GRAND: Giant Radio Array for Neutrino Detection

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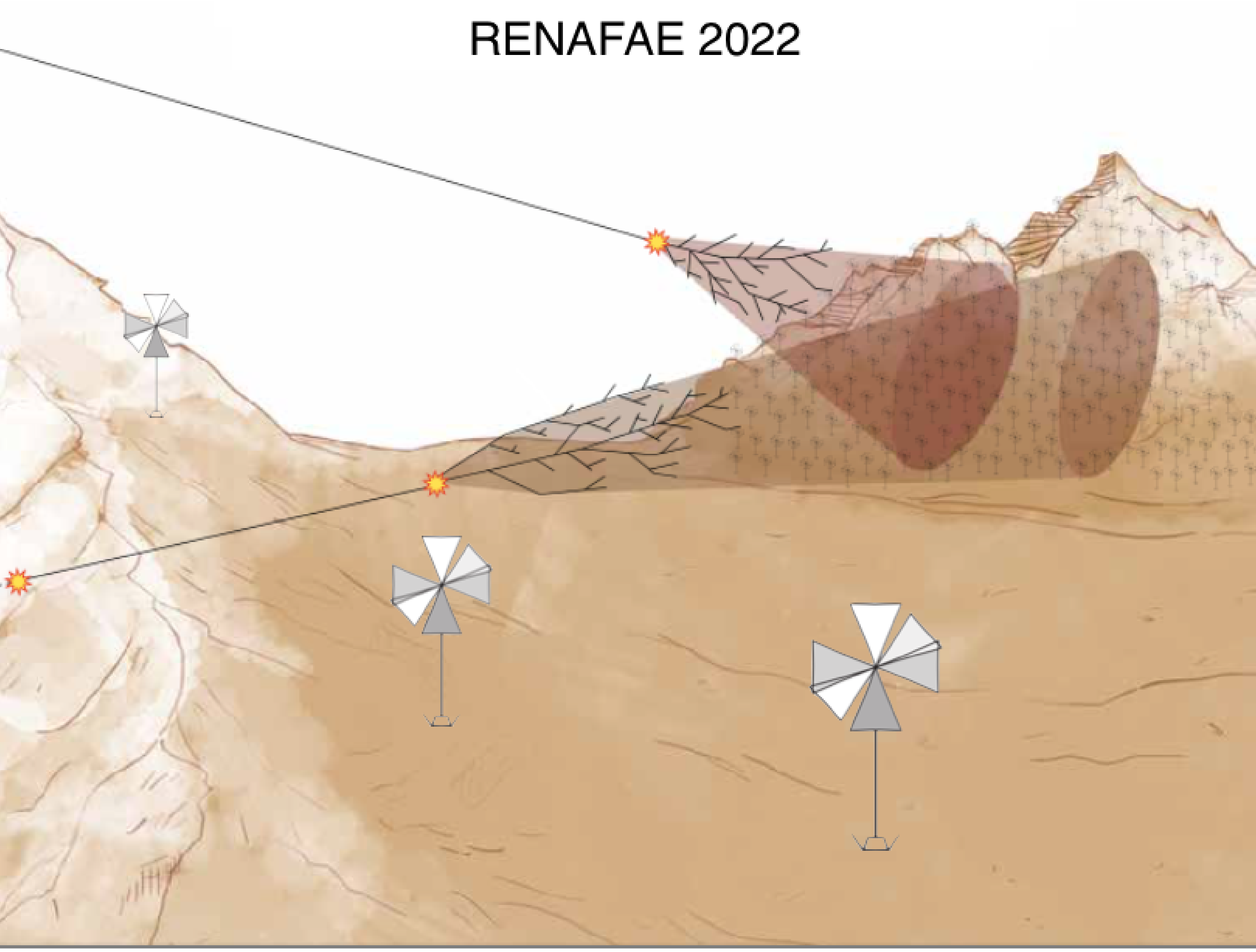

The Giant Radio Array for Neutrino Detection (GRAND)

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Abstract

The Giant Radio Array for Neutrino Detection (GRAND) is a planned observatory whose main goal is to study the Universe at ultra-high energies. GRAND will detect UHE cosmic rays, gamma rays, and neutrinos with unprecedented sensitivity. Using large arrays of antennas, GRAND will detect the radio emission from extensive air showers initiated by cosmic particles impinging on the atmosphere. Approximately twenty sub-arrays, each containing 10000 antennas, will be deployed over $\sim$ 10,000 km^2 in radio-quiet areas around the world. GRAND will be constructed in stages, to ensure that the techniques employed are properly validated. Already in the early phases, it will be possible to realise important scientific goals, including accurate measurements of cosmic-ray and gamma-ray showers with energies between 30 PeV and 1 EeV, studies of the Epoch of Reionisation, and detection of Fast Radio Bursts. When completed, GRAND will reach sub-degree resolution and cover the whole sky, enabling neutrino astronomy and follow-ups of electromagnetic and gravitational-wave transients. Finally, the final design of GRAND will likely enable the detection, for the first time, of cosmogenic neutrinos with energies $\gtrsim 100$ PeV, shedding light on the yet-unresolved issue of the origin of the highest-energy particles in the Universe.

Thematic areas: Astroparticle Physics, Astronomy and Astrophysics, Neutrino Physics

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1 Scientific context

Ultra-high-energy cosmic rays (UHECRs) are atomic nuclei with energies exceeding $\sim 10^{18}$ eV whose origins are a mystery [1]. The mechanisms whereby they attain their extreme energies are not well understood. From the moment cosmic rays start to be accelerated, until they reach Earth, they can interact with matter and radiation fields present along the way. This produces copious amounts of secondary particles including neutrinos and photons, thereby establishing the *multi-messenger connection*. UHECRs are deflected by intervening magnetic fields and can be absorbed during propagation. Photons, too, can be absorbed. Neutrinos, on the other hand, travel to Earth virtually unimpeded, thus being arguably the best messenger to probe the Universe up to large distances.

The Giant Radio Array for Neutrino Detection (GRAND) [2] is a proposed large-scale observatory designed to discover and study the sources of UHECRs. GRAND will detect the radio signals produced by the interaction of UHE cosmic rays, gamma rays, and neutrinos with the atmosphere. Its set-up also enables studies of fundamental particle physics, cosmology, and radioastronomy. In the next subsections each of these scientific cases are briefly described.

1.1 Ultra-high-energy messengers

The interaction of UHECRs with the pervasive cosmic microwave background (CMB) and extragalactic background light (EBL) produces fluxes of photons and neutrinos of cosmogenic origin. Due to our limited knowledge about UHECR sources, it is hard to predict these fluxes, but they are *guaranteed* nonetheless. A detailed model requires knowledge of spectrum and composition of CRs at the sources [3–5], the distribution of sources and magnetic fields [6, 7], among other factors [5, 8, 9].

Even under pessimistic assumptions [4] GRAND may be able to severely constrain the parameter space or, under more optimistic assumptions [10], to reach the required sensitivity to detect cosmogenic neutrinos, as shown in fig. 1 (left).

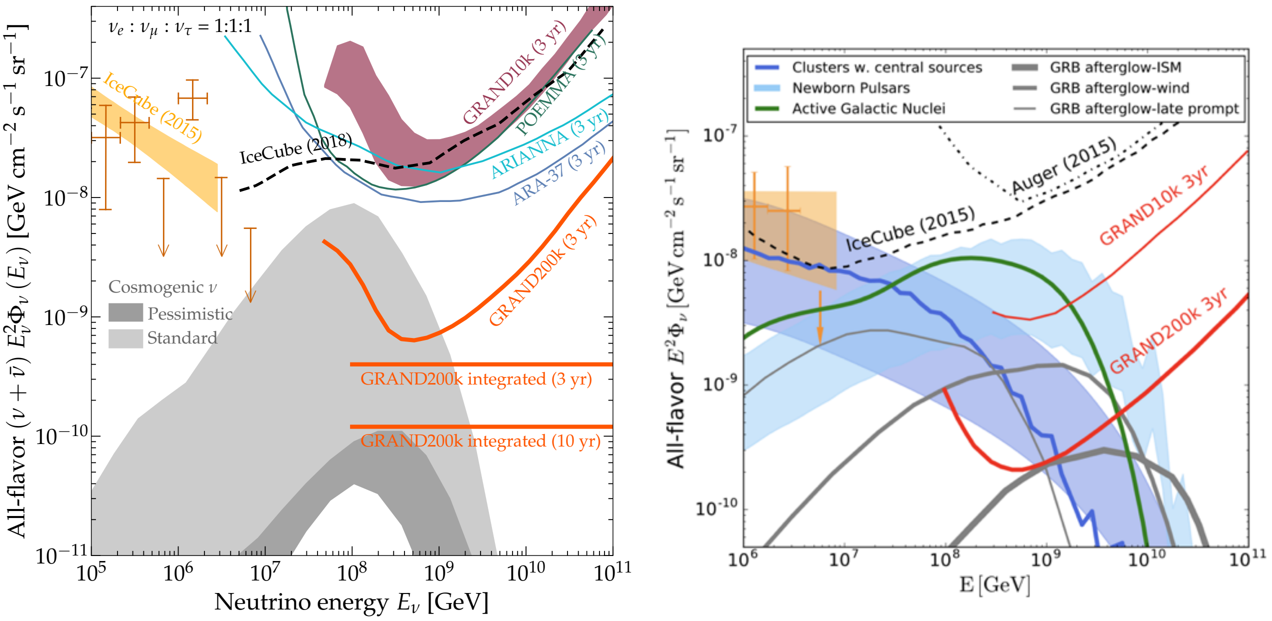


Figure 1: The figures show all-flavour upper limits and sensitivities for various experiments. The left panel indicates the pessimistic [4] and optimistic [10] cosmogenic neutrino fluxes, whereas the right panel shows the expected neutrino fluxes for different populations of astrophysical sources. See ref. [2] for more details.

GRAND's sub-degree angular resolution, combined with its high detection rate, will enable the detection of the first point sources of UHE neutrinos. Several classes of astrophysical objects were suggested as UHECR sources, including active galactic nuclei [11–14], gamma-ray bursts [15–17], pulsars and magnetars [18, 19], galaxy clusters [20–22], and tidal disruption events [23–25]. If an object can accelerate CRs to ultra-high energies, then it can also produce neutrinos in situ, which are potentially detectable by GRAND, as indicated in fig. 1 (right).

GRAND is the *only proposed experiment* that will reach a differential sensitivity of $\sim 4\times10^{-10}$ GeV cm^{-2} s^{-1}. Thus, it will enable constraints on the composition and source evolution of UHECRs [26, 27].

Similarly to UHE neutrinos, the cosmogenic flux of UHE photons is also guaranteed. They may be emitted by astrophysical sources, depending on their opacity. However, distant objects cannot be directly observed as they are absorbed by the CMB/EBL and reprocessed to lower energies. These photons can then be observed with gamma-ray observatories such as the Cherenkov Telescope Array (CTA) [28]. The most stringent upper limits on UHE photons were derived by the Pierre Auger Observatory [29], but can be improved by two orders of magnitude after three years of data-taking by GRAND [2].

GRAND's final stage, GRAND200k, will have an exposure of $535,000$ km^2 sr yr at energies $\gtrsim 10^{19}$ eV after five years of operation [2]. This implies a detection rate about 15 times larger than the Pierre Auger Observatory [30], and an yearly detection rate at $E \gtrsim 10^{19.5}$ eV a ten-fold higher than all other UHECR experiments combined. This places GRAND in a unique position to study the Universe at the highest energies, characterising the end of the cosmic-ray spectrum, and drastically improving our understanding of cosmic-ray acceleration and propagation.

Already in the early stages, GRAND's prototype, GRANDProto300, will be able to study the transition between galactic and extragalactic CRs ($E \sim 10^{16.5} - 10^{18.5}$ eV) in great detail [31].

1.2 Multi-messenger Astronomy

We have recently witnessed the dawn of the era of multi-messenger astrophysics. It was marked by the detection of gravitational waves from binary neutron star by LIGO [32, 33] in coincidence with electromagnetic counterparts, and by the observation of high-energy neutrinos from a blazar flare by IceCube [34] together with radiation across the whole electromagnetic spectrum [35].

Due to its excellent angular resolution and large sky coverage, GRAND could identify UHE neutrinos from transient events in coincidence with electromagnetic emission. Its instantaneous field of view is $\lesssim 5\%$, but if all azimuthal angles are observed at any given instant, this yields a daily coverage of about 80% of the sky. In practise, this number will be larger because the final configuration will be comprised of several sub-arrays in various geographical locations.

As a triggering partner, GRAND will make it possible to reconstruct the arrival direction of neutrino-induced air showers close to the horizon with sub-degree accuracy with sub-minute latency. Thus, it will be able to send alerts to other experiments or coordinated system like the Astrophysical Multimessenger Observatory Network (AMON) [36]. As a follow-up partner, GRAND will be able to quickly validate alerts issued by other experiments such as IceCube and IceCube-Gen2 [37], as well as gravitational-wave detectors. If the target directions are within the instantaneous field of view of GRAND, limits on UHE neutrino emission from the observed transient can be derived.

1.3 Fundamental Physics

The cosmos is a laboratory to test fundamental physics using ultra-high-energy particles. Typically, new-physics models predict specific signatures in neutrino-related observables, namely the energy spectrum [38, 39], angular distribution [40, 41], and flavour ratios [42–44]. These effects depend on the neutrino energy and the baselines involved. GRAND could probe such scenarios with unprecedented sensitivity [2]. Many of the aforementioned new-physics scenarios involve neutrino interactions with dark matter [44–47]; GRAND will enable extremely stringent astrophysical constraints on some of these models. Moreover, it can test Lorentz invariance violation and improve the existing limits [42, 43, 48, 49].

GRAND is able to extend the measurement of the cross section for neutrino-nucleon interactions inside the Earth. This was measured up to $\sim$ PeV by IceCube [50, 51]. It could extend this measurement up to $\sim$ EeV energies [2].

Ultimately, the ability of GRAND to probe fundamental physics at the EeV scale will depend on the level of the cosmogenic neutrino flux. If the flux is low as in [4], finding small new-physics signatures will be challenging due to the limited statistics.

1.4 Radioastronomy and Cosmology

With its wide field of view and frequency range, GRAND will also work as a radiotelescope to probe millisecond-scale phenomena. Astrophysical transients such as fast radio bursts (FRBs) and Giant Radio Pulses (GRPs) can be measured with unmatched statistics at low frequencies [2, 52]. By mapping the sky temperature with mK precision, GRAND could also measure the global signature of the Epoch of Reionisation (EoR) and study the Cosmic Dawn. These measurements will be feasible even during the intermediate construction stages (GRANDProto300 and GRAND10k).

2 Objectives

GRAND's primary goal is *to solve the long-standing mystery concerning the origins of the UHECRs*. It will also serve as a neutrino telescope to study point sources of UHE neutrinos. The summary of GRAND's science goals, both primary and secondary, is shown in fig. 2.

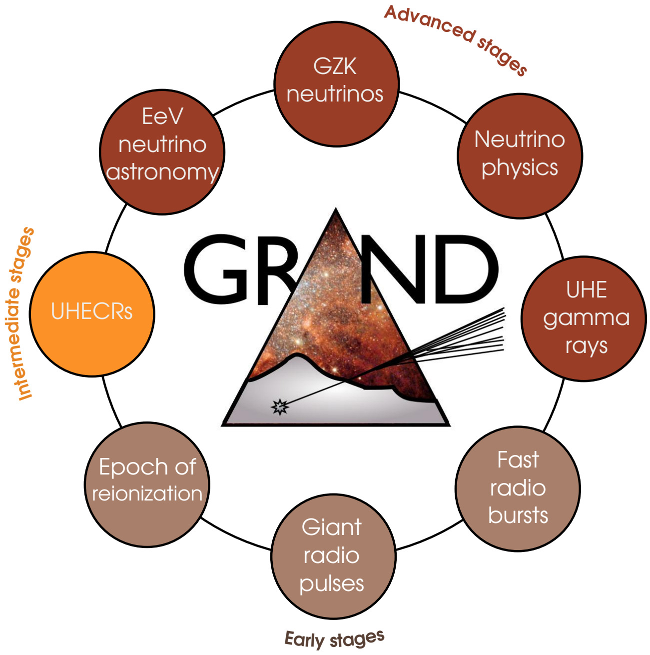


Figure 2: The science goals of GRAND, grouped according to the detector construction stage at which they first become accessible.

3 Technical Overview

Radio detection of extensive air showers (EAS) is becoming increasingly popular. It has been successfully implemented in the Auger Engineering Radio Array (AERA), the LOw-Frequency ARray (LOFAR), the COsmic ray Detection Array with Logarithmic Electro-Magnetic Antennas (CODALEMA), the Tunka Radio Extension (Tunka-Rex), and the Tianshan Radio Experiment for Neutrino Detection (TREND).

The cost of deploying radio antennas is lower than for other types of detectors. Moreover, their duty cycle is extremely high. Furthermore, because we are aiming for inclined showers, the expected radio footprint is ~ 100 km^2, which allows for a relatively sparse array of antennas. The most remarkable novelty of GRAND is that it uses a self-trigger technique. Although very challenging, this is feasible, as demonstrated by TREND [53]. Therefore, GRAND can be a stand-alone radio detector!

One of the advantages of radio detection is that it provides a direct calorimetric measurement of the electromagnetic component of the shower [54], which minimises the reliance on hadronic interaction models and makes the direct comparison with fluorescence measurements possible. Moreover, radio waves in the $\sim$ MHz band are not absorbed by the atmosphere. Furthermore, due to the length scales involved ($\sim$ a few metres), waves emitted via the geomagnetic and Askaryan effects add up *coherently*, thus implying that the amplitude of the signal is approximately proportional to the particle number in the EAS. These two components have different polarisations and, for inclined showers, they lead to azimuthally asymmetric signals.

3.1 Antenna design

GRAND targets very inclined air showers, with zenith angles close to 90°, with nearly horizontal polarisation. This poses a challenge for detecting radio emission from EASs as the the topography of the terrain affects the response of the antennas. For this reason, our antennas — HorizonAntenna — were specifically designed to increase the detection efficiency along the horizon. They are placed on top of 5-metres high wooden poles and operate in the frequency range between 50 MHz and 200 MHz, instead of the 50-100 MHz range used in most other arrays. This way, the design enables the detection of radio Cherenkov rings, improves the signal-to-noise ratios, and lowers the detection threshold [55].

The HorizonAntenna is an active bow-tie antenna with a relatively flat response in the azimuthal direction and in frequency. Its design is inspired by the “butterfly antenna” developed for CODALEMA [56], and later used in AERA [57]. It has 3 perpendicular arms oriented along two horizontal directions and a vertical one. In fig. 3 we show the gain of the HorizonAntenna at 50 MHz as a function of the direction. A first prototype of the HorizonAntenna was successfully tested in 2018 during a site survey for GRAND in China. Further experimental verification of the response as a function of direction remains to be performed.

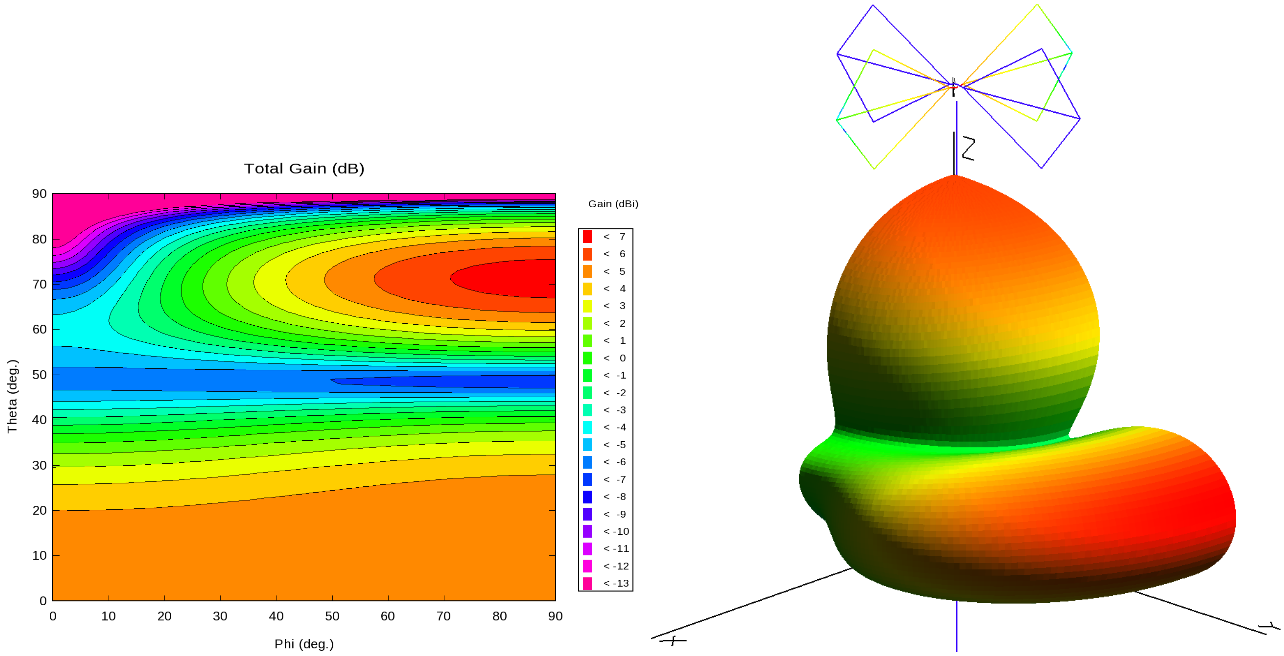


Figure 3: Two- (left) and three-dimensional (right) view of the total gain of the X-arm of GRAND’s HorizonAntenna, as a function of direction, at a frequency of 50 MHz.

3.2 Array layout

The large radio footprint of very inclined showers enables us to deploy sparse instrumentation over a large area. The final GRAND array will be modular, with ~ 20 geographically separate sub-arrays of ~ 10000 km^2 each. The sites will be chosen based on the local radio-loudness and topography. Mountainous terrains are ideal for this purpose, since slopes with an elevation of $\sim 1-2$ km act as efficient interaction targets for forward-beamed radio signals of neutrino-induced air showers that emerge from the ground, while antennas lying in a valley would fail to detect the signal [58]. The difference in antenna altitudes on a slope also provides an improved reconstruction of the zenith angle of very inclined showers. Ideally, the sub-arrays will be deployed on mountain slopes facing other mountains, improving background rejection by using the relief to shield the antennas from very inclined UHECR-induced showers. One requirement is that the stationary noise level should be close to the Galactic radio background in the 50–200 MHz band. Moreover, the rate of transient signals with peak amplitudes larger than five times the stationary noise should be below ~ 1 kHz in this frequency band.

Logistics requirements are also important. This includes: reasonably easy access to the antennas, availability of solar power to run the DAQ system, and broadband internet connection, as well as favourable weather conditions (for stable operation of the electronics, in particular of the solar panels). We found several sites in China that meet these requirements. We will deploy the first prototypes in these areas. Finally, the modular layout proposed is advantageous to increase GRAND’s field of view, detection rate of transient events, and to improve the angular resolution.

3.3 Background rejection

GRAND’s design adopts various strategies for reducing natural and anthropogenic radio noise, either stationary and transient. A complete understanding of the background and its rejection requires performing prolonged on-site tests, which we are starting to do at the moment. The main noise sources at 50-200 MHz are the galactic synchrotron radio emission and the thermal emission from the ground, which can be discriminated by looking for coincident triggers among multiple antennas. There is also a wide variety of background sources that emit transient electromagnetic signals in a wide frequency range. Depending on the local environment, the rate of detected background events ranges from tens of Hz per antenna in the most remote areas to kHz or more. These rates are much higher than the rate of shower detections, which requires efficient background rejection methods. Experiments like TREND [53] and ARIANNA [59] successfully demonstrated an excellent background discrimination based on specific features of the showers such as polarisation patterns, pulse length, beamed emission, Cherenkov ring, among others, and also features of the background itself (clustering in time and position).

3.4 Detector performance

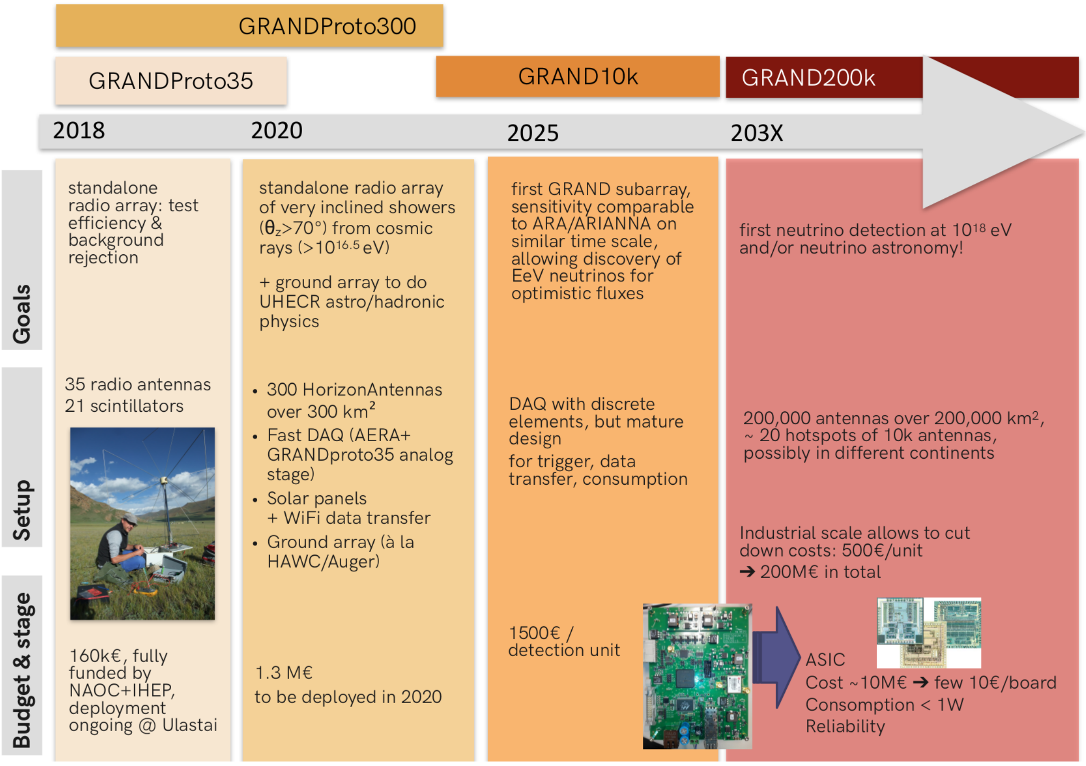
The end-to-end simulation pipeline to determine GRAND's sensitivity takes into account the non-trivial topography of the array site and the vast instrumented area. Given the complexity of the problem at hand, we ensure that all relevant physics is included, whilst striving to optimise computational performance. We validate each part of the simulation individually, by comparison with existing codes. The full simulations chain is described in detail in ref. [2]. It yields a 3-year sensitivity of $\sim 4 \times 10^{-10}$ GeV cm^{-2} sr^{-1} s^{-1} at energies of $\sim 10^{18}$ eV, and a total aperture between $20,000$ and $25,000$ km^2 sr, depending on the detection threshold. At $E \sim 10^{19}$ eV, the effective area is $\sim 107,000$ km^2 sr.

GRAND will be fully efficient for detecting UHECRs and UHE photons above 10^{19} eV arriving at zenith angles $> 65°$. We estimate the rate of detection of UHECR-initiated showers above 10^{19} eV to be ~ 200 events/day. Our simulations also demonstrate that we can potentially detect UHE photons even in more pessimistic scenarios wherein UHECRs are heavy [2].

Radio detection of vertical showers (i.e., those with zenith angles $\lesssim 60°$) performs as well as other techniques. It can achieve angular resolutions $\sim 1°$ [53], energy resolutions $\sim 20\%$ [60], and $\Delta X_{\rm max} \sim 20$ g cm^{-2} [61]. However, this has not been thoroughly checked for inclined showers, although our preliminary results suggest that we can already reach $\Delta X_{\rm max} \lesssim 20$ g cm^{-2} [2].

4 Timeline

The timeline for the construction of GRAND is neatly summarised in fig. 4.



	GRANDProto35 GRANDProto300 2018	2020	GRAND10k 2025	GRAND200k 203X
Goals	standalone radio array: test efficiency & background rejection	standalone radio array of very inclined showers (θ_z>70°) from cosmic rays (>$10^{16.5}$ eV) + ground array to do UHECR astro/hadronic physics	first GRAND subarray, sensitivity comparable to ARA/ARIANNA on similar time scale, allowing discovery of EeV neutrinos for optimistic fluxes	first neutrino detection at 10^{18} eV and/or neutrino astronomy!
Setup	35 radio antennas 21 scintillators	300 HorizonAntennas over 300 km^2 Fast DAQ (AERA+ GRANDproto35 analog stage) Solar panels + WiFi data transfer Ground array (à la HAWC/Auger)	DAQ with discrete elements, but mature design for trigger, data transfer, consumption	200,000 antennas over 200,000 km^2, ~ 20 hotspots of 10k antennas, possibly in different continents
Budget & stage	160k€, fully funded by NAOC+IHEP, deployment ongoing @ Ulastai	1.3 M€ to be deployed in 2020	1500€ / detection unit	Industrial scale allows to cut down costs: 500€/unit ➔ 200M€ in total ASIC Cost ~10M€ ➔ few 10€/board Consomption < 1W Reliability

Figure 4: Timeline of the construction stages of GRAND.

4.1 GRANDProto35 (2018-2020)

GRANDProto35 [62] (GP35) is the first construction stage of the experiment. It is an array of 35 radio antennas plus surface particle detectors (plastic scintillators). Its main goal is to demonstrate an efficiency higher than

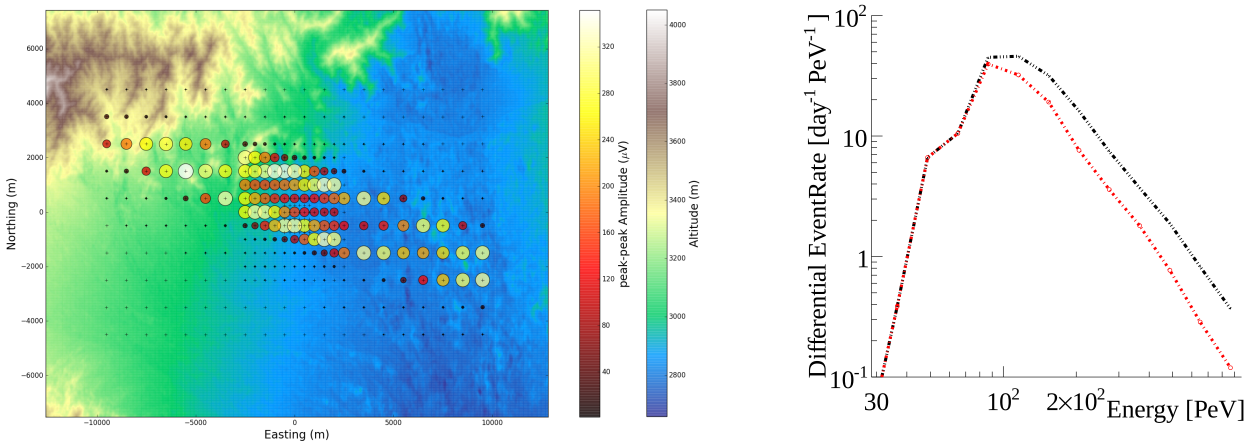


Figure 5: The left panel shows the array layout of GP300 (black stars) over the site topography, together with a simulated air shower, with $E = 4.2 \times 10^{17}$ arriving with a zenith angle of $83°$. The simulated antennas are represented by circles with radii proportional to the signal peak-to-peak amplitude at the antenna output. The differential event detection rate for GP300 is shown in the right panel, as a function of the energy of the primary, for the preliminary layout. The black line indicates the total detect event rate, whereas the red line represents the detected events whose shower cores are contained inside the array, which provides better reconstruction performances.

80% for the radio-detection of (vertical) EAS and a background rejection that keeps the ratio of false triggers to true signals below 10%.

GP35 builds on the experience from TREND [53], and is deployed at the same site, in the Tian Shan mountains in the Xin- Jiang province of China. The prototype is under deployment, and twelve antennas are taking data. We tested that the DAQ system achieves 100% detection efficiency for trigger rates up to 20 kHz [62]. Therefore, it can record all transient signals under standard background conditions at the array site, which will significantly improve the air-shower detection efficiency compared to TREND. The DAQ system is also stable under real conditions. GP35 also includes an autonomous surface array of particle detectors to measure the efficiency of the antennas. It is co-located with the antenna array, and consists of scintillator tiles. The DAQ chain and trigger logic of the scintillator array are independent from the radio array. The radio-detection efficiency and the background contamination will be quantified by comparing the scintillator and radio data.

4.2 GRANDProto300 (2019–2024)

GRANDProto300 (GP300) will be an array of 300 antennas deployed over ~ 200 km^2 . Its main goal is to demonstrate the feasibility of autonomous detection of nearly horizontal EASs with high efficiency, and to reconstruct the properties of the primary particles with an accuracy similar to other techniques employed for cosmic-ray detection. The deployment is currently underway in LengHu, QingHai province, in China.

The preliminary layout of GP300 is composed by 196 antennas and is complemented with a 25 km^2 infill of 85 antennas with spacing of 50 m, and by an even denser array of 26 antennas spread over ~ 2 km^2, with 250 m spacing (see fig. 5). This hierarchical layout allows us to cover energies between $10^{16.5}$ and $10^{18.5}$ eV. In this stage, muon detectors will be installed, in addition to the antennas. By tapping into both the electromagnetic and the muonic components of the shower, we will be able to further check the performance of the antennas as stand-alone detectors. Three independent measurements will be possible: (i) the EAS energy thanks to the autonomous radio detection; (ii) the X_{max} of the shower from radio data; and (iii) the muon content of the shower (ground array).

4.3 GRAND10k (2024–2034)

GRAND10k will be the first large sub-array of GRAND, and the first construction stage sensitive to UHE neutrinos. It will consist of 10,000 antennas covering $\sim 10,000$ km^2. Our simulations show that GRAND10k will reach an integrated sensitivity of $\sim 8 \times 10^{-9}$ GeV cm^{-2} sr^{-1} s^{-1} after three years of operation [2]. This sensitivity is enough to probe part of the parameter space for cosmogenic neutrinos with performance comparable to the planned final configurations of future experiments such as RNO [63] and ARIANNA [59].

With an aperture of $\sim 12,000$ km^2 sr, GRAND10k will be the largest UHECR detector ever built, about twice the aperture of Auger at $E \gtrsim 10^{19}$ eV. More details about the design will follow from the experience acquired with GP300, with further optimisation of power consumption, triggers, and data transfer.

4.4 GRAND200k (2034–2040)

GRAND200k is the planned final configuration of GRAND. It will be comprised of about 20 independent sub-arrays of $\sim 10^5$ antennas each, at different locations. We expect to use a design similar to GRAND10k, since at this stage electronics, trigger, and data collection will already have been validated. With an unmatched sensitivity of $\sim 4 \times 10^{-10}$ GeV cm^{-2} sr^{-1} s^{-1}, GRAND200k will likely be able to detect cosmogenic neutrinos even under pessimistic assumptions [4].

5 Construction and operational costs

The cost of the hardware for GRANDProto35 was €125k, driven mostly by the digitizers €100k, and the low-noise amplifiers €25k. The costs for GRANDProto300 were about €1.2M, excluding deployment and computing costs. Science costs are not included in this estimate. Individual collaborators will apply for funds from their respective funding agencies to support data analysis and low-level monitoring and calibration activities. The total cost of GRANDProto300 and GRAND10k will be funded by the international collaboration. The exact cost sharing has yet to be determined.

6 Computing requirements

One important component of the project is the simulation of cosmic rays. Their propagation from their sources to the Earth is performed with the CRPropa simulation framework [8]. It takes into account the main physical processes that can potentially affect the propagation of cosmic rays through Galactic and extragalactic environments. After the particles interact with the atmosphere, the GRAND collaboration simulates the air showers using two codes: CORSIKA[64] and AIRES[65]. The CORSIKA program is the leading tool for shower simulations. It contains the CoREAS [66] (CORSIKA-based Radio Emission from Air Showers) program that simulates the radio emission expected to be detected at GRAND's antennas. In a simular way, the program ZHAIRES [67] runs after AIRES to provide the signal at the antennas of the experiment.

GRAND will need shower libraries (including the simulated signals at the antennas) containing hundreds of thousands showers. The Brazilian collaboration plans to use the Supercomputer Santos Dumont[5] and the Supercomputer Lobo Carneiro[6] to generate these libraries, in addition to local university clusters.

7 The Collaboration

The GRAND Collaboration is comprised of ~ 60 scientists and engineers from 10 countries. A Memorandum of Understanding (MoU) is being signed by 8 institutions, coordinating the scientific and technical efforts towards building, operating, and extracting scientific information from the experiment. These institutions are:
Brazil: Universidade Federal do Rio de Janeiro (UFRJ)
China: Nanjing University, National Astronomical Observatory of China (NAOC)
France: Institut d'Astrophysique de Paris
Germany: Karlsruhe Institute of Technology
Netherlands: Nationaal Instituut voor Kernfysica en Hoge Energie Fysica (Nikhef)
USA: Pennsylvania State University

The Collaboration is represented by the 3 co-founders, acting as co-Spokespersons (K. Kotera, O. Martineau, X.-P. Wu), managed by a Project Manager (C. Timmermans) and will be overseen by a board with members appointed by the participating institutions. The deployment sites of the first prototypes are managed by the NAOC.

The Brazilian group currently working on the experiment is composed of:
Rafael Alves Batista - Universidade Autónoma de Madrid - Madrid, Spain
Rogerio Menezes de Almeida - U. Federal Fluminense
João Torres de Mello Neto - Instituto de Física, U. Federal do Rio de Janeiro
Bruno Lago - Centro Federal de Educação Tecnológica Celso Suckow da Fonseca

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[5] https://sdumont.lncc.br
[6] http://www.nacad.ufrj.br/pt/recursos/sgiicex

8 Brazilian activities and responsabilities in the experiment

Latin American has a strong tradition in cosmic-ray physics. For instance, the prominent role played by many groups in the successful commissioning and operation of the Pierre Auger Observatory, in Argentina, is noteworthy. The expertise thus acquired can be applied to the next large observatory of this sort — GRAND.

Brazilian scientists have been active in GRAND since its early stages. The work that provided the theoretical basis for GRAND's main science case — cosmogenic neutrinos — was carried out mostly in Brazil, in the states of São Paulo (USP) and Rio de Janeiro (UFF, CEFET); see [4].

The UFRJ group is currently developing signal processing techniques to improve the signal-to-noise ratio in measurements of radio signals from extensive air showers. The techniques include adaptive filters and wavelet for event selection and denoising. The group is also developing algorithms to estimate the energy from the primary particle from the signals in the antennas. Another activity is the generation of shower libraries using the CORSIKA code in parallel with other libraries generated using AIRES at IAP.

Bruno Lago is the leader of the GRAND physics analysis group and João de Mello Neto is a member of the Collaboration Board. Rafael Alves Batista closely collaborates with the group preparing for the physical interpretation of the upcoming data.

Rogerio de Almeida is working on a better description of the Auger antenna response by using the Galactic emission and a detailed model of signal chain as a calibration source with which to compare measured data. By using real data collected by the Pierre Auger Observatory, he is also investigating the behaviour of the calibration constant as a function of time (in a time scale of a decade) and estimating the impact of the temperature on the Galactic calibration constant. The idea is to apply the same methods to data collected by GRAND. This is very important since a better description of the antenna response reduces the cosmic ray energy uncertainty.

9 Executive summary

With Brazilian scientists active in the collaboration since the beginning of the efforts, in the long run, it is conceivable that one or more of the sub-arrays could potentially be constructed in South America. This justifies the involvement of south-american scientists at these early stages, and allows for a future position of leadership in this experiment with great potential for breakthroughs.

References

[1] R. Alves Batista, J. Biteau, M. Bustamante, K. Dolag, R. Engel, K. Fang et al., *Open Questions in Cosmic-Ray Research at Ultrahigh Energies*, Frontiers in Astronomy and Space Sciences **6** (2019) 23, [`1903.06714`].

[2] GRAND Collaboration, *The Giant Radio Array for Neutrino Detection (GRAND): Science and Design*, Science China: Phys. Mech. Astron. **63** (2018) 219501, [`1810.09994`].

[3] A. Romero-Wolf and M. Ave, *Bayesian inference constraints on astrophysical production of ultra-high energy cosmic rays and cosmogenic neutrino flux predictions*, Journal of Cosmology and Astroparticle Physics **2018** (2018) 025, [`1712.07290`].

[4] R. Alves Batista, R. M. de Almeida, B. Lago and K. Kotera, *Cosmogenic photon and neutrino fluxes in the Auger era*, Journal of Cosmology and Astroparticle Physics **2019** (2019) 002, [`1806.10879`].

[5] J. Heinze, A. Fedynitch, D. Boncioli and W. Winter, *A New View on Auger Data and Cosmogenic Neutrinos in Light of Different Nuclear Disintegration and Air-shower Models*, The Astrophysical Journal **873** (2019) 88, [`1901.03338`].

[6] PIERRE AUGER collaboration, D. Wittkowski, *Reconstructed properties of the sources of UHECR and their dependence on the extragalactic magnetic field*, PoS **ICRC2017** (2018) 563.

[7] D. Wittkowski and K.-H. Kampert, *On the flux of high-energy cosmogenic neutrinos and the influence of the extragalactic magnetic field*, Monthly Notices of the Royal Astronomical Society (2019) L88, [`1810.03769`].

[8] R. Alves Batista, D. Boncioli, A. di Matteo, A. van Vliet and D. Walz, *Effects of uncertainties in simulations of extragalactic UHECR propagation, using CRPropa and SimProp*, Journal of Cosmology and Astroparticle Physics **2015** (2015) 063, [`1508.01824`].

[9] R. Alves Batista, D. Boncioli, A. di Matteo and A. van Vliet, *Secondary neutrino and gamma-ray fluxes from SimProp and CRPropa*, Journal of Cosmology and Astroparticle Physics **2019** (2019) 006, [`1901.01244`].

[10] K. Kotera, D. Allard and A. V. Olinto, *Cosmogenic neutrinos: parameter space and detectabilty from PeV to ZeV*, Journal of Cosmology and Astroparticle Physics **2010** (2010) 013, [`1009.1382`].

[11] K. Murase, Y. Inoue and C. D. Dermer, *Diffuse neutrino intensity from the inner jets of active galactic nuclei: Impacts of external photon fields and the blazar sequence*, Physical Review D **90** (2014) 023007, [`1403.4089`].

[12] E. Resconi, S. Coenders, P. Padovani, P. Giommi and L. Caccianiga, *Connecting blazars with ultrahigh-energy cosmic rays and astrophysical neutrinos*, Montly Notices of the Royal Astronomical Society **468** (2017) 597–606, [`1611.06022`].

[13] B. Eichmann, J. P. Rachen, L. Merten, A. van Vliet and J. Becker Tjus, *Ultra-high-energy cosmic rays from radio galaxies*, Journal of Cosmology and Astroparticle Physics **2018** (2018) 036, [`1701.06792`].

[14] X. Rodrigues, A. Fedynitch, S. Gao, D. Boncioli and W. Winter, *Neutrinos and Ultra-high-energy Cosmic-ray Nuclei from Blazars*, The Astrophysical Journal **854** (2018) 54, [`1711.02091`].

[15] K. Murase, K. Ioka, S. Nagataki and T. Nakamura, *High-energy cosmic-ray nuclei from high- and low-luminosity gamma-ray bursts and implications for multimessenger astronomy*, Physical Review D **78** (2008) 023005, [`0801.2861`].

[16] P. Baerwald, M. Bustamante and W. Winter, *Are gamma-ray bursts the sources of ultra-high energy cosmic rays?*, Astroparticle Physics **62** (2015) 66–91, [`1401.1820`].

[17] M. Bustamante, P. Baerwald, K. Murase and W. Winter, *Neutrino and cosmic-ray emission from multiple internal shocks in gamma-ray bursts*, Nature Communications **6** (2015) 6783, [`1409.2874`].

[18] K. Fang, K. Kotera and A. V. Olinto, *Newly Born Pulsars as Sources of Ultrahigh Energy Cosmic Rays*, The Astrophysical Journal **750** (2012) 118, [`1201.5197`].

[19] K. Fang, K. Kotera, K. Murase and A. V. Olinto, *Testing the newborn pulsar origin of ultrahigh energy cosmic rays with EeV neutrinos*, Physical Review D **90** (2014) 103005, [`1311.2044`].

[20] K. Kotera, D. Allard, K. Murase, J. Aoi, Y. Dubois, T. Pierog et al., *Propagation of Ultrahigh Energy Nuclei in Clusters of Galaxies: Resulting Composition and Secondary Emissions*, The Astrophysical Journal **707** (2009) 370–386, [`0907.2433`].

[21] K. Murase, S. Inoue and K. Asano, *Cosmic Rays above the 2ND Knee from Clusters of Galaxies*, International Journal of Modern Physics D **18** (2009) 1609–1614.

[22] K. Fang and K. Murase, *Linking high-energy cosmic particles by black-hole jets embedded in large-scale structures*, Nature Physics **14** (2018) 396–398, [`1704.00015`].

[23] C. Guépin and K. Kotera, *Can we observe neutrino flares in coincidence with explosive transients?*, Astronomy and Astrophysics **603** (2017) A76, [`1701.07038`].

[24] R. Alves Batista and J. Silk, *Ultrahigh-energy cosmic rays from tidally-ignited white dwarfs*, Physical Review D **96** (2017) 103003, [`1702.06978`].

[25] C. Guépin, K. Kotera, E. Barausse, K. Fang and K. Murase, *Ultra-high-energy cosmic rays and neutrinos from tidal disruptions by massive black holes*, Astronomy & Astrophysics **616** (2018) A179, [`1711.11274`].

[26] A. van Vliet, R. Alves Batista and J. R. Hörandel, *Determining the fraction of cosmic-ray protons at ultra-high energies with cosmogenic neutrinos*, Physical Review D **100** (2019) 021302(R), [`1901.01899`].

[27] K. MØller, P. B. Denton and I. Tamborra, *Cosmogenic neutrinos through the GRAND lens unveil the nature of cosmic accelerators*, Journal of Cosmology and Astroparticle Physics **2019** (2019) 047, [`1809.04866`].

[28] CTA Consortium, *Science with the Cherenkov Telescope Array*. World Scientific, 2019, 10.1142/10986.

[29] Pierre Auger Collaboration, *Search for photons with energies above 10^{18} eV using the hybrid detector of the Pierre Auger Observatory*, Journal of Cosmology and Astroparticle Physics **2017** (2017) 009, [`1612.01517`].

[30] O. Martineau, *The Giant Radio Array for Neutrino Detection*, in *36th International Cosmic Ray Conference (ICRC2019)*, vol. 36 of *International Cosmic Ray Conference*, p. 958, July, 2019.

[31] V. Decoene, *The GRANDProto300 experiment: a pathfinder with rich astroparticle and radio-astronomy science case*, in *36th International Cosmic Ray Conference (ICRC2019)*, vol. 36 of *International Cosmic Ray Conference*, p. 233, Jul, 2019. `1909.04893`.

[32] LIGO Scientific Collaboration and Virgo Collaboration, *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*, Physical Review Letters **119** (2017) 161101, [`1710.05832`].

[33] LIGO Scientific Collaboration, Virgo Collaboration, INTEGRAL, IceCube Collaboration, A. Balasubramanian, S. Mate et al., *Multi-messenger Observations of a Binary Neutron Star Merger*, The Astrophysical Journal Letters **848** (2017) L12, [`1710.05833`].

[34] IceCube Collaboration, *Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert*, Science **361** (2018) 147–151, [`1807.08794`].

[35] IceCube Collaboration, Fermi-LAT Collaboration, MAGIC Collaboration, AGILE Team, ASAS-SN Team, HAWC Collaboration et al., *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A*, Science **361** (2018) eaat1378, [`1807.08816`].

[36] H. A. Ayala Solares, S. Coutu, D. F. Cowen, J. J. DeLaunay, D. B. Fox, A. Keivani et al., *The Astrophysical Multimessenger Observatory Network (AMON): Performance and science program*, Astroparticle Physics **114** (2020) 68–76, [`1903.08714`].

[37] IceCube-Gen2 Collaboration, *IceCube-Gen2: A Vision for the Future of Neutrino Astronomy in Antarctica*, *arXiv e-prints* (2014) arXiv:1412.5106, [1412.5106].

[38] I. M. Shoemaker and K. Murase, *Probing BSM neutrino physics with flavor and spectral distortions: Prospects for future high-energy neutrino telescopes*, Physical Review D **93** (2016) 085004, [1512.07228].

[39] M. Bustamante, J. F. Beacom and K. Murase, *Testing decay of astrophysical neutrinos with incomplete information*, Physical Review D **95** (2017) 063013, [1610.02096].

[40] M. Blennow and D. Meloni, *Nonstandard interaction effects on astrophysical neutrino fluxes*, Physical Review D **80** (2009) 065009, [0901.2110].

[41] M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler and N. Song, *Non-standard neutrino interactions in the earth and the flavor of astrophysical neutrinos*, Astroparticle Physics **84** (2016) 15–22, [1605.08055].

[42] G. Barenboim and C. Quigg, *Neutrino observatories can characterize cosmic sources and neutrino properties*, Physical Review D **67** (2003) 073024, [hep-ph/0301220].

[43] M. Bustamante, A. M. Gago and C. Peña-Garay, *Energy-independent new physics in the flavour ratios of high-energy astrophysical neutrinos*, Journal of High Energy Physics **2010** (2010) 66, [1001.4878].

[44] C. A. Argüelles, T. Katori and J. Salvado, *Effect of New Physics in Astrophysical Neutrino Flavor*, Physical Review Letters **115** (2015) 161303, [1506.02043].

[45] J. Kopp, J. Liu and X.-P. Wang, *Boosted dark matter in IceCube and at the galactic center*, Journal of High Energy Physics **2015** (2015) 105, [1503.02669].

[46] P. F. de Salas, R. A. Lineros and M. Tórtola, *Neutrino propagation in the Galactic dark matter halo*, Physical Review D **94** (2016) 123001, [1601.05798].

[47] M. M. Reynoso and O. A. Sampayo, *Propagation of high-energy neutrinos in a background of ultralight scalar dark matter*, Astroparticle Physics **82** (2016) 10–20, [1605.09671].

[48] D. Hooper, D. Morgan and E. Winstanley, *Lorentz and CPT invariance violation in high-energy neutrinos*, Physical Review D **72** (2005) 065009, [hep-ph/0506091].

[49] J. Ellis and N. E. Mavromatos, *Probes of Lorentz violation*, Astroparticle Physics **43** (2013) 50–55, [1111.1178].

[50] IceCube Collaboration, *Measurement of the multi-TeV neutrino interaction cross-section with IceCube using Earth absorption*, Nature **551** (2017) 596–600, [1711.08119].

[51] M. Bustamante and A. Connolly, *Extracting the Energy-Dependent Neutrino-Nucleon Cross Section above 10 TeV Using IceCube Showers*, Physical Review Letters **122** (2019) 041101, [1711.11043].

[52] P. Zarka and F. Mottez, *Observations of Fast Radio Bursts and perspectives at low frequencies*, in *SF2A-2016: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics* (C. Reylé, J. Richard, L. Cambrésy, M. Deleuil, E. Pécontal, L. Tresse et al., eds.), pp. 347–351, Dec., 2016.

[53] D. Charrier, K. D. de Vries, Q. Gou, J. Gu, H. Hu, Y. Huang et al., *Autonomous radio detection of air showers with the TREND50 antenna array*, Astroparticle Physics **110** (2019) 15–29, [1810.03070].

[54] Pierre Auger Collaboration, *Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy*, Physical Review Letters **116** (2016) 241101, [1605.02564].

[55] A. Balagopal V., A. Haungs, T. Huege and F. G. Schröder, *Search for PeVatrons at the Galactic Center using a radio air-shower array at the South Pole*, European Physical Journal C **78** (2018) 111, [1712.09042].

[56] D. Charrier and CODALEMA Collaboration, *Antenna development for astroparticle and radioastronomy experiments*, Nuclear Instruments and Methods in Physics Research A **662** (2012) S142–S145.

[57] Pierre Auger Collaboration, *Antennas for the detection of radio emission pulses from cosmic-ray induced air showers at the Pierre Auger Observatory*, Journal of Instrumentation **7** (2012) P10011, [1209.3840].

[58] F. Montanet, D. Lebrun, J. Chauvin, E. Lagorio and P. Stassi, *NOY: a neutrino observatory network project based on stand alone air shower detector arrays*, Astrophysics and Space Sciences Transactions **7** (2011) 369–372.

[59] S. W. Barwick, D. Z. Besson, A. Burgman, E. Chiem, A. Hallgren, J. C. Hanson et al., *Radio detection of air showers with the ARIANNA experiment on the Ross Ice Shelf*, Astroparticle Physics **90** (2017) 50–68, [1612.04473].

[60] Pierre Auger Collaboration, *Energy estimation of cosmic rays with the Engineering Radio Array of the Pierre Auger Observatory*, Physical Review D **93** (2016) 122005, [1508.04267].

[61] S. Buitink, A. Corstanje, H. Falcke, J. R. Hörandel, T. Huege, A. Nelles et al., *A large light-mass component of cosmic rays at 10^{17}-$10^{17.5}$ electronvolts from radio observations*, Nature **531** (2016) 70–73, [1603.01594].

[62] Q. Gou, O. Martineau-Huynh, M. Bustamante, D. Charrier, W. Carvalho, Jr., J. David et al., *The GRANDproto35 experiment*, in *35th International Cosmic Ray Conference (ICRC2017)*, vol. 35 of *International Cosmic Ray Conference*, p. 388, Jan., 2017.

[63] J. A. Aguilar, P. Allison, S. Archambault, J. J. Beatty, D. Z. Besson, O. Botner et al., *The Next-Generation Radio Neutrino Observatory – Multi-Messenger Neutrino Astrophysics at Extreme Energies*, *arXiv e-prints* (2019) arXiv:1907.12526, [`1907.12526`].

[64] D. Heck, J. Knapp, J. N. Capdevielle, G. Schatz and T. Thouw, *CORSIKA: A Monte Carlo code to simulate extensive air showers*, .

[65] S. J. Sciutto, *AIRES: A system for air shower simulations*, `astro-ph/9911331`.

[66] T. Huege, M. Ludwig and C. W. James, *Simulating radio emission from air showers with CoREAS*, in *American Institute of Physics Conference Series* (R. Lahmann, T. Eberl, K. Graf, C. James, T. Huege, T. Karg et al., eds.), vol. 1535 of *American Institute of Physics Conference Series*, pp. 128–132, May, 2013. `1301.2132`. DOI.

[67] J. Alvarez-Muñiz, W. R. Carvalho and E. Zas, *Monte Carlo simulations of radio pulses in atmospheric showers using ZHAireS*, *Astroparticle Physics* **35** (2012) 325–341, [`1107.1189`].