

Sensitivity of cosmic-ray experiments to ultra-high-energy photons: reconstruction of the spectrum and limits on the superheavy dark matter

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Abstract. We estimate the sensitivity of various experiments detecting ultra-high-energy cosmic rays to primary photons with energies above 10^{19} eV. We demonstrate that the energy of a primary photon may be significantly (up to a factor of ~ 10) under- or overestimated for particular primary energies and arrival directions. We consider distortion of the reconstructed cosmic-ray spectrum for the photonic component. As an example, we use these results to constrain the parameter space of models of superheavy dark matter by means of both the observed spectra and available limits on the photon content. We find that a significant contribution of ultra-high-energy particles (photons and protons) from decays of superheavy dark matter is allowed by all these constraints.

Keywords: sensitivity , photons, SHDM

I. SENSITIVITY TO THE PHOTON COMPONENT

To calculate the spectrum of photons reconstructed by a given experiment it is important to account both for the energy estimation of a particular photon and for the experiment's exposure to photons. We obtain approximate estimates in the following way:

AGASA. The array has a geometrical exposure for hadronic primaries with energies above $10^{18.5}$ eV. The probability to accept an event by the ground detector depends only on the detector signal which is, for a given arrival direction, in one-to-one correspondence with the reconstructed energy of the event. Therefore, the exposure is geometrical for photons with reconstructed energies above $10^{18.5}$ eV. To calculate reconstructed energies for primary photons we run Monte-Carlo simulations using CORSIKA 6.611 with GHEISHA as a low-energy hadronic interaction model and EPOS 1.61 as a high-energy hadronic model. Since the hadronic component carries a small fraction of energy of a photon-induced shower, dependence of the results on the choice of hadronic model is negligible within our precision. PRESHOWER code is used to account for possible interactions of the primary photons with the geomagnetic field. The reconstructed energy for primary photons is calculated by means of the standard AGASA procedure [1] using the detector response obtained from the GEANT simulations [2]. The results of the analysis are presented in Fig. 1, left column. Photon-induced

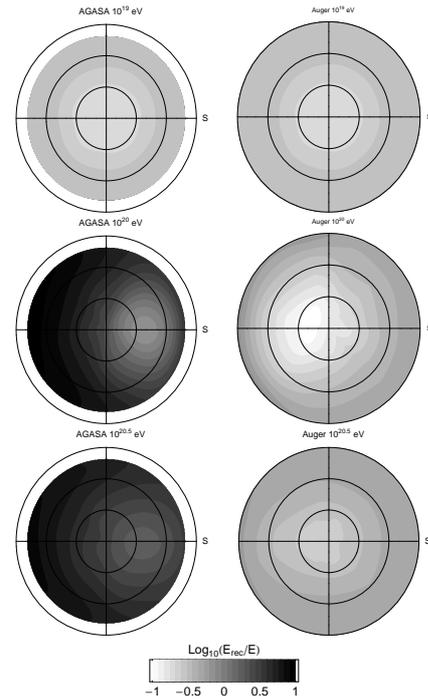


Fig. 1: Energy overestimation factor for photon showers observed by AGASA (left column) and by the surface detector of PAO as a function of energy (shown for three values marked on the plots) and arrival direction (radial coordinate: zenith angle, angle coordinate: azimuth; zenith is in the center and South is to the right of the plots). The logarithmic colour code is shown in the bottom panel.

showers penetrate deeply and are therefore younger when they reach the surface detector, as compared to the hadronic ones. This fact results in overestimation of the primary energy because of a bias in the attenuation correction (which was fit to the bulk of – presumably hadronic – showers by means of the constant intensity cuts method). On average, energies of showers with $E > 10^{19}$ eV are overestimated by a factor of ~ 2 , but for particular energies and arrival directions where the geomagnetic cascade does not compensate the LPM suppression, the overestimation may reach a factor of ten.

HiRes. The exposure of the HiRes fluorescent detector for the primary photons was calculated in Ref. [5] and has been found to be almost twice smaller than the exposure for protons. The reason is the reduced efficiency of reconstruction of deep showers, so that a significant part of them does not pass strict quality cuts determined for the spectrum-related studies. Energies reconstructed by the fluorescence method for different primary particles differ only by the contribution of particles not taking part in the electromagnetic cascade. The correction is calculated in Ref. [6]; its application for the gamma-ray showers results in overestimation of energy of primary photons by about 10%, well within the systematic uncertainties.

Pierre Auger. The surface detector of PAO also has the geometrical exposure at the highest energies we are interested in. The detector response of Auger water tanks is not published and therefore we use $S(1000)$ values for photon-induced showers without geomagnetic preshower from Fig. 3 of Ref. [3]. We perform preshower simulations using the CORSIKA PRESHOWER module for El Nihuil location and use data from Ref. [3] for secondary photons. Finally we reconstruct the primary energy using formulae of Ref. [4]. The results of our analysis are presented in Fig. 1, right column. It turns out that the photon primary energies are underestimated (for the spectrum derivation) by the PAO surface detector by the factor of four in average. The underestimation may reach an order of magnitude for particular energies and arrival directions. The physical reason for the photon energy underestimation is hypersensitivity of the water tanks to the muon component of the shower, while the latter is strongly suppressed in photon-induced showers. A completely different energy reconstruction procedure, which assumes primary gamma rays, has been applied [16] for the calculation of the photon limits. The latters are therefore insensitive to this problem.

Yakutsk. The exposure of the Yakutsk EAS array is also geometrical. The spectrum below 10^{19} eV is obtained using a small subarray [7], so the exposure depends on the energy in a known way. To obtain reconstructed energies for the primary photons we use the Monte-Carlo simulations (similar to those described above for AGASA) and the Yakutsk detector response obtained from GEANT simulations in Ref. [8]. Qualitatively, the results are very similar to those obtained for AGASA.

The results of our analysis for various experiments are illustrated in Figs. 1, 2.

With the statistics presently available it is not possible to explain the difference in spectra at the highest energies by means of the photon component. Our consideration nevertheless illustrates that the presence of a non-standard component might influence the interpretation of experimental results. We note that the gamma limits of Refs. [14], [15], [16] have been calculated with the account of the energy reconstruction for primary photons.

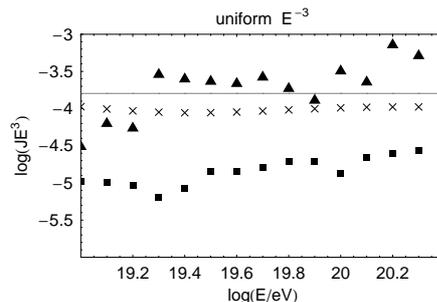


Fig. 2: The spectra reconstructed by different experiments (triangles: AGASA, crosses: HiRes, boxes: Auger) for thrown isotropic photon flux E^{-3} (gray line).

II. CONSTRAINTS ON THE SHDM PARAMETERS

As an example of application of our results, we study how the systematics in the determination of the spectrum in the presence of primary photons may affect constraints on the SHDM obtained from the limits on the primary gamma rays.

The SHDM models predict very hard spectrum with a large fraction of photons and therefore both the spectral shape and gamma limits can be used to constrain the models. We perform a joint fit of spectra of four experiments above 10^{19} eV with the sum of astrophysical and SHDM components and obtain constraints on the parameters of SHDM model. The full spectral fit is performed as described below and 95% C.L. limits listed in Sec. I are imposed as theta-functional constraints. For the photon component, we use the spectrum reconstruction for each experiment as described above, while for hadronic primaries, we consider the energy scale as a parameter of fit individual for each experiment. We take into account both photons and protons produced in SHDM decays.

The astrophysical contribution. We simulate propagation of cosmic rays from astrophysical sources using the numerical code described in Ref. [9]. The code uses the kinematic-equation approach and calculates the propagation of nuclei, nucleons, stable leptons and photons using the standard dominant processes. We take the spectrum of an individual UHECR source to be of the form

$$F(E) = fE^{-\alpha}\Theta(E_{max} - E),,$$

where f provides the flux normalization, α is the spectral index and E_{max} (E_{max}) is the maximum energy to which protons can be accelerated at the source.

We assume the standard cosmological model with the Hubble constant $H = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, the dark energy density (in units of the critical density) $\Omega_{\Lambda} = 0.7$ and a dark matter density $\Omega_{\text{m}} = 0.3$. We define total source density in this model as $n(z) = n_0(1+z)^{3+m_z} \Theta(z_{max} - z)\Theta(z - z_{min})$, where m_z parameterizes the source density evolution, in such a way that $m_z = 0$ corresponds to non-evolving sources with constant density per comoving volume, and z_{min}

and z_{\max} are respectively the redshifts of the closest and most distant sources. In this paper we use a fixed value of $z_{\max} = 3$.

The SHDM contribution. Decays of the SHDM particles may be described in a more or less model-independent way because the most important physical phenomenon of relevance is hadronization which involves light particles and is well understood. Denote $x \equiv \frac{2E}{M_X}$, where E is the energy of a decay product of the SHDM particle with mass M_X . Then for $10^{-4} \lesssim x \lesssim 0.1$, spectra of the decay products calculated by various methods are in a good agreement with each other; moreover, the shape of the spectral curve $\frac{dN}{dE}(x)$ does depend only mildly on M_X and we may consider the dependence negligible. For this study, we use the spectra of decay products from Ref. [10].

The SHDM decay rate is determined by the concentration n_X and lifetime τ_X of the SHDM particles, $\dot{n}_X = n_X/\tau_X$. The flux of secondary particles at the Earth is then determined by

$$j = \mathcal{N} \frac{1}{\tau_X} \frac{dN}{dE},$$

where

$$\mathcal{N} = \int d^3r \frac{n_X(\mathbf{r})}{4\pi r^2} \quad (1)$$

is the geometrical factor (\mathbf{r} is the radius-vector from the Earth; though in principle one should integrate over the Universe and account for relativity effects, in most interesting cases the dominant contribution comes from the Galactic halo).

The flux is assumed to be a sum of two components, one of which corresponds to the ‘‘bottom-up’’ contribution while the second one is due to the SHDM decays. While the former is assumed to be isotropic, the latter is not because of non-central position of the Sun in the Milky Way; we account for this anisotropy assuming the Navarro-Frank-White [11] dark-matter distribution and with obvious account of the exposure (field of view) of particular experiments. The account of the anisotropy reduces the difference in the reconstructed spectra for the SHDM-related photons because the energy underestimation by PAO is partially compensated by the larger flux of photons seen in the Southern hemisphere, with an opposite effect for AGASA.

The fitting procedure. Up to the normalizations (depending on τ_X for the dark-matter part), the spectra are determined by four parameters (α , E_{\max} , m_z and z_{\min}) for the astrophysical part and by M_X for the SHDM part. We scan over these parameters which are let to take their values on a grid. For the astrophysical spectrum, we use the grid described in Ref. [9]; for M_X we allow values $2^k \times 10^{22}$ eV for seven integer values of k , $-3 \leq k \leq 3$. For each point on the five-dimensional grid, we fit four experimental energy spectra (AGASA [1], Yakutsk [7], HiRes [12] and PAO [13]) with four independent energy shifts representing energy-independent systematic errors of the four experiments

and with two overall normalization factors (for the astrophysical and for the dark-matter parts), allowing these six parameters to change continuously.

We fit binned numbers of events detected by four experiments using the analog of χ^2 for the Poisson data. Technically, potential systematic errors of the energy determination of hadronic primaries (fit parameters) are taken into account as shifts of the theoretical curve and not of the data. We fix the experiments’ exposure and do not fix the total number of the detected events.

Statistical errors in energy estimation are taken into account as described in Ref. [9]. They are assumed to be Gaussian in logarithmic scale with widths 25%, 20%, 6% and 17% for AGASA, HiRes, PAO and Yakutsk respectively.

The goodness of fit is determined by the Monte-Carlo simulations. We consider a fit as acceptable if its goodness exceeds 0.05.

Results. The best fit without SHDM has a goodness of 0.19 and corresponds to energy scaling factors of 0.92, 1.04, 0.70 and 0.60 for HiRes, PAO, AGASA and Yakutsk respectively (astrophysical model $z_{\min} = 0$, $m_z = 4$, $\alpha = 2.45$, $E_{\max} = 1.28 \times 10^{21}$ eV). The best fit with SHDM has a goodness of 0.25 and corresponds to an SHDM model with $M_X = 2.5 \times 10^{21}$ eV and energy shifts 0.95, 1.07, 0.72 and 0.61 for HiRes, PAO, AGASA and Yakutsk respectively (astrophysical model $z_{\min} = 0$, $m_z = 4$, $\alpha = 2.45$, $E_{\max} = 6.4 \times 10^{20}$ eV). At (true) energies higher than 10^{20} eV, the SHDM-related component (photons and hadrons) comprises 43% of the total cosmic-ray flux for the best fit parameters. The best fit to the spectra is presented in Fig. 3.

Most relevant photon limits for constraining SHDM are AGASA+Yakutsk limit [14] on ϵ_γ above 10^{20} eV and PAO gamma flux limit [16] above 10^{19} eV. The impact of these limits on the SHDM parameter space is demonstrated in Fig. 4. All photon limits are satisfied for the best-fit values quoted above.

III. CONCLUSION

Modern experiments have different sensitivities to the photon component and this should be taken into account when testing particular models. The AGASA experiment overestimated the energy of primary photons with energies $E \gtrsim 10^{19}$ eV by a factor of 2 in average, though the overestimation reaches a factor of ~ 10 for particular energies and arrival directions. Contrary, the surface detector of the Pierre Auger Observatory underestimates the energy of primary photons in this energy range by a factor of ~ 4 in average, while underestimation by a factor of ~ 10 happens for particular energies and arrival directions. The HiRes detector overestimates the photon energies by a factor of ~ 1.1 , uniformly over arrival directions and well within the systematic uncertainties. However, it has a significantly lower exposure for primary photons than for primary hadrons.

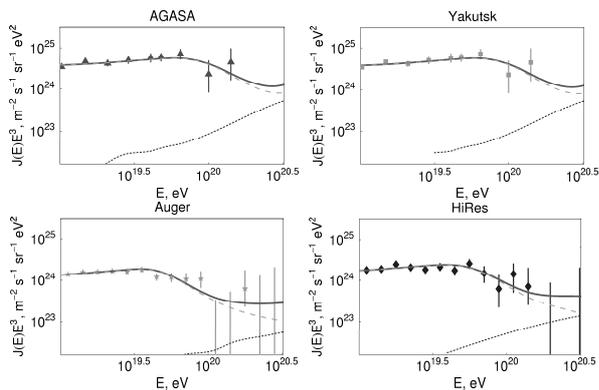


Fig. 3: The best fit of the spectra observed by different experiments with the “extragalactic plus SHDM” model. Symbols with error bars represent experimental data points, thick lines represent the best fit, dashed lines – the extragalactic component of this best-fit function, dotted lines – contribution of photons from the SHDM decays. One and the same best-fit physical spectrum looks different for different experiments because the energy reconstruction is taken into account: for the hadronic component it is encoded in the energy shifts – parameters of the fit; for the gamma-ray component it is obtained explicitly in Sec. I.

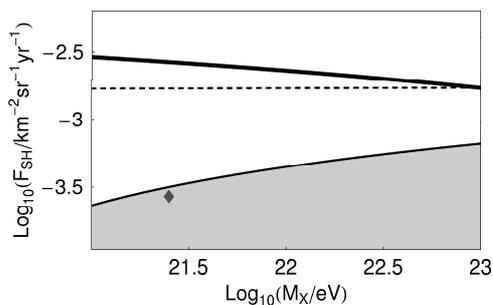


Fig. 4: Parameter space of the SHDM models: the total integral flux F_{SH} of the cosmic rays from SHDM decays at energies $E > 10^{20}$ eV (proportional to the lifetime τ_X of the SHDM particle in particular models) versus the mass M_X of the SHDM particle. The area above the thick line is excluded by the spectral fits; the area above the dashed line is excluded by the limit on ϵ_γ at $E > 10^{20}$ eV [14]; the area above the thin line is excluded by the limit on the gamma-ray flux at $E > 10^{19}$ eV [16]. The shadowed area is allowed by any constraints. The diamond indicates parameters of the best spectral fit described in the text.

One of the scenarios predicting a significant amount of primary UHE photons is the superheavy-dark-matter model. We analyzed constraints on its parameters from the observed spectra and limits on the photon content. While the most restrictive photon limits [14], [16] account for peculiarities in the energy reconstruction for photons, a dedicated study was required and performed for the spectral fits. A significant SHDM component is still allowed by all limits. More precise tests of this scenario by means of spectra, anisotropy and gamma-ray content would become possible with larger statistics.

As a final remark, we note that the example of photons should warn one against naive tests of models predicting “exotic” primaries with the experimental data. For instance, the correlations with BL Lac type objects observed by HiRes require neutral primary particles. If the latter were photons, apparent absence of correlations in the preliminary data of the PAO surface detector is easily explained by underestimation of their energies as compared to the bulk of hadronic primaries. With more exotic primary particles, the analysis becomes even less trivial.

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