The GRAND proposal

1- The GRAND project

GRAND is a project for a giant radio array, composed of ~200'000 antennas deployed over a total area of 200'000km², dedicated to the detection of very high energy cosmic particles of (E>10^{17}eV typically). The extensive air showers (EAS) initiated by these particles in the atmosphere generate coherent radio emission, mostly through interaction with the Earth magnetic field. This emission produces brief (<100ns) transient signals on radio antennas working in the 30-200MHz frequency range [Ardouin05, Falcke05].

GRAND aims in priority at detecting cosmic neutrinos. Neutrinos are unique messengers that let us see deeper in objects, further in distance, and pinpoint the exact location of their production. These characteristics will help unveil the mystery behind the most violent astrophysical phenomena from which high-energy neutrinos should originate, and identify the source of their parent ultrahigh energy cosmic rays (UHECRs).

a. Detection principle

Even at ultra-high energies, the atmosphere remains nearly transparent to neutrinos. Cosmic neutrinos can however produce leptons underground through charged current interaction. τs travel to the surface of the Earth and decay in the atmosphere, generating EAS [Fargion99, Bertou02] that will also produce 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 next paragraph) show that only Earth-skimming trajectories are associated with non-zero detection probabilities, and even for these most favorable trajectories, probabilities remain very low. The strong beaming of the electromagnetic emission along the shower axis combined with the transparency of the atmosphere to radio waves allows the radio-detection of EAS initiated by τ decays at distances up to several tens of kilometers [Gorham10]. Radio antennas are thus ideal instruments for this purpose. Furthermore, they offer practical advantages (limited unit cost, easiness of deployment, etc.) that allow the deployment of an array over giant areas, as required by the expected low neutrino rate.

Remote sites, with low electromagnetic background, should obviously be considered for the array location. In addition, mountain ranges are preferred, first because they offer an additional target for the neutrinos, and also because mountain slopes are better suited to the detection of horizontal showers compared to flat areas, parallel to the showers trajectories.

GRAND antennas are foreseen to operate in the 30−100MHz frequency band. Short wave background prevents detection below this range, and above the coherence of the geomagnetic emission fades. Extension of the antennas bandwidth upper limit to 200 or 300MHz could be considered in the perspective of detection of the Cerenkov ring or transition radiation (see chapter 4 and 5).

b. Expected performances

A preliminary determination of GRAND neutrino detection potential was performed. Given the very large computation time for EAS electromagnetic field calculation (~2hours for each antenna position), and the need to properly simulate the E-field interaction with soil, it is not yet possible to perform an end-to-end simulation of the neutrino detection process. In a first step, only the neutrino interaction, tau propagation and decay in atmosphere were simulated with CTEQ4-DIS, GEANT4 and Pythia-TAUOLA respectively. It was then considered that the induced EAS would be detectable if its energy was above 10^{16.5}eV (aggressive) or 10^{17}eV (conservative) and if 8 antennas are in direct view of the tau decay point, at a distance ranging between 20 and 120km, and within a cone of half-angle between 3-20° (depending on the shower energy) around the shower propagation axis. These parameters are consistent with...
experimental results [Rebai12, Gorham10]. A detection area of 60'000km² was considered for this study over a mountain area in western China, the Tianshan mountains, with an antenna density equal to 1km².

The results are the following:

- **Sensitivity:** The effective area calculated in this study is presented in figure 1. It is maximal for slightly ascending trajectories (shower emerging with 1° above the horizontal) and remains significant for trajectories between ~±4° around this value. This preliminary analysis also demonstrates that mountains constitute a sizable target for neutrinos, with ~40% of down-going events corresponding to neutrinos interacting inside the mountains.

Assuming a spectrum of the form $\phi = \phi_0 E^{-2}$, this 60'000km² array would allow to reach an integral limit equal to $3.1 \times 10^{-10}$ GeV·cm²·s⁻¹ on the neutrino flux if no candidate is observed in 3 years. It also appears that specific parts of the array (large mountains slopes facing another mountain range at distances of 30−80 km) are associated with a detection rate well above the average (see figure 2). A factor 10 improvement in sensitivity may be reached with a factor of 3 increase in the detector area, provided the detector is composed of several sub-arrays of smaller size (few 10'000 km²) deployed solely on favorable sites. This is the envisioned GRAND setup.

![Figure 1](image1.png)

**Figure 1:** left: Effective area of the 60 000 km² simulated set-up as a function of zenith angle $\theta$ for various initial $\nu_\tau$ energies. Zenith angles = 0° corresponds to nadir. Color code: black: $10^{17.5}$ eV, red: $10^{18.5}$ eV, green: $10^{19.5}$ eV, blue: $10^{20.5}$ eV. right: Differential sensitivity limit of the 60 000 km² simulated set-up (red dashed lines, thin: conservative, thick: aggressive), of the projected 3 times larger GRAND array (red thick long-dashed), and for other instruments, and estimated theoretical cosmogenic neutrino fluxes for all flavors [Kotera10]. The blue line gives the most pessimistic fluxes (pure iron UHECR injection and low maximum acceleration), while the gray shaded-region indicates the “reasonable” parameter range.

- **Field of view:** the instantaneous field of view of the GRAND detector is about 8x360 deg², corresponding to less than 5% of the sky. However, since all azimuth angles are observed at any instant, ~80% of the full sky is observed within 24 hours (see figure 3).

- **Angular resolution:** with an expected resolution better than 3 ns on the antenna trigger time, analytical calculations [Ardouin11] show that the direction of origin of a shower can be reconstructed with a mean precision of 0.05°. At GRAND energies, the shower and neutrino directions of origin can be assimilated. GRAND expected angular resolution allows performing point source neutrino astronomy.
Energy reconstruction: it is not possible to directly access the incoming neutrino energy with GRAND. The fraction of energy transferred to the tau lepton during the neutrino interaction or the quantity of energy lost during tau propagation for example are not accessible experimentally. The shower energy, which can be reconstructed with a ~20% precision [Aab15] obviously provides a lower limit for the neutrino energy. Yet, some measurable variables – such as the tau decay length (see figure 3)- correlate to the neutrino energy. It may be possible to estimate the most probable neutrino energy from the reconstructed tau flight distance and eventually establish an energy spectrum that would become meaningful with enough statistics.

In summary, a very preliminary simulation, based on simplified but realistic hypothesis, indicates that the GRAND 200000km² radio array could reach sensitivities to neutrino fluxes far better than competing projects, with an expected mean angular resolution equal to 0.05°.
Let us now detail what physics goals could be pursued with GRAND.

2- GRAND science case
We receive on Earth cosmic particles with energies orders of magnitudes higher than those accelerated at the Large Hadron Collider (LHC). These particles probably come from violent sources in the Universe which remain unidentified to date. Their detection, combined with the observation of electromagnetic radiations at all wavelength (from infrared to very high energy (VHE) gamma rays) is the only tool at our disposal to study mechanisms of energy production in these astrophysical objects. The detection of VHE cosmic particle has also always been and remains a great mean to study interactions of fundamental particles.

a. Very high energy neutrino astronomy

Neutrinos are very valuable cosmic messengers: electrically neutral, subject to weak interaction only, these particles propagate without attenuation or deflection over cosmological distances. Unlike other cosmic messengers, neutrinos allow seeing deep in the core of their sources, and do not leave any ambiguity on their origin, being produced through high energy hadronic processes only. For all these reasons detection of VHE (> 10^{17}\text{eV}) cosmic neutrinos would be a great tool to study violent phenomena in the Universe and the related processes of particle acceleration. Development of neutrino astronomy would certainly be a revolution in the field of high energy astrophysics.

Let us now detail more specifically few topics which would greatly benefit from neutrino astronomy.

- **Cosmogenic neutrinos:** ultra-high energy cosmic rays (UHECRs) are likely produced in extragalactic sources, given the strength of Galactic magnetic fields and the lack of correlations with the Galactic plane. They are certainly mostly of hadronic nature [Abbasi15]. Some fraction of their energy is converted to high-energy neutrinos through the decay of charged pions produced by interactions with ambient matter and radiation. This can happen in the source environment or during the flight in the intergalactic medium (cosmogenic neutrinos). The range of expected cosmogenic neutrino fluxes can be calculated precisely, and depends mostly on parameters inherent to the cosmic rays (Figure 1) [Kotera10], and in particular the chemical composition of the UHECRs and the source emissivity evolution over time. The detection of cosmogenic neutrinos should provide strong constraints on the nature of UHECRs. Combining EeV and PeV neutrino information, one will be able to select between competing models of cosmic ray composition at the highest energy and the Galactic to extragalactic transition at ankle energies. The detection of events around ZeV energies would place limits on the maximum acceleration energy.

If GRAND reaches its expected sensitivity, it will detect cosmogenic EeV neutrinos. For reasonable source scenarios (Figure 1), GRAND aims at collecting in the order of 100 events per year above 3\times10^{16} \text{eV}, which will help to understand the underlying components. An energy resolution of 50\% would enable us to picture the shape of the diffuse energy spectrum, but the most important information would stem from the precise (< 0.1°) angular resolution on the arrival directions. Cross-correlating the position of sources and of events, it will be possible to discriminate between cosmogenic neutrinos and those produced in the source environment. The former should indeed correlate with the large-scale structures at high redshift where the integrated flux is maximal.

- **Active Galaxy Nuclei:** AGNs are supermassive black holes (10^8 solar masses typically) at the center of galaxies that convert potential energy of accreting mass into relativistic jets through processes that are still largely unknown. AGNs are among the most popular candidates of UHECRs sources [Berezinsky02]. The best insight on the particle population in AGN relativistic jets currently comes from multi-wavelength observations, from radio to gamma-rays. However, there are still several open problems, such as the location and geometry of the emitting region, and the nature of particles (leptons or hadrons) at the origin of the photon emission. With regard to the latter aspect, neutrino astronomy has the unique potential to remove this degeneracy, constraining the hadronic component of the jet. Furthermore, the non-detection of neutrinos
at the location of the brightest active galactic nuclei will constrain the acceleration efficiency of particles within their outflows, as well as the opacity of the acceleration region for UHECRs to escape.

Whether transients can accelerate cosmic rays to ultrahigh energies is a paramount question. Above $E > 10^{19}$ eV, the observed cosmic-ray flux constrains the source energy budget to $\text{EUHECR} = 10^{44.5}$ erg/Mpc$^3$/yr, which is not easily reached by most astrophysical populations. Additionally, for UHECRs, the source density for steady candidates is highly constrained by the absence of observed anisotropy in the arrival direction of cosmic rays [Abreu13]. Constraints on the density of transient sources are subject to the time spread $\tau$ experienced by particles as they are deflected in the intergalactic magnetic fields (IGMF): $n = \rho_s / \tau$, where $\rho_s$ is the real source density, and $\tau$ is bounded by lower and upper observational limits obtained on Galactic and IGMF structures respectively [Murase09]. Even rare transient events could thus mimic a rather dense population. Among transient sources candidates for UHECRs productions, two can be singled out:

- **Gamma ray bursts:** GRBs correspond to brief (less than an hour for the burst itself) and random electromagnetic emissions, most likely associated to the death of massive stars for the long bursts. They are the brightest known events in the Universe. They could be a great tool for cosmology [Wang15]. GRAND sensitivity is within range of most popular GRBs neutrino emission models, while its angular resolution would allow performing individual survey of GRBs. Based on the Swift detection rate of $\sim$100 high energy GRB/year, a preliminary analysis let us believe that $\sim$5 GRBs/year would be in GRAND field of view at burst time (and probably more, given the finite detection efficiency of Swift). Moreover, GRAND would be able to study the afterglow emission of most GRBs, since its 24h field of view is about 80% of the sky. This is of great interest, since most GRBs afterglows are associated with highly energetic neutrinos emissions [Murase07].

- **Fast-spinning newly born pulsars:** Young magnetized neutron stars born with millisecond periods are a promising UHECR source candidate, due to their important electromagnetic energy reservoir. Because they can supply enough energy to produce the highest energy particles only in the first years of their lives, these objects and their associated emissions can be considered as transient. Their existence is supported by pulsar population studies [Faucher2006]. All the UHECR observables can be successfully fit with such a pulsar scenario [Fang13]. Secondary messengers such as neutrinos and gamma-rays are expected to be abundantly produced while particles cross the SN ejecta. Quantitative estimates for the neutrino signatures have been derived [Fang13], which will be in the sensitivity range of GRAND (see Figure 4).

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**Figure 4:** left: neutrino fluxes from various GRB models [Murase07] and GRAND sensitivity (M. Bustamante, GRAND meeting, 12/10/2015) Right: expected diffusive neutrino fluxes for various type of objects and experimental sensitivities for IceCube, ARA [Allison15], and GRAND 60'000km² setup [Martineau15].
b. **Ultra-High energy cosmic rays**

An intense experimental effort (AGASA, HiReS, Auger, Telescope Array, ...) was carried out in the last two decades to determine the nature and origin of UHECRs. But to date, there is no definite answer to this puzzle. Measurement of UHECRs energy spectrum and chemical composition [Abbasi15] disfavor “exotic” models (such as the decay of ultra-massive relic particles, or those relying on a “new physics”) and point to an astrophysical solution, where hadronic particles are accelerated through violent phenomena up to the highest energies. Because of the limited number of events detected beyond $5 \times 10^{18}$eV, and the systematic effects at play in the determination of the nature of the primary, sources and mechanism of productions of UHECRs however remain largely unknown, even if various realistic hypotheses exist, as mentioned above.

Given its gigantic size, GRAND is likely to detect a large number of UHECRs. This detection would be valuable only if it is associated with a precise determination of the nature of the primary. A $25g/cm^2$ seems achievable under certain condition for radio data [Schröder14]. A dedicated study will be carried out to estimate the reachable level of performances for GRAND (see section 5.b).

c. **Other physics**

Given its huge number of detectors and expected frequency range (30-100MHz, possibly going up to 300MHz more if we aim at detecting the Cerenkov ring or transition radiations, see chapter 4), GRAND could possibly be used for other science cases, such as the study of the epoch of reionization [Zaroubi13], fast radio bursts [Thornton15] or transient luminous events in the upper atmosphere [Boccippio95], assuming the data needed for the corresponding analysis can be recorded by GRAND. Frequency range or recorded signal length are key issues in this respect.

3- **Experimental context and state of the art**

a. **Neutrino telescopes**

Neutrino astronomy has been a major motivation for astrophysicists and high-energy experimentalists for many years through projects like AMANDA, Antares, KM3Net or IceCube. A milestone was reached in 2013, when 28 signatures of neutrino interactions inside the IceCube detection volume were identified, while 10 only were expected from atmospheric background [IceCube13]. 25 more events were detected since then for a total exposure of 1347 days over 4 years of operation [DeYoung15], and there is now a $5.7\sigma$ evidence that IceCube detected neutrinos of astrophysical origin (see figure 5). These events are compatible with an isotropic distribution of the direction of arrival and a power law energy spectrum with spectral index $\alpha = -2.50\pm0.09$ [Aartsen15].

![Figure 5: spectrum of the events detected as neutrinos interacting inside the IceCube detection volume (High Energy Starting Events) during 4 years of operation, compared to expected backgrounds. Taken from [deYoung15]](image-url)
These results are obviously extremely exciting, as they show that neutrino astronomy is possible. It should however be pointed out that for most of these events (the so-called shower events, corresponding to either a neutral current interactions of a $\nu_e$, $\nu_\mu$, $\nu_\tau$, or a charged-current interaction for $\nu_e$ and $\nu_\tau$), the resolution on the reconstructed direction of origin is about $10^\circ$, and only 3 of the detected events have energies above $5 \times 10^{14}$ eV. Other projects, allowing detection at EeV energies are therefore requested to cover the high-end of the neutrino energy spectrum. Two [Allison15, Barwick15] have been proposed and are presently in their development phase in Antarctica for this purpose. Both are based on the radio-detection of the electromagnetic radiation generated through the Askaryan effect by in-ice showers initiated by cosmic neutrinos. Both are limited by their angular resolution ($1^\circ$ at best), and have similar sensitivity expectations, about ~50 times worse than GRAND in the $10^{17}$-$10^{19}$ eV energy range (see figure 1).

In conclusion to this part, GRAND would be a very competitive detector of cosmic neutrinos if it reaches the expected sensitivity, and a complementary instrument to neutrino telescopes (IceCube, KM3Net) running at lower energies.

b. Multi-messenger astronomy

Thanks to unprecedented instrumental developments, we are witnessing today the birth of high-energy multi-messenger astronomy (astronomy combining various high-energy messengers: photons, neutrinos, cosmic-rays and gravitational waves). Significant increase in sensitivities and angular/time resolution of gamma-ray telescopes will indeed be obtained in the coming years with HESS-II, HAWC, LHAASO and CTA. The Auger Observatory and the Telescope Array are also reaching full maturity, while the neutrino experiment IceCube has just opened the breach for high-energy neutrino astronomy. Thrilling discoveries in the transient sky are also expected with the launch of the Large Synoptic Survey Telescope (LSST), the Square Kilometer Array (SKA) and synergies with gravitational waves, with upgraded interferometers such as Advanced LIGO, Advanced Virgo and the Einstein Telescope are obvious. The three main non-thermal messengers (cosmic rays, neutrinos and gamma-rays) are now being detected together, and it is time to collect more particles, span the whole energy range up to $>10^{18}$ eV energies, and move to a point-source and timing analysis. GRAND expected performances should make it a key instrument to participate in this quest, in a field where IN2P3 has major experimental contributions and established expertise.

4- GRAND methodological and technological challenges

Here we detail several issues that have to be solved to make GRAND a viable project, and discuss ways to address them.

a. Background sources

Not more than few tens of neutrino events are expected per year on GRAND. It is therefore vital to perform an extremely efficient rejection of events from a different origin. Two types of backgrounds have to be considered: those linked to cosmic particles (atmospheric neutrinos and muons, or UHECRs) and those associated with terrestrial sources (anthropic or atmospheric noise).

- **Cosmic background**: atmospheric neutrinos follow a $E^{-3.7}$ spectrum [Honda07] ($E^{-2.7}$ [Enberg08] for prompt neutrinos), and their flux drops below that of neutrinos of astrophysical origin (with harder spectrum) at energies around $10^{14}$ eV [Aartsen15]. They are therefore a negligible background for GRAND. Atmospheric muons could also go through mountains and eventually generate air showers in the atmosphere, but a calculation based on [Chirkin04] shows that the chance probability for such an event occurring over the GRAND array is below $10^{-3}$/year. The most challenging cosmic background is UHECRs themselves, as a very inclined EAS could be wrongly reconstructed below the Earth surface and therefore interpreted as a neutrino signal. This issue will have to be carefully study through dedicated simulations, but it should be noted that very inclined (background) EAS induced by UHECRs will have developed much further from the detector compared to the neutrinos-induced ones. This will translate in a much broader and flatter wavefront, and a smaller value for the position of the maximum shower development. Cutting all trajectories
reconstructed 1° below the horizon and higher should additionally provide a radical suppression of this flux, given GRAND expected angular resolution. This cut corresponds on the other hand to a marginal cost in terms of neutrino sensitivity, as the corresponding Earth mass (the mountain crests) does not represent a significant target for neutrinos. This is an additional positive aspect of a detector deployed in a mountain area.

- **Terrestrial sources:** the event rates associated to terrestrial sources (human activities, thunderstorms, ...) that will be detected by GRAND are difficult to evaluate, but a conservative estimate can be derived from the results of the Tianshan Radio Experiment for Neutrino Detection (TREND). TREND [Ardouin11] is an array of 50 self-triggered antennas deployed in a populated valley of the Tianshan mountains, with antenna design and sensitivity similar to what is foreseen for GRAND. The observed rate of events triggering antennas over a surface of 1 km² was 15 events/day in TREND, which scales to a safe estimate of 10⁹ events/year for a 200'000 km² array. A background rejection rate better than 10⁹ is therefore probably necessary to reach the expected sensitivity of GRAND. Meeting this requirement without affecting the neutrino detection efficiency is a key challenge for the GRAND project.

b. **Background identification**

- **Antenna amplitude patterns:** the pattern of measured signal amplitude at ground should be a striking feature for EAS-induced signals, with a radio emission beamed within few degrees around the shower axis and a rapid drop of the amplitude lateral distribution. Also a Cerenkov ring is associated with the shower radio emission [Nelles14, Werner13] and represents a sizable fraction of the total electromagnetic signal. It may provide an unambiguous signature for background rejection if the antenna bandwidth upper limit is extended to 200 or 300MHz.

- **EAS radio field polarization pattern:** EAS radio emission is at first order linearly polarized, in a direction perpendicular both to the shower direction of propagation and to the Earth magnetic field because electrons and positrons from the shower drift in opposite direction thanks to the Lorentz force $F = q v \times B_{\text{geo}}$ with $q$ and $v$ charge and velocity of the particle and $B_{\text{geo}}$ the Earth magnetic field. This process represents the major contribution to the total radio emission. The moderate excess of negative charges in the shower induces a ~10% correction to the E-field vector direction towards the shower axis (see Figure 6). These very peculiar features of the EAS radio signal are predictable from the shower geometry and have been observed experimentally [Abreu12]. We thus believe that polarization of the signal could be used to perform discrimination from background. A proposal will be submitted to the Auger collaboration in order to test specifically this hypothesis on the AERA radio setup, using the Auger FD detector as a validator for EAS signals. In parallel, the GRANDproto experiment is being set up on the TREND site to evaluate quantitatively the potential of polarization measurement for background rejection.

- **GRANDproto setup:** GRANDproto is a hybrid network composed of two independent arrays of 35 radio antennas and 21 plastic scintillators. It is fully funded and being deployed over a total area of ~2 km² on the site of the TREND experiment [Ardouin11] in the Tianshan mountains (see Figure 6). The antennas were designed by the SUBATECH laboratory, on the same model as those used in the Auger AERA radio network, and produced by the Xi'An University. They are composed of 3 perpendicular arms with a 30-100MHz bandwidth, allowing a measurement of the x, y and z components of the E-field at each antenna location. Following the readout strategy developed by the AUGER-EASIER experiment, the 3 analog signals at antenna output are fed into a power detector, which reconstructs the signal envelope. The ~60MHz oscillations observed on the antenna signal being caused by the antenna limited bandpass (20-100MHz), the physics information of the electromagnetic signal –amplitude and duration- is fully contained in the signal envelope and is not altered by this process (see figure 7). If the analog signal on one of the 3 channels exceeds a (programmable) threshold value, then a 5µs subset of each of the 3 signals at power detector output are digitized at a 100MS/s rate and sent to the central DAQ through the optical fiber, together with the trigger time information given by a GPS. This DAQ readout is developed at LPNHE (P. Nayman, D. Martin, J.
David, J.F. Huppert, P. Bailly) through a contract with the National Astronomical Observatories of China. A prototype is presently being evaluated at LPNHE, and will be tested in real conditions on the GRANDproto site in March 2016. If successful, the 35 DAQ cards should be produced in spring 2016 and the full deployment of GRANDproto should be achieved in summer 2016. Six antennas and six scintillators are already deployed on site in order to develop and test DAQ and data analysis programs. The scintillators, developed by IHEP, have an area of 0.5m². They are installed on a frame tilted by 50° towards North (see figure 6) to maximize the scintillator acceptance for showers coming from the North with angles larger than 45°, those also best seen by the radio array. The trigger system and DAQ are identical to those developed for the TREND experiment [Ardouin11], with a PMT signal directly fed into the optical fiber and digitized at the 100MS/s rate at the DAQ level.

![Figure 6: left: the GRANDproto layout. Antennas are shown as yellow triangles, scintillators as red squares. The white diamonds correspond to the 21CMA pods supplying power and optical fibers to transfer the GRANDproto data. Top: GRANDproto scintillator and antenna being deployed in summer 2015.](image1)

![Figure 7: top: background signal recorded on TREND antenna. Bottom: simulated response of the power detector to the signal above.](image2)
GRANDproto principle: for each electromagnetic wave triggering 5 antennas or more, the direction of origin of the wave will be reconstructed from the antenna trigger times, as well as the direction of the E-field vector. An estimator of the E-field vector on a given antenna \( j \) can be given by 
\[
\tan \eta_j = \frac{E_{NS}}{E_{EW}}
\]
and 
\[
\tan \beta_j = \left( \frac{V_{EW} + V_{NS}}{V_z} \right)^{0.5}
\]
for the azimuthal and zenithal angles respectively, where \( V_{EW}, V_{NS} \) and \( V_z \) are the maximum values of the voltage measured on the 3 arms of antenna \( j \). These angles will be compared to the values \( \eta_{sim} \) and \( \beta_{sim} \) computed through simulation for an EAS with same geometry. The foressen selection criterion is to consider that event will be tagged as an EAS radio candidate if values \( \{ \eta_j, \beta_j \} \) and \( \{ \eta_{sim}, \beta_{sim} \} \) are within \( \pm 15^\circ \) for all triggered antennas. Due to various effects (in particular random noise on the antenna signal), it is indeed expected that the polarization vector reconstructed from the recorded radio data may differ up to \( 15^\circ \) (for signals close to threshold) from its actual value (see figure 8). However, even when accepting mismatch between the experimental and expected angle values up to this value, a random polarization would be tagged as valid with a probability of 0.05 only, yielding a total probability of \( 3 \times 10^{-7} \) that a (background) event with random polarization triggering 5 antennas is wrongly tagged as an EAS radio candidate. This selection algorithm will be refined, but from this very preliminary study, the polarization measurement looks as a promising discrimination tool for EAS. Scintillator data recorded in coincidence, with compatible reconstructed direction of origin, will provide an offline validation of the nature of the event, as only shower particles are likely to trigger several scintillators in coincidence.

The GRANDproto experiment will allow computing quantitatively the potential for EAS identification by polarization measurement. GRANDproto being (willingly) deployed close to sources of electromagnetic background, a background event rate higher than 10Hz is expected on GRANDproto, corresponding to a total statistics of \( 1.5 \times 10^9 \) events/year. It is expected that during the same period of time the scintillator network will record several hundreds of EAS that should also trigger the radio array [Gou15].

c. Detection unit, data collection and architecture of the GRAND network

Deploying, running and collecting data from a network of 200'000 detectors spread over 200'000km² is a major technological challenge. It is yet not unrealistic, thanks to radio detectors characteristics and up-to-date technologies.
- **Detector:** radio antennas foreseen for GRAND are very basic mechanical structures. Composed of 3 arms for a total span of 1.5m, they weight 5kg in total. Two prototypes were deployed on the TREND site in January 2014 and work since then without any major problem. The technical team, based on the TREND site, who took in charge the deployment of the radio-interferometer 21CMA (10287 antennas) has the necessary skills and knowledge to coordinate the deployment of the GRAND network.

- **Front-end electronics:** most past or present experiments performing EAS radio-detection (CODALEMA, LOPES or AERA) rely on a fine sampling of the signal (up to 1GHz) detected by the antennas, and an external trigger realized by standard EAS detectors. These technological options significantly attenuate the specific assets of radio detection (in particular the antennas easiness of deployment and operation and their low cost). The GRAND project is based on a radically different philosophy, inspired by the TREND experiment [Ardouin11] of autonomous radio-detection of EAS autonomous radio detection units, and a volume of recorded information reduced to a minimum. These options are the only realistic ones for a setup of this size, both for technological and financial aspects. If the information recorded by an antenna is reduced to the maximal amplitude of the transient radio signal, and the antenna trigger time, robust and cheap commercial solutions exist for timing (GPS), trigger and digitization of the signal (ADCs, FPGAs), making a target price of 200€ realistic, for a total power consumption of 1W, provided by solar panels & batteries. Various treatments are considered at the level of the front-end electronics in order to optimize the detection threshold and the background rejection:
  
  o As done for GRANDproto, we plan to read the antenna signals with a power detector. The signal at its output would be digitized at a rate of 60MS/s without any significant loss of the information quality.
  
  o Various numerical treatments realized on the fly on the digitized signal through a standard FPGA – but never applied so far before signal triggering- are considered in order to perform the data selection. An adaptive filter is considered. It would allow adjusting the shape of the filter to the (fluctuating) environment conditions. A search of EAS-induced signals through correlation with a simulated signal pattern is another lead. Such algorithms could significantly improve background rejection at the antenna level, as well as the detection threshold compared to standard radio trigger strategies. We will stress here that the flux of neutrinos is expected to follow a $E^{-2}$ power law spectrum, thus corresponding to a factor 100 suppression when energy is multiplied by 10. An improved threshold on EAS detection could obviously translate in a sizeable increase in the rate of detected neutrinos.
  
  o The amplitude and polarization of the radio signal would be reconstructed from the x,y and z antenna channels, and the frequency content of the signal computed by the FPGA through FFTs. A finer treatment of this information is foreseen at the Front-End electronics level in order to optimize background rejection before data transfer.

The GRAND readout system will be tested in real conditions on the GRANDproto site in order to validate or improve the technological options implemented.

- **Data transfer:** data transfer is a key issue in the GRAND project. Assuming an average trigger rate of 10Hz for each antenna (same as the one observed on TREND, obtained with similar antennas for a noisier electromagnetic background), and considering that 4 words of 16 bits are recorded on each antenna (trigger time, total signal amplitude and the 2 angles of polarization), we obtain a data rate of 640 bits/s per unit, scaling to 16MBy/s for the full array. Commercial solutions (long range Wifi, GSM, etc.) would then be accessible to guarantee the data transfer and connection to the internet network for reasonable costs (about 10€/antenna).
5- Work plan

If GRAND preliminary sensitivity study makes the proposal appealing, the many issues listed above have to be tackled before this project can be considered as viable. The path defined towards completion of the project is detailed below. Contributions by LPNHE are explicitly detailed.

a. GRAND neutrino sensitivity estimation
Our priority should be to determine more reliably the sensitivity of the GRAND experiment to cosmic neutrinos through a robust, end-to-end (from neutrino trajectory down to antenna output) Monte-Carlo simulation. This task has been initiated in March 2015, and involves about 10 researchers from Brussels, Santiago di Compostella, Ohio State University, LPC Clermont-Ferrand and LPNHE. The last non-implemented (but most critical) element of the simulation chain is the simulation of the E-field emission and propagation. Two simulation codes will be used, both validated against experimental data: ZHAireS and EVA. The present task consists in validating these simulations for very inclined EAS trajectories. The TREND data (see section 7) is being used for this task, as EAS could be recorded for zenith angles down to 85° with this experiment. Interaction with soil (sensitive issue for horizontal trajectories) will be included in the code, as well as the simulation of the transition radiation emitted when a particle shower generated underground by a neutrino reaches the atmosphere [deVries16]. Cosmic particles background (see section 4.a) will be included in the simulation chain.
When the simulation chain is completed and tested, a massive simulation will be performed on a 1'000'000km² area corresponding to the Western part of China. This will allow identifying the zones with best topologies where sub-arrays could be deployed. The proposed layout, antenna characteristics (angular aperture and frequency range) and the expected neutrino sensitivity for GRAND will also be derived from this analysis.
Clementina Medina will take a significant part in the set-up and test of the simulation chain, while Olivier Martineau is coordinating the task. The GRIF grid could contribute to the task, as was done for the analysis of the TREND data. It is expected that first results of this analysis can be released before the end of 2016.

b. GRAND science case
The GRAND science case will have to be defined in further details, specifying exactly what science is achievable from the expected GRAND performances. Clementina Medina (on AGNs) will be involved in this task, led by Kumiko Kotera (IAP), where about 10 more researchers are involved. Jean-Philippe Lenain will be consulted for transient analysis in particular, where his expertise will be extremely valuable. A GRAND science case workshop is organized in Chicago on December 15, 2015, and a second one in IAP in May 2016.
Julien Aublin will take in charge the UHECRs science case dedicated analysis (see section 2.b), aiming at determining what results are achievable on the UHECRs analysis with GRAND, given its nominal performances.

From an internal LPNHE perspective, the synergies between GRAND, HESS, CTA and Auger science cases are obvious in particular for a multi-messenger analysis. Far from competing, these 4 projects should be seen as complementary.

c. GRANDproto
The prototype of the DAQ readout, developed in LPNHE in the framework of a contract signed with NAOC, is presently being tested at IHEP. It should be tested on site in March 2016. The GRANDproto detector should be fully deployed in summer 2016 and should run for ~3 years.
GRANDproto is co-led by Gu Junhua (NAOC, radio part) and Gou Quanbu (IHEP, ground array). 2 post-docs are also involved at NAOC (one of them being a former PhD from AUGER-EASIER), 4 permanent researchers and one PhD student in IHEP. GRANDproto benefits from the support of 4 technicians on site. All equipment and running costs are covered by NAOC and IHEP. Olivier Martineau will devote 50% of his research time to GRANDproto data analysis. A PhD subject focusing on this topic was also proposed and a NPAC M2 student is identified as a candidate.

d. GRAND engineering array
Detailed design of the GRAND detector will be refined once the technical requests associated to the definite science case of GRAND have been defined. Yet, given the complexity of the task and the timelines of technical
developments, it seems crucial to us that these technical developments are initiated as soon as possible. Given its world-leading expertise on fast signals trigger & sampling, LPNHE is a natural candidate to get involved in the signal front-end treatment and trigger strategy (see section 4.c). The team involved in the GRANDproto development (Nayman, Martin, David, Bailly) expressed his interest to take in charge this task.

Before considering the complete GRAND layout, and provided that the project is accepted by funding bodies, an engineering array of size ~1000 km² will be deployed in order to test the proposed technological solutions. This array will obviously be too small to perform a neutrino search, but cosmic rays should be detected above ~10¹⁹ eV. Their reconstructed properties (energy spectrum, directions of arrival, nature of the primary) will enable us to validate this stage, if found to be compatible with the expectations. The absence of events below the horizon should also validate our EAS identification strategy, given the fact that the chance probability to detect a shower induced by an Earth-skimming neutrino for an array of this size will be extremely low. This engineering phase could start in 2020, with a deployment of the full array possibly starting 3 years after that.

6. People involved

GRAND proposal finds its roots in the TREND experiment (see section 7). Discussions with Kumiko Kotera in June 2014 then led to the organization of a seminal workshop in LPNHE in February 2015, with support from Institut Lagrange. Several individuals have expressed their interest in the GRAND project since then, and for most of them, wish to contribute the prospective phase. This collaboration remains so far unformal, but aims at getting structured as soon as institutes validate their participation in the project.

<table>
<thead>
<tr>
<th>Name</th>
<th>Institute</th>
<th>Status</th>
<th>Other involvements</th>
<th>First contact with GRAND</th>
<th>Fraction of dedicated time</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olivier Martineau</td>
<td>LPNHE</td>
<td>Ass. Prof</td>
<td></td>
<td>January 2013</td>
<td>75%</td>
<td>GRANDproto data analysis, GRAND neutrino sensitivity simulation, management</td>
</tr>
<tr>
<td>Julien Aublin</td>
<td>LPNHE</td>
<td>Ass Prof</td>
<td>AUGER</td>
<td>October 2015</td>
<td>25%</td>
<td>GRAND science case (UHECRs)</td>
</tr>
<tr>
<td>Jean-Philippe Lenain</td>
<td>LPNHE</td>
<td>CNRS</td>
<td>CTA – HESS</td>
<td>September 2015</td>
<td>consultant</td>
<td>GRAND science case (transient)</td>
</tr>
<tr>
<td>Clementina Medina</td>
<td>LPNHE</td>
<td>Visitor</td>
<td>CTA</td>
<td>September 2015</td>
<td>50%</td>
<td>GRAND neutrino sensitivity simulation, GRAND science case (AGN) – CTA multi messenger analysis</td>
</tr>
<tr>
<td>Patrick Nayman</td>
<td>LPNHE</td>
<td>Engineer</td>
<td>CTA</td>
<td>March 2014</td>
<td>20%</td>
<td>GRANDproto radio array FE readout</td>
</tr>
<tr>
<td>Jacques David</td>
<td>LPNHE</td>
<td>Engineer</td>
<td>?</td>
<td>March 2014</td>
<td>20%</td>
<td>GRANDproto radio array FE readout</td>
</tr>
<tr>
<td>Jacques David</td>
<td>LPNHE</td>
<td>Engineer</td>
<td>?</td>
<td>March 2014</td>
<td>20%</td>
<td>GRANDproto radio array FE readout</td>
</tr>
<tr>
<td>Philippe Bailly</td>
<td>LPNHE</td>
<td>Engineer</td>
<td>?</td>
<td>September 2014</td>
<td>10%</td>
<td>GRANDproto radio array FE readout</td>
</tr>
<tr>
<td>Valentin Niess</td>
<td>LPC Clermont</td>
<td>CNRS</td>
<td>LHCb, TauMuVol</td>
<td>January 2013</td>
<td>20%</td>
<td>GRAND neutrino sensitivity simulation, GRANDproto simulations and data analysis</td>
</tr>
<tr>
<td>Didier Charrier</td>
<td>SUBATECH Nantes</td>
<td>Engineer</td>
<td>AERA</td>
<td>January 2013</td>
<td>consultant</td>
<td>GRANDproto antenna design, GRAND antenna study</td>
</tr>
<tr>
<td>Kumiko Kotera</td>
<td>IAP</td>
<td>CNRS</td>
<td>Phenomenology</td>
<td>June 2014</td>
<td>100%</td>
<td>GRAND science case, management</td>
</tr>
<tr>
<td>Nicolas Renault-Tinacci</td>
<td>IAP</td>
<td>Post-doc</td>
<td>Phenomenology</td>
<td>February 2015</td>
<td>*</td>
<td>GRAND science case (neutrinos)</td>
</tr>
<tr>
<td>Julia Schmid</td>
<td>Irfu</td>
<td>Researcher</td>
<td>CTA</td>
<td>June 2015</td>
<td>*</td>
<td>GRAND science case (neutrinos)</td>
</tr>
<tr>
<td>Wu XiangPing</td>
<td>NAOC Beijing</td>
<td>Prof.</td>
<td>21CMA</td>
<td>January 2013</td>
<td>10%</td>
<td>Management, GRAND science case (Epoch of Reionization)</td>
</tr>
<tr>
<td>Gu Junhua</td>
<td>NAOC Beijing</td>
<td>Ass. Prof</td>
<td>21CMA</td>
<td>January 2013</td>
<td>50%</td>
<td>GRANDproto radio array deployment, GRANDproto DAQ, GRAND science</td>
</tr>
</tbody>
</table>
Sandra Le Coz | NAOC Beijing | Post-doc | October 2015 | 100% | GRANDproto data taking & analysis

Zhang Jianli | NAOC Beijing | Post-doc | January 2013 | 100% | GRANDproto data taking & simulations

Zhao Meng | NAOC Beijing | Engineer | January 2013 | 20% | GRANDproto DAQ

Gou Quanbu | IHEP Beijing | Prof. | January 2013 | 100% | GRANDproto scintillator array deployment

Hu HongBo | IHEP Beijing | Prof | ARGO, As-Gamma | January 2013 | 10% | Management, GRANDproto scintillator array simulations

Zhang Yi | IHEP Beijing | Ass. Prof | ARGO, As-Gamma | January 2013 | 10% | GRANDproto scintillator array development

Feng Zhaoyang | IHEP Beijing | Ass. Prof | ARGO, As-Gamma | January 2013 | 10% | GRANDproto scintillator array simulation

Wang Zhen | IHEP Beijing | PhD | ARGO, As-Gamma | January 2014 | 10% | GRANDproto scintillator array simulation

Kotha Murase | Penn State U | Researcher | Phenomenology | February 2015 | * | GRAND science case (neutrinos)

Ke Fang | Chicago | Post doc | Phenomenology | February 2015 | * | GRAND science case (neutrinos)

Foteini Oikonomou | Penn State U | Post-doc | Phenomenology | February 2015 | * | GRAND science case (neutrinos)

Mauricio Bustamante | Ohio State | Post-doc | Phenomenology | September 2015 | * | GRAND science case (neutrinos)

Jordan Hanson | Ohio State | Post-Doc | ARA | September 2015 | 30% | GRAND neutrino sensitivity simulation

Tim Ruhe | Dortmund | Post-Doc | IceCube | September 2015 | <10% | GRANDproto data analysis

Washington Carvalho | Santiago di Compostella | Post-Doc | EAS simulations (ZHAireS) | February 2015 | 20% | GRAND neutrino sensitivity simulation

Krijn de Vries | VUBrussels | Researcher | EAS simulations (EVA) | February 2015 | 20% | GRAND neutrino sensitivity simulation

Chad Finley | Stockholm U | Professor | IceCube | February 2015 | 0% | GRAND neutrino sensitivity simulation

Sijbrand de Jong | NIKHEF | Professor | AUGER – AERA | February 2015 | 0% | GRAND neutrino sensitivity simulation

Charles Timmermans | NIKHEF | Professor | AUGER – AERA | February 2015 | 0% | GRAND neutrino sensitivity simulation

*: it is not possible to estimate the fraction of time devoted to GRAND for phenomenologists: in general they do not work specifically for a project, but their transversal activities benefit to GRAND and all other experimental projects in the fields.

The project was or will be presented at the 34th ICRC conference (Den Haag, August 2015 [Martineau15]), the VLVNT Workshop (Roma, September 2015, O. Martineau-Huynh), the KIAA workshop on Astroparticle physics (Beijing, September 2015, K. Kotera), the VHEPA conference (Hawai, Januray 2016, M. Bustamante) and the KICP workshop on new detector technics (Chicago, March 2016, K. Fang)

Olivier Martineau-Huynh is invited in Chicago Kavli Institute on December 14-17, 2015 to discuss with Angela Olinto’s group and others (Paolo Privitera, Abby Vieregg, Toshihiro Fujii, Markus Ahlers, Keith Bechtol, Andres Romero-Wolf, Albert Stebbins) about the GRAND project.

He will also be in NIKHEF in February 2016 to participate in the thesis jury of the PhD student of Sijbrand de Jong and will discuss at that occasion on the GRAND topics in which NIKHEF could get involved.

He is also invited to present the project at the Karlsruhe Institute of Technology in February 2016.

7. TREND
The Tianshan Radio Experiment for Neutrino detection is a project developed between 2009 and 2014, aiming at performing the autonomous radio detection of air showers with a self-triggered antenna array. TREND was developed
in collaboration with NAOC (Wu XiangPing’s group) and IHEP (Hu HongBo’s group), also benefiting from the expertise of SUBATECH CODALEMA group. TREND was deployed on the site of the 21CMA radio-interferometer in the Tianshan mountains (Ulastai, XinJiang autonomous province, China), fully benefiting from the financial, logistical, human and technical support of the 21CMA project.

TREND driving concept was to design a DAQ system able to cope with large trigger rates and perform EAS offline selection from the specific signatures of ESA radio signals (random direction & times of arrival, flat wavefront, linear polarization of the signal). Indeed it was foreseen that even in a clean electromagnetic environment like Ulastai (see figure 9), transient signals generated by surrounding radio sources (HV lines, electric transformers, cars, trains, etc.) would overwhelm the EAS event rate. A large acquisition live time is therefore a critical issue in this type of acquisition. Despite distinct scientific objectives, it is therefore the seed for the GRAND proposal.

The antennas were originally log-periodic dipole antennas taken from the 21CMA array, then upgraded to one-arm butterfly antennas (see figure 9). Antenna signals were amplified (64dB) at the antenna foot, filtered in the 50-100MHz frequency range, and the analog signal was fed into an optical fiber to the central DAQ room, where it was digitized with 100MS/s ADCs. A digitized sample exceeding $8\sigma_{\text{noise}}$ would then trigger the acquisition of a 5µs subset of data from that specific antenna. Temporal coincidences between antennas were identified offline.

TREND went through 4 distinct phases. In January 2009, a 6-antennas test array was deployed to validate the experimental concept, develop the DAQ and reconstruction processes.

In January 2010 the array was then extended to 15 antennas. 3 scintillators were running independently at the same location. Time coincidences observed between radio EAS candidates selected from our reconstruction procedure and triggers on the scintillators allowed to establish the autonomous radio-detection and fully independent identification of EAS [Ardouin11].

The radio array was then extended to 50 units. Data was taken between January 2011 and January 2013 with antennas oriented towards the East-West direction. The corresponding dataset (317 live days), $3.7 \times 10^9$ antenna triggers were recorded, corresponding to $2.4 \times 10^8$ reconstructed coincidences. From those, 465 events passed the EAS selection cuts detailed in [Ardouin11]. The distribution of their reconstructed directions of arrival was then

![Figure 9: left: Noise power spectrum measured on the TREND site. The green curve shows the spectrum recorded when the input cable is disconnected from the antenna. The dashed blue curve is the simulated response of an ideal system to the Galactic signal only. Right: a TREND butterfly antenna. The antenna is composed of one arm, allowing the measurement of the E-field projection along its axis only.](image)
compared to the one expected for EAS. The latter was built through simulations, using a chain composed of CONEX (shower simulation) + EVA (radio emission) + NEC (antenna response) and TREND reconstruction software (detector response). The GRIF grid was extensively used in this analysis through the France – Asia Virtual Organization. Experimental and simulated distributions were found to match reasonably well when selecting simulated events with energies between $8 \times 10^{16}$ and $10^{17}$eV (see figure 10) for zenith angles above 70°. In particular the very distinctive North-South asymmetry expected from the geomagnetic origin of the EAS radiation is clearly visible. This result shows that TREND succeeded in detecting EAS with limited background contamination. The divergence observed for inclined showers may be explained by issues in the EVA radio simulation code when handling this type of geometry. Work carried out these past weeks by Krijn de Vries (VUBrussels), Clementina Medina (LPNHE) and Valentin Niess (LPC Clermont-Ferrand) allowed solving this issue. The simulated showers for $\theta > 60°$ will now be re-processed with the upgraded EVA version and should hopefully lead to the completion of the TREND analysis in the first months of 2016.

8. References
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[Berezinsky02]. V. Berezinsky et al, <astro-ph/0210095>
[Boccippio95]: Boccippio et al. Science 269 (5227): 1088–1091
[Chirkin04] D. Chirkin <hep-ph/0407078>

Left: zenithal distribution of the 465 TREND EAS radio candidates (black) and of simulated EAS events with energies between $8 \times 10^{16}$ and $10^{17}$eV (green). The simulation distribution is normalized to the experimental one at 65°. Right: same for azimuthal distribution.
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