MEMORIA CIENTÍFICO-TÉCNICA PROYECTOS COORDINADOS
Convocatoria 2022 - «Proyectos de Generación de Conocimiento»

***IMPORTANT** – The research proposal cannot exceed 35 pages. Instructions to fill this document are available in the website. If the project cost is equal or greater than 100.000 €, this document must be filled in English.*

1. DATOS DEL PROYECTO

TÍTULO DEL PROYECTO COORDINADO (ACRÓNIMO):
Las diversas facetas de la formación estelar en el Universo (ESTALLIDOS 8)

TITLE OF THE COORDINATED PROJECT (ACRONYM):
Multifaced study of star formation in the Universe (ESTALLIDOS 8)

DATOS DE LOS SUBPROYECTOS - *SUBPROJECTS DATA*

SUBPROYECTO 1: nodo IAC
IP 1 COORDINADOR 1: Jorge Sánchez Almeida
IP 2 COORDINADOR 2 : Casiana Muñoz Tuñón
TÍTULO - *TITLE*: Key aspects of star formation in a cosmological context

SUBPROYECTO2: nodo IAA
IP 1 (Nombre y apellidos. *Name and surname*)**:** José M. Vílchez Medina
IP 2 (Nombre y apellidos. *Name and surname*)**:** Jorge Iglesias Páramo
TÍTULO - *TITLE*: Challenges of extreme star formation and advanced instrumentation for first-class telescopes: TARSIS and MOSAIC

SUBPROYECTO 3: nodo CAB-UAM
IP 1 (Nombre y apellidos. *Name and surname*)**:** Miguel A. Cerviño Saavedra
IP 2 (Nombre y apellidos. *Name and surname*)**:** Ángeles I. Díaz Beltrán
TÍTULO - *TITLE*: Starbursts throughout the evolution of the Universe

2. JUSTIFICACIÓN Y CONTRIBUCIÓN DE LA COORDINACIÓN. *JUSTIFICATION AND CONTRIBUTION OF COORDINATION.*

The ESTALLIDOS collaboration includes experts in observational astrophysics, numerical simulations, theoretical modelling, and instrumentation. The collaboration has already played a leading role in the development of tools and methodologies to analyze observational data, and on the generation of chemical evolution models needed for physical interpretations. We have a long experience in the analysis of spectroscopic data, with significant presence in many international observational campaigns, including HST, GTC, and VLT. The advent of integral-field and multi-object spectroscopy (MOS) has revolutionized our field of research, and we have actively contributed to this change participating in projects like CALIFA or MANGA. We know how to infer properties of stellar populations and gas, and we also known how to automatize the procedures to analyze massive data sets. Built up over many previous editions of ESTALLIDOS, this expertise belongs to the whole team rather than to the team members.

Our group bases its strength on the complementarity and effective coordination of the participants whose objectives (**OBs**) are often intertwined. The added value of our research stems from the combination of expertise and specialization of the scientists from the different nodes. Each node is strong in a particular aspect: CAB and UAM lead the theoretical modelling of galaxy formation and evolution, whereas the expertise at IAA and IAC is more oriented towards astronomical observations, interpretation, and instrumentation. As we will describe in this proposal, many of the specific **OBs** and tasks will be completed through the work of researchers spread among the three nodes. They could not be addressed without this synergy

and our combined knowhow. Being this true, some objectives result from the initiative of the individual nodes which should maintain identify for an effective use of the resources. Thus, the model of *coordinated project* fits in very well the needs of our team. This statement is not just wishful thinking but a conclusion following from the experience gained from the last seven ESTALLIDOS projects, which were organized according to this model.

The project will be coordinated following a management structure that has proven extremely successful in past editions. Since this structure works, it will be maintained with small improvements in ESTALLIDOS 8. The coordination scheme and management involves a *coordination team* (CT) and a number of nested *coordination meetings*:

1. - ***Coordination Team***, formed by PIs and seniors responsible for specific **OBs**. In alphabetical order, they are Ángeles I. Díaz (AID), Carolina Kehrig (CK), Casiana Muñoz Tuñón (CMT), Enrique Pérez Montero (EPM), Jorge Iglesias Páramo (JIP), Jorge Sánchez Almeida (JSA), José M. Vílchez (JMV), Miguel Cerviño Saavedra (MCS), and Miguel Mas Hesse (MMH). (MMH has been an active member of ESTALLIDOS since its beginning in 2001. MMH continues to be a key member of ESTALLIDOS 8 and part of the CT, even if formally he is an external collaborator.)
2. ***Management and coordination meetings***, to facilitate the monitoring of the everyday operation of the collaboration. These monthly meetings will be held by telecom to save travel time and expenses. All CT members are invited to participate. Cadence and participants can change on demand as needed.
3. ***Review Meetings.*** Once a year cadence. The CT members will meet every year (mixed in-person–telecom) to supervise the correct scientific progress of the project and the foreseen achievements of each objective. To be attended by the leaders of each objective and the members of the CT. If possible, it will be combined with a management meeting to optimize time.
4. ***Science Meetings***. We plan them in two flavors, ESTALLIDOS workshops, and specific seminars. We plan an initial (first year) and a final (4th year) ESTALLIDOS workshop. The final one is expected to be an international conference (at International Symposium level). In addition, specific seminars (typically 20 participants) driven by the project objectives will be organized. We have in mind several of these seminars on, e.g., *Metallicity diagnostics for JWST*, *Wandering black holes, Binarity, mass-loss and stochasticity in population synthesis models,* and *Feedback with WEAVE.*

3. JUSTIFICACION Y NOVEDAD DE LA PROPUESTA. *JUSTIFICATION AND NOVELTY OF THE PROPOSAL.*

3.1. Adecuación de la propuesta a las características y finalidad de la modalidad seleccionada. *Adequacy of the proposal to the characteristics and purpose of the selected modality*.

We are applying for a non-oriented research project, where neither the topic of research nor the timescale are constrained, and where the emphasis is placed on advancing knowledge. Thus, our project, on *the multiple faces of star-formation in the Universe,* fits in very well these loose requirements. It deals with improving our understanding on star formation (SF), which is a fundamental process in astrophysics (see Sect. 3.2). Unfortunately, SF is intrinsically complex and multifaced, and significant advances result only after many smaller steps. ESTALLIDOS 8 addresses several of these steps carefully selected because they are timely and fit in well the present evolution of the research on SF.

3.2. Justificación y contribución esperada del proyecto a la generación de conocimiento en la temática de la propuesta. Hipótesis de partida. *Justification and expected contribution of the project to the generation of knowledge on the theme of the proposal. Starting hypothesis*.

ESTALLIDOS started formally as a coordinated team to study the formation and evolution of massive stars in starbursts in the Plan Nacional I+D back in 2001, continuing the activities of the *grupo de estudios de formación estelar* (GEFE). Thanks to the expertise gained during

more than 20 years of working in collaboration, we are now a large, consolidated team, and an international reference in the field. Our distinctive traits are, on the one hand, the combination of observational and theoretical expertise, including the analysis of data at different wavelengths, and the development of new statistical, analytical, and numerical techniques. On the other hand, we have always taken advantage of detailed studies in the local Universe to improve our comprehension of the starbursts that took place in the distant past and the early phases of the formation of galaxies. As a result of this work, ESTALLIDOS has published >1000 papers in major journals, directed >30 PhD theses, and organized > 15 science meetings and workshops. Students formed within ESTALLIDOS are now mature researchers holding permanent positions in research institutions throughout the word (Argentina, Australia, Chile, Italy, Mexico, The Netherlands, Portugal, Spain, and the UK). ESTALLIDOS 8 is built upon this solid foundation.

SF is one of the few key physical processes driving the evolution of the Universe. It marks the born of galaxies and determines the production of observable light in most wavelengths. Over the last two decades, our group has made significant contributions to our understanding of starbursts and their impact on their host galaxies. Originally, we gained expertise about the massive SF process and its consequences by studying in great detail massive star formation in the local objects, from data obtained with good spatial and spectral resolution. During the last decade, observations at intermediate and high redshift have increased extraordinarily and, taking this opportunity into account, we initiated the application of our knowledge and techniques also to distant objects. The improvement in the quantity of these data is large, decreasing extraordinarily the statistical errors. However, the recipes used to interpret them are either simplistic or not adequate, leading to systematic errors and erroneous physical interpretations. In the present proposal, we keep going forward, applying our techniques and knowledge obtained from the study of objects observed at redshift zero, to the early Universe, when the first stars and galaxies were forming in extreme physical conditions. The moment is ideal to take this step, with large JWST datasets publicly available and a number of integral field units (IFU), ideal for follow up studies, becoming operational in first class telescopes. As an additional challenge, ESTALLIDOS 8 will explore two novel pathways: using artificial intelligence (AI) tools for data handling and interpretation, and leading the construction of large instruments that fit our science goals.

4. OBJETIVOS, METODOLOGIA Y PLAN DE TRABAJO. OBJETIVES, *METHODOLOGY AND WORK PLAN*.

4.1. Objetivos generales y específicos. *General and specific objetives*.

Our project addresses the study of the following general objectives,

I. The study of structures within spiral galaxies
II. Multi-wavelength characterization of star formation
III. Key aspects of star formation in a cosmological context
IV. Understanding reionization-era galaxies and their local analogues: massive star formation from the earliest galaxies to the cosmic noon
V. Star formation, metallicity, and galaxy evolution in extreme environments
VI. Construction of advanced instrumentation for large telescopes: TARSIS and MOSAIC

They include a fairly broad set of open questions, all of them steaming from the importance of understanding SF to unravel how galaxies formed and evolved. Given our expertise (Sect. 3.2), they were selected to be timely and to foster the present evolution of the field. This section introduces the different science cases in the context of our project. An overview of each case and our own advances in the field precede the description of the specific **OBs**. The tasks required to accomplish them are detailed in Sect. 4.2. The working team is listed after each title, with the leader highlighted in bold-face. (The equivalence between initials and names is included at the end of this document.)

I. <u>The study of structures within spiral galaxies</u>

Most spiral galaxies of the local Universe show metal abundance variations revealed by the new IFUs (e.g., Sánchez+12, 14, González-Delgado 14, 15). They are related to the process of disk buildup through gas infall and mergers. Within ESTALLIDOS, we developed MulChem (Mollá & Díaz 05), a powerful a chemical evolution model to interpret observed emission line intensities in terms of SFR and elemental abundances. It has been updated several times to include new physics (Mollá+15, 16, 17, 19). An application of the updated code to external spirals appears in the review paper by Mollá+18, showing the time evolution of the metallicity gradient. It rapidly flattens after the early disk formation, with the evolution being faster in more massive galaxies. Today, all model galaxies have a very similar normalized radial gradient, in agreement with observations (Díaz 89; Sánchez+14; Sánchez-Menguiano+16). We are able to calculate the SEDs across the disks using single or composite stellar populations resulting from our own evolutionary synthesis codes (PopStar and SED@, see 4.6). At present, the main limitation of most codes is in the ionizing spectrum, where the contribution of young stellar populations, X-ray binaries, and AGN-like non-thermal emission is difficult to assess but becomes critical. In addition, it is also fundamental to study large violent SF bursts (as we do in ESTALLIDOS), and its study constitute the main science driver of the IFU TARSIS, approved to be operated at 3.5m telescope of the CAHA Observatory. ESTALLIDOS (IAA and CAB-UAM) leads the construction of TARSIS, as we detail in **OB.VI.1**.
Thus, the main purpose of this general objective is updating the models with improved ionizing and X-ray contributions, and make them available to the scientific community through a friendly open access interface. The associated tasks are very well suited for a PhD student (ST), which we request in this proposal. In addition, we plan to apply the updated models to various science cases.

I.1. Models and simulations

Team: **AID**, MCS, IMY, AC, JJB, OC, JMV, EPM, FRO, SZ, PD/CAB-UAM, ST/CAB-UAM

This objective pursues to develop further the existing models and to use them to understand the formation and evolution of structures in spiral galaxies, like arms, bars, bulges, and halos. The specific **OBs** are:

OB.I.1.1 Produce of a completely new updated version of the chemical evolution grid by Mollá & Díaz 05. Make it available to the community in through a friendly open-access interface.

OB.I.1.2 Study the relation of the radial gradient of abundances with the formation of the disks. This work is already in an advanced state (Mollá+17b, 18).

OB.I.1.3 Compute the evolution of SEDs and colors with time, hence producing the radial distribution of stellar metallicity and ages through the galaxy disks. They are difficult to obtain because of the required spatially resolved information to decouple bulge, bars, disk, and halo. However, IFU data can provide the necessary information on the 2D distribution of stellar ages and metallicities across galactic disks to circumventing degeneracies.

OB.I.1.4 Update of the MulChem code to carefully incorporate the time delay in the injection of metals and kinetic energy into the ISM depending on the star that explodes as SN. We will take advantage of the population synthesis codes elaborated by our group to self consistently incorporate the instantaneous yields and kinetic energy produced by stellar winds and SN explosions. This item is closely related to **OB.II.2**.

I.2. Follow-up IFU observations of galaxies with HI maps (HI-KIDS)

Team: **ALS**, PCC, AID, AC, FRO

Stars are formed out of gas and so the SFR is controlled by the gas locally available (e.g., Kennicutt 98), mostly in the form of HI. Thus, the global and local HI mass fraction indicates the evolutionary state of a galaxy (e.g., Ascasibar+15). Nowadays, galaxies with HI maps and optical IFU data are uncommon, despite they are eagerly needed to understand SF. Our group is deeply involved in the HI KOALA IFU Dwarf Galaxy Survey (HI-KIDS), which is a large observational effort to carry out follow-up optical IFU observations of HI-selected targets. It covers a range of stellar and atomic hydrogen masses between 10^6 and 10^{10} $M_\odot$, metallicities from 0.1 to 0.5 $Z_\odot$, and SFRs from 10^{-3} to several $M_\odot$ yr^{-1}. These observations will provide local information about the stellar population and the warm ionized gas. On the other hand, the spatially-resolved intensity and kinematics of the HI line provide information about the cold gas

reservoir, as well as possible flows into and out from the disk, and interactions with neighboring galaxies. The specific **OB** is,

OB.I.2 Participate in the interpretation of the HI-KIDS dataset in terms of chemical and spectrophotometric models, and in the connection between gas, stars, and metals in dwarf galaxies. Develop and test different techniques to derive possible evolutionary histories and to detect peculiar sources (e.g. massive stars, SN remnants, or AGNs in dwarfs).

I.3. Studies of extremely metal-deficient (XMD) star forming galaxies with MEGARA

Team: **MGV**, EC, ET, RJT, MCS, ALS

XMD galaxies are difficult to find (e.g., Sanchez Almeida+16). Because of the luminosity metallicity relation (e.g., Skillman+89), XMD galaxies are intrinsically weak even if a burst of SF boosts the luminosity. Thus, most XMD galaxies have been observed while experiencing a strong burst and young stars ionize the ISM (< 5.5 Myr; Mollá+09). The MEGARA@GTC LCB mode (IFU with FOV of 12.5 x 11.3 arcsec^2 and R ~ 6000-18000) provides a unique tool to improve our understanding on XMD. As an example, we (Carrasco+22) observed the Leoncino galaxy (12 + log[O/H] = 7.02, equivalent to 2% of the solar metallicity), object close enough to map the ionized gas distribution with a resolution of 22 pc. We found not only an unexpected low central value of [OIII]5007/Hb (~1.4) but also a spatial gradient. If this [OIII]5007/Hb gradient is common in other galaxies, it would lead to an *aperture effect*, i.e., a bias in the measured metallicity depending on the galaxy distance to us.

We are carrying out a program to study with unprecedented spatial and spectral resolution nearby XMD galaxies (currently 16 galaxies and 5 more coming up in the next 2 years; see Fig. 1). We have chosen galaxies with previously measured low O abundance 6.9 < 12 + log (O/H) < 7.8 (< 10% $Z_\odot$). These galaxies are faint and only a few of them have long-slit (not IFU) spectroscopy taken always in top-class large telescopes (LBT or Keck).

OB.I.3 Our final objective is understanding their evolutionary state and why their low-metallicity. We want to answer a number of specific questions: What is the origin their low metallicity gas? How is the gas abundance linked to the stellar metallicity? What are their SFHs?

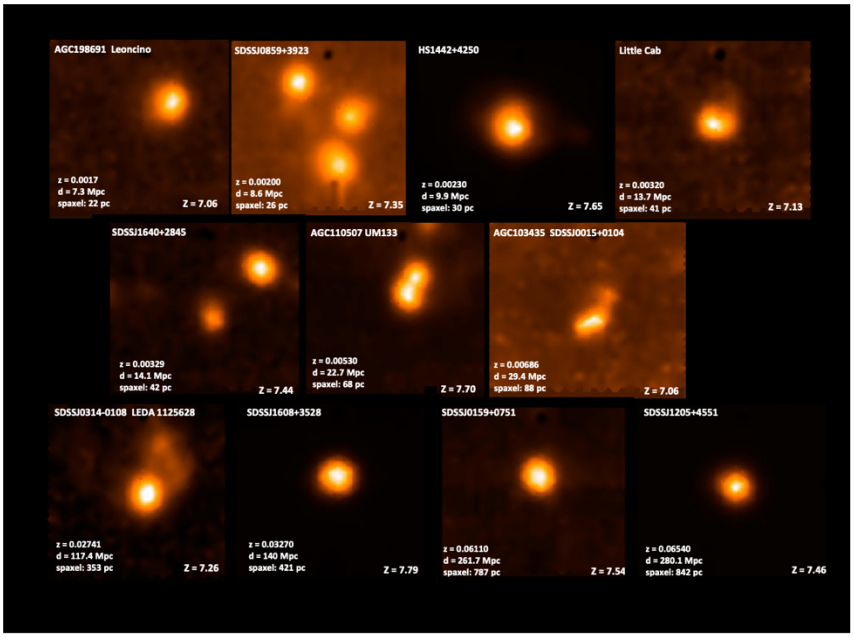


Figure 1: *[OIII]5007 images of the 11 XMD galaxies already observed with MEGARA. Five more are queueing now, to be obtained in the next years.*

I.4. Feedback in low metallicity galaxies with N/O and He/H excess

Team: **AID**, VGF, RAB, RJT, ET, DFA, MCS, ALS, PD/CAB-UAM

Low metallicity starburst HII galaxies are commonly used as cosmological probes, in particular, for deriving the primordial He abundance needed to constraint the cosmological nucleosynthesis (e.g. Peimbert & Torres-Peimbert 74). Some of these galaxies, however, have an excess of N/O and He/H. For example, Fernández+18 found galaxies with N/O values from 2 to 6 times larger than the rest of the galaxy sample, which coincides with objects also having He/H overabundance. Interestingly, three of the six anomalous galaxies are classified as Wolf-Rayet galaxies, so, the chemical anomalies could be produced by contamination from a recent starburst. On the other hand, these anomalies may be related to the globular cluster (GC) formation. Terlevich+18 summarize the similarities between the low and high redshift young massive clusters (YMC) rekindling the YMC to globular cluster connection. Understanding the stellar feedback in nearby HII galaxies and giant HII regions can thus help us to explain GC formation. Our specific **OB** for this item is:

OB.I.4 Try to understand the origin of the detection of N/O excess observed in some galaxies.

II. Multi-wavelength characterization of star formation

The interpretation of spectroscopic data (spectra and SEDs) in terms of SFHs requires of population synthesis models, which are synthetic spectra from stellar populations with known physical properties (age, mass, metallicity, IMF, etc). Our group has a long experience in developing them: we are responsible for PopStar and SED@ (see 4.6), and have collaborated in others such as Starburst99 (Cerviño+01, Gonzalez-Delgado+05) and MILES (Vazdekis+20). The development of population synthesis models is in continuous turmoil, as observations with new facilities require improvements and fine tuning to suit new uses. Here, we address a number of updates of our models to face current challenges. For example, the instrument MEGARA@GTC requires high spectral resolution stellar libraries as obtained with MEGARA itself to interpret indices as Hα or the IR Ca triplet. Providing realistic ionizing fluxes requires increasing the parameter space of theoretical libraries, and expanding the wavelength range to reach X-rays requires accounting for additional pathways of stellar evolution. In addition, new and future observational facilities require to treat semi-resolved stellar populations. These improvements will be validated with observational data. We will also study ways to separate stars and AGNs using multi-wavelength observations. These upgrades are detailed below.

II.1. MEGASTAR and new empirical libraries in our synthesis codes

Team: **MGV**, EC, IMY, MCS, ST/CAB-UAM

During ESTALLIDOS 7, we began the construction of the empirical library MEGASTAR which aims at producing a R~20000 MEGARA@GTC stellar library in the Hα and CaT spectral regions (García-Vargas+20, Carrasco+21). Actually, members of the Gaia community have requested early access to new MEGASTAR products for galactic modeling, stellar classification, stellar and cluster physical parameter determination, and spectral indices calibrations. In addition to keep working on MEGASTAR, we will develop general tools to implement empirical libraries in our synthesis codes. This last task will be performed in the context of a PhD project. Thus, the specific **OBs** to be explored are:

OB.II.1.1 Continue the development of MEGASTAR.
OB.II.1.2 Develop general tools to implement empirical libraries in our synthesis codes.

II.2. Realistic Ionizing Fluxes of massive stars, the inclusion of new evolutionary paths and the extension to the high energy domain

Team: **MCS,** IMY, CSS, EJB, MMH, ST/CAB-UAM

Stellar evolution points out the increasing importance of mass-loss through winds with increasing stellar mass. Unfortunately, the ionizing fluxes produced by massive stars depend critically on this mass-loss, which is poorly constrained. To illustrate the importance, Fig. 2 shows the variation of the number of HeII ionizing photons with the mass-loss, showing that it varies by 2 orders of magnitude depending in the wind. The mass-loss rate depends on the evolution followed by a star, with strong variations depending on rotation and on the presence or not of companion stars. In addition, considering binarity is also needed to provide realistic X-ray predictions. We will address these issues in collaboration with the massive star groups at CAB-UAM and IAC. The specific **OBs** are:

OB.II.2.1 Compute the ionizing flux of massive stars.

OB.II.2.2 Update of evolutionary tracks of the population synthesis models to include rotation and (if possible) binary stars.

OB.II.2.3 Characterize the X-ray emission of star forming regions.

OB.II.2.4 Study of ultra-luminous X-ray sources, which are found in star-forming regions. They are either very active binary stars accreting at super Eddington rate, or IMHs formed by coalescence of stellar-mass BHs or other mechanisms (see **OB.III.2**).

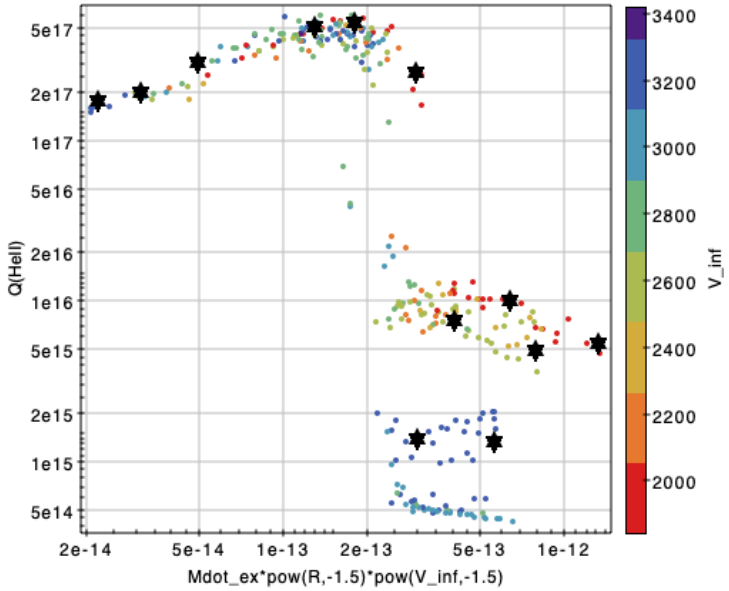


Figure 2: *Variation of the number of HeII ionizing photons, Q(He II), as a function of the mass-loss (Mdot) divided by the radius (R) and terminal velocity (V_inf) for a set of T_{eff} = 40000K, log g=4.0 solar metallicity stars, all compatible with different mass-loss values predicted by different evolutionary tracks of massive stars (from Cerviño+23, in preparation).*

II.3. Modelling semi-resolved populations and sparsely populated stellar systems

Team: **MCS**, JJB, MCS, SS, PRB, ST/CUB-UAM

As we explain above, the modelling of properties of stellar populations has to be done in a statistical sense. Properties such as IMF or SFH describe mean behaviors, however, one should consider statistical fluctuations arising from the finite number of stars either in the burst or the resolution element (e.g. Cerviño+13, 16; Krumholz+15). The problem is usually addressed using Monte Carlo simulations to populate the IMF or the spaxel. However, there is an alternative approach using error propagation in standard codes (Cerviño & Luridiana 06). We plan to continue studing the dispersion in the observables covering the still unaddressed questions posed by Cerviño 13. The work will be included in a PhD project. Specifically, the **OBs** are:

OB.II.3.1 The discreteness of the stellar populations reduces the correlation between different observables, an effect never studied before. Characterize them using covariance matrixes.

OB.II.3.2 Using IFU data, figure out how to distinguish between fluctuations produced by noise and by discreteness in the stellar populations.

II.4. Characterization of the different the components of emission-line galaxies

Team: MSL, MCS, ALL, EJB, IC, LB, JE, LT, PRP

We aim to provide a characterization of the AGN component that is present in some emission line galaxies, specially, in transition objects (Cid Fernandes+11). This characterization is fundamental to disentangle possible contamination of the AGN in emission-line diagnostics such as SFRs inferred from Hα luminosities (Kennicutt 89). In addition, it may help us to disclose the possible feedback of the SMBH winds on the host galaxy. The specific **OBs** are:

OB.II.4.1 Study the effect of the interactions of galaxies in the triggering of AGNs and star formation in galaxies.

OB.II.4.2 Multi-wavelength studies of AGNs and star forming galaxies.

III. Key aspects of star formation in a cosmological context

In the hierarchy of cosmic structures, galaxies are the smallest units where all the key ingredients of cosmology come into play. The global properties of the galaxy population are set by inflation, that provides the initial density perturbations, by the amount of DM, that yields the gravity controlling galaxy formation, and by the dark energy, that sets up the context. All this information is coded in the light emitted by stars and gas, and requires much nontrivial interpretation for the information to be disclosed. Thus, the process of SF has to be mastered not only because it controls the physics of galaxies, but because it allows us to go from observations to actual measurements. SF is a complex multi-face phenomenon evolving with time which has to be approached from several angles and throughout the history of the Universe. Here we propose a few science cases focused on the need to study SF to better understand the evolution of galaxies and their constituents. They have been chosen to be timely, to fit in well our expertise, and to represent the needs of the field. Specifically, we will search for cosmic gas feeding star formation at different redshifts (III.1), for the connections between SF and the underworld (IMBHs; III.2), for SF in the epoch of reionization (III.3), for means to quantify positive SF feedback (III.4), for the time evolution of SF from multi-λ photometry (III.5), and for disentangling SF effects from the nature of DM (III.6).

III.1. Studying the gas feeding star formation at different redshifts

Team: **JSA**, SFS, CMT, JRE, ST/IAC1

Our **OB** will contribute to the detection and characterization of the elusive gas feeding star formation in two different but complementary ways: (1) The cosmic gas shows up in Lyα at a surface brightness of 10^{-19} erg/s/cm^2/arcsec^2, which is routinely achieved by MUSE@VLT. Lyα photons are mostly produced by recombination therefore Hα and other H recombination lines are generated together with Lyα. They can be used to detect the gas around galaxies in the local Universe, where Lyα is not easily detectable. The publicly available MUSE wide or MUSE deep (Urrutia+19; Bacon+22) optical spectra will be used to show the existence of a halo of metal-poor gas around galaxies forming stars in the local Universe. There are hundreds of such local targets in these cosmological field. (2) Chemical inhomogeneities associated with enhanced star formation trace cosmic gas accretion intermingled with gas mixing processes in galaxy disks. The chemical inhomogeneities have been recently proved to exist in virtually all star-forming galaxies of the local Universe (Sánchez-Menguiano+19). They remain to be fully characterized. Thus, our specific **OBs** are:

OB.III.1.1. Detect and characterize gas around local galaxies in Hα emission.

OB.III.1.2. Characterize the local correlation between metallicity other physical parameters. Investigate the physical origin of the relations.

III.2 Connections with the underworld

Team: **JSA**, CMT, NC, PD/IAC1

Each starburst contains many massive stars that are short-lived and end their lives as SNe, leaving BHs and neutron stars as remnants. As the title of the section reads, these remnants are often referred to as *the underworld* (e.g., Sweeney+22). BHs are end products of the regular SF occurring during most of the cosmic history, but they also result from the first starbursts that yielded Pop III stars (when the Universe had no metals; e.g., Banik+19), and from failed starbursts that also occurred at this time. The latter corresponds to the direct collapse of a massive gas cloud that could not fragment into stars (e.g., Habouzit+16, Latif+22). The BHs produced very early on at the beginning of the Universe are particularly massive (10^2 – 10^6 $M_\odot$) and are denoted in the technical jargon as Intermediate Mass BHs (IMBHs). They turn out to be fundamental for the evolution of galaxies. IMBHs are the seeds from which SMBHs grow and have to be created in large amounts because the processed of BH growth is expected to be very inefficient. IMBHs have to exist very early on (e.g., Volonteri+02). Thus, BHs and, in particular, IMBHs, are expected to wander in and around galaxies in large quantities, despite the fact that only a few have been discovered and confirmed so far (Mezcua 17; Greene+20, Reines+22).

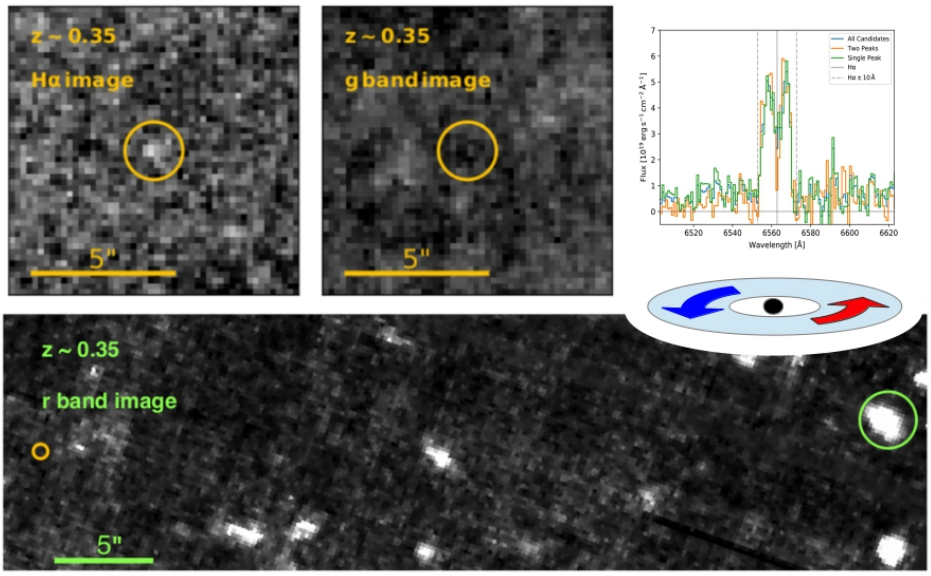


Figure 3: *Double peak Hα emission line in the halo of a local galaxy (the galaxy is marked in green in the bottom panel with the emitting clump in yellow). The emission shows up in Hα but not in continuum (the two top-left panels). Considering all observational constraints, the emission can only be explained if Hα traces an accretion disks around an IMBH wandering in the halo of the galaxy (as shown in the schematic with the arrows indicating the rotation). Adapted from Sanchez Almeida+22.*

For a lucky quirk of fate, the same technique proposed to detect the cosmological gas accretion (**OB.III.1**) also provides a means to detect the elusive IMBHs. Sanchez Almeida+22 discovered faint double peak Hα emission in the halo of a number of local galaxies (118 emitting clumps in 56 galaxies). Double peak Hα are very uncommon. After examining and discarding all other possibilities, the observed Hα profiles are best described as tracers on IMBHs wandering in the halo of the galaxies (see Fig. 3). Taking advantage of this novel IMBH detection channel, we want to search for the double peak Hα emitting clumps in the halos of the galaxies and use them to characterize the local population of wandering IMBHs. Thus, our specific objectives (**OBs**) are:

OB.III.2.1. Develop an automatic algorithm to detect double peak Hα emission in noisy IFU data-cubes. Human-brain guided approaches (e.g., Sanchez Almeida+22) are useless to tackle the interesting data sets.

OB.III.2.2. Apply this tool to existing datasets to detect a new population of wandering IMBHs. Then characterize their physical properties (e.g., BH mass, Eddington ratio, and depletion timescale).

OB.III.2.3. Look for counterparts of the Hα signals in all wavelengths. In particular, IMBHs are expected to reprocess the UV photons of the disk and reemit them in the near IR (e.g., Inayoshi+22). We will look for them in JWST IR images.

OB.III.2.4. With the information yielded by **OBIII.2.2** and **OBIII.2.3**, write a paper providing a new comprehensive picture of the wandering IMBH population.

OB.III.2.5. Use the tool developed in **OB.III.2.1** to search for double peak Hα emission in existing public spectral databases.

III.3. Star formation in the epoch of reionization

Team: **MMH**, CMT, JRE

The intergalactic medium (IGM) was originally neutral. Understanding how it became reionized is a hot topic nowadays. It was likely produced by low luminosity star forming galaxies (Robertson+15, Bouwens+10). These galaxies, however, cannot be easily observed unless they are clustered, so that together produce an ionized bubble large enough for the Lyα photons to get redshifted by the Hubble expansion before leaving the bubble (Dayal & Ferrara18, Calvi+19, Rodríguez-Espinosa+21). The current paradigm assumes the formation of ionized bubbles around individual galaxies, which grooved rapidly to completely ionize the over-dense regions within a large bubble, that through later percolation completed the reionization of the universe by z~6. An alternative option was recently proposed by our team

(Salvador-Solé+22): a first reionization of the Universe could have taken place at redshift z~9, driven by the ionizing photons from Pop III stars produced before the formation of the galaxies. (However, a few galaxies must have formed earlier, e.g., the z=9.76 object in Robert-Borsani 22.) This first reionization would have been followed by a subsequent process of neutralization when Pop III stars died out, with a second and final reionization by z ~ 6 due to ionizing star-forming galaxies, as in the usual paradigm (see Fig**. 4**). Our objective is checking this scenario, which leads to a relative overpopulation of Lyα emitting galaxies at z~8–10, which otherwise would not be detectable since the amount of neutral gas would completely block the Lyα emission. The JWST will provide a wealth of results on the distribution of Lyα emitting galaxies with redshift, which we will compare with the predictions of single and double reionization scenarios.

A key parameter to understand reionization is the ionizing photon escape fraction (LyC photons) in starbursts at high z, which is so far very much unconstrained. We plan to measure its value at different redshifts by studying the redshift evolution of ionized bubbles around early clusters. The intrinsic number of ionizing photons can be derived by applying our set of evolutionary synthesis models on Lyα and LyC observations, and the number of ionizing photons escaping to the IGM can be constrained from the size of the ionized bubbles. Thus, the LyC escape fraction will be measured as a function of the central galaxy. They specific objectives (**OBs**) for this point are:

OB.III.3.1. Disentangling the two reionization scenarios, single or double.
OB.III.3.2. Constraining the LyC escape fraction in the early universe

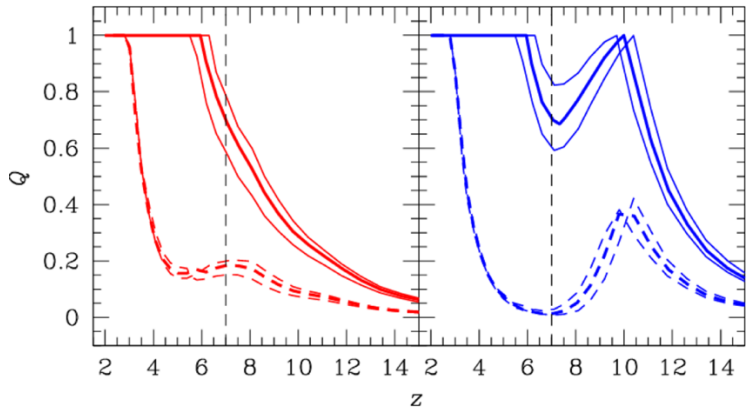


Figure 4: *HI (solid lines) and HeII (dashed lines) reionization histories expressed through their volume filling factors Q variation with redshift in single reionization (left panel) and double reionization (right panel) scenarios. From Salvador-Solé+22.*

III. 4. Quantifying the SF feedback

Team: **CMT**, CF, MGV, JSA, SS, GTT, SMG, NC, ST/IAC2

Past SF episodes impact on future SF episodes. This SF feedback is said to be negative or positive depending on whether it quenches or triggers new SF. Negative feedback is understood to be one of the central processes controlling galaxy formation (Dekel & Silk 86, Scannapieco+02, Ferreras+02, Hopkins+04). Massive stars, which produce photons and mechanical energy through winds and SNe, limit to stop new SF (Tenorio-Tagle & Bodenheimer 88, Elmegreen99a, 99b). However, as shown by Tenorio-Tagle+05, 07, for the case of massive compact young clusters, the stellar feedback may become positive. State-of-the-art models of galaxy formation only include negative AGN and SF feedback (e.g., Silk & Mamon 2012). We want to quantify whether positive feedback is occurring and to what extend is needed to understand galaxy evolution. As we have shown (Tenorio-Tagle+05, 07; Wunsch+08; Silich+10), the assembly of massive galaxies may evolve in a positive feedback mode. Theoretical models distinguish three different regimes: (1) quasi-adiabatic super-galactic winds, (2) bimodal flows, with mass accumulation in the central region and gas expulsion from the outer zones, and (3) a gravitationally bound regime. Which of the three possible solutions takes place depends on the mass of the star-forming region, its mechanical luminosity, and its size (Silich+10, Tenorio-Tagle+10, Muñoz-Tuñon+13). These different regimes can be distinguished observationally by measuring the different components of the emission lines produced in the star-forming region. In ESTALLIDOS 6 and 7, we catalogued

around 3000 emission line galaxies (ELG) from COSMOS, up to z=0.3, and from SHARDS (GOODSN), up to z=1. The studies carried out so far provide detailed photometric information about the sources. We propose to study the nature of the feedback in these galaxies by analyzing the shape of their emission line profiles. We will observe with WEAVE and MEGARA, and will interpret the results with theoretical models developed together with our colleagues in Mexico and the Czech Republic. Our specific **OBs** are:

OB.III.4.1. We have been awarded WEAVE science verification time with the R=20000 mini-IFUs configuration. Use it to assess whether WEAVE can be used for SF feedback studies. Upon positive results, prepare an open time proposal for subsamples or the entire sample.
OB.III.4.2. Quantify the feedback balance (winds from stars and SN) in starbursts in the Universe up to z<1.
OB.III.4.3. Relate the results from **OB.III.5.2** with the underlying structure of the host galaxies.
OB.III.4.4. Evaluate the importance of the positive feedback and its impact on the chemical evolution of galaxies.
OB.III.4.5. Develop theoretical models to define more observables. Include in the models the production of dust from SN in massive stellar clusters.

III.5 Understanding star formation at different z, from multi-λ photometric information

Team: **CMT**, MMH, JRE, NC, JSA, BGE, DME, PD/IAC2

SF can indeed be followed from the early Universe until today (e.g., Kartaltepe+22). Photometric surveys are ideal to identify and characterize star-forming galaxies, and to follow them in time. The SHARDS survey (Perez-González+13) provides star-forming sources up to z=6. The COSMOS Survey includes the peak of star formation at z~2.5. We will continue using these surveys to follow the SF process from z~0 to z~6.5, to understand how the SFR increased so fast early on to then decline by z~0. With SHARDS, we characterized the population of both LAEs and LBGs. We will apply what we did to larger surveys spanning from z~0 to z~7. In particular, the PAU survey (Serrano+22) is much larger than SHARDS (100 squared degrees versus 135 arc-minutes) and almost free from cosmic variance. PAU provides more than 3 million sources detected with excellent redshifts. Our specific **OBs** for this point are:

OB.III.5.1. Use machine learning algorithms to classify the PAU survey. Detect emission line galaxies.
OB.III.5.2. Characterise the sources in terms of SFR, mass, clustering, etc.
OB.III.5.3. Explore the use of other spectrophotometric surveys such as J-PLUS.
OB.III.5.4. Cross match the targets with HST catalogues to connect the general properties with the clump structure of the galaxies.

III.6 Star formation feedback and the nature of dark matter

Team: **JSA**, ARP, NC, BGE

Our ignorance of what dark matter (DM) nature is represents one of the fundamental open questions in physics (e.g., Bauer+15). The standard cosmological model (ΛCDM) assumes the DM to be non-baryonic and collision-less (CDM), i.e., assumes the simplest possibility. Because of small cracks or tensions in the standard model, we know that ΛCDM is certainly not the final model (e.g., Peebles 21). Advancing our knowledge requires using these cracks to find new constraints on the DM properties. In particular, fixing the so-called small-scale problems of the standard model can tell us about whether the DM is or not collision-less (e.g., Del Popolo+17). CDM halos present a wealth small-scale substructure which disappears if the DM is not *cold.* SN explosions and massive stellar winds (i.e., SF feedback) also erase the small-scale structure and thus the uncertainties on the effects of SF limit our ability to constrain the nature of DM. Based on our expertise studying SF feedback in dwarf galaxies, we have come up with a novel procedure to study whether or not the DM particles are collision-less. CDM numerical simulations predict mass profiles with a central *cusp*, where the density increases endlessly as the inverse distance to the center. These cusps are seldom observed (see Fig. 5). The CDM paradigm naturally copes with this seeming discrepancy

invoking baryon feedback; fast gas stirring motions thermalize the potential transforming the DM cusps into cores (Governato+10, Del Popolo+17). However, when the stellar mass of the galaxy is small enough then the energy involved in stellar feedback is insufficient to modify the gravitational energy of a cuspy DM halo, and the process becomes inoperative (e.g., Peñarrubia+12). This happens for galaxies with stellar mass much smaller than 10^6 $M_\odot$ (Di Cintio+14, Read+16). We will search for the presence of cores or cusps in the total mass distribution of these galaxies. Although technically very challenging, this can be achieved though the study of the stellar mass distribution after proving that stars trace DM in these systems. If cores are common in $M_\star < 10^6$ $M_\odot$ galaxies, then the DM cannot be *cold*. This finding would be a major landmark in understanding the nature of DM. Thus, the specific objectives (**OBs**) for this point are:

OB.III.6.1. Using general energy balance arguments (e.g., Peñarrubia+12), set a limit to the stellar mass able to modify a cuspy DM halo into a core. Using general arguments of self-gravitating systems (Binney & Tremaine 08, Lacroix+18), show that stars trace DM in DM dominated systems. It is a non-trivial issue since collision-less self-gravitating systems maintain memory of the initial conditions for longer than the age of the Universe (e.g., Sanchez Almeida & Trujillo 21).

OB.III.6.2. Study the observed stellar mass distribution of low mass galaxies. How common cores are? Common enough to assess that DM particles self-collide through non-gravitational forces?

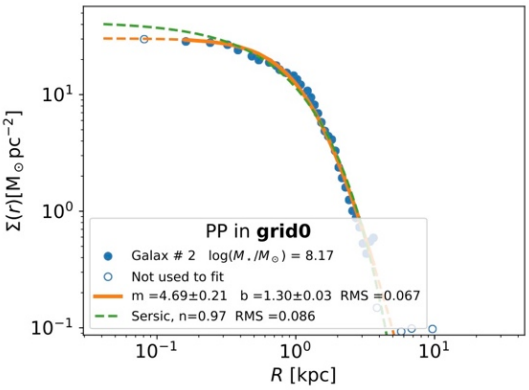


Figure 5: *Mass surface density profile of a low mass galaxy with a central plateau in the baryon mass distribution (known as core; see symbols for R < 1kpc). For galaxies with $M_\star < 10^6$ $M_\odot$, the existence of this plateau necessarily implies that the DM is not collision-less. Adapted from Sánchez Almeida+21.*

IV. Understanding reionization-era galaxies and their local analogues. Massive SF from the earliest galaxies to the cosmic noon

The intergalactic medium (IGM) of the current Universe is fully ionized, and maintained in this state by the UV emission from stars and AGNs. The epoch of reionization (EoR; z > 6) marks a pivotal time in cosmic history when the predicted first stars (Pop III) and their host galaxies transformed the IGM from neutral to transparent by leaking ionizing photons. However, we still know little about this period, and exactly how reionization occurred remains a debated topic in astrophysics (e.g., Bromm & Yoshida 11; Fialkov+14; Dayal+20; Liu+21; Katz+22). An approach to understand the first ionizing sources is studying low redshift galaxies with the properties of galaxies in the early Universe (e.g, Chen+22; Schaerer+22). Overall, the main properties of EoR galaxies are, compactness, low metallicity, extreme emission lines, high-excitation spectral features, and LyC emission (Schaerer 02). This has been recently supported from the new observations with JWST (e.g, Curtis-Lake+22; Robertson+22; Naidu+22). Among these local analogues, we identify the most extreme star-forming dwarfs: green pea galaxies, HeII-emitters, and LyC leakers. Our goal is to perform a detailed analysis of such galaxies combining IFU observations with photoionization codes. The access to ESO and CAHA telescopes, and our guaranteed access to GTC and JPAS (Benítez+14) will play a key role. Moreover, our leadership in TARSIS (co-PI: JIP; co-PS: CK; **OB.VI.1**) and MOSAIC (CK is co-leader of the SWG *first light galaxies and reionization;* **OB.VI.2**) place our team in an unprecedented spot to address very current, attractive, and fundamental questions.

IV.1 High-ionization emission powered by nearly metal-free stars: the missing link to the reionization era?

Team: **CK**, JVM, EPM, JIP, RAB, APP, PD/IAA

The origin of high-excitation emission lines (e.g., HeII, CIV, [NeV]) remains intensely debated and challenging to explain, especially in metal-deficient galaxies where the high-ionization phenomenon is observed to be more frequent. The difficulty in interpreting this emission challenges the interpretation of many JWST spectra. Present photoionization and stellar models suggest that extraordinarily metal-poor (<5% $Z_{\odot}$) massive stellar populations (Pop III-like stars) are required to produce this high-ionization emission as we have demonstrated for IZw18 and SBS0335-052E (Kehrig+15, 18, 21). Figure 6 shows the HeII map of one of them. Our work opened a window onto the highly uncertain ionizing spectrum of very-metal poor massive stellar populations, a very promising research line (e.g., Eldridge & Stanway 22). To keep advancing this topic, spatially resolved studies of metal-poor galaxies showing high-ionization features are essential to constrain properties of the ionizing sources. Understanding the physics behind the nebular HeII line is particularly relevant since this line is suggested as a potential diagnostic of the predicted Pop III stars, and HeII emitters are expected to have contributed significantly to the Universe reionization (e.g., Nakajima & Maiolino 22). The immediate **OBs** of this topic are:

OB.IV.1.1. Derive the energetics of the high-excitation photons and the properties of the high-ionization gas in XMD galaxies.

OB.IV.1.2. Constrain the ionizing sources and characterize the massive stellar population based on up-to-date stellar models and our own tailored photoionization codes (Eldridge+17; Perez-Montero+20). This will be done applying methods similar to those developed by us (Kehrig+15, 18, 21; Perez-Montero+20).

These two objectives will provide unique insight into key open questions: (i) Could nearly metal-free stars be formed post EoR down to z=0? (ii) How frequent are Pop III-like stars in nearby galaxies? (iii) Which properties (e.g., metallicity, sSFR) can be dominant factors to determine the HeII-emitting nature of a galaxy?

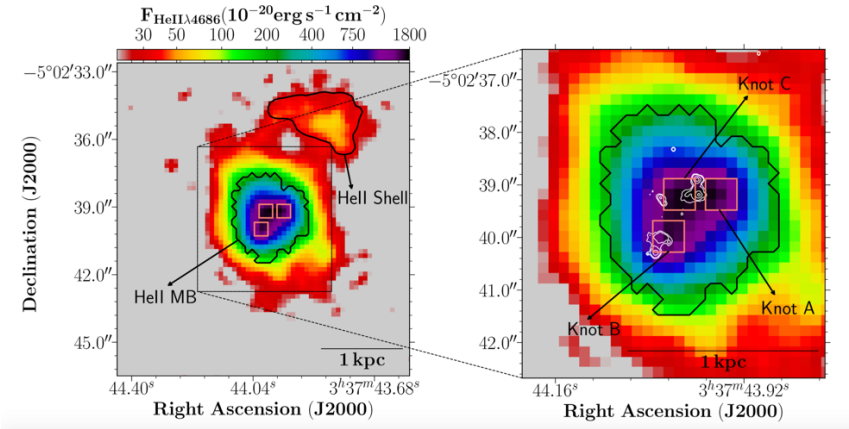


Figure 6: *The extended HeII4686 region of SBS0335-052E unveiled with MUSE showing (left) the HeII shell, HeII main body, and HeII knots A,B,C, and (right) the location of the brightest ionizing Super Star Clusters from HST (Kehrig+18).*

IV.2 Extreme emission line galaxies and LyC leakers

Team: **JMV**, JIP, CK, EPM, AAP, RAB, PP, LSP, IB, PD/IAA

Star-forming dwarfs undergoing extreme starbursts (with specific star-formation rate sSFR > 1 Gyr^{-1}) and showing very high EW in their bright emission lines (e.g., [OIII]5007, Hβ > 300 A) are usually called extreme emission line galaxies (EELGs) and include the *green peas*. Although rare in the local Universe, EELGs are expected to be common in the far Universe. Among these EELGs, LyC leakers produce significant ionizing radiation and are key contributors to the reionization. The physics behind the processes driving the strong star-formation events in EELG that allow LyC photons to escape remain poorly known (e.g., Guseva+20). We have already published several papers on these objects (e.g., Guseva+20, Perez-Montero+21, Fernandez+22, Breda+22, Iglesias-Paramo+22). As part of his PhD thesis, AAP is about to submit a first paper based on 24 EELGs observed with MUSE. To further advance on this fundamental subject, we will study the kinematics, physical properties,

and chemical abundances (chemodynamics) of the ionized gas for a larger sample of EELGs. Our specific **OBs** for this topic are:

OB.IV.2.1. We have already completed MEGARA observations for our sample of northern LyC leakers, to be added to the XShooter@VLT observations, obtained together with our collaborators from the University of Geneva. The process of data reduction of the cubes is ongoing, and it will be followed by extensive spectral and chemodynamical analysis.

OB.IV.2.2. With our collaborators at CEFCA, a sample of more than 400 EELGs candidates at low-intermediate redshift ($0.006 < z < 0.34$) have been selected from the J-PLUS survey (Lumbreras-Calle+22). Spectra (PMAS, IDS) for more than 50 galaxies are already in hand and upcoming observations are expected. Their data reduction and analysis will be finished, and observations of new candidates will continue during ESTALLIDOS 8.

OB.IV.2.3. Apply our method to select EELGs on the miniJPAS survey (Iglesias-Paramo+22) to the JPAS survey, from which we expect to discover new EELGs candidates, and then submit IFU proposals (MEGARA, PMAS) to perform 2D spectroscopic follow-up.

IV.3 Preparatory science for the future first-class IFUs: TARSIS and MOSAIC

Team: **JIP**, CK, JMV, EPM, JAC, IB, PD/IAA

OB.IV.1 and **OB.IV.2** above will serve as fundamental guidance to carry out the objective of preparatory science for **OB.VI** devoted to the construction of advanced instrumentation for 1st class telescopes. They will pave the way for the analysis and interpretation of the galaxies to be discovered by TARSIS and MOSAIC (e.g., metal-free nebulae or Pop III stars). However, given the importance of the two instruments, we have added this independent *grand objective* devoted to the preparatory science of TARSIS and MOSAIC. TARSIS@CAHA, expected to be operative in 5 years from now, and MOSAIC@ELT, planned to see its first light in the 2030´s, will play a transformative role in astrophysics. Meanwhile, we will carry out preparatory science for the science verification, as it is mandatory for **OB.VI**.

TARSIS, the next generation instrument selected for the Calar Alto 3.5-meter telescope, has unique characteristics, in particular it reaches the near UV and has an unprecedentedly large FOV. JIP is one of the two PIs of TARSIS and CK is its co-Project Scientist. During the first years, TARSIS will be largely devoted to its associated CATARSIS survey, which will study distant (z~0.15-0.23) galaxy clusters to better understand early stages of the Universe. MOSAIC, a ground breaking (multi-object and multi-integral field) spectrograph will use the widest possible FOV from the future ELT and will enable massive scale UV spectroscopic surveys of thousands of galaxies at z>6. This will open a large discovery space for science cases where statistics play a key role. CK is one of the three leaders of the MOSAIC Science Working Group (SWG): *First light galaxies and reionization*; as of today, CK is the only Spanish scientist member among the leaders of the MOSAIC SWGs.

The tasks required to complete this grand objective (**OB.IV.3**) are fully detailed in Sect. 4.2 of this document. In addition to serving as preparation for new instruments, the science outcome of these tasks will have impact by its own. It will provide a new view and unique sample of key contributors to the reionization (LyC leakers, Lyα emitters, and HeII emitters).

V. Star formation, metallicity and galaxy evolution in extreme environments

We will apply photoionization models and specialized mathematical tools developed in ESTALLIDOS to study two extreme physical environments, at very different scales in mass and size: (1) the nuclear region of AGNs, which combine extremely hard radiation with bursting SF, and (2) galaxy clusters, the highest galaxy density regions in the Universe, were galaxies suffer from extreme environmental effects, giving rise to the intergalactic matter that originates the ultra-faint intra-cluster light (ICL).

V.1. Metallicity and ionization in the extreme nuclear environments of AGNs and starburst galaxies

Team: **EPM**, JMV, BPD

The metallicity is key to understand galaxy evolution (Mannucci & Maiolino 19). However, most of the widely used methods to derive the metal content in galaxies come from very basic

strong-line calibrations based on local objects observed in the optical (Kewley+19). However, the advent of large ground-based (e.g., VLT, GTC, Keck) and space (HST, JWST) facilities have allowed us to collect large amounts of data in other spectral regions of objects in the early Universe, when galaxies began to assemble and extreme ionization conditions prevail, driven by massive SF and SMBHs actively accreting. Since massive SF and accreting SMBHs determine the evolution of the young objects, it is crucial to figure out methods to derive their chemical abundances separated in different kinematic components. Our group has pioneered the development of these kind of tools, therefore, we are in ideal conditions to develop them further to provide the metal content of primitive objects bypassing the use of calibrations based on local Universe objects. For this purpose, we use photoionization models specially computed for extreme objects observed at specific wavelengths (UV, optical, IR), and a Bayesian approach to estimate the radiation field. This objective will develop the HII-CHI-mistry tool (Pérez-Montero 2014) further, which will be applied to new samples of extreme objects. Past upgrades covered alternative spectral ranges (i.e. UV: Pérez-Montero & Amorín 17; mid-far IR: Fernández-Ontiveros+21; Pérez-Díaz+22) and suited new objects (EELGs, Pérez-Montero+21, and AGNs, Pérez-Montero+19). Our specific **OBs** are:

OB.V.1.1. Identify the nature of the ionization and derive the metal content in the nuclei of spiral galaxies.

OB.V.1.2. Disentangle AGN and circumnuclear star formation in nuclear environments. Provide reliable metal-dependent recipes to disclose AGN in highly star-forming environments in dwarf galaxies.

OB.V.1.3. Derive the hardness of the spectrum and the fraction of leaking ionizing photons in galaxies.

OB.V.1.4. Complete our understanding of dynamically complex ionized environments, such as AGN outflows and EELGs, including shocks in the physical prescriptions.

OB.V.1.5. Apply the abundance derivation methods to very high redshift, for extreme star-forming galaxies and AGNs, and revise the fundamental scale relations.

OB.V.1.6. We are members of the SIGNALS (Rousseau-Nepton+19) collaboration, which has already obtained a wealth of data with panoramic integral field spectroscopy of an extended sample of galaxies using SITELLE, the wide field IFU working at CFHT (Mauna Kea, Hawaii). Determine their 2D metal distribution.

V.2. Galaxy evolution in extreme galaxy density environments: star formation and the origin of intergalactic emission in clusters and groups

Team: **JMV**, YJT, JIP, DRP, SDP, LSP

V.2.1 The nature of the intergalactic emission in clusters of galaxies

Within the current LCDM cosmological model (e.g., Peebles & Ratra, 2002), clusters of galaxies are the latest gravitationally bound structures to form. They are built hierarchically, accreting galaxies and groups that fall into their gravitational potential or merging with other clusters. As a consequence of this process, the loosely bound gas and stars from the infalling-merging objects often end up either caught by the cluster galaxies (especially, the BCG) or freely floating in the intra-cluster space. The stars that become disconnected during these events form a diffuse and faint luminous envelope that permeates the intra-cluster space, called intra-cluster light (ICL). As privileged witness of the assembling history, the ICL records past interactions, telling us about the process of formation and evolution of the cluster. Recent works show a link between the ICL and the dynamical stage of the cluster (Jiménez-Teja+18, 19, 21; de Oliveira+22). The ICL can be used to estimate the time elapsed since the last merger event (Dupke+22). The ICL also provides information about the DM distribution (Montes & Trujillo 19, Deason+21, Gonzalez+21), although recent JWST observations cautions about over-interpretations (Diego+23). Therefore, ICL is an extremely powerful tool to study clusters: assembling history, dynamics, ICM chemical enrichment, and DM. Different mechanisms of production of ICL prevail at different redshifts. For redshift $z>1$, the ICL color is usually flat and similar to that of the BCG. This suggests that the stars that form this ICL primarily come from major mergers with the BCG. Several works report that the ICL is mainly formed at later times, $z<1$ (Burke+12; Montes & Trujillo 14, 18; Morishita+17), with the most dramatic evolution at $z<0.5$ (Montes & Trujillo 2018) which yields a ICL bluer and showing age and metallicity

gradients (e.g., Zibetti+05, Montes & Trujillo 14). Thus, the main mechanisms of ICL formation are not connected with the BCG build up but with tidal stripping of galaxies, cluster-cluster mergers, tidal disruption of dwarf galaxies, ram-pressure stripping, and pre-processing in infalling groups (Durrel+02, Gonzalez+05, Mihos+05, Krick+06, Williams+07, Montes & Trujillo 14, Presotto+14, Jiménez-Teja & Dupke 16, Jiménez-Teja+18, 21, Montes 22). The two **OBs** for this action are:

OB.V.2.1.1. Unveiling the origin and nature of the ICL in nearby clusters (up to z~0.1).
OB.V.2.1.2. Tracing the evolution of the ICL across cosmic time (up to z~1).

V.2.2 SF and intergalactic star-forming regions in clusters and groups of galaxies

The role played by the environment in the evolution of galaxies has been largely discussed in the literature (e.g., Dressler+80). Several physical processes, acting on different galaxy components, are responsible of a differential evolution, including harassment (Moore 96), tidal disruption of dwarf galaxies, stellar tidal stripping, ram-pressure stripping (Gunn & Gott 72), starvation (Larson+80), and pre-processing of galaxies in infalling groups. Observations of intergalactic regions of star formation have been reported, linking environmental effects to the ICL generation (Sun+07, 10). Galaxies with distorted morphologies (filaments and plumes, jellyfish galaxies, and one-armed galaxies) are observed in clusters with young (blue) ICL. This is also relevant in compact galaxy groups, and we have discovered the presence of different kinematical systems of intergalactic star-forming regions within the Stephan's Quintet (Duarte Puertas+19, 21) later confirmed by JWST. In the local Universe, when the density of galaxies increases, the fraction of late type spirals and star-forming galaxies decreases and the average galaxy metallicity increases. At high redshift the situation is less clear. It has been claims of this behaviour reversing at z>~1 (e.g. Elbaz+07; Tran+15) but not without dispute (e.g. Quadri+12). The interaction of cluster galaxies with the intra-cluster medium, and the study of the SFH and chemical evolution of cluster galaxies, are the scientific goals of this item. Specifically, studying the interplay between SF and the gas content of galaxies in a set of nearby clusters (including Hercules, Pegaso, Perseo, and A1367) combining our deep wide-field optical images with radio observations. Further multi-wavelength spectrophotometry is available from own observations and from archival data. With all this information, we will be able to trace the stellar and gas (ionized, neutral, and molecular) components for a number of cluster galaxies. Thus, the **OB** is

OB.V.2.2 Studying the interaction of cluster galaxies with the intra-cluster medium. We will address several key questions: (i) When, how, and where is SF quenched? (ii) What is the impact of gas stripping on the chemical evolution of cluster galaxies? (iii) What is the impact of shocks on their ISM? (iv) Is there SF triggered by the infall? Does it affect differently the different components of the ISM?

VI. Construction of advanced instrumentation for first class telescopes: TARSIS and MOSAIC

Team: **JIP,** CK, JVM, YJT, JMI, MA, RC, ENG/IAA1, ENG/IAA2, ENG/IAA3, ENG/IAA4

Needless to say, the development of new instrumentation is intimately linked to the most outstanding advances in astronomy. The ESTALLIDOS 8 collaboration is well aware of this fact and we are now involved in the development of two new generation instruments that, in turn, will make it possible to complete some of the long term scientific goals pursued in the project. These two instruments are TARSIS, to be installed at the 3.5m telescope of the Calar Alto observatory (Almería, Spain), and MOSAIC, to be installed at the ESO 39m ELT (Cerro Armazones, Chile). TARSIS and MOSAIC are key projects for ESTALLIDOS 8, therefore, we request funding to support our participation in such developments. The guaranteed time of TARSIS and MOSAIC will come in the form of galaxy surveys, and our group will have priority access to these first data, and to get out the very first science results. The funds for TARSIS and MOSAIC are mostly requested to hire the engineers needed for the technological developments. There is also a share to cover the hardware and software required to develop the tasks assigned to the IAA.

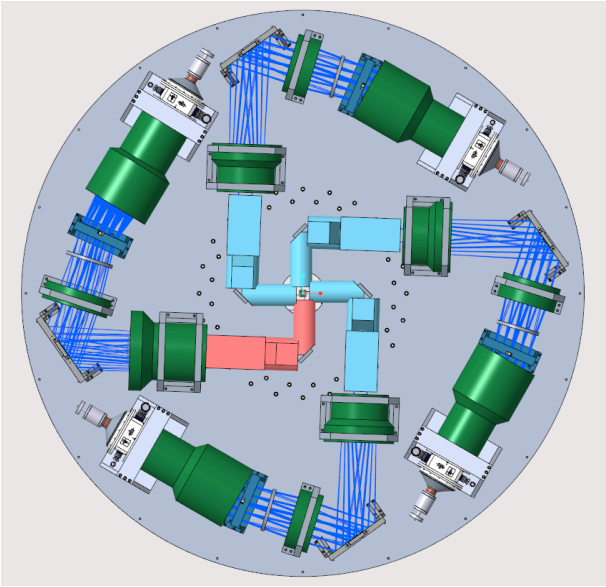


Figure 7: *Layout of TARSIS showing the three blue spectrographs plus the red one. It will be an IFU with a spectral resolution ~1000 in the spectral range [3200,8100]A. It is based on image-slicer technology, and its main specificities are its large field of view (~9 sq. arcmin with spaxel ~2 arcsec) and its capability to reach wavelengths as blue as 3200A (near the atmospheric cutoff).*

VI.1 TARSIS

TARSIS was selected in May 2022 as the new IFU for the 3.5m telescope of Calar Alto observatory. TARSIS first light is estimated for the end of 2026. The TARSIS consortium is composed by the IAA-CSIC and Universidad Complutense de Madrid (UCM), hosts of the two co-PIs (JIP and Armando Gil de Paz), the Universities of Granada, Almería, and Sevilla, the CAB, the Instituto Nacional de Astronomía, Óptica y Electrónica (INAOE, Puebla, México), the company FRACTAL S.L., and the Centro Astronómico Hispano en Andalucía (CAHA). An overview with technical features is given in Fig. 7.

The main goal for the first 5 years of TARSIS is the survey CATARSIS, which will observe a sample of 16 clusters in the range $0.15 < z < 0.23$, which corresponds to an epoch where galaxies were ~25% less massive but formed stars at a rate ~4 times larger. Among the different scientific cases to be addressed by CATARSIS, we highlight the interaction of cluster galaxies with the intra-cluster medium and the SFH of clusters galaxies.

The development of TARSIS is organized in 10 work packages (WPs), shared among all the members of the consortium. IAA-CSIC is in charge of the WPs devoted to develop the instrument control system, the acquisition and guiding system, and the calibration unit. JIP is one of the two co-PIs of the instrument, JVM is the IAA-CSIC representative in the TARSIS consortium, CK is the deputy project scientist, and YJT is assigned to the quality control WP. MA, ENG/IAA1, ENG/IAA2, ENG/IAA3, and ENG/IAA4 will contribute to the technical side of the project.

Thus, this **OB.VI.1** aims at supporting the construction of TARSIS.

VI.2 MOSAIC

MOSAIC will be the first-light MOS of the ESO 39m ELT. Scheduled for 2035, it is currently in phase B1, ending June 2024. MOSAIC will cover the spectral range [0.47,1.80] μm, with a variable resolution ranging from R = 5000-20000. The total FOV will be 40 sq. arcmin but only a few regions of such field will be covered by the observations. There will be three observing modes (1) high multiplex mode in the visible, for up to 200 objects simultaneously, (2) high multiplex mode in the NIR, for up to 80 objects simultaneously, and (3) high definition mode, allowing simultaneous observations of 8 IFUs with a FOV~2.5 arcsec, within a 40 arcmin patrol field. The Spanish contribution to MOSAIC is provided by the IAA-CSIC (via this project) and also by the UCM. This responsibility represents a challenge for the IAA (and the whole ESTALLIDOS collaboration) and also a unique opportunity to contribute at the highest level to the ELT, arguably the top development in ground-based astronomy ever built. Our contribution to the technological development of MOSAIC includes the control system of the cryogenic devices associated to the NIR spectrograph (NIR-SPEC): control electronics, and the low and high-level software. This contribution is linked to two WPs: EICS (Electronics and Intrument Control System), lead by IRAP (Toulouse, France) and NIR-SPEC, lead by LAM (Marseille,

France). Thus, our developments will be carried out in close contact with the researchers and engineers of these institutions, as well as other foreign technical staff involved in these WPs.

JIP is a member of the MOSAIC Institutional Board, representing IAA-CSIC. From the technical side, also JMI, ENG/IAA3, and ENG/IAA4 will contribute to the development of MOSAIC. MOSAIC is driven by several cutting-edge scientific cases, one of them focus on the study of the first galaxies in the Universe, with its SWG lead by CK, member of ESTALLIDOS.

Thus, this **OB.VI.2** aims at supporting the construction of MOSAIC.

4.2. Descripción de la metodología. *Description of the methodology*.

In order to reach the specific OBs described in Sect. 4.1, we will carry out a number of specific **Tasks** following a methodology briefly described next. The ordered list of tasks includes a reference to the **OBs** the task will help us to complete, preceded by the title of the general **OB**. Often there is a **Task** per **OB**, but not always. A chronogram with the timeline of all tasks is included at the end.

⇒ I.1. Models and simulations

Task.I.1.1. (**OB.I.1.1**) Update the MulChem chemical evolution grid originally produced by Mollá & Díaz 05. Make it available to the scientific community in a friendly open-access way. The new version will also include an evaluation of the dispersion due to the discreteness in the number of stars producing metals (Cerviño & Molla 02, Bazan+03, see also task II.3).
Task.I.1.2. (**OB.I.1.2,** and **OB.I.1.3**) Relate the radial gradient of abundances to the formation of the disk. We will use our MulChem models to study the evolution of the radial gradient of abundances in different types of observed galaxies. A special effort will be put on the derivation of chemical abundances in the innermost and outermost regions of the disk to produce reliable abundance gradients. Two different abundance tracers, O and S, will be used. S provides reliable abundances in the high metallicity regime (Díaz & Zamora 22), as needed to measure abundances near the galactic bulges and nuclei, and to explore feedback connections between these structures and the disks.
Task.I.1.3. (**OB.I.1.4**) We will include the constraints on the SNR evolution obtained during the PhD work of A. Castrillo in our synthesis codes, to consider a more realistic output of the instantaneous yield of each element and kinetic energy, and to predict the X-ray emission (see also item **OB.II.2**). We will also include these instantaneous yields in MulChem.

⇒ I.2. Follow-up IFU observations of galaxies with HI maps (HI-KIDS)

Task.I.2 (**OB.I.2**) A large set of about 90 HI-KIDS galaxies has been observed already, and they are currently being reduced. Play a leading role in the process, and contribute to improvement of the official pipeline of the instrument. Get deeply involved in the scientific analysis of the Hi-KIDS dataset, in particular, the chemical analysis connecting gas and stars in dwarf galaxies.

⇒ I.3. Studies of EXtremely Metal-Deficient (XMD) star forming galaxies with MEGARA

Task.I.3 (**OB.I.3**) Finish the observation, reduction, and analysis of the XMD galaxies being observed with MEGARA. We have granted observing time, and will apply for open time until completion. The galaxy distance changes, yielding a varying spatial resolution between ~22 and 850 pc, which will allow us to explore star formation at different spatial scales. We will obtain maps of gas kinematics with a resolution of ~16–50 km s^{-1}, electron density, electron temperature, and oxygen abundance. PopStar models + CLOUDY photoionization code will be used to compare with the MEGARA observations. Our analysis will follow the work on the Leoncino dwarf galaxy that we recently publish (Carrasco+22). Two other papers on SDSSJ0859+3923 and SDSSJ1640+2845 are coming up soon. We plan to study all the galaxies in the sample individually. Then draw conclusions on the whole sample at the end.

⇒ I.4. Feedback in low metallicity galaxies with N/O and He/H excess

Task.I.4 (**OB.I.4**) We have MEGARA observations of SHOC579, a galaxy with chemical anomalies and classified as WR (Fernández+18). We aim to correlate the WR stellar populations and the nebular abundances to understand whether the chemical composition of

the gas is contaminated massive young star clusters. We propose a spectroscopic analysis based in neural networks (NN) developed in Fernández+18, 19. The NN based algorithm will be adapted for IFU datasets to fit chemical models with hundreds of parameters. It will allow to obtain a multi-spatial chemical model: for whole galaxy and the WR region simultaneously. In addition, following Fernández+18, a stellar continuum will be fitted to each spaxel using the MEGASTAR library (see **OB.II.1.1**).

⇒ II.1. MEGASTAR and including of empirical libraries in our synthesis codes:

Task.II.1.1 (**OB.II.1.1**) We plan to continue with the development of the MEGASTAR library. In collaboration with the Massive Star group from Univ. Alicante, we are currently in the process of determining the parameters of the O, B, and WR stars using FASTWIND models extended to the I band. We have also requested and been awarded 75 h GTC time for semester 2023 to extend the library.
Task.II.1.2 (**OB.II.1.2**) Develop general tools to implement empirical libraries in our synthesis codes, and to model semi-resolved populations. This task will be carried out in the context of a PhD project.

⇒ II.2. Realistic Ionizing Fluxes of massive stars, the inclusion of new evolutionary paths and the extension to the high energy domain

Task.II.2.1 (**OB.II.2.1**) The mass loss strongly modifies the ionizing flux to be expected from a star. Unfortunately, the only existing theoretical grid (Gräfener+02, Hainich+19) only has two values of mass-loss rates and does not cover the required parameter space satisfactorily. We will collaborate with the massive stellar group at the CAB to overcome this problem: define the required parameter space, compute the corresponding stellar spectra, and include them in our synthesis codes (SED@ and PopStars).
Task.II.2.2 (**OB.II.2.2**) Together with libraries of stellar spectra (**Task.II.2.1**), isochrones are the other fundamental ingredient of the population synthesis codes. We plan to compute isochrones of stars with rotation and for binary stars. Stellar tracks with rotation have been developed in Geneva (Ekström+12, Yusof+22) and Bonn (Szécsi+22). However, there are two difficulties: (1) the grid in rotational velocity is too coarse and has to be interpolated with an unclear outcome, and (2) their metallicity range excludes the low metallicity regimen ESTALLIDOS is interested in. If suitable tracks are obtained, they will be compared with observational data working together with the massive star groups at CAB and IAC. This task would be performed in the context of a PhD Thesis.
Task.II.2.3 (**OB.II.2.3**) Including X-ray binary systems will allow us to explore the X-ray emission of star forming regions. X-ray sources are variable. We will describe X-ray binaries and SN remnants as a time average plus a dispersion, updating the model by Cerviño+02. This work will be carried out together with experts in variability of low and high mass X-ray binaries, especially in the ESAC community.
Task.II.2.4 (**OB.II.2.4**) We plan to study individual ULX in star forming galaxies like ESO338 or Haro 11. Deep X-ray observations with Chandra will allow us to identify their location and associate them to individual massive star clusters. Study the IR emission lines with JWST will constrain the ionizing continuum of the star forming region, unknown up to now.

⇒ II.3. Modelling semi-resolved populations and sparsely populated stellar systems

Task.II.3.1 (**OB.II.3.1**) Evaluate the correlation between different observables comparing with of Monte Carlo simulations. Once the correlation matrix is obtained, we plan to develop fitting algorithms to infer physical properties.
Task.II.3.2 (**OB.II.3.2**) The dispersion of the observables contains physical information on the system. The problem is how to discriminate between instrumental noise and physically-meaningful dispersion. The surface brightness fluctuations technique (Tonry & Schneider 88) solves this problem in the Fourier domain and under some assumptions which are not applicable to IFUs. We will try to find our way out, following Buzzoni 05.

⇒ II.4. Characterization of the different components of emission-line galaxies

Task.II.4.1 (**OB.II.4.1**) Study the effect of the interaction in the nuclear activity of a sample of nearby ($z<0.05$) and IR bright of major mergers (Sekiguchi & Wolstencroft 92). Detect the

galaxies with enhanced nuclear activity, either related to the SMBH or to SF. The X-rays will allow us to distinguish between them to understand the mechanisms that trigger activity in merging systems.

Task.II.4.2 (**OB.II.4.2**) Study a sample of emission line galaxies at z ~ 0.8 presented in Navarro-Martínez+21, for which we have SEDs from the IR to X-ray. Use SED fitting codes to characterize the SF and the AGN components.

⇒ III.1. Studying the gas feeding star formation at different redshifts

Task.III.1.1. (**OB.III.1.1**) Relying on the public data sets of MUSE Wide (Urrutia+19) and MUSE Deep (Bacon+22), detect extended emission line haloes (Hα, Hb, [OIII], [OII]) in the CGM and IGM of the local galaxies existing in these cosmological fields. Using either haloes of individual galaxies or stacked spectra, constrain the metallicity (Pérez-Montero 2017) and motion of the metal-poor gas around the galaxies. Write a paper with the conclusions.

Task.III.1.2. (**OB.III.1.2**) Characterize the local correlation between metallicity other physical parameters like stellar age and gas mass using MANGA IFU data. Use AI aided tools (Random Forest Trees; e.g., Sanchez Menguiano+19) to investigate the physical origin of the relation, e.g., to figure out which one among the many physical parameters of a galaxy determines best its chemical inhomogeneities.

⇒ III.2 Connections with the underworld

Task.III.1.1. (for **OB.III.2.1**) Using machine learning techniques (matched filters or NN), develop an automatic algorithm to detect double peak Hα emission in noisy IFU datacubes (such as the MUSEW datacubes by Urrutia+19 used by Sanchez Almeida+22). Translate the human-brain guided approach in Sanchez Almeida+22 to an automatic algorithm, since the data volume prevents any other sensible approach to the problem.

Task.III.1.2. (for **OB.III.2.2**) Apply the tool to the MUSE wide data set, together with the MUSE deep field recently released (Bacon+22), expected to be some 10 times deeper than MUSE wide. Through standard scaling relation based on Hα (e.g., Reines+13), characterize the physical properties of the IMBH (e.g., BH mass, Eddington ratio, and depletion timescale).

Task.III.1.3. (for **OB.III.2.3**) MUSE wide and MUSE deep are in GOOD-S, a cosmological field with plenty of ancillary data. Taking advantage of this, look for counterparts of the Hα signals in X-ray, radio continuum, HST optical, and ALMA. Moreover, IMBHs are expected to reprocess the UV photons of the disk and reemit them in the near IR. Therefore, look for counterparts in the JWST IR images of the public cosmological field GOODS-S (PI: Eisenstein, Ferruit+), that will be publicly available in a year from now. Alternatively, apply for JWST time for some of the targets.

Task.III.1.4. (for **OB.III.2.4**) Write the paper.

Task.III.1.5. We do have experience within massive spectral classification (Sanchez Almeida+10,13), and similar AI techniques can be applied to identify spectra with double peaks tracing IMBHs. There are several datasets available (SDSS and the like).

⇒ III.3. Star Formation in the Epoch of Reionization

Task.III.3.1. (for **OB.III.3.1**) We plan to ask for JWST time aiming to improve the statistics on the Lyα emitting galaxies in the redshift range 6–10. The predictions of our models for both cases (single and double reionization) are very different, and the comparison with observations will allow us to distinguish between them. The observations we plan to perform will be complemented with results of other observational programs already being executed by JWST on high redshift galaxies, which aim to study the formation and evolution of the first generations of massive stars, so that the availability of data is guaranteed.

Task.III.3.2. (for **OB.III.3.2**) Different surveys of the high-redshift universe are providing the data on the distribution and properties of ionised bubbles at the end of the epoch of reionization. We will apply our evolutionary synthesis models PopStars and SED@ to infer the LyC escape fractions required to produce the observed ionized bubbles, analyzing their evolution with redshift and dependence on the properties of the ionizing galaxies.

⇒ III.4. Quantifying SF feedback.

(**OB.III.4.1**) Apply for WEAVE observing time in its mini-IFU HSR mode for the sample of ELG at z < 1 in SHARDS (Lumbreras-Calle+19a).

Task.III.4.1. (**OB.III.4.2** and **OB.III.5.4**) Implement an AI algorithms to classify the emission line profiles. Select the best algorithm to fit several components to the emission lines. Apply them to the existing long slit HR spectra taken with IDS@INT and ISIS@WHT for the sample of ELG in COSMOS (Hinojosa-Goñi+16) and Extremely Metal Poor galaxies (XMP, Morales-Luís+11). Exploit the TKRS (Wirth+04) long-slit data available for a subsample of ELGs in GOODS-N.

Task.III.4.2. (**OB.III.4.3** and **OB.III.4.4**) The spectroscopic data from **Task.III.4.2** will be complemented with HST images to identify the clump(s) in each galaxy responsible for the emission. Model the SED of the clumps to derive mass following algorithms already developed in ESTALLIDOS 6 and 7 (Lumbreras-Calle+19b). The emission lines will also provide dynamical masses. Other parameters like the relative location of the clumps in the galaxy and their metallicity will also be considered (Muñoz-Tuñon+14, Sánchez Almeida+13, 16). The results will be analysed in the context of the SF feedback from our theoretical studies.

Task.III.4.3. (**OB.III.4.5**) Explore the observational evidences of dust produced by SN in massive starburst by comparing numerical simulations with IR databases.

⇒ III.5. Understanding star formation at different z, from multi-λ photometric information.

Task.III.5.1. (**OB.III.5.1** and **OB.III.5.3**) The work done in SHARDS will be applied to the much larger PAU survey. Compute luminosity functions, SFRs, mass functions, clustering, classes of sources, etc. Try also with JPLUS.

Task.III.5.2. (**OB.III.5.2** and **OB.III.5.4**) Connect the general properties of the galaxies with the clump structure, as we did in COSMOS (Hinojosa-Goñi+16).

⇒ III.6 Star formation feedback and the nature of dark matter

Task.III.6.1. (**OB.III.6.1**) Use energy balance arguments (e.g., Peñarrubia+12) to compute the smallest stellar mass able to turn a cuspy DM halo into a cored halo. Use the *Eddington inversion method* (Binney & Tremaine 08, Lacroix+18), to show that stars trace DM in the most common DM dominated particle systems. It is not trivial to prove since collision-less systems keep memory of the initial conditions for longer than the age of the Universe. Write a paper with the conclusions.

Task.III.6.2. (**OB.III.6.2)** Use existing data (e.g., Trujillo+20, Carlsten+21) to study the stellar mass distribution of low mass galaxies. Quantify how common cores are. Can we assess that the DM particles are not collision-less? Write a paper.

⇒ IV.1 High-ionization emission powered by nearly metal-free stars: the missing link to the reionization era?

Task.IV.1.1. (**OB.IV.1.1** and **OB.IV.1.2**) New MEGARA/GTC data cubes for 11 objects of our sample of local metal-poor dwarfs with WR bumps are already in hand. Derive their properties.

Task.IV.1.2. (**OB.IV.1.1** and **OB.IV.1.2**) Submit IFU proposals (MEGARA, PMAS, MUSE) to perform 2D follow-up spectroscopy of most metal-poor objects selected from our mother sample of 189 nearby HeII-emitting galaxies and the new HeII-emitting candidates to be found from our guaranteed access to the J-PAS survey (IAA is an institutional partner).

Task.IV.1.3. (**OB.IV.1.1** and **OB.IV.1.2**) Putting together **Task.IV.1.1** and **Task.IV.1.2** we will construct the first reference sample of nearby local, metal-poor HeII-emitting galaxies. Their properties will be described in a paper.

Task.IV.1.4. (**OB.IV.1.1** and **OB.IV.1.2**) Select JWST optical rest-frame spectroscopic line fluxes of distant HeII-emitters (e.g. Trump+22) and compare them with local ones using our tools, i.e., the HeI/HeII vs [OII]/[OIII] ([OII]/[NeIII]) diagnostic diagrams (Pérez-Montero+21) in combination with the photoionization code HII-CHI-mistry (see *material resources*). Then prepare and submit the corresponding publication.

⇒ IV.2. Extreme emission line galaxies and LyC leakers

Task.IV.2.1. (**OB.IV.2.1**) Complete the data reduction of the MEGARA GTC observations of our sample of northern LyC leakers. Then carry out extensive spectral and chemodynamical

analysis using the spectral analysis tool LiMe, to infer line fluxes and kinematics (see *material resources*).

Task.IV.2.2. (**OB.IV.2.2**) Continue the observation, characterization, and analysis of a subsample of the 400 EELGs candidates selected from the J-PLUS survey (Lumbreras-Calle+22).

Task.IV.2.3. (**OB.IV.2.2**) Select new EELG candidates in the J-PAS survey (as in Iglesias-Paramo+22) in the pathfinder JNEP field already observed. After 2024, this search will be extended to the coming fields during full J-PAS operation. Submit IFU proposals (MEGARA, PMAS) to perform their 2D spectroscopic follow-up. The corresponding data reduction and analysis should be carried out during years 2 and 3 of the project.

⇒ IV.3 Preparatory science for the future first-class IFUs: TARSIS and MOSAIC

Task.IV.3.1. (**OB.IV.3**) The large FOV of TARSIS, its blue coverage and the planned deep observations of CATARSIS offer unique opportunities to find new UV-bright objects including HeII-emitting galaxies and Lyα-emitters at 1.6 <z< 3.5, reaching also other relevant UV emission lines to derive properties of the gas. In particular, it will allow us to explore the CIV550/CIII]1909 indicator of LyC escape fraction recently proposed by Schaerer+22. In order to prepare for the TARSIS/CATARSIS science, PMAS (the precursor of TARSIS) observations of a sample of local analogue galaxies are planned to be taken during 2024. The data reduction and analysis of these data will be done in 2025.

Task.IV.3.2. (**OB.IV.3**) With MOSAIC (FOV=44.2 arcmin2), we will search for and characterize the population of very distant high-ionizing emitters population. Thanks to its wavelength coverage (0.8-1.8μm), diagnostic lines (e.g. Lyα, HeII1640, CIV]1540, OIII]1661,66 CIII]1907,09) can be detected at z~4-8 unveiling the properties of objects (density, excitation, metallicity) during reionization. Due to its superb spectral resolution (R=9000-18000), we will be able to search for very distant LyC leaker candidates using the separation between the Lyα peaks, considered the best indirect indicator of fesc(LyC) (e.g., Izotov+18, 21), and we will explore other fesc(LyC) indirect indicators (e.g., intensity of the HeII line). MOSAIC will also allow us to search for Lyα+HeII1640 emitters with no metal lines at 5<z<10, which are unique tracers of primordial galaxy formation. No such galaxies have been observed so far. We will carry out detailed MOSAIC simulations of the above science cases for the *First light galaxies and reionization* SWG, including a full chemodynamical description of the targets. The results will be used in the *Science Reference Programs* to be collected into the MOSAIC Red Book from which the final MOSAIC GTO will be selected.

Task.IV.3.3. We will construct a user-friendly simulator assessing the feasibility of different science cases and target families. This task will be carried out by an experienced PD requested for the IAA node. The PD researcher will assess the feasibility and requirements for such studies with the MOSAIC MOS/multi-IFU modes. To this end, he/she will make use of the MOSAIC scientific simulator together with our collaborators in the UK (R. Sánchez-Jansen, MOSAIC Project Scientist, ATC).

⇒ V.1. Metallicity and physical properties in the extreme environment of AGNS and Starburst galaxies

Task.V.1.1. (**OB.V.1.1** and **OB.V.1.2**) To identify the nature of the ionization and to derive the metal content in the nuclei of spiral galaxies, we will use spatially-resolved integral field spectroscopy both in the optical (MUSE, MEGARA) and the mid-IR (JWST). The mixture of AGN and circum-nuclear star-formation in this extreme nuclear environment will require upgrading the photoionization models. We will provide metallicity-dependent recipes to disentangle both components so as to identify AGNs in low mass galaxies.

Task.V.1.2. (**OB.V.1.3**) To derive the hardness of the incident radiation and the fraction of leaking ionizing photons in our galaxy samples (see **Task V.1.1**), photoionization models will be compared with the emission-line ratios of consecutive ionization stages in the UV, optical and IR. The best matches will set the models used to infer metallicities.

Task.V.1.3. (**OB.V.1.4**) Include the effect of shocks to model dynamically complex extremely ionized environments, such as those observed in AGN outflows and some EELGs. Study the dependence on density of multi-component optical IR emission-lines.

Task.V.1.4. (**OB.V.1.5**) Following our methodology, metal abundances of high-redshift star-forming galaxies and AGNs will be derived based on their rest-frame UV emission lines

(CIII]1909 or CIV]1549), which dominate their spectrum. They will be used to revise and quantify the fundamental relations followed by these extreme objects.
Task.V.1.5. (**OB.V.1.6**) Derivation of 2D chemical abundances for SIGNALS galaxies; application of our code HII-CHI-mistry and chemical evolution modelling. It involves different nodes of ESTALLIDOS 8.

⇒ V.2.1 The nature of the intra-cluster emission in clusters of galaxies

The ICL is very faint and so elusive. Its detection requires deep imaging, given its very low surface brightness, typically > 26.5 mag arcsec^{-2} in V (e.g., Rudick+06). Its analysis must be exquisite to disentangle the ICL from the light of the cluster and foreground galaxies. Analyses in the literature are usually restricted to one or two filters, thus missing information about the nature of the ICL stellar populations that is encoded in the colors. In a detailed study of the ICL in the nearby Coma cluster with narrow and broad-band J-PLUS filters, we observe features in the ICL that are only visible at certain wavelengths (Jiménez-Teja+19). Moreover, the ICL observations in nearby clusters, which in principle should simpler, are often restricted to the cluster core due to insufficient surveyed area. Keeping this in mind, we will cover niches still unexplored focusing in two main tasks:
Task.V.2.1.1. (**OB.V.2.1.1**) Unveil the ICL in nearby clusters, up to z~0.1. We will use deep optical imaging provided by the 3.5m at Calar Alto and the INT to identify tidal features (plumes, loops, shells, and filaments), from which to derive past interactions and the assembly history of the cluster. We will detect intra-cluster globular clusters and planetary nebulae and compare their spatial distribution with the ICL. Compare the mass and ICL distributions for clusters with total mass distributions derived through gravitational lensing. For this analysis, we will use CICLE (see *material resources*) adapted to identify substructures as done for Coma or Virgo (e.g. Mihos+17, Jiménez-Teja+19).
Task.V.2.1.2. (**OB.V.2.1.2**) Constrain the evolution of the ICL with cosmic time up to z~1. We will use the J-PAS survey to analyze low-mass clusters. J-PAS will map an area of 8600 square degrees on the sky, using a set of 54 narrow- and 5 broad-band filters. Given the huge sky coverage and sensible depth, J-PAS will be able to detect clusters and groups up to redshift z~1, down to low masses. J-PAS is expected to identify ~650000 groups with masses >3x10^{13} $M_{\odot}$ (Benítez+14). If necessary, we will stack images of these systems with similar characteristics to increase the signal-to-noise (e.g., Zibetti+05, Zhang+18). Using the whole set of narrow and broad-band filters, we will carry out the most detailed analysis of the ICL in individual clusters to characterize its dependency on redshift, viral mass, BCG mass, etc. As a side product, we will elaborate the largest catalogue of clusters with dynamical information and improve the cluster scaling relations. In addition, we will confirm or refute the similarity between the distribution of ICL, DM, and compact sources using data already available to our group from HST and the JWST (25 clusters of CLASH, Postman+12; 6 Frontier Fields systems, Lotz+17; 41 clusters of RELICS, Coe+19; plus other JWST programs of individual clusters).

⇒ V.2.2. Star formation and intergalactic star-forming regions in clusters and groups of galaxies

Task.V.2.2.1. (**OB.V.2.2**) We will combine spectrophotometry, radio, and other multiwavelength information available from our collaborators (Univ. Porto; ING La Palma) to trace the stellar and gas components for the sample of clusters galaxies. All the spectrophotometric data are already in hand, including deep wide-field broad and narrow-band H images of Hercules, Pegaso, Perseo, and A1367. The main challenge of this task is completing the data reduction and photometric calibration, and constructing the cluster database. This database should contain galaxy catalogues, whether they have spectra (single or IFU), line fluxes, and SED fitting properties such as SFHs.
Task.V.2.2.2. (**OB.V.2.2**) We will apply CICLE (see *material resources*) to analyze our ground-based and space-borne (HST, JWST) data described in **Task.V.2.1.2**. Except for J-PAS, which is just about starting, all other data are available. The algorithm CICLE is also ready and fine-tuned for each dataset, and we have enough computational resources at IAA.

⇒ VI.1 TARSIS (advanced instrumentation)

Task.VI.1 Given the special nature of **OB.VI.1** (the construction of TARSIS), rather than including here a long list of specific tasks, we provide a quick summary of the present state of the project.

IAA is responsible for work packages WP-07, covering the Instrument Control System (ICS), and WP-10, the latter including the design and development of the Acquisition and Guiding System (A&G) and the Calibration Unit (CU). After the final selection of TARSIS (May 2022), preliminary concepts for A&G and CU were put forward. Once the consortium confirmed the need for a rotator specific to the instrument, a first proposal was made for its optics and optomechanics, based on a K mirror type configuration. In WP-07, Beckhoff controllers were definitively selected as the basis for designing the control system. The Conceptual Design Review (CoDR) of the instrument is set for March 2023. Up to then, our efforts will be focused on the conceptual design of the control system structure, which includes capturing requirements, defining interfaces, and identifying the elements that will need control and monitoring. In the case of WP-10, the final concept for the A&G, CU, and rotator will be set during CoDR. At this stage, all the low-level interfaces will be defined and the controllers, temperature and pressure sensors, and actuators will be selected. The acquisition of all optical, mechanical and control elements will begin in this phase, since the delivery times of many of them are long. The detailed design phase will begin after PDR. At its completion, with the Critical Design Review (CDR) scheduled for Nov. 2024, the final hardware and software architecture will be defined, and a design implementation plan will be prepared. Operation tests will begin at subsystem level. In the WP-07 the SW acquires greater importance from this stage, and in the WP-10 the optical design is closed and the optomechanics takes over. Once the detailed design review has been completed, the implementation phase of all the control SW modules will start with duration of 18-24 months. All the subsystems of the instrument will be integrated with the SW, in order to carry out tests at system level. These tests will culminate with the AIV and commissioning stages at CAHA observatory. In WP-10, all the optical and mechanical elements manufactured by external companies will be received and integrated, first at the IAA and then, during the final phases of the project, at CAHA observatory. In parallel to the design, a series of tasks related to the quality management package have to be performed. These tasks will be carried out in practically every stage of the project and will have an impact on all the design and implementation activities.

For further details, see **https://tarsis.caha.es**

⇒ VI.2 MOSAIC (advanced instrumentation)

Task.VI.2 As it is mentioned above in connection with TARSIS, given the special nature of **OB.VI.2**, rather than including here a long list of specific tasks, we provide the activities to be developed during phase B in which the technical IAA team will be involved.
Phase B1 (18 months): the resources to accomplish the main goals of phase B will be defined and reviewed. At the end of this phase (June 2024), the architecture and the specifications will be reviewed. Phase B2 (24 months): the preliminary design has to be completed. There will be an intermediate internal design review in Sep. 2025, and the definite preliminary design review (PDR) in Sep. 2026. Simultaneously, the IAA will define and develop prototypes that will allow us to implement in real models the ideas of the conceptual design of the control system of the cryogenic devices, to perform simulations and tests, to analyze the results, and to improve the design in a progressive way until the final model for manufacturing. We will use hardware and software following the ESO standards and recommendations for ELT, as well as the initial requirements of MOSAIC for the control of de NIR-SPEC devices. During 2022 the first prototype was completed: it will be used for the control of a stepper device under vacuum and cryogenic conditions in the cryostat already available at IAA. The performance of the device under different situations will be characterized. Then, we will assemble the thermal control of the test cryostat, so that additional tests can be carried out under the temperature conditions defined in the specifications of MOSAIC. In addition to the cryogenic prototype, we will continue the development of a non-cryogenic prototype with multiple axes based on a numerical control system (CNC) already existing at the IAA laboratory, so that the performance of the control system in the case of multiple axes can be evaluated. During 2024, new components will be added to the initial cryogenic prototype to produce a more advanced prototype. During 2025, we will start the development of a third multi-axis cryogenic prototype, with two cryogenic engines, and we will perform the design and initial integration of the control

system of this prototype (multi-axis) in a rack according to the ESO standards. This rack will be the basis for the preliminary design that will take place during 2025 and 2026. Such design will pass an internal review in mid 2025, and a final review in Sep. 2026.
In addition to the previously activities, the IAA-CSIC team will carry out the tasks associated to the quality management (PA/QL engineering), as well as to the tasks associated to the management and planning (project management) assigned by the technical office of MOSAIC. Several meetings of the MOSAIC Consortium, devoted to reviews and prototype tests, are foreseen in the different phases of the project.

4.3. Plan de trabajo y cronograma. *Work plan and schedule*.

Each one of the specific objectives in Sect. 4.1, and therefore, each one of the tasks in Sect. 4.2 has a team leader, responsible for the completion of the objective, and a number of collaborators. In case this objective includes the writing of a document or a paper, the leader is responsible for this task too. All the information on the team (members and leader) and schedule to complete the work are summarized in the timeline-cronograma included below. Each researcher is identified with a code, given at the end of this document, with the leader highlighted in boldface. The timeline assumes the project to start on Sep. 1, 2023. If for some reason this date is delayed, then the whole timescale will be shifted accordingly.

TIMELINE - CRONOGRAMA

(1) As defined in Sect. 4.2. (2) As defined in … T1, T2, T3, and T4, stand for 1st (T1) to 4th (T4) four-months interval. lead by IAC. lead by IAA. lead by CAB-UAM.

Task (1)	**Lead,** Team (2)	2023	2024				2025				2026				2027		
		T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3
I.1.1	**AID,** MCS, IMY, JJB, OC, ST/CAB-UAM, PD/CAB-UAM																
I.1.2	**AID,** JMV, EPM, FRO, SZ, PD/CAB-UAM																
I.1.3	**AC,** MCS, AID, PD/CAB-UAM, PD/CAB-UAM																
I.2	**ALS,** PCC, AID, AC, FRO, PD/CAB-UAM																
1.3	**MGV,** EC, ET, RJT, MCS, ALS																
I.4	**AID,** VGF, RAB, RJT, ET, DFA, RC, MCS, ALS, GFH, DRG, PD/CAB-UAM																
II.1.1	**MGV,** EC, IMY, MCS																
II.1.2	**MGV,** EC, IMY, MCS, ST/CAB-UAM																
II.2.1	**MCS**																
II.2.2	**MCS,** IMY, ST/CAB-UAM																
II.2.3	**MCS,** CSS, EJB, IMY																
II.2.4	**MCS,** MSL, EJB, CSS, MVC, MMH																
II.3.1	**MCS,** JJB, OC, ST/CAB-UAM																
II.3.2	**MCS, SS, ST/CAB-UAM**																
II.4.1	**MSL,** MCS, ALL, EJB, IC, LB, JE, LT, PRP, MVC																
II.4.2	**MCS,** EJB, IA																
III.1.1	**JSA,** SFS, CMT, JRE, ST/IAC1																
III.1.2	**JSA,** SFS, CMT, JRE, ST/IAC1																
III.2.1	**JSA,** CMT, NC, PD/IAC1																

III.2.2	**JSA,** CMT, NC, PD/IAC1																
III.2.3	**JSA,** CMT, NC, PD/IAC1																
III.2.4	**JSA,** CMT, NC, PD/IAC1																
III.2.5	**JSA,** CMT, NC, PD/IAC1																
III.3.1	**MMH**, CMT, JRE																
III.3.2	**MMH**, CMT, JRE																
III.4.1	**CMT,** CF, JSA, SS, GTT, SMG, NC, ST/IAC2																
III.4.2	**CMT,** CF, JSA, SS, GTT, SMG, NC, ST/IAC2																
III.4.3	**CMT,** CF, JSA, SS, GTT, SMG, NC, ST/IAC2																
III.4.4	**CMT,** CF, JSA, SS, GTT, SMG, NC, ST/IAC2																
III.5.1	**CMT,** MMH, JRE, NC, JSA, BGE, DME, PD/IAC2																
III.5.2	**CMT,** MMH, JRE, NC, JSA, BGE, DME, PD/IAC2																
III.6.1	**JSA**, ARP, NC, BGE																
III.6.2	**JSA**, ARP, NC, BGE																
IV.1.1	**CK**, JVM, EPM, JIP, RAB, APP, PD/IAA																
IV.1.2	**CK**, JVM, EPM, JIP, RAB, APP, PD/IAA																
IV.1.3	**CK**, JVM, EPM, JIP, RAB, APP, PD/IAA																
IV.1.4	**CK**, JVM, EPM, JIP, RAB, APP, PD/IAA																
IV.2.1	**JMV,** JIP, CK, EPM, AAP, RAB, PP, LSP, IB, PD/IAA																
IV.2.2	**JMV,** JIP, CK, EPM, AAP, RAB, PP, LSP, IB, PD/IAA																
IV.2.3	**JMV,** JIP, CK, EPM, AAP, RAB, PP, LSP, IB, PD/IAA																
IV.3.1	**JIP,** CK, JMV, EPM, JAC, IB, PD/IAA																
IV.3.2	**JIP,** CK, JMV, EPM, JAC, IB, PD/IAA																
IV.3.3	**JIP,** CK, JMV, EPM, JAC, IB, PD/IAA																
V.1.1	**EPM**, JMV, BPD																
V.1.2	**EPM**, JMV, BPD																
V.1.3	**EPM**, JMV, BPD																
V.1.4	**EPM**, JMV, BPD																
V.1.5	**EPM**, JMV, BPD																
V.2.1.1	**JMV**, YJT, JIP, DRP, SDP, LSP																
V.2.1.2	**JMV**, YJT, JIP, DRP, SDP, LSP																
V.2.2.1	**JMV**, YJT, JIP, DRP, SDP, LSP																
V.2.2.2	**JMV**, YJT, JIP, DRP, SDP, LSP																
VI.1	**JIP,** CK, JVM, YJT, JMI, MA, RC, ENG/IAA1, ENG/IAA2, ENG/IAA3, ENG/IAA4																
VI.2	**JIP,** CK, JVM, YJT, JMI, MA, RC, ENG/IAA1, ENG/IAA2, ENG/IAA3, ENG/IAA4																
		T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3
Task (1)	**Lead,** Team (2)	2023	2024				2025				2026				2027		

4.4. Identificación de puntos críticos y plan de contingencia. *Identification of critical points and contingency plan*.

The different **OBs** (Sect. 4.1) and the associated tasks (Sect. 4.2) present different degree of risk. We grouped them in several categories attending to this degree, where explain our contingency plan for each category.

Low risk OBs, where the data are available and the analysis follows up on previous works well within the expertise of the team. They constitute most of the **OBs** in the project. No alternative is given. They are **OB.I.1.2**, **OB.I.1.3**, **OB.I.2**, **OB.I.4**, **OB.II.1.1**, **OB.II.3.2**, **OB.II.4.1**, **OB.II.4.2**, **OB.III.1.2**, **OB.III.4.1**, **OB.III.6**, **OB.IV.1.1**, and **OB.IV.1.2**.

Medium risk OBs, where part of the required data is still missing, or the whole required workforce is not granted. We will have to consider whether (1) finish the work with the data and resources available (including writing a paper) or (2) write a report for the work to be continued when data are resources are available. They are **OB.I.1.1**, **OB.I.3**, **OB.II.2.3**, **OB.II.2.4**, **OB.III.4.2**, **O.III.4.3**, **OB.III.5.1**, **OB.III.5.2, OB.IV.2.3, OB.IV.3**, **OB.V.2**, **OB.V.1**, **OB.V.2.1.2,** and **OB.V.2.2.1**

High risk, high gain OBs: **OB.VI** (due to the especial nature of any construction projects).

Lack of man power, where the tasks heavily depend of the new personal to be hired with funds from the project (PD) or on a ST. If these resources are not assigned, then the tasks will likely be cancelled. These **OBs** are: **OB.II.1.2**, **OB.II.3.1**, **OB.III.1.1**, **OB.III.2.1** to **OB.III.2.3, OB.III.5.3**, **OB.III.5.4, OB.IV.2.1, OB.IV.2.2, OB.VI.1,** and **OB.VI.2.**

Fillers, to be completed in case other OBs fail for something not considered above and there is enough workforce available. They are **OB.III.2.5, OB.III.4.4**, and **OB.III.4.5.**

Special cases:

OB.III.2 All data are available and only depend on workforce. However, there is a chance for the faint signals to be artifacts. Then, we would scale down the original objective to try to figure out where the claimed detections (Sanchez Almeida+22) come from, and then to publish a rebuttal paper with the conclusions.

OB.VI requests funding for engineers to carry out the tasks assigned to the IAA-CSIC in TARSIS and MOSAIC. Not getting funds for TARSIS would mean to depend on a future call for ICTS lead by the *Observatorio de Calar Alto*. However, this is a bad solution since the project will be drastically delayed. For MOSAIC, the countries members of the consortium must contribute with 1000000 euro, either in cash or in kind (contracts, H/W, manpower...). The Spanish ministry of science and innovation, MICINN, has expressed the interest of Spain on this project and has agreed to provide the necessary funds to the institutions responsible of the Spanish contribution to project (IAA-CSIC and UCM), encouraging us to apply through the open national calls, like the present one. The advanced instrumentation project presented here has an important community dimension since its final goal is to provide the Spanish astronomers with new cutting-edge instrument through open access to it; it is mainly on this basis that we kindly ask the AyA division for financial help.

4.5. Resultados previos del equipo en la temática de la propuesta. Previous results of the team in the theme of the proposal.

ESTALLIDOS has been working together for more than 20 years in 7 previous coordinated projects (see Sect. 2). Even though the details have been changing with the evolution of the field, the underlying grand objective remains constant: understanding SF in the Universe, near and far. Thus, ESTALLIDOS accumulate a huge number of previous result in the topic of the proposal. We have published more than 1000 papers in major refereed journals; too many to summarize them in the limited space available here. Thus, we kindly invite the reviewer to check the CVAs enclosed with the proposal for some of the highlights produced during these years.

4.6. Recursos humanos, materiales y de equipamiento disponibles para la ejecución del proyecto. *Human, material and equipment resources available for the execution of the Project*.

We have divided these 'available resources' into three classes: general resources, resources specific to ESTALLIDOS, and special resources required for particular **OBs**.

General resources: All the nodes have access to the facilities that the home institutions make available to them, including offices, computing facilities, access to the different databases and archival data, and supercomputer facilities. All the researchers can apply for observing time at the different national ICTS on a competitive basis as well as to ESO, ESA and NASA infrastructures in open access regime. All the nodes possess the necessary software to reduce and analyze the secured data. ESTALLIDOS have proven experience in getting observing time in these infrastructures.
Specific to ESTALLIDOS: We have developed a number of singular analysis tools often made publically available. Among others, the **HII-CHI-mistry** code, of wide-spread use in the astronomical community (Pérez-Montero 2014 has > 160 citations) provides O/H and N/O using commonly observed emission optical line. It already has an extension to UV lines, tuned to measure O/H and C/H in galaxies up to redshift 4 (Pérez-Montero & Amorín 17). Other extensions include deriving chemical abundances in objects ionized by non-thermal radiation sources, such as Seyfert 2 galaxies (Pérez-Montero+19). **LiMe** (Fernández+22) allows the automated fit of lines in large spectrum data sets. It includes detection, profile fitting, and analysis of the chemical composition in the different kinematics components. **MulChem** (Mollá & Díaz 05) allows to compare observations with predictions from chemical evolution models. **CICLE** (CHEFs Intracluster Light Estimator; Jiménez-Teja & Dupke 16) is the only algorithm capable to disentangle the ICL emission from the galactic light without assuming any a priori hypothesis on the properties of the BCG or the ICL. In fact, CICLE was crucial to predict that Earendel, the more distant star known ever, was not a transient event (Welch+22). **PopStar** (Mollá+09, Martín-Manjón+10, García-Vargas+13, Millán-Irigoyen+21) is an evolutionary synthesis model. A large grid for stellar populations with a wide range of ages and metallicitie widely used by our community. **MEGASTAR** is an empirical stellar library for population synthesis models specifically developed for the interpretation of MEGARA@GTC IFU data. Still ongoing, it obtained 75h GTC hours. **ASK** (Sanchez Almeida+10) is an automated spectral classification for SDSS spectra used to identify extreme objects with special characteristics (e.g., extremely metal poor galaxies, Sanchez Almeida+16, or EELG Perez-Montero+21). Publicly available. **SED@** (Mas-Hesse & Kunth 1991, Cerviño+02, Cerviño & Luridiana 06) is a population synthesis that includes random population of the IMF, as required for systems with low number of stars (low mass clusters or high spatial resolution observations).

Special for particular OBs: The instrumental development of TARSIS and MOSAIC described in **OB.VI** will have available all the facilities existing in the Instrumental and Technological Development Unit (UDIT) at IAA-CSIC, like workshops, clean-room, and laboratories of various kinds.

5. IMPACTO ESPERADO DE LOS RESULTADOS *IMPACT OF THE RESULTS*.

5.1. Impacto esperado en la generación de conocimiento científico-técnico en el ámbito temático de la propuesta. *Expected impact on the generation of scientific-technical knowledge in the thematic area of the proposal*.

Some of the objectives we attempt have the potential to revolutionize the field. To mention a few, the discovery of metal-free starts (**OB.IV.1**), proving DM to be self-colliding (**OB.III.6**), providing tools to measure metallicities at z > 10 (**OB.V.1**), discovering the double reionization of the Universe (**OB.III.3**), or proving the positive stellar feedback to be effective (**OB.III.4**). Whether they will do, is hard to judge at this moment, but investing in high-risk high-gain science is fundamental. On the other hand, many other objectives will certainly have a long-term impact, as the development of new tools for diagnostics (**OB.II.1**, **OB.II.2,** and **OB.II.3**), the characterization of LyC leakers (**OB.IV.2**), or of the ICL (**OB.V.2**). All together will have a

significant impact on the community as it can be understood from a simple back-of-the-envelope estimate. Roughly speaking, for every 2 **OBs** listed in Sect. 4.1 we expect to publish a paper in a major journal (MNRAS, ApJ, A&A, and the like). This makes around 30 papers during the timespan of ESTALLIDOS 8. (This number is well within reach given the record of past ESTALLIDOS editions.) The impact factor of the major astronomical journals is ~5 or larger, implying > 600 citations (=30 papers x 5 citations yr^{-1} $paper^{-1}$ x 4 yr) during the lifetime of the project, equivalent to ~1 citation every 3 days.

A different kind of impact corresponds to the construction of astronomical instrumentation (**OB.VI.1** and **OB.VI.2**). In the short timescale, ESTALLIDOS will acquire the knowhow to deal with large instrumentation projects, opening up a new venue for STs and PDs. However, more importantly, the new instrumentation will be later on used by many other astronomers amplifying the impact of our effort by a large (although unknown) factor.

5.2. Impacto social y económico de los resultados previstos. *Social and economic impact of the expected results.*

The constructions of astrophysical instrumentation will have a clear economic impact, potentially at the 10MEU level, and it will produce the development of high-profile technical skills for a number of researches and engineers (optics, electronics, mechanics, and managing). On a completely different level, astronomy is closely connected with the preservation of the dark night sky, which in turn, has a direct economic impact on remote and economically depressed areas (see, e.g., https://en.fundacionstarlight.org/). Outreach activities help local communities to develop self-awareness on the importance of maintaining dark skies, and ESTALLIDOS is highly committed to carry out these activities as required. We consider that the transmission of the results of our research must be shared with the society at all the possible levels.

5.3. Plan de comunicación científica e internacionalización de los resultados (indicar la previsión de publicaciones en acceso abierto). *Plan for scientific communication and internationalization of the results (indicate the forecast of open access publications.*

ESTALLIDOS is international by construction. The team members are working all over the word (Argentina, Australia, Brazil, Chile, Germany, Mexico, Portugal, Spain, Ukraine, USA) and will naturally disseminate our scientific results internationally. Firstly, publishing papers in major journal (Sect. 5.1) and then attending scientific meetings and workshops to present our results, whenever possible in the form of review or invited contributions. Needless to say, ESTALLIDOS follows an open-science approach including publishing in open-access and sharing the papers in the public repository arXiv. In addition, as we know of the importance of being a world-leading group in our research area, we plan to participate at the highest level in the organization of international collaborations and networks, and to become members of advisory panels of institutes, journals, and facilities. An international conference organized (mostly) by ESTALLIDOS members will be proposed for the last year of the duration of the project as an EAS or IAU symposium. Press releases are planned for results of special relevance. A webpage to headline ESTALLIDOS is in progress.

5.4. Plan de divulgación de los resultados a los colectivos más relevantes para la temática del proyecto y a la sociedad en general. *Plan for dissemination of the results to the most relevant groups for the theme of the project and to society in general.*

See Sect. 5.2

En los casos en que sea de aplicación: In cases where it is applicable:

5.5. Plan de transferencia y valorización de los resultados. *Transfer plan and valorization of results.*

Does not apply.

5.6. Resumen del plan de gestión de datos previsto. *Summary´s management plan of the planned data*.

The results of simulations, observations, new codes, etc. will be publicly available by the adequate interfaces, such as the Virtual Observatory, webpages of the corresponding journals, or other resources created “ad-hoc”. In particular, we are planning a public GIT-HUB page to include all our chemical and spectrophotometric models (Sect. 4.6). The idea is to make our tools available for everyone interested in the astronomical community.

5.7. Efectos de la inclusión de género en el contenido de la propuesta. *Effects of gender inclusion in the content of the proposal*.

According to the document *Nota informativa sobre evaluación de la Integración del Análisis de Género en la Investigación (IAGI) en las convocatorias de la Agencia Estatal de Investigación*

https://www.aei.gob.es/sites/default/files/page/field_file/2021-01/Nota_IAGI_2020.pdf

our project does not present a potential risk of missing the required integration of the gender analysis into the research (Integración del Análisis de Género en la Investigación). It is not research directly or indirectly on humans or about humans, and the results do not involve producing products or services affecting daily life. If anything, we have to watch out for how the presentation of our results is carried out, to avoid unconscious gender bias.

Obviously, PDs and STs will be selected following all recommendations from the *Instituto de la Mujer para la Igualdad de Oportunidades*

(http://www.inmujer.gob.es/elInstituto/historia/home.htm).

We are particularly committed to the activities that promote gender balance in science. As we did in the past, we will actively participate in the *11-F Día Internacional de la Mujer y la Niña en la Ciencia*, following the general trends and policies of our host institutions.

Even if not ideal, we are approaching gender balance in the teams. Women represent 36% of the total number, 33% of the research team, and the same percentage among PIs.

6. JUSTIFICACIÓN DEL PRESUPUESTO SOLICITADO. *JUSTIFICATION OF THE REQUESTED BUDGET*.

The requested budget is properly justified in the form presented by each one of the subprojects individually. Here we just give a brief outline of the share.

IAC node: Most of the budget (66.6%) is used hire two post docs (referred to as PD/IAC1 and PD/IAC2 in this document). They will be responsible for **OB.III.2** and **OB.III.5.** The second part of the share goes to attending meetings, workshops, and schools (23.8%), which we regard as an essential activity of the collaboration, and which also includes PDs and STs. The expenses associated to the coordination come next (4.3%), to be used in the organization of internal workshops and specific seminars (Sect. 2). Outreach activities would need 2.6% whereas we devote 1.6% to upgrading four of our aging laptops. Finally, 1.1% is requested to publish in open-access journals of the AAS, when demanded by the topic of research.

IAA node: We request four engineer (ENG) contracts to perform **OB.VI** for the development and construction of TARSIS and MOSAIC: 1 electronic ENG/IAA1, 1 optical ENG/IAA2, 1 mechanical ENG/IAA3, and 1 control software ENG/IAA4. All ENGs will work for TARSIS whereas only ENG/IAA3 and ENG/IAA4 will do it for MOSAIC. The work plan for the four engineers is designed to optimize their contribution to the two projects; in doing so, ENG/IAA1 and ENG/IAA2 will work for TARSIS; ENG/IAA3 and ENG/IAA4 will work for both TARSIS and MOSAIC. ENG/IAA1 is needed for the conceptual design of the control system and selection of controllers, sensors and actuators based on the instrument requirements. On later phases, the candidate will be dedicated to the planning of laboratory tests and the development of prototypes. ENG/IAA2 will carry out the optical and optomechanical design of the subsystems including tolerance and stray-light analysis. ENG/IAA3 will carry out the conceptual design of the opto-mechanics for all the optical elements of the A&G and CU. On later phases, will have to deal with the integration of the subsystems. ENG/IAA4 will be engaged in all the phases of the software development lifecycle of TARSIS, participating in the definition, detailed design,

implementation. More details, including the share with MOSAIC, are given in the document individually presented by the IAA sub-proyect.
In addition, we also request in this node one 3 year PD contract to complete **OB.IV**, which is corresponds to the preparatory science for MOSAIC.

CAB-UAM node: We plan to hire a 2-year PD (PD/CAB) which represents about 53% of the budget. Another 42% will be used for visits within the collaboration, attending conferences (with an additional small budget for virtual conferences fees), and for observing campaigns. Next expenses are related to the diffusion of results, which include fees for open-access publication (3.7%) and the development of a web interface to provide a user-friendly access to our models (2.4%). Outreach activities represent around 2.4% of the share. Finally, we request 3.5% of the budget to replace the 13 years old computer daily used by one of the PIs, and for another one for the PhD student.

7. CAPACIDAD FORMATIVA. *TRAINING CAPACITY.*

7.1. Programa de formación previsto en el contexto del proyecto solicitado. *Training program planned in the context of the requested Project.*

A significant part of the training will come from an almost daily contact with the supervisors and the rest of ESTALLIDOS. The PhD students are expected to pay working visits to the other nodes of the collaboration. The PhD students usually have their master completed, and so this part of the training is not contemplated in here. However, they are expected to attend a course or a scientific meeting every year as part of their education. In particular, we are very much interested in courses on AI, or for observing proposal writing in telescopes like JWST or ALMA. The fact that our relaxed, fluent, but effective way of training works is supported by the numbers given in Sects. 7.2 and 7.3.

7.2. Tesis realizadas o en curso en el ámbito del equipo de investigación (últimos 10 años). *Theses completed or in progress within the scope of the research team (last 10 years).*

For lack of space, we mention the total numbers and then list the theses, one after the other, including title (partly), student, date, university, and initials of supervisors in ESTALLIDOS.

IAC node: 8 PhD theses and a similar number of master theses. The last two PhD students defend the PhD thesis right before the covid19 lockout, and there has been a blank period ever since. The time is ripe for the group to accept new students; therefore, we are requesting two FPI grants.

Search and characterization of.... A.B. Morales, ULL, Abril 2014 (JSA, CMT). *Observational properties of fossil...* S. Zarattini, ULL, Mayo 2015 (CMT). *Search and characterization of ….* R. Hinojosa Goñi, Marzo 2016 (CMT). *Automated algorithms for…. By* Garcia Dias, R. ULL. Sept. 2018 (JSA). *Precipitable water vapour a… .* By Castro Almazán, J., ULL. April 2019 (CMT). *Cold Flows in the Local….* del Olmo García, A.. ULL. July 2019 (JSA, CMT). *Searching for and characterising the high….* Arrabal Haro P., ULL. January. 2020 (CMT, JRE). *El papel de los estallidos de formación estelar….* By Lumbreras- Calle, A., ULL. December. 2019 (CMT)

IAA node: 6 PhD theses

Star Formation in nearby clusters of…, V. Petropoulou, UGR, 2012 (JMV, JIP). *Estructura de ionización y composición…,* A. Fernández Martín, UGR, 2013 (JMV, EPM). *Star formation and …,* S. Duarte Puertas, UGR, 2020 (JVM, JIP*). Exploring the population of emission line galaxies…,* A. Arroyo Polonio, expected 2023 (JIP, KC*). Intracluster and intragroup … t,* N. O. Lopes de Oliveira, Observatorio Nacional, Río de Janeiro, expected 2024 (YJT). *Interpretation of infrared lines spectra from…*, B. Pérez Díaz, UGR, expected 2025 (EPM, JMV).

CAB-UAM node: 6 PhD theses plus 4 ongoing.

*Submillimetric study of …*I. Villicaña Pedraza, UAM, Sep. 2015 (AID). *A new perspective on the evolution of galaxies:…*, J. Casado, Nov. 2016 (AID). *Primordial helium abundance determination…,* V. Fernández Gutiérrez, Sep. 2018, UAM, (ET, AID). *A differential study of*

the massive star formation … M. Rodríguez Baras, UCM, Mar. 2019 (AID, FRO). *Spatially resolved photometric study on H II… ,* A. P. Torres Licastro, INAOE , Jul. 2019 (ET, AID). *Morphology and metallicities…*, J. Nadolny, ULL, May 2021 (MCS). *A comprehensive study of star formation processes… ,* S. Zamora, UAM, ongoing (AID). *Extragalactic supernovae and supernova…,* A. Castrillo, UAM, ongoing (AID). *Surface Brightness Fluctuations…*, P. Rodríguez Beltrán, ULL, ongoing (MCS). *Curvas de rotación de galaxias:...*, C. Rodrigo, UCM, ongoing (MCS).

7.3. Desarrollo científico o profesional de los doctores egresados. *Scientific or professional development of graduate doctors*.

Students formed within ESTALLIDOS are now mature researchers holding **permanent positions** in research institutions throughout the word. At the moment of closing this project we do not have a comprehensive list with all of them. However, the list already includes an impressive number: A. Monreal Ibero (Leiden University, The Netherlands), EPM (CSIC, Spain), R. Sanchez-Jansen (UKATC, UK), R. Amorín (Univ. La Serena, Chile), CK (IAA, Spain), R. Garcia Benito (IAA, Spain), C Ramos Almeida (IAC, Spain), J. Castro Almazán (IAC, Spain), Alba Fernández Martín (CAHA, Spain), Mónica Cardaci (U. La Plata, Argentina), M. Rodriguez Baras (OAM, Spain), etc The most recent students are still holding Post Doc positions throughout the world. Some other students ended up in industry and economy: e.g, M. Martín Manjón (Consultant BBVA, Spain), J. Casado (Data Scientist at MHP, Germany), Ismael Martínez Delgado, (FRACTAL SL, Spain), R. Garcia Dias (Decision Scientist at Monzo, UK). Other are high-shool teachers: A.B. Morales-Luis, Olmo-Garcia, etc.

Overall, our students have significant chances of pursuing a career in astronomy or related fields. In a broader context, they usually get positions in jobs somewhat related to the skills developed while working with us for their Theses.

INITIALS OF PARTICIPANTS
(*equipo investigacion)

MMH Miguel Mass-Hesse

IAC
ARP Angel Ricardo Plastino
AVP *Antonia Varela Perez
BGE Bruce G. Elmegreen
CF *Cecilia Fariña
CMT *Casiana Muñoz Tuñón
DME Debra Elmegreen
GTT Guillermo Tenorio Tagle
JSA *Jorge Sánchez Almeida
MGV Macarena García del Valle
NC *Nicola Caon
PAH Pablo Arrabal Haro
SFS Sebastián F. Sánchez
SMG Sergio Martínez Gonzalez
SS Sergiy Silich
ST *Stefano Zarattini

IAA
AAP Antonio Arroyo Polonio
BPD Borja Pérez Díaz
CK *Carolina Kehrig
DRP *Daniel Reverte Payá
EPM *Enrique Pérez Montero
IB Iris Breda
JAC *Jesús Aceituno Castro
JIM *José Miguel Ibáñez Mengual
JIP *Jorge Iglesias Páramo
JMV *José Manuel Vílchez Medina
JRE José Miguel Rodríguez Espinosa
LSP Leonid S. Pilyugin
MA *Miguel Abril Martí
PP Polychronis Papaderos
RAB Ricardo Amorín Barbieri
RC Rocío Calvo Ortega
SDP Salvador Duarte Puertas
YJT Yolanda Jiménez Teja

CAB-UAM
AC *Asier Castrillo
AID: *Angeles I. Díaz
ALL Anna Lia Longinotti
ALS Ángel R. López Sánchez
CSS Celia Sánchez Sánchez
DFA David Fernandez Arenas
DRG Daniel Rosa González
EC Esperanza Carrasco
EJB Elena Jiménez Bailón
ET Elena Terlevich
FRO Fabián Rosales Ortega
GFH Guillermo F. Hägele
LB Lucia Ballo
IA Itziar Arexaga
IC Ignacio de la Calle
IMY Iker Millán-Irigoyen
JJB Juanjo Bazan Casado

JE Jacobo Ebrero
LT Laura Tomas
MCS: *Miguel Cerviño Saavedra
MGV Marisa García Vargas
MSL *María Santos Lleó
MVC Monica Viviana Cardaci
PCC Pablo Corcho-Caballero
RC Ricardo Chávez
OC Oscar Cavichia
PRP Pedro Rodriguez Pascual
RJT Roberto Terlevich
SZ Sandra Zamora
VF Veronica Firpo
VGF Vital G.Fernández

ACRONYMS

AGN: Active galactic nuclei
AI: artificial intelligence
BCG: Brightest cluster galaxy
BH: Black holes
CAHA: Centro astronómico hispano en Andalucía
CALIFA: Calar Alto legacy integral field area survey
CDM: cold DM
CEFCA: Centro de estudios de física del cosmos de aragón
CGM: circum-galactic medium
CT: Coordination team
DM: dark matter
ELT: Extremely large telescope
ENG: Engineer
EoR: Epoch of reionization
ESA: European space agency
ESAC: European space astronomy centre
ESO: European southern observatory
FOV: Field-of-view
GC: Globular cluster
GTC: Gran telescopio Canarias
HI-KIDS: HI KOALA IFU dwarf galaxy survey
HST: Hubble Space Telescope
ICL: Intra cluster light
ICM: Intra cluster medium
ICTS: Instalaciones públicas singulares
IFU: Integral field unit
IGM: inter-galactic medium
IMBH: Intermediate mass black hole
IMF: Initial mass function
INT: Isaac Newton telescope
ISM: inter-stellar medium
JWST: James Webb space telescope
J-PAS: Jabalambre physics of the accelerating Universe astrophysical observatory
LCDM: Lambda CDM
MEGARA: Multi-Espectrógrafo en GTC de alta resolución para astronomía
MOS: Multi-object spectrograph
MUSE: Multi-unit spectroscopic explorer
NASA: National Aeronautics and Space Administration
NN: Neural networks
OB: Objective
PD: Post Doc
PMAS: Potsdam multi-aperture spectrophotometer
SBF: Surface brightness fluctuations
SF: Star formation
SFH: Star formation history
SFR: Star formation rate
SN: Supernova
sSFR: Specific SFR
ST: PhD STudent
SWG: Science working group
TARSIS: Tetra-arm super-ifu spectrograph
UAM: Univ. Autónoma Mad.
ULX: Ultra-luminous X-ray sources
UCM: Univ. Complutense Mad.
UG: Univ. de Granada
ULL: Univ. La Laguna
SED: Spectral energy distribution
WP: Working package
YMC: Young massive cluster
XMD: eXtremely metal-deficient

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