

21 CM CONSTRAINTS ON THE LIFETIME OF THE STERILE NEUTRINO AND MIXING ANGLE WITH ACTIVE NEUTRINOS*

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Sterile neutrinos are promising candidates for dark matter, particularly in addressing small-scale challenges of the Λ CDM model. These particles are radiatively unstable, decaying into active neutrinos and photons, thereby injecting energy into the intergalactic medium (IGM) during the cosmic dawn. The energy injection can alter the temperature and ionization history of IGM, impacting the global 21 cm absorption signal predicted by standard cosmological models. Using the observed 21 cm signal from the EDGES Collaboration, we derive constraints on the sterile neutrino lifetime and their mixing angle with active neutrinos. Our bounds, obtained without assuming non-standard cooling mechanisms or additional radio backgrounds, are compared with the existing astrophysical limits, such as those from X-ray observations. For sterile neutrino masses between 2 keV and 50 keV, the lifetime is constrained to be greater than 8.3×10^{27} s to 9.4×10^{25} s for a 21 cm brightness temperature of -150 mK at $z = 17.2$. These results provide model-independent probes of sterile neutrino parameters relevant to dark-matter phenomenology.

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1. Introduction

Approximately 3×10^5 years after the Big Bang, electrons and protons recombined to form neutral hydrogen atoms. Within the framework of the standard Λ CDM cosmology, recombination is completed near redshift $z \approx 1100$, after which baryonic matter thermally decouples from the cosmic microwave background (CMB) radiation. This marks the onset of the so-called cosmic dark ages. During this epoch, residual free electrons maintain thermal coupling with CMB photons through Compton scattering until $z \sim 200$. Beyond this redshift, the gas undergoes adiabatic cooling, following $T_{\text{gas}} \propto (1+z)^2$. In the absence of exotic energy sources, the Λ CDM model provides precise predictions for the gas temperature and residual ionization fraction throughout the interval from recombination to the onset of cosmic dawn. Any additional energy injection into the intergalactic medium (IGM) has the potential to modify both the thermal and ionization evolution of the Universe. Consequently, precise measurements of IGM properties during the cosmic dawn offer powerful constraints on non-standard energy sources.

Despite its remarkable success in describing large-scale structure, CMB anisotropies, and Big Bang nucleosynthesis, the Λ CDM paradigm encounters well-known difficulties on sub-galactic scales (≤ 1 Mpc) — see, *e.g.*, [1] and references therein. These include the missing satellite problem [2, 3], the too-big-to-fail issue [4, 5], and the core-cusp discrepancy [6]. In response, several alternative dark-matter models have been proposed, including self-interacting dark matter (SIDM) [7–10], ultralight “fuzzy” dark matter [11, 12], and warm dark matter (WDM) candidates [13–17]. Sterile neutrinos in the keV mass range constitute one of the most extensively studied WDM scenarios [18–20].

In recent years, a variety of observational strategies have been developed to probe previously inaccessible regions of the sterile neutrino parameter space [21–26]. For example, NuSTAR has placed stringent limits excluding anomalous X-ray lines in the 10–40 keV mass window, with future upgrades expected to reach sensitivities down to 6–10 keV [23]. In the context of the EDGES 21 cm anomaly, Ref. [27] derived a lower mass bound of 63_{+19}^{-35} keV for the Dodelson–Widrow sterile neutrinos. Additional constraints from various astrophysical probes appear in Refs. [28–36]. In the present contribution, we focus on the radiative decay channel of sterile neutrino dark matter and derive new bounds on its lifetime and mixing angle with active neutrinos using the physics of the global 21 cm signal during the cosmic dawn.

During this epoch, the baryonic content of the Universe is dominated by neutral hydrogen, with only a trace fraction of helium. The hyperfine transition in neutral hydrogen serves as a unique probe of the thermal and ionization state of the IGM at high redshift. The 21 cm line arises from the spin-flip transition between the singlet ($F = 0$) and triplet ($F = 1$)

hyperfine levels of the $1S$ ground state. The relative population of these states is characterized by the spin temperature T_S via

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(-\frac{E_{10}}{T_S}\right), \quad (1)$$

where $E_{10} = h\nu_{21} \approx 5.9 \times 10^{-6}$ eV corresponds to the 21 cm wavelength, and g_0, g_1 are the statistical weights of the singlet and triplet states, respectively.

In a cosmological context, the spin temperature is determined by three coupling processes: (i) atomic collisions (H–H and H– e^-), (ii) resonant scattering of CMB photons, and (iii) Ly α pumping from the first luminous sources [37–39]. The inverse spin temperature is given by

$$T_S^{-1} = \frac{T_R^{-1} + (x_\alpha + x_c)T_{\text{gas}}^{-1}}{1 + x_\alpha + x_c}, \quad (2)$$

where x_c and x_α are the collisional and Wouthuysen–Field coupling coefficients, respectively [37, 40–42], and T_R is the background radiation temperature ($T_R = T_{\text{CMB}} = 2.725(1+z)$ K in the standard scenario [43]).

The corresponding 21 cm differential brightness temperature reads [38, 39, 44]

$$T_{21} = 27x_{\text{HI}} \sqrt{\frac{0.15}{\Omega_m} \frac{1+z}{10}} \left(\frac{\Omega_b h}{0.023}\right) \left(1 - \frac{T_R}{T_S}\right) \text{ mK}, \quad (3)$$

with $x_{\text{HI}} = n_{\text{HI}}/n_{\text{H}}$, the neutral hydrogen fraction and standard cosmological parameters $\Omega_m = 0.31$, $\Omega_b = 0.048$, and $h = 0.68$ [45].

Detection of T_{21} depends sensitively on the ratio T_{CMB}/T_S : emission occurs for $T_S > T_{\text{CMB}}$, absorption for $T_S < T_{\text{CMB}}$, and vanishing signal when $T_S = T_{\text{CMB}}$. The EDGES Collaboration recently reported on a deep absorption feature centered at 78 MHz ($z \approx 17.2$), with amplitude $T_{21} = -500_{-500}^{+200}$ mK (99% C.L.) [46]. Interpreting this as $T_S \approx T_{\text{gas}}$ yields $T_{\text{gas}}(z = 17.2) \approx 3.26_{-1.58}^{+1.94}$ K, significantly colder than the Λ CDM expectation of $T_{\text{gas}} \approx 7$ K, which predicts $T_{21} \approx -220$ mK. Reconciling this discrepancy requires either an enhanced radio background temperature or additional gas cooling mechanisms in the redshift window $15 \lesssim z \lesssim 20$ [47–58]. While several proposals exist (including baryon–dark matter interactions [56]), many face theoretical or observational challenges [59–65]. Moreover, decaying or annihilating dark matter typically heats rather than cools the IGM [66–69]. Independent analyses have also questioned the astrophysical origin of the EDGES signal, citing possible foreground modeling issues [70–72]. In light of these discrepancy, we adopt the theoretically expected 21 cm absorption depth in the Λ CDM model ($T_{21} \approx -220$ mK at

$z = 17.2$) and require that any additional energy injection from sterile neutrino radiative decay does not suppress this amplitude by more than a factor of $1/4$ or $1/2$ (*i.e.*, $T_{21} \gtrsim -150$ mK or -100 mK).

Sterile neutrinos can decay radiatively via $\nu_s \rightarrow \nu\gamma$ (in addition to the three-body channel $\nu_s \rightarrow \nu\bar{\nu}\nu$). Only the radiative mode deposits photon energy into the IGM, thereby heating the gas and potentially reducing the depth of the 21 cm absorption trough. The radiative decay width is given by [20, 73]

$$\Gamma_{\nu_s \rightarrow \nu\gamma} = 5.52 \times 10^{-22} \sin^2(\theta) \left(\frac{m_{\nu_s}}{\text{keV}} \right)^5 \text{ s}^{-1}, \quad (4)$$

where θ is the active–sterile mixing angle ($\theta \ll 1 \Rightarrow \sin^2(2\theta) \approx 4 \sin^2 \theta$), m_{ν_s} is the sterile neutrino mass.

2. Evolution of the IGM gas and effect of sterile neutrinos

Thermal and ionization evolution of the IGM in the presence of radiative decay of sterile neutrinos can be written as [66, 67, 74–78]

$$\frac{dT_{\text{gas}}}{dz} = \frac{2T_{\text{gas}}}{(1+z)} + \frac{\Gamma_C}{(1+z)H} (T_{\text{gas}} - T_{\text{CMB}}) - \frac{2}{3H(1+z)} \frac{(1+2x_e)\epsilon}{3N_{\text{tot}}}, \quad (5)$$

$$\begin{aligned} \frac{dx_e}{dz} = & \frac{\mathcal{P}}{H(1+z)} \left[n_H x_e^2 \alpha_B(T_{\text{gas}}) - (1-x_e) \beta_B(T_{\text{gas}}) e^{-E_\alpha/T_{\text{gas}}} \right] \\ & - \frac{1}{H(1+z)} \left(\frac{\mathcal{P}}{E_0} - \frac{1-\mathcal{P}}{E_\alpha} \right) \frac{(1-x_e)\epsilon}{3n_H}, \end{aligned} \quad (6)$$

where $x_e = n_e/n_H$ stands for the ionization fraction, n_e represents the free electron number density. Γ_C is the Compton scattering rate. α_B and β_B represent the case-B recombination coefficient and photo-ionization rate, respectively [67, 74, 75]. $E_0 = 13.6$ eV and $E_\alpha = (3/4)E_0$ represent the ground-state binding energy and Ly α transition energy for the hydrogen atom, respectively. $N_{\text{tot}} = n_H(1 + f_{\text{He}} + x_e)$ is the total number density of gas, $f_{\text{He}} = n_{\text{He}}/n_H$ is the helium fraction. \mathcal{P} is the Peebles coefficient [66, 67, 79]. The last term in equations (5) and (6) describes the additional effect of sterile neutrinos decay on the thermal and ionization evolution of the IGM. $\epsilon \equiv \epsilon(z, m_{\nu_s})$ is the energy injection rate per unit volume into the IGM gas due to radiative decay of sterile neutrinos. It can be written as [66, 67, 80, 81]

$$\epsilon(z, m_{\nu_s}) = f_{\text{abs}}(z, m_{\nu_s}) \rho_{\nu_s,0} \tau_{\nu_s}^{-1} (1+z)^3, \quad (7)$$

where $\rho_{\nu_s,0} = m_{\nu_s} n_{\nu_s,0}$ represents the present-day density of sterile neutrinos, τ_{ν_s} is the lifetime of the sterile neutrino, and $n_{\nu_s,0}$ is the present-day

number density of sterile neutrinos. We consider that all the dark matter is composed of sterile neutrinos, $\rho_{\nu_s,0} \equiv \rho_{\text{DM},0}$, and $\rho_{\text{DM},0}$ is the present-day dark-matter energy density. The energy deposition efficiency into the IGM by decaying sterile neutrinos, and it depends on the redshift, mass of sterile neutrino, and decay channel [80]. The mass of decaying particles enters only through $f_{\text{abs}}(z, m_{\nu_s})$.

Following Refs. [66, 67], we consider the ‘SSCK’ approximation, in which $(1 - x_e)/3$ fraction of deposited energy goes into ionization, nearly the same amount goes into excitation, while $(1 + 2x_e)/3$ fraction goes into the IGM heating. To include the heating of the gas due to energy transfer from CMB photons to the random motions of the gas, we follow Ref. [82] (here we write this heating of the gas as VDKZ18). The authors claim that it can increase the gas temperature by the order of ($\sim 10\%$) at $z \sim 17$. Including the heating due to the VDKZ18 effect, equation (5) will modify as

$$\frac{dT_{\text{gas}}}{dz} = \left. \frac{dT_{\text{gas}}}{dz} \right|_{[\text{Eq. (5)}]} - \frac{\Gamma_R}{(1+z)(1+f_{\text{He}}+X_e)}, \quad (8)$$

where $dT_{\text{gas}}/dz|_{[\text{Eq. (5)}]}$ represents the temperature evolution in equation (5). Γ_R represents the heating rate due to energy transfer from CMB photons to the thermal energy of gas by Ly α photons [82].

3. Result and discussion

We solve the coupled equations (5) and (6) for different mass and lifetime of sterile neutrinos to get x_{HI} and T_{gas} at redshift $z = 17.2$. To obtain an absorption signal in the redshift range 15–20, the gas temperature should be lower than the CMB temperature in the shaded region. By requiring $T_{21} \simeq -150$ mK or -100 mK at $z = 17.2$, equation (3), we can constraint the lifetime of sterile neutrinos. Subsequently, using equation (4), we can also constrain the mixing angle of sterile neutrinos with active neutrinos.

In Fig. 1, we present the lower limits on the sterile neutrino lifetime τ_{ν_s} as a function of its mass m_{ν_s} . These limits are derived by requiring that the 21 cm brightness temperature T_{21} at $z = 17.2$ remains within a factor of approximately 1/4 to 1/2 of the standard Λ CDM prediction $T_{21}(z = 17.2) \approx -220$ mK. Adopting even stricter thresholds (*e.g.*, $T_{21} \lesssim -150$ mK) would further tighten the resulting constraints.

The red curves show the lower bounds on τ_{ν_s} obtained when $T_{21} \simeq -150$ mK, whereas the black curves correspond to the $T_{21} \simeq -100$ mK case. The dashed lines represent results that exclude the additional heating effect described in VDKZ18, while the dotted lines include this contribution. Incorporating the VDKZ18 mechanism (energy transfer from CMB

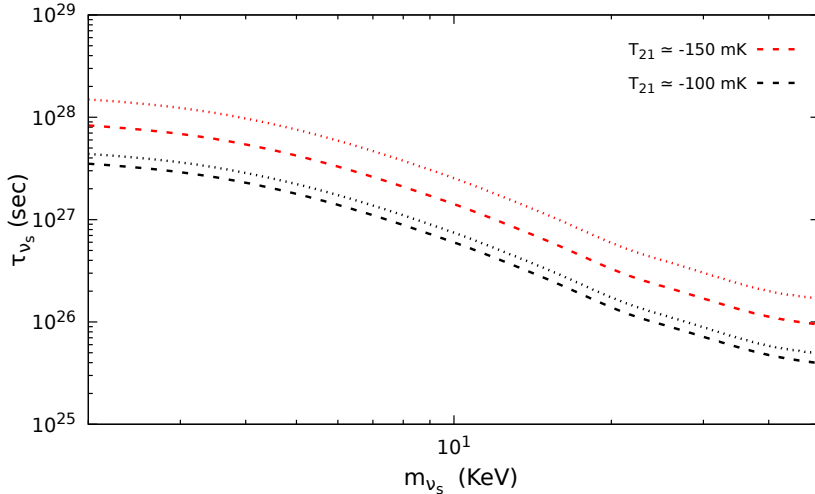


Fig. 1. The figure represents lower projected bounds on the lifetime of sterile neutrinos as a function of mass.

photons to the gas mediated by Ly α scattering) leads to stronger (more restrictive) lower limits on the lifetime, since it raises the gas temperature and therefore demands even longer lifetimes to avoid excessive suppression of the absorption signal.

In Fig. 2, we display the corresponding upper limits on the active–sterile mixing angle $\sin^2 \theta$ as a function of m_{ν_s} . For comparison, the existing X-ray exclusion region (blue shaded area) is also shown, taken from Ref. [20]. These X-ray bounds arise from the non-observation of the expected monochromatic X-ray line associated with the radiative decay $\nu_s \rightarrow \nu\gamma$, assuming sterile neutrinos decay solely through this channel.

The red and black curves indicate the upper limits on the mixing angle for $T_{21} \simeq -150$ mK and -100 mK, respectively. As before, the dashed curves exclude, and the dotted curves include the VDKZ18 heating term. Importantly, these 21-cm-derived constraints are independent of dark matter clustering properties and therefore do not rely on astrophysical uncertainties such as the dark-matter density profile, halo mass function, or substructure abundance. The constraints shown in Fig. 2 are competitive with (and in some mass ranges stronger than) the X-ray limits: they become comparable at higher masses ($\gtrsim 10$ – 20 keV), while providing significantly tighter bounds at lower masses where X-ray sensitivity weakens.

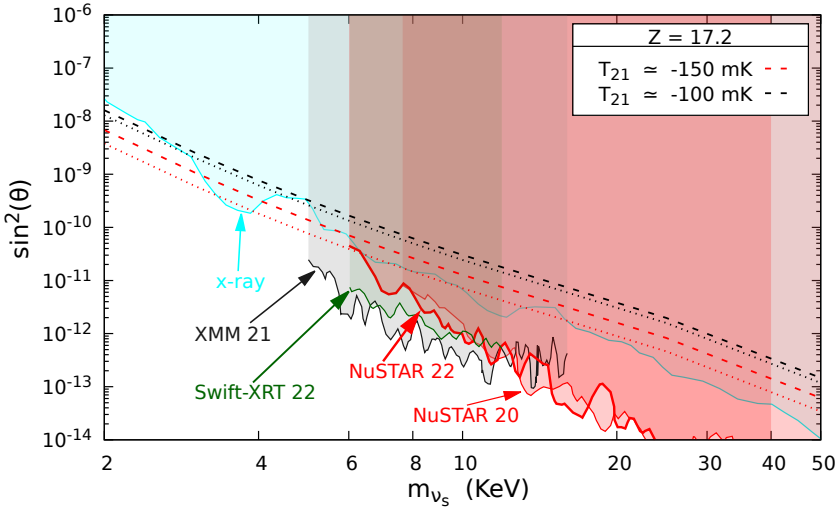


Fig. 2. The figure represents upper projected bounds on the mixing angle of sterile neutrinos with active neutrinos as a function of mass of sterile neutrinos by keeping 21 cm differential brightness temperature, $T_{21} \simeq -150$ and -100 mK. The dotted (dashed) line represents the case when energy transfer from CMB photons to gas is included (excluded) [82]. The shaded regions are excluded for corresponding observations. The X-ray constraint on mixing angle (cyan shaded region) has been taken from Ref. [20]. The red shaded region depicts the upper bounds on $\sin^2(\theta)$ from the NuSTAR observations [23, 83]. Here, we have also plotted the recently reported bounds (after publication of our article) on $\sin^2(\theta)$ by NuSTAR — represented by NuSTAR 22 [83] and by Swift-XRT — represented by Swift-XRT 22 [84]. The grey shaded region is excluded by XMM-Newton [29].

4. Summary

We derive constraints on the radiative lifetime and active–sterile mixing angle of sterile neutrino dark matter as functions of its mass m_{ν_s} . These limits ensure that photon energy injected via the $\nu_s \rightarrow \nu\gamma$ decay does not reduce the depth of the standard Λ CDM 21 cm absorption signal (expected amplitude ~ -220 mK at $z = 17.2$) by more than a factor of $\sim 1/4$ ($T_{21} \gtrsim -150$ mK) or $\sim 1/2$ ($T_{21} \gtrsim -100$ mK).

Two different treatments of IGM physics are examined: (i) evolution of the IGM gas without the additional heating channel mediated by Ly α scattering of CMB photons (the VDKZ18 effect), and (ii) full evolution including the VDKZ18 heating term.

The main results for the $T_{21} = -150$ mK threshold are the following: (i) Without the VDKZ18 heating, the lower limit on the radiative lifetime ranges from 8.3×10^{27} s (at $m_{\nu_s} = 2$ keV) to 9.4×10^{25} s (at $m_{\nu_s} = 50$ keV). The allowed lifetime shortens with increasing mass because the present-day number density $n_{\nu_s} = \rho_{\text{DM}}/m_{\nu_s}$ falls as m_{ν_s} rises; fewer particles imply fewer decays at fixed redshift, permitting more energy deposition before the absorption signal is excessively suppressed. The corresponding upper limit on the mixing angle varies from $\sin^2 \theta = 6.8 \times 10^{-9}$ (2 keV) to 6.1×10^{-14} (50 keV). (ii) When the VDKZ18 heating is included, the constraints become significantly stronger: the lower lifetime bound extends from 1.5×10^{28} s (2 keV) to 1.7×10^{26} s (50 keV), and the upper bound on $\sin^2 \theta$ ranges from 3.8×10^{-9} to 3.42×10^{-14} over the same mass interval.

For comparison, existing X-ray search limits are also shown; they exclude part of the parameter space assuming purely radiative decay. While the present analysis assumes sterile neutrinos constitute 100% of the dark matter, a subdominant sterile component would proportionally weaken the bounds on both the lifetime and mixing angle.

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