Development of telescopes for extremely energetic neutrinos: AMANDA, ANITA, and ARIANNA

Steven W. Barwick*

Dept. of Physics and Astronomy, University of California, Irvine 92697, USA

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Abstract

Dedicated high-energy neutrino telescopes based on optical Cherenkov techniques have been scanning the cosmos for about a decade. At TeV scales, limits on the diffuse flux have improved by several orders of magnitude, eliminating the most optimistic models that tend to be normalized to the extragalactic x-ray or gamma-ray luminosity. At higher energies, neutrino telescopes have provided the first flux limits from point sources and diffusely distributed sources such as cosmogenic neutrinos generated by the GZK process, whose existence is relatively secure but predicted flux is frustratingly small. To substantially improve the experimental capabilities at the very highest energies, new techniques are required. I will briefly discuss preliminary results from the radio-based Cherenkov detector ANITA, and describe a new concept called ARIANNA that promises to increase the sensitivity to neutrinos with energies in excess of 10^{17} eV. Radio Cherenkov telescopes have already ruled out some of the more exotic predictions for neutrino intensity and may soon test more conventional GZK models. In addition to flux measurements, these devices can probe for non-standard particle physics by investigating the neutrino cross-section.

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* Steven W. Barwick. Tel.: +00-949-824-2626; fax:+00-949-824-7478; e-mail: barwick@hep.ps.uci.edu.

1. Introduction

The scientific promise of high-energy neutrino astronomy remains as compelling and elusive as ever. Although powerful neutrino telescopes such as AMANDA-II [1] and NT-200 [2] in Lake Baikal have uncovered no evidence for astrophysical neutrino sources, these first-generation detectors , optimized to detect neutrinos with energies between 10^{12}-10^{15} eV, have paved the way for more capable telescopes with instrumented volumes as large as one cubic kilometer [3] [4]. These detectors are based on the optical Cherenkov technique. During the past decade, the limits on the diffuse flux of neutrinos provided by the first generation of neutrino telescopes have improved by two orders of magnitude [5], and currently at $E^2(dN/dE) \sim 2x10^{-7}$ GeV/cm^2/s summed over all ν-flavors. Equally noteworthy, the energy interval probe by these telescopes has been extended from $\sim 10^{12}$ eV to encompass energies between 10^{12}-10^{18} eV. Similarly impressive improvements on the flux limits for point sources have been reported over the same period of time [5]. These results have ruled out most models of neutrino production that are connected to x-ray luminosities [6].

The existing diffuse flux limits can be used to gain further insight on the maximum flux expected from extragalactic (EG) point sources [7]. Sec. 2 discusses this intimate relationship and the robustness of the calculation.

At yet higher neutrino energies, new techniques were developed that detect *coherent* Cherenkov emission at *radio* wavelengths from high energy neutrino interactions. This emission mechanism, known as the Askaryan effect[8], was experimentally confirmed less than a decade ago [9] [10]. The balloon-borne ANITA payload and the South Pole based RICE array have exploited this effect to produce important constraints on the extraterrestrial neutrino flux.

About 40 years ago, Greisen, Zatsepin and Kuzmin (GZK) predicted that the highest energy cosmic rays would rapidly lose energy by colliding with cosmic microwave background photons, thereby limiting the maximum energy that can be observed on earth [11]. It was soon realized that high energy neutrinos [12] were a natural by-product of these collisions, and these cosmogenic, also called GZK neutrinos, remain of one of the most secure predictions for a cosmic neutrino flux. Recently, the Auger [13] and HiRes [14] collaborations have reported strong evidence for GZK suppression in cosmic ray spectra, thereby increasing confidence in the existence of cosmogenic neutrinos. GZK ν provide a powerful new tool to help understand the origins of the highest energy cosmic rays. For example, the neutrino energy spectrum helps to break model degeneracy between source distribution and evolution [15]. In addition, as discussed in Sec. 3.1, GZK ν may be used to probe for new physics at center-of-mass energies in excess of 100 TeV, significantly above the energy scale probed by LHC .

Unfortunately, the predicted flux of GZK neutrinos is frustratingly small, and their observation requires new and radically different detector concepts. One such idea is called ANITA [16], a balloon-borne telescope that launched in December 2006 and circled high above Antarctica for about 35 days. It scanned for neutrino signals over an area larger than 1 million square kilometers. This and subsequent flights are expected to explore the sky at $E_{\nu} > 10^{18.5}$ eV. Sec. 3 discusses the ANITA concept, outlines the calibration and verification procedures, and presents preliminary results including limits on the neutrino cross-section.

The RICE [17] detector, and more recently, AMANDA-II [18], Auger [19] and HiRes [20] have searched for neutrino emission in the intermediate energy regime between 10^{16} and 10^{18} eV (Fig. 2 displays several reported limits). The Auger ν_τ capabilities will improve with continued operation, and IceCube [3], will be completed by 2011. However, neither expect to measure more than a few GZK neutrinos per year. Therefore, a gap exists in the energy coverage of current-generation high-energy neutrino detectors.

To acquire sufficient statistics to definitively establish the existence of cosmogenic neutrinos, measure the full energy spectrum, and gain experimental insight on the neutrino cross-section at ultra-high energies (UHE), new concepts based on radio detection in salt domes (SALSA) [21] and Antarctic ice (AURA [22], IceRay[23], and ARIANNA[24]), and acoustic detection in salt, water and ice media are under investigation[25][26].

It remains to be seen if any salt dome provides suitable radio attenuation characteristics [27], and current acoustic efforts are focused on technology development and baseline studies, such as characterizing the attenuation and ambient noise of the water and ice environments. ARIANNA, located only 150 km (~70 miles) from McMurdo Station, the primary supply hub of US Antarctic operations, utilizes the Ross Ice Shelf, whereas AURA and IceRay are located on the high Antarctic plateau at the Amundsen-Scott South Pole Station. IceRay, like ARIANNA, uses receivers buried near the surface, while AURA is based on the RICE concept of deeply buried linear dipoles.

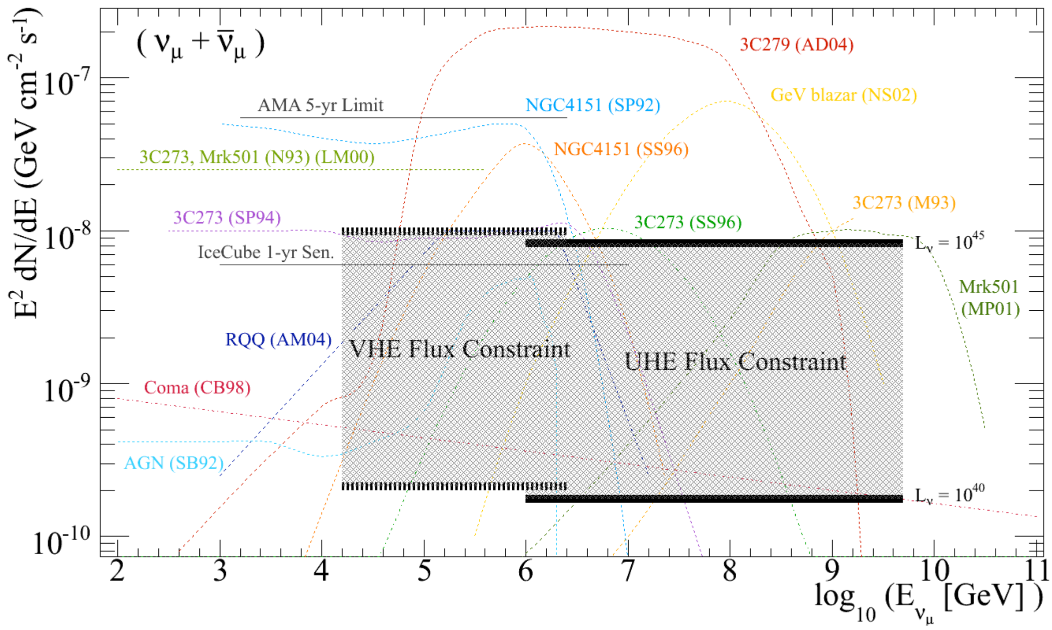

Fig. 1: Muon type ν-flux constraints [5] for point sources are shown in grey band. The VHE (UHE) constraint is based on diffuse experimental limits of [28] and [5], respectively. The upper boundary is defined by assuming that the average n-luminosity of the distribution is 10^{45} erg/s per decade, and the lower boundary defined by $L_n=10^{40}$ erg/s per decade. A representative survey of theoretical models is given by the dashed curves (see ref. [5] for the explanation of the labels). Also shown are point flux limits from AMANDA-II (AMA 5-yr Limit) by direct search [29], and the 1 year sensitivity of IceCube (thin horizontal solid black line).

2. Constraints on the EG point source flux

As previously discussed, no point sources of neutrino emission have been observed, making it difficult to establish much of anything concrete regarding the nature of the neutrino sources. They may or may not be correlated with the sources of extragalactic cosmic rays. They may be correlated with the most powerful emitters of electromagnetic radiation in any band, or hidden from view of astronomical telescopes. Given the lack of experimental observation and the considerable variety of theoretical models and flux predictions, some insight on the flux from *point* sources may be gained from the experimental limits on the *diffuse* neutrino flux. If the diffuse n flux is generated by an ensemble of extragalactic (EG) sources, then only the nearest would generate several neutrinos from the same direction, and therefore be detectable as distinct point sources. It is possible to compute a constraint on the flux from an EG point source based on the experimentally determined diffuse flux limit. First, we compute the number of detectable point sources, N_s, for a specified sensitivity to point sources and the known diffuse flux limit. By setting N_s=1, the EG point flux constraint is obtained.

The calculation of N_s is based on three sensible assumptions:

1. EG ν sources are common, and uniformly distributed in space
2. The luminosity distribution is characterized by a power (possibly broken) law
3. Sources emit neutrinos with energy spectrum proportional to E^{-2}.

Of course, the matter density in the local universe is not uniform and if neutrino sources are traced by matter density, then this can impact the constraint. In Sec. 2.1, we discuss the degree of validity of these assumptions and caveats to the derived constraint.

Lipari [7] established that N_s is computed from the expression:

$$N_s \approx \frac{\sqrt{4\pi}}{3}\frac{1}{\sqrt{\ln(10)}}\frac{H_o}{c}\frac{K^{diff}}{(C_p)^{3/2}}\frac{\langle (L_\nu)^{3/2}\rangle}{\langle L_\nu\rangle}\frac{1}{\xi}$$

for an ensemble of sources that first "turn-on" at the Hubble radius, d_H (= c/H_o ~ 4 Gpc) and characterized by an arbitrary luminosity distribution , where L_ν is the ν_μ luminosity of the source per decade of energy, and K_{diff} is related to the all-flavor diffuse flux limit by K_{diff}= $E^2(dN/dE)/3$= 5.6x10^{-8} GeV cm^{-2}s^{-1}sr^{-1} [5], valid for an energy spectrum proportional to E^{-2} over the energy interval of 10^{15}eV < E_ν <$10^{18.5}$ eV, and C_p is related to the instrumental ν_μ sensitivity to point sources with an assumed E^{-2} energy spectrum, so $C_p=E^2(dN/dE)$ [GeV cm^{-2}s^{-1}]. The effect of source evolution is governed by the parameter ξ, ranging from 0.5 to a few. It also slightly depends on assumed cosmology. For standard Λ=0.7 cosmology, and source evolution as observed for AGN, then ξ=2.2.

If the luminosity distribution of neutrino sources is characterized by a power law or broken power law (Assumption 2), which is commonly used to describe luminosity distributions in electromagnetic bands, then the expression for N_s simplifies to:

$$N_s \approx \frac{\sqrt{4\pi}}{3}\frac{1}{\sqrt{\ln(10)}}\frac{H_o}{c}\frac{K^{diff}}{(C_p)^{3/2}}\frac{\langle L_\nu\rangle^{1/2}}{\xi} \quad (1)$$

which indicates that N_s can be computed from the mean luminosity of the source distribution, and implies that the brighter sources are too rare to significantly alter the naïve expectation that the most likely source detected will have average intrinsic luminosity.

Using the 5 yr AMANDA-II point source limit [29] to estimate the detector point sensitivity for E^{-2} spectra, giving C_p = 5x10^{-8} GeV cm^{-2}s^{-1}, we find N_s = $0.06(L_\nu/L_{45})^{1/2}$, where the mean neutrino luminosity is scaled to 10^{45} erg/s per decade (=L_{45}), a convenient value that characterizes AGN x-ray luminosities. We note that $N_s \ll 1$ is compatible with the non-observation of neutrino point sources by AMANDA-II.

The point flux constraint is obtained by setting N_s=1 and solving for C_p, giving [5]:

$$E^2(dN/dE) \leq 8.2\times10^{-9}(L_\nu/L_{45})^{1/3}\mathrm{GeVcm^{-2}s^{-1}} \quad (2)$$

This constraint, valid for the energy interval 10^{15}eV < E_ν <$10^{18.5}$ eV, is a factor of 6 more stringent than current experimental limits, and excludes a variety of models as shown in Fig. 1. A similar constraint can be calculated from the VHE diffuse limit [28] and indicated in the region labeled "VHE Flux Constraint" in Fig. 1. The lower boundary of the constraint bands are computed for weaker sources, characterized by L_ν=10^{40} erg/s per decade. Also note that the constraint applies to sources that are highly beamed and/or time variable, such as GRBs, if L_ν is the *observed* mean luminosity per decade of the source distribution. However, since the observed optical (and predicted neutrino) luminosities for GRB's is of order 10^{51} erg/s , more restrictive flux limits are obtained from dedicated searches [30].

Within the next year, it is expected that the AMANDA-II UHE diffuse analysis based on TWR technology will include data from 2004 and 2005, increasing the live-time by roughly a factor of 3, further improving the sensitivity. From Eq. 1, it can be seen that the point source constraints strengthen with improving diffuse flux limits as C_p ~ $(K_{diff})^{2/3}$. The constraint also strengthens for sources that turn-on at redshift greater than 1.

2.1. Robustness of constraint

It is not certain that the ν sources nearest our galaxy will be located at approximately the mean distance between neutrino sources, d_s, given by

$$d_s^3 = cL_\nu /[4\pi H_0 \ln(E_{\max}/E_{\min})K_{diff}] \quad (3)$$

where E_{max} and E_{min} correspond to the relevant maximum and minimum neutrino energies involved in the calculation of the diffuse flux limit. For sources with L_ν=L_{45} and K_{diff} determined from the AMANDA-II limit, d_s= 375 Mpc. Suppose the nearest neutrino source in the ensemble is fortuitously located at distance d that is significantly smaller than d_s, then the flux constraint should be adjusted to

$$C_p^{new} = C_p\left(\frac{d_s}{d}\right)^2 \quad (4)$$

How likely is this scenario? The answer depends on the mean ν luminosity of the source distribution, which is unknown. If, as often the case in theoretical modeling of neutrino sources, electromagnetic (EM) luminosities are used to provide an approximate estimate of neutrino luminosities, then one finds that no sources with L_{45} or greater (in any EM band) exist within d_s of the detector. In addition, the mean matter density within d_s is less than a factor 2 of the global average [31] so there is no reason to believe that the source density is significantly enhanced. Thus, the adjustment described by Eq. 4 is not very likely. However, the situation is less clear for ensembles with smaller mean luminosities. Again, using EM luminosities per decade (in any EM band) as a surrogate for ν-luminosity at VHE/UHE energies, there are several nearby sources that have the potential to necessitate adjustment. However, Eq. 2 shows that the unmodified constraint, C_p, is also dramatically lower compared to the one obtained for L_{45}. Suppose Cen A, the AGN nearest the Milky Way, emits ν with luminosity in the vicinity of 10^{41} erg/s and representative of an ensemble of sources. The point flux constraint, given by the lower boundary in Fig. 1, should be increased by a factor of 25 since the distance to this particular source (3.4 Mpc) is smaller than d_s (17 Mpc) for L_ν=10^{41} erg/s. Nevertheless, the modified constraint remains significantly below current limits. In addition, the probability for a source to be in such close proximity is roughly given by the volumetric ratio, P ~ $(d/d_s)^3$ = 0.008 for random uniform distribution of sources, which is uncomfortably small even if sources follow the local matter density within d_s.

The constraint was derived for a power law energy spectrum, dN/dE~$E^{-\gamma}$ with spectral index, γ, of 2. It slightly strengthens by a factor of 2 for sources with γ=1 and weakens by a factor of 2 for γ= 3. For the latter case, neutrino emission is restricted to energies directly probed by the VHE and UHE diffuse limits. In the γ=3 scenario, it may be more sensible to constrain the source density since the connection between UHE/VHE L_ν and EM luminosity at lower energies must necessarily be strongly model dependent.

The VHE and UHE constraints are based on current experimental diffuse flux limits and will strengthen as diffuse flux limits improve. They span the broad energy interval between 10^{12} and 10^{18} eV, and are valid for hidden, transient, or beamed sources. The constraints are more restrictive that limits imposed by direct searches for ensembles with average L_ν<10^{49} erg/s per decade. Conversely, the constraint for transient, high luminosity sources such as GRBs is weaker than limits obtained by direct searches. The constraint does not apply to Galactic sources, nor to unique local EG sources not commonly replicated throughout the universe.

3. ANITA

ANITA launched from Williams Field, Antarctica on December 15, 2006 and remained aloft for almost 35 days. Despite instrumental problems during the last 10 days of the flight and an unusual flight path that kept ANITA within view of strong transmitters for a large fraction of the time, the integrated sensitivity of the first flight represents a dramatic leap forward, creating an unprecedented opportunity for discovery.

The ANITA payload consists of 32 quad ridge horn antennas, arranged to view 2π. A cluster of 16 horns is separated vertically from a lower ring of 16 horns by a distance of ~3m. Quad ridge horn antennas were chosen for ANITA (and flown on ANITA-lite) because of their excellent frequency response over the frequency band of interest, between 0.2-1.2 GHz, and their tight temporal response. Since the Askaryan impulses are coherent to 1.2 GHz, the observed impulse will be band-limited barring significant propagation effects.

Neutrino signals are identified by (1) short duration transients with the proper shape and frequency content, (2) arriving with time delay compatible with emission from the ice and direction away from known sources of Anthropogenic RF interference, and (3) compatible with 100% linearly polarized [10] in the (mostly) vertical direction and other expected characteristics. Two independent analyses, with different blindness criteria, found no candidates with the expected neutrino characteristics.

A SLAC test beam characterized the performance of the antenna array and trigger system. A solid ice target was assembled and Askaryan-effect radio signals were observed by ANITA with the appropriate field strength[10]. In addition, the studies established that the width of the Cherenkov cone varies with frequency, as expected from analytic and monte-carlo based calculations of the Askaryan pulse. The ANITA technique relies on off-cone emission to detect neutrino signals.

A ground calibration system at the launch site transmitted pulsed signals to ANITA from both buried and surface antennas. These signals were used to monitor instrument health, demonstrate excellent timing and angular resolution of the reconstruction [32], and verify predictions of the absolute signal strength and Fresnel losses at the snow-air surface [33]. Diurnal variation of the solar and galactic radio emission verified end-to-end system operation and overall system gain [34].

Preliminary studies of surface roughness indicate that its impact on aperture is rather modest [35]. Surfaces characterized by sastrugi and snow dunes with rms amplitude variation between 0.3-0.7m and correlation lengths between 8-13m (typical of surfaces covering about 50% of Antarctica) reduce the aperture for incident angles just below the critical angle, but this loss is compensated by scattered power escaping for incident angles slightly larger than the critical angle. These conclusions are tentative because the characteristics of the pulse in the time domain are still in progress. It is important to verify that the scattered signals for outgoing for nearly horizontal transmitted waves retain their pulse shape in the time domain. Strong deviations from this outcome would impact the trigger and analysis efficiency.

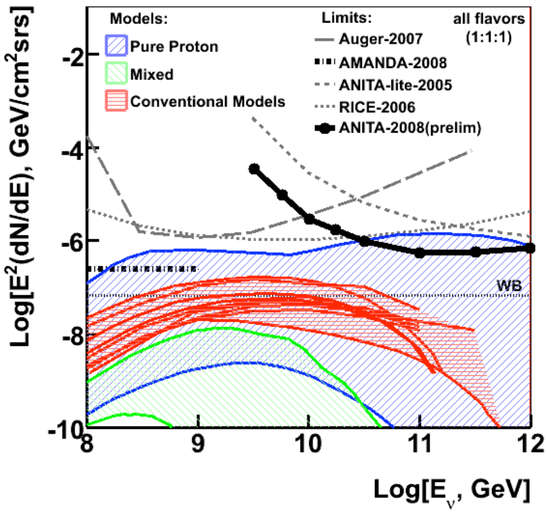

Fig. 2: Representative set of theoretical predictions for all-flavor GZK neutrino flux and experimental limits. See text for additional details.

Fig. 2 provides a representative survey of models of the cosmological ν flux and diffuse flux limits (see [36] for list of references). If required, limits are converted to a sum over all-flavors assuming a 1:1:1 flavor ratio. The most widely discussed models fall within the central red band (labeled "conventional models"). The upper extreme of the blue band represents a class of proton models whose scientific relevance is more difficult to assess, and the lower band (green) illustrates the general reduction in flux for mixed composition models. The ANITA curve requires some explanation. A common method for determining a flux limit within a specific logarithmic energy interval Δ(logE) is given by

$$\frac{dN}{dE} \leq \mu_{\text{lim}} \Big/ \left[\ln(10) E (V\Omega)_{eff}\, t_{live} \Delta(\log E)\delta / \lambda_\nu\right] \qquad (5)$$

where t_{live} is the instrumental livetime, λ_ν is the neutrino interaction length in ice, μ_{lim} is 90% CL upper limit for allowed signal based on 0 observed events in the data. The term $(V\Omega)_{eff}$ is the effective volumetric aperture calculated from detector simulation programs. For ANITA, this quantity is averaged over neutrino flavor. The ANITA curve used $\Delta(\log E)=0.5$ and the parameter δ is set to 1. Unfortunately, this procedure then requires additional calculation to determine if a theoretical model is excluded by the experimental result. To circumvent this difficulty, a simpler visual interpretation can be achieved by adjusting the experimental curves by a constant factor δ derived according to the idea that a model is excluded if it crosses the experimental curve. This is equivalent to enlarging the $\Delta\log(E)$ interval by δ, which depends on the experimental response and the shape of the theoretical energy spectrum. For ANITA, $\delta\sim 2$ for conventional GZK models in the red band. In other words, a GZK flux prediction is excluded if it crosses a curve determined by dividing the ANITA limit by 2.

The preliminary ANITA limit [37], based on the geometric averaging of the experimental estimates for $(V\Omega)_{eff}$ by two detector simulation programs, contains considerable uncertainty. At this point in time, the two simulation programs differ by about a factor of 3 at lower energies; somewhat less at higher energies. It is comforting to see that the measured neutrino limit is compatible with conventional predictions (e.g, [38]).

The next flight of ANITA, scheduled for December 2008, should begin to test conventional GZK models that predict a relatively large flux at high energies.

3.1. Constraints on neutrino cross-section

The measured flux (or limit) of cosmogenic neutrinos depends on the neutrino interaction cross-section. Within the context of the standard model, the uncertainties at the relevant energies are relatively modest[39]. Perhaps more intriguing, the cross-section may dramatically increase relative to extrapolations from standard model calculations due to the onset of new physics processes [47]. Barwick and Wu [40] describe a method that uses ANITA data to determine or constrain the cross-section without strong assumptions on the normalization of energy spectrum. The central idea takes advantage of two strikingly different ice formations in Antarctica - the thick *ice sheet* and floating *ice shelves*. Given sufficient statistics, the cross-section can be determined from the relative rate of events emerging from the ice shelves along the coast of Antarctica ("reflected") compared to the rate from the interior ice sheets ("direct").

In the absence of signal, constraints can be inferred given an assumed neutrino spectrum. Fig. 3 shows the preliminary ANITA upper bound on σ_ν relative to the standard model prediction [39] for assumed GZK [38] and E^{-2} power law spectra[18]. The results were conservatively derived from the more-pessimistic version of the ANITA simulation program.

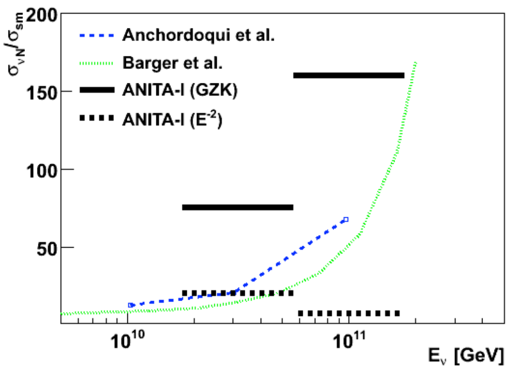

Fig. 3: Preliminary upper limit on σ_ν from ANITA-1 assuming GZK [38] and E^{-2} power law spectra normalized to existing limit [18]. Previous limits also shown (thin dash [41]; thin green solid [42]).

4. ARIANNA

While ANITA represents a powerful advance in neutrino sensitivity, it primarily probes only the high-energy tail of the conventional GZK energy spectrum. The fundamental reasons are two-fold: the power of coherent radio emission grows as the square of the shower energy (and therefore neutrino energy) and the distances to balloon-borne detectors are quite large (up to ~ 600 km). Therefore, these devices tend to yield interesting apertures above 10^{18} eV, creating a gap in the energy coverage of current-generation high energy neutrino detectors. ARIANNA, first described a few years ago[24][43], is designed to bridge this gap in sensitivity and move beyond the discovery phase of cosmogenic neutrino physics. The technical and scientific advantages of ARIANNA are discussed next.

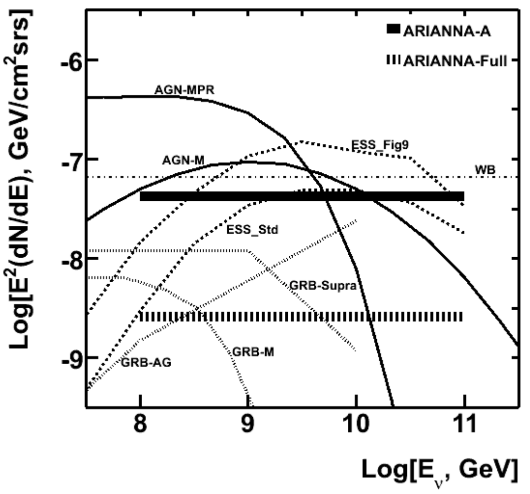

Fig. 4: Integral sensitivity for Phase A (thick solid) and full (thick hash) configuration of ARIANNA, assuming spectra proportional to E^{-2}. Also shown are differential flux predictions for AGN (labeled AGN-MPR and AGN-M), GRB (labeled GRB-M , GRB-AG, and GRB-supra), and GZK models (labeled ESS_Fig9, ESS_baseline), and Waxman-Bahcall bound [WB]. See [44] for complete list of references and description of Phase A design.

The idea of using a surface array of radio receivers to search for astrophysical sources has a long history [45]. The ARIANNA concept utilizes the Ross Ice Shelf near the coast of Antarctica to increase the sensitivity to cosmogenic neutrinos by roughly an order of magnitude when compared to the sensitivity of existing detectors and those under construction. ARIANNA capitalizes on several remarkable properties of the Ross Ice Shelf: shelf ice is relatively transparent to electromagnetic radiation at radio frequencies and the water-ice boundary below the shelf creates a good mirror to reflect radio signals from neutrino interactions with incoming trajectories in any downward direction. The high sensitivity of the telescope results from nearly six months (or possibly more) of continuous operation, low energy threshold (~$3x10^{17}$ eV), and more than 2π of sky coverage.

The baseline concept for ARIANNA consists of moderately high gain antenna stations arranged on a 100 x 100 square grid, separated by about 300m. Each station consists of eight linearly polarized antennas residing just beneath the snow surface, facing downwards. They communicate with each other and with a central control hub by wireless links to generate global triggers. A suitable site for ARIANNA has been identified and assessed [43].

The science missions are summarized as:

(1) ARIANNA increases the sensitivity for the detection of GZK neutrinos by an order of magnitude over state-of-the-art detectors currently under construction (Fig. 4) . Simulations indicate that the full ARIANNA detector can observe **~40 events per 6 months** of operation based on a widely-used prediction for the GZK neutrino flux (Fig. 9 of Ref [38]).

(2) The "low" energy threshold of ARIANNA, combined with high statistics, provides an unparalleled opportunity to measure the flux over a broad interval of the GZK neutrino energy spectrum. Neutrino energy spectra provide critical constraints on source evolution, distribution, and cosmic ray injection spectra. ARIANNA can test models that assume that the extragalactic cosmic rays are mixed elemental composition.

(3) ARIANNA can survey the southern half the sky for point sources of high-energy neutrinos from AGN or GRB with unprecedented sensitivity for neutrino energies between 10^{17}-10^{19} eV. Preliminary reconstruction studies show that ARIANNA can achieve angular resolution of 1.1 degrees [24]. Point sensitivity is expected to be E^2(dN/dE)~ $3x10^{-9}$ GeV/cm^2/s after one year.

(4) ARIANNA can probe for physics beyond the standard model by measuring the neutrino cross-section at center of mass energies of 100 TeV. Preliminary studies [46] indicate that the cross-section can be measured with a precision of 25%, benefiting from the large statistical sample of 400 events spanning 2π solid angle.

Thus, ARIANNA can broadly impact a variety of fields spanning astronomy, elementary particle physics and cosmic rays by improving the sensitivity at energies that naturally complement the capabilities of the cubic kilometer ν telescopes.

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