eXTP perspectives for the $\nu$MSM sterile neutrino dark matter model

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We discuss the potential of the eXTP X-ray telescope, in particular its Soft Focusing Array (SFA) and Large Area Detector (LAD), for the detection of a signal from keV-scale decaying dark matter. We show that the sensitivity of the eXTP is sufficient to improve existing constraints on the mixing angle of the neutrino Minimal extension of the Standard Model ($\nu$MSM) by a factor of 5 within the dark matter mass range 2–50 keV, assuming a zero level of systematic uncertainty. At the same time the minimal level of systematic uncertainty ($\sim 0.5\%$) can significantly impair obtained constraints for $m_{DM} > 20$ keV. We argue that even in this case the eXTP will be able to probe previously inaccessible range of $\nu$MSM parameters and serve as a precursor for the Athena mission in decaying dark matter searches.

I. INTRODUCTION

Astrophysical sources offer attractive laboratories for testing and constraining the properties of dark matter (DM) through indirect detection of its annihilation or decay products (e.g. photons, neutrinos, charged particles). With the lack of any firm detection so far, the search remains ongoing and will be aided by the next generation of satellites. These future missions will allow access to previously unavailable sensitivities in search of DM, enabling better constraints of DM properties or, finally, measurements of its parameters.

The lowest mass range for fermionic dark matter is known to be located in the keV band [1–4]. One of the most perspective theories accommodating a candidate particle (the sterile neutrino) for such dark matter is the minimal neutrino extension of the Standard Model of particle physics ($\nu$MSM) [5–9].

A sterile neutrino of mass $m_{DM}$ can decay producing a Standard Model neutrino and a monochromatic keV photon with an energy of $E = m_{DM}/2$ [9–11]. The decay signal can appear as a narrow line-like feature in X-ray spectra of astrophysical DM-dominated objects, e.g. clusters of galaxies or dwarf spheroidal galaxies (dSphs). The strength of the signal is determined by the active-sterile neutrino mixing angle $\theta$.

The parameters of the $\nu$MSM model (the mass of sterile neutrino $m_{DM}$ and mixing angle $\theta$) are constrained from below and above and only a narrow window of the parameter space remains unexplored so far, see e.g. Fig. 2 and [9] for a recent review.

The lower bound on the mass of fermionic dark matter particles $m_{DM} \gtrsim 1$ keV is imposed by the requirement that the phase-space density of dark matter particles in small (dwarf spheroidal) galaxies does not exceed the fundamental limit imposed by the uncertainty relation [1, 3, 4, 12].

High values of mixing angle $\theta$ are forbidden because the abundance of sterile neutrinos produced in the Early Universe with such mixing angles would exceed the observed DM density in the present day (see e.g. [2, 7] and [9] for a recent review). Additional upper limits originate from non-detection of the described line-like feature in multiple DM-dominated objects with the current generation of instruments [9].

The lower bound on the mixing angle indicates the region where the lepton asymmetries required for resonantly enhanced thermal sterile neutrino production to work are ruled out. Mixing angles lower than this bound would result in the abundances of light elements produced during Big Bang Nucleosynthesis to be in disagreement with the current measured values. [13–17].

In the following, we study the capabilities of the forthcoming eXTP mission to probe the remaining "island" of allowed parameters’ range of the $\nu$MSM model, which is unexplored by the current generation X-ray instruments. Namely, we propose deep observations of a DM-dominated object (dwarf spheroidal galaxy) aiming either to detect the line from decaying dark matter or to constrain ($m_{DM}, \theta$) sterile neutrino parameters.

The enhanced X-ray Timing and Polarimetry mission (eXTP [18]) is a forthcoming Chinese-European mission primarily designed for the study of the equation of state of matter in neutron stars, measurements of QED effects in highly magnetised stars and studies of accretion in the strong-field gravity regime.

The mission will host a set of state of the art scientific instruments operating in the soft to hard X-ray band (0.5–30 keV). The main instruments on board the eXTP are:

- The Spectroscopic Focusing Array (SFA), consisting of nine X-ray modules operating in $0.5-10$ keV band with

1 As of 2019 the launch is planned to 2027
FIG. 1: Left: eXTP/SFA and eXTP/LAD simulated spectra of 1 Msec observations of a region of blank sky (red and blue points). Cyan and magenta curves illustrate the levels of the instrumental background for both instruments. Right: Sensitivity of the SFA and LAD to a narrow Gaussian line present in the whole FoV of the instrument. Dashed lines show the change in the sensitivity of the instrument to the flux, given different assumed values of systematic uncertainty.

a field of view (FoV) of 12′ (full width half-maximum, FWHM), total effective area of ≈ 0.8 m² at 2 keV and energy resolution better than 10%;
- The Large Area Detector (LAD) – non-imaging instrument operating at 2 − 30 keV energies, with a FoV of 60′ (FWHM), effective area of ≈ 3.4 m² and energy resolution better than 250 eV.

In addition to the instruments described above, the eXTP will host two other modules – the Polarimetry Focusing Array (PFA) and the Wide Field Monitor. These instruments have moderate effective area and energy resolution which makes them comparable to current-generation instruments. Thus, in our work, we will only focus on the perspectives of the SFA and the LAD for indirect decaying dark matter searches in the keV mass scale.

II. SEARCH FOR DECAYING DM WITH eXTP

The flux of a DM-decay line at energy \( E = \frac{m_{DM}}{2} \) from an object covering entire FoV of the instrument is given by

\[
F = \frac{\Gamma}{4\pi m_{DM}} \cdot J_{\text{FoV}}
\]

\[
J_{\text{FoV}} = \int_{\text{FoV, l.o.s.}} \int \rho_{\text{DM}} d\ell d\Omega
\]

where \( \Gamma \) is the radiative decay width [10, 19] which, for a sterile neutrino, is given by

\[
\Gamma = \frac{9\alpha G_F^2}{256 \cdot 4\pi^4} \sin^2(2\theta) m_{DM}^5;
\]

\( J_{\text{FoV}} \) – is the total J-factor of decaying DM within the field of view; the corresponding integrations are performed over the field of view of the instrument (FoV) and the line of sight distance (l.o.s.) to the object. Substituting the expression for \( \Gamma \) into Eq. 1 one obtains

\[
F_{DM} \approx 10^{-7} \left( \frac{\sin^2(2\theta)}{10^{-11}} \right) \left( \frac{m_{DM}}{10 \text{ keV}} \right)^4 \times \left( \frac{J_{\text{FoV}}}{10^{17} \text{ GeV/cm}^2} \right) \text{ph/cm}^2\text{s};
\]

The J-factor in the direction of a distant object (and consequently its DM-decay signal), is composed of foreground emission from DM present in the Milky Way galaxy and the signal from DM residing in the source.

As a matter of fact the DM-decay signal is comparable for a variety of DM-dominated objects with masses ranging from dSphs, to clusters of galaxies [20]. Thus, additional considerations such as low levels of astrophysical background, well-measured J-factor, etc., should be taken into account when selecting a target for a deep DM-search observation.

Given this, in this study we consider dSphs as the main targets for decaying DM search in the keV band. Contrary to e.g. clusters of galaxies, in this energy range dSphs are characterised by low astrophysical backgrounds and can provide a “clean” decay-line signal.

The dark matter density profiles for dwarf spheroidal galaxies have been intensively studied in literature [see e.g. 21–24]. In our work we rely on numerical J-factors values reported in [23] as a function of the distance from the dSph center.

We estimated the MW contribution to the expected signal of a decaying dark matter assuming Navarro-Frenk-White (NFW [25]) profile for dark matter density:

\[
\rho_{\text{DM}}(r) = \frac{\rho_0 r_0^3}{r(r+r_0)^2}
\]
with the $\rho_0 = 7.8 \cdot 10^6 M_\odot/\text{kpc}^3$, $r_0 = 17.2 \text{kpc}$ parameters adapted from the best-fit NFW model of the recent MW-mass distribution study [26]; the integration in Eq. 1 was performed numerically.

Corresponding values (for both MW and dSph contributions) for the SFA and LAD instruments for a sample of dwarf spheroidal galaxies are summarized in Table 1. The uncertainties on J-factors for dSphs illustrate the differences between minimal and maximal J-factor profiles reported in [23].

Statistics of the DM-decay signal collected within the exposure time $T$ are determined by the line flux (Eq. 3) as well as the intrinsic properties of the instrument. These include, effective area $A_{\text{eff}}(E)$, energy resolution $\Delta E$ and the level of background (instrumental and astrophysical, in $\text{ph}/(\text{cm}^2 \text{s} \text{keV})$) present in the signal. The minimal detectable flux of a line can be estimated as

$$F_{\text{min}} = 2 \sqrt{\frac{B \Delta E}{A_{\text{eff}} T}} \frac{\text{ph}}{\text{cm}^2 \text{s}}$$

where the factor of 2 stands for a $2\sigma$ (or $\sim 95\%$ c.l.) detection or upper limit significance. Comparing $F_{\text{min}}(E)$ derived from the data to the expected $F_{\text{DM}}(E)$, one can derive the range of $(\theta, m_{DM})$ values to which the instrument is sensitive.

To perform such a comparison we simulated 1 Msec long observations of a dwarf spheroidal galaxy with the eXTP/SFA and the eXTP/LAD instruments. The simulated spectra were assumed to originate from contributions over the whole FoV and to be composed of instrumental and astrophysical background components.

The instrumental background component was given by the XTP\_sfa\_v6. bkg\(^2\) and LAD\_40mod\_300eV. bkg templates for SFA and LAD correspondingly, provided by the eXTP collaboration\(^3\).

For the astrophysical (cosmic X-ray) background for the eXTP/LAD we adopted a cut-off powerlaw model [27–30]

$$F_{\text{CXB}} = 7.877E^{0.29} e^{-E/41.13\text{keV}} \frac{\text{keV}}{\text{keV cm}^2 \text{s sr}}$$

which well describes the existing data in the $3 - 60 \text{ keV}$ range. For the eXTP/SFA, which has an energy range extending significantly below 3 keV, we instead adopted the model of CXB derived from XMM-Newton observations of a set of dwarf spheroidal galaxies [31]. We verified explicitly that at intersecting energy ranges both models agree within an accuracy of $\sim 10 - 15\%$.

The observations described above were performed with the fakeit XSPEC (version: 12.10.1f) command. The resulting spectra (normalized per FoV of corresponding instrument) are shown in the left panel of Fig. 1. Blue and red points illustrate the total expected flux seen by SFA and LAD correspondingly, while cyan and magenta lines present the level of the instrumental background.

We would like to note that the instrumental background of the LAD is much stronger and substantially more complicated than the SFA’s. While the SFA’s background is featureless and can be adequately modelled by a sum of two powerlaw models (convolved and not convolved with the effective area), the background of LAD hosts many instrumental lines and can not be modelled accurately with any simple model.

Given this we propose somewhat different observational strategies of a dSph by the SFA and LAD instruments. For the SFA we propose that the observation should be centered on the dSph and accompanied with subsequent modelling of instrumental and astrophysical background. Thus, a DM-decay line can be searched for on top of the modelled background. This strategy is similar to one widely used in decaying dark matter searches in astrophysical objects, see e.g. [9] for a review.

For the LAD however, we propose performing a set of “ON-OFF” observations, where “ON”-observations are centered on the dSph and “OFF” – on an empty sky region close to the object, but for which the contribution from dSph DM-decay signal is minimal. In this case we propose that rather than modelling astrophysical/instrumental backgrounds, to use “OFF” observations as a background for “ON” observations. The DM-decay line in this case is searched for in the obtained, background subtracted, (consistent with 0) spectrum. Such a strategy allows one to avoid modelling the complex LAD background and/or potential systematic effects connected with our poor knowledge of it.

Following our proposed strategy for the SFA, we perform a search for a narrow Gaussian line originating from the whole FoV, on top of the modelled backgrounds (specifically, the sum of the instrumental and astrophysical background models as described above). For the LAD we performed an additional 1 Msec long simulation of an “OFF” region characterised by the same astrophysical/instrumental backgrounds as an “ON” observation of a dSph. In this case we performed the search for a narrow Gaussian line in background subtracted spectrum. $2\sigma$ ($\sim 95\%$ confidence level) upper limits on normalization of such line\(^4\) are shown with solid blue (SFA) and red (LAD) curves in the right panel of Fig. 1. These limits are exact equivalents of the minimal detectable flux in Eq. 5.

We would like to stress the significance of the potential effects of systematic uncertainties on the limits which can be derived by the LAD instrument. To simulate this

\(^2\) Note, that the provided template corresponds to the background in $\sim 3'$ and has to be re-scaled by a factor of 16 to match 12' FoV of SFA.

\(^3\) See eXTP website

\(^4\) The upper limits were calculated with error 4.0 XSPEC command.
### TABLE I: Parameters of a sample of dSph galaxies. J-factor

| dSph   | Galactic coordinates | \( J_{\text{FoV}}(6') \) | \( J_{\text{FoV}}(30') \) |
|--------|----------------------|---------------------------|---------------------------|
| Segue I | (220.5; 50.4)        | 0.84 + 2.0 \(_{-1.2}^{+2.1}\) | 9.8 +14.8 \(_{-8.4}^{+10.6}\) |
| Draco   | (86.4; 34.7)         | 1.1 + 2.2 \(_{-0.5}^{+0.5}\) | 33.4 +17.8 \(_{-16.0}^{+10.2}\) |
| Carina  | (260.1; -22.2)       | 1.0 + 0.9 \(_{-0.2}^{+0.2}\) | 7.9 +7.4 \(_{-4.1}^{+4.1}\) |
| Fornax  | (237.1; -65.7)       | 0.95 + 1.0 \(_{-0.2}^{+0.3}\) | 7.9 +1.7 \(_{-4.4}^{+4.4}\) |
| Sextans | (243.5; 42.3)        | 0.90 + 0.5 \(_{-0.2}^{+1.0}\) | 7.8 +6.3 \(_{-5.3}^{+5.3}\) |
| Sculptor| (287.5; -83.2)       | 1.1 + 1.7 \(_{-0.3}^{+0.3}\) | 15.5 +5.9 \(_{-3.9}^{+14.2}\) |
| Ursa Minor| (105.0; 44.8)       | 1.0 + 2.4 \(_{-0.8}^{+0.8}\) | 10.7 +4.4 \(_{-7.3}^{+3.2}\) |
| Ursa Major I | (159.4; 54.4)  | 0.8 + 0.7 \(_{-0.1}^{+0.4}\) | 4.1 +7.3 \(_{-3.2}^{+3.2}\) |
| Ursa Major II | (152.5; 37.4) | 0.75 + 2.3 \(_{-1.5}^{+3.5}\) | 23.9 +48.3 \(_{-18.1}^{+18.1}\) |
| Bootes I | (358.0; 69.6)        | 1.4 + 0.9 \(_{-0.5}^{+0.9}\) | 8.0 +13.7 \(_{-6.3}^{+6.3}\) |
| Coma Ber| (241.9; 83.6)        | 1.1 + 1.8 \(_{-1.6}^{+2.1}\) | 9.2 +13.9 \(_{-6.0}^{+6.0}\) |

Effect we modified STAT_ERR column of both the “ON” and “OFF” observations by adding a value proportional to the total number of counts observed each channel. Dashed and dot-dashed curves in the right panel of Fig. 1 present limits on the line normalization which can be obtained by LAD in the presence of a 0.1% and 0.5% systematic uncertainty respectively. We conclude that in the case where the systematics of the LAD are poorly controlled (worse than \( \sim 0.1\% \)), the subsequent limits for decaying DM available to be obtained by the instrument will be worsened by a factor of \( \sim 10 \). On the contrary, a low instrumental background for the SFA will allow the limits it can impose to be only weakly dependent on the systematic uncertainty (see the dashed cyan curve in Fig. 1 presenting limits by SFA for 1% added systematic case).

Using the derived results for the eXTP’s sensitivity to a narrow Gaussian line, we obtain the corresponding minimal value of the mixing angle \( \theta \) at which a DM-decay line can be detected at a given energy \( E = m_{DM}/2 \). Corresponding limits for 1 Msec long Segue 1 dSph observations (assumed \( J_{\text{FoV}} = 2.84 \cdot 10^{17} \text{ GeV/cm}^2 \) for the SFA and \( J_{\text{FoV}} = 9.8 \cdot 10^{17} \text{ GeV/cm}^2 \) for the LAD) are shown in Fig. 2 along with current theoretical and observational constraints of sterile neutrino parameters (see e.g. [9] for the review). Also displayed for comparison are the expected limits, for the same exposure and target, on observations by the forthcoming Athena mission [32]. Note, that the presented limits correspond to a zero level of systematic uncertainty. The expected limits from observations of other low astrophysical background DM-dominated objects can be obtained by re-scaling presented limits according to the \( J_{\text{FoV}} \) of the target, see e.g. Table I.

![FIG. 2: 2σ sensitivity reach of the eXTP/SFA and eXTP/LAD to the parameters of the sterile neutrino from 1 Msec observations of Seg I dSph. These assume a zero level of systematic uncertainty for both instruments and J-factors corresponding to mean values reported in Tab. I. The green dashed curve illustrates 2σ Athena constraints from 1 Msec observations of the same target [32]. The light blue region shows the existing constraints (adapted from [9]). Phase space density [1, 3, 4, 12], thermal overproduction (see [2] and [9, 33] for the review) and the bounds originating from the abundances of light elements produced during BBN [14] are shown as grey regions. The black point represents the sterile neutrino parameters from the tentative detection of an unidentified \( \sim 3.55 \text{ keV} \) line in certain DM-dominated objects (see [34],[35] and [9] for a recent review)](image)

### III. DISCUSSION AND CONCLUSIONS

This study has demonstrated the capability of the upcoming eXTP satellite in searching for decaying dark matter and found it can impose significantly better limits than current observational means. 1 Msec long eXTP observations of DM-dominated dSphs, e.g. Segue 1, have the potential to improve existing 2σ X-ray observational constraints by a factor of \( \sim 5 \) within the 2–50 keV dark matter particle mass range (see Fig. 2), assuming a zero level of systematic uncertainty.

This systematic uncertainty will play a significant role in constraining decaying DM parameters from the LAD data. Uncontrolled systematics at a level of \( \gtrsim 0.5\% \) can worsen obtained constraints by a factor of \( \gtrsim 10 \) and make them comparable to, or even worse than, current X-ray constraints. Low instrumental background of the SFA makes the systematic effects less significant for this instrument. The systematic at a level of 1% (comparable to the estimated flux systematic uncertainty of XMM-Newton\(^5\)) will lead to a further deterioration of the ob-

\(^5\) See e.g. EPIC Calibration Status document
tained constraints by only a factor of $\sim 1.5$.

The constraints presented in Fig. 2 indicate also that the eXTP will be sensitive enough to exclude or detect at 3$\sigma$ level sterile neutrino with the mass of $m_{\nu_D} \sim 7$ keV and mixing angle mixing angle $(\sin^2(2\theta) \sim 2 \cdot 10^{-11})$. This angle roughly corresponds to minimal discussed in the literature mixing angle of a sterile neutrino producing a $\sim 3.55$ keV line. This line has been tentatively detected in some DM-dominated objects and is still actively being discussed in literature (see [34, 35] and [9] for a recent review). The corresponding range of mixing angles discussed is denoted by the black point with error-bars in Fig. 2.

With the optimistic assumptions on the mixing angle $\sin^2(2\theta) \sim 8 \cdot 10^{-11}$ (corresponding to 2$\sigma$ limits on mixing angle from current X-ray observations), the DM-decay line can be detected with a significance of 15$\sigma$ (10$\sigma$ in a presence of 1% systematic) with the eXTP/SFA only.

The strength of such a significant line could be compared among the sample of other DM-dominated objects in order to correlate its intensity with the known $J_{FOV}$ value draw conclusions on its DM-decay origin.

Alongside its numerous other scientific objectives, eXTP will be a precursor to the forthcoming Athena mission’s decaying dark matter searches. The improved sensitivity of eXTP in comparison to the current generation of instruments will lead to a significant reduction of the sterile neutrinos unobserved parameter space. We argue that with well controlled systematic uncertainties, the eXTP has the potential to discover decaying dark matter and make the first estimations of its parameters which can be further verified with Athena.

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