

Prospects for detection of the lunar Cerenkov emission by the  
UHE Cosmic Rays and Neutrinos using the GMRT and the Ooty  
Radio Telescope

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## Abstract

Searching for the Ultra high energy Cosmic rays and Neutrinos of  $> 10^{20}eV$  is of great cosmological importance. A powerful technique is to search for the Čerenkov radio emission caused by UHECR or UHE neutrinos impinging on the lunar regolith. We examine in this paper feasibility of detecting these events by observing with the Giant Metrewave Radio Telescope (GMRT) which has a large collecting area and operates over a wide frequency range with an orthogonal polarisation capability. We discuss here prospects of observations of the Čerenkov radio emission with the GMRT at 140 MHz with 32 MHz bandwidth using the incoherent array and also forming 25 beams of the Central Array (effective collecting area of  $14250 m^2$ ) to cover the moon. We also consider using the Ooty Radio Telescope (ORT) which was specially designed in 1970 for tracking the Moon. The ORT consists of a 530m long and 30m wide parabolic cylinder that is placed in the north south direction on a hill with the same slope as the latitude of the station. Thus it becomes possible to track the Moon for 9.5 hours on a given day by a simple rotation along the long axis of the parabolic cylinder. ORT operates at 325 MHz and has an effective collecting area of  $8000 m^2$ . Recently a digital system has been installed by scientists of the Raman Research Institute (RRI), Bangalore and the Radio Astronomy Centre (RAC) of NCRA/TIFR, at Ooty allowing a bandwidth of 10 MHz with 40 ns sampling. It is possible to form 6 beams covering the Moon and 7th beam far away for discrimination of any terrestrial RFI. Increasing the bandwidth of the existing 12 beam analogue system of the ORT from 4 MHz to 15 MHz to be sampled digitally is planned. It is shown that by observing the Moon for  $\geq 1000$  hrs using the ORT it will provide appreciably higher sensitivity than past searches made elsewhere and also compared to the search being made currently in Netherlands using the Westerbork Synthesis Radio Telescope (WSRT) at 140 MHz. Using the GMRT and ORT, it may be possible to reach sensitivity to test the Waxman-Bachall limit based on theoretical arguments on the UHE particle flux.

## I. INTRODUCTION

Several theoretical predictions and scenarios have been proposed for the existence of ultra high energy (UHE) cosmic rays (UHECR) and UHE neutrinos  $> 10^{20} eV$ . Detection of the UHECR and particularly UHE neutrinos would be of great importance for understanding the energy of powerful AGNs, gamma ray bursts and possible existence of massive particles predicted by the GUT theories. For detecting UHECR and UHEN several ambitious terrestrial experiments are being carried out and also planned with very large collecting areas  $> 1 km^2$  and volumes  $> 1 km^3$  [1].

Askaryan noted in 1960s [2], that electromagnetic cascades in dense medium by the UHE particles will develop an excess of negative charge giving rise to incoherent Čerenkov radiation. Later, Dagkesamanski and Zheleznykh [3] noted that UHE particles impinging on the lunar regolith at  $\sim 10$  m-20 m deep layers of the Moon will give rise to radio pulses of nanosecond (ns) durations. The large surface area of the Moon effectively provides a large surface area for detection of the rare UHE particles. Observations have been made towards the Moon at 1.4 GHz using the Parkes 64 m diameter radio telescope [4], and at 2.2 GHz using the JPL/NASA 70 m and 30m antennas (GLUE experiment) [5] and using a single 64 m telescope at Kalyazin Radio Astronomical Observatory [6]. These have put upper limits on the existence of UHE particles but these are appreciably higher than the predictions by Waxman and Bahcall [7]. Askaryan effect has been tested using different media in a series of accelerator experiments. One of such experiment is done in Silica sand which resembles composition of lunar regolith [8].

As shown by Alvarez-Muniz et al. [9], the angular distribution of the electric field emitted by 10 Tev shower in ice, salt and the lunar regolith is much wider at 0.1 GHz than at 1 GHz. Scholten et al. [10] have calculated differential detection probability for cosmic rays of energy  $4 \times 10^{21}$  eV and neutrinos of energy  $2 \times 10^{22}$  eV hitting the Moon as a function of apparent distance from the centre of the Moon for different detection frequencies. It is shown that the radio emission at higher frequencies arises mostly from UHE particles impinging near the rim of the Moon but at lower frequencies from a major part of the Moon, indicating the advantage of making observations at lower frequencies using already existing or planned radio telescopes of large collecting areas in the frequency range of about 30 to 300 MHz. For detecting UHECR and UHE neutrinos, observations are currently being carried out by

radio astronomers in Netherlands using the Westerbork Radio Telescope (WSRT) [11] at 140 MHz. Observations are also planned with the LOFAR [12] under construction.

In Section II, we summarize equations giving the expected value of the electric field and flux density for UHE particles as well as 25 times rms detection threshold of a radio telescope of collecting area  $A_{eff}$ . Panda *et al* [13] have recently considered prospects of using the Giant Metrewave Radio Telescope (GMRT) [14] for observing radio pulse emission arising from the UHE particles interacting with the surface of the Moon. In Section III, we describe appropriate parameters of the GMRT for searching the lunar Čerenkov emission and also summarize expected values of the signal strength as a function of energy of UHE particles and the receiver noise threshold.

In Section IV, we propose observations of the Čerenkov radiation from the lunar regolith using the large Ooty Radio Telescope (ORT) [15] that has an effective collecting area,  $A_{eff} = 8000 \text{ m}^2$  and is operating at 325 MHz. At present ORT provides a bandwidth of only 4 MHz but its receiver system has been modified to provide  $\Delta\nu = 10 \text{ MHz}$  [16] and is being extended to 15 MHz. In contrast to the GMRT providing dual polarizations at several frequency bands, the ORT provides only a single polarization but it would be possible to get observing time of  $> 1000$  hours, as it is being used mostly for day time interplanetary scintillations.

As discussed in Sections IV and V, search for UHE particles will also allow simultaneous observations of lunar occultation of radio sources in the path of the Moon and also variation of brightness temperature of the Moon with the lunar phase, the latter yielding parameters such as dielectric constant and electrical conductivity of the lunar regolith upto depths of 30 m to 100 m.

In Section VI we discuss model independent limits for detection of UHECR and UHE neutrinos for several current and planned experiments, including LOFAR, WSRT, GMRT and ORT. Discussions and Conclusions are given in Section VII.

## II. ESTIMATED STRENGTH OF RADIO WAVES FROM CASCADES IN THE LUNAR REGOLITH

The electric field of radio waves on Earth,  $\mathcal{E}$ , from a Čerenkov shower in the lunar regolith due to UHE neutrinos, with energy  $E_s$ , has been parameterized based on accelerator

measurements and Monte Carlo simulations [9, 10] (neglecting angular dependence) giving

$$\mathcal{E}(Vm^{-1}MHz^{-1}) = \left(\frac{2.53 \times 10^{-7}}{R}\right) \left(\frac{E_s}{\text{TeV}}\right) \times \left(\frac{\nu}{\nu_0[1 + (\nu/\nu_0)^{1.44}]}\right). \quad (1)$$

where  $R$  is the distance between the emission point on the Moon's surface to the telescope,  $\nu$  is the radio frequency of observations and  $\nu_0 = 2.5$  GHz for the lunar regolith material.

The power flux density at Earth,  $F_s$  is given by

$$F_s = (\mathcal{E}^2/Z_0)(\Delta\nu/100MHz) \times 10^{22} Jy. \quad (2)$$

where free space impedance,  $Z_0 = 377$  ohms, receiver bandwidth,  $\Delta\nu$ , is in units of 100 MHz and  $1 Jy = 10^{-26}Wm^{-2}s^{-1}$ .

Substituting from Eq. 1, we get

$$F_s = 1.7 \times 10^6 \left(\frac{1}{R}\right)^2 \left(\frac{E_s}{1TeV}\right)^2 \times \left(\frac{\nu}{\nu_0[1 + (\nu/\nu_0)^{1.44}]}\right)^2 (\Delta\nu/100MHz) Jy. \quad (3)$$

Panda et al. [13] has given the following value of the power flux density

$$F(E_s, \theta, \nu) = 5.3 \times 10^5 f(E_s, \theta) \left(\frac{E_s}{\text{TeV}}\right)^2 \times \left(\frac{1\text{ m}}{R}\right)^2 \left(\frac{\nu}{\nu_0[1 + (\nu/\nu_0)^{1.44}]}\right)^2 \frac{\Delta\nu}{100\text{ MHz}} Jy. \quad (4)$$

Furthermore there is an angular dependence given by

$$f(E_s, \theta) = \left(\frac{\sin \theta}{\sin \theta_C}\right)^2 \exp(-2Z^2) \quad (5)$$

with  $Z = \sqrt{\kappa}(\cos \theta_C - \cos \theta)$  and  $\kappa(E_s) = (\nu/\text{GHz})^2(70.4 + 3.4 \ln(E_s/\text{TeV}))$ . Here we used Gaussian approximation for our calculation where the forward-suppression factor  $\sin^2 \theta$  in (5) is ignored. For high frequencies this has no effect. For low frequencies, the differences at small angles only plays a role for showers nearly parallel to the surface normal, while the effects of changing the normalization near the Čerenkov angle is important also for more horizontal showers. A measure of the effective angular spread  $\Delta_C$  of the emission around the Čerenkov angle  $\theta_C$  is given in terms of

$$\Delta_C = \sqrt{\frac{\ln(2)}{\kappa(E_s) \sin \theta_C}} \frac{1}{\sin \theta_C}. \quad (6)$$

It is seen from above that the value of  $F_s$  as given by Panda et al. is about 3 times lower than that given by Eq.(2). We find that the value of  $F$  by Panda *et al* [13] is 0.92 that given by Scholten *et al* [10]. We have used here Eq.4 as per Panda *et al* [13].

By equating the power,  $\Delta p$ , received by a radio telescope, due to the incident input threshold power flux density,  $F_s = F_N$ , with the minimum detectable receiver noise power,  $k\Delta T\Delta\nu$ , we have  $\Delta p = \frac{1}{2}F_N A_{eff}\Delta\nu$ , where the factor 1/2 is due to the reception of a single polarization,  $A_{eff}$  the effective area of the telescope,  $\Delta\nu$  the bandwidth and the receiver rms noise,  $\Delta T = \frac{k_B T_s}{\sqrt{\Delta t \Delta\nu}}$ ,  $T_s$  being the system temperature,  $k_B$  Boltzmann's constant and  $\Delta t$  the integration time. Hence  $F_N$  is given by

$$F_N = \frac{2k_B T_s}{\sqrt{\Delta t \Delta\nu} A_{eff}}. \quad (7)$$

For detection of a narrow pulse with width  $\Delta t$  using an optimum bandwidth  $\Delta\nu$ ,  $(\Delta\nu\Delta t)^{1/2} \approx 1$ , and hence rms noise  $F_N$  is given by

$$F_N = \frac{2k_B T_{sys}}{A_{eff}}. \quad (8)$$

In Tables I, II, III we list the system temperatures at the different observation frequencies and the corresponding noise levels of two different configurations of GMRT and ORT. Using equation (4), we can solve for  $E_s$  at the threshold required for measurement with the radio telescope (obtained for  $\theta = \theta_C$  and  $F = F_N$ ). If we take a required signal-to-noise ratio  $\sigma$ , the threshold shower energies  $E_{th}$  which can be measured at the different observation frequencies at the GMRT and the ORT are given in Tables I, II, III.

### III. PROSPECTS FOR SEARCHING USING THE GIANT METREWAVE RADIO TELESCOPE (GMRT)

The GMRT is a Synthesis Radio Telescope consisting of 30 nos. of fully steerable parabolic dish antennas each of 45 m diameter. Fourteen antennas are located in a somewhat random array within an area of about 1  $km^2$  and other sixteen antennas along 3 Y-shaped arrays with a length of each  $\sim 14$  km. The GMRT is currently operating in 5 frequency bands ranging from about 130 MHz to 1430 MHz. The receiver system provides output at two orthogonal polarizations from each of the 30 antennas with a maximum bandwidth of 16 MHz for each polarization, being sampled at 32 ns each. The  $A_{eff}$  of each antenna is nearly 950  $m^2$  in the frequency range of 130 to 630 MHz and only 600  $m^2$  at 1430 MHz.

Panda et al. have made estimates of the sensitivity of the GMRT for observations of UHE CR and UHE neutrinos. They have considered the  $A_{eff}$  of the GMRT = 30,000 $m^2$

at 150, 235, 325 and 610 MHz and  $18,000 m^2$  at 1390 MHz. However, we may note that the GMRT provides the above area only when the voltage outputs of all the 30 antennas are added in phase resulting in antenna beam of  $\sim 2$  arcsec at the highest frequency and  $\sim 15$  arcsec at 150 MHz and therefore covering only a small part of the Moon. However the receiver correlator allows incoherent addition of the outputs of the 30 antennas, covering the entire front surface of the Moon and resulting in  $A_{eff-incoherent} \sim 30^{1/2} \times 950 = 5203m^2$  at the lower 4 frequency bands and  $30^{1/2} \times 600 = 3286m^2$  at 1390 MHz. Instead if we measure coincidences of the power outputs of the 30 antennas, the effective area will also be  $5203 m^2$  at the lower frequency bands but would have the advantage of discrimination between the lunar Cerenkov emission and any terrestrial radio frequency interference(RFI) as the GMRT antennas are located in an array of  $\sim 25$  km extent.

An alternative strategy will be more effective if we use the recently installed software correlator at the GMRT for cross multiplications of the voltage outputs of the 30 GMRT dishes with  $\Delta\nu = 16$  MHz. It allows 32 ns sampling of the voltage outputs of each of the 30 antennas. By combining these voltage outputs for the central 14 antennas of the GMRT with appropriate phase values, it would be possible to form 25 phased beams covering the Moon, each beam having a resolution of about 6 arcmin at 140 MHz. The effective area for each of the 25 beams will be  $14250 m^2$  at the lower frequency bands and  $9000 m^2$  at  $\sim 1$  GHz, providing a competitive radio telescope for searching for UHE neutrinos. Contributions by the Moon's temperature to the system temperature of the GMRT receiver is negligible at 140 MHz but is appreciable at higher frequencies. Using the system parameters of the GMRT as given in Tables I and II, we have estimated sensitivity of UHE CR and UHE neutrinos fluxes as given in Figs 3, 4, 6, 7 and 8.

#### **IV. PROSPECTS FOR SEARCHING UHE CR AND NEUTRINOS USING THE OOTY RADIO TELESCOPE(ORT)**

The ORT consists of a 530m long and 30m wide parabolic cylinder that is placed in the north south direction on a hill with the same slope as the latitude of the station [15]. Thus it becomes possible to track the Moon for 9.5 hours on a given day by rotating the parabolic cylinder along its long axis. The ORT operates only at 325 MHz and has effective collecting area of  $\sim 8000m^2$ . A phased array of 1056 dipoles is placed along the focal line of

$\nu$ (MHz)	$\Theta_b$ (deg)	$(T_m - T_{sky})$ (K)	$T_s$ (K)	$\Delta\nu$ (MHz)	$F_N$ (Jy)	$\mathcal{E}_N$ ( $\mu\text{V}/\text{m}/\text{MHz}$ )	$E_{\text{th}}(0)/\sqrt{\sigma}$ (eV)
140	3.0	0	450	16	238	.0075	$3.56 \times 10^{20}$
235	1.9	150	187	16	99	.0048	$1.4 \times 10^{20}$
325	1.4	190	132	16	70	.004	$8.62 \times 10^{19}$
610	0.73	220	204	16	108	.005	$6.13 \times 10^{19}$
1390	0.32	225	297	16	249	.0076	$5.16 \times 10^{19}$

TABLE I: GMRT parameters, sensitivity and threshold sensitivity at different frequencies for an incoherent array.  $\Theta_b$  is the full width half maximum(FWHM) beam of the 45m dishes,  $T_m$  is the temperature of the Moon at frequency  $\nu$ .  $F_N$  is the expected threshold flux density (noise intensity) of the GMRT and  $\mathcal{E}_N$  the corresponding electric field. The threshold energy  $E_{\text{th}}$  is given in the last column.

$\nu$ (MHz)	$\Theta_b$ (deg)	$(T_m - T_{sky})$ (K)	$T_s$ (K)	$\Delta\nu$ (MHz)	$F_N$ (Jy)	$\mathcal{E}_N$ ( $\mu\text{V}/\text{m}/\text{MHz}$ )	$E_{\text{th}}(0)/\sqrt{\sigma}$ (eV)
140	3.0	0	450	16	87	.0045	$2.14 \times 10^{20}$
235	1.9	150	187	16	36	.0029	$8.38 \times 10^{19}$
325	1.4	190	132	16	25	.0024	$5.15 \times 10^{19}$
610	0.73	220	204	16	39	.003	$3.68 \times 10^{19}$
1390	0.32	225	297	16	91	.0046	$3.12 \times 10^{19}$

TABLE II: GMRT parameters, sensitivity and threshold sensitivity at different frequencies for 25 beams case.  $\Theta_b$  is the full width half maximum (FWHM) beam of the 45m dishes,  $T_m$  is the temperature of the moon at frequency  $\nu$ .  $F_N$  is the expected noise intensity of GMRT and  $\mathcal{E}_N$  the corresponding electric field. The threshold energy  $E_{\text{th}}$  is given in the last column.

the parabolic cylinder. Each dipole is connected to an RF amplifier followed by a 4 bit phase shifter. Signals received by 48 dipole units are connected to a common amplifier branching network [17]. The 22 outputs of the phased array are brought to a central receiver room. An analogue system that was originally built for lunar occultation observations [15] provided 12 beams to cover the Moon; each beam is 6 arcmin in the north side direction and 126 arcmin ( $\sim 2$  deg.) in the east west direction. Recently a digital system has been installed by the Raman Research Institute (RRI), Bangalore and the Radio Astronomy Centre of NCRA/TIFR, at Ooty allowing formation of phased array beams with collecting area =

$\nu$ (MHz)	$T_s$ (K)	$\Delta\nu$ (MHz)	$F_N$ (Jy)	$\mathcal{E}_N$ ( $\mu\text{V}/\text{m}/\text{MHz}$ )	$E_{\text{th}}(0)/\sqrt{\sigma}$ (eV)
325	200	15	67.5	.0041	$8.74 \times 10^{19}$

TABLE III: ORT parameters, sensitivity and threshold sensitivity.  $F_N$  is the expected noise intensity of ORT and  $\mathcal{E}_N$  the corresponding electric field. The threshold energy  $E_{\text{th}}$  is given in the last column.

8000  $m^2$  and a bandwidth of 10 MHz with  $\sim 40$  ns sampling [16]. It is possible to form 6 beams covering the Moon and 7th beam far away for discrimination of any terrestrial RFI. The proposed upgrade of the 12 beam analogue system will provide a bandwidth of 15 MHz. The measured receiver temperature of the ORT is 140 K + a contribution by moon of  $(31.5/126) \times 230$  K = 57 K. Thus  $T_s$  of ORT for lunar observations at 327 MHz is about 200 K. As discussed in the next Section, observations of the Moon for 1000 hrs using the ORT at 325 MHz will provide appreciably higher sensitivity than the past searches made by various workers and also compared to a search being made currently in Netherlands using the Westerbork Synthesis Radio Telescope (WSRT) at 140 MHz. Using the ORT, it may be possible to reach sensitivity to test the predictions of the Waxmann-Bachall model based on theoretical arguments. Proposed observations, particularly with the ORT will also provide arcsec resolution for galactic and extragalactic radio sources occulted by the Moon, and may also search for any transient celestial sources in the antenna beam outside the disc of the Moon.

## V. MEASUREMENT OF DIELECTRIC CONSTANT AND ELECTRICAL CONDUCTIVITY OF THE LUNAR REGOLITH

It would be quite valuable to make passive radio maps of the Moon using the GMRT at decimetre and metre wavelengths. The surface temperature of the Moon is about 130 K in its night time and  $\sim 330$  K in its day time. Since Moon's surface consists of lossy dielectric material, the radio waves emitted by its thermal properties arise from few cm at microwaves to more than 100 m deep at wavelength of several m. Therefore, the observed values of brightness temperature of the Moon varies by tens of degrees at microwaves to less than a degree at radio wavelengths. The GMRT provides a resolution of about 2 arcsec at  $\sim 1420$  MHz and  $\sim 15$  arcsec at 150 MHz. Polarization observations are also possible

with the GMRT. Therefore, maps of radio emission of the Moon for its night and day with the GMRT will provide estimates of the dielectric constant and electric conductivity of the lunar regolith. The data will be complimentary to the radar measurements [18].

## VI. SENSITIVITY CALCULATIONS FOR SEARCH OF UHE NEUTRINOS AND DISCUSSIONS

In this Section we calculate model independent limits for detection of UHE CR and UHE neutrinos for GMRT and ORT using the procedure given in Panda *et al* [13].

Scholten et al. [10] have considered dividing the WSRT antennas into 3 groups for the proposed search for neutrinos, whence A is likely to be  $1000m^2$ . They give a value of  $F_N = 600$  Jy for WSRT and  $F > 25F_N = 15000$  Jy. The system temperature for the ORT,  $T_s = 200K$ , at 327 MHz including contribution by the Moon and  $A_{eff} = 8000m^2$ . Hence  $F_N = 67.5Jy$  and  $F > 25F_N = 1687.5$  Jy, which are much lower than for the WSRT.

The event rate that would be expected at the telescope can be related to an isotropic flux  $\Phi$  of UHE particles on the Moon through

$$\frac{dN_i}{dt} = \int \frac{d\Phi_i}{dE} A_i(E) dE, \quad (9)$$

where  $i = \{CR, \nu\}$  denote the type of primary particle and  $A_i(E)$  is an aperture function corresponding to the effective detector area. The aperture can be further decomposed into an angular aperture  $\Delta\Omega_i(E, \theta_s)$  and a geometric area factor for the Moon

$$A_i(E) = 2\pi R_M^2 \int \Delta\Omega_i(E, \theta_s) d\cos\theta_s \quad (10)$$

with  $R_M = 1760$  km. To evaluate the aperture, we use the analytical methods described in [19]. For the case of strongly interacting cosmic rays which can mainly interact on the surface of the Moon, the angular aperture is given by

$$\Delta\Omega_{CR}(E, \theta_s) = \int \cos\beta \Theta[\mathcal{E}(E, \theta_s) - \mathcal{E}_{th}] \times \Theta(\cos\beta) d\alpha d\cos\beta, \quad (11)$$

where  $\beta$  and  $\alpha$  are the polar and azimuthal coordinates of the ray normal to the Moon's surface in a system where the shower direction defines the  $z$  axis. The full geometry and the different angles are described in Fig. 1.

When the UHE primary is instead a neutrino, it can produce showers deep below the surface of the Moon and there will be considerable attenuation of the radio waves which

travel distances longer than  $\lambda_r$  below the surface. For the neutrino induced showers, the aperture is defined in the same way as for the CR, but the angular aperture is now given [19] by

$$\Delta\Omega_\nu(E, \theta_s) = \int \frac{dz}{\lambda_\nu} \int \Theta\{\mathcal{E}(E, \theta_s, \theta) \exp[-z/(2\lambda_r \cos i)] - \mathcal{E}_{th}\} \times \exp[-L(z, \beta)/\lambda_\nu] \times d\alpha d \cos \beta, \quad (12)$$

where  $L(z, \beta)$  is the distance the neutrino travels inside the material to reach the interaction point at a distance  $z$  below the surface. In performing this integration we allow  $z$  to go below the known depth of the regolith. Despite the attenuation, the aperture therefore picks up contributions coming from deep showers, especially for the lower frequencies. Numerically we find for the worst case (when  $\nu = 150$  MHz), that imposing a sharp cutoff at a depth of 20 m would reduce the aperture by nearly an order of magnitude, similarly to what was discussed in [10].

As for the cosmic rays, the total aperture is obtained by substituting (12) into (10) and integrating over the polar angle  $\theta_s$ .

To estimate the sensitivity of GMRT and ORT to cosmic ray and neutrino events we have evaluated the angular apertures by employing this technique and performing numerical integrations for the different parameters given in Tables I,II, III. In the next section we will discuss these results further in the context of prospective flux limits.

If no events are observed at GMRT and ORT over a time  $T$  then an upper limit can be derived on UHE CR and neutrino fluxes at the Moon. The conventional model-independent limit [20] is given by

$$E_i^2 \frac{d\Phi_i}{dE_\nu} \leq s_{\text{up}} \frac{E_i}{A_i(E_s = y_i E_i) T}, \quad (13)$$

where still  $i = \{\nu, \text{CR}\}$ ,  $y_{\text{CR}} = 1$  and  $y_\nu = 0.25$ . The Poisson factor  $s_{\text{up}} = 2.3$  for a limit at 90% confidence level. In Fig.2, are shown prospective limits on the flux of the UHE CRs for  $T=100, 1000, 8760$  hours (one year) of the observation time with ORT. Plots for WSRT and LOFAR for  $T=100$  hours of the observation time are also shown. In Figs 3 and 4 are given model independent limits on UHE CR flux at different frequencies of the GMRT for an incoherent array and 25 beams case respectively for 100 hours of observations.

Similarly for the UHE neutrinos, prospective limits on their flux for  $T=100, 1000$  and  $8760$  hours of observation with ORT are given in Fig. 5. Figs 6 and 7 give limits on the UHE neutrinos at different frequencies of the GMRT for an incoherent array and 25 beams

case respectively for 100 hours of observations. For all our calculations we take  $\sigma = 25$  [10].

It is clear from the plots that that low frequency observations give more stringent limits on the flux at the expense of a higher threshold. This is due to the well-known increase in the aperture [10, 13] from radiation spreading at lower frequencies. Since many radio experiments exist for UHE neutrino detection, we have compiled a comparison in Fig.8. This figure contains, the predicted thresholds of the ORT at 325 MHz for 1 year of observation time, of the GMRTB (25 beams case) at 140 MHz for 100 hrs and 30 days of observation time and the already existing limits from RICE [21], GLUE [5], FORTE [20] and ANITA-lite [22]. Also we have indicated the prospective future limits that has been calculated for ANITA [22], LOFAR [10] or LORD [19]. James and Protheroe [24] have recently calculated sensitivity of the next generation of lunar Cerenkov observations for UHE CR and neutrinos.

In addition to search for UHE CR and neutrinos, simultaneous observations with the full array of the GMRT will provide radio maps of the Moon as a function of the lunar phase, giving information about the average thermal and electrical conductivity of the Moons regolith up to depth of  $\sim 30$  m to 100 m. Therefore, for the two experiments to be carried out simultaneously, it may be possible to get  $2 \times 50$  hours of observations in two GMRT Time Allocation Cycles. Also, observations with the ORT at the same time will allow discrimination against man made RFI transients.

## VII. DISCUSSIONS AND CONCLUSION

It will be prudent to use both the ORT and the GMRT for searching for the UHE neutrinos. The new software correlator being installed at the GMRT will allow forming  $\sim 25$  beams at 140 MHz to cover the Moon at  $\sim 140$  MHz providing 2 bands of 16 MHz and  $A_{eff} \sim 14250 m^2$ . One may also conveniently use the incoherent mode of the GMRT with  $A_{eff} \sim 5203 m^2$ . Although ORT with  $A_{eff} = 8000 m^2$  operates only at 325 MHz, it is well suited to track the Moon for hundreds of hours. The RFI is also much lower at Ooty than at the GMRT site. By using the new digital system installed recently at Ooty by Prabhu *et al* [16] of the Raman Research Institute, in conjunction with the 12 beams of the analogue system ORT and also it's upgrade, it should be possible to reach adequate sensitivity to test the Waxman Bahcall limit proposed on theoretical arguments on the UHE particle flux.

Proposed observations, particularly with the ORT will also provide arcsec resolutions for celestial radio sources occulted by the Moon, and may also detect any transient celestial sources present in the antenna beam outside the disc of the Moon. Search for UHE neutrinos will also allow simultaneous observations for making radio maps of the Moon as a function of the lunar phase (full Moon, 5 and 15 days earlier and later), providing information about the average thermal and electrical conductivity of the Moon's regolith up to a depth of  $\sim 30$  m.

The existence of UHE Neutrinos of  $> 10^{20}$  eV is implied by the detection of for  $\sim 10^{19}$  eV. The extremely high luminosity of the star burst galaxies, AGNs, gamma ray burst are likely to accelerate protons to very high energies that get scattered by the CMBR photons producing a flux of UHE neutrinos. There are also predictions of their occurrence by more exotic sources in the early universe. As may be seen from Fig. 8, observations with the ORT and GMRT will provide a threshold sensitivity of  $\sim 10^{-8}$ , being comparable to the current searches being made by other investigators. Detection of the UHE CR and neutrinos of  $> 10^{20}$  eV would be of great importance for testing theories of high energy physics and for understanding several phenomena of cosmological and astrophysical importance.

**Acknowledgement** We thank T. Prabhu of the Raman Research Institute, P.K. Manoharan and A.J. Selvanayagam of the Radio Astronomy Centre Ooty and S. Sirothia of NCRA, Pune for many valuable discussions. The work of S.P. was supported by the Ministerio de Educacion y Ciencia under Proyecto Nacional FPA2006-01105, and also by the Comunidad de Madrid under Proyecto HEPHACOS, Ayuda de I+D S-0505/ESP-0346.

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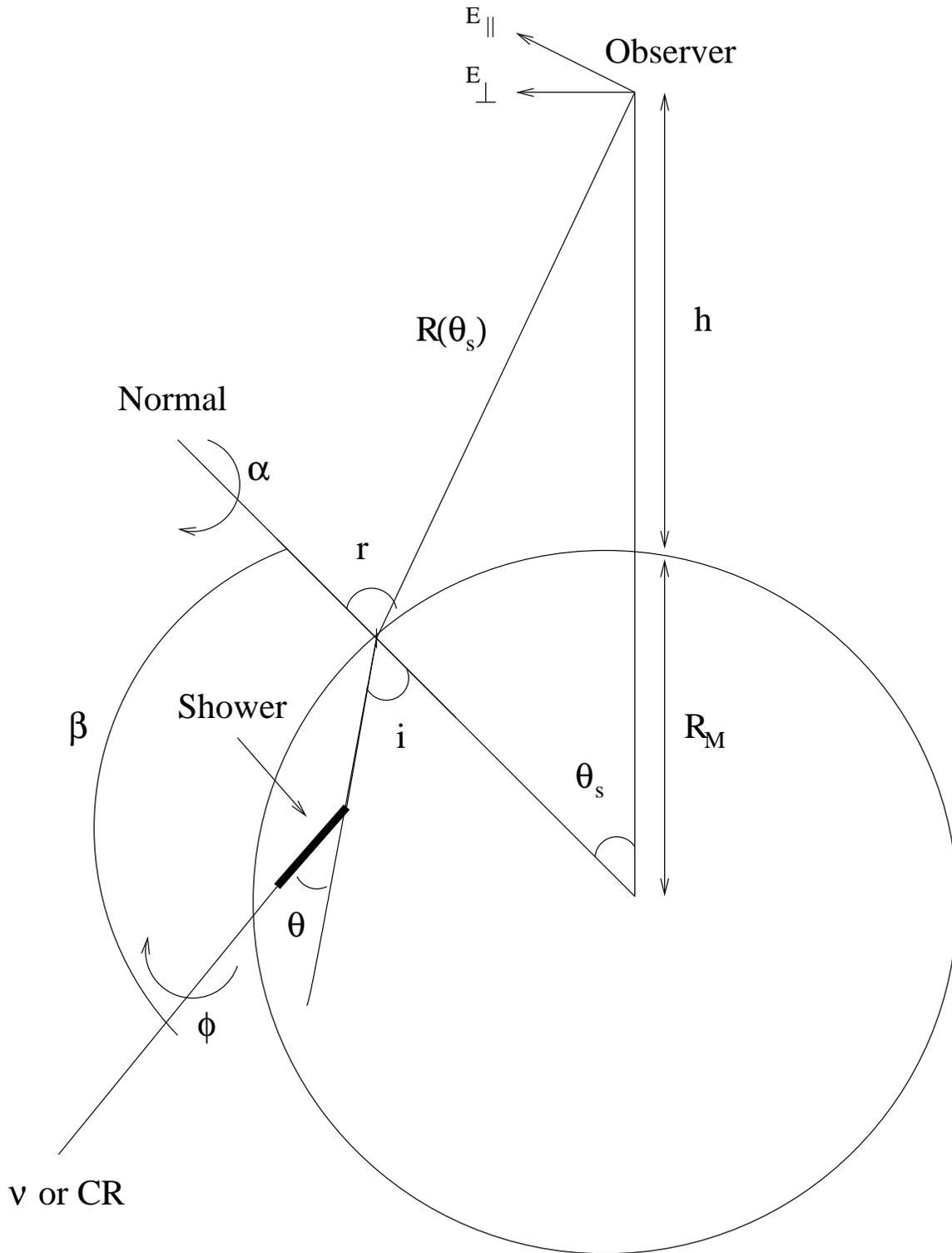


FIG. 1: Geometry of an UHE CR or neutrino event which generates Čerenkov radiation of radio waves in the lunar regolith. The Earth is located at a mean distance  $h$  from the lunar surface [13].

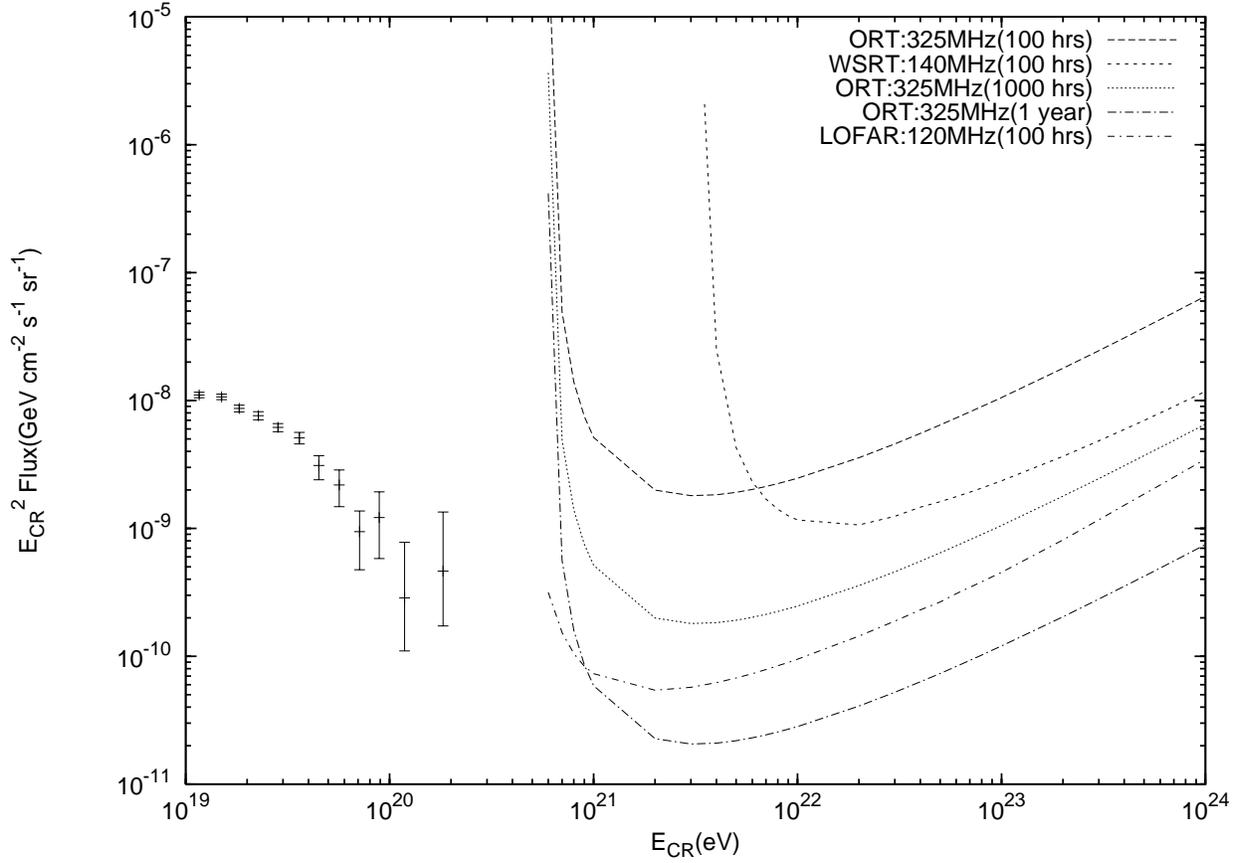


FIG. 2: Model independent limits on UHECR flux at different frequencies for 100, 1000 hours and one year (8760 hours) of observation time with the ORT and 100 hours of WSRT and LOFAR. Auger data points reproduced from [23] on the CR flux are shown on left side for comparison.

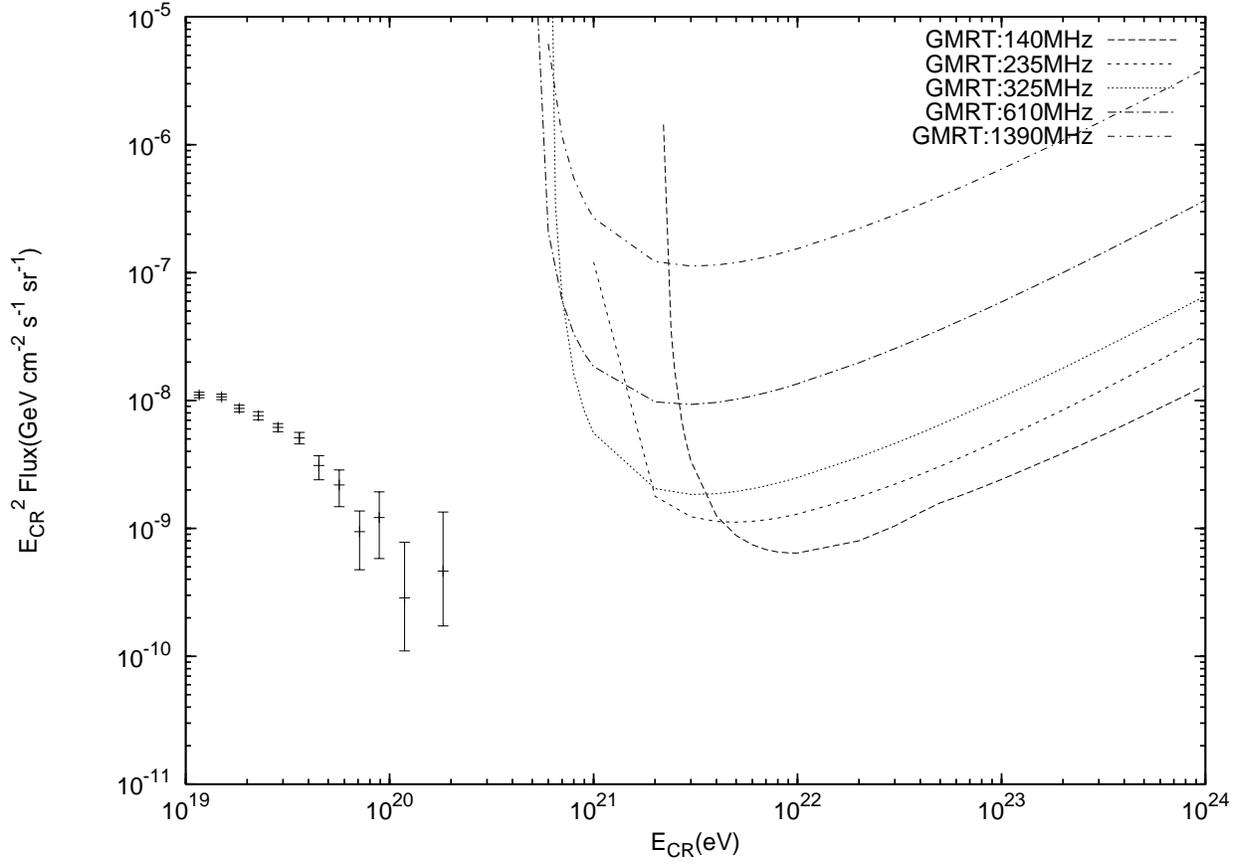


FIG. 3: Model independent limits on UHECR flux at different frequencies for 100 hours of observation time with the GMRT for an incoherent array. Auger data points reproduced from [23] on the CR flux are shown on left side for comparison.

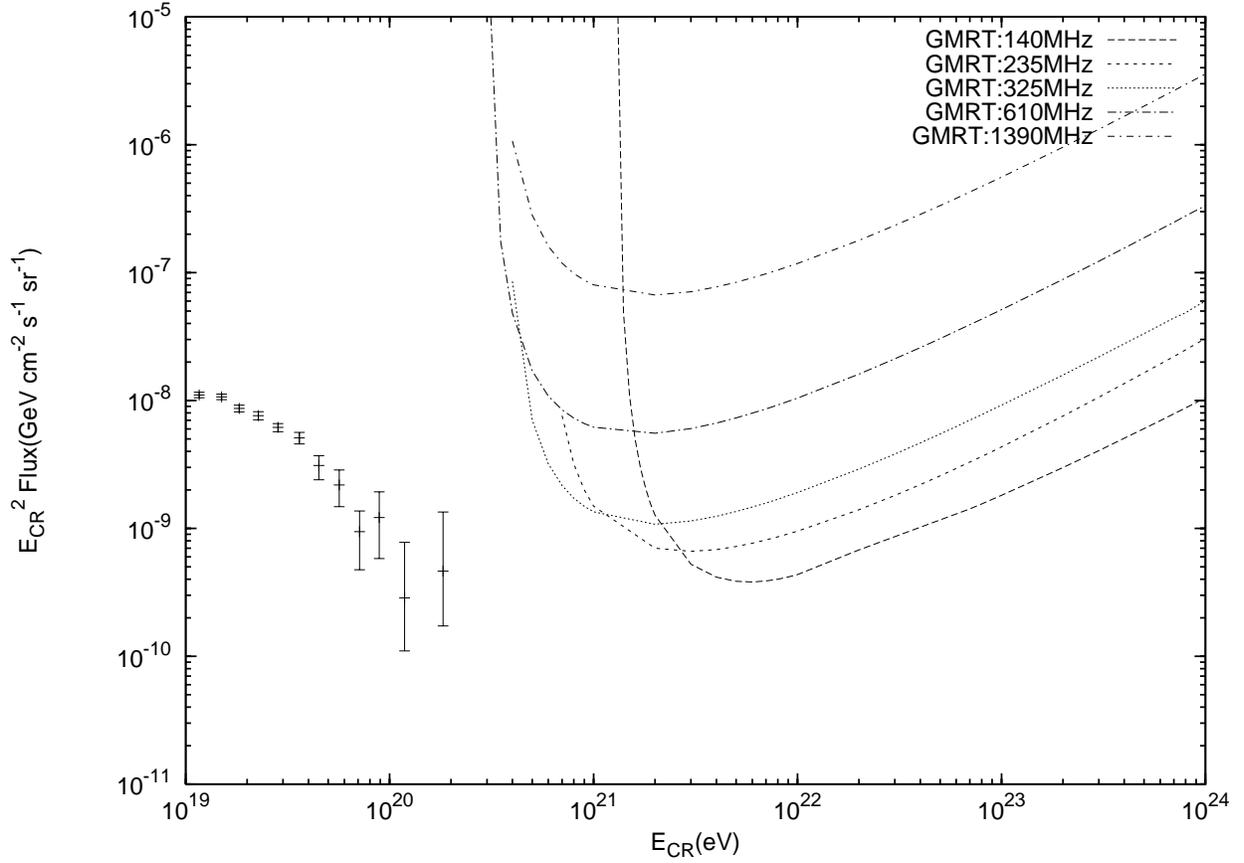


FIG. 4: Model independent limits on UHECR flux at different frequencies for 100 hours of observation time with the GMRT for the 25 beams case. Auger data points reproduced from [23] on the CR flux are shown on left side for comparison.

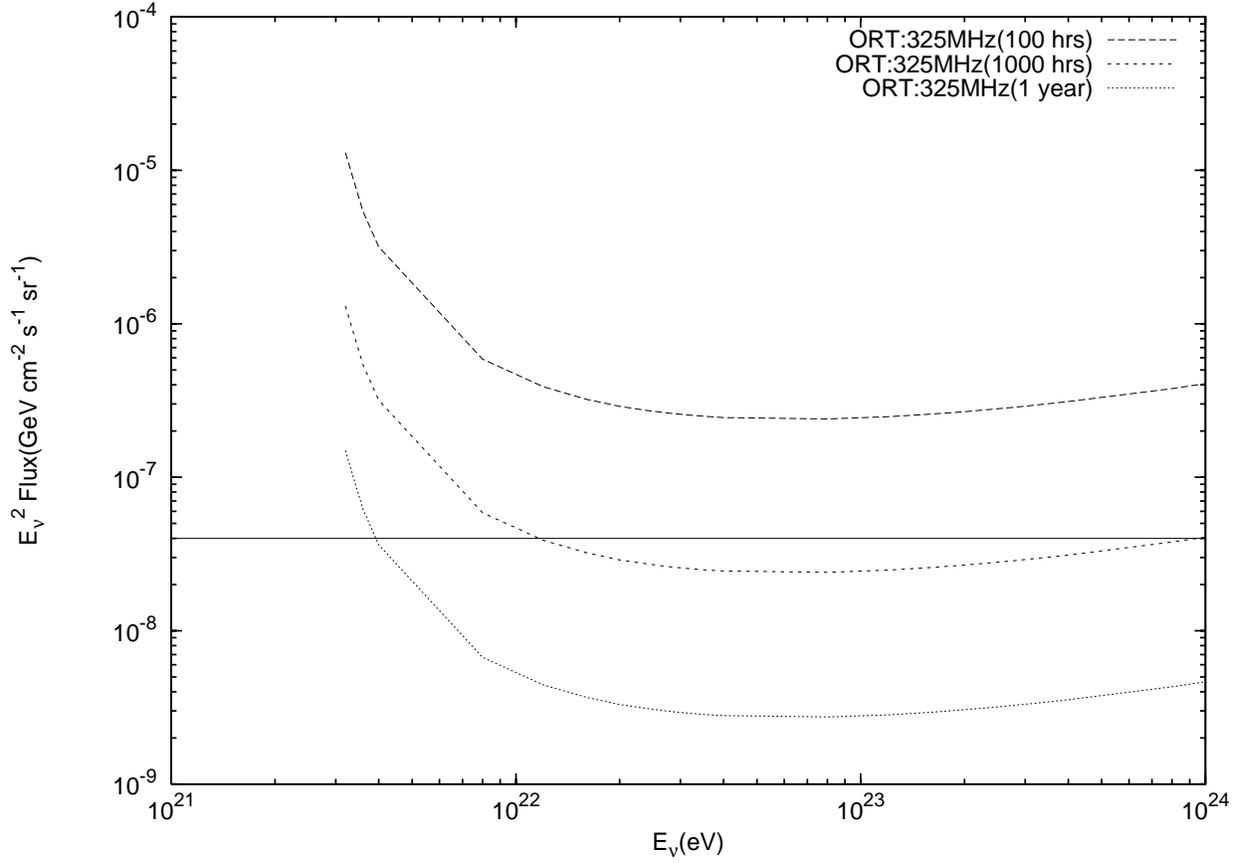


FIG. 5: Model independent limits on UHE neutrino flux at different frequencies for 100, 1000 hours and one year of observation time with the ORT. The solid horizontal line refers to the Waxman-Bahcall limit [7].

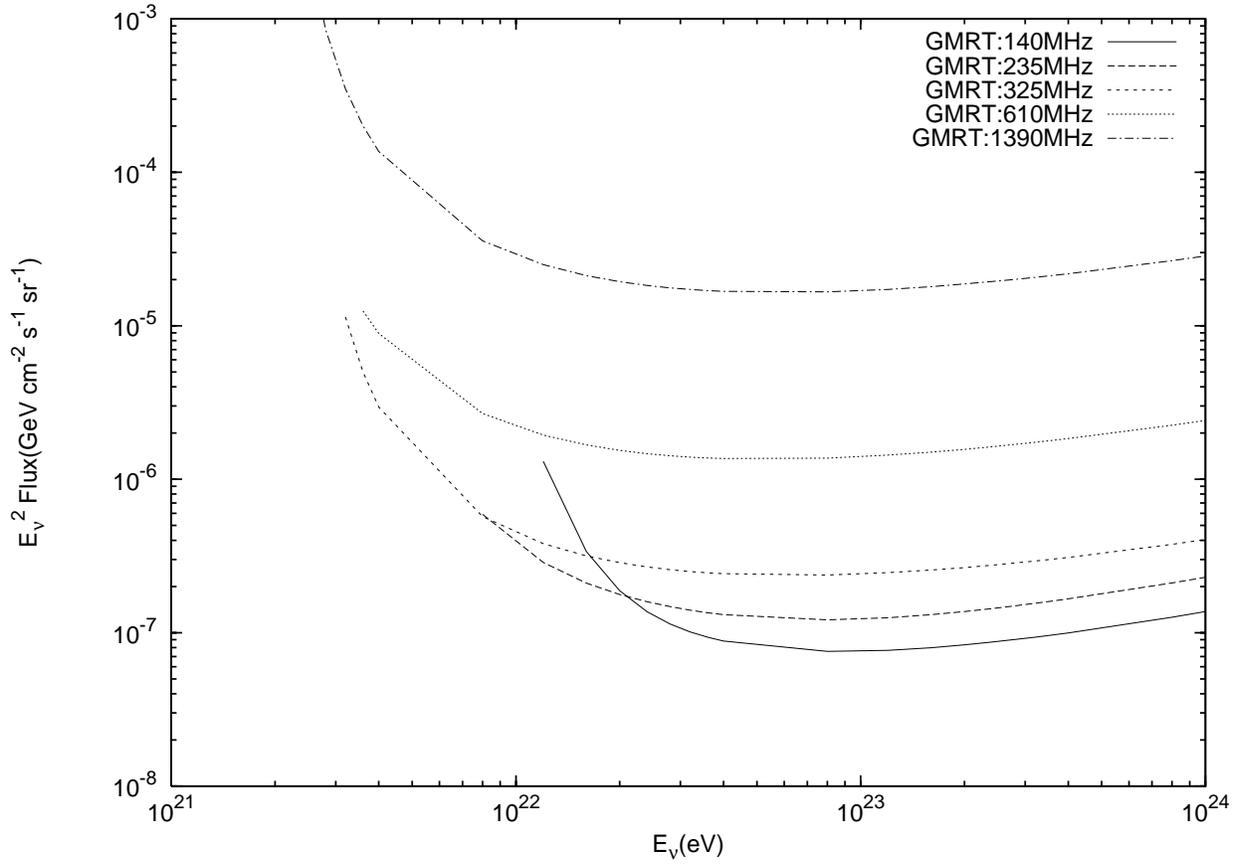


FIG. 6: Model independent limits on UHE neutrino flux at different frequencies for 100 hours of observation time with the GMRT for an incoherent array.

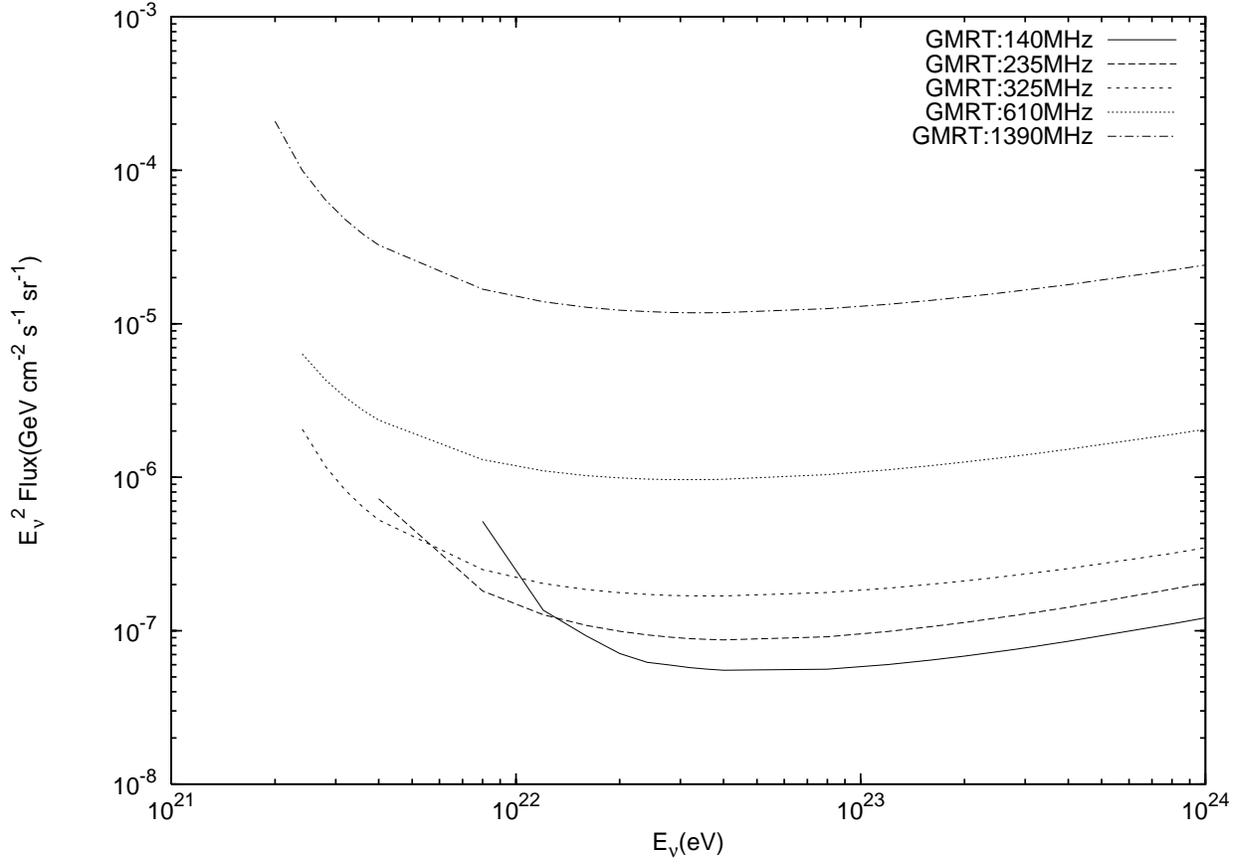


FIG. 7: Model independent limits on UHE neutrino flux at different frequencies for 100 hours of observation time with the GMRT for the 25 beams case.

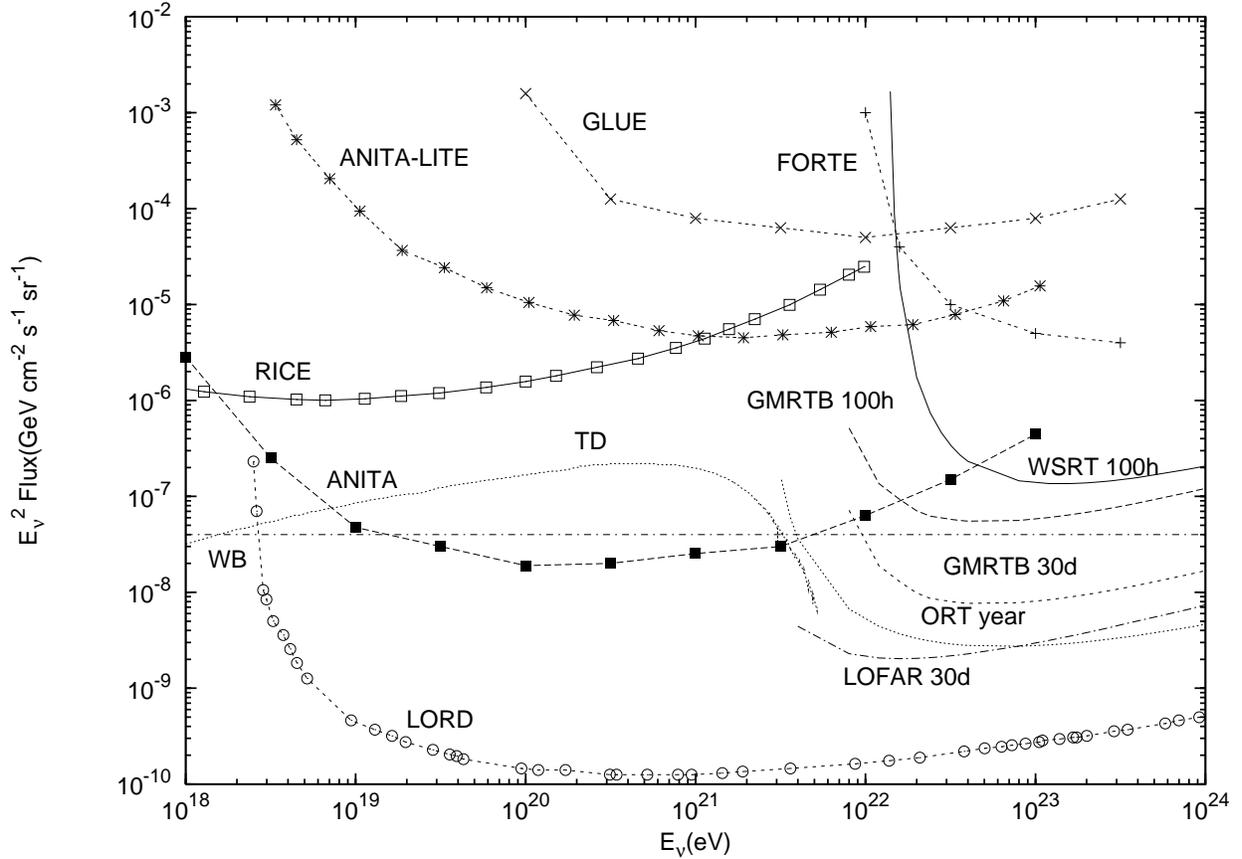


FIG. 8: Prospective flux limits on UHE neutrinos from GMRTB (25 beams), ORT, WSRT and LOFAR are shown for effective exposure times of 100 hours, 30 days, 1000 hours and 1 year (8760hours). The current best limits from radio experiments ANITA-lite [22], GLUE [5], FORTE [20], and RICE [21] are shown. For comparison the expected limits from future experiments ANITA [22] and LORD [19] are also included. The dotted horizontal WB line indicates the theoretical upper limit of Waxman-Bahcall [7] on the cosmogenic neutrino flux. TD refers to the Topological Defect model with mass  $M_X = 2 \times 10^{22}$  eV described in [25].