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PROGRAMA DE INVESTIGACION ASOCIATIVA
RESEARCH TEAM PROJECTS IN SCIENCE AND TECHNOLOGY
CHILEAN INSTRUMENTATION FOR ASTRONOMICAL SURVEYS
Proyecto Anillo ACT 1417

PROJECT DESCRIPTION

Introduction:

We live in a very exciting time in history when we are finally able to answer some of the deepest questions about the Universe: how did it all begin? how old is it? what is it made of? how did the Earth form? Is there life beyond the Earth? However, with every new answer many more questions arise. For example, today we believe that 95% of the Universe is made out of things we don't understand: completely transparent matter or "dark matter" (23%) and some sort of vacuum energy which fills up all space or "dark energy" (72%). After learning about the evolution history of the Universe, mysterious epochs like Inflation, the dark ages and reionization became new unknowns. The same situation happens with galaxy formation, structure formation including early effects of dark energy, the effects of neutrino mass and the effective number of neutrino species, among many others. For all these reasons Cosmology and the study of the largest and deepest structures in the Universe have become very active and prolific areas of astronomy, capturing a huge amount of effort and funds throughout the world. Among them, most of the experimental efforts involve studies over large areas of the sky, measuring thousands of high redshift galaxies or the temperature and polarization landscape of the Cosmic Microwave Background (CMB).

Such surveys require specialized telescopes and instruments, together with long dedicated telescope time, producing huge amounts of data that require high performance computing (HPC) facilities to be reduced and analyzed. Altogether, survey projects generally require large collaborations from multiple international institutions devoting important resources and experts, assuming tasks that range from the instrumental design, building and testing; installation and operations at the site; data acquisition, handling and reduction; scientific analysis and publication of the results; and theoretical modeling and development of new physical ideas. These projects are also very long in time, starting from an instrumental proposal, which involves one set of scientists and experts, and ending in the data analysis results which happen a few years later and generally involves a different set of scientists who produce the final publications. For this reason, it is increasingly accepted that the whole team is acknowledged as co-authors of the main publications, providing credit to all those who made the result possible by developing the experiment.

Thanks to the quality of the chilean observing conditions, many of these efforts have bases in Chile, providing data access to the chilean astronomical community, producing an exponential development of national astronomy. Soon 70% of the total telescope collecting area will be in Chile, out of which 10% of the observing time is reserved to chilean observers. Most of these telescopes operate in wavelengths ranging from the optical to the millimeter, being the optical and infrared suitable for large photometric and spectroscopic surveys of galaxies, stars and variable objects, exoplanet detections, and the millimeter wavelengths required to map the CMB.

Chilean astronomers have already joined these large survey collaborations at different levels, often contributing through the use of chilean telescope time. The IA hosts several ongoing international collaborations, including CMB maps for Cosmology and Large Scale Structure like ACT, POLARBEAR and CLASS projects, centered at Princeton, UC Berkeley and Johns Hopkins University respectively, photometric and spectroscopic redshift galaxy surveys like RCS2, DES and U-band/ATLAS in collaboration with Durham QSO and survey group (T. Shanks), CASU UK (Irwin) and OSA (Edinburg).

All these projects have significant areas of scientific overlap, especially in the areas of Cosmology and Large Scale Structure, and all of them share the common denominator of being surveys over large areas of the sky, having common experimental needs, like requiring dedicated instruments, automatized observation systems, custom made data reduction pipelines to run over large amounts of data, etc. These natural connections can be exploited synergistically to generate working network, boosting the scientific outcome. This proposal will do this by improving the interaction between them and by boosting the technical man force available for developing instrumentation and contributing to data processing within these existing collaborations.

So far the development of chilean astronomy has been based on the use of chilean telescope time, but with minimal chilean participation in the design, fabrication and implementation of the instrumentation itself, leaving aside a huge part of the scientific activity. Extending chilean collaboration to experimental aspects of astronomy would not only raise the scientific leadership of chilean investigators and groups in cutting edge astronomy, but also produce a strong technological transfer to other areas of knowledge including new capabilities and technologies with applications for the local industry. Moreover, given the level of development of astronomical instrumentation and our proximity to it, bringing such activities within the context of chilean universities would certainly boost the formation of highly qualified chilean personnel that could then feed the developing chilean industry, helping it to achieve ever higher technical standards and diversify its activities into new areas. In this context, the Center for Astro-Engineering (AIUC) at Pontificia Universidad Católica (PUC) was created with the purpose of developing national astronomical instrumentation, extending the existing international collaborations to more technical aspects in a progressive strategy to assume increasingly more challenging instrumental goals within each experiment or instrument. These activities have strengthened our international collaborations, bringing in new interdisciplinary research activities that connect astronomy with engineering, having strong net effects in the chilean technology industry.

In the following we will describe the ongoing projects and people that form this Anillo proposal and show how this fund will be used to achieve the goals described above.

The UC Center for Astro-Engineering

The AIUC was created in 2010 as a joint venture between the PUC Institute of Astrophysics and the PUC Faculty of Engineering. The Center's mission is to serve as channel to carry out research and to generate new technological and computational opportunities in the area of astronomy and engineering in Chile. Currently the AIUC includes three main parts: a Laboratory of Astronomical Instrumentation, a Center of data mining and numerical computation and an Astronomical Service area. The purpose of the first is to generate alliances with international observatories present in Chile, participate in the construction of optical and infrared instruments and trigger technological transfer to the country. The Computer Lab offers to the chilean astronomical community a powerful tool for numerical computation and data analysis and provides the computing capability needed to handle large amounts of data collected by telescopes in Chile. Finally, the mission of the Service Area is to provide astronomical and engineering support to the international observatories located in Chile and facilitate specialized human resources.

Cosmology through the CMB (science and observations)

The study of the Cosmic Microwave Background, CMB, has developed very rapidly in the last 20 years revolutionizing our understanding of the Universe. Among other things, it has allowed us to precisely measure the energy content of the Universe, determine its age and evolution, and construct a widely accepted cosmological model consistent with many other datasets. The study of the CMB temperature fluctuations established the standard model of cosmology, called L-CDM, enabling us to measure its parameters with high precision (e.g [1-9]).

Today the effort continues, extending the measurements to finer angular scales, multiple frequency bands, polarization maps and deeper observations, with the aim of improving the determination of primary and secondary cosmological parameters, deepen our understanding of the very early universe, study the reionization epoch, find galaxy clusters, study the growth of structure and characterize dark energy, test alternative models for gravity, determine fundamental properties of neutrinos, understand galaxy evolution and characterize dark matter. A significant part of the effort is focused in measuring two important phenomena: the gravitational lensing signal produced by foreground structure at redshift $z \approx 2$ and the plausible signature of primordial gravity waves produced during an hypothetical early inflationary period of the Universe called Inflation. The former could lead both to the first measurement of the sum of the neutrino masses and of the early effects of dark energy, and the latter to the confirmation of the existence of Inflation and gravity waves themselves. Both of these phenomena manifest as a particular pattern of the polarization field called B-modes (as opposed to the expected E-modes), which is not expected from the surface of last scattering unless there are primordial gravitational waves perturbing the field during the epochs of recombination or reionization (primordial B-modes, [10]), or if gravitational lensing effects distort the polarization pattern as the background radiation travels through the whole age of the Universe in its way to us (lensed B-modes [11]). Primordial and lensed B-modes appear at relatively different scales in the CMB power spectrum, with the primordial ones dominating at large angular scales and the lensed ones at small angular scales, and a significant area of overlap between them. Fortunately, the lensed B-modes formed correlations between spatial modes which can be used to reconstruct the lensing deflection field [12] and "de-lense" the polarization field to "clean" the primordial power spectrum, for which a good measurement at small angular scales is required.

B-modes are not easy to detect. Their signal is very small, below 3 uK, at least 10 times smaller than the E-mode signal, and it is susceptible of various systematic effects and foreground contamination, meaning that an exquisite understanding of the instrument is required, as well as measurements in several bands. The level of polarized foregrounds (mostly dust) is highly uncertain and distinguishing the primordial B-mode signal is tricky, requiring measurements over large regions of the sky and at different frequency bands. Measuring this pattern will not only prove the existence of inflation, but could also give us the energy scale at which is occurred, which is probably close to the GUT scale, teaching us about nature at energies impossible to achieve in a particle accelerator. A few months ago, the BICEP2 experiment measured a B-mode power spectrum at large scales. The primordial origin of the detected signal is still under discussion, but it fired up the race to achieve this measurement.

The lensing B-modes are relatively easier to detect, such that a couple of experiments have already claimed its detection including POLARBEAR [16]. The lensing signal is a powerful tool to measure the matter distribution up to redshifts well beyond the limit of spectroscopic galaxy surveys, which are restricted to redshifts below 2. Moreover, the lensing signal peaks at redshifts between 2 and 3, making it ideal to characterize the evolution of structure including early effects of dark energy and the mass of the neutrinos [13]. When combined with galaxy surveys, it is possible to constrain the sum of the neutrino masses with unprecedented precision ($\sigma m \approx 0.05$ eV), measure the effects of dark energy, improve the measurement of the curvature of the Universe to better than 0.5%, and contribute to constrain the determination inflationary B-modes at larger scales. Lensing B-modes dominate at multiples $\ell \sim 1500$, and therefore should be measured using arcminute resolution polarization sensitive experiments, like ACT and POLARBEAR.

Out of the many experiments that have been developed to study the CMB polarization, several have chosen the Atacama desert to deploy their telescopes, such as ACTPol, POLARBEAR, CLASS or ABS. The CMB group at PUC is involved in all of them, being in a preferential position to contribute to this historical discovery. Dr. Dünner is leading this effort, supported by the FONDECYT 1114113 grant, and proposed to be extended with this proposal.

Atacama Cosmology Telescope (ACT), is a 6m off-axis gregorian telescope located at Cerro Toco, near to the Chajnantor Plateau at 5200m. The project is lead by Dr. Lyman Page, from Princeton University, and involves an international collaboration of over 20 institutions. With an angular resolution of 1.5 arcminutes, ACT is ideal for measuring the fine scale fluctuations of the CMB, where most of the secondary cosmological parameter information and foregrounds manifest, connecting it to a rich followup science.

During the first phase of the project, ACT measured the CMB temperature fluctuations at intermediate and very small-scales in 3 bands, 145, 220 and 270 GHz, with 3K bolometers, releasing more than 30 scientific papers in which PUC members were deeply involved, producing new cosmological parameter constraints, detecting gravitational lensing effects on the CMB for the first time, making the first detection kinetic Sunyaev-Zel'dovich (kSZ) effect, finding dozens of new clusters of galaxies through the thermal Sunyaev-Zel'dovich (SZ) effect, making the first detection of early dark energy effects on the CMB, among many other significant contributions.

During his PhD thesis, Rolando Dünner participated in all the aspects of the experiment, from the development of the instrument to the production of CMB maps. Later as a professor, he has lead several research projects related to ACT, involving students working on 1 PhD thesis, 3 MSc thesis, 6 Senior Thesis, and 4 other students working as research assistants. We have been supported by several funds including FONDAP and BASAL. Dr. Dünner has been awarded two grants (Inicio VRAID-Nº39/2010 and FONDECYT Iniciación 11100147: Chile ACT Ultradeep Survey (CACTUS)) to develop this area of research, including data reduction techniques, calibration and map making, characterization of systematics, optical characterization and electromagnetic modeling, extragalactic source characterization and followup. The group gained significant experience analyzing the CACTUS region, which is a 30 deg2 area centered at 4h 30m; 00s, -53 00' 00", which added to the rest of the ACT data produced the deepest area within the whole ACT survey. For

CACTUS we developed our own semi-independent mapper, implemented new calibration techniques, and produced our own source flux catalogs. Leopoldo Infante and Felipe Barrientos worked on the SZ cluster detection and optical infrared follow up.

The second phase of the project was to install a polarization-sensitive camera, ACTpol, specifically designed to study B-modes from intermediate to small-scales, where the gravitational lensing signal is stronger. ACTPol completed its first season of observations in 2013 with 1K detectors at 150 GHz and recently released a first cosmology result paper focused on E-mode polarization [cite]. The observed areas were chosen to maximize the overlap with existing galaxy surveys like SDSS, BOSS, u-band/ATLAS, to run matter distribution studies. The improved design of the bolometers are 4 times less noisy than the previous generation, while operating at only 100mK. In 2014 another optic tube with 1K detectors at 150 GHz was added, and in 2015 a dichroic detector array working at 90 and 150 GHz with another 1K detectors, summing up to 3K detectors on the focal plane. During the 2013 campaign, the PUC group participated in the telescope maintenance at the site, optics characterization and panel/camera alignment using simulations and photogrammetric measurements, calibration and data reduction. Dr. Dünner was also granted 10% of ACTPol's time (until 2015) to observe a 30 deg^2 area overlapping the XMM-LSS field (8x8 deg^2 centered at 2h 18m 00s, -7º 00' 00'', J2000, CNTAC 2012A-114). This area overlaps with several X-ray and optical existing observations, which can be cross-correlated with the lensing signal to study matter distribution, as well as cluster physics and small scale CMB fluctuations. The survey will be called Chile ACT Ultradeep Survey XMM (CACTUS-XMM), as it is a continuation of our previous project called CACTUS. When added to the other observation areas of ACTPol, it will help to constrain the sum of the neutrino masses with a precision of σm ≈ 0.05 eV, the running of the spectral index of inflation-induced fluctuations, and the primordial Helium abundance to better than 1%. These constraints will be improved by cross correlating the CMB lensing data with the Lyman alpha forest power spectrum and Baryonic Acoustic Oscillations (BAO) from other surveys. In this respect, the chosen area will benefit from its overlap with other surveys like BOSS, HSC deep field, CFHTLS W1 and Herschel deep survey (HERMES). Also a postdoc, Loic Maurin, was hired in 2013 to strengthen the PUC team working on data reduction, funded by the ALMA-CONICYT 31120012 grant.

Succeeding ACTpol, a new upgraded version of the experiment called Advanced-ACT (AdvACT), lead by Suzanne Staggs, also from Princeton University, is already funded and will replace the current camera by the end of 2015. It will incorporate several advances from ACTpol, including simultaneous observations in 5 frequency bands (28, 41, 90, 150 and 230 GHz) which will be combined with Planck's 353 GHz bands to fully characterize polarization foregrounds. It will also incorporate half-wave plate polarization modulators to overcome the 1/f noise and reach accurate measurements over large angular scales, reaching those of primordial B-modes with tensor to scalar ratios of order r=0.01. Dr. Dünner is an associate researcher of the AdvACT project, producing a strong link with the CMB group at PUC. See Fig 1 for sensitivity prospects for

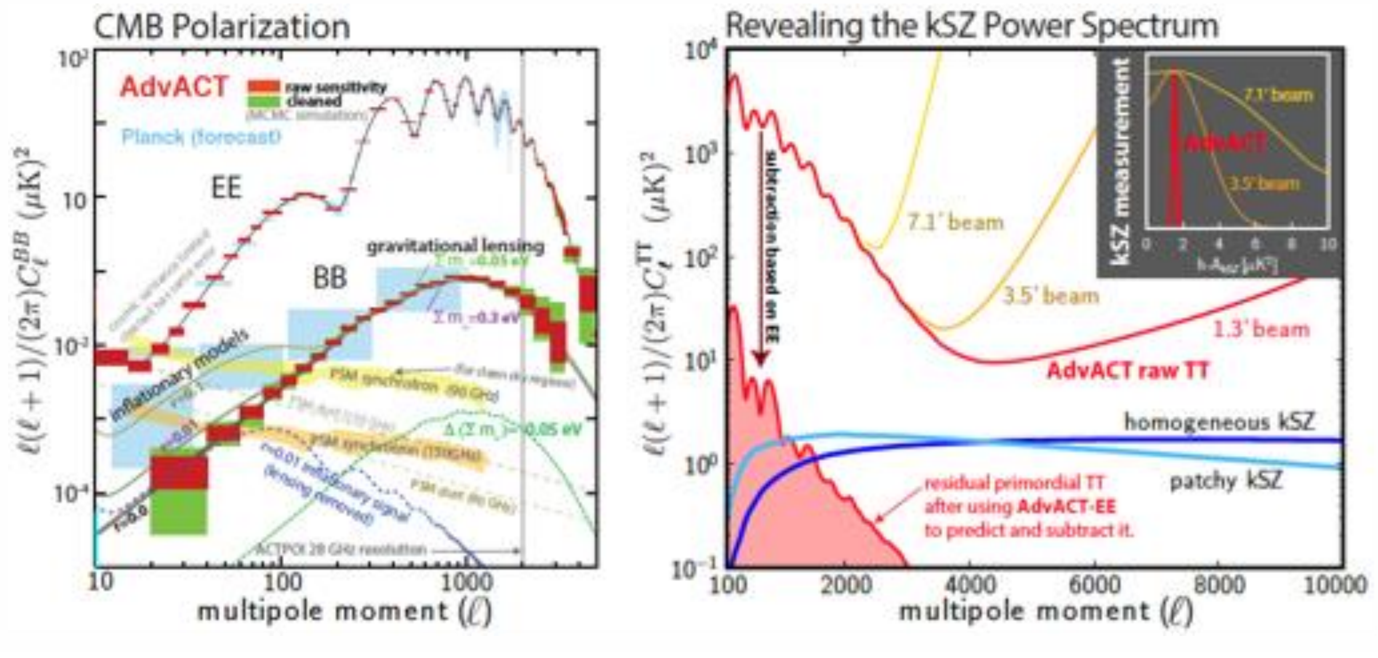


Fig 1: Sensitivity prospects for AdvACT. See text for details.

AdvACT.

POLARBEAR is located next to ACT on Cerro Toco. It is currently operating with a single 3 m Gregorian-Dragone telescope, which provides a 3.5 arcminute beam at 150 GHz. The first generation POLARBEAR camera, POLARBEAR-1, uses 1,274 detectors at 150 GHz. In the last 6 months, POLARBEAR has released three papers based on data with this camera measuring the lensing B-modes with three different techniques [14,15,16], including the first released measurement of a B-mode power spectrum. These results were based on the first year of POLARBEAR data concentrating on a small region of the sky.

The major goal of the POLARBEAR project is to perform a deep, large sky-area, multi-wavelength CMB mapping campaign. The science benefits of such a program are significant. This survey will allow for powerful constraints on the presence of primordial gravitational waves at the surface of last scattering, with multiple frequency bands providing the ability to distinguish between foreground and primordial sources. It will also enable a search for massive neutrinos via their impact on the gravitational lensing experienced by CMB photons. When combined with Baryon Acoustic Oscillation data, this will provide a measurement of the known 58 meV minimum total neutrino mass with 3σ significance, also addressing the question of the neutrino hierarchy.

The survey will also deliver a large-scale structure map of 80% of the sky derived from CMB lensing. The survey region will overlap with optical surveys like DES, HSC, DESI, and LSST, enabling important cross-correlation work to be done. For instance, this will enable a calibration of the mass-to-light bias of galaxy surveys, helping to improve cosmological constraints drawn from optical data. In combination with other data the large-scale structure map will also constrain the time-evolution of dark energy.

Another important goal of the survey is to provide a sample-variance limited measurement of the CMB E-mode power spectrum to $\ell \sim 2000$, which will be used to improve constraints on important cosmological parameters like the scalar spectral index ns, the running of the spectral index, the primordial helium abundance Y_{He}, and the effective number of relativistic species Neff.

In order to meet these ambitious goals the POLARBEAR project is undertaking major hardware upgrades, to be deployed in phases, to improve both its sensitivity and spectral coverage. The first of these upgrades is called POLARBEAR-2, which is a new, more sensitive receiver that will be deployed onto a new telescope, identical to the first, at the same observatory site. The POLARBEAR-2 receiver will operate at both 90 and 150 GHz with a total of 7,588 detectors. This focal plane will have an instantaneous noise equivalent temperature of 5.7 $\mu K\sqrt{s}$. POLARBEAR-2 will deploy in 2015, and another upgraded receiver will deploy onto a third identical telescope in 2016. Finally, the receiver on the original telescope will be upgraded. This full configuration of three telescopes operating with upgraded receivers will be called the Simons Array, and has a target noise equivalent temperature of 2.5 $\mu K\sqrt{s}$. All of these hardware upgrades, including the additional telescopes, are already fully funded.

A postdoc, David Boettger, was hired in 2014 to consolidate our work with the POLARBEAR collaboration. He was deeply involved in the initial POLARBEAR-1 campaign, and will continue his work with the upgraded versions of POLARBEAR while searching for PUC students to become involved in this work as well. His experience with different aspects of the project will provide opportunities for PUC students to become involved in hardware, software, and data analysis work.

CLASS is an array of 4 telescopes with 1 meter apertures operating at four frequencies: 38, 93, 148 and 220 GHz, with 72, 1036, 2000 and 2000 detectors respectively in each band. These frequencies were selected to straddle the galactic foreground minimum, which is dominated by synchrotron emission at low frequencies and by dust at higher frequencies. The detectors will be horn coupled TES bolometers operating at 150 mK (cooled down using a Dilution Refrigerator or DR), with a noise goal of reaching 200 uK-rts at 150 GHz and 140 uK-rts at 90 GHz. The first element of the off-axis optical design is a Variable-Delay Polarization Modulator (VPM), consisting of a polarizing wire grid followed by a movable mirror, such that the path length of each polarization can be modulated at a frequency of 5 Hz, decoupling the CMB signal from any systematics from the optics and receiver. This kind of modulation provides sensitivity to circular polarization (V Stokes parameter). Given that no circular polarization is expected from the CMB, this can be used as a Null check for detecting systematics, calibration from the atmosphere signal produced by the Earth's magnetic field, and for searching unexpected results. The system is being currently built and tested in GSFC, Johns Hopkins University (JHU) and Columbia University, such that the first telescope is expected to be deployed by the end of 2013.

The science goal of CLASS is to directly measure primordial gravity wave B-modes from the epochs of recombination ($\ell \sim 70$) and reionizaton ($\ell < 10$), with emphasis on the latter ones because they are less polluted by gravitational wave B-modes that dominate at higher multipole numbers. To measure such large features in the sky (with angular scales larger than 10 degrees) it is necessary to observe over a large area of the sky. For this reason the experiment could only be done in the Atacama and not in the South Pole, as the lower latitude gives access to around 65% of the extragalactic sky. Moreover, to connect such long baselines, the system must be extremely stable, which is why modulating the signal before it enters the optical system becomes so important.

Our group at PUC has been collaborating with this project since the very beginning, helping with the site determination, legal paperwork, finding contractors for setting up the site conditioning and infrastructure, and other administrative tasks. Together with this, we have participated from part of the design discussions involving detectors and data pipeline. In 2012, we raised funding (QUIMAL-120001) to develop a metrology system to align and characterize the optics of the telescope (the same as for ACT), so our system will become an integral part of the project when the telescope is here. We have also started scientific collaborations, sending our PhD student Pedro Fluxá for an internship in JHU during the first semester of 2014, before the system is sent to Chile, to learn the details of the camera and much more.

All the previous studies involve performing statistical and spectral analysis of the maps and fitting cosmological models by marginalizing over the parameters using Markov Chain Monte Carlo (MCMC) methods. Also the data reduction process and map making require significant software development and high performance computing. Here at the DAA-PUC we have access to Geryon (512 cores, 1T RAM) and Geryon II (520 cores, 4.2T RAM) cluster computers, plus a GPU server with 3000 cores, which can be used to analyze the data from this proposal. In this proposal we propose to buy a new Geryon II node for dedicated use to CMB data analysis, plus one RAID storage unit per year to keep a copy of the data at PUC for local use.

CMB experimental prospects:

The ambitious scientific goals from above require measuring the polarization of the CMB in scales that range from a couple of arc-minutes to many degrees on the sky, and with a precision better than 0.1 uK-arcmin, which is a great experimental challenge. The next generations of CMB surveys will require measuring a huge area of the sky with high resolution and high mapping speed. The great success of CMB science have been mostly possible thanks to the development of new detector technologies that have significantly increased the mapping speed of the instruments available. With the current achievement of photon-limited detectors, further increases in mapping speed require placing more detectors on the focal plane, or the construction of arrays of CMB telescopes, each one containing thousands of detectors. Also, achieving arc-minute resolutions at millimeter wavelengths requires telescopes larger than 5 meters in diameter. Moreover, to correctly sample large angular scales of the sky, these telescopes must be located in places with access to a large portion of the sky. Building 5 meter telescope arrays in space is prohibitively expensive, strongly favoring ground based telescopes, which must be located at low latitude sites to be able to see most of the sky. Thus a natural location for such a future experiment is the area of Chajnantor, in Chile, which have proven its optimal observing conditions through a long list of CMB experiments including CBI, ACT, QUIET and POLARBEAR. Moreover, the Report of the Particle Physics Project Prioritization Panel (P5, http://www.usparticlephysics.org/p5/), dated in May 2014, puts the CMB - Stage 4 project as prioritary under any funding scenario, in a time scale of 5 to 8 years from now. This project considers building such array of mm-wave telescopes. It is thus a very appealing idea to think that chilean universities and companies could participate as part of the design, fabrication and setup of those telescopes, especially considering that the technology needed to build mm-wave mirrors is far more reachable than the equivalent for optical telescopes, plus all the already gained experience doing metrology and telescope characterization.

Developing the capabilities to do this, both within the universities and within the chilean industry, is certainly a task that could take several years to do, but if succeeded the reward would be enormous just in terms of the number of highly trained scientists, engineers and technicians that would be produced, the experience and capabilities gained within the universities, and the formation of a new industry of high precision machining and telescope engineering that could serve the future demand in a country known to be the most promising one in this matters. Moreover, given that every telescope costs of the order of 20 million US dollars, and that we expect that a few of those need to be constructed, then this volume of a business is interesting enough to convince some of the local companies to bring the necessary equipment and knowhow to achieve this technical challenge.

Following the baby steps approach, our first step will be to build a small prototype of a mm-wave telescope, with a mirror not larger than 1 meter in diameter to mount a decommissioned camera donated by ESO to our group (APEX1). This camera was developed by Onsala Space Observatory and installed in the SEST telescope in 1989. It contains 2 heterodyne SESIS detectors operating in the 78-116 GHz and 128-170 GHz respectively, and cryogenically cooled to 4K, and will arrive to PUC in October 2014. Our plan is to refurbish this camera at the AIUC, upgrading it using new electronics and adapting it to be installed in our prototype telescope. The immediate goal of this project is to teach students in these technologies and observing at mm-waves, but the main goal is to gain experience on how to build these kind of instruments in Chile, with chilean universities and industry. The prototype must be low-cost, as it won't have mayor astronomical impact, and will be installed in a location (yet to be defined) near Santiago for easy access of our students. This project is expected to last 3 years, the length of this proposal, and will be partially supported by it through the use of part of the new personnel hired with this fund. The rest of the funds will come from other funding opportunities like QUIMAL and FONDEQUIP. For this development we count with support from experts from our international collaborations, and will incorporate graduate students and postdocs working at PUC.

Technically speaking, the surface precision required for mm-wave telescopes is of the order of 20 um, so they can be machined out of aluminum using standard industrial machining techniques, many of which are already in Chile providing services to the great mines. An example of one of such companies is “Maestranza Giglio”, which is already studying the possibility of building a mirror for CLASS to operate in the 150 and 220 GHz bands. We are currently in the prototype stage, to test the surface accuracy that can be achieved by their manufacturing process, and look forward to fabricate the first mm-wave mirror for CMB studies made in Chile. On another front, we have started conversations with the chilean office of the german company MT Mecatronica to develop the engineering required to design and build mm-wave telescopes in Chile. Moving forward in this direction, we are organizing a workshop on antenna fabrication, where we will invite senior technicians to teach us about the techniques, equipment and processes required, and to which we will invite all the interested companies and research groups in Chile, producing interconnections and promoting this area of business.

One of the most important technical challenges when mapping extended sources like the CMB is to have an exquisite understanding of the optics of the telescope, including shape of the main beam and sidelobes, the antenna response to polarized radiation, optical stability, etc. This is achieved by properly characterizing the antenna response, the illumination and spillover, and the mechanical stability of the mirrors. This is complemented with electromagnetic simulations used to understand the expected behaviour of the optics under the effects of diffraction and scattering on the elements of the telescope. Professor Carlos Jerez has developed mathematical techniques, known as multiple traces formulations, to model high-frequency scattering problems using FFT and parametric formulation. Based on the availability to produce experimental data, the purpose of this line of research is to achieve a fully functional 3D computational code able to provide a rigorous computer-aided-design tools for next generation radio-frequency telescopes.

In another front, these telescopes produce a huge volume that needs to be properly analyzed and turned into CMB maps. This implies development of high performance computing techniques and data reductions algorithms that can take care of systematics and clean up the atmospheric effects. In this sense, Dr. Andrés Guesalaga has developed advanced algorithms to model atmospheric turbulences used for adaptive optics and could be implemented to CMB data reduction. Moreover, Dr. Guesalaga will contribute in the development of control and readout systems for our prototype telescope.

Wrapping up, our goal is to develop CMB experiments in Chile, becoming a leading group at international level and the epicenter of the chilean effort. We are looking forward to participate in ambitious instrumental projects that will incorporate the chilean industry and leak new capabilities to the chilean society.

Cosmological and Matter Distribution theory and simulations

In parallel with the experimental efforts, the group lead by Jorge Alfaro is working in new theories about Gravity that depart from the standard L-CDM model. These theories must be contrasted against experimental evidence, opening a clear collaborative line with the CMB experiments described before, as well as with galaxy surveys. In particular, the studies involve aspects of Quantum Field Theory and Quantum Gravity that may be relevant for the understanding of Quantum Gravity phenomenology, Cosmology, Physics beyond the Standard Model as well as non-perturbative phenomena in Quantum Field models.

We have already been able to simulate modified gravity models and have studied the differences between these and a general relativity model with a cosmological constant. We will take advantage of this first attempt and attempt to extend it to these new models, using our connection to the Durham gropu where Baojiu Li, the owner of ECOSMOG is based. ECOSMOG is a code that allows to include extra degrees of freedoms to gravity, that could be adapted to other alternative gravity models.

Astroparticle Physics and Gravitation. In recent years, there has been an enormous progress in the understanding of the basic forces of Nature. The strong, weak and electromagnetics interactions can be described to a great degree of accuracy by gauge theories of the Yang-Mills type. This guaranties its renormalizability and unitarity, producing a beautiful scheme which is both mathematically consistent and highly successful in its experimental predictions. A couple of years ago, the Higgs particle, fundamental to generate masses for the particles in the Standard Model(SM) through spontaneous symmetry breaking, was discovered at the LHC [17]. Surprisingly no extra particles or symmetries are needed at this stage to explain the experimental results of the LHC. Nature was shown to be very conservative at the available energies.

In the SM, neutrinos are massless. But the existence of neutrino oscillations have shown that neutrinos are massive. This fact makes necessary a modification of the SM.

We know that general relativity (GR) works very well at the macroscopic scales [18]. Nevertheless, its quantization has proved to be difficult, though. The theory is non-renormalizable, which prevents its unification with the other forces of nature. Trying to make sense of quantum GR is the main physical motivation of string theories [19, 20]. Moreover, recent discoveries in cosmology [21, 22] have revealed that most part of matter is in the form of unknown matter, dark matter (DM), and that the dynamics of the expansion of the Universe is governed by a mysterious component that accelerates the expansion, dark energy (DE). Although GR is able to accommodate both DM and DE, the interpretation of the dark sector in terms of fundamental theories of elementary particles is problematic [23]. Although some candidates exists that could play the role of DM, none have been detected yet. Also, an alternative explanation based on the modification of the dynamics for small accelerations cannot be ruled out [24, 25].

In GR, DE can be explained if a small cosmological constant (Λ) is present. In early times, this constant is irrelevant, but at the later stages of the evolution of the Universe Λ will dominate the expansion, explaining the acceleration. Such small Λ is very difficult to generate in quantum field theory (QFT) models, because Λ is the vacuum energy, which is usually very large.

One of the most important mysteries in cosmology and cosmic structure formation is to understand the nature of dark energy in the context of a fundamental physical theory [26, 27].

Recently, in [28] a field theory model explores the emergence of geometry by the spontaneous symmetry breaking of a larger symmetry where the metric is absent.

Delta gravity. In this model, the gravitational field is described by two tensors g_(μν) and g~_(μν). Massive particles do not move on geodesics, but massless particles move on null geodesics of a metric given by a linear combination of g_(μν) and g~_(μν). First results are presented in [29] and [30]: A very important result of the model is that the Cosmology derived from δ gravity shows accelerated expansion without a cosmological constant. Moreover the quantum theory is shown to be finite [31].

In this part of the anillo we want to study the following problems: 1) To study the classical limit of the model and compare it with experiments. In particular: The Post Newtonian Approximation and Neutron Stars. Obtain rotation curves for stars in galaxies. 2) To study the evolution of matter and energy fluctuations in the early Universe and compare it with the CMB data of Planck. 3) Compute relevant finite quantum corrections and explore their phenomenological consequences. We would like to see if inflation in the early universe can be produced by the quantum corrections to the effective action in the model. In the near future, Chile ACT Ultradeep Survey XMM (CACTUS-XMM) will measure the running of the spectral index of inflation-induced fluctuations, and the primordial Helium abundance to better than 1%. 4) To study the physical interpretation of delta matter. Can it be a component of Dark Matter? 5) Confront the predictions of the model on the accelerated expansion of the Universe with the measurements of AdvACT. These observations will improve measurements of dark energy properties and test whether cosmic acceleration is due to the breakdown of General Relativity. So they are an ideal arena to test Delta Gravity at the largest scales.

AdvACT will trace the growth rate of structure using three independent measurements: CMB lensing; cluster counts and the galaxy momentum field.

Emergence of Gravity from a gap equation, Cosmology and Black Holes. Inspired in the technique of Spontaneous Symmetry Breaking(SSB) in non-perturbative Quantum Field theory, we propose to start from an action invariant under a larger symmetry than general coordinate transformations where there is no trace of a metric tensor. Minimizing the action, we obtain a gap equation that determines the vacuum. The vacuum breaks the original symmetry of the action to general coordinate transformations as appropriate to GR.

In a couple of works [28], we computed Einstein equations from this approach. Using our microscopic model of gravity, we want to study Cosmology of the early universe. In principle, we have control on the divergences of the model in the ultraviolet limit, so it is interesting to identify the dominant degrees of freedom relevant for the early universe, in the inflationary epoch. Again, comparison with the results of CACTUS-XMM, CLASS, Planck and BICEP2 will put very stringent bounds on the model. CLASS will measure primordial gravity wave B-modes from the epochs of recombination ($l \sim 70$) and reionizaton ($l<10$).

Another aspect of this approach is to study the emergence of Black Holes(BH) solutions from the microscopic theory. A particularly interesting idea that we want to incorporate in our model is contained in [32]. There a black hole is understood as a quantum Bose condensate of gravitons.

We expect to be able to compute the BH entropy from the microscopic theory.

This part of the project is done in collaboration with Prof. D. Espriu (Universitat de Barcelona).

Very Special Relativity and Gravitation. In this section of the Anillo, we are planning to extend the results of [33] to General Relativity. It is well known that non-abelian gauge theories can be cast in the language of differential forms. So we plan to express VSR non-abelian gauge theories in this language and translate this to the formulation of General Relativity in terms of forms [34].

VSR introduces non-local terms that are important in the infrared region. Thus we expect that new large scale effects must appear in VSR gravity that could be relevant for both Dark Matter and Dark Energy.

Within the collaborative effort of the proposed anillo, we find deep and fruitful connections with the work of N. Padilla in simulations of galaxy formation, Dark Matter and new theories of gravity; with R. Dunner providing data from observations of the CMB to be compared with the new proposed theories of gravity as well as the observations of MOONS(L. Vanzi) , L. Infante (BAOs,.the ISW effect,LSS surveys) and F. Barrientos(large scale structures and galaxy distributions).

Optical and Infrared surveys of galaxies (observational)

VST ATLAS and the u-band extension

Large-scale redshift surveys are prime probes of the “standard” lambda cold dark matter (LCDM) cosmology and galaxy formation and evolution. Some of the leading surveys are the SDSS, and particularly the $z \approx 0.35$ SDSS-LRG survey [35], and the recently completed WiggleZ Dark Energy Survey ($0.3 < z < 0.9$, [36]). These have detected the baryon acoustic oscillation (BAO) signal in the galaxy clustering [37, 38] with results consistent with a constant dark energy. Both surveys have also measured the rate at which structure grows in the universe [39, 40] with the WiggleZ result showing that LCDM cosmology describes our Universe out to $z \approx 1$. The BOSS [41] survey, currently in progress, will probe a large volume but is limited to low redshifts ($z < 0.6$).

There is clear motivation to extend these surveys to higher redshift to study the evolution of dark energy via BAO and gravitational growth rate. The growth rate measurements also allow us to test modified gravity models. These can have the same expansion history as a dynamical dark energy model but predict a growth rate that varies with both time and length scale, distinguishable from standard LCDM. At higher redshifts, the sensitivity to primordial non-Gaussianity is also greater. The volume enclosed in a given sky area is also larger which is ideal for testing whether the matter power spectrum shows the expected turnover to its initial Harrison-Zeldovich form. Thus moving to higher z will not only probe the evolution of dark vacuum energy but it will also probe conditions in the Universe close to the inflationary epoch.

To tackle these problems two groups have joint efforts, the UK ATLAS and the Chile u-band groups, led by T. Shanks and L. Infante respectively. They are carrying out a large imaging survey of the southern hemisphere sky with the European Southern Observatory VLT Survey Telescope (VST). On the one hand, the aim of VST ATLAS is to make a panoramic survey of the Southern sky to the approximate depth of the SDSS imaging survey in the North (e.g. [42]). Initially, during the first two years, VST will make an ugriz survey of area 4700 deg2 of VST. On the other hand, Chile (PI L. Infante) will be providing a second pass in the u-band to the VST ATLAS (the u-band extension) that will allow us a significant improvement of the detection of the Baryonic Acoustic Oscillations (BAO) scale while matching the expected depth of the X-ray AGN survey from e-Rosita. This u-band extension is thus improving the overall scientific potential of the ATLAS survey, benefiting all its related projects. The survey will become public in due time and will constitute an extraordinary tool for astronomical research.

This will be the largest cosmic volume ever surveyed in the southern hemisphere, capable of measuring large-scale modes past the turnover of the primordial spectrum. We will be able to put constraints on cosmology by studying the evolution of dark energy via Baryonic Acoustic Oscillations (BAO) scale, by testing of non-Gaussianity and by putting constraints on the evolution of gravitational growth rate. These data will allow accurate photometric redshift surveys of galaxies and quasars, which will be used to detect and study star forming galaxies and Lyman-break dropouts. In doing so, we will develop big data analysis tools, contributing to technological transfer and innovation, build up computing experience and implement the survey data in the UK OSA archive and in Chile’s AIUC archive. Researchers, students and postdocs will be trained in big data handling and analysis in preparation for the coming Large Synoptic Survey Telescope (LSST) era.

We will also perform mock catalogues of the VST ATLAS survey with the Chilean u-band to test the statistical methods applied to the data, in order to detect possible systematics in the statistical methods used. This in an of itself will be a great simulation challenge, as we will need to expand our capabilities for high-z mock catalogues beyond those currently available in our team. We will use the semi-analytic model [43] with the method to construct lightcones of the same sky area coverage as the VST-ATLAS u-band extension [44].

MOONS and massive spectroscopic surveys

Over the last two decades several observational keystones have dramatically changed our knowledge of the Universe. Measurements of the Cosmic Microwave Background, high-redshift supernovae and large-scale structure have revealed that 96% of the density of the Universe consists of currently unexplained Dark Energy and Dark Matter, and less than 4% is in the form of baryons. On the other hand, exploiting new large multi-wavelength surveys we are now able to trace this baryonic component from the local Universe up to the epoch of first light and reionization at $z>7$, when the Universe was just few hundred million years old. However, understanding the nature of these dark components - which dominate the global expansion and large-scale structure – and the physical processes that affect baryons and shape the formation and evolution of stars and galaxies, are still amongst the most fundamental unsolved problems in science. This leads to key questions for to be answered with the help of the next generation of instruments.

- Do we understand the extremes of the Universe?
- How do galaxies form and evolve?
- What is the origin of stars and planets?

Answering these key questions requires an accurate reconstruction of the assembly history of stars and galaxies over virtually all of cosmic time, to decode the building blocks of the Universe. Observationally, the imprint of Dark Energy or modification of the laws of gravity can be identified by accurate measurements of the growth rate of structure, while crucial insights into the properties of Dark Matter can be inferred from detailed studies of groups/clusters of galaxies and their clustering properties.

At the same time, comprehensive observations of the chemical and dynamical properties of stars in our own Galaxy can provide the fossil records to understand its star-formation and assembly history. However, to fully understand the physical processes driving the growth of galaxies and black holes, it is also essential to trace the evolution of galaxy properties (star-formation, metallicity, mass-assembly, etc.) as a function of cosmic time and environment. Ideally, such studies should be pushed up to the highest redshifts at $z>7$, where young Lyman-α emitting galaxies carry the key to understand the physics of the early Universe and cosmic reionization.

Addressing these fundamental science goals requires the accurate determination of physical properties and precise measurements of the three-dimensional distribution of stars in the Milky Way, and the 3-D distribution of galaxies at different epochs. This is only achievable with spectroscopy. For this purposes in recent years, several large spectroscopic surveys at optical wavelengths (0.3μ m - 1μ m) have been undertaken and have provided key information on the formation and evolution of galaxies in the local Universe and up to $z\approx 1$. However, they have arguably now reached their limits and spectroscopy at $\lambda > 1\mu m$ is now crucial to extend our knowledge beyond $z\approx 1$, through the redshift desert ($1.5<z<2.5$) and into the uncharted epochs at $z>7$. In fact, observations in the near-IR are essential because many of the objects of interest are red and therefore brighter in the near-IR compared to the optical, due to either i) extreme redshift, in the case of galaxies and black holes at $z>7$ or ii) dust obscuration, in the case of stars in the Bulge of our Galaxy and the extreme dust-enshrouded star-forming galaxies revealed by Herschel, or iii) age, in the case of the oldest, passively evolving galaxy population or iv) low intrinsic temperature, as in the case of low-mass stars in our own Milky Way.

Another key point to achieve these science goals is the ability to obtain spectra for a large number of sources over a wide area. In fact, this enables studies of representative cosmological/galactic volumes, accurate measurements of clustering properties, follow-up of rare objects and statistical samples of sufficient size for the determination of accurate galaxy properties as a function of redshift, mass, age and environment. However, not just the sheer number, but also the quality and resolution of the spectra are essential to derive accurate redshifts, proper classification of the sources (e.g. passive, star-forming, AGN), line fluxes and velocity widths to determine the physical properties.

Over the past decade a variety of precise cosmological observations have revolutionized our view of the Universe by showing that it is currently undergoing a phase of accelerating expansion [45, 46]. The origin of cosmic acceleration is one of the most important problems in physics as it poses fundamental questions about our current understanding of the basic laws of nature.

Within the context of general relativity, cosmic acceleration cannot be explained if the Universe is filled with matter and radiation only, implying that its energy-density budget must be dominated by a Dark Energy component, which counteracts the attractive force of gravity. Although we can infer the presence of this component, we know practically nothing about its nature, and there is currently no compelling theoretical explanation of its existence or magnitude. Alternatively, cosmic acceleration might indicate the failure of general relativity to describe gravitational physics on cosmological scales. In general, modifications to general relativity cannot be distinguished from dark energy models solely on the basis of observations of the rate of cosmic expansion but require additional measurements of the growth rate of large-scale structure with cosmic time.

As with the VST ATLAS survey, we will also apply our technique to build simulated lightcones to produce mock MOONS surveys. The definitions of the survey will be decided in forthcoming science workshops of the MOONS collaboration, and these will be replicated in our mock catalogues so that the different statistical measurements of galaxy evolution in the high-redshift survey can be tested with our mock catalogues.

The growth of structure. A fingerprint of the growth of structure is provided by redshift-space distortions. In spectroscopic surveys distances are inferred from the measured redshifts. In a homogeneous Universe the redshift of a galaxy would be given purely by the cosmological expansion, providing an accurate estimation of its distance. In reality, coherent motions generated by the gravitational growth of inhomogeneities induce peculiar velocities to the galaxies, which introduce an extra component in the observed redshifts leading to a difference between the real and the apparent position of a galaxy. This gives rise to a particular anisotropy pattern in the observed galaxy clustering, which contains information on the underlying matter distribution and can be used to probe the rate at which cosmic structures grow. Observations of this anisotropy pattern are expected to play a major role in the measurements of the growth of cosmic structures from future surveys [47]. Monte Carlo simulations show this anisotropy and evolving galaxies biases that affect these measurements can be overcome by observing large numbers of galaxies with redshifts. Therefore a large field of view spectrograph with 1000 fibers is the ideal instrument for tackling these questions.

Understanding how galaxies form and evolve over cosmological time is a key goal in astrophysics. Over the last decade our understanding of the underlying cosmology has improved to such an extent (e.g. [48]) that we now have a reasonable understanding of the structure formation in the underlying dark matter distribution [49]. The physical processes that affect baryons (e.g., gas heating and cooling, star formation) are more difficult to model than the gravitational growth of dark matter structure. This has prevented the development of a sophisticated cosmological simulation, or even of a simple analytical framework, to describe comprehensively the growth of galaxies in the universe.

Because of the many ways in which galaxies can build their stellar mass (e.g. many small bursts of star-formation, a few large bursts of star-formation, continuous or slowly declining star-formation) measurements of stellar mass and instantaneous star formation rate alone do not provide a complete picture of galaxy growth over cosmic time. Ideally we want to detect “transition states” such as post-starburst galaxies [50]. Additionally, stellar mass growth is only one aspect of galaxy evolution; measuring the build-up of metals and dust is equally important for understanding the properties of present-day galaxies [51]. Constraining the physical processes responsible for the observed evolution of galaxies requires good quality spectroscopic observations of the stellar continuum and a wide range of nebular emission lines within cosmologically representative large-volume samples (in order to facilitate meaningful comparison with theory).

The success of the SDSS optical survey of the “local” Universe has demonstrated the enormous power of assembling high-quality spectroscopy for ~ 1 million galaxies and active galactic nucleii (AGN) from, e.g., SDSS DR8 . Both size and spectral quality have been key to the success of SDSS: (i) the size has enabled the astronomical community to subdivide galaxy samples by redshift, luminosity, colour, morphology etc. while still retaining sub-samples with sufficient size/statistical-power to achieve robust measurements of the interdependence of key physical parameters such as age, metallicity and stellar mass; (ii) the unprecedented quality of SDSS spectra (wide wavelength range, high SNR per-pixel, superb calibration) made SDSS the first large galaxy “redshift” survey to also provide measurements of stellar and gas-phase metallicities, accurate instantaneous star formation rates, dust contents, star formation histories, and properties of central AGN. All these parameters are required to start to understand the complex baryonic processes occurring in galaxies

However, because the SDSS was undertaken with a relatively small, optical, ground-based telescope, it can tell us very little about the evolution of even the most massive galaxies beyond $z \sim 0.5$. Most stellar mass was formed at $z > 0.5$ therefore to really understand the dominant physical processes responsible for galaxy evolution over cosmic time, we must have access to similar information (i.e. rest-frame wavelengths $0.35\mu m < \lambda\_rest < 0.9\mu m$) at $z > 0.5$. Only a NIR spectrograph on a larger telescope can provide this. Some examples of science achievable from a survey providing SDSS quality spectra of z ~ 1 galaxy are (references are to SDSS results at z~0.1):

- Observe the evolution of the bimodality in galaxy characteristics, such as stellar mass and star formation rate [52, 53].
- Accurately determine the relation between galaxy stellar mass, SFR and metallicity as a function of cosmic epoch, crucial for understanding the chemical build-up of galaxies [51, 54].
- Study the effect of local environment on the structural and stellar population differences of galaxies. At low redshift the SDSS showed this effect was surprisingly weak [55], but results may be very different at high-z.
- Study the effect of recent star formation history on the presence and accretion rate of central AGN during the epoch of most rapid galaxy and black hole growth [56].

Optical and Infrared surveys of galaxies: MOONS INSTRUMENT

One of the goals of project Anillo ACT-86 was to involve the AIUC into the construction of a major astronomical instrument for a large telescope. The first AIUC work in this sense was the participation in the answer to the ESO call for the E-ELT instruments. The AIUC participated as part of the international consortium that proposed SIMPLE, a high resolution spectrograph for the near IR spectral range. The idea was selected by ESO and a phase A study was developed by the consortium. SIMPLE though was not selected as first light instrument for the E-ELT; possible initiative to follow up this line of work are currently being examined by all interested parties (including the AIUC). Later the AIUC was involved in a new project to answer the call for ideas for a new multi object spectroscopic facility for a ESO telescope. We joint a new international consortium led by the ATC-UK and proposed MOONS. The idea was selected by ESO for a phase A study (made during 2012-2013) and then for the detailed (2013-2014). At the end of this process the project was approved for construction and funded by ESO at a base level of 6.2 MM Eur. The total cost of the instrument in hardware is 8.4 MMEur. The difference in cost must be provided by the consortium together with the nearly 180 FTE needed to build the instrument. In exchange for this effort the consortium will receive a significant amount of guaranteed observing time (> 300 nights, equivalent of 30,000 euro per night) at the VLT+MOONS. In September 2014 the formal agreement between ESO and the MOONS consortium was signed (see http://www.eso.org/public/announcements/ann14072/). The aim is to have MOONS operational by 2019.

The consortium of MOONS is led by the UK Astronomy Technology Center UK-ACT and includes the Italian National Institute of Astrophysics INAF, the French CNRS, Observatoire de Paris and University Paris Diderot, the Portuguese Center of Astronomy University of Lisboa CAAUL, the Dutch NOVA Optical IR Lab and the Astro-Engineering center at Universidad Catolica (AIUC). The AIUC participation in MOONS is large, about 8%, and requires strong support. The AIUC will provide the entire fibre metrology system whose hardware cost is estimated in 70.000 Eur and will require about 3 FTE, the AIUC will contribute with the installation of 150 fibre positioning systems with a total cost of 75.000 Eur and finally the AIUC will provide the entire instrument control software which will require 12 FTE.

MOONS is the ideal instrument to provide the essential deep spectroscopic follow up of imaging surveys undertaken with facilities in optical and near-IR (VISTA, UKIDSS, VST, Pan-STARRS, Dark Energy Survey, LSST) and facilities operating at other wavelengths (ALMA, Herschel, eRosita, LOFAR, WISE, ASKAP).

MOONS will play also an important role for the recently approved ESA mission Euclid, covering the same spectral range of the space observations and provide uncontaminated and higher resolution spectra of galaxies that will be very useful to independently assess the level and impact of spectral "confusion", as well as to investigate and correct potential biases introduced by slitless spectroscopy (e.g. redshift accuracy, success rate, emission line properties, galaxy types, etc).

The grasp of the 8.2m Very Large Telescope (VLT) combined with the large multiplex and wavelength coverage of MOONS – extending into the near-IR – will provide the observational power necessary to study galaxy formation and evolution over the entire history of the Universe, from our Milky Way, through the redshift desert and up to the epoch of re-ionization at z>8-9. At the same time, the high spectral resolution mode will allow astronomers to study chemical abundances of stars in our Galaxy, in particular in the highly obscured regions of the Bulge, and provide the necessary follow-up of the Gaia mission. Such characteristics and versatility make MOONS the long-awaited workhorse near-IR MOS for the VLT, which will perfectly complement optical spectroscopy performed by FLAMES and VIMOS.

Instrument

The baseline design consists of ~1000 fibers deployable over a field of view of ~500 square arcmin, the largest patrol field offered by the Nasmyth focus at the VLT. The total wavelength coverage is 0.6-1.8µm and two resolution modes: medium resolution and high resolution. In the medium resolution mode (R~4,000-6,000) the entire wavelength range 0.64m-1.8m is observed simultaneously, while the high resolution mode covers simultaneously three selected spectral regions: one around the CaII triplet (at R~9,000) to measure radial velocities, and two regions at R~20,000 one in the J-band and one in the H-band, for detailed measurements of chemical abundances.

In order to enable the exploitation of the full 25 arcminute field of view (FOV) of the VLT Nasmyth focus, the use of a field corrector is necessary. The corrector is formed by two large lenses with approximately 110 mm of thickness in the axis and a diameter of 880 mm. The first lens is a plano-convex and the second is a symmetrical biconcave; this option allows minimizing manufacturing costs without influencing performances. To provide a glass internal transmission better than 95% for the full MOONS wavelength range (800 nm to 1800 nm), the selected material is Fused Silica. Compared to a no-corrector option, this corrector improves the image quality over the full FOV by a factor of 8, better than 0.1 arcsec (80% geometric energy for full FOV), the exit pupil is practically concentric to the field curvature and the field curvature is reduced to half (from a radius of 2090 mm to 4210 mm).

The fibers for science observations are deployed on the focal plane via a fiber positioner. Due to the different requirements on sky subtraction for bright and faint targets, the pick-off system must be able to allocate the 1000 fibers both independently – e.g. all on different targets – or in pairs to perform the cross-beam switching, in which each target has got its dedicated sky fiber at a distance of few arcsec. Another key requirement for the positioner is the reconfiguration time, which should be < 5 minutes in order to have acceptable overheads. For the Phase A study two possible implementations have been considered: a micro-mechanical pick-off system and a pick and place spine system.

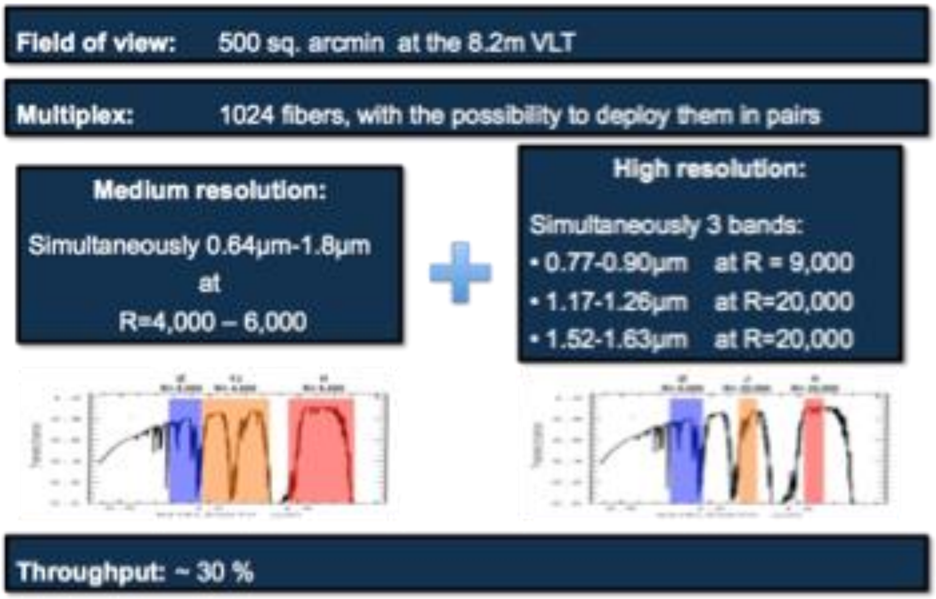
In the micro-mechanical pick-off solution the idea is to cover the focal plane with modular fibre positioners each of which has a fixed patrol area. In this concept design each pick-off unit has got two rotating arms (as shown in Figure 2). To cover the Nasmyth focal plane with ~1000 units, each positioner should have a physical size of ~30mm in diameter, which corresponds to ~1 arcmin on sky. In order to have a high allocation efficiency of the fibres on targets, some overlap between neighboring patrol fields is needed, with one fibre being able to patrol up to the centre of the neighboring cell.

The baseline design of the MOONS spectrograph consists of two identical cryogenic spectrographs [57]. Each of them collects the light from over 500 fibers and feeds, through dichroics, 3 spectrometers covering the ”I” (0.64–0.94 µm), ”YJ” (0.94–1.35 µm) and ”H” (1.45–1.81 µm) bands, simultaneously (see Figure 3 and Table 1). The low resolution mode provides a complete spectrum with a resolving power ranging from R>4,000 in the YJ-band, to R>6,000 in the H-band and R>8,000 in the I-band. A higher resolution mode with R>20,000 is also included. It simultaneously covers two selected spectral regions within the YJ and H bands. The whole spectrometer is in a vacuum vessel cooled to cryogenic temperatures. Each spectrograph, utilizes two Hawaii-4RG-15 devices, from Teledyne Imaging (one for the YJ and one for H-band channel) and one 4k x 4k optical CCD from e2v technologies for the I-band channel.

MOONS metrology

Mapping of the fibre positioners will be necessary to compensate for geometric errors. In principle this could be a one-off calibration carried out at the AIT stage. However it would be useful to have on instrument

Fig 2: Fiber positioner design in MOONS focal plane.



Field of view: 500 sq. arcmin at the 8.2m VLT

Multiplex: 1024 fibers, with the possibility to deploy them in pairs

Medium resolution:

Simultaneously 0.64μm-1.8μm
at
R=4,000 – 6,000

High resolution:

Simultaneously 3 bands:

- 0.77-0.90μm at R = 9,000
- 1.17-1.26μm at R=20,000
- 1.52-1.63μm at R=20,000

Throughput: ~ 30 %

Fig 3: Optical and infrared bands for MOONS.

Parameter	Specifications		
Telescope	VLT		
Field of View	500 arcmin^2		
Multiplex	1000 objects, with possibility to deploy fibre pairs (500 obj+500 sky)		
Sky-projected diameter of each fibre	1.05 arcsec		
Close packaging	At least two fibres within 10 arcsec		
Observing modes	medium resolution (MR) and high resolution (HR)		
Simultaneous λ-coverage in MR	0.64μm - 1.8μm		
Resolving power in MR	R ~ 4,000 – 6,000		
Simultaneous λ-coverage in HR	[0.76μm – 0.9μm] +	[1.177μm – 1.268μm] +	[1.521μm – 1.635μm]
Resolving power in HR	R~9,000	R~20,000	R~20,000

Table 1: Technical specifications for MOONS

feedback of the exact fibre positions. This can provide information to avoid clashes on initialization and feedback on the fibre positions once deployed. There are other potential benefits such as dealing with contractions (thermal variation) or replacement of positioners and possibly flexure compensation (the fibers can be moved to compensate if required).

The 1000 optical fibers will be moved by 2-DOF (degrees of freedom) fiber positioning units (FPU) which have been arranged in a configuration similar to that of a SCARA robot, which allows to position the fibers anywhere within a 70 mm disc around each FPU. The arrangement of the FPUs is such that the entire focal plane having 880 mm in diameter can be completely covered by the overlapping work areas of each positioner. The FPUs are arranged in a honeycomb-like subdivision of the focal plane as shown in Fig. 4, thus the grid of hexagons with the FPUs will be referred to as focal plane array (FPA). Each FPU employs Faulhaber DC-motors with encoders having 2048 counts per revolution and backlash-compensated planetary gear-heads with a very large speed reduction ratio of over 2000:1. Therefore, the positioning accuracy achievable with the feedback from the encoders is expect to be around 50 μm. However, the system requires that each fiber is positioned with an error smaller than 15 μm with respect to the reference observation position. To achieve such positioning accuracy requirement, a metrology system capable of providing position measurements with an accuracy of 7.5 μm has been designed.

The current concept of the metrology system consists of a circular array of 12 cameras located on VLT's de-rotator ring around the Nasmyth focus shown in Fig. 5. In other words, multiple off-axis cameras are employed unlike the metrology of the Prime Focus Spectrograph (FPS) of the Subaru telescope, in which a single camera is located at the Cassegrain focus to directly image the fibers on the focal plane of the prime focus. This ideal on-axis location is not possible in the case of VLT due to other instruments in the telescope's calibration arm with which the metrology system for MOONS must not interfere. Another aspect that is to be noted is that each FPU's workspace may not only contain its corresponding fiber, but can also be populated by the fibers of the six neighboring FPUs. This requires the metrology system to uniquely identify each fiber and its associated FPU. Since the fibers are covered by an optical lens with a 2.7° field of view and the cameras are mounted off-axis, with a significant slant angle with respect to the optical axis, the approach of using back-lit fibers as implemented for the FPS of Subaru2 for fiber identification and location is not feasible. Thus, the fiber identification system for MOONS requires a set of reflective coded targets. The reflective targets are fixed around the fiber, as explained later in this paper, instead of employing back-illuminated fibers, which would have been the ideal situation if a single on-axis camera could have been used.

Since the metrology system produces 12 views of overlapping regions of the FPA, an alignment procedure of the results to a common coordinate reference frame must also be implemented.

The metrology system has to be able to resolve the position of each fiber of MOONS with an accuracy of 7.5 μm or better in order to achieve a positioner control accuracy of 15 μm. Covering the whole FPA with the required 7.5 μm resolution using a single camera is already challenging considering that the FPA has 880 mm in diameter. A brute force approach would require a camera 120k×120k pixels (14.4 Giga-pixels!). This number can of course typically be reduced using centroiding techniques by an order of 10 (cf.3) and theoretically even to microfractions of a pixel under very specific conditions and accurate sensor characterizations. Therefore, a conservative centroiding-based solution with a 1/10 pixel accuracy using a single-camera would involve a sensor with 12k×12k pixels, which is still beyond the large format commercial sensors that can be found with sizes like 8k×6k (e.g. Kodak KAF-50100 CCD) and 13k×9k (Canon APS-H CMOS). For this reason, in addition to the previously mentioned fact that the metrology system must be mounted off-axis, it was decided to use an array of cameras. The camera chosen for the metrology system is the IDS UI-1490SE-M-GL camera, which has an Aptina CMOS 3840×2748 pixels sensor. The main characteristics of the sensor are summarized in Table 1.

Considering the sensor dimensions and the position (orientation and working distances) of the metrology cameras with respect to the FPA as depicted in Fig. 5, the lenses' focal length, the cameras' FOV and their working areas were calculated. A ray-tracing routine was also implemented to compute the actual area covered by each pixel on the spherical surface of the FPA as shown in Fig. 4 for the array of twelve cameras. From these computations it was possible to determine the raw spatial sampling resolution of the FPA. Due to the fact the cameras are not orthogonal to the FPA's surface, the spatial resolution is not uniform. The computed values are listed in Table 1. The raw resolution in the worst case is approximately 100 μm, which has to be reduced by a factor of 1/15 in order to ensure the required positioning accuracy. Sub-pixel accuracies of the order of 1/10 pixel are possible with standard centroiding techniques and further improvements using noise reduction techniques that rely on PSF modeling allow to achieve 1/20 to 1/25 pixel accuracies.

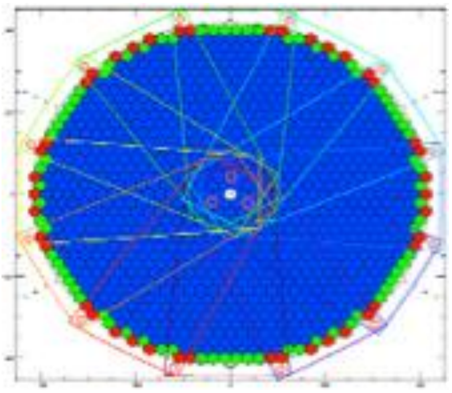


Fig 4: Metrology cameras FOV on MOONS focal plane.

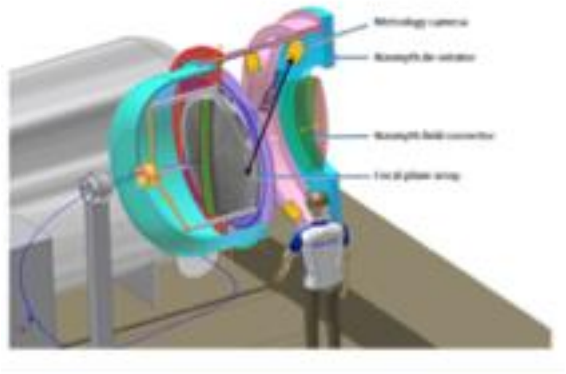


Fig 5: Retractable rotator ring for metrology design.

MOONS Software

The MOONS Instrument Control Sub-System (MICS) is responsible for the control and monitoring of all the instrument parts. This sub-system will be based on several servers and software that can interact with the telescope and thus has to be designed and developed according to the strict ESO standards (VLTSW).

At the hardware level the system includes local controllers (MICE) that supervise and control the spectrographs and fiber positioners (FPS) Fig. 2. The MICE is based on PLCs and are designed to control:

- The MOONS Calibration Sub-system (MCS)
- The MOONS Secondary Guidance Sub-System (MSGS)
- The Fibre Positioning Sub-System (FPS)
- The Fibre Positioning Measurement Sub-System (FPMS)
- The MOONS Triple Arm Spectrographs (MTAS)

In the framework of the MICS the AIUC will develop the following specific systems:

- The sequencer scripts (SEQ): This is high level sub-system in the context of the VLTSW where there are included the logic of observing, science algorithms, coordinate conversion and some basic instrument diagnostic tools.
- MOONS (SOS): This is the observing sub-system that controls and coordinates the sub-systems MOONS1 and 2. This is to simplify them operation of the system by using a modular approach.
- MOONS1: This subsystem controls the two spectrographs hardware and interacts with the detector (DCS) to synchronize with the image capture.
- FPMS (DCS): Sub-system that allows the communication of the results obtained by the FPMS with the sub-instrument control MOONS2 (OS). It handles the configurations and status machines, and simulation of the FPMS.
- FPMS: Corresponds to control interface of the 12 high resolution cameras. This is in charge of the acquisition and online processing of the images. Based on the photogrammetry algorithms it will resolve the positions of the 1000 optical fibers.

The participation of the AIUC in MOONS is large and it requires strong support. As mentioned above the AIUC will provide the entire fibre metrology system whose hardware cost is estimated in 70.000 Eur and will require about 3 FTE, the AIUC will contribute with the installation of 150 fibre positioning systems with a total cost of 75.000 Eur and finally the AIUC will provide the entire instrument control software which will require a total of 12 FTE, 5 of which will provided in the context of this proposal.

We will develop the full metrology system of MOONS in the AIUC Lab, this system will then be implemented and tested in the Labs of the ATC of Edimburgh before going back to Chile for the installation in the VLT. The first light of the instrument is foreseen in 2020. The metrology of MOONS will be completed within the time scale of this project i.e. 2018. The software control of MOONS will be developed according to the ESO VLT standards by the AIUC in collaboration with the Chilean private company BlueShadow. We will install a MOONS office in the Innovation Center UC Anacleto Angelini. As partners in the development of MOONS, we will also develop experience and know-how in the design and implementation of high accuracy micro-positioning actuators. The mechanics, electronics and control software for two MOONS fiber positioners will be entirely built here in Chile. The performance of the high precision actuators will be compared and validated against the other set of actuators built by the collaborating group at the Astronomy Technology Centre in Edinburgh. Our participation in this aspect of the MOONS instrument will play an important role in future projects with ESO or other research groups in which the capability established in Chile to develop high precision actuators will be a key asset, especially for instruments that will become part of the astronomical infrastructure in the country. On the other hand, maintenance of new instruments will also require highly qualified engineers and researchers capable of solving advanced manufacturing and system integration challenges, as well as new software requirements associated to leading edge astronomical instruments.

Human capital training and formation

One of the main goals of this effort is to produce new experts to increase the number of chilean technicians and scientists working in this kind of technologies and servicing the experiments hosted in the country. This will help us to overcome the critical mass required to participate in increasingly more challenging technologies, assuming more demanding roles within large instrumental projects and gaining leadership within the science being made, leaking at the same time experts into other areas of the national technological

industry, injecting new capabilities and knowhow that can be used in a wide variety of economical activities for the country.
We expect to have at least 3 students working with each professor associated to the Anillo at every time, which means nearly 30 students trained in technical matters, including computer science, electronics, optics, cryogenics and mechanics.

International Cooperation

All the activities that will be developed as part of this project will be based on extensive cooperation within our team at the AIUC and with international partners. In this way we will fully exploit the opportunity offered by the privileged conditions offered by Chile for ground based observational astronomy to develop and bring to Chile high technologies from abroad. Our international partners are among the leading institutions in the most advanced technologies for astronomy. The MOONS consortium includes some of the most experienced teams in astronomical instrumentation. The UK-ACT is a leading technological center in Europe with decades of experience in the development of highly advanced astronomical instruments (http://www.stfc.ac.uk/ukatc/default.aspx). On the other hand, our collaborations with CMB experiments have opened prolific exchange opportunities with important universities like Princeton University, Johns Hopkins University, University of Pennsylvania and UC Berkeley. Collaborating with these institutes we will have the unique opportunity to take advantage of their experience and to work with top level professionals. The students members of our team will access the unique opportunity to be exposed to a highly stimulating environment. All members of our team (including students) will have the opportunity to make short to medium term visits abroad, we will host visits of scientists and engineers from abroad.

Dissemination of results and knowledge transfer to non-academic environments.

An important specific goal of this project is to invest in transferring the results of our work to the society in terms technology, development, scientific knowledge and culture. Our plan to succeed in this involves three main points. i) establish contact with Chilean companies interested in taking advantage of the area of astro engineering to acquire and develop new know-how and/or technologies ii) form a new generation of young professionals interested in technology and science and motivated to start new ventures in the field of astro engineering in the form of spin off companies related/supported to the AIUC iii) boost a powerful program of outreach in science and technology.
Contacts with a few companies in Chile were already established in the frame of Anillo ACT-86, some of them are heavily involved in the work presented as part of this proposal. The AIUC and its members are actively committed training young scientists and high level professionals. We created a program of courses in the area of Astro Engineering and, since its creation, the AIUC hosted already tens of undergraduate, graduated students and postdocs. With proper support we expect this trend to grow in the near future.
PUC owns the Historic UC Observatory Manuel Foster, which was installed in 1903 on the Cerro San Cristobal, in what today is a central area of the town. The observatory is equipped with a 1 m telescope and with a prism spectrograph, both original from the installation time, i.e. older than 100 years, which contributed significantly to the spectral survey of stars in the southern hemisphere. In 2010 the observatory was declared historic monument. The IA and AIUC started a work to recover this resource and to create a center of dissemination of science and technology. As a first step in 2012 we started to receive visits in occasion of the yearly National Heritage day. Starting in 2013 we opened the observatory to schools during the week of Science. In few years only, the observatory received hundreds of visits. We started a project to recover the observatory photographic archive and to digitalize the old spectroscopic plates. Finally, with the support of the University, we engaged in a project to create a museum that will exploit the huge potential of the site. Because the main value of the observatory is its technological equipment, it is the perfect place where our project Anillo can reach the public. The main researchers of this proposal are part of the team that have been working on the Foster project during the past years, because we are also leading major projects of Astro Engineering in Chile, we believe to have all the elements needed involve the public. Incidentally one of the main lines of our current work is spectroscopy and in particular spectroscopic surveys, therefore perfectly aligned with the tradition of research that during many decades was developed by UC astronomers at the Foster Observatories, with the technologies available at that time. The privileged access to the historic perspective of surveys allows us to create a powerful frame to our work. PUC, the IA, AIUC and the School of Engineering UC have a press office highly committed with the involvement of the public. For instance, thanks to the work of the UC outreach office, the MOONS agreement signed in September 2014 was widely covered by the national news (Emol, LUN, Financiero). We plan to invest a fraction of the resources of the Anillo to support the Foster project and through it transmit our results to the society.

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