Influence of a keV sterile neutrino on neutrino-less double beta decay – how things changed in the recent years

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Abstract

Earlier studies of the influence of Dark Matter keV sterile neutrinos on neutrino-less double beta decay concluded that there is no significant modification of the decay rate. These studies have focused only on a mass of the keV sterile neutrino above 2 and 4 keV, respectively, as motivated by certain production mechanisms. On the other hand, alternative production mechanisms have been proposed, which relax the lower limit for the mass, and new experimental/observational data is available, too. For this reason, an updated study is timely and worthwhile. We focus on the most recent data, i.e., the newest Chandra and XMM-Newton observational bounds on the X-ray line originating from radiative keV sterile neutrino decay, as well as the new measurement of the previously unknown leptonic mixing angle $\theta_{13}$ by the Daya Bay, RENO, and Double Chooz experiments. We find that, while the previous works had been too short-sighted, the new observational bounds do indeed render any influences of keV sterile neutrinos on neutrino-less double beta decay small. This conclusion even holds in case not all the Dark Matter is made up of keV sterile neutrinos. The bounds are so powerful that they strongly constrain form-dominant neutrino mixing, which is of interest for models of keV sterile neutrinos.

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1 Introduction

Sterile neutrinos with relatively small masses have been studied intensely within the recent years, due to both their phenomenological richness and due to experimental hints which could point towards their existence [1]. One particularly interesting aspect of sterile neutrinos is that they can be the Dark Matter (DM) in the Universe [2] if they have a mass of a few keV. A minimal framework for such neutrinos has been proposed in the form of the neutrino minimal standard model (νMSM) [3], which is used to simultaneously accommodate for a wide variety of phenomena, such as neutrino oscillations, DM, or the baryon asymmetry of the Universe [4, 5]. A particularly interesting point is that keV sterile neutrinos in such a framework typically have a warm spectrum, i.e., they are neither highly relativistic (hot) DM, which would lead to problems with cosmological structure formation [6, 7], nor are they non-relativistic (cold) DM. Extensive studies on neutrinos with masses of a few keV in the context of structure formation are present in the literature [8, 9, 10, 11, 12, 13, 14]. In addition, surveys such as ALFALFA [15] and model-independent analyses as the ones in Refs. [16, 17] seem to point towards a DM mass of a few keV.

From the particle physics side, keV sterile neutrinos are consistent with a variety of frameworks, from variants of the scotogenic model [18, 19, 20] to Left-Right symmetry [21, 22]. A raising field of research is the construction of mechanisms that can, to some extent, motivate the existence of the keV mass scale, see e.g. Refs. [23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38]. Ideally, these models should give predictions in combination with one of the known production mechanisms: while non-resonant thermal production (Dodelson-Widrow mechanism [39]) is excluded for the case of zero lepton asymmetry [4, 5], a large enough primordial asymmetry can lead to resonant non-thermal contributions (Shi-Fuller mechanism [40]), which is still consistent with all bounds. Further possibilities are the production via scalar decays [41] or the dilution of a thermal overproduction by entropy-producing decays of particles [42]. These mechanisms have been applied, e.g., in Refs. [21, 22, 43, 44, 45, 46, 47, 48, 49, 50, 51].

In particle physics, one of the most interesting questions is about the nature of neutrinos: are they Dirac or Majorana fermions? This question can, realistically, only be answered by neutrino-less double beta decay ($0\nu\beta\beta$), a process where a nucleus decays to another one via the emission of only two electrons, $(A, Z) \rightarrow (A, Z + 2) + e^- + e^-$, as recently reviewed in several references [52, 53, 54]. An observation of $0\nu\beta\beta$ would unambiguously prove that lepton number is violated [55, 56], in contrast to the diagram-level prediction of the Standard Model. However, if this is the case, we still need more new physics besides the $0\nu\beta\beta$ in order to generate a phenomenologically acceptable neutrino
mass \[57\]. This observation opens up the possibility to investigate \(0\nu\beta\beta\) in connection to neutrino mass models. Since many models for neutrino masses involve also sterile neutrinos, it is worthwhile to investigate \(0\nu\beta\beta\) in this respect. Up to now, most investigations studied the contributions of very light (\(\sim\) eV) \[58, 59, 60, 61, 62\] or relatively heavy (\(\gg 100\) MeV) \[63, 64, 65\] sterile neutrinos.

The influence of keV sterile neutrinos on the effective mass in neutrino-less double beta decay has also been discussed a few years ago in Ref. \[66\], see also Ref. \[67\]. It was concluded that the restricted mass range, \(2\) keV \(\lesssim M \lesssim 5\) keV, in combination with the hard X-ray bound \[68, 69, 70, 71, 72\] and the Ly-\(\alpha\) bound \[10\], renders the new contribution invisibly small. However, the caveat in that argument is two-fold. First of all, the lower bound from Ly-\(\alpha\) is altered \[73\] if an alternative production mechanism is considered \[21, 22, 48\]. Secondly, in 2012 we have measured the previously unknown mixing angle \(\theta_{13}\) to be relatively large \[74, 75, 76, 77\]: this, in turn, increases the variability of the effective mass \[78\]. Based on Ref. \[66\], the statement of a negligible influence of the keV sterile neutrino on \(0\nu\beta\beta\) was repeated in several subsequent references \[79, 80, 81, 82, 83\]. In particular, the authors of Ref. \[83\] have applied an oversimplification by neglecting the CP-phase of the keV-neutrino contribution, which is however necessary to quantify its influence.

Recently, the authors of Refs. \[25, 84\] showed that, in a seesaw type I setting with 3 left-handed and 3 right-handed neutrinos, the effective mass \(m_{ee}\) has to vanish if all six neutrino mass eigenstates have masses below the nuclear momentum transfer \(|\vec{q}| = \mathcal{O}(100\) MeV). This theorem shows that the influence of low-lying sterile states can be relevant. In addition, this cancellation can even appear generation-wise \[25\] in the case of a form-dominant \[85, 86\] Dirac mass matrix \(m_D\).

We will in the following explicitly calculate the influence of a keV sterile neutrino on \(0\nu\beta\beta\) for a comparatively light sterile neutrino mass. We thereby illustrate how our improved knowledge on the parameters involved has changed the picture within the last two years. Indeed, the arguments given in Refs. \[66, 83\] disregarded exactly the part of the parameter space where a significant influence of a DM keV sterile neutrino would have been present. However, in particular the X-ray bound – which has been considerably improved recently – destroys this big influence. Thus, due to the new experimental results the conclusion of Refs. \[66, 83\] remains correct after all, even if the low mass range below 2 keV had been disregarded. In the second part of our study, we focus on the possibility of a form-dominant Dirac neutrino mass matrix. We show that this framework is now strongly constrained by the new data, which can have important implications for the model building aspects of keV sterile neutrinos.

The paper is organized as follows. In Sec. \[2\] we review the main expressions for the
effective mass and present a detailed discussion of the bounds of the active-sterile neutrino mixing angle currently available. In Sec. 3 we discuss the possible influence of really light keV sterile neutrinos on the effective mass. We compare the situation before 2011 with the current one after the new Chandra and XMM-Newton observational results. The power of the new X-ray bounds is explicitly shown in Sec. 4, where we analyse the form-dominant case. In Sec. 5 we summarize our results.

2 The effective mass

The standard expression for the effective mass in neutrino-less double beta decay is given by (see, e.g., Refs. [52, 53, 78, 87])

\[
|m_{ee}^{(3)}| = |m_1 c_{12} c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha} + m_3 s_{13}^2 e^{2i\beta}|,
\]

where \( s_{ij} \equiv \sin \theta_{ij} \) and \( c_{ij} \equiv \cos \theta_{ij} \) are functions of the mixing angles \( \theta_{ij} \), and where \( \alpha \) and \( \beta \) are the Majorana phases. The superscript “(3)” refers to the fact that three generations of active neutrinos are contributing. If we now have one keV sterile neutrino in addition, where any other sterile neutrinos have masses larger than the nuclear momentum transfer \( |q| = \mathcal{O}(100 \text{ MeV}) \), the keV neutrino contribution will modify the above effective mass to [26, 59, 60, 61, 62, 84]

\[
|m_{ee}^{(4)}| \simeq |m_{ee}^{(3)} + M \theta^2 e^{2i\gamma}|,
\]

where \( M \) and \( \theta \) are the mass and the active-sterile mixing angle of the keV neutrino. We have left it unspecified to which generation the keV neutrino belongs. The phase called \( \gamma \) is actually a linear function of the fundamental Majorana phases in the full 6 \( \times \) 6 neutrino mass matrix. Note that the authors of Ref. [83] have neglected the CP phase of the new keV sterile neutrino contribution, but this is however needed to quantify the influence on the effective mass.

In the following, we will analyse Eq. (2) for the two cases of normal (NO: \( m_1 = m < m_2 = \sqrt{m^2 + \Delta m^2_A} < m_3 = \sqrt{m^2 + \Delta m^2_\odot} \)) and inverted (IO: \( m_3 = m < m_1 = \sqrt{m^2 + \Delta m^2_\odot} < m_2 = \sqrt{m^2 + \Delta m^2_\odot + \Delta m^2_A} \)) mass ordering of the light neutrinos, where \( m \) is the smallest neutrino mass and \( \Delta m^2_\odot \equiv \Delta m^2_{21} \) (\( \Delta m^2_A \equiv |\Delta m^2_{31}| \)) denotes the solar (atmospheric) mass square difference.

The important point to take into account is that the active-sterile mixing angle \( \theta^2 \) is strongly bounded by the non-observation of a monoenergetic X-ray photon line stemming from the decay \( N \rightarrow \nu \gamma \), where \( N \) is the keV neutrino and \( \nu \) is some light active neutrino. This bound cannot be avoided as long as active-sterile mixing is present (one could switch it off by artificially stabilizing the keV neutrino [27]), but at the moment there is no
Figure 1: Current and former X-ray bounds on the active-sterile mixing as functions of the keV sterile neutrino mass $M$, as well as the new bounds and suggested fits. Note that, within the fit formulas depicted in the lower two panels, $M$ is always taken to be measured in keV, but the unit is not shown for simplicity.

A convincing model known which predicts such a stabilization while at the same time giving a mechanism to generate the keV scale)\footnote{Note that stable keV neutrinos have been discussed in the context of the scotogenic model \cite{18,19,20}. However, this framework did not yield a mechanism to suppress the sterile neutrino mass scale.}. The explicit observational bound, as valid before 2011, was summarized by Canetti, Drewes, Frossard, and Shaposhnikov (CDFS) in Refs. \cite{4,5}. This bound is based on the observations reported in Refs. \cite{68,69,70,71,88,89,90,91,92,93,94,95}. A simplified form of the X-ray bound has been given by Boyarski, Ruchayskiy, and Shaposhnikov in Ref. \cite{81}:

$$\theta^2 \lesssim 1.8 \cdot 10^{-5} \left(\frac{\text{keV}}{M}\right)^5.$$  

However, our information on the mixing angle has changed considerably within the recent
years. We have depicted the evolution using several example bounds in Fig. 1. In the upper left panel, the “old” observational bounds are depicted by the CDFS bound (green) and the XMM-Newton observations [89] of the Large Magellanic Cloud (LMC; purple), which goes down to slightly lower masses than CDFS. In 2011, there had been new bounds by the results from the Chandra satellite [96], both for Nearby Sources (gray) and for the Andromeda galaxy (red). In addition, in 2012 this was extended by the bounds obtained by XMM-Newton from the observation of Willman I [97] (orange).

However, we have not yet discussed how to combine these bounds. This is a subtle question, since after all different satellites have made observations of different galaxies, and when taking all observations at face value there could be unknown systematic errors involved. In order to show how such considerations can modify the results, we have decided to use three different cases. This means we consider the limit as valid before 2011, consisting of the CDFS and the LMC bounds, of which we always take the strongest limit for a given mass. This limit is depicted as the red line in the upper right panel of Fig. 1 and will later on be called “OLD” in the plots. We also use two different limits including the newer observations: the scenario “NEW conservative” adds only the Chandra observations of the nearby sources, while “NEW restrictive” contains also the Andromeda and Willman I observations. These two scenarios are depicted in the upper right panel by the black dashed and dotted curves, respectively. We would like to stress that we make no judgement on which of the observations mentioned should be included into a more robust combined bound, or not. However, any possible choice is likely to yield results in between our two “NEW” scenarios. In the lower two panels of Fig. 1 we also suggest linear fits in the $\log \theta^2 - \log M[\text{keV}]$ plane for our two scenarios. These fits can, to some extent, replace the older fit in Eq. (3) if an easy formula is desired to make a rough estimate.

An equally interesting development as for active-sterile mixing has taken place in the leptonic mixing data. In particular, the discovery of the non-zero value of the previously unknown leptonic mixing angle $\theta_{13}$ by the Daya Bay [74], RENO [75], and Double Chooz [76, 77] experiments has improved our knowledge considerably. Accordingly, new

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2Note that already in 2008, there has been a seemingly even stronger bound for very low masses originating from the Suzaku observations of Ursa Minor [95]. For larger masses, this data is included in the CDFS-fit [4, 5], but in particular for the small mass region the resulting bound seems to be stronger than the LMC limit [89]. However, it is highly non-trivial to compare the different data sets among themselves, as discussed explicitly in Sec. 3 of Ref. [95], and there could be different scientific opinions on which limits to take into account, or not. We have, therefore, decided not to include the Suzaku bound in our OLD scenario, in order to take on a conservative approach to the old limits. If the reader would like to recover the results including the Suzaku-limit, the bound would be very close to our scenario “NEW restrictive” to be discussed in the following, and its effect is therefore to some extent implicitly included in our plots.
Figure 2: The change of the standard effective neutrino mass $|m^{(3)}_{ee}|$ in neutrino-less double beta decay with the new data.

global fits on the neutrino mixing data have recently appeared [98,99,100]. To give a flavour of the changes, we compare a recent global fit [98] (free fluxes) on the new data with an older fit [101] (old Gallium fluxes) which had been updated in 2011. The decisive mixing parameters and their values (best-fit values and 3σ ranges) are:

| Parameters | Old fit [101] | New fit [98] |
|------------|---------------|--------------|
| $\sin^2 \theta_{12}$ | 0.32 (0.27–0.37) | 0.30 (0.27–0.34) |
| $\sin^2 \theta_{13}$ | 0.0095 (0.000–0.047) | 0.023 (0.016–0.030) |
| $\Delta m^2_{\odot}$ [$10^{-5}$eV$^2$] | 7.59 (6.90–8.20) | 7.50 (7.00–8.09) |
| $|\Delta m^2_{\text{NO}}|$ [$10^{-3}$eV$^2$] | 2.46 (2.09–2.83) | 2.47 (2.27–2.69) |
| $|\Delta m^2_{\text{IA}}|$ [$10^{-3}$eV$^2$] | 2.36 (1.99–2.73) | 2.43 (2.24–2.65) |

We will consider the old fit together with the X-ray limit before 2011, and the new fit with the conservative and restrictive limits after the Chandra and XMM-Newton results.

The standard plot of the effective mass $|m^{(3)}_{ee}|$, cf. Eq. (1), is shown in Fig. 2 while in the following sections we will present in details the results for a keV-sterile neutrino contribution. Note that in the $0\nu\beta\beta$ plots, certain regions in the parameter space are disfavoured. From cosmology, we can obtain an upper limit on the sum $\Sigma$ of light neutrino masses, which in our setting (without sterile neutrinos at the eV scale) means that $\Sigma = m_1 + m_2 + m_3$. We take the upper limit $\Sigma < 0.44$ eV @95% C.L. from the WMAP.
9-year data in combination with other CMB measurements, BAO data, and $H_0$ data, see Ref. [102]. This limit can be translated into an upper limit on the lightest neutrino mass $m$, which is depicted in the plots. However, there could be unknown systematic errors involved, which are actually known to be able to lead to wrong conclusions about the absolute neutrino mass scale [103]. This is why we mark that region as “disfavoured” rather than “excluded”. We want, moreover, to add that the South Pole Telescope (SPT) collaboration has recently reported a hint for a non-zero neutrino mass, $\Sigma = (0.32 \pm 0.11) \text{ eV}$ [104], see Ref. [105] for the implications of this measurement on $0\nu\beta\beta$ experiments. However, the Atacama Cosmology Telescope (ACT) collaboration [106] did not confirm this evidence and, probably, the situation will be clarified only by the upcoming Planck results, which is why we will not comment further on this point.

Similarly, for limits coming from searches for neutrino-less double beta decay, there are always uncertainties from unknown nuclear physics details present [52]. Analogously, we take the corresponding parameter region to be “disfavoured” as well, and as example bound we take the most optimistic limit obtained on |$m_{ee}$| from EXO-200 [107]. Both disfavoured regions are marked by the gray areas in Figs. 2 to 5.

3 Dependence for low masses

The lowest possible sterile neutrino mass is given by $M \sim 1 \text{ keV}$ [108, 109]. It corresponds to the Tremaine-Gunn [110] (lower) bound on the keV neutrino mass, which originates from the fact that neutrinos are fermions. This bound can be regarded as more or less model-independent lower limit. If stronger Ly-\(\alpha\) bounds are desired, the production mechanisms should be taken into account. For example, if the keV sterile neutrinos [21, 22, 43, 44] are produced by thermal overproduction with subsequent dilution by entropy production [42], the bound is relatively weak, $M \gtrsim 1.6 \text{ keV}$ [21], since the production of additional entropy leads to an effective cooling of the keV sterile neutrino component of the Universe [1]. One could also build up part of the DM by a resonant non-thermal production, known as Shi-Fuller mechanism [40]. This production mechanism also leads to a cooler DM-spectrum, and hence the Ly-\(\alpha\) bound could be rescaled to a value of about 2 keV [111]. Note that the resonant behaviour appears because in the case of large enough primordial lepton-antilepton asymmetries in the early Universe, Mikheev-Smirnov-Wolfenstein like [112, 113, 114, 115, 116, 117] level-crossings could appear. Similarly, the production by scalar decays at higher temperatures could lead to a diluted spectrum, and an example lower bound on the keV neutrino mass is given by

\footnote{Note that some authors go down to even lower values, see e.g. Ref. [22], where a mass of $M = 0.5 \text{ keV}$ has been considered.}
2.7 keV [73]. Finally, the simplest production mechanism of keV sterile neutrinos in the \(\nu\)MSM – the Dodelson-Widrow mechanism [39] – produces a too warm DM spectrum, for which the lower Ly-\(\alpha\) bound on the mass is between 8 and 10 keV [111]. This region is, in the case of vanishing primordial lepton asymmetry, already excluded by the X-ray bound [4, 5].

The plots of \(|m_{ee}^{(4)}|\) for different values of the mass of the keV sterile neutrino are displayed in Fig. 3. In the left column we consider the OLD X-ray bounds as valid before 2011, and we vary the neutrino oscillation parameters within the corresponding old \(3\sigma\) ranges [101]. In the middle and right columns, we display the results considering the bounds that we have derived using the NEW Chandra and XMM-Newton limits: the conservative and the restricted bounds, respectively. For these cases, we use the newer best-fit values and \(3\sigma\) ranges of Ref. [98]. We show three different values of the sterile neutrino mass: \(M = 1, 1.6, 2\) keV (upper, middle, and lower rows, respectively). We have checked that higher DM masses would not lead to a significant contribution of the keV sterile neutrino to \(0\nu\beta\beta\). Note that, in all cases, we have taken the active-sterile mixing \(\theta^2\) to have the largest allowed value for a given keV neutrino mass.

Let us at first consider the situation valid before 2011, cf. left column of Fig. 3. looking at the variation of the effective mass with \(M\), we can see that the change in \(|m_{ee}^{(4)}|\) is actually quite dramatic for very small values of \(M\): while the keV neutrino mass only changes by a factor of 1.6 from the upper left to the middle left row in Fig. 3, we can see that for \(M = 1\) keV the region where a full cancellation of the effective mass is possible is very different from the one for \(M = 1.6\) keV. This is a characteristic behaviour for the different elements of the neutrino mass matrix [78, 118]: the different contributions to the effective mass can be viewed as vectors in the complex plane which can, depending on their respective lengths and the values of their phases, add up to zero or not. Similarly in our case, if the lengths are appropriate, a cancellation can always be achieved by varying the Majorana phases \(\alpha, \beta,\) and \(\gamma\) accordingly. However, if the lengths of the vectors do not have the correct proportions (e.g., if one of the four is considerably longer than the three other ones), one can never build a zero length vector out of them, and then the effective mass will always be non-zero. From the plots we see that for \(M = 1\) keV the best-fit regions and the \(3\sigma\) regions are both different compared to the standard case. For \(M = 1.6\) keV, instead, mainly the best-fit regions change compared to the standard case.

We can try to understand this behaviour analytically by glancing at Eqs. (1) and (2). Using the OLD limit, the maximal contribution \(M\theta^2\) of the keV neutrino amounts to 0.0064 eV (0.0006 eV) for \(M = 1\) keV \((M = 1.6\) keV). Since the decisive region in the plot is the area around \(m \simeq 0\) for NO, we can approximate the situation by normal
hierarchy: $m_1 \simeq 0$, $m_2 \simeq \sqrt{\Delta m_{12}^2}$, $m_3 \simeq \sqrt{\Delta m_{13}^2}$. According to Eq. (11), this leads to

$$|m_{ee}^{(3)}| \simeq \sqrt{\Delta m_{12}^2 s_{13}^2 e^{-2i\alpha}} + \sqrt{\Delta m_{A}^2 s_{13}^2 e^{2i\beta}} \simeq \sqrt{\Delta m_{12}^2 s_{12}^2} + \sqrt{\Delta m_{A}^2 s_{13}^2 e^{2i(\beta-\alpha)}}. \quad (4)$$

Varying the phases for the best-fit values of the OLD oscillation parameters (the phases and the OLD oscillation parameters within their $3\sigma$ ranges), this quantity is between 0.0023 and 0.0033 eV (between 0 and 0.0059 eV). Clearly, both the best-fit value and the $3\sigma$ range are always smaller than the contribution of the keV neutrino for $M = 1$ keV, which makes a cancellation to practically zero impossible. The $M = 1.6$ keV contribution, in turn, is always smaller than the best-fit range, which again hinders a cancellation. However, if the oscillation parameters are varied within their $3\sigma$ ranges, then a cancellation can indeed appear for $M = 1.6$ keV, cf. first and second plot in the first column of Fig. 3.

For $M = 2$ keV, the influence of $M$ is not visible anymore. This can be seen most easily by comparing the lower left panel of Fig. 3 where $M = 2$ keV, to the standard plot of the effective mass, cf. left panel of Fig. 2. Indeed, the two plots look practically indistinguishable. Thus, for a large enough $M$, the effective mass is unchanged, just as stated in Refs. [66, 83]. However, the plots corresponding to a lower $M$ differ significantly from the standard plot. This yields an interesting connection to the production mechanisms, which allow for lower keV sterile neutrino masses, with experiments on neutrino-less double beta decay.

Let us now see how the situation has changed after the new limits from Chandra. For the NEW conservative bound, the main difference with respect to the standard contribution is present for $M = 1$ keV. In this case, the best-fit and $3\sigma$ regions for both NO and IO are different compared to the standard effective mass. The new bounds, even if taken into account in a conservative way, are so strong that the effect of a sterile neutrino with $M = 1.6$ keV is already really tiny. For $M = 2$ keV, practically no difference is present. For the case of the NEW restrictive bound, essentially no effect is visible for any value of the sterile neutrino mass. This result shows that the actual X-ray bounds taken at face value are extremely strong, and they wash out any possible influence of the keV neutrino on the effective mass, even for a mass as low as $M = 1$ keV.

In Fig. 4 we present the results for the case in which the sterile neutrino constitutes only 50% of the DM. This could easily be the case in a scenario with more than one type of DM, see e.g. Ref. [28] for a setting where keV DM is mixed with heavier DM. The rough effect of this assumption is that the upper bound on the active-sterile mixing $\theta^2$ gets weaker by a factor of two, simply because the amount of keV sterile neutrino DM and hence the number of expected decays $N \to \nu \gamma$ is reduced by the same factor. Note that this is only an approximation, since the statistical error of the number of possible
events in a certain bin (and most probably also some systematical errors) depend on the amount of keV sterile neutrinos in the Universe. However, such effects should be small compared to the errors involved in the nuclear physics uncertainties in $0\nu\beta\beta$.

For the situation valid before 2011, a visible effect is present for masses of 1 and 1.6 keV. Note that, while the keV neutrino mass only changes by a factor of 1.6 from the upper left to the middle left row in Fig. 3, we can see that, for $M = 1$ keV, the region where a full cancellation of the effective mass is possible is very big for IO (if the neutrino oscillation parameters are varied within their 3σ ranges), while it is only relatively small for NO. However, for $M = 1.6$ keV the situation is nearly turned round: the cancellation is not anymore possible for IO, while a large cancellation region suddenly opens up for NO.

Again aiming at analytically understanding this behaviour we note that, for the OLD limit, the maximal contribution of the keV neutrino making up only 50% of all DM in the Universe amounts to 0.0128 eV (0.0011 eV) for $M = 1$ keV ($M = 1.6$ keV). The variation of $|m^{(3)}_{ee}|$ for NO is the same as described after Eq. (4), whereas for IO we can approximate the interesting parameter region by inverted hierarchy: $m_1 \simeq m_2 \simeq \sqrt{\Delta m^2_{A}}$, $m_3 \simeq 0$. We can immediately see that

$$|m^{(3)}_{ee}| \simeq \sqrt{\Delta m^2_{A}} c^{2}_{13} |c_{12} + s^{2}_{12} e^{2i\alpha}|,$$

which is between 0.0177 and 0.0491 eV (0.0113 and 0.0532 eV) for the best-fit values (3σ ranges) of the OLD oscillation parameters. Evidently, for $M = 1$ keV a cancellation is only possible for IO if the oscillation parameters are varied within their 3σ ranges, while for NO it can never happen for small values of $m$. This situation is indeed just reversed for $M = 1.6$ keV, where the phases for the NO 3σ ranges can be varied such that a cancellation appears, while the corresponding values of $|m^{(3)}_{ee}|$ for IO are always larger than the contribution of the keV neutrino. These considerations are in full accordance with the plots, cf. first and second plot in the first column of Fig. 4.

For the NEW conservative bound, analogously the main differences with respect to the standard case are present for $M = 1$ keV and $M = 1.6$ keV. For $M = 1$ keV, the IO region is significantly different from that of the standard case, cf. right panel of Fig. 2 and the cancellation region is shrunk. For $M = 1.6$ keV the main difference is present for the 3σ variation for the NO case and, consequently, in the cancellation region. For the NEW restrictive bound, also in this case there are no significant differences present compared to the standard light neutrino contribution.
4 Form Dominance

In this section we present the case of form dominance (FD) \[85, 86\]. FD essentially means that, in a basis where the right-handed mass matrix $M_R = \text{diag}(M_1, M_2, M_3)$ and the charged lepton mass matrix are both diagonal, the columns Dirac mass matrix $m_D$ are proportional to the columns $\vec{U}_i^{\ast}$ of the complex conjugate PMNS matrix,

$$m_D = -i(\sqrt{m_1 M_1} \vec{U}_1^{\ast}, \sqrt{m_2 M_2} \vec{U}_2^{\ast}, \sqrt{m_3 M_3} \vec{U}_3^{\ast}). \quad (6)$$

Such a situation could be enforced by a suitable flavour symmetry (similar to what is done in, e.g., Refs. \[119, 120, 121, 122, 123, 124, 125, 126, 127, 128\]). It was shown in Ref. \[25\] that in the case of FD, more dramatically than for a general seesaw type I setting, there appears a generation-wise cancellation in $|m_{ee}^{(4)}|$. Hence, depending on whether the keV sterile neutrino $N$ belongs to the first (FD1), second (FD2), or third generation (FD3), the new contribution to $|m_{ee}|$ will cancel different terms. For this reason, it is particularly interesting to study the FD framework after the new X-ray bounds on the active-sterile mixing have been obtained.

Let us check in how far these scenarios can be brought into agreement with the existence of one keV sterile neutrino, where we again assume the two heavier sterile neutrinos to have masses that are significantly larger than the nuclear momentum transfer $|\vec{q}|$:

1. FD1: $N = N_1 (\Rightarrow M = M_1)$, cf. first row of Fig. 5

Here we require that $m_1 c_{12}^2 c_{13}^2 + M_1 \theta_1^2 e^{2i\gamma} = 0$ for the FD cancellation to happen, which implies that $\gamma = \frac{\pi}{2} \mod 2\pi$ and $|m_{ee}^{(4)}| = |m_2 s_{12}^2 c_{13}^2 + m_3 s_{13}^2 e^{2i(\beta - \alpha)}|$. Setting the absolute values of the two contributions equal yields $M_1 \theta_1^2 = m_1 c_{12}^2 c_{13}^2$, and applying the X-ray bound in combination with $M_1 \gtrsim 1$ keV leads to an absolute upper bound on the smallest active neutrino mass $m$. Inserting the best-fit values of the oscillation parameters (Ref. 101 for “OLD”, Ref. 98 for “NEW conservative” and “NEW restrictive”), one obtains $m = m_1 < 0.0095 (0.0094, 4.1 \cdot 10^{-5})$ eV in the case of NO and $m = m_3 < 0 (0, 0)$ eV in the case of IO for the OLD (NEW conservative, NEW restrictive) scenario. Thus, IO has already been excluded for the OLD data, cf. first row of Fig. 5 while for NO $m_1$ is pushed to very low values for the NEW restrictive scenario, which essentially implies a neutrino mass spectrum of the form $(m_1, m_2, m_3) \simeq (0, \sqrt{\Delta m_{21}^2}, \sqrt{\Delta m_{13}^2})$. Hence, if a model for keV sterile neutrinos is based on FD1, it must predict a very strong normal hierarchy among the active neutrino masses, in order not to be excluded.

2. FD2: $N = N_2 (\Rightarrow M = M_2)$, cf. second row of Fig. 5
Here we require \( m_2 s_{12}^2 c_{13} e^{2i\alpha} + M_2 \theta_2^2 e^{2i\gamma} = 0 \), which implies that \( \gamma - \alpha = \frac{\pi}{2} \mod 2\pi \) and \( |m_{ee}^{(4)}| = |m_{12}^2 c_{13}^2 + m_{23} s_{12}^2 c_{13} e^{2i\beta}| \). Setting the absolute values of the two contributions equal yields \( M_2 \theta_2^2 = m_2 s_{12}^2 c_{13} \), and applying the X-ray bound in combination with \( M_2 \gtrsim 1 \) keV leads to an absolute upper bound on the smallest active neutrino mass \( m \). Inserting the best-fit values of the oscillation parameters (Ref. [101] for “OLD”, Ref. [98] for “NEW conservative” and “NEW restrictive”), one obtains \( m = m_1 < 0.018 \ (0.020, \ 0) \) eV in the case of NO and \( m = m_3 < 0 \ (0, \ 0) \) eV in the case of IO for the OLD (NEW conservative, NEW restrictive) scenario. Here one can nicely see that, while the NEW conservative scenario hardly pushes the situation (apart from making the band slimmer), the NEW restrictive scenario excludes both mass orderings completely, cf. second row of Fig. 5 so that FD2 is in that case no valid situation anymore for a model attempting to yield keV sterile neutrinos. Note that the upper bound on \( m_1 \) actually gets weaker from OLD to NEW conservative. This might seem strange at first sight, but it is actually not a surprise when considering that the input values of the mixing parameters are quite different for the two scenarios.

3. FD3: \( N = N_3 \ (\Rightarrow M = M_3) \), cf. third row of Fig. 5

Here we require \( m_3 s_{13}^2 c_{13} e^{2i\beta} + M_3 \theta_3^2 e^{2i\gamma} = 0 \), which implies that \( \gamma - \beta = \frac{\pi}{2} \mod 2\pi \) and \( |m_{ee}^{(4)}| = |m_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13} e^{2i\alpha}| \). Setting the absolute values of the two contributions equal yields \( M_3 \theta_3^2 = m_3 s_{13}^2 \), and applying the X-ray bound in combination with \( M_3 \gtrsim 1 \) keV leads to an absolute upper bound on the smallest active neutrino mass \( m \). Inserting the best-fit values of the oscillation parameters (Ref. [101] for “OLD”, Ref. [98] for “NEW conservative” and “NEW restrictive”), one obtains \( m = m_1 < 0.67 \ (0.27, \ 0) \) eV in the case of NO and \( m = m_3 < 0.68 \ (0.28, \ 0.0012) \) eV in the case of IO for the OLD (NEW conservative, NEW restrictive) scenario. While for the OLD and NEW conservative scenarios both orderings are allowed, the NEW restrictive scenario excludes NO, cf. third row of Fig. 5. On the other hand, there is some room left for IO, which still allows for models based on FD3 as long as they yield IO and a small enough \( m_3 \).

The FD frameworks for keV sterile neutrinos are, indeed, strongly constrained by the new X-ray bounds. In particular, it is visible that there are strong variations between the NEW conservative and NEW restrictive scenarios (e.g., FD2 being perfectly allowed or completely excluded, respectively, in the case of NO), which justifies our statements made in Sec. 2 about the importance of the way the bounds are combined. This is particularly interesting from the model building point of view, since some flavour symmetries have a tendency to predict FD scenarios. Depending on how seriously the NEW bounds are
taken, there is a very strong handle to constrain or even right away exclude certain types of models.

5 Conclusions

We have re-analyzed the contribution of one keV sterile neutrino to neutrino-less double beta decay, focusing especially on the low mass region. We have shown that, considering the existing X-ray limits before 2011, sterile neutrinos could have had a visible influence on the effective mass if they were as light as $M < 2$ keV. This was apparently missed by earlier references. We have then updated our study considering the recent Chandra and XMM-Newton results, taking the new limits with both a conservative and a restrictive approach. We found that for the conservative case the sterile neutrinos can still produce a visible modification on the effective mass for really light mass values, $M \simeq 1$ keV, while for higher masses the effect is tiny. However, when using the Chandra and XMM-Newton limits at face value, the influence of a keV sterile neutrino on the effective mass is completely washed out. This is a consequence of the really strong new limits on the active-sterile neutrino mixing angle that are present at the moment from the satellite experiments mentioned.

We have then moved into analyzing the case in which the sterile neutrino constitutes only 50% of the DM. Also in that case, with the limits before 2011 the effect on the effective mass is actually quite significant for light sterile neutrinos, $M < 2$ keV. For the conservative scenario, the biggest effect is present close to the lower bound, $M \simeq 1$ keV, but a small modification is also present for $M \simeq 1.6$ keV. Considering the restrictive limit, no effect is visible even for really light sterile neutrino masses.

We have, moreover, studied the dependence in the case of form dominance. This notion is extremely restrictive, which is reflected in strong bounds on or even exclusions of different mass orderings for the various cases of form dominance. In particular when considering the restrictive limits, only a tiny parameter region survives for NO in the case of FD1. The scenario FD2 is, instead, completely excluded, and for FD3 only a small region is allowed for IO.

Our study explicitly shows how the current X-ray bounds can be used to put strong constraints on models for keV sterile neutrinos.

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Figure 3: Effective mass $|m_{ee}^{(4)}|$ as a function of the lightest neutrino mass $m$. The left columns refer to the X-ray bounds before 2011 and to the old neutrino fits for mixing and mass parameters. The middle (right) columns refer to the updated conservative (restrictive) Chandra bounds and to the new neutrino fits. We refer to Sec. 3 for more details. The plots assume that the sterile neutrinos constitute all the DM present in the Universe.
Figure 4: Same as Fig. 3 but assuming that the sterile neutrinos constitute only 50% of the DM present in the Universe.
Figure 5: Same as Fig. 3 but for the form-dominant case. The upper panels refer to FD1, the middle to FD2 and the lower to FD3. We refer to Sec. 4 for more details.