

Sterile neutrino dark matter bounds from galaxies of the Local GroupShunsaku Horiuchi,^{*} Philip J. Humphrey, Jose Oñorbe, Kevork N. Abazajian,
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We show that the canonical oscillation-based (nonresonant) production of sterile neutrino dark matter is inconsistent at $> 99\%$ confidence with observations of galaxies in the Local Group. We set lower limits on the nonresonant sterile neutrino mass of 2.5 keV (equivalent to 0.7 keV thermal mass) using phase-space densities derived for dwarf satellite galaxies of the Milky Way as well as limits of 8.8 keV (equivalent to 1.8 keV thermal mass) based on subhalo counts of N -body simulations of M 31 analogs. Combined with improved upper mass limits derived from significantly deeper x-ray data of M 31 with full consideration for background variations, we show that there remains little room for nonresonant production if sterile neutrinos are to explain 100% of the dark matter abundance. Resonant and nonoscillation sterile neutrino production remain viable mechanisms for generating sufficient dark matter sterile neutrinos.

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I. INTRODUCTION

The particle nature of dark matter (DM) is among the most intriguing questions in modern physics, and many extensions to the Standard Model of particle physics have been considered [1–3]. Among the highly motivated candidates is the sterile (singlet) neutrino with a mass in the keV range [4,5]. In the simplest original Dodelson–Widrow (DW) scenario [6], they are produced in the early Universe via oscillations with active neutrinos that are nonresonant in the presence of negligible lepton asymmetry (see also Refs. [7,8]). Production via resonant oscillations in the presence of a lepton asymmetry (resonant production, [RP] [8–10]), via interactions with the inflaton [11,12], and via scalar production [13] have also been proposed. In addition to DM, sterile neutrinos may also explain the observed velocities of pulsars [11,14].

The DW sterile neutrino is warm dark matter (WDM) with a non-negligible velocity dispersion. This suppresses the matter power spectrum below the free-streaming scale and affects DM structures. Conversely, information of the matter power spectrum on small scales can be used to constrain the sterile neutrino properties. By modeling the Sloan Digital Sky Survey (SDSS) Lyman- α forest flux power spectrum, lower limits of $m_s^{\text{DW}} \gtrsim 13$ keV have been found [15–18]; with recent Keck data, $m_s^{\text{DW}} \gtrsim 22$ keV at 2σ [19]. Lower limits of $m_s^{\text{DW}} \gtrsim 13$ keV have also been placed by requiring the number of subhalos in N -body simulations to be larger than the number of observed dwarf spheroidal galaxies (dSphs) of the Milky Way (MW) [20]. Limits have also been placed using high- z observations of gamma-ray bursts [21] and galaxies [22].

At the same time, sterile neutrinos are not completely stable, and their radiative decays into active neutrinos provides a compelling search opportunity [23]. Because of detector capabilities, current x-ray searches probe masses of a few keV and above. Many DM sources have been studied, ranging from the x-ray background, galaxy clusters, nearby galaxies, and our own MW (see, e.g., Ref. [24] and references therein). The M 31 galaxy yields some of the strongest constraints, and for the DW sterile neutrino, previous works have limited the mass to $m_s^{\text{DW}} \lesssim 3$ keV [25–27].

When combined, the lower and upper limits seemingly already rule out the DW sterile neutrino. However, modeling the Lyman- α forest flux requires hydrodynamic simulations with implicit assumptions about the thermal history of the absorbing gas and its ionizing background. When these assumptions are relaxed, the mass limits are diluted (see, e.g., Figs. 11 and 12 of Ref. [19] and discussions therein). The comparison of subhalos to MW dSphs assumes a factor of ~ 4 correction for the number of dSphs being missed by current surveys; without the correction, limits are weakened. Although dSphs are no doubt being missed, this introduces a large uncertainty in the limit. Given these large systematic uncertainties, additional constraints are required to make definitive conclusions regarding the viability of the DW mechanism.

More robust lower limits have been placed by exploiting the limited phase-space packing of sterile neutrinos [28,29]. For a given primordial momentum distribution of sterile neutrinos, a theoretical maximum phase-space density exists. Comparing these to the phase-space densities estimated from MW dSphs, limits of $m_s^{\text{DW}} \gtrsim 1.8$ keV have been set [30,31], leaving a small window for the DW sterile neutrino production mechanism to generate 100% of the observed DM abundance [31].

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In this paper, we revisit the lower and upper limits on sterile neutrinos and address the viability of the DW mechanism in explaining 100% of the observed DM abundance. We improve both lower limits placed from phase-space arguments and subhalo counts, as well as x-ray upper limits. For phase-space limits, we consider new MW dSphs not considered in previous works, and we also address the main uncertainty in estimating the DM velocity dispersion. For subhalo counts, we focus on M 31 and do not rely on uncertain incompleteness corrections. Finally, for x-ray constraints, we use the largest and deepest data assembled of M 31 and include full background uncertainties. Using our improved and more robust constraints, we are able to rule out the DW sterile neutrino as a viable DM candidate at more than 99% C.L.

In Sec. II, we discuss our new phase-space constraints, followed by subhalo count limits in Sec. III. We discuss x-ray constraints in Sec. IV and conclude in Sec. V. Throughout, as our focus is on the DM sterile neutrino, we opt to use the mass m_s^{DW} as our main parameter. However, it is also common to quote the mass of a thermal WDM particle, m_{WDM} , which is related to m_s^{DW} by $m_s^{\text{DW}} \approx 4.379 \text{ keV} (m_{\text{WDM}}/1 \text{ keV})^{4/3} (\Omega_m/0.238)^{-1/3} (h/0.73)^{-2/3}$ [32].

II. PHASE-SPACE DENSITY LIMITS

A. General considerations

Lower limits on the DM particle mass are based on Liouville's theorem. For dissipationless and collisionless particles, the phase-space density cannot increase, and its maximum does not change with time. Estimates of the coarse-grained phase-space density made using astrophysical observations must therefore satisfy $Q < q_{\text{max}}$, where Q is the coarse-grained phase-space density and q_{max} is the maximal fine-grained phase-space density [33]. Since q_{max} depends on the primordial DM properties, the inequality can be used to limit, e.g., the DM mass.

The momentum distribution of DW sterile neutrinos at production is well approximated by $f_s(p) = \beta(e^{p/T} + 1)^{-1}$. Here, p is momentum, and T is temperature. If $\beta = 1$, one recovers the thermal Fermi–Dirac distribution, and the fine-grained phase-space density maximum is [31],

$$q_{\text{max}}^{\text{FD}} = \frac{gm^4}{2(2\pi\hbar)^3} \approx 5 \times 10^{-4} \left(\frac{g}{2}\right) \left(\frac{m}{1 \text{ keV}}\right)^4 M_{\odot} \text{pc}^{-3} (\text{km/s})^{-3}, \quad (1)$$

where g is the number of spin degrees of freedom. For the DW sterile neutrino, β can be set by the requirement to obtain the correct relic density, $\beta \approx \Omega_{\text{dm}} h^2 (m_s^{\text{DW}}/94 \text{ eV})^{-1}$ [6], so that

$$q_{\text{max}}^{\text{DW}} = \eta \frac{\beta gm^4}{2(2\pi\hbar)^3} \approx 6 \times 10^{-6} \left(\frac{\eta}{1.25}\right) \left(\frac{g}{2}\right) \left(\frac{m_s^{\text{DW}}}{1 \text{ keV}}\right)^3 \left(\frac{\Omega_{\text{dm}} h^2}{0.105}\right) M_{\odot} \text{pc}^{-3} (\text{km/s})^{-3}. \quad (2)$$

Here, the additional η factor is a correction factor due to the fact that β is not strictly a constant. The $\beta = \text{constant}$ estimate is only valid for $T \lesssim 200 \text{ MeV}$, where the number of particle degrees of freedom can be taken to be constant; above this, the activation of the extra gluon and quark degrees of freedom requires a numerical treatment [34–36]. The earlier production momenta have the effect of shifting the momentum distribution colder (see, e.g., Fig. 1 of Ref. [34]), implying larger fine-grained phase-space maxima. We find the effect to be a $\sim 20\%$ – 25% increase over a wide sterile neutrino mass range and conservatively adopt $\eta = 1.25$.

The coarse-grained phase-space density Q is defined as the mass density in a *finite* six-dimensional phase-space volume at time t . There are multiple definitions in the literature. A popular choice is the pseudo-phase-space density [33],

$$Q_{\text{HD00}} \equiv \frac{\bar{\rho}}{(3\sigma^2)^{3/2}}, \quad (3)$$

where $\bar{\rho}$ is the average DM density and σ is the one-dimensional DM velocity dispersion. A more realistic phase-space volume can be defined from adopting a Maxwellian velocity distribution [37],

$$Q_{\text{MB}} \equiv \frac{\bar{\rho}}{(2\pi\sigma^2)^{3/2}} \approx 0.33 Q_{\text{HD00}}, \quad (4)$$

where $(2\pi\sigma^2)^{-3/2}$ is the maximum density in velocity space. Finally, the mass density can be defined very conservatively based on the whole available phase-space volume $\Delta x \Delta v = (4\pi/3)^2 R^3 v_{\infty}^3$, with $v_{\infty} = \sqrt{6}\sigma$ [31],

$$Q_{\text{Boy}} \equiv \frac{\bar{\rho}}{(8\pi\sqrt{6}\sigma^3)} \approx 0.08 Q_{\text{HD00}}. \quad (5)$$

For the rest of the paper, we focus on Q_{MB} , but results for other definitions can be easily obtained from the above scaling relations.

The dSph satellites of the MW provide the optimum locations for estimating the coarse-grained phase-space density [29] and have been recently investigated by Refs. [30,31]. We estimate the coarse-grained phase-space assuming that the density is constant within r_h and use the mass estimator $M_h \approx 3\sigma_*^2 r_h/3$ [38]. The mean density can then be written $\bar{\rho} = (9\sigma_*^2)/(4\pi G r_h^2)$, which yields

$$\begin{aligned}
Q_{\text{MB}} &= \frac{9}{2(2\pi)^{5/2} G r_h^2 \eta_*^3 \sigma_*} \\
&\approx 1.1 \times 10^{-4} \eta_*^{-3} \left(\frac{\sigma_*}{10 \text{ km/s}} \right)^{-1} \left(\frac{r_h}{100 \text{ pc}} \right)^{-2} \\
&\text{M}_\odot \text{pc}^{-3} (\text{km/s})^{-3}, \tag{6}
\end{aligned}$$

for the Maxwellian phase-space density. While simple, this method has a large uncertainty associated with how to estimate the dark matter velocity dispersion, σ , from the observed stellar velocity dispersion, σ_* . In previous works, this has been replaced by an ignorance parameter, $\eta_* = \sigma/\sigma_*$, assumed to be of order unity [30,31]. Since the mass limit scales as $Q^{1/3}$, the uncertainty in η_* directly affects the limit, $m_s^{\text{DW}} \propto 1/\eta_*$.

Nevertheless, we first estimate Q_{MB} for the MW satellites, adopting values of σ_* and r_h from Ref. [38] and assuming $\eta_* = 1$. These are shown in the sixth column of Table I. We stress that these are conservative approximations of the mean phase-space density within r_h , rather than the true central densities. The values of Q_{HD00} and Q_{Boy} are obtainable via the scalings, Eqs. (3)–(5).

The uncertainties on Q_{MB} are derived assuming Gaussian statistics and follow from the uncertainties in the measured σ_* and r_h only. However, systematic effects likely dominate the uncertainty. For example, Ursa Major II shows circumstantial evidence of ongoing tidal disruption [39]. Coma Berenices shares some properties with Ursa Major II, although there is no known tidal stream near its position [39] and additional observations are consistent with no ongoing tidal disruption [40]. At the extreme is Willman I. It has a large estimated $Q_{\text{MB}} \approx (1.1 \pm 0.6) \times 10^{-3} (\text{M}_\odot/\text{pc}^3)(\text{km/s})^{-3}$, but there is compelling evidence of tidal disruption by the MW, and this is

likely an overestimate. We therefore omit Willman I from Table I. Segue 1, which also has a high inferred Q , is among the faintest dwarfs recently discovered by the SDSS [41], and its properties are determined with limited stellar spectroscopy data [39,42].

B. Phase-space constraints from N -body simulations

In the previous section, the phase-space density was estimated assuming $\eta_* = \sigma/\sigma_* = 1$. However, this is not expected to be generally true. Here, we estimate the phase-space density directly from the DM density profiles of subhalos that can host the MW dSphs. For this purpose, we use the subhalos of the Via Lactea II (VL2) simulation [43]. Although this is a Λ CDM simulation, cold dark matter (CDM) subhalos are good approximations for WDM subhalos on scales greater than the core radius. For the WDM masses of interest, the core radii are small enough that we are in the CDM-like regime (see also, e.g., Refs. [44,45]). To illustrate this point, however, we will consider both the NFW profile and the pseudoisothermal profile and derive Q estimates for both (columns 8 and 9 of Table I).

The NFW profile is a commonly used two-parameter fit to dissipationless N -body simulations [46],

$$\rho_{\text{NFW}}(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}, \tag{7}$$

where r_s and ρ_0 can conveniently be written as functions of the maximum circular velocity, V_{max} , and the radius at which V_{max} is reached, R_{max} .

The pseudoisothermal density profile is a good fit to WDM density profiles on scales comparable to the core

TABLE I. Column 1): name, column 2): distance, column 3): stellar dispersion, column 4): half-light radius, column 5): the total mass within r_h ; all from Ref. [38]. Column 6): Q values [in units of $10^{-5} (\text{M}_\odot/\text{pc}^3)(\text{km/s})^{-3}$] estimated with Eq. (6) using columns 3) and 4). Column 7): number of matched subhalos in VL2 used to obtain columns 8) and 9). Column 8): \bar{Q} values [in units of $10^{-5} (\text{M}_\odot/\text{pc}^3)(\text{km/s})^{-3}$] estimated using the NFW profile. Column 9): \bar{Q} values [in units of $10^{-5} (\text{M}_\odot/\text{pc}^3)(\text{km/s})^{-3}$] estimated using a pseudoisothermal profile. Column 10): lower mass m_s^{DW} estimated using column 9).

Name 1)	d [kpc] 2)	σ_* [km/s] 3)	r_h [pc] 4)	M_h [$10^6 M_\odot$] 5)	$Q_{\text{MB}}(\eta_* = 1)$ 6)	N_{sh} 7)	$\bar{Q}_{\text{sim}}^{\text{NFW}}$ 8)	$\bar{Q}_{\text{sim}}^{\text{Iso}}$ 9)	m_s^{DW} [keV] 10)
Draco	76 ± 5	10.1 ± 0.5	291_{-14}^{+14}	$2.11_{-3.1}^{+3.1}$	1.2 ± 0.1	3	0.53 ± 0.15	0.59 ± 0.07	$>1.1 \pm 0.04$
Carina	105 ± 2	6.4 ± 0.2	334_{-37}^{+37}	$9.56_{-0.90}^{+0.95}$	1.5 ± 0.3	8	0.67 ± 0.14	0.66 ± 0.06	$>1.1 \pm 0.03$
Hercules	133 ± 6	5.1 ± 0.9	305_{-26}^{+26}	$7.50_{-3.14}^{+5.72}$	2.2 ± 0.5	37	0.75 ± 0.21	0.71 ± 0.23	$>1.0 \pm 0.1$
Leo II	233 ± 15	6.6 ± 0.5	233_{-17}^{+17}	$7.25_{-1.01}^{+1.19}$	3.0 ± 0.5	30	1.1 ± 0.3	1.2 ± 0.3	$>1.2 \pm 0.1$
Ursa Major II	32 ± 4	6.7 ± 1.4	184_{-33}^{+33}	$7.91_{-3.14}^{+5.59}$	4.7 ± 1.9	8	1.1 ± 0.4	1.1 ± 0.4	$>1.2 \pm 0.2$
Leo T	407 ± 38	7.8 ± 1.6	152_{-21}^{+21}	$7.37_{-2.96}^{+4.84}$	5.9 ± 2.0	33	1.4 ± 0.4	2.0 ± 0.7	$>1.5 \pm 0.2$
Leo IV	160 ± 15	3.3 ± 1.7	151_{-44}^{+34}	$1.14_{-0.92}^{+3.50}$	14 ± 11	80	2.4 ± 0.8	1.6 ± 0.8	$>1.4 \pm 0.2$
Canes Venatici II	160 ± 5	4.6 ± 1.0	97_{-13}^{+18}	$1.43_{-0.59}^{+1.01}$	24 ± 10	18	4.6 ± 1.5	5.3 ± 2.7	$>2.0 \pm 0.3$
Coma Berenices	44 ± 4	4.6 ± 0.8	100_{-13}^{+13}	$1.97_{-0.60}^{+0.88}$	26 ± 8.7	15	5.2 ± 2.4	5.7 ± 2.9	$>2.1 \pm 0.4$
Segue I	23 ± 2	4.3 ± 1.1	38_{-7}^{+10}	$0.60_{-0.28}^{+0.51}$	170 ± 100	7	30 ± 16	36 ± 23	$>3.9 \pm 0.8$

size and furthermore gives a good estimate of the phase-space density [37],

$$\rho_{\text{iso}}(r) = \frac{\rho_c}{1 + (r/r_c)^2}, \quad (8)$$

where ρ_c and r_c are the core density and radius. The circular velocity asymptotes to $V_{\text{max}} = (4\pi G\rho_0 r_c^2)^{1/2}$, so the profile can be defined by the parameters (V_{max}, r_c) .

First, values of $(R_{\text{max}}, V_{\text{max}})$ for all VL2 subhalos are obtained. For the NFW profile, these parameters define the density profile. However, there is no well-defined R_{max} for the pseudoisothermal profile, and V_{max} alone does not define the profile. We therefore also require that the subhalo has the correct mass M_h within the half-light radius to estimate the pseudoisothermal profile parameters.

Next, subhalos that can host the MW dSphs are selected. This involves selecting subhalos that have the correct distance to the main host halo and a reasonable V_{max} . A tolerance of $\pm 3\sigma$ is adopted for the MW dSph distances. Subhalos with $V_{\text{max}} > 60$ km/s are considered LMC/SMC analogs and are excluded. Subhalos with unreasonably small $V_{\text{max}} < 10$ km/s are also excluded. For the NFW profile, subhalos must also have the correct mass within r_h ; once again, a tolerance of $\pm 3\sigma$ is adopted. The isothermal profile by construction already has the correct mass. The resulting number of subhalos that can host MW dSphs in both the NFW and pseudoisothermal profiles, N_{sh} , is listed in Table I.

Finally, the phase-space density within r_h is calculated for each subhalo following Eq. (4), both for NFW and pseudoisothermal profiles. The average density is obtained from the profiles, and the DM velocity dispersion is determined for each profile from the spherical Jeans equation assuming an isotropic velocity dispersion tensor. The mean of N_{sh} subhalos, $\bar{Q}_{\text{sim}}^{\text{NFW}}$ and $\bar{Q}_{\text{sim}}^{\text{Iso}}$, as well as their standard deviations, are listed in Table I.

It is clear that the estimates made assuming NFW and pseudoisothermal profiles agree with each other within uncertainties. As stated, this is because the core radius is typically smaller than the scales of interest (r_h), and the phase-space density is calculated on scales where the NFW and pseudoisothermal profiles are similar. Secondly, it is clear that the estimates based on VL2 are smaller than those from stellar kinematics. The differences are some factors of ~ 2 – 5 , indicating $\eta_* \sim 1.3$ – 1.7 . In the case of Leo IV, it is as large as a factor of ~ 9 , or $\eta_* \sim 2$.

Lower-mass limits on the DW sterile neutrino are then derived. The NFW and pseudoisothermal profiles yield very similar results, and in column 10 of Table I, results for the pseudoisothermal case are shown. The errors have been symmetrized conservatively such that both the upper and lower error bars are enclosed if they are asymmetric. From these, we determine the one-sided 95% C.L. lower mass limits, $m_s^{\text{DW}} \geq 2.5$ keV for Segue I, and the next strongest limits are Coma Berenices and Canes Venaviti II, which are both $m_s^{\text{DW}} \geq 1.5$ keV.

III. M 31 DSPH COUNT LIMITS

The suppression of small-scale power due to DM streaming also manifests itself in the number of subhalos of massive halos. The suppression scale, and therefore the DM mass, can be constrained by comparing the subhalo distributions of suitable N -body simulations to observations of MW dSph [20]. However, the census of MW dSphs suffers from significant radially biased incompleteness [47], and since it is a single galaxy, the comparison must also take into account significant statistical and systematic uncertainties.

The dSphs of our nearest neighbor, M 31, provide a compelling comparison set. In particular, we have the benefit of being outside the galaxy yet close enough to detect dSphs down to fairly low luminosities. The Pan-Andromeda Archeological Survey (PAndAS) has complete coverage out to ~ 150 kpc from M 31 and sensitivity to dSphs down to luminosities of $\sim 10^5 L_\odot$ [48]. The dSph distributions were recently analyzed in Ref. [49]. They find that the M 31 dSph distributions are a better match to Λ CDM predictions than the MW dSph distributions and argue for significant incompleteness of MW dSph under the Λ CDM paradigm.

We derive m_s^{DW} limits based on comparisons of the observed M 31 dSph population to a series of WDM collisionless zoom-in simulations, requiring that the subhalo counts match or exceed the observed dSph counts. The details of the simulations are described in Ref. [50]; here, we summarize the relevant properties. All simulations were conducted with the N -body simulation code GADGET-2 [51] with WMAP7 parameters [52]. We use initial conditions simulated as part of the ELVIS project, which is a suite of 48 zoom-in simulations designed to study the Local Group [53].¹ The suite consists of 24 halos in paired systems that are chosen to resemble the MW and M 31 in mass and phase-space configuration, in addition to 24 halos that are isolated mass-matched analogs. The halo mass varies between 1.0 and $2.8 \times 10^{12} M_\odot$, with associated virial radii $r_{\text{vir}} = 263$ – 370 kpc and maximum circular velocities $V_{\text{max}} = 155$ – 225 km/s. To build the WDM initial conditions, CDM transfer functions generated using the CAMB code [54] for the ELVIS project were modified according to the analytic prescriptions of Ref. [34], Eqs. (10)–(12) to produce the WDM transfer functions. The simulations were run with identical mass resolution (particle mass $1.9 \times 10^5 M_\odot$). At this resolution, the simulations are complete to subhalos with $V_{\text{max}} \gtrsim 8$ km/s [53]. Halo substructure was identified with the Amiga Halo Finder [55].

The subhalo distributions, as functions of $V_{\text{max}}/V_{\text{vir,host}}$, where $V_{\text{vir,host}}$ is the host halo virial velocity, are shown in Fig. 1. A distance cut of < 250 kpc is applied. The

¹The data are available at <http://localgroup.ps.uci.edu/elvis/>.

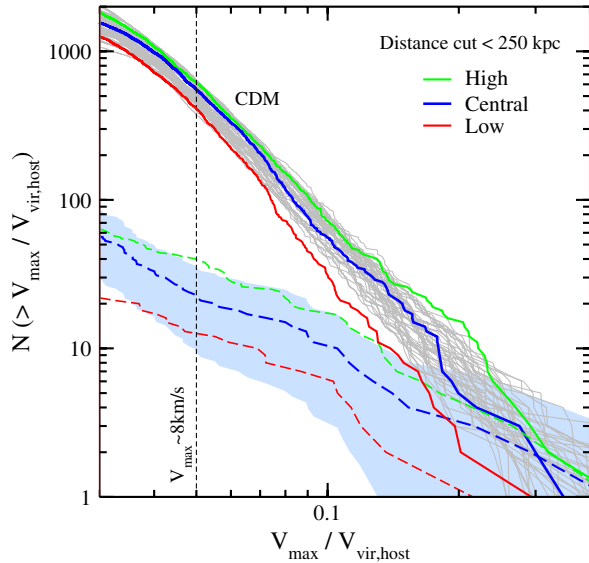


FIG. 1 (color online). Cumulative subhalo counts as functions of V_{\max} normalized to the host virial velocity. The series of simulations labeled CDM are from the ELVIS suite of Λ CDM simulations of the Local Group; the three highlighted runs encompass the extremes (high and low in green and red) and the central (in blue). The dashed lines are the WDM analogs, all for $m_s^{\text{DW}} = 6$ keV. The shaded region denotes the 2σ scatter in the central WDM estimated from CDM, which is consistent with the high and low WDM runs (see the text for details).

resolution limit $V_{\max} > 8$ km/s is plotted for the mean V_{vir} of ≈ 263 km/s for clarity. By normalizing by $V_{\text{vir,host}}$, some of the scatter in subhalo distributions is reduced, but it still captures the more dominant and important scatter in the total number of subhalos, which, as described below, is used to obtain limits on sterile neutrinos. The 48 ELVIS simulations are shown in grey and provide a measure of the scatter in predictions for a single Λ CDM cosmology, i.e., the combined systematic uncertainty due to cosmic variance, range of plausible M 31 halo mass, and low-number Poisson scatter. We take a flat prior on the host halo mass; thus, the scatter is a conservative overestimate of the true

TABLE II. Subhalo counts for CDM and WDM simulations with mass $m_s^{\text{DW}} = 3, 6, 10,$ and 15.5 keV (corresponding to thermal masses of $0.76, 1.28, 1.88,$ and 2.62 keV, respectively), with cuts of $8 < V_{\max}/(\text{km/s}) < 60$, and various distance cuts are applied as indicated. The number of observed dSph of M 31 is also shown.

Simulation	$D < 250$ kpc	$D < 200$ kpc	$D < 150$ kpc
Central CDM	454 ± 122	368 ± 100	246 ± 62
Central 15.5 keV	72 ± 16.4	53 ± 13.2	32 ± 8.1
Central 10 keV	37 ± 9.3	28 ± 7.5	13 ± 4.3
Central 6 keV	19 ± 5.7	13 ± 4.3	8 ± 3.0
Central 3 keV	6 ± 2.4	5 ± 2.2	4 ± 2.0
Observed	> 29	> 26	18

scatter due to the uncertainty of the mass of M 31. The overall scatter is non-negligible, being some factors of ~ 2 at the minimum and increasing as the number of subhalos decrease.

To test whether the scatter in CDM changes in WDM, we adopt three runs from ELVIS, capturing the two extremes (indicated by the green and red lines) and the central behavior (indicated by the blue line). These are simulated for $m_s^{\text{DW}} = 6$ keV, shown by the dashed lines. To compute the subhalo scatter for CDM, we calculate the mean $\bar{N}_{\text{subs}}^{\text{CDM}}$ and standard deviation $\sigma_{\text{subs}}^{\text{CDM}}$ of the cumulative subhalo counts according to the ELVIS suite and determine the normalized standard deviation, $\hat{\sigma} = \sigma_{\text{subs}}^{\text{CDM}} / \bar{N}_{\text{subs}}^{\text{CDM}}$, as a function of N_{subs} . We then apply this distribution according to the number of subhalos in WDM simulations, i.e., $\hat{\sigma}(N_{\text{subs}} = N_{\text{subs}}^{\text{WDM}})$. The blue shaded band in Fig. 1 shows the 2σ region about the central-6 keV run estimated by this method. The inclusion of the two extreme WDM simulations within this band demonstrates the applicability of this method.

Having established the validity of applying the CDM scatter to WDM, we simulate the central initial condition for m_s^{DW} masses of 3, 6, 10, and 15.5 keV (equivalent to thermal masses of 0.76, 1.28, 1.88, and 2.62 keV, respectively). The subhalo counts using cuts of $8 \text{ km/s} < V_{\max} < 60$ km/s and various distance cuts are summarized in Table II. We compare these to the observed M 31 dSph counts, which are derived mainly from Ref. [56], with the

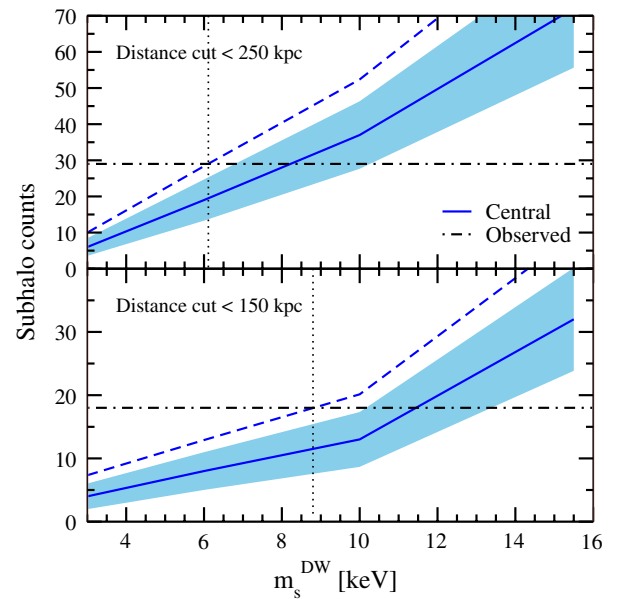


FIG. 2 (color online). The number of subhalos seen in simulations (solid) and its 1σ uncertainty (shaded), compared to the number of dSphs of M 31 (dotted-dashed line) for distance cuts of 250 kpc (top panel) and 150 kpc (bottom panel). The dashed line denotes the one-sided 95% uncertainty, and the vertical dotted lines indicate the resulting one-sided 95% C.L. mass limit.

addition of the recently discovered And XXX [57], And XXXI, and And XXXII [58]. The vast majority of these have estimated V_{\max} greater than 8 km/s [59]. We exclude from this list M 33, since our focus is on dwarf galaxies, consistent with our upper V_{\max} cut.

Unsurprisingly, our smallest distance cut < 150 kpc, which is consistent with the completeness range of M 31 dSph, provides the strongest constraint: at 1σ deviation, our 10 keV run has barely enough subhalos to match the observed number of M 31 dSphs. The interpolation with mass is shown in Fig. 2 and shows that at $m_s^{\text{DW}} = 8.8$ keV the one-side 95% scatter matches the (minimum) required number of M 31 dSph; we quote this mass as our one-sided 95% C.L. lower mass limit. The limits for the other distance cuts are 6.1 keV and 7.2 keV for < 250 kpc and < 200 kpc, respectively.

IV. M 31 X-RAY LIMITS

To obtain improved x-ray constraints on the mixing angle (θ) between sterile and active neutrinos, we take advantage of significantly deeper Chandra Advanced Charge-coupled device Imaging Spectrometer (ACIS) data than has been used in previous work [60]. The central part of the galaxy, where the signal is expected to be strongest, has been repeatedly imaged as part of monitoring programs, enabling a very deep composite image. This is optimal for the detection and removal of the faint point sources that constitute most of the x-ray emission from M 31. In this respect, Chandra is far superior to XMM-Newton or Suzaku.

We assembled all 70 Chandra data sets taken in the ACIS-I configuration that were centered on the nucleus of M 31 and were publicly available as of March 6, 2013. We used ACIS-I due to its lower, more stable, instrumental background and larger unobstructed field of view than ACIS-S. Each data set was reduced and processed with the CIAO 4.3 software suite following standard procedures, and the astrometry was corrected onto a standard reference frame by matching bright sources detected in each observation, as described in Ref. [61]. Images and spectra were coadded to produce a total on-axis exposure of 267 ks. Source detection was performed on the coadded image with the *wavdetect* CIAO tool, and data within three times the 90% encircled energy ellipses estimated for each source were excluded from subsequent analysis. A composite spectrum, and count-weighted response matrices, were extracted from the exposed regions of the charge-coupled devices, excluding the central $2'$ and any detected sources. In Fig. 3, we show the spectral data, along with the equivalent data extracted from identical regions of the standard “blank sky field” event files, which provides a rough estimate of the background. These data were supplemented by 17 additional ACIS-I data sets that were offset from the center of the galaxy by ~ 1 – $5'$. These data were analyzed separately and their spectra added, for a total

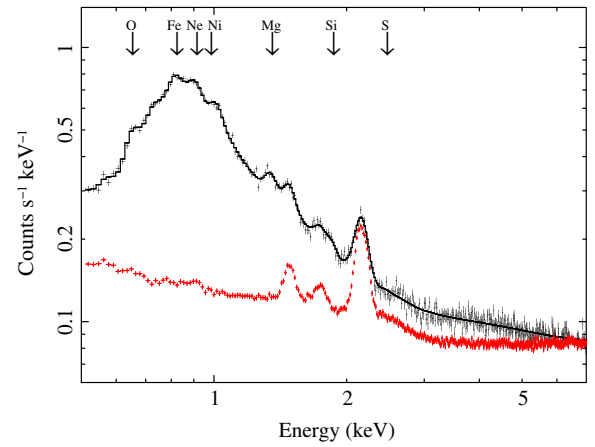


FIG. 3 (color online). Coadded on-axis ACIS-I spectral data (black points), without background subtraction. In red, we show an estimate of the background extracted from identical regions of blank sky fields. The solid black line is the best-fitting model, folded through the instrumental response, which fits the data well. We note the location of astrophysically important emission lines expected for the collisionally ionized plasma present in the bulge of M 31.

exposure of 137 ks. The effective area curves were averaged, weighting by the relative expected line flux.

Following Ref. [62], we fitted the spectra with a physically motivated model using version 12.7.1 of the XSPEC spectral fitting package [63]. The data were mildly rebinned (to ensure > 20 photons per bin), which aids in error bar computation, and we minimized the Cash-C goodness-of-fit statistic [64]. The model comprised a power law and two thermal (APEC, [65]) plasma components to account for the cosmic and Galactic x-ray background, plus two broken power law models (not multiplied by the effective area) and three Gaussian lines to account for the instrumental background. To account for emission from M 31, we included a power law and two APEC plasma components ($kT = 0.32$ and 0.78 keV) that were modified by photoelectric absorption with the nominal hydrogen column density for the center of M 31 ($1.27 \times 10^{21} \text{ cm}^{-2}$, Ref. [66]). We allowed the abundance of Fe, N, O, Ne, Mg, Si, and Ni to fit freely. Other elements were tied to Fe in their Solar ratios ([67]), except He, which was fixed at its Solar value. This gives a satisfactory fit to the spectrum (Fig. 3). The temperature of the softer component is close to that inferred from XMM-Newton observations of M 31 [68], while the hotter component and power law are expected to be a good parametrization for residual, unresolved sources [69].

All of the obvious emission lines in the spectrum are well fitted by our model, since they are coincident either with astrophysically interesting lines expected from a thermal plasma or with the instrumental fluorescent features (Fig. 3). To obtain upper limits on $\sin^2\theta$, we therefore

added an additional, narrow, photoabsorbed Gaussian line to the spectral model at energy $E_\gamma = m_s/2$ and with flux (F_γ) given, after Refs. [60,70], by

$$F_\gamma = 10^{-7} \text{ erg s}^{-1} \text{ cm}^{-2} \times \left(\frac{M_{\text{DM}}^{\text{FOV}}}{10^{11} M_\odot} \right) D^{-2} m_s^5 \sin^2 2\theta, \quad (9)$$

where $M_{\text{DM}}^{\text{FOV}}$ is the projected mass in the field of view of the observation, and D is the distance in Mpc (for which we adopt 0.784 Mpc). We estimated $M_{\text{DM}}^{\text{FOV}}$ ($1.6 \times 10^{10} M_\odot$ for the on-axis spectrum) by integrating the DM surface density, estimated from the model of Ref. [71], over the field of view of each individual pointing. We then appropriately averaged each value to ensure the correct line count rate in the composite spectra.

To determine an upper limit on $\sin^2 \theta$ for a given m_s , the line (at fixed energy) was added simultaneously to the on-axis and offset spectra, and its normalization varied (while fitting all other parameters) until the fit statistic increased by 4.61, corresponding to a 95% confidence interval for two parameters of interest. This approach is similar to the “statistical” method of Ref. [70], although we have

appropriately included the required statistical uncertainties on the background model. In Fig. 4, we show our measured upper limits on $\sin^2 \theta$. Because the fluxes of the astrophysical and instrumental lines are not known *a priori*, they are degenerate with any coincident sterile neutrino decay line. This reduction in sensitivity is immediately apparent in the jagged upper limit curve. A major source of uncertainty in this measurement is the precise value of $M_{\text{DM}}^{\text{FOV}}$ [70]. For example, if we use the DM profile model C_1 of Ref. [72], $M_{\text{DM}}^{\text{FOV}}$ is increased by $\sim 15\%$ in the core, resulting in correspondingly tighter constraints on $\sin^2 \theta$.

V. DISCUSSION

The one-sided 95% C.L. lower and upper limits from the Local Group are shown in Fig. 4. These include lower limits from phase-space arguments of MW dSphs ($m_s^{\text{DW}} \gtrsim 2.5$ keV), lower limits from subhalo counting comparison to M 31 dSphs ($m_s^{\text{DW}} \gtrsim 8.8$ keV), and upper limits based on x-ray observations of M 31. Combined, these decisively constrain the canonical DW production mechanism for generating sufficient sterile neutrinos to match the DM abundance at $> 99\%$ C.L.

Phase-space arguments have been argued to be among the most robust methods to constrain WDM, but they have not been strong enough to rule out the DM sterile neutrino when coupled with x-ray limits [31] (indicated by the larger arrow in Fig. 4 at 1.8 keV). Our newly added Segue I dSph, combined with updated x-ray limits based on deep Chandra observations of M 31, excludes the entire DW model parameter space, including the wider range due to hadronic model uncertainties [35] (red hatched), at 95% C.L. The exception is around $m_s^{\text{DW}} \approx 4.3$ keV, where a strong x-ray background line in the M 31 data prevents a strong limit on a sterile neutrino decay line. However, limits from Suzaku—with vastly different backgrounds and in particular weaker lines—already exclude this region [73], as shown in Fig. 4. If Segue I is not included, the mass limit is weakened to 1.5 keV (dashed vertical line) and allows a DW sterile neutrino of $m_s^{\text{DW}} \approx 2$ keV to generate the observed cosmological DM abundance. However, including limits from subhalo counting, all of the DW parameter region is comfortably excluded at $> 99\%$ C.L.

For the same dwarfs, our limits are weaker than those of Ref. [30], where the authors adopted significantly higher phase-space density estimates [e.g., $5 \times 10^{-3} (M_\odot/\text{pc}^3)(\text{km/s})^{-3}$ for Leo IV and Canes Venatici II]. These follow from Ref. [39], where the *central* density is used to estimate Q , as opposed to our conservative estimate based on the mean density within r_h . Also, the stellar velocity dispersion is assumed in that work to be the same as the DM velocity dispersion ($\eta_* = 1$). For these reasons, we obtain weaker but more robust limits. Our limits are similar in numerical value to those of Ref. [31], where the authors assume $\eta_* = 1$, but consider the phase volume defined by the escape velocity of DM particles.

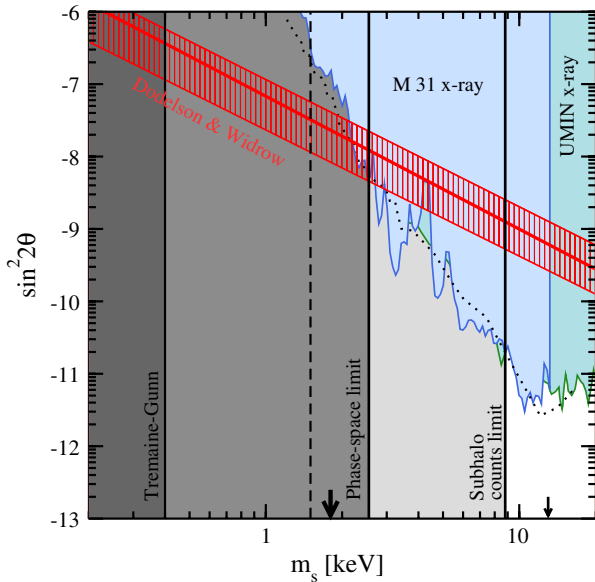


FIG. 4 (color online). Constraints on sterile neutrino parameters. Shaded areas are excluded regions: 95% C.L. upper limits derived from the x-ray modeling of M 31 (labeled “M31 x ray”), the results from Ref. [60] shown for comparison (dotted; see text), and upper limits from Suzaku observations of Ursa Minor [73] (labeled “UMIN x ray”); vertical lines show lower mass limits from Tremaine–Gunn phase-space considerations ($m_s \sim 0.4$ keV) [28], Coma Berenices phase space ($m_s^{\text{DW}} \sim 1.5$ keV, dashed line), Segue I phase space ($m_s^{\text{DW}} \sim 2.5$ keV), and M 31 subhalo counts ($m_s^{\text{DW}} \sim 8.8$ keV). The big and small arrows on the abscissa indicate lower limits from Refs. [31] and [20], respectively. The DW sterile neutrino model of Ref. [6] and its associated upper and lower bounds [35] are shown and labeled.

Our limits from the subhalo count are somewhat weaker than the previous constraints placed using MW dSphs [20] (indicated by the smaller arrow in Fig. 4 at 13.3 keV). However, bearing in mind that these MW limits rely on corrections of factors of 2–4 for missing dSphs—for example, in their most constraining distance bin (< 50 kpc from the MW), the correction is from 7 to 16 dSphs—our results compare quite favorably. Part of the reason is the different method used to obtain the limit. We take the Bayesian approach as follows: given an observed number of dSphs, then what is the probability that a model with mass m_s^{DW} could produce the observation? On the other hand, Ref. [20] included fluctuations in both the model and the observed number of dSph to set their limits, which weakens their limits. Our limits are stronger than those of the MW without incompleteness corrections (7 keV) [74].

For x-ray limits, despite the significantly deeper data used in our analysis (~ 400 vs 50 ks), the limits of Ref. [60] are tighter for some range of m_s . This is particularly true for $m_s \sim 4.3$ keV, corresponding to $E_\gamma \sim 2.1$ keV, which is coincident with a strong background line. In practice, Watson *et al.* [60] adopted the value of $\sin^2\theta$ for which the line flux equaled the background-subtracted flux at each energy. This, however, requires the background to be known exactly, whereas we explicitly included background uncertainties in our measurements, which most likely accounts for the differences.

Although we disfavor the DW mechanism as the sole production of DM, sterile neutrinos may be generated by resonant oscillations or nonoscillation channels. These result in “mixed” DM consisting of a warm (nonresonant production) and a colder (the resonant or nonoscillation production) component. They are not as constrained by our limits [18,75]. For example, resonant oscillation allows for a smaller mixing to generate the required DM abundance, which helps evade the x-ray constraints. Furthermore, the velocity dispersion is colder, meaning q_{max} is larger than for DW, relaxing the phase-density limits. For example, we estimate that in the mixed models of Ref. [18], a 3 keV sterile neutrino generating the required DM abundance in lepton asymmetries of $L_6 = 10^6(n_{\nu_e} - n_{\bar{\nu}_e})/s = 10$ (16, 25) results in primordial $q_{\text{max}}^{\text{res}} \approx 35$ (160, 30). These are

significantly larger than the fine-grained phase-space maximum for the DW model, $q_{\text{max}}^{\text{DW}} \approx 14$ [all in units $10^{-5} (M_\odot/\text{pc}^3)(\text{km/s})^{-3}$]. In nonoscillation production mechanisms, the mixing angle may be arbitrarily small, and the velocity dispersion is also colder [11–13].

WDM models have been investigated as attractive solutions to many of the challenges faced by CDM on subgalactic scales (see, e.g., Ref. [76] for a recent coverage of key issues). One recent example is the “too big to fail” problem [77,78]. Various WDM models have been investigated in the literature, including WDM of thermal particle masses $m_{\text{WDM}} = 1\text{--}4$ keV [74,79,80], and mixed WDM models with mass $m_{\text{WDM}} = 2$ keV and smaller [79,81]. These studies find that masses of $m_{\text{WDM}} = 1\text{--}2$ keV are required to solve too big to fail; above 2 keV, there is insufficient difference from CDM in the subhalo kinematics [82]. Hence, the lower end of the solution mass range is inconsistent with our limits, leaving only a narrow range of possible mass. We caution that the physically relevant quantity for a detailed comparison is the cutoff scale and shape; the mass alone is insufficient since a mixed model of a given mass has a more diluted cutoff due to the cold component than a sterile neutrino of the same mass.

Our conclusion, while similar to those discussed for some Lyman- α and MW dSphs abundance matching limits [18,20], are independent and most importantly robust, making them decisive on whether the DW mechanism can generate the entire DM abundance. Future dSph discoveries are expected by upcoming surveys, which will enable stronger limits that go deeper into the parameter space of mixed sterile neutrino models.

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