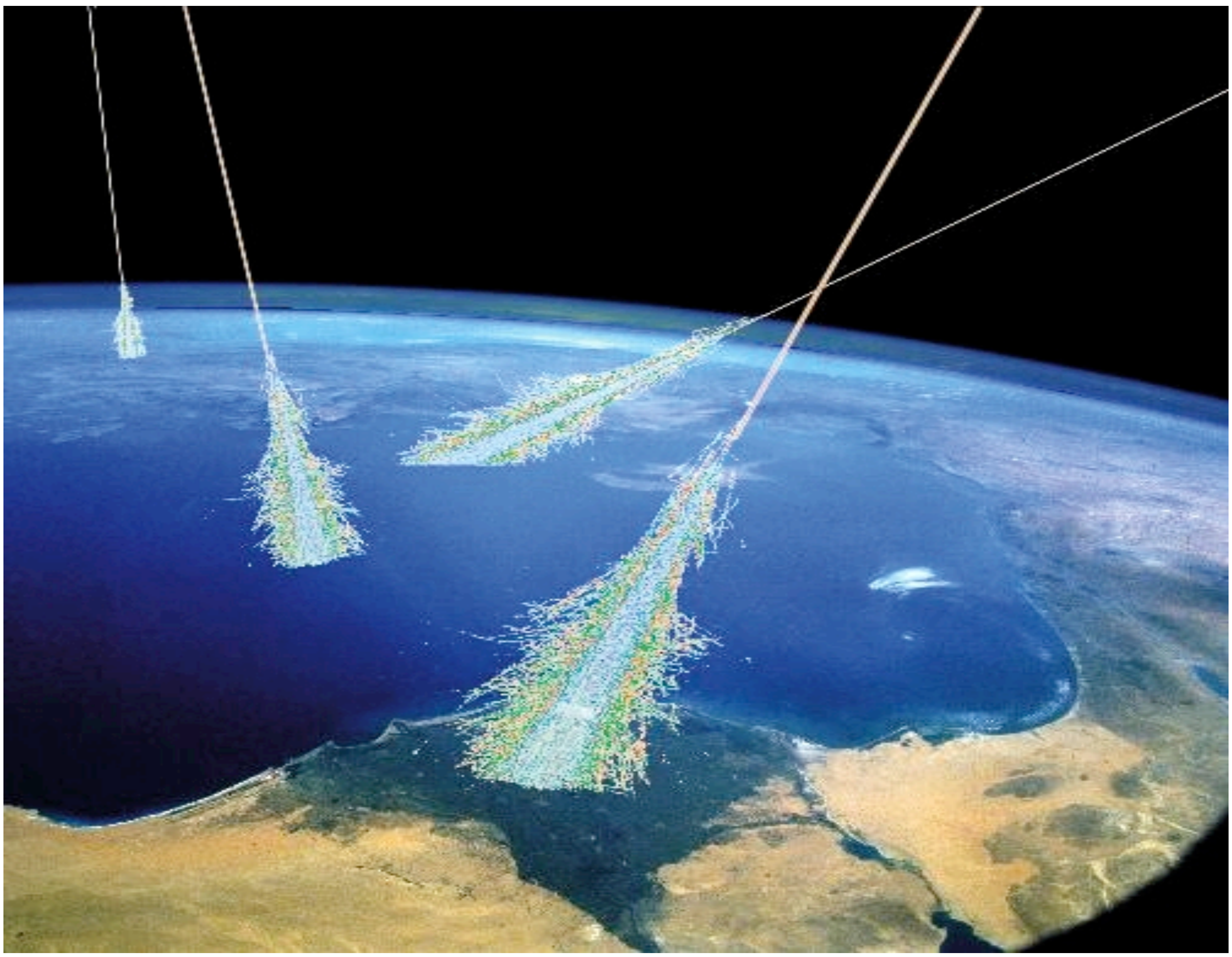
FOM-program proposal 2007

The origin of cosmic rays

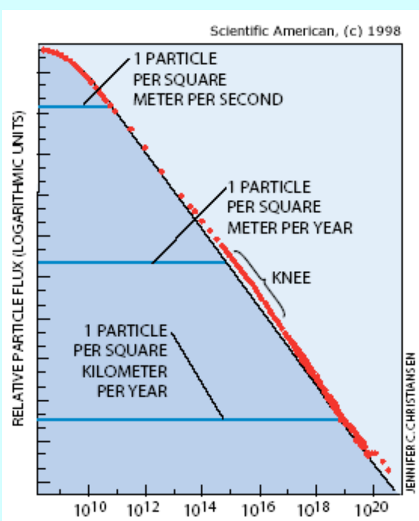


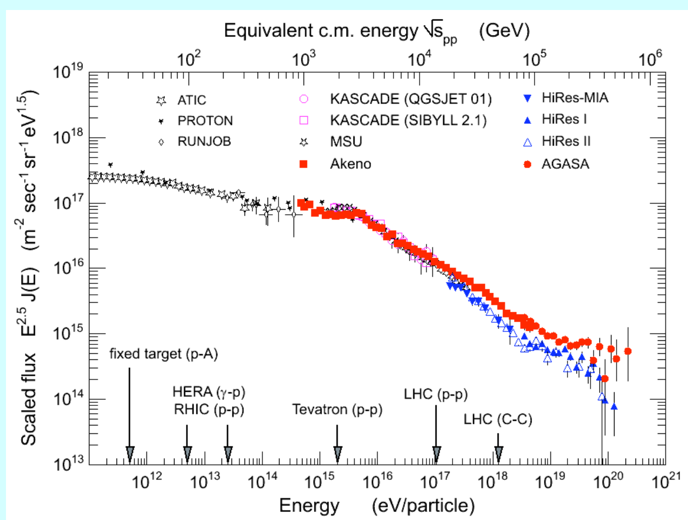
Acronym: **OCRAY-07** ***31 August 2007***

Cover page: Artist's impression of air showers developing in the Earth's atmosphere in response to several cosmic-ray particles hitting an atom in the outer layers of the atmosphere.

Ultra-high energy cosmic rays

The Earth is continuously bombarded by charged particles that give rise to extensive air-showers, which have been observed over a large range of energies (left panel). The energy spectrum of the observed cosmic rays is rather featureless, mainly showing a steep decline with increasing energy. The observed cosmic-ray rates are mentioned as well in the left panel below. When scaled with $E^{2.5}$ (where E is the energy of the primary cosmic ray) inconsistencies between experiments become apparent beyond 10^{17} eV (right panel). The origin of these very high-energy particles is unknown.





1. Title of the proposed FOM-program

The origin of cosmic rays

2. Applicants

National institute for subatomic physics (Nikhef)

G. van der Steenhoven[1,2], M.P. Decowski[1], M. de Jong[1,3], P.M. Kooijman[1,4,5], Th. Peitzmann[1,5], J.J.M. Steijger[1], Ch.W.J.P. Timmermans[1,6], E. de Wolf[1,4]

1. *FOM instituut voor subatomaire fysica NIKHEF, Amsterdam*
2. *Kernfysisch Versneller Instituut (KVI), University of Groningen*
3. *Leids Instituut voor Onderzoek in de Natuurkunde (LION), Universiteit Leiden*
4. *Instituut voor Hoge-Energiefysica (IHEF), Universiteit van Amsterdam (UvA)*
5. *Department of Subatomic Physics, Utrecht Universiteit (UU)*
6. *Institute for Mathematics, Astrophysics & Particle Physics (IMAPP), Radboud Universiteit*

The FOM-instituut NIKHEF, UvA and UU participate through Nikhef in the present proposal.

Institute for Mathematics, Astrophysics and Particle Physics (IMAPP)

H. Falcke[1], J.R. Hörandel[1], S.J. de Jong[1,2], J. Kuijpers[1]

1. *Institute for Mathematics, Astrophysics & Particle Physics (IMAPP), Radboud Universiteit*
2. *National institute for subatomic physics (Nikhef), Amsterdam*

Kernfysisch Versneller Instituut (KVI)

A.M. van den Berg[1], N. Kalantar-Nayestanaki[1], H. Löhner[1], O. Scholten[1]

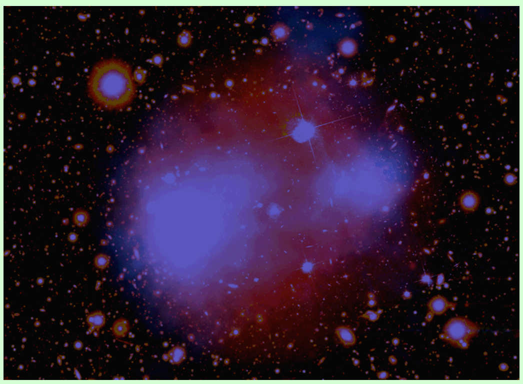
1. *Kernfysisch Versneller Instituut (KVI), University of Groningen*

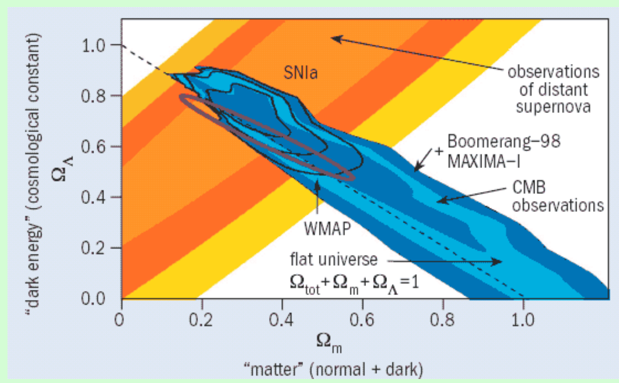
Designated program leader and contact person: **Prof. dr. Gerard van der Steenhoven**
FOM instituut voor subatomaire fysica NIKHEF
P.O. Box 41882
1009 DB Amsterdam
Email: gerard@nikhef.nl

3. Objectives and focus

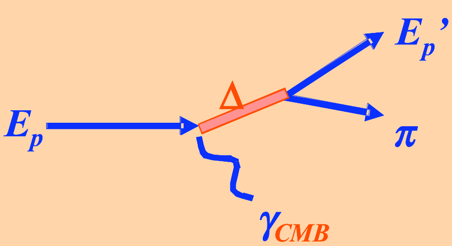
One of the key unresolved issues in astroparticle physics concerns the unknown origin of cosmic rays of very large energies. Cosmic rays are a collective name for a variety of subatomic particles that are continuously bombarding the outer layers of the Earth's atmosphere. While the Sun is a well-known source of low-energy cosmic rays, the origin of particles with energies in excess of 10^{12} eV has not yet been unambiguously identified. Supernovae explosions, for instance, are commonly believed to be the source of cosmic rays with energies up to 10^{15} eV, but so far it has not been possible to prove this observationally. Beyond this energy domain cosmic-ray particles must originate from unknown extra-galactic sources at very large distances. As can be seen from the figure on the opposite page some of these particles are reaching energies well in excess of the highest energies that can be produced in the

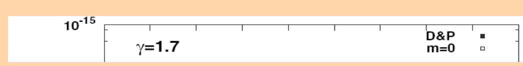
Dark matter
One of the most striking pieces of evidence supporting the existence of large amounts of dark matter in the Universe comes from the Bullet Cluster (left panel, which is an overlay of various astronomical observations): a pair of galaxies that is moving away from each other at high velocities. By combining gravitational lensing data (obtained with the Hubble Space Telescope) and X-ray data (from the Chandra Satellite) a distinction has been made between the alleged locations of dark matter (blue) and ionized gas (red). The observation that the centre of gravity of the two galaxies (blue) did not coincide with that of the visible matter (red) provides evidence for the existence of large amounts of dark matter. In the right-hand panel data from distant supernovae (type Ia) and the Cosmic Microwave Background radiation are combined to provide further evidence for the existence of large amounts of dark energy (vertical scale; ~ 70%) and dark matter (horizontal scale ~ 25%) in the Universe. It is noted that the horizontal scale represents the sum of normal and dark matter.





The GZK threshold
A cosmic particle (such as a proton) may collide with a photon of the Cosmic Microwave Background radiation. If the energy of the proton is larger than 6 x 10^{19} eV, there is sufficient energy in the centre-of-mass of the proton-photon system to excite the so-called Δ(1232)-resonance, i.e. the first excited state of the proton. Subsequently, the Δ(1232)-resonance decays through pion and/or photon emission (see left-hand figure below). Effectively, the primary cosmic particles – which are protons most likely – are slowed down through this interaction. This process also leads to a precisely calculable source of high-energy neutrinos (see right-hand figure below) that result from the decay of the pions produced in the proton-CMB interactions. These so-called *cosmogenic* neutrinos can be searched for with the new high-energy neutrino telescopes.





most advanced man-made particle accelerators. In fact, cosmic rays are the only observed ultra-high energy (UHE) particles on Earth, i.e. with energies in excess of 10^{16} eV. Still, the acceleration mechanism(s) leading to such ultra-high energies and their sources remain largely unknown.

We propose to use two complementary techniques to search for the origin of high-energy cosmic rays. These observational techniques will be exploited (and further developed) in an effort to discover (for the first time) extra-galactic point sources of cosmic rays in the Universe and measure their energy spectrum. This is the main objective and focus of the present proposal.

The proposed research program will enable us to study several frontier questions in the emerging field of astroparticle physics:

- Point-source searches. The measured cosmic-ray spectrum extends to energies of 10^{20} eV and beyond. How do cosmic rays acquire such energies? It seems natural to associate these energies with the most energetic explosions in the Universe such as Active Galactic Nuclei, Gamma Ray Bursts, Micro-quasars or Supernova Remnants. Can we obtain evidence in support of this hypothesis by searching for ultra-high energy cosmic rays originating from (optically or otherwise) known sources of this kind?
- Dark matter. The motion of stars within galaxies and the motion of galaxies within clusters provide evidence for the existence of large amounts of dark matter in the Universe. In fact, all current estimates, including those derived from satellite-based observations of the Cosmic Microwave Background (CMB) radiation indicate that dark matter constitutes about 23 $\pm$ 4% of the total energy content of the Universe. Can part of the (high-energy) cosmic rays be attributed to the annihilation of two dark-matter particles? As it is becoming increasingly likely that dark matter is composed of particles not contained in the Standard Model of particles and fields, such particles may decay or annihilate giving rise to the production of photons, quarks and neutrinos that can be observed on Earth. Can we obtain information on the nature of dark matter by observing such secondary particles on Earth?
- Composition of cosmic rays. By identifying the type of primary particle hitting the Earth's atmosphere important information can be obtained about the origin of cosmic rays. An iron nucleus, for instance, is more likely to originate from a supernova explosion, while a neutrino can be associated with the annihilation of two dark-matter particles. As the various possible sources of cosmic rays are expected to contribute differently in different energy domains, it is usually assumed that the (chemical) composition of primary cosmic rays will change with energy. At the highest energies, for instance, a transition is expected to occur at the so-called Greisen-Zatsepin-Kuzmin (GZK) threshold of about 6 x 10^{19} eV, the highest energy a proton can maintain before being slowed down due to collisions with the CMB radiation (see inset at opposite page). Beyond this threshold primary cosmic rays are not expected to consist of heavy atomic nuclei as they should long have been disintegrated by CMB photons. However, experimental information on the (chemical) composition of cosmic rays beyond 10^{15} eV is scarce and often ambiguous. Can we perform new measurements that will enable us to identify the nature of high-energy cosmic rays?

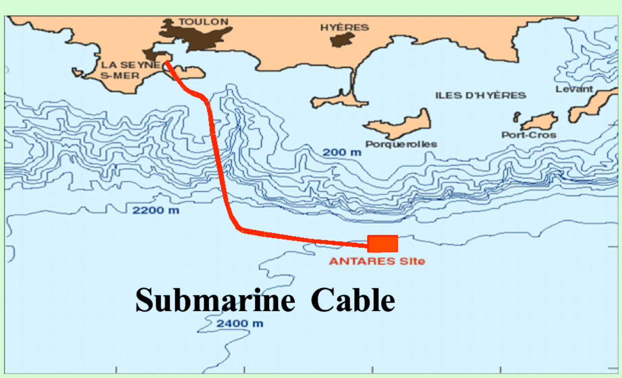
To address these questions the sources of cosmic rays need to be identified, the primary composition of cosmic rays needs to be determined and their energy spectrum needs to be measured up to the highest possible values. Given the large range of energies involved complementary probes are needed. We propose to use *neutrinos* in the energy domain up to 10^{16} eV (and possibly beyond) and *air showers* induced by protons or heavy atomic nuclei for energies above 10^{18} eV[1]. In practice, the proposed searches will be carried out with the Antares deep-sea neutrino telescope, which is presently being built on the bottom of the Mediterranean Sea near Toulon at a depth of 2480 m, and the almost completed Pierre Auger air-shower Observatory (or Auger for short) in western Argentina near the city of Malargüe. As Antares and Auger are largely viewing the same part of the (southern) sky, these observatories do

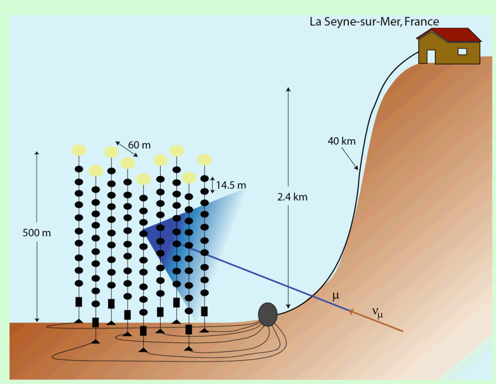
[1] The energy range in between the *nominal* energy limits of the two observatories proposed to be used (Antares and Auger), i.e. in between 10^{16} and 10^{18} eV, will also be explored in the framework of this research program by searching for downward going high-energy tracks in Antares and lowering the Auger energy threshold using new equipment. More details can be found in the project descriptions contained in the appendix of this proposal.

not only cover a complementary energy domain, but also allow for the observation of the same cosmic sources using different probes. In fact, the detection of neutrinos and ultra-high energy protons from the same cosmic source would represent a profound breakthrough and issue – at the same time – the start of particle astronomy.

The Antares neutrino telescope

The Antares collaboration is constructing a large-area water-Cherenkov detector in the deep Mediterranean Sea, optimized for the detection of muons originating from high-energy astrophysical neutrinos. The location of Antares near Toulon is shown in the left panel, below. The observation of high-energy neutrinos will open a new window on the Universe. The aim of the experiment is to use neutrinos as a tool to study particle-acceleration mechanisms and thereby shed light on the origin of high energy cosmic rays. At somewhat lower energies, non-baryonic dark matter particles may be indirectly observed through neutrinos produced when gravitationally captured dark-matter particles annihilate in the core of the Sun. The detection principle of Antares, which is based on the reconstruction of the neutrino direction by measuring Cherenkov light, is illustrated on the right.





4. Scientific challenges

Scientific challenges

The main scientific challenge of the proposed research program is the search for extra-galactic cosmic-ray point sources. Neutrinos are an almost ideal tool for this purpose. Since neutrinos are uncharged and interact very weakly, they do not suffer from intergalactic magnetic fields or interstellar molecular (dust) clouds. Hence, the observed neutrino direction points back to its source. For the highest energies, however, the neutrino yield becomes very low. In this domain, air showers induced by protons or heavy atomic nuclei can be used to search for particle-point sources, as the magnetic rigidity and penetrating power of protons of 10^{19} eV and above is such that the influence of the magnetic fields and dust clouds can be neglected. So, in order to realize the central objectives of the proposed research program, a high-energy neutrino telescope and an air-shower array that is suitable for the highest-energy cosmic rays are needed. As will be explained below, the Antares neutrino telescope in France and the Pierre Auger Observatory in Argentina are providing exactly the right instruments for the proposed research program.

Neutrinos can be detected using the Earth both as a target and a filter. When a neutrino interacts with a particle in the Earth a muon is emitted that can be detected in sea water if it is produced sufficiently close to the bottom of the sea. Muons that emerge from the bottom of the sea can therefore be exclusively associated with high-energy neutrinos that propagated through the entire Earth. Any other particle would have long been stopped in the Earth's interior[2]. Since muons are charged particles, they emit Cherenkov radiation when moving through sea water with a speed faster than the speed of light in sea water. This light can be detected with an array of underwater photo-sensitive detectors. From the measured arrival times of the Cherenkov photons, the direction and energy of the original neutrino can be reconstructed. This concept is at the basis of the Antares neutrino telescope, which will consist of 900 photo-sensitive devices covering an effective sea-water volume of 0.05 km^3. The successful operation of the first detector strings of the Antares neutrino telescope[3] has proven the feasibility of this technique.

Air showers induced by ultra-high energy cosmic rays are very rare and have a wide lateral spread. Hence, a detector array covering a very large surface area is needed to observe them. The Pierre Auger Observatory is such an array. At Auger two independent methods are employed to detect and study high-energy cosmic rays. One technique is ground-based and detects high-energy particles through their interaction with water. The other technique tracks the development of air showers by observing ultraviolet light emitted high in the Earth's atmosphere. The first detection method uses 1,600 water tanks spread over an area of 3000 km^2, separated from each other by 1.5 km. These water tanks are completely dark inside - except when particles from a cosmic-ray air shower pass through it. A muon or electron from an air shower passing a water tank produces Cherenkov light that is measured by photo-sensitive detectors. The direction and energy of the primary cosmic-ray particle is derived from the complementary signals collected by both detector techniques. Auger has already reported first scientific results[4].

The proposed research program is centred on the use of these two new scientific instruments, Antares and Auger, which have been developed within large international collaborations. Antares was built with a substantial participation from the Netherlands. It is anticipated that both Antares and Auger will be used for a period of at least 5 years starting from 2008, which makes the proposed FOM program quite timely. The Netherlands can play a leading role in this process if a sufficiently large team of junior scientists is available. The bulk of the proposed research effort is aimed at the scientific exploitation of these instruments. This will require a considerable effort of many PhD students, postdocs, engineers and

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[2] Above 10^{16} eV neutrinos no longer propagate through the Earth because their interaction cross section, which increases with energy, becomes too large. In order to observe neutrinos with energies in excess of 10^{16} eV, downward going muon tracks with a large energy deposit in Antares have to be identified. This possibility will be pursued in the framework of projects 11 and 12 of this research program, as described in the appendix.

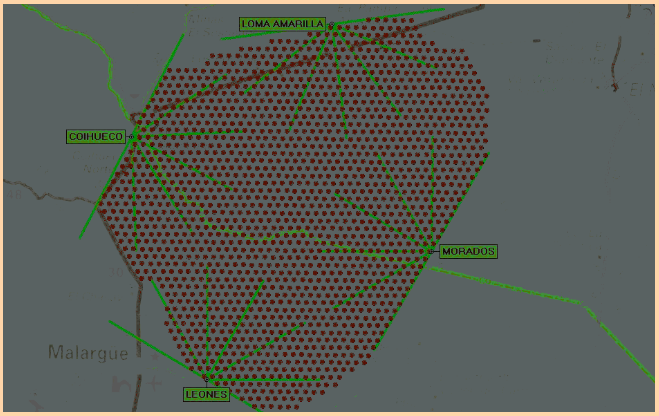
[3] G. Giacomelli and P. Kooijman, CERN Courier **46** (September 2006) 24.

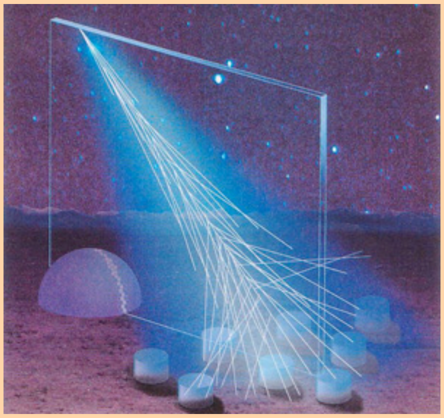
[4] A. Watson, CERN Courier **46** (July/August 2006) 12.

senior scientists, as data will be collected continuously, i.e. 24 hours per day for many years. The junior

The Pierre Auger Observatory

The Pierre Auger Observatory is studying ultra-high energy cosmic rays (UHECRs), i.e. the most energetic particles in the Universe. When these rare particles strike the Earth's atmosphere, they produce extensive air showers made of thousands of particles. While cosmic rays with low to moderate energies are well understood, those with extremely high energies remain mysterious. The layout of the observatory is shown in the left panel below. The hybrid nature of the Pierre Auger Observatory provides for two independent methods to detect cosmic rays. The first method uses an array of (water-filled) surface detectors (red dots in left plot), while the second method uses a collection of air-fluorescence telescopes (labeled by the yellow boxes in the figure). A conceptual view of how these systems complement each other is shown in the figure on the right.





scientists, in particular, will be asked to contribute to the general operation of the observatories – i.e. calibrations, reliability studies, event reconstruction, acceptance simulations, extraction of physics quantities, systematic studies and reporting – together with pursuing a specific research goal that is closely linked to the general scientific goals of the proposed research program that were outlined above. A more precise description of the various research projects that will be carried out by the junior scientists within the framework of the proposed research program is presented in the appendix of this document.

In order to extend the reach of the proposed searches – both in terms of larger cosmological distances and larger energy coverage – additional development work will be performed. To increase the sensitivity of Antares to neutrinos beyond 10^{16} eV, methods will be developed to distinguish downward moving high-energy neutrinos from atmospheric muons. As the lead-time for the construction of a next generation of neutrino telescopes is long, some limited effort will also be spent on R&D and simulations for improved optical modules and readout systems[5]. Ultimately, this will lead to the construction of a future neutrino telescope with an effective volume of 1 km^3 or more[6]. Moreover, radio-detection techniques will be developed for Auger aimed at providing additional information on the composition of cosmic rays and improving the duty cycle of (part of) the observatory[7]. It will also be explored whether it is possible to observe cosmic rays (including neutrinos) of energies well in excess of 10^{20} eV, a domain where Big-Bang relics are predicted to exist[8]. These examples illustrate the synergy of the Auger and Lofar[9] projects, which is of particular importance to Dutch astroparticle physics research.

Milestones

The Antares neutrino telescope is presently under construction on the bottom of the Mediterranean Sea near Toulon. At the time of this writing (summer 2007) 9 of the 12 detector lines have been deployed, of which the first 5 are connected to the shore station and have been collecting data since February 2007. This has resulted in first (preliminary) scientific results. The remaining detector lines will be deployed in the last months of 2007. Operations with the fully completed neutrino telescope will thus be possible by early 2008. This will mark the beginning of a 5 year data-taking period. First scientific results will be published in 2009, while results related to the search for cosmic neutrino-point sources are anticipated in 2012 after four years of data taking.

The Pierre Auger Observatory will also be completed in 2008. First results obtained with the (partly completed) observatory have already been published since 2005. In fact, in the summer of 2007 a normalized energy spectrum of air showers observed at Auger in the energy domain between $10^{18.2}$ and $10^{20.2}$ eV was shown at the International Cosmic-Ray Conference (see figure 3 on page 12). If confirmed by future data these results do show the existence of a GZK threshold at the expected energy value. More results related to the composition of cosmic rays, and the possible discovery of particle-point sources are anticipated in the coming years. Given the low event rates for the highest energy cosmic rays, the full particle point-source searches will require 4 years of data taking leading to final results in 2012. Moreover, in the months prior to the submission of this proposal, a proof-of-principle has been obtained for the use of radio antennas at Auger (see figure 4 on page 12). Coincidences were observed between signals recorded by the Auger water tanks and prototype radio antennas mounted on 5 m high poles. As a next step some 25 radio antennas will be installed and operated in Argentina in the period 2008 – 2010. The full array of 140 antennas covering an area of 20 km^2 will be completed in 2012.

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[5] These subjects are addressed by projects 11 and 12, which are both described in the appendix.

[6] A separate investment proposal has been submitted to the science funding agency NWO, in which finances are requested for a Dutch contribution to the development and construction of this new European project – known as KM3NeT. This project will be completed in 2014, when the presently proposed FOM program has been concluded.

[7] The hardware expenses for the development and purchasing of radio antennas for Auger are the subject of two separate investment proposals; one in the framework of a NWO program to stimulate international collaboration, and one in the framework of medium-sized investment projects of the Dutch astronomy research school NOVA.

[8] This subject, which is described in more detail in the appendix (project 13), may lead to a novel application of the radio synthesis telescope Lofar (see footnote 9) as a telescope for observing extremely high-energy cosmic rays.

[9] Lofar is large array of low-frequency radio antennas currently under construction in the Eastern part of the Netherlands; see www.lofar.org.

Antares: first results

The Antares neutrino telescope started collecting data in March 2006 when the first detector line was connected to the shore station in La-Seyne-sur-mer. The analysis of the data obtained with this first detector line has been carried out by a Nikhef graduate student (R. Bruijn, PhD Thesis, *Universiteit van Amsterdam*, December 2007). Some of his results are displayed in figure 1. The data are seen to be well understood and compare well to similar data obtained in previous experiments.

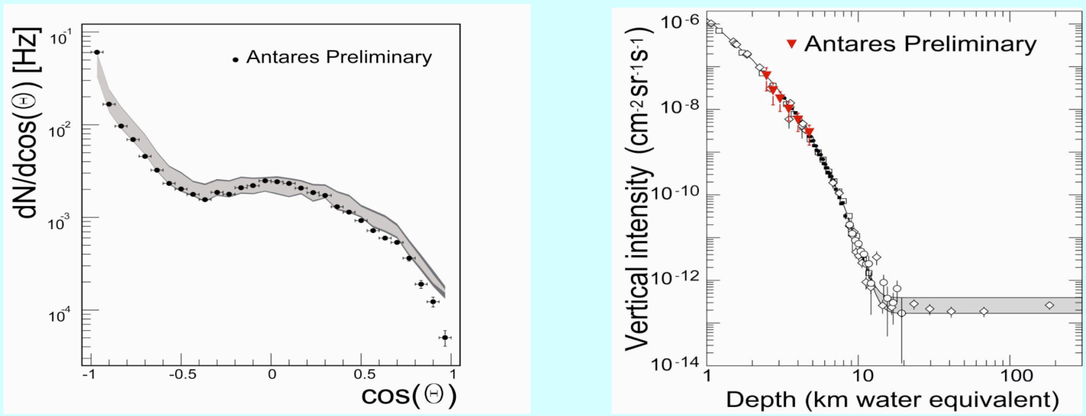

Figure 1. On the left the distribution of reconstructed muon tracks is shown as a function of the cosine of the zenith angle θ for data collected with the 1st detector line of Antares. (Events coming from straight above correspond to $\cos(\theta) = -1$.) The data are compared to simulations based on the MUPAGE *event generator. No renormalization was applied. The width of the band represents the systematic uncertainty associated with the acceptance of the photomultiplier tubes. On the right the observed reduction of the downwards going muon rate (solid triangles) with water depth is compared to existing data.*

Following the start of data taking with Line 1, eight more detector lines were deployed up until the summer of 2007. Five lines were put into operation in early 2007, enabling successful data taking with the first 5-line neutrino telescope in the Mediterranean Sea since that time. This led to the observation of the first upward moving muon tracks that can be associated with high-energy neutrinos (figure 2).

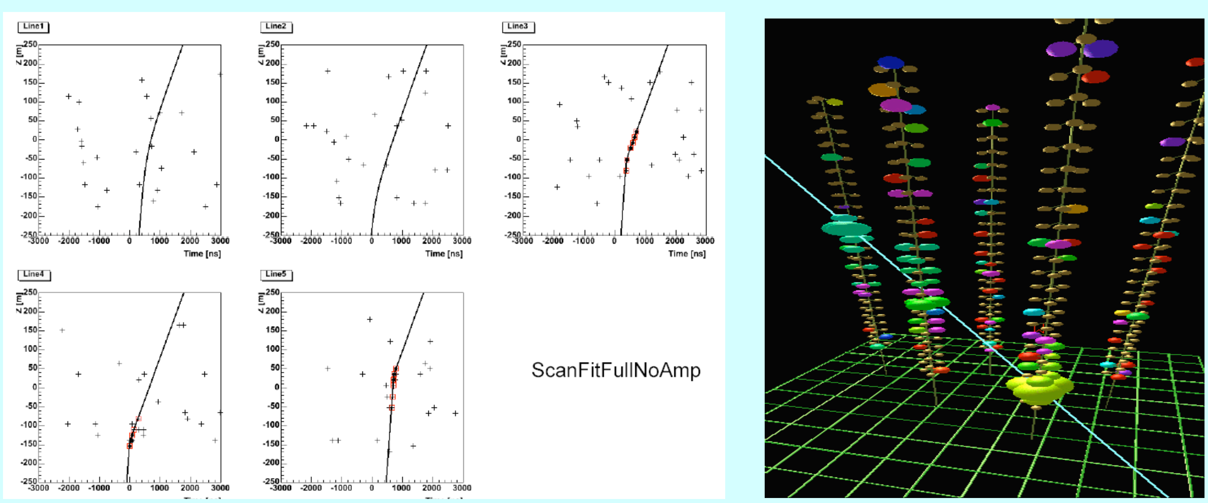

Figure 2. On the left the single-photon events of the first five Antares detector lines are shown versus time. The vertical scale gives the vertical position of the PMTs that fired. The curves represent a fit to the data, which is also graphically represented in the right-hand panel (the size of the spheres represents the number of photons while the timing of the signals is colour-coded). The data shown in this figure represent one of the first high-energy neutrino events observed by Antares.

International perspective

The search for the origin of cosmic rays belongs to the field of *Astroparticle Physics*, a rapidly growing research field at the interface of astronomy, cosmology and physics. Within Europe, the astroparticle physics community (as coordinated by ApPEC[10]) is in the process of preparing a roadmap[11], in which the scientific exploitation of both Antares and Auger figure prominently. The funding agency for fundamental physics research in the Netherlands (FOM) is participating in this process as one of the leading partners in the FP6-funded ERA-NET project ASPERA[12], in which European funding agencies – apart from preparing a roadmap – collaborate in an effort to develop common (or compatible) methods for benchmarking and managing large European astroparticle physics infrastructures. This is important in view of the ambitions of the European astroparticle physics community to construct several new research infrastructures, including a km^3-sized deep-sea neutrino telescope (KM3NeT) and a large cosmic-ray observatory on the Northern Hemisphere (known as Auger-North).

The proposed research program will make it possible for Dutch astroparticle physicists to play a prominent role in the scientific exploitation of the Antares neutrino telescope and the Pierre Auger Observatory. Since the aforementioned KM3NeT and Auger-North projects can be regarded as the successors of Antares and Auger-South, the proposed program also paves the way for a leading position of the Dutch research community in these future projects. This is particularly important now that the KM3NeT project has been included by ESFRI (*European Strategic Forum for Research Infrastructures*) in its recently published list of 35 most important large-scale scientific infrastructures that need to be built in Europe in the coming decade[13]. The European Community has already approved a FP6-funded *Design Study* for KM3NeT, in which FOM (through Nikhef) is involved. Earlier this year a *Preparatory Phase Proposal* for KM3NeT was submitted to the EU as part of a special program for future research infrastructures that are listed by ESFRI. The Netherlands is also involved in this proposal[14].

The Netherlands has a strong starting position in the growing field of astroparticle physics because of its expertise in information technology (which has already been shown to be successful in the framework of the Antares project) and its expertise in radio astronomy (as can be illustrated by the successful application of the Lofar radio technique to Auger). In order to benefit and further exploit this position in Europe, programmatic funding of astroparticle physics in the Netherlands is essential.

National perspective

The emerging Dutch astroparticle physics community has recognized that a country like the Netherlands can only have a significant impact in the field if the research effort is focussed on a limited number of projects. For that reason the *Strategic Plan for Astroparticle Physics in the Netherlands*[15] was written in 2005. This plan identified the search for particle point sources with Antares and Auger as key projects for the development of this field in the Netherlands. The time lines involved in neutrino and cosmic-ray observations at these facilities span 5-6 years. Hence, a long-term financial commitment is required. This cannot be realized on the basis of small project grants, but ideally fits the FOM program structure.

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[10] Astroparticle Physics European Coordination (ApPEC); appec.in2p3.fr/

[11] The first version of the roadmap for astroparticle physics research in Europe can be found at http://www.aspera-eu.org/images/stories/files/Roadmap.pdf/. This roadmap will be further developed in the coming years.

[12] ASPERA is a network of national funding agencies responsible for coordinating and funding national research efforts in Astroparticle Physics. The home page of ASPERA is http://www.aspera-eu.org/

[13] The European Roadmap for Research Infrastructures published by ESFRI is available at the following web-site: http://cordis.europa.eu/esfri/roadmap.htm

[14] Just before the submission of the present proposal, the EU invited the applicants of this FP7-proposal to start the contract negotiations. This means that this EU-funded proposal is - in principle – approved as well.

[15] This report can be downloaded from the web-site www.astroparticlephysics.nl/papers.php.

Auger: first results

The Pierre Auger Observatory has been collecting data since 2005, although the entire detector will only be finished by early 2008. Examples of first results obtained by Auger are shown in figure 3, in which (on the left) an event display illustrates the detection of an air shower that can be associated with a cosmic ray of about 3 x 10^{19} eV. On the right-hand side a very preliminary (normalized) energy spectrum is shown, revealing an abrupt change at an energy of about 6 x 10^{19} eV, representing the so-called Greisen-Zatsepin-Kuzmin (GZK) threshold – explained on page 4.

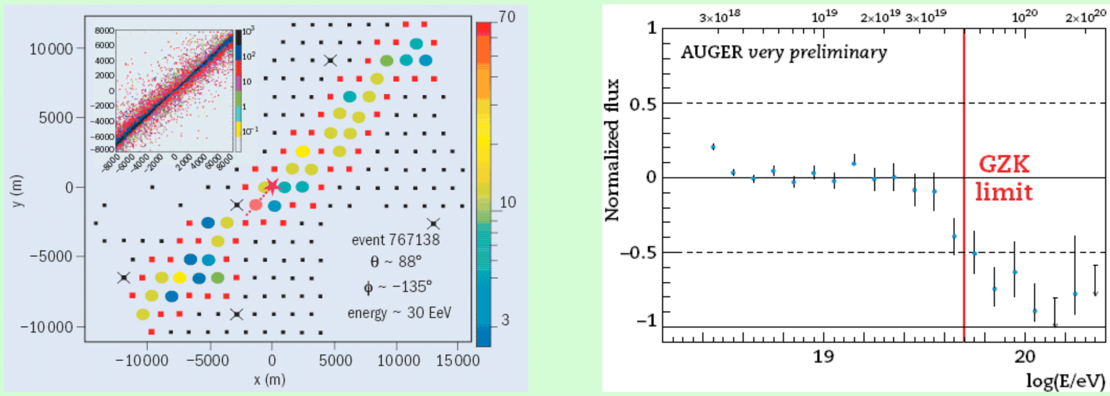

Figure 3. The left panel shows an ultra-high energy air shower observed at the Pierre Auger Observatory. The black dotted grid represents the array of water Cherenkov tanks that was operational at the time of this event; coloured water tanks have observed a signal. The inset shows the signal observed by the air-fluorescence detectors of the same event. The angle of incidence and an estimate of the energy were obtained by analyzing the energy of all detectors together. On the right a flux spectrum is shown of cosmic-ray events observed by Auger. The spectrum was renormalized to enhance the change in slope observed near an energy of 6 x 10^{19} eV, the GZK threshold.

The air-fluorescence detectors of Auger can only be used during moonless nights. Consequently they are only available during about 10% of the data taking time. In order to supplement the air-fluorescence detectors, it has been proposed to build radio antennas which can always be used. Moreover, such antennas provide complementary information about the location and development of air showers in the atmosphere. Given the known expertise of the Netherlands in radio astronomy (as exemplified by the Lofar project), the Dutch team in the collaboration was invited to coordinate the development of radio antennas for Auger. First results obtained with a simple prototype antenna, which are illustrated in figure 4, demonstrate the basic feasibility of this technique.

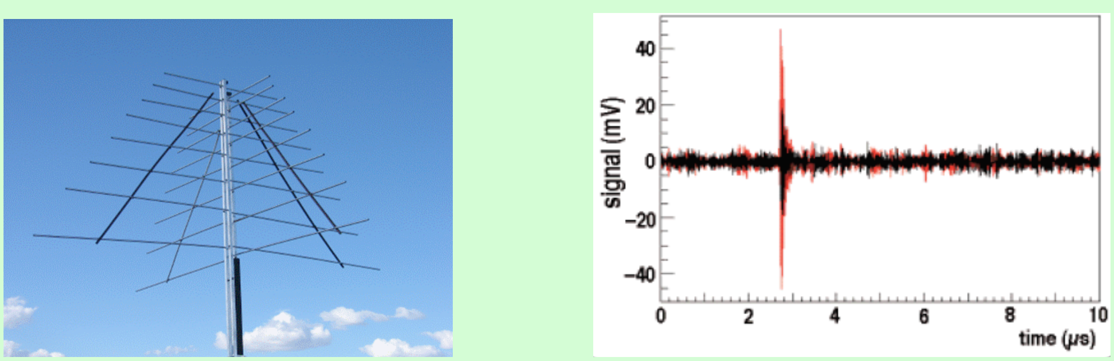

Figure 4. On the left a simple prototype antenna is shown, which was used to study the basic feasibility of observing radio signals at Auger. Using a set of scintillators as a trigger, and requiring a coincidence with a nearby Auger water tank, the signal displayed on the right was obtained.

5. Distribution of scientific tasks

The proposed scientific program is carried out by 5 closely collaborating research groups. The research projects related to the Antares neutrino telescope are carried out by the groups in Amsterdam (NIKHEF and IHEF) and Groningen (KVI), while those related to the Pierre Auger Observatory are carried out by IMAPP, KVI, UU and NIKHEF. More specifically, the role of each group in the proposed research program is outlined below.

- The Astroparticle Physics Group of the *FOM instituut voor subatomaire fysica NIKHEF* has been involved in neutrino astroparticle physics since 2000. It has developed an entirely new concept for the read-out of neutrino telescopes based on advanced photonic techniques, sophisticated software algorithms and novel triggering concepts. The leadership of this group has been recognized by the appointment of Prof. Maarten de Jong both as deputy spokesperson of the Antares collaboration (since 2005) and as coordinator of the information-technology work package of the FP6 KM3NeT design study. The group is also involved in the Auger project, and is exploring the combination of data collected with complementary observatories (the co-called "Multi-messenger technique"). The coordination of the presently proposed FOM research program will also be based at NIKHEF.

- The *Instituut voor Hoge-energiefysica (IHEF)* of the *Universiteit van Amsterdam* has developed advanced track-reconstruction algorithms for neutrino telescopes, which have broadened the scientific program of Antares. Moreover, the group is pioneering new detector and readout concepts for future neutrino telescopes, aimed at improving the performance-to-cost ratio of the next generation neutrino telescopes.

- The *Department of Subatomic Physics* of *Utrecht University (UU)* will be involved in the analysis and interpretation of the Auger data. The group has a unique position because of its combined expertise on cosmic acceleration mechanisms, reactions of high-energy protons and nuclei, and the influence of atmospheric conditions on fluorescence detectors (via connections with the Institute of Marine and Atmospheric Research at the University).

- The *Institute for Mathematics, Astrophysics and Particle Physics (IMAPP)* of the *Radboud Universiteit* in Nijmegen has pioneered the detection of high-energy cosmic rays by means of radio antennas. IMAPP is the analysis centre for cosmic-ray observations obtained by Lofar. By combining their expertise in radio astronomy, particle physics and astroparticle physics the group will be able to play a central role in the analysis of data collected by all present and new instruments available at Auger with particular emphasis on the search for anisotropies.

- The *Kernfysisch Versneller Instituut (KVI)* of the *University of Groningen* is leading the Dutch team in the Auger collaboration and coordinates within this international collaboration the development and construction of a distributed array of radio antennas. The group is also involved in the search for extremely-high energy cosmic particles using radio techniques at Lofar (and possibly Auger) and the Antares neutrino telescope.

The expertise available in the various groups will be combined, whenever possible, when addressing specific research questions.

The proposed research program is organized along five distinct scientific themes:
- point-source searches;
- dark matter;
- composition of cosmic rays;
- ultra-high energies;
- exotics.

Within the first three themes, which represent the bulk of the proposed research program, the frontier research questions introduced in section 3 are being investigated. The fourth theme (*Ultra-high energies*) is aimed at the development and extension of the detection techniques used by Antares and

Auger towards higher energies. This is of interest for various reasons. By extending the sensitive domain of the Antares neutrino telescope beyond 10^{16} eV, i.e. by looking for downward going muon tracks, an overlap with the energy domain of Auger can be realized, which is particularly interesting when studying the composition of primary cosmic rays. By going beyond the standard energy domain of the Pierre Auger Observatory, the sensitivity for the possible observation of exotic dark-matter candidates such as the so-called *topological defects* is substantially increased. The fifth theme has been added to illustrate that new general-purpose observatories like Antares and Auger offer some unexpected opportunities as well. With Antares, for instance, it will be possible to search for magnetic *monopoles* and so-called *nuclearites*. At Auger, on the other hand, one might search for extremely high-energy photons that – according to the so-called *top-down models* – are predicted to result from the decay of very massive GUT-scale particles, if they exist. These exotic subjects illustrate that serendipity may also play a role in the proposed research program, as the new window on the Universe offered by Antares and Auger may also lead to unexpected chance discoveries.

For each of the five themes a number of specific projects has been defined that – one by one – will form the basis of the research work of one PhD student. These individual PhD projects are briefly summarized in the appendix. The senior staff members who will lead these individual research projects are also mentioned. It is noted that more PhD projects are listed in the appendix than can be (financially) supported by the proposed research program. It is therefore assumed that some supplementary funding will be obtained through the *FOM project competition,* the *NWO junior fellowship program ('VENI scheme')* or the *European Marie Curie fellowship program*. In recent years, the participating institutions have been very successful in attracting such externally paid fellows.

In order to illustrate the cohesion of the proposed FOM program, the table below correlates the five scientific themes mentioned above to the five research groups involved. Also shown (in the 2nd and 3rd columns of the table) is the observatory that is being used for investigating a given theme. As can be seen almost all themes require the use of both Antares and Auger, and the involvement of more than one research group.

	Antares	*Auger*	NIKHEF	UvA	Utrecht	IMAPP	KVI
Point-source searches	o	o	X	X		X	
Dark matter	o	o	X	X			
Composition of cosmic rays		o			X	X	X
Ultra-high energies	o	o	X	X			X
Exotics	o	o	X				

6. Organisational structure

The proposed research program is led by a single *program leader*, Prof. Gerard van der Steenhoven (NIKHEF/RuG), who carries the full executive responsibility. The program leader receives administrative support from the coordinating institution, the *FOM Instituut voor Subatomaire Fysica NIKHEF*, in Amsterdam. The program leader has formed – in consultation with all applicants – a management team in which all research groups are represented. Apart from the program leader, it has the following members: Dr. Ad van den Berg (KVI), Prof. Sijbrand de Jong (IMAPP) and Prof. Paul Kooijman (UvA/UU). The membership of the management team (MT) will be reviewed every two years. The MT advises the program leader regarding all executive decisions, including the hiring of PhD students, appointing their supervisors, the organization of scientific meetings, and the allocation of resources. As a starting point for all management decisions the following set of rules has been agreed upon:

- The available resources will be allocated among the various groups as described in section 8 of this proposal, but subject to a re-evaluation on an annual basis.
- The responsibility for the recruitment and supervision of PhD students hired by one of the participating groups in the framework of the present program rests with that same group.
- Each PhD student will be associated with one of the two research schools “OSAF” (for students based at NIKHEF, IHEF, IMAPP or UU) or “Fantom” (for KVI-based students). The mentioned research schools provide graduate courses and will monitor the progress of each student.
- Scientific progress will be exchanged on a quarterly basis in public meetings of all participants.
- Scientific publications resulting from research work financed through the present program are subject to the internal review system of either the Antares or Pierre Auger Collaborations, whenever use has been made of either one of these observatories.
- Each participating group informs the program leader whenever scientific output has been produced or expenses have been made associated with the present research program.

The scientific objectives of the present research program are well defined (see Section 3). Based on these objectives a list of specified research topics was made, reproduced in the appendix of this proposal. For each of these topics the observatory involved (Antares or Auger) and the project supervisor is identified. Hence, no additional competitive mechanism is needed to allocate the PhD positions within the proposed research program. Moreover, as there are many national and European fellowship programs available for hiring postdocs, it has been decided to focus the present program on PhD students. In practice, each PhD student will spend part of his/her time on the various operational tasks that are needed for the scientific exploitation of instruments of the size of the Antares neutrino telescope or the Pierre Auger Observatory (see section 4), and part of his/her time on a scientific analysis of data collected at one of these observatories.

7. Application perspective

Direct industrial application of the scientific results obtained from the measurement campaigns at the Antares neutrino telescope and the Pierre Auger Observatory is not to be expected. Nevertheless, the proposed research program will have valorisation aspects: (i) the development of improved techniques for the detection of ultra-high energy neutrinos with future large-scale neutrino telescopes involves manufacturers of photo-sensitive devices; such contacts may increase chances for successful orders for Dutch industry (such as Photonis-DEP in Roden) once the European tendering for a future km^3-sized neutrino telescope has begun; (ii) the deployment of radio antennas for Auger requires the development of new low-power wireless systems that are of interest to companies involved in commercial distributed sensor networks (such as Hopling Technologies in Almere); (iii) past experience shows that research projects involving cosmic rays have a significant outreach[16]; the continuous observations from the bottom of the sea by Antares and the stand-alone radio antennas at Auger provide new opportunities for appealing outreach projects.

[16] In the award-winning HiSparc project high-school students are building cosmic-ray detectors that are installed on the roof of their school. By coupling various detector stations, i.e. schools, a distributed array of high-energy cosmic ray detectors has been realized (see http://www.hisparc.nl).