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High Energy Neutrino Observatories

(HENAP Report to PaNAGIC)

The High Energy Neutrino Astrophysics Panel

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1. Executive summary

1.1 Introduction

The High Energy Neutrino Astrophysics Panel (HENAP) was created by the PaNAGIC Committee with the specific purpose of writing a report on the ongoing efforts to detect neutrinos of cosmic origin. The report is presented here and collects the findings of the panel, starting with the main recommendations in section 1.2 and continuing with several chapters structured according to the points of the mandate. Following each of the recommendations is a short paragraph with supporting arguments.

Shortly after the first HENAP meeting in March of 2001, the IceCube experiment was approved by the Science Board of the U.S. National Science Foundation and by other agencies in Europe. Therefore, HENAP assumed that the IceCube detector was going to be built at the South Pole and some of the report reflects that point of view. Nevertheless it should be stressed that one of the recommendations of the panel, based on physics arguments, is that two detectors should be built, one in each of the Southern and Northern hemispheres. HENAP also considers that the technology to build the detectors is available, as proven by the successful deployment and operation of the Lake Baikal and AMANDA experiments.

The mandate and composition of HENAP are described in Section 1.3, and a reminder of the meetings is given in Section 1.4. The meetings also provided a forum for members representing the main ongoing projects to discuss some of their common problems. These discussions have proven very valuable and we cannot but encourage the continuation of communication between those involved in the current efforts. Indeed, one of the recommendations of HENAP is that the Northern deep-water detector projects establish, already now, a mechanism for discussion through the creation of an international collaboration. The great scientific opportunity of a very large deep-water detector requires the collaboration of all those involved in this endeavor.

1.2 Recommendations

The observation of cosmic neutrinos with energies above a few hundred GeV will be of the highest scientific importance in that it will open an entirely new window to the most energetic phenomena in the Universe. Unlike charged particles, neutrinos point directly to the source of their production and provide unambiguous evidence for the acceleration of hadrons in those sources. Unlike photons, they can penetrate enormous amounts of intervening matter, thus providing a unique way to probe into the interior of known sources or to reveal new sources.

The feasibility of using deep water and polar ice as a detecting medium has been proven by the Lake Baikal experiment, and the AMANDA experiment at the South Pole, respectively. The experience of these projects also indicates that the technology to increase the size of the detectors to a km^3-scale is now available. This is the scale where one can also reasonably expect, from theoretical models, to see high-energy neutrino signals from discrete astrophysical sources.

The cosmic-ray induced background limits high-energy neutrino detection to upward-going neutrinos that originate from the hemisphere opposite to that of the detector location. Complete coverage of the sky, which is important given the exploratory nature of these experiments, thus requires two detectors located in opposite Earth hemispheres.

The experiments are technologically challenging and will require the involvement of a number of industrial contractors. The sea experiments in particular will provide a testing ground for deployment of communication equipment and for the use of remotely operated vehicles, which are of interest to industry. The experiments also provide a platform for the deployment of measuring equipment for other scientific fields.

The scale of the experiments is very large and therefore requires a large number of scientists and engineers. The likely available resources and the number of scientists involved at present indicate the need for concentrating all the efforts in two distinct large projects, one in each hemisphere.

All the above considerations lead us to the following recommendations:

· **Recommendation 1**

The observation of cosmic neutrinos above 100 GeV is of great scientific importance. Such neutrinos open a new window to the most energetic phenomena in the Universe and represent an opportunity for scientific discovery that should be pursued.

From cosmic- and gamma-ray observations, we know that astrophysical processes accelerate particles to very high energies, extending to 10^{20} eV and above. There are good arguments to expect the production of high-energy neutrinos as well. Detecting such neutrinos is of high importance for three reasons:

1. neutrinos provide unambiguous evidence for the cosmic acceleration of hadrons,
2. neutrinos point directly back to their production site, and
3. neutrinos can traverse all intervening diffuse matter in the Universe and reveal hidden sources.

· **Recommendation 2**

The detectors should be of km^3-scale, the construction of which is considered technically feasible.

Conservative flux estimations from astrophysical sources imply that detectors with masses equal to or larger than 1 Gton should detect several neutrinos of energy 1 to 10^3 TeV per year. Even larger detectors may be required at higher energies. Plausible scenarios are being discussed where higher fluxes of TeV neutrinos are produced, leading to positive signals in smaller detector volumes.

· **Recommendation 3**

The driving motivation for km^3-scale neutrino detectors is the observation of cosmic point sources. For this purpose a complete coverage of the sky is an important goal, and thus a km^3-scale detector in the Northern hemisphere should be built to complement the IceCube detector being constructed at the South Pole.

Sources are not isotropically distributed in the local universe at redshift $z << 0.1$, and this, coupled with the likely small rates of potential sources, calls for a complete coverage of the sky. The Galactic center is of particular interest and only Northern hemisphere sites are able to see upward-going neutrinos from this region.

· **Recommendation 4**

The existence of two detectors with different technologies is an important asset

Deployment and simultaneous usage of other detectors on the surface is easier in ice, while the reconstruction of Cherenkov light in water enables better angular resolution, and therefore potentially better pointing accuracy.

- **Recommendation 5**

The scientific objectives of km^3-scale detectors of cosmic neutrinos are strongly enhanced by contemporaneous observations of a broad spectrum of electromagnetic radiation, and thus it is important to set up coordination and communication between neutrino observatories and other major astronomy projects.

The contemporaneous observation by neutrinos of point-like sources observed in other instruments with much better pointing accuracy will be decisive in the identification of the sources and the understanding of their physics mechanism. Lines of communication between the neutrino and photon communities should be established through joint scientific committees and meetings.

- **Recommendation 6**

The km^3-scale detector projects are unique facilities that should be open to all interested scientific teams who wish to contribute to their construction and exploitation.

Opening the collaborations to world-wide participation is very desirable. The Northern hemisphere deep-water detector project should be open to all interested scientific teams from the outset. IceCube, which is already an international project, should examine possibilities for greater participation of other teams.

- **Recommendation 7**

The km^3-scale detectors should be regularly monitored by international peer-review.

The projects should be monitored by regular peer-reviews of the scientific program, and of the engineering and managerial aspects.

- **Recommendation 8**

Adequate planning to make the data collected by the detectors available to the scientific community is strongly encouraged.

Large facilities in many fields of science are required to make their scientific data available to the scientific community at large. This requires considerable organization and resources, which should not be neglected in the planning of the experiments. In order not to lose the opportunities for data collection for broader dissemination, those interested in the data should get involved in the planning.

- **Recommendation 9**

There is at this point no justification for more than one Northern hemisphere deep-water neutrino detector of km^3-scale.

Arguments for more than one detector in the Northern hemisphere stem from continuous coverage of the Southern hemisphere sky, and from the virtues of different detector technologies and different systematic errors. These arguments do not outweigh the advantages from pooling resources in a single, optimized detector.

- **Recommendation 10**

The timely formation of an international collaboration for the construction and exploitation of a km^3-scale Northern hemisphere deep-water detector is encouraged.

The commitment of the scientists to build a km^3-scale detector can start in the next few years. This commitment is needed to assemble an international collaboration with the required technical strength and to select the appropriate site for the detector. The start of construction should be set by the progress on the current-generation detectors (ANTARES, Lake Baikal and NESTOR). Valuable experience will be gained in the next few years from the development of instrumentation and from the deployment and operation in the sea by ANTARES, NEMO and NESTOR. The lessons learned from their efforts should be incorporated into the design of the km^3-scale detector.

1.3 Mandate and composition of HENAP

The foundational text of HENAP (Report of PaNAGIC to IUPAP; presented to the meeting of the Council and Commission Chairs of IUPAP, Beijing, 6 October 2000), states the following:

"The Cherenkov detection of high-energy (> 1 TeV) neutrinos in the deep sea or Antarctic ice promises to open an important new window onto the cosmos. The uncertainties in the current neutrino-rate calculations, the fragmentation of the interested community, and the high price tag of the future large size projects have raised a number of questions among scientists, funding agencies, and governments alike. Following the conclusions of the OECD MegaScience workshop of Taormina in May 1997, the PaNAGIC of IUPAP has set up a High Energy Neutrino Astrophysics Panel with the following charge:

1. *Firm up the scientific justifications: likely sources, expected rates and their uncertainties, astrophysical importance of detecting such neutrinos, and connection with other astronomical observations.*

2. *Establish the needed sensitivity and volume and examine the potential justifications for more than one site.*

3. *Identify the needed steps to reach the required detector sensitivity, and establish the scientific milestones that should be reached by the successive generations of instruments, before proceeding to the next step.*

4. *Define with the scientists involved the elements of comparison of the proposed technologies: performance, reliability, maintenance, cost effectiveness etc.*

5. *Identify the opportunity for R&D collaboration between the various projects.*

6. *Define the scientific and technical criteria for the choice of site(s) for a high-energy neutrino observatory.*

7. *Suggest international collaboration guidelines.*

8. *Examine the potential for involvement of industry.*

9. *Explore the benefit of the facilities for other fields of science".*

The members of HENAP were nominated by PaNAGIC as follows: Enrique FERNANDEZ (Spain) Chair, Steve BARWICK (US), John CARR (France), Charles DERMER (US), Friedrich DYDAK (CERN), Grigorij DOMOGATSKY (Russia), Emilio MIGNECO (Italy), Rene ONG (US), John PEOPLES (US), Leonidas RESVANIS (Greece), Yoji TOTSUKA (Japan), Eli WAXMAN (Israel).

1.4 HENAP meetings

HENAP had a first meeting in Venice on March 10, 2001, following the IX International Workshop on Neutrino Telescopes. A second meeting took place on September 7, 2001 at the Gran Sasso National Laboratory, before the TAUP2001 Conference. The third and fourth meetings took place at Laguna Beach, California on November 28-29, 2001 and in Barcelona on March 26-28, 2002. A fifth meeting was held in Munich on May 27, 2002, during the Neutrino2002 Conference.

2. Scientific motivation

2.1 A new window onto the cosmos

At present, several neutrino telescopes monitor solar MeV neutrinos, thus permitting direct observations of nuclear reactions in the optically opaque core of the Sun and studies of fundamental neutrino properties. These telescopes are also capable of detecting MeV neutrinos from supernova explosions, such as supernova 1987A, in our local galactic neighborhood at distances $< 10^5$ light years. The construction of high-energy neutrino telescopes with thresholds at GeV to TeV energies is aimed at extending the distances accessible to neutrino astronomy by five orders of magnitude. This new window onto the cosmos will provide a probe of the most powerful sources in the universe through observations of high-energy neutrinos.

Observations of cosmic rays with energies beyond 10^{20} eV imply the existence of sources of high-energy neutrinos. The flattening of the cosmic-ray spectrum near 10^{19} eV, accompanied by hints for a composition change from heavy to light nuclei with no clear evidence of anisotropy, suggest that a Galactic component dominated by heavy nuclei below 10^{19} eV is overtaken by an extra-galactic proton component at higher energies. Irrespective of the nature of the cosmic-ray sources, some fraction of these particles will produce pions as they escape from the acceleration site, either through hadronic collisions with ambient gas or through interaction with ambient photons, leading to electron and muon neutrino production from the decay of charged pions.

No consensus has been reached on a mechanism that accelerates hadrons to energies above 10^{20} eV. Candidate acceleration sites may have magnetic fields that are too weak, acceleration regions that are too small, or confinement times that are too short. If the sources of ultra-high-energy cosmic rays are extra-galactic and the particles are hadronic, then these particles lose energy by interacting with the cosmic microwave background photons over relatively short distances (< 100 Mpc). Two observational consequences ensue: first, the collisions will reduce the energies of $> 10^{20}$ eV particles to $\sim 5 \times 10^{19}$ eV, independent of their initial values, and second, ultra-high-energy “GZK neutrinos” are produced. The GZK effect provides a strong motivation to develop new devices with improved sensitivity in order to search for ultra-high-energy neutrinos. The detection of GZK neutrinos will represent an important milestone in neutrino astronomy. It will help to determine the spatial distribution of the sources of ultra-high-energy particles, and will constrain the identity of the constituent particles.

Extra-galactic objects, such as the sources of gamma-ray bursts (GRBs) and active galactic nuclei (AGN), plausibly generate cosmic rays up to the maximum observed energies, and are therefore likely sources of neutrinos in the TeV to PeV energy range. GRBs are transient flashes of gamma-rays lasting typically for 1 – 100 s, that are observed from sources at cosmological distances. The apparent isotropic luminosities of GRBs are of order 10^{53} erg/s. They are believed to be powered by the rapid accretion of a fraction of a solar mass of matter onto a newly born solar-mass black hole. AGN consist of both persistent and flaring sources with apparent luminosities reaching about 10^{48} erg/s. They are thought to be powered by mass accretion onto $10^{6} – 10^{9}$ solar-mass black holes that reside at the centers of galaxies. In both GRBs and AGN, mass accretion is believed to drive a relativistic plasma outflow that results in the acceleration of high-energy particles, which emit non-thermal radiation. A similar process could also power Galactic microquasars, which may be considered as a scaled-down version of AGN, though powered by stellar-mass black holes or neutron stars. In all cases, neutrino observations will provide unique information on the physics of the underlying engine, which is not well understood despite many years of research. Neutrino observations are specifically interesting because the detection of high-energy multi-TeV neutrinos will provide unambiguous evidence for cosmic acceleration of protons and nuclei, and their arrival direction will point to the location of the accelerators.

Neutrino telescopes permit us not only to look into the engines driving powerful sources such as distant AGN and GRBs that cannot be explored directly with photon observations, but also to look far into the universe. Cosmological (redshift $z > 1$) sources cannot be observed at photon energies exceeding 100 GeV because of attenuation by γ-γ pair production on the diffuse intergalactic infrared background radiation. By contrast, high-energy neutrinos will propagate unhindered directly to us from their sources. Thus, neutrinos provide a window to explore high-energy phenomena in the distant universe.

Detection of neutrinos could also allow us to study fundamental neutrino-physics issues involving neutrino oscillations and weakly interacting massive particles (WIMPs), to test Lorentz invariance, and to test the weak equivalence principle.

Estimates indicate that neutrino telescopes with km^2 effective area are needed to detect neutrino point sources, as discussed in more detail in Section 2.2. Full coverage of the sky by such telescopes is important for three major reasons. First, the brightest neutrino sources are few in number and could be distributed anisotropically on the sky. Second, detection of transient neutrino sources will benefit from detectors observing the full sky. Third, the AMANDA detector currently operating at the South Pole, and its planned extension IceCube, view the Galactic center only via contained events (where the pointing accuracy is bad) or via muons of extremely high energy (which may not be typical for Galactic sources). Since the density of Galactic candidate neutrino sources such as microquasars, type II supernovae and supernova remnants (see the discussion in section 2.2.2 below) is enhanced in the Galactic center, a Northern hemisphere detector is required to supplement the field of view of the Southern hemisphere IceCube detector.

2.2 Estimates of cosmic neutrino fluxes

2.2.1 Phenomenological considerations

An estimate for the required neutrino telescope size can be obtained by considering the minimum flux of a source that can be detected by a neutrino telescope with effective area *A* (in the plane perpendicular to the source direction) and exposure time *T*. The probability that a muon produced by the interaction of a muon neutrino with a nucleon will cross the detector is given by the ratio of the muon and neutrino mean free paths. For water and ice, this probability is

$$P_{\nu\mu} \approx 10^{-4} \left(\varepsilon_\nu / 100 \text{ TeV}\right)^{\alpha} ,$$

with α 1 for $\varepsilon_\nu < 100$ TeV and α 0.5 for $\varepsilon_\nu > 100$ TeV. Note that the mean free path of muons of energy > 0.3 TeV is of order 1 km. Thus, a detector with effective cross-sectional area *A* corresponds to a detector with an effective volume $\sim A \times$ (1 km). We will use in this report the term "km^3-scale" detector to denote a detector with effective volume ~ 1 km^3, and with effective area (perpendicular to any direction) ~ 1 km^2.

A source with energy flux f_ν in neutrinos of energy ε_ν will produce $N \approx (f_\nu/\varepsilon_\nu)P_{\nu\mu}AT$ events in the detector. Thus, the flux required for the detection of *N* events is

$$f_\nu \approx 5\times 10^{-12}\, N \left(\frac{\varepsilon_\nu}{100 \text{ TeV}}\right)^{1-\alpha} \left(\frac{AT}{\text{km}^2 \text{ yr}}\right)^{-1} \quad \text{erg}/(\text{cm}^2\text{s}).$$

A lower limit to the source flux is also set by the requirement that the signal would exceed the background produced by atmospheric neutrinos. The flux of atmospheric neutrinos, averaged over zenith angle, is approximately given by

$$\Phi_\nu^A \approx 5\times 10^{-8} \left(\frac{\varepsilon_\nu}{100 \text{ TeV}}\right)^{-\beta} \quad \text{GeV}/(\text{cm}^2\text{s sr}),$$

with β 1.7 for $\varepsilon_\nu < 100$ TeV and $\beta = 2.0$ for $\varepsilon_\nu > 100$ TeV. For a neutrino detector with angular resolution $\Delta\vartheta$, the source flux for which the signal constitutes a 5σ detection over the atmospheric background flux is

$$f_\nu \approx 3\times10^{-12}\left(\frac{\varepsilon_\nu}{100\ \mathrm{TeV}}\right)^{-\beta/2}\left(\frac{\Delta\theta}{1\deg}\right)\left(\frac{AT}{\mathrm{km}^2\ \mathrm{yr}}\right)^{-1/2}\ \mathrm{erg}/(\mathrm{cm}^2\mathrm{s}).$$

Thus, for km^3-scale detectors, the atmospheric neutrino background is a less stringent constraint on source flux than the requirement of a detectable signal (except at low energies).

For cosmological sources with characteristic distance of $d \sim c/H_0 \approx 4$ Gpc $\approx 10^{28}$ cm, the minimum apparent luminosity for neutrino detection is therefore

$$L_\nu = 4\pi d^2 f_\nu > 10^{46}\ N\left(\frac{d}{10^{28}\ \mathrm{cm}}\right)^2\left(\frac{\varepsilon_\nu}{100\ \mathrm{TeV}}\right)^{1-\alpha}\left(\frac{AT}{\mathrm{km}^2\ \mathrm{yr}}\right)^{-1}\ \mathrm{erg/s}.$$

Objects with observed isotropic luminosities ~ 10^{47} erg/s, which is more than 13 orders of magnitude higher than the Solar luminosity, are rare. In fact, the only known persistent sources that produce such high luminosities are blazar AGN. It is therefore clear that km^3-scale neutrino detectors are required for the detection of cosmological sources. This argument holds also for transient sources at cosmological distances. The brightest known transients are GRBs, with apparent isotropic luminosities > 10^{52} erg/s lasting over ~ 100 s. Replacing T = 1 yr with T = 100 s in the above equation implies a minimum isotropic luminosity $L_\nu \sim 10^{52}$ erg/s.

The above conclusions are strengthened by gamma-ray observations. The production of charged pions by interaction of nucleons with photons or nucleons is accompanied by the production of neutral pions and hence high-energy photons. Searches for astrophysical high-energy discrete gamma-ray sources resulted in upper limits of 10^{-11} erg/(cm^{2}s) on the flux of such sources at ~ 40 and ~ 100 TeV. At ~ 1 TeV, the Galactic supernova remnants SN 1006 and Cas A were detected at approximate levels of 10^{-11} and 10^{-12} erg/(cm^{2}s), respectively. Relatively nearby extra-galactic active galaxies (Mkn 501, Mkn 402) were detected at approximate levels of 10^{-11} – 10^{-10} erg/(cm^{2}s), while more distant active galaxies, e.g. the flat-spectrum quasar 3C 279, were detected above 100 MeV at ~ 10^{-10} erg/(cm^{2}s) (these sources exhibit day-long “flares” during which the flux is larger by one order of magnitude). At energies > 100 MeV, an all-sky survey of EGRET with a high Galactic-latitude sensitivity of 10^{-11} erg/(cm^{2}s) resulted in high-confidence detection of 66 blazar AGN and 27 lower-confidence blazar sources, in addition to the detection of 170 unidentified sources.

Assuming that the high-energy neutrino and photon fluxes are similar, gamma-ray observations imply that a km^3-scale detector is required for the detection of high-energy neutrino sources. Two points should be made here regarding the relation between high-energy photon and neutrino fluxes. First, although pion-decay neutrinos should be accompanied by high-energy photon production, high-energy photons may be prevented from escaping the source because of absorption via pair-production. This implies that "hidden" sources may exist which emit only high-energy neutrinos without an accompanying high-energy photon flux.

On the other hand, it should be realized that gamma-ray photon production does not guarantee high-energy neutrino production. The high-energy photon fluxes in SN remnants, AGN and GRBs could be dominated by synchrotron and inverse-Compton emission from electrons rather than by pion decay. For example, X-ray observations seem to support a Compton origin of high-energy photons from SN1006, and most AGN and GRB models are based on direct acceleration of electrons. Although acceleration of protons with power comparable to that of electrons –and hence the production of neutrinos – should be expected, the predicted neutrino fluxes are model-dependent.

2.2.2 Point sources

2.2.2a Gamma ray bursts

Widely discussed current models of GRB sources involve dissipation of the kinetic energy of a relativistically expanding fireball caused by either a cataclysmic collapse of a massive star, or by the coalescence of two compact objects. The resulting shocks may accelerate particles via the Fermi process to ultra-relativistic energies. Accelerated electrons emit non-thermal radiation that can explain the observed MeV gamma-ray spectra. This model has received support from the verification of the predictions of an afterglow at lower (X-ray, optical, radio) energies. However, the model remains largely phenomenological. The underlying progenitor remains unknown, and the physics of electron coupling and magnetic field amplification by the shocks is not well understood.

Internal shocks, which may produce the gamma-ray luminous phase of GRBs, occur at relatively small radii from the center of the outburst. In this scenario, the observed gamma-ray emission implies a high co-moving photon density, leading to the possibility of efficient production of pions and > 100 GeV neutrinos by interaction of accelerated protons with observed photons. External shocks due to the interaction of the expanding GRB blast wave with its surroundings can also produce energetic neutrinos through interaction of accelerated protons with hadrons and photons. Shocks occurring from the deceleration by the external medium that involve the reverse shock moving into the ejecta can produce optical photons which interact with shock-accelerated protons to produce ultra-high-energy neutrinos. The predicted flux of ~ 100 TeV neutrinos implies a rate ~ 10 events per year in a km^3-scale detector. The detection of even a few neutrino events will constitute a signal with high statistical significance if neutrinos are detected in coincidence with gamma-rays from GRBs.

The most widely discussed progenitor scenarios for long-duration GRBs involve core collapse of massive stars. In these "collapsar" models, a relativistic fireball jet breaks through the stellar envelope to produce a GRB. For extended or slowly rotating stars, the jet may be unable to break through the envelope. Both penetrating (GRB producing) and "choked" jets can produce a burst of ~ 5 TeV neutrinos by interaction of accelerated protons with jet photons, while the jet propagates in the envelope. The estimated event rates vary between a few hundred and a few thousand per year, depending on the ratio of non-visible to visible fireballs. This model argues for good sensitivity at TeV energies, but unequivocal detection of non-visible GRBs with neutrinos may be difficult owing to the meager energy resolution for muon-neutrino events, unless the associated supernova photons are detected.

In the two-step "supranova" model, interaction of the GRB blast wave with the supernova shell can lead to detectable neutrino emission, either through nuclear collisions with the dense supernova shell or through interaction with the intense supernova and backscattered radiation field.

Production of lower energy (~ 10 GeV) neutrinos is also predicted in the fireball model. GRB fireballs should contain an admixture of neutrons and protons in all progenitor scenarios. Inelastic collisions between protons and neutrons in the fireball would produce muon neutrinos of ~ 10 GeV and electron neutrinos of ~ 5 GeV. The predicted event rate is ~ 7 events per year in 1 km^3 detectors. Although the energy threshold of km^3-scale neutrino telescopes is expected to be higher than 10 GeV, time coincidence with satellite observations may significantly increase the capability of high-energy neutrino telescopes at low energies.

In summary, high-energy neutrino telescopes can help to clarify several critical features of GRB models. The internal shock models predict detectable neutrino emission during the prompt phase, whereas external shock models predict undetectable fluxes from smooth-profile GRBs. Detection of high-energy neutrinos (and photons) will provide constraints on the progenitors of GRBs and will allow stringent tests on the underlying GRB model.

2.2.2b Active galactic nuclei and blazars

The presence of jet outflows determines whether AGN are radio-loud or radio-quiet. Radio-loud AGN with luminous and rapidly variable (hours to days) non-thermal electromagnetic radiation and strong optical polarization are referred to as blazars. These sources are often strong sources of GeV and, in some cases, TeV gamma-radiation. Blazars are thought to be AGN where the jet is nearly aligned with the direction to the observer.

One of the major questions that neutrino astronomy can address is whether AGN jets are powerful accelerators of protons and ions to ultra-high energies. If relativistic leptons were mainly accelerated in the jets, then few or no neutrinos would be emitted. If relativistic hadrons are accelerated with comparable power to non-thermal electrons, then observable fluxes of neutrinos would be produced in the jet through pion production by nuclear and photo-hadronic interactions.

If neutrino production is dominated by inelastic nuclear interactions, then the neutrino spectrum is expected to reflect the spectrum of relativistic particles from GeV to the highest energies. The spectrum of neutrinos formed by photo-hadronic interactions depends on the target photon field, which can be internal or external in origin. Detectable fluxes of neutrinos above 10 TeV might be expected from flat-spectrum radio quasars, such as 3C 279 and PKS 0528+134, owing to interaction of protons with external optical/UV radiation. Qualitatively different fluxes and neutrino spectra, peaking above ~ 10^{17} eV, are expected from BL Lac objects, such as Mkn 421 and Mkn 501, where interaction with internal synchrotron photons dominates.

The morphology of large-scale extra-galactic radio jets may support efficient photomeson production associated with the acceleration of hadrons to ultra-high energies in the inner jets. Intense, collimated high-energy neutron and gamma-ray beams formed in flat-spectrum quasars could power the lobe-dominated FR II radio-galaxies, whereas weaker neutral beams in BL Lac objects would power the FR I radio-galaxies with the twin-jet structure. A proposed scenario for evolution from merging galaxies to AGN jet sources would be supported if some ultra-luminous infrared galaxies were high-energy neutrino sources. This would also test whether the radio-loud/radio-quiet dichotomy is related to the spin of the black hole or to the accretion rate. Thus, detection of neutrinos at TeV to PeV energies can establish whether jets are mass-loaded and will test models of AGN radiation and evolution.

2.2.2c Microquasars

The jets associated with Galactic microquasars are believed to be ejected by accreting stellar-mass black holes or neutron stars. Much like for AGN, the content of the jets is an open issue. The dominant energy carrier in the jet is at present unknown (with the exception of the jet in SS433). Scenarios whereby energy extraction is associated with spin-down of a Kerr (rotating) black hole favor electron–positron composition (although baryon admixture is an issue), while scenarios in which an initial rise of the X-ray flux leads to ejection of the inner part of the accretion disk imply electron–positron jets, as widely claimed to be suggested by the anti-correlation between the X-ray and radio flares seen during major ejection events. A possible diagnostic of electron–positron jets is the presence of Doppler-shifted spectral lines, such as the H_α line as seen in SS433. The detection of such lines from jets having a Lorentz-γ factor well in excess of unity (as is the case in the superluminal microquasars) may, however, be far more difficult than in

SS433, as the lines are anticipated to be very broad. Neutrino telescopes may prove to be a much sharper diagnostic tool. If the energy content of the jets in the transient sources is dominated by electron–proton plasma, then a several hour outburst of 1 to 100 TeV neutrinos (and high-energy photons) produced by photo-production of pions should precede the radio flares associated with major ejection events. Several neutrinos may be detected during a single outburst by a km^3-scale detector, thereby providing a powerful probe of microquasar jet physics and of their innermost structure.

2.2.2d Supernovae and supernova remnants

Loeb and Waxman have suggested that simultaneous detection of MeV and TeV neutrinos from a supernova may be possible, with the MeV neutrinos detected by Super-Kamiokande, SNO, or future detectors such as UNO or IceCube. When a type II supernova shock emerges from the progenitor star, it becomes collisionless and may accelerate protons to TeV energy and higher. Inelastic nuclear collisions of these protons produce a burst of TeV neutrinos over durations ~ 1 hour. This occurs about 10 hours after the thermal neutrino burst from the cooling neutron star. A galactic supernova explosion of a red supergiant star would produce ~ 100 muon events in a km^3-scale neutrino detector, thus providing important constraints on both supernova models and neutrino physics. Given the most probable direction for the next galactic supernova, this objective is best achieved by a Northern hemisphere detector. Unfortunately, these events are rather rare, as type II supernovae occur only once every 40 years in the Galaxy.

The calculation of the neutrino flux from supernova remnants (SNRs) is straightforward, assuming that a supernova remnant converts an amount of energy E_{CR} to non-thermal cosmic rays with a number index of ~ 2.2. In this case, the energy flux in muon neutrinos is given by

$$f_\nu^{SNR} \approx 5\times10^{-12}\left(\frac{\varepsilon_\nu}{1\,\mathrm{TeV}}\right)^{-0.2}\left(\frac{E_{CR}}{10^{50}\,\mathrm{ergs}}\right)\left(\frac{n}{1\mathrm{cm}^{-3}}\right)\left(\frac{d}{1\,\mathrm{kpc}}\right)^{-2}\ \mathrm{erg}/(\mathrm{cm}^2\mathrm{s}).$$

Here, n is the number density of the inter-stellar medium surrounding the SNR. Comparison with our earlier equations shows that several neutrinos could be detected from nearby SNRs for a $km^3\times$yr exposure. If the SNR is too close or too extended, however, the cosmic-ray induced background may limit the detection significance.

2.2.2e Other possible neutrino sources

Although GRBs and AGN are favored high-energy neutrino source candidates, a case can be made that any medium-energy gamma-ray source is a potential neutrino source.

This includes young pulsars that accelerate electrons either at the charge-depleted inner gaps or at the outer gaps in the pulsar magnetosphere. Associated electrostatic acceleration of hadrons is expected, a possible mechanism for the acceleration of cosmic-rays to ultra-high energies. Other possible point sources of neutrinos could be related to the unidentified EGRET gamma-ray sources, which could be associated with pulsar wind nebulae, or isolated accreting black-holes in the Galaxy, or particle acceleration in shocks from stellar winds in OB associations (stellar groups dominated by massive and luminous O and B main-sequence stars).

Arguments have also been made that some of the unidentified EGRET sources are associated with non-thermal particles accelerated by shocks formed in merging clusters of galaxies, in which case related neutrino production is expected. Calculations indicate that neutrino production from cosmic rays accelerated in clusters of galaxies, as well as in nearby normal and star-burst galaxies or in the extended lobes of radio-galaxies, will be too weak to be detected with km^3-scale high-energy neutrino telescopes.

2.2.3 Diffuse neutrino flux

Waxman and Bahcall have shown that cosmic-ray observations set an upper bound to the neutrino flux from sources which, like candidate sources of > 10^{19} eV protons, are optically thin for high-energy nucleons to gamma–proton and proton–proton (neutron) interactions. For sources of this type, the energy generation rate of neutrinos can not exceed the energy generation rate of high-energy protons implied by the observed cosmic-ray flux above 10^{19} eV. The resulting upper bound is compared in Fig. 2.1 with the flux sensitivity of neutrino telescopes.

Sources may exist where pion production losses prevent the escape of high-energy nucleons and allow only neutrinos (and possibly low-energy gamma rays) to escape. While cosmic-ray data do not constrain the possible neutrino flux from such sources, which may therefore exceed the bound shown in Fig. 2.1, the data also do not provide evidence for the existence of such “hidden” sources.

Figure 2.1 also shows current limits for diffuse flux given by the AMANDA-B10 and Lake Baikal telescopes, and the anticipated performance by a 0.1 km^2 detector such as AMANDA-II, which also approximately characterizes the minimum detectable flux by ANTARES and NESTOR. Since the Earth attenuates the flux of muon and electron neutrinos if their energy exceeds ~ 1 PeV, very high-energy neutrino detectors must search in the lateral and downgoing directions. Hundertmark et al. have provided evidence that neutrino events in AMANDA-B10 can be extracted from the large flux of low-energy atmospheric muon background. At such enormous energies, the events are spectacularly unique and the effective volumes vary between 0.1 and 0.4 km^3, i.e. a sizeable fraction of the km^3 sensitivity.

As shown in Fig. 2.1, detectors with instrumented volumes of one cubic kilometer provide an improvement in the minimum detectable diffuse flux. However, charm-induced backgrounds begin to impact the minimum detectable fluxes in such next-generation detectors. Currently, model predictions for charm-induced atmospheric neutrinos vary by several orders of magnitude or more because the relevant production cross-sections are not measured. The component from charm decay has a harder spectrum than the component from decay of charged kaons and pions. If sufficiently large, the charm component is expected to become dominant above an energy of 100 TeV. Unfortunately, charm backgrounds will be difficult to differentiate from the diffuse signal because the energy spectra for both sources of events are quite similar. Since the charm-induced backgrounds may rival the signal fluxes uniquely accessible to km^3-scale detectors, and since the relative amount of information carried by a diffuse signal is rather limited without additional spectral or directional information, km^3-scale detectors should rather focus on detection of point-like neutrino sources.

Finally, we note that another important challenge for high-energy neutrino astronomy is the detection of GZK neutrinos at ultra-high energies (GZK in Fig. 2.1). Unless km^3-scale water or ice detectors deviate from a uniformly volumetric design, they are too small to observe the flux induced by the GZK mechanism. Nevertheless, several new techniques are being developed to observe the low fluxes expected at this energy frontier: Sensitivity limits expected to be achieved by ANITA, a balloon-borne antenna to measure radio emission from particle cascades, and by Auger-tau, referring to tau detection by the Auger detector being constructed in Argentina, are shown in Fig. 2.1

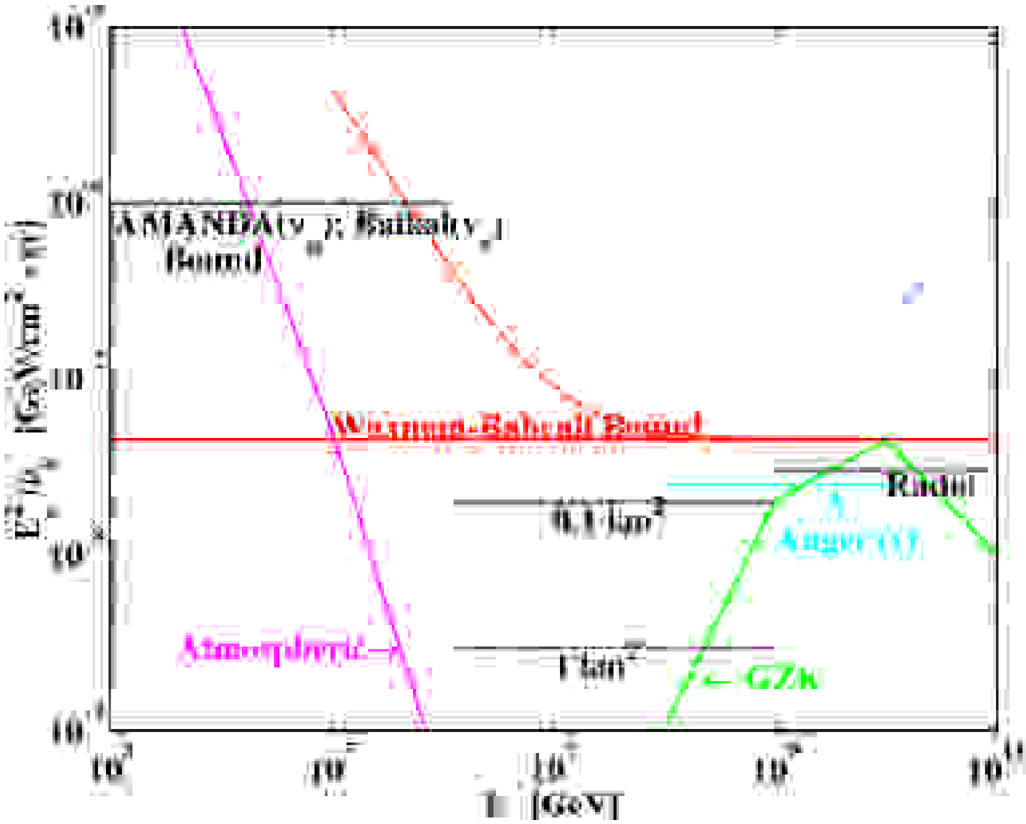

Fig. 2.1 The dark solid line gives the experimental upper bound on neutrino intensity established by the AMANDA-B [E. Andres et al., Nucl. Phys. B (Proc. Suppl.), **91**, 423 (2001)] and Lake Baikal [G. Domogatsky, Proc. Neutrino 2002, ed. G. Raffelt (Munich 2002)] detectors, compared to sensitivities achievable by 0.1 and 1 km^2 detectors. The sensitivity of the detectors to variable point sources is greater than shown, since the background is much reduced for a search in given time and direction windows. The atmospheric neutrino background (averaged over zenith angle) is shown by the magenta line (labeled "atmospheric" in the figure).

The solid red line shows the upper bound imposed by cosmic-ray observations on the intensity of muon neutrinos [E. Waxman & J. N. Bahcall, Phys. Rev. **D59**, 023002 (1999); K. Mannheim, R. J. Protheroe & J. P. Rachen Phys. Rev. **D63**, 023003 (2001); J. N. Bahcall & E. Waxman, Phys. Rev. **D64**, 023002 (2001)]. The dashed red line extension to lower energies is the bound obtained under the assumption that the extra-galactic proton energy generation rate below 10^{17} eV, which is uncertain due to Galactic cosmic-ray background, exceeds the generation rate derived from observations at higher energy. The dotted blue line extension to high energies is obtained under the assumption that the extra-galactic proton-energy generation rate increases rapidly beyond 10^{20} eV, where the cosmic-ray flux is not well constrained by observations.

2.3 Other scientific objectives

2.3.1 Flavor oscillations

Neutrinos are expected to be produced in astrophysical sources via the decay of charged pions. Production of high-energy muon and electron neutrinos with a 2:1 ratio is therefore expected (tau neutrinos may be produced by photo-production of charmed mesons; however, the higher energy threshold and lower cross-section for charmed-meson production, compared to pion production, typically imply that the ratio of charmed-meson to pion production is ~ $1{:}10^4$). Because of neutrino oscillations, neutrinos that get here are expected to be almost equally distributed between flavors for which the mixing is strong. In fact, if the atmospheric neutrino anomaly has the explanation it is usually given, then one should detect equal numbers of muon and tau neutrinos. Upgoing taus, rather than muons, would be a distinctive signature of such oscillations. It may be possible to distinguish between taus and muons in a km^3-scale detector, since at 1 PeV the tau decay length is ~ 1 km. This will allow a “tau appearance experiment”.

2.3.2 Tests of Lorentz invariance and of the weak equivalence principle

Detection of neutrinos from GRBs could be used to test the simultaneity of neutrino and photon arrival to an accuracy of ~ 1 s (~ 1 ms for short bursts), checking the assumption of special relativity that photons and neutrinos have the same limiting speed. (The time delay due to the neutrino mass is negligible: for a neutrino of energy ~ 1 TeV with mass ~ 1 eV traveling 1 Gpc the delay is ~ 0.1 s.) These observations would also test the weak equivalence principle, according to which photons and neutrinos should suffer the same time delay as they pass through a gravitational potential. With 1 s accuracy, a burst at a distance of 1 Gpc would reveal a fractional difference in limiting speed ~ 10^{-17}, and a fractional difference in gravitational time delay of order 10^{-6} (considering the Galactic potential alone). Previous applications of these ideas to supernova 1987A, where simultaneity could be checked only to an accuracy of order several hours, yielded much weaker upper limits: of order 10^{-8} and 10^{-2} for fractional differences in the limiting speed and time delay, respectively.

2.3.3 Dark matter detection

Weakly Interacting Massive Particles (WIMPs) are possible constituents of the cold dark matter. If WIMPS populate the halo of our galaxy, the Sun or Earth would capture them where they would annihilate occasionally into high-energy neutrinos. The rate depends on the details of the model. A widely discussed WIMP candidate is the lightest neutralino in minimal supersymmetric models. High-energy neutrino telescopes complement direct search detectors by reaching good sensitivity at high neutralino masses, typically in excess of a few hundred GeV, and by allowing us to probe regions of parameter space with large branching fractions to W and Z bosons. Neutrino telescopes currently under construction, with ~ 0.1 km^3 effective volumes, are expected to probe fluxes that are ultimately constrained by the intrinsic background from atmospheric neutrinos. km^3-scale telescopes will provide only modest improvement over such telescopes, since the flux limits scale in this case only as the square root of the effective detection volume.

2.4 Summary of the scientific case

1. The existence of extra-galactic, high-energy neutrino sources is implied by high-energy cosmic-ray observations.

2. Phenomenological, model-independent arguments based on cosmic- and gamma-ray observations imply that km^3-scale telescopes are required to detect signals from known extra-galactic sources.

3. The detection of high-energy neutrinos may resolve the puzzles associated with the observation of ultra-high-energy cosmic-ray particles.

4. High-energy neutrino telescopes will provide unique constraints, complementary to those provided by photon observations, on models of the most powerful known astrophysical objects: GRBs and AGN. In particular, they may provide constraints on the unknown progenitors of GRBs and on the black-hole energy extraction mechanism in both GRBs and AGN.

5. km^3-scale neutrino telescopes may also detect, and provide unique constraints on models of, Galactic sources such as microquasars, type II supernovae and supernovae remnants.

6. In order to achieve the scientific goals, neutrino point sources would need to be detected and associated with astrophysical objects identified by photon observations.

7. km^3-scale telescopes would provide only modest improvement over current experiments in the detection of a diffuse neutrino flux.

8. Prospects for the achievement of the above scientific goals will be greatly enhanced by full sky coverage.

9. km^3-scale telescopes may also allow the study of neutrino flavor oscillations, WIMP detection, and tests of Lorentz invariance and of the weak equivalence principle.

3. Techniques for cosmic-neutrino detection

3.1 Muon detection through Cherenkov light

The essential characteristics of a neutrino telescope have been known for more than two decades. The most important features were elaborated during a series of workshops devoted to developing the DUMAND concept, and put into practice by the Lake Baikal experiment. Already more than four decades ago, Markov had suggested that the ocean would be a suitable site for constructing a large neutrino detector based on the detection of Cherenkov light emitted by neutrino-induced muons or neutrino-induced electromagnetic and hadronic showers. Halzen and Learned introduced a twist on this idea by promoting polar ice as suitable medium.

All current architectures for cosmic-neutrino telescopes deploy a sparse array of optical sensors within deep ice, sea or lake waters. The optical sensors respond to the UV-blue dominated Cherenkov radiation.

Very large detector masses are required because the predicted flux of cosmic neutrinos and the known interaction probabilities at the energies of interest are very small. In comparison, the background from cosmic-ray muons is large.

The required combination of large mass to compensate for the small signal, large overburden to ease the background from cosmic-ray muons, and the need to minimize material costs leaves no options other than to construct a detector within a naturally occurring transparent medium such as ice or water (no excavated caves or mines are large enough).

At the energies of interest to cosmic-neutrino telescopes, the range of the muon in water or ice is 3 – 20 km. Therefore, upward-traveling muons may be generated by neutrino interactions well outside the instrumented volume of the optical array. Because the largest *effective* detector volumes are achieved by measuring high-energy muons, we concentrate our discussion on the detection of muons induced by charged-current muon-neutrino interactions.

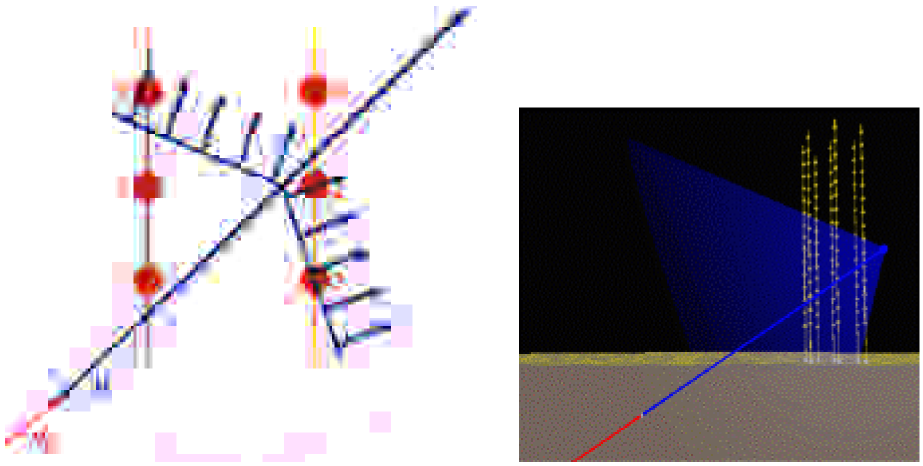

Fig. 3.1: Schematic of detection method for charged-current muon-neutrino interactions. All Cherenkov photons are emitted at a characteristic angle of 42 degrees with respect to the muon direction. Muon trajectories can be reconstructed by timing the passage of the wave front of Cherenkov light.

The Cherenkov technique is well understood and illustrated in Fig. 3.1. A high-energy neutrino can be detected through its conversion to a charged lepton, such as a muon, or the initiation of an electromagnetic or hadronic shower. Directional information is preserved because the muon direction is aligned with the incident neutrino to within 0.65 degrees if $E_\nu > 3$ TeV. The mean angular correlation between outgoing charged lepton and parent neutrino improves as $1/\sqrt{E_\nu}$, so at high enough energies multiple Coulomb scattering becomes the dominant factor in the angular resolution. Ideally, the angular resolution of the detector should be smaller than the limiting intrinsic angular resolution. Water-based detectors have the potential to achieve a muon angular resolution of ~ 0.1 degrees, compared to the ~ 0.5 degrees expected in an ice detector. This angular resolution is not competitive with the one offered by conventional astronomy. Therefore sources are more likely to be identified by correlating with transient phenomena (e.g. SN, GRBs), time-dependent fluctuations at other wavelengths (e.g. AGN), or statistical methods (by searching for a similar class of objects that lie within the angular error boxes).

Muons from neutrino interactions are detected by distributing large-diameter photomultiplier tubes (PMTs) over the largest possible volume of transparent medium and recording the arrival times and intensity of the wave front of Cherenkov light. Accurate reconstruction relies on tracking events over many tens of meters and measuring the arrival of the Cherenkov wave front to nanosecond accuracy. Array geometries are optimized according to the optical properties of the medium in which the detector is embedded (those media that cause more scattering of Cherenkov photons generate less precision in the arrival time of the Cherenkov wave front). To compensate, larger detectors with greater average path length are designed. Utilizing a medium with a large optical attenuation length and long scattering lengths simplifies the dominant design goal to achieve a large instrumented volume.

Muons created by cosmic-neutrino interactions are distinguished from the vastly more numerous muons created by cosmic-ray collisions in the atmosphere by direction. Upward-going muons can only originate from nearby neutrino interactions. The Earth filters out all other known particles. Since the direction of the muon is the most important criterion for neutrino identification, great care must be taken to reject efficiently the overwhelming down-going atmospheric muons. Complications arise from the lack of fixed fiducial volume, the presence of events containing multiple muons, muons decaying in flight, and fluctuations in the generation of Cherenkov photons.

3.2 Shower detection through Cherenkov light

Muons created in charged-current muon-neutrino interactions provide the most sensitive probe in the arsenal of cosmic-neutrino telescopes. At TeV energies, muons can travel several kilometers, which exceeds already the dimensions of the instrumented volume of the next-generation arrays. At PeV energies, the range of the muon exceeds 10 km.

However, there are additional signatures available to cosmic-neutrino telescopes. They are distinguished from the muon signature by the topological distribution of photon density: cascade signatures produced by charged-current electron-neutrino and tau-neutrino interactions and, to a lesser extent, neutral-current interactions by all known neutrino flavors.

As opposed to the continuous photon distribution produced by muons, electron-initiated electromagnetic (and hadronic) showers produce bright localized regions of photon production. The longitudinal development of the particle cascade reaches its maximum over a distance of less than 10 m, which is point-like on the scale of a detector with kilometer dimensions. Therefore, the interaction vertex must lie within the instrumented volume to estimate properly the energy and reject background. This signature enjoys two very important advantages over the previously discussed muon signature: superior energy resolution and reduced intrinsic background from atmospheric neutrinos (the flux of atmospheric electron neutrinos is suppressed relative to muon neutrinos as the energy increases because, at higher energies, atmospheric muons are more likely to interact than decay). On the other hand, the directional information of the parent neutrino is much harder to extract from a shower topology than from a muon track. Since directional information is very subtle in high-energy cascades, water-based detectors may enjoy a critical advantage over ice detectors because of their superior timing resolution. The water Cherenkov technique may achieve angular resolution for cascades as small as a few degrees. Although not yet studied in detail, the angular resolution for cascades in ice-based detectors is unlikely to approach this value because of the scattering properties of ice.

With the evidence from SNO and Super-Kamiokande that electron, muon and tau neutrinos oscillate into each other, a beam of cosmic neutrinos is expected to contain all neutrino flavors with comparable fluxes.

Several methods have been suggested to detect tau neutrinos in a kilometer-scale cosmic-neutrino telescope. At sufficiently high energy, tau-neutrino events will produce two separate regions of localized photons: one from the initial production vertex and the other from the subsequent decay vertex of the tau lepton ("double bang" signature). The tau decays into a final state with hadrons or an electron which carry about 80% of the initial energy. This signature is striking when both bursts of photons are contained within the detector, but the effective volume relative to other signatures is small. The utility of this mode can be better judged after a few more years of operation by current-generation cosmic-neutrino telescopes.

At PeV energies, the Earth becomes opaque to electron and muon neutrinos, but Halzen and Saltzberg have argued that it remains transparent to tau neutrinos. Their charged-current interactions create a tau lepton, which decays before losing all its energy. A regeneration occurs because one of the tau-decay products is always a tau neutrino. The process ultimately results in an up-going flux at the Earth's transparency limit, which is at an energy of about 100 TeV ("transparency energy"). While interesting in principle, several practical details affect the utility of this signature to infer the presence of tau neutrinos. First, the tau neutrino events will have similar topology to electron neutrinos, which traverse the Earth at the transparency energy and which constitute a background for tau-neutrino identification. If the source flux is governed by a power-law energy distribution, then the additional events from higher energies will be relatively small compared to the number of events measured at the transparency energy. Consequently, the tau-neutrino signal can be extracted only if the statistics are very large, which likely implies fluxes that should be observed in current-generation cosmic-neutrino telescopes. Therefore, it is not evident that tau-neutrino detection will lead to a breakthrough in capabilities.

3.3 Present neutrino telescopes

The pioneering effort to develop a neutrino telescope was carried out by the DUMAND collaboration, starting more than twenty years ago. After several years the project was abandoned, mainly because of the problems encountered in the deployment of the equipment in the sea.

At present two neutrino telescopes are in operation, one at Lake Baikal and the other, AMANDA, under the ice of the South Pole. A brief description of these experiments follows.

3.3.1 The Lake Baikal experiment

The Lake Baikal Neutrino Experiment exploits the deep fresh water of the great Siberian lake as a detection medium for high neutrinos via Cherenkov radiation from muons or from high-energy electromagnetic or hadronic showers generated in neutrino interactions. The lifetime of the Lake Baikal Neutrino Experiment spans almost two decades, from small initial experiments with a few light detection modules to the present large-scale neutrino telescope NT-200, which was put into operation in 1998. The experiment is located in the southern part of Lake Baikal, 3.6 km from the shore and at a depth of 1 km. The water transparency at the detector site is characterized by 20 – 24 m absorption length and 20 – 50 m scattering length. In 1993 a first array of 36 optical modules started operation, referred to as NT-36. This constituted the first permanent underwater muon and neutrino telescope ever built. Today's NT-200 array consists of 192 optical modules attached to eight strings arranged in an umbrella-like frame. The capability of the Baikal experiment to search for neutrinos has been proven by the detection of first neutrino candidates during the years 1994 – 1996.

Given the relatively low energy threshold for muon detection and the high water transparency, the Baikal neutrino telescope exploits the neutrino energy range extending from 10 – 30 GeV up to 10^6 – 10^8 GeV. The physics program includes not only neutrinos but also searches for a variety of non-conventional sources. Cosmic rays are also studied using atmospheric muons, triggering at a rate of 15 Hz. The effective area for high-energy muon detection ranges from 1500 to 5000 m^2 for energies between 10 and 10^4 GeV. For electromagnetic and hadronic showers, the effective volume ranges from 0.8 to 6 Mt for shower energies of 10^3 – 10^7 GeV. Apart from its own goals, the Lake Baikal set-up is exploited as a unique environmental laboratory to study water processes in Lake Baikal.

Three additional strings with 18 (or 36) optical modules at a distance of 100 m from the NT-200 center increase the fiducial volume up to 0.01 km^3 for neutrinos with energy above 10^{14} eV. This project, referred to as NT-200+, is approved and is planned to be operational in the spring of 2004. This detector is considered as a prototype module for a 1 km^3 detector at Lake Baikal.

3.3.2 AMANDA

The AMANDA detector uses the deep Antarctic ice as the detecting medium. It is located below the surface within a kilometer of the Amundsen–Scott Research Station at the geographic South Pole. The present version, AMANDA-II, consists of 667 optical modules attached to 19 strings. The outer nine strings are deployed around a circle of 200 m diameter and span depths between 1150 m and 2350 m. The innermost 10 strings with 302 optical modules are deployed in a cylinder of 120 m diameter at depths between 1500 and 2000 m. This inner array is known as B-10 and has been operational since 1997. AMANDA-II was completed in January 2000 and has been operational since then.

Each optical module contains an 8-inch PMT controlled by passive electronics and housed in a glass pressure vessel. The optical modules are connected to the surface by a cable that provides the high voltage and transmits the signals. This simple, but reliable system architecture is responsible for the low failure rate of optical modules (< 10% after several years of B-10 operation, although most failures occur within a week of deployment).

AMANDA has proven the feasibility of the deployment technology (hot water drilling) and of the operation of a large array. The cold, radioactivity-free ambient conditions are responsible for low PMT noise rates of 0.3 – 2 kHz. The low dark-current capability is important for the detection of MeV neutrinos from supernova explosions within the Galaxy. AMANDA has also proven that the ice medium has adequate optical properties to reduce backgrounds from atmospheric muons to manageable levels, while still maintaining significant efficiency for the signal.

The AMANDA architecture has been improved by a half-decade of R&D. Many innovations in the transport and treatment of the signal, and in data analysis, have been made over the years. Air-shower arrays on the surface above (such as SPASE or the planned IceTop facility) can be used to calibrate pointing resolution and absolute pointing accuracy. They also provide a tagged beam of high-energy events for background studies. IceTop triggers (and therefore provides a veto) on cosmic-ray initiated air showers with 100% efficiency if the energy is greater than ~ 1 PeV. In summary, the experience with, and operation of, AMANDA provides a solid base for the deployment and operation of IceCube.

3.4 Alternative detection techniques

As the energies of the neutrinos increase to 10 PeV and beyond, minuscule fluxes and attenuation by the Earth drive the main experimental challenges. For example, neutrinos generated by the GZK mechanism require apertures in excess of 100 $km^3 \times sr$, but optical Cherenkov neutrino telescopes can barely reach the most optimistic predictions. Several new concepts are being developed to boost the sensitivity at the highest energies. The most widely discussed ideas involve calorimetric detection of cascades. The Pierre Auger Project intends to detect ultra-high-energy neutrinos via horizontal air showers and tau neutrinos via showers initiated by tau leptons emerging from distant mountains or from interactions that graze the surface of the Earth. The detection of coherent radio emission from neutrino-initiated cascades (the Askaryan effect) provides another possibility to extend the sensitivity, and several prototype experiments have exploited this signature.

The Lake Baikal experiment investigates acoustic techniques to detect neutrino-induced cascades, the RICE project employs an array of antennas in the ice at the South Pole, and the GLUE project uses two radio telescopes at the Goldstone facility in California to search for events induced by ultra-high-energy particles interacting with the surface of the moon. Recently, a balloon-borne radio detector called ANITA has been proposed to search for GZK neutrinos. Their radio signals are detected by an antenna that circles about the edge of Antarctica at an altitude of 35 – 40 km. All the radio-related efforts were recently boosted by experimental confirmation of the Askaryan effect in experiments performed at SLAC. Over the longer term, there is discussion of space-based telescopes (EUSO, OWL), which measure the air fluorescence induced by large air showers over a circular patch of the atmosphere as large as 3000 km in diameter. They should be more sensitive to fluxes of high-energy neutrinos and cosmic rays by 1 – 2 orders of magnitude.

The quest for ever-higher sensitivity in the search for proton decay has motivated several conceptually straightforward ideas to expand the fiducial mass beyond that of the Super-Kamiokande detector. A detector with roughly 20 times its fiducial mass (the Hyper-Kamiokande and UNO concepts) can collect a sample of 10^3 neutrino interactions from a supernova burst near the Galactic center and a clear signal from a supernova in the Andromeda galaxy, at a distance of 1 Mpc. Such a detector can also search for point sources of cosmic neutrinos, and WIMP dark matter in an energy range that is difficult to cover efficiently by the sparsely instrumented underwater or under-ice neutrino telescopes.

4. Characteristics of deep-sea Cherenkov detectors

4.1 Signal versus background

The rare signal events must be extracted from a very large background of atmospheric muons generated by the decay of pions and kaons from the interactions of cosmic rays with nuclei in the atmosphere. At sea level, the number of such cosmic-ray muons exceeds by ~ 10^{11} the muons induced by atmospheric muon neutrinos. Fortunately, the flux of cosmic-ray muons decreases with increasing overburden, so neutrino detectors are deployed at large depths to reduce this background. Yet even at depths of 2 km of water equivalent, the background from down-going cosmic-ray muons exceeds the predicted signal by a factor of ~ 10^5.

Other backgrounds, albeit much less severe, arise from ^{40}K decays in sea water, and from bioluminescence. While ^{40}K decays are a nuisance because of the high single-count rate of the optical sensors, they constitute a short-range phenomenon and a single hit cannot fake a neutrino interaction. Many noise hits per event, however, can deteriorate the angular resolution and can result, in extreme cases, in fake upward-going events. This is prevented by local coincidences. Bioluminescence is perhaps more of a concern, however experience shows that it occurs only at certain times during which data acquisition can be suspended if necessary. Ice detectors are not concerned with such problems.

4.2 Optical properties of sea water

Sea water absorbs and scatters photons depending on water temperature, salinity and as a function of concentration, size and refraction index of dissolved and suspended organic and inorganic particulate. Since salinity and concentration of the particulate may vary significantly in different marine sites, and also as a function of time, it is important to measure optical parameters *in situ.*

In the literature the absorption coefficient $a = 1/L_a$, the scattering coefficient $b = 1/L_b$, and their sum, $c = (L_a + L_b)/(L_a \times L_b)$, the attenuation coefficient, are used to characterize light transmission in matter. Each length L represents the path after which a photon beam with wavelength λ traveling along the emission direction is reduced to 1/e of its initial intensity by absorption or scattering phenomena.

In water, light absorption and scattering are strongly wavelength-dependent. Light transmission in pure water is favored in the range 350 – 550 nm, which overlaps the region in which PMTs exhibit the highest quantum efficiency. In the visible spectrum of light, absorption is minimal at 420 nm. Scattering refers to processes in which only the direction of the photon is changed. Scattering phenomena in which also the photon wavelength changes (e.g. through the Raman effect) occur less frequently. Scattering can take place either on molecules (Rayleigh scattering) or on dissolved particulate (Mie scattering).

To highlight the generally good optical properties of the Mediterranean Sea, measurements performed by the three collaborations currently active there indicate absorption lengths for blue light of the order of 50 m or better, and average attenuation lengths of ~ 35 m.

There are substantial differences between the optical properties of water and ice. Most notably, the scattering of light in water can be up to one order of magnitude smaller than in ice. Also, water is free from inhomogeneities arising from dust layers which are a concern in ice. On the other hand, ice is more transparent at UV wavelengths and therefore collects better Cherenkov light.

Water is better suited than ice for optimal muon pointing resolution, although it is noted that the sensitivity to point sources of neutrinos is not only determined by the muon angular resolution.

4.3 Criteria for site selection

Also from a logistics point of view, the Mediterranean Sea offers good conditions for the location of an underwater neutrino telescope. Several sites exist, at depths of 2000 m or beyond, that are potentially interesting to host an underwater neutrino telescope. The site selection is a highly non-trivial issue, and quite diverse criteria apply.

- The minimum depth to shield daylight is about 1000 m. However, the site should be located much deeper, so as to reduce by orders of magnitude the down-going cosmic-ray muon background to permit the unambiguous observation of upward-going muon tracks from the interactions of upward-going neutrinos in the Earth. The deeper the better. The needed background rejection is a function of the muon angle and of the muon energy. Of course, it is helped by high-quality detector instrumentation and a highly efficient muon reconstruction algorithm.
- The site should be close to the coast to facilitate the data transmission to the on-shore laboratory and the transmission of power from the laboratory to the off-shore detector. Practical considerations such as the use of commercial systems which permit data and power transmission without special hardware requirements (e.g. amplifiers) argue for a distance below 100 km or so. Generally, the cost of

the submarine cable links from the detector to the shore is proportional to the distance. The issue of proximity of the detector site to the coast and its infrastructure has further ramifications. A major component of the cost of commercial sea operations is the total time spent at sea: therefore, the transit time between the ship base and the site should be as short as possible. Last but not least, issues of safety argue strongly for a detector site from where the coast can be reached within few hours.

- The site should be a safe distance from shelf breaks and underwater canyons since turbulent water currents may occur in their proximity.
- The site should exhibit good optical underwater properties. The effective detection area is not only determined by the size of the instrumented volume but also by the light transmission properties of water. Light absorption reduces the effective area of the detector. Light scattering has an adverse effect on track reconstruction because it deteriorates the measurement of the photon arrival time.
- The sedimentation rate at the site should be as low as possible. The presence of sediments in the water can seriously affect the detector performance since they increase the scattering and absorption of light. Moreover, a deposit on the sensitive part of photon detectors reduces the detector efficiency. Another effect to be considered is the growth of bacterial films or the settling of marine organisms, termed biofouling. It degrades the light transmission of the glass spheres that are used to host the optical sensors and thus determines their operational lifetime.
- Underwater currents should be small and have stable direction. This is important for several reasons: it avoids special requirements on the mechanical structure; it facilitates detector deployment and positioning; and the optical noise due to bioluminescence which is excited by strong variation of water currents is reduced.

4.4 Detector design and deployment techniques

A common problem of all deep-sea detectors is the choice of materials. The aggressive environment imposes tight requirements on the material characteristics. The structures must resist corrosion and withstand pressures up to 400 bar.

In the following, the site properties measured, and technical solutions pursued by the three collaborations currently operating in the Mediterranean Sea, are briefly reviewed. Generally speaking, all three sites appear to conform with requirements from the physics goals.

4.4.1 ANTARES

The ANTARES site is located near the French coast at Toulon. The seabed has a depth of 2400 m, the shore is at a distance of 45 km.

The sedimentation rate is typically 100 $mg/m^2/day$, which leads to a 50% loss of transparency for upward-looking glass surfaces after three months. This permits only downward-looking PMTs.

The ANTARES collaboration has chosen a detector array with optical modules suspended on individual mooring lines, with readout via cables connected to the bottom of the lines. This technology is similar to the solution originally chosen by the DUMAND collaboration. As with DUMAND, the ANTARES detector requires connections made on the seabed by underwater vehicles. However, in the last 10 years the relevant underwater technology has advanced dramatically due to the needs of the off-shore oil industry, enabling the construction of an experiment like ANTARES. Currently a wide range of suitable deep-sea connectors is available and extensively used in industry, including electro-optical connectors which are wet-mateable on the site. Many commercial underwater vehicles exist which are capable of making these connections. Although experts in underwater technology consider the ANTARES instrumentation on the prototype 0.1 km^2 scale as not significantly new, the successful connection of the first mooring line will be a major milestone for the ANTARES project.

From the chosen mechanical layout, the detector readout architecture follows. The ANTARES readout design is based on maximizing the reliability of the detector by dividing the system into independent sections such that there is no single active component in the sea whose failure causes the loss of the whole detector. The detector signals are digitized in local electronics in the sea and then transmitted to the shore on high-bandwidth optical links. On the shore, a computer farm makes the trigger decisions that determine which data are recorded to tape. While the electronics system associated with the data readout requires extensive custom design and integration to fit into the electronics containers in the sea, the technology is widely used and does not involve special milestones.

A major aspect of the ANTARES approach is the possibility to recover and repair all elements of the detector deployed in the sea.

4.4.2 NEMO

The NEMO site is located near the Italian coast at Capo Passero of Sicily. The seabed has a depth of 3500 m, the shore is at a distance of 80 km. The attenuation length of blue light exceeds 35 m and the absorption length is close to 70 m. Interestingly, at the end of winter, the water transparency improves by ~ 20%.

The sedimentation rate measured near Capo Passero is typically 20 $mg/m^2/day$. Although the Ionian plateau has a particularly low rate of sedimentation, PMTs could still not look upwards for longer than about one year. Preliminary studies over 40 days showed no evidence for biofouling. The low value of the bacterial concentration in the Ionian Sea is advantageous for both biofouling and the optical noise level induced by bioluminescent organisms.

The water currents at Capo Passero about 500 m above the seabed have been measured. Over 36 months the currents proved stable both in direction and intensity: the average value is about 3 cm/s, the maximum value 10 cm/s.

The proposed detector array consists of “towers” with a spacing of about 200 m. Each tower can be viewed as a sequence of “stories”, each one supporting four optical sensors mounted on a 20 m long beam (two on each end). A cost-effective solution seems to be the use of a tube of composite material which combines mechanical strength with the absence of corrosion. The stories are interconnected by four cables. Each tower is moored to the seabed with an anchor and tensioned by a buoy located at the top of the structure. The anchor is composed of a recoverable structure and a dead weight. It also hosts the electronics for the whole tower. Tentatively, the number of stories is 16 and their vertical gap is 40 m, resulting in an active tower height of 600 m.

A 100 km long electro-optical cable will link the detector with the shore station. Cables connecting the towers will be branched off by means of junction boxes.

The deployment of the submarine cables and of the tower structures is considered the most complex and delicate phase of the detector construction. The deployment procedures are strongly linked with the mechanical design of the detector structure. The interconnection of the tower structures with the cable network is envisaged to be done underwater using Remotely Operated Vehicles (ROVs). Ease and reliability of the operations, possibility of recovery in case of malfunction, optimization of the ship and ROV use are important considerations of the undertaking.

4.4.3 NESTOR

The NESTOR site is located at Pylos near the Greek coast. The seabed has a depth of 4000 m, the shore is at a distance of 15 km. A possible site with 5000 m depth is nearby. The Ionian Sea is very clean at the NESTOR location: the transmission length of blue light is about 55 m, improving further with greater depth.

The underwater currents have been monitored for the last ten years and they average a few centimeters per second.

Among the three candidate sites, the NESTOR site has the greatest depth and, related to that, very good water conditions and the smallest atmospheric muon background. While the greater depth seems not to pose additional problems for the instrumentation from the point of view of pressure resistance and leak tightness, it does aggravate deployment logistics.

The NESTOR concept has one notable difference with respect to the concepts of ANTARES and NEMO in that the use of ROVs for underwater cable connection is *a priori* avoided. Instead, the concept of a specialized surface vessel (a self-propelled triangular platform with 51 m side length) is being put into practice.

Another important difference (though still to be corroborated by practical experience) with respect to the ANTARES concept is that half of the optical sensors are planned to look upwards, on grounds of a negligible rate of sedimentation and biofouling.

The detector array is composed of "towers" of 12 hexagonal "floors" with diameter 32 m, spaced vertically by 30 m, and made of titanium. At each apex of the hexagon, and at the center, there are two PMTs: one looking up and the other down. The PMT signals are digitized inside a titanium sphere located in the center of the floor, and from there sent to shore via optical fibers. Each floor has its own signal and power connections and is thus independent of other floors. First-level trigger requirements can be applied at floor level. All connections are made before lowering the floor into the sea. A tower can be retrieved, serviced, and redeployed.

4.5 Operation and maintenance

All three deep-sea projects plan to operate the detector remotely from a counting house on shore. A major challenge for detector operation is the continuous transmission of data.

The capacity of the data transmission system can be estimated based on the count rate expected from a single optical sensor. This is essentially due to the background produced by ^{40}K decays and amounts (for a PMT of 10" diameter) to 50 kHz. Assuming that each such signal is digitized with 100 bits, a data rate of 5 Mbit/s for each optical module results, or 25 Gbit/s for 5000 optical sensors.

Commercially available telecommunication systems exist, which offer the needed bandwidth to support the data transmission to the shore. Transmission of the raw data to the shore avoids the installation of an underwater first-level trigger. The proponents of this approach claim two advantages: first, the trigger system need not comply with the tough specifications for the electronics installed underwater (in terms of dimensions, reliability and power consumption); second, it can be easily upgraded to keep up to date with technical progress and changes in the physics objectives.

It is perhaps useful to recall that the availability of the raw data and their archiving on shore may potentially be interesting for other scientific purposes, and may justify a reasonable investment in this direction.

All three collaborations foresee the repair of faulty equipment. While ANTARES and NEMO retrieve single strings, which are redeployed using unmanned underwater vehicles, NESTOR plans to retrieve and redeploy whole towers by making use of their specialized triangular surface vessel.

4.6 Milestones

The studies and R&D work done so far leave no doubt in principle that technologies exist, in industry as well as in the framework of the respective collaborations, to construct and operate a km^3-scale cosmic-neutrino telescope in the deep sea.

Nevertheless, constructing and operating a neutrino telescope in the deep sea remains a challenging endeavour with many risks and unknowns. A reliance on industrial partners to an extent which is untypical for particle physics experiments will be needed. To ensure success, industrial partners should be integrated into the project from the very beginning.

The project proper relies in essence on technologies which are already mastered. Therefore, there are no major milestones in the way of the project. Only the environment of the open sea poses problems of a new nature, which cannot be solved by paper studies alone but need practical demonstration. In this light, once the R&D work carried out by the ANTARES, NEMO and NESTOR collaborations has been successfully completed, with several strings deployed and working in the deep sea, not only will a necessary condition have been fulfilled but also sufficient confidence for success with a km^3-scale detector will have been generated.

4.7 Cooperation in R&D

There is already quite some overlap of R&D activities, mostly involving the development of analysis techniques. For example, AMANDA has made a major investment in the measurement of high-energy muons in the downgoing direction.

At the present time the ANTARES and NEMO collaborations are working together to build a first-generation detector at the ANTARES site. NEMO, Lake Baikal and ANTARES have a common program of site measurements and instrument cross-calibration. Lake Baikal and NESTOR cooperate on various design issues.

Another area of common R&D work is the electronics readout. The three Mediterranean experiments rely on waveform digitization techniques which generate a large amount of data. A common event format could well be beneficial.

Yet, on a whole, HENAP feels that there could be, and should be, more cooperation than is at present the case, especially in view of the practical impossibility of constructing three different deep-sea detectors in the Mediterranean Sea. To foster such cooperation, an annual workshop on the results of the ongoing R&D work and on the planned designs of km^3-scale detectors, under the auspices of PaNAGIC, is considered a worthwhile first step.

5. Cooperation with industry

5.1 Industrial involvement

All the planned high-energy neutrino telescopes have a high cost per scientist involved, when compared with average high-energy experiments in accelerator laboratories or in other areas of particle astrophysics. This is indicative of the need for industrial partners to carry out these projects.

The involvement of industrial companies in the experiments is of two types: involvement in shared R&D where the industrial partner draws a benefit for different applications; and involvement as a subcontractor to provide components of the neutrino telescope.

Furthermore, a large effort is needed to integrate and coordinate all the technological and logistics resources required for these projects. This is particularly obvious for the IceCube experiment which needs the participation of the industrial contractor responsible for the operation of the South Pole station, as well as logistics assistance for the transportation to and from the site. Therefore, only an organization in which the companies are fully integrated as partners in the project since day one could be successful. A synergistic cooperation with these companies to plan all the project phases, defining milestones and the use of technical and human resources, will be needed. The experience of these industrial partners in the engineering and logistics support of large-scale projects in the sea environment will be invaluable.

The technology needed for underwater neutrino-telescope projects is common to two major industrial areas: underwater communications and underwater oil exploration. Telecommunication companies have been developing high-bandwidth transmission on underwater fiber-optic links for the past twenty years and the oil industry is now routinely exploring for reserves in the deep sea at depths of up to 2000 m. Existing industrial submarine components such as cables and connectors developed for these applications are an important element for the success of the new underwater neutrino telescope projects. In addition, instruments and techniques developed for oceanographic and military applications are used in the neutrino-telescope projects.

We expand on the two types of industrial involvement in the following sections.

5.2 Industrial involvement in shared R&D

As in many other scientific projects, the participating companies will benefit from the testing of equipment requiring the highest available performance under difficult conditions. Certain requirements imposed by the experiments will need innovative solutions. Some of the areas of shared R&D are outlined below.

- **Submarine cable design and manufacturing**. There has been a considerable increase in the use of submarine energy and transmission cables in the past twenty to thirty years. Four major factors have contributed and continue to contribute to this trend:
    - growth of electrical power demand;
    - energy crisis;
    - environmental impact;
    - off-shore oil.
- **Durable mechanical structures in an aggressive environment**.
- **High-bandwidth data transmission**. Factors fuelling the demand of high-capacity fiber-optic transmission include the following:
    - expansion of the energy industry in the deep-water environment;
    - growing interest in extending connections from control centers and network nodes to off-shore locations;
    - progress in feasibility studies of, for example, a "complex network underwater platform" to support high-speed telecommunication;
    - operations cost reduction by employing innovative hardware and software solutions to support off-shore oil projects.
- **Underwater connection systems**. Underwater connection systems are needed in off-shore oil and other commercial markets, scientific research, and military applications. They are typically used to connect optical sensors and communication cables for underwater production control, drilling control, and for the readout of seismic sensors. As the high-voltage capability of most underwater connectors is not in the range that cable designers define as high voltage, the goal of leading companies in underwater connection will be the development of high-voltage electro-optical connectors to match cable requirements. There is also great industrial interest in the development of contact-less underwater power systems. This is of interest for power delivery to deep-sea submersibles, oil rigs, and deep-sea mining operations. Underwater installations often require the use of wet-mateable electric connectors. Inductive couplers have no contacts to align when making a connection, and their use is growing in submarine oil- and gas-production installations.
- **Deployment operations**. There has been much progress in deployment and recovery techniques in the past few years.

- **Development of ROVs.** The need for fast communication (telecom and internet) and transport of energy (power, oil and gas) has resulted in an ever increasing network of submarine installations (cables, pipelines, etc.). The underlying technology is being developed down to water depths of 3500 m. Longevity is a growing concern. A major factor in the overall cost is inspection, preventive maintenance and repair. These activities are currently carried out by ROVs deployed from dedicated support vessels and connected to them by an umbilical. More recently, companies have been considering the use of unmanned semi-submersible systems for deploying ROVs on the seabed in order to optimize efficiency and cost of operations. As a consequence of the technical difficulties and the time needed for the deployment in very deep water, the cost of ROV operations is significant and explains the interest in Autonomous Underwater Vehicles (AUVs).
- **Development of AUV**s. The medium-term future for AUVs lies in the use of many vehicles from one support vessel, thereby increasing its cost-effectiveness. The long-term future is to dispense with the support ship entirely – it is envisaged to launch AUVs by helicopter and recover them several days later.

- **Oceanographic instrumentation and data collection**. Oceanographic data are of interest to commercial firms, governments, and research institutions alike. The data support decision-making, improve oceanographic and marine related products and service, and serve scientific and engineering research. Demand for such data is ever increasing: oil and gas operations are now taking place at water depths that previously had been considered technically unfeasible and uneconomic; the scientific and social interest in global climate change is well known. These developments have spawned a new concept in oceanographic data collection: operational oceanography. The idea behind it is large-scale data collection independent from the users of the data. In operational oceanography, resources are shared and used more efficiently, so that much more data can be collected and analysed by more users. The concept relies on a high-volume, low-cost communication system with two-way capability and real-time transmission. Two-way capability is of importance for oceanographers with a view to changing sensor parameters in response to interesting phenomena.

5.3 Industrial involvement as subcontractor

Industrial involvement as subcontractor has numerous possibilities. For example, it appears logical to subcontract the assembly of the optical module components to industry. Another example is the development and production of an acoustic positioning system that gives the location of each optical module in space to a precision of 5 cm. As an example of the capability of the industry working in this area we refer to the development of modular subsystems for the exploitation of off-shore oil reserves, which progresses to ever-greater distances from the shore and water depths.

Today, companies supply complete submarine production systems capable of operating at depths of up to 2000 m, with a goal of 3000 m. Based entirely on the seabed, they represent a new method of extracting oil and gas. This opens up new horizons and renders the exploitation of previously unreachable reserves economically and environmentally viable. Underwater installations are considered not only more cost-effective than floating ones, but also use less material and less energy and reduce the risk of leakage and contamination. The modular submarine systems include equipment for pull-in and connecting, processing, electrical controls and instrumentation. In addition, they have the aesthetic advantage of not being visible on the surface.

This new technology marks probably the beginning of a trend away from using traditional off-shore platforms.

6. Synergy with other fields of science

6.1 Deep-sea science

Deep-sea neutrino observatories will provide the community of deep-sea scientists with a continuous supply of electrical energy and a data highway enabling them to make local real-time studies. The information provided by the PMTs and other oceanographic monitoring equipment needed for running the observatory can be of use to oceanographers and marine biologists.

More generally, other types of instrumentation can be added to the observatory array. For example, ocean bottom seismometers can transmit their recordings in real time, thus permitting the localization of the epicenters of seismic events with greater accuracy.

The data collected by the neutrino observatories can be made available to scientists in other disciplines. Integration of this requirement into the project planning, with the evaluation of the corresponding funds, is strongly encouraged.

6.2 Seismic and environmental monitoring

The international geophysics and oceanographical scientific community has recently defined as a priority the acquisition of data in those areas of the globe, like the ocean depths, for which at the moment we have few or no data at all. These data are necessary to develop and test the models which simulate the dynamics of the oceans and their interaction with the atmosphere. The monitoring of the water column parameters that can be performed by a deep-sea laboratory will provide very useful data for the study of the global circulation of waters in the Mediterranean.

The intense seismic activity that characterizes the Mediterranean is not limited to the land. The presence of seismically active structures located off-shore is well known. Earthquakes generated by these structures have caused in the past great damage to coastal regions, generating in a few cases tsunamis. Events originating at sea can only be precisely located by using on-land and underwater seismic stations together.

The Ionian area is particularly interesting, since the study of the crustal and lithospheric structures of this region is essential for the comprehension of the whole dynamics of the Mediterranean Sea. These geological structures offer a great opportunity for the development of our knowledge in the field of seismology and vulcanology, since they are unique “natural laboratories”.

A permanent network of underwater stations will complement the existing land network, enhancing its performance. A further advantage of underwater stations is that, if suitably located, they suffer from a much lower background noise than land stations. A first step in the direction of on-line integration of underwater stations will soon be operational in the Catania area, where a Geostar-like station will be connected to the shore using the electro-optical cable already deployed by the INFN for its underwater test site. This station will be integrated into the existing network that monitors eastern Sicily.

6.3 Study of the time dependence of rock deformation

The time-dependent properties of brittle rock deformation are of prime importance for understanding the long-term behavior of the Earth's upper crust. Water-saturated rocks are ubiquitous in the crust, and the chemical influence of water leads to time-dependent deformation and failure through mechanisms such as “stress corrosion cracking” that can allow rocks to fail over extended periods of time at stresses far below their short-term failure strength and at low strain rates.

The traditional way of investigating this has been to carry out laboratory “brittle creep” experiments on rock samples held at constant differential stress, and to measure the resulting strain as a function of time. The Rock and Ice Physics Laboratory of the University College of London has pioneered this field. Typically, results have been interpreted involving three individual creep phases: primary (decelerating), secondary (constant strain rate or steady state) and tertiary (accelerating or unstable). The deformation may be distributed during the first two phases, but localizes onto a fault plane during the third. Classical models to explain this behavior have concentrated on the secondary phase, while those attempting to explain accelerating creep are necessarily more complex, requiring large numbers of degrees of freedom. In practice, the latter are not solvable with the limited data currently available.

More recently, other approaches have been developed which involve a two-stage failure process representing a transition from distributed micro-crack damage up to some critical threshold where crack interaction leads to accelerated failure on a localized fault plane. Recent experimental observations support this approach. While the applied creep stress has a crucial influence on the creep strain rate and overall time-to-failure, the level of damage at the onset of the acceleration phase remains essentially constant. However, model predictions outside the range of laboratory values are strongly dependent on the precise mathematical form of the equation describing the stress corrosion mechanism. Therefore it is difficult to distinguish between competing models given the lower limit of strain rates achievable in the laboratory. A possibility to address this problem by extending significantly the strain rates is to use the deep-ocean pressures to realize much longer-term experiments (10 years). The Rock and Ice Laboratory has proposed the installation of a platform on the seabed, carrying a few tens of rock samples, each one equipped with appropriate sensors to monitor deformation and the acoustic emission from micro-crack formation and connected to the deep-sea laboratory infrastructure for the on-line data acquisition.

6.4 Deep-sea biology

The Mediterranean Sea is an intercontinental sea situated between Europe to the north, Africa to the south, and Asia to the east. It covers an area, including the Sea of Marmara but excluding the Black Sea, of 2,512,000 km^2. It has an east-to-west extent of some 3860 km and a maximum width of about 1600 km. Generally shallow, with an average depth of 1500 m, it reaches a maximum depth of 5150 m off the southern coast of Greece.

The Mediterranean Sea is an almost completely closed basin where the continuous inflow of surface water from the Atlantic Ocean is the sea's major source of replenishment and water renewal. It is estimated that waters take over a century to be completely renewed through the Strait of Gibraltar, which is only 300 m deep.

The scarce inflow, coupled with high evaporation, makes the Mediterranean much saltier than the Atlantic Ocean. In the south–east, the Suez Canal connects the Mediterranean Sea with the Red Sea. Through it many xenobiotic species are now colonizing the eastern Mediterranean basins.

The low concentration of phosphates and nitrates, necessary for marine pastures, limits the food availability and thus quantity of marine life in the Mediterranean which should be considered an oligotrophic sea. In this context, overexploitation of the sea's marine resources is a serious problem. On the contrary, some areas, like the Corso–Ligurian Basin and the Gulf of Lyon, are characterized by high levels of primary productivity related with up-welling of nutrients.

Deep-sea regions have been generally considered as stable environments, not subjected to the strong and rapid modifications related to human influence that characterize the coastal regions. Until recently the oceanographic characteristics of the deep-sea regions were considered as almost unchangeable or at least subject to variations on a geological time-scale only.

More recent studies have demonstrated, however, that deep-sea regions are subject to strong variations of the trophic and sedimentation rate, even on a seasonal scale. An observatory able to monitor the deep-sea environment by measuring *in situ* biological, chemical and physical parameters will have a major impact. The observatory should host sensors for chemical on-line analysis of the water. An interesting possibility offered by the neutrino telescope is to monitor continuously the bioluminescence produced by deep-sea organisms.

6.5 Bioacoustics

The Mediterranean Sea is known to have hosted as many as 19 species of cetaceans. Bioacoustics studies can be an invaluable tool to study the behavior of these animals for which communication by sound is an essential survival tool. Locating the time and routes of the seasonal displacements of cetaceans, together with possible annual variations due to climate or human influence, will greatly contribute to the knowledge we have of these marine mammals and their role in the ecosystem, and will help in defining strategies to protect them.

Each species is known to emit characteristic acoustic signals. Therefore researchers can use bioacoustics as a means to spot their presence and follow their movements even at a long distance. A permanently operational on-line underwater station will be an excellent tool for such studies.

7. Outreach opportunities

7.1 Public education and outreach

HENAP notes that the construction and operation of a deep-water cosmic-neutrino detector has an unusually large potential for outreach to the general public. The detection of cosmic neutrinos combines several elements that are likely to generate interest:

- Neutrinos are intriguing because they are unusual, extremely penetrating particles that act as special and unique messengers from far away and are capable of telling us about the most cataclysmic events in the universe.
- Neutrino observations are related, and complementary at the same time, to observations carried out with the various means of traditional astronomy, and also of modern astronomy in many bands of the electromagnetic spectrum.
- These projects are technically very challenging as they require the development and deployment of equipment in deep waters, or under the Antarctic ice, capable of withstanding the harsh environment.
- The experiments require the communication with remote regions, and data transmission from them to the observing stations, aspects that are of high interest for the information-technology enthusiast.
- In the sea there are interesting side-aspects such as bioluminescence and water currents, for more biologically-oriented people.
- Finally, the story of the daily life of the people who dare to enter the forbidding environment to deploy the detectors, service them, run shifts day and night, and work towards obtaining their eagerly awaited scientific results adds a human dimension to the enterprise, of interest for the general public.

All in all, the outreach opportunities should match those of the manned space program, and should be actively pursued.

The AMANDA and IceCube collaborations have already established the IceCube Education Resource Center where many educational resources are being generated.

The establishment of a visitor center at the on-shore laboratory of the deep-water detector, welcoming the general public, is encouraged.

8. Guidelines for international collaboration

8.1 Introduction

HENAP was asked to suggest guidelines for international collaboration. These guidelines need to be part of the general consideration of the management and oversight of the very large high-energy neutrino detectors. While the main focus of this report is on a deep-water detector in the Northern hemisphere, some of our suggestions for international collaboration should be useful for IceCube. We have taken as a given that IceCube will be constructed and exploited by an existing international collaboration. Moreover we have assumed that IceCube operations at the South Pole will be under the direction of the (US) National Science Foundation Office of Polar Programs.

The management of the construction of the deep underwater detector, its operation and exploitation by a scientific collaboration, and the oversight of these activities will need at least three types of organization to be successful and each has an important role in an international collaboration. Traditionally, a large scientific project starts with the realization that an important scientific objective can be achieved provided sufficient resources can be focused on the objective. Typically, one or more collaborations of scientists and technical specialists provide the vision for the scientific requirements for the detector and the source of much of the effort that is needed to build and exploit the detector. When the cost of the detector is so large that it is likely that only one can be afforded and thus only one collaboration is able to exploit it, an effort is made to include as many active participants as possible. HENAP has concluded that this will be the case for a large underwater detector in the Northern hemisphere. In addition to the collaboration, a corporation, a legal instrument, is needed to execute contracts for the construction and the operation of the detector and its associated laboratory. It is also essential to have a group of independent overseers who are responsible for assuring that the funds contributed to the project are spent wisely and in accordance with the mandates established by the sponsors. If more than two national funding agencies fund the construction and operation of the detector and if there is no single dominant institution or agency, a fourth ingredient is very useful and perhaps essential. This is a board composed of representatives from the national funding agencies that can set financial policies and develop a sustainable funding plan for construction, operation and exploitation of the detector. HENAP notes that projects of the scale of the underwater detector have been successfully accomplished in a variety of ways in the past. HENAP chose to examine the governance and management of the Kamiokande and Super-

Kamiokande detectors, the Sudbury Neutrino Observatory, and the Pierre Auger Observatory since they provide three successful but different examples of international collaboration. Moreover they illustrate the evolution of a collaborative project from a national project carried out in a pre-existing laboratory to a complex international project executed by a multinational collaboration that had to create every aspect of its governance from the beginning. HENAP concludes that the governance models of the Sudbury Neutrino Observatory and Pierre Auger Observatory offer reasonable paths for the governance of the underwater detector in the Northern hemisphere.

8.2 Examples of international project organizations

8.2.1 Kamiokande and Super-Kamiokande

Scientists from the Institute of Cosmic Ray Research conceived the Kamiokande detector in order to search for proton decay. Since the scale of the project was appropriate for their institute, they formed a collaboration to build and operate a large water Cherenkov detector in a deep mine in Japan. The legal instrument that executed the construction and operation contracts for the Kamiokande detector was the University of Tokyo, which exercised its oversight through the Institute for Cosmic Ray Research. This was a natural and sensible arrangement, since the scientists and technical specialists belonged to the Institute. The Kamioka mine in western Japan provided the deep site, with low background and easy access for the construction of a proton decay detector. The Institute for Cosmic Ray Research and the Kamioka Mining and Smelting Company negotiated an agreement that gave the Institute access to a cavern that the Company agreed to construct. The agreement allowed the Institute to construct and operate the Kamiokande detector. All of the work carried out in the mine by the Institute and its collaborators was under the direction of the Kamioka Mining and Smelting Company. Monbusho provided the funding for the construction and operation of the detector, including the construction of the cavern and the use of the mine facilities. When the construction of the Kamiokande detector started in 1980 there were six other detectors of comparable scale in various stages of construction throughout the world. In each case a single institute or a small consortium undertook their construction, since the scale was not so large.

Later, when it became clear that the scientific goals of Kamiokande could be expanded to include the observation of solar neutrinos (and still later atmospheric neutrinos) a much larger detector was proposed. The success of Kamiokande made it possible to consider Super-Kamiokande, a much more ambitious project and the inclusion of groups from the United States in the collaboration brought more resources to the project. Initially admission to the collaboration was limited to institutions that could make significant contributions to the construction and operation of the detector. In return for their contributions members of the collaboration gained access to the data. Since the project had a very focused scientific goal no consideration was given to making the data available to scientists outside of the collaboration. At the time such an effort would have been expensive and a distraction from the primary goals. The collaboration established an Executive Board that sets policies for matters related to data access, data analysis, publication of results in journals, including the qualifications for being an author, and the presentation of results in conferences.

Super-Kamiokande has been immensely successful and its results have established the existence of neutrino oscillations and pointed the way to the resolution of the solar-neutrino problem. While there were no new formal oversight mechanisms created to advise Monbusho (and its successor Mobukagakusho) and the U.S. Department of Energy (DOE), DOE reviewed the status of the detector construction periodically in order to monitor the U.S. contribution to the detector. Each agency also used their traditional peer-review process to judge the scientific merit of the project, and the need for a detector of this scope was considered in the formulation of each nation's long-range plans for high-energy physics. It is worth noting that while Super-Kamiokande is a large international collaboration, almost all of the funding came from the two agencies, Monbusho (and its successor Mobukagakusho) and DOE. Japan provided the largest financial contribution and the Japanese groups provided the largest effort.

8.2.2 Sudbury Neutrino Observatory

The success of IMB and Kamiokande, the two pioneering large water Cherenkov detectors, led others to propose different detectors to study the solar-neutrino problem. Scientists in Canada, the U.K. and the U.S. recognized that a detector which could separately measure the flux of electron neutrinos arriving on Earth through charged-current interactions and the flux of all types of active neutrinos arriving on Earth through neutral-current interactions could provide a resolution of the solar neutrino problem. They proposed to build a heavy-water neutrino detector in a deep underground mine. The deuteron provided the nearly-free neutron target for the measurement of the charged-current neutrino interaction. Since Canada possessed a large supply of heavy water and a very deep underground site in the INCO mine in Creighton, it was a natural choice as the host country. The scientists formed a collaboration of Canadian, U.K. and U.S. institutions, primarily universities, to carry out the experiment.

The collaboration agreed at the outset that a Canadian institution would be responsible for the administration of the project and Queens University was selected by the Canadian institutions to serve in that capacity. Subsequently the Canadian universities formed the Sudbury Neutrino Observatory (SNO) Institute, which is part of Queens University, to execute the construction and operations contracts and serve as the legal agent. The Institute has a Board of Trustees and each of the participating Canadian universities has a representative. In addition, there is a representative on the Board from INCO. A Constitution and Trust Agreement detailing the roles and responsibilities of the SNO Institute members is currently in place for the Canadian institutions. The Board of

Trustees is responsible for the financial and independent technical oversight of the Observatory. Queens University serves as the corporate home for the Institute.

The Canadian, U.K. and U.S. groups prepared a proposal that was submitted jointly to NSERC in Canada, DOE in the U.S. and PPARC in the U.K., the appropriate funding agencies in the three countries for this type of project. In 1989 these agencies jointly reviewed the financial, scientific, and technical aspects of the proposed project. They also selected a set of independent advisors to assist them with their review. On the basis of that review the agencies concluded that the collaboration could achieve the scientific goals with the proposed management plan and agreed to fund the construction, operation and exploitation of the detector. This initial review committee evolved into a standing agency review committee of the three agencies (ARC). Perhaps because the mine was in Canada and the Canadian government proposed to make the largest contribution the agencies designated NSERC the lead international agency. The three funding agencies have permanent representatives on ARC and it meets twice a year. One of these meetings is used to review the scientific and technical progress that has been made by the collaboration in the previous year as well as the financial status of the project. For this review they select five independent experts to serve as their advisors on the scientific and technical matters. ARC also reviews the budget requests for future years. The review reports and the minutes of the meetings are transmitted to the agencies for their consideration and to the SNO Institute. The reports and minutes are used by the Board of Trustees of the SNO Institute to carry out their oversight of the Observatory.

NSERC and NRC provide funding from the Canadian government. The DOE provided funding for the in-kind contributions made by the U.S. institutions to the construction of the detector. PPARC and its predecessors provided the U.K. funding for the contributions made by the U.K. institutions. The U.K. and U.S. agencies contribute cash to a common fund that is used to pay for the cost of operations. In addition to the oversight provided through ARC each nation has its own peer-review process to examine the scientific and technical contributions that their institutions make to the Observatory.

The collaboration established a Collaboration Board to manage the scientific affairs of the collaboration and the construction of the detector. It determines the criteria for admission of an institution to the collaboration. Initially admission was limited to institutions that could make significant contributions to the construction and operation of the detector. The Collaboration Board determined the assignments for construction, maintenance, and data analysis through consensus. It also established the rules for data access, policies for the publication of the results in journals and the selection of speakers for the presentation of results. Once funding was assured Memoranda of Understanding (MoUs) were prepared with the participating institutions and Queens University.

The SNO Institute made agreements with INCO and the Canadian Government that enabled the collaboration to construct and operate the detector in the INCO mine. Safety at the site is under the direction of INCO. MoUs were prepared for each collaborating institution and signed by the three national spokespersons and the leader of the group from the collaborating institution. These MoUs describe the contributions that each collaborating institution will make to the Observatory. Since bilateral treaties covering scientific and technical cooperation exist between Canada and the US and Canada and the U.K., international issues were managed under the umbrella of these treaties. In general these treaties made the resolution of these issues straightforward.

8.2.3 Pierre Auger Observatory

Scientists active in ultra high-energy cosmic-ray research conceived the Pierre Auger Project after several experiments had reported detecting a few cosmic-ray events with energy greater than 10^{20} eV. If these events were real, the flux of these energetic cosmic rays created a paradox that had been pointed out in 1965 by Greisen and independently by Zatsepin and Kuzmin. They noted that a cosmic-ray proton with energy greater than 10^{20} eV that was produced at a distance greater than 50 Mpc from the Earth would interact with the cosmic microwave background and produce pions, and these interactions would reduce the energy of the proton to below 10^{20} eV. The scientists interested in resolving this apparent paradox initiated a series of workshops that were held in Paris (1992), Adelaide (1993), and Tokyo (1993), and culminated in a six-month design study at Fermilab (1995). The initial focus of these workshops was to assess the evidence for cosmic rays with energy greater then 10^{20} eV and to determine how to detect the sources of these energetic cosmic rays if they existed.

Fermilab hosted the Design Group for the Auger Project from January 30 through July 31, 1995. This group produced a design report containing a reference design and a cost estimate for the proposed detector. The scientists participating in the 1995 design study recognized that a detector larger than any previous cosmic-ray detector was needed to resolve the paradox and that it should simultaneously employ the two techniques that had reported the detection of cosmic rays with an energy greater than 10^{20} eV. The two techniques would be able to provide the assurance that the energy of the ultra-high-energy cosmic rays could be accurately determined. They further recognized that the scale of such a detector was beyond the reach of the individual groups engaged in the detection of these ultra-high-energy cosmic rays. The workshops and the design study were open to all scientists interested in ultra-high-energy cosmic rays and they facilitated the formation of the collaboration. It is important to note that individual participants were not excluded from participation if they were unable to bring resources to a future project. Desire and brains were the ticket for admission.

In November of 1995, a meeting was held in Paris to form the collaboration to build the detector. The collaboration was formed and the members chose Mendoza, Argentina for the location of the observatory in the Southern hemisphere. In September of 1996, the collaboration met in Mendoza, Argentina and selected Millard County, Utah, U.S. for the Northern-hemisphere observatory. The Pierre Auger Project now includes more than 250 scientists from Argentina, Armenia, Australia, Bolivia, Brazil, China, the Czech Republic, France, Germany, Greece, Italy, Japan, Mexico, Poland, Russia, Slovenia, the U.K., the U.S. and Vietnam. It is a very inclusive consortium.

The global organization was established through the “Agreement for the Organization, Management, and Funding of the Pierre Auger Observatory” signed by the national funding agencies that committed support to the construction and operation of the Observatory. This document also describes the rules for the movement of experimental equipment through customs, and defines the details of property ownership and tax status. This Agreement established the Finance Board.

The Finance Board governs the financial aspects of the collaboration. It provides financial oversight of the construction and operation of the Observatory and assures its members that the project is meeting its funding objectives. It also provides a forum to address financial issues created by differences in accounting procedures, currency fluctuations, and short-term availability of funds within each country. The Finance Board establishes policies for the collection and disbursement of construction and operating funds. It determines the apportionment of the total funds to in-kind contributions and common funds to construction. The contribution of cash made by each funding agency for the operation of the Observatory is proportional to the number of authors from that country. Each funding agency designates a representative for the meetings of the Finance Board. An agency may designate the country representative of the Collaboration Board as its representative to the Finance Board.

The Executive Financial Institution was created to collect and disburse the common funds for the construction of the Observatory and the operating funds required to operate the Observatory. It maintains a bank account for these funds and provides access to legal and accounting services. It receives the cash fund contributions from the national funding agencies in national currencies and then converts these to Swiss francs. CERN has been chosen as the Executive Financial Institution.

A *Cooperadora*, a non-profit foundation incorporated in Argentina, was created by CNEA (Argentina AEC) to serve as the legal instrument to construct and operate the Southern Observatory. The *Cooperadora* can hold and receive money. The Executive Financial Institution transfers operating funds that it holds in Swiss francs to a bank in Buenos Aires, which in turn transfers these funds in pesos to a bank account in Malargue held by the *Cooperadora*. It disburses the money that is spent in Argentina for labor and materials for the operation of the Observatory. It purchases insurance to offset the risk of damage to equipment and injury to collaboration staff and workers it hires. It has a written agreement with the Project Management.

Many of the campus buildings were built as in-kind contributions from the Province of Mendoza and the University of Chicago provided the funds for the construction of the campus office building. The Province owns the Observatory Campus site and leases it to the project. Farmers and other landowners collectively own the Southern-hemisphere site. The Mendoza Province Government rents the site from the landowners and has a written agreement with the Project Management.

The Project Manager submits a progress report and a budget request to the Finance Board. The Finance Board approves financial polices and the budget. At the start of the project, the Finance Board reviewed the proposed project with the assistance of independent experts in the field. The review team reported to the Finance Board Chair.

The Collaboration Board is the principal governing body of the collaboration and it provides scientific oversight for the collaboration as one of its responsibilities. It oversees all scientific and technical aspects of the project. It monitors the construction and operation of the Observatory to ensure that the scientific objectives of the collaboration are met. It also manages all issues that concern the collaboration as a whole, including governance, scientific policy, admission policies for new members and institutions, and publication policy.

Each collaborating institution appoints one member to the Collaboration Board from among the scientists participating in the collaboration. In order for an institution to gain full membership in the collaboration it must provide three scientists or engineers who spend 50% of their time on the project, and the institution must commit to make a contribution through its national funding agency to the construction and operation of the Observatory. Typically the contribution to operations is in proportion to the number of authors from the institution. The commitments are defined in the MoU between the national funding agency and the Pierre Auger Project. Each full-member group has signed an MoU with the collaboration. The Project Manager informs the Finance Board of each MoU. The MoUs are the basis for admitting an institution to the collaboration and provide a major tool for management planning. Each national funding agency separately acts on the national proposals that they receive for Pierre Auger and their decisions are made with the knowledge of the Finance Board actions.

In addition to full members the Collaboration Board has associate members. In the event a country cannot make a contribution that meets the standards of full membership a provision has been made that will allow a group to participate with associate status. Associate Countries participate in the project through a full member, the latter being solely responsible for relations with the Project Management and the Finance Board. The country with full standing must pay the operating share of the participants from the

Associate Country. This arrangement made it possible for groups from Armenia, Bolivia and Vietnam to participate in the project through Germany (Karlsruhe), Brazil, and France (PCC-College de France), respectively. Each associate may appoint a non-voting country representative to the Collaboration Board.

8.3 Suggestions for international collaboration

As the preceding three examples suggest, the first step in the creation of a management organization that will be responsible for the design, construction, and exploitation of a Northern-hemisphere deep-water detector should be the formation of an international collaboration. It should be open to all interested scientific teams that wish to contribute to construction and exploitation of the detector, since it will represent a unique facility in the world. An international workshop on high-energy neutrino detectors that will be open to all interested teams would be an excellent vehicle to facilitate the formation of this international collaboration. This process was used to create the Pierre Auger Collaboration, many features of which deserve consideration. In particular, the open process that was used to form their collaboration, the commitment to find a means to include teams from developing nations in the collaboration, and the intent to distribute the data beyond the collaboration deserve careful study. While an international collaboration for IceCube has already been formed, HENAP believes that the IceCube Collaboration should also consider creating opportunities for the participation of additional scientific teams.

The admission of a scientific team must be based primarily on its ability to contribute to the scientific vigor of the collaboration. Each team should contribute technical and financial resources to the design, construction, and exploitation of these detectors. Moreover, the collaboration governance and project management must be constructed so that this can be done efficiently. The SNO and Pierre Auger organizations have all of the appropriate features that provide strong management within the framework of a successful international collaboration. The collaboration and project management of the Northern-hemisphere deep-water detector should adopt the most appropriate features of these organizations. HENAP notes that the IceCube organization appears to have the appropriate ingredients for a successfully managed organization, although it did not specifically review this aspect of IceCube.

An international peer-review process should be used to regularly monitor all aspects of the design, construction and operation of these km^3-scale detectors. HENAP considers that this should be done through standing committees that report both to the funding agencies and the collaboration governing board. If one of the committees is composed exclusively of representatives of national funding agencies, this committee should be augmented by outside experts who can provide the committee with independent advice.

The oversight committees for SNO and Pierre Auger provide good examples of effective oversight committees. HENAP notes that the specific composition of the oversight committees and their reporting procedures will need to be shaped by the funding agencies and the collaboration. Since it is likely that funds for the km^3-scale detector will be provided by funding agencies from many countries these agencies will need to coordinate their individual funding strategies. This coordination could be achieved through a Finance Board as in the case of the Pierre Auger, or an Agency Review Committee as in the case of SNO. It is essential that such a coordinating committee exists for the km^3-scale detector, in order to ensure an orderly implementation of construction and operations.

The corporation responsible for executing contracts for the construction and operation of the km^3-scale underwater detector needs to be formed with care. Since the detector is likely to be located in international waters the corporation will need to address a number of national and international legal issues. Commercial corporations engaged in underwater operations have already addressed most of these issues. The project will need a home port for the local project management team and operations staff that will be responsible for coordinating construction and collecting and testing equipment prior to its deployment. It will also serve as a campus for the collaboration members when they need to be near the detector site. Finally it will provide the location for recording the data on a permanent medium prior to the initial distribution to the participating institutions. It is important that the corporation be organized so that it strengthens the collaboration since it must adapt to a variety of national and international laws and regulations. While this may take some effort the benefits of a successful international collaboration outweigh the effort of doing it the right way. The examples that we have described show that it can be done.

Since the km^3-scale detectors will be unique in regard to their environments in ice and deep water, they may open up opportunities for other fields of science. It is important that an active effort be made to bring consultants from other scientific fields that might benefit from the capabilities of these detectors into the planning process. At this time, the degree to which other scientific disciplines could benefit from access to the data is not clear, but it would be surprising if there were no benefits. Outreach to these fields will require considerable organization and resources and if it can be done successfully the data collected by these detectors should be made available to the scientific communities that can use the data. This could be done by placing it in the public domain when it is reasonable to do so from a scientific point of view. Data produced by the large publicly funded astronomical observatories have been successfully placed in the public domain and it took time, money and effort to achieve this. If the funding agencies wish to accomplish a similar objective for the km^3-scale detectors they must be prepared to support it from the beginning. The collaboration and the funding agencies should establish rules for distribution once the feasibility of the distribution has been established.

The three examples show that there is no simple formula for building a successful collaboration, responsive project management, and effective oversight. There are many ways to do this, but a successful enterprise will possess all of these elements.

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