos from Suzaku Observations of the Ursa Minor Dwarf Spherical Galaxy,” Astrophys. J. 700, 426–435 (2009), arXiv:0812.2710 [astro-ph].

[35] K. C. Y. Ng, S. Horiuchi, J. M. Gaskins, M. Smith, and R. Preece, “Improved Limits on Sterile Neutrino Dark Matter using Full-Sky Fermi Gamma-ray Burst Monitor Data,” Phys. Rev. D92, 043503 (2015), arXiv:1504.04027 [astro-ph.CO].

[36] H. Yuksel, J. F. Beacom, and C. R. Watson, “Strong Upper Limits on Sterile Neutrino Warm Dark Matter,” Phys. Rev. Lett. 101, 121301 (2008), arXiv:0706.4084 [astro-ph].

[37] A. Boyarsky, D. Malyshev, A. Neronov, and O. Ruchayskiy, “Constraining Dark Matter Properties with SPI,” Mon. Not. Roy. Astron. Soc. 387, 1345 (2008), arXiv:0710.4922 [astro-ph].

[38] E. Carlson, T. Jeltema, and S. Profumo, “Where Do the 3.5 keV Photons Come From? A Morphological Study of the Galactic Center and of Perseus,” J. Cosmol. Astroparticle Phys. 2015, 009 (2015), arXiv:1411.1758 [astro-ph.HE].

[39] S. Riemer-Sørensen, “Constraints on the Presence of a 3.5 keV Dark Matter Emission Line from Chandra Observations of the Galactic Centre,” Astron. Astrophys. 590, A71 (2016), arXiv:1405.7943 [astro-ph.CO].

[40] T. E. Jeltema and S. Profumo, “Discovery of a 3.5 keV Line in the Galactic Centre and a Critical Look at the Origin of the Line across Astronomical Targets,” Mon. Not. Roy. Astron. Soc. 450, 2143–2152 (2015), arXiv:1408.1699 [astro-ph.HE].

[41] D. Malyshev, A. Neronov, and D. Eckert, “Constraints on 3.55 keV Line Emission from Stacked Observations of Dwarf Spherical Galaxies,” Phys. Rev. D90, 103506 (2014), arXiv:1408.3531 [astro-ph.HE].

[42] M. E. Anderson, E. Churazov, and J. N. Bregman, “Non-Detection of X-ray Emission From Sterile Neutrinos in Stacked Galaxy Spectra,” Mon. Not. Roy. Astron. Soc. 452, 3905–3923 (2015), arXiv:1408.4115 [astro-ph.HE].

[43] O. Urban, N. Werner, S. W. Allen, A. Simionescu, J. S. Kaasstra, and L. E. Strigari, “A Suzaku Search for Dark Matter Emission Lines in the X-ray Brightest Galaxy Clusters,” Mon. Not. Roy. Astron. Soc. 456, 2447–2461 (2015), arXiv:1411.0050 [astro-ph.CO].

[44] T. Tamura, R. Iizuka, Y. Maeda, K. Mitsuda, and N. Y. Yamasaki, “An X-ray Spectroscopic Search for Dark Matter in the Perseus Cluster with Suzaku,” Publ. Astron. Soc. Japan 67, 23 (2015), arXiv:1412.1869 [astro-ph.HE].

[45] N. Sekiya, N. Y. Yamasaki, and K. Mitsuda, “A Search for a keV Signature of Radiatively Decaying Dark Matter with Suzaku XIS Observations of the X-ray Diffuse Background,” Publ. Astron. Soc. Jap. 68, S31 (2016), arXiv:1504.02826 [astro-ph.HE].

[46] E. Figueroa-Feliciano et al. (XQC Collaboration),
“Searching for keV Sterile Neutrino Dark Matter with X-ray Microcalorimeter Sounding Rockets,” Astrophys. J. 814, 82 (2015), arXiv:1506.05519 [astro-ph.CO].

[47] S. Riemer-Sørensen et al., “Dark Matter Line Emission Constraints from NuSTAR Observations of the Bullet Cluster,” Astrophys. J. 810, 48 (2015), arXiv:1507.01378 [astro-ph.CO].

[48] D. Iakubovskyi, E. Bulbul, A. R. Foster, D. Savchenko, and V. Sadova, “Testing the Origin of ∼3.55 keV Line in Individual Galaxy clusters observed with XMM-Newton,” (2015), arXiv:1508.05186 [astro-ph.HE].

[49] T. E. Jeltema and S. Profumo, “Deep XMM Observations of Draco Rule out at the 99% Confidence Level a Dark Matter Decay Origin for the 3.5 keV Line,” Mon. Not. Roy. Astron. Soc. 458, 3592–3596 (2016), arXiv:1512.01239 [astro-ph.HE].

[50] O. Ruchayskiy, A. Boyarsky, D. Iakubovskyi, E. Bulbul, D. Eckert, J. Franse, D. Malyshev, M. Markevitch, and A. Neronov, “Searching for Decaying Dark Matter in Deep XMM-Newton Observation of the Draco Dwarf Spheroidal,” Mon. Not. Roy. Astron. Soc. 460, 1390–1398 (2016), arXiv:1512.07217 [astro-ph.HE].

[51] J. Franse et al., “Radial Profile of the 3.5 keV Line out to R200 in the Perseus Cluster,” Astrophys. J. 829, 124 (2016), arXiv:1604.01759 [astro-ph.CO].

[52] E. Bulbul, M. Markevitch, A. Foster, E. Miller, M. Bautz, M. Loewenstein, S. W. Randall, and R. K. Smith, “Searching for the 3.5 keV Line in the Stacked Suzaku Observations of Galaxy Clusters,” Astrophys. J. 831, 55 (2016), arXiv:1605.02034 [astro-ph.HE].

[53] F. Hofmann, J. S. Sanders, K. Nandra, N. Clerc, and M. Gaspari, “7.1 keV Sterile Neutrino Constraints from X-ray Observations of 33 Clusters of Galaxies with Chandra ACIS,” Astron. Astrophys. 592, A112 (2016), arXiv:1606.04091 [astro-ph.CO].

[54] F. A. Aharonian et al. (Hitomi Collaboration), “Hitomi Constraints on the 3.5 keV Line in the Perseus Galaxy Cluster,” Astrophys. J. 837, L15 (2017), arXiv:1607.07420 [astro-ph.HE].

[55] 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 with Chandra: the 10 Ms Observations,” Astrophys. J. 854, 179 (2018), arXiv:1701.07932 [astro-ph.CO].

[56] A. Boyarsky, D. Iakubovskyi, O. Ruchayskiy, and D. Savchenko, “Surface Brightness Profile of the 3.5 keV Line in the Milky Way Halo,” (2018), arXiv:1812.10488 [astro-ph.HE].

[57] T. Tamura et al., “An X-ray Spectroscopic Search for Dark Matter and Unidentified Line Signatures in the Perseus Cluster with Hitomi,” Publ. Astron. Soc. Japan 71 (2019), arXiv:1811.05767 [astro-ph.HE].

[58] C. Dessert, N. L. Rodd, and B. R. Saffé, “Evidence against the Decaying Dark Matter Interpretation of the 3.5 keV Line from Blank Sky Observations,” (2018), arXiv:1812.06976 [astro-ph.CO].

[59] F. Hofmann and C. Wegg, “7.1 keV Sterile Neutrino Dark Matter Constraints from a Deep Chandra X-ray Observation of the Galactic Bulge Limiting Window,” Astron. Astrophys. 625, L7 (2019), arXiv:1905.00916 [astro-ph.HE].

[60] K. N. Abazajian, “Resonantly Produced 7 keV Sterile Neutrino Dark Matter Models and the Properties of Milky Way Satellites,” Phys. Rev. Lett. 112, 161303 (2014), arXiv:1403.0954 [astro-ph.CO].

[61] D. P. Finkbeiner and N. Weiner, “X-ray Line from Exciting Dark Matter,” Phys. Rev. D94, 083002 (2016), arXiv:1402.6671 [hep-ph].

[62] T. Higaki, K. S. Jeong, and F. Takahashi, “The 7 keV Axion Dark Matter and the X-ray Line Signal,” Phys. Lett. B733, 25–31 (2014), arXiv:1402.6965 [hep-ph].

[63] V. Brdar, J. Kopp, J. Liu, and X.-P. Wang, “X-Ray Lines from Dark Matter Annihilation at the keV Scale,” Phys. Rev. Lett. 120, 061301 (2018), arXiv:1710.02146 [hep-ph].

[64] M. H. Namjoo, T. R. Slatyer, and C.-L. Wu, “Enhanced N-Body Annihilation of Dark Matter and its Indirect Signatures,” J. High-Energy Phys. 03, 077 (2019), arXiv:1810.09455 [astro-ph.CO].

[65] K. Nakayama, F. Takahashi, and T. T. Yanagida, “Revisiting the Number-Theory Dark Matter Scenario and the Weak Gravity Conjecture,” Phys. Lett. B790, 218–224 (2019), arXiv:1811.01755 [hep-ph].

[66] L. Gu, J. Kaastra, A. J. J. Raassen, P. S. Cumbee, D. Lyons, and P. C. Stancil, “A Novel Scenario for the Possible X-ray Line Feature at ∼3.5 keV: Charge Exchange with Bare Sulfur Ions,” Astron. Astrophys. 584, L11 (2015), arXiv:1511.06557 [astro-ph.HE].

[67] L. Gu, J. Mao, J. de Plaa, A. J. J. Raassen, C. Shah, and J. S. Kaastra, “Charge Exchange in Galaxy Clusters,” Astron. Astrophys. 611, A26 (2018), arXiv:1710.04784 [astro-ph.HE].

[68] E. G. Speckhard, K. C. Y. Ng, J. F. Beacom, and R. Laha, “Dark Matter Velocity Spectroscopy,” Phys. Rev. Lett. 116, 031301 (2016), arXiv:1507.04744 [astro-ph.CO].

[69] D. Powell, R. Laha, K. C. Y. Ng, and T. Abel, “Doppler Effect on Indirect Detection of Dark Matter Using Dark Matter Only Simulations,” Phys. Rev. D95, 063012 (2017), arXiv:1611.02714 [astro-ph.CO].

[70] A. Neronov, D. Malyshev, and D. Eckert, “Decaying Dark Matter Search with NuSTAR Deep Sky Observations,” Phys. Rev. D94, 123504 (2016), arXiv:1607.07328 [astro-ph.HE].

[71] K. Perez, K. C. Y. Ng, J. F. Beacom, C. Hersh, S. Horiuchi, and R. Krivonos, “Almost Closing the νMSM Sterile Neutrino Dark Matter Window with NuSTAR,” Phys. Rev. D95, 123002 (2017), arXiv:1609.00667 [astro-ph.HE].

[72] K. C. Y. Ng, B. M. Roach, K. Perez, J. F. Beacom, S. Horiuchi, R. Krivonos, and D. R. Wik, “New Constraints on Sterile Neutrino Dark Matter from NuSTAR M31 Observations,” Phys. Rev. D 99, 083005 (2019), arXiv:1901.01262 [astro-ph.HE].

[73] R. A. Krivonos, S. S. Tsygankov, I. A. Mereminskiy, A. A. Lutovinov, S. Yu. Sazonov, and R. A. Sunyaev, “New Hard X-ray Sources Discovered in the Ongoing INTEGRAL Galactic Plane Survey after 14 yr of Observations,” Mon. Not. Roy. Astron. Soc. 470, 512 (2017), arXiv:1704.03364 [astro-ph.HE].

[74] R. Launhardt, R. Zylka, and P. G. Mezger, “The Nuclear Bulge of the Galaxy. 3. Large Scale Physical Characteristics of Stars and Interstellar Matter,” Astron. Astrophys. 384, 112–139 (2002), arXiv:astro-ph/0201294 [astro-ph].

[75] M. Revnivtsev, S. Molkov, and S. Sazonov, “Map of the Galaxy in the 6.7-keV Emission Line,” Mon. Not. Roy. Astron. Soc. Lett. 373, L11–L15 (2006), arXiv:astro-ph/0605693 [astro-ph].
[76] F. A. Harrison et al., “The Nuclear Spectroscopic Telescope Array (NuSTAR) High-Energy X-ray Mission,” Astrophys. J. 770, 103 (2013), arXiv:1301.7307 [astro-ph.IM].

[77] D. R. Wik et al., “NuSTAR Observations of the Bullet Cluster: Constraints on Inverse Compton Emission,” Astrophys. J. 792, 48 (2014), arXiv:1403.2722 [astro-ph.HE].

[78] K. K. Madsen et al., “Calibration of the NuSTAR High Energy Focusing X-ray Telescope,” Astrophys. J. Suppl. 220, 8 (2015), arXiv:1504.01672 [astro-ph.IM].

[79] Gaia Collaboration et al., “The Gaia Mission,” Astron. Astrophys. 595, A1 (2016), arXiv:1609.04153 [astro-ph.IM].

[80] Gaia Collaboration et al., “Gaia Data Release 2. Summary of the Contents and Survey Properties,” Astron. Astrophys. 616, A1 (2018), arXiv:1804.09365.

[81] W. Voges et al., “The ROSAT All-Sky Survey Bright Source Catalogue,” Astron. Astrophys. 349, 389 (1999), arXiv:astro-ph/9909315 [astro-ph].

[82] H. Mori, Y. Maeda, Y. Ueda, T. Dotani, and M. Ishida, “Suzaku Observations of Unidentified X-ray Sources toward the Galactic Bulge,” Publ. Astron. Soc. Japan 64 (2012), 10.1093/pasj/64.5.112.

[83] H. An, K. K. Madsen, N. J. Westergaard, S. E. Boggs, F. E. Christensen, W. W. Craig, C. J. Hailey, F. A. Harrison, D. K. Stern, and W. W. Zhang, “In-flight PSF calibration of the NuSTAR hard X-ray optics,” Proceedings, SPIE Space Telescopes and Instrumentation 2014: Ultraviolet to Gamma Ray: Montreal, Quebec, Canada, June 22-26, 2014, Proc. SPIE Int. Soc. Opt. Eng. 9144, 91441Q (2014), arXiv:1406.7419 [astro-ph.IM].

[84] E. Churazov et al., “INTEGRAL Observations of the Cosmic X-ray Background in the 5-100 keV Range via Occultation by the Earth,” Astron. Astrophys. 467, 529–540 (2006).

[85] H. Kaneda, K. Makishima, S. Yamauchi, K. Koyama, K. Matsuzaki, and N. Y. Yamasaki, “Complex Spectra of the Galactic Ridge X-rays Observed with ASCA,” Astrophys. J. 491, 638–652 (1997).

[86] T. Yuasa, K. Makishima, and K. Nakazawa, “Broadband Spectral Analysis of the Galactic Ridge X-ray Emission,” Astrophys. J. 753, 129 (2012), arXiv:1205.1574 [astro-ph.GA].

[87] R. Krivonos, D. R. Wik, and K. Perez, (2019), (in prep).

[88] R. K. Smith, N. S. Brickhouse, D. A. Liedahl, and J. C. Raymond, “Collisional Plasma Models with APEC/APED: Emission-Line Diagnostics of Hydrogen-like and Helium-like Ions,” Astrophys. J. 556, L91–L95 (2001).

[89] M. G. Revnivtsev and S. V. Molkov, “Results from a Deep RXTE/PCA scan across the Galactic Plane,” Mon. Not. Roy. Astron. Soc. 424, 2330–2338 (2012).

[90] M. Revnivtsev, S. Sazonov, E. Churazov, W. Forman, A. Vikhlinin, and R. Sunyaev, “Discrete Sources as the Origin of the Galactic X-Ray Ridge Emission,” Nature 458, 1142 (2009), arXiv:0904.4649 [astro-ph.GA].

[91] R. Krivonos, S. Tsygankov, M. Revnivtsev, S. Sazonov, E. Churazov, and R. Sunyaev, “INTEGRAL Constraints on the Galactic Hard X-ray Background from the Milky Way Anticenter,” Astron. Astrophys. 537, A92 (2012), arXiv:1109.2471 [astro-ph.GA].

[92] J. Wilms, A. Allen, and R. McCray, “On the Absorption of X-rays in the Interstellar Medium,” Astrophys. J. 542, 914–924 (2000), arXiv:astro-ph/0008425 [astro-ph].

[93] J. M. Dickey and F. J. Lockman, “H I in the Galaxy,” Ann. Rev. Astron. Astrophys. 28, 215–261 (1990).

[94] P. M. W. Kalberla, W. B. Burton, D. Hartmann, E. M. Arnal, E. Bajaja, R. Morras, and W. G. L. F"oppel, “The Leiden/Argentine/Bonn (LAB) Survey of Galactic H I: Final Data Release of the Combined LDS and IAR Surveys with Improved Stray-Radiation Corrections,” Astron. Astrophys. 440, 775–782 (2005), arXiv:astro-ph/0504140 [astro-ph].

[95] T. Venumadhav, F.-Y. Cyr-Racine, K. N. Abazajian, and C. M. Hirata, “Sterile Neutrino Dark Matter: Weak Interactions in the Strong Coupling Epoch,” Phys. Rev. D94, 043515 (2016), arXiv:1507.06655 [astro-ph.CO].

[96] E. Jones, T. Oliphant, P. Peterson, et al., “SciPy: Open source scientific tools for Python,” https://www.scipy.org/ (2001–), [Online, accessed August 27, 2019].

[97] Astropy Collaboration et al., “Astropy: A Community Python Package for Astronomy,” Astron. Astrophys. 558, A33 (2013), arXiv:1307.6212 [astro-ph.IM].

[98] A. M. Price-Whelan et al., “The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package,” Astronomical J. 156, 123 (2018).