



Cosmology with a continuous tower of scalar fields

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ABSTRACT

We study the cosmological evolution for a universe in the presence of a continuous tower of massive scalar fields which can drive the current phase of accelerated expansion of the universe and, in addition, can contribute as a dark matter component. The tower consists of a continuous set of massive scalar fields with a gaussian mass distribution. We show that, in a certain region of the parameter space, the *heavy* modes of the tower (those with masses much larger than the Hubble expansion rate) dominate at early times and make the tower behave like the usual single scalar field whose coherent oscillations around the minimum of the potential give a matter-like contribution. On the other hand, at late times, the *light* modes (those with masses much smaller than the Hubble expansion rate) overcome the energy density of the tower and they behave like a perfect fluid with equation of state ranging from 0 to -1 , depending on the spectral index of the initial spectrum. This is a distinctive feature of the tower with respect to the case of quintessence fields, since a massive scalar field can only give acceleration with equation of state close to -1 . Such unique property is the result of a synergy effect between the different mass modes. Interestingly, we find that, for some choices of the spectral index, the tower tracks the matter component at high redshifts (or it can even play the role of the dark matter) and eventually becomes the dominant component of the universe and give rise to an accelerated expansion.

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1. Introduction

More than a decade after the first evidences for the accelerated expansion of the universe [1], the true underlying mechanism responsible for it still remains unclear. After all this time, a simple cosmological constant still seems to succeed in explaining most of the cosmological observations by using one single additional parameter [2]. This has lead to establish the so-called Λ CDM model as the standard model of cosmology, in which we include the cosmological constant Λ accounting for about 70% of the energy content of the universe and the Cold Dark Matter component comprising 25% of the universe content, that amounts to 85% of the matter component. Despite its remarkable phenomenological success, alternatives to the standard Λ CDM model have been extensively explored because it is not completely satisfactory from a pure theoretical point of view. In particular, we need to assume that 95% of the cosmological budget is due to unknown fields or exotic forms of energy. Concerning the dark energy sector, alterna-

tives to explain the accelerated expansion have been considered in part due to the tiny required value for Λ , which turns out to be many orders of magnitude smaller than its expected *natural* scale (see [3] for an extensive review on the cosmological constant problem). This naturalness problem is also linked to the *coincidence* problem referred to the fact that dark matter and dark energy give comparable contributions to the total energy density of the universe precisely today, while they have evolved very differently throughout the universe expansion history.

A simple step forward is to assume that the accelerated expansion is not caused by a cosmological constant, but it is driven by some dynamical field [4] whose evolution could solve the naturalness and/or coincidence problems of the cosmological constant. Of course, in these alternative set-ups, the cosmological constant is assumed to be set to zero by some unknown mechanism. The most widely studied alternative models for dark energy are by far those based on scalar fields with a certain potential (quintessence) or non-standard kinetic terms (K-essence) [5], very much like in the inflationary models for the early universe. However, also higher spin fields have been considered as dark energy candidates, like vector fields [6] or general p -forms [7]. The difference between inflationary models and dark energy models are the involved scales and that, whereas during inflation the accelerated expansion must end, for dark energy models is desirable to have the accelerated

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solutions as attractors so that the natural evolution of the universe is towards an accelerated phase. Besides its simplicity, scalar fields are a common feature of high energy physics that extend the standard model of particles, so it is natural to think that they can be present in the universe and play a relevant role in the cosmological evolution. An alternative explanation for the cosmic acceleration could also be that the gravitational sector is modified on large scales, i.e., the validity of General Relativity could break-down in the infrared regime. In this context we could mention the so-called $f(R)$ theories [8] or those based on extra dimensions like the DGP model [9]. It is however a typical feature of modified theories of gravity that the new effects can be captured by a certain scalar degree of freedom like $\partial f(R)/\partial R$ in the $f(R)$ theories or the bending mode in braneworld models. This is so because any modification of General Relativity necessary leads to the appearance of new degrees of freedom and this generally results in a scalar field.

Although the kind of models mentioned in the previous paragraph can give equally consistent explanations for the cosmic acceleration as a cosmological constant does, naturalness problems usually still remain. For instance, in the simplest case of quintessence with a canonical massive scalar field, we need its mass to be $m \lesssim H_0 \simeq 10^{-33}$ eV, again a tiny value when compared to what one would expect from high energy physics [4]. Moreover, such a value is unstable when including quantum corrections. This constraint on the effective mass is necessary for the potential energy to dominate over the kinetic energy of the field today and thus its equation of state is near -1 . The situation does not improve much by resorting to more sophisticated potentials or non-standard kinetic terms. Most of the times, the naturalness problems reappear hidden behind some parameters of the potential.

On the other hand, dark matter models resorting to scalar fields also exist. For instance, the lightest massive mode of a Kaluza–Klein (KK) tower corresponding to the compactification of one extra dimension is a viable candidate for dark matter. Stability of such a particle is guaranteed by KK-parity corresponding to momentum conservation associated to spatial translation in the fifth dimension. Also resorting to extra dimensions we can mention the vibrations of our brane in the extra dimension (branons) that can play the role of dark matter [13]. More recently, an ensemble of scalar particles which can interact among them has been considered as a dark matter candidate [11]. The interesting feature of this approach is that the scalar particles do not need to be stable, but a certain balance between the width of the decays and the abundances allows to have a dynamical scenario in which the different effects conspire to give an overall dark matter contribution. In [12], it was also considered a scenario with multiple Kaluza–Klein dark matter candidates.

In this work we present a novel approach to the dark energy problem based on scalar fields that, in addition, allows to unify it with the dark matter component. Unlike previous studies, we do not rely on one single scalar field, nor a finite discrete collection of (perhaps interacting) scalar fields. Here we shall study a cosmological scenario with a continuous tower of massive scalar fields which only interact with each other by means of gravity. Towers of scalar fields arise in a natural manner in nonlocal theories [14–16] or theories with extra dimensions as we have discussed above. If one considers one compact extra dimension, a massless scalar field leads to a spectrum in the 4 large non-compact dimensions consisting of a massless scalar field plus a discrete tower of massive scalar fields, being the corresponding masses determined by the compactification scale of the extra dimension. Moreover, the mass gap between two consecutive modes of the tower is inversely proportional to such a scale. Thus, as the size of the extra dimension

gets larger, the mass gap between the different components of the tower gets smaller and, in the limit when the extra dimension is infinite, the tower becomes continuous. This actually happens in models with extra large dimensions like the Randall–Sundrum or DGP models. Another context in which a continuous distribution of massive fields appear is as an effective description of the unparticle fields [10].

Here however we shall adopt a more phenomenological approach and shall simply assume the presence of a continuous tower of massive scalar fields in our universe, without paying special attention to the underlying mechanism generating it, that could be either unparticle physics or braneworld scenarios, or even more exotic set-ups. Our aim is to show that a continuous tower of simple massive scalar fields can lead to accelerated expansion and, in addition, it can simultaneously give a dark matter contribution and, thus, allowing for the unification of both dark components of the universe. It is important to keep in mind that the specific generating procedure for the tower could also give an additional contribution to the cosmological constant (as it happens for instance with KK towers). We do not attempt to tackle the cosmological constant problem here and we shall assume that such contributions do not play a relevant role, as it is done in most dark energy models in the literature.

The Letter is organised as follows. In the next section we give our starting action for the continuous tower that we shall use for our analysis and we will derive the relevant equations. In Section 3 we study the cosmological evolution of the tower during the standard radiation and matter dominated epochs and show how the light modes of the tower eventually dominate the universe and can produce an accelerated expansion. In Section 4 we study the case in which the tower dominates the universe and show how we can indeed have a transition from matter domination to accelerated expansion in a tower dominated universe. Finally, in Section 5 we discuss the results of the Letter.

2. A continuous tower

As we have mentioned in the Introduction, we are not concerned about the true underlying mechanism generating the tower, but we shall adopt a phenomenological approach. Thus, we simply assume that our tower is described by the action

$$\mathcal{L}_\phi = \frac{1}{2} \int dm \mathcal{P}(m) (\partial_\mu \phi_m \partial^\mu \phi_m - m^2 \phi_m^2) \quad (1)$$

where $\mathcal{P}(m)$ is the spectral mass distribution of the tower, that we assume to be gaussian with zero mean

$$\mathcal{P}(m) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{m^2}{2\sigma^2}}. \quad (2)$$

It is interesting to note that the only free parameter present in the action is the dispersion of the distribution σ . Notice that, although m runs over the real numbers, no tachyonic modes are actually present because m^2 is always positive. In fact, since the mass distribution peaks at $m = 0$, the corresponding equations will remain invariant under the change $m \rightarrow -m$, i.e., we have a *mass reversal symmetry* and we could consider just $m \geq 0$ without affecting the physics of the system. One could of course consider different spectral mass distributions like a gaussian distribution for m^2 , a χ^2 -distribution or even more sophisticated distributions. However, the key point for our purposes here is that the distribution peaks at the origin¹ and has a given width, being the particular

¹ This also prevents the introduction of additional dimensionfull parameters in the theory to specify where the distribution peaks. In our case, one could use

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