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THE GIANT RADIO ARRAY FOR NEUTRINO DETECTION

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Abstract. The Giant Radio Array for Neutrino Detection (GRAND) project aims at detecting ultrahigh-energy neutrinos and cosmic rays with a $\sim 10^5$ radio antenna array over 200'000 km^2 in mountainous regions in China, in order to solve the mystery of the origin of these two linked particles. Its strategy is to detect extensive air showers of the highest energies, above 10^{17} eV, that are triggered by the interaction of high-energy particles in the atmosphere or underground. In its first stages, GRAND will be competitive to detect the first cosmogenic neutrinos for favorable source scenarios. Ultimately, GRAND aims at reaching a sensitivity and angular resolution that should launch neutrino astronomy, and that will ensure the detection of these neutrinos, even in the most pessimistic cases. We present preliminary results of our simulations, plans for the ongoing, staged approach to the construction of GRAND, and the rich research program made possible by the design of GRAND.

Keywords: air shower, radio emission, radio detection

1 Hunting ultrahigh energy neutrinos with radio antennas

Ultrahigh energy neutrinos, with energies $\sim 10^{18}$ eV, remain unchartered territory: they have not been detected yet, and their sources are unknown. Their existence is guaranteed however, as they are bound to be produced by the interaction of ultrahigh energy cosmic rays (charged nuclei that bombard the Earth with energies $> 10^{20}$ eV, and that are routinely detected), with the cosmic photon backgrounds, on their way from their source to the Earth. The sources of these ultrahigh energy cosmic rays (UHECRs) has been a long-standing enigma (Kotera & Olinto 2011). The GRAND experiment aims at unveiling these mysteries by reaching a sensitivity that ensures the detection of such neutrinos, even in the most pessimistic UHECR source models. For standard source models, it should detect enough events to launch neutrino astronomy. The project consists of an array of $\sim 10^5$ radio antennas deployed over an area of $\sim 200\,000$ km^2 in a mountainous site. GRAND will search for the radio signal emitted by the air showers of τ leptons produced by the interaction of cosmic neutrinos underground.

Earth-skimming cosmic ν_τs can produce τ particles underground through charged-current interaction. τs travel to the surface of the Earth and decay in the atmosphere, generating extensive air showers (EAS) (Fargion 1999; Bertou & et al 2002). Coherent electromagnetic radiation is associated to the shower development at frequencies of a few to hundreds of MHz at a detectable level for showers with $E > 10^{17}$ eV. The strong beaming of the electromagnetic emission combined with the transparency of the atmosphere to radio waves will allow the radio-detection of EAS initiated by τ decays at distances up to several tens of kilometers. Inclined showers can leave footprints of several kilometers on the ground after traveling such large distances in the atmosphere, allowing a sparse antenna distribution. Furthermore, radio antennas offer practical advantages (limited unit cost, easiness of deployment, ...) that allow the deployment of an array over very large areas, as required by the expected low neutrino rate.

GRAND antennas are foreseen to operate in the $30 - 200$ MHz frequency band. Short wave background prevents detection below this range, and above the coherence of the geomagnetic emission fades. 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.

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2 Detector Performance

Simulation chain. We present here a preliminary simulation, based in particular on a parametrization of the radio emission process. A complete, end-to-end simulation chain is being finalized and will produce results early 2018. The area considered for the present study is a rectangle of $300 \times 300\,\text{km}^2$ in the Tianshan mountain range, in China, centered on the TREND site (86°44'E, 42°57' N). The topography of the site is interpolated from a 200 m step elevation map derived from public NASA satellite data. A square grid with 800 m step size deployed over the full area is considered for the antenna layout.

For the incoming ν_τs, fixed values are considered for energies ($10^{17}\,\text{eV} < E < 10^{20.5}\,\text{eV}$), as well as zenith ($86° < \theta < 93°$) and azimuth angles ($0° < \phi < 360°$). For each (E, θ, ϕ) set, n_{Gen} random trajectories are generated until 100 showers with $E_{\text{sh}} > 10^{16}$ eV are produced. A simplified 1D tracking of the processes is performed through a Monte-Carlo simulation process for each randomly chosen trajectory. Neutrino interaction lengths in rock are taken from Gandhi et al. (1998) and the energy-dependent interaction depths for Neutral Current (NC) or Charged Current (CC) events are sampled accordingly and located along the trajectory. The kinematic of the neutrino DIS event is delegated to Pythia6.4, using CTEQ5d probability distribution functions. If a CC interaction occurs with a rock target in the simulation volume, a τ simulation starts. The τ energy loss and proper time distributions are parametrized from GEANT4.9 simulations performed or various primary energies and depths in Standard Rock (Dziewonski & Anderson 1981). Photonuclear interactions are of prime importance for UHE leptons. They have been extended in GEANT4.9 above PeV energies following Dutta et al. (2000). If a decay of the τ occurs after it has emerged above the Earth surface, it is simulated with the TAUOLA package (Davidson et al. 2012). If the induced shower energy E_{sh} (computed as the τ final energy minus the energy of νs and μs secondaries) is above 10^{16} eV, then radio detection is simulated.

However the CPU request of computing programs simulating air shower radio emission is too large (several hours for a single shower) to allow for a full treatment of all simulated showers over the considered detection area. An end-to-end simulation chain overcoming this technical issue, called *radio morphing* (Zilles 2017) is being developed, but at present only a geometric parametrization of the EAS radio emission is used to determine if a simulated shower can be detected by the GRAND antenna array. In an agressive scenario –where means to improve the background rejection could be implemented in the GRAND DAQ system– the detection threshold of the integrated electric field amplitude in the 30-80 MHz frequency range, is taken equal to 30 μV/m, twice the background noise level expected from Galactic emission in this frequency range. A more conservative threshold value of 100 μV/m –achievable with present, standard trigger algorithm– is also considered.

Preliminary results. Assuming a 3-year observation with no neutrino candidate detected in this 60 000 km^2 simulated array, a 90% C.L. integral upper limit of 2.0×10^{-9} GeV^{-1} cm^{-2} s^{-1} can be derived for an E^{-2} all-flavor neutrino flux in our agressive scenario (4.0×10^{-9} in our conservative scenario), as displayed in Fig. 1. This preliminary analysis also shows that mountains constitute a sizeable target for neutrinos, with $\sim$50% of down-going events coming from neutrinos interacting inside the mountains (see Fig. 1). It also appears that specific parts of the array (large mountains slopes facing another mountain range at distances of $30 - 80\,\text{km}$) are associated with a detection rate well above the average. Our simulations for such a hotspot of 7 500 km^2 for example yield an effective area about one third of the value computed for the total 60 000km^2 area. By splitting the detector into smaller subarrays of $\mathcal{O}$(10,000) km^2 each, deployed solely on such favorable *hotspots*, an order-of-magnitude improvement in sensitivity could probably be reached with only a factor-of-3 increase in detector size, compared to the 60 000 km^2 simulation area. This is the envisioned GRAND setup. The associated 2.0×10^{-10} GeV^{-1} cm^{-2} s^{-1} sensitivity limit extrapolated to the 200 000 km^2 GRAND complete configuration would then correspond to a detection rate of 1 to 60 cosmogenic neutrino events per year assuming fluxes from Kotera et al. (2010).

Background rejection. A few to a hundred cosmic neutrinos per year are expected in GRAND. The rejection of events initiated by high energy particles other than cosmic neutrinos should be manageable, as: i) the flux of atmospheric neutrinos is negligible above 10^{16} eV (Aartsen et al. 2014), ii) the rate of showers generated by muon decay above GRAND is expected to be few per century (Chirkin 2004), and iii) rejection of all trajectories reconstructed down to 1° below the horizon would strongly suppress the measured rate of EAS initiated by standard cosmic rays, without significantly affecting GRAND neutrino sensitivity. On the other hand, man-made background noise is too diverse in nature and intensity to be properly modeled. Only an experimental implementation of the event selction procedure will thus validate it. Amplitude patterns on the ground (emission beamed along the shower axis or signal enhancement along the Cherenkov ring), as

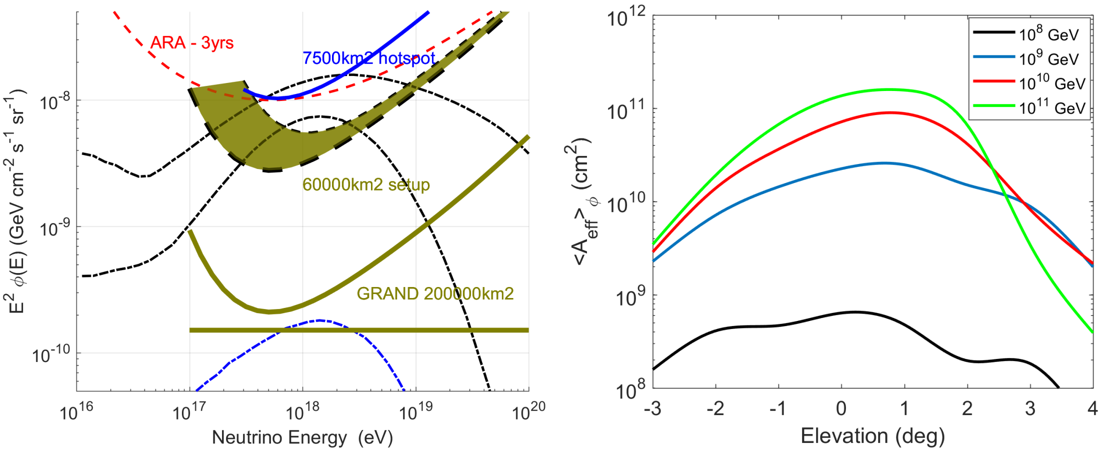

Fig. 1. *Left:* 90% C.L. differential limit on a E^{-2} ν_τ astrophysical flux for 3 years of observation with 0 candidates for aggressive (thick dashed line) and conservative thresholds (thin dashed line). Also shown are the projected limit for the envisioned 200 000 km^2 GRAND array (thick brown solid line), for the 7 500 km^2 GRAND hotspot (blue) and limits for the ARA project (Allison et al. 2016)(red dotted line), as well as the estimated theoretical cosmogenic neutrino fluxes for a single neutrino flavor (Kotera et al. 2010). *Right:* Differential effective area $\mathcal{A}_{\rm eff}^{E,\theta,\phi}$ as a function of zenith angle θ for various ν energies for the 60 000 km^2 simulated array, assuming an agressive threshold (see text). The curves are averaged over azimuth angles ϕ. Following GRAND angular conventions, $\theta < 90^\circ$ corresponds to upward-going showers.

well as wave polarization (Aab et al. 2014) are strong signatures of ν-initiated air showers that could provide efficient discrimination tools. These options are being investigated within GRAND, through simulations and experimental work. In 2017 the GRANDproto35 project (Gou 2015) in particular, will deploy an hybrid detector composed of 35 3-arm antennas (allowing a complete measurement of the wave polarization) and 24 scintillators, that will cross-check the EAS nature of radio-events selected from a polarization signature compatible with EAS. Testing the background rejection performances will also be one purpose of GRANDproto300, the subsequent prototype phase of the GRAND instrument.

3 Physics Case: High-energy neutrino astronomy, UHECRs and Fast Radio Bursts

The sensitivity of GRAND should guarantee the detection of cosmogenic EeV neutrinos produced during the propagation of UHECRs to the Earth. A 5σ identification of individual point sources out of a diffuse background requires $\sim 100-1000$ events with a sub-degree angular resolution for sources that have a local density of $10^{-9}-10^{-7}\,{\rm Mpc}^{-3}$ (Fang et al. 2016). Assuming a neutrino flux of $10^{-8}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$, the GRAND neutrino sensitivity corresponds to a detection of $\sim$ 100 events after three years of observation. The unprecedented sensitivity of GRAND, the non-detection of events would strongly constrain UHECR models. The ideal way to identify high-energy neutrino sources would be to observe a point source. GRAND opens this possibility with its excellent spatial resolution and its sky coverage. In the simulation layout, the instantaneous field of view of GRAND is a band corresponding to zenith angles $80^\circ \leq \theta \leq 100^\circ$, and its integrated exposure $\sim 10^{16}\,{\rm cm^2\,s}$ for 3 years in the energy range $\sim 10^{17-20}\,{\rm eV}$, over a large portion of the sky (Fig. 2).

GRAND will observe UHECRs with an effective area that is at least an order of magnitude larger than Auger. The high statistics will resolve any small-scale anisotropies and features near the end of the cosmic ray spectrum. GRAND will also reach an UHE photon sensitivity exceeding that of current experiments. Future simulation studies will be dedicated to performance of energy and $X_{\rm max}$ reconstructions.

GRAND will contribute in a unique way to the measurement of fast radio bursts and giant radio pulses by collecting unprecedented statistics at low frequencies. For instance, GRAND could record giant pulses from the Crab pulsar above 5 Jy at 200 MHz with a rate about 200 per day. In addition, GRAND could be a preferred instrument for other science topics such as the study of the epoch of reionization.

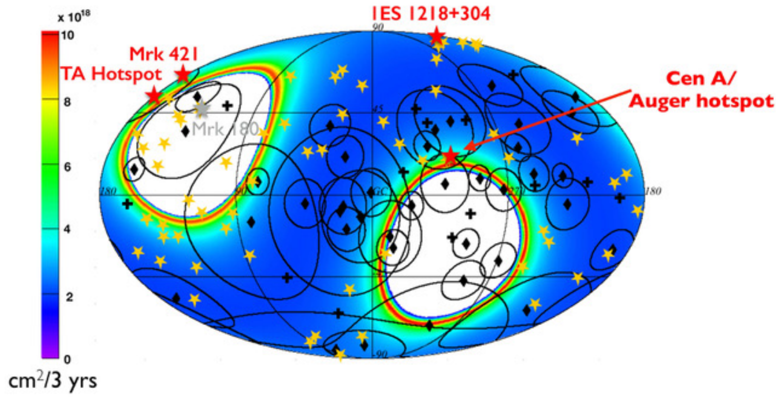

Fig. 2. Integrated 3-year exposure of GRAND to UHE neutrinos of 3×10^9 GeV. Within the GRAND field of view are known TeV-emitting AGN and starburst galaxies (yellow stars), from TeVCat. IceCube High-Energy Starting Events (HESE) from the 4-year data release are shown as diamonds (for showers) and crosses (for tracks). Circles around diamonds represent the angular uncertainty; for tracks, it is smaller than the symbol size.

4 Development plan

The GRAND project aims at building a next-generation neutrino telescope composed of a radio antenna array deployed over 200,000 km^2. Preliminary simulations indicate that 5% of the array deployed in favorable sites will improve the sensitivity over that of current-generation telescopes by an order of magnitude. The full array will offer a sensitivity that ensures a detection of cosmogenic neutrinos in the most pessimistic scenario, and an identification of individual point sources in an optimistic scenario. GRAND will also be a powerful instrument for UHECR observations with high statistics. Simulation and experimental work is ongoing on technological development and background rejection strategies. The GRAND development plan consists of several steps. Presently, deployment of a prototype array with 35 antennas and scintillator detectors is underway in the mountainous region of Ulastai, China. Following this step, a dedicated setup with a size of 300 km2 will be deployed. This array will establish the autonomous radio detection of very inclined EAS with high efficiency and excellent background rejection, as a validation for the future GRAND layout.

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