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Interacting scalar radiation and dark matter in cosmology

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ABSTRACT

We investigate possible cosmological effects of interacting scalar radiation and dark matter. After its decoupling, scalar radiation can stream freely as neutrinos or self-interact strongly as perfect fluid, highly depending on the magnitude of its self-couplings. We obtain the general and novel structure for self-scattering rate and compare it with the expansion rate of our Universe. If its trilinear/cubic coupling is non-zero, scalar radiation can be eventually treated as perfect fluid. Possible effects on CMB are also discussed. When this scalar also mediates interaction among dark matter particles, the linear matter power spectrum for large scale structure can be modified differently from other models. We propose to use Debye shielding to avoid the singularity appearing in the scattering between scalar radiation and dark matter.

1. Introduction

According to our current understanding, nearly 95% of energy density in our universe consists of dark components, namely dark energy and dark matter. The standard cosmological model, a cosmological constant with cold dark matter, called ΛCDM, is very successful at large scales [1]. At small scales, there are controversies that allow scenarios beyond collisionless CDM, see Ref. [2] for a recent review.

Although not all of these dark components are necessarily connected, it should not be very surprising that some could have new interactions. If dark matter has significant interactions beyond gravitation, there could be dramatically different predictions that can be tested by observations. For instance, when a light particle mediates the interaction between dark matter, we can get enhanced annihilation cross section, a possible scenario for positron fraction excess in cosmic ray data [3].[1] If dark matter has large self-interaction, its density distribution around galactic center tends to have a flat profile [5]. If dark matter interacts with some relativistic particle in cosmic background, matter power spectrum could get suppressed [6–11], relaxing the "missing satellite" problem [12,13].

There are various models in particle physics that can provide the above mentioned interaction. DM with gauge or global symmetries is extensively discussed in [14–31]. Atomic and mirror DM can also have similar phenomenology [32–35]. Different DM models within supersymmetric framework are explored in [36,37]. Closely related model-independent analyses about effects on astrophysics are conducted in [38–47].

In this paper, we investigate a new, illustrating model with interacting scalar radiation and dark matter, and discuss the possible cosmological effects on cosmic microwave background (CMB) and large scale structure (LSS). Scalars can have cubic and quartic self-interactions, which can affect their cosmological evolution. If these interactions are small enough, scalar radiation is streaming freely after decoupling and behaves just as neutrinos. If these interactions are not negligible, scalar may be treated as perfect fluid and affects CMB differently. The interaction between dark matter and scalar radiation also induces novel temperature dependences in scattering cross section, which are crucial in cosmological context and lead to imprints on linear power spectrum.

This paper is organized as follows. In Sec. 2 we set the theoretical framework by introducing the explicit model. Then in Sec. 3 we investigate how scalar contributes as radiation by changing the effective number of neutrinos, whether it streams freely or behaves as perfect fluid, and what the possible effects on CMB. Next in Sec. 4, we consider the cosmological effects of scattering between DM and scalar radiation. We propose to use Debye shielding to

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[1] The excess can also be explained by models in which DM in scenario with non-standard cosmology and interactions can have enhanced perturbation at small scales [4]. More substructures or subhalos could arise and give a large boost factor.

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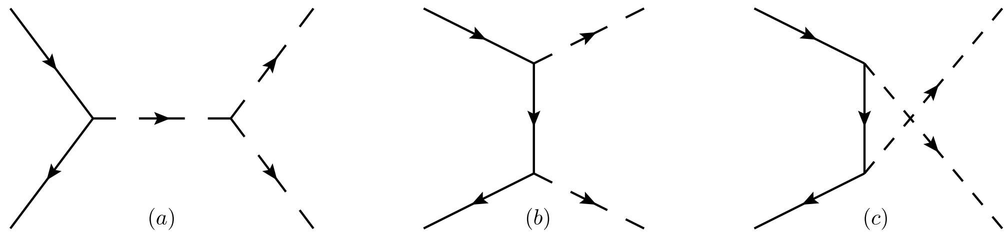

Fig. 1. Thermal processes for $\bar{\psi}+\psi \leftrightarrow \phi_i+\phi_j$. Here and after, solid and dashed lines represent fermion ψ and scalar ϕ_i, respectively.

avoid the singularity appearing in the scattering process. Finally, we give our conclusion.

2. Interacting scalar radiation and dark matter

We start with the very simple but general Lagrangian density with (pseudo-)scalars ϕ_i and fermionic dark matter ψ,

$$\mathcal{L}=\mathcal{L}_{\rm SM}+\bar{\psi}(i\partial\!\!\!/-m_\psi)\psi-\bar{\psi}(g_i^s+ig_i^p\gamma_5)\psi\phi_i+\frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i-\mathcal{V}(\phi_i,H)\,, \quad (2.1)$$

where m_ψ is the mass of ψ, g_i^s and g_i^p are respectively the scalar and pseudo-scalar type coupling constants, and H is the standard model Higgs doublet. Repeated index is summed. We have introduced a set of scalars ϕ_i for reasons which we shall discuss shortly. It is surprising that the above Lagrangian has not been discussed in the cosmological context. As we shall show in this paper, such a simple model has some novel features and interesting implications. If dark matter is a scalar field X, we can study the phenomenology of X and ϕ_i similarly by introducing interaction terms like $X^\dagger X\left(\mu_i\phi_i+g_{ij}\phi_i\phi_j\right)$.

Scalars ϕ_i can be massive or massless, and the resulting cosmology could be quite different. Throughout our discussion, we shall not specify the fundamental origins of these scalars. In particle physics, scalars are ubiquitous, such as Higgs field, axion, inflation field, bound states, dark energy, and so on. Without loss of generality, we may first discuss the ϕ part in the potential $\mathcal{V}$,

$$\mathcal{V}(\phi_i,H)\supset\frac{1}{2}m_i^2\phi_i^2+\frac{\mu_{ijk}}{3!}\phi_i\phi_j\phi_k+\frac{\lambda_{ijkl}}{4!}\phi_i\phi_j\phi_k\phi_l, \quad (2.2)$$

where the individual m_i,μ_{ijk} and λ_{ijkl} can be zero or non-zero. Introduction of interaction terms with $H^\dagger H$ has at least one immediate effects that ψ and ϕ_i can be thermalized in the early Universe. To have the correct electroweak vacuum, the potential need satisfy some conditions, see Appendix for detailed discussion. It is also possible to introduce other non-renormalizable terms like $\frac{1}{\Lambda}\bar{\psi}\psi H^\dagger H$ to do the thermalization.

The relic density of DM ψ is basically determined by the couplings to ϕ_i (see Fig. 1). ψ can be produced either through usual thermal freeze-out or freeze-in process, it can also produced by heavy ϕ's decay. If ψ and all ϕ_i are heavy, say heavier than GeV, phenomenologies in these aspects are the same as traditional cold dark matter and it makes no difference in our model, Eq. (2.1).

However, if there is a light state in ϕ_i, although the relic density calculation is probably only modified by including Sommerfeld effects [48,49], there are other very important consequences on cosmological observables, such as CMB and large scale structure (LSS), which are the main topics in this paper. As we shall show that the details not only depend on the interaction between DM ψ and ϕ_i, but also on self-interaction terms μ_{ijk} and λ_{ijkl}.

3. Scalar radiation and CMB

Assume ϕ_1 is the light state, massless or having a very tiny mass compared with its temperature $\left(m_{\phi_1}\ll T_{\phi_1}\right)$, one immediate effect is that ϕ_1 will contribute as radiation in cosmic background. The convenient quantity to account for this contribution is the effective number of neutrino species, $N_{\rm eff}$, which describes how much relativistic species are present in our Universe. ϕ_1 would increase $N_{\rm eff}$ by

$$\delta N_{\rm eff}^{\phi_1}\equiv\frac{\rho_{\phi_1}}{\rho_\nu}=\frac{4}{7}\frac{T_{\phi_1}^4}{T_\nu^4}=\frac{4}{7}\left[\frac{g_{*s}(T_\nu)}{g_{*s}^\phi(T_{\phi_1})}\times\frac{g_{*s}^\phi(T_{\phi_1})\,T_{\phi_1}^3}{g_{*s}(T_\nu)\,T_\nu^3}\right]^{\frac{4}{3}}$$
$$=\frac{4}{7}\left[\frac{g_{*s}(T_\nu)}{g_{*s}^\phi(T_{\phi_1})}\frac{g_{*s}^\phi\left(T^{\rm dec}\right)\left(T^{\rm dec}\right)^3}{g_{*s}\left(T^{\rm dec}\right)\left(T^{\rm dec}\right)^3}\right]^{\frac{4}{3}}$$
$$=\frac{4}{7}\left[\frac{g_{*s}(T_\nu)}{g_{*s}^\phi(T_{\phi_1})}\frac{g_{*s}^\phi\left(T^{\rm dec}\right)}{g_{*s}\left(T^{\rm dec}\right)}\right]^{\frac{4}{3}}, \quad (3.1)$$

where T is the temperature, g_{*s} counts the effective degrees of freedom for entropy density in standard model sector, or particles that are in kinetic equilibrium with neutrinos, while g_{*s}^ϕ denotes the effective degrees of freedom that are in kinetic equilibrium with ϕ_1. And we have used entropy conservation in the last equality. Although the exact value depends on the kinetic decoupling temperature $T^{\rm dec}$ and ratios of degrees of freedom before and after decoupling, the typical value for $\delta N_{\rm eff}$ would be around $\mathcal{O}(0.1)$ which is definitely allowed by present data [1,50,51]. For instance, if $T^{\rm dec}\sim 1$ GeV, we have $\delta N_{\rm eff}\simeq 0.045$. If more than one scalar contributes as radiation, we should rescale $\delta N_{\rm eff}$ correspondingly. The exact value of $T^{\rm dec}$ is determined by the interaction with standard model particle. Simple calculation shows that an interaction term $\lambda_{\phi H}\phi_1^2H^\dagger H$ with $\lambda_{\phi H}\sim 10^{-3}$ would give $T^{\rm dec}\sim 1$ GeV.

We shall note there could be other relativistic particles that are in kinetic equilibrium with ϕ_1, which would also contribute to extra $\delta N_{\rm eff}$, and $\delta N_{\rm eff}$ is then changing with time. For example, in the paper we considered $T^{\rm dec}\sim 1$ GeV. If the dark matter ψ is lighter than 1 GeV, ψ could be still in kinetic equilibrium with ϕ_1 and would contribute to $\delta N_{\rm eff}$. After its decoupling from ϕ_1 at $m_\psi/25$, ψ would transfer its entropy to ϕ_1 and ϕ_1's temperature is effectively increased. This is all encoded in counting $g_{*s}^\phi\left(T_{\phi_1}\right)$ in the above formula, Eq. (3.1).

We know in standard model neutrinos are decoupled after BBN time and then start *free-streaming*, which means the interactions of neutrinos can be neglected so that perturbations in its anisotropic stress and high multipole can develop. However, in our model ϕ_1 is not necessarily free-streaming after its kinetic decoupling from standard model thermal bath and it may self-scatter a lot and acts like a perfect fluid that has no anisotropy and high multipole. Whether and when ϕ_1 is streaming freely depends crucially on its self-couplings or interaction with other relativistic particles.

The self-scattering rate of ϕ_1 is dominantly determined by $\phi_1+\phi_1\to\phi_1+\phi_1$ through the Feynman diagrams shown in Fig. 2.