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NEUTRINO ASTROPHYSICS IN DEEP UNDERGROUND DETECTORS

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Abstract. The present observational status of higher energy neutrino astrophysics employing large underground detectors is reviewed.

1. Introduction

The interest in *neutrino astronomy* is connected with the great penetrating power of neutrinos, which allows to look deeply into the interior of a star and into distant cosmological sources.

Low energy neutrinos of $\sim$ 1 MeV come continuosly from the interior of stars like the sun; slightly higher energy neutrinos ($\sim 10 - 14$ MeV) come in bursts from supernovae explosions. High energy neutrinos, with hundreds of GeV, may come from non-thermal point sources. Thus the number of neutrinos in the Universe is increasing. The Universe moreover should be filled with "fossil" low-energy neutrinos from the Big Bang. Neutrinos of (1-100) GeV may also come from the Sun and from the Earth, where annihilations of Weakly Interacting Massive Particles (WIMP's) could take place.

Large underground detectors have opened up the field of neutrino astronomy. Two positive results exist: the detection of solar neutrinos [1] and the detection of the burst of neutrinos from SN1987A [2]. Larger detectors are needed to really open up the field of high energy neutrino astronomy [3].

High energy neutrinos are produced in celestial objects as in typical particle physics "beam dump experiments". One needs to find which are the celestial proton accelerators and which are the beam dumps.

For very high energy neutrinos (VHE) of hundreds of GeV the accelerators may be a young supernova envelope or a pulsar of a binary stellar system; the beam dumps may be provided by the interaction of the accelerated protons with the material of the supernova envelope or with the matter of the other star of the binary system. The following chain of reactions and decays may thus happen: $p+p \rightarrow \pi^{\pm}+X$, $\pi \rightarrow \mu+\nu_{\mu}$, $\mu \rightarrow e\ \nu_{\mu}\nu_{e}$.

For ultra high energy neutrinos (UHE) of millions of GeV the accelerators could be one of the above mentioned accelerators or more likely an active galactic nucleus or some hidden sources, like a black hole surrounded by a gas cloud ("black hole in a cocoon"). A beam dump may be the photon gas. The following are the interactions

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and the decays: $p+\gamma \rightarrow \pi^{\pm}+X$, $\pi \rightarrow \mu+\nu_{\mu}$, $\mu \rightarrow e\ \nu_{\mu}\nu_{e}$. In this case the neutrino energy is above a certain threshold energy.

The interaction of VHE neutrinos is well examplified by the reaction $\nu_{\mu}+p \rightarrow \mu+X$, while the interaction of UHE neutrinos is better examplified by a resonant interaction $\overline{\nu}_{e}+e^{-} \rightarrow W^{-} \rightarrow$ adrons.

With VHE neutrinos one hopes to perform neutrino astronomy of galactic sources; with UHE neutrinos the hope is to perform neutrino astronomy of extragalactic sources. Very probably the flux of UHE neutrinos from an extragalctic source is too feeble to be detected. In this case one would look for a diffuse flux of UHE neutrinos. Moreover this would be possible only for neutrinos with energies larger than approximately one hundred GeV, because for lower energies the background of *atmospheric neutrinos* would be too large. On the other hand, atmospheric neutrinos may be useful to study neutrino properties, like neutrino oscillations.

There are important connections between high energy astrophysics and particle physics, that can be studied with large underground detectors. For istance the dark matter in the halo of our galaxy could be made of WIMPs like neutralinos, of nuclearites, of magnetic monopoles, etc. WIMPs could concentrate in celestial bodies like the Earth and the Sun, annihilate into $\nu_{\mu}+\overline{\nu}_{\mu}$ pairs; the ν_{μ} or $\overline{\nu}_{\mu}$ could interact in a detector or in the surronding rock yielding a high energy muon.

It has to be remembered that large underground experiments detect a sizable downward flux of high energy muons, single and multiple, mostly coming from high energy cosmic rays. In *muon astronomy* one assumes that high energy muons remember the arrival direction of the parent higher energy particle and one hopes that the parent particle has not deviated. One may thus search for celestial point sources, DC or modulated, for large scale anisotropies and for time variations. The interest in muon astronomy started in 1985 with reports of an excess of underground muons from the direction of Cyg. X-3. The flux of muons from above and of muon neutrinos (atmospheric neutrinos) from below constitute sources of background for neutrino astronomy.

This review shall concentrate on supernovae neutrinos and on high energy neutrinos. It will start with a brief discussion on underground detectors and will then proceed to neutrinos from stellar collapses, high energy neutrino astronomy, neutrinos from WIMPs and neutrino oscillations. There are obvious overlaps with several reports at this meeting [4-9].

2. Existing and future large underground detectors

Most of the initial underground detectors were built for proton decay searches. Other large detectors were built for searches of rare phenomena, like neutrinos from supernovae. Several underground laboratories were thus started. The latest addition, the Gran Sasso Laboratory, will be for the near future the largest underground non-accelerator facility [3,10]. The Gran Sasso National Laboratory (LNGS) of the Istituto

Nazionale di Fisica Nucleare (INFN) is located on the highway Rome-Teramo, about 120 km east of Rome. The lab has a complex of three underground tunnels, each about 100 m long, and an EAS array on top of the mountain at an altitude of 2000 m.a.s.l., about 25° off the vertical from the underground lab. The underground lab has a low activity environment. Three large detectors relevant to this review are or will be located there: LVD, MACRO and ICARUS.

The large detectors for astrophysics work may be classified in 3 categories: a) large-mass detectors, suitable for 14 MeV neutrinos from stellar collapses and b) large-area detectors, suitable for muon astronomy, and c) very large-area detectors suitable for high energy neutrino astronomy.

The most important parameter of supernovae neutrino detectors is the amount of sensitive mass. Water, heavy water and liquid scintillators are used as the sensitive medium. The second parameter is energy resolution, in particular energy threshold. Some directionality is provided by Cherenkov counters.

Surface is the must important parameter for underground detectors searching for magnetic monopoles and studying high energy muons; the area requirement is even more stringent for high energy neutrino astronomy.

Table 1 lists present and future large area and large mass detectors. For each detector the table lists the detecting methods, the sensitive medium, the effective area, and the sensitive mass. A few comments follow.

MACRO (Monopole, Astrophysics and Cosmic Ray Observatory) at Gran Sasso [3,11] has three types of detector (Fig. 1): a) Horizontal planes of liquid scintillators, each $(0.75 \times 0.25 \times 12)\ m^3$ in size. b) Horizontal layers of streamer tubes, each $3 \times 3\ cm^2$ in cross section. Between layers there are slabs of concrete absorbers. c) A track-etch detector with layers of CR39 and of lexan. The sides are sealed by one layer of scintillators and 6 layers of streamer tubes. MACRO has a modular structure. At present 6 lower supermodules are operating with streamer tubes ($S \simeq 850\ m^2$) and 2 also with scintillators ($S = 280\ m^2$, $m = 110\ t$; other 220 t are being commissioned). The upper part should be completed in early 1993, and MACRO will have then have $S\Omega \sim 10000\ m^2\ sr$ for an isotropic flux.

LVD (Large Volume Detector) is being installed in hall A-north at Gran Sasso [12]. It has two types of detectors: a) Liquid scintillation counters, each of $1 \times 1 \times 1.5\ m^3$ seen by three photomultipliers; b) Horizontal and Vertical layers of limited streamer tubes, each $1 \times 1\ cm^2$ in cross section. LVD is a scaled up version of the smaller **LSD** detector under mont Blanc. At present are operating about 170 tons of liquid scintillator.

Two water Cherenkov detectors are operating, **KAMIOKANDE-II** and **IMB** [2-3], the last one being temporarely shut-down.

The **SOUDAN 2** fine sampling tracking calorimeter is being assembled in the Soudan mine in Minnesota, (USA) at 92.25° W, 47.28° N, at a depth of 2090 m.w.e [13]. It is specifically designed for proton decay searches. It will have a mass of 1100 t. At present it has a size of $8\ m \times 9\ m \times 5\ m$.

ICARUS (Imaging Cosmic And Rare Underground Signals) will be a large liquid argon drift chamber, where one should "see" tracks with a space resolution comparable to that of bubble chambers, and with many precise dE/dx samplings along the paths of the particles. A prototype of 2 tons is operating and is up to expectations [14].

The list of future approved experiments of the water Cherenkov conventional type includes:

The **SUPERKAMIOKANDE** detector, with 32000 t of water, will be a direct upgrade of the present Kamioka detector, using large photomultipliers [3].

The **SUDBURY** Cherenkov detector (SNO) will have 1000 t of D_2O, surrounded by an H_2O anticoincidence blanket. The primary purposes of this detector are the studies of solar and supernovae neutrinos [15].

Two Cherenkov water detectors are being deployed in deep ocean and lake waters.

DUMAND (Deep Underwater Muon and Neutrino Detector) uses ocean water as the active Cherenkov medium [3]. Stage 1, consisting of a 60 m string with 7 photomultipliers (PMT) at a depth of 4 km, is working in the Pacific, 30 km west of Hawai. Stage 2 DUMAND will consist of 216 16-inch hemispherical photomultipliers arranged in 9 vertical strings at the vertices and center of an octagon at an average depth of 4700 m. The effective sensitive area will be larger than 20000 m^2. The first three strings of the array should be operating by the end of 1992.

A similar layout is being deployed in the **Baikal** lake, where one string equipped with 6 detecting stations located 50 m apart at a depth of 1350 m is operational [3,16]. The Baikal lake has a thick ice crust for two months each year: this makes the deployment of instruments easier. They plan to deploy for 1993 eight strings with 200 PMT at an average depth of 1200 m. It should have $S\Omega \sim 5 \times 10^4\ m^2\ sr$ and a sensitive volume $v \geq 5 \times 10^5\ m^3$. The group is also developing a surface Cherenkov array to detect EAS for energies larger than 100 TeV.

Several surface detectors are in different stages of proposal. Three are water Cherenkov detectors and one is a structure of tubes and absorbers.

LENA, GRANDE, NET would be large ($> 10000\ m^2$) ring-imaging Cherenkov detectors to be located in pits or lakes [3-4,17]. In each of these projects there are several layers of water. Two or three of this layers would behave as "neutrino telescopes" and would look downward, whereas one or two "gamma telescopes" would look upward.

DOUGHNUTS would be a set of doughnuts-shaped, large underground water detectors [3].

SINGAO would be a large modular array of resistive tubes and absorbers [3].

More exotic detectors have been proposed and some tests are being performed, see for instance the use of clear polar ice at great depths to be used as a Cherenkov detector (**AMANDA**) [17], and the use of small radiotelescopes to detect the radiowaves emitted in ice by large cascades initiated by neutrino interactions (**RAMAND**).

3. Neutrinos from stellar collapses

Massive stars, with mass $m > 6\ m_\odot$, on the main sequence, evolve gradually as increasingly heavier nuclei are produced and then burnt at their centers in a chain of thermonuclear processes, ultimately leading to the formation of a core composed of iron and nickel. Further burning in the shells surrounding the core may make the core mass exceed the Chandrasekar limit, $m_{ch} = 5.76\ y_e^2\ m_\odot$ (y_e= lepton fraction in the core, $y_e < 0.5$). In such case the core implodes in a time slightly longer than the freefall time and leads to the formation of a neutron star.

The total energy released during a stellar collapse is at least the gravitational binding energy of the residual neutron star, $E = 3 \times 10^{53}\ (m/m_\odot^2)$ (10 km/R) ergs, that is typically 10^{53} ergs $= 0.1\ m_\odot$, mostly in the form of neutrinos with an average energy of 10-14 MeV, depending on models [18]. Thus typically 4×10^{57} neutrinos of each species are emitted. Three stages of neutrino emission may be identified:
Neutronization: $e^- p \rightarrow n\nu_e$. Only ν_e are emitted at this stage, which lasts few ms.
Deleptonization: $e^- e^+ \rightarrow \nu_e \overline{\nu}_e$ leads to ν_e and $\overline{\nu}_e$, which leave the core. The more abundant reactions $e^+ e^- \rightarrow \gamma\gamma$ lead to γ's recreating $e^+ e^-$ pairs. This phase lasts about 1 s.
Cooling: The neutron star is very hot and is cooled by escaping neutrinos. Thermal neutrino emission from the "neutrinosphere" lasts about 10 s. Most neutrinos, of all types, are emitted during this phase.

All types of neutrinos may be detected via their neutral current interactions with electrons, $\nu_e e^- \rightarrow \nu_e e^-$, $\overline{\nu}_e e^- \rightarrow \overline{\nu}_e e^-$, etc, with a cross section $\sigma = 1.7 \times 10^{-44}\ E_\nu$ (MeV cm^2), which leads to a small number of events. The dominant observed reaction, $\overline{\nu}_e p \rightarrow n e^+$, with $\sigma = 7.5 \times 10^{-44}\ E_\nu^2$ (MeV^2) cm^2, is energetically possible only on free protons, as in H_2O and in $C_n\ H_{2n+2}$ detectors. The produced positron annihilates immediately, $e^+ e^- \rightarrow 2\gamma$, while the neutron is moderated and captured after a mean time of about 180 μs ($np \rightarrow d\gamma$, with $E_\gamma \sim 2.2$ MeV). Detectors with D_2O may also detect $\nu_e n \rightarrow p e^-$. Because of the strong dependence of the cross section on neutrino energy, the average e^- or e^+ energy is about 2 MeV larger than the average neutrino energy.

Supernova 1987A produced bursts of neutrinos in the Kamioka (12 events), IMB (8 events) and Baksan detectors (3 events) [2]. The Mont Blanc detector observed 5 events, 4 hours earlier. The neutrinos arrived within 10 seconds, few hours earlier than visible light. A collapse at the center of our galaxy should yield 25 times more neutrinos.

Many detectors will be capable of yielding information on supernovae neutrinos (see Table 1). For future work a crucial point is the expected rate of type-II supernovae in our galaxy. An optimistic estimate is a rate of one every 10-20 years. Thus, ideally, the detectors must all be kept alive all the time and a worldwide cooperation, a supernova watch, seems to be important.

The MACRO Collaboration presented a paper dealing with technical aspects and with a search fo supernova neutrinos from October 1989 till December 1991 [19]. Some of the technical aspects concerned calibrations of the long scintillation counters ($0.75\ m \times 0.20\ m \times 12\ m$). Besides using laser lights and traversing muons, they used an Am/Be source, from which one observes the two γ-ray peaks at 2.2 and 4.4 MeV and the continuum from the neutrons which yield recoil protons. Once a trigger (primary) happens in a counter, the threshold on that counter, and some neighbouring ones, is reduced from 7 MeV to 1.5 MeV for 1 ms. One thus has a sensivity to the delayed 2.2 MeV γ-rays from neutron capture. The efficiency for detecting such γ-rays is 25% in the same counter and globally 40%, including neighboring counters. The search was carried out using the horizontal scintillation counters of the first supermodule (44 t of scintillators). The primary threshold was raised to 10 MeV in the off-line analysis. In this condition the background rate was 15 mHz. The analysis was performed counting the number of events in 2 s, 3 s,..,10 s, sliding windows. No candidate supernova was observed in the last 2.5 y (Fig. 2). The detector was working 84% of the time (because of tuesday's maintenance periods). Also the other large detectors didnot see any candidate after SN1987A [20].

Kamiokande II searched also for diffuse neutrinos from past supernovae. Based on 104 days of detector live-time, and assuming an effective temperature of 4 MeV, they established an upper limit at the level of 780 $\overline{\nu}_e\ cm^{-2}s^{-1}$ [20].

MACRO started a supernova watch, which includes a continuous recording on line, an alarm, a quick off-line analysis and a number of quick checks.

4. High energy neutrino astronomy

High energy neutrinos may be detected in large underground detectors as *contained events*, produced by neutrino interactions with the nuclei of the detector, or as *upward going muons* produced in the rock below the detector. We shall concentrate on this second method.

Downgoing muons from neutrino interactions are indistinguishable from the more abundant cosmic ray muons. Upward going muons are seen directly in Cherenkov detectors and may be separated by time of flight from downward going muons in scintillators. At very high energies the $\nu - \mu$ angle is small and the effective target mass is large. In order to see point sources of neutrinos one needs angular resolutions of about 1°, which is slightly larger than the effective muon multiple scattering angle in the rock.

The search for extraterrestrial sources may be performed by plotting the neutrino induced muon events on a sky plot of declination versus right ascension. A source would reveal itself as an excess of events (in a certain direction) above the atmospheric neutrino background.

Several large underground experiments performed such a search with negative results. Fig. 3 shows the sky plot for the IMB data [21], which corresponds to a total

live time of 885 days. In the figure are indicated a number of potential source locations; the dashed line indicates the location of the galactic plane.

In order to establish a flux limit for a specific source one may consider an error circle corresponding to the resolution of the detector about that direction (5° for the IMB experiment), determine the number of events in that circle and subtract the corresponding number of events expected from atmospheric neutrinos. The 90% luminosity limits are at levels corresponding to 10^{39} erg/s for the Crab Nebula and Hercules X-1, about 10^{42} for SN1987A.

Some experimenters estimate that detectors like Baikal and Dumand should be able to yield a significant number of very high energy neutrinos from young pulsars, supernova shells and possibly other short terms sources (Fig. 4). According to other authors one needs extremely large detectors, of the order of 1 Km^2 [4,17]. The energy dependence of the high energy neutrino cross section is shown in Fig. 5 [3].

5. Dark matter astronomy.

Several astronomical observations indicated the presence of non luminous, dark matter, since several decades. The presence of dark matter (DM) in our galaxy is suggested by the rotation curves of stars in the galaxy halo (Another interpretation could be a breakdown of Newton's law). The nature of the dark matter remains a mistery. In what follows we shall be interested in *cold heavy dark matter* in the form of heavy particles, typically with masses of tens of GeV. These could be detected directly with detectors of the germanium type (high resolution, low background) through coherent scattering of the WIMPs with the nuclei of the detector. Other methods are indirect. We are here interested in WIMPs which could be trapped inside the Sun or the Earth, would annihilate and would give a flux of high energy neutrinos.

The dark matter particles considered here would have been generated in the Early Universe and would have decoupled from ordinary particles before the time of the QCD phase transition at the temperature of few hundred MeV. Examples of such particles could be Dirac or Majorana neutrinos and the lightest supersymmetric particles.

These particles should be located in the galactic halo, their abundance in the vicinity of the solar system should typically be 0.3 GeV/cm^3 and their velocity would be 300 km/s.

The WIMPs would be captured by the Sun (Earth) by coherent scattering with nuclei, would concentrate in the center of the Sun (Earth) and would annihilate into heavy quark-antiquark pairs or tau leptons. These would subsequently decay into high energy neutrinos. The heavy Dirac neutrinos would in addition directly produce pairs of $\nu_e\overline{\nu}_e$, $\nu_\mu\overline{\nu}_\mu$, $\nu_\tau\overline{\nu}_\tau$.

5.1 Neutrinos from WIMPs annihilating in the Sun or in the Earth.

The Kamioka, Frejus, IMB, Nusex and Macro detectors have looked for neutrinos coming from the Sun. No signal was detected. Together with LEP results and with the results of direct searches these experiments have essentially excluded the Dirac heavy neutrino as an important component of the dark matter. Majorana neutrinos are also excluded, al least for $m < 80$ GeV.

As far as high energy neutrinos from the Earth, the observed upper going muons may come from atmospheric neutrinos from the other side of the Earth or from WIMPs, which should have been captured by the Earth, thermalized and concentrated close to the Earth center. Eventually the density would be large enough so that annihilations of WIMPs and antiWIMPs would happen.

One interesting WIMP candidate is the supersymmetric neutral particle with the smallest mass which would be stable because of R-conservation. In the Minimal Supersymmetric Standard Model (MSSM) there are four neutralino mass eigenstates which can be expressed as linear combinations of superpartners of the gauge bosons and of the neutral Higgses:

$$\chi = c_1\tilde{\gamma} + c_2\tilde{z} + c_3\tilde{H}_1^\circ + c_4\ \tilde{H}_2^\circ \tag{3}$$

The stable neutralino is the lowest mass linear superposition of photino $\tilde{\gamma}$, zino $\tilde{z}$ and higgsinos $\tilde{H}$. For certain parameter combinations the neutralino may coincide with the photino ($\tilde{\gamma}$) or the higgsino ($\tilde{H}^\circ$).

There are three independent parameters in the MSSM; they may be taken to be the W_3 mass parameter M_2, the Higgs mixing parameter μ and the parameter $tg\ \beta = v_2/v_1$, where v_1, v_2 are the vacuum expectation values for the two Higgs doublets.

Neutralino masses below 20 GeV are excluded by the LEP experiments. The interpretation of the searches for neutralinos from the Earth necessitates many hypotheses, which will be here repeated. The neutralino dark matter density near the Earth is taken as $\rho_x = 0.3\ GeV/cm^3$ and their velocity $v_x \sim 300\ km/s$. Capture of neutralinos by the Earth is due to coherent interactions with nuclei and the capture rate is particularly high for neutralinos with masses close to those of the atomic nuclei in the Earth (30-80 GeV). Neutralinos and anti-neutralinos should then concentrate toward the center and annihilate into neutrinos. They would lead to a steady flux of high energy neutrinos coming from the center of the Earth in a relatively narrow cone of about 15°. The calculation of these processes requires a complicated Monte Carlo which includes evaluation of the contribution from atmospheric neutrinos.

In Fig. 6 is shown a typical neutrino spectrum coming from neutralino-antineutralino annihilations in the Earth [7]. The figure also shows the atmospheric neutrino background, assumed to be a power-law spectrum with a spectral index of 3.2; the background muon spectrum is normalized to a rate of $2\ 10^{-13} cm^{-2} sr^{-1} s^{-1}$ for upward going muons with energy greater than 2 GeV.

Limits were obtained by Kamiokande and MACRO [22], see Figure 7.

Until now no signal has been detected which can be attributed to neutralino. The results may be used to place constraints in the models parameters [7,23]. It may be that the limits are already at such levels that in part of the parameter space the neutralino hypothesis cannot provide the total amount of invisible matter of the galactic halo.

6. Neutrino oscillations

Atmosferic neutrino events are usually considered to be the source of unavoidable background for many subjects of underground experiments, from the search of proton decay to the study of high energy neutrino astronomy. But atmospheric neutrinos are sensitive to neutrino oscillations and thus may provide important informations on neutrino properties. The search for neutrino oscillations is rather sensitive because of the large range of distances traveled by atmospheric neutrinos.

Most underground experiments detect muon neutrinos via their interaction in the rock surrounding the detectors: in practice only upward going muons are usable for this purpose and only high energy muons are detected with high efficiency. Some experiments detect muon neutrinos and electron neutrinos via their interactions inside the detector (contained events) [24-27]. The measured rates of atmospheric neutrino events have to be compared with the rates calculated on the basis of the knowledge of the neutrino flux, of the cross sections and of the experimental apparatus. The fluxes of atmospheric neutrinos calculated by a number of authors differ by at most 30% [24].

For massive proton decay detectors it is more interesting to measure the ratio of the number of contained muon neutrino events to electron neutrino events because this eliminates a number of uncertainties in the determination of the neutrino flux and in the low energy cross sections. The ratio is expected to be about 2 because a charged pion or charged kaon decay yields one muon neutrino and one muon; the muon decays into a muon neutrino and an electron neutrino. The relevant cross sections of neutrinos in matter, specifically on O^{16} of the water Cherenkov detectors, are well known, with the exception of low energies, $E_\nu < 0.2$ GeV, where nuclear effects alter the cross sections.

In a recent preprint the Kamiokande collaboration presented results from a global exposure of 4.92 kton year [24]. The contained events were classified in showering [electrons, photons] and non showering [muon] events. The sample has 159 electron events with momenta between 0.1 and 1.33 GeV/c and 151 muon events with momenta between 0.2 and 1.5 GeV/c (see Fig. 8).

The momentum spectra of the events are shown in Fig. 9. For the electron events the Monte Carlo simulations reproduce fairly well the experimental distribution and the integrated number. Instead there seems to be a deficit of observed muons compared with the Monte Carlo predictions.

The authors consider the ratio $R_{\nu_\mu/\nu_e} = R_{data}/R_{montecarlo}$, where R_{data}=(observed number of muon events)/(observed number of electron events) and similarly $R_{montecarlo}$=(MC expected number of muon events)/(MC expected number of electron events). The R ratio is expected to be much less dependent on absolute normalization. From the momentum dependence of this ratio shown in Fig. 9 one sees that on the average experimentally it is 0.60, instead of the predicted value of about 1. The departure from unity is essentially due to the muon deficit.

The authors analyze in detail possible experimental uncertainties, in particular those connected with particle identification in a Cherenkov water detector. From the analysis of the two independent methods used they estimate a systematic uncertainty of 0.05 in the ratio. Thus their experimental value is $R(\nu_\mu/\nu_e) = 0.60 \pm 0.07 \pm 0.05$.

The above value is comparable to the value $R(\nu_\mu/\nu_e) = 0.67 = 0.17$ found by IMB-3 [24], where the error combines statistical and systematic uncertainties. The Frejus experiment did not find any effect [25]. The comparison with the Frejus results is less straightforward because the Frejus data include also inelastic events and the energies involved are slightly larger. The data from NUSEX and Baksan have smaller statistics.

If the data are interpreted in terms of neutrino oscillations, in particular in terms of two possible and independent channels, $\nu_\mu \leftrightarrow \nu_e$, $\nu_\mu \leftrightarrow \nu_\tau$, one has the contour limits of Fig. 10 in the plane $(\Delta m^2, \sin^2 2\theta)$. Assuming that the other experiments have only limits, while Kamiokande has a signal, the allowed regions of the parameters $\Delta m^2 - \sin^2 2\theta$ are those in the cross hatched areas. Assuming dominance of the $\nu_\mu \rightarrow \nu_\tau$ channel, one has $\Delta m^2_{\nu_\mu \nu_\tau} = 0.8 \times 10^{-2}$ and $\sin^2 2\theta_{\nu_\mu \nu_\tau} = 0.87$ (with parameters α=-7% and β=0%).

It is not easy to reach a definite conclusion; probably more work in this area in needed [14,27-28].

7. Conclusions

A large amount of work is going on in the field of Neutrino Astrophysics with large Underground Detectors. There are many interesting problems at the interface of nuclear physics-particle physics-astrophysics.

Larger underground detectors are needed for high energy Neutrino Astronomy; the proposed technical solution are challenging.

I would like to thank many colleagues, in particular all the members of the MACRO collaboration, for discussions and advices.

Table 1

Large underground detectors which search for high-energy neutrino point sources and/or neutrinos from stellar collapses. a) operating, b) approved, c) planned.

Detector	Detection material	Effective area Now Future (m^2)	Effective mass Now Future (t)	Overburden (m.w.e.)	Primary purpose
a) Kamioka-2	H_2O	150	2140		Proton decay
IMB	H_2O	390			Proton decay
KGF	Tubes	240			Proton decay
Baksan	Scint.	72	300		ν stellar col.
Mt. Blanc	Scint.		90		ν stellar col.
Soudan-2	Fine grain	110 → 145 (430)		2090	Proton decay
LVD	Scint. + Tubes		20 →	3700	ν stellar col.
MACRO	Scint. + Tubes	850 → 1000	165 → 1000	3700	Muons mon.
DUMAND-2	H_2O (sea)	→ 20000		4700	High energy ν_μ
Baikal	H_2O (lake)	→ 4000		1200	High energy ν_μ
b) Superkamioka	H_2O	~ 1000	32000		Proton decay
SNO	D_2O		1000		ν stellar col.
ICARUS	Ar		2 → 4000	3700	Proton decay
BOREX	Scint.		2000	3700	Solar neut.
c) GRANDE	H_2O	31000		Surface	High energy ν_μ
NET	H_2O	90000		Surface	High energy ν_μ
LENA	H_2O	30000		Surface	High energy ν_μ
SINGAO	Tubes	10000		Surface	High energy ν_μ
Doughnuts	H_2O	20000		Underground	High energy ν_μ

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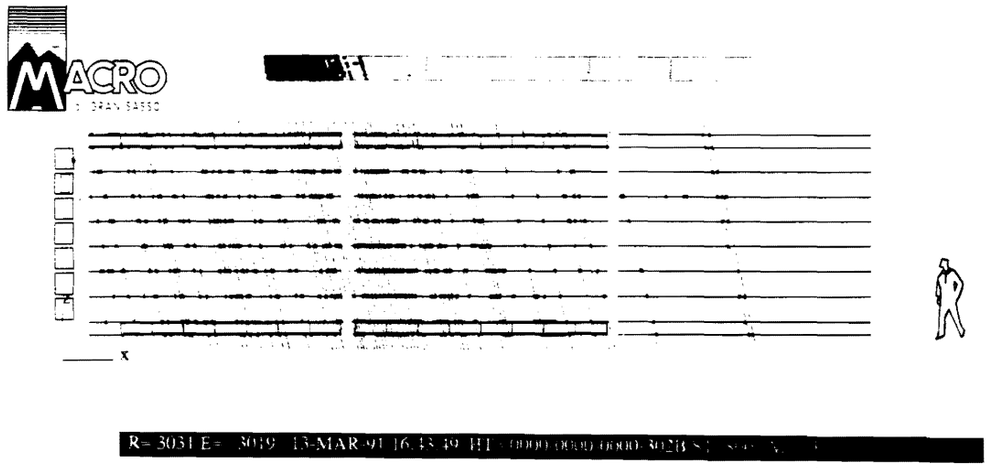

Fig. 1 On-line display of a multi-muon event in the MACRO detector.

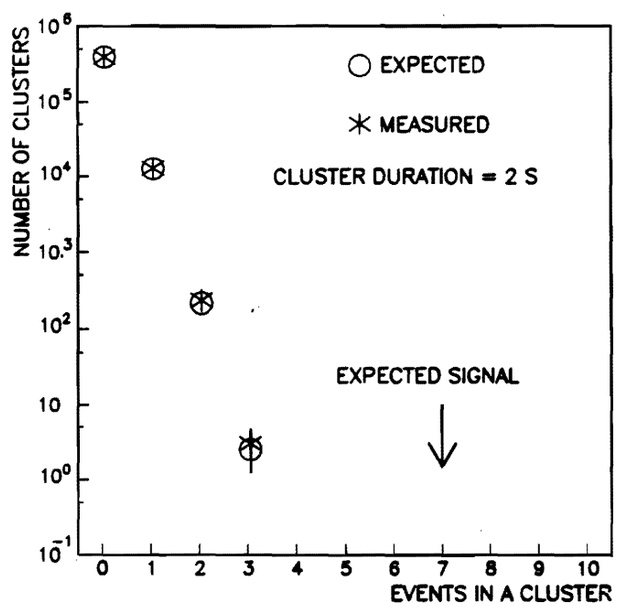

Fig. 2 MACRO search for supernova neutrinos. Number of clusters plotted versus number of events in a cluster for a cluster duration of 2s. Data (*) and expectation for a collapse at the center of the Galaxy (histogram) for a 14 month period.

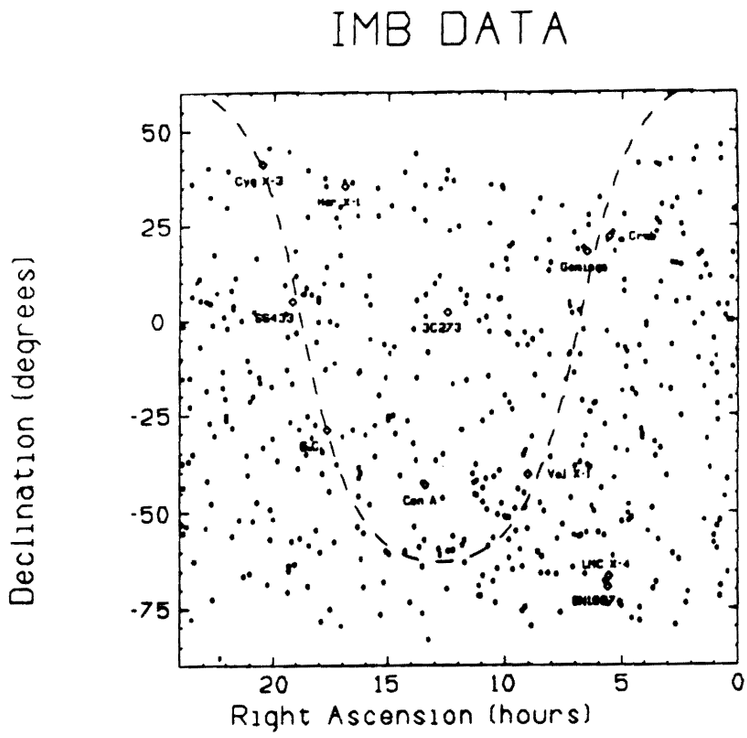

Fig. 3 A sky plot of the neutrino data from 885 days live of the IMB experiment. The dashed line indicates the location of the galactic plane. Several potential sources are indicated.

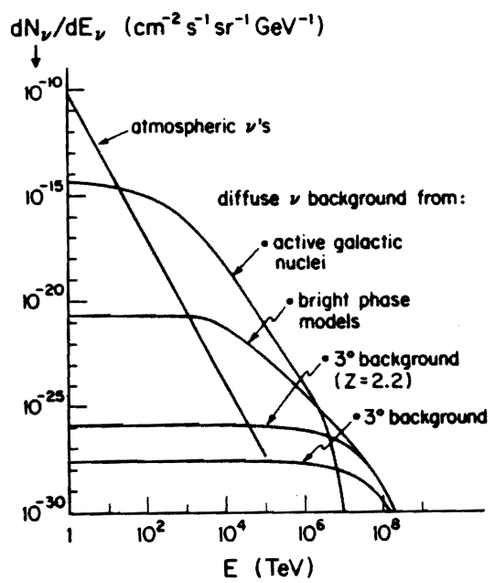

Fig. 4 A selection of predicted diffuse neutrino fluxes is compared to the atmosheric neutrino flux. Sources include active galactic nuclei, neutrinos produced by extra-galactic cosmic ray interacting with 3°K cosmic photons. The latter flux is also shown integrated over cosmic time to red shift 2.2 and to galaxy formation (bright phase models).

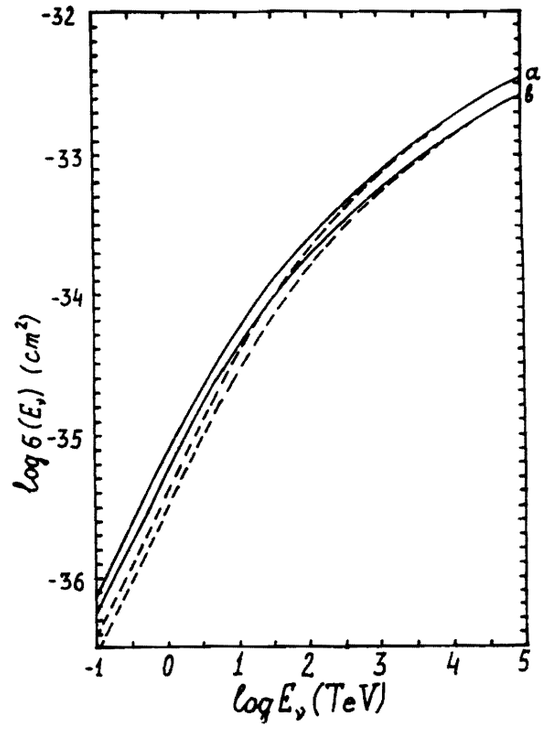

Fig. 5 The energy dependence of the neutrino-nucleon cross section. Curves a refer to the processes $\nu_\ell + N \rightarrow$ anything (solid line) and $\overline{\nu}_\ell + N \rightarrow$ anything (dotted curve), and curves b refer to the production of only charged leptons ℓ ($\ell = e, \mu, \tau$): $\nu_\ell + N \rightarrow \ell^- +$ hadrons (solid line) and $\overline{\nu}_\ell + N \rightarrow \ell^+ +$ hadrons (dotted line) [3].

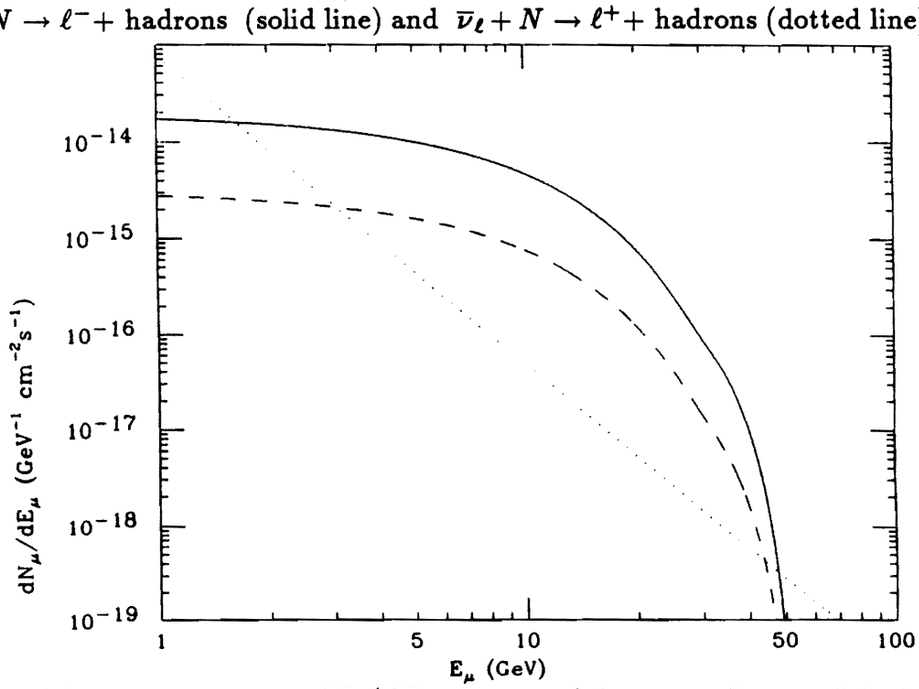

Fig. 6 Differential muon spectrum, dN_μ/dE_μ, computed for neutralino annihilation in the Earth yielding neutrinos which interact in the rock below the detector [7]. Solid line: $m_h = 50$ GeV; dashed line: $m_h = 80$ GeV. The dotted line gives the expected muon spectrum from atmospheric neutrinos.

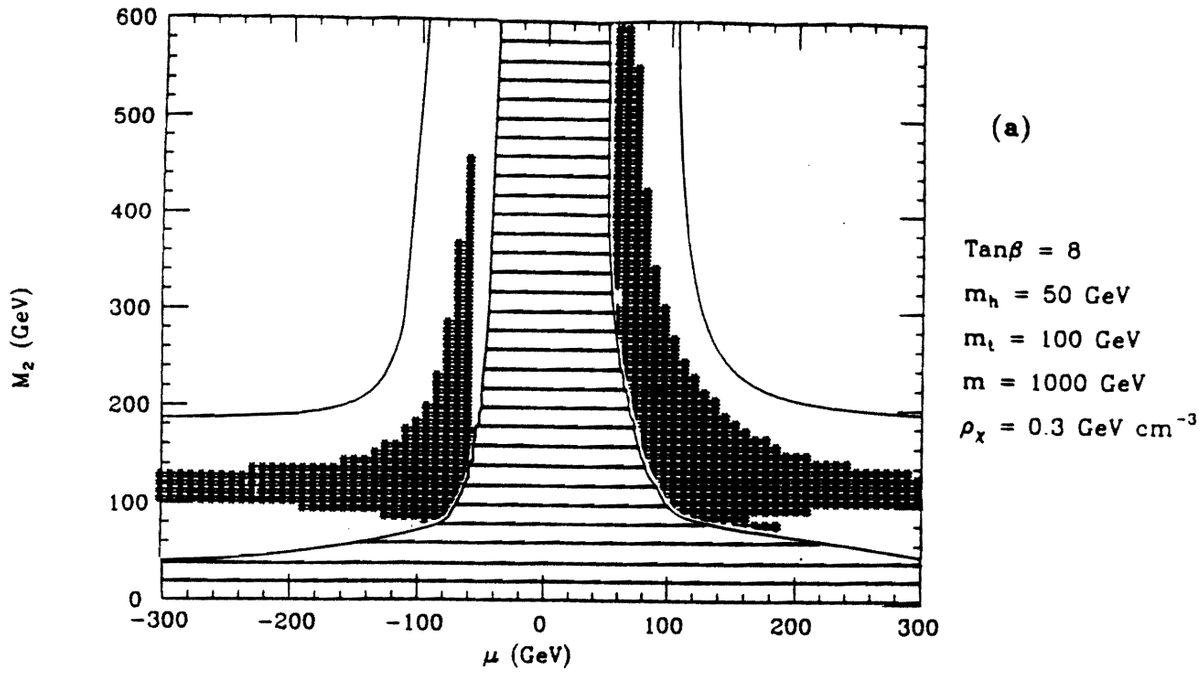

Fig. 7 Limits on the parameters M_2 and μ from direct and indirect neutralino searches for $\tan\beta = 8$, $m_h = 50$ GeV and radiative corrections with $m_t = 100$ GeV and $m_H = 1000$ GeV; Higgs couplings $g^h = 39$ MeV, $g^s = 354$ MeV [7]. Hatched regions are excluded by LEP, regions with stars are excluded by Kamiokande if $\rho_\chi = 0.3$ GeV cm^{-3}.

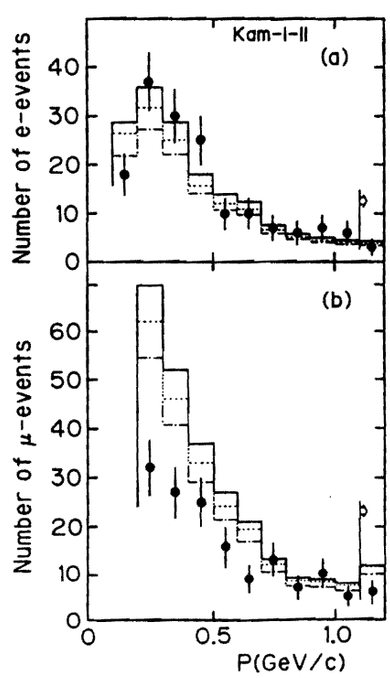

Fig. 8 Number of e-events and μ-events versus momentum for atmospheric neutrinos detected in the Kamiokande detector (black points) [24]. The histograms represent the predictions of various Monte Carlos.

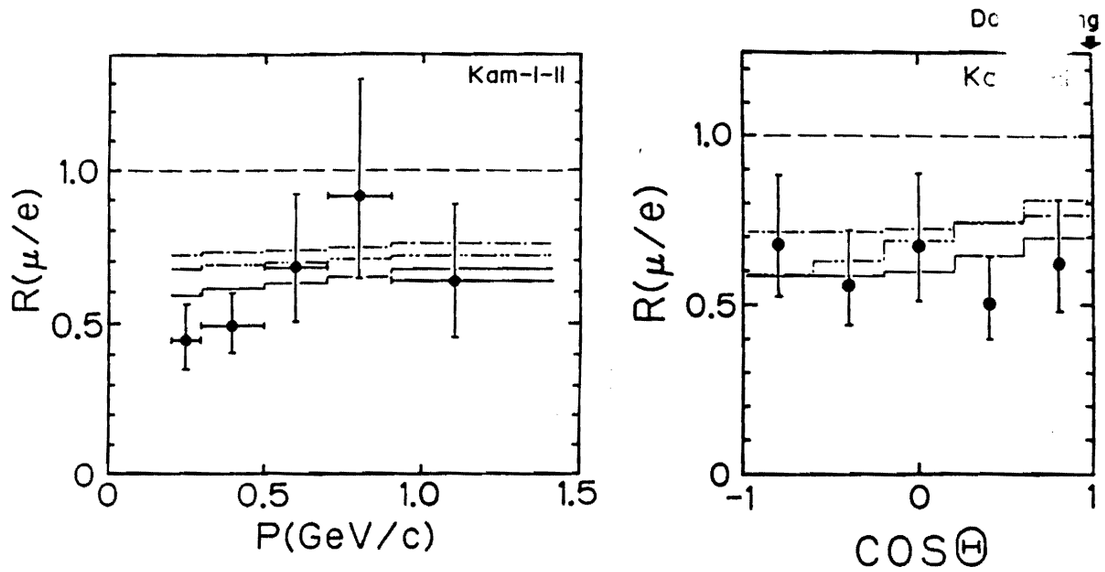

Fig. 9 The ratio $R(\mu/e)$ plotted versus momentum and $\cos\theta$ [24].

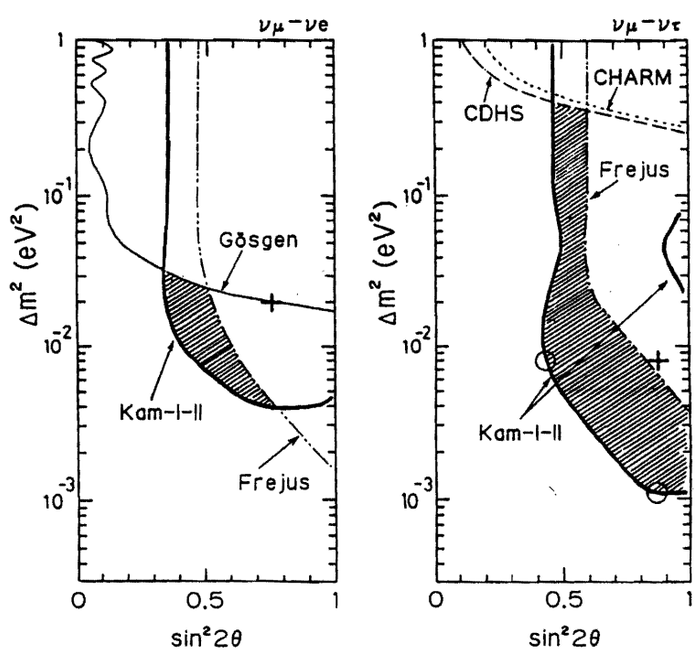

Fig. 10 The limits in the $(\Delta m^2 - \sin^2 2\theta)$ plane for $\nu_\mu \to \nu_\tau$ oscillations. The dashed lines indicate the allowed regions [21].