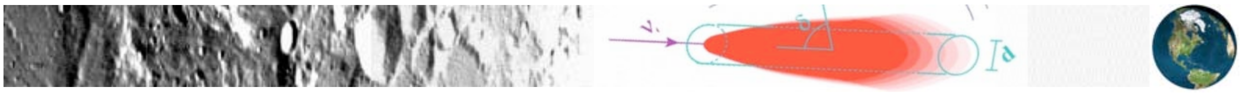
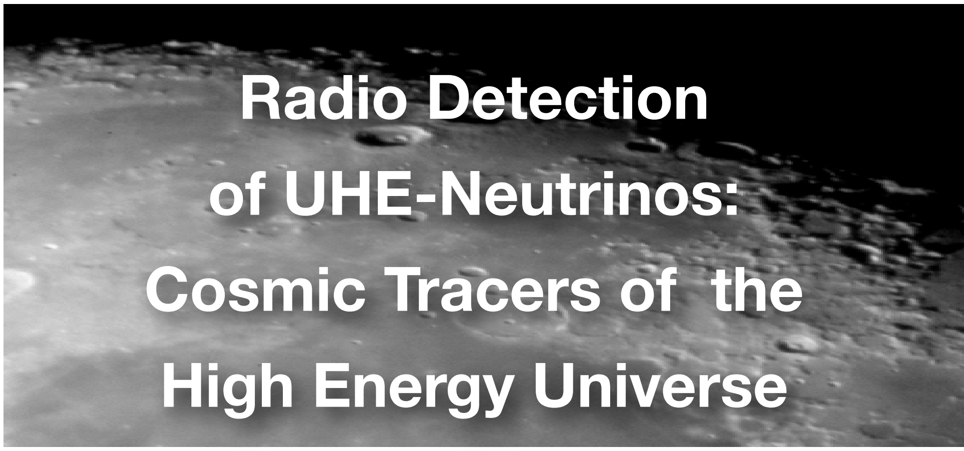
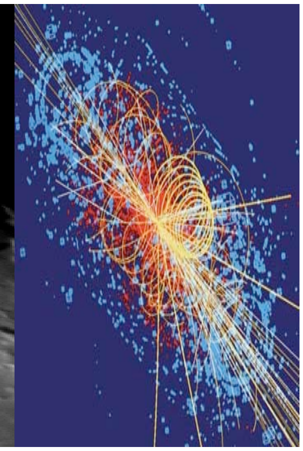


Presentation to the Astro 2010 Decadal Survey Panel: Feb 14, 2009



Radio Detection of UHE-Neutrinos: Cosmic Tracers of the High Energy Universe



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Executive Summary

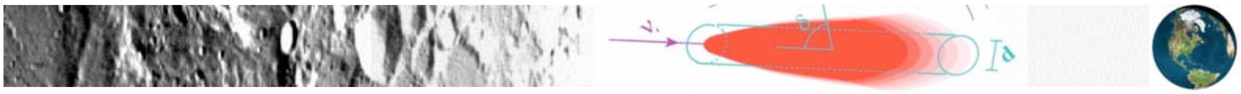
Objective

Identifying the sources of the highest energy cosmic rays is a fundamental unsolved problem in both high-energy physics and astrophysics. Ultra-high energy (UHE) neutrinos provide a key probe to the nature and location of cosmic ray engines since they travel essentially unimpeded from their source to our solar system, providing a directional tracer of their origin. The first generation of UHE neutrino astronomy experiments will detect UHE neutrinos, *for the first time*, by searching for Cerenkov radio pulses associated with grazing neutrino interactions with the lunar regolith.

Why Now?

Recently experimenters at linear colliders have detected the Cerenkov radiation spectrum predicted for neutrino interactions. Astronomical detectors are excellent tools for revealing the nature of UHE neutrino physics. Technological developments have made wide-band radio detection of very short duration (few nano second) transient events feasible. Several telescope array receiver systems are under development that allow very high sensitivity detections of neutrino interactions.

The time is right to begin neutrino astronomy and build the next generation of telescope systems dedicated to detection of UHE neutrinos.



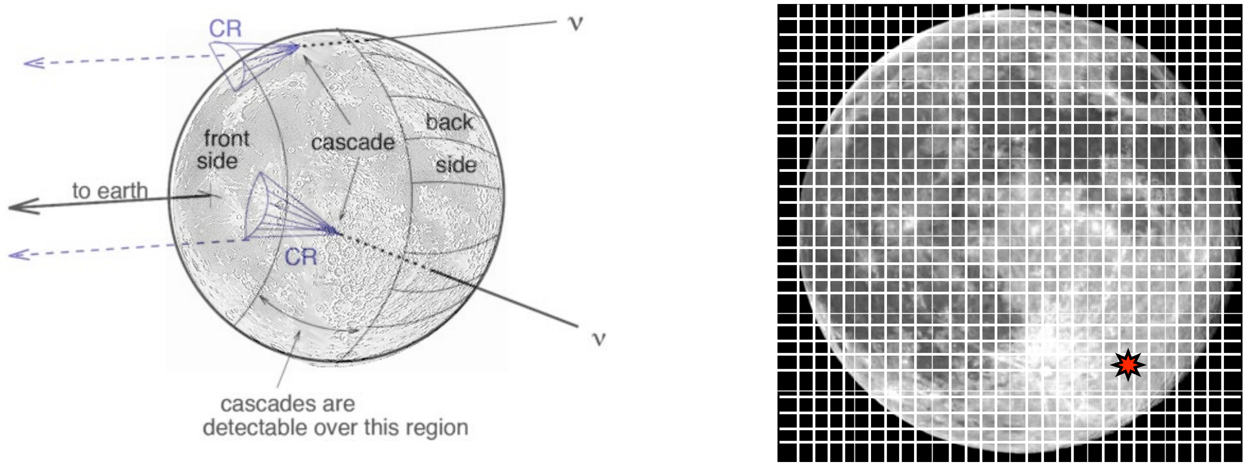


Figure 1: Configuration of incoming neutrinos striking the moon, generating high energy Cosmic Ray (CR) particles, which decay to produce photons with peak emission at radio wavelengths. Peak radio emission is expected on the edge of the moon. (from Gorham et al. 2004 left). A Neutrino Telescope must resolve the origin of the radio transient, in order to constrain the neutrino cross section and reject interference (right).

Science Overview

High-energy neutrinos are unique messengers of some of the most extreme processes occurring throughout the universe. The detection of neutrinos with energies greater than 10^{12} eV, which is as high as current terrestrial accelerators reach, would enable the discovery of new astrophysical systems and possibly new physical processes. The lack of strong and electromagnetic interactions gives neutrinos the special ability to traverse the universe unimpeded by magnetic fields and thus point directly back to their sources.

However, this same feature of the neutrino also makes them extremely difficult to detect. Because neutrino interaction cross section increases with energy, our experiment will focus on Ultra-High-Energy (UHE > 10^{18} eV) cosmic neutrinos. To date, no UHE neutrinos have yet been detected.

In ground based experiments, a neutrino is detected indirectly by the energy released after it strikes a nucleon. The debris, consisting of an electron or hadrons depending on the neutrino type and mediation boson involved, produces a shower within the detector, which creates a short pulse of optical or radio radiation by way of the Cerenkov effect. To achieve sufficient sensitivity for the detection of high-energy neutrinos from distant sources, experiments require a huge amount of detector mass. The lunar regolith provides a detector volume that is orders of magnitude greater than can be achieved using terrestrial instruments.

Several research groups have attempted to observe such pulses from the Moon using radio telescopes, but none have been successful. The limitations of these past efforts are understood. We urge the panel to support construction of a dedicated instrument to detect these UHE neutrinos, based on detection of radio pulses created when UHE neutrinos interact with the lunar regolith. The high angular resolution is required to reject radio frequency interference (RFI) which strongly limited the sensitivity of previous instruments. RFI from terrestrial sources is dominated by transmitters on the horizon.

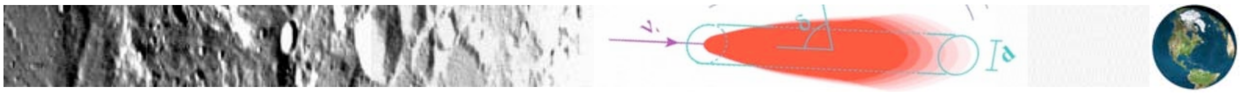
The determination of the point of origin on the Moon is critical for constraining the neutrino cross section versus energy function. The neutrino cross section increases with energy(Saltzberg 2005). Detection of a significant gradient in the number interactions versus distance from the center of the Moon will strongly constrain the energy distribution of the interacting neutrinos.

UHE cosmic rays (UHECR) will also cause Čerenkov bursts upon impacting the lunar surface, and hence cause short radio bursts similar to the UHE neutrino encounters. Indeed, the probability of detection for UHECR is much larger, since they all interact with the lunar regolith very close to the surface. If the Čerenkov radiation cone is favorably aligned, radiation will escape the surface and be detectable at Earth. The event rate for a given energy should naively scale as the ratio of the mean free path of a neutrino (~100 km at 10^{20} eV) to the extinction length of the radio photon (~10 m at 1 GHz), i.e. of order 10^4 to 1. However, most trajectories are directed inward, so the radiation cone does not reach the surface, and this calculation overestimates the detectable UHECR rate. Monte Carlo studies of simulated showers from isotropic UHECR show that the ratio is closer to 100:1, becoming more favorable at lower frequencies where the width of the Čerenkov cone is much larger (Schloten et al. 2006). Nevertheless, as described above, extragalactic UHECR with energies above the GZK cutoff (as pertains to the proposed experiments) should be scattered off CMB photons and lost unless the source is relatively close (within 10 Mpc or so). Recent results from the Auger Observatory (Yamamoto et al. 2007) appear to confirm the UHECR cutoff at the GZK cutoff.

UHE Neutrino Processes

An important class of AGNs are the blazars which produce high-energy gamma radiation with a relativistic jet. If relativistic hadrons are accelerated with power comparable to that of the gamma rays, then detectable fluxes of neutrinos would be produced in the jet through pion production by nuclear and photo-hadronic interactions (Falcke 2004). When the jet is aligned with the direction of the Earth, we could detect neutrinos having energies as high as 10^{15} eV. If inelastic nuclear interactions are important, the neutrino spectrum is expected to reflect the spectrum of relativistic particles that reach 10^{20} eV or higher.

The observation of cosmic rays with energies in excess of 10^{20} eV reaching Earth isotropically from all directions indicates that hadrons are accelerated to ultrahigh energies in extragalactic sources. A number of ultra high energy accelerators, proposed to explain the origin of the highest energy cosmic rays, could also be sources of detectable neutrinos. Greisen 1966 and Zatsepin and Kuzmin (1966) (GZK) predicted a cosmic ray energy cutoff due to pion production when a cosmic ray particle Ground based observatories have detected cosmic ray showers with energies in excess of the GZK limit, $10^{19.5}$ eV (Figure 2).



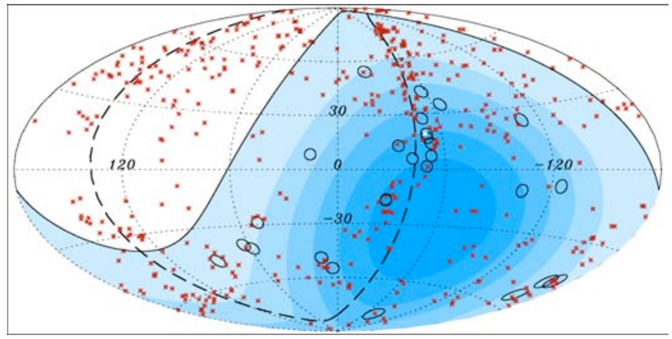


Figure 2: Map of the sky in galactic coordinates, showing the region observed by the Pierre Auger cosmic ray experiment (Red dots indicate locations of the closest AGN). The circles indicate directions of the source of the highest energy cosmic rays. White dot indicates the location of Centaurus A. From Abbasi et al. 2008.

ČERENKOV PULSE CHARACTERISTICS

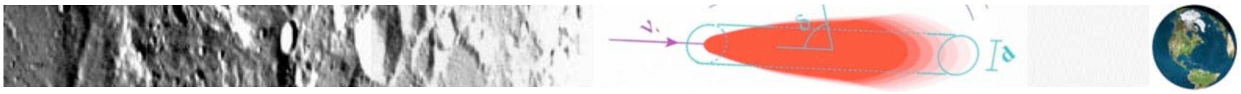
EXPECTED FLUX DENSITY, ANGULAR WIDTH, AND TIMESCALES

The basic parameters for predicting for the radio Čerenkov pulse created by an UHE neutrino impacting the lunar regolith are given below. The qualitative physical picture is that UHE neutrinos continuously impact the Moon, each one creating a hadronic shower in a mean path of order L ~ (100/E) km, where E is in units of 10^{20} eV. Most of the shower energy is eventually carried by an e+ e- current, but the e+ are selectively absorbed, resulting in a negative charge current which survives a distance of order l ~ 0.1 m- 1m, or t ~ 0.3 to 3 ns in time. Since the electrons are moving at c, much faster than the local phase velocity of the regolith soil (c/n ~ 0.6c), a Čerenkov pulse with Fourier components up to 1/t ~ 1 to 10 GHz is created. Unfortunately, most such pulses are absorbed in the Moon's interior, since the 1/e absorption length for regolith is very small (d_{abs} ~ 10/v meters where v is in GHz) compared with the mean free path. This means that only surface 'skimming' neutrino trajectories can produce Čerenkov pulses which are close enough to the surface to escape. A complication is that the escaping radiation must exceed the critical angle at the (probably irregular) surface to avoid total internal reflection. A neutrino of energy E_s, which induces a hadronic shower creates a conical Čerenkov beam whose peak flux density as a function of angle can be written as (Schloten et al. 2006; Buitink et al. 2008):

$$F(\theta,\nu,E_s) = 3.86\cdot 10^4 \exp^{-Z^2}\left(\frac{\sin\theta}{\sin\theta_c}\right)^2\left(\frac{E_s}{10^{20}\mathrm{eV}}\right)^2\left(\frac{d_{\mathrm{moon}}}{d}\right)^2 \left(\frac{\nu}{\nu_0(1+(\nu/\nu_0)^{1.44})}\right)^2\left(\frac{\Delta\nu}{100\mathrm{MHz}}\right)\mathrm{Jy}$$

with Z defined as and where n is the refractive index of the medium (n ~ 1.8 for lunar regolith), $\theta_c = \cos^{-1}(1/n)$ is the Cerenkov angle (θ_c ~ 56^o for regolith), Δv is the bandwidth, v the central frequency, and v_0 = 2.5 GHz.

$$Z = (\cos\theta - 1/n)\left(\frac{n}{\sqrt{n^2-1}}\right)\left(\frac{180}{\pi\Delta_c}\right)$$



$$L(E_s) = \left[12.7 + 0.67\log\left(\frac{E_s}{10^{20} eV}\right)\right] \cdot X_0$$

where X_0 is the radiation length ($X_0 \sim 0.13$ m for lunar regolith). Hence the shower length for energy $E_s \sim 10^{20}$ eV is L ~ 1 m and the Čerenkov pulse width is L/c ~ 3 nsec,

PULSE DISPERSION BY THE IONOSPHERE

The Earth's ionosphere causes a frequency-dependent delay given by

$$t(\nu) = 13ns \cdot \left(\frac{N}{10^{17} m^{-2}}\right) \cdot \left(\frac{\nu}{GHz}\right)^{-2}$$

where N_e is the column density of ionospheric electrons (typically $N_e \sim 10^{17}$ m^{-2} at night, 10^{18} m^{-2} during daytime, but). At a observing frequency of 1.5 GHz and a bandwidth 1 GHz, this results in a broadening of the pulse between 5 and 50 nsec depending on time of day.

PULSE OCCURRENCE RATE

The pulse occurrence rate depends on the incident neutrino energy spectrum and flux density, the detailed physics of the interaction region (especially the surface roughness and optical depth at the observing frequency), and the beaming pattern of the Čerenkov pulse. An accurate estimate of the effective cross-sectional area for converting incident neutrino flux to observable radio photons at the Earth must take into account the nature of the interaction region, and the propagation of the radiation in the lunar interior. This has been done for an assumed isotropic neutrino flux (e.g. Williams 2004; Schloten et al. 2006) and for anisotropic flux (James et al. 2008). The results are stated in terms of an effective target area. For an isotropic neutrino flux I(E) [particles m^{-2} s^{-1} sr^{-1} GeV^{-1}], the predicted event rate N_{obs} can be written (James & Protheroe 2006)

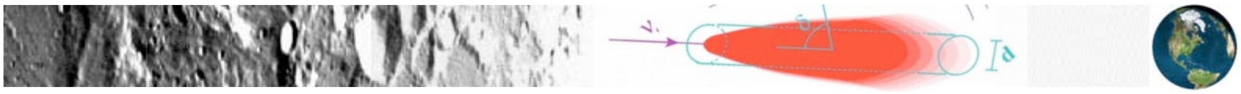
$$N_{obs}(t_{obs}) = t_{obs}\int_{E_{\min}}^{\infty} I(E)A_{eff}(E)dE$$

where t_{obs} is the observation time, and A_{eff} is the effective target aperture (m^2 sr) on the Moon. For the effective aperture, we scale the numerical Monte Carlo results of James et al. (2007) for Parkes (10% limb coverage) to full limb coverage for an array of a few (8 to 12) 25m diameter telescopes.

$$A_{eff}(E) = 60 \cdot \left(\frac{E}{10^{21} eV}\right) km^2 \cdot sr$$

We can now estimate the expected count rates for model neutrino sources by integrating the model flux curve I(E) over energy. For example, for topological defects models (e.g., Yoshida et al. 1997), the expected count rate for such an experiment varies from 0.01 to 0.1 counts per hour, or between 20 and 200 events for a 2000 hour experiment.

Neutrino production is also possible via the Z-burst process, in which UHE neutrinos at $10^{23\text{-}24}$ eV interact with CMB background photons, produce Z_0 bosons which then decay to UHECR and UHE neutrinos (Kalashev et al. 2002). The predicted flux ranges correspond to count rates between 0.005 to 0.2 counts per hour, or 10 to 400 events in 2000 hours. The predicted count rate for GZK-generated neutrino models are at most 0.008



events per hour or one event every 130 days of observing. Detecting the GZK neutrino signature will likely require the use of next-generation, large low frequency arrays, such as LOFAR or even the Square Kilometer Array (SKA).

Previous Attempts at Radio Detection of Neutrinos

Previous attempts to detect neutrinos via radio emission have been performed in laboratories, in experiments based in Antarctica and by observations of the Moon. The sensitivities of the neutrino detection experiments are shown in Figure 3. The figure includes lunar experiments as well as the predicted sensitivity for a proposed experiment, the *Green Bank Lunar Interferometer for Radio Transients, (GLINT)*.

Antarctic Ice experiments

A very large collector mass is required for the detection of neutrinos. A large U.S. project currently under construction at the South Pole is IceCube. Here, one cubic kilometer of Antarctic ice is used at the detecting medium. A radio instrument based on the Askaryan effect is RICE - the Radio Ice Cerenkov Experiment, deployed in the ice at the South Pole.

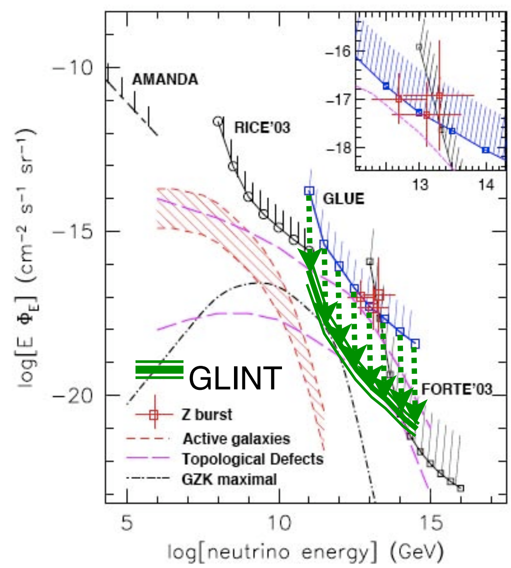


Figure 3: Limits on fluxes of neutrinos from previous experiments, including an estimate for this proposal. The GLINT sensitivity is estimated with a factor of two range in sensitivity.

ANITA

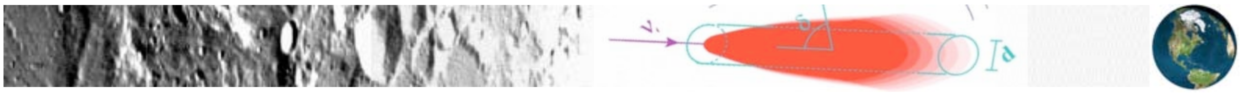
Anita is a balloon experiment that observed radio emission from neutrinos interacting with the Antarctic ice. The frequency range for ANITA 200 to 1100 MHz (Barwick 2006).

Lunar Neutrino Experiments

As shown by Alvarez-MInız et al 2001, the flux density of neutrino generated Cerenkov radiation is intense, but of very short duration. At 1 GHz, a 10^{20} eV neutrino event could produce a pulse with intensity greater than 2000 Jy.

The first attempt to detect such pulses using a radio telescope was performed by Hankins et al. 1996 using the Parkes 64-meter in 1996. They observed the Moon for ten hours using two 100 MHz wide receiver channels spaced 200 MHz apart (around 1400 MHz) and attempted to use ionospheric dispersion to identify pulse events. No pulses were detected that met the detection criteria.

Another attempt was made by Gorham 2004 (project GLUE) who searched for coincident pulses from two NASA Deep Space Antennas at Goldstone separated by 22 km, operating at 2.2 GHz. The detection bandwidth of 100 MHz was used. No positive detections were found after 120 hours of operation.



Group	Freq. (MHz)	Band-Width (MHz)	Diam-eter (m)	System Temp (K)	Neutrino Beam (degree)	Relative System Sensitivity	Obs. Duration (hours)	Rel. Counts
Parkes	1400	200	64.0	100	3.1	131	10	1
GLUE	2200	70	48.1	110	2.0	33	120	3
Westerbork	140	20	93.5	200	30.9	40	200	6
							500	15
GLINT	1300	2000	53.6	110	3.3	337	2000	513
							4000	1025

Table 1: Estimated relative number of lunar neutrino counts, normalized to Parkes experiment, based on data from Hankins 1996,Gorham 2004, Falke 2004 and Salzberg 2005. For Westerbork and GLINT we estimate the relative number of events detected based on two observing durations.

The importance of using interferometers to distinguish terrestrial interference from astronomical sources has been recognized by several groups, including Scholten (2006), Saltzberg (2005). The Westerbork array of 14 twenty-five meter diameter telescopes is carrying out a 500 hour experiment over a few years duration (Falcke 2004). The relative sensitivity of the lunar experiments is summarized in Table 1.

Technical Description

Antennas Array

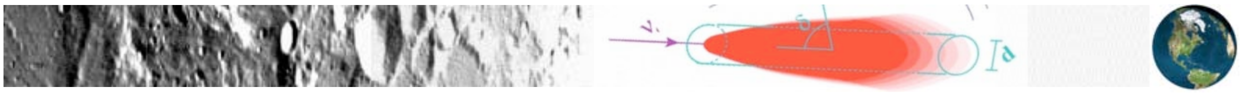
An array of antennas is required to have sufficient angular resolution to triangulate the location of the origin of the transient radio event. Observations with an array allows rejection of short term RFI events that will likely be generated on the earth surface, and will not add in phase when the detection scheme is properly phased.

Wide-band Receiver system

The wide band width and low Receiver (Rx) temperature (< 50 K) are required to reach the sensitivity needed to detect a significant number of neutrino events. Recent technological developments in wide bandwidth, low frequency feeds enables this generation of neutrino telescopes. The wide bandwidth is achieved using a new design for log periodic feed system, and low system temperature is achieved by cryogenically cooling the first stage amplifiers.

Digital Data Acquisition

Numerous radio groups have Field Programmable Gate Array experience, suitable for use in high speed detection systems. A notable example is the University of California at Berkeley-CASPER IBOB/BEE2 high-speed data acquisition and signal processing



system. We urge the decadal committee to support the technology development efforts, as they enable new experiments.

Data Analysis

Time-tagged transient candidates will be stored for post-processing if coincident pulses are found from the Moon. The recorded data will provide spectral energy densities.

Near Term Experiments

Our group has carried out a number of previous neutrino detection experiments. We strongly support existing ground breaking experiments, such as the on going RESUN experiment, which uses the EVLA for placing limits on the UHE neutrino flux.

We propose a next step in the study of UHE Neutrino astronomy by building a dedicated instrument, *Green Bank Lunar Interferometer for Neutrino Transients.* GLINT will connect an existing 43-meter diameter telescope with two 26-meter telescopes at the NRAO Green Bank WV, as a dedicated interferometer for detection of very short duration (few nano-second) pulses of emission when a UHE neutrino interacts with the Lunar surface. The GLINT system is optimized for detection of emission from these neutrinos and our newly created event detection system is able to efficiently capture events from the telescopes and interferometrically determine the location on the Moon of neutrino collision events. The interferometer will also reject terrestrial interference. This experiment will be 300 times more sensitive than previous searches for lunar neutrinos. (See http://www.gb.nrao.edu/glint and Langston et al. 2008)

Detecting lower energy neutrinos, which are more numerous, requires more sensitive detectors. Future large telescope arrays, such as LOFAR, the LWA and the SKA, will be required. These instruments will have greater sensitivity to faint transient events.

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