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Searching for multi-messenger signals with the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory [1], primarily designed for the detection of ultra-high energy (UHE) cosmic rays, has been proven to be also an excellent tool in multi-messenger searches. With its unprecedented exposure to UHE particles, it is exploited to set stringent upper limits on the diffuse flux of UHE photons and neutrinos and to look for neutral particles associated with steady sources and transient events, such as gravitational waves. All these searches can provide key information to investigate the most energetic phenomena in the Universe and answer some of the most important still-open questions in astrophysics.

1 Introduction

Multi-messenger astronomy aims at combining the information from any particle and radiation coming from astrophysical objects to get a deeper insight on their nature. Such studies underwent a significant boost after the first detection of gravitational waves and the rise of neutrino astronomy [2, 3].

The Pierre Auger Observatory, the largest experiment in the world for the detection of ultra-high energy particles, exploits the properties of air showers to identify the ones induced by UHE photons and neutrinos among the hadronic background. Since many models for the origin of UHE cosmic rays predict the production of neutral particles either at the sources or during the propagation through the Universe, the current upper limits have already set strong constraints on them. Moreover, neutral particles directly point back to their production site, which allows their association with specific sources or events. An overview of the on-going multi-messenger activities within the Pierre Auger Collaboration is here presented.

2 Searches for photons

In many models UHE photons originate from the decay of neutral pions produced by the interactions of protons with the Cosmic Microwave Background (CMB) photons and/or with photon fields within the source environment. However, since UHE photons also interact during their propagation and may be eventually absorbed, only distances to about a few tens of kpc can be explored with photons around 10^{15} eV, which rises to few Mpc around 10^{19} eV.

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The identification of photon-induced air showers relies on the fact that they are dominated by electromagnetic interactions, hence they exhibit a deeper maximum development in the atmosphere $X_{\max}$, which is discriminated with the Fluorescence Detector (FD), and a smaller amount of muons at the ground, which is associated with a slower-rising signal in the single SD stations. Both the deeper $X_{\max}$ and the lower number of muons are reflected in a steeper lateral distribution function (LDF) measured by the Surface Detector (SD) [4]. No UHE photon has been unambiguously detected so far, but Auger set the most stringent upper limits on their flux.

2.1 Diffuse photon flux

Upper limits on the unresolved flux of photons have been set above 2×10^{17} eV. Different techniques are used depending on the energy range.

For the lowest energies the low-energy extensions of the Pierre Auger Observatory are used in a hybrid configuration, i.e. the 750 m SD array and the High Elevation Fluorescence Telescopes (HEAT); three quantities are combined in a multivariate analysis using a Boosted Decision Tree (BDT): the $X_{\max}$ measured by the FD, the number of triggered SD stations and a SD observable sensitive to the difference in LDF called S_b [5]. In the energy range between 10^{18} eV and 10^{19} eV hybrid events are also used in a linear Fisher discriminant analysis, to combine $X_{\max}$ with a parameter F_μ, related to the muon content and derived through the air shower universality concept [6]. As concerns energies above 10^{19} eV, only the SD data are used because of the lack of FD statistics and a Fisher discriminant analysis is used to combine two variables, one related to the steepness of the LDF and one to the risetime of the SD signals [7]. The upper limits on the photon flux at 95% confidence level are shown in Fig. 1 in the whole energy range [8].

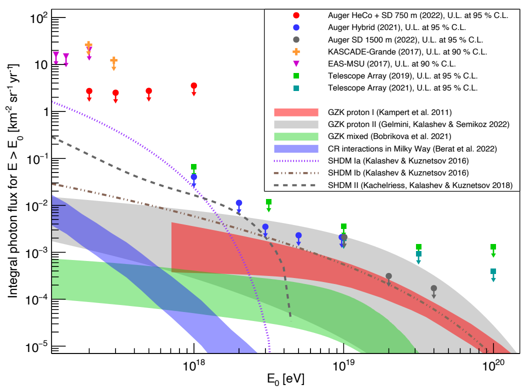

Figure 1. Upper limits on the photon flux at 95% C.L., shown together with predictions from models and other experimental results [8].

2.2 Photons from point-like sources and transient events

Both blind and targeted searches for point-like steady sources of UHE photons are performed in Auger. The analyses are applied to the energy range between $10^{17.3}$ eV and $10^{18.5}$ eV; a BDT is used to select photon-like air showers, with $X_{\max}$ and S_b as the main input variables. No evidence for an excess of photon-like events from any considered direction has been found with the blind search and the corresponding upper limits on the flux of UHE photons are shown in Fig. 2 for each direction [9]. In the case of the targeted search, 12 predefined target classes are chosen, which

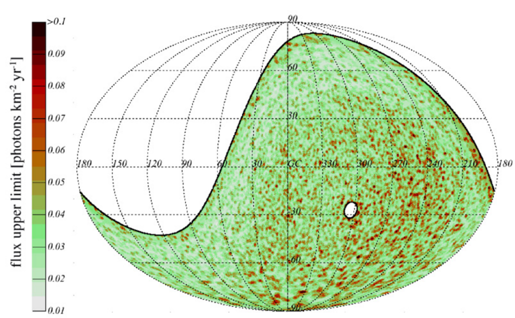

Figure 2. Upper limits on the photon flux as a function of the Galactic coordinates in the celestial map [9].

contain mostly Galactic sources, as well as two extragalactic target sets (three sources of γ-rays in the Large Magellanic Cloud and the core region of Centaurus A) and the Galactic center. No evidence for sources emitting photons in the considered energy range has been found [10].

The Pierre Auger Observatory also performs follow-up searches for photons in association with gravitational waves. Since the UHE photons are significantly attenuated because of the interactions with background radiation fields, the gravitational wave (GW) events are carefully selected to accept only close or well-localized sources; UHE photons are looked for in specific time windows after and around the gravitational wave event. Preliminary results have been obtained by considering a selection of four GW events and no photon candidate was identified, but the first upper limits were set [11].

3 Searches for neutrinos

Similarly to photons, neutrinos at UHE are also produced as a result of the decay of charged pions generated in the interactions of cosmic rays with photon fields. They can travel very long distances without being absorbed and hence are excellent probes into the extragalactic sources and their cosmological evolution.

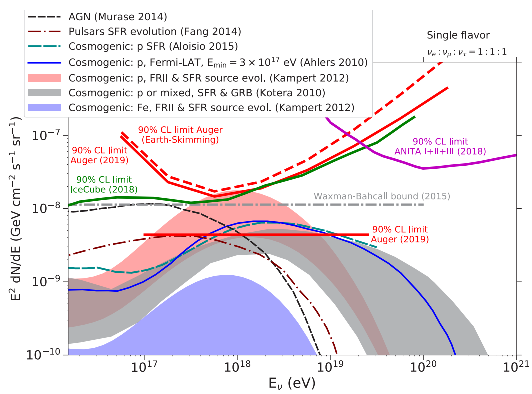

Figure 3. Upper limits at 90% C.L. to the normalization k of the diffuse flux of neutrinos, shown together with predictions from models and other experimental results [12].

Neutrinos, having a greater interaction length with respect to hadrons, interact deeper in atmosphere. As a consequence, inclined showers induced by neutrinos are still "young", i.e. rich in electromagnetic component, when they reach the ground and exhibit broader signals in the SD stations. Hence, inclined showers ($\theta > 60^o$), the ones associated to a very elongated footprint on the SD stations, are used to discriminate neutrinos. In addition to inclined down-going (DG) showers, also Earth-skimming (ES) upward-going showers can be considered ($90^o < \theta < 95^o$): they are associated to the decay in atmosphere of τ leptons, produced by the interactions of ν_τ in the Earth's crust. Even if no UHE neutrino has been unambiguously identified so far, the current upper limits set by Auger are among the most stringent ones.

3.1 Diffuse neutrino flux

Neutrinos with energies above 10^{17} eV can be detected with the SD of the Pierre Auger Observatory. The search for ES showers is performed considering the average signal Area over Peak over the triggered stations, which is related to the broadness of the shower front. As concerns DG showers, the neutrino selection is performed with a multivariate analysis by using different observables depending on the zenith angle, which are combined together in a Fisher discriminant. Assuming a differential flux $\phi = k \times E^{-2}$, the upper limit at 90% C.L. is set through the normalization k and is shown in Fig. 3. The integrated limit to k is 4.4×10^{-9} GeV cm^{-2} s^{-1}sr^{-1}, defined as the value needed for ~ 2.19 expected events, which is the Feldman-Cousins factor for non-observation of events in the absence of background. The maximum sensitivity of Auger is reached at ∼ EeV, where most cosmogenic models peak, so that several models are already disfavoured by the current upper limits [12].

3.2 Neutrinos from point-like sources and transient events

Neutrinos from point-like sources can also be searched with the SD of Auger, with the same exposure calculation used for the diffuse flux but without integrating over the whole sky. A blind search for steady point-like sources is performed and upper limits as a function of declination are found for each data set, which are shown in Fig. 4. Being sensitive to energies above 10^{17} eV, Auger provides complementary information with respect to the limits given by other experiments, e.g. IceCube, which are sensitive to lower energies [13]. In order to look for neutrinos associated with transient events, the effective area over the relevant time interval has to be considered. The sensitivity to transient sources also depends on the efficiency of the detection during the time interval of interest and may exceed that of other dedicated neutrino detectors for some energies and some inclinations. The future detection of neutrinos in coincidence with a GW event could help in localizing the position of the source [14].

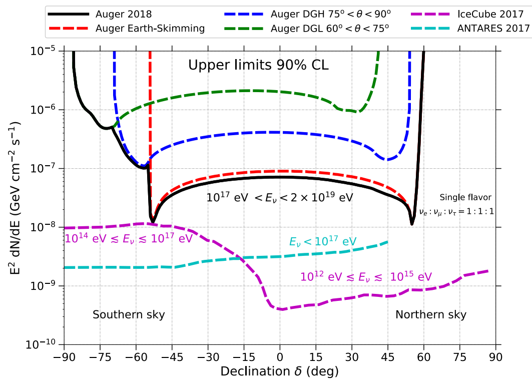

Figure 4. Upper limits at 90% C.L. to the normalization of the point-like flux of UHE neutrinos as a function of declination, together with results from other experiments [13].

4 Future prospects

The Pierre Auger Observatory will continue to monitor the UHE sky and contribute to multi-messenger studies. The on-going upgrade of the experiment, dubbed AugerPrime, will signficantly improve the discrimination between the electromagnetic and muonic components in air showers, which is a crucial aspect in the identification of neutral particles. Such an enhancement will further strengthen the capabilities of the Pierre Auger Observatory as a multi-messenger observatory in the near future [15].

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