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Constraining dark matter lifetime with a deep gamma-ray survey of the Perseus galaxy cluster with MAGIC

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ABSTRACT

Clusters of galaxies are the largest known gravitationally bound structures in the Universe, with masses around 10^{15} $M_\odot$, most of it in the form of dark matter. The ground-based Imaging Atmospheric Cherenkov Telescope MAGIC made a deep survey of the Perseus cluster of galaxies using almost 400 h of data recorded between 2009 and 2017. This is the deepest observational campaign so far on a cluster of galaxies in the very high energy range. We search for gamma-ray signals from dark matter particles in the mass range between 200 GeV and 200 TeV decaying into standard model pairs. We apply an analysis optimized for the spectral and morphological features expected from dark matter decays and find no evidence of decaying dark matter. From this, we conclude that dark matter particles have a decay lifetime longer than $\sim 10^{26}$ s in all considered channels. Our results improve previous lower limits found by MAGIC and represent the strongest limits on decaying dark matter particles from ground-based gamma-ray instruments.

1. Introduction

Decades of observational evidence show that the Standard Model (SM) of Particles Physics cannot entirely explain the gravitational balance observed at all cosmological scales, from that of Milky Way satellite dwarf spheroidal galaxies (dSphs) to that of cluster of galaxies (CGs, see [1,2]). In order to explain these observations, Dark Matter (DM) has been suggested to exist in the form of a new elementary particle, currently only seen through its gravitational imprint. Weakly-Interacting Massive Particles (WIMPs) are generic massive particles with an expected mass range between few GeV (Lee–Weinberg limit, see [3]) and few hundreds of TeV (unitary bound, see [4]). WIMPs are expected to interact with SM particles with strengths at the weak scale, and to be either stable or very long lived. A WIMP can either annihilate or decay into SM particles, or even be decoupled from the SM. The WIMP paradigm has been long debated, as the WIMP self-annihilation in the early Universe naturally accounts for the DM density observed at present (typically referred to as the *WIMP miracle*), being possibly within reach of different currently operating instruments. The case of DM annihilation has received greater attention in the literature [5] but there is no experimental or theoretical guarantee that DM particles are absolutely stable. The only constraint is that decaying DM particles' lifetime should be comparable or larger than the Hubble time of $\sim 10^{17}$ s in order to explain the current DM density. Among others, decaying DM particles may produce e.g. leptons, quarks, or gauge bosons, which can subsequently provide electromagnetic radiation due to prompt emission or secondary interactions. Lately, DM models that favor decays into leptons (known as "leptophilic" models) have received increased attention, due to the excess of positron events observed in the local cosmic ray (CR) flux by PAMELA, AMS-II and Fermi-LAT [6–9].

The standard cosmological model predicts CGs to be the latest and most massive structures to form in the Universe [10]. With higher DM concentration and closer distances, dSphs and the Galactic Center are among the best regions to search for annihilating WIMPs. CGs however, with masses of the order of 10^{14-15} $M_\odot$ (~80% of it in the form of DM, see e.g., [11,12]), are excellent laboratories to study decaying DM. The Perseus CG is a cool-core cluster located at a distance of 77.7 Mpc (redshift $z = 0.0183$). Perseus is very bright in X-rays, and one of the best candidates for detecting CR induced gamma rays that come from particle acceleration at the cluster core [13–15]. The Perseus CG is considered among the most promising CGs for gamma-ray indirect DM detection [16].

The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes [17] have observed the Perseus CG since 2009, the deepest exposure the instrument has carried out. The campaign took place over several consecutive years and comprised almost 400 h of recorded data until 2017. MAGIC is a system of two 17 m diameter Imaging Atmospheric Cherenkov Telescopes (IACTs) capable of detecting gamma rays in the very high energy (VHE, $E > 50$ GeV) band. For low zenith angle observations, MAGIC has an angular resolution of $\sim 0.1°$, a trigger threshold of ~50 GeV, and sensitivity for point-like sources of ~0.66% of Crab Nebula flux above 220 GeV in 50 h of observation [17]. The MAGIC campaign on Perseus CG proved to be very fruitful, producing the strongest limits on CR acceleration and CR pressure in the core of the cluster [13,18]; a clear detection and model for the radio galaxy NGC 1275, at the center of the cluster [19,20]; and the detection of the peculiar radio galaxy IC 310, located at 0.6 deg from the Perseus CG center, which provides important evidence related to the acceleration of CRs close to black holes [21–23].

In this work we focus on the search for signatures of decaying DM in an extended region from the Perseus CG with observations from MAGIC. We do not consider the annihilation case since the expected signal of DM annihilation in the Perseus CG would be one order of magnitude smaller than the signal expected for the typical case of dSphs [16]. More importantly, the expected morphology of the signal of annihilating DM is more concentrated towards the center of the cluster that of decay where, in the case of the Perseus