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The Giant Radio Array for Neutrino Detection Experimental & technical aspects

The Giant Radio Array for Neutrino Detection (GRAND) is a proposal for a giant (60'000km²) array of radio antennas aiming at detecting cosmic neutrinos with E>5 10^{16}eV. We briefly present here some preliminary ideas about the detection principle of GRAND, a possible design and discuss physics & technical challenges of the project.

I. Detection principle

Even at ultra-high energies, the atmosphere remains nearly transparent to neutrinos. A denser target is required to detect these particles. As proposed by [Fargion] and others, this target can be rock. The leptons produced by neutrino charged current interaction may then emerge in the atmosphere and eventually generate EAS in the atmosphere, which will be associated to detectable radio emission. Electrons short range in matter and muons large decay length make tau neutrinos the only appropriate species for this type of scenario. Tau neutrinos are expected to reach Earth in equal proportion to the two other species thanks to neutrino oscillations during their cosmic journey. Simulations (see section III) show that only Earth-skimming trajectories (zenith angle θ within few degrees below horizon) are associated to non-negligible detection probabilities above 10^{16} eV.

II. The GRAND setup

Layout

Our preliminary proposal is a layout composed of 90'000 detection units deployed on a square grid of 800m side length over a total area of 60'000 km². This layout has to be considered as a start point for sensitivity studies, and will eventually be optimized. Larger step lengths, different unit cell geometries or non-continuous layouts will in particular be considered. It is possible that this optimisation could lead to a much reduced number of detection units (factor 2 or more) for a comparable detection potential.

In the preliminary sensitivity study presented here, the deployment site considered is the Tianshan mountain range. This is certainly a good candidate site (mountain area & limited electromagnetic background emissions), but other options will surely be considered in due times.

Detection unit

The detailed design of the GRAND detection unit to be used in a giant array will be defined during the GRAND R&D phase (see section V). Only general concepts can be outlined at this stage. Obviously the solution for a giant array should correspond to a robust, autonomous, light & cheap unit, providing only the minimal necessary information on the detected signal. The preferred idea at present is that the detection unit should be composed of three antenna arms orientated along three perpendicular directions. Maximum amplitudes measured on the three corresponding channels for a given transient signal would allow determining the polarization information of the electromagnetic radiation, which may prove to be a key element for EAS identification (see section V).

A very basic trigger logic would be preferred: the raw analog signals from the three channels would be independently compared to a fixed threshold set at a few times the electromagnetic background noise level, and the signals from all three channels would be recorded when a transient pulse exceeds the threshold on any of these channels. This straightforward solution is valid as long as no strong background noise source dominates the electromagnetic background: as the trigger is built on the raw analog signal, there is indeed no way that a specific frequency or source could be filtered out before trigger stage.

The format of data registered is still to be discussed, but reducing it to the antenna trigger time and maximal amplitudes on the three channels at this moment seems to be a very appealing concept: these reduced information should in principle still allow to fully determine the electric field associated to a shower at the antenna position, an information which is probably sufficient to identify & reconstruct all necessary information on the shower (amplitude, polarization, direction…).

Besides, reducing the data recorded to four words (4x12=48 bits) would dramatically eases things up for data transfer. It may in particular be possible to consider Wireless UART protocols to collect data, a technology for which commercial products have been successfully developed for industrial usage since several years now, making this solution very competitive in terms of costs. Assuming a 100Hz trigger rate for all individual units, this would lead to a –easily manageable- 54MB/s data rate for the whole GRAND array. Online search of time coincidences between triggered units at the DAQ level could then cut the rate of data to be written to disk down by an estimated factor 5 to 10.

Timing with ~ns resolution is achievable with a commercial GPS and standard off-the-shelf ADC+FPGA. Log-amplifiers would allow an amplitude measurement with precision ~5% over the full dynamic range of the radio signal.

III. Sensitivity to neutrinos

Simulation setup

An end to end MC simulation –from neutrino trajectory definition down to DAQ- is being set up in order to perform a precise estimation of GRAND's potential for the detection of cosmic neutrinos and define its optimal size and layout. All elements of the MC chain down to the EAS generation (neutrino trajectory generation, interaction, tau energy loss and decay, …) have already been developed and successfully tested, but simulation of EAS radio emission still requires additional work (especially for very inclined trajectories) before it can be considered as fully reliable.

Still, it is possible to provide a preliminary estimate for GRAND neutrino sensitivity by making rough assumptions on radio signal detection. We will consider that neutrinos-induced EAS is detected if:

- the shower energy is larger than $10^{16.5}$ eV,
- 5 antennas are in direct view of the shower, at least 5km away from the tau decay point, but within a cone[1] of half-angle Ω from it, where Ω goes like log(E), with Ω=3° @ 10^{17}eV and Ω=15°@10^{20}eV.

These assumptions are based on the following experimental facts:

- CODALEMA experiment has a detection threshold below $10^{16.5}$ eV [CODALEMA].
- CODALEMA has measured EAS signals 400m away from the shower core for ~vertical showers, corresponding to a detection cone of 3° at 10^{17}eV. The log(E) dependency of Ω is a direct consequence of the linear dependence of the electric field with energy, if we also assume an exponential law for the lateral amplitude profile, both behaviours being observed experimentally [CODALEMA], [LOFAR].
- EAS radio signals have been detected by the ANITA experiment more than 100km away from their emission point [ANITA].

We therefore believe that the sensitivity derived from this preliminary study is a conservative value, and should be confirmed –if not improved- by the more detailed MC study to come , which will include the radio simulation part.

[1] Ω = 3° @ 10^{17}eV, 15°@10^{20}eV. See annex for details.

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Simulation results

180'000 neutrino trajectories have been simulated, covering the energy range 10^{16}-3 10^{20} eV, zenith angle values 85-95° and all azimuth angles.

As shown on Fig. 1, only Earth-skimming trajectories (θ in [88-92°] induce non-negligible detection probabilities. This is a direct consequence of Earth opacity to UHE neutrinos, an effect increasing with energy. Also noticeable from this plot is the fact that downward trajectories (θ<90°) contribute as much as upward ones (θ>90°) to the total cross-sections: mountains therefore constitute a significant target for neutrinos.

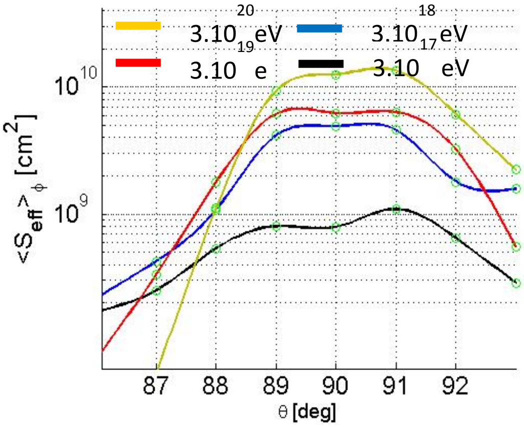

Figure 1 : GRAND detector effective area as a function of zenith angle for various neutrino energies between 3 10^{17} and 3 10^{20} eV. Here θ = 0° corresponds to the zenith and θ = 90° to the horizon.

Another striking result of the simulation is the large extension of the triggered area. This is illustrated in figure 2, where the trigger track extends along more than 100 km. Over all simulated events, the average distance from a triggered antenna to the tau decay point is ~70km, while the median number of triggered antennas per detected neutrino event is 20 (average: 180 antennas). This feature, to be cross-checked through dedicated radio simulation, is a direct consequence of the good propagation of radio waves in the atmosphere and the strong beaming of the radio signal. The large extension of the triggered area woull be a powerful tool for background rejection (see next section), and will also allow to improve the angular resolution. Assuming a ~1 ns timing resolution, an average angular resolution of 0.05° can indeed be expected from the analytical computation presented in [TREND]. The angular resolution is better than 0.2° for 99.9% of the simulated showers.

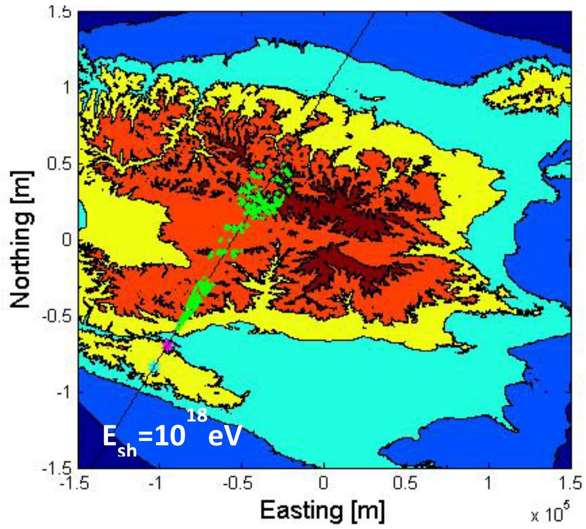

Fig 2: display of a simulated neutrino event over the GRAND array. The neutrino trajectory is shown as a black line, neutrino interaction point in ground as a cyan star and tau decay point as a magenta star. Triggered antennas are shown in green. Neutrino energy is 10^{18}eV and θ = 90°. Here 472 antennas are triggered with a detected track extending along more than 100km.

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It is possible to determine a limit on the GRAND detection sensitivity from the computed effective area. The integral limit at 90% CL is calculated by considering a power-law spectrum for the neutrino flux $\phi = \phi_0 E^{-2}$, and no neutrino candidate (⇔ 2.44 events @ 90% CL) detected within 3 years of data. A differential limit is also calculated by considering that no event is detected in each decade of energy. GRAND integral and differential sensitivity limits are presented in Fig. 3, as well as expectations for different emission models and sensitivity limits by other neutrino telescopes (see legend for details). It is in particular noticeable that GRAND performs 5 to 10 times better than ARA or ARIANA in the energy range 10^{17} – 10^{19} eV. ARA (Askaryan Radio Array, [ARA]) is a project supported by the IceCube collaboration to build an array of radio antennas buried 200m below the South Pole ice surface and covering a total area of 200km², while ARIANNA [ARIANNA] aims at deploying antennas just below the surface over 900km² of the Ross IceShelf in Antarctica. Both setups plan to detect cosmic neutrinos through the Askaryan radio emission associated with the development of a particle shower initiated by a neutrino interaction in the ice.

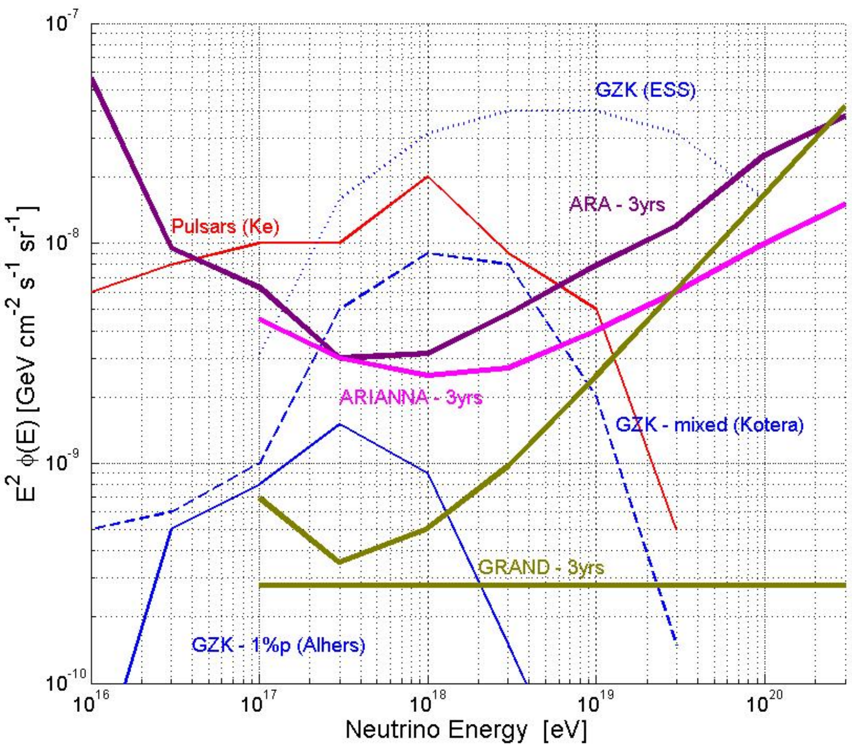

Fig. 3 : expected differential limits on the all-flavor neutrino flux (90%CL assuming E^{-2} spectrum and full mixing neutrino oscillation) for 3 neutrino telescopes projects: ARIANNA (magenta, [ARIANNA]), ARA (purple, [ARA]) and GRAND (brown). For GRAND the integral flux limit is also shown as a straight line. Also shown are estimates for neutrino fluxes for pulsars [Ke] or some models of cosmogenic neutrinos ([ESS], [Kotera], [Alhers]).

IV. Backgrounds

Two types of backgrounds have to be considered:

- background radio signals induced by terrestrial sources: human activities, natural electric discharge in the air, thunderstorms, etc.
- background radio signals of cosmic origin, associated to EAS induced by particles other than neutrinos. These particules may be standard UHECRs, for which the shower trajectory has

been misreconstructed below the horizon, or high energy muons and atmospheric neutrinos crossing the mountains and generating an EAS afterwards.

Background EAS signals

Simulations of background EAS signals will be included in our MC study in order to perform a reliable estimation of their contribution. Still, it is already possible to say that:

- Mountains can be used to screen 'standard' EAS induced by UHECRs with trajectories misreconstructed below the horizon: assuming a very conservative σ=0.2° angular resolution for the reconstruction (see previous section), rejecting all events with $\theta \geq 1°$ below horizon would correspond to a 5σ cut (or better) on events coming from the sky. This cut brings the flux of misreconstructed standard EAS down by a factor better than 10^{-6}, making it negligible (<1/year over the whole array) compared to the expected neutrino flux. Meanwhile, this cut would affects neutrino detection marginally only (<10%), as trajectories close to the horizon usually correspond to a too short path in rock to allow for neutrino interaction.

- High energy muons decaying after crossing matter will also be included in our full MC simulation chain in order to evaluate precisely how these backgrounds can affect our results. But here again, it is expected that this background is negligible: even assuming a flat detection site, the flux of muons above 10^{16} eV is estimated to 1.5/year/km² for θ>80° (ie within 10° from horizon) [Chirkin]. With a muon decay length L(km) = 6.5 10^6 . (E/10^{15}eV), this corresponds to an annual rate of 3 10^{-6} muon decays above the array. The mountains would act as an additional shielding to these particles, thus reducing the expected flux even below that value.

- Finally, at energies above 10^{16}eV, the flux of atmospheric neutrinos falls below that expected for cosmic neutrinos by orders of magnitudes [Honda].

Terrestrial signals

The event rate expected from terrestrial radio sources will be overwhelmingly larger than the EAS event rate in GRAND. In the present phase of TREND (so called TREND-50) for example, the total event rate is of the order of ~10Hz over a detection area of 1.5km², for an EAS event rate of few/day [TREND]. However, as the amplitude of background signals is expected to decrease ~linearly for isotropic emission, the background event rate should be significantly smaller with the 800m GRAND array step length than with the present 150m TREND-50 array step length. A total rate of ~15 events/day/km² for GRAND is a conservative estimate based on TREND-50 data. This yields 3 10^8 events/year for the whole array, which would require a background rejection factor R>10^9 to allow for an efficient neutrino search.

Rejecting background terrestrial events at a level of 1 false positive per a billion without affecting the neutrino detection efficiency constitutes, in our opinion, the main challenge for the GRAND project. This issue will be studied in the next phase of TREND, called GRAND-proto, and is detailed in the next section.

V. Giant Radio Array for Neutrino Detection - R&D phase

Due to their fluctuant, varied –and often unknown- nature and origin, background signals cannot be simulated satisfyingly. The only efficient way to study the background rejection potential of a radio array is therefore to develop a prototype dedicated to this study.

Principle and concept

We have seen in section III that the trigger pattern of neutrino induced EAS events should be very specific, with a trigger track extending over tens of kms along the shower trajectory, and a signal amplitude ~constant along this track, while it drops quickly when moving laterally. Background events should on the contrary exhibit ~isotropic patterns, with amplitude decreasing in a similar way in all directions when moving away from the source. However, a cut based on the detected amplitude pattern is certainly not sharp enough to reach the targeted 10^9 background rejection factor, especially for events triggering few antennas (in half of the cases, less than 20 antennas are triggered according to our simulation). Another criterion therefore has to be considered.

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A strong signature of EAS radio signals is their polarization. Electromagnetic radiations emitted by EAS are mainly due the geosynchrotron effect, a phenomenon corresponding to the deviation of the shower's electrons and positrons from their trajectory under the influence of the Lorentz force $\mathbf{F}=\pm e\mathbf{v}\wedge\mathbf{B}_{geo}$, where $\mathbf{B}_{geo}$ is the Earth magnetic field and $\mathbf{v}$ the particle velocity. This induces at first order[2] a linear polarization of the EAS radio signal, orientated perpendicularly both to the geomagnetic field and to the direction of propagation of the shower. We believe that the measurement of this polarization pattern on all triggered antennas is an efficient criterion to discriminate EAS from background events.

An array composed of antennas measuring the polarization of the detected signals will be deployed in summer 2015 on the TREND site to check this hypothesis and assess its discrimination power. Only events with the polarization pattern expected for EAS will be selected as EAS candidates, all others rejected. An array of particle detectors will be installed on the same site for cross-check: independent detection and compatible reconstruction by the two arrays would clearly sign the EAS nature of the events. This hybrid setup, called GRAND-proto, will allow performing a detailed, extended R&D study of the background rejection potential of the polarization measurement. Note that EAS detected by the R&D array would be initiated by "standard" cosmic rays: given the size of the array, probability to detect EAS induced by neutrinos is indeed negligible. However, results of the rejection potential obtained from these standard EAS would be perfectly valid for neutrino-induced ones, as the properties of the two types of showers are identical.

GRAND-proto setup design and status

Layout: GRAND-proto will be deployed on the TREND site from summer 2015. The excellent electromagnetic environment, the existence of infrastructures (a DAQ room, optical fibers already deployed between the romm and the field, a life base, ...) and the 5 years of work already carried out there are strong arguments in favour of this choice. A 32-antennas array will be deployed along the South-North baseline of the 21CMA. The array will extend over a total of ~4km along the North-South direction for a lateral extension of ~800m. As the radio emission is collimated along the shower axis direction, showers developing along the North-South direction would induce an elliptical-shaped pattern at ground, with a North-South elongation increasing with the shower inclination. The proposed layout is therefore optimal for the detection of inclined showers developing in the North-South axis.

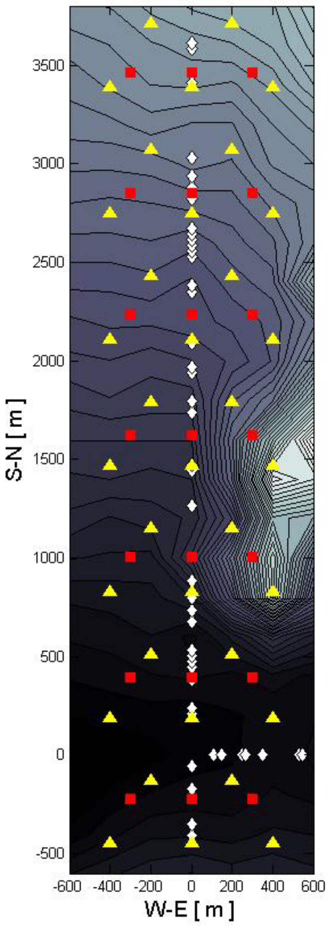
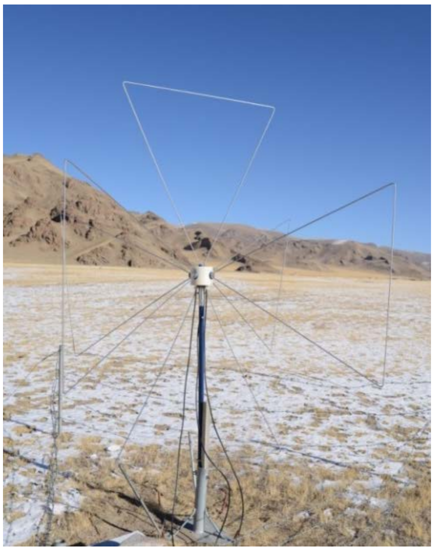


Fig. 4: proposed layout for GRAND-proto. Antennas are shown as yellow triangles, scintillators as red squares. The white diamonds correspond to 21CMA pods.

[2] 2nd order effects (global negative charge excess of the EAS in particular) can be taken into account in simulations in order to compute a precise 3-D map of the polarization field induced by EAS.



Detection unit: the detection unit is composed of three antennas orientated perpendicularly, allowing for a complete measurement of the electromagnetic field polarization. The 35 units have been built in collaboration between Xi'An XiDian university and SUBATECH (IN2P3), following the design of the 2-arms "butterfly" detector built for the AUGER-AERA project [AERA]. Each of the three antennas is an active detector, as a custom ASIC LNA is installed between the 2 arms of the antenna. 10 such detection units have been deployed on site and tested successfully.

Fig. 5: one GRAND-proto detection unit at test on site.

DAQ: the DAQ system is developed by LPNHE, which acquired significant expertise both on radio detection and trigger+digitization of high rate prompt signals through their leading role in EASIER [EASIER] and HESS projects [HESS]. A DAQ board is installed at the foot of each detection unit. A trigger order is given if a transient signal at antenna output exceeds a fixed threshold. The envelopes of the signals from the 3 channels are then digitized through 12bits+100MSPS ADCs, and sent to the DAQ through optical fibres. The signal envelope is formed from the antenna output signal thanks to a power detector, following a principle successfully tested by EASIER. A time stamping is computed at the ns precision level from a standard GPS using the internal FPGA clock.
Simulations show that polarization information of the electromagnetic wave can be reconstructed from the antenna digitized signals with a precision better than 2°.

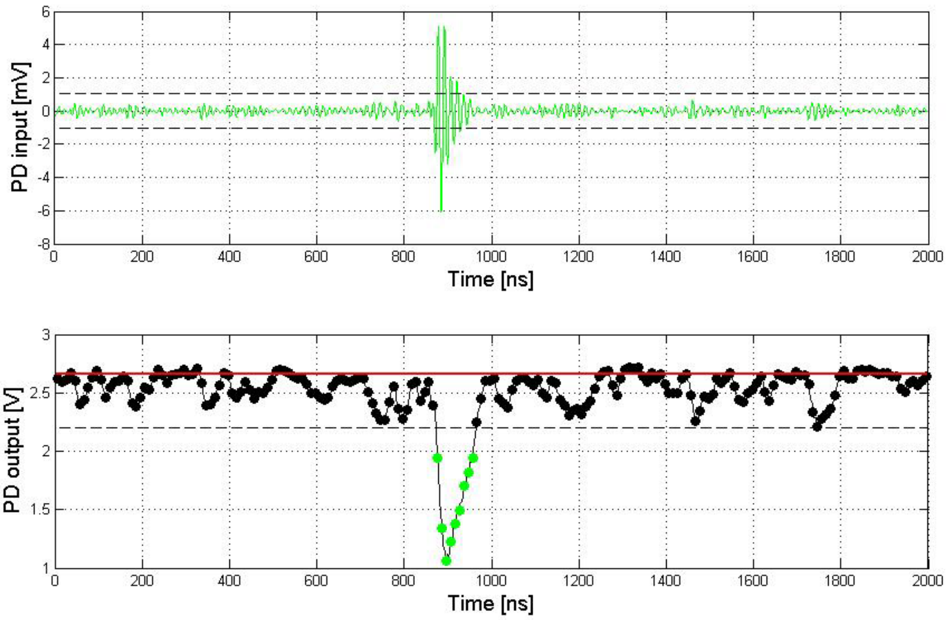


Fig. 6: top: simulated signal at antenna output. Dashed lines correspond to threshold levels. Bottom: same signal at power detector's output. Dots correspond to digitized signals at 100MSPS rate.

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The DAQ is fully funded. A prototype DAQ board will be tested on site in summer 2015. Provided this test is successful, production of the 35 boards should be completed in the next 3 months, allowing for a deployment of the DAQ system early 2016.

Particle detector array: an array of 20 scintillators detectors will be installed on site to perform an off-line cross-check of the radio data analysis. The layout of this array is being optimised for the detection of inclined showers developing along the North-South axis through extensive MC simulations. Scintillator prototypes are also being tested in IHEP. The array, funded by an NSFC grant, will start in summer 2015.

VI. Time schedule and budget

The deployment of the GRAND-proto array will start in summer 2015 and should be completed early 2016. It is expected that reliable results on the rejection power of polarization measurements will be available within 1 ½ year after that. If these results are positive, the door will be open for the GRAND array.

Building on the expertise acquired with the TREND-50 and GRAND-proto experiments, it is expected that a design for the GRAND detection unit –which should be initiated in parallel to GRAND-proto- can be finalized in a relative short time (<2 years typically) after that. A target price of 500$ per detection unit seems realistic, corresponding to a total cost for materials of ~50M$ for an array of 90'000 antennas.

References

[Fargion] D. Fargion, Astrophys.J.570 (2002) 909-925 arXiv :0002453
[TREND] D. Ardouin et al, the TREND collaboration, Astropart.Phys. 34 (2011) 717-731 arXiv:1007.4359
[CODALEMA] D. Ardouin et al., the CODALEMA collaboration, Astropart.Phys. 31 (2009) 192-200A. A. Rebai et al., arXiv:1210.1739
[LOFAR] P. Schellart et al., the LOFAR collaboration, A&A 560 (2013), A98, arXiv:1311.1399
[ANITA] P. W. Gorham et al., the ANITA collaboration, . arXiv:1003.2961.
[ARA] P. Allison, J. et al, .the ARA collaboration, Astropart. Phys., 35 (2012) 457–477
[ARIANA] S. Barwick for the ARIANNA collaboration, International Cosmic Ray Conference proceedings, (2011). 4-23
[Ke] K. Fang et al, J. Cos. and Astro. Phys. (2013), 3:10–31
[ESS] R. Engel et al, Phys.Rev. D64 (2001) 093010 arXiv : 0101216
[Kotera] K. Kotera et al., MNRAS (2013)
[Alhers] M. Alhers & F. Halzen, arXiv :1208.4181
[Chirkin] D. Chirkin, arXiv:0407078
[Honda] M. Honda et al, Phys.Rev. D75 (2007) 043006 arXiv : 0611418
[AERA] P. Abreu et al, the AUGER collaboration, arXiv : 1209.3840
[EASIER] R. Gaior, PhD thesis, UPMC-Paris 6 university (2013).
[HESS] J. Bolmont et al, Nucl.Instrum.Meth. A761 (2014) 46-57, arXiv:1310.5877