Experimental facilities in Latin America

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Abstract
These lecture notes briefly describe the current and planned experimental facilities for high-energy physics research in Latin America. The list is not exhaustive nor the descriptions are complete, but I tried to select some of the most representative facilities and large international experiments at the time. Given that particle physics today is tightly related to cosmology and astrophysics, and South America is where most of the major astronomical observatories in the world are located, I start by listing some of the representative observatories. Then we move on to the main accelerator facilities, which are few and mainly for applications, but the core of particle physics research infrastructure in Latin America is in astroparticle physics, which is where I take most of the time to describe. The name and location of each infrastructure are listed, the scientific goals and some introductory description of the detecting techniques. Specific details are not included, which can be found in the literature.

Keywords
Latin America; experimental facilities; accelerators; detectors; telescopes; cosmology; particle physics; dark matter; dark energy.

1 Introduction: a short historical view of experiments in particle physics

One can historically classify the experiments in particle physics in three types according to a mixed criterion of size, technique: (a) those built on a table top, (b) those that detect cosmic rays, which were originally done at high altitude either on top of mountains or aboard of flying balloons, and (c) those that accelerate subatomic particles to make them collide at high energies. This order is also a progression in time, for the simple reason of the increasing level of difficulty: cosmic ray experiments require detectors, but accelerator experiments require, obviously, to build accelerators in addition to detectors, and this task has been a major technological achievement on its own. Now, the observation of cosmic rays is an interesting subject on its own, and so it has continued developing in parallel to experiments with accelerators and colliders. Moreover, due to the ever increasing size and cost of accelerator facilities, there has been an increasing interest in cosmic ray observation facilities in the last decades, a fact that is particularly noticeable in Latin America.

The discovery of the electron by J.J. Thomson in 1897 can be considered as the beginning of subatomic physics, and the gold foil experiment of H. Geiger and E. Mardsen, led by E. Rutherford (former disciple of J.J. Thomson) on the discovery of the atomic nucleus, as the beginning of experimental particle physics. Indeed, the experiment of bombarding a thin gold foil with alpha particles has the essence of all subsequent particle physics experiments: to observe what comes out of collisions of subatomic particles. These experiments and several others at that time are part of the class of experiments done on a table top. Within this class is also the discovery of the neutron by James Chadwick in 1932, himself a disciple of Rutherford.

Concerning experiments done by observing cosmic rays, one must add that the transition from the table top on a laboratory is not sharp: some cosmic ray (CR) experiments can be done on top of a table as well! The main point here is to stress the origin of the particles that are detected: they do not come from a piece of material or an apparatus in a laboratory, but from outer space. The discovery of cosmic rays is attributed to Victor Hess who, in a remarkable experiment in 1912, showed that there was a radiation that increased with altitude, by climbing with instruments in a free balloon flight up to 5 300 m. He even ruled out the Sun as the source of the radiation by flying during a solar eclipse, noticing that the measurement did not change during the eclipse itself.

A series of experiments with cosmic rays followed, where several of the subatomic particles we know today were discovered, in particular the positron, the muon, the pions and kaons. Without disregarding the value of all these experiments, we want to mention specifically the work of C. Powell, G. Occhialini and C. Lattes in 1947, where they were able to resolve a pending issue at that time. About twelve years earlier, Hideki Yukawa had predicted a "meson", a particle that would mediate the force between protons and neutrons, with a mass around one or two hundred MeV. Such a particle would be expected to interact strongly and be absorbed by nuclei. A particle with such a mass was found but in some experiments it was shown not to be absorbed by nuclei. The work of Powell, Occhialini and Lattes, using photographic emulsions in experiments on top of Pic du Midi in the Pyrenees, and then on mount Chacaltaya, Bolivia, at an altitude of 5 240 m, was able to show that there were actually two particles with mass in the range predicted by Yukawa: a strongly interacting one that fitted Yukawa's prediction, and a slightly lighter and weakly interacting particle that did not. These are the pion and the muon, respectively. We single out this experiment for two reasons: first because it was done in Latin America, and second because one of the key experimentalists was the then young Brazilian physicist Cesare Lattes. The leader of the team, Cecil Powell, received the Nobel Prize for this work in 1950, Giuseppe Occhialini was honored in recent years with the naming of the BeppoSAX Satellite for X-ray Astronomy ("Beppo" was Occhialini's nickname), and Cesare Lattes's name is being honored with a proposed ground array observatory of cosmic gamma rays that is mentioned further in this lecture.

Our third class of experiments is comprised by those that use particle accelerators. The accelerated particles are most commonly electrons or protons and their antiparticles, but there are also accelerators for heavier ions. The advantage of using particle accelerators instead of cosmic rays is that the collisions are more controlled: we know precisely what particles collide, with what energies, where they collide and how often they collide. In these controlled conditions, the detectors can be placed right around the interaction point and can be much more specialized in their detecting capabilities. Several types of accelerators have been invented since the 1920's, which go from electrostatic accelerators such as the Van de Graaff and the Cockcroft-Walton generators to the most modern and large scale accelerators with varying fields: the linear accelerators (linacs) and synchrotrons. Moreover, two types of collisions can be devised: a single beam of accelerated particles hitting a fixed piece of material (fixed target collisions) or two beams colliding against each other. The latter can reach much higher centre-of-momentum (CM) energies. The largest linear accelerator in existence is the 3 km long Stanford Linear Accelerator in the USA, and the largest synchrotron was LEP, an electron positron collider with almost 27 km circumference at CERN, which was dismantled in order to install in the same tunnel the currently operating Large Hadron Collider, a proton (and heavy ion) collider, to date the highest energy accelerator, achieving 6.5 TeV per proton, and thus 13 TeV of CM energy in the collisions. It is in high energy particle accelerators where most of the known subatomic particles and antiparticles have been discovered, including the elementary tau lepton, muon-neutrino, tau-neutrino, the top quark and finally the Higgs boson.

With the success of particle accelerators, cosmic ray experiments became less prominent for many decades. However, with the cost and complexity of building ever larger accelerators, there has been again a growing attention to experiments with cosmic rays. Moreover, with a continuous improvement in detector, telescope and satellite technology, major breakthroughs in astrophysics and cosmology have been achieved in the last decades, which have turned again our attention to the heavens. Examples of this are the discovery of gamma ray bursts (GRB) in far away galaxies, which are the most powerful electromagnetic events known in the Cosmos (in a few seconds a GRB releases the energy that our Sun will release in its entire 10-billion year lifetime), the measurement of the cosmic microwave background (CMB) spectrum by a succession of experiments starting with the COBE satellite in 1992, and the discovery of the accelerated expansion of the Universe.

Here we will present some of the current and planned experimental facilities in Latin America, within the context of particle physics. Our list tries to be representative, but not exhaustive. We will start by briefly mentioning the few existing or planned accelerator facilities in Latin America, although they are mainly oriented to applications than to basic research in particle physics. As we will see, most of the Particle research facilities in Latin America are astroparticle observatories. Moreover, since most of the optical and radio astronomical observatories in the world today (and increasingly so in the near future) are in South America, We will include a short description of some of the most representative astronomical observatories operating, or planned for the near future. Then we will move on to describe the main astroparticle physics facilities and experiments in Latin America starting from those that are operating today and continuing with those that are planned, concluding with the initiative where I am most involved, which is the proposal of an international underground laboratory inside a road tunnel under the Andes mountains between Chile and Argentina. This laboratory will be one of the deepest in the world, the first in South America and, unless another initiative catches up quickly, the first of its kind in the Southern Hemisphere.

2 Accelerator facilities in Latin America

Here we will mention two existing facilities, which are Tandem accelerators for ions, and one facility under planning or construction, which is a major Synchrotron Radiation source.

2.1 The USP Pelletron

The USP Pelletron is a tandem accelerator existing at the University of São Paulo (USP) since 1972 [1]. The general layout of the facility is shown in Fig. 1(top).

A tandem accelerator is an electrostatic accelerator for ions, derived from simpler types such as Van de Graaf accelerators. In a tandem accelerator there are two stages of acceleration, aligned one after the other. A high positive voltage (let us call it, without much imagination, V) is located in the mid point along the acceleration trajectory. Negative ions (with charge -1 in units of the fundamental charge e) are produced externally in an ion source, where their mass is selected. These ions are injected into the accelerator and are attracted by the positive terminal at the midpoint, where they reach a kinetic energy eV. There, the ions cross a thin sheet of material (e.g. carbon), where some or all the electrons of the ion are removed by the collisions, resulting in positive ions with charge Ne (N being the number of electrons removed—the ions' atomic number Z or less). In the second stage, these positive ions are repelled by the central positive terminal, being again accelerated to the end of the machine, gaining an additional kinetic energy NeV. In total the ions emerge from the accelerator with a kinetic energy $(N + 1)$eV.

The name "pelletron" has to do with the method for the charge transport to the positive terminal, which is basically a current of electrically charged metal pellets bound to each other by plastic insulator material.

The USP pelletron has a 8 Megavolt positive terminal, so ions can reach several tens of MeV of energy. The ions are used for different research and application purposes, such as nuclear physics, crystal structure and properties, material analysis, the development of high energy instrumentation, among many other applications.

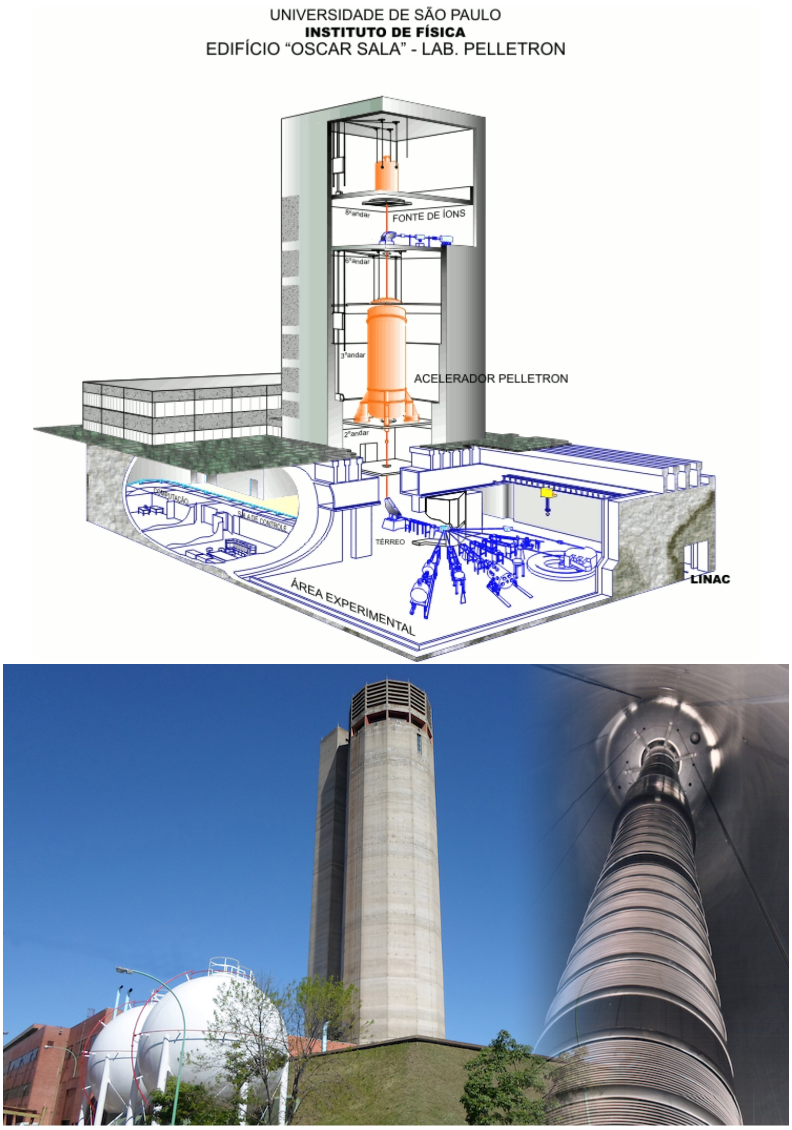

Fig. 1: Top: Drawing of the USP Pelletron (credit: Physics Department, University of São Paulo, Brazil). Bottom: TANDAR at Centro Atómico Constituyentes, Buenos Aires, Argentina. Bottom left: view of the acceleration tower and the SF_6 tanks. Bottom right: insert view of the accelerating column.

2.2 TANDAR

TANDAR is another tandem accelerator, operating since 1985, located at the *Centro Atomico Constituyentes*, Buenos Aires, Argentina, a national scientific laboratory that belongs to CNEA (the Argentinian National Atomic Energy Commission) [2]. The accelerator, similar to the USP pelletron, is a 34.84 m long vertical column inside 73 m tall tower, with a central terminal at 20 MV, as shown in Fig.1(bottom). The high voltage terminal is also charged using the pelletron technique. The ion beam runs inside a vacuum tube at 10^{-8} mbar, inside a cylindrical tank with SF_6 (sulphur hexafluoride) at 10 atm to provide dielectric insulation and avoid discharges.

TANDAR is used for advanced education in science and nuclear technology in the country, basic research in nuclear physics and condensed matter physics, applications to material science, biology, environmental studies and many other applications.

2.3 LNLS

LNLS (Brazilian Synchrotron Light Laboratory) is a centre that hosts two synchrotron light sources: UVX, operating since 1997 [3], and SIRIUS, a new and much larger synchrotron radiation apparatus currently under construction and planned to start operations in 2020 [4], both shown in Fig. 2.

UVX, a second generation synchrotron radiation source, is a 1.37 GeV electron storage ring of 29.7 m average circumference that provides synchrotron radiation. The injection system comprises a 120 MeV linac and a 500 MeV booster synchrotron. The storage ring provides 17 synchrotron radiation beamlines (experimental stations), where experiments in microscopic analysis techniques using infrared, ultraviolet and X-ray radiation are performed. Most of the beams are in the X-ray range (1 to 30 keV), two beams in the soft X-ray range (100 to 1 500 eV), one in the UV range (3 to 330 eV) and one in the IR range (70 to 300 mm^{-1}).

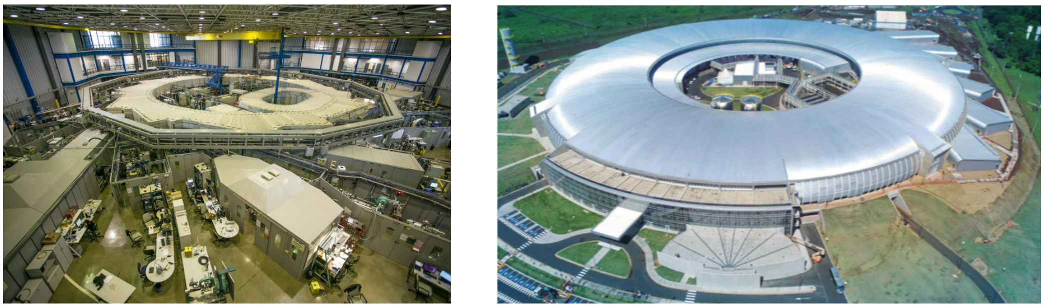

Fig. 2: Synchrotron light source facilities at LNLS, Campinas, Brazil; left: UVX; right: SIRIUS. Credit: LNLS.

SIRIUS is one of the few 4th generation synchrotron radiation sources in the world. Still under construction, it is planned to start operations in 2020. It is an 3 GeV electron synchrotron, 165 m in diameter. It is a sizable improvement over UVX, not only with twice the energy in the electron beam, but also with an emittance (electron beam divergence) about 360 times smaller, resulting in a much brighter radiation beam. Due to the higher energy and brightness it will allow the study of dense materials at depths up to a few centimetres. Also due to the extremely focused radiation beam, it will be a great improvement over experiments in nano- and biotechnology.

3 A brief account on astronomy in Latin America

While astronomy is a different field than high-energy physics with facilities that are different in many respects, we have two reasons to include here a brief description of the astronomical observatories in Latin America.

First, as the two fields advance they have more and more points in common, not only in technology but also in research interests. It is clear that the observation of the Cosmos today implies not only detection of light, be it IR, visible, UV or even X-ray, but also very high energy gamma rays, cosmic rays and neutrinos; even the unraveling of the mystery of dark matter is a subject of interest to both fields.

Second, a large proportion of the main astronomical observatories of the world are located in Latin America. In particular, due to the optimal conditions for astronomical observation provided by the desert skies in northern Chile, more than 70% of the light-catching surface of telescopes in the world will be in the Chilean deserts in the near future.

We cannot do justice here to the whole history or set of astronomical observatories in Latin America, so we will limit ourselves to describe just a few representative current facilities and some of those planned or in construction to start operating in the near future.

3.1 VLT — the Very Large Telescope

VLT is operated by ESO (European Southern Observatory), and is located in Cerro Paranal, northern Chile, at 2 635 m.a.s.l., coordinates 24°37'38"S, 70°24'15"W. It is about 100 km south of the city of Antofagasta [5]. It is a set of four large 8.2 m diameter telescopes (called Antu, Kueyen, Melipal and Yepun—words in Mapuche language for astronomical objects), and four movable auxiliary telescopes 1.8 m diameter. See Fig. 3 for a photograph showing the general layout,with a schematic overlay illustrating the interferometry light path.

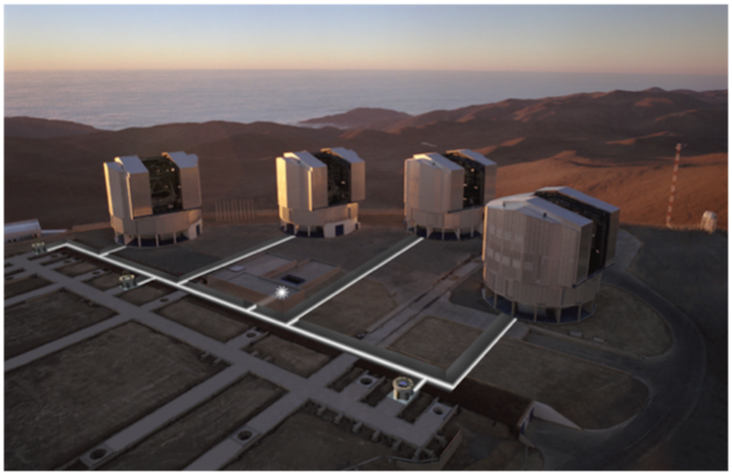

Fig. 3: The Very Large Telescope (VLT), showing the four large telescopes. Three of the four (much smaller) auxiliary telescopes are superimposed on the picture. White lines show the paths of the light beams for interferometry. The asterisk shows the site of the interferometric lab, part underground. Credit: ESO.

VLT is the most modern and the most productive ground-based optical telescope facility in the world today. It operates at visible and IR light. Each telescope can operate independently reaching an angular resolution of 0.05 arc-sec, or all four combined reaching 0.02 arc-sec. It uses interferometry and adaptive optics to overcome diffraction effects in the atmosphere. VLT has been the first telescope to get an image of an exoplanet, has tracked stars around the supermassive black hole (SMBH) at the centre of our galaxy, and has seen the afterglow of the furthest known gamma ray burst (GRB) to date.

3.2 ALMA — Atacama Large Millimeter Array

ALMA is the world's largest observatory in the millimetre wavelength (range 9.6 mm to 0.3 mm). It is located on the Chajnantor plateau, in the Atacama desert in Chile, at an altitude of 5 059 m.a.s.l. [6] The very dry desert site at high altitude is necessary to avoid the high absorption of the microwave by water in the atmosphere. Its coordinates are 23°01'09"S, 67°45'12"W.

ALMA is an interferometric array of 66 movable radio telescopes or *antennas*. The main array (Fig. 4, left) has 50 antennas of 12 m diameter arranged in specific layouts at distances from 150 m up to 16 km, simulating a giant telescope. While each antenna gives an angular resolution of about 20 arcseconds, the giant array working with interferometry as a single device gives an angular resolution higher than the Hubble Space Telescope. Four additional 12 m antennas and twelve 7 m antennas form the Atacama Compact Array (ACA). The different antenna configurations allow the study of both the general structure of astronomic sources as well as its minute details. The 100 ton antennas can be moved by a special transporter that places them on concrete pads with millimetre precision (see Fig. 4, right).

ALMA, the most expensive ground-based observatory to date, is a partnership of ESO (Europe), NSF (USA) and NINS (Japan), in collaboration with the Republic of Chile, and funded by ESO, NSF,

Fig. 4: The Atacama Large Millimeter Array. Left: view of the array. Right: telescope being transported. Credit: ALMA.

NRC (Canada), NSC (Taiwan) and KASI (South Korea). ALMA can study star-forming regions seeing through interstellar dust, chemical compounds of the stellar medium, disks and structures around stars, distant galaxies, dynamics of black holes, and many other astronomical phenomena not accessible to any other observatory.

3.3 DSA 3— Deep Space Antenna 3

The Deep Space Antenna 3 (Malargüe Station) shown in Fig. 5 (left), is part of the European Space Tracking Network (ESTRACK) for the European Space Agency (ESA). It is a 35 m diameter radio antenna, located 40 km south of Malargüe, Argentina, at an altitude of 1 550 m.a.s.l. Its coordinates are 35°46’34”S, 69°23’54”W.

DSA3 is a 35 m diameter parabolic radio antenna, working in the range of 8 GHz to 32 GHz. It has has two sister stations for very long baseline interference, one in Spain and the other in Australia. DSA3 provides support for communication and tracking with several deep space probes and other scientific probes such as XMM-Newton Rosetta, Herschel, Solar Orbiter, Gaia, Mars Express and Planck. It is also used in radio astronomy to study gamma ray sources, radio galaxies, AGNs, nebula chemistry, and other astronomical radio sources.

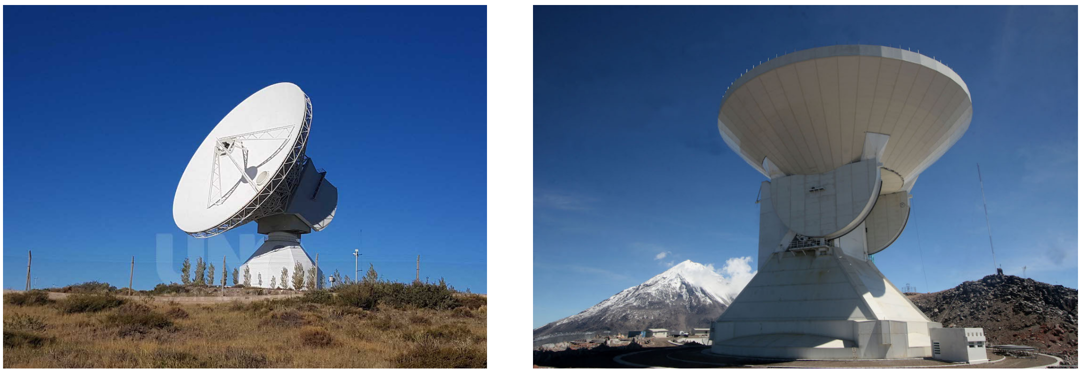

Fig. 5: Left: DSA3 in Malargüe, Argentina. Right: LMT Alfonso Serrano, Sierra Negra mountain, Mexico.

3.4 LMT — Large Millimeter Telescope

Its full name in Spanish is Gran Telescopio Milimétrico Alfonso Serrano [7] (see Fig. 5, right). It is the world’s largest single-aperture telescope in its frequency range, built for observing millimetre wavelengths from 0.85 to 4 mm. It is located at 4 600 m.a.s.l. on top of the Sierra Negra mountain near Puebla, Mexico. The location is 18°59'06"N, 97°18'53"W.

LMT is a bent Cassegrain optical system with a 50 m-diameter reflecting primary surface (M1) formed by 180 segments, distributed in five concentric rings, a 2.6 m diameter reflecting secondary surface (M2), and a reflecting tertiary surface (M3) almost flat, elliptical with a 1.6m major axis.

Millimetre wavelength allows observation through the interstellar dust and of relatively cold objects that emit mainly at millimetre wavelengths. Among the objects of interest are: comets, planets, protoplanetary discs, evolved stars, star-forming regions and galaxies, molecular clouds, active galactic nuclei (AGNs), high-redshift galaxies, clusters of galaxies and the cosmic microwave background.

LMT is also part of the Event Horizon array of telescopes around the globe, dedicated to obtain images of black holes. ALMA is also part of the Event Horizon.

3.5 DES — Dark Energy Survey

The Dark Energy Survey (DES) [8] is an international collaboration dedicated to map several hundreds of millions of galaxies and the patterns of the cosmos, in order to reveal the character of the so called dark energy that seems cause the accelerated expansion of the Universe. It aims at measuring with high precision the history of cosmic expansion. The survey mapped 5 000 sq. degrees of the southern skies, through five optical filters to obtain additional spectral information of each galaxy. It also focused on smaller patches of the sky to look for thousands of supernovae and transient sources.

The DES Collaboration built a highly sensitive 570 megapixel digital camera, called DECam, that was installed on the Victor Blanco 4 metre telescope at Cerro Tololo Inter-American Observatory (CTIO) [9], 84 km southeast of the city of La Serena, Chile. It is located on top of cerro Tololo, a hill at 2 200 m.a.s.l., with coordinates 30°10'11"S, 70°48'23"W, as shown in Fig. 6 (left).

DES took data for over six years, from 2013 to 2019.

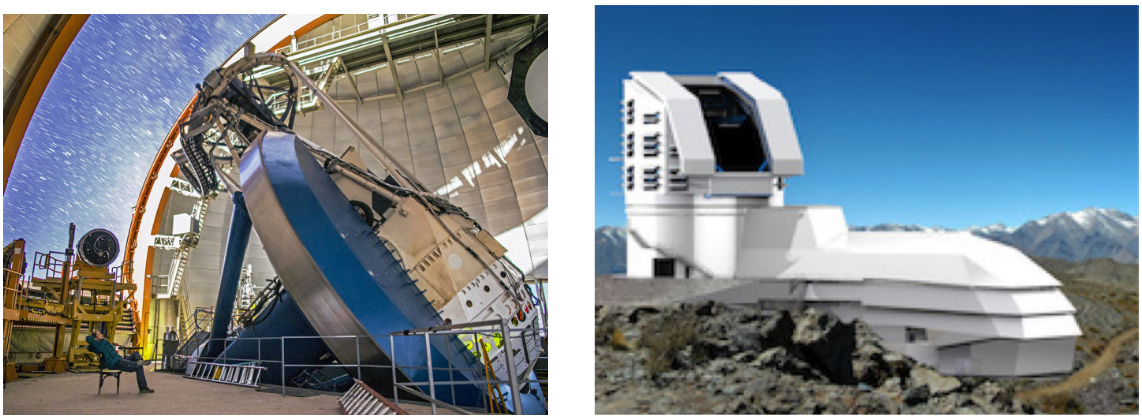

Fig. 6: Left: Dark Energy Survey: Victor Blanco telescope at Cerro Tololo, with the camera DEScam installed (credit: DES). Right: Artist rendition of the LSST telescope and building for operations and maintenance at Cerro Pachón, Chile (credit: LSST).

3.6 LSST — Large Synoptic Survey Telescope

The Large Synoptic Survey Telescope [10], Fig. 6 (right), is currently under construction at Cerro Pachón, at an altitude of 2 662 m.a.s.l. and 20 km away from Cerro Tololo and part of the CTIO Observatory [9]. The site is at 30°14'40.7"S, 70°44'58"W.

LSST has a wide field 8.4 metre telescope formed by a three-mirror and three-lens optical assembly. A single exposure has a field of view of 3.5 degrees, which is about 40 times the solid angle of the moon. Its camera of 3.2 gigapixels, is the largest digital camera ever built, 3 m $\times$ 1.65 m, weighing 2.8 ton. LSST also includes a data management system, processing and storing 20 terabytes of data per night, whose ultimate deliverable is the fully reduced data.

Aiming at transient phenomena in the cosmos, LSST will map the entire visible sky with extremely high resolution every 3 nights, storing 45 terabytes of data, building the deepest and widest image of the Universe. This survey will be done over a period of 10 years.

LSST is designed to study primarily four science issues: explore the transient sky in the optical range, understand the nature of dark matter and dark energy, study the formation of the Milky Way, and study the remote solar system, including survey of possible dangerous asteroids.

3.7 LLAMA — Large Latin American Millimeter Array

LLAMA [11] is a joint proposal of Argentina and Brazil to install a 12 m single radio telescope, similar to those of ALMA, in Alto Chorrillos, northern Argentina, coordinates 24°11’31”S, 66°28’29”W, at an altitude of 4 820 m.a.s.l.

LLAMA will detect in the 35 to 1 000 GHz frequency band, with an angular resolution of 8 arcsec at 900 GHz to 3 arcmin at 35 GHz. The telescope is also planned to be one of the first in a series of antennas of a very long baseline interferometry (VLBI) network in Latin America. In this sense, working with ALMA will increase 10 times the angular resolution of the latter, to about 1 millisecond of arc.

LLAMA aims at studying the solar atmosphere, exo planetary systems, molecules and other features of the intergalactic medium, and the distortion of space around black holes.

3.8 GMT — Giant Magellan Telescope

The Giant Magellan Telescope [12] is a planned optical telescope composed of seven 8.4 m mirrors that form a 24.5 m diameter array, with a total of 368 m^2 of light-catching surface. GMT is planned to see first light in 2029, and is rendered in Fig. 7 (left).

GMT will be located at Las Campanas Observatory [13], coordinates 29°0’52.6”S, 70°41’33.4”W, at an altitude of 2 550 m.a.s.l. GMT will use adaptive optics, reaching a resolving power 10 times higher than the Hubble Space Telescope. Operating in the visible to near IR spectrum (320 nm to 25 000 nm), it will study extra-solar planets, search for their chemical composition and possible evidence of life, galaxy formation and evolution, evidence of dark matter and dark energy, and the evolution of the Universe.

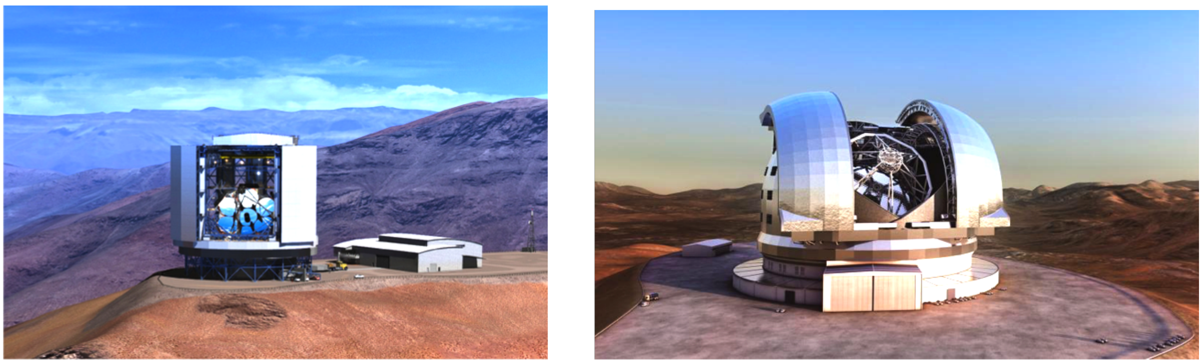

Fig. 7: Renderings of the future giant telescopes in northern Chile. Left: the Giant Magellan Telescope, GMT at Las Campanas Observatory. Right: the european Extremely Large Telescope, ELT, at Cerro Armazones.

3.9 ELT — Extremely Large Telescope

The Extremely Large Telescope (ELT) [14] of the European Southern Observatory (ESO) is under construction at Cerro Armazones, in the northern desert of Chile, 140 km south of the city of Antofagasta, and close to Cerro Paranal where VLT is located. The site is at an altitude of 3 046 m.a.s.l., with coordinates 24°35'36"S, 70°11'50"W. A rendering of this future telescope is shown in Fig. 7 (right).

ELT is a reflecting telescope with a 39.3 m segmented primary mirror and a 4.2 m secondary mirror. It will have adaptive optics with 8 laser guide star units to correct for atmospheric distorsion. It will have the largest light gathering area ever built, 256 times the Hubble Space Telescope and should provide images 16 times sharper than the Hubble. It is expected to see first light in 2025. ELT will provide detailed studies of extra solar planets, detect water and organic molecules in extra solar protoplanetary disks, see the first galaxies of the Universe, study their formation and evolution, study supermassive black holes, study the nature of dark matter and dark energy and the evolution of the Universe.

4 Current astroparticle physics facilities in Latin America

After this brief description of some of the Astronomy facilities in the continent, we now describe some of the main astroparticle physics facilities operating Latin America: the cosmic ray observatories Pierre Auger and LAGO, and HAWC, the high energy gamma ray observatory. Our descriptions will be general, focusing on the infrastructure and science goals. More details on cosmic ray or gamma ray physics can be found in the literature [15].

4.1 The Pierre Auger Observatory

The Pierre Auger Observatory [16] is currently the largest cosmic ray detector array in the Southern Hemisphere and the world, aiming at the detection of the highest energy cosmic rays. It combines water Cherenkov detectors and fluorescence telescopes, and grew from previous ground arrays in the north, such as CASA-MIA [17] and HiRes [18].

Auger is located near the town of Malargüe, Argentina, approximate coordinates 35°28'00"S, 69°18'41"W, at altitudes 1 330 to 1 620 m.a.s.l., covering an area of about 3 000 km^2 with a surface array of 1 600 water Cherenkov detector (WCD) separated by about 1.5 km from one another, and 27 fluorescence telescopes concentrated in four sites. An overview is shown in Fig. 8.

Each water Cherenkov detector (Fig. 9, left) is a plastic tank with 12 m^3 of ultra pure water inside a Tyvek light diffusing bag, with three 9 inch photomultiplier tubes (PMTs) on the upper part of the tank looking down. Each tank is a self-supported unit with solar panel and batteries, with GPS time, 40 MHz analog to digital converter and radio communication with the control centre. The PMTs detect the Cherenkov light emitted in the water when a relativistic charged particle (muons or electrons) from the secondary cosmic shower enters the tank.

Each fluorescence telescope (Fig. 9, right) is a 14 m^2 parabolic mirror with a camera at its focal plane formed by 440 PMTs. Each set of fluorescence telescopes cover a field of view (FoV) of 30°x180°. The telescopes catch the fluorescence light emitted by the nitrogen gas in the atmosphere which is excited by the pass of the secondary shower of particles created by a incoming cosmic ray. However this light is very dim (about 1 visible photon per metre per electron or positron in the shower), so that the fluorescence telescopes have a low duty cycle of about 10% only (they operate only during moonless nights).

Some words on cosmic rays

Cosmic rays are actually relativistic charged and massive particles, mainly protons and heavier nuclei, that fly around the galaxy and the whole Universe, that constantly hit the atmosphere. For energies below

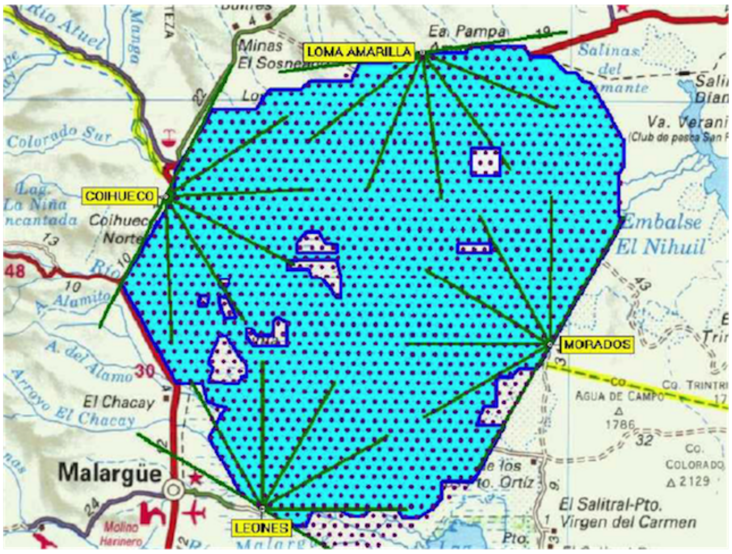

Fig. 8: Map of Auger, showing the extension of the surface array and the fluorescence telescope sites.

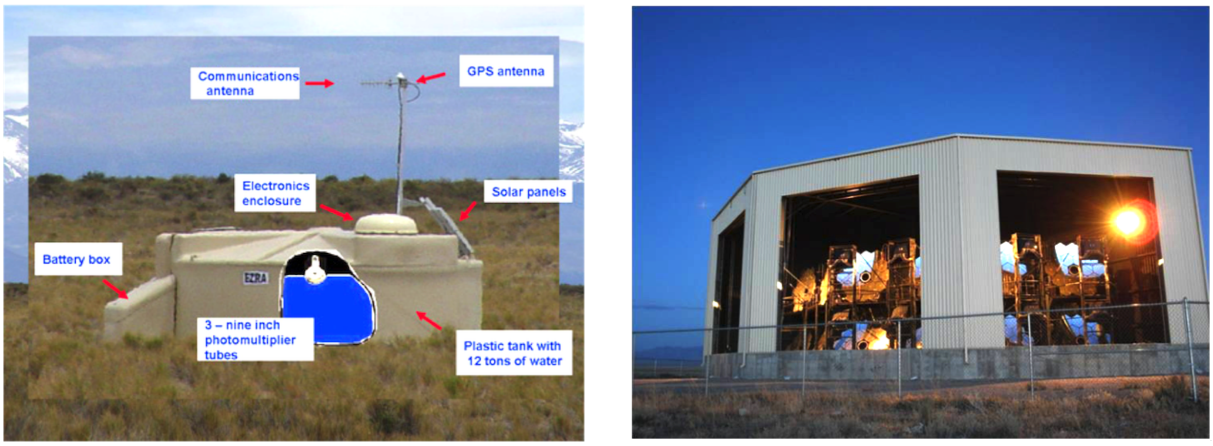

Fig. 9: Left: Auger water Cherenkov detector. Right: Auger fluorescence telescope site.

10 GeV they are mostly of solar origin, and are easily deflected by the solar magnetic field. They have the highest flux, but they are absorbed in the upper atmosphere, so they can only be detected by satellites or in high altitude balloons. For higher energies the flux decreases sharply (about a factor $1/1\,000$ per decade of energy). For energies above 100 TeV, the flux is so low that it is difficult to detect them with the small area of detectors in balloons or satellites. However, when they enter the atmosphere they produce *extensive air showers* (EAS) of secondary particles. These secondary particles are more hadrons, mainly pions. Charged pions then decay in muons, electrons and neutrinos, while neutral pions decay quickly into photons. Electrons, positrons and photons keep splitting by bremsstrahlung and pair production until the energy per particle goes below some threshold (near 80 MeV): this is the *electromagnetic* component of the shower. The muons on the other hand, are the remains of the hadronic component of the shower. This extensive shower can even reach the surface of the earth. The higher the energy of the primary particle, the larger the multiplicity of secondary particles, the lower in the atmosphere the shower reaches before it stars getting absorbed, and the wider the spread of the shower at ground level. The point along the shower where it reaches maximal multiplicity is usually called (without much creativity) X_{MAX}. The multiplicity, spread and X_{MAX} are the important quantities to measure in order to estimate the energy and composition of the primary ray.

One last issue we should mention on cosmic rays is the so called GZK cutoff [19] of the spectrum at ultra high energies. UHECR cannot be trapped by the galactic magnetic field, so they must be of extragalactic origin. However, for energies above 10^{20} eV, Greisen Zatsepin and Kuzmin conjectured that cosmic rays would degrade their energy by producing pions due to collisions with the photons of the cosmic microwave background at the Δ resonance, and consequently cosmic rays of higher energies cannot originate from sources beyond 150 megaparsecs. Since there are not many possible sources in such a small neighbourhood (!), the spectrum should show a cutoff at those energies.

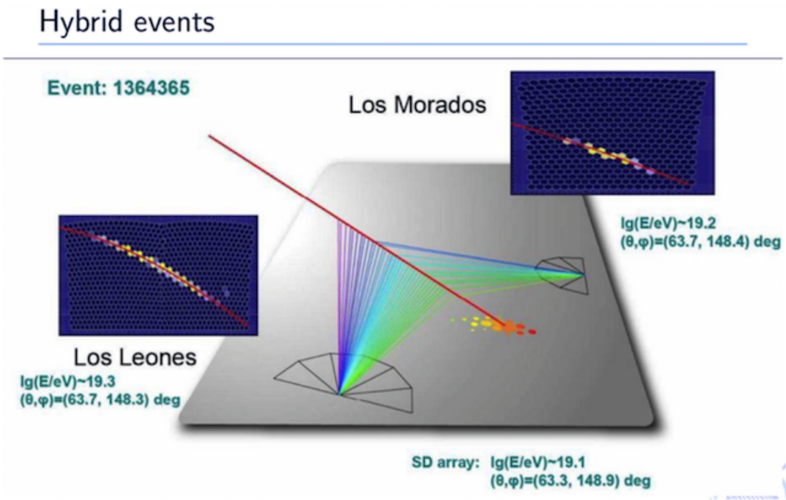

Fig. 10: A hybrid event detected by Auger: two telescope sites reconstruct the shower path in the atmosphere and the WCD's detect the hit on the ground. The timing on different WCD's also reconstruct the incoming direction of the CR. (credit: X. Bertou).

After that digression on cosmic rays, let us go back to Auger. Auger aims at the highest energies (the ultra high energy cosmic rays or UHECR), above 10^{18} eV, where the flux is very low (the flux of the highest UHECR are about 1 CR per km^2 per century). That is why the WCD tanks cover such a large area of 3 000 km^2. On the other hand, the shower spread on the ground of the UHECR is large, so the WCD can be quite far apart (near 1.5 km). For this same reason, Auger is insensitive to $E_{CR} \ll 10^{18}$ eV. With this in mind, we can understand the design of Auger: the WCD tanks will detect the spread and shape of the shower on the ground, while the fluorescence telescopes can get a picture of the development of the shower as it goes down the atmosphere, and have a better estimate of X_{MAX}. In events with surface water tanks hits only, or fluorescence detectors only, it is possible to obtain an estimate of the energy and composition of the primary, but having hybrid events with signals at the water tanks as well as more than one fluorescence telescope, the resolution is much improved. An example of such a hybrid event is shown in Fig. 10.

Auger has obtained many novel scientific results, such as: UHECR are nuclei (H to Fe), no gammas, no neutrinos; at the highest energies, they seem to be composed more of heavier elements; there may not be a GZK cutoff; there seem to be no excess of UHECR from the galactic centre.

An upgrade of Auger is planned, where scintillator plates will be placed on top of each WCD and a muon detector underground for better separation of electromagnetic vs. muon components.

4.2 LAGO — Latin American Giant Observatory

LAGO, the Latin American Giant Observatory [20] (formerly called Large Aperture Gamma ray Observatory) is a set of surface WCDs distributed all along the continent, in order to have an ultra long baseline array of cosmic ray detectors. The tanks are located one per site, each one at different altitude along the continent (from sea level to about 5 000 m.a.s.l.). The sites so far are Mexico, Guatemala, Venezuela, Colombia, Brazil, Ecuador, Bolivia, Perú, Argentina and recently Chile.

The design of the water Cherenkov tanks aims at being simple, inexpensive and reliable. Commercial tanks with a detection area from 1.5 m^2 to 10 m^2 are preferable, with an inner coating of Tyvek for light diffusion, and they must be filled with purified water. The PMT and the electronic design are available for new sites to join in.

The LAGO network is designed to measure the temporal evolution of cosmic radiation at ground level. Its basic research focuses on three areas: high energy phenomena, space weather and atmospheric radiation at ground level. As such, it studies the high energy component of GRB at the very high altitude sites. It also monitors cosmic radiation at the continental scale, observing the effect of solar activity on cosmic rays. These science goals are complemented by two academic goals, which are to train students in astroparticle and high-energy physics techniques and to support the development of astroparticle physics in Latin America [21].

4.3 HAWC — High Altitude Water Cherenkov

HAWC, the High Altitude Water Cherenkov gamma ray observatory [22] is an *air shower array*, that is, an array of water tanks at high altitude, designed to detect the shower of secondary particles created in the atmosphere, in this case of interest for high-energy gamma rays. HAWC is located on the side of Sierra Negra mountain, near Puebla, Mexico (nor far from the Alfonso Serrano Telescope, see Section 3.4), at high altitude (4 100 m.a.s.l.). Its coordinates are 18°59'41"N, 97°18'28"W.

HAWC aims at the detection of *very high energy* (VHE) gamma rays (GR), from 1 TeV to 100 TeV. These are the highest GR expected to exist.

The array is composed of 300 steel tanks filled with ultrapure water, each tank 7.3 m in diameter and 4.5 m tall, with four PMT's at the bottom of each tank looking up. Unlike the Auger water tanks where the PMT's detect from the top of the tank the diffuse Cherenkov light, here they detect the direct Cherenkov light from the bottom. The array covers a ground surface of about 20 000 m^2, see Fig. 11.

Fig. 11: Views of the HAWC array of water tanks. Left: ground view (J. Goodman, 2016). Right: satellite view; at the centre is the Counting House with the electronics and computing; on the right is the HAWC Utility Building with the water filtration plant (Google Earth, 2016).

HAWC is a design improved over MILAGRO [23] (a humorous name for a serious scientific experiment), a previous detector of GR showers at Los Alamos, New Mexico, USA. MILAGRO was a 80 m × 60 m, 8 m deep pond at an altitude of 2 530 m.a.s.l. HAWC's higher altitude and water tank isolation makes it 15 times more sensitive to VHEGR than MILAGRO. Nevertheless, MILAGRO proved to be a successful experiment by detecting the first TeV GR from the galactic plane, obtaining a map of diffuse galactic TeV GR, discovering a TeV GR emission from Cygnus, as well as TeV GR from the Crab Nebula and AGN's.

Some words on VHE gamma rays

VHE gamma rays, which are photons with energies above 10 GeV up to 100 TeV, produce extensive air showers in the atmosphere as cosmic rays do, but only (or mainly) electromagnetic (electrons, positrons and photons), while cosmic ray showers also have the hadronic component that produces many muons. The electromagnetic showers tend to be more regularly spread around the shower axis, while CR showers, with their hadronic components, are more irregularly scattered and tend to have several lumps away from the axis. Also GR showers do not reach so deep down in the atmosphere, so ground arrays have to be set at quite high altitudes. Another important distinction is that the flux of VHE cosmic rays is about 10^3 times more intense than that of gamma rays, so a ground array aimed at observing GR must have a good technique to separate them from the large background of cosmic rays.

HAWC discriminates the GR from the CR background by the pattern of the shower on the ground. The collaboration developed a very clear and user friendly website, which includes a game to illustrate this method [24]. The CR rejection is better the higher the energy of the shower, because the GR and CR patterns become more and more distinct (see Fig. 12, left). Figure 12 (right) show the sensitivity of HAWC compared to other GR detectors, including MILAGRO. It is clear that HAWC performs better at the highest energies. This is due in part to its large area, high altitude and the large duty cycle and large field of view (FoV) of a surface array in comparison to air Cherenkov telescopes (see next sections); however the latter have a better energy and angular resolution.

HAWC is able to study VHE gammas up to 100 TeV from galactic sources (point sources), detect unfrequent events such as extreme galactic accelerators thanks to its large duty cycle and FoV, study extended TeV sources (most sources are extended), diffuse emission from the galactic plane (form interactions of CR with gas and dust), extragalactic CR sources such as AGN's. It can also do multimessenger and multiwavelength searches in collaboration with other observatories (can do early detection of most transient sources due to its large duty cycle and FoV to warn other observatories with better resolution).

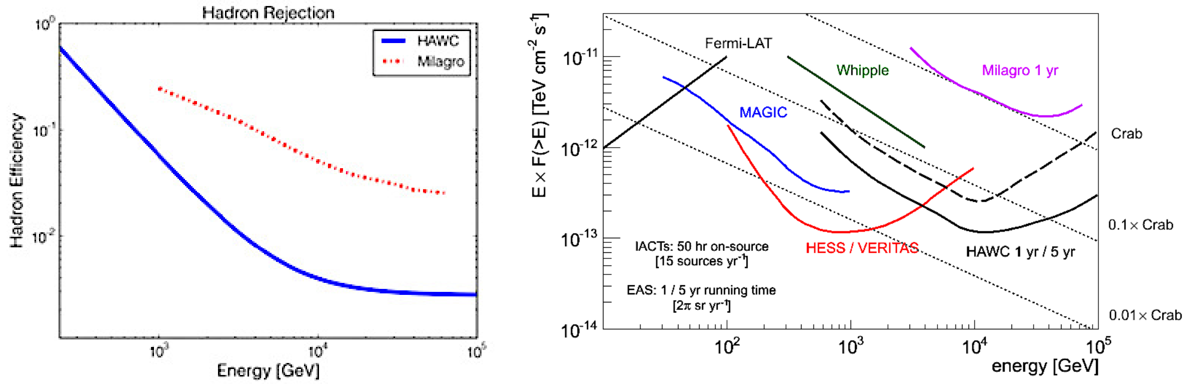

Fig. 12: Left: Cosmic ray rejection power of HAWC and MILAGRO. Right: HAWC sensitivity, compared to other observatories based on air Cherenkov telescopes, and the Fermi satellite.

5 Future astroparticle physics facilities in Latin America

Finally, we move on to the future of the astroparticle research infrastructure in Latin America. From this growing field of research we will describe the CTA gamma ray observatory, the cosmic ray detector ALPACA, the proposed LATTES gamma ray detector, SWGO (previously called SGSO) which is an upgrade of HAWC in the south, and ANDES, the proposed first deep underground laboratory in the Southern Hemisphere.

5.1 CTA — Cherenkov Telescope Array

CTA, the Cherenkov Telescope Array [25] will be by far the largest VHE gamma ray observatory ever built. It will have one North site in La Palma island (Islas Canarias, Spain, altitude about 2 200 m.a.s.l. and coordinates 28°45'42"N, 17°53'30"W) and one South site near Cerro Paranal, in the Atacama Desert, Chile, close to the VLT optical observatory. The south site is at an altitude of 2 100 m.a.s.l. and at the coordinates 24°41'0.34"S, 70°18'58.84"W.

CTA consists of two large arrays of imaging air Cherenkov telescopes (IACT), a design and technique evolved from previous experiences with the smaller arrays MAGIC (La Palma), HESS (Namibia) and VERITAS (Arizona, USA). An IACT is essentially a spherical or parabolic mirror with a camera on its focal plane, that detects the Cherenkov light (mainly visible and UV) emitted by the relativistic charged particles of a shower as they travel through the atmosphere at speeds greater than light in the medium.

VHE gamma ray showers are produced at high altitudes, of the order of 10^4 m.a.s.l. For example a 1 TeV gamma-ray produces a shower that reaches maximum multiplicity at ~ 8 km.a.s.l. (see Fig. 19 below in Section 5.3), in a cone opening of $\sim 1°$. At 2 000 m.a.s.l. the light pool (ground illuminated area) reaches a radius of $\sim$ 120 m, with a photon density $\sim$ 150 photon/m^2. For lower energy gamma rays the light pool is of the same size, but much thinner (e.g. $\sim$ 10 photon/m^2 for a 100 GeV GR). However, while GR of lower energy produce a dimmer signal, they arrive more frequently.

As a consequence of these GR features, in order to observe lower energy GR's one needs larger size telescopes (more light-catching are for dimmer signals), but there is no need to cover large ground areas (large GR flux—many GR's per unit area per unit time). On the other hand, to detect higher energy GR's the telescopes can be smaller (intense signals) but one needs many of them to cover a lot of ground (low GR flux).

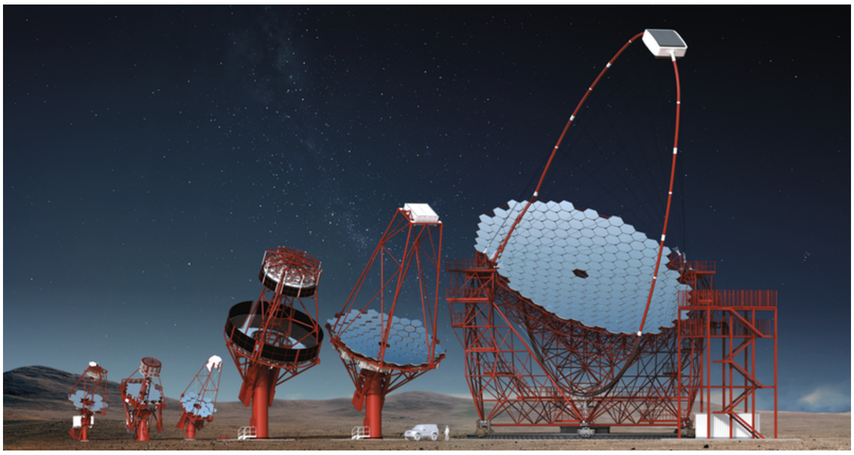

Fig. 13: CTA telescopes: three different SST prototype designs, the two MST prototype designs and the LST design (credit: G. Pérez Díaz).

Each IACT has a field of view of a few degrees only. Therefore, to see the shower it has to be looking more or less in the right direction and the shower must be pointing more or less towards the telescope to be inside the light pool. The camera then registers a very short and dim signal that lasts about 10 nanoseconds. Because of that, IACT's are only operated on moonless nights, and therefore they have a duty cycle of less than about 18% or 1,500 h/year (without considering the time loss due to bad weather).

CTA will have IACT of three different sizes (see Fig. 13): small size telescopes (SST) 4 m diameter to cover the high energy range 1 TeV to 300 TeV, medium size (MST) 12 m diameter to cover the core energy range 150 GeV to 5 TeV, and large size (LST) 23 m diameter to cover the lower energy range 20 to 150 GeV, although they are sensitive up to TeV.

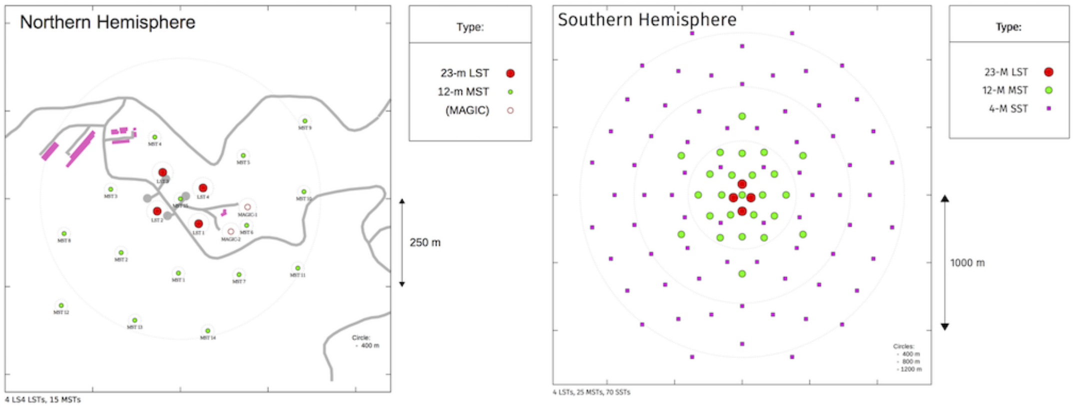

Fig. 14: CTA layouts in the North Site (left) and South Site (right).

Figure 14 shows the array layouts on both sites. The North Site in La Palma will be a smaller array, with 4 LST and 15 MST, covering 20 GeV to 20 TeV. The South Site in Chile will have the larger array, as one of the main goals is the galactic centre, which is visible only from the south. The array will consist in 4 LST, 25 MST and 70 SST.

The CTA Observatory headquarters is in Bologna, Italy, while the Science Data Management Centre in Berlin-Zeuthen, Germany.

CTA is expected to cover higher energies and improve on the sensitivity by an order of magnitude with respect to all previous IACT observatories. Figure 15 shows the differential flux sensitivity for CTA and several other observatories. Notice that at the high end of 100 TeV, HAWC gives a comparable sensitivity but for a much longer observation time. Nevertheles, one must take into account that CTA has a much lower duty cycle, 18% or less.

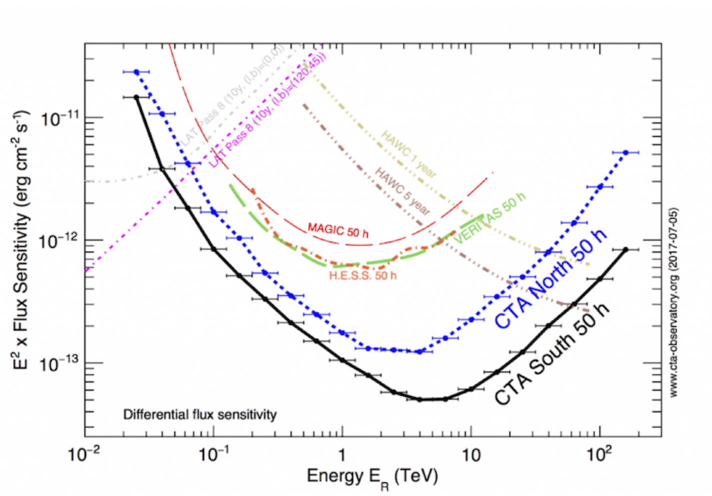

Fig. 15: Differential flux as a function of reconstructed GR energy for CTA and other observatories.

The science goals of CTA can be classified in three major groups, that cover astroparticle physics, cosmology and fundamental physics: a) the origin and role of relativistic cosmic particles (where are high energy particles accelerated, what are the CR acceleration mechanisms, what is the role of CR on star formation and galaxy evolution); b) the exploration of extreme environments (what processes occur near neutron stars and black holes, what are the features of relativistic jets, winds and explosions, how are radiation and magnetic fields in cosmic voids); and c) the exploration of frontiers in physics (what is dark matter, are there quantum gravity effects on photon propagation, are there axion-like particles).

5.2 ALPACA — Andes Large area Particle detector for Cosmic ray physics and Astronomy

ALPACA [26], a collaboration between Japan and Bolivia, is a proposal to build an air shower array at very high altitude (4 740 m.a.s.l.) on the Estuquería plateau near mount Chacaltaya, Bolivia (this site is close to the historical Cosmic Ray Observatory at Mt. Chacaltaya, mentioned in the Introduction). The approximate site coordinates of ALPACA are 16°23'S, 68°08'W.

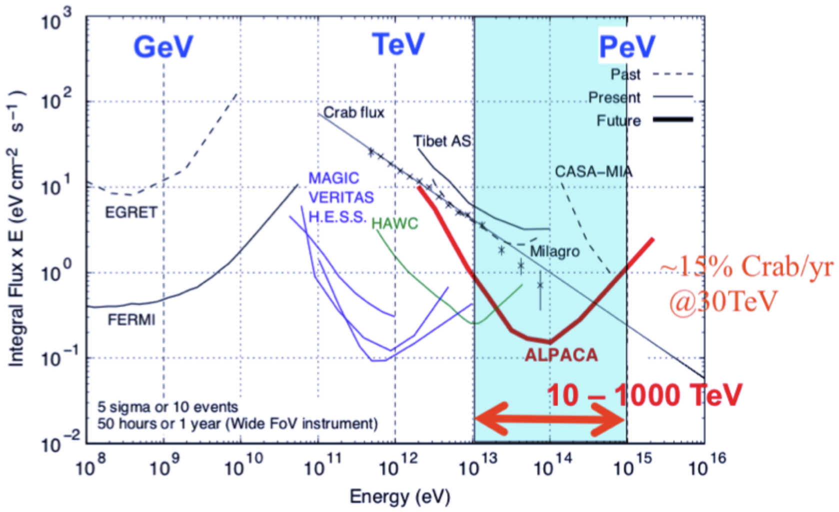

Fig. 16: The ALPACA sensitivity to gamma ray point sources.

ALPACA aims at the detection of ultra high energy cosmic rays, or UHECR ($> 10^{18}$ eV) and very high-energy gamma rays, or VHEGR from 10 to 1 000 TeV (indicated in Fig. 16). Figure 17 displays the layout of the ALPACA array, which consists of 401 plastic scintillator detectors 1 m^2 each, covering a ground surface of 82 000 m^2, together with 96 water Cherenkov detector (WCD) tanks underground, 56 m^2 each, in some specific points under the surface array, covering a total area of 5 400 m^2. The underground WCD's serve to detect the muons in the shower, thus providing a discrimination between cosmic and gamma rays.

The scientific goals of ALPACA can be summarized as the study of: the 10 to 1 000 TeV gamma ray sources; galactic and nearby extragalactic sources of UHECR; the CR composition around the "knee" of the spectrum ($\sim 10^{15}$ eV) in order to understand the CR acceleration mechanisms; the solar coronal magnetic field by detecting the Sun's shadow to CR; the flux form young SNR's (supernova remnants); the cosmic ray anisotropy for energies above TeV in the southern sky; very extended GR sources.

5.3 LATTES — Large Array Telescope for Tracking Energy Sources

LATTES, with a clever acronym that honors the famous Brazilian physicist Cesare Lattes, is a proposed surface detector array at very high altitude for gamma ray showers, dedicated to fill the gap in sensitivity

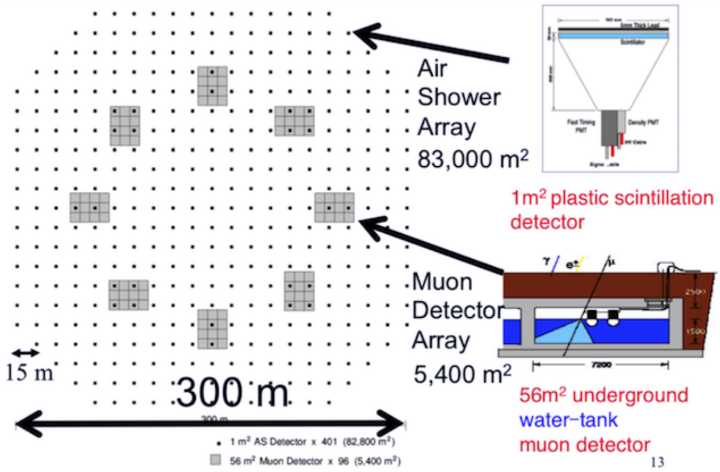

Fig. 17: A schematic drawing of the ALPACA air shower array, showing the surface plastic scintillator detectors an the underground water tank muon detectors.

between satellite and VHE ground arrays, i.e. from below 100 GeV up to 100 TeV [27]. It is a collaboration from Brazil, Portugal and Italy. LATTES is proposed to be built on the Chajnantor plateau in northern Chile, near the ALMA astronomical observatory, at an altitude of 5 200 m.a.s.l. and an approximate location 23°01'S, 67°45'W.

The LATTES design consists of a dense surface array covering an area of 20 000 m^2. Each unit is a hybrid detector composed of two resistive plate chambers (RPC) 1.5×1.5 m^2 each, covered by a thin lead slab (5.6 mm), all on top of a water Cherenkov detector (WCD) of dimensions $3 \times 1.5 \times 0.5$ m^3 with two PMT's on the smallest vertical faces, as shown in Fig. 18.

An upgrade to "Full LATTES" is also envisioned by adding an additional array of sparse detectors around the core array of 20 000 m^2, covering a total area of 100 000 m^2.

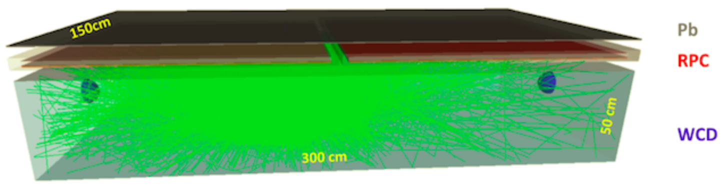

Fig. 18: LATTES detector unit, showing the lead plate on top, the two resistive plate chambers and the water Cherenkov detector at the bottom with the two photomultiplier tubes on the left and right walls (credit: B. Tomé, LATTES coll.).

The sensitivity to lower GR is achieved by being able to trigger on the shower secondary photons which are 5 to 7 times more numerous than secondary charged particles. The thin lead slab converts the secondary photons which have stronger correlation with the shower axis, while absorbs the lower energy electrons which have poorer correlation. In turn, the RPC's give good timing and geometry resolution, and the WCD gives a good calorimetric measurement of the shower.

The very high altitude location is necessary for a relatively low energy electromagnetic shower reach the ground. Figure 19 shows how the e.m. shower develops and then it is absorbed as it travels down the atmosphere. For lower energy gamma rays it is clear that a high altitude is essential.

In summary, LATTES will be a surface array designed to explore gamma rays in the 100 GeV region, covering the gap between satellite and other ground based observatories. Due to its wide field

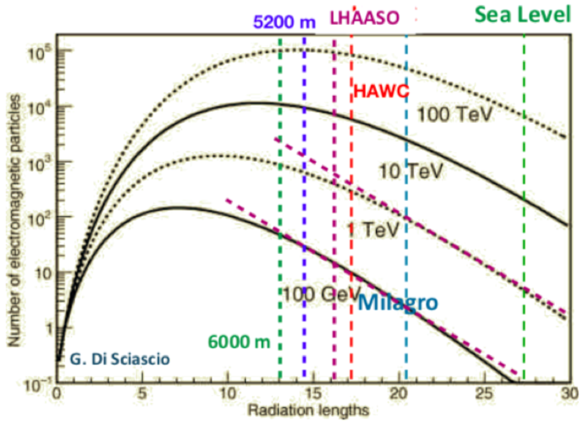

Fig. 19: Particle multiplicity in an electromagnetic shower as a function of atmospheric depth, for various primary GR energies. Vertical lines correspond to the altitudes of several GR ground array experiments (credit: G. di Sciascio).

of view and large duty cycle, it will be able to trigger observation of variable sources for other observatories like CTA, survey the southern sky and in particular the galactic centre, and detect galactic and extragalactic transient phenomena.

5.4 SGSO — now SWGO

SGSO, the Southern Gamma-Ray Survey Observatory [28, 29], is a proposed large water Cherenkov surface array for VHE gamma rays in South America. SGSO grows from the experience of HAWC and other observatories, with the intention to observe the southern skies. One of the main motivations for having a ground air shower array is the complementarity with air Cherenkov observatories like CTA, by providing a much larger duty cycle and field of view than the latter. This is a major advantage for finding variable sources and transient phenomena. A south site for a ground array is particularly important if one of the goals is the study of the galactic centre, which has a ground view only from the South.

As all surface observatories for gamma ray showers, it needs to be at high altitudes. The site is not defined yet, but possible candidate sites are: Cerro Vecar, Argentina (altitude 4 800 m.a.s.l., latitude 24°S), which is near the LLAMA site; Chajnantor plateau, Chile (5 300 m.a.s.l., 23°S), near ALMA; and Lake Sibinacocha, Cuzco Region, Peru (4 870 m.a.s.l., 13°S).

The optimization of the design of SGSO, supported by simulations, is still in progress. A "strawman detector" is considered, with larger size than HAWC, as well as higher altitude and larger *fill factor* (the fraction of the full area covered with detectors). The strawman design, shown in Fig. 20, considers a core array of 80 000 m^2 with a fill factor of 80%, surrounded by a sparse outer array of 221 000 m^2 with a fill factor of 8%. These figures can be compared to HAWC, which covers 20 000 m^2 with a fill factor of 57%.

SGSO main science goals are *i*) unveil galactic and extragalactic CR accelarators (galactic centre, galactic plane, star-forming regions, pulsars, Fermi bubbles); *ii*) monitor VHE GR transients (AGN's, Blazars, GRB's, G Waves, HE neutrinos); *iii*) probe new particle physics (dark matter, axion-like particles, Lorentz violation); and *iv*) characterize the CR flux (CR spectrum and composition, flux anisotropy, space weather, heliosphere physics).

Please notice that from the time I gave this lecture to the time I wrote these proceedings, the name of this observatory and collaboration changed from SGSO to SWGO, the *Southern Wide-Field Gamma-Ray Observatory* [29,30], the name it should be referred to from now on. Thus have we observed another

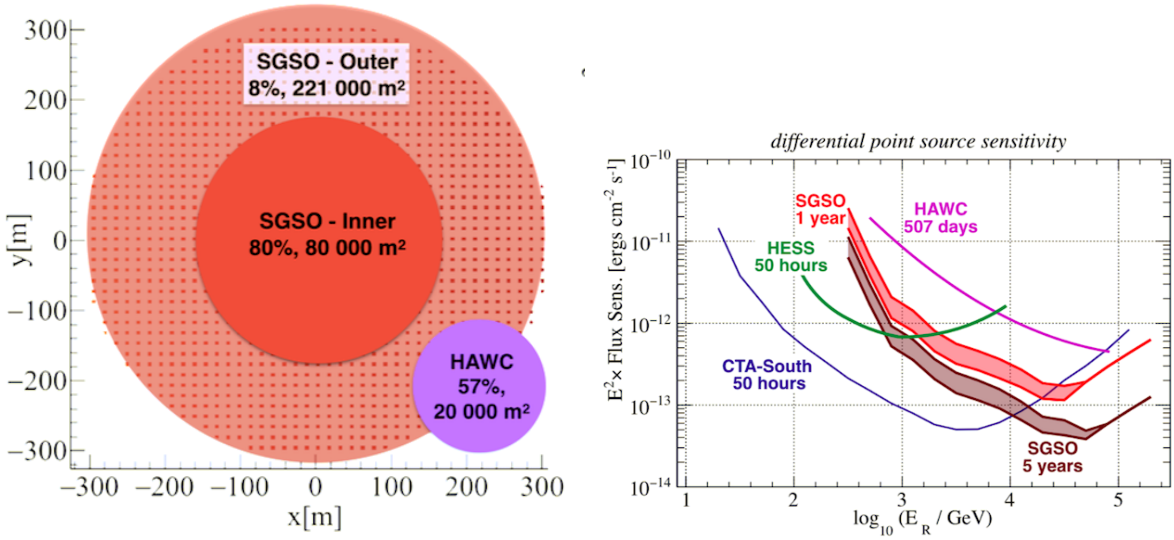

Fig. 20: SGSO strawman design; left: layout with instrumented areas and fill factors; right: differential point source sensitivity vs. reconstructed gamma-ray energy, compared to other GR observatories (from A. Albert *et al.* [28]).

type of transient phenomenon.

5.5 ANDES — Agua Negra Deep Experiment Site

ANDES (Agua Negra Deep Experiment Site) [31] is a proposal between Argentina, Chile, Brazil and Mexico to build a world class deep underground international laboratory under the Andes mountains, at the border between Argentina and Chile. The proposal takes advantage of the future construction of a 14 km long road tunnel, *Tunel Agua Negra* that will cross the Andes between the Region of Coquimbo (Chile) and the Province of San Juan. The nearest major cities are about 250 km away from the tunnel: La Serena in Chile and San Juan in Argentina. La Serena is also an active centre for astronomy in the region, close to the observatories Cerro Tololo, Las Campanas and La Silla. The underground site will be at an altitude about 3 900 m.a.s.l., with coordinates 33°11'34"S, 69°49'25"W.

ANDES will be the first underground laboratory of its kind in the Southern Hemisphere and among the deepest in the world, with 1750 m of rock overburden in all directions, providing excellent shielding against background radiation from cosmic ray muons, as illustrated in Fig. 21.

ANDES should be managed by an international Consortium formed by country members and possible Associate members. The line of organization of ANDES should follow that of SESAME, the international Synchrotron Laboratory in the Middle East [32]. Membership will be open to countries around the world. The laboratory is designed to host a large experiment in neutrino physics, and other experiments in astroparticle physics for e.g. dark matter searches, as well as nuclear astrophysics, biology, and geophysics.

The site of ANDES is special in many ways. Besides being in the Southern Hemisphere, it is in a region with much tectonic activity, and with very little background from nuclear power plants. The quality of the rock at the underground site is not yet known, although samples from 600 m depth were obtained, showing a proportion of andesite and rhyolite with normal level of radioactivity.

The underground site will lie at the deepest point along the tunnel. The tunnel is actually a pair of two-lane 14 km long tunnels separated by about 100 m. The laboratory will be on the south side of the eastbound tunnel, so the access will be about 4 km from the Chilean entrance. The underground

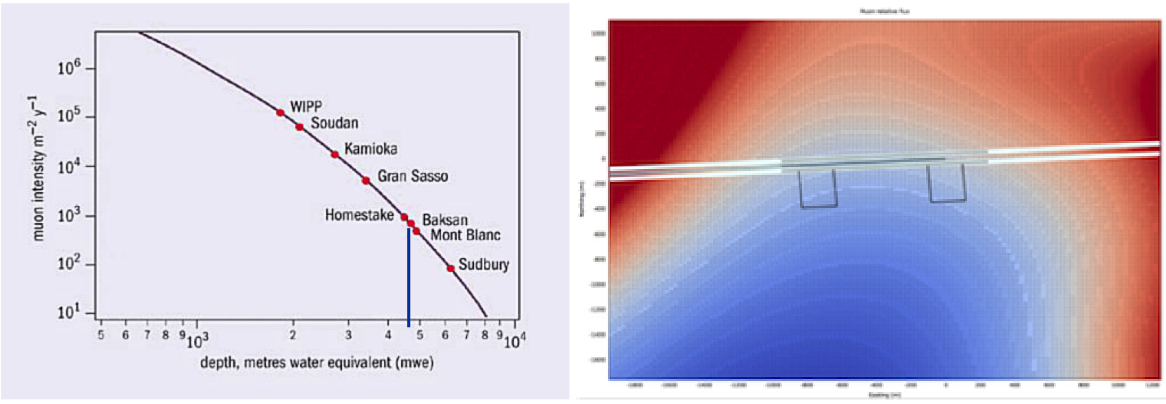

Fig. 21: Left: muon flux attenuation for different laboratories; ANDES is shown by the vertical line. Right: muon multidirectional relative flux; blue denotes more attenuation; the left box corresponds to the border between the countries and the right box the position of the ventilation plant; the actual site must be determined by the quality of the rock (credit: X. Bertou)

site will have an entrance and exit for vehicles, and the following caverns: a) one large cavern for large experiments, 42 m long × 21 m wide × 23 m high, with a 40 ton curved bridge crane; b) a secondary cavern for several smaller experiments and offices, 30 m long × 16 m wide × 14 m high, also with a 40 ton bridge crane; c) main pit for large neutrino experiments, 30 m diameter × 38 m high, with access from the top and from the bottom. d) insulated room 30 m long × 10 m wide and 5 m high, designed for nuclear astrophysics experiments. e) Biology room 16 m long × 9 m wide × 3.5 m high. f) Two clean rooms 10 m × 10 m × 8 m, ISO Class 7. g) Tunnel for Geoscience installations, 200 m long × 3 m wide × 3.5 m high. f) Emergency cavern with office space, dining room, meeting room, emergency first aid and data processing and communications centre, 10 m long × 10 m wide × 8 m high. h) Technical room, for transformers, compressors and generally noisy installations, and welding workshop. The general layout is shown in Fig. 22.

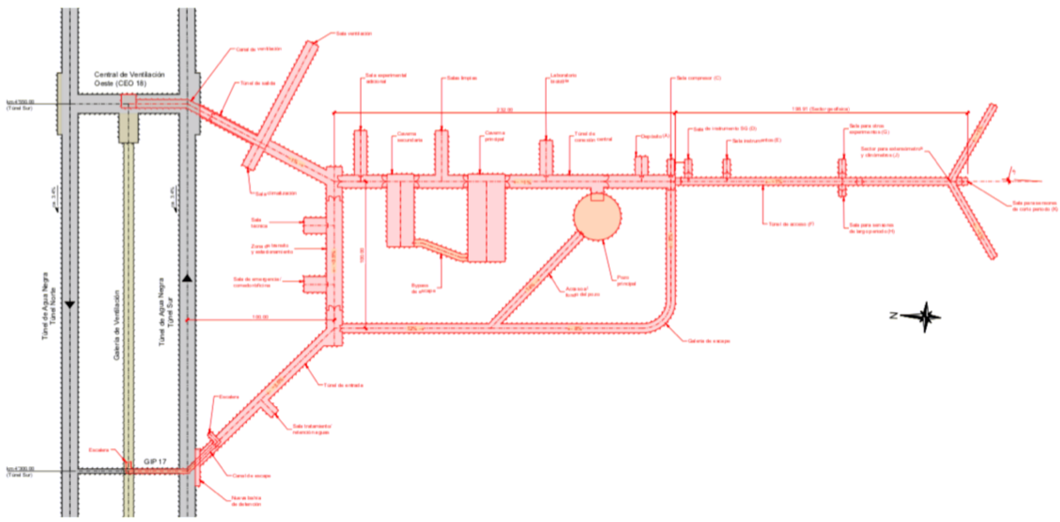

Fig. 22: ANDES underground site layout, showing the different caverns and main pit, with the access galleries connecting to the eastbound tunnel (credit: Lombardi S.A.)

6 Final words

I presented a brief description of some of the major current and future facilities in Latin America, knowing that I could not possibly do justice to all of them, and possibly I may have missed some important details, but my goal was to convey a flavour of the opportunities that exist and what can be expected in the near future. Facilities in Latin America have clearly grown in the last decades, and this tendency seems to continue for the next decades. This is clearly so for Astronomy due to the clean skies of the South American desert; in fact, more than half of the optical telescope surface in the world will be in northern Chile in the next decades. Moreover, as astronomy and particle physics have growing common interests as research fields, world level astroparticle physics facilities are also planning to find sites in the continent. Finally, the high-energy physics community in Latin America shows a steady growth for a variety of reasons we may argue, but a clear one is the appearance of large experiments that require worldwide collaborations.

Acknowledgements

I want to thank the organizers for the wonderful hospitality, as well as the lecturers, discussion leaders and students for the warm and stimulating atmosphere of this School. This work was supported in part by Fondecyt, Chile grant 1170171 and Conicyt, Chile PIA/Basal FB0821.

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Appendix: Exercises for the Lecture on experimental facilities in Latin America

Notice: the problems are not self-contained; you may need to look up some formulae somewhere else. I listed some suggested references at the end.

1. The radiation length of electrons in air is $X_\mathrm{r} \simeq 37\,\mathrm{g/cm^2}$. Considering that the atmospheric pressure at sea level is $p_0 \simeq 1 \times 10^5\,\mathrm{N/m^2}$, show that the vertical thickness of the atmosphere is about 30 radiation lengths.
2. (a) Determine the Cherenkov radiation emission angle θ_C in the atmosphere at sea level for a charged particle moving with $\beta \sim 1$. The refractive index of the atmosphere at sea level is $n_\mathrm{at} \simeq 1.00029$.
   (b) Same question but when the medium is liquid water.
   (c) Determine the threshold (minimum) energy for an electron to emit Cherenkov light in air.
   (d) Same question but for a muon.
3. Considering that the average galactic magnetic field is a few microgauss, show that cosmic rays (protons) with energies below $10^{18}\,\mathrm{eV}$ should be of galactic origin while those with energies $10^{19}\,\mathrm{eV}$ or above should be extragalactic.
4. What components of galactic cosmic rays can have a larger energy, protons or heavier nuclei?
5. Consider observatories of cosmic rays and gammas based on IACT (imaging atmospheric Cherenkov telescopes) and SDA (surface particle detector arrays). Explain the meaning of the following concepts:
   (a) Field of view
   (b) Energy threshold
   (c) Sensitivity
   (d) Duty cycle
   (e) Effective area of detection of a ground array. Explain why it depends on the energy of the CR or gamma ray.
6. (a) Why are IACT's (Cherenkov Telescopes) in general more sensitive to lower energies than surface arrays?
   (b) Why IACT's have a much shorter duty cycle than surface arrays?
   (c) Which one of the detector techniques, IACT's or surface arrays, have a larger field of view? Why is that?
   (d) How can a surface array measure the energy of the primary CR or gamma ray? How is that done with IACT's?
7. In an extensive air shower (EAS), a primary proton produces pions as it collides with the atmospheric nuclei. As it develops, the shower contains many muons and also many electromagnetic cascades as well. Explain why it contains muons and additional e.m. cascades.
8. In an EAS, a muon is produced at an altitude of 10 km. If the muon is able to reach sea level before decaying, determine the minimum energy it should have. Will this muon produce Cherenkov light in the atmosphere?
9. From the graph of the CR spectrum, in the region $10\,\mathrm{GeV} < E < 1\,\mathrm{PeV}$, the spectral flux (particles per unit area, time, solid angle and energy) can be fitted to a function:

$$j(E) = A\left(\frac{\mathrm{eV}}{E}\right)^{\alpha}, \quad \text{with } \alpha \simeq 2.7$$

(a) By fitting the graph (choosing an adecuate point), find the value of A in [1/(m^2· s· sr · eV)]. (sr = steradian)

(b) Consider a satellite with a flat detector face of 1 m^2. Determine the rate of primary cosmic rays with energies above 1 TeV that hit the detector (do not forget that the incidence is from the outside only, and do the solid angle integration correctly).

(c) What about energies above 100 TeV? Express the result in [particles/(m^2· day)].

10. Consider an electromagnetic shower caused by a vertical cosmic gamma ray of 1 TeV. Assume that the shower begins at 20 km.a.s.l. ($x = 0$) and as it develops, all particles in the shower (electrons, positrons and photons) at a given height have the same energy.

    (a) Determine the number of particles in the shower as a function of depth x. You will need the radiation length X_r from (1).

    (b) The shower reaches its maximum when the energy of the particles reaches the critical value $E_\mathrm{C} \simeq 80$ MeV. Determine x_MAX.

    (c) E_C occurs when the energy loss in electrons and positrons start to be dominated by ionization instead of bremsstrahlung. Find in the literature the expression for the energy loss by ionization and show that E_C for electrons is indeed around 80 MeV.

11. Consider the Sun, a star 1.5×10^{11} m away from Earth. The luminous solar radiation intensity on Earth is about 1.5 kW/m^2.

    (a) Determine the total power emitted by the Sun.

    (b) The net reaction where that power is produced is $\mathrm{p} + \mathrm{p} \to {}^4_2\mathrm{He} + 2\mathrm{e}^+ + 2\nu$, releasing about 26 MeV per reaction. Most of this energy is eventually emitted as photons. However the neutrinos escape, carrying in average about 0.4 MeV each (these are the so-called "pp neutrinos"). There are other reactions in the Sun that produce neutrinos, but these are the most abundant. Determine the flux of neutrinos on Earth, in 1/cm^2 s.

    (c) The solar neutrinos that are detectable by Super KamiokaNDE (SuperK) are not pp neutrinos. They have energies above 5 MeV and they come from the decay of the isotope ${}^8_5\mathrm{B}$ (boron-8), and they constitute are a very small fraction of the total flux that arrive to Earth, about 5×10^6 1/cm^{2}s. Try to estimate roughly the number of Solar neutrinos detected by SuperK per day. (You need to look up the size of SuperK and the ν-e cross section at those energies).

12. Let us try to recreate a Cherenkov emission from the e.m. shower produced by a 1 TeV primary photon. Assume that the shower is vertical and initiates at 12 km.a.s.l. Also assume for simplicity that the radiation length is a fixed value of 400 m, independent of altitude. An e.m. shower is quite collimated, with a spread not more than 0.5°, while the Cherenkov angle in air is about 1.5°. So clearly the size of the light pool on the ground will be determined mainly by the Cherenkov spread. Now consider that, along the shower, each electron or positron as it travels, emits about 10 Cherenkov photons per metre travelled. Consider this emission only up to X_MAX, which is where the shower has maximal multiplicity (particles reach the critical energy $E_\mathrm{C} \simeq 80$ MeV).

    (a) Determine the diameter of the Cherenkov light pool on the ground, which is at an altitude of 2 000 m.a.s.l.

    (b) Determine the number of Cherenkov photons in the light pool (here we are disregarding absorption in the lower atmosphere, which is not quite realistic).

    (c) Assuming that the Cherenkov photons are uniformly spread inside the light pool, determine how many photons will be caught by a 12 m diameter IACT that lies completely inside the light pool.

13. How can one learn about the acceleration regions of cosmic rays by measuring gamma rays?

14. Find out about the mechanism called *Fermi Acceleration*.

15. Why is it important to measure the VHE gamma rays that come from the galactic centre?
16. How can one test Lorentz invariance by measuring cosmic gamma rays?
17. Why gamma rays are better to identify the sources of cosmic rays than the cosmic rays themselves?
18. What are "Fermi bubbles"?
19. Concerning the search for the particles that constitute the dark matter of the Universe, explain what is called "direct searches" and "indirect searches".
20. The GZK cutoff is the upper limit for the energy of CR that can reach the Earth from very far extragalactic distances, due to the energy loss of a CR particle (e.g. a proton) when it collides with a CMB photon and produces a pion at the resonance of the Δ baryon, e.g.:

$$\mathrm{p} + \gamma_{\mathrm{CMB}} \to \Delta^+ \to \mathrm{p} + \pi^0$$

Determine the energy of the GZK cutoff.

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