


Axion effects on gamma-ray spectral irregularities with AGN redshift uncertainty

Hai-Jun Li^{*} and Wei Chao[†]

Center for Advanced Quantum Studies, Department of Physics,
Beijing Normal University, Beijing 100875, China

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We investigate the photon-axionlike particle (ALP) oscillation effects on TeV gamma-ray spectral irregularities from the uncertain redshift active galactic nuclei (AGN) VER J0521 + 211. The gamma-ray spectra are measured by Fermi-LAT and VERITAS with the three flux states in 2013 and 2014. We set the combined constraints on the ALP parameter ($m_a, g_{a\gamma}$) space with these states and test the extragalactic background light (EBL) absorption effect on ALP constraints with the redshift limit scenarios $z_0 \sim \mathcal{O}(0.1 - 0.3)$. The 99% C.L. photon-ALP combined constraints set by VER J0521 + 211 are roughly at $g_{a\gamma} \gtrsim 2.0 \times 10^{-11} \text{ GeV}^{-1}$ for $1.0 \times 10^{-9} \text{ eV} \lesssim m_a \lesssim 1.0 \times 10^{-7} \text{ eV}$. We find no clear connection between the redshift limit scenarios and the photon-ALP constraints. Both the underestimated and overestimated redshifts can affect the constraint results.

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I. INTRODUCTION

Axions [1–4] and axionlike particles (ALPs) [5,6] are ultralight pseudo-Nambu-Goldstone bosons (pNGBs), which are potential dark matter (DM) candidates if non-thermally generated in the early Universe through the misalignment mechanism [7–12]. See, e.g., Refs. [13–15] for recent reviews. The interaction between ALPs and very high energy (VHE; $\sim \mathcal{O}(100)$ GeV) photons in the astrophysical magnetic fields with Lagrangian $-\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$ could lead to detectable effects, such as a reduced TeV opacity of the Universe [16,17].

The TeV gamma-rays from extragalactic sources are affected by the extragalactic background light (EBL) absorption effect through the pair production process, $\gamma_{\text{TeV}} + \gamma_{\text{EBL}} \rightarrow e^+ + e^-$. In this case, the photon-ALP interaction provides a natural mechanism to reduce the EBL absorption and constrain the ALP properties (the ALP mass m_a and the photon-ALP coupling $g_{a\gamma}$) [18–26]. The common mechanism is considering the photon-ALP conversions and back-conversions in the astrophysical magnetic fields. If there is significant photon-ALP mixing, the Universe would appear to be more transparent

than expected based on the pure EBL absorption. See, e.g., Refs. [27–36] for recent studies on photon-ALP conversions from the different extragalactic astrophysical sources.

In this work, we focus our attention on the photon-ALP oscillation effects on TeV gamma-ray spectral irregularities from the uncertain redshift active galactic nuclei (AGN) VER J0521 + 211. VER J0521 + 211 (RA = 05^h21^m45^s, Dec = 21°12′51.4″, J2000) is classified as the intermediate frequency peaked BL Lac (IBL) object, which was first observed by the Very Energetic Radiation Imaging Telescope Array System (VERITAS) in 2009 [37]. Since the lack of optical emission features of the IBL object, the redshift of VER J0521 + 211 is still unknown. Many studies show the redshift limits of this source with $0.108 \leq z_0 \leq 0.34$ [37–39]. Recently, VERITAS reported the TeV gamma-ray observations of VER J0521 + 211 in 2013 and 2014 with the Fermi-LAT and VERITAS data [40], suggesting the redshift upper limits $z_0 \leq 0.31$. Here we use these gamma-ray data and redshift limits of VER J0521 + 211 to investigate the photon-ALP oscillation effects on TeV gamma-ray spectral irregularities and test the EBL absorption effect on ALP constraints. Since the latest gamma-ray data, the redshift uncertainties, and the magnetic field parameters of VER J0521 + 211 are given in Ref. [40] together, it may be a choice for us to investigate the photon-ALP oscillation effects with this source.

This paper is structured as follows. In Sec. II, we describe the VHE gamma-ray data and the redshift limits of VER J0521 + 211. In Sec. III, we briefly introduce the ALP constraint method and the magnetic field parameters

^{*}lihaijun@bnu.edu.cn

[†]chaowei@bnu.edu.cn

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setup. The resulting ALP constraints are shown in Sec. IV. Finally, we conclude in Sec. V.

II. GAMMA-RAY DATA AND REDSHIFT LIMITS

In this section, we describe the TeV gamma-ray data and the redshift limits of VER J0521 + 211. In Ref. [40], the gamma-ray spectra of VER J0521 + 211 in 2013 and 2014 are performed by the Bayesian block (BB) analysis [41], which are defined as the flux states BB1, BB2, and BB3, respectively.

- (i) BB1: MJD 56580.0–MJD 56628.5
Corresponds to the intermediate state.
- (ii) BB2: MJD 56628.5–MJD 56632.5
Corresponds to the high state.
- (iii) BB3: MJD 56632.5–MJD 56689.0
Corresponds to the low state.

The redshift lower limits of VER J0521 + 211 are not confirmed, which can be defined as the limit scenarios L1 and L2, respectively.

- (i) L1: $z_0 \geq 0.108$ from Ref. [38].
Based on a weak emission feature, which however is not confirmed by Ref. [37].
- (ii) L2: $z_0 \geq 0.18$ from Ref. [39].
The result is also not confirmed, which therefore is still unknown.

The redshift upper limit of VER J0521 + 211 can be defined as the limit scenario H1.

- (i) H1: $z_0 \leq 0.308$ from Ref. [40].
The results in the literature are around $z_0 \leq 0.31$, here we take a typical value.

Using these flux states and redshift limits, we could investigate the photon-ALP oscillation effects on gamma-ray spectral irregularities.

The main effect on VHE photon (with the energy E) in the extragalactic space is the EBL photon (with the energy ω) absorption effect with the factor $e^{-\tau}$. The corresponding optical depth can be described by [42]

$$\tau = c \int_0^{z_0} \frac{dz}{(1+z)H(z)} \int_{E_{\text{th}}}^{\infty} d\omega \frac{dn(z)}{d\omega} \bar{\sigma}(E, \omega, z), \quad (1)$$

where $H(z) = H_0 \sqrt{(1+z)^2(1 + \Omega_m z) - z(2+z)\Omega_\Lambda}$ is the Hubble expansion rate, with the source redshift z_0 , the threshold energy E_{th} , the integral pair-production cross section $\bar{\sigma}(E, \omega, z)$, the EBL proper number density $dn(z)/d\omega$, $H_0 \simeq 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m \simeq 0.315$, and $\Omega_\Lambda \simeq 0.685$ [43]. In this work, the spectrum of EBL is taken from the model F-08 [42].

In our analysis, the gamma-ray intrinsic spectrum $\Phi_{\text{int}}(E)$ is selected with the minimum best-fit reduced χ^2_{null} from the four spectra models as discussed in Ref. [44]. Here we adopt the log-parabola model, which can be

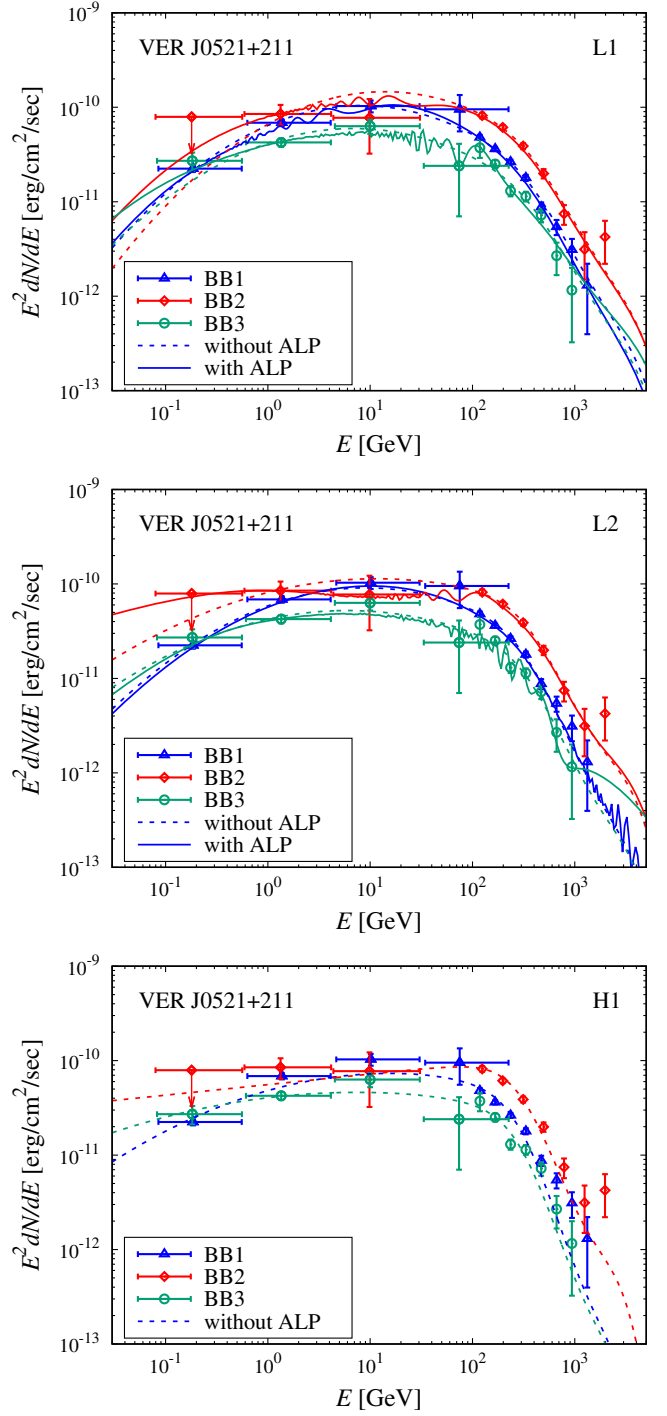


FIG. 1. The SEDs of the three states of VER J0521 + 211 for the redshift limit scenarios L1 (top; with $z_0 = 0.108$), L2 (middle; with $z_0 = 0.18$), and H1 (bottom; with $z_0 = 0.308$). The blue triangles, red diamonds, and green circles correspond to the three states BB1 (12 points), BB2 (10 points), and BB3 (11 points), respectively. The solid and dashed lines correspond to the best-fit SEDs with/without ALP, respectively. The experimental points are taken from Fermi-LAT and VERITAS [40]. For comparison, the EBL models used in these three plots are taken as F-08 [42]. Note that we do not make the ALP analysis with H1.

described by

$$\Phi_{\text{int}}(E) = N_0 \left(\frac{E}{E_0} \right)^{-\Gamma - b \log\left(\frac{E}{E_0}\right)}, \quad (2)$$

where N_0 is the normalization constant, Γ is the spectral index, E_0 and b are free parameters. Then the χ^2 value is given by

$$\chi^2 = \sum_{i=1}^N \left(\frac{\Phi_i - \psi_i}{\delta_i} \right)^2, \quad (3)$$

with the expected spectrum $\Phi_i = e^{-\tau} \Phi_{\text{int}}(E_i)$, where N is the gamma-ray spectral point number, ψ_i and δ_i are the detected flux and its uncertainty, respectively.

We first take the three redshift limit scenarios L1 [$z_0 \sim \mathcal{O}(0.1)$], L2 [$z_0 \sim \mathcal{O}(0.2)$], and H1 [$z_0 \sim \mathcal{O}(0.3)$] for comparisons. We show the best-fit gamma-ray spectral energy distributions (SEDs) of the three states BB1, BB2, and BB3 of VER J0521 + 211 with these redshift limit scenarios in Fig. 1. The dashed lines represent the best-fit SEDs under the null hypothesis. The corresponding best-fit χ^2_{null} values are listed in Table I. For the scenario H1, we note that the value of $\chi^2_{\text{null}}/\text{d.o.f.} = 5.52$ of BB1 is obviously larger than that of BB2 and BB3, which may be caused by the small uncertainty of the observed spectrum. In this case ($z_0 = 0.308$), the other intrinsic spectra models are also checked, of which the log-parabola is still the best-fit model. Therefore, the redshift upper limit $z_0 \leq 0.308$ may be an overestimate for BB1. Since the large value of $\chi^2_{\text{null}}/\text{d.o.f.}$ in H1-BB1, we will not set the ALP constraint with the scenario H1. Adopting the redshift

TABLE I. The best-fit χ^2 values under the null/ALP hypotheses of the three states of VER J0521 + 211 for the scenarios L1, L2, H1, and R1. The combined results are also shown. The values of χ^2_{min} correspond to the minimum best-fit points on the ALP parameter space. The effective d.o.f. for the ALP combined analyses are also listed.

State	χ^2_{null}	$\chi^2_{\text{null}}/\text{d.o.f.}$	χ^2_{min}	Effective d.o.f.
L1-BB1	4.89	0.61	2.43	...
L1-BB2	6.69	1.11	4.25	...
L1-BB3	14.20	2.03	8.24	...
L1-combined	25.78	...	18.82	5.58
L2-BB1	6.62	0.83	2.25	...
L2-BB2	3.24	0.54	2.22	...
L2-BB3	11.47	1.64	6.76	...
L2-combined	21.33	...	17.30	5.46
H1-BB1	44.12	5.52
H1-BB2	15.67	2.61
H1-BB3	19.64	2.81
R1-BB1	11.92	1.49	2.50	...
R1-BB2	4.00	0.67	2.12	...
R1-BB3	12.43	1.78	7.27	...
R1-combined	28.35	...	18.04	5.41

upper limit will lead to excessive EBL absorption, and this redshift limit is not suitable to make the further analysis with other flux states (BB2 and BB3).

In order to discuss the redshift uncertainty, here we take the another redshift value of VER J0521 + 211, which can be defined as the redshift scenario R1.

(i) R1: $z_0 = 0.22$.

This redshift value should be around at the middle of L2 and H1 (i.e., $z_0 \simeq 0.24$), and the reduced χ^2_{null} of R1-BB1 should be small. We test three values of $z_0 = 0.24, 0.23$, and 0.22 with R1-BB1, showing the values of $\chi^2_{\text{null}}/\text{d.o.f.} = 2.12, 1.79$, and 1.49 , respectively. Therefore, we take the value $z_0 = 0.22$ as R1.

For the scenario R1, we show the best-fit SEDs under the null hypothesis in Fig. 2. The best-fit χ^2_{null} values are also listed in Table I. Compared with H1, the χ^2_{null} values of R1-BB2 and R1-BB3 are also dramatically depressed. In the following, we will just discuss the ALP hypothesis with the scenarios L1, L2, and R1.

III. ALP SETUP

In this section, we briefly introduce the ALP constraint method and the magnetic field parameters setup. The photon-ALP oscillation probability in the homogeneous magnetic field can be simply described by

$$\mathcal{P}_{\text{ay}} = \left(\frac{g_{\text{ay}} B_T}{\Delta_{\text{osc}}} \right)^2 \sin^2 \left(\frac{\Delta_{\text{osc}} x_3}{2} \right), \quad (4)$$

where g_{ay} is the photon-ALP coupling constant, B_T is the transverse magnetic field, Δ_{osc} is the oscillation wave number, and x_3 is the propagation direction of photon-ALP. The general photon-ALP oscillations in the magnetic field can be found in Ref. [45]. Here we introduce the parameters associated the photon-ALP beam propagating from the gamma-ray source region to the Earth, which is composed of (i) the source region, (ii) the extragalactic

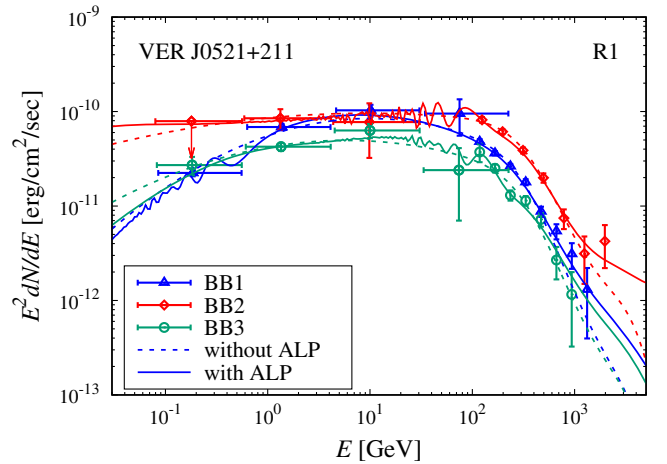


FIG. 2. Same as Fig. 1 but for the scenario R1 ($z_0 = 0.22$).

space, and (iii) the Milky Way. In this case, the final photon-ALP-photon oscillation probability $\mathcal{P}_{\gamma\gamma}$ for the propagation distance s is given by [21]

$$\mathcal{P}_{\gamma\gamma} = \text{Tr}((\rho_{11} + \rho_{22})\mathcal{T}(s)\rho(0)\mathcal{T}^\dagger(s)), \quad (5)$$

where $\mathcal{T}(s) = \mathcal{T}(s_3)_{\text{iii}} \times \mathcal{T}(s_2)_{\text{ii}} \times \mathcal{T}(s_1)_{\text{i}}$ is the whole transfer matrix, $\rho_{11} = \text{diag}(1, 0, 0)$, $\rho_{22} = \text{diag}(0, 1, 0)$, $\rho(0)$, and $\rho(s)$ are initial and final density matrices of the photon-ALP beam, respectively.

For (i) the source region of the BL Lac object VER J0521 + 211, we consider the photon-ALP oscillation in the blazar jet magnetic field, which can be described by the poloidal and toroidal components. As discussed in Ref. [26], here we consider the jet magnetic field with the transverse magnetic field model $B(r) = B_0(r/r_{\text{VHE}})^{-1}$ and the electron density model $n_{\text{el}}(r) = n_0(r/r_{\text{VHE}})^{-2}$, where r_{VHE} is the distance between the source central black hole and the VHE emission region, B_0 and n_0 are the core magnetic field and electron density at r_{VHE} , respectively. For the jet region $r > 1$ kpc, we take the magnetic field $B = 0$. The Doppler factor $\delta_{\text{D}} = E_L/E_j$ is also considered, which represents the energy transformation between the laboratory and comoving frames, E_L and E_j , respectively. The magnetic field parameters B_0 , r_{VHE} , n_0 , and δ_{D} for the three states BB1, BB2, and BB3 of VER J0521 + 211 are listed in Table II. We note that the parameters B_0 and r_{VHE} in Ref. [40] are 1.5×10^{-2} G and $\sim \mathcal{O}(0.9)$ pc, respectively, while they are taken as 0.25×10^{-2} G and $\sim \mathcal{O}(2.5)$ pc in Ref. [37]. We also note that the latter observations are performed to constrain the ALP in Ref. [29] with other parameter values. For self-consistency, the parameters setup used in this work are taken from Ref. [40]. Additionally, for the host galaxy region of VER J0521 + 211, the photon-ALP oscillation in this part can be totally neglected.

For (ii) the extragalactic space, we just consider the EBL absorption effect on VHE photon due to the pair-production process. Since the magnetic field in the extragalactic space is very weak with the upper limit $\sim \mathcal{O}(1)$ nG [46,47], we neglect the photon-ALP oscillation in this region.

Finally, we also take into account the photon-ALP oscillation in (iii) the Milky Way with the Galactic magnetic field model [48,49], which is composed of the disk and halo components (both parallel to the plane of the

Milky Way), and the so-called ‘‘X-field’’ component (out-of-plane) at the center of the Milky Way. See also Refs. [50,51] for the latest version of this model.

IV. ALP CONSTRAINTS WITH THE REDSHIFT UNCERTAINTY

Using Eqs. (2) and (5), the expected gamma-ray spectrum under the ALP hypothesis can be described by $\Phi_{\text{ALP},i} = \mathcal{P}_{\gamma\gamma} \Phi_{\text{int}}(E_i)$, where $\Phi_{\text{int}}(E_i)$ is the gamma-ray intrinsic spectrum. For one ALP parameter ($m_a, g_{a\gamma}$) set, we can derive the best-fit χ^2_{ALP} from Eq. (3) with the notation $\Phi_i \rightarrow \Phi_{\text{ALP},i}$. Then we can derive the best-fit χ^2_{ALP} distributions on the whole ALP parameter space, which are shown in Fig. 3 with the redshift limit scenarios L1, L2, and R1. In these panels, the distributions of χ^2_{ALP} correspond to the three states BB1, BB2, and BB3 of VER J0521 + 211. The minimum best-fit gamma-ray SEDs under the ALP hypothesis of these three states with the scenarios L1, L2, and R1 are also shown in Figs. 1 and 2 for comparisons, respectively. The values of minimum best-fit χ^2_{min} on the ALP parameter space can be found in Table I. Compared with the null hypothesis, the minimum best-fit χ^2_{min} under the ALP hypothesis can be dramatically depressed.

As considered in Refs. [26,28], we also set the combined constraints on ALP with the multistate analysis. In this case, the two or more states of the same source are selected to fit with the corresponding magnetic field setup. In order to obtain the $\chi^2_{99\%}$ value at 99% C.L., 400 sets of the gamma-ray spectra observations in the pseudoexperiments by Gaussian samplings are simulated to derive the test statistic (TS) distribution, $\text{TS} = \hat{\chi}_{\text{null}}^2 - \hat{\chi}_{\text{ALP}}^2$, with the best-fit χ^2 of the null and ALP hypotheses in the Monte Carlo simulations, $\hat{\chi}_{\text{null}}^2$ and $\hat{\chi}_{\text{ALP}}^2$, respectively. Here the TS distribution obeys the noncentral χ^2 distribution with the effective d.o.f. and the noncentrality λ . Then we assume this TS distribution is approximated with the ALP hypothesis and can be used to derive $\Delta\chi^2_{99\%}$. Finally, the value of the 99% C.L. χ^2 can be obtained by $\chi^2_{99\%} = \chi^2_{\text{min}} + \Delta\chi^2_{99\%}$. More details about the statistical method can be found in Ref. [30].

Then we show the ALP combined constraint results set by VER J0521 + 211 in Fig. 4. For comparison, we also show the other latest photon-ALP constraints [52] in this plot. The dashed blue, red, and green contours represent the 99% C.L. combined results of L1, L2, and R1 with the three states combined, respectively. The corresponding best-fit χ^2_{min} values and the effective d.o.f. are also listed in Table I with $\lambda = 0.01$. Compared with the two redshift limit scenarios L1 ($z_0 \geq 0.108$) and L2 ($z_0 \geq 0.18$), we find the more stringent ALP combined constraint with the underestimated redshift. The 99% C.L. exclusion region of L2-combined is completely covered by L1-combined, which shows significant difference in the low mass region 1.0×10^{-9} eV $\lesssim m_a \lesssim 1.0 \times 10^{-8}$ eV. This is probably

TABLE II. The source jet magnetic field parameters of the three states of VER J0521 + 211. These values can be directly or indirectly obtained from Ref. [40].

State	$B_0(10^{-2} \text{ G})$	$r_{\text{VHE}}(\text{pc})$	$n_0(10^{-3} \text{ cm}^{-3})$	δ_{D}
BB1	1.5	0.85	0.88	26
BB2	1.5	0.89	0.95	26
BB3	1.5	0.93	0.68	26

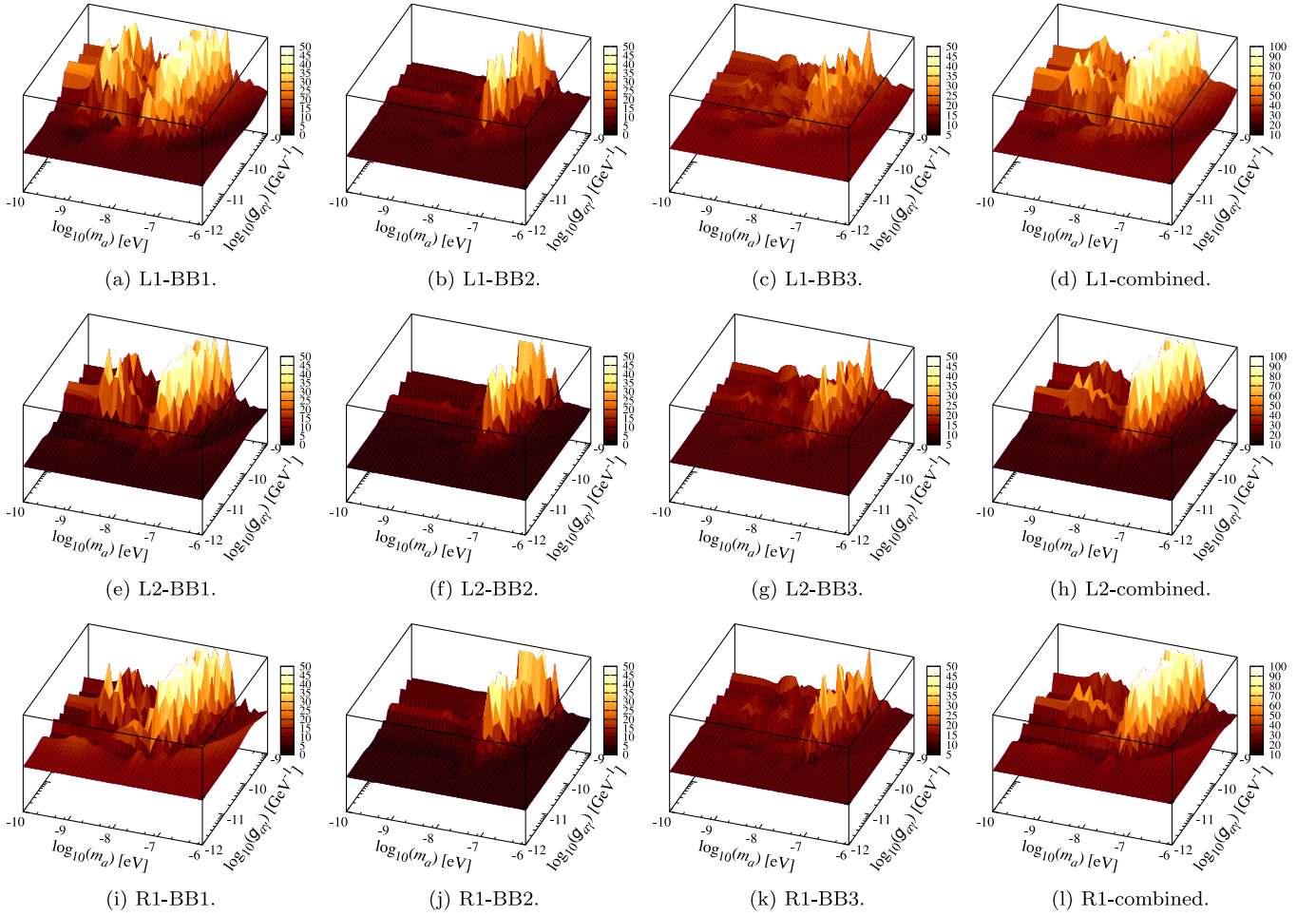


FIG. 3. The best-fit χ^2_{ALP} distributions on the ALP parameter ($m_a, g_{a\gamma}$) space for the redshift limit scenarios L1 (top), L2 (middle), and R1 (bottom). The combined results are also shown. These panels correspond to the scenarios L1-BB1 (a), L1-BB2 (b), L1-BB3 (c), L1-combined (d), L2-BB1 (e), L2-BB2 (f), L2-BB3 (g), L2-combined (h), R1-BB1 (i), R1-BB2 (j), R1-BB3 (k), R1-combined (l), respectively.

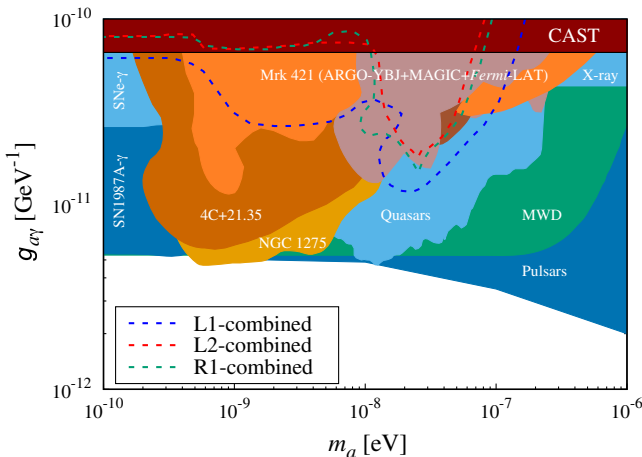


FIG. 4. The 99% C.L. photon-ALP combined constraints set by VER J0521 + 211. The dashed blue, red, and green contours represent the 99% C.L. combined results of the scenarios L1-, L2-, and R1-combined, respectively. The other limits are taken from the package AXIONLimits [52].

because the null hypothesis SEDs of L1-BB2 and L1-BB3 in low energies ($0.1 - 1$ GeV) cannot be fitted well with $z_0 = 0.108$, see Fig. 1. While compared with the scenarios L2 and R1 ($z_0 = 0.22$), we find they show similar ALP exclusion regions (the dashed red and green contours in Fig. 4). The small difference of redshifts (0.18 and 0.22) will reduce the constraint difference on the ALP parameter space. Therefore, no clear connection is confirmed between the redshift limit scenarios and the photon-ALP constraints.

Finally, we give the 99% C.L. ALP combined constraints set by VER J0521 + 211, which are roughly at $g_{a\gamma} \gtrsim 2.0 \times 10^{-11} \text{ GeV}^{-1}$ for $1.0 \times 10^{-9} \text{ eV} \lesssim m_a \lesssim 1.0 \times 10^{-7} \text{ eV}$. Additionally, we note that our results are generally similar to the 99% C.L. limit set by the 2009 TeV observations [37] of VER J0521 + 211 in Ref. [29], which is performed with the different data (VERITAS + HAWC) and magnetic field parameters. Since HAWC can measure the VHE gamma-rays exceeding $\sim 1 - 100$ TeV, in this case, the photon-ALP oscillation effects will become more significant.

However, the limited energy resolution of HAWC can also affect the ALP signal sensitivity in this high energy region.

V. CONCLUSION

In this paper, we have presented the effects of photon-ALP oscillation on TeV gamma-ray spectral irregularities from the AGN VER J0521 + 211, which is classified as the IBL object with the uncertain redshift $0.108 \leq z_0 \leq 0.34$. The gamma-ray spectra are measured by Fermi-LAT and VERITAS in 2013 and 2014 with the three flux states (BB1, BB2, and BB3), and analyzed with the four redshift limit scenarios L1 ($z_0 \geq 0.108$), L2 ($z_0 \geq 0.18$), H1 ($z_0 \leq 0.308$), and R1 ($z_0 = 0.22$). The SEDs of these states under the null and ALP hypotheses are shown for comparisons. Then we set the combined constraints on the ALP parameter space with these states and test the effect of EBL absorption on ALP constraints with these redshift limit scenarios. Since the redshift upper limit scenario H1 may be an overestimate for BB1, we do not set the ALP constraint with H1. In addition, we take the another redshift scenario R1 to discuss the redshift uncertainty.

The 99% C.L. photon-ALP combined constraints set by the scenarios L1, L2, and R1 on the ALP parameter space are roughly at $g_{ay} \gtrsim 2.0 \times 10^{-11} \text{ GeV}^{-1}$ for $1.0 \times 10^{-9} \text{ eV} \lesssim m_a \lesssim 1.0 \times 10^{-7} \text{ eV}$. Compared with the results of L1- and L2-combined, we find the more stringent ALP combined constraint with the underestimated redshift. While compared with the scenarios L2- and R1-combined, we find they show similar ALP exclusion regions. Then we have the conclusion that no clear connection is confirmed between the redshift limit scenarios and the photon-ALP constraints. Both the underestimated and overestimated redshift limit scenarios can affect the constraint results. In this work, the underestimated redshift (L1) shows a stringent ALP exclusion region, while the overestimated redshift (H1) is not suitable to make the ALP analysis.

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