Final Report

ILIAS

Integrated Large Infrastrutures for Astroparticle Science

Integrating Activity

implemented as

Integrated Infrastructure Initiative

Contract number: RII3-CT-2004-506222

Project coordinator: Gilles Gerbier - CEA-IRFU

Project website: *ilias-cea.fr*

Project Duration : 60 months from 01/04/04 to 31/03/09

Project funded by the European Community
under the "Structuring the European Research Area" specific programme
Research Infrastructures Action

A. ACTIVITY REPORT

Astroparticle science is an emerging field of physics linking investigation of the microscopic world, ie particle physics, and investigation of the largest scales of the universe, ie astronomy and astrophysics.

The best illustration of this new field has been the investigation of the solar neutrino puzzle. In the 1950's, from a single pioneering experiment, there was indication that not enough neutrinos were coming from the Sun if one believed the model of Hydrogen burning in the sun. Thanks to dedicated new and more sensitive installations, it has been concluded that indeed this observation was confirmed and that correct understanding of this observations could be accounted for by new properties of the neutrino and not by the functioning of the sun.

Another typical example is the understanding of the dark matter of our Universe. This long standing question, which has its origins in the 1930's, is now recognised best accounted for by new particles bathing the Universe since the Big Bang. Detecting these particles is now one of the major challenge of the field.

In both cases and many others illustrated in the following report, the issues can only be solved with the help of dedicated infrastructures, the deep underground laboratories. Only such sites, deep underground, are well enough protected against cosmic rays from the Universe to provide an environment free of parasites and background for the very sensitive experiments dedicated to observe the very rare processes at work in this field.

There are four major running Deep Underground Laboratories in Europe and 2 major Gravitational Waves installations. The goal of the present integrating activity was to initiate and strengthen coordination between these infrastructures for a better service to users, promote integration of communities involved, in particular for larger scale projects, develop techniques that will allow next generation investigations and facilitate, promote and organise access to Deep Underground labs to enlarged community.

This gives the context and scope of ILIAS (Integrated Large Infrastrutures for Astroparticle Science), which main achievements are described in the following.

The ILIAS web site (*http://ilias-cea.fr*) has known two major phases. A first site, built shortly at the beginning of the project has shown not to be fully adequate to the communities that were visiting it. It has then been upgraded to a version with publication data base, regular update of news, and workable links to outreach pages.

N2: Deep Underground Science Labolatories (DUSL)

The **network N2** (DUSL) was set up as a core component of ILIAS, to act as a focus for the first formal cooperation and communication between the four deep laboratories of Europe, the Boulby facility (UK), LNGS Gran Sasso (Italy), LSC Canfranc (Spain) and LSM Frejus (France). To provide a clear pivot for this new cross-laboratory interaction, N2 was assigned three workpackages, with clear annual deliverables totalling over 50 items, with remit to work together on: performance improvements, possible extensions of the deep underground laboratories and scientific coordination (WP1); safety problems and accident prevention in the underground sites (WP2); and public communication (WP3). Driven by over 40 meeting held by the group, all deliverables over the 5 years of ILIAS were met in full and in some cases, as the programme developed, well exceeded.

An important further aspect of N2 was progress with the CoMag (Coordination and Management of DUL's) committee of laboratory directors. This forum developed strongly over the period, feeding on the progress with N2, to produce a lasting communication structure for the labs based on regular meetings between the directors where previously there were none.

Furthermore, given the recognized success and interest of this initiative, agencies responsible for the running of the main underground in Europe decided to give a permanent status to this entity by signing a Memorandum of Understanding creating EULabs, an entity gathering all directors of Underground labs.

A first activity was to gather, compare and assess, for the first time, all the technical characteristics of the labs. This database of information was then maintained and updated through regular reports from each lab and via specific site visits of the group. From these tables it was possible to formulate an overview of the infrastructures and, by gathering also information on the plans for use of space at each lab and plans for expansions, start to explore coordination in allocation of space to experiments. This was progressed further by agreements to allow exchanges between the members of the existing scientific committees of each labs and access to the minutes of those committees. Later the information gathering was extended to include non-EU facilities and new emerging facilities in Europe, notably the Phyasalmi site in Finland, to develop closer relationships with those labs. The result, built over 5 years, has been the first comprehensive understanding of our deep underground facilities and the first real progress towards actual managerial coordination in Europe that is now improving the service to users.

The action to start, for the first time, real cooperation on safety across the labs (WP2) has been a particular success story in N2. A series of dedicated site visits to all the labs by experts from each lab has produced a real exchange of best practice and a critical assessment of each lab's strengths and weaknesses. This also gave a nw forum to discuss particular safety-significant incidents as they occured, for instance, the fire in the Frejus tunnel and a power failure in Boulby, and jointly to learn lessons from them. It allowed greater understanding of the different approaches used, particularly by contrasting the tunnel sites with the mines. We held and developed very successful joint safety training sessions at the different sites to learn and develop better techniques, and to develop recommendations for the future. Particular lessons have been leant and propagated with new techniques, for instance recognition of the importance of controlling access by staff underground and monitoring their location at all times. This helped stimulate instalation of an infrared beam system for automatic counting of staff at Modane. Progress has also been made on how to establish an external auditing panel, a recommendation of ours for any future major expansions underground. Finally, the first joint link has been established with safety forums in the high energy physics lab communities, again to exchange best practice.

Making our science accessible and interesting to the public is of the highest importance to all the labs. Our final workpackage addressed this issue, recognising again that all participants could gain by pooling and exchanging experience to develop better and more efficient approaches, broadening also our audience. By this means, through many animated discussions, we have produced new and better posters together; a new joint lab brochure with text describing our science; and a new joint web-site resource. For the first time all the labs have participated together, every year, in the very successful LNGS open day. For this we developed and used together, new ideas, for instance live web-cam links to each lab to allow the public a more interactive experience. Most successful, and challenging to achieve, has been our production of a joint professional film featuring all the laboratories, aimed at conveying to a lay audience the excitement of the experiments we perform there. All the labs participated in filming, giving us a unique and lasting outreach resource for use by schools, TV companies and almost all outreach situations.

Last, but not least, by working on N2 and with the CoMag together, we have developed a deeper understanding between the labs and a sense of community where previously there was none. This is perhaps the greatest success of this network.

Figure 1 - The N2 cross-lab safety group on a visit to Boulby mine.

JRA1: Low Background Techniques for Deep Underground Science (LBT-DUSL)

Research in underground laboratories concerns rare processes: the detection of dark matter particles, very weakly interacting, colliding with the nucleus of a detector, or of a rare type of nuclear decay, yet unobserved, the so-called double beta decay. In order to allow for these observations, every other possible event in the detectors has to be suppressed, or else it would completely hide the searched signal.

Underground laboratories provide the conditions for the reduction of backgrounds for these very sensitive experiments. In particular, their location, deep underground, eliminates a large fraction of the cosmic rays that continuously hit the Earth surface. Radioactivity of rock and materials, producing neutrons and gamma rays, is also a source of environmental background, as it is the radioactive radon gas, which is commonly present in air.

One of the activities carried out in ILIAS has been the identification and quantification of the different background components at the four European underground laboratories (LNGS, LSC, LSM and Boulby). A complete survey of previous measurements, complemented with new measurements made possible by ILIAS (see Fig. 2), was carried out at the different labs, and the results collected in a database which has been made available to the whole community. These data will be of great importance in the design and choice of location for new experiments requiring a certain maximum level of background. In such an experiment, some aspects are crucial, such as shielding and the selection of materials of the appropriate radiopurity.

A number of activities inside ILIAS have contributed to help defining the best strategy for shielding configurations. For example, numerical simulations are used in order to, given the environmental background at the lab as an input, design an adequate shielding for the detector (see Fig. 3). A reliable library of simulation codes for the interpretation of data and for planification of future experiments has been produced after a systematical analysis of available codes and comparison between them and experimental data.

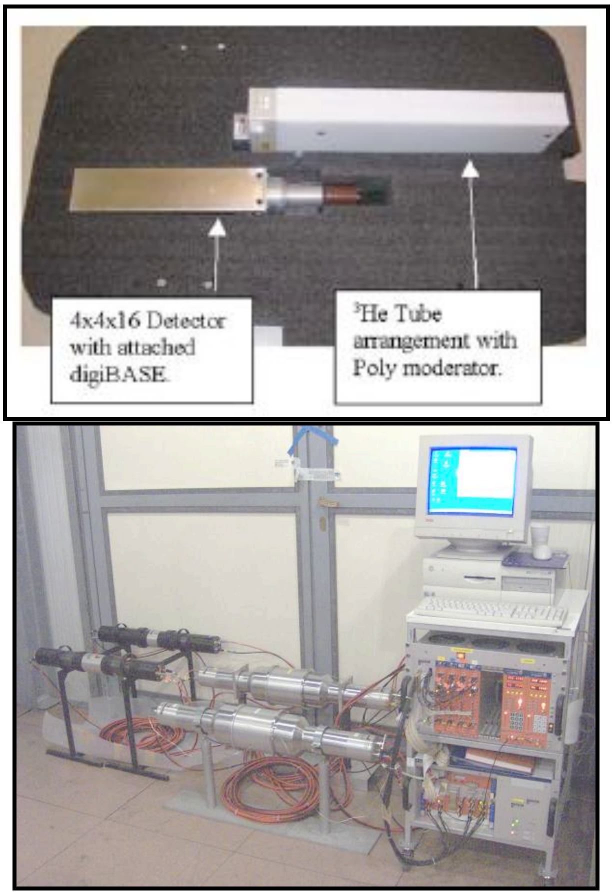

Figure 2: Equipment acquired for new background measurements at LNGS: portable 16 kg NaI(Tl) for measurements of gamma spectrum (left), and cells of liquid scintillator to determine the spectrum and intensity of the neutron flux (right).

Figure 3 - Construction of a shielding castle (8 cm of copper surrounded by 15 cm of lead) for a high-purity germanium detector at Boulby.

In order to help future experiments with the selection of materials, collaboration within ILIAS has also made possible a collection of new and old data on radioactive contamination and cosmogenic activation of materials used in different experiments, which has been made available to the community as a free-access database.

Finally, ILIAS has also cofinanced the construction and upgrading of ultra low background facilities at the different laboratories, such as: the development of new generation of high-purity germanium detectors for measurements of ultra-low levels of contamination of materials (LNGS), a radon trapping facility to provide air with very low levels of radon gas (LSM, see Fig. 4), or a new facility to produce pieces of high-purity electroformed copper to be used in different experiments (LSC, see Fig. 5).

Figure 4 - Anti-radon factory at LSM, designed to provide 125 m^3/h with a radon level of approximately 15 mBq/m^3.

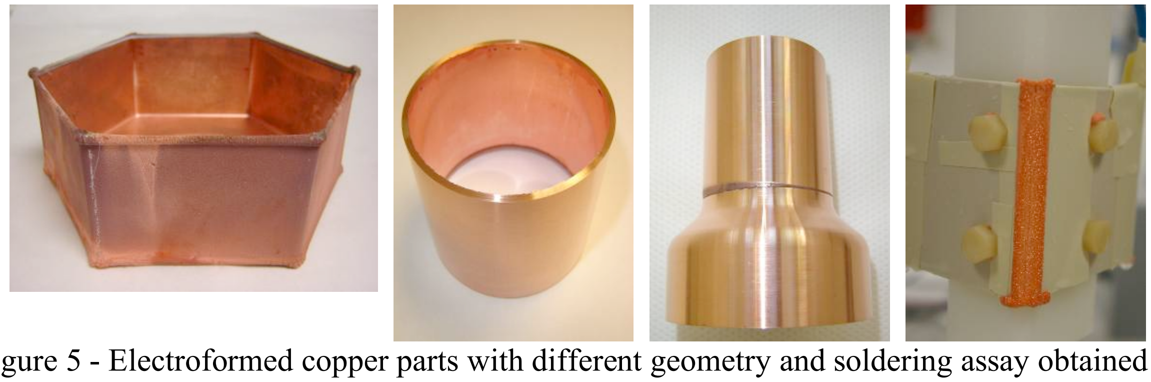

Figure 5 - Electroformed copper parts with different geometry and soldering assay obtained in the electroforming setup at the University of Zaragoza.

N3: Direct Dark Matter Detection (DMB)

Dark matter search and identification is one of the 7 objectives of the European Astroparticle Roadmap. It is recognized as one of the major challenge of modern physics.

The identification of this new particle, massive but with very weak interactions with matter (so called WIMP, Weakly Interacting Massive Particle) could be achieved through the detection of its relics from the Big Bang. Still present in our universe at all scales, and in particular in our immediate surroundings, they require a very quiet environment with no radiation background to be detected, in particular in underground environment.

While no detection has been yet performed with the current investigations, better quality and larger detectors are required to improve the sensitivity to the search. Would a signal be detected, this would constitute a major discovery, solving this 70 years old puzzle, and would change our view on our universe.

The main goal of the N3 network was to reach convergence in the assessment of the different detector concepts (cryogenic, liquid noble gases, conventional, potential new types) for a large-scale direct dark matter search project. Considerable progress has been achieved in this respect. In particular, two main techniques have been identified as priorities for future direct detection dark matter experiments, namely liquid/gas noble targets and cryogenic detectors.

On the cryogenic side, a strong convergence was achieved with the CRESST, EDELWEISS and ROSEBUD experiments, joining their efforts towards EURECA (European Underground Rare Event Calorimeter Array) involving about 120 members from 16 institutions. A baseline solution has been defined for the setup of EURECA, with a water shield, housed in two independent water pools, acting as an active shield against gamma-ray and, most importantly, neutron external backgrounds. It is foreseen that this active water shield will host two independent cryogenic systems (see Fig. 6). The Laboratoire Souterrain de Modane (LSM, 4800 m.w.e.), the deepest underground laboratory in Europe, has been chosen as the site for EURECA.

At an international level, a MoU has been signed between the main three cryogenic dark matter experiments EURECA, CDMS and GEODM, the last two experiments in the US. These three collaborations have initiated a cooperation in data analysis, Monte Carlo simulations, shielding, R&D activities and radiopurity measurements.

The other main technical solution identified for dark matter direct detection is constituted by noble gas/liquid detectors, which has demonstrated impressive progress over the last years. In particular, several xenon detectors have now been successfully operated. The one operated at Gran Sasso (Xenon10), is among the few leading experiments in the world. Building upon the gained experience, the European groups of the XENON and ZEPLIN collaborations have joined together in collaborative effort DARWIN. In addition, ZEPLIN III joined with US colleagues in the LUX collaboration.

The liquid argon and xenon communities have also reached convergence on scale-up designs, with a two-phase design and a combination of the Pulse Shape Discrimination (PSD) and charge/light discrimination techniques. In addition, the Argon group is studying a promising single phase design combing the previous two discrimination techniques.

Complementing these two main experimental lines, a line of R&D was identified as directional detectors, gathering the community involved in this technique, both in Europe and in the US (MIMAC and DRIFT, resulting in the DM-TPC collaboration in the US, and the CYGNUS collaboration in Europe). This development is made in cooperation with the axion community in order to detect Kaluza-Klein axions. Two other lines of conventional Ge-diodes have joined with their expertise in the GERDA and GEDEON projects, while for sodium iodide scintillation detectors , the ANAIS (Annual modulation with NaIs) intends to provide an independent test of the DAMA effect.

The network achieved important progress on simulations, shielding strategy and material purity requirements. In particular, the main reference Monte Carlo simulation codes were extensively tested and benchmarked, with exchange of software libraries between the network participants, This has led to agreement on simulation codes to be used, and recommendations for the shielding strategies. In particular, two alternative solutions (20-25 cm of lead complemented by 50-60 cm of polyethylene, or 3 m of water) were defined as the two recommended lines of shielding. Also, a list of the main radiopure materials, such as copper and acrylic, was defined, which can be used without additional shielding in the detector construction. The network also studied the constraints on the amount and nature of materials with higher concentrations of radio-isotopes.

Another important conclusion of the network has been that the main underground laboratories involved in ILIAS are suited for high-sensitivity dark matter experiments. Monte Carlo simulations were tested and compared to the measurements of neutron background carried out within the ILIAS TA and JRA programme.

The work of the network on material purity and purification methods has led to extensive data on the radiopurity of 90 different materials, representing a crucial input for Monte-Carlo simulations. These data have been organized in a database system (http://radiopurity.in2p3.fr/)

The network has also been involved in the study of axions in relation to the CAST axion helioscope, which has established the best world limits on the axion-to-photon coupling constant. Exchanges between the WIMP and AXION communities have been developed with joint workshops, developing ideas on common detector concepts.

The network has also fostered exchange of PhD students among different groups, with a PhD thesis funded by the network between the Sheffield and Tuebingen participants. Three training sessions on WIMP data analysis, Supersymmetry and Axion Physics were organized by the network with emphasis on the participation of young physicists.

The network has a fundamental participation to the definition of the roadmaps for Astroparticle physics in Europe and the US. In particular, the network coordinated the gathering of information from all European DM experiments in response to the request of the ASPERA Eranet European roadmap for Dark Matter Phase II.

In addition, an interactive Data Tool Webpage has been developed within ILIAS-N3, allowing to compare sensitivities between experiments using actual data and to evaluate performances of experiments in the context of particle physics SuperSymmetric model (see http://pisrv0.pit.physik.uni-tuebingen.de/darkmatter/).

Finally, the network has initiated a public data exchange policy, with a first definition of common data format exchange between dark matter experiments. This ambitious program, which will only be realized within the context of a future I3, will eventually lead to the full open access policy of all Dark Matter experiments recognized by ASPERA/ApPEC.

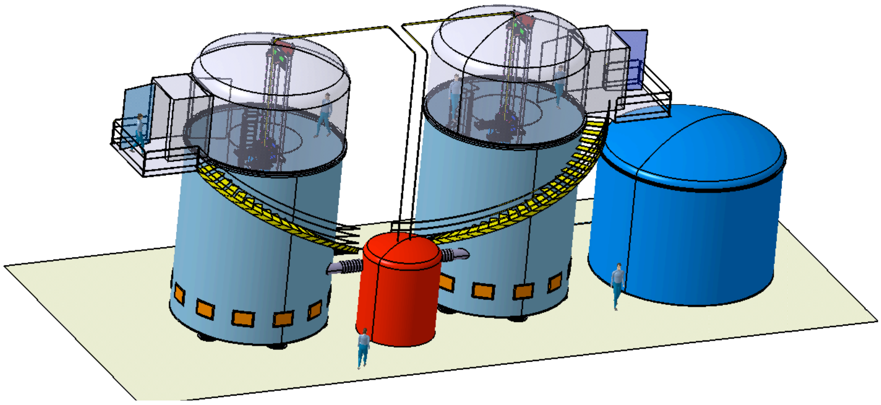

Figure 6 - EURECA design concept for a tonne-scale Dark Matter direct detection experiment

N4: Search on double β Decay (DBD)

When Wolfgang Pauli postulated the existence of the neutrino in the Thirties of the last century, he was persuaded that no experimentalist would be able to detect and to study this particle. In fact, neutrino is a little bit more than just nothing. No mass, it was believed until a few years ago. And a so tiny interaction with ordinary matter, that a neutrino emitted by the sun can travel in water for 100 light-years without any effect. However, this "almost nothing" has a terrific importance for the comprehension of the mechanisms at the roots of the behavior of particles and forces.

It has been indeed discovered that neutrino have small masses but we don't know currently their absolute values. In addition, neutrino is a strange particle since it is the only elementary particle of matter (fermions) which has no electric charge, and then it could be the anti-particle of itself, a so-called Majorana neutrino.

Such a possibility would help understanding why their mass are so tiny and would answer one major question beyond neutrino itself : why is there an asymmetry in the matter-antimatter distribution in the universe observed today. If neutrino is really its own anti-particle, it would be a major discovery of new physics beyond the Standard Model.

The only experimental method today to answer to this fundamental question is to search for neutrino-less double beta decay, an expected extremely rare process. Such a research requires to have a detector with the lowest background in the energy region of interest. Unfortunately the dominant background in this energy range comes from the natural radioactivity (^{238}U and ^{232}Th chains) and also gammas and neutrons interactions. So the only way is to build ultra radiopure detectors without any natural radioactive contaminations, to install them inside ultra radiopure shields against external gammas and neutrons radiations and to run them in a deep underground laboratory to reject indirect interactions from cosmic rays.

Three major techniques have been developed in Europe since the 1980s and are still under developments. The first technique uses enriched Germanium semiconductor crystals to measure ^{76}Ge double beta parent nucleus (GERDA experiment). The second technique uses cryogenic bolometers, mainly natural Telluride crystals to measure ^{130}Te isotope (CUORICINO experiment). The third technique NEMO combines a tracking detector and a calorimeter (plastic scintillators) to detect and reconstruct directly the two electrons emitted from a very thin double beta foil. An innovative European approach, COBRA, which proposes to use CdZnTe semiconductor must be also mentioned.

The overall objective of the N4 network was to co-ordinate the European double beta decay community, enhancing thus the ability of the proponents to produce proposals for the next generation experiments, beyond the current above cited experiments. The network activities were based on three working groups dedicated to the following topics: (i) Coordination of the double beta decay searches; (ii) Enrichment of pure isotopes and (iii) Nuclear matrix elements. We summarize here the main goals and results of these three working groups.

The first objective was to produce guidelines for improvements of current techniques exploring the different technical approaches and investigating the ultimate background of each technique. All these experiments indeed have to fight against the same backgrounds due to natural radioactivity contaminations. As an example, the radon level in the surrounding of the detector has to be decreased for all these experiments. Study of the material (bulk and surface) contaminations is also a common R&D task and methods to reduce but also to measure the remaining contaminations have been discussed in this Working Group. Meetings and discussions have been organized with joined meetings of JRA2 R&D activities. The final deliverable gives recommendations on the techniques for the next generation of European double beta experiments. As an example, one major result is to encourage the recent developments of scintillating bolometers measuring ^{82}Se, ^{116}Cd, ^{100}Mo and ^{48}Ca isotopes with very promising results for the backgrounds rejection.

Isotope enrichment will have a large impact on the cost of future experiments. The production of a large amount of isotopes is possible though ultra-centrifugation, laser separation (AVLIS) or Ion Cyclotron Resonance (ICR) techniques. The centrifugation technique allows enriching isotopes like ^{76}Ge, ^{130}Te, ^{82}Se, ^{100}Mo, ^{116}Cd. Facilities exist in Russia. The AVLIS process, based on the ionization of the isotope through a laser, has been used for uranium enrichment with the MENPHIS facility in France. This facility could allow enriching ^{150}Nd and producing hundreds of kilograms of ^{150}Nd. The ICR method based on the isotopic separation in a plasma through electric and magnetic fields allows enriching isotopes like ^{48}Ca or ^{150}Nd. The second objective was to study in details the feasibility of the AVLIS and ICR techniques, and to develop contacts and negotiations first with Russian institutions for centrifugation enrichment, secondly with experts in the world who already developed prototypes of AVLIS and ICR enrichment.

Theoretical uncertainties in the calculation of the double beta nuclear matrix elements (NME) are very crucial for the next generation of double beta experiments. There exist mainly three schools of calculation. All of them are in Europe: shell Model in Strasbourg and Madrid, QRPA in Tubingen and QRPA in Jyvaskyla. The third objective was to coordinate these three different theoretical approaches. Very important progresses have been achieved via this network on the convergence of the nuclear Matrix-element calculations. Special studies have been done to understand the important parameters which can notably modify the results or which can explain discrepancies between the different results. The final deliverable gives a summary of the current results of the Nuclear Matrix Elements calculated with QRPA and Shell Model. These results have been used to give a summary of the expected performances of each experimental technique.

JRA2: Integrated Double Beta Decay (IDEA)

The purpose of IDEA is to set the bases for future underground searches for $0\nu\beta\beta$ with a substantial improvement of the present discovery potential.

A next-generation sensitive DBD search needs three basic ingredients i) a large amount of candidate isotopes, ii) a detector technology tailored to the most promising candidates, iii) a deep knowledge and control of the background sources. The three work packages of IDEA, divided in 7 tasks, deal exactly with these 3 topics.

The first one, comprising one task, has allowed to achieve 4 kg of selenium enriched in ^{82}Se, a very interesting 0nbbisotope with a Q-value as high as 3 MeV. This is a very important production, useful for different approaches to 0νββsearch. In addition, deep studies have been performed to explore the feasibility of non-conventional enrichment techniques, based on plasma (ICR technology) and laser (AVLIS). The analyses performed and the documentation gathered will constitute the required basis for any future development in this field, which is essential for the realization of 1-ton-isotope experiments.

The second working package comprises two tasks. In the first one, several techniques were successfully explored to bring the selenium produced in the first work package to the required purity for 0νββ experiments. The second task was affected by a major change of program along the project development, but resulted at the end as one of the most successful. Initially, a full study on the feasibility of Nd-based bolometers was performed. Indeed, ^{150}Nd is one of the most appealing 0nbb candidates. Unfortunately, due to the magnetic properties of Nd, all the tested compounds were found to be unpractical for bolometric operation as affected by a high specific heat at low temperatures. Keeping the spirit of this task, the research was then redirected towards other high Q-value candidates, with the additional features to be included in scintillating compounds. Several scintillating bolometers were developed, containing many promising isotopes as ^{100}Mo, ^{116}Cd, ^{48}Ca and ^{82}Se, and able to tag alpha particles through the comparison of the light and heat yield. An alpha-background rejection efficiency larger than 99% was demonstrated for most of the candidates, opening the way to a virtually zero-background experiment.

The third work package, divided in four tasks, has studied several aspects of the background for 0nbb experiments, with an approach cutting the boundaries among the various 0nbbexperimental methods and opening the way to more sensitive technologies, based often on the exchange among close but different teams.

The first task has allowed to develop reliable tools to study the cosmogenic activation and to assess properly its real danger for various 0nbbcandidates. A careful validation of the codes for the activation estimate was performed through dedicated experiments at accelerators and long exposure analysis. Today, all the researchers active in the 0νββ field can count on a set of validated tools to evaluate the cosmogenic induced background.

The second task has provided a full recipe for the development of ultrapure TeO$_2$ crystals to be used in bolometric experiments. Several steps are common to other crystallization processes, therefore the work done can be useful for the preparation of crystalline 0nbbsources in general.

The third task deals with a general problem of bolometer-based rare-event searches: the background of superficial origin. Some recipes have been developed for the cleaning of copper surface, a material common to many experimental set-ups. In addition, very promising surface-sensitive bolometers were developed, that can in principle improve by 1 order of magnitude the present background of TeO$_2$-based searches, and therefore to bring the sensitivity to neutrino mass well inside the so-called inverted hierarchy region. This would improve dramatically the discover potential of the bolometric experiments. Two types of devices were developed: in one case, the surface sensitivity is achieved thanks to thin slabs applied at the main-crystal sides and acting as auxiliary bolometers; in the second case, the thermometric element is in the form of a thin NbSi film, and it can recognize surface events thanks to a fast component of the bolometric signal, induced by out-of-equilibrium phonons. This second approach represents an excellent example of integration performed by the ILIAS program, since the structure of the surface-sensitive detector for 0νββ was borrowed by germanium detectors developed in Orsay for Dark Matter searches.

The fourth task has studied the purity and the purification methods of liquid nitrogen and liquid argon, to be used as a coolant and as a shielding medium for Ge diodes for the search of 0nbḅof ^{76}Ge. This nuclide is at the center of a controversial claim of evidence of 0νββ̣ , still to be scrutinized. Even in this case, the activity performed has wide applications, since the purity of liquid argon is a key-issue for many searches in astroparticle physics: not only 0nbb, but also dark matter and proton decay.

In conclusion, IDEA was successful under two aspects: from one side, it has enabled substantial progresses in most of the technologies crucial for 0nbḅ; on the other hand, it has contributed to the formation of a really unified 0νββ European community, facilitating the exchange of ideas, people and technological solutions to common problems. It would not be surprising if the IDEA experience would work as an incubator for new sensitive approaches to the study of a process which is fundamental for the comprehension of the elementary constituents of matter and the structure of the Universe.

N5: Gravitational Wave antenna (GWA)

Gravitational waves are a prediction of the General Relativity of Einstein and are generated by stellar bodies under large acceleration. Even if an indirect demonstration of their existence permitted to J. Taylor and R. Hulse to win, in 1993, the Nobel prize, a direct detection of these waves never occurred, because of the tremendous technical difficulty to realize an apparatus capable to identify the interaction between the gravitational wave and the detector itself.

The present network focused the 5 years activity on three major subjects: commissioning of the current gravitational wave interferometric detectors, developing of common data analysis methodology and harmonization of the upgrade strategies in Europe and in the world.

The first kind of gravitational wave detectors has been the so-called resonant or acoustic detectors, based on a metallic cylinder (of about one ton of mass), cooled at cryogenic temperature, that should resonate and excite a transducer, when traversed by a gravitational wave. Currently, there are three detectors of this kind operative in the world, but they are approaching the conclusion or their life.

A new kind of detector has been designed and realized to overcome several limitations of the resonant detectors in terms of sensitivity and frequency band amplitude: the interferometric detectors. These detectors are giant interferometers (with arm length of few km) located in Europe (Virgo, http://www.virgo.infn.it/, located in Italy, close to Pisa, a French-Italian-Dutch-Polish-Hungarian collaboration; GEO600, http://geo600.aei.mpg.de/, located in Germany, close to Hannover, a British-German collaboration), in USA (LIGO, http://www.ligo.caltech.edu/) and in Japan (TAMA, http://tamago.mtk.nao.ac.jp/tama.html). They are detecting the space-time deformation, caused by a gravitational wave, shooting photons on a system of suspended large mirrors and measuring the interference between two beams traveling through two orthogonal arms.

At the beginning of the ILIAS initiative, these detectors were in the commissioning phase and the novelty of the design of these machines was causing many difficulties to the scientists and engineers involved in the experiments. The nominal sensitivity, promised by the design characteristics, was far from the effective performance of the machine. The intense commissioning activity, realised within the present network, permitted to improve the effective performances of the machines, approaching the nominal sensitivity, as reported in

Fig. 7. To image the impressive performances of these detectors, the sensitivity reached by Virgo permits to detects, at 100Hz, a fluctuation of the mirrors, located at a reciprocal distance of 3km, of about 3×10^{-19}m (260 millions smaller than an atom of hydrogen, or 30 billion smaller than a virus). The reached sensitivity of the Virgo detector could permit the detection of the gravitational signal generated by a binary system of neutron stars, at a distance of about 20 million of light years.

The identification of the gravitational wave signal, embedded in the detector output, requires a deep development of the analysis tools and a riche exchange of information and data between all the scientists involved in the experiments. For this reason a worldwide collaboration, involving the European and American detectors, has been realized within the network, to share the data, to cooperate in the analysis and in the understanding of the results. Scientists belonging to this collaboration will publish together the results of their analysis.

Because of the weakness of the searched signal and because of the limited probability that a detectable event happens within the current sight distance, an upgrade strategy has been developed by the scientists involved in all these experiments. Then has been developed a coordination, at the European level, of the upgrade strategy; currently, the largest interferometer in the world, LIGO and Virgo, are in the “enhanced” phase, consisting in small improvement of the original design, that should act as an intermediate step toward the so-called, 2nd generation or advanced detector phase, where a factor 10 in sensitivity improvement (or noise reduction) is considered. Extending the sight distance by 10 times, increases the volume of explored universe (and the detection probability) by about a factor 1000. The GEO detector, instead, because of its limited size (600m arm length), will specialize its activity toward a narrow band configuration, where the sensitivity will be improved in a small fraction of the frequency range, to detect specific signal sources. The gravitational wave detection is expected to occur with the advanced detector after about one year of operation at full sensitivity; after that, a new astronomy could be open, looking at the universe through a new kind of telescope. In fact, the evolution of the Astronomy passed through the evolution of the tools adopted to look at the sky; starting from the optical telescope of Galileo, trough the modern large telescopes, based on the detection of electro-magnetic waves (micro-waves, X-ray and γ-ray), trough the astro-particle detectors (cosmic rays and neutrinos). The conceptual design of a 3rd generation gravitational wave observatory, proposed by European scientists, coordinated by the ILIAS initiative, has been approved by the European Commission under the Frame Programme 7 and it will realize the design of a tool that could open the era of the gravitational wave astronomy.

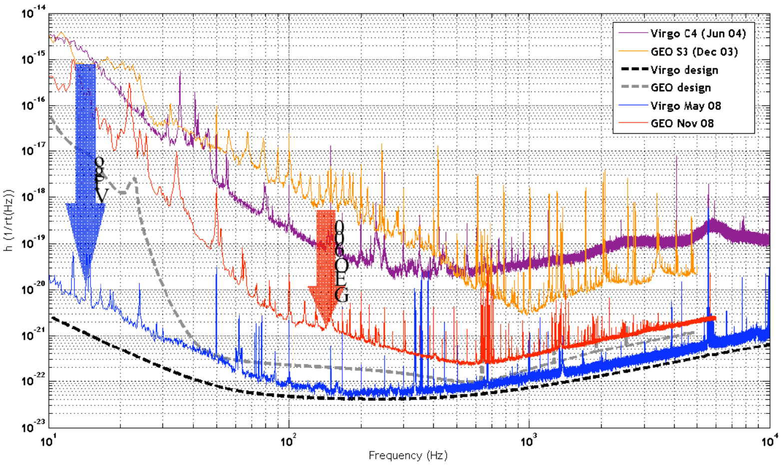

Figure 7 - Improvement of the effective sensitivities of the GEO600 and Virgo detectors, thanks to the commissioning activity, object of this network. GEO600: dashed grey curve (nominal sensitivity), red curve (Nov. '08), yellow curve (Dec. '03). Virgo: dashed black curve

(nominal), blue (May 08), purple (Jun. ’04). An improvement of sensitivity corresponds to a reduction of the noise level, reported in this plot.

JRA3: Study on Thermal Noise Reduction in Gravitational Wave Detectors (STREGA)

The joint research activity on gravitational waves (JRA3), deals with the “ Study of Thermal noise REduction in Gravitational Antennas” (nicknamed STREGA, Italian for witch). It has brought together scientists from various European laboratories (in France, Italy, United Kingdom, Netherlands and Germany) dealing with experimental topics that seem apparently very far and uncorrelated, but that all share the same common target: figthing thermal noise, one of the fundamental limiting causes for sensitivity of all detectors.

A renowned physics principle, known as Fluctuation-Dissipation Theorem states that any physical system where dissipation is present (be it a resistor, a frictional joint or a gas of molecules) is driven by a fluctuating force (or noise) with a non predictable time evolution, but with a variance proportional to the temperature of the system itself and to the dissipation coefficient. Therefore, in order to reduce the influence of thermal noise on a g.w. detector, we need to reduce its operating temperature and to reduce its dissipation coefficient F of its components. Often, when dealing with vibrating systems, instead of F, we talk of the quality factor Q of the oscillator, that is inversely proportional to F, and need then be maximised.

For this reason both resonant gravitational waves detectors (since the early ‘80s) and interferometric detectors (for the third generation, expected in the next decade), have steered toward cryogenic environments: this reduces the temperature of the detector and, in many instances, also decreases the losses.

That is why, within JRA3, we find projects aiming at evaluating the losses of material and shapes of key components of future interferometers: suspensions, mirror substrates and coatings, and losses due to photoelastic, photothermal effect, cosmic ray heating, as well as losses in prototype superconducting cavity detectors, ultra-cryogenic spherical detectors and still more.

Among the achievements of this program of activities during the five years of the ILIAS project, we want to mention:

The completion and first test of a complete 1:1 scale prototype of a cryogenic interferometer “payload”, ie the large (30 cm diameter) end mirror and the complex system of suspensions needed to isolate it from external vibrations while allowing fine positioning for optical alignment. The challenge of providing a thermal path suitable to cool the masses involved down to 5 K, while barring all mechanical paths to vibrations has been successfully met.

The material studies for the realization of a payload for a 3rd generation detector focused on the thermo-mechanical properties of several candidates. The research demonstrated that Silicon is the most interesting material both for the suspension and for the mirror substrate, thanks to its low thermal expansion coefficient and high thermal conductivity at low temperature. The possibility to realize complex mechanical components in Silicon through the Silicate bonding technique has been demonstrated. Therefore it will be possible to realize a silicon suspension through the growth of a crystalline fiber, that will be bonded to the mirror, in order to avoid dissipation at the contact point. These so called “monolithic suspensions”, will also be tested at low temperature in the cryogenic facility, located at the EGO site.

A test system was set-up in Glasgow to allow direct measurement of thermal noise in fused silica suspensions and composite structures built using hydroxy-catalysis (silicate) bonding. This set-up consisted of a quasi-monolithic measurement cavity, one of the few of its kind. Much useful experience was obtained in the construction and assembly of this test cavity. A composite mass has also been constructed by silicate bonding and this will be used to investigate excess thermal noise introduced by the bond.

Losses in optical coatings were also investigated down to low temperature, singling out a type of coating which appears to be broadly suitable for a future detector. Moreover, the structure of the mechanical dissipation as a function of temperature has revealed a dissipation peak at ~ 20 K, which may arise from thermally activated transitions of atoms or molecules between stable orientations, as postulated for other amorphous material above 10 K. Such information gives us the first handle on the possible origin of the low temperature dissipation and thus possible methods by which this may be reduced.

We carried out a deep experimental investigation of the photothermal noise induced by the fluctuations of the laser power absorbed by the mirrors and converted into surface displacements through thermal expansion. Using the dynamical effect induced by an intensity modulation of the light entering a Fabry-Perot cavity, we have investigated this effect over a wide frequency range, different spot sizes, substrate materials and temperatures. One of the main results of our work is the demonstration of the coating effects: the frequency dependence of the photothermal noise enables us to separate the contributions of the substrate and of the coating which appears at higher frequency, as well as the finite mirror size effects at low frequency. We have also investigated the competition between photothermal and radiation-pressure effects in high-finesse cavities and interferometers, theoretically showing an unstable behavior resulting from the interplay between these two nonlinear phenomena, and we have experimentally demonstrated some consequences of radiation pressure, such as the possibility to cancel back-action noise and the observation of optomechanical correlations.

In the field of resonant, or acoustic detectors, we record impressive advances by the Minigrail spherical detector, that was operated at temperatures as low as 60 mK, and that features innovative solutions both for suspensions, cooling and readout transducers. The mechanical properties of a hollow sphere were also investigated, measuring its quadrupolar normal mode frequencies and Q factors.

The acoustic wide band DUAL detector was extensively studied, with respect to both material choice, shape and readout techniques. A small scale prototype was finally produced. Finally, R&D work on an electromagnetic detector based Parametric Conversion of microwave radiation between two cavities (PACO) was brought to completion, measuring mechanical thermal noise away from its mechanical resonance.

Overall, a wide variety of experimental challenges has been faced and solved, many efforts, independently started, have merged toward common goals or solutions. The research groups have produced excellent physics, tackling and solving problems that will be crucial in the development and construction of next generation of gravitational wave detectors.

Figure 8 - The MINIGRAIL spherical resonant detector.

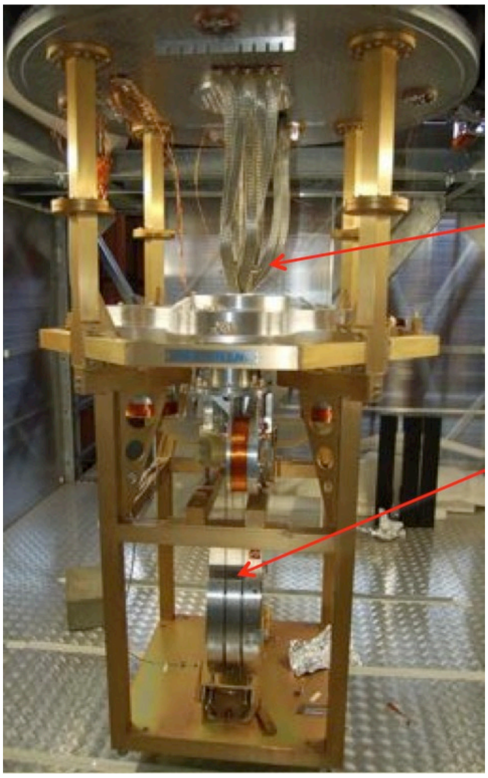

Figure 9 - The cryogenic “payload” prototype for future interferometers end mirrors

N6: Theoretical Astroparticle Physics (ENTApP)

The ENTApP (European Network of Theoretical Astroparticle Physics) activity covered the theoretical aspects of ILIAS science and thus comprised theoretical work on the neutrino-less double beta decay, on dark matter and on gravitational waves. Specialized meetings on each of these topics were held to assemble the relevant theory experts and the intersections between these different theory activities were discussed in common annual meetings.

If neutrinos are their own anti-particles, lepton number is not conserved and certain nuclei can decay by emitting two electrons and no neutrinos. The rate of such decays depends both on their (Majorana) mass and on the relevant nuclear matrix elements. A measurement or an upper limit on the neutrino-less double beta decay can thus be translated into a value of or an upper limit on the neutrino mass, provided the matrix elements are known to sufficient accuracy. While experimental activities in ILIAS focused on the experimental realizations of these neutrino-less double beta decays, considerable progress has been achived in the first working group on the calculation of these matrix elements by using different calculational techniques. Some of the not very well known parameters in these calculations such as the two-nucleon interaction constant and the axial-vector constant were determined by applying analogous calculations to other, well measured nuclear reactions such as double beta decays with emission of two neutrinos, ordinary beta decay and electron capture. The different calculation techniques now differ by less than a factor two in the matrix elements.

As a result, the decay of 150 Neodymium into 150 Samarium was identified as one of the most promising decays in terms of sensitivity to the Majorana neutrino mass. Neutrinos also play a cosmological role because massive neutrinos constitute part of the dark matter and the large scale distribution of galaxies is sensitive to the neutrino mass. Members of the network used current observations to establish an upper limit on the neutrino mass in the electron Volt range which is comparable to the sensitivity of beta decay experiments and thus provides complementary information. Furthermore, neutrinos of different flavors have been experimentally observed to oscillate into each other, with rates that depend on the neutrino masses and part of the theoretical activities on neutrinos was devoted to extract information on neutrino masses and mixing angles from these observations. Finally, neutrinos can be produced in the annihilations of dark matter and can thus be used to learn more about dark matter properties. This interdisciplinary topic links neutrino and dark matter activities and was discussed in various annual meetings of this network.

About 95% of our Universe consists of unknown ingredients, namely dark energy and dark matter. Whereas their abundance is now rather well determined by cosmological and astrophysical measurements, their nature is still largely unknown. It is likely that the dark matter consists of still unknown elementary particles, but there are many candidates covering a large range of masses and interactions strength with ordinary matter. The identification of the nature of dark matter requires a multi-pronged approach using data from different realms, including particle accelerator experiments and searches for dark matter interaction signatures in extremely low background detectors, as they are studied and developed in the experimental ILIAS activities on dark matter. Another important observational channel that could provide important information are indirect signatures in high energy cosmic radiation (gamma-rays, anti-matter and neutrinos) from the self-annihilation or decay of these dark matter particles. These indirect signatures recently received renewed interest from the detection of an excess of galactic positrons by the PAMELA satellite that could be due to dark matter annihilation.

This working group focused on working out many of the possible dark matter signatures in accelerator experiments and direct and indirect detection experiments. A particular emphasize was on a statistical analysis that translates available experimental and observational constraints into confidence regions of dark matter mass and interaction cross sections. To this end, the SuperBayeS (SUpersymmetry Parameters Extraction Routines for BAYEsian Statistics) code was developed and the impact of prior knowledge and observables from particle physics and cosmology on parameter inferences in specific dark matter scenarios was studied. It was concluded that while data is not yet sufficient to infer parameters independently of assumed priors, the dark matter primordial abundance is one of the most constraining parameters and prospects for direct dark matter detection in the near future is good in some of the main scenarios for physics beyond the Standard Model.

The main sources of gravitational waves at kHz frequencies where the European gravitational wave detectors VIRGO and GEO600 are sensitive are binary stars consisting of black holes or neutron stars, the supernova explosions that form black holes or neutron stars at the end of the life of a massive star, spinning neutron stars in X-ray binaries and young and isolated neutron stars.

The main focus of this working group was the detailed prediction of the gravitational wave signals from these sources. A major achievement was that for the first time reliable waveforms for merging black holes were produced by techniques of numerical relativity. Although gravitational waves have not yet been detected directly, this will play an important role in extracting gravitational wave signals from the detector signals which are always noise dominated and thus require precise general knowledge of the signal searched for. Core collapse supernovae are complicated physical systems which can emit gravitational waves from the collapse, subsequent oscillations and dynamical instabilities, and even from anisotropic emission of neutrinos which provided a link to the activities on the physics and astrophysics of neutrinos of WG1. Significant progress was made by the European groups involved in ILIAS in modeling these processes. Isolated neutron stars can emit gravitational waves by free precession, small mountains on the surface of these compact stars, and accretion. For the first time, data from the gravitational wave detectors have been used to derive upper limits on the deformations of isolated neutron stars. This provides valuable information on the physics of neutron stars such as the nuclear equation of state.

TA: Transnational access to the Deep Underground laboratories

The aim of the TA-DUSL activity within ILIAS was to coordinate the access of external users to the deep underground laboratories in the EU and to provide free-of-charge access to their scientific infrastructures, with full scientific, technical and technological support. The European underground laboratories (and the corresponding ILIAS contractors) involved in the TA-DUSL activity are: Gran Sasso (LNGS), managed by INFN, Modane (LNGS), managed by CEA and CNRS, Canfranc (LSC), managed by UNIZAR and Boulby (IUS), managed by USFD.

Support was offered to small- or medium-scale scientific projects, ranging from a few weeks to a few months, that required specific infrastructures or facilities available in the deep underground sites. In fact, the extremely low level of the total radiation noise makes the underground laboratories best suited to host science experiments looking for very rare events or requiring a low-radiation environment.

European research teams requesting access to an underground site were asked to submit a written proposal within periodical calls. Access to the underground sites had to be transnational, namely the majority of the research group and the team leader had to work in EU Countries other then where the requested site is located. The selection of the proposals was coordinated by one single User Selection Panel for all four installations. The main figures of merit for the evaluation of the user projects were the scientific interest and the effective need to use an underground infrastructure (namely, taking advantage from an underground site with respect to an other laboratory on the surface). During the 5 years of the ILIAS contract, nine calls for proposals have been opened (approximately, one every six months). 38 scientific projects have been successfully performed by researcher teams in the underground installations; the total access delivered to scientific users amounts to 3406 person-days, which is largely exceeding the minimum access foreseen by the ILIAS Contract (2700 person-days). The access anticipated in the ILIAS contract has been delivered in all installations. During the five years of ILIAS 117 different individuals have been supported coming from Institutions of 12 Countries (see Fig 9).

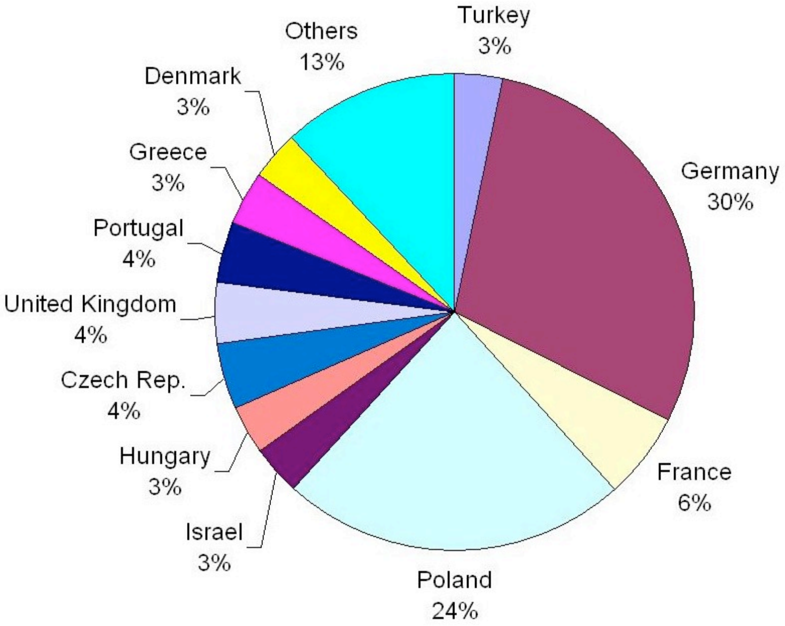

Figure 10 - Distribution of the nationality of scientists participating TA projects

Four users have participated in TA-DUSL projects involving different underground laboratories. More than 50% of the supported participants were new users of the particular underground infrastructure that they visited within TA-DUSL (this includes a number of under-graduate and Ph.D. students).

The amount of delivered access, the number of users and the number of user groups in each installation are summarized in the table below.

Organisation short name	Installation (s)		Country code of operator or "INO" for International Organisations	Unit of access	For the whole duration of the project		
	Number (s)	Short name(s)			Access provided	Number of users	Number of user groups
CEA and CNRS	1	LSM	FR	user-day	560	19	5
INFN	1	LNGS	IT	user-day	2415	85	26
UNIZAR	1	LSC	ES	user-day	134	5	2
USFD	1	IUS	GB	user-day	297	15	6

From the point of view of science, projects supported by TA-DUSL were mostly related to the traditional fields of underground laboratories (low-background techniques, background measurements, astroparticle physics, nuclear physics, particle physics). More than 20 projects were devoted to the development of new techniques and methods (hardware and software) eventually aiming to improve the sensitivity of future physics experiments, e.g. methods for purification of detectors by radioactive impurities, suppression of selected background sources, general analysis tools for next-generation experiments, methods to measure very low radioactivity levels, etc. In many cases, TA-DUSL user projects provided relevant information and/or ancillary measurements of interest for other ILIAS activities or for existing physics experiments in the underground laboratories. In eight of the projects the final result was the (re-)measurement of a characteristic background (γ-rays, neutrons or muons) of one underground site, in some cases testing newly developed techniques (e.g. spherical ^{3}He proportional counters for neutrons) or using parts of existing experiments. The same portable Germanium detector has been deployed in three of the four installations, allowing a direct comparison of γ-ray backgrounds.

Four projects were carried on by researchers involved in Earth sciences, as a demonstration that the infrastructures offered by deep underground laboratories (notably, the low-radiation environment) can be exploited also by science fields other than particle and astroparticle physics. The projects supported within TA-DUSL were related to geo-physics/seismology (survey and time variability of Rn emanation from rocks, Rn concentration in groundwater) and climatology (correlation of aerosol in the atmosphere with the level of ionising radiation). The latter has a potential impact on atmospheric physics (e.g. cloud formation, climate changes studies), and possibly public/environmental health (effect of aerosol on human beings through inhalation).

During the 5 years of the ILIAS contract, almost 60 scientific publications have been produced, based fully or partially on work carried out within TA-DUSL projects and containing and explicit acknowledgement to the EU support. A number of scientific publications related to TA projects is currently in preparation and will appear after the end of the contract.