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The Giant Radio Array for Neutrino Detection (GRAND) Project

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The GRAND project aims to detect ultra-high-energy neutrinos, cosmic rays and gamma rays, with an array of 200, 000 radio antennas over 200, 000 km^2, split into $\sim$ 20 sub-arrays of $\sim$ 10, 000 km^2 deployed worldwide. The strategy of GRAND is to detect air showers above 10^{17} eV that are induced by the interaction of ultra-high-energy particles in the atmosphere or in the Earth crust, through its associated coherent radio-emission in the 50 − 200 MHz range. In its final configuration, GRAND plans to reach a neutrino-sensitivity of $\sim 10^{-10}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ above 5×10^{17} eV combined with a sub-degree angular resolution. GRANDProto300, the 300-antenna pathfinder array, is planned to start data-taking in 2021. It aims at demonstrating autonomous radio detection of inclined air-showers, and study cosmic rays around the transition between Galactic and extra-Galactic sources. We present preliminary designs and simulation results, plans for the ongoing, staged approach to construction, and the rich research program made possible by the proposed sensitivity and angular resolution.

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GRAND is a proposed large-scale observatory designed to discover and study the sources of ultra-high-energy cosmic rays (UHECRs). GRAND will detect the radio signals made in the Earth's atmosphere by ultra-high-energy (UHE) cosmic rays, gamma rays, and neutrinos. The sub-degree angular resolution of GRAND will make possible the discovery of the first point sources of UHE neutrinos. We present the detection concept, the expected performances, and the rich science case of the experiment, as well as the different stages planned to achieve the ultimate array.

1. Detection concept

GRAND is designed to detect *inclined* extensive air-showers (EAS) produced by UHE cosmic particles [1]. While entering the atmosphere, UHE particles produce EAS, which in turn generate electromagnetic emission, mainly through the deflection of charged particles in the shower by the geomagnetic field. UHE tau neutrinos can also produce such electromagnetic signals by interacting with the Earth crust, giving birth to a tau lepton that can typically traverse a few tens of km of rock before exiting in the atmosphere and decaying, hence generating an Earth-skimming EAS. The geomagnetic emission is coherent in the 10s of MHz frequency range, generating short ($< 1\,\mu$s), transient radio pulses, with high enough amplitudes for the detection of showers with energy $\gtrsim 10^{16.5}$ eV [2, 3].

GRAND will build on the mature radio-detection experience of past and existing radio-detection experiments (AERA, CODALEMA, LOFAR, TREND, Tunka-REX). These instruments have focused on vertical EAS. Because of relativistic effects, the radio emission is strongly beamed forward, with an opening angle corresponding to the Cherenkov angle $\theta \lesssim 1^\circ$. For vertical EAS, the radio-signal propagates over the $\sim$ 10 km thickness of the atmosphere, and leads to a footprint on the ground of few 100s m^2. The sampling of such a signal necessitates a dense radio array. For very inclined air-showers on the other hand, the radio emission can propagate over several tens of kilometers, inducing a footprint on the ground of several squared kilometers, which can be sampled with a sparse (kilometer-step) array.

Radio antennas are ideal components to build giant arrays, being cheap, robust and scalable. In its final configuration, GRAND will consist of of $200,000$ antennas over $200,000\,\mathrm{km}^2$, split into ~ 20 sub-arrays of $10,000$ antennas located in different locations across the Earth. The locations of the sub-arrays will be chosen in radio-quiet environments with relatively easy access, and favorable topographies. An ideal topography consists of two opposing mountain ranges, separated by a few tens of kilometers. One range acts as a target for neutrino interactions, while the other acts as a screen on which the ensuing radio signal is projected. Simulations show that ground topographies inclined by few degrees only induce detection efficiencies typically three times larger than those obtained for flat areas [4].

2. Expected Performances

The development of a GRAND end-to-end simulation chain and of several reconstruction tools dedicated to inclined EAS have enabled to assess the performances of GRAND for UHE neutrino, cosmic ray, and gamma-ray detection. The simulation chain comprises a 3-D Monte-Carlo sampler

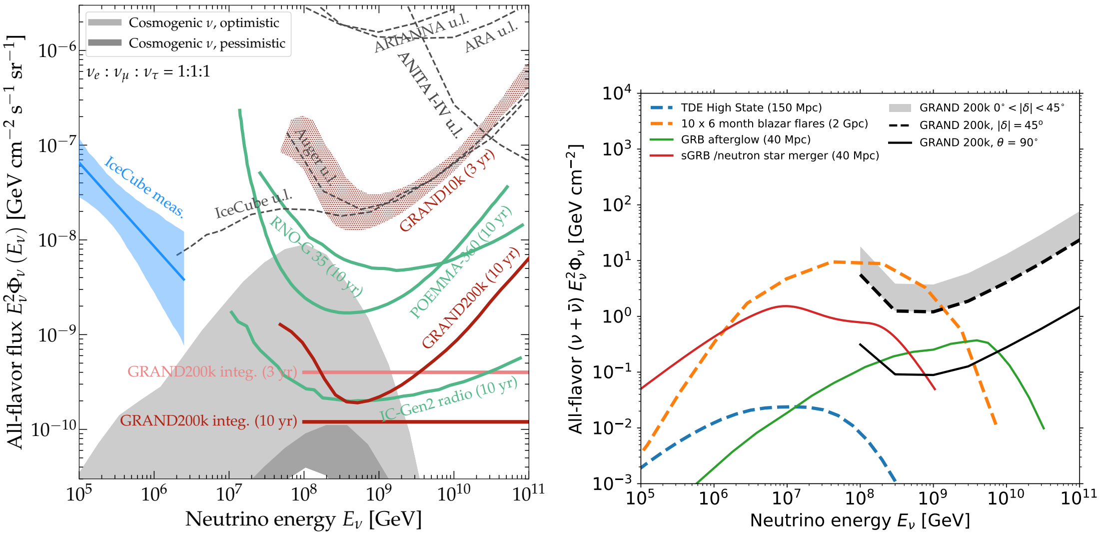

Figure 1: *Left:* Differential and integrated neutrino sensitivity limits calculated from the 10,000 antennas simulation ("GRAND10k", pink area) and the extrapolation for the 20-times larger GRAND array ("GRAND200k", maroon line). The gray region represents the all-flavor cosmogenic neutrinos flux expectations derived from the results of the Pierre Auger Observatory [5]. Adapted from [1]. *Right:* GRAND point source sensitivity limits [1]. Short-duration transients (short GRBs, GRB afterglows) are compared to the GRAND200k instantaneous sensitivity at zenith angle $\theta = 90°$ (solid black line). Long-duration transients (e.g., TDE) are compared to declination-averaged sensitivity (gray-shaded band). The stacked fluence from 10 six-month-long blazar flares in the declination range $40° < |\delta| < 45°$ is compared to the GRAND200k sensitivity for a fixed $\delta = 45°$ (dashed black line). The GRAND limits assume that the 200k antennas are deployed at a single location.

of tau leptons generated by ν_τ interactions underground (DANTON [6]), a semi-analytical radio-signal fast computation tool (Radio-Morphing [7, 8]), and an antenna response module (NEC4 [9]). The final step is the detector trigger simulation. Our trigger condition requires ≥ 5 units in one 9-antenna square cell to be triggered, and the peak-to-peak amplitude of the voltage signal at the output of the antennas to be $\geq 30[75]\mu$V (twice the expected stationary background noise in the 50 − 200 MHz frequency range) in the aggressive [conservative] scenario.

This simulation chain was run over a 10,000 km^2 area, with 10,000 antennas deployed along a square grid of 1 km step size in a basin surrounded by high peaks of the TianShan mountain range in China. The 10-year 90% C.L. GRAND sensitivity limit (Fig. 1, *left*) is scaled from the simulated region to 200,000 km^2 (GRAND200k). The integrated limits correspond to the Feldman-Cousins upper limit per decade in energy at 90% C.L., assuming a power-law neutrino spectrum $\propto E_\nu^{-2}$, for no candidate events and null background. The 10-year GRAND integrated sensitivity limit is $\sim 10^{-10}$ GeV cm^{-2} s^{-1} sr^{-1} above 5×10^{17} eV [1].

For UHECR detection, GRAND will be fully efficient above 10^{18} eV and sensitive to cosmic rays in a zenith-angle range of 65° − 85°. The geometrical aperture of the experiment will be 107,000 km^2 sr. However, when including events with shower cores outside the instrumented area and when taking trigger conditions into account, UHECR air-shower simulations indicate that GRAND would have a 4 − 5 times higher exposure. Figure 2 (*left*) presents an example of the

GRAND exposure to UHECR detection, assuming 10 random locations of sub-arrays of 20,000 antennas uniformly spaced between geographical latitudes 60N and 40S. An uniform acceptance was assumed over zenith angles of $65° - 85°$. A full-sky coverage is obtained with such a configuration.

The aperture of GRAND to UHE gamma rays is similar to the one of UHECRs. Figure 2 (*right*) shows that the sensitivity of GRAND200k to UHE gamma rays is sufficient to detect them even in the pessimistic case where UHECRs are heavy. To compute the preliminary sensitivity of GRAND200k to UHE gamma rays, we assumed that the detector is fully efficient to gamma ray-initiated air showers with energies above 10^{10} GeV in the zenith range 60°–85°. The sensitivity shown is the Feldman-Cousins upper limit at the 95% C.L., assuming no candidate events, null background, and a UHE gamma-ray spectrum $\propto E^{-2}$. The assumption of a background-free search is reasonable in the 10^{10}–$10^{10.5}$ GeV range, even for the conservative hypothesis that GRAND reaches a resolution in $X_{\max}$ of only 40 g cm^{-2}.

Novel reconstruction methods performing fits to the strength of the radio signal as a function of the angle from the shower axis (angular distribution function) have demonstrated that angular resolutions of $\sim 0.1°$ could be achieved on the particle arrival direction [10, 11], rendering neutrino and gamma-ray astronomy possible with GRAND. For a given sub-array location, the instantaneous neutrino field of view of GRAND is a band between zenith angles $85° \leq \theta \leq 95°$, corresponding to <5% of the sky. Assuming that all azimuth angles are observed at any instant, approximately 80% of the sky is observed every day by each sub-array. With $10 - 20$ locations spread around the globe, GRAND will offer a continuous full-sky coverage which enables multi-messenger astronomy in combination with any other experiment on Earth or in space.

Preliminary results obtained on the energy resolution are encouraging, as expected generally for energy reconstruction with radio measurements. A preliminary reconstruction method using the radio signal lateral distribution function, with no detector response implemented, leads to a 4% energy resolution. Another preliminary global reconstruction method using the angular distribution function leads to a 20% energy resolution [11]. Hence a final energy resolution of 10% is likely to be achieved. Finally, resolutions on $X_{\max}$ better than 40 g cm^{-2} were achieved in preliminary studies based on [12]. More refined and optimized methods are being developed to improve the reconstruction of all EAS parameters.

3. A rich science case

GRAND ambitions to tackle a variety of long-standing astrophysics and fundamental physics questions. We list the major questions on which GRAND has a potential to make breakthroughs.

Diffuse neutrino fluxes. With an increase of almost two decades in neutrino sensitivity compared to existing experiments, GRAND ensures the detection of EeV neutrinos. Cosmogenic neutrino studies show that the results from GRAND should severely constrain the sources of UHECRs whatever the outcome of the measurements [5, 13], and constrain the proton fraction at UHE [14]. The GRAND sensitivity, combined with its sub-degree angular resolution, will open the possibility to perform UHE neutrino astronomy, by identifying point-sources [15]. Note that the sources of UHECRs and UHE neutrinos could be different: transparent source environments are indeed favored to let UHECR escape from the sources, while thicker environments could lead to more abundant neutrino production. Hence, even if a heavy composition was measured for observed UHECRs, it would not necessarily imply that the flux of neutrinos at EeV should be suppressed.

Transient EeV neutrino astronomy. Thanks to its sub-degree angular resolution and its full-sky coverage, GRAND could identify EeV neutrino sources by detecting neutrinos from transient events in coincidence with electromagnetic emission [16, 17]. Figure 1 (*right*) compares theoretical neutrino fluence estimates from transient sources to the GRAND point-source sensitivities. We present a short-duration gamma-ray burst (sGRB) possibly associated with a double neutron-star merger [18] at 40 Mpc and a GRB afterglow [19] at 40 Mpc, a tidal disruption event (TDE) at 150 Mpc [20], and the stacked fluence of 10 blazar flares in the declination range $40° < |\delta| < 45°$, calculated using as template a 6-month long flare of the blazar 3C66A at 2 Gpc [21]. The sources were assumed to lie at distances such to allow for a conservative rate of $\sim$1 event per century.Depending on the background discrimination efficiency, GRAND will be able send alerts to other experiments or coordinated systems like AMON [22] for follow-up campaigns.

UHECR and gamma rays. According to preliminary simulations, GRAND will have full detection efficiency for cosmic rays with zenith angles larger than 70° and energies above 10^{18} eV [1]. This will yield an exposure $\gtrsim$ 15 times larger than the Pierre Auger Observatory. Further, it would be a full-sky instrument, which is crucial to study anisotropy [23].

Assuming that an $X_{\rm max}$ resolution of $40\,{\rm g\,cm^{-2}}$ is achieved –a realistic goal given present experimental results [24, 25] and preliminary simulations results (see Section 2)–, GRAND will be able to distinguish between UHECR and UHE gamma-ray showers. The non-detection of cosmogenic gamma rays within 3 years of operation of GRAND would exclude a light composition of UHECRs, while a detection of UHE gamma rays from nearby sources would probe the cosmic radio background [26].

Fundamental physics. High-energy cosmic neutrinos provide a chance to test fundamental physics in new regimes [27]. Numerous new-physics models have effects whose intensities are proportional to some power of the neutrino energy and to the source-detector baseline. GRAND could probe new physics with exquisite sensitivities, see e.g., [28], and will be able to test dark matter models through neutrino and photon constraints.

Transient radio-astronomy. By incoherently adding the signals from the large number antennas in a subarray, GRAND will also be able to detect a 30-Jy fast radio burst (FRB) with a flat frequency spectrum [1]. As incoherent summing preserves the wide field of view of a single antenna, GRAND may be able to detect several hundreds of FRBs per day. In addition, the detection of a single FRB by several sub-arrays would enable to reconstruct the arrival direction of the radio signal.

4. Technical challenges

Autonomous radio-detection, i.e., identifying EAS radio signals with radio antennas alone, is a major challenge due to the ubiquitously dominant radio background, which necessitates an important rejection efficiency. It has been shown that EAS radio signatures differ from background events, with much shorter time traces [30] and specific amplitude [31] and polarization patterns

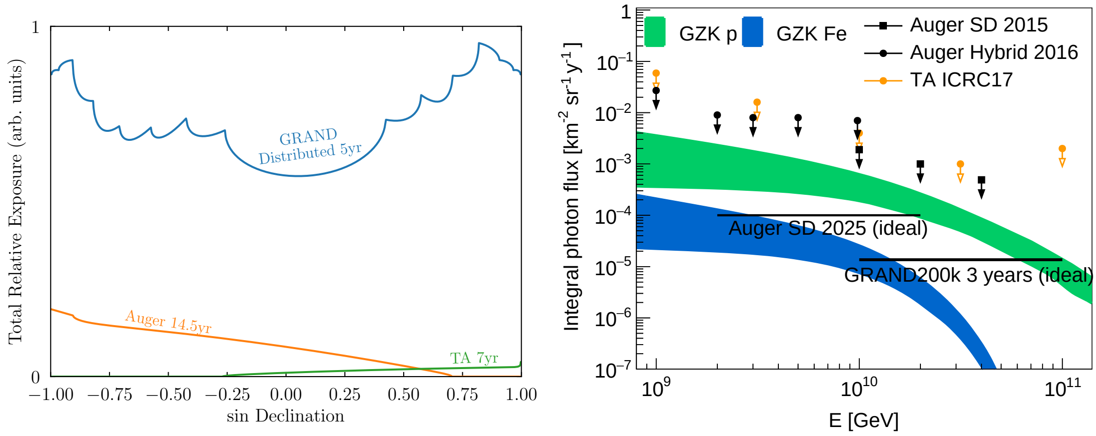

Figure 2: *Left:* The relative annual geometric exposure to UHECRs of GRAND for a uniform distribution of 10 sub-arrays on the Earth, compared to Auger and the Telescope Array (TA). *Right:* Projected upper limits of GRAND on UHE photon sensitivity after 3 years of operation. For comparison, we include the existing upper limits from Auger and TA, and the projected reach of Auger by 2025. Overlayed are the predicted cosmogenic UHE photon flux from pure-proton and pure-iron UHECRs, as estimated in [29].

at ground [32]. These unique features have been used by the TREND-experiment to perform an efficient rejection of the background signals using radio data only [33]. An efficient background rejection criterion ($\sim 99.9\%$ of noise-induced event rejection) at the data acquisition level has also been developed recently, based on the projection of the total electric field along the direction of the local magnetic field [8]. Interestingly, this criterion can also be used to discriminate neutrino and cosmic-ray EAS. These methods are being refined, and sophisticated data treatment techniques (adaptative filtering, machine learning, etc.) are being developed in parallel [34, 35].

From a hardware point-of-view, an adequate DAQ system, which can treat signals at a high-enough frequency rate ($\sim$ kHz) should enable to perform efficient triggering. This system has been implemented in the first 300-antenna prototype, GRANDProto300 (GP300) [36]. The prototype will serve as a test bench to validate solutions for the next stages of GRAND. It will be deployed over 200 km^2 in an environment with excellent radio quality, presenting a low rate of transient radio pulses in particular. The protocol used in the site survey for the GP300 phase of GRAND will be extended and optimized when validating the locations of the GRAND sub-arrays.

5. The road to neutrino astronomy

GRAND will be modular and built in stages. Between 2021 and 2025, the 300-antenna pathfinder, GP300, will validate the GRAND detection principle, test and optimize the detection units design, the autonomous trigger and data transfer strategies. GP300 will also conduct an ambitious science program on cosmic rays between $10^{16.5-18}$ eV [36]. 10,000 detection units of the finalized design will be produced and deployed in 2025 to create GRAND10k, the first GRAND sub-array. This array will serve to test challenges related to large-scale arrays, such as communication and data transfer/storage. GRAND10k likely has the sensitivity to detect the first EeV neutrinos. By the 2030s, once this first sub-array has been demonstrated to operate successfully, its design will be frozen. Industrial companies will be prospected to replicate this sub-array and take care of the mass-production and deployment of the units with predefined specifications in terms of reliability, costs etc. The design of each sub-array may be adapted, depending on location and topography, or to address specific science cases.

References

[1] GRAND Collaboration, J. Álvarez-Muñiz, R. Alves Batista, A. Balagopal V., et al., The Giant Radio Array for Neutrino Detection (GRAND): Science and design, Science China Physics, Mechanics, and Astronomy 63 (1) (2020) 219501. arXiv:1810.09994, doi:10.1007/s11433-018-9385-7.

[2] T. Huege, Radio detection of cosmic ray air showers in the digital era, Phys. Rept. 620 (2016) 1–52. arXiv:1601.07426, doi:10.1016/j.physrep.2016.02.001.

[3] F. G. Schröder, Radio detection of cosmic-ray air showers and high-energy neutrinos, Progress in Particle and Nuclear Physics 93 (2017) 1 – 68. doi:https://doi.org/10.1016/j.ppnp.2016.12.002.

[4] V. Decoene, N. Renault-Tinacci, O. Martineau-Huynh, et al., Radio-detection of neutrino-induced air showers: The influence of topography, NIMA 986 (2021) 164803. doi:10.1016/j.nima.2020.164803.

[5] R. Alves Batista, R. M. de Almeida, B. Lago, K. Kotera, Cosmogenic photon and neutrino fluxes in the Auger era, JCAP 1901 (01) (2019) 002. arXiv:1806.10879, doi:10.1088/1475-7516/2019/01/002.

[6] V. Niess, O. Martineau-Huynh, DANTON: a Monte-Carlo sampler of τ from ν_τ interacting with the Earth (2018). arXiv:1810.01978.

[7] A. Zilles, O. Martineau-Huynh, K. Kotera, et al., Radio Morphing: towards a fast computation of the radio signal from air showers, Astroparticle Physics 114 (2020) 10–21. doi:10.1016/j.astropartphys.2019.06.001.

[8] S. Chiche, Radio-Morphing: a fast, efficient and accurate tool to compute the radio signals from air-showers, in: Proceedings, 37$^{\text{th}}$ International Cosmic Ray Conference (ICRC 2021): Berlin, Germany, July 12-23, 2021.

[9] G. Burke, Numerical Electromagnetic Codes – User's Manual (1992).
URL http://physics.princeton.edu/~mcdonald/examples/NEC_Manuals/NEC4UsersMan.pdf

[10] V. Decoene, Sources and detection of high-energy cosmic events, Theses, Sorbonne Université (2020).
URL https://tel.archives-ouvertes.fr/tel-03153273

[11] V. Decoene, A reconstruction procedure for very inclined extensive air showers based on radio signals, in: Proceedings, 37$^{\text{th}}$ International Cosmic Ray Conference (ICRC 2021): Berlin, Germany, July 12-23, 2021.

[12] S. Buitink, et al., Method for high precision reconstruction of air shower X_{max} using two-dimensional radio intensity profiles 90 (8) (2014) 082003. arXiv:1408.7001, doi:10.1103/PhysRevD.90.082003.

[13] K. Møller, P. B. Denton, I. Tamborra, Cosmogenic neutrinos through the GRAND lens unveil the nature of cosmic accelerators, J. Cosmology Astropart. Phys.2019 (5) (2019) 047. arXiv:1809.04866.

[14] A. van Vliet, R. A. Batista, J. R. Hörandel, Determining the fraction of cosmic-ray protons at ultrahigh energies with cosmogenic neutrinos, Physical Review D 100 (2) (Jul 2019). doi:10.1103/physrevd.100.021302.
URL http://dx.doi.org/10.1103/PhysRevD.100.021302

[15] K. Fang, K. Kotera, M. C. Miller, et al., Identifying Ultrahigh-Energy Cosmic-Ray Accelerators with Future Ultrahigh-Energy Neutrino Detectors, JCAP 1612 (12) (2016) 017. arXiv:1609.08027.

[16] C. Guépin, K. Kotera, Can we observe neutrino flares in coincidence with explosive transients?, Astron. Astrophys. 603 (2017) A76. arXiv:1701.07038, doi:10.1051/0004-6361/201630326.

[17] T. M. Venters, M. H. Reno, J. F. Krizmanic, et al., POEMMA's target-of-opportunity sensitivity to cosmic neutrino transient sources, Phys. Rev. D102 (12) (2020) 123013. arXiv:1906.07209.

[18] S. S. Kimura, K. Murase, P. Mészáros, K. Kiuchi, High-energy neutrino emission from short gamma-ray bursts: Prospects for coincident detection with gravitational waves, The Astrophysical Journal 848 (1) (2017) L4.

[19] K. Murase, High energy neutrino early afterglows gamma-ray bursts revisited, Phys. Rev. D 76 (2007) 123001.

[20] C. Guépin, K. Kotera, E. Barausse, K. Fang, K. Murase, Ultra-High Energy Cosmic Rays and Neutrinos from Tidal Disruptions by Massive Black Holes, Astron. Astrophys. 616 (2018) A179. arXiv:1711.11274.

[21] K. Murase, Y. Inoue, C. D. Dermer, Diffuse Neutrino Intensity from the Inner Jets of Active Galactic Nuclei: Impacts of External Photon Fields and the Blazar Sequence, Phys. Rev. D 90 (2) (2014) 023007. arXiv:1403.4089.

[22] H. A. Ayala Solares, S. Coutu, D. Cowen, et al., The astrophysical multimessenger observatory network (amon): Performance and science program., Astroparticle Physics 114 (2019) 68 – 76.

[23] P. B. Denton, T. J. Weiler, Sensitivity of full-sky experiments to large scale cosmic ray anisotropies, Journal of High Energy Astrophysics 8 (2015) 1–9.

[24] S. Buitink, et al., A large light-mass component of cosmic rays at $10^{17} - 10^{17.5}$ eV from radio observations, Nature 531 (2016) 70. arXiv:1603.01594, doi:10.1038/nature16976.

[25] P. A. Bezyazeekov, et al., Measurement of cosmic-ray air showers with the Tunka Radio Extension (Tunka-Rex), Nucl. Instrum. Meth. A 802 (2015) 89–96. arXiv:1509.08624, doi:10.1016/j.nima.2015.08.061.

[26] D. J. Fixsen, E. Dwek, J. C. Mather, C. L. Bennett, R. A. Shafer, The Spectrum of the extragalactic far infrared background from the COBE FIRAS observations, Astrophys. J. 508 (1998) 123. arXiv:astro-ph/9803021.

[27] A. Vieregg, M. Ackermann, M. Ahlers, et al., Fundamental Physics with High-Energy Cosmic Neutrinos, in: BAAS, Vol. 51, 2019, p. 215.

[28] P. B. Denton, Y. Kini, Ultrahigh-energy tau neutrino cross sections with GRAND and POEMMA, Phys. Rev. D102 (12) (2020) 123019. arXiv:2007.10334, doi:10.1103/PhysRevD.102.123019.

[29] B. Sarkar, K.-H. Kampert, J. Kulbartz, Ultra-High Energy Photon and Neutrino Fluxes in Realistic Astrophysical Scenarios, in: Proceedings, 32nd International Cosmic Ray Conference (ICRC 2011): Beijing, China, August 11-18, 2011, Vol. 2, p. 198.

[30] S. W. Barwick, et al., Radio detection of air showers with the ARIANNA experiment on the Ross Ice Shelf, Astropart. Phys. 90 (2017) 50–68. arXiv:1612.04473, doi:10.1016/j.astropartphys.2017.02.003.

[31] A. Nelles, et al., Measuring a Cherenkov ring in the radio emission from air showers at 110–190 MHz with LOFAR, Astropart. Phys. 65 (2015) 11–21. arXiv:1411.6865, doi:10.1016/j.astropartphys.2014.11.006.

[32] H. Carduner, et al., The CODALEMA/EXTASIS experiment: Contributions to the 35th International Cosmic Ray Conference (ICRC 2017) (2017). arXiv:1710.02487.

[33] D. Charrier, K. de Vries, Q. Gou, J. Gu, H. Hu, Y. Huang, S. Le Coz, O. Martineau-Huynh, V. Niess, T. Saugrin, et al., Autonomous radio detection of air showers with the trend50 antenna array, Astroparticle Physics 110 (2019) 15–29.

[34] F. Führer, T. Charnock, A. Zilles, M. Tueros, Towards online triggering for the radio detection of air showers using deep neural networks, arXiv e-prints (2018) arXiv:1809.01934arXiv:1809.01934.

[35] M. Erdmann, F. Schlüter, R. Šmída, Classification and recovery of radio signals from cosmic ray induced air showers with deep learning, Journal of Instrumentation 14 (4) (2019) P04005. arXiv:1901.04079.

[36] Z. Yi, Self-trigger radio prototype array for GRAND, in: Proceedings, 37^{th} International Cosmic Ray Conference (ICRC 2021): Berlin, Germany, July 12-23, 2021.

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