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Decaying dark matter in dwarf spheroidal galaxies: Prospects for X-ray and gamma-ray telescopes

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In this work we revise the estimate of dark matter (DM) decay signals from dwarf galaxies in the Milky Way. They are ideal for indirect DM searches, since they are known to be DM dominated systems. We test both warm and cold DM candidates, i.e. sterile neutrinos decaying into X-ray photons and a heavier DM candidate decaying into gamma rays. We analyze the sensitivity to such a signal for both ground- and space-based detectors: Athena, XRISM and eROSITA for X-rays and HAWC and CTA for very-high-energy gamma rays. We consider sterile neutrinos with masses between 4-20 keV and masses for the heavier DM candidate in the range of 200 TeV to 20 PeV, decaying via a $b\bar{b}$ or a $\tau^+\tau^-$ channel. We make projections for future dwarf galaxies that would be newly discovered with the Vera Rubin Observatory Legacy Survey of Space and Time, which will further improve the expected sensitivity to DM decays both in the keV and TeV mass ranges. Our results show that all of these X-ray telescopes will be able to critically assess the claim of 7 keV sterile neutrino decays from stacked galaxy clusters and nearby galaxies, reaching sensitivities of $\sin^2(2\theta) \sim 10^{-12} - 10^{-13}$. For TeV dark matter, both HAWC and CTA will be sensitive to DM lifetimes of $10^{27} - 10^{28}$ seconds.

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1. Introduction

The lack of detection of DM in collider experiments, indirect and direct detection has motivated the need to investigate DM candidates other than weakly interacting massive particles (WIMPs) [3, 7, 8, 10, 13, 14]. We have investigated the ability to detect decay signatures in dwarf spheroidal galaxies (dSphs) of two DM candidates: keV sterile neutrinos [7] and heavy DM [8, 12] in the TeV to PeV range.

1.1 Sterile neutrino dark matter

Sterile neutrinos ν_s are a decaying DM candidate that exist as a mass eigenstate mixed very weakly with active neutrino flavors. Through decay into an active neutrino species and a photon with an energy corresponding to half of the sterile neutrino mass, these sterile neutrinos become a candidate for indirect detection. The claimed detection of a 3.5 keV excess in the X-ray spectra of galaxy clusters [5], and a similar claim for such a signal originating from the Perseus cluster and M31 [4], sparked great scientific interest in the origin of this claimed excess. If this excess is due to sterile neutrino decay, it would correspond to a particle with $m_{\nu_s} = 7.1$ keV mass and mixing angle of $\sin^2(2\theta) = 7 \times 10^{-11}$. With this claim in mind, we study the sensitivity of upcoming telescopes to sterile neutrino decay, focusing on XRISM, Athena and eROSITA telescopes.

1.2 Heavy dark matter

Although WIMPs have typical mass scales in the GeV-TeV range, heavier DM candidates exist, extending the mass range well into the PeV range. Through data from TeV gamma-ray observatories such as HAWC, CTA and LHAASO, and TeV-PeV neutrino telescopes such as IceCube, IceCube-Gen2 and KM3NeT, it is possible to place constraints on the lifetimes of heavy DM candidates. The Fermi-LAT telescope has already placed strong constraints on the decay lifetime of DM in the 1 TeV to 10 PeV mass range. In our work, we have focused on the prospected increase on these constraints for the HAWC and CTA gamma-ray observatories. The HAWC observatory has a wide field of view and is sensitive to an energy range between 500 GeV and a few hundred TeV. It detects particles from air showers through the use of 300 Cherenkov water tanks. The CTA observatory is able to achieve close to full sky coverage through the use of two locations, denoted CTA-north and CTA-south. It covers an energy range from 20 GeV to 300 TeV and has a 10° field of view.

1.3 Dwarf spheroidal galaxies

dSphs - satellites of the Milky-Way galaxy, make good targets for indirect DM searches due to their proximity and lack of astrophysical componets, such as stars and gas. We have used both known dSphs and prospective dwarf candidates from the Vera C. Rubin Observatory (formally LSST). Density profiles of dSphs determine the rate of DM decay. Through revised models for the subhalo and satellites, we are able to make projections for the number of, and density profiles of dwarfs that will be detected with the LSST. The quantitative assessment of the combination of known and prospective dSphs is used to produce estimates that inform the viability of current and future indirect DM search strategies.

2. Dark matter decay

The flux received from dSphs is given by

$$\frac{dF}{dE} = \frac{\Gamma_\chi}{4\pi m_\chi}\frac{dN_{\mathrm{decay}}}{dE}D \tag{1}$$

where m_χ is the mass of the DM particle χ and Γ_χ is the decay width. The energy spectrum of the particle is defined through dN_{decay}/dE. Obtaining the lifetime of the particle is done through the inversion of the decay width, i.e. $\tau_\chi = 1/\Gamma_\chi$. The flux received scales with the so-called D factor, which is the line-of-sight integral of the density profile of the dSph over the region of interest given by

$$D_{\mathrm{dSph}} = \int_{\Delta\Omega} d\Omega \int d\ell \rho_\chi(r(\ell,\psi)). \tag{2}$$

Here, ψ is an angle coordinate subtending from the center of the dwarf galaxy and $d\Omega = 2\pi\sin\psi d\psi$. The density profile of the dSphs is assumed to be approximated by a spherically symmetric Navarro-Frank-White (NFW) profile

$$\rho_\chi(r) = \frac{\rho_s}{(r/r_s)(r/r_s+1)^2} \tag{3}$$

We also assume that outside of the tidal truncation radius r_t, the density cuts off sharply, i.e. $\rho_\chi(r > r_t) = 0$. Under assumption of the NFW profile, the D-factor of each dwarf galaxy is computed as

$$D_{\mathrm{dSph}} = \frac{4\pi\rho_s r_s^3}{d^2}\left[\ln\left(\frac{\min[\alpha_{\mathrm{int}}d, r_t]}{2r_s}\right) + X\left(\frac{\min[\alpha_{\mathrm{int}}d, r_t]}{2r_s}\right)\right], \tag{4}$$

3. Distribution of *D*-factors

Previous works have used non-informative prior distributions for the density profile parameters of the dSphs, where data of stellar kinematic observations is insufficient. We employed more physically motivated priors to get to reasonable limits with Bayesian parameter inference. Instead of the non-informative log-uniform priors we follow the procedure of [1] to estimate the density profile of observed dSphs and the expected dwarf D-factor distributions. Using several different conditions on the formation of dSphs, we find that the informative priors yield narrower posterior D-factor distributions with a smaller median than the uninformative priors. For the potential dSphs discovered by LSST we need the spatial distribution in addition to the distribution of the expected subhalo properties. To that end, we incorporate findings of hydrodynamical simulations of [6] together with corrections from [9]. The used D-factor posterior distributions are then calculated with eq. 4 for both the known and LSST dSphs.

4. Sterile neutrino dark matter

The probability, that a sterile neutrino can convert to an active neutrino is proportional to $\sin^2(2\theta)$, where θ is the so-called mixing angle between the two neutrino species. The decay rate of the sterile neutrino is linked to this quantity as

$$\Gamma_{\nu_s}(m_{\nu_s},\theta) = 1.38\times 10^{-29}\ \mathrm{s}^{-1}\left(\frac{\sin^2 2\theta}{10^{-7}}\right)\left(\frac{m_{\nu_s}}{1\ \mathrm{keV}}\right)^5. \tag{5}$$

With the flux per eq. 1, where the energy spectrum is given by a Delta function enforcing the energy of the photon to be half that of the rest mass of the sterile neutrino, we can calculate the event counts in an energy bin ranging from energies E_1 to E_2 with

$$N = T \int_{E_1}^{E_2} dE A_{\text{eff}}(E) \int dE' P(E, E') \frac{dF}{dE'}, \tag{6}$$

where A_{eff} and $P(E, E')$ account for the effective area and energy resolution of the detector respectively. We added a contribution from the cosmic X-ray background [11] on top of the detector-specific background.

We then simulated two data sets with Poisson distribution, where one is background only and one has an additonal DM decay signal on top of the background. We then test how likely it is, that the signal hypothesis generates the background-only mock data set with a maximum likelihood estimation on the decay rate Γ. If the test statistic (proportional to the logarithm of a likelihood ratio) falls below a certain upper limit, we have an acceptable hypothesis with a certain decay width with a 95% confidence level.

We generated a sensitivity band for the detectors Athena and XRISM for two dSphs, Draco and Ursa Major II. By randomly choosing a D-factor of our Monte-Carlo generated sample we calculate the corresponding 95% confidence level upper limit on Γ and by repeating this procedure we get a distribution on these upper limits, which are then converted to upper limits on $\sin^2(2\theta)$ with eq. 5. For the all-sky telescope eROSITA, we consider known dSphs together and dSphs potentially discovered in the future with LSST. We again generate upper limits on $\sin^2(2\theta)$, this time employing a joint-likelihood analysis of all dSphs.

5. Heavy dark matter

We consider a DM particle with a mass between 200 TeV-20 PeV decaying into $b\bar{b}$ or $\tau^+\tau^-$ channels. For DM masses beyond 200 TeV, we use an energy scaling given by

$$\frac{dN}{dE} = \frac{m_A}{m_\chi} \frac{dN_A}{dE'} \quad (E' = E \frac{m_A}{m_\chi}), \tag{7}$$

where $m_A = 200$ TeV is the reference mass and dN_A/dE is the spectrum calculated at that mass. We accounted for the most prominent background contributions in the form of energetic electrons and protons.

We targeted the detection of a signal in a gamma-ray energy range between 300 GeV and 100 TeV. Taking the 21 known dSphs, which are inside the field of view of HAWC, we calculated the lower limits on the decay lifetime of these heavy DM particles for both channels. As CTA-north has a high angular resolution but a more narrow field of view than HAWC, we focused on the best dSphs, namely Draco and Ursa Major II. Since CTA-south will survey the entire southern sky, it will observe the prospective LSST dSphs. We used the best possible LSST dSph candidate, i.e. the dSph possessing the largest D-factor in our Monte Carlo simulations, to arrive at the decay lifetime constraints.

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6. Discussion and conclusions

We have conducted an in-depth study of DM decay signals coming from dSphs of the Milky Way. We then proceeded to estimate the sensitivities to such signals for X-ray telescopes such as Athena, XRISM and eROSITA and high-energy gamma-ray observatories such as HAWC and CTA. We showed, that with our considered priors, the distribution of D-factors are narrower and lower, a similar effect to what has been shown in the case of DM annihilation [2]. The revised estimates concerning the D-factors are thus weaker but more robust.

For all the considered X-ray telescopes, we showed that they will be able to critically assess the much debated 3.5-keV X-ray lines, in the case of a lighter DM candidate as a sterile neutrino. In case of the more heavy DM considered in this work, the two detectors HAWC and CTA will be able to probe a similar range for the decay lifetimes of the heavy DM in the range of $10^{27} - 10^{28}$s for the $b\bar{b}$ channel, while the limits are weaker up to an order of magnitude for the $\tau^+\tau^-$ channel for masses ranges greater than PeV. The reason for this is because most of the gamma-ray photons emmitted by DM in this mass range have energies beyond the energy range that we consider, caused by the harder spectrum of the $\tau^+\tau^-$ channel compared to the $b\bar{b}$ channel. We expect that these detectors will provide complementary constraints to future neutrino telescopes, such as IceCube-Gen2 and KM3NeT, by using these messengers.

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