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$\mathcal{O}(1)$ eV STERILE NEUTRINO IN $f(R)$ GRAVITY

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We refer [1] to the role of an additional $\mathcal{O}(1)$ eV sterile neutrino in modified gravity models. We find parameter constraints in particular $f(R)$ gravity model using the following up-to-date cosmological data: measurements of the cosmic microwave background (CMB) anisotropy, the CMB lensing potential, the baryon acoustic oscillations (BAO), the cluster mass function and the Hubble constant. It was obtained for the sterile neutrino mass $0.47 < m_{\nu,\,\mathrm{sterile}} < 1$ eV (2σ) assuming that the sterile neutrinos are thermalized and the active neutrinos are massless, not significantly larger than in the standard cosmology model within the same data set: $0.45 < m_{\nu,\,\mathrm{sterile}} < 0.92$ eV (2σ). But, if the mass of sterile neutrino is fixed and equals ≈ 1.5 eV according to various anomalies in neutrino oscillation experiments, $f(R)$ gravity is much more consistent with observation data than the ΛCDM model.

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INTRODUCTION

It is known that the Universe is undergoing an accelerated expansion today. The present Dark Energy (DE) provides such Universe behaviour in ΛCDM model. Corresponding DE fraction is considered lately as evolving and unstable by analogy with the inflation stage in the early Universe. We work within $f(R)$ formalism [2], which modifies General Relativity (GR) by replacing the scalar curvature (Ricci curvature) R with a new phenomenological function $f(R)$ in the Einstein–Hilbert action. Cosmology based on modified gravity can explain cosmic acceleration today without introducing cosmological constant Λ, so $f(0) = 0$.

New theory must be viable and consistent with the past Universe evolution. Hence, it should satisfy the following conditions in the region of R where we want to use the theory [3]:

$$f'(R) > 0, \qquad f''(R) > 0, \tag{1}$$

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and for $R \gg R_0$

$$|f(R) - R| \ll R, \qquad |f'(R) - 1| \ll 1, \qquad f''(R)R \ll 1, \tag{2}$$

where prime denotes a derivative with respect to argument R and R_0 is the present Ricci curvature in the Universe. The last three conditions are necessary to provide the correct Newtonian limit for the matter- and radiation-dominated stages in the past and smallness of non-GR corrections to a space-time background metric of compact astrophysical objects at present epoch.

There is a dramatic difference between cosmological model based on $f(R)$ gravity and standard cosmology: matter density perturbations in modified gravity grow faster on scales smaller than the Compton wavelength of the scalaron field that occurs at recent redshifts. Therefore, if we add one additional sterile neutrino in the model described by $f(R)$ gravity, the net result can be zero because modified gravity and rest mass of sterile species play opposite roles in the evolution of matter density perturbations on small scales [4]. As we know, small massive particle suppresses structure formation below Jeans length through free-streaming effect.

If mixing angle is not extremely small, sterile component is produced and thermalized in the early Universe before the decoupling of active neutrinos. We add one sterile neutrino with mass $\mathcal{O}(1)$ eV to Standard Model by mixing with active ones. Importantly, the recent research of the primordial helium abundance does not forbid the existence of one extra neutrino species [5]: an effective number of neutrinos is $N_{\rm eff} = 3.58 \pm 0.40\,(2\sigma)$.

The light sterile neutrinos are required by several anomalies results in neutrino oscillation experiments [6]. For instance, the so-called gallium anomaly observed by GALLEX [7] and SAGE [8] experiments is nicely explained if the electron neutrino oscillates into sterile neutrino of 1.5 eV mass [9].

1. BACKGROUND UNIVERSE

The $f(R)$ gravity is defined by the following action:

$$S = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} f(R) + S_m, \tag{3}$$

where $\kappa^2/(8\,\pi) \equiv G$ is the Newton gravitational constant and S_m is the action of matter fields minimally coupled to gravity.

We consider the particular modified gravity model [3]

$$f(R) = R + \lambda R_s \left[\left(1 + \frac{R^2}{R_s^2} \right)^{-n} - 1 \right], \tag{4}$$

where n, λ, R_s are model parameters. Discussion about different instabilities and how to cope with them can be found in [10].

From derived field equations by varying the action (3) with respect to space-time metric* $g_{\mu\nu}$ we find the effective equation-of-state parameter $\omega_{\rm DE}$ for the DE fraction defined by

$$\omega_{\rm DE} \equiv \frac{P_{\rm DE}}{\rho_{\rm DE}} = -1 + \frac{2\dot{H}(f'-1) - H\dot{f}' + \ddot{f}'}{-3H\dot{f}' + 3(H^2+\dot{H})(f'-1) - (f-R)/2}, \tag{5}$$

where $\rho_{\rm DE}$ and $P_{\rm DE}$ are density and pressure for DE in the following equation written in Einsteinian form: $R_{\mu\nu} - (1/2)g_{\mu\nu}R = \kappa^2 \left(T_{\mu\nu}^{(M)} + T_{\mu\nu}^{(DE)}\right)$.

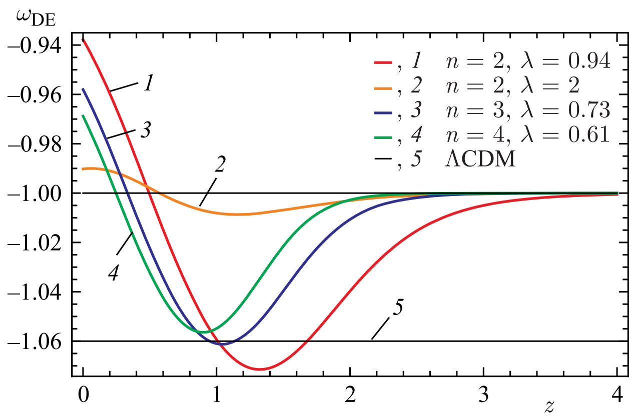

Fig. 1. Evolution of the equation-of-state parameter $\omega_{\rm DE}$ for DE fraction in the $f(R)$ model (4) for different values of parameters

Figure 1 depicts the behaviour of $\omega_{\rm DE}$ as a function of redshift z obtained in numerical analysis assuming $\Omega_m = 0.3$ and $H_0 = 72$ km/s/Mpc. We observe generic feature for modified gravity models which obey $f''(R) > 0$, the phantom boundary crossing ($\omega_{\rm DE} = -1$), at small redshifts $z \leqslant 1$.

2. MATTER PERTURBATION

We turn to evolution matter density perturbations in linear regime in modified gravity models using the quasi-static approximation and considering only sub-

*We use the following metric signature: $ds^2 = -dt^2 + a^2(t)\,d\mathbf{x}^2$, where $a(t)$ is the scale factor.

Hubble modes. From [11]

$$G_{\text{eff}}(t,k) \equiv \frac{G}{f'} \frac{1 + 4\dfrac{k^2}{a^2}\dfrac{f''}{f'}}{1 + 3\dfrac{k^2}{a^2}\dfrac{f''}{f'}} \,. \tag{6}$$

We introduce the effective scalaron mass [11] $M_s^2 \approx 1/3f''(R)$ in the quasi-GR regime $(f' \approx 1)$. Hence, matter density fluctuations evolve by two different ways: $M_s \gg k/a$ and $M_s \ll k/a$. The first one corresponds to $G_{\text{eff}} \approx G$ (density evolution mimics that in GR), whereas the latter corresponds to $G_{\text{eff}} \approx 4G/3$ (enhancement of growth rate mentioned in Introduction). Consequently, the effective gravitational "constant" can be increased by $33\,\%$ irrespective of the function form of $f(R)$.

3. PARAMETER CONSTRAINTS

We carry out the Markov Chain Monte Carlo (MCMC) analysis and compare the ΛCDM model with the $f(R)$ gravity described by Eq. (4) with one additional massive sterile neutrino, assuming active neutrinos are massless. Sterile species is taken to be thermalized and shares the same temperature as the active ones. We have modified the MGCAMB [12] plugged into CosmoMC package [13] that allows us to describe $f(R)$ gravity by adopting (6). In the fit we use eight free parameters: $\Omega_b h^2$, $\Omega_c h^2$, $\theta_* \equiv 100 r_s/D_A(z_*)$, τ, n_s, $\ln(10^{10}A_s)$, $m_{\nu,\,\text{sterile}}$ and λ, so that $\Omega_{\text{DM}} = \Omega_c + \Omega_\nu$. We also fixed $n = 2$ in gravity law (4).

In our simulations we use measurement of the CMB from the Planck satellite [14] supplemented with the low-ℓ polarization measurements [15] and extended with CMB measurements at high-ℓ by the Atacama Cosmology Telescope (ACT) [16] and the South Pole Telescope (SPT) [17]. We also consider different measurements of baryon acoustic oscillation (BAO): the LOWZ [18] and CMASS [19] samples of BOSS (SDSS DR11) in the redshift range $0.15 < z < 0.43$ and $0.43 < z < 0.7$, respectively, and also the 6dF Galaxy Survey [20] at $z = 0.106$. In addition, we use the Hubble constant measurement [21] and the full-sky lensing potential from Planck maps [22]. Finally, we include observations of galaxy clusters [23] in recent redshifts. In the latter data we use a sample of 86 massive galaxy clusters in the ranges $z < 0.2$ and $z \approx 0.4{-}0.9$ with masses measured with about 10% accuracy by the *Chandra* X-ray telescope (the subsample of distant massive clusters was taken from the *400d* X-ray galaxy cluster survey [24]).

In Fig. 2, *a* we see the modified gravity influence on the growth of matter density contrast using all data sets without galaxy clusters. In order to constrain

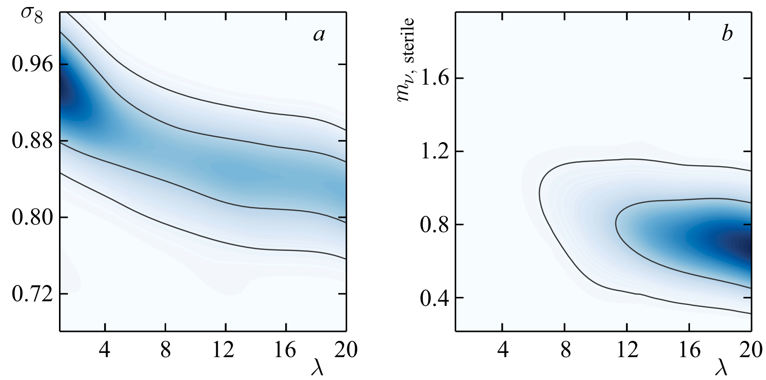

Fig. 2. The regions of parameter space consistent with full cosmological data without measurements of cluster mass function (*a*) and with that (*b*) at the 65 % and 95 % confidence levels for $f(R)$ gravity in σ_8-λ (*a*), $m_{\nu,\,\mathrm{sterile}}$-$\lambda$ (*b*) planes, assuming one massive sterile and three massless active neutrinos

the value of σ_8 (matter density contrast averaged by regions with the size $8h^{-1}$ in linear regime), we take the cluster mass function measurements in our consideration. From Fig. 2, *b* we deduce that degeneracy between the mass of sterile neutrino $m_{\nu,\,\mathrm{sterile}}$ and the free parameter of $f(R)$ gravity λ is not so prominent as suggested before. Moreover, modified gravity consideration changes the constraint on the sterile neutrino mass insignificantly: $0.47 < m_{\nu,\,\mathrm{sterile}} < 1$ eV (2σ) in $f(R)$ model against $0.45 < m_{\nu,\,\mathrm{sterile}} < 0.92$ eV (2σ) in ΛCDM.

We can also explore the function form $f(R)$ by getting a constraint on the $f(R)$ gravity parameter λ. We find $\lambda > 9.4$ (2σ) in the case of the fourth massive sterile neutrino and others taken massless. When the systematic uncertainty of the cluster mass function $\delta M/M \approx 0.09$ [23] is included in the likelihood functions, the constraints are relaxed: $\lambda > 8.2$ (2σ).

However, the Universe with one massive sterile neutrino remains slightly more preferable in case of modified gravity by 1.3σ as compared to ΛCDM consideration. Moreover, if the sterile state of mass ≈ 1.5 eV really exists for explanation of various anomalies in neutrino oscillation experiments, we find significant improvement of $f(R)$ gravity which corresponds to $\chi^2 = 19.05$ with one degree of freedom.

CONCLUSIONS

We find that 1.5 eV sterile neutrino is much better consistent with the $f(R)$ gravity rather than with the standard ΛCDM model. Besides, if the mass of sterile neutrino is free parameter, modified gravity improves the maximum likelihood slightly in comparison with standard cosmology.

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