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DOI
10.1088/1742-6596/718/4/042067

Publication date
2016

Document Version
Final published version

Published in
Journal of Physics: Conference Series

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To cite this article: Fabio Zandanel *et al* 2016 *J. Phys.: Conf. Ser.* **718** 042067

Journal of Physics: Conference Series **718** (2016) 042067 doi:10.1088/1742-6596/718/4/042067

Angular power spectrum of sterile neutrino decay lines: the role of eROSITA

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Abstract. We study the potential of the angular auto and cross-correlation power spectrum of the cosmic X-ray background in identifying sterile neutrino dark matter taking as reference the performances of the soon-to-be-launched *e*ROSITA satellite. The main astrophysical background sources in this case are active galactic nuclei, galaxies powered by X-ray binaries, and clusters of galaxies. We show that while sterile neutrino decays are always subdominant in the auto-correlation power spectra, they can be efficiently enhanced when cross-correlating with tracers of the dark matter distribution. We estimate that the four-years *e*ROSITA all-sky survey will potentially provide very stringent constraints on the sterile neutrino decay lifetime by cross-correlating the cosmic X-ray background with the 2MASS galaxy catalogue. This will allow to firmly test the recently claimed 3.56-keV X-ray line found towards several clusters and galaxies and its decaying dark matter interpretation. We finally stress that the main limitation of this approach is due to the shot noise of the galaxy catalogues used as tracers for the dark matter distribution, a limitation that we need to overcome to fully exploit the potential of the *e*ROSITA satellite in this context.

1. Introduction

The study of the non-gravitational nature of the dark matter particle is one of the most important goals of modern physics. Sterile neutrinos with keV masses are well-motivated candidates for dark matter (e.g., [1, 2]) and they are observationally interesting as they behave as warm dark matter (WDM) with the potential to alleviate some of the small-scale problems of the cold dark matter (CDM) scenario (e.g., [3]).

Sterile neutrinos can decay into photon-neutrino pairs. Therefore, a clear smoking gun signal for sterile neutrino dark matter would be the detection of monochromatic photons at half of the dark matter mass. Monochromatic lines from sterile neutrinos have been searched for in various different targets, such as nearby galaxies and galaxy clusters. Recently, there have been claims of the detection of an unidentified 3.56-keV line from a stacked sample of galaxy clusters [4], and from Andromeda and the Perseus cluster [5], with a subsequent number of works on the issue, some of which confirmed the claim [6, 7, 8, 9] and some not [10, 11, 12, 13, 14, 15, 16]. This is an ongoing debate that deserves further investigation.

Auto and cross-correlation searches aim at detecting the dark matter signal coming from cosmological distances, and have the advantage of exploiting simultaneously spatial and spectral information from the full sky (e.g., [17, 18, 19, 20, 21, 22]). In this proceeding, we summarise the main findings of our paper [23], where we investigate for the first time the potential of an angular power spectrum analysis of the cosmic X-ray background (CXB) in identifying sterile

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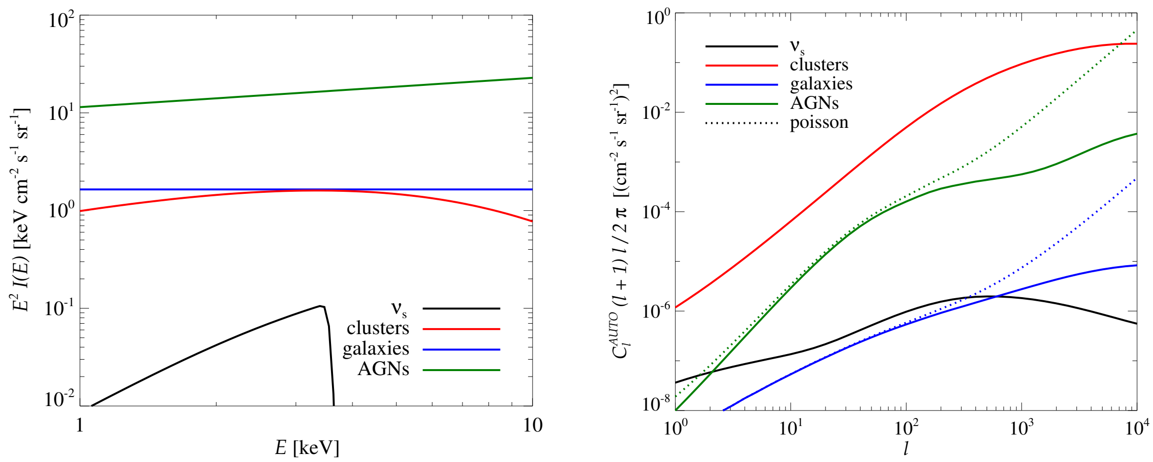

Figure 1. Left. Contributions to the CXB mean intensity as a function of energy. We show the sterile neutrino signal compared with unresolved AGNs and galaxies, and galaxy clusters (both resolved and unresolved). **Right.** Auto-correlation angular power spectrum of CXB in the 3.4 − 3.6 keV energy band. For AGNs and galaxies, both the correlation term (solid) and total including Poisson term (dotted) are shown. Figures adapted from Ref. [23].

neutrino dark matter. The next X-ray all-sky survey will be performed by *e*ROSITA [24], whose launch is scheduled for 2017, and, therefore, it is the reference instrument for our predictions. The methods that we present are very general and can be used for all scenarios with decaying dark matter.

2. Angular auto-correlation power spectrum

Besides the signal from the decay of sterile neutrinos, ν_s, coming from all the structures in the Universe, we have to consider other potential contributions to the CXB that will represent our main background. This is made of fluxes from active galactic nuclei (AGNs), X-ray binaries hosted in galaxies, and emission from clusters of galaxies. In the left panel of Fig. 1, we show the mean intensity of each of these components together with the sterile neutrino one. We refer the reader to Ref. [23] for details on the modelling of each component and summarise here the main steps. The sterile neutrino decays are modelled according to the scenario motivated by the 3.5-keV line interpretation by Refs. [4, 5]. Clusters of galaxies are modelled by using a halo mass function and the phenomenological model by Ref. [25]. AGNs and galaxies are modelled via luminosity functions adopting the prescriptions of Refs.[26] and [27], respectively. The figure shows that the sterile neutrino component is largely subdominant, in particular with respect to the dominant CXB contribution coming from unresolved AGNs. Note that we model the sterile neutrino signal coming from all the structures in the Universe, the unresolved AGNs and galaxies, and both the resolved and unresolved clusters of galaxies as these are the best objects were to look for a dark matter decay signal considering their large masses.

We define the auto-correlation angular power spectrum of a given source population A ($=\nu_s$, AGN, galaxies, clusters) at the multipole ℓ as

$$C_\ell^A(E) = \int_0^\infty \frac{d\chi}{\chi^2}\, W_A([1+z]E,z)^2\; P_A\left(k=\frac{\ell}{\chi},z\right), \qquad (1)$$

where the integral is over he comoving distance χ, W_A is the so-called window function of the given source A (see [23] for details), and $P_A(k,z)$ is the power spectrum at redshift z and wave number k. In the case of dark matter decay, the latter is the nonlinear matter power spectrum ($P_{\nu_s} = P_\delta$) modelled as sum of the 1-halo and 2-halo terms [28] as

$$P_\delta^{1h} = \left(\frac{1}{\Omega_{dm}\rho_c}\right)^2 \int dM_{200} \frac{dn}{dM_{200}} \left[\int 4\pi r^2 dr \rho_{dm}(r) \frac{\sin(kr)}{kr}\right]^2 , \quad (2)$$
$$P_\delta^{2h} = \left[\left(\frac{1}{\Omega_{dm}\rho_c}\right) \int dM_{200} \frac{dn}{dM_{200}} b(M_{200}, z) \int 4\pi r^2 dr \rho_{dm}(r) \frac{\sin(kr)}{kr}\right]^2 P_{lin}(k, \chi) ,$$

where ρ_{dm} is the Navarro-Frenk-White profile [29], the mass integration starts from $M_{200}^{\nu_s,\lim} \times h = 10^6$ M$_\odot$, the radial integration goes up to R_{200}, $P_{lin}(k, \chi)$ is the linear matter power spectrum [30], dn/dM_{200} is the halo mass function [30], and $b(M_{200}, z)$ is the linear bias [31].

In the case of clusters, $P_{A=cl}(k, \chi)$ is similar to that of Eqs. (2), but with $M_{200}^{cl,\lim} \times h = 10^{14}$ M$_\odot$, and substituting $\rho_{dm}(r)$ with $\rho_{gas}(r)^2$ and $(1/\Omega_{dm}\rho_c)$ with $(1/\Omega_b\rho_c)^2$. We assume that AGNs and galaxies are good tracers of the dark matter density. Therefore, $P_{AGN,gal}(k, z) = b^2_{AGN,gal}(z)P_\delta(k, z)$, where we again use Eq. (2) for P_δ. For the AGNs, we adopted the halo linear bias and assume that they reside in dark matter halos with mass of $10^{13.1} M_\odot$ [32], while for the X-ray emitting galaxies we adopt the bias from Ref. [33]. Note also that since AGNs and galaxies are point-like sources, there is an additional shot-noise contribution to the angular power spectrum that is independent of angular scale ℓ, the so-called *Poisson* term (e.g., [34]).

In the right panel of Fig. 1, we show the auto-correlation angular power spectrum integrated over the 3.4–3.6 keV energy band. Sterile neutrino decays are completely subdominant with respect to clusters at all multipoles, as well as with respect to AGNs and galaxies for most angular ranges.

3. Cross-correlation with 2MASS

Since sterile neutrino decays should follow the distribution of dark matter in the Universe, a cross-correlation between the X-ray signal and tracers of the dark matter distribution is a promising way to highlight the dark matter component. Therefore, we will compute the cross-correlation with a large galaxy catalogue from the 2MASS Redshift Survey (2MRS) [35] that nicely traces the dark matter distribution in the *local* Universe.

We define the cross-power spectrum of a given source population A with 2MRS as

$$C_\ell^{A,2MRS}(E) = \int \frac{d\chi}{\chi^2} W_A([1+z]E, z) W_{2MRS}(\chi) P_{A,2MRS}\left(k = \frac{\ell}{\chi}, \chi\right) , \quad (3)$$

where $W_{2MRS}(\chi) = (dz/d\chi)(dN_{2MRS}/N_{2MRS}dz)$ is the galaxy catalogue window function (normalised to unity), and $P_{A,2MRS}(k, z)$ is the cross-power spectrum. See Ref. [23] for details on these two factors. The left panel of Fig. 2 shows the cross-correlation of the different considered components with 2MRS integrated over 3.4–3.6 keV.

The 2MRS cross-correlation analysis shows that we are able to highlight the sterile neutrino component despite the fact that its auto-correlation is completely dominated by clusters, AGNs and galaxies. While the contribution from resolved and unresolved clusters of galaxies is strong also in the cross-correlation case, we show that by excluding them completely from the analysis, and reducing the sterile neutrino component only to structures up to $M_{200}^{\nu,\lim} \times h = 10^{13}$ M$_\odot$, we do not loose a significant fraction of sterile neutrino decays. However, we will show that we are able to test the claimed 3.56-keV dark matter scenario also when including clusters in the analysis.

4. Projected limits and conclusions

In the right panel of Fig. 2, we show our *e*ROSITA projected limits for the sterile neutrino mixing angle. These are obtained by performing a χ^2 fit to mock data, taking properly into

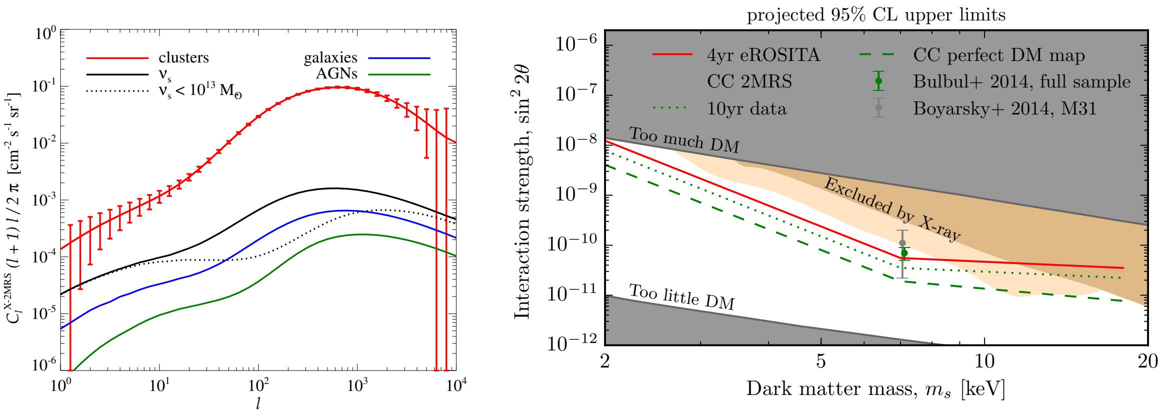

Figure 2. Left. Cross-correlation of CXB with 2MRS in the 3.4–3.6 keV energy band. For sterile neutrinos, we also show the case when the integration upper mass limit is fixed to $M_{200}^{\nu,\mathrm{lim}} \times h = 10^{13}$ $\mathrm{M}_\odot$ to asses the effect of excluding clusters from such an analysis. We overlay the error bars to the cluster component. **Right.** Projected 95% CL upper limits on the sterile neutrino mixing angle as function of mass. For our baseline result, shown with the red solid line, we assume 4 yr of observations with eROSITA. We also show the limits obtained for 10 yr of observations, and when cross-correlating 4 yr of data with a hypothetical *perfect* tracer of dark matter (i.e., no shot noise, same window function as for 2MRS, and negligible bias). We derived projected limits for three reference energies and interpolate otherwise. Figures adapted from Ref. [23].

account the covariance of the different components. We perform our analysis on three cases of sterile neutrino mass: $m_s = 2.0$, 7.2 and 18.0 keV. For each of these, we fit simultaneously over three energy bands that are centred on the line, and are at slightly lower and higher energies: (0.5–0.8, 0.9–1.1, 1.2–1.5), (3.0–3.3, 3.4–3.6, 3.7–4.0) and (8.5–8.8, 8.9–9.1, 9.2–9.5) keV. As already mentioned, we take the performances of the soon-to-be-launched eROSITA as reference X-ray satellite [24].

Our model is a linear combinations of the contributions from sterile neutrinos, unresolved AGNs and galaxies, and resolved and unresolved cluster emission. In order to derive projected upper limits, we generate mock data with the sterile neutrino flux set to zero, and adopt the standard $\Delta\chi^2$ method to derive 95% CL upper limits by increasing the signal flux, while refitting the other parameters, until the χ^2 function changes by $\Delta\chi^2 = 2.71$.

We find that 4 yr of eROSITA observations are sensitive to the sterile neutrino scenario motivated by the dark matter interpretation of the claimed 3.5-keV feature. Therefore, if this interpretation is correct, eROSITA could be able to detect the corresponding cross-correlation signal. In the right panel of Fig. 2, we also show the limits that would be obtained if the galaxy shot noise or the photon shot noise terms are negligible. These correspond, respectively, to the cases of perfect knowledge about the dark matter distribution or 10 yr of observation time. It is interesting to note that the galaxy noise term is the most important limiting factor for such an approach. This suggests that an improved measurements of the dark matter distribution in the local Universe, together with a good knowledge on the uncertainties in the theoretical modelling of the different components, will be fundamental to fully exploit the eROSITA potential for cross-correlation studies.

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