High energy extraterrestrial neutrinos are believed to be produced in energetic accelerated environments through proton-proton or proton-photon interactions via pion production and decay. Such an accelerator might be the core of an active galaxy, powered by a supermassive black hole. In their pioneering work, Stecker, Done, Salamon, and Sommers [1] calculated the expected diffuse flux of neutrinos from the sum of all active galaxies and found that such a flux could be observable deep underground in a large neutrino detector. Further predictions have followed (for a summary see, for example, the review of Learned and Mannheim [2]), and with the construction and operation of the first high energy neutrino detectors, the sensitivity has been reached to enable such predictions to be tested. Searches have been made and limits have been reported by the DUMAND
before the energy sensitive channel multiplicity cut was finally applied, 69 events remained in the data sample, whereas a full simulation of the detector response to the atmospheric neutrino (Lipari [12]) flux (neglecting neutrino oscillations, which would reduce the prediction by only a few percent) predicts 85 events for the 130 days of live time. The absolute difference in the numbers of events is consistent with Poisson fluctuations, or with the ±25% [13] uncertainty in the atmospheric neutrino flux, or with uncertainties in the simulation efficiencies (30%–40%). The distribution of the data and atmospheric simulation are shown in Fig. 1. The error bars on the data are 90% unified confidence intervals [16] for the fixed but unknown value of the mean rate (signal plus background) for each bin. Only one bin (N_{ch} = 25–30) has a background prediction inconsistent with the confidence interval. More specifically, a generalized likelihood ratio test of the shape of the atmospheric neutrino hypothesis as the parent distribution of the data yields a chance probability of 20%, which is too large to reject the shape of the atmospheric neutrino hypothesis. We choose to treat the rate of observed atmospheric neutrinos as a constraint on the overall detector efficiency and then carry through an efficiency uncertainty from the atmospheric neutrino flux prediction and Poisson error on the observed rate. Therefore, to calibrate the overall detector sensitivity, we take the 69 events as the best-fit estimate of the number of atmospheric neutrinos and rescale all efficiencies by a factor 69/85. This is conservative, since if the first bin discrepancy was due, e.g., to a simulation effect, then no renormalization would be needed, and the limits would improve slightly. We combine the Poisson error on the observed rate of
atmospheric neutrinos with the theoretical flux uncertainty (taken as a uniform probability distribution centered about the best-fit flux \( \Phi \) and extending to \( \pm 0.25 \Phi \)) to compute the correlations between the background and efficiency for later use in the probability distribution function used in the confidence interval construction. To incorporate these systematic uncertainties in the efficiencies into the limit calculations, we follow the prescription of Cousins and Highland [17], as implemented by Conrad et al. [18] with the unified Feldman-Cousins ordering and improved by a more appropriate choice of the likelihood ratio test [19]. We also report all limits and sensitivities with and without the assumed uncertainty.

In addition to the data and atmospheric neutrino prediction, Fig. 1 also shows the prediction for an \( E^{-2} \) signal flux at a level \( E^2 \Phi(E) = 10^{-5} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV} \), a flux that would have been readily detected. Setting a limit on a flux \( \Phi(E) \) involves determining an experimental signal event upper limit \( \mu(n_{\text{obs}}, n_b) \), which is a function of the number of observed events, \( n_{\text{obs}} \), and expected background, \( n_b \), after the cuts are applied. A simulation chain accounting for neutrino absorption, interaction and neutral current regeneration, muon propagation, and detector response gives the number of signal events, \( n_s \), expected from the source flux \( \Phi(E) \). The limit on the source flux will then be \( \Phi_{\text{limit}}(E) = \Phi(E) \times \mu(n_{\text{obs}}, n_b)/n_s \). The choice of final cut for \( N_{\text{ch}} \) is optimized before examining the data by minimizing the average “model rejection factor” (MRF) \( \overline{\mu}(n_b)/n_s \) [20], where the as yet unknown experimental event limit \( \mu(n_{\text{obs}}, n_b) \) is replaced by the average upper limit \( \overline{\mu}(n_b) \) [16]. Over an ensemble of hypothetical repetitions of the experiment, this choice of cut will lead to the best average limit \( \Phi_{\text{limit}}(E) \).

When calculating the expected signal from an extraterrestrial source at the earth, it is necessary to take into account maximal mixing of neutrinos between \( \nu_\mu \) and \( \nu_\tau \) during propagation to the earth due to neutrino oscillations [21,22]. We would expect to lose half the \( \nu_\mu \) signal to \( \nu_\tau \); however, some of these \( \nu_\tau \) would regenerate \( \nu_\mu \) in the earth (\( \nu_\tau \rightarrow \tau \rightarrow \nu_\mu \)) lessening the effect [23,24]. In what follows, we calculate the signals and model rejection factors as if there were no loss of signal during passage to the earth (in order to more easily compare to previous experiments), but note that the limits and model rejection factors would be increased by a factor near but less than 2 in the presence of oscillations and \( \nu_\tau \rightarrow \nu_\mu \) regeneration in the earth.

The integrated channel multiplicity distribution is shown in Fig. 2. Also shown is the 90% confidence level Feldman-Cousins average upper limit which is a function of the expected background. The optimal cut is the one where the model rejection factor \( \overline{\mu}(n_b)/n_s \) is minimized. Figure 2 also shows the average flux upper limit \( (E^2 \Phi \times \text{MRF}) \) as a function of the choice of multiplicity cut. The minimum flux limit occurs at a cut of \( N_{\text{ch}} \geq 54 \), where we expect \( n_b = 3.06 \) and an average signal event upper limit of 4.43 ignoring the uncertainties in the efficiency and background, and 4.93 when the uncertainties are included. The \( 10^{-5} E^{-2} \) signal flux would produce 56.7 events. This leads to corresponding expected average limits on the source flux of \( E^2 \Phi_{90\%}(E) = 7.8 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV} \) (excluding uncertainties), and \( 8.7 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV} \) (including uncertainties).

We note that the expected overall flux limit is relatively insensitive to the choice of cut, with a broad minimum seen in Fig. 2 in the range of multiplicities 50–70. We now apply this optimal multiplicity cut to the data, and find that three events remain. Ignoring the systematic uncertainties gives an event limit of 4.36 and a flux upper limit of \( E^2 \Phi_{90\%}(E) = 7.7 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV} \). Including the systematic uncertainties leads to an event limit of 4.75 and our final flux limit on an \( E^{-2} \) spectrum of \( E^2 \Phi_{90\%}(E) = 8.4 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV} \).

Figure 3 shows the neutrino energy spectrum of the simulated events before and after the multiplicity cut of 54 channels, for both atmospheric neutrinos and neutrinos from an \( E^{-2} \) spectrum. The multiplicity cut corresponds to a sensitive energy range of 6–1000 TeV, which contains 90% of the expected \( E^{-2} \) signal. The peak response energy is just below 100 TeV.
the observed event limit are excluded at the stated classical confidence level. The results of these calculations are shown in Table I and in Fig. 4. For each flux, we again report two sensitivities and limits—one assuming no systematic uncertainties and the second including systematic uncertainties. We find that the predictions of Szabo and Protheroe (SPH92L [25], P96pypp [26]) are excluded. The quasar core (SSQC) prediction of Stecker and Salamon [11] is just excluded (MRF = 0.98), but the blazar jet (SSBJ) prediction is not. The limit of the original Stecker, Done, Salamon, and Sommers flux [1] (SDSS) is a factor of 2 above the prediction and therefore the prediction is not excluded.

We also place a limit on a model of prompt charm induced neutrinos [27] (ZHV92) in the earth’s atmosphere and find that the detector sensitivity is about a factor of 4 away from excluding the prediction. More recent predictions are even further below the sensitivity of the detector [28]. Since most events will originate from neutrinos near the peak of the detector sensitivity ($E_\nu \sim 10^5$ GeV), the

![FIG. 3. Energy spectrum of the incident atmospheric (dashed lines) and $E^{-2}$ (solid lines) neutrinos for events that pass the initial cuts and have channel multiplicity greater than the optimum cut of 54 channels.](image)

![FIG. 4. Summary of experimental 90% classical confidence level flux limits from various detectors assuming an $E^{-2}$ spectrum. From top: AMANDA-B10 (νµ) [8], Frejus [4], MACRO [7], Baikal [6], and AMANDA-B10 (νµ) (this work). The background atmospheric neutrinos [12] are indicated by the hashed region representing the angular dependence of the flux. Also shown are the predicted fluxes (dashed), and AMANDA-B10 experimental flux limits (solid) for a diffuse neutrino prediction (SSQC [11]—nearly overlapping dotted and dashed curves—MRF = 0.98) and for one prediction of prompt charm neutrino production in the earth’s atmosphere [27]. Since most events will originate from neutrinos near the peak of the detector sensitivity ($E_\nu \sim 10^5$ GeV), the limits at that point for different spectral shapes are similar.](image)

**Table I.** Flux limits calculated for individual models of diffuse neutrino emission. The optimal $N_{\text{ch}}$ cut, expected background, and signal for each model are shown. The average upper limit [$\mu(n_{\text{obs}})$] and average model rejection factor [$\mu(n_{\text{obs}})/n_\text{ch}$] are shown with and without the inclusion of systematic uncertainties. Finally, the experimental limits [observed events $n_{\text{obs}}$, event limit $\mu_\text{o} = \mu(n_{\text{obs}}, n_\text{ch})$] and model rejection factor ($\mu_\text{o}/n_\text{ch}$) are given for both systematic uncertainty assumptions.

<table>
<thead>
<tr>
<th>Flux</th>
<th>$N_{\text{ch}}$ cut</th>
<th>$n_\text{ch}$</th>
<th>$n_\text{b}$</th>
<th>$n_\text{s}$</th>
<th>$\mu(n_{\text{obs}})/n_\text{ch}$</th>
<th>$\mu(n_{\text{obs}})$</th>
<th>$n_{\text{obs}}$</th>
<th>$\mu_\text{o}$</th>
<th>$\mu_\text{o}/n_\text{ch}$</th>
<th>$\mu_\text{o}$</th>
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<tbody>
<tr>
<td>$10^{-5}E^{-2}$</td>
<td>54</td>
<td>3.06</td>
<td>5.67</td>
<td>4.43</td>
<td>0.781</td>
<td>1.73</td>
<td>3</td>
<td>4.36</td>
<td>0.769</td>
<td>4.75</td>
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<td>SDSS [1]</td>
<td>73</td>
<td>0.69</td>
<td>2.42</td>
<td>3.01</td>
<td>1.240</td>
<td>3.38</td>
<td>2</td>
<td>5.22</td>
<td>2.157</td>
<td>5.61</td>
</tr>
<tr>
<td>SPH92L [25]</td>
<td>58</td>
<td>2.12</td>
<td>12.66</td>
<td>3.97</td>
<td>0.314</td>
<td>1.393</td>
<td>3</td>
<td>5.30</td>
<td>0.419</td>
<td>5.69</td>
</tr>
<tr>
<td>SSQC [11]</td>
<td>71</td>
<td>0.80</td>
<td>5.59</td>
<td>3.11</td>
<td>0.556</td>
<td>3.45</td>
<td>2</td>
<td>5.11</td>
<td>0.914</td>
<td>5.50</td>
</tr>
<tr>
<td>SSBJ [11]</td>
<td>57</td>
<td>2.36</td>
<td>12.66</td>
<td>4.13</td>
<td>0.963</td>
<td>4.50</td>
<td>3</td>
<td>5.06</td>
<td>1.179</td>
<td>5.45</td>
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<tr>
<td>P96pypp [26]</td>
<td>49</td>
<td>4.83</td>
<td>21.95</td>
<td>5.11</td>
<td>0.233</td>
<td>5.90</td>
<td>4</td>
<td>3.76</td>
<td>0.171</td>
<td>4.54</td>
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<tr>
<td>ZHV Charm D [27]</td>
<td>41</td>
<td>10.9</td>
<td>2.58</td>
<td>6.97</td>
<td>2.702</td>
<td>8.42</td>
<td>14</td>
<td>10.60</td>
<td>4.109</td>
<td>12.31</td>
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</tbody>
</table>

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limits at that point for the three different spectral shapes ($E^{-2}$, SSQC, and Charm D) are similar, as seen in Fig. 4.

The limits presented in this Letter, based on the first real-time year of operation of the AMANDA-B10 detector, are the strongest placed to date on extraterrestrial diffuse neutrino fluxes. Since that year, we estimate that about 10 times the exposure has been achieved in total with AMANDA-B10 (1997–1999) and the expanded AMANDA-II detector (2000–the present). We anticipate this combined data set to have a limit-setting potential more than 3 times better than the results presented here.

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