Cosmological constraints on the Multi Scalar Field Dark Matter model

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Abstract

In this poster, based on the article [1], we briefly introduce the Multi Scalar Field Dark Matter model. Using a modified version of the CLASS code we obtained the evolution of the background, Matter Power Spectrum and CMB Power Spectrum for three potentials in particular. Also, using a modified version of Monte Python we present the constraints for the scalar field parameters using Ly-alpha, BAO and SN data.

1 Introduction

We know that the ΛCDM model, considered as the standard model of Cosmology, still has problems to solve. For this, alternatives such as the Scalar Field Dark Matter model have been proposed. However, this model also has problems. For example, the mass value is different depending on the observations used to constrain it. To alleviate these discrepancies, in this work, we open up the possibility that dark matter is made up of different types of scalar fields each with a different potential. We study the background dynamics and the linear perturbations of the model. As a first approximation we consider the scalar fields are spatially homogeneous, real and with no interaction among each other. The evolution is obtained with a modified version of the CLASS code for the background, mass power spectrum and CMB power spectrum for different combinations of potentials. We show too the model constraints obtained with a modified version of Monte Python code using Ly-alpha, BAO and SN data.

2 Background dynamics

We base our analysis on a flat Universe filled up with the standard components: baryons, dark energy in the form of a cosmological constant (Λ), photons and neutrinos as relativistic species and dark matter (DM). Assuming a Friedmann-Lemaitre-Robertson-Walker metric, the equations of motion for the background dynamics are

$$H^2 = \frac{\kappa^2}{2}\left(\sum_I \rho_I + \sum_i \rho_{\phi i}\right), \tag{1a}$$

$$\dot{\rho}_I = -3\frac{\dot{a}}{a}(\rho_I + p_I), \tag{1b}$$

$$\ddot{\phi}_i = -3H\dot{\phi}_i - \partial_{\phi i} V_i(\phi_i). \tag{1c}$$

The Klein-Gordon equations (1c), for each of the fields, can be written in a more manageable form by using the following polar transformation with the potential variables y_{1i} and y_{2i}

$$\frac{\kappa\dot{\phi}_i}{\sqrt{6}H} \equiv \Omega_{\phi i}^{1/2}\sin(\theta_i/2), \quad \frac{\kappa V_i^{1/2}}{\sqrt{3}H} \equiv \Omega_{\phi i}^{1/2}\cos(\theta_i/2), \tag{2a}$$

$$y_{1i} \equiv -2\sqrt{2}\frac{\partial_{\phi i} V_i^{1/2}}{H}, \quad y_{2i} \equiv -4\sqrt{3}\frac{\partial^2_{\phi i} V_i^{1/2}}{\kappa H}, \tag{2b}$$

where $\Omega_{\phi i} \equiv \kappa^2\rho_{\phi i}/3H^2$ represents the dimensionless density parameter, and similarly θ_i is an angular degree of freedom directly related to the equation of state (EoS) for each one of the fields, $w_{\phi i} \equiv p_{\phi i}/\rho_{\phi i} = -\cos\theta_i$.

We focus our study on the following potentials

$$V_i(\phi_i) = \begin{cases} m^2_{\phi i} f_i^2 \left[1 + \cos(\phi_i/f_i)\right] & \cos \\ (1/2) m^2_{\phi i}\phi_i^2 & \text{quadratic} \\ m^2_{\phi i} f_i^2 \left[\cosh(\phi_i/f_i) - 1\right] & \cosh \end{cases}. \tag{3}$$

and their possible combinations. Then, for each field, the associated Klein-Gordon equation (1c) is represented by the following set of coupled equations

$$\theta_i' = -3\sin\theta_i + y_{1i}, \tag{4a}$$

$$\Omega_{\phi i}' = 3\left(w_{tot} + \cos\theta_i\right)\Omega_{\phi i}, \tag{4b}$$

$$y_{1i}' = \frac{3}{2}\left(1 + w_{tot}\right) y_{1i} + \frac{1}{2}\lambda_{\phi i}\Omega_{\phi i}^{1/2}\sin\theta_i, \tag{4c}$$

with $w_{tot} = \sum_I \Omega_I w_I + \sum_i \Omega_i w_i$, where $\Omega_I \equiv \kappa^2\rho_I/3H^2$ and $w_I = p_I/\rho_I$. The prime denotes derivative with respect to the number of e-folds $N = \ln a$, and for any given variable q we have the relationship $\dot{q} = Hq'$. Where $y_{1i}^2 = 4\frac{m^2_{\phi i}}{H^2} - 2\lambda_{\phi i}\Omega_{\phi i}$ and $y_{2i} = \lambda_{\phi i} y_{1i}$. Defining $\lambda_{\phi i} = 3/\kappa^2 f_i^2$ we can compress the information of the three potentials in a single system of equations with $\lambda_{\phi i} > 0$ describe the cosine potential and $\lambda_{\phi i} < 0$ the cosh potential, whereas the quadratic case corresponds to $\lambda_{\phi i} = 0$.

3 Linear density perturbations

We consider the linear perturbations for the scalar fields by expanding the field to the leading order, with $\phi_i(\vec{x}, t) = \phi_i(t) + \varphi_i(\vec{x}, t)$, where $\phi_i(t)$ are the background fields and φ_i are the field linear perturbations. In Fourier space, the perturbed Klein-Gordon equation for each field is given by

$$\ddot{\varphi}_i = -3H\dot{\varphi}_i - \left(\frac{k^2}{a^2} + \partial^2_{\phi i} V_i\right)\varphi_i - \frac{1}{2}\dot{h}\dot{\phi}_i. \tag{5}$$

Following the idea presented for the background, we use a polar variables and the new quantities to rewrite (5),

$$\sqrt{\frac{2}{3}}\frac{\kappa\dot{\varphi}_i}{H} = -\Omega_{\phi i}^{1/2} e^{\alpha_i}\cos\left(\frac{\vartheta_i}{2}\right), \quad \frac{\kappa y_{i,1}\varphi_i}{\sqrt{6}} = -\Omega_{\phi i}^{1/2} e^{\alpha_i}\sin\left(\frac{\vartheta_i}{2}\right), \tag{6a}$$

$$\delta_{0i} = -e^{\alpha_i}\sin\left(\frac{\theta_i - \vartheta_i}{2}\right), \delta_{1i} = -e^{\alpha_i}\cos\left(\frac{\theta_i - \vartheta_i}{2}\right), \tag{6b}$$

where α_i and ϑ_i are the new perturbation quantities and the density contrast is $\delta_{\phi i} \equiv \delta\rho_{\phi i}/\rho_{\phi i} = \delta_{0i}$, then the perturbed Klein-Gordon equation (5) can be rewritten as

$$\delta_{0i}' = -\left[3\sin\theta_i + \frac{k^2}{k^2_{Ji}}(1 - \cos\theta_i)\right]\delta_{1i} + \frac{k^2}{k^2_{Ji}}\sin(\theta_i)\,\delta_{0i} - \frac{1}{2}h'(1 - \cos\theta_i), \tag{7a}$$

$$\delta_{1i}' = -\left[3\cos\theta_i + \left(\frac{k^2}{k^2_{Ji}} - \frac{\lambda_{\phi i}\Omega_{\phi i}}{2y_{1i}}\right)\sin\theta_i\right]\delta_{1i} + \left(\frac{k^2}{k^2_{Ji}} - \frac{\lambda_{\phi i}\Omega_{\phi i}}{2y_{1i}}\right)(1 + \cos\theta_i)\,\delta_{0i} - \frac{1}{2}h'\sin\theta_i. \tag{7b}$$

4 Numerical Results

We obtain the background evolution, mass power spectrum (MPS) and CMB power spectrum for different combinations of potentials, using a modified version of the CLASS code. We use the ratio $R = \Omega_{\phi 1,0}/\Omega_{\mathrm{DM},0}$ to parameterize the energy density of the scalar fields, where $\Omega_{\mathrm{DM},0} = \Omega_{\phi 1,0} + \Omega_{\phi 2,0} + \Omega_{\mathrm{cdm},0}$ represents the current total dark matter contribution from the scalar fields sector. In general for the background, we found slight differences at early times with respect to ΛCDM, where the oscillations presented could give us information about how light the scalar fields masses can be. We found too a cut-off at small scales in the mass power spectrum that differentiates our model from the CDM, and the shape below the cut-off depends on the multi-field dynamics. Regarding the CMB spectrum, for masses greater than $m_{\phi i} > 10^{-26}$ eV the same CMB power spectrum is obtained as for ΛCDM regardless of the value of λ_ϕ or R. See Fig. 1 and Fig. 2 for an example.

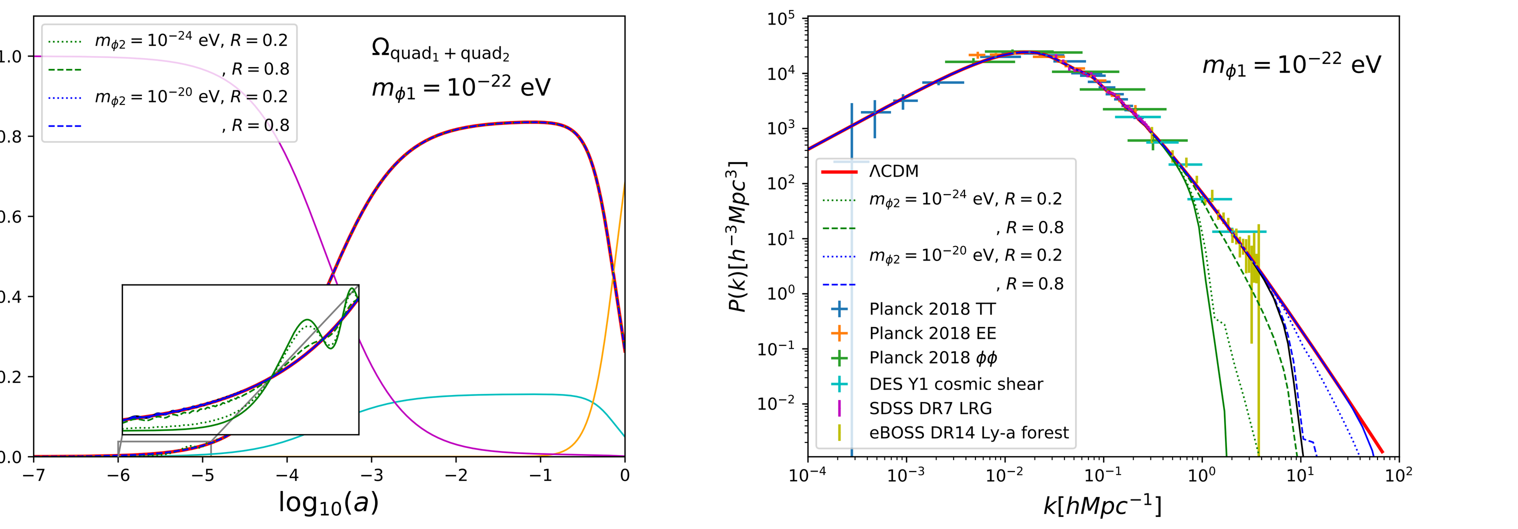

Figure 1: Evolution of the density parameters Ω (left) and the linear matter power spectrum (right) at $z = 0$, for a double field model. The potential for both fields is the quadratic one $V(\phi) = \frac{1}{2}m^2_\phi\phi^2$, and R represents the ratio of the fields contribution to the total DM. The red, cyan, orange and magenta solid curves represent CDM, baryons, dark energy and relativistic species, respectively. As reference, the green, black and blue solid lines represent the evolution for a single scalar field with quadratic potential for $m_\phi = 10^{-24}$, 10^{-22} and 10^{-20} eV respectively.

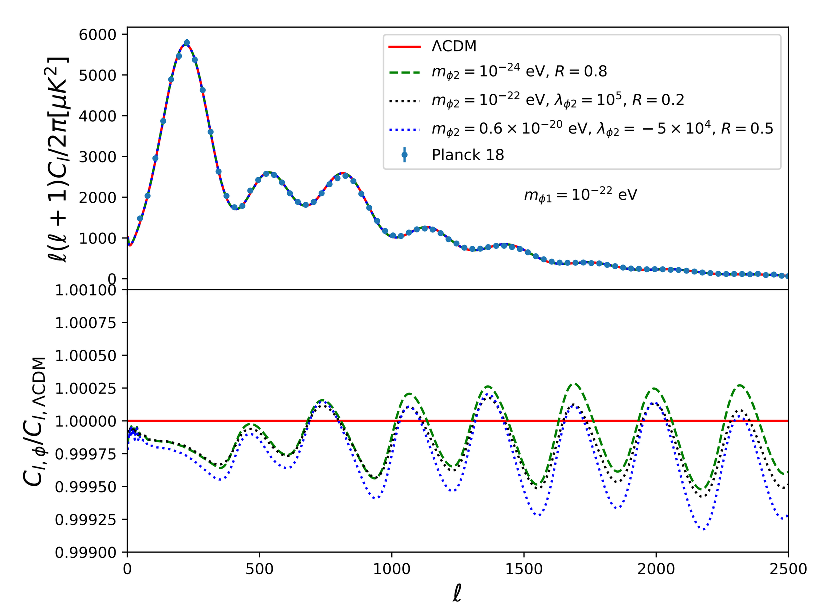

Figure 2: The CMB power spectrum (upper panel) and the ratio (lower panel) using ΛCDM as reference (solid red lines), for $V(\phi_{1,2}) = \frac{1}{2}m^2_{\phi 1,2}\phi^2_{1,2}$ (green dashed line), $V(\phi_1) = \frac{1}{2}m^2_{\phi 1}\phi_1^2$ with $V(\phi_2) = m^2_{\phi 2}f^2\left[1 + \cos(\phi_2/f)\right]$ (black dotted line) and $V(\phi_1) = \frac{1}{2}m^2_{\phi 1}\phi_1^2$ with $V(\phi_2) = m^2_{\phi 2}f^2\left[\cosh(\phi_2/f) - 1\right]$ (blue dotted line).

5 Cosmological constraints

With the numerical study we found that the main difference throughout the models rests on the mass power spectrum at small scales, hence we use a modified version of Monte Python code with the 3D matter power spectrum inferred from Lyman-α data from BOSS and eBOSS collaboration. We also use the Ly-α BAO from eBOSS DR14, the Galaxy BAO from DR12, 6dFGS and SDSS DR7, and the SNe Ia survey Pantheon to improve the constraining power. For the interested readers, all references used to develop this work can be seen in [1]. In Figure 3 we show the posteriors for the combinations $V(\phi_1) = 1/2m^2_{\phi 1}\phi_1^2$ with $V(\phi_2) = 1/2m^2_{\phi 2}\phi_2^2$, $V(\phi_1) = 1/2m^2_{\phi 1}\phi_1^2$ with $V(\phi_2) = m^2_{\phi 2}f^2\left[1 + \cos(\phi_2/f)\right]$ and $V(\phi_{1,2}) = m^2_{\phi 1,2}f^2\left[1 + \cos(\phi_{1,2}/f)\right]$.

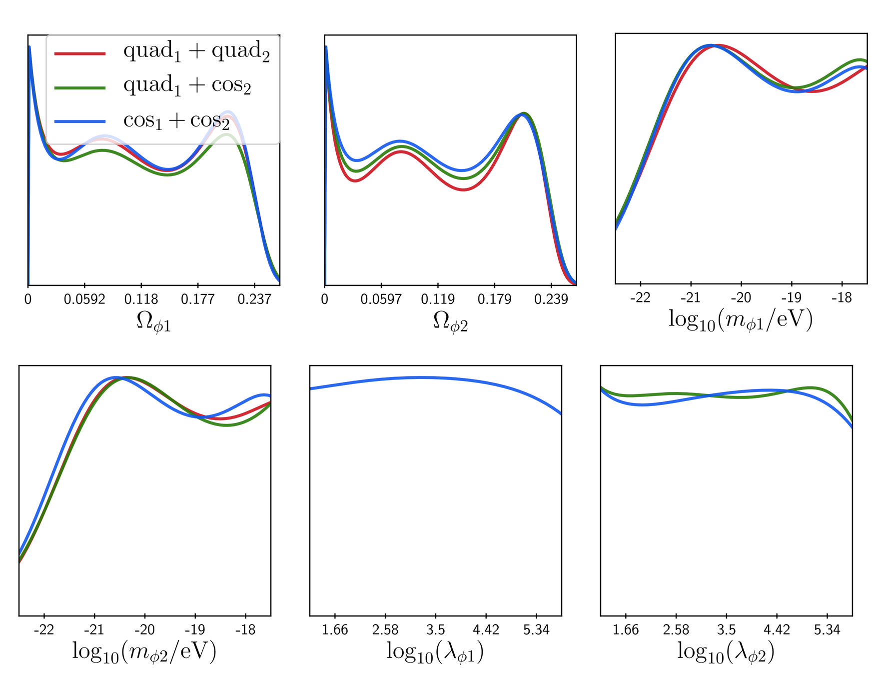

Figure 3: 1D posterior distribution for the two SFDM with the potentials $V(\phi_{1,2}) = 1/2m^2_{\phi 1,2}\phi^2_{1,2}$ (red), $V(\phi_1) = 1/2m^2_{\phi 1}\phi_1^2$ with $V(\phi_2) = m^2_{\phi 1}f^2\left[1 + \cos(\phi_1/f)\right]$ (green) and $V(\phi_{1,2}) = m^2_{\phi 1,2}f^2\left[1 + \cos(\phi_{1,2}/f)\right]$ (blue).

6 Conclusions

The main result of this work is that adding more scalar fields does not affect the known cosmology. So the MSFDM can be an alternative candidate to dark matter that can explain the observations at the cosmological and astrophysical levels. The results presented here can be generalized to a greater number of fields with different potentials.

References

[1] L. O. Téllez-Tovar, Tonatiuh Matos, and J. Alberto Vázquez. Cosmological constraints on the Multi Scalar Field Dark Matter model. 12 2021.