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The ANDES Deep Underground Laboratory

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Abstract
Deep Underground Laboratories (DUL) provide a unique environment to address some key questions in basic and applied science. A penetrating radiation due to cosmic rays is present at ground level at a rate of a few hundred particles per square meter per second. Moving deep underground with more than 1000m of overburden allows a reduction of this flux by 5 to 8 orders of magnitude. Frontier experiments in search for dark matter or neutrino properties can be designed and operated in DUL thanks to this background reduction. The ANDES DUL is foreseen to be built at the same time as the Agua Negra tunnel planned between the Argentine province of San Juan and the Chilean region of Coquimbo. It is designed to be a world class deep and large laboratory, operated by an international consortium.

Keywords:
Deep Underground Laboratories (DUL), dark matter, ANDES DUL, Agua Negra tunnel

Introduction

Everywhere on Earth a background flux of ionizing secondary particles from cosmic ray interactions in the upper atmosphere is present. While the precise flux depends on the altitude and geomagnetic latitude (higher at highest altitudes and closer to the magnetic poles), it is roughly of the order of a few hundred particles per square meter per second, half of which being electrons, positrons and gammas, the other half being mostly muons (neutrons, protons and more exotic particles are found in smaller amounts). They have been of utmost importance in the first stages of the construction of particle physics as we know it nowadays, and are still one of the main topic of interest in Astroparticle Physics, with the Pierre Auger Observatory as the flagship experiment for their observation. However, for many measurements this background flux of ionizing particles is more of a hindrance, and experiments try to reduce it by using active or passive shielding. For a small reduction, using lead and polyethylene (to absorb neutrons) can be quite efficient, and with some active muon veto, background flux reductions of up to 4 orders of magnitude can be achieved (see [1] for example). However, if more reduction is needed, the only viable option is to go deep underground to use a large rock overburden as natural shielding.

Since the 1960s experiments have been installed deep underground to study neutrino physics, starting with the precursor experiments in India and South Africa in 1965 discovering atmospheric neutrinos and the Homestake experiment in the US, measuring solar neutrinos. In the late 1970s/early 1980s it was decided to go forward with permanent underground installations and the first DUL were built (Baksan in Russia, Modane in France, Gran Sasso in Italy, Kamiokande in Japan). Built under more than 1000 m of rock overburden, they provide strong reduction in the cosmic background and opened the way to detailed neutrino physics studies, and the search of dark matter, among other topics. They have been key in the advance of neutrino physics, providing site for the experiments that resulted in the last Nobel prizes in the area (2002 and 2015). Current DUL are constantly being improved and new ones have been built recently (such as CJPL in China, 2010), while other are planned for the near future (SURF in the USA, SUPL in Australia, and hopefully INO in India).

DUL are mostly of two types, either built together with a road tunnel, or in an already existing mine. Building a laboratory in a tunnel implies almost surely having to build it at the same time as the tunnel, meaning there are little windows of opportunity to build those. They however benefit from an horizontal access to the laboratory helping significantly the installation of large pieces of equipment and experiments. Some mines or otherwise already built tunnel (such as the CJPL one) also benefit from horizontal access. While they differ in many aspects (size, depth, access, radioactive environment, water presence...), there are many common issues to DUL and a global network of DUL is being worked upon to address them, with the most critical one being safety.

Finally, as of 2019 all DUL in operation are in the northern hemisphere. While it may not appear as an important laboratory parameter when studying neutrinos or other particles that can cross the Earth almost without interacting, there are reasons to look for sites in the southern hemisphere, as eventual effects of propagation through the Earth could be relevant, and some sources of background are location dependent. A worldwide well distributed network of DUL can be of specific interest to study dark matter signal modulation or MSW effects on neutrino propagation. It furthermore pushes for more international collaboration and enlarges the underground science community. It is in this context and with the construction of a new tunnel between Argentina and Chile that the ANDES project was proposed.

1. Science in Deep Underground Laboratories

DUL were initially built to access weakly interacting particle properties, driven by particle physics and basic science. Neutrino physics and dark matter search are the two main research topics in these laboratories. However, the extremely low background of DUL opened the window to many other studies, from nuclear astrophysics to biology. A complete review of these topics is out of the scope of this article, but a brief overview is given below.

1.1. Neutrino physics

Neutrino physics is a very active topic in DUL and has been extremely successful in the last 20 years, leading to the discovery of neutrino oscillations, changing significantly the view the high energy physics community had on the neutrino and solving the long lasting issue of the solar neutrino flux. The measurement of the neutrino mixing angles has been performed from solar [2], atmospheric [3], and nuclear power plant [4] neutrinos, but there are still many unknowns. First, while the mass squared difference between the different neutrino types is well determined by the oscillation measurements, the absolute scale for masses and the mass hierarchy are still unknown (see for example the review [5]). Then, it is still unclear whether neutrinos and anti-neutrinos are 2 different particles or the same, as proposed by E. Majorana in 1937 [6]. Finally, a last parameter from the oscillation parameters is missing. This phase, δ_{CP} could be violating the CP symmetry in the leptonic sector, and could lead to an explanation on why we live in a matter dominated universe. Other topics such as existence of a fourth sterile neutrino (or three right handed neutrinos [7]), effects of propagation in matter [8, 9], are also of importance for the understanding of neutrino physics. Most of these topics are searched for nowadays either by pointing a beam of man-made neutrinos to an underground laboratory hosting a huge neutrino detector (see for example [10]), or by looking for an elusive phenomenon, the neutrinoless double-beta decay [11].

Then neutrino themselves can be used as probes to understand macroscopic objects given their capability to escape most dense environments. There are still many fusion reactions in our Sun to be explored through neutrinos [12], and the role of neutrinos in supernovae explosion is still not fully understood. The observation of a supernova exploding in our galaxy would bring a whole new set of data to understand the phenomena (up to now only a distant supernova has been observed in neutrino [13]). Neutrinos are also produced in natural radioactive decays in the Earth (from uranium, thorium and potassium) and these geoneutrinos have been recently observed [14]. Better understanding of them could bring significant information in the geoscience sector, starting from the thermal balance of the Earth.

1.2. Dark matter search

The current understanding of the structure of the Universe is described by the cosmological standard model called ΛCDM, where Λ stands for the cosmological constant, explaining the observed acceleration of the universe [15, 16], and CDM referring to Cold Dark Matter. Dark matter is a form of non baryonic matter that we don't directly observe but which existence we infer from numerous observations, from rotation curves of galaxies [17], cluster formation [18], gravitational lensing [19], observation of collisions of galaxies [20], the Cosmic Microwave Background [21], and more. All these observations are compatible with our understanding of gravity if in addition to the normal observed matter, an extra component, the dark matter, is added, at a ratio of 6 to 1 (i.e. 85% of the total matter content of the Universe is in form of dark matter). It should mostly be cold, ie not relativistic, in order to explain the observations.

For many years, the best candidate for dark matter was thought to be the WIMP, Weakly Interactive Massive Particle, as in order to get the correct amount of dark matter via thermal production in the early universe a 100 GeV particle with a cross-section at the electroweak level is needed, and supersymmetric models naturally propose such a candidate. This coincidence is widely referred as the "WIMP miracle" [22]. After decades of search, the absence of signal in large detectors optimized for WIMP detection (noble gas double phase TPC such as Xenon [23]) and at the LHC [24] motivated alternative explanations for dark matter. Recently, lighter dark matter particles from a dark sector are becoming a well motivated target for direct searches [25], for which the LHC is already producing relevant limits [24].

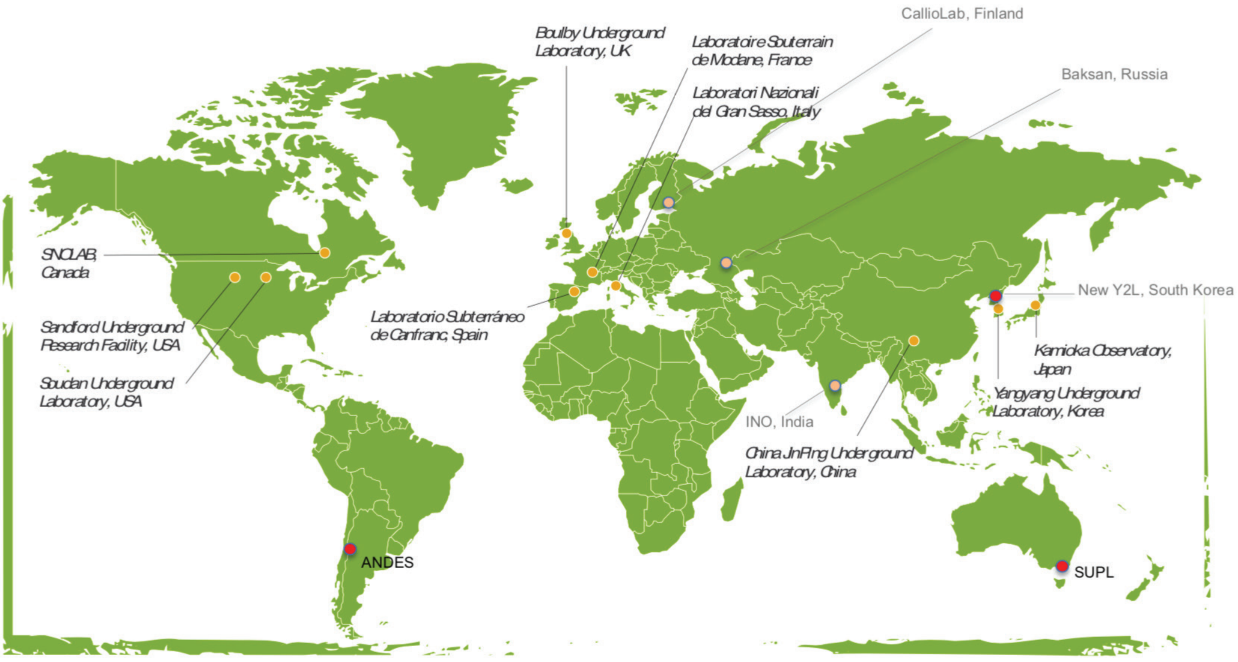
While a lot of efforts in dark matter searches are done outside of DUL (searches for axions [26], production at LHC, indirect astrophysical searches for annihilation signals [27]), the most promising research is done in DUL. For dark matter candidates above 10 GeV, double phase noble gas TPC are leading the effort using Xenon [23] or Argon [28]. At lower mass, a lot of different detection techniques and target materials are used, from cryogenic crystals [29], silicon sensors [30, 31], and liquid or gaseous detectors [32]. In most of these detectors a characteristic interaction signal is searched on as low a background as possible (ideally zero-background detectors once all the rejection techniques are applied). While most detectors have reported no signal and set limits in the mass-cross section plane of parameters, one experiment has reported a modulation in their detector counting compatible with the observation of a WIMP wind due to the movement of the Sun within the Galaxy, modulated by the movement of the Earth around the Sun [33]. Most interpretations of this signal are in contradiction with other experimental limits, and new experiments are trying to confirm or reject this observed modulation [34]. One of the arguments against this modulation being caused by dark matter are potential seasonal atmospheric effects. This is an example of measurement where a complementary detector in the southern hemisphere could give a final statement (if the effect is atmospheric, as the seasons are inverted in the southern hemisphere the phase of the modulation should change by 6 months, while if it is a genuine extra-solar signal then the phase wouldn't change). Finally, one can try to distinguish dark matter from potential noise (including neutrino coherent interactions when looking for extremely low cross sections [35]) by trying to measure the direction of propagation of dark matter particles [36].

1.3. Multidisciplinary studies

The very low cosmic background of DUL is essential for neutrino physics and dark matter searches, but can also be used for many other measurements and experiments. Extremely low levels of radioactive decays can be measured in DUL, measurements that would be impossible at the surface as they would be dominated by noise from cosmic ray interactions. This research area is quickly growing and has still a lot of potential as many possible users are not aware of the existence of DUL with unique environmental capabilities, and DUL directors and staff can't imagine all the areas which could benefit from it and contact the relevant researchers.

As examples of a wide range of different studies, one can mention the impact of cosmic radiation on cells, where it has been determined that a minimum of exposition to radiation seems necessary to train cells into repairing damage [37], evolution of fish populations over long periods of time [38], environmental studies [39], impact of cosmic rays on microchips [40] or even wine evaluation against fraud [41]. Specific experiments can be also instrumented to measure nuclear processes at energies relevant for astrophysics [42], and have led to some reestimation of the age of globular clusters [43].

2. The Agua Negra Deep Experiment Site



Aldo Ianni, TAUP 2017

Figure 1. Map of existing (yellow dots) and planned (red dots) DUL over the world [44].

Figure 1 shows the existing and planned DUL. As already stressed all the existing DUL are in the northern hemisphere. Two DUL are in planning for the southern hemisphere, the Stawell Underground Physics Laboratory (SUPL) in Australia, planned 1 km deep in the Stawell Goldmine, a small size laboratory aimed at hosting the Sodium Iodide with Active Background Rejection Experiment (SABRE) [45], and the Agua Negra Deep Experiment Site (ANDES), planned as a world class laboratory at the border between Argentina and Chile to be constructed along a new tunnel in the Andes, the Agua Negra tunnel.

2.1. The Agua Negra tunnel

The world economic evolution with the growing importance of the Asian market makes it crucial for Argentina and Brazil to access the pacific. The current main pass through the Andes is the Cristo Redentor tunnel, and is becoming insufficient for the growing commercial exchange. It furthermore suffers from closure during strong snowfalls in winter time. Many options have been looked forward to improve the situation, and the most advanced one as of 2019 is the Agua Negra tunnel.

The Agua Negra tunnel is planned where the current Agua Negra international crossing is located, 300 km north of the Cristo Redentor tunnel, connecting the San Juan Argentine province to the Coquimbo province in Chile. It is planned as a high altitude tunnel, at roughly 4000 m of altitude, but in a dry region where snowfalls are no major issue. It will consist of two 14 km long, 12 m diameter road tunnels, the southern one allowing to drive from Chile to Argentina, while the northern one will go from Argentina to Chile. Feasibility studies were started in 2005, and the presidents of Argentina and Chile signed a Bi-National Integration treaty, which included the San Juan - Coquimbo tunnel option, in October 2009. This treaty was then approved by both countries parliaments. In August 2010, a MERCOSUR meeting in San Juan marked the launch of the final part of the planning of the tunnel, with strong support from the Argentine, Chilean, and Brazilian presidents. The EBITAN (bi-national entity in charge of the political and technical aspects of the Agua Negra tunnel) was formed and approved by the congress of both countries. In 2012 a first international tender process was started, where companies were supposed to bid for the construction and provide a financing scheme. 3 years later, the Inter-American Develop Bank (IDB) approved the financing of the project and the tunnel entered a new phase. A fifth of the estimated 1.5 B$ cost of the tunnel has already been put forward by the IDB and the last phase of the tender process is expected to end in 2021. Construction would last 8 years, likely 2022-2029.

2.2. ANDES design and layout

The ANDES design and layout was developed starting in 2011 around the central idea of having a main hall about the height and width of a Gran Sasso hall, but only half its length, as this is the typical size needed for next generation large experiments searching for dark matter. A large pit able to host a next generation neutrino detector was also planned since the beginning. Then a few extra halls were thought to host technical services and other experiments.

In 2014 the design was assessed by a former director of SNOLAB and the resulting documents were submitted to the Lombardi company, in charge of the design of the Agua Negra tunnel. In 2015 a conceptual design was requested to the company [46]. The resulting design was discussed in an international workshop in 2017 and then presented to the EBITAN that approved its inclusion in the tunnel civil work plan. In 2018 the basic engineering design was requested to Lombardi (for a cost of about 0.5 M$, financed by the San Juan province), and was finalized in June 2019 [47]. With these documents (and the technical tender documents to include ANDES in the tunnel civil work, not yet finalized), it is expected to have ANDES at the same level of design as the tunnel by the end of 2020, ready for the construction to start in 2021. The construction of ANDES would start once the tunnel is excavated to the planned location of the laboratory, after 4 years of civil work. The laboratory itself would take 6 years of construction to completion. The total cost of the underground civil work for the laboratory is expected to be around 73 M$ [47].

The final design can be observed in figure 2, and its main features are described below.

2.2.1. Location and access

The laboratory is foreseen to be located at the km 4.5 of the tunnel (from the Chilean side), at the same level as the main ventilation hall where a specific ventilation tunnel coming from Chile ends. This location has been chosen in order to optimize the integration to the tunnel and the ventilation processes. A study of the muon background expected in areas between this location and another location at the frontier between both countries shows the muon flux is minimum in this area and changes by less than 10% in between these 2 locations. While the baseline design is to locate the laboratory at km 4.5, the final location may change if the geology is not adequate for the construction.

The laboratory will be accessed directly from the southernmost road tunnel, going from Chile to Argentina. In order to access it from Argentina one will have to go to Chile by the northernmost tunnel and then come back to the laboratory. It should be noted that the whole area will be bi-national so no migration duties will be necessary as long as one goes back to the corresponding country. Safety doors will allow entering the laboratory space, where a large parking space will be available, giving access to technical halls (for ventilation, cooling, water waste, technical services) and the main office hall. A safety exit allowing to access the second tunnel in case of a fire in the Chile-Argentina tunnel is also located in this access zone.

The laboratory section will not be accessible by vehicles except large tucks needing to discharge containers. In that case they will be able to maneuver and move backwards to the main access tunnel for the laboratory, where various cranes will unload the containers. An internal escape gallery allows a safety exit in case of fire in the laboratory.

2.2.2. Main, secondary hall and large pit

The main, secondary halls and the large pit are the three main areas foreseen for large experiments, in particular for direct dark matter search and neutrino physics.

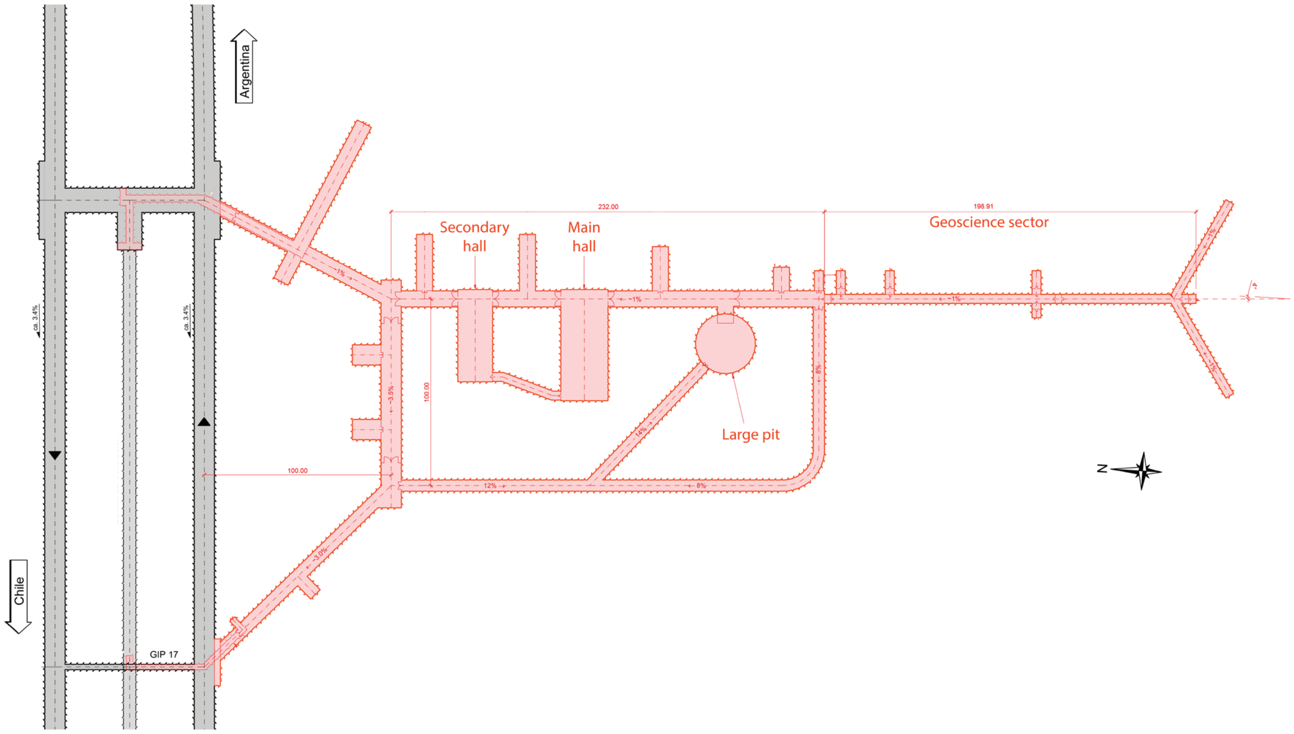


Figure 2. Final design for the ANDES deep underground laboratory, adapted from the basic engineering phase [47]. See text for details.

The main and secondary halls mainly differ in their dimensions. The main hall is 50 m × 21 m × 22 m while the secondary is 40 m × 16 m × 14 m. They both are overlooked by a 40 t crane that follows the cavern shape to optimize the available height. To reach optimally the full height in the main cave, the central part is below the access tunnel level by one meter. This is a design similar to the main hall of Canfranc (in a larger size). This also helps containing eventual material leak from experiments.

The secondary hall is mainly foreseen for modular structures that can host specific long term laboratories or short term experiments subject to regular changes. The main hall on the other hand is foreseen for two or three major long term experiments, especially for direct dark matter search or neutrinoless double beta decay.

The Large pit is the single large cavern of the laboratory. Its useful volume is 30 m of diameter and 30 m of altitude. It is foreseen for a single large experiment, in particular a large neutrino experiment [48]. The size was fixed in order to host a 3 kt scintillator neutrino experiment (10 times the size of Borexino [12]). The main access is from the top with a rotating crane allowing to access any place within the pit. A secondary access from the bottom is available for the installation of the experiment. The bottom access door can be sealed and the full pit is designed to be waterproof allowing it to be filled with purified water shielding without mixing with the water from the rock.

2.2.3. Geoscience sector

The geoscience sector was added to the ANDES design in 2017, and is based on the experience of the Black Forest Observatory [49]. It is located at the end of the main laboratory access tunnel and consists of a long tunnel with 2 final tunnels in a Y shape, designed for the installation of a tiltmeter. Different halls are foreseen for the installation of specific instruments, such as superconductive gravimeters, strainmeters, long period and short period seismometers.

The overburden is not of the highest importance for the geoscience sector. On the other hand, the stability of the sensors environment is of the utmost importance for a precise measurement, and this can be achieved with a significant overburden, as long as the geoscience sector is air tight. This implies the use of air-locks, with the whole geoscience sector being sealed except during the installation of new equipment or reparation phases.

In addition to the sealed sector, a specific geomaterial laboratory will be installed in the secondary hall, allowing on one hand a continuous analysis of the gasses and fluids at the rock face, and on the other hand studies of geomaterials from other sources. It will be strongly integrated to the low radiation measurement laboratory.

2.2.4. Multidisciplinary halls

Multiple extra halls will host a variety of experiments. While it is probably ambitious to plan for all the uses an underground laboratory can have for the next 100 years, at start the distribution of the halls is foreseen based on current activity in other underground laboratories. In particular, the first room, isolated from the other rooms, is foreseen to possibly host a particle accelerator to do nuclear astrophysics similar to the LUNA experiment in Gran Sasso [42]. As it can produce noise to other experiments it is oriented in a way that points away from other caverns.

The second supplementary hall is foreseen for the clean laboratories. Two clean rooms will be installed, one accessible only from the other one through an air shower. The first one will act as a clean room available for activities in the underground laboratory, while the second one will host the low radiation laboratory, featuring high purity germanium detectors for very low radioactive material measurements.

The last specific area will be a biology dedicated laboratory, with different sectors for plants, cells, multipurpose experiments, and a specifically designed area for work on animals, to ensure no contamination to other areas of the laboratory.

2.3. ANDES operation and organization

Since its start ANDES was foreseen not only as a laboratory that would host international experiments, but as an international laboratory. It is currently coordinated by the ANDES Unit within the CLAF (Latinamerican Center for Physics, a type II UNESCO institute recognized by most latinamerican countries), with representatives of Argentina, Brazil, Chile and Mexico. Advanced contacts aim at widening the unit to include more partners, not necessarily from Latin America. In the short term Colombia, France and Germany could be added to the coordination, while other countries such as Italy could act as observers of the structure.

In the longer term a more structured organization is being designed, based on similar international science oriented institutions such as the CERN [50] and SESAME [51]. In particular the SESAME model (itself based on CERN) is being pursued given the similar expected organizational size of ANDES and SESAME. ANDES would therefore be run by a council formed by *member* and *observer* states, in charge of taking the scientific decisions needed to guarantee the excellence of the laboratory and funding the basic operation of the laboratory.

In addition to the underground laboratory and its operational organization, two support centers are foreseen, one in Argentina and one in Chile. Given the geography and relatively high altitude of the planned tunnel, cities are at some distance. The Chilean support laboratory is foreseen in La Serena, a large connected city with well developed local scientific infrastructure. It is however at 200 km from the tunnel. A closer center is therefore foreseen in Argentina and aimed at being more operational, running daily activities at the underground site. Each support center will be associated with national authorities (local universities, local research centers) and a strong focus will be put in order to host a visitor center in each country, as these will allow a direct contact between the population and a world class research center, something uncommon in the region.

Finally a strong effort will be done in order to link the local universities in Argentina and Chile to the laboratory, through the organization of undergraduate and graduate courses. A strong link to existing underground laboratories and foreign educational structures will be pursued, in particular with the Canfranc laboratory in Spain and the Gran Sasso Science Institute [52].

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Xavier Bertou has a PhD in Astrophysics from the University of Paris VI. He has been a member of the Pierre Auger Collaboration for 25 years and is the impulsor and coordinator of the ANDES initiative through the ANDES-CLAF unit. He works in astroparticle physics (mostly neutrino physics and dark matter search lately) at the Particle and Radiation Detection Laboratory at the Bariloche Atomic Center in Argentina.