Detection of Neutrinos from Active Galactic Nuclei

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abstract

A new model$^{(1)}$ of neutrino production from Active Galactic Nuclei implies a detectable rate of muon neutrino induced muon flux in large detectors. In DUMAND II, perhaps 2000 muons per year, 1/2 with energy above 10 TeV at the detector, would arise due to the sum of muon neutrinos from all AGN. These muons have a distinct angular distribution, being attenuated near the nadir due to absorption in the earth. In fact operation of DUMAND for several years would yield a few percent measurement of the earth's core density.

In this note we emphasize the detection of electron anti-neutrino resonant W^- production events which result in 6.4 PeV particle cascades. Such contained events in DUMAND II are estimated to occur at about 14/year given the Stecker et al. model$^{(1)}$. Perhaps as many as 1400 events per year may be seen from the surrounding ocean near DUMAND II. Also, about 50 UHE muons/yr from W^- decay events would also be seen in the zenith angle range from about 80° - 94° traversing DUMAND II. Other resonant W^- detection possibilities are discussed.

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Introduction

A recent model (Stecker, et al.[1]) of neutrino production in Active Galactic Nuclei (AGNs) yields fluxes that verge upon detectability in present underground detectors, and would be eminently detectable in DUMAND II (20,000 m^2, scheduled to be operational in late 1993). The flux results from $\gamma + p \rightarrow \Delta^+$ in the dense photon field surrounding a supermassive black hole undergoing Eddington limited infall of matter. Proton acceleration in the accretion shock is invoked to explain various facets of the observed radiation in UV and X-rays. The proximate reason for the new high flux predictions seems to be the high AGN X-ray luminosities observed with the GINGA satellite. A particularly dramatic implication of their model is that the high flux of neutrinos could be the source of the observed broad line region in AGNs via neutrino induced stellar disruption, with the startling implication of the possible importance of neutrinos for galactic dynamics.

The idea for such neutrino production is not new, and traces back to Silberberg and Shapiro[2], Berezinsky and Ginzburg[2], or perhaps even earlier. The present authors[1] however calculate neutrino fluxes from the sum of all AGNs, employing models for density and luminosity evolution. The resulting flux of muon neutrinos is of the order of 4000 muons per year through DUMAND II (2.35 π sr), but with the distinctive characteristic of having a mean energy of about 10 TeV at the detector, as compared to the muons from atmospheric neutrinos with mean muon energy <100 GeV (near minimum ionizing). We have used transport calculations[3] that include Earth attenuation and convert muon neutrino and anti-neutrino fluxes to muon rates in a detector. The attenuation includes both charged and neutral current cross-sections. This is illustrated in Figure 1, which shows the rate of muons traversing DUMAND II as a function of muon energy threshold[3]. The threshold for muon detection in DUMAND II is about 25 GeV. At sufficiently high energies DUMAND II will be able to make a cut on the muon energy, via observation of the total light in the array (which grows roughly linearly with muon energy above 1 TeV, but with much fluctuation). Studies are still in progress, but we take such a cut to be 10 TeV for illustrative purposes, and one sees from Figure 1 that the predicted AGN flux would only be cut by one half, while the atmospheric neutrino induced muon flux would be virtually eliminated. Also shown is the flux through IMB (400 m^2). IMB has a threshold of about 2.5 GeV, and it appears from Figure 1 that a quarter of all upward going muons in IMB are due to AGN neutrinos. This experiment, however, may well have a bias against high energy muon events (now under study) so it may not see the AGN flux as predicted. However other detectors such as Baksan, Kamiokande and MACRO may be able to discern the AGN flux, if the flux is close to the Stecker et al. prediction level.

In Figure 2 we present the predicted angular distribution of muons from the sum of AGNs and from the atmosphere (Volkova flux(3)). One see that the angular distribution of AGN neutrinos peaks at the horizon, as does the atmospheric flux (but for different reasons: the AGN flux peaks near the horizon due to earth absorption otherwise, while the atmospheric flux peaks due to the larger probability for pion decay for horizontally arriving cosmic rays). Three angular distributions are plotted for both AGN neutrino induced muons and atmospheric neutrino induced muons, with muon energy thresholds of 25 GeV, 1 TeV and 10 TeV. The strong attenuation for AGN neutrinos coming through the earth's core is particularly striking. While the statistics in one year's observation with DUMAND II are not impressive (25%), the multiplication due to the absorption being exponential would yield perhaps a 5% measurement of the core density in one year!

In the model of Stecker et al., the pions and muons are all said to decay. They further claim that the neutrons do not escape the photon field, which neutrons also get excited to Δ^o which yields $\pi^- p$ half the time (the π^o's from both Δ^+ and Δ^o yield γ's that add to the photon soup). Thus through $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_\mu \nu_e$, and charge conjugate for π^-, one would get nearly equal fluxes of particle and anti-particle, but twice as many ν_μ as ν_e. Electron neutrinos and anti-neutrinos will both interact inside a large detector and produce contained electron showers coming largely from the upper hemisphere. Electron anti-neutrinos have an additional detection channel trough the resonant W^- production. In this note we particularly consider the implications of the electron neutrino flux.

Are the $\overline{\nu}_e$'s Detectable?

First we consider the rate of UHE cascades due to resonant W^- production in a fixed volume detector.

1) $\overline{\nu}_e$ flux: From the Stecker et al. paper we find the electron neutrino (or anti-neutrino) flux of their Figure 2 to be about $10^{-18}(E/E_o)^{-3}/cm^2/sec/sr/GeV$ above $E_o = m_W{}^2/2m_e = 6.4$ PeV. The integrated flux then translates to $\Phi_{\nu e}(>E_o) = 10^{-4}/cm^2/sr/yr$ above E_o.

2) Target volume: take the volume to be DUMAND II enclosed volume of $2x10^6$ tons, or $N_e = 6x10^{35}$ electrons.

3) Crossection: take as $\sigma_{eff} = 3\pi G_F/\surd 2 = 3x10^{-32}cm^2$ (4).

4) Rate: use the Berezinsky formula(4), $R_W = 2\pi N_e \sigma_{eff}(\gamma - 1)\Phi_\nu(>E_o)$. Putting in the values above, yields 14 events/yr in DUMAND II.

The signal would be a huge cascade, with roughly 10^5 times the light of the typical muon traversing the array! Additionally, the DUMAND II effective volume would be larger than the 2 megaton contained volume, since such events can be seen at some distance (though it remains to be investigated how well they may be fitted). First estimates from a simple Monte Carlo calculation indicate an effective volume for DUMAND II in excess of 1/5 km^3 for triggering on such 6.4 PeV cascades, leading to a predicted rate of 1440 events/year, or 1/5.6 hours, from the Stecker, et al., model flux.

Are there any other (anticipated) sources of such high energy cascades in the array? The atmospheric neutrino rate for such cascades is totally negligible (<1/100,000 years). Downgoing cosmic ray muons are a potentially more serious competition. The flux of cosmic ray muons at the earth's surface is less than $10^{-17}\mu/cm^2/yr$ above E_o, integrated over 2π sr. This corresponds to $0.4\mu/yr$ through DUMAND II (20,000 m^2), were it at the surface. Thus the muons do not provide a background problem, and indeed there does not seem to be any process even remotely like the signal from the resonant W^- production in DUMAND II or any other underground neutrino detector, at least from "normal" sources.

A potential background for the resonant W^- production resulting in energetic particle cascades in a detector is the cascades due to the muon neutrinos of similar AGN origin to the electron neutrinos. The ratio of rates of cascades of similar energy will be given roughly by the muon neutrino flux at an energy somewhat higher than the resonant energy for the electron neutrinos, (about $1/<y> \approx 4$ times higher neutrino energy), times the crossection at that energy compared to the effective crossection at the resonant energy, times the ratio of baryons to electrons in the target (2/1), times the flux ratio (which should be 2 for most astrophysical sources), and times the ratio of solid angles (<2:1). For the Stecker et al. flux, falling off as $1/E^3$ in this energy range, the resonant electron cascades will dominate by about 50:1 over muon neutrino induced cascades of equal or higher energies. Furthermore, muon neutrino induced cascades will be upcoming as well as downgoing at these energies, whereas, resonant electron neutrino events will only be from the upper hemisphere.

Another background to resonant W^- production of cascades inside the detector are those simply due to electron neutrino and anti-neutrino charged (and less so, but also neutral current) interactions. We calculate the angular distribution of these cascades as shown in Figure 3, to be mostly in the upper hemisphere above 1 PeV. They thus present a non-negligible background for resonant W^- detection, though with somewhat differing angular distribution.

A second means of detecting the W^- resonant production arises from the muons resulting from the W^- decay, which occurs $B_\mu = 10\%$ of the time. These muons have about 1/4 the energy of the neutrino (spin gives the outgoing neutrino preference), 1.6 PeV, and have a range of typically $R_\mu = 20$ kmwe. One sees then that the muons from W^- decay will exceed the contained W^- event rate for any likely sizes of detectors: with detector characteristic dimension D, the contained cascade to throughgoing muon ratio will be given roughly by $\Delta\Omega\ B_\mu R_\mu/2\pi D$. For a DUMAND II size detector of D = 100 m, this ratio is about 20 incoming muons per contained

6.4 PeV cascade in a given direction, but over a restricted range of zenith angles. The W^- decay muons are almost all in the upper hemisphere because the resonant neutrinos are attenuated with an effective attenuation length of about 1100 kmwe, restricting them to arrival directions of above a few degrees below the horizon (<94 degrees for DUMAND). On the upper side, the resonant W^- muons will arrive predominantly beyond 80 degrees in zenith angle (target thickness limitation), and so they are constrained to a fairly narrow 15 degree range of arrival zenith angles.

Putting in numbers we find a predicted rate of 50 near horizontal muons per year from W^- decay, as indicated in Figure 2, to be contrasted with the muons from charged current muon neutrino interactions expected at a rate of 2000/yr in similar energy ranges, but from the whole lower hemisphere. It does thus appear difficult to distinguish the electron neutrino signal from the muon neutrino signal only by muon detection. The benefit of a detector that has the capability to observe neutrino events arriving from near and slightly above the horizon for observing muons is evident, and the benefit of the ability of a detector to sense UHE cascades from nearly a km^3 volume is also evident for 6.4 PeV electron neutrino detection.

The various predicted AGN rates and expected atmospheric rates for comparison are summarized in the Table I.

Other Means of Detection?

The above estimate of ordinary UHE cosmic ray muon background as relatively negligible even at the earth's surface compared to resonant W^- production suggests that one might search for the W^- cascade events in other detectors of sufficient mass (megaton range), in such instruments as MILAGRO, NET or GRANDE. Even though events will be down or side-going and not upcoming, they would not resemble Extensive Air Showers, because of their point origin (EAS of these energies arrive as a nearly plane wave of lateral extent of order 100 m). Single unaccompanied hadrons or gammas are similarly unlikely at these energies. Such detectors will not generally see the muons from distant W^- decays, except in a narrow acceptance region around the horizon.

Present and future underground detectors such as IMB and Superkamiokande are probably not large enough to see the resonant W^- cascade signal in contained events. Even if big enough, the dynamic range requirements are daunting for detectors designed to observe events to as low as a few MeV. While showers of such energy would not be likely to be contained, there should be many entering cascades from interactions in the surrounding rock. Perhaps some of the peculiar cascades seen in the old Kolar Gold Fields neutrino experiments were hints at this?

The resonance energy is near the acoustic detection threshold calculated years ago for particle cascades(5), and a look at that work suggests that the signal-to-noise in the deep ocean would be near 0db for 100 m distances (near field, and assuming near thermal deep ocean high frequency noise background). Given the 45 hydrophones incorporated into DUMAND, it may thus even be possible to hear the events! For such events occurring within 100 m or so of the array, the acoustic signal may perhaps be employed to reconstruct the interaction vertex.

Another tantalizing possibility is the employment of radio detection in ice, RAMAND, as a Soviet group has been pursuing at Vostok Station in the Antarctic over the last few years. New threshold calculations(6) indicate that 5 PeV would be detectable in microwaves at 1 km range in cold ice. The hypothesized AGN ν_e flux will doubtless encourage the the RAMAND group in their feasibility studies.

Summary

The new predictions of substantial muon neutrino fluxes from AGNs would yield readily detectable fluxes of >10 TeV muons in >10,000 m^2 neutrino detectors now under construction, and this flux may even be detectable in present instruments. As a bonus, these AGN neutrinos, if they exist at the level suggested by the Stecker et al.

model, will lead to such exotic opportunities as earth neutrino tomography, permitting us to measure the earth core density to a few percent by UHE neutrino absorption.

The model also predicts electron neutrino of 1/2 the flux of muon neutrinos which may well lead to detection of cascades from W^- resonant production at 6.4 PeV in massive detectors, as well as interesting fluxes of muons from distant interactions and subsequent W^- decays. Distinctive energy and angle distributions of ν_μ and $\bar{\nu}_e$ produced μs may permit separation of these fluxes.

While present generation detectors may just be large enough to detect the AGN flux, DUMAND should be able to collect such events even if the predicted flux is high by several orders of magnitude. The predicted AGN UHE neutrino flux may also open the way for new techniques to enter neutrino astronomy.

Acknowledgements

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Table I

Some estimated rates for AGN neutrinos and atmospheric background.

Event type Source (angle range)	Thresh Energy	Rate ($1/m^2/yr$)	IMB (1/yr)	DUMAND II (1/yr)
Muons			($400\ m^2$)	($20{,}000\ m^2$)
AGN $\nu_\mu \rightarrow \mu$	>2.5 GeV	0.17	70	
(90°–180°)	>25 GeV	0.17	69	3500
	>1 TeV	0.14	60	3000
	>10 TeV	0.089	35	2000
AGN $\bar{\nu}_e \rightarrow W^- \rightarrow \mu$	>10 TeV	0.274	110	50
(80°–94°)				
Atm $\nu_\mu \rightarrow \mu$	>2.5 GeV	0.47	180	
(0°–180°)	>25 GeV	0.22	90	4475
	>1 TeV	0.14	4	220
	>10 TeV	0.089	0.1	5
Cascades, contained	(E_{cas})	($1/10^9$ T yr)	(8000 T)	(2×10^6 T)
AGN $\nu_e \rightarrow$ cas	1.0 PeV	15000		30
AGN $\nu_e \rightarrow$ cas	10.0 PeV	2000		4
(0°–120°)				
AGN $\bar{\nu}_e \rightarrow W^- \rightarrow$ cas	6.4 PeV	7200	0.06	14.4
(0°–90°)				
uncontained				(2×10^8 T)
AGN $\bar{\nu}_e \rightarrow W^- \rightarrow$ cas	6.4 PeV	7200		1440
(0°–90°)				

Fig. 1: Integral spectrum of upcoming muons.

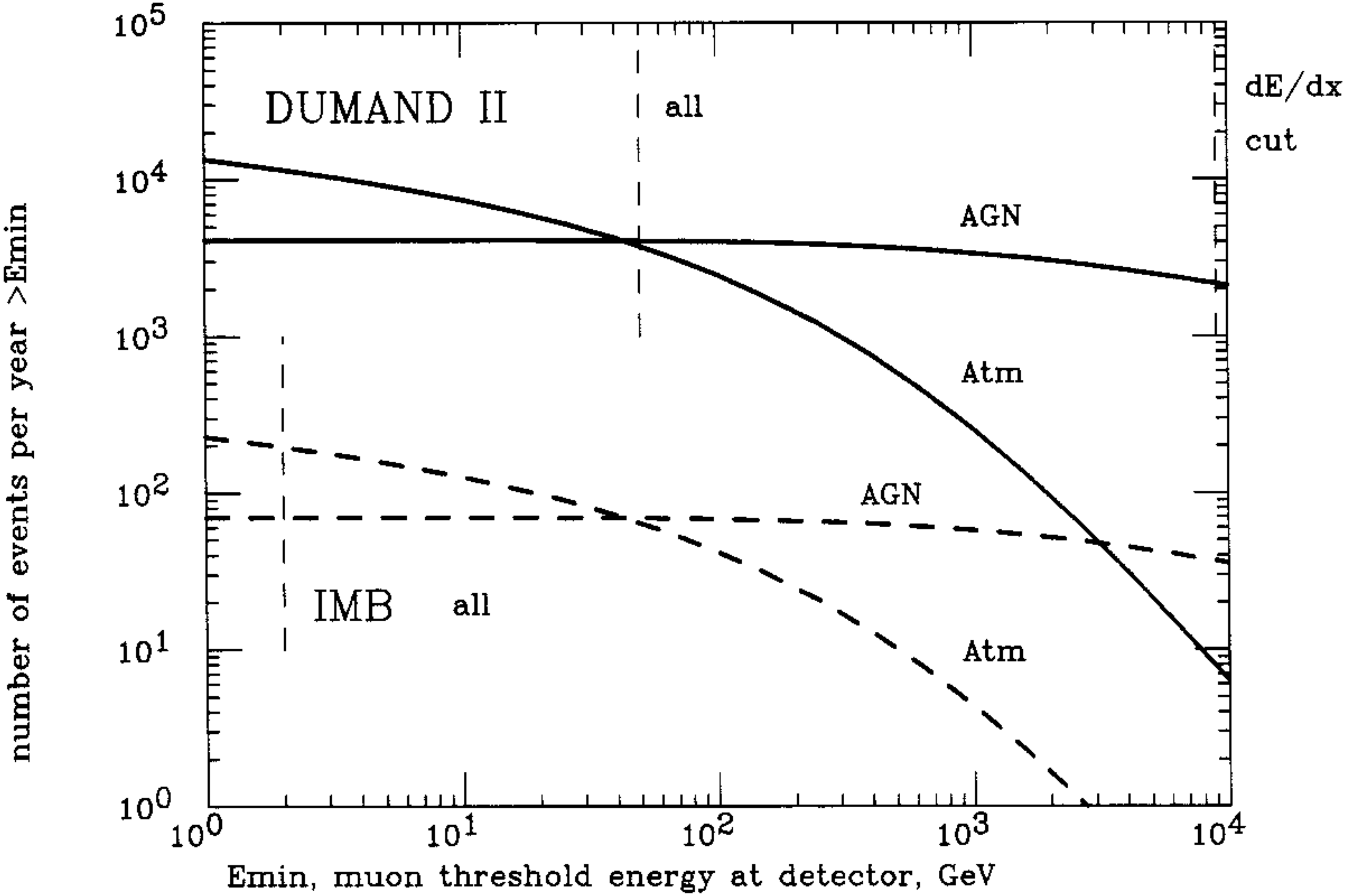

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Fig. 2: Muon angular distributions.

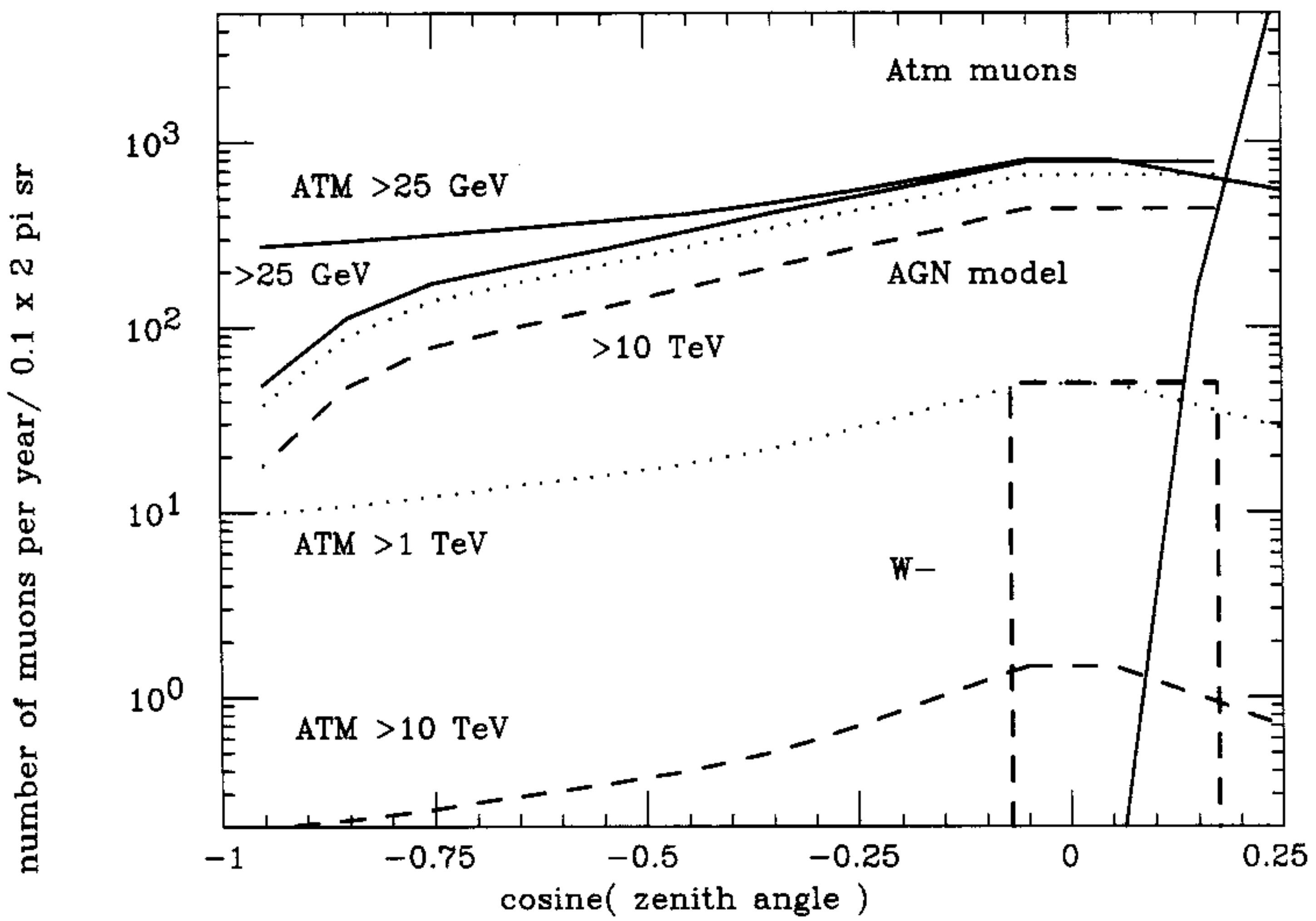

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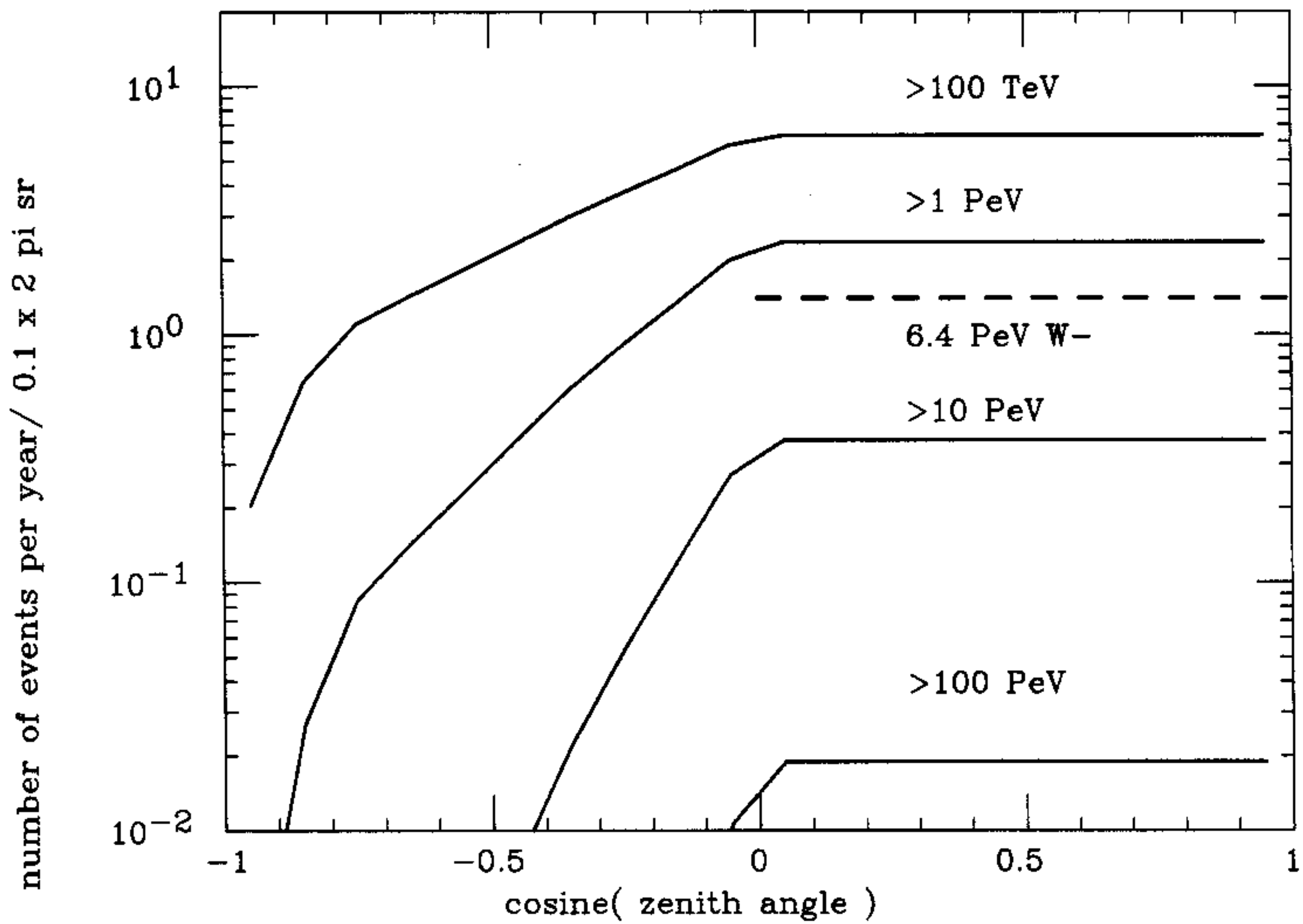
Fig. 3: DUMAND contained nu−e, AGN model



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