Future of High Energy Neutrino Astronomy

John G. Learned

Department of Physics and Astronomy, University of Hawaii, Manoa
2505 Correa Road, Honolulu, HI 96822 USA

Abstract

The present status of experiments and prospects for future high energy neutrino astrophysics endeavors are summarized. Present and near-future underground experiments (7 mine based detectors, in the 100 - 1000 m^2 muon detection area range) may not be large enough to detect point sources of neutrinos. However, it seems that there are perhaps 6 third generation detectors (in the >10,000 m^2 class) in various stages of proposal, test or construction. Some of these will come to operation by the mid-nineties. The DUMAND II detector, now in construction for deployment in Hawaii for operation beginning in 1993, is described in some detail. Several novel detection techniques being explored elsewhere, particularly in the Antarctic, are briefly mentioned. Finally, it is pointed out that discussions are beginning for a much larger detector (or detectors) in the 10^6 m^2 class to be built around the turn of the century, conditionally upon the success of the next generation of instruments now under active testing and construction.

HDC-8-90
submitted to
Proceedings of the Venice Workshop on "Neutrino Telescopes",
13-15 February 1990

I Introduction

Neutrino astronomy has been a dream of many physicists since the mid '60s[1]. We hardly need remind the reader of the importance of neutrinos in cosmology, in that they are so numerous (outnumbering protons by 10^9 or so) that if they have only a small mass (>30 eV, summed over flavors), they may dominate the mass of the universe. Unfortunately there is no practical plan at present to detect these relic neutrinos, so we must begin with the much more easily detected higher energy neutrinos, which are also surprisingly abundant. For example, there are more cosmic ray neutrinos at the earth's surface and below, at all energies, than any other (free) particle of similar kinetic energy (eg. high energy muons).

One might attempt to 'see' the universe in neutrinos produced by nuclear processes, in the 10 MeV range. Unfortunately, though the fluxes of neutrinos due to stellar burning are high, we have had a very hard time even detecting our own sun (see the papers of Davis[2] and Suzuki[3] at this meeting). There is little chance in the foreseeable future of detecting these lower energy neutrinos from point sources beyond our solar system (or even the aggregate of many sources, as from the whole galactic nucleus), except in the case of the tremendous burst of neutrinos from a supernova, as was the case for the observation of supernova SN1987A by IMB[4] and Kamiokande[5]. However, the rate of Type II supernovae in our galaxy is generally thought to be no more frequent than one in 10 to 50 years[6]. Since this is a long time to wait, one would like to observe neutrinos from throughout our supercluster, but the distance makes detection impractical (>10^9 tons of heavily instrumented detector to sense SN out to the Virgo cluster[7]).

The DUMAND group has long recognized that the best beginning for neutrino astronomy is likely to be in the TeV neutrino regime, and via the use of detection of muons from ν_μ charged current interactions[8]. Since the νP cross section rises with energy, the muon range increases with energy, the angle between the neutrino and muon decrease with energy, and the cosmic ray neutrino background is more steep ($E_\nu^{-3.8}$) than expected sources (E_ν^{-2}), we expect that the signal–to–noise gains strongly with energy (see Figure 1). The rationale for anticipating flat neutrino spectra is fairly broadly based[9], coming independently from observations in gamma rays, acceleration models, and the

relation to the cosmic ray spectrum (and we have no example model for a steep neutrino spectrum). When all these factors are folded together, the time required to detect a given source falls with increasing muon threshold energy, out to an energy in the range of 100 GeV to 1 TeV[10] (see Figure 2). Depending upon the flux level, one soon runs out of signal, so further raising of the threshold is not useful. Hence a detector sensitive to >100 GeV muons is desirable, which corresponds to neutrino detection in the TeV range (for the hypothesized flat spectrum neutrino sources).

Given that TeV neutrinos are the best region to focus upon for beginning neutrino astronomy, the crucial design question is how large a muon detection area is needed to get into business? There have been calculations of neutrino flux based upon energetics of celestial objects[11], but all they really demonstrate is that detectable fluxes, even with existing underground detectors, are allowed. It is an amusing 'catch-22' that one of the motivations for building such neutrino detectors, which is that the enigmatic acceleration mechanisms are not understood, also prevents us from making definitive predictions of fluxes. This forces us to take an incremental exploratory approach, true to science but an unhappy situation for modern funding managers who prefer sure bets.

We do have one way to calculate lower limits on possible neutrino fluxes with reasonable reliability, and that is via the observations of very high energy (VHE, TeV energy range) and ultra high energy (UHE, PeV energy range) gamma rays. It is generally believed that at least the UHE gammas are beam dump products, not electromagnetic in origin. The somewhat delicate requirement of a target thick enough to make gamma rays, but not so thick as to absorb them (10 - 100 gm/cm^2), makes it seem *a priori* unlikely that one would see any gamma rays. While existing underground neutrino detectors, in the range of 100 to 1000 m^2 of muon counting area, could potentially detect point sources based upon the observed gamma fluxes, they have not yet done so (and sensitivity will only go up as the square root of time, unless a burst should be observed). Hence it seems that detectors one or two orders of magnitude larger in area, and with an order of magnitude higher muon energy threshold, may be necessary to detect the first neutrino point sources. However, it has been long recognized that probably a full 10^6 m^2 will be needed to really begin regular neutrino astronomy[12].

Thus because of the unavoidable insecurity in predicting threshold detector size, the brave souls working in the neutrino astronomy business need to be concerned about guaranteed additional and useful results from the massive detectors being planned or under construction. Fortunately this is natural because such huge detectors move into untrampled territory in several ways (more about this below). Considering that we have not even made muon detectors as large (in effective area) as gamma ray detectors as yet, there could be many surprises in store.

It is also worth pointing out that the only scientific group with the expertise to carry out these explorations is the high energy physics community: we cannot leave it to the astronomers. Neutrino astrophysics represents the essence of the much talked about convergence of astrophysics and particle physics: we shall be doing both astronomy and particle physics, to their mutual and synergistic benefit.

II Survey of HE Neutrino Detectors

The first natural neutrinos were observed in detectors located in deep mines in South Africa[13] and in India[14] in the mid–sixties. Prior to that, electron anti–neutrinos had been first identified at reactors, and then muon neutrinos at accelerators. The first experiments lasted for about five years and the larger of them, CWI, collected about 100 events. Another experiment in Utah collected a few events[15].

The first experiments did not have very good directionality, and for most events one could only deduce the projected direction. The energy threshold was low as well, in the 100 MeV range, so that one could not hope to do much with point source astronomy. Nevertheless these experiments made the first atmospheric neutrino flux measurements, and did set the first limits on extraterrestrial neutrino fluxes.

There was little activity in the field then for about a decade, until the search for proton decay became fashionable, in the late seventies. Since the early

eighties there have been 8 large detectors in operation, 6 of them are continuing, and several more are in various stages of proposal, feasibility testing, or construction (see Table I).

The 90's will see the completion of several new underground detectors, such as MACRO[16] and LVD[17] in Gran Sasso, and SuperKamiokande[8] in Japan, so that there will be about 9 ongoing experiments underground through the middle of the decade. These detectors are close to the limit that is practical in mines due to cavity stability. A summary of the larger underground neutrino detectors may be found in Table I.

The situation with respect to detectors beyond the underground instruments is less clear, as indicated in Table II. We can divide the new 10^4 m^2 initiatives into two classes: surface and underwater. In the former category are the GRANDE proposal[19], which aims at using a covered pond for extensive air shower (EAS) studies as well as upcoming muons for neutrino research. The detection, as in the deep water detectors, is via the Cherenkov radiation of particles in water, the light being sensed by large photomultipliers (PMTs). An exception in the surface category is the SINGAO proposal[20] which will employ novel resistive plate chambers. The second category is characterized by deep water Cherenkov detectors employing open natural bodies of water, generically of the DUMAND type, with strings of PMTs floating upwards from bottom moorings.

Some of the surface arrays are well described by other papers in these Proceedings, but the entries in Table II which have leading question marks are not well documented as yet[21]. The underwater approach is being pursued by the International DUMAND collaboration in Hawaii[22], about which more below, and other groups in the USSR. The Soviet approaches are described in the reports of I. Zheleznykh and N. M. Surin[23]. In looking at Table I one should be aware that deep underearth detectors have a solid angle advantage of about a factor of 3 over flat surface arrays, so that area comparison alone is misleading.

III DUMAND Hawaii

The DUMAND organization got started with a series of workshops in the mid-to-late seventies, with the goal of building a very large under-ocean detector. This stimulated the first serious considerations of types of neutrino experiments, venues, energy ranges, and techniques. The best location was soon realized to be in the abyssal deep off Hawaii (see Figure 3). It took several years to conclude that the most practical energy region for finding point sources of neutrinos was in the TeV range. Various techniques were explored, and in one case (acoustic detection) experimental work was carried out at accelerators. The DUMAND group finally settled upon the use of bare photomultipliers for detection of the Cherenkov radiation from muons in the deep ocean. Since the early '80's the collaboration has been engaged in studying the environment and backgrounds, developing the necessary technology, and carrying out system design studies. A prototype experimental demonstration (DUMAND I, see illustration in Figure 4) was carried out in 1988. Some results are shown in Figure 5.

The group received scientific approval in 1989, and final US DOE approval in April 1990, to proceed with a 20,000 m^2 octagonal array (see Figure 6), which is scheduled for full operation in mid-1993. The total project cost is estimated at US$10M.

The design goal for DUMAND II[24] was for a deep ocean moored instrument with 20,000 m^2 of muon area and an angular resolution of order of 1°. The configuration arrived at is an octagon of strings, with a ninth string in the center, illustrated in Figure 7. These strings will float upwards from a 4.8 km deep ocean bottom, about 30 km off the Island of Hawaii, at $19^\circ\ 44'$ N, $156^\circ\ 19'$ W. Each string consists of 24 optical modules, plus laser calibration units, hydrophones (3 per string), and environmental monitoring instruments. The strings will have instrumentation beginning 100 m off the bottom, optical detectors every 10 m for 230 m above, and a float package at the string top, some 350 m off the bottom, to provide tension to keep the strings near vertical in the small ocean bottom currents.

The 216 optical modules will consist of a mix of Hamamatsu R2018C and Philips XP2600 photomultipliers with 40 cm hemispherical photocathodes,

placed in 1 cm thick pressure tolerant glass instrument housings. Each module will have an electronics package with networked reprogrammable microprocessor. PMT high voltage and discriminator setting may be adjusted and verified. One can remotely monitor conditions in the module, including PMT noise rate.

The fast PMT data streams, consisting essentially of time-over-threshold pulses, will travel in parallel down each string riser cable on a multi-mode fiber optic link to a string bottom digitization and multiplexing package. The pulse start and stop times will be encoded to a 1 ns precision. The signals, including data from hydrophones and calibration modules, will be multiplexed and sent shoreward in two colors on single-mode fibers (one for each string) at a 256 Mdb rate per channel. This is illustrated in Figure 8.

There will be two fibers dedicated to the command and control network, which will also carry the clock synchronization from shore to each string. All nine strings will be attached to a junction box at the terminus of the 32 km shore cable. This 12 mm diameter cable will have 12 fibers in an insulated and armor jacketed (2 mm diameter) tube, which conductor also serves to transport power to the array (at 370 VDC delivered, 5 kw with seawater return).

The deployment operation will begin with the cable and junction box installation, scheduled for 1991. The cable will be layed from a standard oceanographic vessel (the UH R/V Moana Wave), and the junction box lowered by a passive line at the end of the operation. The shore end will enter the Keahole Point laboratory through a pipe, slant-drilled from the shore to emerge at a depth of approximately 20 m. The junction box design includes lights and television, which will permit on-line viewing of the touchdown and later connection operations. The junction box will also have some instrumentation to study environmental variations during the period before instrument string installation, as well as hydrophones for acoustic ranging.

In summer 1992 it is planned to place the first 3 strings on the ocean bottom, employing the SSP Kaimalino, as used for the prototype tests. This will be followed by the connection operation, to be carried out with a remotely operated vehicle (ROV), or a research submarine (there are several

options). The connection activity consists of pulling the cable from the string anchor package for about 200 m, and then plugging a connector assembly into the junction box. The strings will thus be removable, in case of need for service or replacement. The final six strings will be connected in 1993, by which time the software should well tested on 3 strings, so that data taking should proceed immediately. With funds, diligence, and a bit of luck, the first sources could be reported by 1994.

The physics to be carried out with the array has been described in detail in the Proposal[24], to which the interested reader is directed. The Monte Carlo predicted angular response is shown in Figure 9, and resulting muon detection rates versus zenith angle in Figure 10. DUMAND II will not be background limited for several years (this is in contrast to underground detectors, as indicated in Figure 2). It is a dangerous business to make predictions about detection of inherently unpredictable phenomena, such as the present case in the attempt to begin high energy neutrino astronomy. However, if the gamma observations at VHE and UHE are correct, we should expect to see at least a half dozen neutrino point sources with DUMAND II (see Figure 11).

DUMAND II will have some opportunity to resolve diffuse sources, such as the galactic nucleus, employing a dE/dx data cut as shown in Figure 12. There is the potential to carry out astronomy with the downgoing muons too. Calculations indicate that DUMAND II will have little chance to do this if the downgoing muons are at the 'normal' level expected from gamma rays[25]. But DUMAND II will be in a good position if the anomalous muon levels indicated by the Kiel and CYGNUS experiments are correct (μ production increased by a factor of 10 or more from conventional expectations, and if the resultant μ spectrum is not steeper than the cosmic rays).

In general DUMAND II will have no low energy ($<$ 10 GeV) neutrino detection capability, so that solar neutrinos and such will remain the exclusive domain of the underground experiments. However, it may be (depending sensitively upon some as yet undetermined parameters which can only be measured *in situ*), that DUMAND II will be able to at least confirm a galactic gravitational collapse neutrino burst recorded by other instruments.

There are cosmic ray and particle physics experiments to be carried out as well. An example of standard cosmic ray studies is the study of muon multiplicity, which relates to both cosmic ray composition and to interaction physics. Particle physics studies include a search for muon neutrino oscillations using the cosmic ray neutrinos (similar to that done with the underground detectors, but with far better statistics and slightly better solid angle). Another example is the search for various of the exotica proposed to resolve the cosmological dark matter problem (WIMPS, nuclearites, Rubakov process monopoles, etc.). Because of sheer size DUMAND II will push experimental limits to new levels on many fronts.

DUMAND will also have considerable capabilty for overlapping observations with detectors at other geographical locations. This is illustrated in Figure 13, which shows the zenith angle at DUMAND versus the zenith angle at several other sites for simultaneous observation of Cygnus X-3. One sees that DUMAND II will have substantial exposure (the tick marks in the figure are one hour apart) for observing neutrinos (zenith angle greater $>80^\circ$) while other locations, such at Gran Sasso and Soudan are observing the same source in downgoing muons (zenith angle $<<90^\circ$).

Finally, an experiment has been proposed to employ the proposed Fermilab Main Injector[26] (see predicted event spectrum in Figure 14). While convincing Fermilab to invest in the 30° downward neutrino beamline will certainly be difficult, the physics to be done is quite unique because the typically 20 GeV ν_μ's will have the possibility to experience significant matter oscillations in traversing the 6000 km distance to DUMAND[27]. For an optimal $\delta m^2 \approx 0.01$ ev^2, DUMAND II would observe a measurable deficit out to a (surprisingly small, due to resonance) mixing angle of $\sin^2(2\theta) \approx 0.02$[27] (see Figure 15).

IV Future Prospects

Beyond the third generation high energy neutrino detectors discussed above there are several prospects for the farther future. These are listed in Table II (which should be regarded with due caution). Igor Zheleznykh has described the far thinking investigations being carried out by the Institute for Nuclear Research in Moscow. These include employing microwave radiation from UHE

showers in ice (RAMAND), and acoustic detection in the ocean. Explorations are now beginning, as well, for the possibility of employing Cherenkov radiation in the deep clear antarctic ice (see paper of R. March in proceedings of the previous Venice workshop[28], and the 1989 Bartol workshop[29]). There have even been discussions of neutrino detection on the moon (see NASA workshop Proceedings[30]).

All of the above mentioned detection possibilities are, unfortunately, quite a few years from practical application, and this author estimates that none will be realized before the turn of the millennium. Even if realized, the threshold energy may be very high for the microwave technique and the acoustic techniques, though surprises are always possible. The optical technique in ice is new, and we need to understand the environment (optical characteristics of ice, depth for bubble free ice, verification of lack of optical background, etc.) before realistic plans for a large detector can be put forward, which could take place within several years[31]. Hence it appears that the competitors for beginning very high energy neutrino astronomy in this decade will be (some of) the Soviet and Hawaii DUMAND detectors, and the GRANDE and SINGAO style detectors.

It is a healthy situation for there to be several such instruments, and with various techniques employed. The first signals are not likely to be large, so confirmation will probably be necessary (and usually teaches one something). The author hopes that a dector in the Mediterranean region will be built, as it would nicely compliment the Hawaii DUMAND. Such a pair of detectors would cover the neutrino sky at all times, an important capability since we know that the favorite galactic potential sources, the X–Ray binaries, are low duty factor objects.

Beyond the mid 90's we need to begin to contemplate the next step, which on a logarithmic scale suggests a 1 km^2 detector. While such a device will almost surely not be realized before the turn of the millennium, it is certainly not too soon to begin to work on the means to achieve such an instrument. The author's favored approach is an extension of the DUMAND approach, which does scale well to great size. It would appear that surface arrays become unreasonably expensive at such sizes due to civil engineering costs and the high photocathode (or counter) density needed to reject downgoing background.

We know from the extensive DUMAND Monte Carlo studies that we need about 1 optical module (>35 cm PMT) per 100 m^2 of detector muon area, so that such an instrument would require about 10^4 such modules. At a cost of US\$$10^4$ per module, in large quantities, integrating over all project costs, such an instrument would be in the US\$100 Million class. While this cost scale is reasonable by present day accelerator standards, it will probably require a large international collaboration to obtain the necessary resources.

However, in order to proceed with such grand visions we must have success in detecting the first astrophysical point sources of high energy neutrinos in the shorter term. Indeed the physics might point in other directions, which we cannot now know. Perhaps also, new technology will come along that will make other techniques more attractive. We must continue exploring detection technology, and most important, make the upcoming generation of instruments work as well as planned.

Acknowledgements

The author would first like to thank Prof. Milla Baldo–Ceolin and the other hosts for a wonderfully organized meeting in a most delightful and stimulating setting. I want to thank all the DUMAND collaborators for the work of theirs upon which I have drawn so heavily for this report. I must say also that the material about other experiments reported herein may well be wrong, particularly in reference to those detectors in the proposal stage, about which I have used preliminary and in some instances guessed numbers. I think the scale of things presented herein (in Table II in particular) are about right, but one should be careful about inferring anything other than overall trends.

Footnotes and References

1) It is a little hard to say just who thought of the idea first, but early dreamers were certainly K. Greisen, M.A. Markov and F. Reines.
2) Ray Davis, these Proceedings.
3) A. Suzuki, these Proceedings.
4) R.M. Bionta, *et al.*, Phys. Rev. Lett. **58**, 1494 (1987).
5) K. Hirata, *et al.*, Phys. Rev. Lett. **58**, 1490 (1987).
6) S.T. Dye, University of Hawaii doctoral dissertation, December 1988 (preprint UH-511-667-89), contains a good summary of various means of inferring the supernova rate in the Milky Way. See also ref 7, below.
7) G.A. Tammann, Proceedings of the 1976 DUMAND Summer Workshop (hereafter D76), University of Hawaii, Honolulu, Hawaii, September 6-19, 1976, A. Roberts ed. (1976).
8) see D76, *op. cit.*
9) P. Bosetti, *et al.*, DUMAND II Proposal, HDC-2-88 (August 1988), section 2.2.5 and references therein.
10) J.G. Learned, Hawaii preprint HDC-7-90 (1990).
11) DUMAND II Proposal, *op. cit.*
12) D76, *op. cit.*
13) F. Reines and M.F. Crouch, Phys. Rev. Lett. **32**, 493 (1974).
14) M. R. Krishnaswamy, *et al.*, Proceedings of the 16th ICRC, Kyoto **13**, 14, 24 (1979).
15) H.E. Bergeson, *et al.*, Phys. Rev. Lett. **19**, 1487 (1967).
16) A. Marzari-Chiesa, these Proceedings.
17) A. Zichichi, these Proceedings.
18) A. Suzuki, these Proceedings.
19) H. Sobel, these Proceedings.
20) M. Ambrosio, these Proceedings.
21) M. Genoni, these Proceedings addressed issues pertaining to a GRANDE style detector to be located near Gran Sasso. M. Koshiba has widely discussed another GRANDE style detector, LENA. The Soviet DUMAND and GRANDE style efforts are from personal communications from I. Zheleznykh and A. Petrukhin.
22) The DUMAND Collaboration consists of groups from Aachen, Bern, Boston, Hawaii, KEK, Kiel, Kinki, Kobe, Okayama, Scripps, Tohoku, Tokyo, Vanderbilt, Washington and Wisconsin.
23) N. Surin and I. Zheleznykh, these Proceedings.
24) DUMAND II Proposal, *op. cit.*
25) V. J. Stenger, Hawaii preprint HDC-8-89 (1989), and DUMAND II Proposal, *op. cit.*
26) J.G. Learned and V.Z. Peterson, Proceedings of the Workshop on Physics at the Main Injector, Fermilab, 18 May 1989, Hawaii preprint HDC-5-89 (1989).

27) J. Pantaleone, Hawaii preprint UH-511-699-90 (1990).
28) F. Halzen, J.G. Learned and R. March, Proceedings of the 1989 Workshop on Neutrino Telescopes, Venice 1989, M. Baldo-Ceolin, ed. (1989).
29) F. Halzen, J. Learned and T. Stanev, Astrophysics in Antarctica, Newark, Delaware 1989, AIP Conference Proceedings **198**, eds. D. Mullian, M. Pomerantz and T. Stanev, 39 (1990).
30) see Session on Neutrino Physics, Physics and Astrophysics from a Lunar Base, First NASA Workshop, Stanford, CA 1989, AIP Conference Proceedings **202**, eds. A. Potter and T. Wilson (1990).
31) S. Barwick, D. Lowder, B. Price and A. Westphal at LBL are attempting to initiate studies of the suitability of Antarctic ice during the 1990-1991 season.
32) K. Tsui, Y. Minorikawa and T. Kitamura, Proc. 20 ICRC, Moscow, HE **4.3**-14 (1987).
33) J. Babson, *et al.*, Submitted to Phys. Rev. D, Hawaii preprint HDC-89-1 (1989).
34) J. Learned, Hawaii preprint HDC-4-90 (1990).

Table I
Summary of large underground instruments with high energy neutrino detection capability, 1960's through mid 1990's.

Detector, Location	Status	μ Area (m^2)	Dir Sens	Technique	Primary Purpose
KGF, South India	X	110	N	LS + FT	obs ν's
CWI, South Africa	X	10	N	PS + FT + Fe	obs ν's
Silver King, Utah	X	30	Y	WC + Ctrs + Fe	obs ν's
KGF, South India	R	20	N	St Tubes	PDK
Baksan, Caucasus	R	250	Y	LS tanks	ν's
IMB, Ohio	R	400	Y	WC	PDK
HPW, Utah	X	100	Y	WC	PDK
Kamioka, Japan	R	120	Y	WC	PDK
NUSEX, Mt Blanc	R	10	N	ST + Fe	PDK
Frejus	X	90	N	ST + Fe	PDK
Soudan I	R	10	N	ST + Concrete	PDK
Soudan II	C/R	100	N	DT + Concrete	PDK
MACRO	C/R	1100	Y	LS + ST +	Monopoles
LVD	C	800	Y	LS tanks + ST	SN ν's
SNO	C '96	300	Y	D_2O	Solar ν's
SuperKamiokande	P>'96	740	Y	WC	PDK
Borex	P	<100	Y	LS	Solar ν's

Key for Table:
P = proposal
T = testing and development
C = construction
R = operating
X = shut down
WC = water Cherenkov
ST = streamer tubes
LS = liquid scintillator
PS = plastic scintillator
FT = flash tubes

Table II
Summary of new initiatives in high energy neutrino astronomy.

Detector	Location	Status	μ Area (m^2)	Depth (mwe)	Techn	Threshold
DUMAND II	Hawaii	C '93	20,000	4,800	WC	20 GeV
Baykal DUMAND	Siberia	C '95	2,000	1,200	WC	10 GeV
SINGAO	S. Italy	T	15,000	10–0	RPC	2 GeV
GRANDE	Arkansas	P	30,800	0–50	WC	6 GeV
GRANDE type	Gran Sass	P	100,000?	0–65?	WC	8 GeV?
?? Medit. DUM	SW Grec?	D/T	?	4,000	WC	?
?? Sov. DUM, East	Pacific?	D/T	?	?	WC	?
?? GRANDE type	USSR	D	?	0–?	WC	?
?? LENA	Japan?	D	?	0–?	WC	?
?? GRANDE type	Austral	D	?	0–?	WC	?
SPICE	S. Pole	T	?	>1,000	WC in ice?	
RAMAND	Antarct	T	10^6	0–1,000	ice μwv	>100 TeV
?? World Detector	?	D	10^6	>4,000	WC	>100 GeV

Key for Table:

D = discussion
P = proposal (possible operational date)
T = testing and development
C = construction (operational date)

WC = water Cherenkov detector
RPC = resistive plate chamber
μwv = microwave detection

Figure Captions

1) Example of a predicted point source neutrino signal from Cygnus X-3 in DUMAND II and background to that signal from cosmic ray neutrinos, versus muon energy at a fixed location underearth[32]. Note improvement of signal-to-noise with higher muon energy threshold.

2) Detection time versus muon threshold energy for a hypothetical flat spectrum (1/E integral) neutrino flux in DUMAND. The flux is that which produces 1 μ/1000 m^2/yr from an infinite earth target. The background is taken to be worst case, near horizontal, as would be the case for Cygnus X-3 observed from anywhere North of the earth's equator. For the same flux level, the detection time for a Southern hemisphere source would be reduced as much as a factor of 10 (due to lower backgound and higher muon energy detector threshold in that direction) for DUMAND II. For comparison with underground instruments, a Cygnus X-3 flux that would take 1.4 years for detection in DUMAND II would require greater than a millennium in IMB (due to lower threshold and smaller area). The descending curves on the left are in the background limited region, while the slow rise on the right is due to signal limitation[10].

3) DUMAND location West of the Big Island of Hawaii, and within sight of the major astronomical observatories on Mauna Kea and Haleakala. The Hawaii DUMAND Center is located at the University of Hawaii, in Manoa Valley, on Oahu.

4) Sketch of the DUMAND I experiment, suspended below the research platform Kaimalino. The instrument string was about 60 m long and contained 7 optical detectors, 2 laser calibrators, 2 hydrophones, environmental monitoring and the digitization and control unit. Signals were sent to the ship for coincidence detection and recording on a single optical fiber[33].

5) Muon depth intensity relation as measured in the ocean by DUMAND I, along with previous data. Data was recorded at approximately 2, 2.5, 3, 3.5, and 4 km depths[33].

6) DUMAND II conceptual drawing, showing the cable descending the 20% subsurface grade West of Keahole Point, to the subsidence basin flat region at a depth of 4.8 km, with a cable run of about 32 km.

7) DUMAND II octagonal array configuration. There are 216 optical modules, 15 laser calibration units, 28 hydrophones, 10 environmental packages, and 9 string bottom digitizer/multiplexer/controller units.

8) DUMAND II connections are shown schematically. Data is transmitted in parallel to the string bottom, where it is digitized and multiplexed onto one fiber per string to shore. The shore cable carries 12 fibers and DC power for the array. There is a separate

duplex network for command and control, and for transmitting absolute clock time from shore to the strings.

9) The angular variation of the effective area for (minimum ionizing) muon detection in DUMAND II. The PMTs are faced downwards to maximize the response for upcoming muons from neutrino interactions. The simulated trigger algorithm involves close coincidences on any one string. (Figure from V.J. Stenger).

10) The angular variation of the predicted muon rate from muons generated directly in the atmosphere (downgoing), and from muons resulting from cosmic ray neutrino interactions (horizontal and upcoming). The total background for astrophysical source detection, predicted for DUMAND II at <3500 per year due to cosmic ray neutrinos, implies <1/3 per resolution bin on the sky per year.

11) A sample of predicted astrophysical neutrino fluxes versus source distance (in parsec). The vertical bars represent limits depending upon observations in gamma rays and reasonable model parameters (mostly the ν/γ flux ratio). The upper limits are just reached for underground detectors such as IMB, which are heavily background limited[24].

12) Monte Carlo predicted distribution of energy deposition for atmospheric neutrinos and a flat spectrum (1/E integral) source in DUMAND II. While individual energy measurements are not meaningful generally (except for multi-TeV muons), the distributions are fairly well separated. This can be employed in testing observed sources, measuring the spectral index, and in making data selection to search for diffuse sources[24].

13) The simultaneous zenith angle of a particular source, Cygnus X-3, at DUMAND and several other locations, as an illustration of the common observation capability of such detectors. For DUMAND II, all events beyond a zenith angle of 80° are taken to be neutrinos. Events arriving from smaller zenith angles will be dominated by downgoing muons. Hence for times when the source is in the lower right hand quadrant the source will be observable in neutrinos in DUMAND and in muons in the other detectors. The tick marks on the trajectories are at 1 hour intervals[34].

14) Muon energy spectrum predicted for a 6 month Fermilab Booster run with a neutrino beam directed (1/3 duty factor) at DUMAND II in Hawaii. Several thousand events could be collected in through going muons with energies above 20 GeV, with muons coming from 30° below the horizon towards DUMAND II[26].

15) Contours of constant flux depletion (10%) versus mixing angle and mass squared difference for a neutrino beam travelling from Fermilab to DUMAND Hawaii. Figure a) shows the vacuum oscillation case, which obtains for $\nu_\mu \rightarrow \nu_\tau$. The depletion is the same for both

neutrinos and anti-neutrinos. Figure b) Illustrates the case for $\nu_\mu \rightarrow \nu_e$, and shows significant matter effects, demonstrated by the large asymmetry between the prediction for neutrinos and anti-neutrinos. The existing limits from reactors are shown also[27].

FIG 1

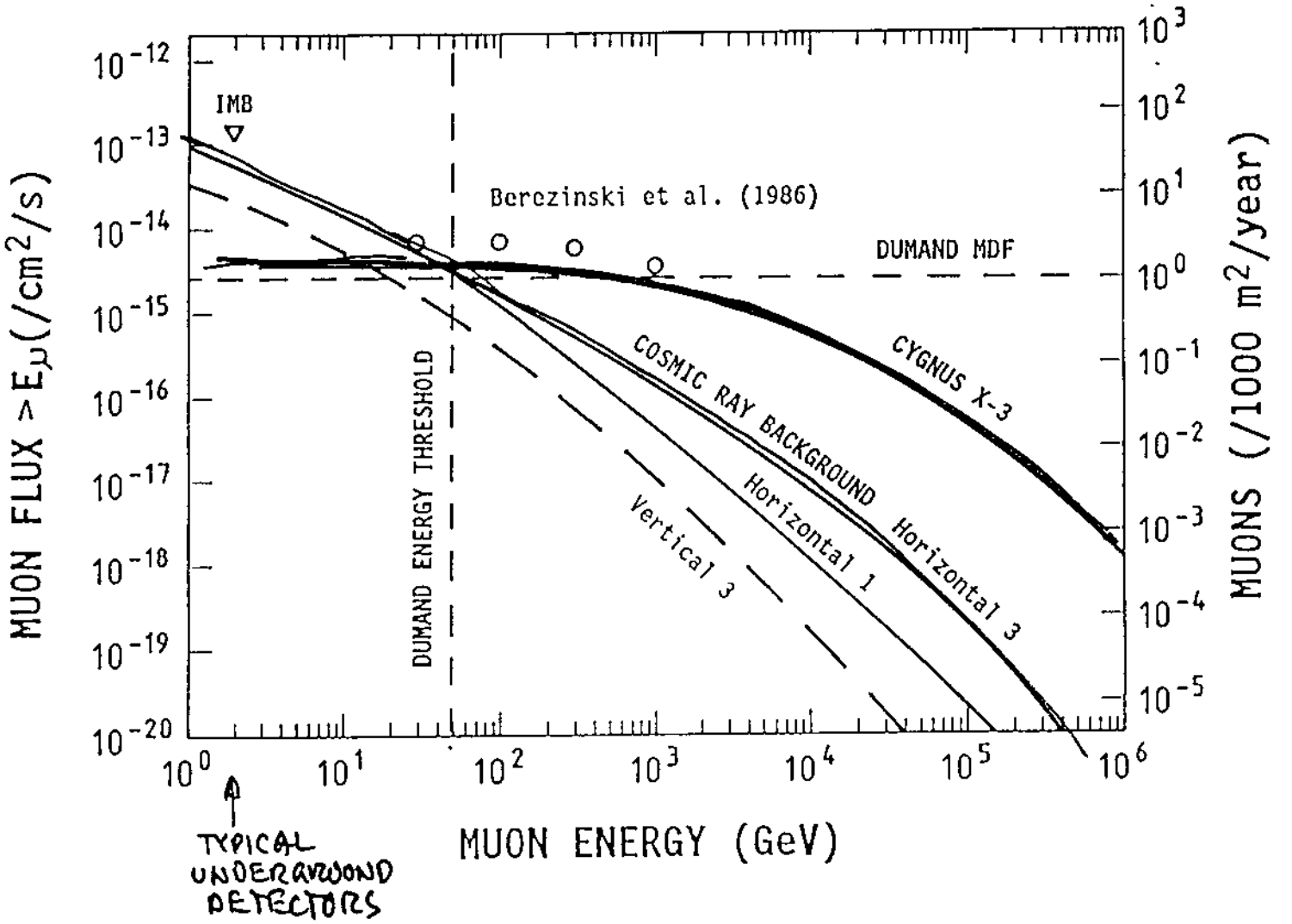

MUON FLUX > Eμ(/cm²/s)
MUONS (/1000 m²/year)
MUON ENERGY (GeV)
IMB
Berezinski et al. (1986)
DUMAND MDF
DUMAND ENERGY THRESHOLD
CYGNUS X-3
COSMIC RAY BACKGROUND
Horizontal 3
Horizontal 1
Vertical 3
TYPICAL UNDERGROUND DETECTORS

FIG. 2

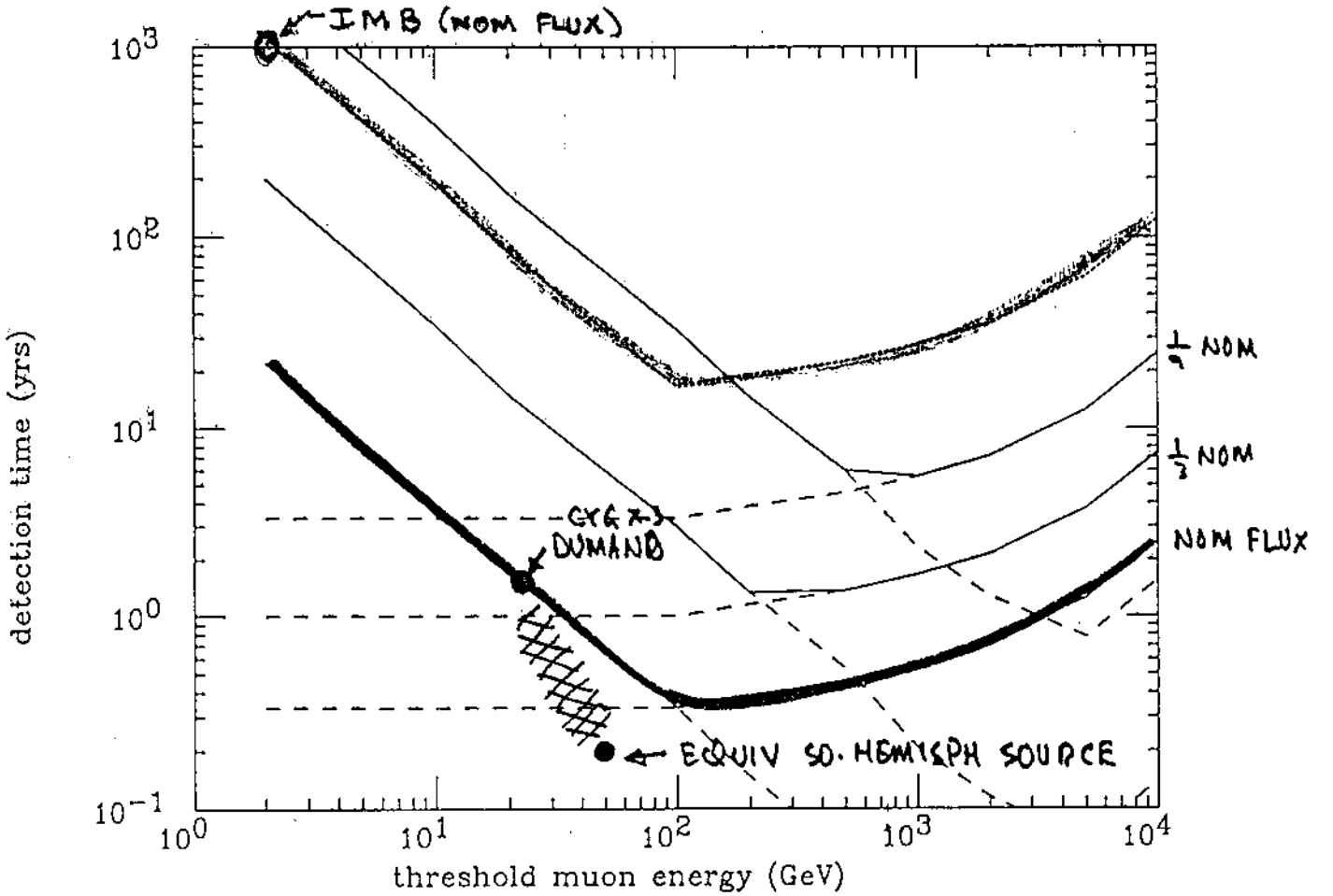

IMB (NOM FLUX)
10^3
10^2
10^1
10^0
10^{-1}
detection time (yrs)
$\frac{1}{9}$ NOM
$\frac{1}{3}$ NOM
NOM FLUX
CYG X-3
DUMAND
EQUIV SO. HEMISPH SOURCE
10^0
10^1
10^2
10^3
10^4
threshold muon energy (GeV)

FIG 3

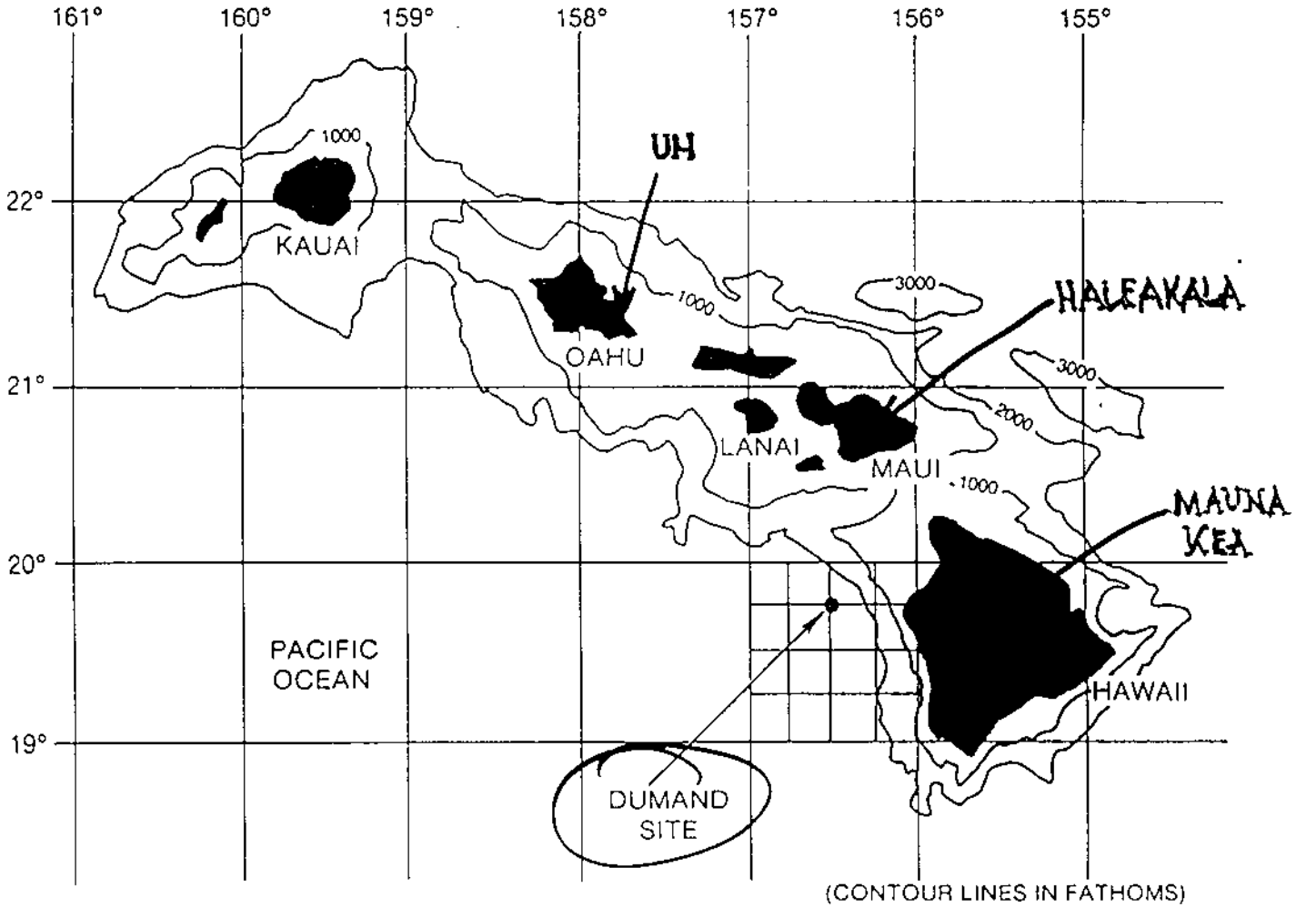

161°
160°
159°
158°
157°
156°
155°
22°
21°
20°
19°
1000
KAUAI
UH
OAHU
1000
3000
HALEAKALA
3000
2000
LANAI
MAUI
1000
MAUNA KEA
PACIFIC OCEAN
HAWAII
DUMAND SITE
(CONTOUR LINES IN FATHOMS)

FIG 4

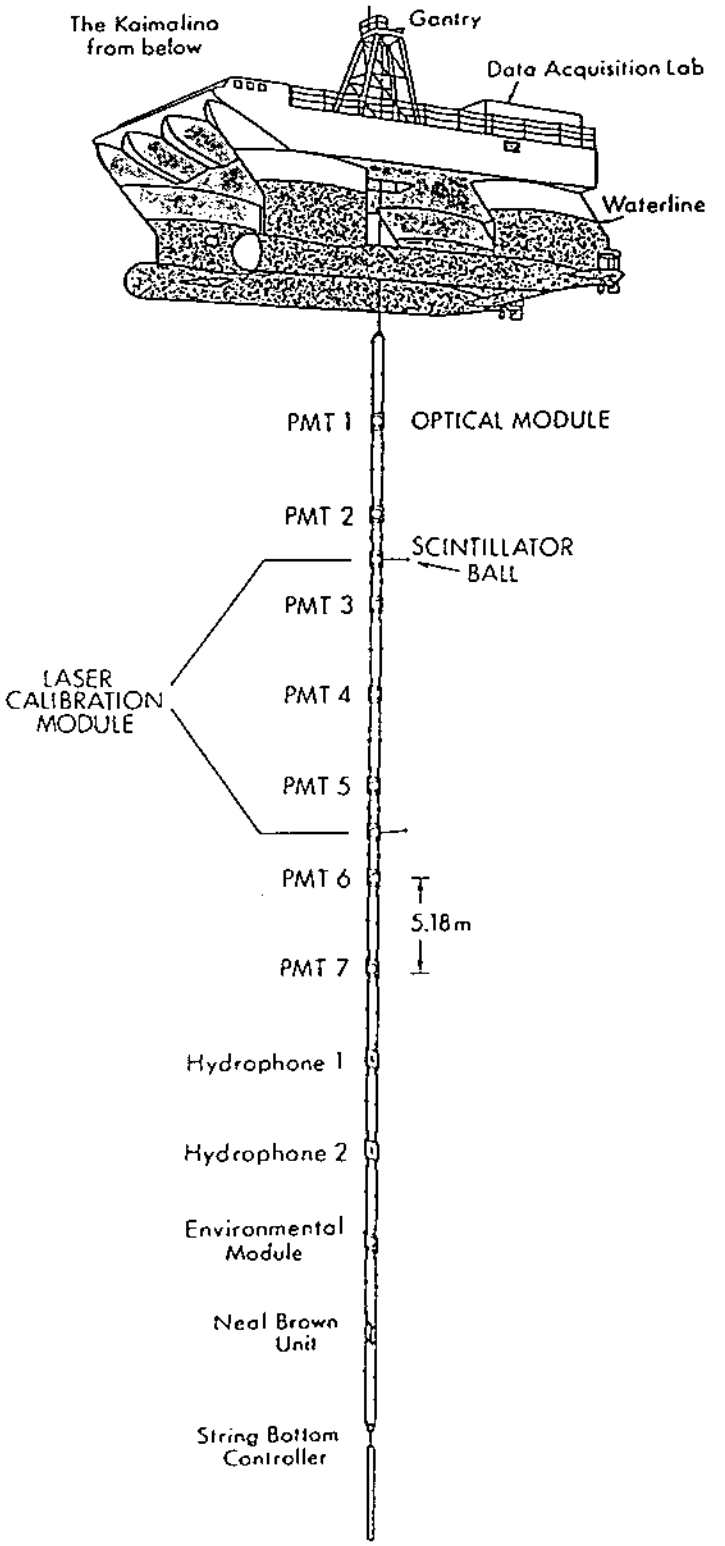

The Kaimalino from below
Gantry
Data Acquisition Lab
Waterline
PMT 1
OPTICAL MODULE
PMT 2
SCINTILLATOR BALL
PMT 3
LASER CALIBRATION MODULE
PMT 4
PMT 5
PMT 6
5.18m
PMT 7
Hydrophone 1
Hydrophone 2
Environmental Module
Neal Brown Unit
String Bottom Controller

FIG 5

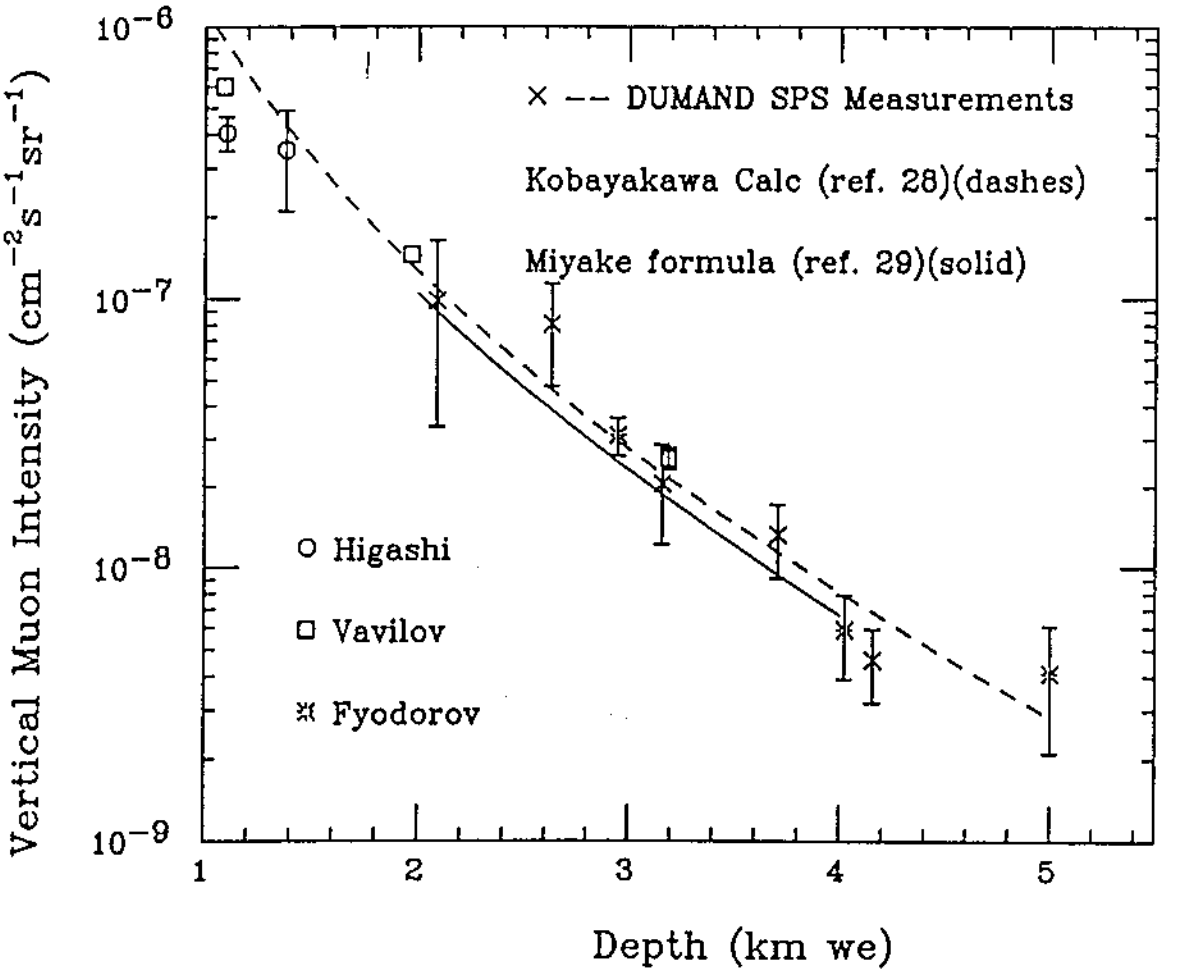

× -- DUMAND SPS Measurements
Kobayakawa Calc (ref. 28)(dashes)
Miyake formula (ref. 29)(solid)
○ Higashi
□ Vavilov
✳ Fyodorov
Vertical Muon Intensity (cm^{-2}s^{-1}sr^{-1})
Depth (km we)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
1
2
3
4
5

FIG. 6

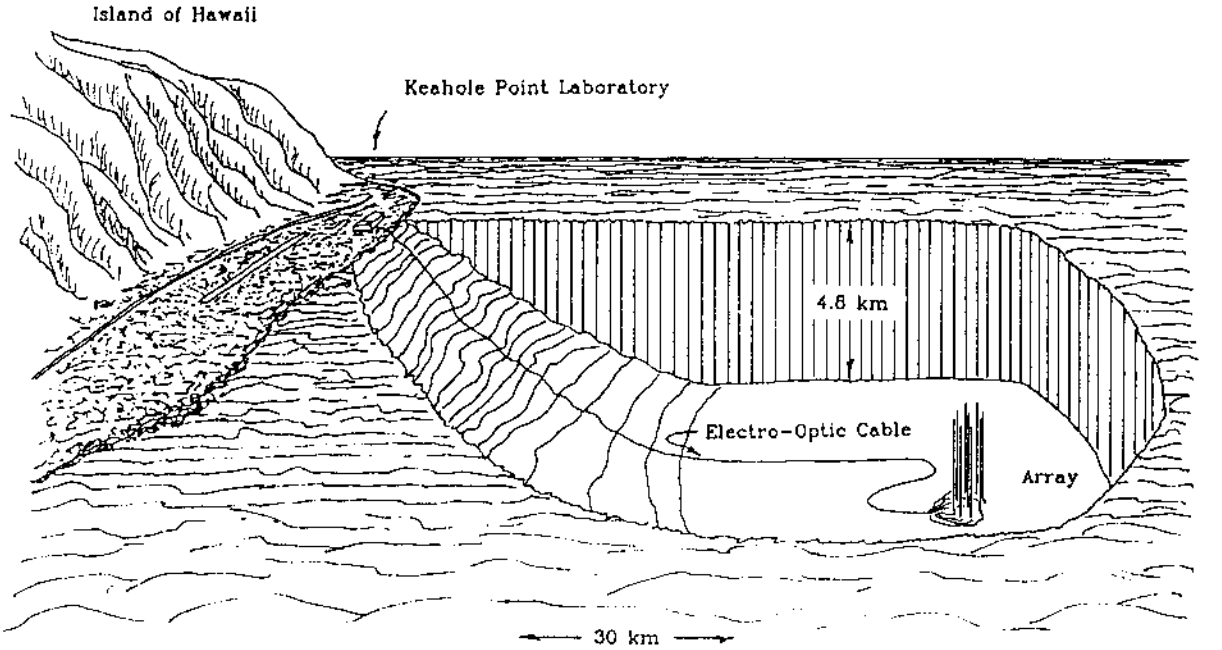

Island of Hawaii
Keahole Point Laboratory
4.8 km
Electro-Optic Cable
Array
30 km

FIG.7

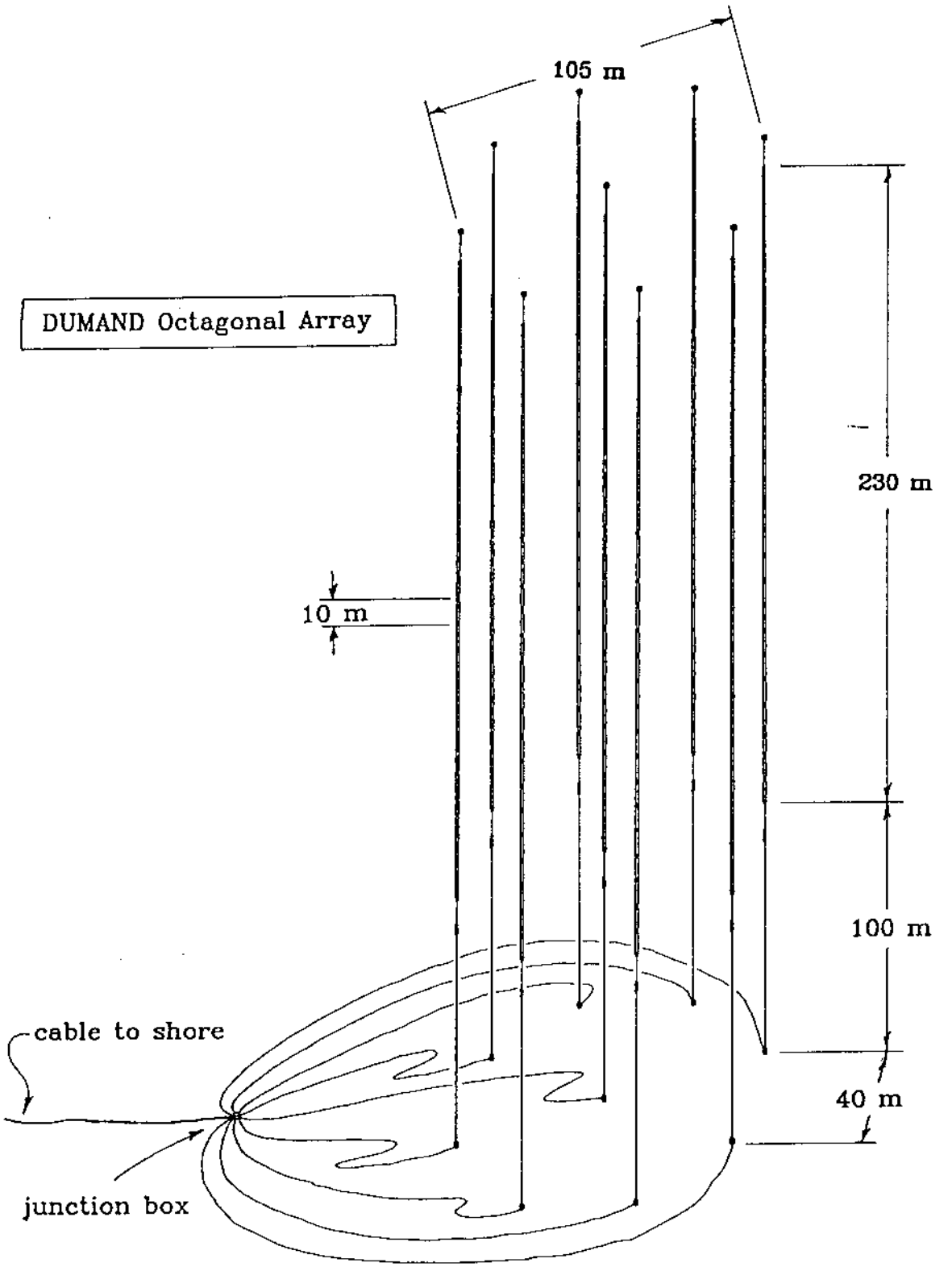

105 m
DUMAND Octagonal Array
230 m
10 m
100 m
cable to shore
40 m
junction box

FIG. 8

DUMAND II SCHEMATIC

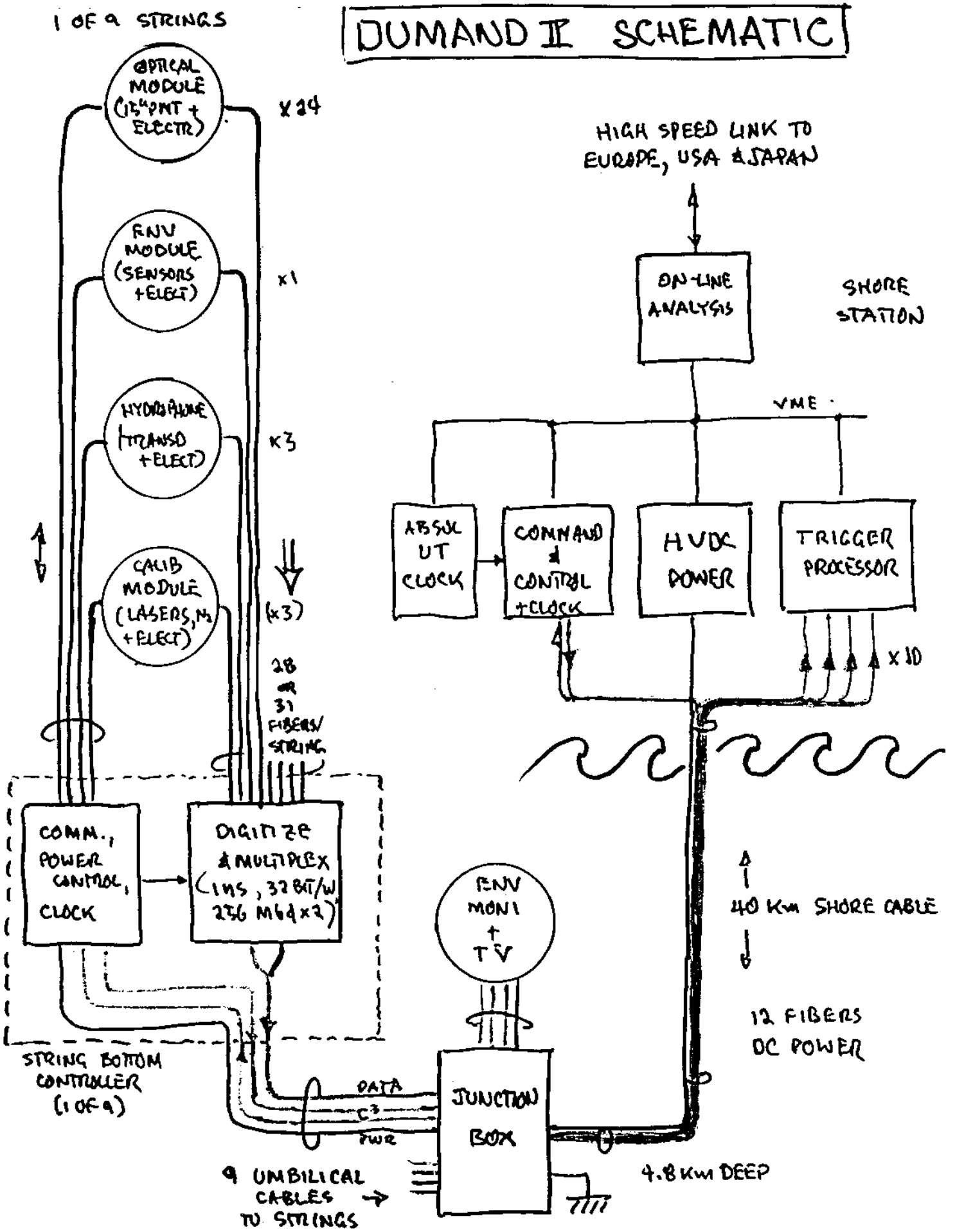


FIG.9

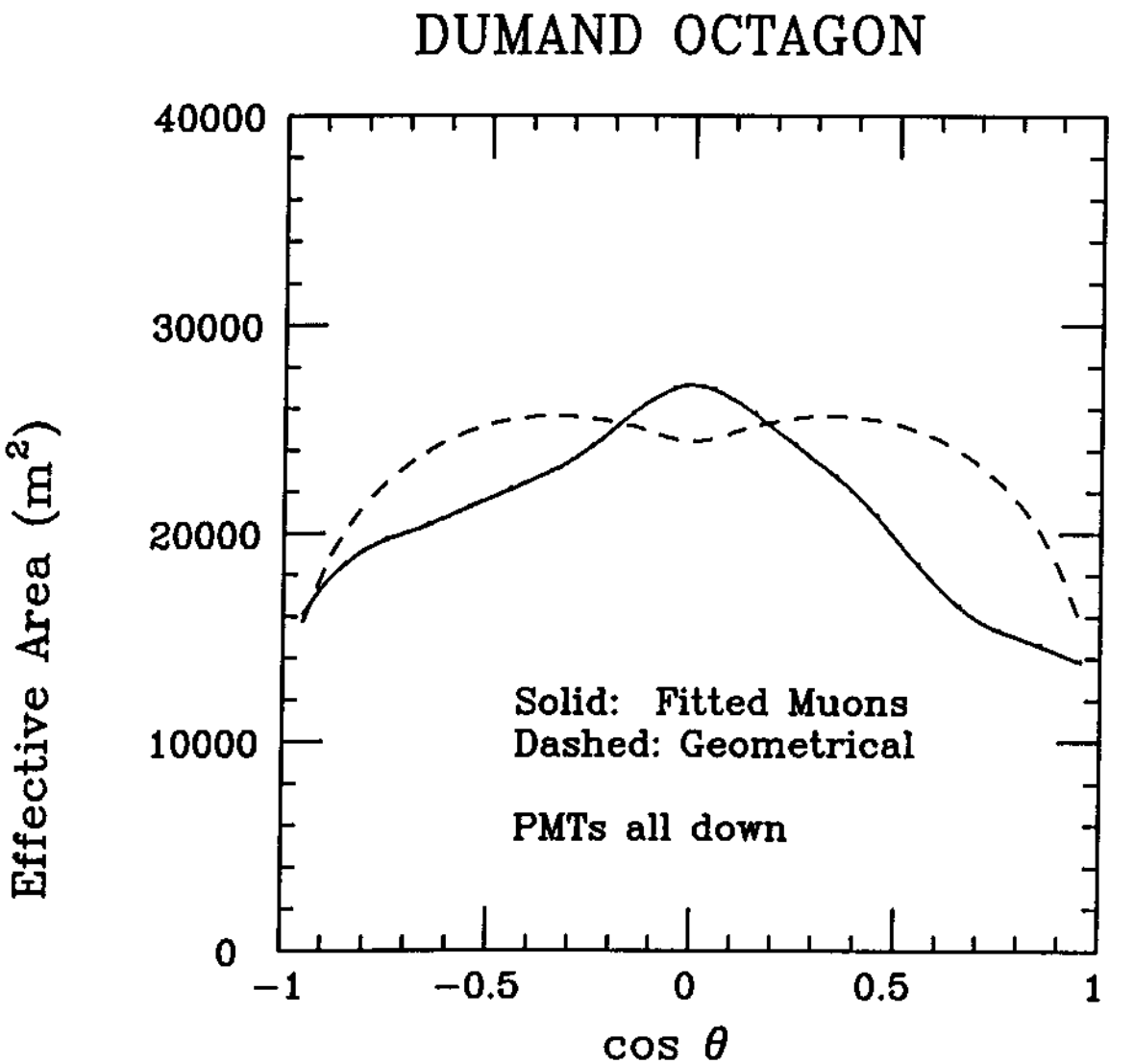

DUMAND OCTAGON
40000
30000
20000
10000
0
Effective Area (m²)
−1
−0.5
0
0.5
1
cos θ
Solid: Fitted Muons
Dashed: Geometrical
PMTs all down

FIG. 10

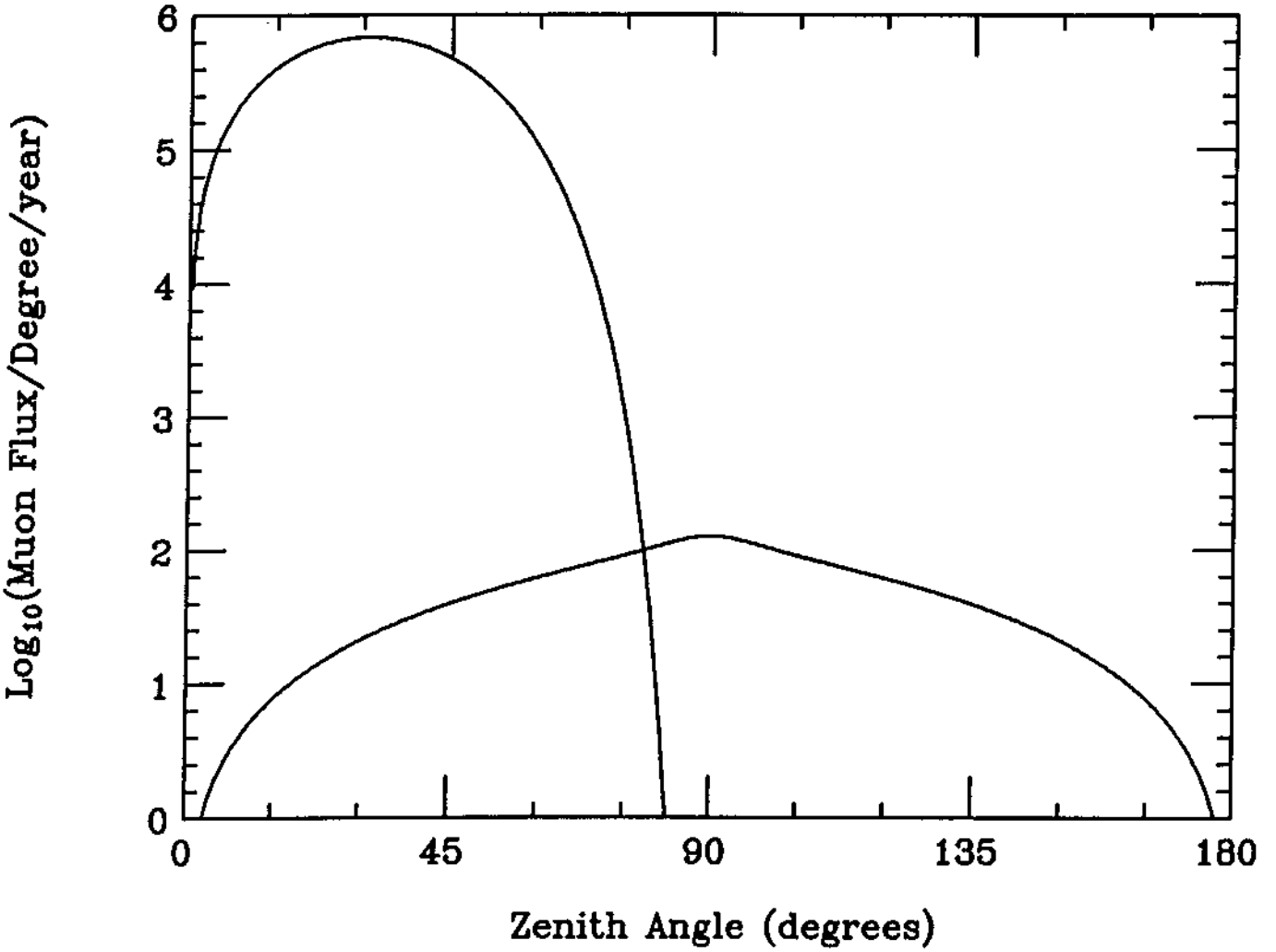

6
5
4
3
2
1
0
0
45
90
135
180
Log10(Muon Flux/Degree/year)
Zenith Angle (degrees)

FIG. 11

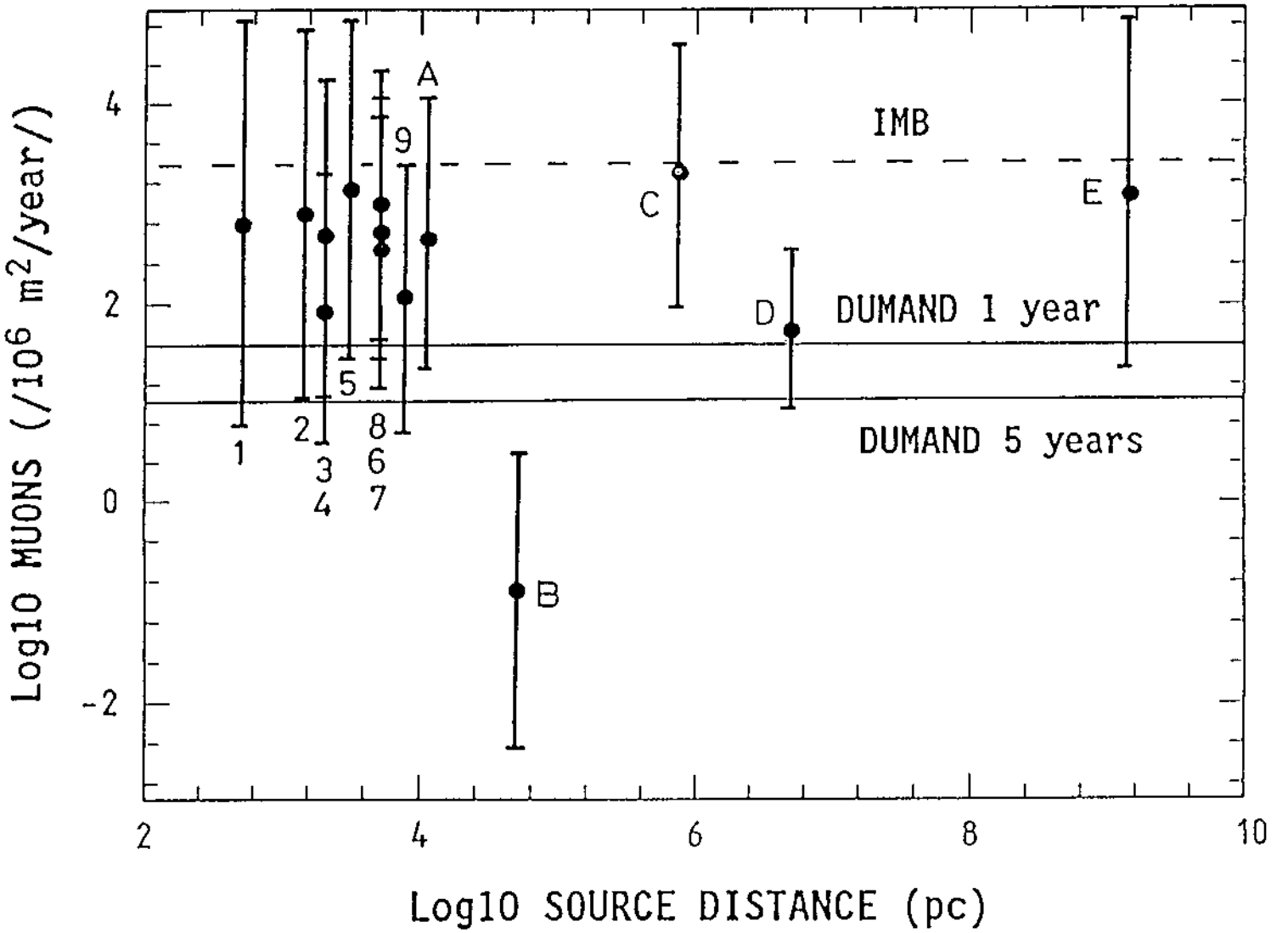

Log10 MUONS (/10^6 m^2/year/)
Log10 SOURCE DISTANCE (pc)
IMB
DUMAND 1 year
DUMAND 5 years
A
B
C
D
E
1
2
3
4
5
6
7
8
9
4
2
0
-2
2
4
6
8
10

FIG. 12

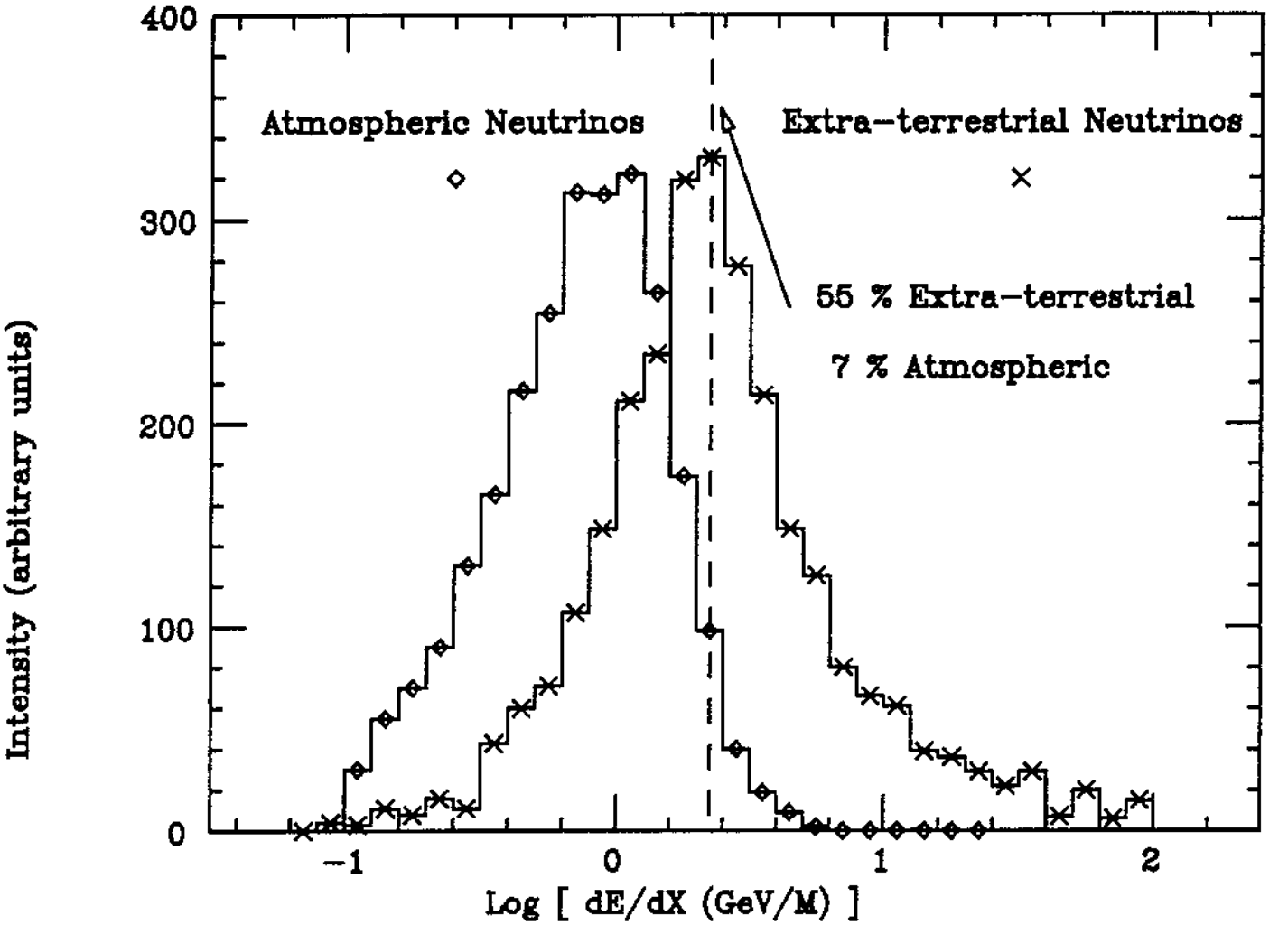

Atmospheric Neutrinos
Extra-terrestrial Neutrinos
55 % Extra-terrestrial
7 % Atmospheric
Intensity (arbitrary units)
Log [dE/dX (GeV/M)]
400
300
200
100
0
-1
0
1
2

FIG. 13

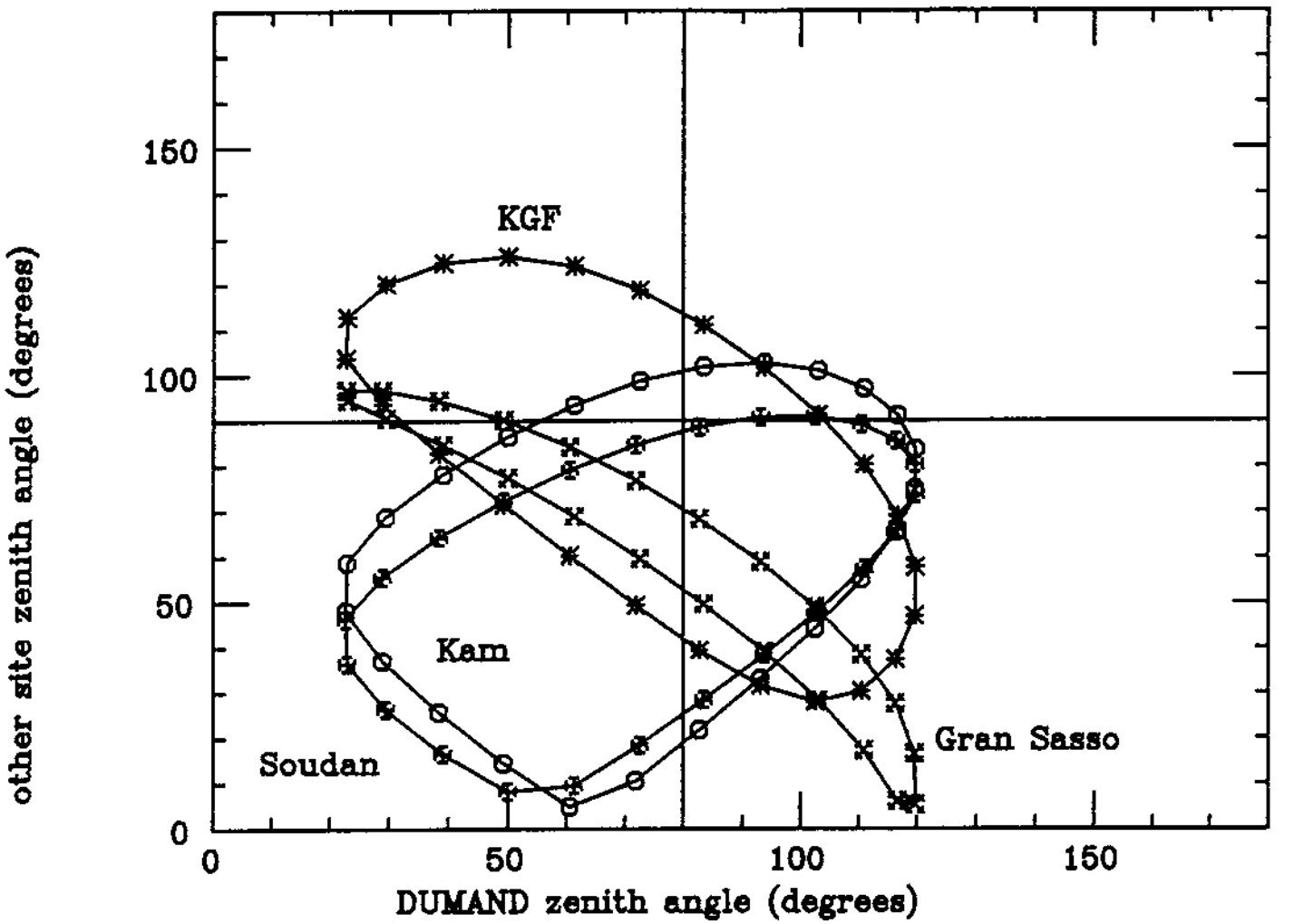

KGF
Kam
Soudan
Gran Sasso
other site zenith angle (degrees)
DUMAND zenith angle (degrees)
0
50
100
150
0
50
100
150

FIG. 14

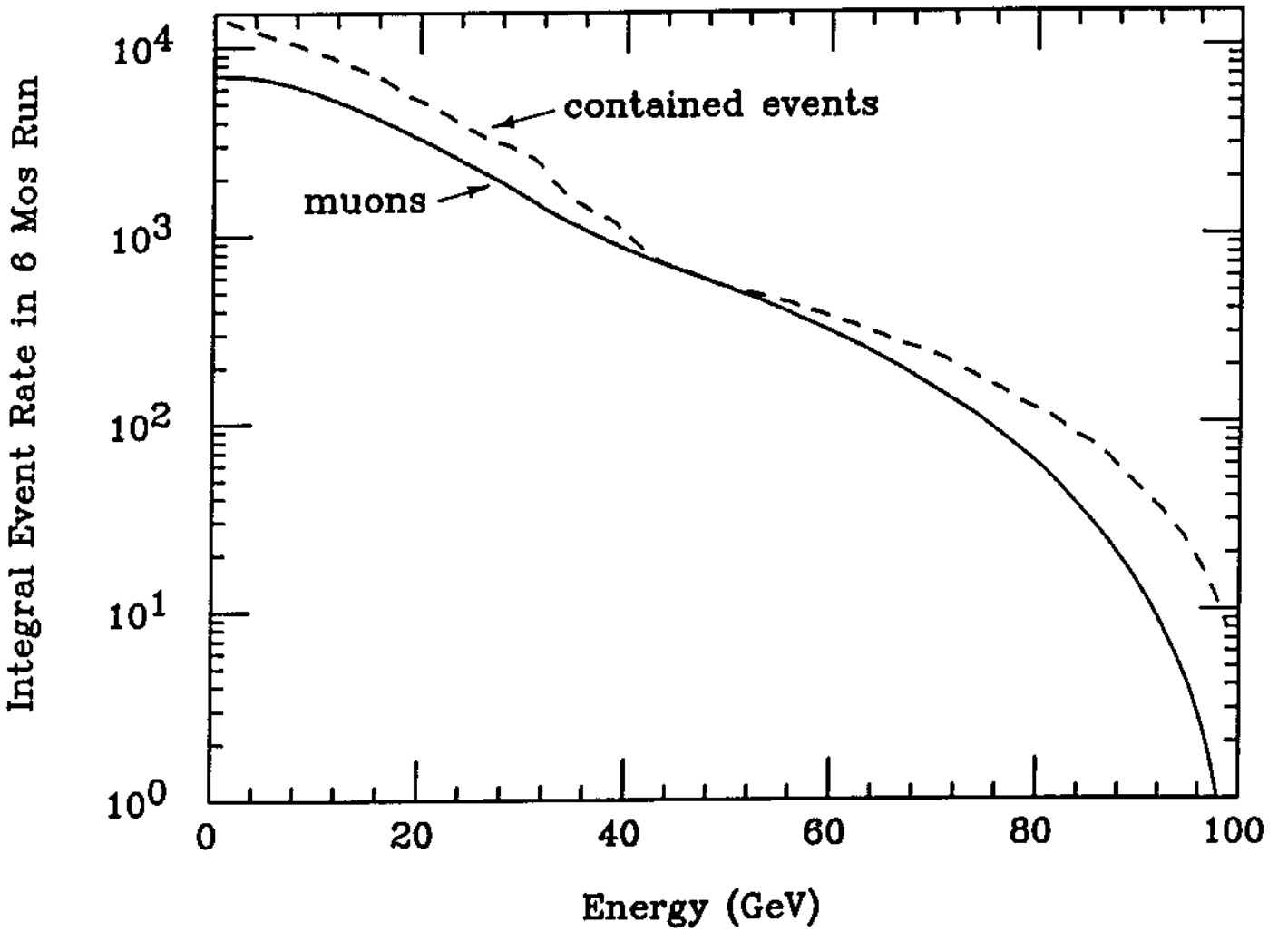
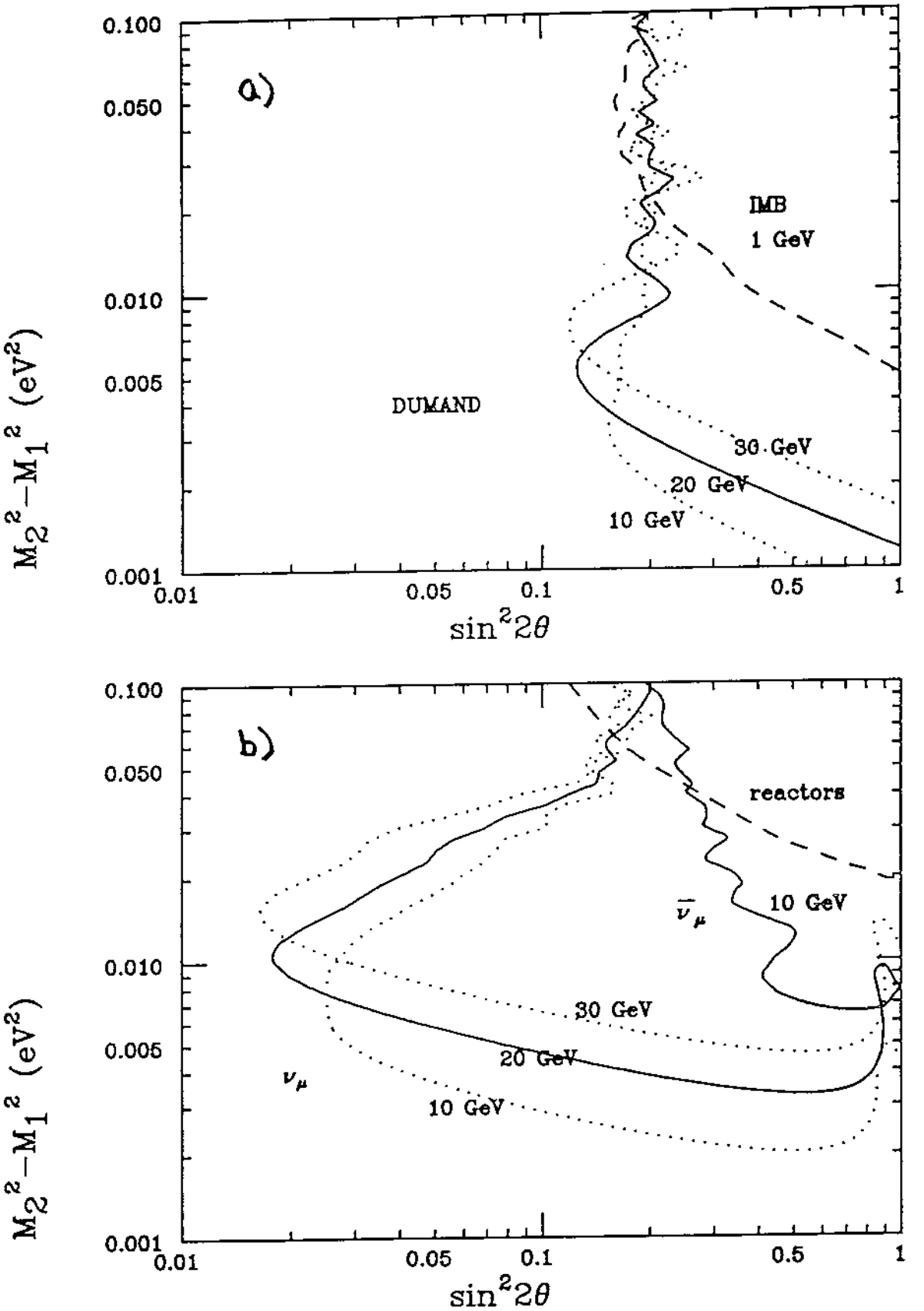

Integral Event Rate in 6 Mos Run
10^4
10^3
10^2
10^1
10^0
contained events
muons
0
20
40
60
80
100
Energy (GeV)

FIG. 15


a)
0.100
0.050
0.010
0.005
0.001
0.01
0.05
0.1
0.5
1
$M_2^2 - M_1^2$ (eV^2)
$\sin^2 2\theta$
IMB
1 GeV
DUMAND
30 GeV
20 GeV
10 GeV
b)
reactors
$\bar{\nu}_\mu$
10 GeV
30 GeV
20 GeV
ν_μ
10 GeV