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Light dark photon and fermionic dark radiation for the Hubble constant and the structure formation

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ABSTRACT

Motivated by the tensions in the Hubble constant H_0 and the structure growth σ_8 between Planck results and other low redshift measurements, we discuss some cosmological effects of a dark sector model in which dark matter (DM) interacts with fermionic dark radiation (DR) through a light gauge boson (dark photon). Such kind of models are very generic in particle physics with a dark sector with dark gauge symmetries. The effective number of neutrinos is increased by $\delta N_{\rm eff} \sim 0.5$ due to light dark photon and fermionic DR, thereby resolving the conflicts in H_0. The elastic scattering between DM and DR induces suppression for DM's density perturbation, but without acoustic oscillations. For weakly-interacting DM around 100 GeV, the new gauge coupling should be $\sim 10^{-4}$ to have sizable effect on matter power spectrum in order to relax the tension in σ_8.

1. Introduction

It has been established that about 83% of matter content ($\Omega_m = 0.3065 \pm 0.0072$) [1] in our universe is composed of dark matter (DM). The standard cold DM (CDM) together with cosmological constant Λ, ΛCDM model, is very compelling and convincing to explain our current observations. Despite of this remarkable success, we are still struggling to disentangle the particle identities of DM since all the confirmed evidence for DM come from gravitational interaction of DM. Any unexpected signatures in astrophysics, cosmology and particle physics may help us to better understand particle physics nature of DM.

Meanwhile, there are still some persistent tensions in the measurement of the Hubble constant H_0 and the structure growth rate σ_8 (the amplitude of matter fluctuations at scale around 8 Mpc). The latest analysis [2] of Hubble Space Telescope (HST) data gives $H_0 = 73.24 \pm 1.74$ km s^{-1}Mpc^{-1}, which is about 3.4σ higher than the value given by Planck [1] within the ΛCDM model. Also, Planck data yields $\sigma_8 = 0.815 \pm 0.009$ which is relatively larger than the low redshift measurements, such as weak lensing survey CFHTLenS [3], $\sigma_8(\Omega_m/0.27)^{0.46} = 0.774 \pm 0.040$.

The above tensions could be due to systematic uncertainties, or they may indicate new physics model beyond the standard ΛCDM. For example, increasing the effective number of neutrinos by $\delta N_{\rm eff} \simeq 0.4 - 1$ with dark radiation (DR) could resolve the conflict between Planck and HST data [2], which, however, unfortunately would give an even larger σ_8. Or it is possible to extend the six-parameter ΛCDM with varying dark energy, dark matter, neutrino mass, running spectral index, and so on [4–10], to relax these tensions in H_0 and σ_8.

In this letter, we shall explore a dark sector model in which DM interacts with DR through light dark photon and address the above issues. The interaction between DM and DR causes a suppression of the matter power spectrum through diffusion or collisional damping which can give a smaller σ_8. Also the natural presence of DR would relieve the tension between HST and Planck.

This paper is organized as following. Firstly, we shall introduce our model setup with the conventions and the relevant parameters. Then we discuss the corresponding phenomenologies, DM relic density, prediction of $\delta N_{\rm eff}$ and the DM-DR scattering with late kinetic decoupling. Later, we show some numerical results on the matter power spectrum. Finally, we give our summary.

2. The model

We introduce a dark sector with a new $U(1)$ dark gauge symmetry and coupling g_X, dark photon field V_μ, scalar Φ, massive fermion χ (DM) and massless ψ (DR). All these new fields are living in the dark sector, thereby being SM gauge singlets. We assign

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$U(1)$ charges $q_f = 1, 2, 2$ to χ, ψ, Φ, respectively. Then the general gauge invariant Lagrangian is

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + D_\mu\Phi^\dagger D^\mu\Phi + \bar{\chi}\left(i\not{D} - m_\chi\right)\chi + \bar{\psi}i\not{D}\psi - \left(y_\chi\Phi^\dagger\bar{\chi}^c\chi + y_\psi\Phi\bar{\psi}N + h.c.\right) - V(\Phi, H), \tag{1}$$

where N is the singlet right-handed (RH) neutrino which couples to the left-handed (LH) neutrinos in the SM through usual Yukawa terms, the superscript 'c' stands for charge conjugate, the covariant derivative is defined as $D_\mu f = (\partial_\mu - iq_f g_X V_\mu)f$, $\not{D} \equiv \gamma^\mu D_\mu$ and $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$. Note that Φ does not develop a vacuum expectation value (VEV) and this new $U(1)$ is a good symmetry. We could introduce a mass for V_μ and possible gauge kinetic mixing term,[1] which however is not essential for our discussions, and which we shall come back to later.

Except for the Higgs and Yukawa terms, our model is very similar to the structure in standard model. Some simple variants of this model is equally suited for our interests in the paper. For example, Φ can be a singlet and couples as $y_\chi\Phi\bar{\chi}\chi + y_\psi\Phi\bar{\psi}\psi$. In any case Φ is not stable and can decay into ψ, and ψ can be thermalized with χ, Φ and V_μ through the Yukawa couplings with Φ.

We note that a similar setup was discussed in Ref. [10], where the authors assumed $q_\chi = 1 \neq q_\psi$, but did not consider possible Yukawa interactions between ψ with the Φ. Yukawa interaction among Φ and ψ can lead to thermalization of ψ at high temperature, which is different from thermalization mechanism at lower temperature through dark gauge interactions considered in Ref. [10], and the resulting $\delta N_{\rm eff}$ would be different.

Finally, the connection to the SM sector can be established in a straightforward manner through the Higgs portal term, $V \supset \lambda_{\Phi H}\Phi^\dagger\Phi H^\dagger H$, where H is the SM Higgs doublet. Simple estimation shows that Φ and dark sector can be in thermal equilibrium with SM particles when the Universe is around TeV if $|\lambda_{\Phi H}| \gtrsim 10^{-6}$.

3. Phenomenology

Now, let us discuss some relevant phenomenology and constraints, based on the Lagrangian of Eq. (1).

Relic density: For thermal DM χ and $m_\chi > m_\Phi$, its relic abundance is mostly determined by the annihilation process $\chi + \bar{\chi} \to \Phi + \Phi^\dagger$. At tree-level approximation, we have the thermal cross section

$$\langle\sigma v\rangle \sim \frac{y_\chi^4}{16\pi m_\chi^2}, \tag{2}$$

and the total relic density of χ and $\bar{\chi}$ would be

$$\Omega h^2 \simeq 0.1 \times \left(\frac{y_\chi}{0.7}\right)^{-4}\left(\frac{m_\chi}{\rm TeV}\right)^2. \tag{3}$$

The value of y_χ determined by Eq. (3) can be treated as the upper limit for y_χ, since if there were other annihilation processes contributing to the depletion of χ particles, then y_χ could be smaller. For instance, $\chi + \bar{\chi} \to \psi + \bar{\psi}$ can be important if $y_\psi > y_\chi$. However, for our interests in this paper, the qualitative relation above between y_χ and m_χ would be sufficient, which means that for TeV-scale χ it is expected to have $y_\chi \sim 0.7$ to get the correct relic density.

DM χ's self-scattering through exchanging Φ can be sizable if the mass of Φ (m_Φ) is small, which is the central topics in recent self-interacting dark matter scenarios (see Refs. [12–49] for examples). In general, for $\mathcal{O}(100\ {\rm GeV})$ DM χ, Φ with $m_\Phi \sim \mathcal{O}(0.1\ {\rm GeV})$ would be able to provide large self-interaction to alleviate the so-called small scale problems, namely "cusp-vs-core" and "too-big-to-fail" [50].

Dark radiation: V_μ and ψ in the thermal bath with temperature T_D will contribute as dark radiation by shifting the $N_{\rm eff}$ with

$$\delta N_{\rm eff} = \left(\frac{8}{7} + 2\right)\left[\frac{g_{*s}(T_\nu)}{g_{*s}(T^{\rm dec})}\frac{g_{*s}^D(T^{\rm dec})}{g_{*s}^D(T_D)}\right]^{\frac{4}{3}}, \tag{4}$$

where T_ν is neutrino's temperature, $T^{\rm dec}$ for the temperature at which dark sector is kinetically decoupled from standard model thermal bath, g_{*s} counts the effective number of degrees of freedom (dof) for entropy density in standard model [51], or particles that are in kinetic equilibrium with neutrinos, g_{*s}^D denotes the effective number of dof that are in kinetic equilibrium with V_μ.

Note that ψ can be in thermal equilibrium with V_μ and Φ at high temperature due to the Yukawa interactions because it can leads to an interacting rate $\Gamma_\psi \propto g_\psi^2 T^5/m_\Phi^4$. However, the gauge interaction gives rise to $\Gamma_\psi \propto g_X^2 T$ and g_X could be too small to keep ψ in equilibrium with V_μ and Φ at high temperature, which results in a smaller $\delta N_{\rm eff}$ as discussed in Ref. [10].

The above formula, Eq. 4, is valid in general contexts. In the literature, the factor $g_{*s}^D(T^{\rm dec})/g_{*s}^D(T_D)$ in the bracket is usually ignored, which simply neglects the possible changes of dof in the dark sector. However, as shown above, this ignorance is valid only if $g_{*s}^D(T^{\rm dec}) \simeq g_{*s}^D(T_D)$ which is not always the case. For instance, when $T^{\rm dec} \gg m_t \simeq 173$ GeV for $|\lambda_{\Phi H}| \sim 10^{-6}$, we can estimate $\delta N_{\rm eff}$ at the BBN epoch as

$$\delta N_{\rm eff} = \frac{22}{7}\left[\frac{43/4}{427/4}\frac{11}{9/2}\right]^{\frac{4}{3}} \simeq 0.53, \tag{5}$$

which shows that $g_{*s}^D(T^{\rm dec}) = \frac{22}{9}g_{*s}^D(T_D)$ in our case. The lower bound can be obtained $\delta N_{\rm eff} \simeq 0.21$ when $g_{*s}^D(T^{\rm dec}) = g_{*s}^D(T_D)$.

We can also get the temperature ratio for V_μ to that of neutrino ν and photon γ,

$$T_D \simeq 0.64T_\nu = 0.46T_\gamma, \tag{6}$$

where we have used $T_\nu = (4/11)^{\frac{1}{3}}T_\gamma$.

Based on the above discussion, the total $\delta N_{\rm eff}$ in our model is predicted to be around 0.5, which lies in the preferred range for $\delta N_{\rm eff} \simeq 0.4$–1 to resolving the conflict between `Planck` and HST data [2]. One prediction of our model is that $\delta N_{\rm eff} > 0.21$ which can be definitely either confirmed or excluded by next-generation CMB experiments.

χ–ψ (DM-DR) scattering: One of the key quantities for the structure formation is the elastic scattering cross section for $\chi + \psi \to \chi + \psi$, which would modify the cosmological evolutions for χ and ψ's perturbations. More explicitly, similarly to the baryon–photon system [52], the Euler equations for χ and ψ would be approximately modified to

$$\dot{\theta}_\chi = k^2\Psi - \mathcal{H}\theta_\chi + S^{-1}\dot{\mu}\left(\theta_\psi - \theta_\chi\right), \tag{7}$$

$$\dot{\theta}_\psi = k^2\Psi + k^2\left(\frac{1}{4}\delta_\psi - \sigma_\psi\right) - \dot{\mu}\left(\theta_\psi - \theta_\chi\right), \tag{8}$$

where dot means derivative over conformal time $d\tau \equiv dt/a$ (a is the scale factor), θ_ψ and θ_χ are velocity divergences of radiation ψ and DM χ's, k is the comoving wave number, Ψ is the gravitational potential, δ_ψ and σ_ψ are the density perturbation and the anisotropic stress potential of ψ, and $\mathcal{H} \equiv \dot{a}/a$ is the conformal

[1] This could be achieved by a nonzero VEV of Φ, or by introducing another $U(1)$-charged scalar with nonzero VEV. See Ref. [11] for constraints on kinetic mixing.