Ultralight boson fields and structure formation in the universe

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Abstract

Ultralight boson fields, also known as fuzzy dark matter or wave dark matter, are one of the most studied alternative dark matter models in cosmology in the recent years. In this talk, we discuss the general properties of the model and their connection to the formation of structure in the universe, at the linear and semi-linear regimes. Conversely, we also present the constraints that can be obtained for the model from observations of the large scale structure, specially for the mass of the boson particles and their self-interaction.

Introduction

One of the most amazing riddles in modern Cosmology is the existence of dark matter, which is allegedly driving the evolution of galaxies in the Universe. Being the precise nature of DM unknown, it is common to assume that is a cold component without any interaction with standard matter. For this reason it is called cold dark matter (CDM)[2].

One alternative model to CDM, and which is one of the compelling proposals in the recent years, is that of Scalar Field Dark Matter (SFDM). For SFDM, the dark matter particle is represented by a scalar field ϕ, endowed with quadratic potential of the form $V(\phi) = (1/2)m_\phi^2\phi^2$. The mass of this boson particle is usually considered to be of the order of $mc^2 \sim 10^{-22}\mathrm{eV}$

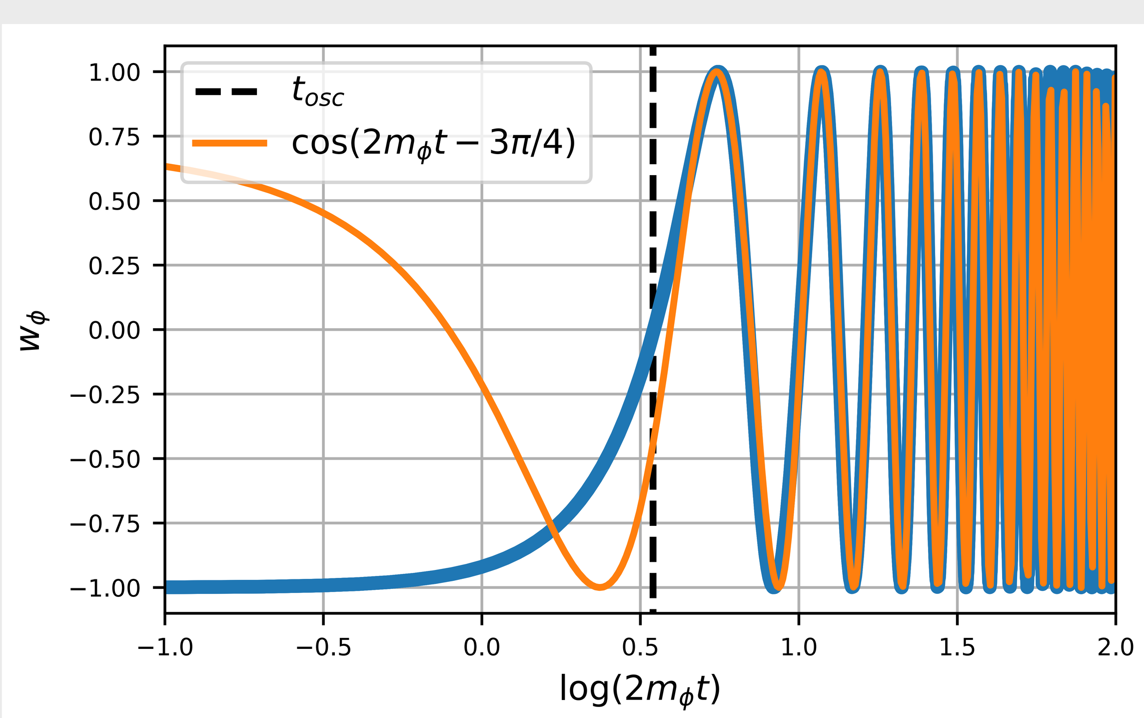

Fig. 1. Evolution of the SFDM equation of state as a function of cosmic time t, the latter being normalized in terms of the boson mass m_ϕ. At early times $w_\phi \simeq -1$, but at late times the field enters a stage of rapid oscillations in the form $w_\phi \simeq -\cos(2m_\phi t)$. See the text for more details.

Scalar field dark matter

Mathematical background

We consider a spatially flat, homogeneous and isotropic universe described by the FRW metric filled with barotropic fluids and a real scalar field ϕ endowed with a potential $V(\phi)$. The Klein-Gordon equation of motion is $\ddot{\phi} = -3H\dot{\phi} + m_\phi^2\phi$, where H is the Hubble parameter. By means of a change to polar-like variables[3,4]: $\frac{\kappa\dot{\phi}}{\sqrt{6}H} \equiv \Omega_\phi^{1/2}\sin(\theta/2)$, $\frac{\kappa V^{1/2}}{\sqrt{3}H} \equiv \Omega_\phi^{1/2}\cos(\theta/2)$, $y_1 \equiv 2\frac{m_\phi}{H}$, the new equations of motion are: $\theta' = -3\sin\theta - y_1$, $y_1' = \frac{3}{2}\gamma_{tot}y_1$, $\Omega_\phi' = 3(\gamma_{tot} - \gamma_\phi)\Omega_\phi$. We show in Fig. 1 the evolution of the SFDM EoS, $w_\phi = -\cos\theta$, in which we see clearly the stage of rapid oscillations at late times. The numerical solutions were obtained from an amended version of CLASS[5], where all other cosmological parameters were fixed to their Planck18 values.

Observational constraints on the models parameters

In this work, we are interested in SFDM and its influence on the formation of cosmological structure. For this, we also describe the mathematical process to obtain accurate numerical solutions of the equations of motion, for the background and the regime of linear density perturbations. To obtain all the solutions, we work with an amended version of the Boltzmann code CLASS[4], using the equations of motion in the form of a dynamical system, which is appropriate to deal with the phase of rapid oscillations necessary for the scalar field to behave as CDM.

We can see in Fig. 2 the so-called matter power spectrum (MPS) of linear density perturbations of SFDM, and in comparison with those of standard CDM. Also shown are the data points of different experiments for the same MPS. The solid red curve represents the MPS for a boson mass of $m_\phi c^2 = 10^{-24}\mathrm{eV}$, which presents the typical sharp cutoff of density perturbations at small scales, a well known footprint of dark matter with ultralight bosons.

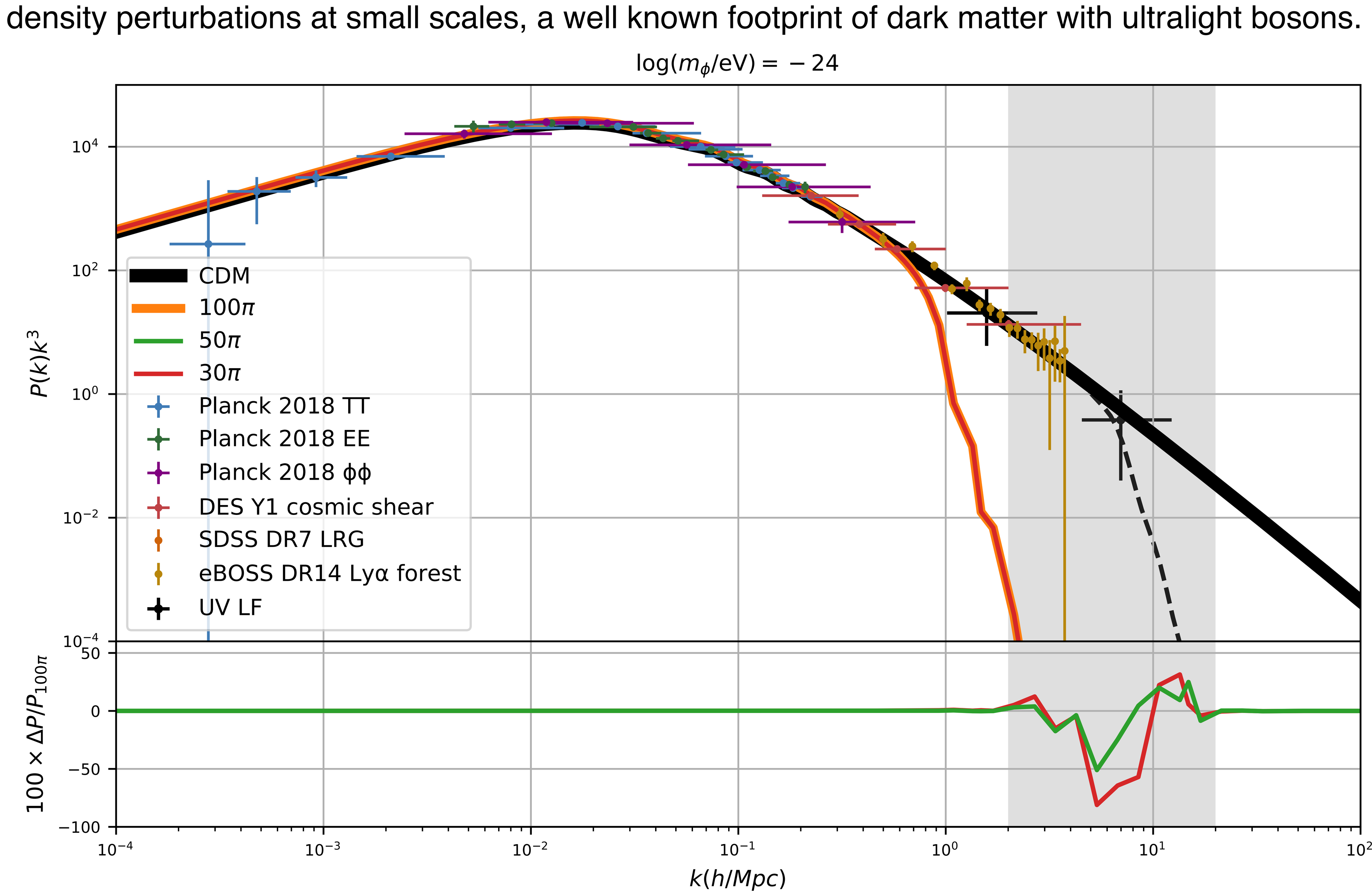

Fig. 2. MPS of linear density perturbations of SFDM for a mass of $m_\phi c^2 = 10^{-24}\mathrm{eV}$. The MPS has a cutoff at small scales, which means small structure is suppressed with respect to standard CDM. The data points were obtained form different experiments as listed in the figure. See the text for more details.

Conclusions

The stage of linear density perturbations, in the form of the MPS, can be used to put constraints on the boson mass. From Fig. 2, we can see, even by eye, that a mass as low as $m_\phi c^2 = 10^{-24}\mathrm{eV}$ is not allowed by data. Considering the last point on the right hand side of the MPS, it can be see that the boson mass should comply with $m_\phi c^2 \gtrsim 10^{-22}\mathrm{eV}$, as the MPS for the latter mass is given by the dashed line in Fig. 2.

For a better determination of the observational constraints on the boson mass, we use MontePython[5] and its likelihoods related to recent experiments like BOSS and UVLF. The resultant posteriors are shown in Fig. 3, and all of them show that experiments can only put lower constraints on the mass, being the strongest one that of UVLF with $m_\phi c^2 > 10^{-22}\mathrm{eV}$.[1]

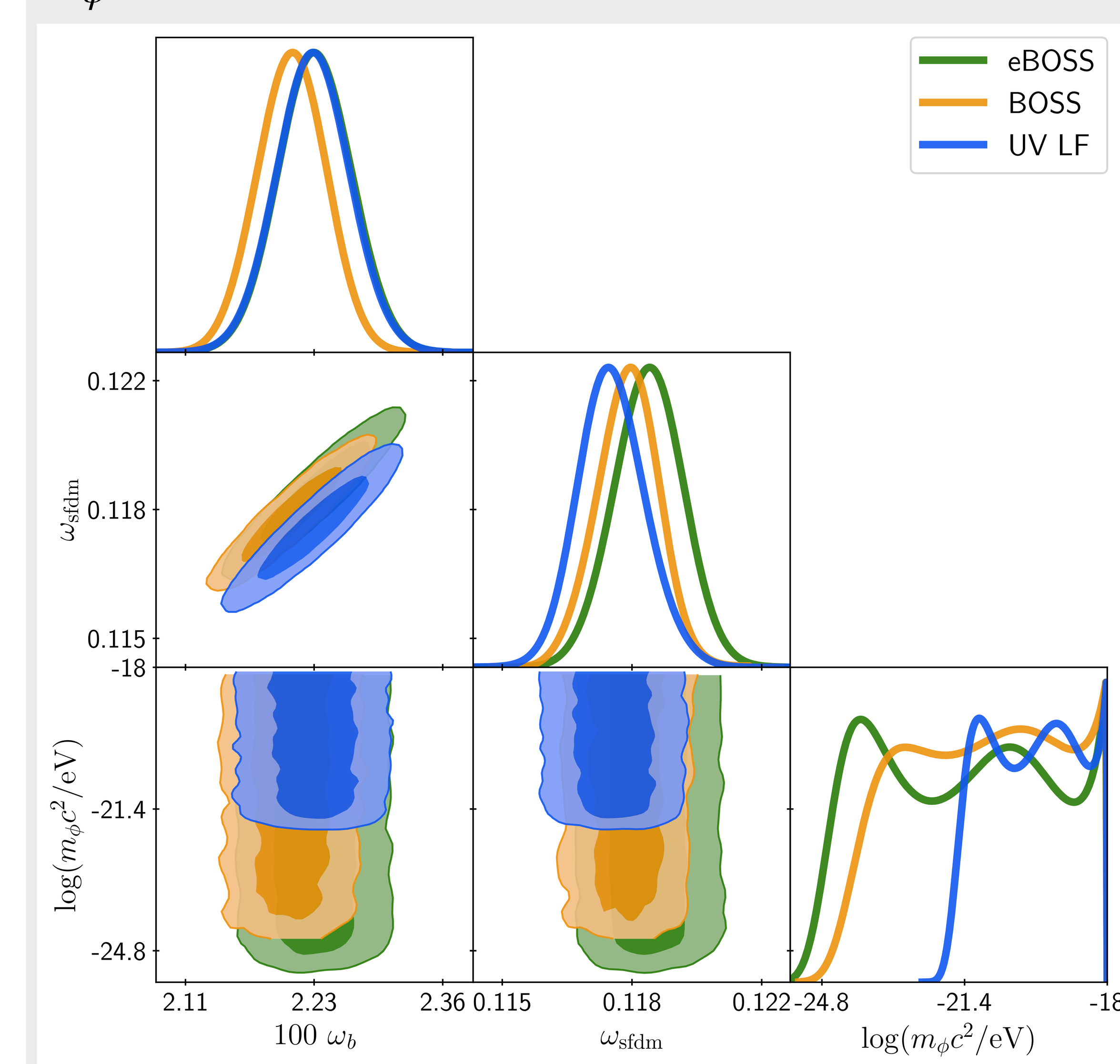

Fig. 3. Observational constraints on the boson mass m_ϕ from eBOSS, BOSS and UVLF. See the text for more details.

References

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4.https://github.com/lesgourg/class_public.

5. https://github.com/brinckmann/montepython_public.

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