The latest result on UHE-photons at the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory is the most sensitive detector to primary photons with energies above 0.2 EeV providing unprecedented exposure to ultra-high-energy (UHE) cosmic rays and specifically to UHE photons. The Observatory measures extensive air showers using a hybrid technique that combines a fluorescence detector (FD) with a ground array of particle detectors (SD). The signatures of a photon-induced air shower are a larger atmospheric depth of the shower maximum (X_{max}) and a steeper lateral distribution function, along with a lower number of muons with respect to the bulk of hadron-induced background. Using observables measured by the FD and SD, various photon searches in different energy bands are performed. These efforts have produced some of the most stringent upper limits on the diffuse fluxes of UHE photons. These limits place significant constraints on current models for the origin of UHE cosmic rays, highlighting the leading role of the Observatory in multimessenger astronomy at the highest energies. In this contribution, an overview of current activities related to the search for UHE photons is shown, using more than 15 years of data from the Pierre Auger Observatory. The latest results of the searches for diffuse fluxes of photons will be presented, as well as follow-up searches for UHE photons in association with transient events, such as gravitational wave events, will be summarized.

1 Introduction

Photons play a pivotal role in the quest to unravel the origins of ultra-high-energy (UHE) cosmic rays, These photons, often produced alongside cosmic rays, can emerge directly from their sources (as "astrophysical" photons) or result from interactions during cosmic-ray propagation through the Universe (yielding "cosmogenic" photons). While cosmic background interactions limit UHE photons to those originating from the local Universe, within scales of a few Mpc, they remain invaluable messengers for studying both astrophysical phenomena and potential new physics [1], such as the properties of dark matter [2].

Due to their extremely low flux, UHE photons cannot be directly detected using instruments located onboard satellites or balloons. Instead, they are identified indirectly when they interact with Earth's atmosphere, initiating extensive air showers analogous to those produced by charged cosmic rays. As a result, cosmic-ray observatories designed for air-shower detection inherently serve as photon detectors, complementing specialized instruments and contributing critical data to multimessenger studies.

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The discussion focuses on the latest UHE photon studies using the Pierre Auger Observatory. A brief introduction to the Observatory is provided in Section 2. Diffuse photon searches are discussed in Section 3, followed by targeted follow-up analyses in Section 4.

2 The Pierre Auger Observatory

The Pierre Auger Observatory [3] is the largest cosmic-ray detector in the world, situated near Malargüe in the Argentinian Pampa Amarilla. Its hybrid design combines a Surface Detector (SD) array with a Fluorescence Detector (FD), offering complementary approaches to air shower observation. The SD consists of approximately 1600 water-Cherenkov detectors deployed in a triangular grid with a spacing of 1500 meters, covering an area of around 3000 km^2. Overlooking this array is the Fluorescence Detector (FD), composed by 24 fluorescence telescopes, distributed across four sites at the perimeter of the SD array.

The SD operates continuously, recording the lateral particle distribution at ground level with nearly 100% uptime. In contrast, the FD observes the longitudinal development of air showers in the atmosphere but is limited to clear, moonless nights, resulting in a duty cycle of about 15%. To enhance sensitivity to lower-energy air showers (below 10^{18} eV), two denser sub-array with a spacing of 750 meters and 433 meters have been implemented within the SD array. To complement these measurements, three High-Elevation Auger Telescopes (HEAT) have been installed near the Coihueco FD site. These telescopes extend the observational range to higher elevation angles (30° to 60°), supplementing the standard Coihueco telescopes, which observe the 0° to 30° range. By combining data from both the HEAT and Coihueco systems (referred to as "HeCo" data), the Observatory enables fluorescence observations over a broader range of air shower geometries, enhancing its capability to study cosmic rays across a wide spectrum of energies.

3 Photon diffuse analyses at the Pierre Auger Observatory

The identification of ultra-high-energy (UHE) photons at the Pierre Auger Observatory relies on the ability to distinguish photon-induced extensive air showers (EAS) from those initiated by the dominant background of protons and nuclei. Photon showers differ fundamentally due to the dominance of electromagnetic interactions during their development [4]. This results in a deeper atmospheric depth of the shower maximum ($X_{\max}$) and a significantly reduced muon content compared to hadronic showers. Consequently, photon showers have steeper lateral distributions and smaller footprints on the ground. These features are exploited in various analyses tailored to different energy ranges and sub-detectors.

For energies above 2×10^{16} eV, the muon densities measured by the UMD stations of the 433 m array are combined into a single event-wise observable [5]. The relative background contamination ranges between 10^{-4} to 10^{-7} under the assumption of a pure-proton background, conservative in light of the deficit of muons identified in the air-shower simulations. The photon candidate cut was applied to 15 months of data, equivalent to an exposure of ~ 0.6 km^2 sr yr, and no photon candidate events were identified.

For energies between 2×10^{17} and 10^{18} eV, the analysis employs three key observables [6]: $X_{\max}$, a parameter, S_b, related to the lateral steepness of the shower, and the number of triggered stations, N_{stations}. These observables are combined using a boosted decision tree (BDT), trained on simulated photon- and proton-induced showers. Applying this analysis to data collected between 2010 and 2015 revealed no photon candidates, leading to stringent upper limits on the diffuse photon flux.

In the range 10^{18} to 10^{19} eV, the analysis incorporates $X_{\max}$ alongside F_μ, a proxy for the muon content of the shower [7]. The parameter F_μ is reconstructed using a model based on air shower universality [8, 9], taking as input the signals measured by the surface detector (SD), the geometry of the shower, and X_{max} from the fluorescence detector (FD). These observables are combined using a Fisher discriminant analysis, achieving high background rejection. The analysis of data from 2005 to 2017 identified no significant excess of photon-like events.

Above 10^{19} eV, the limited data from fluorescence detectors (FD) necessitates relying solely on surface detector (SD) data, which benefits from a nearly continuous duty cycle. Two key observables are used to analyze the events in this energy range: L_{LDF} and Δ [10]. The observable L_{LDF} characterizes how the signals measured at the detector stations deviate from the expected lateral distribution of the air shower. The parameter Δ, on the other hand, assesses deviations in the timing of the signal rise, comparing them to reference values from background events.

These two observables are combined using a Fisher discriminant analysis to identify potential photon candidates in SD data collected from 2004 to 2020. No unambiguous photon candidates were identified.

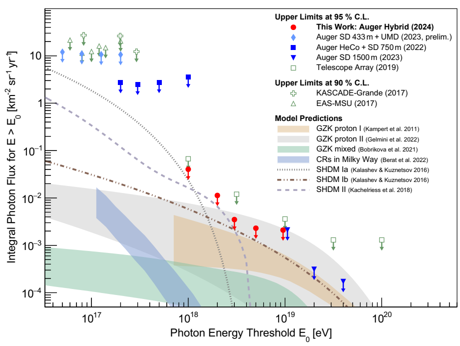

Figure 1. Current Pierre Auger upper limits on the integral photon flux (solid markers) [6, 7, 10], along with preliminary results from [5]. For comparison, limits from other experiments are included: KASCADE-Grande (green crosses) [11], EAS-MSU (green triangles) [12], and Telescope Array (green squares) [13]. The expected photon fluxes are also depicted: the GZK photon flux for pure-proton models (brown and gray bands) [14, 15], the GZK flux for a mixed composition consistent with Auger data (green band) [16], and photon fluxes from cosmic-ray interactions in the Milky Way (light blue band) [17]. Predicted fluxes from the decay of super-heavy dark matter particles are shown for different masses and lifetimes [18, 19].

The combined results of these analyses yield the most stringent upper limits to date on the diffuse photon flux, as shown in Figure 1. These constraints provide critical tests for theoretical models [20, 21] and predictions for cosmogenic photon fluxes.

4 Follow-up searches with UHE-photons

Photons traveling over cosmological distances are significantly attenuated due to interactions with cosmic background radiation fields, resulting in a suppressed flux at Earth. For gravitational wave follow-ups, a dedicated selection strategy has been developed to enhance sensitivity by focusing on close or well-localized events. This approach prioritizes sources within a small 50% C.L. localization contour and at limited luminosity distances [22]. Notably, events like GW170817—associated with a neutron star merger and a gamma-ray burst—were analyzed for coincident UHE photons within a time window of one sidereal day. Despite the comprehensive analysis, no photon candidate events were detected, and preliminary upper limits on the spectral fluence were established.

The same framework has been applied to other transients, such as flares from the blazar TXS 0506+056, observed during periods of enhanced neutrino activity reported by IceCube. No coincident photon events were identified in these analyses.

These findings reaffirm the importance of UHE photon searches for probing extreme astrophysical phenomena and exploring potential new physics scenarios. Future efforts, bolstered by advancements from AugerPrime, aim to enhance sensitivity and refine our understanding of UHE photon propagation and sources.

5 Conclusions

The search for ultra-high-energy (UHE) photons remains a vital component in advancing our understanding of the high-energy Universe and exploring fundamental physics. Analyses at the Pierre Auger Observatory have set the most stringent upper limits to date on the diffuse flux of UHE photons, leveraging observables correlated to key shower features of the extensive air showers such as X_{max} and the number of muons. These results provide essential constraints on astrophysical models and exotic scenarios, including super-heavy dark matter decay.

Future improvements in the ongoing AugerPrime upgrade will play a transformative role. The installation of scintillation detectors atop the water-Cherenkov stations will allow for a more direct separation of photon- and hadron-induced air showers, enhancing the discrimination power of the Surface Detector. Furthermore, the integration of radio antennas will provide complementary information about the electromagnetic component of air showers, further refining photon searches.

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