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Review of the Multimessenger Working Group at UHECR-2012

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Abstract. The current status of searches for ultra-high energy neutrinos and photons using air showers is reviewed. Regarding both physics and observational aspects, possible future research directions are indicated.

1. INTRODUCTION

What is the status of searches for ultra-high energy neutrinos and photons using air showers? What might be the future prospects, in particular in the next couple of years? What is (are) the physics case(s) for multimessenger observations, and what are the observational experiences and challenges? These questions may summarize the main objective of the Multimessenger Working Group that was formed, together with four other Working Groups, a few months before the UHECR-2012 symposium. At this symposium, possible future directions of the field of ultra-high energy cosmic rays were discussed, bringing the major collaborations from air-shower experiments as well as colleagues from theory together.

Given this objective, one can think of many issues to inspect. In particular, one can compare neutrinos versus photons; neutrinos and photons versus charged cosmic rays; air shower observations versus other techniques; shower observations from ground versus those from space; ground shower techniques versus each other; current data versus models; various models versus each other; and, above all, the present status versus future directions. Given these many aspects in a highly dynamic field, it is evident this review does not claim to be complete, or even finished. Rather, certain considerations of possible relevance to the aim of the symposium are compiled and highlighted.

We start with both neutrinos and photons before each one is examined individually.

2. UHE NEUTRINOS AND PHOTONS

Multimessenger observations are a key ingredient for discovering and for better understanding various phenomena in the Universe. Boosted by the invention of the telescope about 400 years ago, photon observations cover now an impressive energy range from radio wavelengths up to about 100 TeV. The discovery of (charged) cosmic rays dates back (at the time of writing these proceedings quite

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precisely) 100 years ago, with cosmic rays being measured now from sub-GeV to more than 100 EeV in energy. First non-terrestrial neutrinos were observed about 40 years ago, in the MeV energy range.

Various efforts are underway for opening new observational windows to the Universe and for deeper observations of already accessible energy regimes of the different particle types. Examples of significant discoveries in new windows are the cosmic microwave background or gamma-ray bursts for the case of photon messengers, the muon for the case of cosmic-ray messengers via the air showers they produce, or the discovery of neutrinos from SN 1987A in the case of neutrino messengers. Two things can be seen from this small list. Firstly, some of the discoveries were not expected or predicted beforehand; they gave their rewarding justification for the efforts made to proceed into unknown regime only afterwards: an important feature that also decision-makers should keep in mind. And secondly, these discoveries impacted (or even helped to establish) different fields of nowadays' physics, including astrophysics, particle physics, cosmology and fundamental physics. In this sense, astroparticle physicists should remain open-minded as to what kind of physics they can "do" by using the astroparticles.

In the remainder of this section, we sketch the "life" of UHE neutrinos and photons from production over propagation to searching for them using air showers. Along this path, we will see structural similarities and differences in their appearance as multimessenger particles.

2.1 Production

Both UHE neutrinos and photons are thought to be typically produced as decay secondaries, i.e. they come from higher-energy cosmic rays. These cosmic rays (nucleon or nucleus) may interact with matter, e.g. with gas around a source, or with background photons, e.g. the CMB or photon fields around a source. The produced secondaries include in particular pions, and neutrinos (photons) can be generated in the decay of the charged (neutral) pion. An important example is the GZK process, where a proton above 50 EeV interacts with the CMB and gives rise (in about $1/3$ of the cases) to finally 3 neutrinos of about 5% each of the initial proton energy, or (in about $2/3$ of the cases) to 2 photons of about 10% each of the initial proton energy.

As alternative scenarios, top-down models were proposed where the pions can emerge from the decay or annihilation of exotic particles; as will be commented on below, these models are now strongly constrained by searches for UHE photons and neutrinos. In any case, both messengers can emerge from the same type of initial process, and finally from (pion) decay.

2.2 Propagation

Both UHE neutrinos and photons propagate along a straight line and are not deflected by magnetic fields, in contrast to charged cosmic rays. This opens the possibility of doing "astronomy" by directional pointing. The neutrinos, to good approximation, also do not interact. For propagation over cosmological distance, maximum mixing of flavors is typically assumed. UHE photons, with an energy loss length of order of 10 Mpc at around 10 EeV, initiate an electromagnetic cascade down to GeV-TeV energy. Thus, there is complementarity due to the different interaction cross sections between the messengers, with UHE photons testing the more local Universe, while UHE neutrinos (as well as down-cascaded GeV photons) can reach us from cosmological distances (assuming standard physics in all cases).

2.3 Searches using air showers

Both UHE neutrinos and photons can be searched for using air showers. In the case of UHE photons, fairly "normal" showers (compared to hadron showers) are produced and typical shower detectors can be used. The separation of photon-induced and hadron-induced showers is based on composition-sensitive

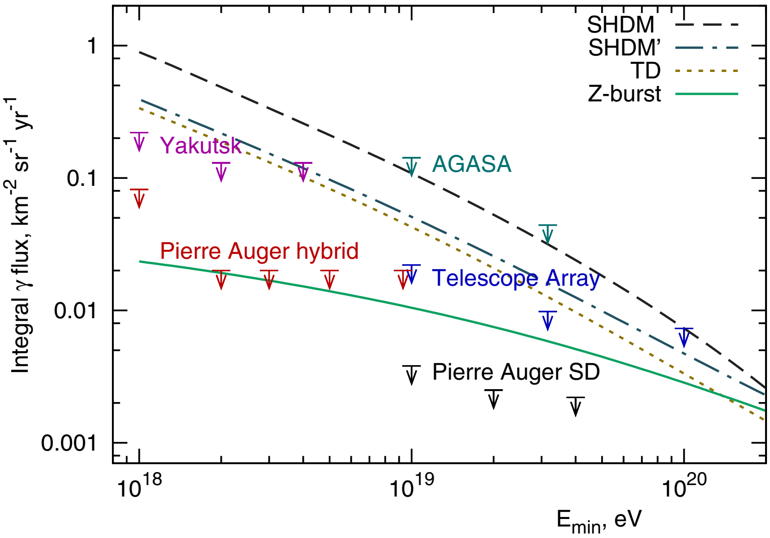

Figure 1. Constraints on selected top-down models of UHE photon production by current UHE photon flux limits. See Section 3 for more details on the photon limits.

shower observables. This might be a larger challenge for currently planned observations from space compared to ground-based experiments. Overall, there is no competitive technique to shower detectors so far to search for UHE photons.

In the case of UHE neutrinos, the probability to initiate an air shower at all is quite small ($\sim 10^{-5}$ at 1 EeV within a depth of 1000 g cm^{-2}). But if a shower is produced, also the extreme phase space can be populated, e.g. near-horizontal showers starting at very large depths, or upward-going showers starting in the Earth's crust. Due to this, a strong background reduction is possible, with the limitation of trying to keep a large exposure. This might be an opportunity for future space observations to try to add significant exposure. Overall, the search for UHE neutrinos using air showers is in competition with other techniques, e.g. with neutrino telescopes using ice or water as a medium.

For both UHE neutrinos and photons, no discovery has been claimed so far, and upper limits were derived. In case of UHE photons, candidate events exist that are usually close to the detector threshold and compatible with expectations from hadronic background. For conservative limits, this background is typically not subtracted to avoid uncertainties in modeling high-energy hadronic interactions. In case of UHE neutrinos, no candidates emerged so far from searches using air showers such that the current search is not limited by background but by exposure.

For deriving limits, in both cases a fairly robust interpretation of shower observations with regard to theory uncertainties is possible, which is in some contrast to the more uncertain interpretation of hadron showers: photons showers are mostly just electromagnetic. And for neutrinos, while there is an uncertainty in cross-section and τ energy loss, the uncertainty in shower development is less important since the identification relies mostly on the electromagnetic component of the shower.

2.4 Previous impacts

Searches for UHE neutrinos and photons gave already important contributions to the scientific landscape. As can be seen in Figs. 1 and 2, strong constraints on top-down models could be achieved by the photon, as well as the neutrino limits. Further impacts will be discussed below.

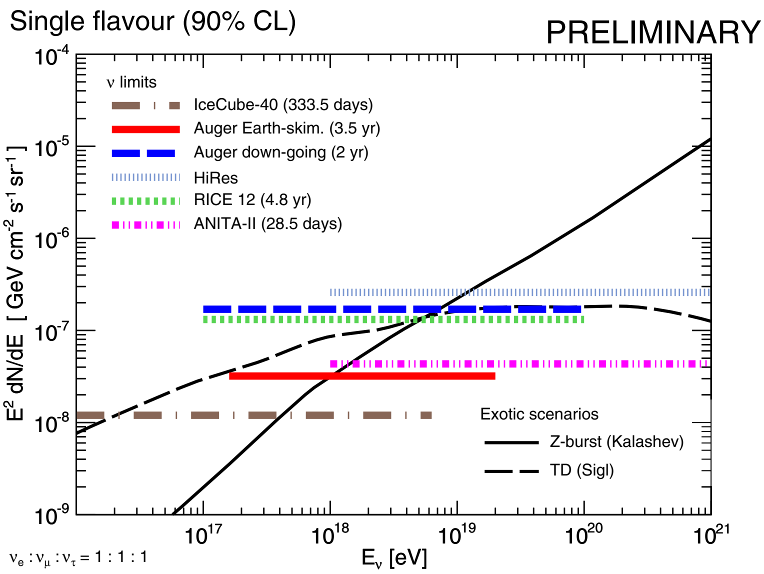

Figure 2. Constraints on selected top-down models of UHE neutrino production by current UHE neutrino flux limits. See Section 4 for more details on the neutrino limits.

Table 1. UHE photon flux limits and corresponding techniques.

Experiment	Technique	Observables	Ref
Haverah Park	SD: water Cherenkov	attenuation of inclined showers	[4]
AGASA	SD: scintillator & muon	muon density	[5, 8]
Yakutsk	SD: scintillator & muon	muon density	[6, 7, 9]
Pierre Auger	SD: water Cherenkov	front curvature, rise time	[11]
Observatory	hybrid: fluorescence + SD	X_{max}, particle density far from the core	[10, 12]
Telescope Array	SD: scintillator	front curvature	[13]

3. UHE PHOTONS

Photon-induced showers are mostly electromagnetic with the first interaction dominated by electron-positron pair production in the Coulomb field. At the highest energies (above 10 EeV) two additional effects come into play: the Landau, Pomeranchuk [1] and Migdal [2] (LPM) effect and preshower in the geomagnetic field (see [3] for a review). Photon-induced showers are deeper and have significantly less muons compared to hadronic showers. The observables used for photon-hadron separation include the muon density at ground level, the depth of shower maximum ($X_{\rm max}$) and the properties of the shower front (curvature, rise time,...), see Table 1. The best photon-hadron separation is achieved using the muon detection technique, which at the same time has the highest price per exposure. A hybrid technique using fluorescence and muons could possibly perform even better. All methods result in a merit factor (defined as the ratio of separation power and price per exposure) of the same order. Generally, any technique good for hadronic composition study is adequate for photon search (as long as electromagnetic showers can trigger the detectors).

3.1 Present status

The findings of independent experiments in both North and South hemispheres are similar: no photon candidates were found at the highest energies and the number of candidates found can be attributed

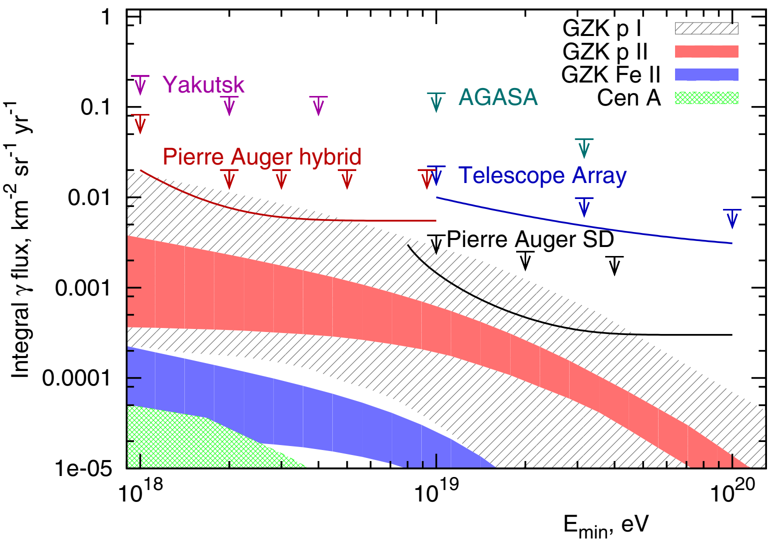

Figure 3. Limits to the UHE photon flux placed by several experiments namely, AGASA [5], Yakutsk [7], Pierre Auger [11, 12] and Telescope Array [13] experiments. Also shown are estimates of the sensitivity with data until 2015 as derived by scaling the current limits to account for the relative expected increase of the exposure, and assuming the number of background events remains constant. The flux predicted in several cosmogenic models of UHE photon production [22, 23] and a Cen A source model [24] are shown in the shaded region.

to hadronic background (deep proton-induced showers). The existing photon flux limits along with the predictions of the models are shown in Fig. 3. Also shown are estimates of the sensitivity with data until 2015 as derived by scaling the current limits to account for the relative expected increase of the exposure, and assuming the number of background events remains constant. The flux of GZK photons critically depends on the source model, and the existing limits are getting close to the predictions of the most optimistic scenarios (with proton primaries).

Presently there is an unexplored energy gap 10^{16}–10^{18} eV between the flux limits at lower energies established by KASCADE [14] and the limits set in UHECR experiments, see Fig. 4. The gap is a target for the low energy extensions of Pierre Auger and Telescope Array observatories and future large scale air Cherenkov detectors (e.g. HiSCORE [15]).

3.2 Possible impact of UHE photon searches

Photons, as the gauge bosons of the electromagnetic force, at such enormous energy can be regarded as unique messengers and probes of extreme and, possibly, new physics. Implications are related to the production of photons, their propagation, and interactions at the Earth. Many aspects of the following, incomplete list (cf. [3]) of possible impacts of UHE photon searches and connections to other research subjects require more study.

Large UHE photon fluxes are a *smoking gun* for current non-acceleration models. Stringent photon limits give parameter constraints such as a lower limit on the lifetime of relic SHDM particles [18, 19].

Findings on photons are needed to reduce corresponding systematics in other air shower studies, such as the primary composition, energy spectrum or when trying to constrain interaction parameters such as the proton-air cross-section [20, 21] from showers.

UHE photons may be helpful for diagnostics of sources accelerating nuclear primaries, as the photon fluxes from UHE hadron interactions are expected to be connected with source features such as the

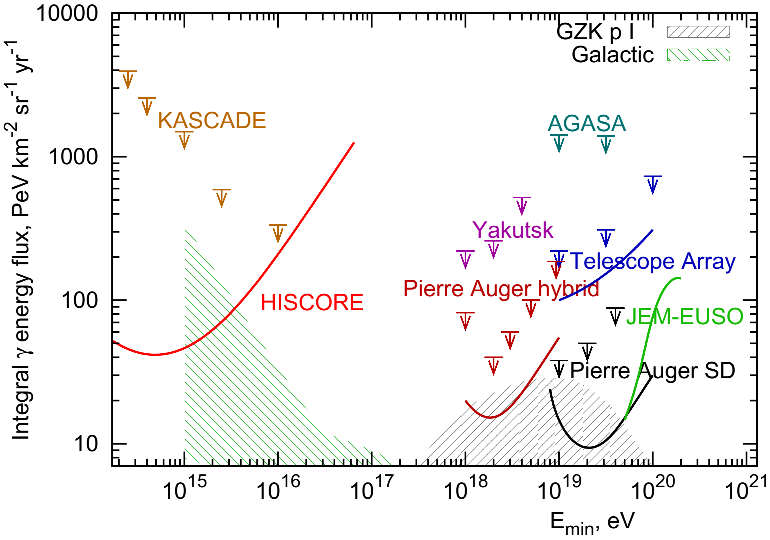

Figure 4. Limits to the photon flux from $\sim 10^{14}$ eV to $\sim 10^{20}$ eV, including the results of KASCADE [14] and the expected sensitivities of the Pierre Auger Observatory and Telescope Array by 2015, HiSCORE [15] and JEM-EUSO [16]. The prediction for the flux of galactic gamma rays at PeV energies is taken from Ref. [17].

type of primary, injection spectrum, possible beam dump at the source, or source distribution (see also [22, 23]).

UHE photons point back to the location of their production. Possibly, the arrival directions of photons may correlate better with the source direction than those of charged primaries. There may be an enhanced UHE photon flux from the galactic center region depending on the spectra of nuclear primaries [25]. In certain SHDM scenarios, an enhanced flux of $\sim 10^{18}$ eV photons from the galactic center is possible without a higher-energy counterpart [26].

Propagation features of UHE photons are sensitive to the MHz radio background [27]. The photon flux at Earth is also sensitive to extragalactic magnetic fields [28].

Already a small sample of photon-induced showers may provide relatively clean probes of aspects of QED and QCD at ultra-high energy via the preshower process and photonuclear interactions (see, e.g., [29]).

There are several connections to Lorentz invariance violation [30, 32–34]. The production of GZK photons can be affected as well as interactions of photons during propagation and when initiating a cascade at the Earth. Particularly, photon conversion (interaction with background fields or preshower process) may be suppressed. The observation of GZK secondaries may set the strongest limits on the Lorentz invariance violation at Planck scale [31].

It is interesting to check whether UHE photon propagation could be affected by the presence of axions or scalar bosons. The formal requirements for photon-axion conversion regarding photon energy and magnetic field strength, appear to be fulfilled [35, 36]. Photon conversions to non-electromagnetic channels may differ from the standard QED process due to an absence of electromagnetic sub-cascade. Photon-axion conversion may ultimately increase the propagation distance of the UHE photons thus allowing to identify distant sources [37].

UHE photon propagation can be modified in certain models of brane worlds [38] quantum gravity theory [39, 40] or spacetime foam [41, 42]. For instance, depending on fundamental length scales significant scattering of photons on structures (defects) in spacetime foam can occur. In turn, constraints may be derived when actually observing UHE photons, even with one gold-plated event only [41, 42].

Table 2. Channels, ν flavors and interactions that can be detected in ground arrays of particle detectors in the EeV range. Also shown are the zenith angle ranges where the two main channels (Earth-skimming and downward-going) are most sensitive, as well as their relative sensitivity.

Channel	Earth-skimming	Downward-going
Flavours & interactions	ν_τ CC	ν_e, ν_μ, ν_τ & CC + NC
Zenith angle range	$90^\circ - \sim 95^\circ$	$\sim 60^\circ$–90°
Target for νs	Earth's crust	Atmosphere
Density [$\mathrm{g\,cm^{-3}}$]	$\rho \sim 2 - 3\,\mathrm{g\,cm^{-3}}$	$\rho \sim 10^{-3}\,\mathrm{g\,cm^{-3}}$
Relative sensitivity	$\sim$2.5–3	1

4. UHE NEUTRINOS

The observation of UHE neutrinos (UHEνs) in the EeV energy range and above has become a priority in experimental Astroparticle Physics. The recent observation of two candidates in the 1–10 PeV energy range with the completed IceCube detector [43] – still of unknown origin – encourages the search for these elusive particles with ground arrays of particle detectors.

4.1 UHE neutrino detection

The observation of UHEν in ground arrays is currently limited by exposure but not by background. UHEνs can induce extensive air showers that populate regions of phase space in zenith angle and injection depth in the atmosphere that are very unlikely to be accessed by showers initiated by UHECRs and photons. Using Monte Carlo simulations it has been established that neutrino identification at ground arrays can be performed with a large efficiency as long as the search is restricted to very inclined showers (typically above 60° zenith angle), starting deep in the atmosphere close to ground [44], and to upward-going showers [45]. Since the injection depth is not directly measured in ground arrays, other surrogate observables are used. Unlike UHECR-induced cascades, a nearly-horizontal neutrino-induced shower initiated close to ground will have a significant electromagnetic component at the detector. As a consequence the shower front is typically broader in time than the corresponding one in a UHECR-induced shower interacting high in the atmosphere which is mainly constituted by muons. This is the basis for the identification of neutrino candidates in all ground arrays currently operating in the UHE range, namely the Pierre Auger Observatory and the Telescope Array, and it calls for detectors with both sensitivity to highly inclined showers and timing capabilities.

The sensitivity of ground arrays extends to all neutrino flavors and all type of interactions (charged-current CC or neutral-current NC) relevant at UHE energies [46]. Neutrinos of electronic, muonic and tauonic flavor can collide with nuclei in the atmosphere and induce an EAS close to the ground that can be identified in a broad zenith angle range from $\theta \sim 60^\circ$–90°. In this so-called "downward-going" neutrino channel, all flavours and both CC and NC interactions contribute to the neutrino event rate. The sensitivity to UHE tau neutrinos is further enhanced through the detection of the shower induced by the tau lepton generated after the propagation and interaction of an upward-going ν_τ inside the Earth [45], the so-called Earth-skimming mechanism. In this case only CC ν_τ interactions can be efficiently detected. The angular range in which this technique is viable at EeV energies is restricted to $\theta = 90^\circ - - \sim 95^\circ$. At larger zenith angles the Earth is opaque to UHE ν_τ and/or the shower emerging from the Earth is too upward-going to reach ground. Despite these limitations, the Earth-skimming mechanism is roughly a factor $2.5 - 3$ more sensitive than the downward-going one in the EeV energy range, mainly due to the $\sim$2000 times larger density of the target for neutrino interactions (the Earth crust) when compared to the atmosphere. The possibility to detect Earth-skimming neutrinos of electronic flavor has also been explored, but the sensitivity is expected to be smaller than other channels [47, 48]. This information is summarized in Table 2.

In principle the search for UHE neutrinos can also be done with fluorescence detectors which are directly sensitive to the shower longitudinal profile and can in principle identify very penetrating inclined showers. However fluorescence telescopes can only work during moonless nights, and this limits their duty cycle to approximately 10–15% of the total time. As a consequence, this reduces the exposure to UHEνs compared to that of ground arrays of particle detectors.

Other techniques for UHE neutrino detection are being applied in other experiments [49]. Neutrinos can interact in a "dense" medium such as water or ice, and the charged debris of their collisions – that typically travel at a speed larger than the speed of light in the media – emit Cherenkov light. This technique is exploited in experiments such as IceCube and ANTARES, which benefit from the abundance and relatively large density of the target, and from the transparency of water and ice to visible wavelengths which allows a sparse array of detectors buried/submerged inside the target itself. Cherenkov radiation is also emitted in the MHz-GHz frequency range. These wavelengths are typically larger than the dimensions of the neutrino-induced shower in a dense medium, and radiation is emitted coherently, with the power in radiowaves scaling as the square of the ν energy. This so-called radio technique has been already exploited in experiments which attain their maximum sensitivity in the UHE regime, such as ANITA and RICE, and it is starting to be explored in initiatives such as ARA [50] and ARIANNA [51]. The radio technique is also the basis of neutrino detection in experiments using existing radio telescopes to try to detect radio pulses produced in neutrino-induced cascades in the Moon. In Table 3 we summarize the main characteristics of the different UHE neutrino detection techniques.

4.2 UHE neutrino production models

All experiments working in the EeV range aim at detecting the cosmogenic neutrino flux produced in interactions of UHECRs above $\sim$50 EeV with the Cosmic Microwave Background (CMB) [63]. Despite the existence of these neutrinos should be guaranteed by the observation of both projectiles of that energy and target photons, the level at which this flux is realized in Nature is dependent on many unknown parameters such as the composition of UHECR at the sources, the spatial distribution of the sources and their evolution with time, the features of the UHECR spectra at the production sites, etc. [64, 65]. The large phase space leads to a wide range of predictions as shown in Fig. 5. In particular if the primary UHECR flux at the sources is dominated by iron, the fluxes are at least one order of magnitude smaller then in the case of proton dominated fluxes. However cosmogenic neutrinos are key to constrain this parameter space. Observations of UHECR alone do not uniquely determine both the injection spectrum and the evolution of the sources, mainly because interactions of UHECR during propagation obscure the early Universe from direct observation. It is these same interactions that produce the cosmogenic neutrinos that keep memory of the parameters of the sources [66].

The cosmogenic neutrino flux is accompanied by electrons, positrons and gamma-rays that quickly cascade on the CMB and intergalactic magnetic fields to lower energies and generate a γ-ray background in the GeV-TeV region. By measuring this $\gamma-$ray flux the neutrino production rate can be constrained [67]. An example, shown in Fig. 5, is the cosmogenic neutrino flux in [68] which is constrained by the diffuse GeV-TeV γ-ray flux observed by the Fermi satellite [67]. UHE neutrinos can also be produced at the potential sources of UHECRs themselves, and in particular in Active Galactic Nuclei (AGN) [69]. An example [70] is shown in Fig. 5. A benchmark model included in Fig. 5 is the Waxman-Bahcall neutrino flux bound [71], a theoretical bound obtained normalizing the energy density in neutrinos to the energy production rate in protons needed to sustain the observed UHECR spectrum above 10^{19} eV.

4.3 Present status

The two main ground arrays of particle detectors currently working in the EeV range, namely the Pierre Auger Observatory in Argentina and the Telescope Array in Utah have reported no neutrino candidates

Table 3. Description of ν detection techniques in the EeV range along with limits to the diffuse flux of UHEνs (when available in the bibliography).

Experiment	Technique $\nu-$flavors Target	Observables	Single flavour limit (90% C.L.) [GeV cm^{-2} s^{-1} sr^{-1}] Livetime / E_ν-range (EeV)	Ref.
Pierre Auger Observatory	Array of water stations Earth-skimming ν_τ Earth's crust	Shower zenith angle Time-structure of front	$k = 3.2\,10^{-8}$ 3.5 yr full Auger/ $\sim 0.16 - 20$	[52]
Pierre Auger Observatory	Array of water stations Downward-going $\nu_{e,\mu,\tau}$ Atmosphere, mountains	Shower zenith angle Time-structure of front	$k = 1.7\,10^{-7}$ 2.0 yr full Auger/ $\sim 0.1 - 100$	[53]
HiReS	Fluorescence telescopes Earth-skimming $\nu_{\tau,e}$ Earth's crust	Shower incidence (upward-going)	$k \sim 2.6\,10^{-7}$ $\sim$ 6.5 yr datataking/ $\sim 1 - 100$	[54]
Telescope Array	Array of scintillators Downward-going $\nu_{e,\mu,\tau}$ Atmosphere, mountains	Shower incidence Time-structure of front	– $\sim$ 3 yr datataking/ > 1	[55]
IceCube	3D array buried PMTs Up/Horizontal $\nu_{e,\mu,\tau}$ Ice	Shower or μ incidence Cherenkov light	$k = 1.2\,10^{-8}$ 333.5 days/$2.0\,10^{-3} - 6.3$	[56]
ANITA-II	Antenna Balloon Upward-going $\nu_{e,\mu,\tau}$ Antarctic Ice	Shower incidence Cherenkov at MHz – GHz (Askaryan radiation)	$k = 4.3\,10^{-8}$ 28.5 days/$1.0 - 3.1\,10^5$	[57]
RICE	Array buried antennas Upward-going $\nu_{e,\mu,\tau}$ Antarctic Ice	Shower incidence Cherenkov at MHz – GHz (Askaryan radiation)	$k = 1.3\,10^{-7}$ 4.8 yr/ $\sim 0.1 - 100$	[58]
RESUN	Radio telescope	Cherenkov at MHz-GHz from the Moon	$k \sim 7.5\,10^{-6}$ 200 $h.$/ $\sim 1.6\,10^3 - 3.1\,10^4$	[59]
NuMoon	Moon-skimming $\nu_{e,\mu,\tau}$		– 50 h./ $> 4\,10^4$	[60]
LUNASKA	Moon regolith		$k \sim 1.0\,10^{-5}$ 33.5 h./ $\sim 10^3 - 10^5$	[61, 62]

in their data. This allows to put a limit to the UHE neutrino flux. Conventionally, limits are displayed in integrated and differential formats. In the integrated format an energy dependence of the neutrino flux following a power-law function $k \cdot E^{-2}$ is assumed. This flux is integrated in energy with the energy-dependent exposure of the detector obtained through Monte Carlo simulations, and the total event rate is calculated. A limit can then be put to the value of the flux magnitude k that would be needed to produce 2.44 events in the observation period, corresponding to the upper bound of the confidence belt at 90% C.L. in the Feldman-Cousins treatment of a null detection [73]. The integrated limits for different neutrino experiments obtained in a similar way as explained here are shown as straight lines in Fig. 5. [1] Integrated limits to the flux of point-like potential sources of UHEνs also exist [52, 74].

The limits can also be shown in differential format. In this case the integrated limits are obtained in several energy bins of fixed width. These limits obtained by several experiments are shown in Fig. 6. This

[1] A candidate event has been reported by the ANITA Collaboration [57]. The event is fully compatible with background and is included in the final value of the integrated limit through the Feldman-Cousins confidence belt approach. Note also that for the IceCube case we show the limit obtained with the IceCube-40 configuration with no candidates reported and published in [56].

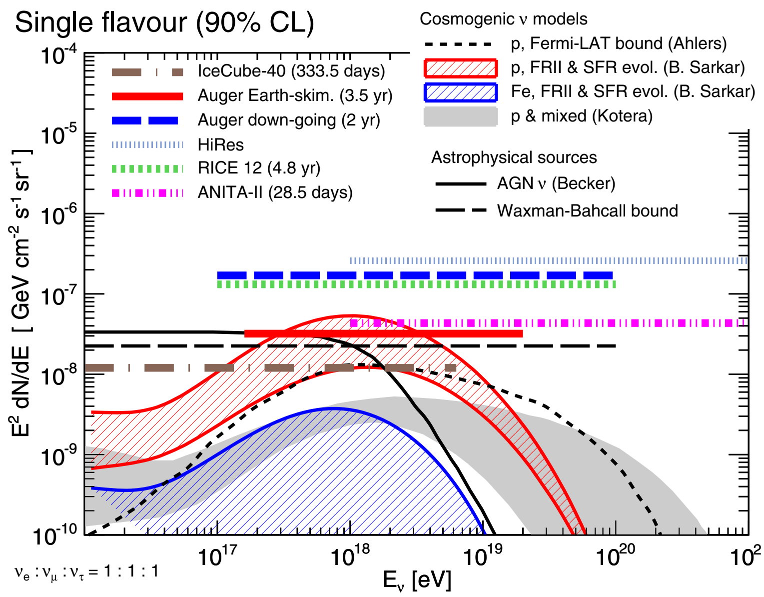

Figure 5. Expected fluxes for several models of cosmogenic neutrinos [65, 68, 72]. The upper (lower) edge of the red band at the top corresponds to a model where proton primaries are injected at the sources which are assumed to follow a strong-FRII (weak-Star Formation Rate) evolution with redshift. The blue band at the bottom assumes the same but for iron primaries at the sources. In both cases power law source distributions with an injection index of $\gamma = -2$ have been assumed and a maximum energy of $E_{max} = Z \times 10^{20}$ eV [72]. The gray band represents a set of models with pure proton and mixed compositions at the sources, and different assumptions on the evolution of the sources as well as on the transition from Galactic to extragalactic sources [65]. The dashed line is the cosmogenic ν model in [68] (best-fit and $E_{min} = 10^{19}$ eV) constrained by Fermi-LAT observations of the GeV-TeV diffuse γ-ray background. The solid black line corresponds to a model of neutrino production in AGN [70]. The dashed horizontal line is the Waxman-Bahcall bound for redshift evolution of the sources. Also shown are the integrated upper limits (at 90% C.L.) to the diffuse flux of UHE neutrinos (assumed to behave with energy as $dN/dE = k\,E^{-2}$) from experiments with sensitivity to νs in the EeV range and above. See Table 3 for full details and relevant references. The Auger downward-going limit was obtained with data between zenith angles 75° and 90°. All limits and flux models have been rescaled to single flavour when necessary, assuming equipartition of flavors at Earth.

format has the advantage that it displays the energy range at which the experiments are most sensitive. As can be seen in Fig. 6 the best sensitivity at the Auger Observatory is reached in the energy bin around 1 EeV which corresponds to the peak of the cosmogenic neutrino flux in an E^2 times flux plot, while for IceCube the largest sensitivity is achieved typically at 2-3 orders of magnitude smaller energy. On the contrary, the ANITA sensitivity peaks between 1-2 orders of magnitude larger energy than Auger [2].

The best way to compare the sensitivity of the experiments is to quote the expected number of events during the data taking period of the detector for a few reference models. This is shown in Table 4 for two representative cosmogenic neutrino flux predictions and the AGN neutrino model shown in Fig. 5 and for the current exposures of IceCube-40 and the surface detector of the Auger Observatory (see Table 3 for more details on the exposures). With data unblinded up to 31 May 2010, the surface detector of the Auger Observatory provides a poor constraint to models of cosmogenic ν production normalized to Fermi-LAT observations.

[2] The differential ANITA limit does not account for the background event.

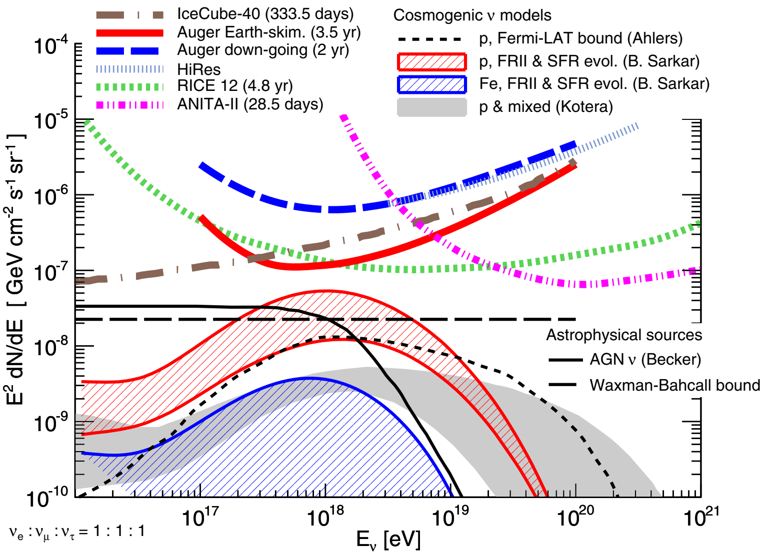

Figure 6. Same as in Fig. 5 but with the limits displayed in differential format (see text for details). The limits have been scaled to single flavour when necessary, and the IceCube differential limit is further scaled down by a factor 1/2 due to the different binning in energy with respect to the Auger differential limits. For the calculation of the RICE and ANITA differential limits we refer the reader to the original references [57, 58].

Table 4. *Top*: expected number of ν events for several models of ν production given the current exposures of IceCube-40 and the surface detector of the Pierre Auger Observatory to Earth-skimming νs only (see Table 3 for details). *Bottom*: expected number of events for 3 yrs of data taking with the full IceCube detector, and for the Earth-skimming and downward-going channels at the SD of the Auger Observatory up to June 2015.

Model / Detector	IceCube-40	Auger (Earth-skimming)
Cosmogenic ν [68] Primary p, Fermi-LAT constrained (dashed black line Fig. 5,6)	$\sim$0.4	$\sim$0.6
Cosmogenic ν [72] Prmary p, FRII source evolution (top band top edge Figs. 5,6)	$\sim$1.8	$\sim$2.2
Active Galactic Nuclei ν [70] (solid black line Figs. 5,6)	$\sim$5.5	$\sim$1.2
Model / Detector	**IceCube-86 (3 yrs)**	**Auger 2015. Up + Down (60° − 90°)**
Cosmogenic ν [68] Primary p, Fermi-LAT constrained (dashed black line in Figs. 5,6)	$\sim$2.3	$\sim$2.5
Cosmogenic ν [72] Primary p, FRII evolution (top band top edge Figs. 5,6)	$\sim$10.3	$\sim$9.2

4.4 Future prospects

As reflected in the projected number of events shown in Table 4, if UHEν are not discovered by $\sim$ 2015, experiments will be able to put strong constrains on models of cosmogenic ν fluxes that assume a pure primary proton composition injected at the sources.

5. CONCLUSIONS

We have reviewed the status of searches for ultra-high energy neutrinos and photons, touching different aspects:

- Neutrinos versus photons: Both are produced typically from the same initial process, namely as secondaries from pion decay. Photons test the local, neutrinos the whole Universe. Photons produce fairly normal air showers (but with larger $X_{\max}$ and fewer muons compared to hadronic ones), with small background (deep proton showers). Neutrinos have a minute probability (order 10^{-5}) to produce an air shower at all, but if so, it can be an extreme one (very deep or even upward) with no background. The effective aperture ratio of a ground array at 10 EeV is about 10^4 comparing photons to neutrinos.
- Neutrinos and photons versus charged cosmic rays: Both neutrinos and photons are neutral which may allow source pointing ("astronomy"). Both may act as messengers of the GZK process. For both, the interpretation of air shower observations is more robust than that of hadron showers.
- Current data versus models: searches using air showers were already performed and have already been useful by providing constraints on top-down models, on Lorentz violation, and (starting) on astrophysics. Discoveries of neutrinos and photons are well possible though not guaranteed in the near future.
- Various models versus each other: There is a large uncertainty concerning predictions. It is and will be an on-going task for phenomenology to combine the various constraints.
- Air shower observations versus other techniques: For photon searches, there is no competing technique. For neutrinos, air shower searches are (presently) comparable to other techniques; possible findings by other techniques may strongly impact future plans also for neutrino searches by air showers.
- Shower observations from ground versus those from space: The separation of primaries seems better from ground. Some balance might come if large exposures can be reached from space.
- Ground shower techniques versus each other: For photon searches, each technique is OK with some (dis-)advantages. As they have some complementarity, the best would be a combination. In a simplified way, one can state that what is good to determine (hadron) composition is fine to search for photons. For neutrino searches, a large exposure to inclined showers is the key, which favours, e.g., a large array of water detectors.
- Present status versus future directions: New observational windows to the Universe always gave new discoveries with large impact, also beyond astroparticle physics. This is expected to continue also for the windows which remain to be opened. At the highest-energy frontier, the air shower community has the means in hand to proceed towards the observation of neutrinos and photons.

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