

WAS THE HIGHEST ENERGY COSMIC RAY A PHOTON?*

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The hypothetical photonic origin of the most energetic air shower detected by the Fly’s Eye experiment is discussed. The method used for the analysis is based on Monte Carlo simulations including the effect of precascading of ultra-high energy (UHE) photons in the geomagnetic field. The application of this method to data expected from the Pierre Auger Observatory is discussed. The importance of complementing the southern Auger location by a northern site for UHE photon identification is pointed out.

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1. Introduction

The existence of cosmic rays of ultra-high energies (UHE), *i.e.* around 10^{20} eV, is experimentally proven, but their composition and origin are still unknown. Classic acceleration “bottom-up” scenarios favor hadrons as primary cosmic rays. These scenarios require that potential accelerating sites should exist within several tens of Mpc from Earth. Because of the interaction with the cosmic microwave background radiation, UHE particles from more distant objects are not expected to reach the Earth. Due to the lack of obvious candidate sources in our astronomical vicinity, “bottom-up” scenarios face serious difficulties in explaining the existence of UHE cosmic rays. Another class of scenarios, so-called “top-down” models, generally predicts

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a large fraction of photons in the observable UHE cosmic-ray flux. In these scenarios exotic physics effects are assumed including decays of supermassive “X-particles” which could be produced by topological defects like cosmic strings or magnetic monopoles [1]. Some of the “top-down” scenarios predict a reduced fraction of photons in the flux, and also certain fraction of photons reaching the Earth’s atmosphere is admitted by “bottom-up” scenarios. In any case, the identification of photon primaries, measurement of the UHE photon flux, or specifying the upper limit for it will provide strong constraints on models of cosmic-ray origin.

With this motivation we attempted to analyze the highest energy air shower detected by the Fly’s Eye experiment [2] in Utah, USA (40° N, 113° W), on 15 October 1991. The event parameters were finally reconstructed in 1995 [3]. The primary particle arrived at zenith angle of $43.9^{+1.8}_{-1.3}$ deg and azimuth of $31.7^{+4.2}_{-6.1}$ deg (measured counter-clockwise from East), its energy was $3.20^{+0.92}_{-0.94} \times 10^{20}$ eV and the atmospheric depth of shower maximum was found at 815 ± 60 g/cm². The primary particle mass was also discussed in Ref. [3], but only qualitative conclusions were drawn, namely that the shower profile agrees to expectations for hadron-induced events. It could have been either a proton or a heavy nucleus, but the best fits of the observed parameters to the expected ones were obtained for mid-size nuclei.

The hypothetical photonic origin of the shower was discussed by Halzen *et al.* [4]. The effect of precascading of primary gamma (preshower effect) in the geomagnetic field was taken into account in order to find the depth of photon-induced shower maximum. The comparison of this value to the experimental data led the authors to the conclusion that the hypothesis of the event being a γ -ray was inconsistent with the observations.

A more accurate analysis of hypothetical photonic origin of the Fly’s Eye record event is discussed in this work. We focus on the main results that are described in more detail in Ref. [5]. With detailed Monte Carlo simulations including CORSIKA [6,7] and our original code PRESOWER [8] described in Section 2, we obtained a set of complete photon-induced shower profiles, compared them to the observed profile and computed the probability of the event being a photon (Section 3). Probabilities for different hadron primaries are also given for completeness. Our software includes a more accurate model of the geomagnetic field than the one used in Ref. [4]. The results presented in this work are also free of a numerical error (to be commented on later) present in the publication by Erber [9]. This publication is widely cited, also in Ref. [4], as a standard reference for the cross sections necessary for computation of the cascades originated by UHE photons before they enter the Earth’s atmosphere. The present, updated analysis weakens the conclusion given in Ref. [4] by showing that the photon primary hypothesis cannot be excluded.

The presented study is also an important step towards an analysis of the UHE data from the forthcoming cosmic-ray experiments with extremely large apertures like Pierre Auger [10] or EUSO [11]. Our method of analysis can be easily adopted to any geographical position and any parameters of the primary particle. In Section 4 we discuss the sensitivity of the Pierre Auger Observatory to UHE photon primaries. In particular we compare the southern and northern site of the Observatory with respect to their local geomagnetic conditions that influence the characteristics of UHE photon-induced showers in a different way.

2. Simulations

To check for a photonic origin of the Fly's Eye event, the following analysis chain is applied. First, the propagation of UHE photons before entering the Earth's atmosphere is simulated with a Monte Carlo code. This includes the proper accounting for creation of preshowers — the effect of precascading of UHE photons in the presence of the geomagnetic field. Thereafter, another Monte Carlo simulation is involved to produce extensive air showers (EAS) induced by single UHE photons or, in cases where a preshower was created, by the resulting bunches of less energetic particles. Then the profiles of such simulated showers are compared to the data to estimate the probability of an UHE cosmic-ray primary being a photon. We stress that due to shower fluctuations and measurement uncertainties, in general it is not possible to assign unambiguously a primary particle type to an observed event. Thus we only estimate a probability for a photon and, for completeness, for other primary types.

2.1. Preshower formation

Preshower features have been investigated by various authors, see for instance [4, 8, 12–20]. Below we give only a short description of the preshower formation process.

A photon of energy above 10^{19} eV, in the geomagnetic field, can convert into an electron-positron pair before entering the atmosphere. The conversion probability depends on the primary photon energy E_0 and on the magnetic field component transverse to the direction of photon motion (B_{\perp}). The resultant electrons subsequently lose their energy by magnetic bremsstrahlung (synchrotron radiation). The probability of emitting a bremsstrahlung photon depends on the electron energy and also on B_{\perp} . If the energy of the emitted photon is high enough, it can create another electron-positron pair. In this way, instead of the primary high-energy photon, a cascade of less energetic particles, mainly photons and a few electrons,

will enter the atmosphere. We call this cascade a “preshower” since it originates and develops above the atmosphere, *i.e.* before the “ordinary” shower development in air.

A more detailed analysis of the preshower effect (see Ref. [8]) shows that other accompanying phenomena like deflection of $e^{+/-}$ trajectories in the magnetic field, influence of solar wind, time delay of particles moving slower than photons or γ conversion in the Sun’s magnetosphere are of minor importance and can be neglected in the simulations. Therefore, the approximation in which all the preshower particles have the same trajectory and arrival time at the top of atmosphere can be regarded as sufficient.

2.2. Simulation tools

A detailed description of PRESOWER, the code dealing with the preshower effect which was applied in the present analysis, is given in Ref. [8]. In brief, the geomagnetic field components are calculated according to the International Geomagnetic Reference Field (IGRF) model [21]. The primary photon propagation is started at an altitude corresponding to five Earth’s radii. The integrated conversion probability at larger distances is sufficiently small. The photon conversion probability is calculated in steps of 10 km until the conversion happens or the top of the atmosphere (112 km) is reached. After conversion, in steps of 1 km, the resultant electrons are checked for bremsstrahlung emission with an adequate probability distribution of the emitted photon energy. A cutoff of 10^{12} eV is applied for the bremsstrahlung photons, as the influence of photons at lower energies is negligible for the air shower evolution. The preshower simulation is finished when the top of atmosphere is reached.

As an example, the resultant energy spectrum of the preshower particles for the primary photon with energy and arrival direction of the Fly’s Eye record event is shown in figure 1. We note that the photons and electrons reach the atmosphere with energies below 10^{20} eV and most of the initial energy is stored in particles of $\simeq 10^{19}$ eV. These results don’t suffer from the numerical error decreasing gamma conversion probability which is present in the standard reference [9] on the subject. For the Fly’s Eye event parameters, calculations with this error would yield the energy fraction contained in the particles at energies above 10^{19} eV higher by about 15% and the number of particles in the preshower smaller by about 20%.

In order to analyze the properties of showers induced by UHE photons, we combined PRESOWER with a widely used air shower Monte Carlo simulation — CORSIKA. Electromagnetic interactions are simulated in CORSIKA via the EGS4 code [22] and also the Landau–Pomeranchuk–Migdal (LPM) effect [23] is taken into account which is responsible for the

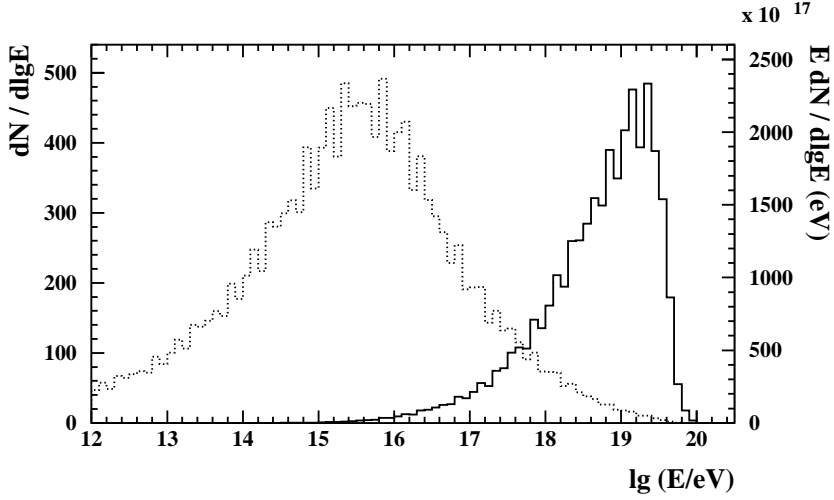


Fig. 1. Energy spectrum of the preshower particles (dotted line) and spectrum weighted by energy (solid line) for the conditions of the Fly's Eye event (average of 1000 simulation runs).

increase of mean free path of electromagnetic particles. This increase causes a significant delay of shower development for the electromagnetic primaries at energies 10^{19} eV and larger. Also the shower-to-shower fluctuations might be larger due to the LPM effect.

The connection between PRESOWER and CORSIKA is organized as follows. PRESOWER computes the energies and types of all the preshower particles, assuming for all of them the same trajectory and arrival time at the top of atmosphere. Preshower particle data are subsequently passed to CORSIKA which processes each particle independently, *i.e.* each preshower particle initiates an atmospheric subshower and a final EAS is a superposition of these subshowers.

We want to stress that this simulation chain allows to accurately reproduce features of UHE photon-induced showers that can be compared to the measurements. In particular, the shower fluctuations predicted by the MC simulations are preserved this way.

3. Fly's Eye record event

The arrival direction of the Fly's Eye record event makes an angle of 63° with the local magnetic field \mathbf{B} . According to our results, this indicates that if the primary particle were a photon, it would have produced a pair with almost 100% probability, and the resulting preshower would have been

rather large. Now we focus on the properties of an extensive air shower induced by these particles and compare them to showers induced by other primaries.

For the parameters of the Fly's Eye event, the profiles of EAS initiated by different primary particles were produced. We obtained 1000 profiles of photon-induced showers with PRESHOWER + CORSIKA. Shower profiles for p , C and Fe primaries were obtained with CORSIKA alone using two different hadronic interaction models: QGSJET 01 [24] and SIBYLL 2.1 [25]. 1000 profiles per each primary/model were computed. Since the Fly's Eye experiment used only the fluorescence technique of cosmic-ray detection, in this work we concentrated on longitudinal profiles of the showers.

The most promising EAS feature characteristic for UHE primary photon — the atmospheric depth of shower maximum X_{\max} — was extracted from the simulated data. For hadron primaries, with any of the two hadronic interaction models, the X_{\max} values between 783 g/cm^2 (Fe, QGSJET 01) and 882 g/cm^2 (p , SIBYLL 2.1) agree well with the measured value of $X_{\max} = 815 \pm 60 \text{ g/cm}^2$. For a photon primary, the value of $X_{\max} = 937 \text{ g/cm}^2$ gives a larger, but not too large, discrepancy between the data and the expected profile — about 2σ . Thus, concerning the conclusions based on the depth of shower maximum, neither any hadron/model combination tested, nor the photon primary hypothesis, can be excluded in the reconstruction of the Fly's Eye event primary type.

For the statistical analysis of complete longitudinal profiles the correlation of the atmospheric depths X_j of the reconstructed data points is taken into account. This is necessary, as the values X_j emerge from a common geometry fit to the observed signal. The calculation of the probability P_i of each individual simulated profile being consistent with the measurements is based on the reconstructed profile data as shown in figure 2. Gaussian probability density functions for the uncertainties σ_{N_j} and σ_{X_j} of the data points were assumed. Other details concerning the method of computing P_i are discussed in Ref. [5]. The overall probability P for a primary photon or other particle being consistent with the data is obtained by averaging the probabilities P_i for the individual profiles. In this way also shower fluctuations are taken into account. The overall probability is $P \simeq 13\%$. This corresponds to a discrepancy between photons and data of about 1.5σ . To illustrate this, we shifted the Fly's Eye event data by 1.5σ and put them onto the simulated photon profiles (Fig. 2) and a reasonable agreement can be noted. The quantitative analysis is published in Ref. [5].

The results obtained for the primary photon and hadron hypotheses are summarized in Table I. From these results a safe conclusion about the hypothetical photonic origin of the Fly's Eye highest energy event can be drawn: the primary photon hypothesis, although not favored by data, cannot be

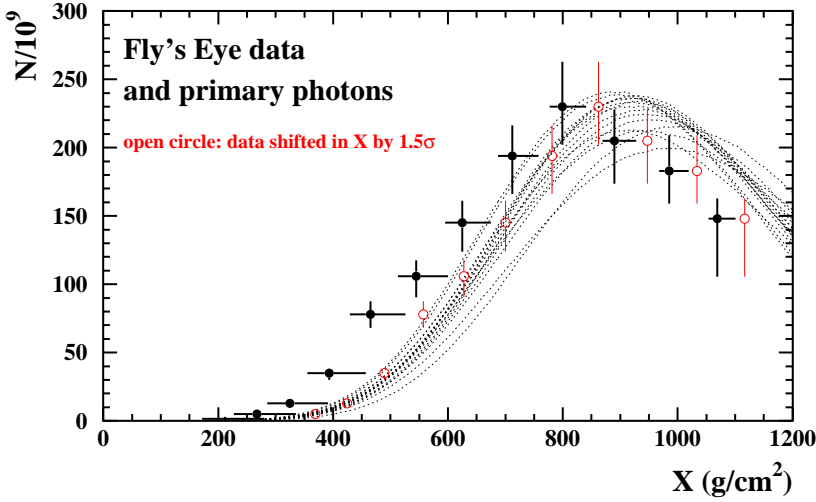


Fig. 2. Random subset of simulated longitudinal profiles of photon-initiated showers compared to the Fly's Eye data as measured by the experiment (circles with vertical and horizontal errors) and the ones shifted by 1.5σ ($X_j \rightarrow X_j + 1.5\sigma_{X_j}$) in the direction of simulated profiles (open circles with only vertical errors).

TABLE I

Probability P of a given primary particle hypothesis to be consistent with the observed Fly's Eye event profile and corresponding discrepancy Δ in units of standard deviations.

		QGSJET 01			SIBYLL 2.1		
	photon	p	C	Fe	p	C	Fe
P [%]	13	43	54	53	31	52	54
Δ [σ]	1.5	0.8	0.6	0.6	1.0	0.6	0.6

excluded. This result does not confirm the previous analysis published in Ref. [4]. Concerning primary hadrons, the previous conclusions are confirmed by this quantitative analysis. Any hadron/model combination tested within this study is consistent with the data.

4. Photon characteristics and the Pierre Auger Observatory

The analysis method that was applied to the Fly's Eye event can be easily adopted for other experiments and used for data analysis on larger scale. As an example, the prospects for identification of photons by the Pierre Auger experiment are discussed.

In Table II are collected the simulation results of photon-induced EAS profiles for conditions of the southern Auger Observatory in Malargüe, Argentina (35.2°S , 69.2°W). For different primary energies and arrival directions, full Monte Carlo simulations of photon-induced EAS were performed with use of PRESHOWER+CORSIKA. Similarly to the Fly's Eye event simulations, the strong and weak B_\perp directions are defined with respect to the local magnetic conditions of Malargüe, in the frame where the azimuth increases counter-clockwise from East.

TABLE II

Basic properties of exemplary photon-induced showers for magnetic conditions of Malargüe (35.2°S , 69.2°W).

E_0 [eV]	arrival direction	fraction of converted	$\langle X_{\text{max}} \rangle$ [g/cm ²]	$\langle \text{RMS}(X_{\text{max}}) \rangle$ [g/cm ²]
$10^{19.5}$	strong B_\perp	1/50	1065	90
$10^{20.0}$	weak B_\perp	1/100	1225	175
$10^{20.0}$	strong B_\perp	91/100	940	85
$10^{21.0}$	weak B_\perp	100/100	1040	40
$10^{21.0}$	strong B_\perp	100/100	965	20

strong B_\perp : $\theta = 53^\circ$, $\phi = 267^\circ$; weak B_\perp : $\theta = 53^\circ$, $\phi = 87^\circ$

Analyzing the values given in Table II, some EAS signatures that could be helpful in identification of primary photons as cosmic rays can be listed. First, the X_{max} value of an EAS initiated by unconverted photon is extraordinarily deep. In this case also the fluctuations of X_{max} are larger than in hadronic showers. For an example, one can look at primary energy of 10^{20} eV and the weak B_\perp arrival direction, where almost no conversion of primary photons occurs and $X_{\text{max}}(\gamma) = 1225 \pm 175$ g/cm² which is much larger than the value typical for proton primaries of the same energy: $X_{\text{max}}(p) = 820 \pm 60$ g/cm². This signature could allow for identification of photons on event-by-event basis.

Another promising feature is the directional dependence of X_{max} and $\text{RMS}(X_{\text{max}})$. As an example of it, consider showers of primary energies equal 10^{20} eV, arriving from two different directions: weak B_\perp and strong B_\perp . Both X_{max} and its fluctuations are smaller for the strong B_\perp direction, for which in most cases gamma conversion took place, than for the weak B_\perp , where almost all primary photons remain unconverted and the EAS they induce have their maxima deeper in the atmosphere. If photons constitute a substantial fraction of UHE cosmic-ray flux, such a directional anisotropy of X_{max} and $\text{RMS}(X_{\text{max}})$ should be seen in the experimental data, provided sufficiently high statistics is available.

The other EAS feature that is characteristic only for UHE photon primaries is the small or negative elongation rate $dX_{\text{max}}/d \log E$. For photon-induced showers between 10^{20} eV and 10^{21} eV coming from the strong B_{\perp} direction the simulated elongation rate 25 g/cm^2 is much less than $\approx 60 \text{ g/cm}^2$ for proton or iron showers. For events between 10^{20} eV and 10^{21} eV arriving from the weak B_{\perp} direction the elongation rate is even *negative* (*i.e.* X_{max} decreases with energy). This is because the preshowering effect for photons at 10^{21} eV splits the initial energy into energies less than 10^{20} eV, and at this energy level, for the weak B_{\perp} direction, almost all the primary photons remain unconverted and they induce air showers with deeper X_{max} . Studies on this feature also require large statistics of UHE events.

To have a rough feeling of how sensitive the Pierre Auger Observatory is to the UHE photon flux, the following evaluation has been performed. Depending on the actual high-energy particle flux and including a duty cycle of 10–15%, the fluorescence telescopes of the Pierre Auger Observatory are expected to record about 30–50 showers with primary energies exceeding 10^{20} eV within a few years of data taking [10]. If for each of these events probability of photon primary would be on the level of $\epsilon = 5\%$, a photon fraction in UHE cosmic-ray flux exceeding 14% (for 30 events) to 10% (for 50 events) could be excluded with 95% confidence level. In case of the Fly’s Eye event, a value of $\epsilon = 5\%$ corresponds to reducing *e.g.* the uncertainties σ_{X_j} by a factor 1.5, which seems well in reach for the Auger experiment. Such an upper limit for the photon contribution to the flux would be a serious constraint for models of cosmic-ray origin.

Besides the already active detectors in Argentina, the Pierre Auger Project includes a plan to build an observatory in the northern hemisphere which probably will be located close to the original Fly’s Eye site. Apart from other advantages of having observatories on two hemispheres, like for instance full sky coverage, there is also a “pro” argument regarding identification of photons.

The local geomagnetic fields differ significantly for Auger North and South both in orientation and in strength, thus the preshower effect for primary photons is different for the two locations. For Auger South, the local magnetic field vector points 35° upwards at an azimuth of 86° , while for Auger North it points downwards with 66° at an azimuth of 75° (azimuth measured counterclockwise from East). With the Auger North location being closer to the magnetic pole, the local field strength of 0.54 Gauss is about twice the Auger South value (0.25 Gauss).

As an example of the consequences on preshower formation, directional conversion probabilities of both sites are given in Fig. 3 for different primary photon energies. In addition to the different directional dependence, the stronger magnetic field at Auger North leads to a lower threshold en-

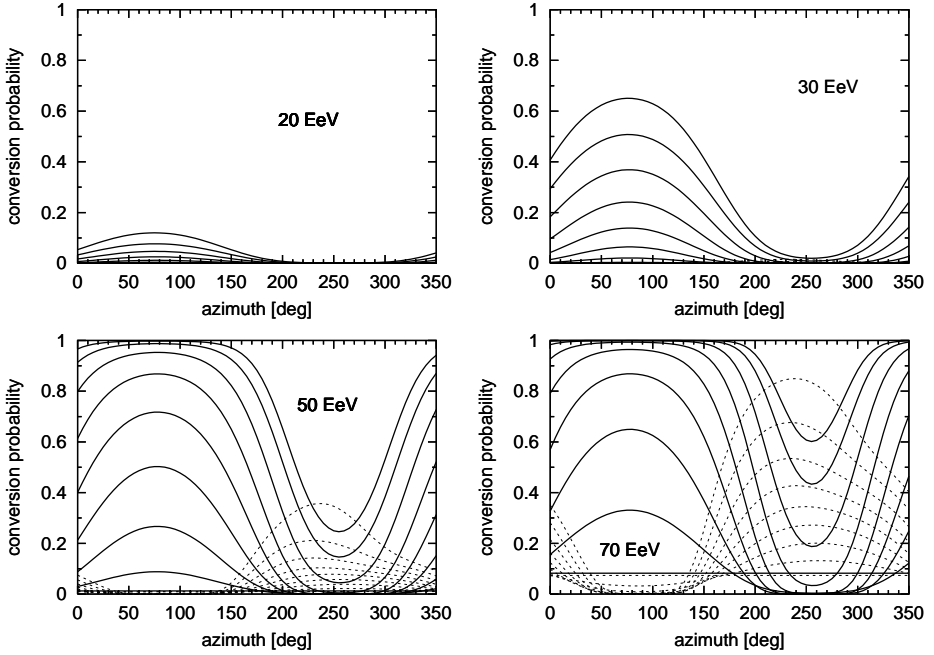


Fig. 3. Probability of photon conversion for different arrival directions and four primary energies. The calculations are shown for Auger North (solid line) and Auger South (dashed line) magnetic conditions for the year 2005. Each curve corresponds to a different zenith angle, from 80° for the uppermost curve down to 0° for the lowest one in steps of 10° . Azimuth is given counterclockwise from East for the incoming photon.

ergy for the preshower onset of about 20–30 EeV, while for Auger South even at 70 EeV a large photon fraction might enter the atmosphere without conversion.

This can be used to perform a photon search in a complementary way, both in case of presence or absence of a photon signal: at Auger South (higher preshower threshold), a larger number of unconverted photons of higher energy would allow better distinction from hadrons on event-by-event basis. On the other hand, at Auger North (lower preshower threshold), the independent photon signature of large directional dependences in the shower observables could be tested with larger event statistics. In particular in case of a photon signal observed at one site, looking for a photon signature at the other site that is expected to differ in a well-predictable way, would allow a serious cross-check and might offer conclusive confirmation of the signal.

5. Summary and outlook

Detailed investigations on the primary particle type of the record Fly's Eye shower were performed. The focus was put on the hypothetic photonic origin of this event. With an accurate simulation tool including preshowering and the LPM effects, the probability of primary particle being a photon was calculated. The discrepancy between the simulated data and measured profile at the level of 1.5σ indicates that although the primary photon hypothesis is not favored by data, it cannot be excluded.

It is pointed out that this analysis method can be applied to any other "fluorescence experiment", and with a generalized observable set also to ground arrays. An application to the Pierre Auger Observatory was discussed. At the time of writing, the southern part of it has started data taking and is already the largest UHE cosmic-ray detector in the world. Measurement of UHE photon flux or specifying the upper limit for it will give a serious constraint for theoretical scenarios explaining the origin of UHE cosmic rays. From our results it appears that UHE event statistics expected during the operation of the Auger experiment will be sufficient to give good prospects for identification of photons as UHE cosmic-ray primaries or to determine the upper limit of their flux. Such an approach to identification of photons will benefit considerably from two observatories located in different hemispheres.

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