Physics Letters B 749 (2015) 469–475

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

The continuous tower of scalar fields as a system of interacting dark matter–dark energy

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ARTICLE INFO

Article history:
Received 7 May 2015
Accepted 12 August 2015
Available online 18 August 2015
Editor: M. Trodden

ABSTRACT

This paper aims to introduce a new parameterisation for the coupling Q in interacting dark matter and dark energy models by connecting said models with the Continuous Tower of Scalar Fields model. Based upon the existence of a dark matter and a dark energy sectors in the Continuous Tower of Scalar Fields, a simplification is considered for the evolution of a single scalar field from the tower, validated in this paper. This allows for the results obtained with the Continuous Tower of Scalar Fields model to match those of an interacting dark matter–dark energy system, considering that the energy transferred from one fluid to the other is given by the energy of the scalar fields that start oscillating at a given time, rather than considering that the energy transference depends on properties of the whole fluids that are interacting.

1. Introduction

One of the deepest problems in Cosmology lies in the lack of understanding of about 95% of the energy content of the universe, the so-called dark sector [1].

Composing this sector, two components with clearly distinct behaviours exist, dark matter (DM) and dark energy (DE), with the energy density of DM being around half the energy density of DE today. While DM behaves like matter, lacking only the capability to interact electromagnetically, DE behaves like a cosmological constant, a fluid with constant energy density (details on why considering a simple cosmological constant would present some problems can be found in [2]).

Scalar fields are generally good candidates for both components of the dark sector, as it is possible to replicate the same behaviour of DM or DE when an adequate potential for the scalar field is chosen. While most DE models consider scalar fields [3], research on DM spans from Cosmology to Particle Physics. On the cosmological side, there are several models considering from Axions [4] to discrete towers of scalar fields [5], with the potential considered for the scalar fields in both mentioned cases being $V = \frac{1}{2}m^2\phi^2$. Despite most models consider scalar fields to explain a single component of the dark sector, there are some models that aim to account for both dark components, like the Continuous Tower of Scalar Fields (CTSF) model presented in [6].

Another field of study that is particularly interesting when it comes to the dark sector lies in possible interactions between DM and DE, which is an obvious possibility when taking into account that the densities of both components are quite similar today, as mentioned before.

The fact that those energy densities are of the same order is the so-called "coincidence problem", despite many argue it is not really a problem (a good discussion on this topic can be found in [7]). This possible interaction between the two components of the dark sector could possibly alleviate this problem, and explain why the energy densities of both components are quite similar today.

The most standard way to model this interaction consists in considering both DM and DE as fluids and add an interaction term to the continuity equations of both fluids in the following way:

$$\dot{\rho}_{DE} + 3H(1+w)\rho_{DE} = Q \ ,$$
$$\dot{\rho}_{DM} + 3H\rho_{DM} = -Q \ . \quad (1)$$

The first parameterisations for the coupling term Q were given by $Q = \delta_{DM} H \rho_{DM}$, [8], which was later generalised to $Q = \delta_{DE} H \rho_{DE} + \delta_{DM} H \rho_{DM}$, [9]. In said parameterisations, the δ terms give the strength of the coupling, which can either be constant or variable in time. By taking into account that the ratio $R = \rho_{DE}/\rho_{DM}$ today must agree with the observations, it is possible to constraint δ, which must obey the following relation for the models

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http://dx.doi.org/10.1016/j.physletb.2015.08.037

mentioned, $|\delta| << 1$. Also, it is relevant to mention that, rather than considering a δH factor, some models chose to describe the strength of the interaction by a Γ factor instead.

With this formalism, it is necessary to resort to dynamical variables and a dynamical systems kind of analysis in order to understand how the energy densities of DE and DM evolve in time, given that it is not possible to solve the differential equations presented in (1) independently.

It is also relevant to mention that DM and DE do not necessarily need to be fluids, and in fact it is also possible to consider the interaction between a fluid and a scalar field, the so-called interacting quintessence model [10], or even the interaction between two scalar fields [11], in which the interaction is achieved by considering a modified potential that contains the coupling between the two scalar fields.

In this paper, the parameterisation for the coupling Q considered will be considerably different to the ones presented before.

Rather than looking at DM and DE as just fluids, those two components will be also looked at as sets of scalar fields that mutate from a DE state into a DM state, and hence the parameterisation of Q will describe this transference of scalar fields. Rather than depending on the total energy of the DM and DE fluids, as done before, Q will depend on the energy of the scalar fields that shift from one state into the other.

The physical motivation for such a parameterisation for Q lies in the CTSF model, in which scalar fields start by behaving as DE, with said behaviour shifting into DM at later times.

Therefore, the paper will develop as follows. In Section 2, a simplified CTSF model, considering a simplified behaviour for the single scalar fields that compose the CTSF is presented and validated, while in Section 3, the interacting DM–DE equations are used in order to obtain the same results for the evolution of the CTSF as in Section 2. The paper ends with Section 4, which features the final discussions of the results obtained in the paper.

2. Simplified continuous tower of scalar fields

As mentioned in the introduction, scalar fields are usually one of the best candidates to explain the dark sector, given that they can behave as DM or DE, depending on the potential chosen.

In [6], a new innovative model was proposed to unify the dark sector. To obtain this unification, a set of minimally coupled scalar fields with $V = \frac{1}{2}m^2\phi^2$ and a continuous distribution of masses is considered. Since no coupling is considered between the scalar fields in said set, each scalar field will independently obey to the usual Klein–Gordon equation:

$$\ddot{\phi}_m + 3H\dot{\phi}_m + m^2\phi_m = 0 \tag{2}$$

and the energy density for each scalar field will therefore be given by:

$$\rho_{\phi_m} = \frac{1}{2}\dot{\phi}_m^2 + \frac{1}{2}m^2\phi_m^2 \tag{3}$$

With the potential mentioned before, the Klein–Gordon equation presented in eq. (2) is equivalent to the equation to a damped harmonic oscillator, with $\omega_0 = m$.

Considering the previous analogy, it becomes clear that it is possible to choose a set of initial conditions for which the scalar fields are constant until $t \approx T$, oscillating afterwards.

Therefore, the scalar field will behave like DE until it starts oscillating. Afterwards, the behaviour will depend on how H evolves in time as well, and it will therefore depend on the era considered.

During radiation and matter domination, H can be parameterised as $H = p/t$, with $p = 1/2$ and $p = 2/3$ respectively, which means the energy of the scalar field will then decay with $a^{-3} \propto t^{-3p}$, behaving like DM.

When the CTSF dominates, the situation becomes much more complex. Generally, it is not possible to parameterise H with a simple expression before solving the Klein–Gordon equation, due to the fact that H will now depend on the energy densities of the individual scalar fields on the CTSF, which means those scalar will in fact be now coupled gravitationally. This leads to two distinct cases for the behaviour of the individual scalar fields, which will depend on which kind of scalar fields that dominates.

If the CTSF is dominated by the scalar fields that are already oscillating, then H can be parameterised by $H = p/t$, with $p = 2/3$, just like during matter domination, and hence the evolution of the individual scalar fields will be the same as during said era, behaving like DM. This case is equivalent to matter domination with DM being given by the sector of the CTSF that contains the oscillating scalar fields, and therefore the results presented for matter domination will be valid in this case as well.

On the other hand, if most of the energy of the CTSF is due to the scalar fields that are frozen, the behaviour of the individual scalar fields will be considerably different. When $t \approx T$, the scalar fields will start experiencing over-damped oscillations for which $\dot{\phi}_m \approx 0$. This means that, despite the scalar fields are oscillating, their behaviour is actually closer to DE than to DM, despite it is still something in between those two regimes. The longer this regime lasts, the longer the scalar fields experience over-damped oscillations, which means the behaviour of a single scalar field is hard to parameterise, but also that the transition from a DE state to a DM state cannot be approximated by an instantaneous transition, as done in the previous eras.

It is also relevant to mention that the asymptotic behaviour of the scalar fields is a DM behaviour, which means that if a given scalar field is already behaving like DM, its behaviour will not change when the universe enters an era dominated by the CTSF.

For the two simple cases mentioned before, radiation and matter domination, the total evolution of ρ_{ϕ_m} can therefore be approximately described by two separate cases. If the scalar field starts oscillating during radiation domination, its evolution can be roughly given by:

$$\rho_{\phi_m} = \rho_{\phi_m}(t_{ini}) \times \begin{cases} 1 & , \ t < t_d \\ (mt)^{-3/2} & , \ t_d < t < t_e \\ \sqrt{t_e}m^{-3/2}t^{-2} & , \ t_e < t \end{cases} \tag{4}$$

with $t_d = 1/m$, which approximates the time for which the scalar fields start oscillating, given that $\omega_0 = m$ and H is of order $1/t$, and t_{ini}, which is the initial time, while t_e is the time of the transition from radiation to matter domination, which means it will be relevant for $m > 1/t_e$. If the scalar field has $m < 1/t_e$, it will not start oscillating before matter domination and so its evolution can be approximately described by:

$$\rho_{\phi_m} = \rho_{\phi_m}(t_{ini}) \times \begin{cases} 1 & , \ t < t_d \\ (mt)^{-2} & , \ t_d < t \end{cases} \tag{5}$$

Physically, this can be seen as if the scalar fields have only the possibility to be in two different states, a DE one (when the scalar fields are frozen), and a DM one (when the scalar fields oscillate), with the transition from one state to the other being instantaneous at $t = t_d$.

However, due to the reasons mentioned before, this kind of simplification is only valid until the DE sector of the CTSF starts to dominate.

For the evolutions of the scalar fields, described by eqs. (4) and (5), to happen, the following initial conditions must be considered: