# Snowmass2021 - Letter of Interest

# *Fundamental Physics with Ultra-High-Energy Photons and Neutrinos at the Pierre Auger Observatory*

**Thematic Areas:** (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) (NF04) Neutrinos from natural sources

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**Abstract:** The Pierre Auger Observatory is the world's largest detector for ultra-high-energy cosmic rays (UHECRs) with energies in excess of $10^{18}$ eV. The Observatory can also efficiently detect and identify the long-sought UHE photons and neutrinos that can be produced along with UHECRs revealing properties of their yet unidentified sources. UHE photons and neutrinos can also be produced in top-down models, which can involve e.g. the decay and/or annihilation of topological defects or decays of Super-Heavy Dark Matter (SHDM) particles, relics of the early Universe. Hence, the detection of UHE photons and neutrinos can help to answer fundamental questions in particle physics and cosmology, such as the nature of dark matter. With UHE photons and neutrinos, Auger can also probe fundamental physics beyond the Standard Model of Particle Physics, such as Lorentz invariance violation (LIV) and photon-to-axion conversion. Last but not least, UHE neutrinos can test the weak interaction and neutrino oscillations at an unprecedented energy scale.

The Pierre Auger Observatory near Malargüe, Mendoza Province, Argentina[1], is the world's largest detector for ultra-high-energy cosmic rays (UHECRs), protons and nuclei of astrophysical origin with energies in excess of $1\,\mathrm{EeV}$ ($10^{18}\,\mathrm{eV}$). The interaction of an UHECR in the EeV range with a (stationary) nucleus in the Earth's atmosphere, initiating a particle cascade (called extensive air shower) within the atmosphere, is equivalent to proton-proton collisions in the center-of-mass frame above $\sqrt{s} \simeq 45\,\mathrm{TeV}$, probing an energy range that is currently not yet accessible in accelerator experiments. The Pierre Auger Observatory features a Surface Detector (SD) array of 1660 water-Cherenkov particle detector stations spread out over an area of $3000\,\mathrm{km}^2$, with a spacing of $1500\,\mathrm{m}$. The SD array is overlooked by 24 air-fluorescence telescopes, the Fluorescence Detector (FD). Combining these instruments, both the footprint of the UHECR-induced extensive air shower at ground level and its development within the atmosphere can be detected in a so-called hybrid measurement. In addition, three high-elevation fluorescence telescopes overlook a $27.5\,\mathrm{km}^2$, 61-detector array with a smaller spacing of $750\,\mathrm{m}$ (the Infilled array). These instruments extend the sensitivity of the Observatory to lower energies.

The origin, nature and production mechanisms of UHECRs are some of the long-standing open questions in astroparticle physics. All theoretical models for the production of UHECRs predict UHE photons and neutrinos as a result of the decay of neutral and charged pions generated in interactions of UHECRs within the sources themselves (*astrophysical* photons/neutrinos), and/or in their propagation through background radiation fields, for example the cosmic microwave background (*cosmogenic* photons/neutrinos). The expected cosmogenic fluxes depend on the composition and maximum energy of UHECRs at the sources, as well as the distribution and cosmological evolution of the acceleration sites. Thus, observing UHE photons or neutrinos can pose constraints on the origin of UHECRs and the properties of their sources. UHE photons can propagate for a few tens of $\mathrm{Mpc}$ without being absorbed in the extragalactic radiation background fields, while neutrinos can travel to the observer with no interaction or deflection over cosmological, i.e. $\mathrm{Gpc}$, distances.

UHE particles are also predicted in exotic hypothetical *top-down* models for the origin of UHECR[2], in which the observed UHE particles are produced as decay products of super-heavy particles with masses in excess of $\sim 10^{21}\,\mathrm{eV}$. In these scenarios, the main components of the UHE particle flux are photons and neutrinos from neutral and charged pion decays with only $\sim 10\,\%$ of nucleons, because at the end of the QCD cascade, quarks combine more easily to mesons than to baryons. These super-heavy particles can be either metastable, produced directly in the early Universe with a lifetime larger than the age of the Universe (super-heavy dark-matter, SHDM[3–5]), or can be emitted by topological defects (TD), produced through a phase transition in the early Universe[6]. SHDM could make up a fraction of the dark matter in the Universe providing a link between cosmology and astroparticle physics, relating the expected flux of UHE photons and neutrinos to the lifetime-and-mass parameter space of SHDM particles.

In another class of models, UHECR are accelerated and can give rise to a secondary neutrino beam in optically thick sources. If this beam is sufficiently strong, it can produce the observed UHECRs within 100 Mpc of the Earth by electroweak interactions with the relic neutrino background[7]. In these so-called *Z-burst* models, Z-bosons, whose decay products can contribute to the UHECR flux, can be resonantly produced by UHE neutrinos of energy $E_\nu \simeq M_Z^2/(2m_\nu) \simeq 4.2 \times 10^{21}\,\mathrm{eV}^2/m_\nu$, with $M_Z$ and $m_\nu$ as the masses of the Z boson and the relic neutrinos, respectively[8].

New physics scenarios related to interaction or propagation effects can also be tested with photons and neutrinos, providing constraints on fundamental theories of quantum gravity involving Lorentz invariance violation (LIV)[9–11] and photon-axion conversion[12]. Violation of Lorentz Invariance also leaves an imprint on the spectrum of cosmogenic neutrinos that, if not seen, would allow placing constraints on it[11]. The main effect of subluminal LIV in the photon sector is an increase in the mean photon free path, which leads to photons traveling farther and, consequently, to an enhanced flux of cosmogenic photons[13]. Already the

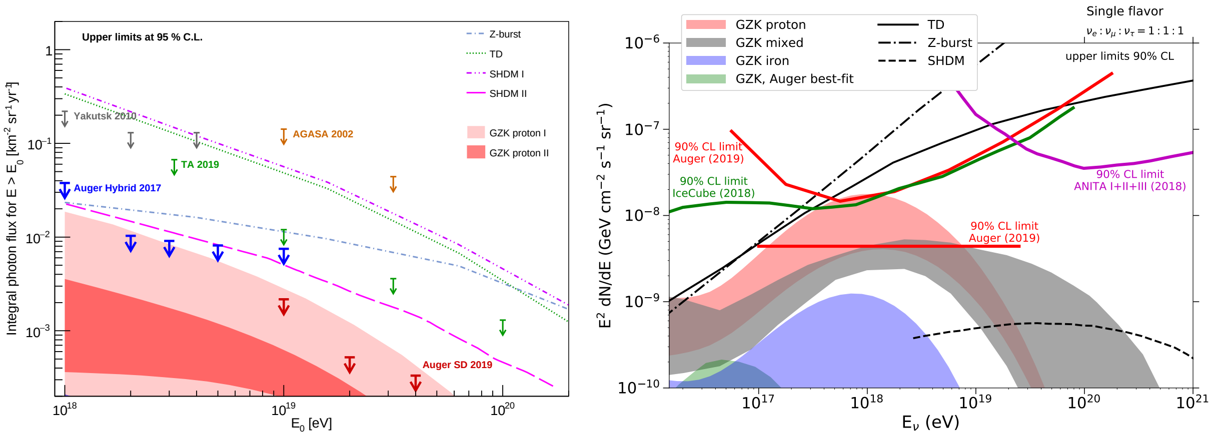

Figure 1: Limits on the flux of photons (left) and neutrinos (right) obtained from the Pierre Auger Observatory. The Auger results (photons: [15;16]; neutrinos: [17]) are shown together with the current limits from other experiments [18;19] and some examples of predicted fluxes: (photons: GZK/cosmogenic [20;21], Topological Defects TD, Z-Burst, Super-Heavy Dark Matter SHDM I [3], SHDM II [5]; neutrinos: GZK/cosmogenic [22–24], Z-Bursts [8], TD [6], SHDM [5]).

unambiguous detection of a single primary photon in the EeV range could significantly improve current limits on LIV in the photon sector [14].

The Pierre Auger Observatory has the capability of efficiently detecting UHE photons [15;16] and neutrinos [17] in the much larger background of showers initiated by UHE protons and nuclei. Air showers induced by UHE photons are more penetrating in the atmosphere and have less muons than those initiated by protons and nuclei, leading to several SD and FD observables that allow their efficient discrimination [15;16]. UHE neutrinos of all flavors are most efficiently identified with the SD by observing showers with large zenith angles that start close to the ground. These showers exhibit a large electromagnetic component in contrast to those induced by UHECRs initiated at the top of atmosphere that are dominated by muons. In Auger, the sensitivity to UHE neutrinos is highest for $\tau$ neutrinos that can undergo charged-current interactions and produce a $\tau$ lepton in the Earth's crust. The $\tau$ lepton leaves the Earth and decays in the atmosphere, inducing an *Earth-skimming* (ES) upward-going shower [17]. $\tau$ neutrinos are not expected to be copiously produced at the astrophysical sources, but as a result of neutrino oscillations over cosmological distances, approximately equal fluxes for each neutrino flavour should reach the earth, probing neutrino oscillations over cosmological distances in the EeV energy range.

No photons or neutrinos with energies above 1 EeV have been unambiguously identified so far. Consequently, restrictive upper limits on the fluxes of UHE photons and neutrinos have been imposed (see Fig. 1). For example, for an energy threshold of 1 EeV, the fraction of photons in the all-particle integral flux has been bound to the 0.1 % level. Some representative examples of predicted fluxes of UHE photons and neutrinos from several top-down models are shown in Fig. 1. The current limits on the UHE photon and neutrino fluxes from the Pierre Auger Observatory indicate that top-down processes cannot account for a significant part of the observed particle flux, probing physics beyond the Standard Model of Particle Physics and providing important constraints on the nature and origin of dark matter in the Universe.

Searches for UHE photons and neutrinos are among the scientific goals of AugerPrime, the upgrade of the Auger Observatory [25]. AugerPrime will feature several enhancements, most prominently a plastic scintillator on each of the SD water-Cherenkov stations and faster electronics, that will allow to disentangle the electromagnetic and muonic components enhancing the resolving power of photons and neutrinos.

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