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Search for neutral particles with the Pierre Auger Observatory

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The Pierre Auger Observatory is the largest and most important hybrid detector designed to investigate the origin and the nature of ultra-high energy cosmic rays (UHECR). The Observatory has been in operation continuously since 2004, and during the currently more than 18 years of research has collected a huge amount of high-quality data which gave us knowledge about the origin of the most energetic particles ever observed in the Universe. This contribution will present the main results obtained in searches for neutral particles during Auger Phase1, i.e., the period before the installation of the upgrade AugerPrime. These include the searches for UHE photons, neutrinos and neutrons, which mainly made it possible to set upper limits on their fluxes and to search for excesses in the direction of candidate acceleration sources and transient events.

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1. Introduction

Multi-messenger astronomy represents a thrilling frontier in our quest to understand the Universe. This approach transcends traditional boundaries by integrating observations from an array of cosmic messengers, such as light, neutrinos, cosmic rays, high-energy gamma rays, and gravitational waves, providing complementary information to study the Universe and transient events. The discovery of neutrinos from SN1987A, arriving to detectors 4 h before the light detected by conventional telescopes, can be recognized to be the event that marked the birth of multi-messenger astronomy [1]. A few years later, in the design stages, the Pierre Auger Observatory (from now simply called Auger) was conceived and realized as a pioneering hybrid detector with known multi-messenger capabilities. During the first sixteen years of Auger's life and data acquisition, numerous efforts were made by the Collaboration to search for sources of UHECRs, taking into account that these particles may produce other types of messengers such as neutrinos, photons, and neutrons [2]. Thus, multi-messenger research in Auger has also developed in the context of cooperation with other observers, sending and receiving real-time triggers of potential multi-messenger interest events with AMON [3], a network in which many observers participate and to which Auger also links.

2. The Pierre Auger Observatory

The Pierre Auger Observatory is the largest observatory built so far for the indirect detection of ultra high-energy cosmic rays with energies above 10^{17} eV[1]. The Observatory is located in a vast table land in the southern hemisphere, near the Argentinian city of Malargüe.

Designed as a pioneering hybrid detection facility, the Observatory [4] is composed by two different and complementary kind of detectors: an array of 1660 surface stations, water-Cherenkov detectors, covering an area of about 3000 km^2 which constitutes the Surface Detector (SD) with a duty cycle close to 100%; and 27 Fluorescence Detector telescopes (FD) that, located in four sites around the SD grid, look at the atmosphere above the surface detectors with a duty cycle of approx 13%. Both SD and FD detect UHECRs indirectly by measuring, respectively, the secondary particles at ground level and the longitudinal development of the showers of secondary particles (EAS) produced by the interaction of the primary cosmic rays with molecules in the atmosphere. The height of the Observatory, 1400 m a.s.l. or equivalently an atmospheric depth $X_{\mathrm{ground}} = 880\,\mathrm{g\,cm^{-2}}$, has been chosen wisely to allow the observation of the average shower maximum at the energy of interest, in order to better reconstruct the energy of the primary cosmic ray and the characteristics of the shower. The chosen site in Malargüe is also optimal to maximize the FD duty cycle: it is characterized by the absence of light pollution, and by a dry climate which favors a clear sky. Moreover, being an hybrid detector is one of the main strengths of Auger. In fact using two techniques to detect the same events has been crucial in the Auger lifetime, since it allowed to cross-check the reconstruction methods and to minimize the need of simulations.

The Observatory has been active continuously since 01 Jan 2004, and from 01 Aug 2008 in its full complete configuration. The idea of developing and using the Auger detector for neutral particle searches in the field of multi-messenger astronomy was already recognized in the design stages of

[1] 10^{18} eV = 1 EeV.

the Surface Detector. Auger SD stations can be described each as cylinders with a height of 1.2 m and diameter of 3.6 m, filled with 12 tons of purified water. The inner walls of each tank are coated with a diffusive Tyvek liner to reflect Cherenkov light produced by the passage of EASs charged particles and allow efficient collection by the three photomultiplier tubes located above the surface of optical contact with the water. An important feature of the SD detector that allows discrimination between electrons and muons, which is useful for multi-messenger astronomy purposes, is the 25 ns time resolution of sampling PMT signals. This feature is helpful in identifying muon-poor air showers mainly induced by photons.
The next sections present some of the major neutral particle searches carried out by the Pierre Auger Collaboration during Phase1, which is the period from 01 Jan 2004 to 31 Dec 2020, ended by the beginning of the deployment of AugerPrime, the Auger detector upgrade [5]. AugerPrime, in an advanced state of installation at the time of writing this proceedings, will further enhance the multi-messenger capabilities of the Observatory, as described in a short dedicated section at the end of this article.

3. Search for UHECR

One of the main tasks of the Pierre Auger Collaboration is looking for the sources of the detected UHECRs. To do so, the best approach would be to identify the best messenger particle in the Universe and backtrack its reconstructed arrival directions.
The ideal features of a particle for investigating the Universe are to be neutral, therefore undeflected by galactic and extragalactic magnetic fields and allowing direct pointing to its source; to be able to travel without interaction or decay for long cosmological distances, allowing a large-scale search of the known Universe; and to be easy to be detected, so as to collect a large enough statistic for the required analysis. Unfortunately, in the known Universe there is no messenger with all these characteristics.
UHECRs are the most energetic particles known in Universe. They mainly consist of protons and atomic nuclei, accelerated by astrophysical sources of various kinds up to the most extreme energies ever observed up to the order of 10^{20} eV. Although they are practically easy to detect (the Pierre Auger Observatory has the full efficiency energy threshold at 3 EeV), and can travel unimpeded long cosmological distances (at energies above $\sim 4\times 10^{19}$ eV their interactions with CMB allow source distances to be up to 100 Mpc for GZK effect [6]), backtracking their arrival direction is considerably complicated by the fact that they are charged particles. The resistance of UHECRs to deflections due to magnetic fields is expressed in terms of the rigidity parameter, the ratio between the energy and the charge of a particle $R = E/eZ$. Taking into account the GZK effect and rigidity, UHECRs can be used to search for sources on medium and large angular scales (tens of degrees) and in high energy ranges (above $\sim$10 EeV). A further complication is that deflections cause delays in the arrival times of ultra-high-energy cosmic rays accelerated at the same instant from the same source, thus making them a difficult instrument to be used for observing transient sources.
At high energy the distribution of the UHECR arrival directions might show anisotropy at intermediate angular scales, mirroring the inhomogeneous distribution of the nearby extra-galactic matter. The most recent analysis completed in Auger for the search for anisotropy at intermediate angular

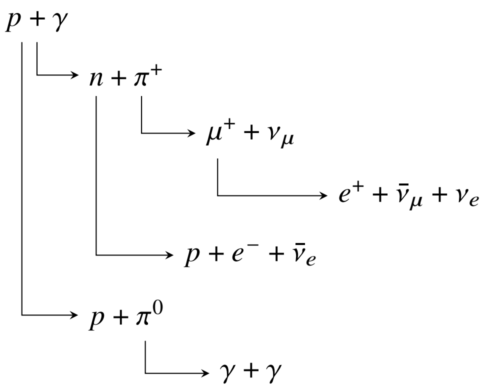

Figure 1: Schematic diagram of interactions and decays leading to production of neutral messengers by ultra-high energy protons.

scales used the largest dataset ever built at the extreme energies[2], with 2625 events collected during the entire Phase1 by SD with E>32 EeV [7]. Three different analyses were carried out: a blind search for overdensities in the totality of the sky visible from Auger, a catalogue-based search with four catalogues of possible sources, and, in light of the results obtained with these two types of analysis, a search focusing on various angular scales and energy ranges in the Centaurus region. The blind search flagged the Centaurus region as a possible area of interest, while with the catalogue search the most promising catalogue turned out to be Starbursts Galaxies with a significance of 4σ. A different research approach is also followed with the Auger data for the study of neutral particles. Charged cosmic rays can produce, in interactions with background radiation (photons, dust, CMB), neutral particles as in the following scheme (figure 1) which can be used as interesting messengers to identify sources of UHECRs and to investigate the emissivity and cosmological evolution of the sources.

3.1 Neutrinos

Neutrinos produced in cosmic ray interactions can travel unimpeded along cosmological distances making them the only messengers of the very high-redshifted Universe at UHE. Moreover, due to their small interaction cross sections, neutrinos can escape from dense cores of astrophysical objects becoming the main instrument to probe the inner workings of sources. Despite these positive characteristics, neutrinos remain particularly difficult messengers to detect, and require, depending on the different instrumentation used, very stringent selection criteria to be recognised.
Although the main purpose of the Pierre Auger Observatory is to detect of ultra-high-energy cosmic rays, its hybrid detector can also be exploited to detect UHE neutrinos. In Auger there are two main channels to search for neutrinos: deep down-going showers (DG) and up-going Earth-skimming showers (ES). The search in the DG channel, sensitive to all the neutrino flavors, is motivated by the fact that inclined neutrinos, with a zenith angle θ greater than 60°, can interact deep in the atmosphere with respect to UHECR showers (because of the fact their interaction length exceeds the matter depth of the atmosphere for any zenith angle). At ground level, inclined neutrinos showers,

[2]`https://doi.org/10.5281/zenodo.6504276`

developing in deep atmosphere, show the characteristics of "young" showers, being rich in electron and photon components, that would be greatly absorbed in the EAS produced by protons or nuclei at the same zenith angle. Their SD induced signals are spread over much wider time intervals than cosmic rays since electrons and photons in the shower front undergo multiple scattering. By analysing the signal traces recorded by the Surface Detector, we could distinguish between inclined air showers of cosmic rays and neutrinos. For reconstruction reasons and accuracy in the DG selection two zenith angle groups are made: "Low" (DGL) for $60° < \theta < 75°$, and "High" (DGH) for $75° < \theta < 90°$. The second research channel, the Earth-skimming one, is sensitive to tau-flavoured neutrinos. Tau neutrinos in fact can interact below the Earth's surface producing tau leptons which escape in the atmosphere, and decay in flight producing up-going air showers. These up going showers can be recognised both from SD and FD making the hybrid design of Auger an extremely effective tool in this search.

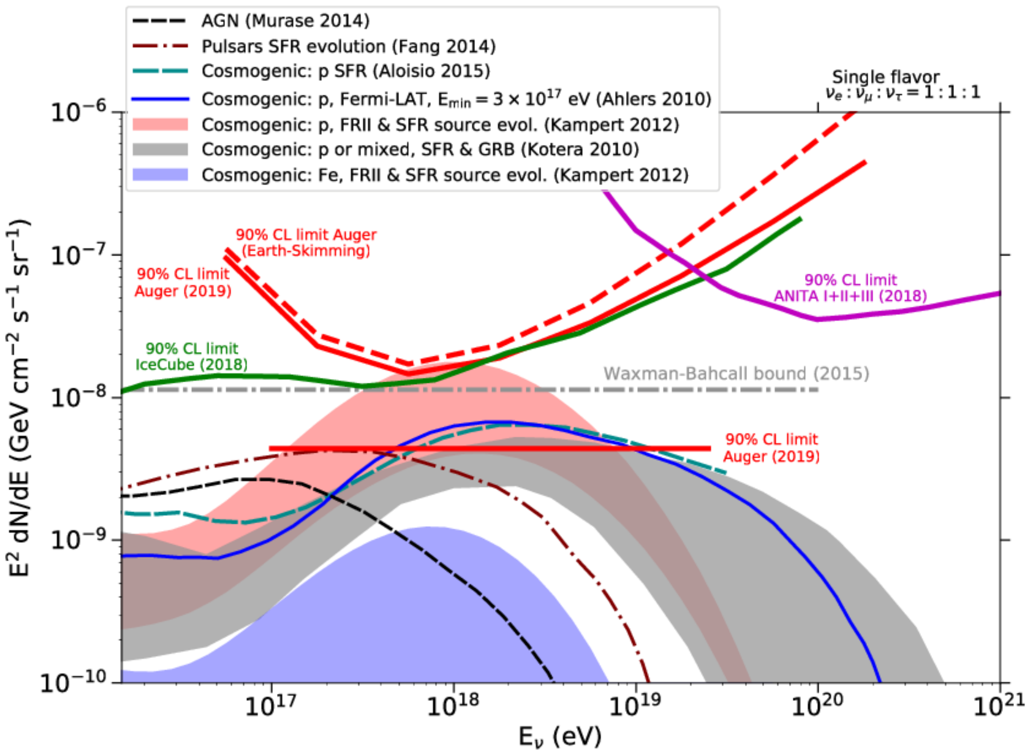

Figure 2: Upper limits on the diffuse flux of neutrinos [8]. The upper limits from IceCube [9] and ANITA [10] and the expected neutrino fluxes under theoretical scenarios and different assumptions [11–17] are also shown.

3.2 Upper limits on neutrino flux

The first kind of neutrino search analysis carried out with data of the Pierre Auger Observatory is the blind search [8] for sources across the sky in the field of view of the Observatory This has been carried out by comparing the number of expected neutrinos with the actual number of detected events.

The expected number of neutrino events in an energy range [$E_{\min}$,$E_{\max}$] from a point-like source located at a declination δ can be calculated as

$$N_{exp}(\delta) = \int_{E_{\min}}^{E_{\max}} dE_\nu\, \phi(E_\nu)\, \mathcal{E}(E_\nu, \delta) \qquad (1)$$

where $\phi(E_\nu)$ is the spectral neutrino flux in the form of $k{\times}\mathcal{E}_\nu^{-\alpha}$, and $\mathcal{E}(E_\nu, \delta)$ the integral exposure which takes into account the effective area of detection of the observatory and the period of observation. Blind searches for UHE neutrinos in the Auger data period have been performed during the Observatory lifetime, and all of them have yielded to no candidate neutrino events in the ES, DGH, and DGL channels analyses. Despite that, a 90% C.L. upper limit on the neutrino flux from point-like sources is derived assuming $\phi = k{\times}E^{-2}$. Upper limits to the neutrino flux in the different search channels are calculated following this analysis as a function of declination, as shown in an example result in figure 2, in which the Auger data between 01 Jan 2004 and 31 Aug 2018 have been analyzed. With these upper limits on the flux the Collaboration was able to place constrain on models of cosmogenic neutrino production that assume pure protons at the sources with strong (FRII-type) evolution with redshift.

3.3 TXS 0506+056

The Pierre Auger Collaboration carried out a search for neutrinos in correlation with the direction of the very high energy blazar TXS 0506+056. The direction of this blazar became object of utmost interest for multi-messenger astronomy on 22 September 2017, when the IceCube Neutrino Observatory detected a high energy muon neutrino with an energy of ~290 TeV, and sent an alert to astronomers with coordinates to search for a possible source [18]. Six days later, just 0.1° from the direction indicated by the Ice Cube reconstruction and with a correlation probability of 3σ, a flaring activity in the γ-ray band was observed by the Fermi Large Area Telescope (Fermi-LAT) [19]. A search of previous events among the IceCube data also revealed a 13 ± 5 more through-going muon events than background expectations between December 2014 and February 2015. This dominated the background neutrino flux from the TXS 0506+056 direction, which was interpreted as a burst of neutrinos over a time window of about 110 days from the same direction [20]. Furthermore, the flaring activity observed by Fermi-LAT was confirmed by a high-energy signal, between 80 and 400 GeV, detected in the MAGIC telescope when integrating observations between 2017 September 24 and 2017 October 4. In light of this, all the data collected with the Pierre Auger Observatory were searched for candidate neutrino events in the direction of TXS 0506+056 [21].

TXS 0506+056 is in the field of view of the Auger neutrino sensitivity in ES, DGH and DGL channels for 21% of the sidereal day, but it was not in the field of view at the exact time of the neutrino detection by Ice Cube. The Collaboration analysed two different time periods in which to look for neutrino signal: six months around the detection of the IceCube event, coinciding with a flare period of TXS 0506+056, and from 2004 January 1 up to 2018 August 31 (from first data acquisition up to last day available at the time of the publication). During both the periods examined, no neutrinos were found [21]. Starting from this negative result, instead of setting a flux limit, the Auger Collaboration calculated the expected flux that should have been measured if a single neutrino had been observed, assuming a steady flux over each period. The figure 3 shows the UHE neutrino flux reference that would give 1 expected neutrino event at the Pierre Auger Observatory over the first a period (22 Mar 2017 - 22 Sept 2017) drawn in solid red line and second period (01 Jan 2004 - 31 Aug 2018) dashed red line. In both cases, a $dN/dE \propto E^{-2}$ spectrum was considered, and the extrapolated flux is compared to the flux that would produce on average one detection like the IceCube event in the same period (the 15 year period must be compared with a 7.5-year period of IceCube, i.e., its total data acquisition period the time). These upper limits placed by Auger are the first at the highest energies for the direction of the TXS 0506+056 blazar.

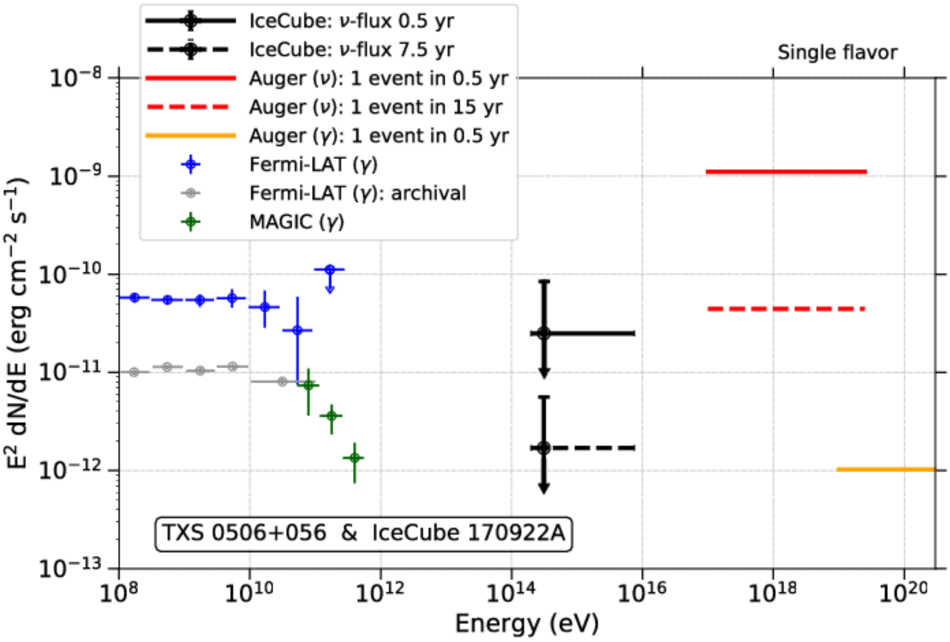

Figure 3: UHE neutrino flux that would give one expected neutrino event detected by the Pierre Auger Observatory over the first period of half a year (22 Mar 2017 – 22 Sept 2017) studied is drawn in solid red line and second period (01 Jan 2004 - 31 Aug 2018) in dashed red line. The extrapolated flux is compared to the flux that would produce on average one detection like the IceCube event in the same periods (black lines). The average UHE photon fluxes measured with Fermi-LAT (blue dots) and MAGIC (green dots) during the first period of search [20], the archival photon measurement from Fermi-LAT (grey dots) [22] and the UHEγ flux from TXS 0506+056 direction that would give one expected photon event in half a year at the Pierre Auger Observatory (gold lines) are also shown. From [21].

4. UHE photons

Always referring to scheme (figure 1), it is clear that photons, produced by the interactions of cosmic rays are a further possible messenger to investigate the Universe. The interactions between UHE photons and cosmic background radiation with the consequent production of e^+e^- pairs limit the horizon for γ-ray astronomy to about 4.5 kpc for energies of the order of EeV [23].
The search for UHE photons in Auger data is performed both with the FD and the SD [24]. The photon induced electromagnetic extensive air shower develops "slower" than hadronic ones, i.e.,

the shower maximum $X_{\max}$ is reached closer to the ground. Based on EAS simulations, proton and photon EAS have average $X_{\max}$ values that differ by about $200\,\mathrm{g\,cm^{-2}}$ in the EeV energy range, even enhanced at energies above 10 EeV. Since the Auger Fluorescence Detector has a resolution of about $15\,\mathrm{g\,cm^{-2}}$ for the observable $X_{\max}$, FD is an ideal instrument to discriminate photon from hadron-induced showers. In Auger it is also possible to search for photon showers using the Surface Detector and some of its observables [24]. UHEγ induced showers have a steeper Lateral Distribution Function (LDF) compared to hadron primaries. The electromagnetic cascade produces relatively few muons compared to hadronic showers, and the number of triggered SD stations is typically smaller for electromagnetic showers. All these features can be combined into a single observable, called S_b. To perform photon searches in Auger, photon identification is developed from a Boost Decision Tree (BDT). Based on simulations of hybrid events which triggered the FD and the SD detector simultaneously, the observables $X_{\max}$, S_b, and N_{stat} (number of stations) are injected into a BDT algorithm, also taking into account the energy and angular dependencies of the discriminating observables. QGSJET-II-04 is used as high-energy hadronic interaction model for these simulations. The BDT response is then analysed to find the best trade-off for the discrimination of hadron-like and photon signals.
One analysis carried out is a targeted search for photon sources. For each candidate direction a cut in the BDT output distribution was optimised also considering the expected number of isotropic background events in that direction. The background number of events was then calculated by applying a scrambling technique that takes into account detector directional efficiencies. To each candidate source was assigned a top-hat region of radius 1°. Averaging over all considered target directions, the multivariate cut was expected to retain 81.4% of photons and reject 95.2% of background hadrons. In none of the sources and source classes could EeV photons be detected, which allowed upper limits to be placed on the photon flux from each of the sources, as shown in figure 4.

5. UHE neutrons

Another messenger of interest to mutimessanger astronomy in Auger is the neutron. Neutrons are expected to be produced in the immediate vicinity of charged UHECR sources in their main pion photoproduction interactions with photons (figure 1). Neutrons, undeflected by magnetic fields, can be exploited to directly target the source. Despite that, two factors must be taken into account that limit this type of analysis: the air showers produced by neutrons and protons are indistinguishable, and a free neutron is subject to decay with an average lifetime of about 15 minutes. Because of the former, it is necessary to search for neutrons on very small angular scales, comparable with the angular resolution of the detector (about 1 degree) for which protons are deflected and with isotropic arrival directions. While for the decay, taking relativistic considerations into account, the neutron can travel a distance of about 9.2 kpc$\times E$[EeV] before decaying. Therefore in the Auger energy range the search for neutron sources must be limited to our Galaxy.
Two separate analyses were performed for the neutron search: a blind search in the Auger field of view up to 20° of declination [34] and a targeted search with candidate Galactic sources up to 25° of declination [35]. The data sets of events detected by the Surface Detector with energy starting at 1 EeV were selected for both analyses. For the blind search, the sky was divided into target directions

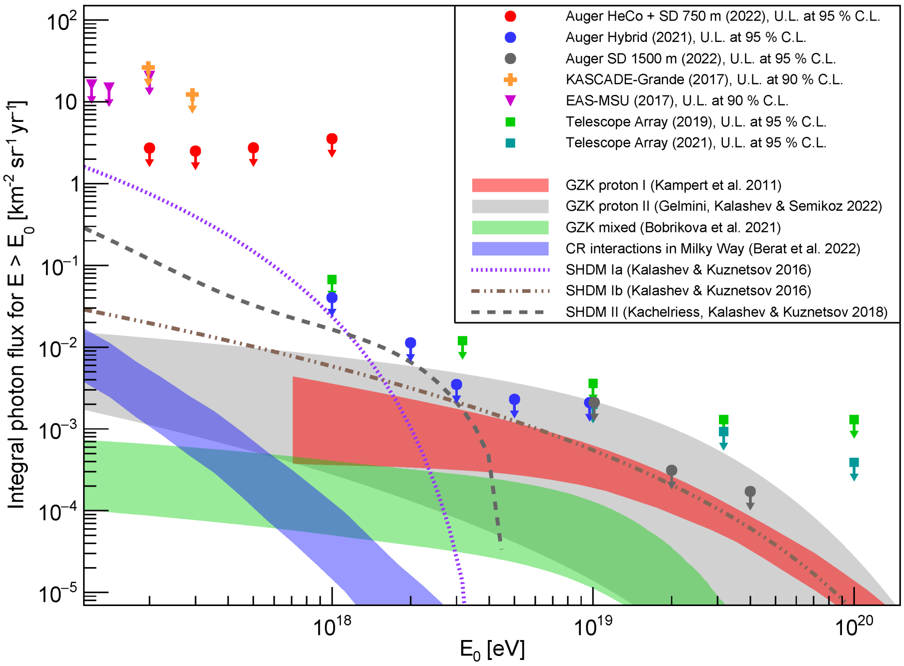

Figure 4: In red, gray and blue dots the upper limits on the integral photon flux calculated from data of the Pierre Auger Observatory [24]. With bands the ranges of expected GZK photon fluxes under the assumption of two different pure-proton scenarios are shown, while other dots represents the experimental upper limits placed by other experiments as in [25–33].

of angular resolution equal to one degree, and the number of observed events counted within this top-hat region of each direction was compared with the expected one obtained by background simulations with scrambling, with a Li-Ma statistical significance analysis [36]. As for the targeted search, each candidate source was associated with a top-hat region of a size calculated from the angular resolutions of events in the same direction of the source. In both cases, no excesses were found from any of the directions studied. However, this result allowed upper limits to be placed on the neutron flux from the studied directions and targets. The results found for the targeted analysis, for the most significant source of each catalog are shown in table 1: important upper limits have been placed on the flux of neutrons from each direction, which can be used to study production processes for these particles at the source. In addition, for the targeted search was also calculated the cumulative significance of each selected target set of compact Galactic objects studied, combining the individual significance of targets. The cumulative significance was also calculated with a weighted analysis that took into account for each candidate source, the Auger directional exposure in its direction, the distance (for neutron flux attenuation), and the electromagnetic flux from the source itself.

6. AugerPrime

As anticipated in the section describing the Observatory, currently the SD detector is being upgraded with the installation of new components [5] that will, among other things, enable better multi-messenger astronomy. For this purpose it is necessary to discriminate as much as possible

Target set	RA[°]	Dec[°]	Flux U.L. [$\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$]	E-Flux U.L. [$\mathrm{eV\,cm}^{-2}\,\mathrm{s}^{-1}$]
msec PSRs	260.27	-24.95	0.019	0.14
γ-ray PSRs	8.59	-5.58	0.024	0.18
LMXB	264.57	-26.99	0.028	0.20
HMXB	152.45	-58.29	0.019	0.14
H.E.S.S. PWN	128.75	-45.60	0.018	0.13
H.E.S.S. other	269.72	-24.05	0.019	0.14
H.E.S.S. UNID.	266.26	-30.37	0.018	0.13
Microquasars	262.75	-26.00	0.022	0.16
Magnetars	81.50	-66.08	0.016	0.11
Gal. Center	266.42	-29.01	0.014	0.10
Gal. Plane	$\lvert$Gal. lat.$\rvert$ < 1.17°		0.077	0.56

Table 1: Main results for the targeted search fot UHE neutrons: detail for the most significant target from each target set. The upper limits are computed at 95% confidence level.

between the different components of the air showers, so as to recognize primaries of different natures.
This purpose is facilitated by the following specifications of the detector upgrade, a station of which is schematized in figure 5. A plastic scintillator called Surface Scintillator Detector (SSD) is installed above each tank. The responses of the plastic scintillators and water-Cherenkov detectors to different components of the swarms are different. Therefore, the use of SSDs will allow to analyze the muon and electronic component with different sensitivities. In addition, a radio antenna will be installed on all SD detectors to measure the signal in the frequency range from tens of MHz up to several GHz produced by the acceleration of charged components of air showers in the atmosphere. AugerPrime will then be completed with the installation of the Underground Muon Detector (UMD). These are placed below the detectors in the Infill region of the array, where the surface detectors form a denser grid. The UMD will be used for verification and tuning of the methods used to extract muon information from SSD and WCD measurements. SD stations are therefore equipped with new, faster and more accurate electronics, the Upgraded Unified Board (UUB). This type of electronics can simultaneously process signals from SD detectors, SSDs, radio detectors, and underground detectors, increasing data quality.

7. Conclusions

The Pierre Auger Observatory is a hybrid detector capable of observing ultra high-energy cosmic rays with energies from 10^{17} eV. Active for nearly two decades, one of the main tasks of the Observatory is to enable the search for sources of the most energetic particles ever observed in the known Universe. During its activities, the Auger Collaboration made a great effort to recognize the detection of neutrinos, photons and neutrons, produced by cosmic rays in the immediate vicinity of their source or by transient events. In this article, the possible messengers of the universe detectable by the Observatory were presented. As is clear, in conclusion, there is not an ideal messenger in

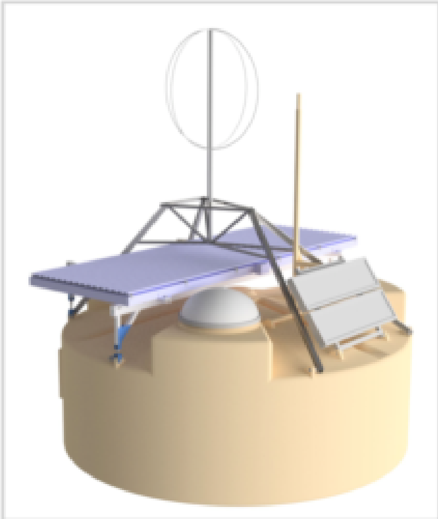

Figure 5: Example drawing of a Surface Detector station with AugerPrime components installed.

the Universe, but the searches presented are promising, and the future prospects with the updated AugerPrime detector will help a lot for a further development of multi-messenger astronomy with the Pierre Auger Observatory.

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DISCUSSION

H. L. MARSHALL: You mentioned an upper limit on the neutrino flux from GW150914 but did you find a good limit or detection for GW170817? I would expect more from a binary neutron star merger.

FEDERICO MARIA MARIANI: Upper limits at 90% C.L. on the neutrino spectral fluence from GW170817 were placed by analyzing Auger data in different time windows around the event detection. The search for high-energy neutrinos from this binary neutron star merger was carried out with ANTARES, IceCube, and the Pierre Auger Observatory.

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