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Constraints on majoron dark matter from cosmic microwave background and astrophysical observations

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ABSTRACT

The origin of dark matter and the generation of neutrino masses could be related if neutrino masses arise from the spontaneous violation of ungauged lepton number. In this case the associated Nambu–Goldstone boson, the majoron, could acquire a mass from non-perturbative gravitational effects and play the role of DM. Here we report our cosmological and astrophysical constraints on majoron dark matter coming from Cosmic Microwave Background (CMB) and a variety of X- and γ-ray observations.

1. Introduction

We know that most of the matter content in the Universe is in the form of non-baryonic "dark matter" (DM). The existence of DM is inferred by gravitational anomalies at very different scales, ranging from galactic scales to cosmological scales. In particular, the 9-year data from the Wilkinson Microwave Anisotropy Probe (WMAP) [1,2], as well as the newly published results from the Planck satellite [3], have provided even stronger support to the six-parameter Λ CDM model, although small-scale experiments like the Atacama Cosmology Telescope (ACT) [4] and the South Pole Telescope (SPT) [5] hint to interesting, albeit discordant, deviations from this simple picture, e.g. the presence of additional relativistic degrees of freedom, or deviations from ordinary gravity [6,7].

In spite of the phenomenological success of the Λ CDM model, the nature of both DM and dark energy, that together make up for more than 95% of the total energy budget of the Universe, is still unknown. These questions may have their solution in some physics beyond the standard model (SM) of particle physics, or maybe in some modification of general relativity. Although its precise nature is still unknown, there is no shortage of candidates for the role of DM. One of the most widely studied candidates to date has been the supersymmetric neutralino; however, recent results from the Large Hadron Collider (LHC), however, have greatly reduced the available parameter space for supersymmetry, at least in its simplest minimal supergravity implementations [8]. Other possible candidates include axions, Kaluza–Klein DM, keV DM, such as sterile neutrinos, and many others.

If the DM has any connection to the world of SM particles, there will be astrophysical signals one can search for, in particular high energy photons from annihilating or decaying DM (see Refs. [9,10] for a recent review). The most studied scenarios are the broad spectrum annihilation signals from neutralinos, but the real smoking gun is line emission (either directly from the decay/annihilation [11,12] or from internal bremsstrahlung [13,14]), for which the spectral and spatial distribution is not easily mimicked by astrophysical sources.

An appealing possibility is that the DM could be related to the origin of neutrino masses [15,16]. In particular, if neutrino masses arise from the spontaneous violation of ungauged lepton number [17,18], the associated Nambu–Goldstone boson, the majoron, could acquire a mass from non-perturbative gravitational effects [19,20], and play the role of DM. The smallness of neutrino masses, as compared to the other SM particles, is puzzling in itself. Most likely it is associated to the properties of the messenger states whose exchange is responsible for inducing them. This is the idea underlying the so-called seesaw mechanism [21–25], whose details remain fairly elusive.

The viability of the majoron as a DM particle has been explored using observations of the anisotropy spectrum of the CMB [26], as well as the possible X-ray signature associated to majoron decay [27]. These constraints have been recently updated in the light of the most recent cosmological and astrophysical data [27]. In this proceeding paper, we briefly review these updated constraints and refer the reader to Ref. [27] for further details.

The paper is organized as follows. In Section 2, we briefly recall the relevant majoron physics. In Section 3, we report observational

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constraints on the majoron decay to neutrinos and photons, and we compare them to the predictions of a general seesaw model. Finally, in Section 4 we draw our conclusions.

2. Seesaw majoron physics

The basic idea of majoron physics is that the lepton number symmetry of the SM is promoted to a spontaneously broken symmetry [17,18]. This requires the presence of a lepton-number carrying complex scalar singlet, σ, coupling to the singlet neutrinos, ν_L^c, as follows:

$$\lambda\sigma\nu_L^c T\sigma_2\nu_L^c + H.c. \tag{1}$$

with the Yukawa coupling λ. This term provides the large mass term in the seesaw mass matrix

$$\mathcal{M}_\nu = \begin{bmatrix} Y_3 v_3 & Y_\nu v_2 \\ Y_\nu^T v_2 & Y_1 v_1 \end{bmatrix} \tag{2}$$

in the basis of "left" and "right"-handed neutrinos ν_L, ν_L^c. The model is characterized by singlet, doublet and triplet Higgs scalars whose vacuum expectation values (vevs) are arranged to satisfy $v_1 \gg v_2 \gg v_3$ obeying a simple vev seesaw relation of the type $v_3 v_1 \sim v_2^2$. The vev v_1 drives lepton number violation and induces also a small but nonzero v_3, while v_2 is fixed by the masses of the weak gauge bosons. The effective light neutrino mass obtained by perturbative diagonalization of Eq. (2) is of the form

$$m_\nu \simeq Y_3 v_3 - Y_\nu Y_1^{-1} Y_\nu^T \frac{v_2^2}{v_1}. \tag{3}$$

Together with the relation $v_3 v_1 \sim v_2^2$, this summarizes the essence of the seesaw mechanism.

The majoron J is given by the following combination of the Higgs fields [18]:

$$J \propto v_3 v_2^2\,\mathrm{Im}(\Delta^0) - 2v_2 v_3^2\,\mathrm{Im}(\Phi^0) + v_1(v_2^2 + 4v_3^2)\,\mathrm{Im}(\sigma) \tag{4}$$

up to a normalization factor. Im() denotes the imaginary parts, while Δ^0 and Φ^0 refer to the neutral components of the triplet and doublet scalars respectively.

One can derive the form of the couplings of the majoron using only the symmetry properties, as described in Ref. [18]. For first approximation, the majoron couples to the light mass-eigenstate neutrinos inversely proportional to the lepton number violation scale $v_1 \equiv \langle\sigma\rangle$ and proportionally to their mass. The DM majoron decay rate to neutrinos can be computed to be

$$\Gamma_{J\to\nu\nu} = \frac{m_J}{32\pi}\frac{\sum_i (m_i^\nu)^2}{2v_1^2}, \tag{5}$$

where the Majoron mass m_J is presumably generated by non-perturbative gravitational effects [19,20]. Moreover, there is a subleading majoron decay mode to photons. Within the general seesaw model this decay is induced at the loop level, resulting in [27]

$$\Gamma_{J\to\gamma\gamma} = \frac{\alpha^2 m_J^3}{64\pi^3}\left|\sum_f N_f Q_f^2 \frac{2v_3^2}{v_2^2 v_1}(-2T_3^f)\frac{m_J^2}{12m_f^2}\right|^2, \tag{6}$$

where N_f, Q_f, T_3^f and m_f denote respectively the color factor, electric charge, weak isospin and mass of the SM electrically charged fermions f. We note that this formula is an approximation valid for $m_J \ll m_f$; however we will always use the exact formula in the actual calculations.

3. Observational constraints on majoron properties

3.1. CMB constraints on the invisible decay $J\to\nu\nu$

The decay of the majoron DM to neutrinos provides the most essential and model-independent feature of the majoron DM scenario, namely, it is a decaying DM model where the majoron decays mainly to neutrinos, a mode that is constrained from the CMB observations. In fact, the main effect of the late DM decay to invisible relativistic particles is an increase of the late integrated Sachs–Wolfe effect, caused by variation of the gravitational potential induced by the presence of the decay products [26]. This is reflected in the CMB power spectrum by an increased amount of power at the largest angular scales (i.e., small multipoles).

We have recently derived constraints on the majoron properties from CMB anisotropy data [27]. We use a modified version of CAMB [28], taking into account the finite lifetime of the majoron, to evolve the cosmological perturbations and compute the anisotropy spectrum of the CMB for given values of the cosmological parameters. In order to compute Bayesian confidence intervals and sample the posterior distributions for the parameters of the model, we have used the Metropolis–Hastings algorithm as implemented in CosmoMC [29] (interfaced with our modified version of CAMB). We have derived our limits using the most recent WMAP 9-year temperature and polarization data [1,2]. In particular, for the temperature power spectrum we have included data up to $\ell_{max} = 1200$. We have used the latest (V5) version of the WMAP likelihood code, publicly available at the lambda website.[1]

The limits on the parameters of the standard Λ CDM model do not change significantly when we allow for the possibility that the DM has a finite lifetime, with the one exception of the present DM density.

For the present majoron density parameter we have found:

$$\Omega_{\rm dm}h^2 = 0.102 \pm 0.010 \quad (68\%\ \text{C.L.}). \tag{7}$$

This estimate is shifted toward smaller values, and has an uncertainty which is a factor two larger, with respect to the WMAP9 Λ CDM result $\Omega_{\rm dm}h^2 = 0.1138 \pm 0.0045$ [1]. This is due to the anticorrelation between the present density of dark matter and its decay rate (see below).

The decay width of majoron to neutrinos, $\Gamma_{J\to\nu\nu}$ is constrained as follows (at 95% C.L.):

$$\Gamma_{J\to\nu\nu} \le 6.4\times10^{-19}\ \mathrm{s}^{-1}. \tag{8}$$

after marginalizing over the remaining parameters of the model. This results in a lower limit to the majoron lifetime $\tau_J \ge 50$ Gyr, roughly four times the age of the Universe.

In Fig. 1 we show 68% and 95% confidence regions in the $(\Gamma_{J\to\nu\nu}, \Omega_{\rm dm}h^2)$ parameter plane. There is an evident anti-correlation between decay rate and abundance that is explained by the fact, already discussed in Ref. [26], that the CMB anisotropy spectrum is mainly sensitive to the amount of DM prior to the time of recombination (through the height of the first peak).

In the limit of cold DM (assumed here) neither the background nor the perturbation equations depend explicitly on the mass of the DM particle. In order to express the constraints on the physical density parameter $\Omega_{\rm dm}h^2$ in terms of the DM mass $m_{\rm dm}$, one needs to know – or assume – a relationship between the two quantities. This relies in turn on the knowledge of the production mechanism of the DM particle and on its thermal history. We can however

[1] ⟨http://lambda.gsfc.nasa.gov/⟩