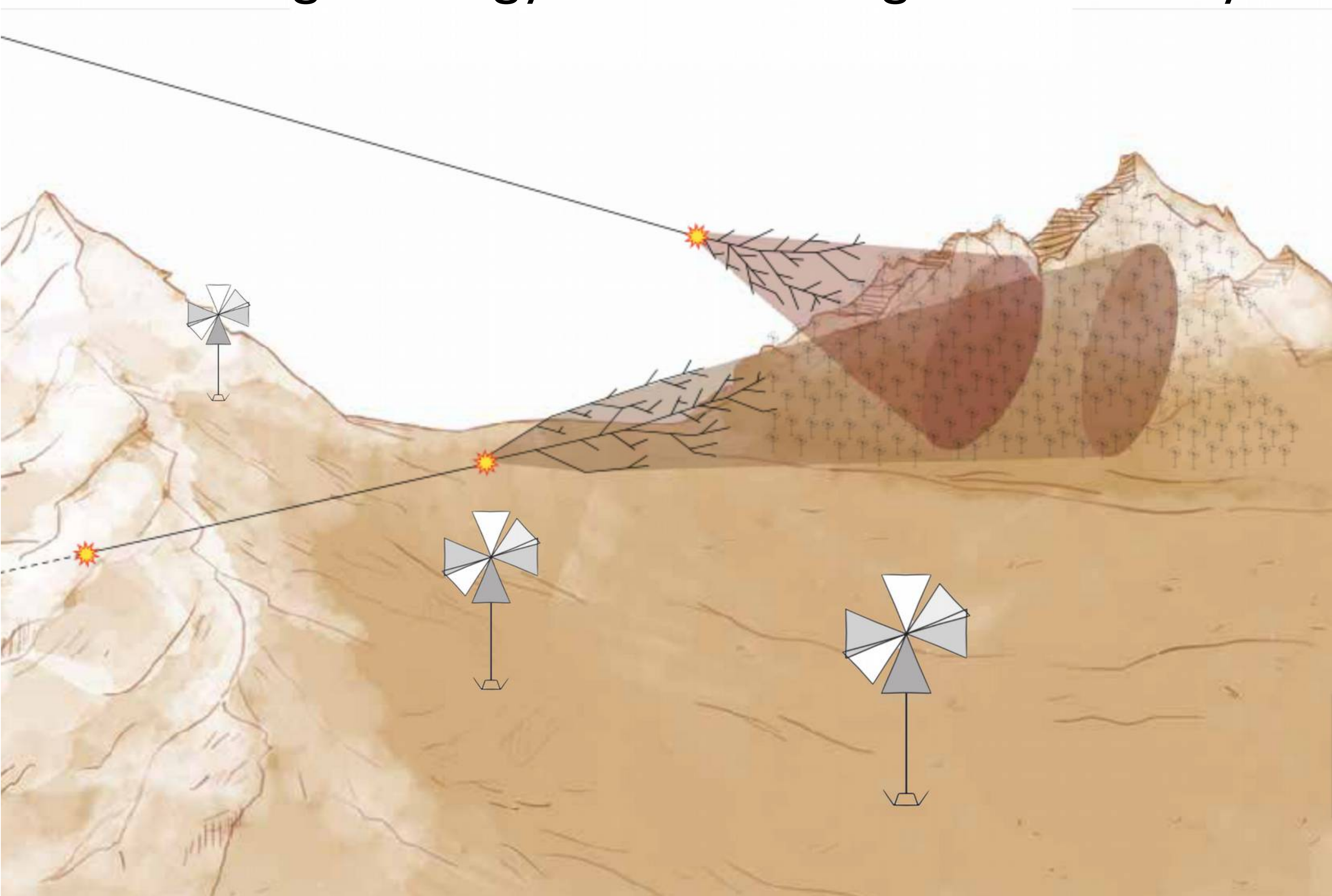
GRAND

Giant Radio Array for Neutrino Detection

Science and Design for the Giant Radio Array for Neutrino Detection (GRAND): A Ground-Based Instrument for Ultra-High-Energy Multimessenger Astronomy



Astro2020 APC White Paper

Science and Design for the Giant Radio Array for Neutrino Detection (GRAND): A Ground-Based Instrument for Ultra-High Energy Multimessenger Astronomy

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☑ Multi-Messenger Astronomy and Astrophysics
☑ Ground-Based Astronomy and Astrophysics

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Abstract: The Giant Radio Array for Neutrino Detection (GRAND) is a planned large-scale observatory of ultra-high energy (UHE) cosmic messengers (cosmic rays, gamma rays, and neutrinos) with energies exceeding 10^8 GeV. The ultimate goal is to solve the long-standing mystery of the origin of UHE cosmic rays. Three key features of GRAND will make this possible: its large exposure, sub-degree angular resolution, and sensitivity to the unique signals made by UHE particles. The strategy of GRAND is to detect the radio emission coming from the extensive air showers (EAS) that develop in the terrestrial atmosphere as a result of the interaction of UHE cosmic rays, gamma rays, and neutrinos. The design of GRAND is modular, consisting of 20 independent sub-arrays, each of 10,000 radio antennas deployed over 10,000 km^2 in radio-quiet locations. A staged construction plan ensures that key techniques are progressively validated, while simultaneously achieving important science goals in UHECR physics, radioastronomy, and cosmology even during the construction stages. Already by 2025, using the first sub-array of 10,000 antennas, GRAND could discover the long-sought cosmogenic neutrinos. By the 2030s, in its final configuration, GRAND will reach an unparalleled sensitivity to cosmogenic neutrino fluxes of $4 \cdot 10^{-10}$ GeV cm^{-2} s^{-1} sr^{-1} within 3 years of operation. Because of its sub-degree angular resolution, GRAND will also search for point sources of UHE neutrinos, steady and transient. GRAND will also be a valuable tool in radioastronomy and cosmology, allowing for the discovery and follow-up of a large number of radio transients (e.g., fast radio bursts, giant radio pulses), and for precise studies of the epoch of reionization.

The majority of the material is drawn from "The Giant Radio Array for Neutrino Detection (GRAND): Science and Design" [1]. If you want to cite results presented in this white paper, please cite the original paper instead.

References highlighted in red boldface are science white papers submitted to the Astro2020 Decadal Survey with particular relevance to the key science goals of GRAND, which include addressing outstanding astrophysics open questions with neutrino astronomy **[2]**, identifying and characterizing multimessenger sources **[3, 4, 5, 6]**, unveiling Galactic particle accelerators **[7, 8]**, probing active galactic nuclei **[9, 10]** and core-collapse supernovae **[11]** with high-energy neutrinos, and revealing new fundamental particles and interactions, and probing energy and distance scales far exceeding those accessible in the laboratory with UHE cosmic particles **[12, 13, 14]**.

Key Science Goals and Objectives

Ultra-high energy messengers

Ultra-high energy cosmic rays (UHECRs), with energies exceeding 10^{11} GeV [15], have been observed for more than fifty years [16], yet their origin is unknown **[6]**[17, 18]. This is because individual UHECRs do not point back to their sources, and the limited statistics hinder the studies of their properties and sources. During the propagation of UHECRs to Earth, UHE neutrinos and gamma rays of energies of 10^9 GeV and higher are created. Because UHE neutrinos travel unimpeded to Earth, detecting them is arguably the best way to probe the high-energy end of the UHECR spectrum and the most distant UHECR sources **[2, 3, 5, 9]**.

GRAND is a proposed large-scale observatory designed to discover and study the sources of UHECRs. GRAND will detect the radio signals made in the Earth's atmosphere by UHE cosmic rays, gamma rays, and neutrinos, even for pessimistic predictions of the cosmogenic fluxes. The sub-degree angular resolution of GRAND will make possible the discovery of the first point sources of UHE neutrinos. The detection of UHE neutrinos will also open up a new regime for fundamental neutrino physics **[12]**.

The observed flux of UHECRs guarantees a diffuse flux of cosmogenic neutrinos produced in the interactions of UHECRs with cosmic background photon fields [19, 20]. Presently, the predictions of this flux are uncertain because they depend on the properties of the unknown cosmic-ray sources. We show in the left panel of Fig. 1 a range of cosmogenic neutrino flux predictions based on the measured UHECR spectrum and mass composition [21]. GRAND is the only proposed experiment with a design differential sensitivity that covers a large part of the standard flux range,

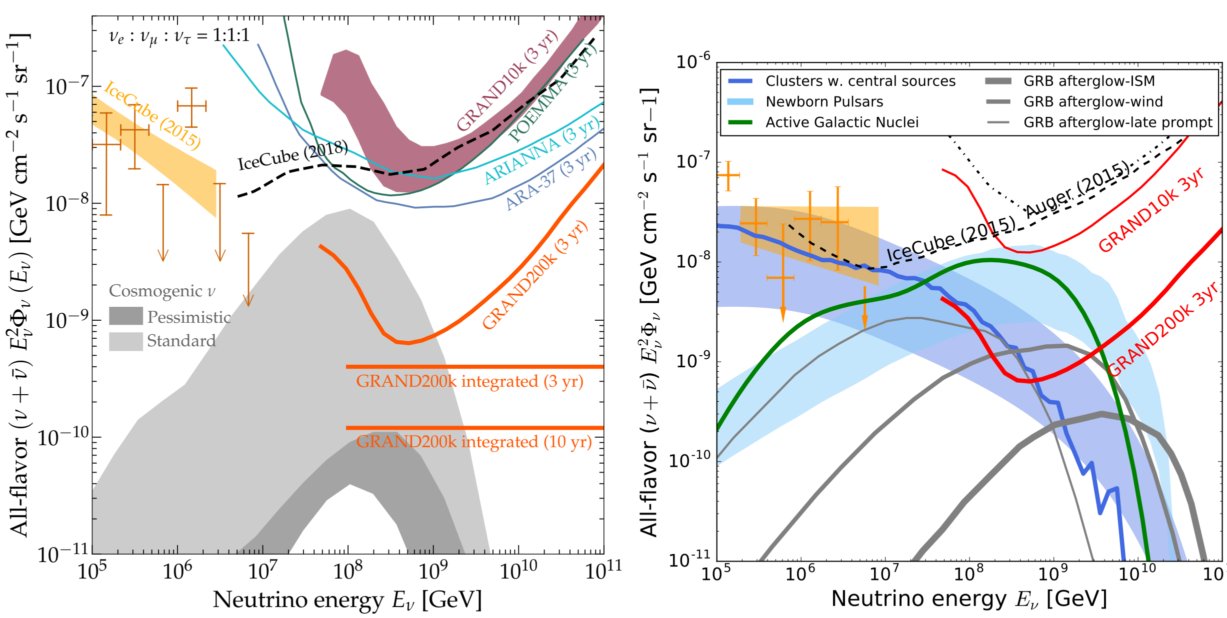

Figure 1: *Left:* Predicted cosmogenic neutrino flux [21] compared to experimental all-flavor upper limits and sensitivities. Gray-shaded regions are generated from UHECR data. *Right:* Predicted neutrino flux from different classes of astrophysical sources compared to all-flavor upper limits from current experiments and the projected sensitivity for GRAND. See Ref. [1] for details.

reaching sensitivities of a few times 10^{-10} GeV cm^{-2} s^{-1} sr^{-1}. Thus, GRAND will be able to constrain the source redshift evolution and the chemical composition of the cosmic ray sources [22].

UHE neutrinos are also produced when UHECRs interact with photons and hadrons inside the sources themselves. The measured diffuse neutrino spectrum will contain important information about the dominant source class because the different classes of astrophysical sources produce neutrinos on different time scales and under different production conditions **[2, 9]**. We summarize the predictions for the diffuse fluxes of EeV neutrinos from astrophysical sources in the right panel of Fig. 1. Several source classes can account for the observed UHECR spectrum. For example, active galactic nuclei [23, 24, 25], gamma-ray bursts [26, 27, 28], galaxy clusters [29, 30, 31], and pulsars and magnetars [32, 33]. GRAND will detect the flux from most of these source models within 3 years of operation and characterize their spectrum.

The existence of UHE cosmogenic gamma rays is also guaranteed as photons are a by-product of UHECR interactions with the CMB. UHE gamma rays have not been detected, and the most stringent upper limits are those from the Pierre Auger Observatory [34]. As in the case of neutrinos, the expected flux of cosmogenic gamma rays depends on the mass composition of the UHECRs. GRAND will be sensitive to cosmogenic gamma-ray fluxes, even for iron-dominated UHECRs.

Measuring the energy spectrum of UHECRs at high precision is of prime importance to understand the mechanisms of cosmic-ray acceleration and propagation. Another important question related to the UHECR energy spectrum is about the origin of the flux suppression observed at the highest energies **[6]**. Given the steeply falling energy spectrum, particularly above $5{\cdot}10^{10}$ GeV, event statistics is obviously important. The statistical power of different observatories can best be compared by their integrated exposures. GRAND will be fully efficient above 10^{10} GeV, and will have an exposure of $535{,}000$ km^2 sr yr after 5 years of live-time. The resulting expected UHECR event rate is 20 times higher than in Auger. In just one year, GRAND should detect 6,400 events above $10^{10.5}$ GeV, an order of magnitude more than all the other UHECR experiments combined.

Multimessenger Astronomy

Due to its excellent angular resolution and large sky coverage, GRAND could identify EeV neutrino sources by detecting neutrinos from transient events in coincidence with electromagnetic emission. The instantaneous field of view of GRAND corresponds to $<5\%$ of the sky. However, assuming that all azimuth angles are observed at any instant, approximtely 80% of the sky is observed every day. Thus, stacking searches for transients lasting longer than a day, such as blazar flares, tidal disruption events, superluminous supernovae, etc., can be performed offline. Depending on the background discrimination efficiency, GRAND will be able send alerts to other experiments or coordinated systems like the Astrophysical Multimessenger Observatory Network (AMON) [35] for follow-up campaigns. In practice, the instantaneous field of view of GRAND will be larger because the final configuration will consist of several sub-arrays placed at different geographical locations. Sub-hour transients that occur within the field of view of GRAND might also be detectable as neutrino point sources. For example, short-duration GRBs (sGRB) possibly associated with binary neutron-star mergers [36] and GRB afterglows [37] as long as they take place within 40 Mpc. See Ref. [38] for more transient source detection possibilities.

GRAND will also play a key role in time-domain astroparticle physics in this new era of multimessenger astrophysics that encompasses neutrinos, cosmic rays, photons, and gravitational waves. GRAND is ideally positioned to detect UHE neutrinos from transient point sources in coincidence with electromagnetic observations. Frequent combined observations of transient phenomena will be a vital step towards revealing the sources of UHECRs [3, 5].

Promising UHE source candidates include short GRBs and their off-axis counterparts, which are accompanied by gravitational wave signals. By the time GRAND is completed, third-generation gravitational-wave detectors will be able to see compact-object mergers up to $z \approx 2$–6. Given that the fluence sensitivity is around $0.1~\mathrm{GeV~cm^{-2}}$, the late emission of short GRBs [36] (or mergers leaving a magnetar remnant [39]) could be detected from distances up to 100 Mpc. These signals are expected to arrive hours or days later than the gravitational wave signal, and will provide critical insights into the fate of neutron-star mergers and the physics of the outflows.

Further, due to its unprecedented UHE neutrino sensitivity, GRAND will be a crucial triggering and follow-up partner in multimessenger programs like AMON [35]. As a triggering observatory, the design of GRAND will make it possible to reconstruct the arrival direction and issue an initial alert of an incoming neutrino-initiated EAS with sub-degree accuracy and with sub-minute latency. As a follow-up observatory, GRAND will be crucial when alerts are issued by experiments without good angular resolution.

Fundamental neutrino physics

High-energy cosmic neutrinos provide a chance to test fundamental physics in new regimes [12]. 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 [1].

New physics could affect several observables, such as the energy spectrum, the angular distribution, and the flavor ratios. Neutrino energy spectra are expected to be power laws. New physics could introduce additional spectral features, like peaks, troughs, and varying slopes. In GRAND, detection of EeV neutrinos with large statistics and sufficient energy resolution would allow us to infer their energy spectrum and potentially identify sub-dominant features introduced by new physics. When neutrinos travel inside the Earth, the neutrino-nucleon cross section imprints itself on the distribution of their arrival directions. This has allowed to measure the cross section up to PeV energies with IceCube [40, 41]. GRAND will be able to extend this measurement to EeV energies. Finally, flavor ratios could provide clean signals of new physics because they are free from uncertainties on the flux normalization.

Radioastronomy and cosmology

The wide field of view, frequency band, and size of GRAND will allow us to probe millisecond astrophysical transients, such as fast radio bursts and giant radio pulses. By mapping the sky temperature with mK precision, GRAND could also measure the global signature of the epoch of reionization and study the Cosmic Dawn. These measurements will be feasible even during the intermediate construction stages GRANDProto300 and GRAND10k [1].

Technical Overview

Radio detection of EAS is a mature technique as demonstrated by experiments such as AERA, CODALEMA, and LOFAR. EAS emit coherent, broadband, and impulsive radio signals that are only weakly attenuated in the atmosphere. Radio antennas are relatively inexpensive and robust, making them suitable for giant arrays to detect small fluxes of UHE particles. GRAND will build on the technological, theoretical, and computational experience in radio detection. We have designed the HORIZONANTENNA to be specially sensitive to horizontal EAS. GRAND will extend the field by demonstrating the autonomous radio-detection of very inclined EAS.

Antenna design

The radio signals from EAS initiated by Earth-skimming neutrinos will arrive with zenith angles close to 90° and a polarization that is mostly horizontal. This introduces a serious challenge for radio-detection, as the diffraction of radio waves off the ground severely alters the antenna response. We have designed an antenna with a high detection efficiency along the horizon to address this problem. We call this design the HORIZONANTENNA. The effect of ground reflection decreases with h/λ, where h is the detector height above ground and λ is the radio wavelength. To minimize this reflection effect, we place the HORIZONANTENNA atop a wooden pole at $h = 5$ m, and we operate in the frequency range above 50 MHz. We then set the upper limit of the frequency range at 200 MHz (instead of the 80 MHz or 100 MHz used in most existing arrays) to be able to detect radio Cherenkov rings. Extending the frequency band to 200 MHz significantly reduces the radio background, improves the signal-to-noise ratio, and lowers the detection threshold [42].

The HORIZONANTENNA is an active bow-tie antenna with a relatively flat response with azimuthal direction and frequency. Its design is inspired by the "butterfly antenna" developed for CODALEMA [43], and later used in AERA [44]. It has 3 perpendicular arms (X, Y, Z) oriented along two horizontal directions and a vertical one. We show the two- and three-dimensional total gain of the HORIZONANTENNA at 50 MHz as a function of direction in Fig. 2. We computed the total gain using the NEC4 simulation code [45]. At all frequencies, the HORIZONANTENNA has an optimized response down to a few degrees above the horizon. A first prototype of the HORIZONANTENNA was successfully tested in 2018 during a site survey for GRAND in China. Further experimental verification of the HORIZONANTENNA response as a function of direction remains to be performed.

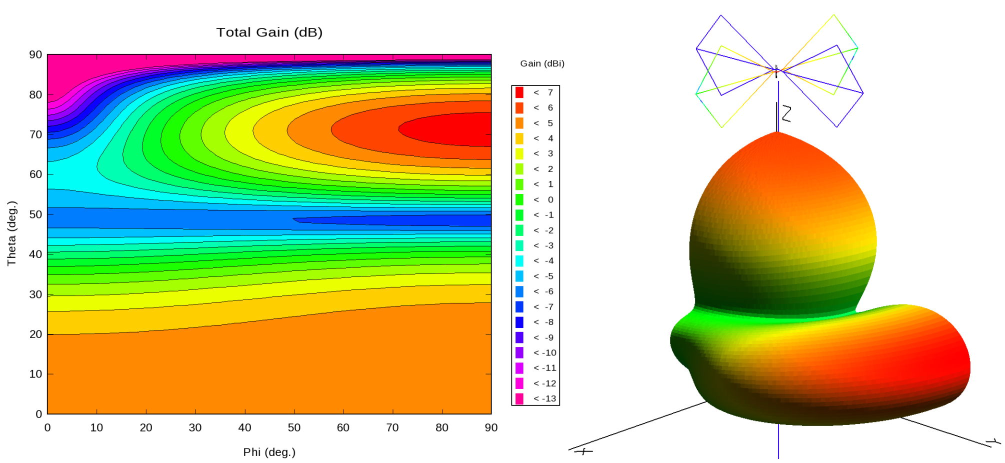

Figure 2: Two-dimensional (*left*) and three-dimensional (*right*) total gain of the X-arm of the GRAND HORIZONANTENNA at 50 MHz as a function of direction.

Array layout

The large size of the radio footprint for very inclined showers makes it possible to instrument a large area using a sparse array. We will implement a modular strategy for deploying GRAND. The final configuration will consist of $\sim$20 geographically separate and independent sub-arrays of $\sim$10,000 km^2 each. Each sub-array will have about 10^4 antennas and, therefore, a rich science program of its own. This modular strategy will allow us to build up sensitivity to progressively smaller fluxes of UHE particles, while distributing the construction efforts.

The sub-arrays will be deployed on sites with topographies favorable to the radio detection of UHE neutrinos. We take several site features into account to maximize the collection efficiency, optimize the antenna sensitivity, and improve the reconstruction. For example, a mountain slope with an elevation of 1,000–2,000 m acts as an efficient projection screen for the forward-beamed radio signal of a neutrino-initiated shower that emerges from the ground, while antennas lying in a valley would fail to detect the signal [46]. The difference in antenna altitudes on a slope also provides an improved reconstruction of the zenith angle for very inclined showers.

The sub-arrays will be ideally deployed on a mountain slope facing another mountain that would serve as a target for the interaction of downward-going neutrinos. Simulations indicate that, for specific topographies, these downward-going "mountain" events could be as frequent as the upward-going "Earth-skimming" events. The opposing mountain will also act as a natural screen to stop very inclined UHECRs, improving the background rejection.

GRAND needs to be deployed in radio-quiet areas. We require the stationary noise level $\sigma_{\rm noise}$ to be close to the Galactic radio background in the 50–200 MHz band, and that the rate of transient signals with peak amplitude larger than $5\sigma_{\rm noise}$ be below 1 kHz in that band.

Logistics requirements are also important, including reasonably easy access to the antennas, availability of solar power to run the DAQ system and broadband Internet connection, and favorable weather conditions (for stable operation of the electronics, in particular of solar panels). Through our surveys we have found several sites in China that fulfill the above requirements, where the first prototype stages will be deployed. The proposed construction of multiple, separate sub-arrays will allow us to take advantage of other ideal sites. Having arrays at different locations enlarges the instantaneous field of view of GRAND, increases the rate of detection of transient events, and improves the reconstruction of the direction of FRBs (detected by multiple sub-arrays).

Background rejection

The design of GRAND has multiple strategies to deal with the natural and man-made radio sources, stationary and transient, which are the background in the search for EAS. Nevertheless, the background at a given geographical location is too diverse in nature and intensity to be accurately modeled. A complete understanding of the background and its rejection requires performing prolonged tests on-site, which will start taking place in 2019.

There are two irreducible sources of stationary noise in the band between 50 and 200 MHz. They are both of natural origin: emission from the sky dominated by synchrotron radiation from the Galactic plane, and thermal emission from the ground. Above 150 MHz, the blackbody radiation of the ground at ambient temperature becomes the dominant source of stationary noise. An efficient way to discriminate between antenna triggers induced by transient radio waves and random coincidences due to stationary noise fluctuations is to look for causal coincidences among antenna triggers. Trigger algorithms usually search for a signal excess above the stationary noise. Thus, this noise sets the detection energy threshold and the extent of the measurable radio footprint.

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. Regardless of the location, this rate is always higher by several orders of magnitude than the rate of detectable cosmic particles. Thus, the technical challenge is to discriminate this background rate from the true EAS events. Several experiments (ANITA, TREND, ARIANNA, etc.) have already successfully demonstrated an excellent background discrimination based on specific features of EAS (polarization patterns, pulse length, beamed emission, Cherenkov ring, etc.), and also features of the background itself (clustering in time and position) [47, 48, 49].

Detector performance

The simulations to determine the sensitivity of GRAND take into account the unique features of the problem like the local topography of the array site, and the large instrumented area. We included all relevant physical processes while optimizing the use of computing resources. To validate it, we successfully tested its different parts against existing codes. We presented the full simulation chain in detail in Ref. [1]. Our simulations predict the 3-year sensitivity to neutrinos to be $4{\cdot}10^{-10}$ GeV cm^{-2} s^{-1} sr^{-1} around 10^9 GeV.

We also estimated the aperture of GRAND to cosmic rays. The resulting total aperture of GRAND at 10^9 GeV is between 20,000 km^2 sr and 25 000 km^2 sr depending on the detection threshold. Near 10^{10} GeV, the effective area approaches 107,000 km^2 sr in all cases. GRAND will be fully efficient for UHECRs and gamma rays above 10^{10} GeV and zenith angles $>65°$. The rate of detected UHECR-initiated showers above 10^{10} GeV is about 200 events day^{-1}. Our simulations also show that the sensitivity of GRAND to UHE gamma rays is sufficient to detect them even in the pessimistic case where UHECRs are heavy [1].

Current methods to reconstruct the properties of the primary particle that initiates an EAS based on radio data alone perform comparably to standard methods used in ground-level particle counters and fluorescence telescopes [50, 51, 52, 53]. However, the performance of the radio-based methods was assessed using dense radio arrays that detect showers with typical zenith angles below $60°$. We are therefore working on adapting these methods and developing new ones. Using a hyperbolic wavefront [54, 55], we achieve an average angular resolution better than 0.2°. Based on our preliminary simulations, we have found that $X_{\max}$ can already be reconstructed with a precision better than 40 g cm^{-2} above $10^{9.5}$ GeV, independently of the antenna spacing, as long as the shower triggers 10 or more antennas. Recent studies have shown that using also the pulse shape measured in each antenna can further improve the accuracy in $X_{\max}$ [56].

Technology Drivers

GRAND will be a major leap forward in the detection of EAS, in particular, and in astroparticle physics, in general. Achieving this will require that we deploy and maintain several radio arrays and autonomously trigger on very inclined EAS, efficiently separate them from the dominant background, and precisely reconstruct the properties of primary UHE particles. The challenge is significant, but the field is mature and ready to tackle it. Recent developments support this claim:

1. Experiments like LOFAR [57] have shown the feasibility of building and operating arrays of thousands of radio antennas. Antennas are relatively inexpensive, structurally robust and stable, and can be deployed easily, making arrays scalable.

2. Features of the radio emission from EAS — such as pulse shape [48, 49], polarization pattern [51], and amplitude pattern [58]— differ significantly from those of the background, and can be used to efficiently discriminate signal from background even under background-dominated conditions [48].

3. Substantial and ongoing progress in data treatment and communication has made it possible to collect large volumes of data reliably across large areas at affordable costs.

4. Existing radio arrays can reconstruct the properties of primary UHE particles, from radio data alone, with an accuracy comparable to that achieved with ground-array and fluorescence data.

We have chosen a staged construction approach that will progressively validate the key steps required to build the final configuration of GRAND. It is also important to mention that the intermediate prototypes are designed to tackle science goals by themselves. To overcome the technical challenges, we need to demonstrate the successful integration of the aforementioned developments into the design of a radio array that triggers autonomously on very inclined showers using affordable, robust, and energy-efficient detection units. This will be the main goal of GRANDProto300, the 300-antenna pathfinder stage of GRAND. GRANDProto300 will then be turned into a testbench for the final, optimized design of GRAND. The following stage, GRAND10k, with 10,000 antennas, is designed to reach a neutrino sensitivity comparable to that of other potential contemporary detectors. The final configuration, GRAND200k, will replicate the GRAND10k sub-arrays in multiple locations, to reach the ultimate target sensitivity of GRAND.

The main challenge in building GRAND200k is its scale, in terms of cost, deployment, and maintenance. The appropriate response to this challenge lies in the size of the project itself, which forces us to adopt an industrial approach to building GRAND200k. For the electronics, developing a fully integrated application-specific integrated circuit board is likely the cheapest solution to build 200,000 units, while providing reduced power consumption and increased reliability. A precise and standardized procedure will have to be defined for detector transportation and installation, and factors linked to detector aging have to be carefully identified. For this purpose, the expertise acquired during previous construction stages will be crucial.

Organization, Partnerships, and Current Status

The GRAND Collaboration unites $\sim$60 international researchers and engineers from 10 countries. A Memorandum of Understanding (MoU) is being signed by 8 institutions, officializing their efforts on various scientific and technical fronts to build the experiment: Institut d'Astrophysique de Paris, Karlsruhe Institute of Technology, Nanjing University, National Astronomical Observatory of China (NAOC), Nationaal Instituut voor Kernfysica en Hoge Energie Fysica (Nikhef), Pennsylvania State University, and Universidade Federal do Rio de Janeiro. 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 (see Schedule below for GRANDProto 35 and GRANDProto300) are managed by the NAOC. The Collaboration aims to provide public access to detected events recorded by GRAND after a reasonable amount of time to allow the astroparticle community at large to interact with and benefit from its results. The Collaboration will endeavor to minimize its impact on the environment by establishing a Carbon Code of Conduct.

Schedule

GRANDProto35 (2018 - 2020)

GRANDProto35 [59], the first construction stage, is an array of 35 radio antennas plus surface particle detectors (plastic scintillators). Its main goal is to demonstrate an efficiency higher than 80% for the radio-detection of (vertical) EAS and a background rejection that keeps the ratio of false triggers to true signals below 10%. GRANDProto35 builds on the experience from TREND [48, 60, 61], and is deployed at the same site, in the Tian Shan mountains in the XinJiang province of China. The prototype is under deployment, and twelve antennas are taking data. We show in the left panel of Fig. 3 the signals recorded by one of the GRANDProto35 units deployed at the site in China. We have tested that the DAQ system achieves 100% detection efficiency for trigger rates up to 20 kHz [59]. 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 as it can be seen in Fig. 3 (left). GRANDProto35 also includes an autonomous surface array of particle detectors to measure the efficiency of the antennas. The surface array 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. We will quantify the radio-detection efficiency and the background contamination by comparing the scintillator and radio data.

GRANDProto300 (2019 - 2024)

GRANDProto300 will be an array of 300 antennas deployed over 100 to 300 km^2. The main goal is to demonstrate that it is possible to trigger a radio array on nearly horizontal EAS, separate

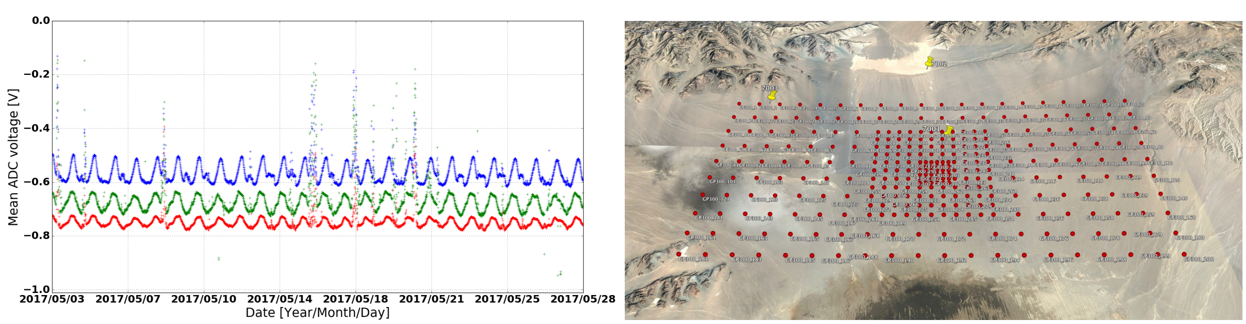

Figure 3: *Left:* Monitoring measurement of the mean voltage of the signal in a GRANDProto35 radio-detection unit during a period of 25 days at the array site, for the West-East (blue), South-North (green), and vertical (red) antenna-arm channels. The periodic fluctuations correspond to the daily transit of the Galactic plane in the antenna field of view. Figure taken from Ref. [59].
Right: Possible layout for the GRANDProto300 radio array at the proposed site in LengHu, QingHai. This includes 152 antennas deployed on a 1-km square grid with two denser in-fills.

them from the background, and reconstruct the properties of the primary particles with a precision similar to standard techniques used for cosmic-ray detection.

Eight candidate sites have been surveyed to host GRANDProto300 in the Chinese provinces of XinJiang, Inner Mongolia, Yunnan, QingHai, and Gansu. Six of them comply with the requirements for radio-quietness. After evaluating additional parameters such as ease of access, availability of infrastructure, support by local authorities, and possible extension to the GRAND10k stage, we selected a site in LengHu, QingHai. We are discussing with the local authorities the contract for site access. The first antennas for a long-term monitoring will be deployed in Summer 2019.

GRANDProto300 will consist of 300 antennas. Once completed, this prototype will be the largest radio array for autonomous air-shower detection, almost 10 times larger than GRANDProto35. The baseline layout is a square grid with a 1-km inter-antenna spacing. We show in the right panel of Fig. 3 one of the possible layouts for GRANDProto300 at the selected site in LengHu, QingHai. Denser in-fills are being considered to improve the statistics down to shower energies of $\sim 10^{7.5}$ GeV, and test the dependence of the array performance as a function of the density of detection units. The exact layout of the array will be defined through dedicated simulations, taking into account the science goals of this prototype and the properties of the site.

The antenna used in GRANDProto300 will be a first version of the HorizonAntenna, which is designed to improve the sensitivity close to the horizon. Based on the experience in GRANDProto300, the antenna design will be optimized for the following stages. We show the expected gain of the HorizonAntenna as a function of direction in Fig. 2. A prototype version of the HorizonAntenna was successfully tested during site surveying in summer of 2018.

The DAQ system of GRANDProto300 will be based on full sampling of a ~ 3 μs subset of the signals from the X, Y, and Z antenna channels using 14 bits at a rate of 500 million samples per second, following passive analog filtering in the 50–200 MHz band. Adjustable digital notch filters will allow to reject continuous-wave emitters that may appear in this band. We will transfer data via WiFi, which allows for a throughput of 38 MB$\cdot$s^{-1} per antenna.

FPGAs in the detection units will allow us to treat the signal to remove RF interference, subtract foreground, and apply spectrum whitening. The resulting signal will be averaged at the antenna level on time scales of minutes or longer, and sent to the DAQ, thus representing a minor contribution to the total data volume. In a second phase, the DAQ system will evolve to include more sophisticated data treatment techniques, such as adaptive filtering and machine learning [62].

The amplitude calibration will be done using the well-known background sky emission, modulated daily, as it was done in TREND [61]. Timing calibration will use airplane radio tracks, as in AERA [63]. A fraction of the antennas could also be used in transmitting mode to calibrate simultaneously amplitude and timing. Trigger rates, power consumption, battery level, air pressure, and temperature at each unit will be collected periodically to monitor the status of the array. The consumption of one detection unit is estimated at 10 W. Thus, a 100-W solar panel, coupled to a battery, should allow for continuous operation.

GRAND10k (2024 - 2034)

GRAND10k will be the first large sub-array (a.k.a., the first *hotspot*) of GRAND, and the first construction stage that is sensitive to UHE neutrinos. It will consist of 10,000 antennas deployed over a 10,000 km^2 area carefully selected for its suitability for the detection of neutrino-initiated EAS. Our simulations show that this array would yield an integrated sensitivity to UHE neutrinos of $8{\cdot}10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1} after 3 years [1]. GRAND10k will be able to probe flux models of cosmogenic neutrinos made by light UHECRs, with a sensitivity comparable to the planned final configurations of RNO and ARIANNA. GRAND10k will be the largest UHECR detector built, with an aperture twice that of Auger, i.e., $\sim$12,000 km^2 sr for energies above 10^{10} GeV. The design of GRAND10k will be informed by the experience with GRANDProto300, with further optimization of power consumption, triggers, and data transfer.

GRAND200k (2030 - 2040)

GRAND200k will be the full planned configuration of GRAND. Following the proposed modular design, it will consist of 20 independent arrays of 10,000 antennas each built at separate geographical locations that are hotspots for neutrino detection. Combined, they will total 200,000 antennas covering 200,000 km^2. We do not foresee important design changes compared to GRAND10k. The antennas, electronics, triggers, and data collection will have been validated at that stage or earlier. GRAND200k will address all of the physics goals presented above, including reaching sensitivities to cosmogenic neutrino fluxes of the order of 10^{-10} GeV cm^{-2} s^{-1} sr^{-1} [1].

Cost Estimate

The cost of the hardware for GRANDProto35 was \$144K[1], driven mostly by the digitizers (\$110K), and the low-noise amplifiers (\$25K). The cost estimates for GRANDProto300 are shown in Table 1. The total, \$1.32M, does not include deployment and computing costs. The current estimates for the first hotspot, GRAND10k, is \$22M, where the main driver is again the digitizers ($\sim$\$15M). Science costs are not included as part of the project as is customary for NSF and DOE HEP. Individual collaborators will propose to their respective funding agencies for scientific support to analyze the data including 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, but it is anticipated that the contribution from the U.S. groups would be about \$5M.

Item	Quantity	Cost (USD)
Antenna mechanics	330	172K
Cable assembly	-	54K
Solar Power	330	98K
Digitizer	330	927K
Local communications	330	67K
Communication system	-	2K
Total Hardware Costs		**1.32M**

Table 1: Cost breakdown for the major hardware components of GRANDProto300.

[1] 1 EUR = 1.12163 USD. Euro to US Dollar Conversion from XE Currency Converter on 2019-07-08.

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