CHAPTER 5

ABSTRACT

This challenge aims at understanding how the large–scale structure of the Universe originated after the Big Bang, starting with the first stars that ignited at around 300 Myr and leading to the diversity of galaxies in the present time. We need to shed light on the mechanisms that regulate the connection between the dark matter halos originated from primordial fluctuations and the growth and evolution of galaxies, filaments, and (super)clusters. The assembly of galaxies depends on non-linear processes such as star formation, feed- back and quenching, black hole accretion, interaction with the environment, and galaxy merging. Key questions are: How did the Universe emerge from the dark ages? How did the structure of the cosmic web evolve? How did the present-day Hubble sequence of galaxies form? What was the formation history of the Milky Way?

KEYWORDS

Structure formation and evolution
Galaxies assembly and evolution
Galaxies, clusters and dark matter haloes
Massive black holes and active galactic nuclei
Gas inflows and outflows
The Milky Way Laboratory

CHAPTER 5

FORMATION AND EVOLUTION OF GALAXIES AND LARGE STRUCTURES

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1. INTRODUCTION AND GENERAL DESCRIPTION

This challenge aims at understanding the present day large–scale structure of the Universe. To properly understand this fundamental question we need to start from the study of the primordial structures and galaxies, traced by the light of the first stars that ignited after the dark ages, around 300 Myr years after the Big Bang. These galaxies are distributed along a web-like filamentary structure, as has been found by the many galaxy surveys performed since the pioneering works in the 1980s. This cosmic web outlines the large–scale picture of the Cosmos and is constituted by dark matter and gas, upon which galaxies are built, with dark matter making up the most important fraction of the Universe's gravitating mass. It is gravity that binds the large structure of filaments, galaxies, clusters and superclusters of galaxies together, along bridges of dark matter and gas which is way too dim for an easy detection. This large–scale structure is pervaded by the dark energy repulsive field, still far from being properly understood in the present days.

We aim to shed light on the mechanisms that regulate the connection between the dark matter halos originated from primordial fluctuations and the growth and evolution of (super)clusters, filaments and galaxies (see also Chapter 4). The growth of these structures and the assembly of galaxies depend on non-linear processes such as star formation, feedback and black hole accretion, or galaxy merging, among others, having led to the diversity of galaxies in the present–day Universe, as reflected in the Hubble sequence of galaxies. Understanding galaxy formation and evolution constitutes one of the paramount challenges for present day astrophysics and space science, in order to obtain a coherent picture of the history of the Universe after the Big Bang, since the early dark cosmic age to our local cosmic backyard. In particular, and more specifically the following questions need to be answered, as different pieces of a big puzzle that only together will provide a coherent view:

1. What are the masses and sizes of dark matter (DM) halos and galaxy cluster structures at all scales?
2. What were the properties of the first luminous objects (stars and accreting black holes) and how did they form? What was the stellar initial mass function at the Cosmic Dawn?
3. How did chemical evolution proceed and influence structure formation?
4. How did galaxies assemble and evolve?
5. What was the origin and growth history of massive black holes?
6. What were the role and properties of gas inflows and outflows (mass, momentum, radiation and feedback)?
7. How did structure formation depend on and influence its environment?
8. What can we learn from “laboratories” in the local Universe: the Milky Way and nearby galaxies?

To advance in the understanding of these key questions a new generation of ground- and space-based observatories and instruments is being developed all over the world.

As we discuss below, the challenges and specific objectives discussed in this chapter are very closely linked to other topics within the Theme “Understanding the basic components of the Universe, its structure and evolution”, creating relevant synergies between researchers working on these questions:

- “Origin and fate of the Universe”
- “Gravity”
- “Understanding the cycle of matter in the Universe”
- “New instrumentation and techniques”
- “Understanding matter and radiation under extreme conditions”

2. IMPACT ON BASIC SCIENCE AND POTENTIAL APPLICATIONS

The questions to be studied in the next decade will have a strong impact on our conception of the Universe as a whole and our place in it, from physics to philosophy. The questions that will be addressed in this challenge lie at the heart of modern astrophysics. We want to stress that the concept of an expanding Universe, originated from a singularity, emerged from the study of the location and velocity of large samples of galaxies almost one century ago. Furthermore, a deeper insight into the large structures of the Universe led to the discovery of both dark matter and dark energy, two elements that revolutionized our knowledge of the Universe and whose nature we don't know yet. Research findings from this challenge will surely contribute to a better understanding of the properties of both dark matter and dark energy, also of central interest for challenge 4 *"Origin and fate of the Universe"*, providing a cosmological model able to reproduce the observational data. Furthermore, the development of the challenge needs a broad and ambitious observational approach that will require to build new observational facilities and advanced astronomical instrumentation, both on Earth and in Space, which will lead to state of the art technological developments. The analysis of the data to be produced will also require the development of new techniques in the fields of Machine Learning, Artificial Intelligence, and Big Data. This means that the development of this challenge will provide in addition a significant feedback in the technical capabilities of our society, that can extend far beyond astronomy (e.g. image processing and pattern recognition techniques in medicine).

3. KEY CHALLENGES

3.1. Precise properties of dark matter haloes and galaxy clustering structures on all scales

In the standard cosmological model (the so–called ΛCDM framework), nearly 85% of the matter in the Universe is composed of a yet unknown form of non-baryonic matter. This so–called dark matter (DM), that is supposed to be collisionless, neutral and weakly interacting with the ordinary, visible matter, is nevertheless instrumental for the formation and evolution of structures across cosmic history. Indeed, ΛCDM predicts that small structures entirely constituted by DM, known as *halos*, were the first ones to form by gravitational collapse and then, by accretion and merging, gave rise to larger structures.

These halos acted as the gravitational seeds in which the baryonic matter would fall and ignite galaxy formation in later times, thus shaping the Universe as we observe it today.

Much progress has been made in the past decades to elucidate the statistical and structural properties of DM halos and their substructures, or subhalos. Nowadays, state-of- the-art hydrodynamical simulations including both DM and baryons, and involving up to hundreds of billions of particles, are capable of forming galaxies whose properties match reasonably well those of actual galaxies. Yet, despite the undeniable advancement, key questions remain.

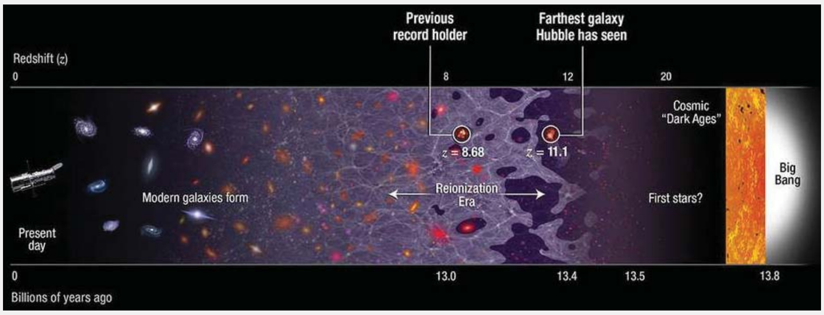
Simulations are not able to resolve the whole halo hierarchy. The current resolution limit of $\sim 10^5\,M_\odot$ (being $M_\odot$ one solar mass) at redshift $z = 0$ is orders of magnitude above the minimum predicted halo mass, of $\sim 10^{-6}\,M_\odot$. ΛCDM predicts the existence of dark, Earth-mass structures while we cannot observe dwarf satellites below $\sim 10^8\,M_\odot$. Yet, different techniques have been proposed to unveil these *dark satellites*, whose discovery would be a definitive support for ΛCDM: study of gaps in stellar streams, strong lensing, and gamma ray emission in case the DM be made of WIMPs (weakly interacting massive particles). With the advent of future observatories like Euclid and CTA, in which CSIC researchers are deeply involved, new data will become available that will allow to probe smaller masses.

A mismatch between simulations and observations occurs at the scale of galaxy clusters as well, the former systematically providing less concentrated DM density profiles with respect to that inferred from actual cluster mass estimates using X-ray measurements, Sunyaev–Zeldovich effect and strong lensing. Being galaxy clusters the largest bound structures being formed in today's Universe, recent assembly history and merging shocks, infall/outflow of material at the outskirts, violent baryonic-related episodes, etc. are all capable of modifying not only subhalo abundances at these extreme scales but also the inner and outer slopes of the cluster's DM density profile.

3.2. The Cosmic Dawn: formation and properties of the first luminous objects

According to the current paradigm the first stars in the history of the Universe ignited around 300 Myr after the Big Bang, when the clouds of primordial hydrogen and helium fragmented and collapsed down to protostellar scales. Since these first generations of stars were composed of only H and He (with some traces of other elements), their properties should have been quite different to the stars in

FIGURE 5.1–GN-z11 is currently the oldest and most distant known galaxy in the observable universe, detected when the Universe was just $\sim$ 400 Myr old. It is 25 times smaller than the Milky Way and has just one percent of our galaxy's mass in stars. However, it is forming stars at a rate about 20 times greater than our galaxy does today (Credit: NASA/ESA).



the present Universe. While the Initial Mass Function (IMF) of these extremely low metallicity Pop III stars is not known, many theoretical studies indicate that stars with unusually large masses (up to 1,000 $M_\odot$) may have formed, even preferentially. On the lower mass end, it is presently assumed that low mass stars ($M < 1\, M_\odot$) could not have formed from the primordial pristine gas.

The evolution to supernovae of these Pop III stars depended critically on their initial mass. Evolutionary models of Pop III stars indicate that in the mass range 130 to 260 $M_\odot$ they exploded in pair-instability supernovae (SNe), releasing about half their mass in metals, but not leaving any black hole as remnant, while those with masses above $\sim 300\, M_\odot$ essentially collapsed into a black hole without producing metals. If such large initial masses were confirmed, these stars would have been extremely short-lived, merely 1–2 Myr, almost a sudden flash in the history of the galaxies.

- Determining the IMF of these Pop III stellar populations is a key challenge for the next decade, since this is essential to understand the formation of the first stars and galaxies, as well as the formation and evolution of the first black holes and the production of metals in the first hundreds Myr.

Only recently we have been able to get hints of these first generations of stars. Combining Hubble and Spitzer photometry and spectroscopy, a galaxy at redshift $z \sim 11.1$ was discovered in 2016, merely 400 Myr after the Big Bang. Unfortunately, present observatories allow to just detect these primordial galaxies, but it is still not possible to characterize their stars.

- Observatories starting operations in the next 5–10 years, to whose development CSIC researchers have contributed and will have thus privileged access, such as the James Webb Space Telescope or the Extremely Large Telescope, will provide for the first time the capability to perform spectroscopy of these first generations of stars, entering a new phase of characterization rather than just identification.

The formation and rapid evolution of very massive Pop III stars would have produced a much stronger relative ionizing flux than for stars below $\sim 120\,M_\odot$. This strong ionizing flux would have produced extremely large values of the Lyman α and $HeII\lambda1640$ emission lines equivalent widths. Moreover, a significant fraction of it escaped and led to the complete reionisation of the Intergalactic Medium (IGM). The reionisation started in bubbles and superbubbles around the galaxies with the highest star formation rates, and through percolation they completed the reionisation of the Universe by $z \sim 6$, within the first 1 Gyr of evolution of the Universe, as shown in Figure 5.1.

While Lyman α would be very difficult to detect, since the mostly neutral IGM would have multiply scattered and in practice destroyed these photons, the $HeII\lambda1640$ emission line and the associated stellar rest-UV continuum should be detectable with the JWST up to redshifts $z \sim 10-12$. A detailed study of star-forming galaxies above $z \sim 7$ with JWST/NIRSPEC will allow to give clues on the properties of the IMF of primordial Pop III stars. CSIC researchers are heavily involved in the development of the JWST, being part of the Scientific Teams of the instruments and having access to guaranteed time.

- Redshifted 21 cm radio emission will reveal the response of the IGM to these sources, allowing to perform a 3-D map of HI during the Epoch of Reionisation. SKA pathfinder facilities such as LOFAR, HERA and MWA will play a key role in the next years collecting data with the goal of measuring this signal.

While galaxies dominated by star formation have been detected very close in time to the onset of the first stars, the X-ray background demonstrates that Activ Galactic Nuclei (AGN) emit one order of magnitude fewer UV photons at $z \sim 6$ than required to reionize the IGM. The relative number of AGN at high redshift is very small, constraining the details on the mechanism that led to the formation of supermassive black holes in the center of galaxies. In any case, the rapid evolution of very massive Pop III stars should have produced a significant population of intermediate mass black holes, that could have merged at the centers of galaxies within the first 1 Gyr. They would have become so the seeds of the supermassive black holes that developed later, as discussed in Sect. 5.3.5.

- A proper identification of accretion dominated vs. star-formation galaxies in the Primordial Universe could be performed by detecting and analyzing the profiles of their Lyman α and *He II*λ1640 emission lines. A detailed analysis of the evolution of the fraction of both mechanisms with time will be essential to understand the process of massive black hole formation in parallel to massive star formation.

3.3. Chemical evolution and structure formation along the history of the Universe

The first metals appeared after the first (massive) stars exploded as supernovae, ejecting the elements synthesized in their nuclei to the interstellar medium. As mentioned above, the short life of Pop III stars implied that the contamination of the interstellar and even the intergalactic media proceeded very rapidly. Since then, the content of metals in galaxies has evolved with cosmic time, being determined by the history of star formation and the massive events of gas accretion and outflows inherent to galaxy formation and evolution. Chemical evolution is then directly linked to galaxy formation and evolution, as exemplified by theoretical simulations. A tight relation between metallicity and total stellar mass of galaxies, the mass-metallicity relation, has been observed to hold locally and at high redshift. In addition, the scatter of this global relation correlates with the rate of star formation in galaxies, as a secondary parameter, resulting in what is dubbed the Fundamental Metallicity relation. It has been claimed that this relation holds since early epochs of galaxy evolution – as expected from simulations – when massive accretion of (near) pristine gas from the cosmic web fed star formation, diluting the interstellar medium metallicity. Little is known about the evolution of these processes of massive accretion over cosmic time, or on how the Fundamental Relation evolved from Cosmic Dawn to Cosmic Noon epoch, when star formation rates peaked.

- How do these processes impact on the early chemical evolution of galaxies remains a challenge to be met; the access to the future Extremely Large Telescope ELT and the new space (e.g. JWST) facilities would give a competitive advantage to our CSIC groups to study this unsolved question.

There are several open questions in nucleosynthesis that constitute relevant challenges for the next 10 years:

- An improved understanding of the nucleosynthesis of heavy elements should decipher the role played by the environment and metallicity of stellar progenitors, their rotation, and the derivation of precise yields. All these factors are essential for interpreting observed abundances in galaxies and can be successfully tackled by CSIC researchers. Critical open questions here include: i) the evolution of binary systems, needed to understand the evolution of Supernovae (SN) Ia progenitors, and ii) the unknown origin of the heaviest neutron rich r-process elements that cannot be created by Core Collapse SNe, which do not explain either the observed anomalies in the abundances of elements beyond $Z = 29$, as Se, As and Ge.

3.4. Assembly and evolution of galaxies

As described in Sect.5.3.1 the evolution of cold dark matter is the current basis for the cosmological picture that explains the large-scale structure and evolution of the Universe, from the first generation of dark matter halos and sub-halos to present day galaxy clusters and superclusters. It is also believed that the stellar components formed at $z \geq 2$ likely evolved into elliptical galaxies and bulges, probably through mergers of the *primordial* star forming disks. However, this framework falls short to explain the properties of the galaxy population at $z \sim 1$ and how the present–day Hubble sequence of galaxies was assembled. The reason is that the growth of galaxies is not related in a simple way to the growth of dark matter structures. The interplay of energy and matter exchange (between the process of gas accretion and cooling and star formation) is essential to understand the growth of the gaseous and stellar components in galaxies.

There are already several observational fundamental results that are key to trace the cosmic evolution of the star formation in the Universe. The star formation rate density in the Universe peaked at redshift z ~ 2, and declined thereafter. At any z, star forming galaxies show a correlation between Star Formation Rate and the total mass in stars, known as the Main Sequence of star formation. A list of important issues yet to understand include the effect of the environment in these relations, the link between total stellar mass and evolutionary state, how much of the stellar mass is already in place at each epoch, and how much of the star formation is related to environmental effects. Further, we do not know which are the evolutionary tracks that gas rich, disk, star forming galaxies formed at very high redshift followed to evolve to the massive-quiescent galaxies observed at $z \sim 2$. Panchromatic large sky surveys led by CSIC researchers will pursue these questions, in particular:

- SKA, the Square Kilometer Array, will play a key role to fully understand the growth of mass, gas and stars in the Universe and their cosmic evolution. SKA will allow radio continuum surveys, where dust obscuration is no longer an issue as is the case of the rest-frame ultraviolet emission. It will trace the star formation rate of obscured and unobscured galaxies of un-biased samples from the high redshift Universe to the present. The dominant emitter population are core–collapse supernovae from evolved stars of 8 $M_\odot$ or higher, that will trace the star formation rate of the obscured and unobscured star forming galaxies that are very abundant at high redshifts. CSIC researchers play a significant role in the development of SKA and will have guaranteed access to its data.
- JWST and J-PAS will be crucial to understand the formation and evolution of massive galaxies (similar to or more massive than the Milky-Way), that are the major contributors to the peak of the star formation activity. Ultra-deep imaging and spectroscopy of galaxies at $z > 2$ from the JWST (MIRI, NIRSpec), and J-PAS narrow band imaging covering from 3500-9500 Å, equivalent to spectra with resolution $R \sim 50$, for galaxies at $z \leq 1$ will be crucial to distinguish between the different scenarios proposed by galaxy formation models for Milky-Way like galaxies.

However, galaxies are not simple structures. During the last decade, we have carried out a significant effort to understand how the present-day Hubble sequence of galaxies was assembled, as traced by their dynamical mass, stellar and gas content, and metals. Integral Field Spectroscopy (IFS) of nearby galaxies has enabled a leap to constrain the spatially-resolved galaxy formation models, providing 2D spatial + 1D spectral information for each galaxy. However, a wide and deep view is not yet available due to the limitations of the number of galaxies in the samples studied. Future IFS surveys led by CSIC researchers will improve significantly these restrictions:

- J-PAS will do IFS-like observations with a spectral resolution equivalent to $R \sim 50$, mapping the stellar population properties of ~100,000 galaxies at $z \leq 0.1$ with a sampling of 0.23 arcsec/pixel to research the effect of the environment in the formation and evolution of the Hubble sequence.
- An Integral Field Spectrograph at the Calar Alto Observatory and WEAVE@WHT will target galaxies of the local Universe to provide constraints to the sub-grid physics for the formation of disks in M31 and galaxies similar to the Milky-Way.

- HARMONI and MOSAIC at ELT will be crucial to get 2D kinematics information and 2D maps of stellar populations properties of galaxies and ionized gas distribution of galaxies at the peak of the star-formation activity of the Universe, and study the progenitors of Milky-Way like galaxies.
- SKA will provide HI galaxy mapping of nearby galaxies, providing 2D spatial +1D kinematic information of the neutral gas and constraining the interplay between gas inflows, outflows, radial gas flows, and the star formation efficiency in galaxies. In combination with IFS surveys, we will study the role that the environment plays to transform galaxies along the Hubble sequence.

3.5. Origin of galactic black holes and evolution of nuclear activity in galaxies

A result emerging from the last decade of observations is that there are apparently supermassive black holes (SMBH) with masses $> 10^6\,M_\odot$ in the centers of most, if not all, major galaxies. These SMBH grow by the gradual accumulation of matter (accretion) which releases its potential energy in the form of radiative and kinetic energy, shining over the full electromagnetic spectrum (giving rise to the Active Galactic Nucleus phenomenon) and generating particle jets and matter outflows with the potential to affect the entire galaxy. This fact, together with the tight relationships of the masses of the SMBH with some properties of their host galaxies and the parallel evolution of the growth of galaxies by star formation and of SMBH by accretion, strongly suggests that AGN and galaxy formation and evolution are strongly linked. AGN are thus fundamental ingredients to understand galaxy evolution, as well as being bright beacons up to the Cosmic Dawn and fascinating objects in their own right.

The discovery of AGN with SMBH when the Universe was less than 1 Gyr old ($z > 6$) poses pressing questions about the assembly and early growth of galaxies and SMBHs. These are thought to grow from seed BHs of $10^2 - 10^5\,M_\odot$ formed either from Pop III stars or direct collapse of primordial gas, as discussed in Sect. 5.3.2. Besides, hundreds of low-mass SMBH ($< 10^6\,M_\odot$) are being found in dwarf galaxies. These are thought to be the relics of the early Universe seed BHs and can shed further light onto this hot topic.

- Moving beyond discovery towards statistical population studies and detailed characterization of high redshift luminous AGN and seed BHs, are two of the main objectives of several observational facilities. Working in multiple electromagnetic bands, CSIC scientists are involved and have significant presence in many of them: JWST will perform deep surveys and detect thermal and line emission of the AGN, ALMA is already and will continue studying dust and molecular gas around the AGN and in the host galaxy, SKA will explore star formation rate and AGN incidence from the mid-2020s on, and ELT will probe rest-frame optical/UV emission of the host galaxy and AGN from 2025 on.

Closer to the current epoch, the emission of radiation by star formation and AGN shows a broad peak around $z \sim 1-3$, but most of the emission produced by accretion in the Universe is obscured. The obscuring medium is responsible for hiding the AGN nature of many sources in different bands and it is also thought to be related to the bewildering variety of AGN types. In addition, some of these obscuring circumnuclear structures (from about a few to ~100 parsec from the SMBH) may be part of the launching pads of some of the galaxy-scale outflows that shape the host galaxy. Understanding the distribution and nature of the obscuring medium and completing the census of the AGN hidden by it is mandatory to fully assess the prevalence of AGN among galaxies and their mutual dependence.

Again, this problem requires a multi-wavelength approach to study different manifestations of the obscuring medium and to uncover AGN signatures. Observations with ALMA are already revealing the geometry and kinematics of the obscuring material and incipient outflows in the nearest AGN, and can study host galaxy properties at higher redshifts. The advent of JWST in the next few years will revolutionize this field by uncovering in the mid-infrared reprocessed continuum radiation from the obscuring material, and detecting direct spectral evidence for AGN presence to larger distances and earlier epochs than currently possible. In the mid-term, ELT spectroscopy in the optical – near infrared will allow disentangling spectroscopically AGN and host galaxy emission in the rest-frame optical/UV in much fainter and farther sources.

- Providing and selecting targets for the studies described above will require sensitive surveys over large areas: J-PAS will provide in the mid-term (≥ 2026) a sensitive multi-filter and multi-band survey of a significant part of the northern hemisphere. Concurrently, the EUCLID space mission (~ 2022 – 2028) will map a third of the sky in the visible and near-infrared bands. By the second half of this decade SKA surveys in the radio band will uncover yet more AGN via their radio excess emission.

An important parameter to deal with in the study of AGN is their intrinsic power, with low luminosity AGN most probably being related to smaller accretion rates onto the SMBH. Athena, at the beginning of the next decade, will detect typical AGN up to $z \sim 7$ and characterize AGN with extreme obscuration up to $z \sim 3$. SPICA/future far IR facilities will detect even less luminous extremely obscured AGN at the same redshifts or equally luminous ones at even younger epochs of the Universe, and characterize low luminosity ones up to $z \sim 2$. This will be done through extensive surveys and targeted observations. The launch of LISA around 2035 will extend the range of AGN studies to the gravitational wave domain.

- The direct detection with LISA of SMBH mergers over the entire history of the Universe will provide precious information on the incidence of this alternative mode of SMBH growth.

3.6. Role and properties of gas inflows and outflows

Galaxies are open systems that evolve into a quasi-stationary state, where inflows and outflows of gas balance the star formation rate and AGN activity, and therefore the global properties of their stellar populations and central black holes. Gas accretion from the cosmic web maintains galaxies forming stars during long periods of time. Star formation (SF) and/or black hole activity due to this gas accretion, in turn, expel the surrounding interstellar medium by the mechanical and radiative energy liberated, generating outflows of gas. The role of outflows governing the subsequent galaxy evolution is believed to be crucial, as they can regulate and quench both star formation and black hole activity, being also the primary mechanism redistributing dust and metals over large scales within the galaxy, or even expelled into the circumgalactic and intergalactic media. Therefore, the galaxy mass function, the mass-metallicity relation, and the black hole-spheroid mass correlation, are thought to be shaped by outflows.

Although this general scenario is relatively well established, it requires the self-regulated balance among gas accretion, gas outflow and SF/AGN activity which depends on the coupling between physical processes that involve multi-phase gas at very different physical scales, from cosmic web structures to molecular clouds. This implies a significant challenge for both theoreticians and observers, and it is therefore clear that it will remain a hot topic of research for the next decade and beyond.

A key element for our advancement in this field will be the advent of new first-class observing facilities over the coming years, like the James Webb Space Telescope (JWST), the Extremely Large Telescope (ELT), and the Square Kilometer Array (SKA), among others. These facilities, which have been (or are being) developed with the active participation of CSIC scientists, will provide unprecedented some uniquely suited capabilities to address the most challenging questions in this field of research like:

What was the role of inflows and outflows in the Early Universe?

Theory predicts that cold gas accretion is particularly important at high redshift, when dark matter haloes have low mass and the accreted cosmic gas remains cold and ready to form stars at high rates. Similarly, strong outflows are expected to play a pivotal role in shaping primeval galaxies, and their subsequent evolution, as well as in redistributing dust and metals into the circum- and the intergalactic medium. The rather limited observational constraints provided by current facilities suggest that galactic winds are ubiquitous at intermediate redshifts (i.e. $z \sim 2$), and may be extremely powerful at very early epochs.

The JWST, with its orders of magnitude improvement in sensitivity, will allow us to explore the epoch of early galaxy evolution with unprecedented detail. Thanks to its multi-object capability, it will obtain a complete census of the properties of galactic outflows across cosmic time. This statistical approach is key to understanding their role in the emergence of the different galaxy populations. Moreover, the integral field unit will obtain spatially resolved spectroscopy (at sub-kpc scales for $z = 2-10$) of the extended structures associated to the outflows, and therefore dig into the physics behind the global integrated properties. On the other hand, observations with the ELT will permit to study high-z galaxies at spatial resolutions similar to the ones we now achieve with local samples.

What is the overall feedback impact of the outflow phenomenon?

Local samples will continue being ideal laboratories to study in detail the physics of outflows, and their effects. Key observational inputs, like precise outflow mass, energy, and momentum rates for the different gas phases will be obtained in nearby objects to evaluate feedback effects on the star formation and AGN activity in the host. Not only *negative* feedback (i.e. reduction of star formation as a consequence of gas ejection) will be a matter of detailed study, but also *positive* feedback (i.e. outflowing gas may foster star formation). Main related questions that need well-grounded answers include: what is the fraction of outflowing gas that escapes the galaxy and is able to enrich with metals the intergalactic medium? are mass-loading and mass-loss rates in low-mass galaxies as high as predicted?

The combination of sensitivity and high angular resolution at optical and near infrared wavelengths provided by the ELT, will provide a detail far greater than never before. Its integral field spectrograph (HARMONI) will explore the vicinity of the AGN and the regions of intense star formation, where powerful galaxy-wide outflows are generated, with resolutions of up to 10 milliarcseconds (equivalent to ∼ 0.15 parsecs at the distance of M82), tracing the ionised, neutral, and warm-molecular gas phases. The cold molecular gas is currently observed with ALMA, while the "MHONGOOSE" Large Program at MeerKAT will be unique to unambiguously detect cold accretion in the next 5 years. It will probe a factor ∼ 50 deeper in column density. Finally, SKA will extend this study to larger samples providing higher angular resolution and access to deeper column densities.

3.7. Interdependence between large structures and galaxy environment

The primeval uniform distribution of matter evolved (through gravitational interaction) into an intricate foam-like structure, with nearly empty voids surrounded by sheets, filaments, and clusters containing most of the mass and galaxies. The void regions account for most of the volume of the Universe but include only a small fraction of all galaxies. Around the voids, sheets of galaxies curve and form filaments in the intersection regions between two sheets. Filaments themselves merge in the nodules of this network forming the densest and massive structures, galaxy clusters, that can harbor up to hundreds of galaxies per Mpc^3.

At the center of these clusters, and as a result of cannibalizing unfortunate neighbors, we find the most massive galaxies, the brightest cluster galaxies, or BCGs (also cD galaxies), with masses well in excess of 10^{12} solar masses. Often supermassive black holes (SMBHs), with masses as high as several times 10^{10} solar masses, lurk at the center of these very massive galaxies. These SMBHs can affect the dynamics and structure of the BCGs (and its surroundings), not only during their active phase and through feedback phenomena from the material falling in them, but also through their quiescent phase through gravitational effects that can eject material, including stars, from the central regions. The centers of these massive galaxies are useful probes of dark matter, in particular if dark matter has a small probability of interaction with itself (parameterized by its cross- section). In addition, the large potential wells of galaxy clusters can heat up the gas in the central region up to several keV. This hot intracluster plasma radiates away energy, mostly through X-ray emission (Bremsstrahlung).

Moreover, galaxy clusters can also cluster, forming vast overdense regions known as superclusters. These superclusters can dominate the dynamics around them, up to scales of hundreds of Mpc. Thus, environment is a key factor in determining the type of evolution of a galaxy. Low and high density environments appear different in terms of the types of galaxies they host. In the local Universe, low density regions contain a large fraction of spiral galaxies. On the contrary, in dense environments like galaxy clusters, elliptical galaxies are the dominant type. The evolution with cosmic time and environment of the early/late type mix in cluster galaxies is a matter of study. Galaxy clusters frequently show also material stripped from galaxies by ram pressure as they cruise through the intracluster medium. Star formation can be triggered in this stripped material which adopts a jellyfish structure, with star forming regions trailing the galaxy.

Answers to all these questions relative to structure formation, galaxy evolution, and its dependence on environment will inevitably require also the theoretical input from numerical simulations.

3. 8. Laboratories in the local Universe: The Milky Way and nearby galaxies

Massive star formation.

Massive stars are the great galactic disruptors, as their influence is found across large distances due to their ionizing radiation, kinetic energy output (winds and supernovae), and chemical enrichment. How efficient these effects are depends, to a large extent, on their proximity in space and time: one supernova alone cannot puncture the interstellar medium of a galaxy but hundreds of them in a stellar cluster exploding within a few million years could be able to do so. Therefore, it is crucial to understand how massive stars aggregate around each other. The standard picture for some time was that "all stars form in clusters" and that the Initial Mass Function was quasi-universal; requiring that hundreds of low-mass stars be formed for each massive star. In the last two decades that has changed and it is now accepted that massive stars can also form in unbound stellar associations, following hierarchical patterns in space and time, and it is possible to find massive stars under conditions very different to those in clusters.

- The challenge for the next decade is to identify how massive stars are distributed within a few kpc of the Sun. This will be accomplished through a variety of surveys: astrometric (Gaia), photometric (e.g. GALANTE), and spectroscopic (e.g. WEAVE). Combining them we should be able to disentangle the impediments posed by extinction, crowding, multiplicity, and distance indetermination and obtain the full 6-D (spatial + velocity) distribution of massive stars in our neighborhood.

On the other hand, massive stars signal on-going star formation in galaxies. They log the latest history of assembly of the bulge of the Milky Way, and can help to understand the processes shaping dwarf irregulars (dIrr), –alleged ancestors of dwarf ellipticals and possible building blocks of massive galaxies–. In the Local Group we can assess the significance of gas inflows/outflows, interactions and other processes such as stripping, for these galaxies.

CSIC is leading the efforts to locate and characterize massive stars in Local Group galaxies but, as of today, the largest telescopes of the world are only scratching the surface. We are promoting the construction of a multi-object spectrograph for the ELT, MOSAIC, and instrumentation for future large space telescopes such as LUVOIR, that will reach individual, faint massive stars. With this study:

- We will identify the processes shaping star-formation in dIrr's, and whether they impinge a specific IMF. Updated star formation rates, complemented with measurements of the elusive molecular gas content with the SKA, will allow a stress-test of the Kennicut- Schmidt law (empirical relation between the gas density and star formation rate in a given region), helping to establish their true star formation efficiency. On the other hand, our recent results indicate that extinction is not negligible in dIrr, implying that the mass stored in dust and stars is underestimated. At CSIC we are also making a fundamental contribution to future FIR missions and we will contribute to:
- Accounting for the dust content that escaped Herschel's sensitivity limit, deriving the total mass locked in gas, stars and dust, fundamental to compute the dark matter budget of dwarf galaxies.

Galactic Archaeology.

The goal of Galactic Archaeology is to reconstruct the history of the Galaxy using the fossil stars present in its structures. This fossil content is made of low mass stars and white dwarfs. This ambitious goal can be achieved thanks to the first maps with information of the chemical composition, positions and kinematic properties provided by Gaia for a statistically significant number of stars. The first results have shown that the evolution of the Galactic structures is probably at odds with what was traditionally assumed (e.g. that the halo is composed by stars of Galactic origin and stars accreted via collisions like the Gaia-Enceladus event).

The chemical and kinematic properties are not enough to extract the historical record contained in the fossil stars and precise dating of the sample is critical. For low-mass stars this quantity can be obtained fitting the color-magnitude diagram (CMD) of a given population if the distance is known. Gaia has provided accurate distances to stars within an important volume (≈ 2 kpc around the Sun) so it has been possible to apply this method. However, to avoid the degeneracy of the CMD method between age and metallicity of red giants it is necessary to go down the turning point, where stars are dimmer; but in the CMD they can overlap within the observational errors for a wide range of masses and evolutionary stages.

With the advent of asteroseismological capabilities from space it is now possible to determine accurate properties from these stars including their age, provided that the metallicity is known (e.g. recent determination of age of νInd). CSIC researchers have a leading role in the M3 ESA mission PLATO (at co-PI level), which will characterize by asteroseismology hundreds of thousands of stars from 2026 on, providing an invaluable database to reconstruct the history of the Galaxy, and complementing Gaia.

An additional, complementary way to obtain the age of a population is through the cooling of white dwarfs. They are the final evolutionary stage of $\leq 8\,M_\odot$ stars, and their cooling age and luminosity are related allowing to use them as chronometers. Main uncertainty comes from metallicity that strongly affects the lifetime of their progenitors, but massive ones have relatively massive progenitors with short lifetimes that can be neglected. A drawback is that white dwarfs are dim objects and for the moment they can provide only local information. This will be overcome in the future when LSST will provide information of an unprecedented deep sample containing ~ 50 million white dwarfs.

The emerging history is that our Galaxy has been growing at the expense of its vicinity and that, at the same time, has been strongly perturbed by its neighbors:

- The challenge is to determine this history answering the associated questions: i) Which is the contribution of external galaxies to the evolution of the Milky Way? ii) When and how the bar and the bulge formed and evolved? iii) Which is the relationship between the thin and thick disks and the origin of their population? iv) How important is the radial migration of disk stars? v) How was the halo assembled? In all cases the estimate of the age of stars with a precision better than the 10% is a must and constitutes one of the key challenges for the next 10 years.