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Signal Detection Time and Energy Threshold in DUMAND II

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abstract

This is a short note to point out the strong benefits in point source neutrino signal detection time which result from making muon energy threshold cuts. It is suggested that we study means to improve low energy muon rejection. It is also shown that the time required to detect a signal in DUMAND II is about 1000 times shorter than in the existing underground detectors.

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The logical beginning of this exercise is presented in Figure 2.17 (from Mitsui et al, updated by Kitamura) of the DUMAND II Proposal, which shows muon spectra of both a hypothetical signal and the cosmic ray neutrino induced background events, included here as Figure 1. The point source signal is taken as the canonical Cygnus X–3 flux, producing 1 event per 1000 m^2 of deep underearth muon detector per year (it could be a factor of 30 larger). The background is taken to be that in an energy dependant cone angle determined by the weak interaction at low energies, and within a constant angle (determined by the detector resolution) at higher energies. One sees that the signal is quite flat as a function of muon energy, out to about 1 TeV. This is due to the well justified assumption of $1/E^2_\nu$ spectral dependance of the source. In contrast, the cosmic ray neutrino produced muon background falls off approximately as $1/E^\mu$, so the signal–to–noise gains steadily with increasing muon energy.

It is quite obvious that one gains greatly by having a higher muon energy threshold, which fact is not news to the DUMAND collaborators. What I want to discuss herein, however, and which has not been set down, is the effect of this on detection time. It is pretty obvious, but you may be a bit surprised by the numerical result.

A few caveats: the background is largest near the detector horizon, and minimum coming upwards, so there is some background dependance upon source location. There are also detection effects due to source observation time versus declination (full time in South beyond a declination of 60°, about 1/2 the time North of there). The detector area and energy threshold depend upon detector zenith angle too. I am going to ignore all these in this note in order to focus upon the scaling of detection time, using a Cyg X–3 as a near worst case example. A better job with full Monte Carlo simulation needs to be done (hint).

In the attached figure I have plotted the time needed for detection of the putative signal mentioned above. The detection requirement is the same as that in the proposal: ≥10 signal events and ≥ 5 standard deviations over the background. The time required for detection is given by:

$$t_d = \mathrm{Max}(\ t_1,\ t_2\ ) \tag{1}$$

$$t_1 = 10\ /\ (\ S * A\ ) \tag{2}$$

$$t_2 = 25 * N\ /\ (\ S^2 * A\ ) \tag{3}$$

where A is the detector area, taken as a constant 20,000 m^2 for this discussion. The lower solid curve applies to the 1 muon per 1000 m^2 signal flux level discussed above. On the low energy side the curve is dominated by the signal–to–noise ratio requirement (t_1), and on the upper side it is dominated by the minimum signal demanded (t_2). I have taken the background as the worst case, near horizontal, and the signal acceptance cone as 1° half angle. This will be somewhat representative of Cyg X–3 for DUMAND, because it does not go very far below the horizon (<30°) as seen from Hawaii.

Given the above assumptions, one would require a minimum time of about 0.3 years for detection with a threshold of 100 GeV. However, the DUMAND II range requirement in the near horizontal direction is only about 100 m, or about 20 GeV in muon energy, at which the detection time is 1.7 years.

A source in the far South will be better located to be near the natural minimum detection time for DUMAND, because bith the detector muon energy threshold is higher (about 50

GeV) and the background is lower (about a factor of 2). This would apply to sources such as those in the LMC or in Vela.

Also plotted are curves for a flux 1/3 and 1/10 the nominal value. One sees that the minimum detection time shifts to higher muon energy threshold, pushing up to a TeV for the latter case, and a detection time of 5 years. However, if we operate only with the 100 meter muon range requirement under the assumtion of this low flux, the detection time will be a depressingly long time (150 years or so!). One possible improvement comes from employing a data cut on energy deposition rate along the track. This was illustrated in the proposal by figure 2.11 (figure 2 here), showing the distributions of measured log(dE/dx) for atmospheric neutrinos and a flat spectrum neutrino source. We have thus long ago noted that we can get a factor of 8 increase in signal–to–noise ratio with only a modest penalty of a factor of 2 in signal. For the nominal Cyg X–3 flux case this takes us from a detection time of 5/3 years to 2/3 year. For a flux smaller by 10 it helps by about a factor of four, going from 150 years to 38 years.

Lest you become too disturbed by these estimates, let me point out that we are using a rather small flux in this illustration, and in the poorest declination region for DUMAND. To set this in perspective, notice the dotted curve in figure 3, which curve applies to a detector the size of IMB, 50 times smaller in area. Worse yet, the IMB threshold is about 2 GeV for through going muons, leading to a detection time in IMB of greater than a thousand years for the assumed flux level! The DUMAND II detection time is shorter by a factor of 1000 for this case. This comparison applies similarly to Kamiokande and MACRO.

On the optimistic side for DUMAND II, things are better for Southern hemisphere sources, not only because of the higher muon energy threshold and lower background rate, but because the detector area is larger and the angular resolution is better. For higher energy muons one also gains in angular resolution and in detector effective area (see the results of Okada's Monte Carlo in ICRR Report–209–90–2). All to ld this helps by about an order of magnitude in detection time for such Southerly sources.

The conclusion of this exercise is that we should seek means to make muon energy threshold cuts on the neutrino data. One simple way to do this for the horizontal direction is to simply make the array large in diameter, for example by a factor of two, resulting in a similar decrease in detection time for sources such as Cyg X–3. It would also be nice to see some a scatter plot of energy versus angular deviation from the source, and to think upon what we can do with that correlation.

FIGURE 1

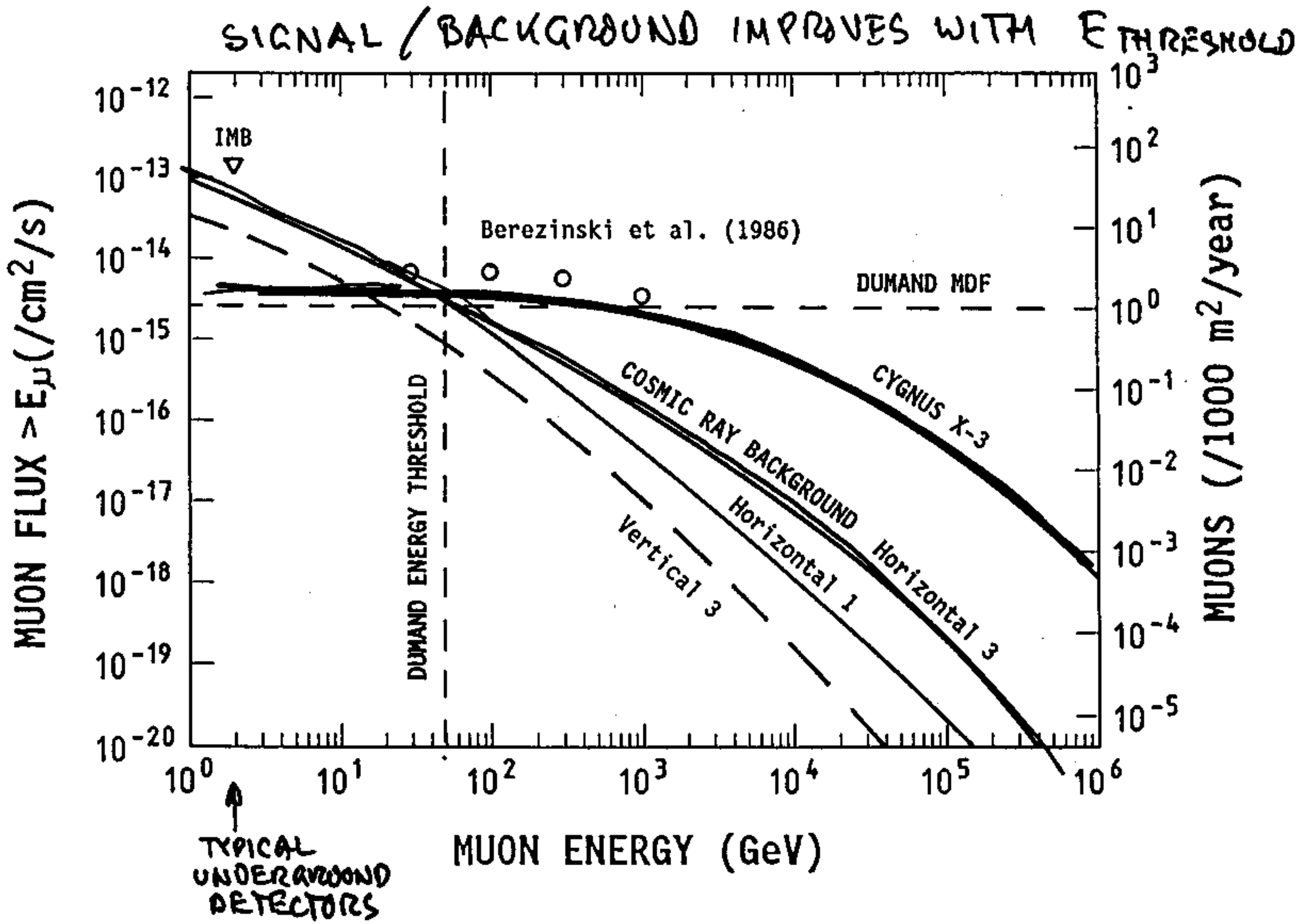

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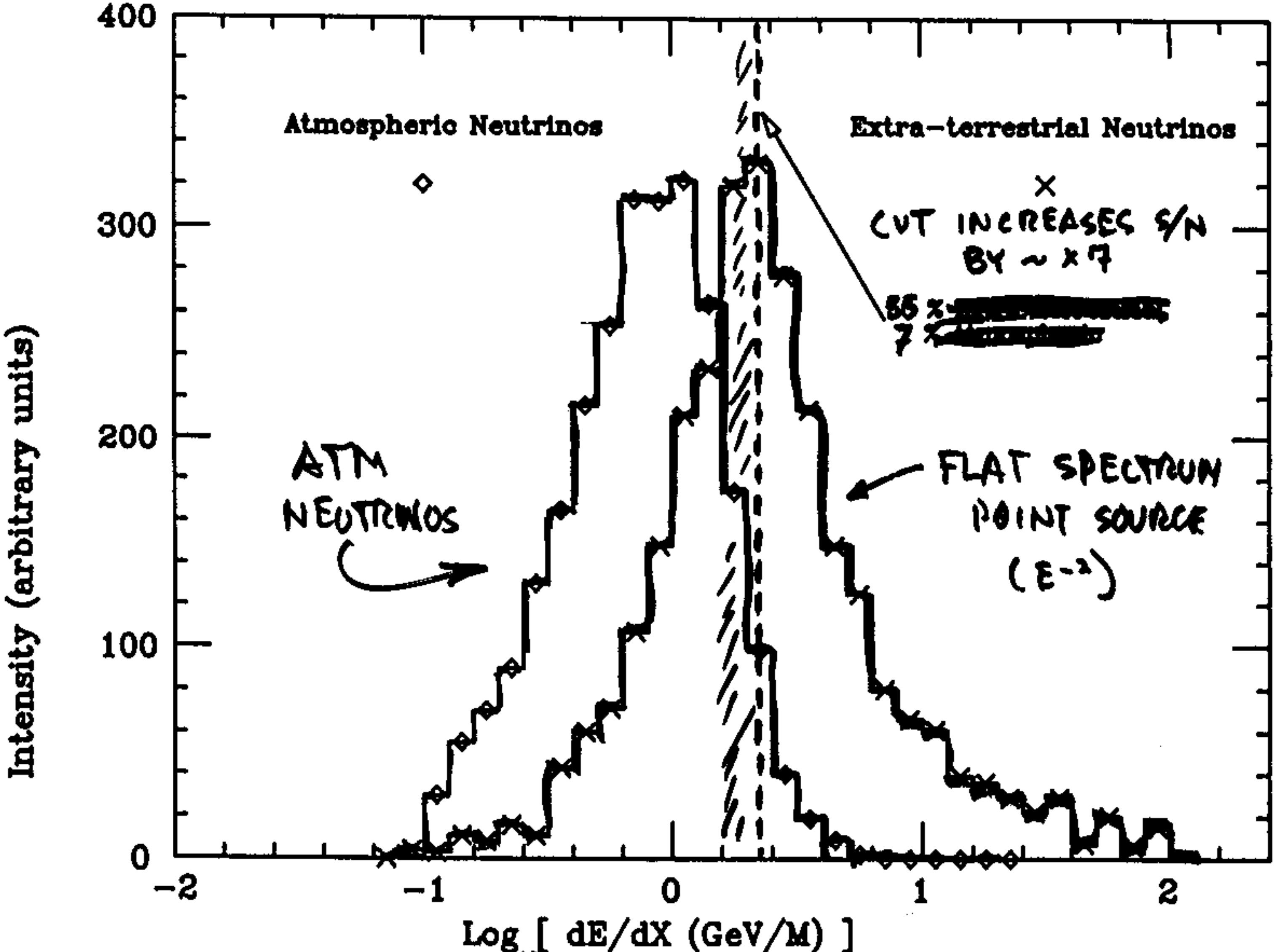
FIGURE 2

MONTE CARLO DATA

Intensity vs Log [Energy Loss]



"OBSERVED" ENERGY LOSS RATE
IN ARRAY

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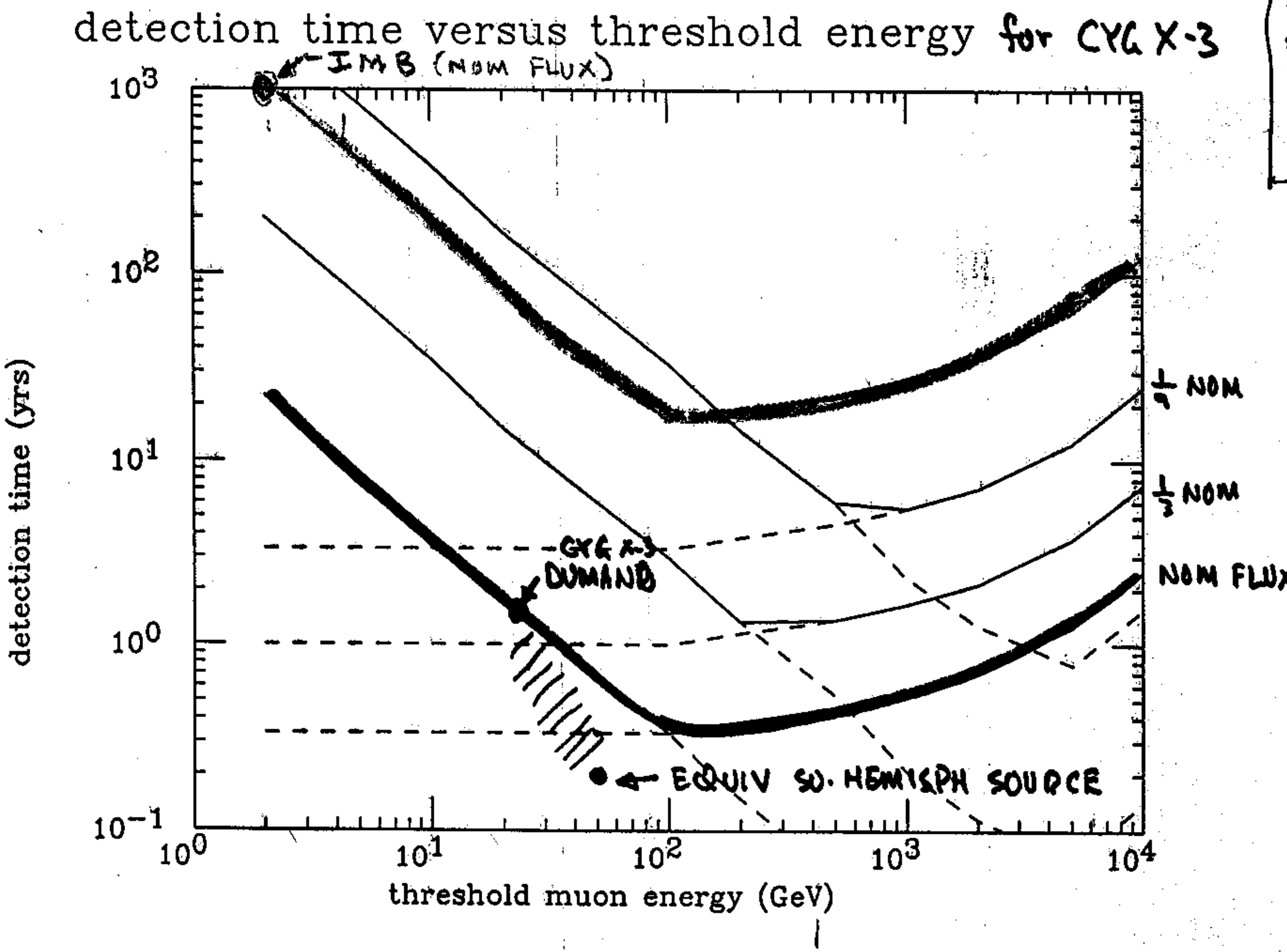
FIGURE 3



detection time versus threshold energy for CYG X-3
IMB (NOM FLUX)
CYG X-3 DUMAND
EQUIV SO. HEMISPH SOURCE
1/9 NOM
1/3 NOM
NOM FLUX
detection time (yrs)
threshold muon energy (GeV)
10^3
10^2
10^1
10^0
10^-1
10^0
10^1
10^2
10^3
10^4