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FRENCH CHILEAN LAB FOR ASTRONOMY: TEN YEARS OF FRUITFUL COOPERATION

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Abstract. The French Chilean Laboratory for Astronomy (FCLA), located in Chile, is an International Research Laboratory (IRL 3386) between the French National Center for Scientific Research (CNRS) and three major Chilean universities (Universidad de Chile, Pontificia Universidad Católica de Chile, and Universidad de Concepción) with the goal to promote and forge fruitful long-term collaborations between France and Chile in the field of Astronomy. In the context of the 10th year anniversary of FCLA, we have decided to review its status, origin, mission and main scientific and collaborative activities. This is a necessary step for nurturing our prolific cooperation to prepare the rich future of ground-based Astronomy in Chile (LSST, CTA, ALMA, ELT) in key science fields (Solar System, planetary formation, exoplanets, stellar physics & galaxy evolution and cosmology).

1 Status, motivation & origin

1.1 CNRS international coorperation toolkit

The CNRS encourages its research units to work with leading laboratories around the world. In this regard, cooperative resources (see Fig. 1) are designed to help the organisation's researchers and their foreign partners to find the best-suited ways of achieving the type of collaboration they wish to establish. In this framework, International Research Laboratories (IRLs) * are international schemes in which research work is jointly conducted around a shared scientific focus (see Fig. 2). They structure, within an identified location, the significant and lasting presence of scientists from a limited number of French and foreign research institutions (a single foreign partner country). They are developed over a year, during which a cooperation agreement is negotiated between the various French and international supervisory bodies involved.

Fig. 1. CNRS international cooperation tools

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*https://international.cnrs.fr/en/cooperer-a-l-international/

Fig. 2. CNRS International Research Laboratories and representative offices

1.2 Why an IRL for Astronomy in Chile?

The motivation of the creation of an IRL for Astronomy in Chile has been driven by:

- The strategic position of Chile for ground-based astronomy (sse Fig. 3), including excellent quality of its sky, the little light pollution and the access to the site, many large projects in operation/progress: ALMA (starting 2012), VLT/I, ELT, LSST, CTA, and important involvement from various countries (USA, China, Europe. . .),
- A long history of scientific cooperation with France (Europe) considering that the 1st IRL has been created in Chile in 2000 (IRL-CMM), with Europe with more than 50 years of European - Chilean Collaboration through ESO in Astronomy,
- A generally shared vision of scientific cooperation including the importance of the human dimension, projects involving the supervision of students, postdocs & young researchers, and innovative and competitive joined projects (ANID, ECOS, ANRs, ERC. . .),
- The specificities of the Chilean Astronomical Community, an expanding, and talented community, strong decision-making power within the universities, a young ministry of science with no current national "Decadal" but joined initiatives (LSST-AlerCe), and the fact that Chile is not a formal member of ESO, but it is the host country. Various aspects for which the French community could contribute and assist the Chilean community in its development and growth.

1.3 FCLA genesis and mission

The French Chilean Laboratory for Astronomy (FCLA)[†], located in Chile, is an International Research Laboratory (IRL 3386) between the French National Center for Scientific Research (CNRS) and three major Chilean universities (Universidad de Chile, Pontificia Universidad Católica de Chile, and Universidad de Concepción) with the goal to promote and forge fruitful long-term collaborations between France and Chile in the field of Astronomy. First founded in 2012, the agreement was recently renewed in the context of the 80 years anniversary of CNRS in 2019 in Santiago with the rich perspective of the growing and prolific Chilean astronomical community, and the development of ambitious and major astronomical facilities in Chile (LSST, CTA, GMT, ELT) in the upcoming decade. More than ever, Chile has become a major international centre for ground-based astronomy. Given the strong scientific and human connection between France and Chile for several decades, the Lab plays a central role to nurture this collaborative endeavour between both countries. In addition to

[†]https://www.fcla.cl/

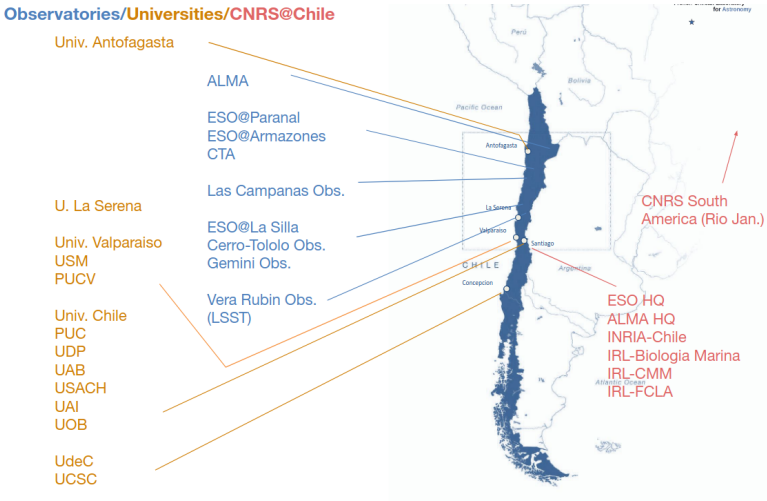

Fig. 3. Institutional landscape in Astronomy in Chile

the professors and students at the three Chilean universities, the Lab counts on the presence of up to four permanent French researchers and on the existence of a visiting program to promote and support French and Chilean students and researchers for shorter term stays and internship (see Fig. 4).

2 Scientific activities

The research that has been and is being carried out at the FCLA concerns a wide range of topics in modern astronomy, ranging from meteors to the high redshift Universe. At present, collaborative projects being developed at FCLA are detailed below, including long-lasting collaborations started in 2012 (see Fig. 5).

2.1 Arc tomography

This collaboration includes Sebastián López, Pasquier Noterdaeme, Felipe Barrientos, Nicolás Tejos, Cedric Ledoux, Evelyn Johnston, Giuseppe D'Ago. The properties and distribution of gas around galaxies (the so-called circumgalactic medium, CGM) is key to the understanding of galaxy evolution. Until recently, absorption line spectroscopy towards bright background point sources provided the only way to probe CGM of distant galaxies. While information can be obtained using a large number of lines of sight, the spatial structure is expected to depend on the host galaxy properties. In this context, the technique of gravitational arc tomography has recently been pioneered in Chile: Integral field spectroscopy of gravitationally stretched sources provides hundreds of spectra that contain absorption-line information of intervening galaxies in the field. Pasquier Noterdaeme has joined this "ARCTOMO" team, bringing his expertise on absorption line studies and derivation of gas incidence.

2.2 Gas in quasar environments

This collaboration includes Sebastián López, Pasquier Noterdaeme. The evolution of bright active galactic nuclei (quasars) and their massive host galaxies is expected to be strongly linked together, not only because both the star-formation and growth of the supermassive black-hole depends on the supply of gas, but also because the release and propagation of radiative and kinetic energy from the accretion disc to the galaxy interstellar medium. However, studying the gas around quasars in the distant Universe is difficult, owing to the bright glow of the nucleus, together with a loss of sensitivity and spatial resolution. Pasquier Noterdaeme has recently proposed to use a recently discovered population of proximate molecular absorbers (i.e. at the quasar redshift) to bring fresh new clues on the complex issue of AGN feedback. The project makes use of multi-wavelength spectroscopy both in absorption and emission, and benefits from wide observational expertise of Chilean astronomers.

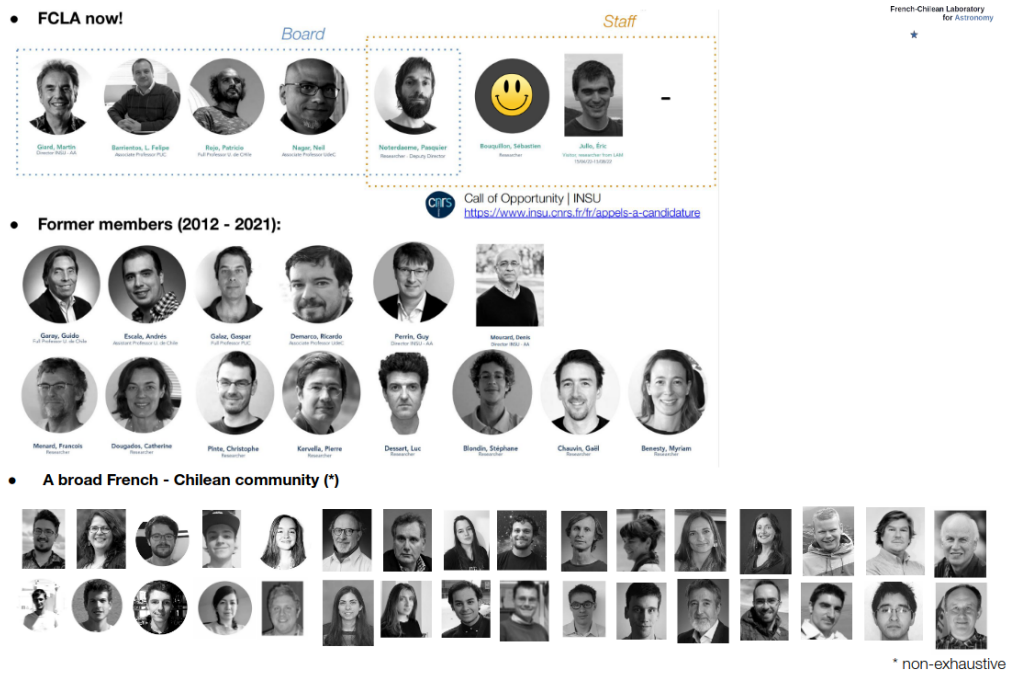

Fig. 4. FCLA members (current and past) and community

2.3 Exploring the limits of digital astrometry and photometry of "moving celestial objects"

This collaboration includes Sebastien Bouquillon, René Méndez, J. Silva, M. Orchard, J. Vaubaillon, F. Colas and D. Souami. In this framework, "moving celestial objects" represent objects close to the Earth for which the Point Spread Function (PSF) on a digital detector is trailed. These objects are, for instance meteors or fireballs in Earth's atmosphere, space debris, artificial satellites and asteroids, specially the closest ones, such as the Near Earth Objects (NEO), Mars-crossers and main belt asteroids. The main aspects of this research project are the following: 1/ Improvement of existing PSF models of moving objects which have to be consistent with the PSF of non-moving objects, to allow for a good astro-photometric calibration of the frames, 2/ Characterization of the precision limits for the joint estimation of photometry and astrometry of moving sources based on the Cramer-Rao lower bound. This part of the project is an extension of the preliminary study conducted by S. Bouquillon and R. Mendez in 2017 on the astrometry of this kind of object (S. Bouquillon et al. A&A 2017), and 3/ Implementation of these new estimators in our reduction code to achieve measurements with a precision as close as possible to the theoretical lower bounds. These improvements will be first applied and validated in the framework of the following ground based astronomical observations in which the FCLA is involved: The Gaia Ground Based Optical Tracking (GBOT) (details here: http://gbot.obspm.fr); The GBOT Asteroid Survey (GBAS) (details here: gbot.obspm.fr/asteroids); Astrometry and Photometry of Meteors and Fireballs with CABERNET and FRIPON networks (details here: https://www.fripon.org/).

2.4 Planet-forming disks

This collaboration has included/includes Myriam Benisty, Laura Pérez, Nicolas Cuello, Simon Casassus, Jorge Cuadra, Sebastian Perez, Bill Dent, Marion Villenave, Paola Pinilia, François Ménard, Christophe Pinte, Miriam Keppler, Antonella Natta and Thomas Henning. We are interested in studying young disks around a sample of Herbig AeBe stars and T Tauri stars with SPHERE/VLT and ALMA, VLA. With SPHERE, we will trace the small grains in the upper layers of the disk at scales of tens of AUs. The combination of optical and near-IR images, unique to SPHERE, allows us to constrain the properties of the dust grains at the surface layers (size, porosity). The images provide constraints on the distribution of small grains by resolving features (such as gaps, warps, spiral arms, dips) in the surface layers at typical scales of few tens of AU. We measure the contrast of these features with the background disk, and measure their location. We can relate these constraints to the mechanisms of disk evolution and look at the time variability of the features, which, if observed, would

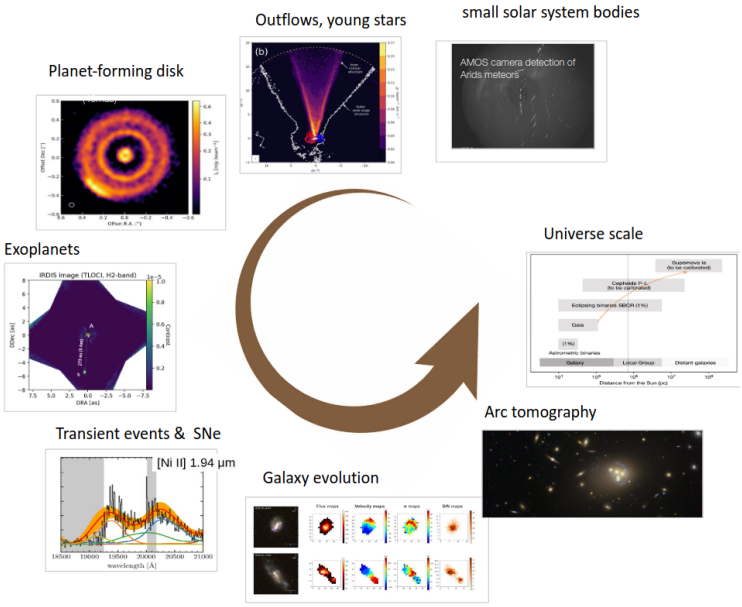

Fig. 5. Illustrations of key scientific results and prospects from meteors to the high redshift Universe obtained at FCLA

indirectly indicate a perturbation in the inner disk. For the objects observable with SPHERE, complementary observations with ALMA and NOEMA are already available in the archive, albeit at moderate spatial resolution of 0.2" and more. Such observations enable to probe the distribution of large grains and of gas at similar spatial scales (but in colder layers close to the disk mid-plane), and to measure any surface density and temperature perturbation deep in the disk.

To form planets, dust in disks around young stars must grow in size by several orders of magnitudes. One of the pressing issues is to measure the growth timescale and identify the physical mechanisms involved. With this programme, we therefore look for the effects of dust accumulations in pressure maxima (or particle traps) and search for a spatial segregation of small and large grains which may constrain the properties of embedded planets, and variations of the spectral index. A spatial discrepancy between small/large grains (traced by complementary sub-mm observations) would indicate dust filtration, induced by a planetary companion, or by hydrodynamical instabilities. Planetary systems are formed inside proto-planetary disks. To understand the formation of planetary systems it is of prime importance to determine their chemical composition. One of the most important questions is the heritage: is the chemical composition of the original gas kept during the stellar and planetary formation? How does the composition of planetary disks differ from the one of their parents, the protostars and protostellar cores? Are the most primitive objects of our solar system, namely the comets and some meteorites, formed from unaltered protostellar or interstellar material? Some signs make one think this idea is correct. With ALMA, we are carrying out dedicated observations with unprecedented sensitivity and spatial resolution. The spatial resolution of this radio-interferometer is of the order of 0.01 arcseconds, i.e. several AUs at a distance of 100 pc. At the same spatial resolution (1 arcsecond) ALMA is about 10 times more sensitive than today's instruments allowing the observation of many more chemical species that can be analyzed with the help of our radiative transfer and chemical models, to determine the chemical composition of proto-planetary disks and their evolution.

2.5 Exoplanets: accretion, atmospheres & architectures

This collaboration includes Gael Chauvin, Patricio Rojo, Laura Perez, James Jenkins, Sebastian Jorquera, Pantoja Blake, Amelia Bayo, Johan Olofsson, Nicolas Godoy, Virginie Faramaz, Alice Zurlo, Hervé Beust, Mickael Bonnefoy, Philippe Delorme, Anne-Marie Lagrange, David Mouillet, Arthur Vigan and Nuria Huélamo. The goal is to provide theoreticians with direct observables of accretion-markers in young exoplanets to test if giant planets share similar accretion processes with stars and brown dwarfs. This can be connected with the disk properties, morphology and chemistry explored thanks to the combination of multi-wavelengths high-

angular resolution instruments (NaCo, SPHERE, ALMA, MATISSE, ERIS). The disk asymmetries (cavity, gap, hole, clump, vortex...) can also constrain the presence and properties of planetary perturbers. Two observing programs dedicated to the search of young accreting proto-planets in transition disks with NaCo in thermal imaging and SPHERE using ZIMPOL in Hα imaging. Moreover, with the past two decades have been critical to improve our vision and knowledge of cool sub-stellar atmospheres with the extension of the standard classification of stars (MK system) to the so-called "L", "T" and "Y" spectral types, now commonly used in Astronomy for low-mass stars, brown dwarfs and giant exoplanets. Today, most imaged exoplanets are young, late-M or L-type, massive planets with dusty atmospheres. In this context, we have initiated with the X-SHYNE (X-SHooter medium-resolution near-infrared survey for Young, Nearby Exoplanet analogs) program aimed at characterizing, at medium resolution, the near-infrared spectral energy distribution of thirty young brown dwarf analogs to exoplanets, recently identified in young, nearby associations. This population of early-L to L/T-type isolated planetary-mass objects, with known distances and ages, offers ideal laboratory to explore the physical processes at play in comparable atmospheres to the ones of known imaged exoplanets. Finally, a third project is devoted to the characterization of extreme planetary systems in the configuration of close binaries that offer an ideal laboratory to test predictions of planetary formation theories in extreme conditions. In this context, a VLTI/GRAVITY, VLT/SPHERE and SOAR program (PI: Chauvin and Mendez) in coordination with Direct Imaging and Radial Velocity programs aimed at exploiting the dual-field capability of Gravity to resolve the astrometric wobbling owing to Hot Jupiters in tight binaries to derive the planet's dynamical mass and to resolve the mutual inclination of the binary and planetary orbits. This will help understand how this planetary system formed and survived in such an extreme dynamical configuration.

2.6 Study of the transient sky: Observations and modelling

Numerous surveys of the transient sky are presently active. Stéphane Blondin and Luc Dessart are part of the ESO large program ePESSTO (operated at the NTT La Silla telescope), which aims at monitoring spectroscopically a large number of relatively bright SNe, either standard SNe nearby or super-luminous SNe further away. Blondin is part of the working groups on "Progenitors and explosion physics of SNe Ia" and "Faint or fast-evolving thermonuclear transients". Dessart is part of the group on luminous Type II SNe (led by Joe Anderson), Type II SNe from low-luminosity (low-metallicity) hosts (led by C. Gutierrez), and early-time Type II SNe with signatures of interaction (led by G. Terreran). These boundaries are loose and, for example, Dessart was part of the study of OGLE-2014-073 led by Terreran et al. on a super-luminous Type II SN or of the study of the electromagnetic counterpart to gravitational wave event GW170817. An important work at FCLA is connected to various activities on the analysis and modelling of the sample of Type II SNe, the study of Type II SNe at low metallicity, tof shock breakout and early-time radiation from core-collapse SNe, the study of Hydrogen-rich interacting SNe, the analysis of explosion mechanism and progenitors of Type Ia SNe.

3 Conclusions & perspectives

The FCLA offers a formidable opportunity for nurturing our cooperation with a rich collaborative environment to prepare the future of ground-based Astronomy in Chile (LSST, CTA, ALMA, ELT...) in key science fields (Solar systems, planetary formation, exoplanets, stellar physics & galaxy evolution...) with key partners including CNRS, INSU, ANID, UChile, UdeC, PUC & the Chilean community IRL-CMM (Applied Mathematics), INRIA Chile, ESO and ALMA. The FCLA can be considered for both communities as a bridgehead for the French international cooperation in Chile in Astronomy. Nevertheless, the FCLA exists thanks to the support of both communities answering to regular Call of Opportunity to work at FCLA, promoting long (1+ year) stays & intermediate (months) stays or French researchers, the FCLA Visiting program: dedicated to short term ($<$ 1-3 months) visits & internships, the support for co-supervised Ph.Ds & internships, and the development of the FCLA community & visibility through workshops and conferences, including the next 10th year Anniversary Workshop that will be organized in Spring 2023 in Santiago, Chile.