Final report

# The origin of the stellar components in galaxies

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## Summary

Galaxies are the basic building blocks of the Universe, and the study of their formation and evolution is of utmost importance in cosmology: they reveal us the cosmic structure up to the largest scales and their properties at different cosmic times allow us to unravel the physical processes occurring during their formation. In the context of the standard cosmology, galaxies form in the very centers of dark-matter halos – structures about ten times more massive and extended than galaxies themselves – which form hierarchically via mass aggregation and mergers. Stars in galaxies are in general distributed into two main components: bulges – spheroidal, compact distributions of stars – believed to be the end-products of galaxy collisions, and discs – rotationally-supported structures – more likely originated at late times during periods of low merger activity.

In this project, we investigate the formation of galaxies similar to our Milky Way using hydrodynamical simulations describing the cosmological co-evolution of galaxies and dark matter halos. Our simulation code produces galaxies with two main stellar components – discs and bulges – which are similar to observational/theoretical expectations considering their different formation channels. The discs are produced naturally in cosmological simulations, without the need to introduce an ad-hoc wind model, and their (in)stability properties allow to explain their evolution along cosmic time, and to identify the most important physical processes taking place. We focus on the formation of the galactic stellar components and study the effects of mergers, accretion and environment on their evolution and final properties. We also develop new routines to include, in a more realistic way, the processes of star formation, feedback and chemical enrichment, as well as create tools to compare simulated and observed galaxies in an unbiased manner. In this way, it is possible to properly identify agreement/disagreement between them, understand observational biases and better interpret observational trends that can be affected by instrumental limitations.

The specific results of our work can be summarized as follows: (*i*) Stellar discs are an ever-changing property of galaxies; they can grow, be partially/fully destroyed and/or re-grow during their evolution. The most important processes determining their fate is the occurrence of mergers and misaligned gas accretion, as well as the time at which they occur. (*ii*) The environment where galaxies form and live does not seem to be the main factor determining the evolution of their disc components, although we find indications that galaxies inhabiting richer environments could accrete more gas producing higher (specific) star formation rates compared to galaxies in more isolated regions. (*iii*) Feedback from stellar evolution is a key factor in the evolution of the galaxies, affecting the cooling and star formation processes through the heating of gas and the enrichment with chemical elements. Feedback is however hard to implement in simulations, as its effects on resolved scales are still not fully understood, producing differences in the predictions of different models. More sophisticated feedback implementations and comparisons between models are clearly needed in future work. (*iv*) Galaxy properties – most notably mean stellar ages, gas/stellar metallicities and star formation rates – are sensitive to the techniques used to derive them. Analysis of synthetic observations of our simulated galaxies shows that significant variations appear when various techniques are applied, indicating that is of prime importance to compare simulated and observed galaxies in an unbiased manner. This requires, in general, the creation of synthetic data mimicking the particular characteristics of the given observations.

The results obtained from our project have allowed us understand that the particular merger/accretion history of a galaxy is key in determining the formation and survival of galaxy discs, while environment might shape the star formation process appearing as a second-order trigger of morphological evolution. The simulation of a much larger sample of simulated galaxies which confirm and statistically quantify environmental effects on disc evolution will be of great benefit in this respect, as well as the development of even more realistic feedback modules that describe the effects of these processes on the resolved scales. Our simulations also show that the oldest stellar components – bulges and stellar haloes – are less affected by formation history, as the bulk of their stars form early, in short time-scales and during periods of intense merger activity.

# The origin of the stellar components in galaxies

## Initial questions and objectives of the project

The main objective of the project is to better understand the formation of the galaxy stellar components using numerical simulations in a cosmological context. According to the concordance cosmological model – the Λ-Cold Dark Matter model (Λ-CDM) – galaxies result from the amplification of small density perturbations in the early Universe, which grow via gravitational instability forming the so-called dark matter haloes within which galaxies form. The formation and evolution of dark matter haloes and galaxies is a complex process: they grow hierarchically through the accretion of mass and substructures along cosmic time, and these processes strongly affect their properties – morphology, dynamics, chemical abundances – leaving imprints in their present-day characteristics.

Galaxy formation in the context of the Λ-CDM model is a highly non-linear, multi-scale process free from any simplifying symmetry, and numerical simulations are the best possible tool to follow such a complex evolution. Cosmological simulations describe the evolution of the dark matter – which interacts only via gravity – and the baryonic component – which is also subject to hydrodynamical forces – starting from an initial condition consistent with the adopted cosmological model. Galaxy formation simulations also include modules to describe relevant processes such as of star formation, cooling (and its dependence on the abundance of chemical species), feedback from supernova (SN) explosions and chemical enrichment due to stellar evolution which have been shown to be essential mechanisms for the formation of galaxies.

Galaxies in the Universe appear in a wide range of morphologies, dynamics and chemical patterns, and are usually well described by a superposition of two main components: discs, in which the luminous mass is arranged in a centrifugally supported rotating disc of gas and stars, and bulges, where luminous mass is arranged in a basically featureless spheroidal structure supported by random motion. The relative contribution of discs and bulges to the total light is what ultimately divides galaxies into (disc-dominated) Spirals and (bulge-dominated) Ellipticals. Bulges and discs have many important differences in their kinematics (bulges are dominated by velocity dispersion while discs are rotationally supported), structural parameters (bulges are generally spheroidal with peaked density profiles while discs are flattened structures with exponential profiles), stellar ages (discs have had continuous star formation through most of their life, while bulges are dominated by old stellar populations), metal content (bulge stars exhibit a higher fraction of heavy elements and feature abundance patterns enriched by α-elements such as Carbon, Oxygen and Silicon), and gas content (discs are gas-rich while bulges are gas-poor). The challenge to galaxy formation models is to account for these differences within the standard cosmological model, where mergers and gas accretion significantly and continuously affect and transform the galaxy properties.

Our project's main objective is then to use simulations to better understand the formation of the discs and bulges in the context of the Λ-CDM model, investigating the effects of gas accretion and mergers in the evolution of galaxy properties. Our investigation is motivated by results expected from on-going and future observational surveys which will provide information on the properties of thousands of galaxies with unprecedented detail providing, for the first time, a detailed picture on the photometric, kinematic and chemical properties of the galaxy population. Simulations provide a theoretical framework to understand the complexity of the formation and evolution of galaxies, beyond the simplified view where galaxies are seen as isolated equilibrium structures transforming their gas into stars.

The anticipated observational progress is particularly relevant for studies of our Milky Way galaxy, where individual stars can be resolved. For this reason, we combine simulations of galaxies that live in quiet environments – the most likely to form galaxy discs – and constrained simulations of the Local Group, where the evolution of two main galaxies, candidates for the Milky Way and its neighbour Andromeda, can be followed. Environmental effects can then be investigated by comparing the properties of galaxies in these simulations to those in simulations of more isolated systems. Furthermore, we develop tools to compare simulations and observations in an unbiased manner, in order to properly identify sources or discrepancies which allow us to improve the models and to interpret observational results that are affected by biases, systematics and instrumental limitations. Finally, we update our chemical enrichment model in order to keep up with the latest results in terms of initial mass functions, chemical yields, AGB stars and cooling functions.

## Development of the work

In the following we describe the development of the work carried out during the duration of the project, in terms of: (*i*) update of several routines of our code, in relation to the treatment of chemical enrichment, (*ii*) development of novel tools to compare simulations and observations in an unbiased manner, and (*iii*) simulations performed and analysed in order to tackle the specific scientific problems.

*(i) Code development: an updated model for chemical enrichment*

Numerical simulations in a cosmological context have experienced significant progress during the last decades, in particular in relation to the formation and survival of galaxy discs in halos similar in mass to our Milky Way. Early simulations in a cosmological context suffered from the so-called "angular momentum problem" (Navarro & Benz 1991; Navarro & Steinmetz 2000) which occurs as baryons transfer a significant amount of their angular momentum to the dark matter during mergers, resulting in excessive cooling and star formation activity at early times and producing spheroidal structures rather than discs. Feedback – the injection of mass and radiation, and thus of energy and momentum – into the interstellar (ISM) and intergalactic media has been proposed as a possible solution for the angular momentum problem. Feedback is a fundamental process in galaxy evolution: the interplay between feedback heating and radiative cooling is what ultimately determines how star formation and mass accretion onto galaxies proceeds. Despite its central role in galaxy formation, feedback modeling turned out to be an extremely complex task, since it originates in parsec/sub-parsec scales, which are not resolved in simulations in the foreseeable future.

At the start of this project, we had already been able to tackle the disc formation problem in a cosmological context, being able to obtain discs from cosmological initial conditions. This important success was possible thanks to the implementation of an efficient modeling of feedback from supernova Type II and Type Ia (SNII and SNIa, respectively), in terms of the chemical and, more importantly, the energy input into the ISM produced during SN explosions. This model, developed by the group leader and described in detail in Scannapieco et al. (2005, 2006), is currently grafted into the cosmological code GADGET3 (Springel 2005; Springel et al. 2008), and has been used in several studies related to the formation, destruction and survival of discs in simulations within the $\Lambda$-CDM model (Scannapieco et al. 2008, 2009, 2010, 2011). During this project, several updates to this code had been made as part of the PhD work of Pierre-Antoine Poulhazan, which mainly relate to the description of chemical enrichment due to SNII and SNIa explosions, as well as the introduction of the contribution of stars in the asymptotic giant branch (AGB) phase. Our new model follows the production and distribution of 12 different chemical elements, namely H, He, C, Ca, N, O, Ne, Mg, Si, S and Fe, that are contributed in different proportions and with different typical time-releases via SNII and SNIa explosions and AGB events. The updates to our model, that involve changes to the Initial Mass Function (IMF) of stars, stellar life-times, and chemical yields and rates of SNII, SNIa and AGB stars are described below.

*Introducing several choices for the assumed Initial Mass Function*

The stellar initial mass function (IMF), which gives the fractional distribution of initial masses of a stellar system, is an important ingredient of galaxy and chemical enrichment models. The choice of the IMF directly affects the chemical enrichment of the interstellar gas, as it determines the relative fraction of long-lived stars with respect to intermediate-mass and massive short-living stars and therefore the relative rates of SNII, SNIa and stars that go through the AGB phase. As a consequence, the IMF impacts the relative abundance of elements contributed by different types of enrichment events, and the amount of energy released to the ISM through SN explosions. Furthermore, changes in chemical abundances driven by the use of different IMFs will be translated into changes in the cooling efficiency, affecting in general the hydrodynamics of the ISM. Despite its global importance, a full consensus on the IMF has not yet been reached on the dependencies of the IMF to factors such as time and environment, and as such we restrict ourselves to considering only adjustments to the shape of a time and environment-independent IMF. Our original model (Scannapieco et al. 2005) assumed a single-slope power law proposed by Salpeter (1955), which is one of the most widely used IMF in galaxy formation studies. Our code has been now adapted to alternatively use two other IMFs, namely the Chabrier (2003) and Kroupa (2001) IMFs. Both these IMFs reduce the fraction of stars (i.e. flatten the slope) of mass below 1 $M_{\odot}$ . In Fig.1, we show a comparison of the three IMFs that are now possible choices of our code.

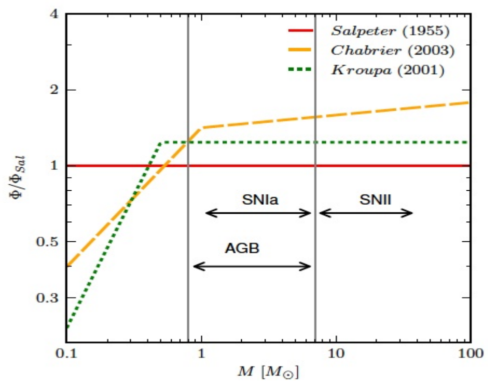



*Figure 1. A comparison of the three Initial Mass Functions (IMFs) of our code*

*Description of the chemical enrichment due to stars in the AGB phase*

Stars in the AGB phase are relevant for the chemical enrichment of galaxies, as they are the main contributors of carbon and nitrogen. These stars are characterized by masses between 0.8 and 7 $M_{\odot}$, and have typical life-times between ~50 Myr and 25 Gyr depending on their metallicity. The release of elements via AGB stars is long, of the order of several Gyrs. Our original model did not account for the effects of stars in the AGB phase; as part of this project we have now developed a model to include the chemical enrichment via AGB. The rate of AGB can be easily calculated as they are determined by the IMF. In order to properly follow the long-timescales characteristic of the release of chemical elements, our new model assumes three enrichment episodes per star particle, that occur after ~100 Myr, ~1Gyr and ~8 Gyr from the formation of the star. The relative contribution of these three episodes is about 25, 55 and 20%, respectively. In order to describe the amount of chemical elements ejected via AGB, we have combined yields given by Marigo (2001) and Portinari et al. (1998) which, together, provide a consistent set of yields for the whole mass range of stars progenitor of AGB.

*Updates to the stellar life-times and chemical yields of stars progenitor of SNII*

Our standard model used the SNII yields of Woosley & Weaver (1995, WW95) which were at the time the most used in similar studies. In our new model, we instead chose those of Portinari et al. (1998, P98), who tabulate the ejecta from stars with metallicities between 0.0004 and 0.05 and with initial masses between 6 and 1000 $M_{\odot}$ and have a series of advantages. In particular, the P98 yields, unlike those of WW95, include the pre-SN mass loss through winds, also accounting for the decay of nickel into iron shortly after the SN event. As an example, we show a comparison of the WW95 and P98 sets of SNII yields, for stars of solar metallicity and masses between 12 and 40 $M_{\odot}$, in Fig. 2. The largest differences appear for Fe and, at a lower level, for Si, S and Ca. Variations are however dependent on the stellar mass and also on the metallicity, with a general trend of P98 giving in general lower yields for the most massive stars (40 $M_{\odot}$) and higher yields for the rest of the stellar populations, compared to WW95. In order to be consistent with the P98 yield calculations, we have also adopted their parametrization of stellar life-times, which are however very similar to those used in our previous implementation (Raiteri, Villata & Navarro 1996).

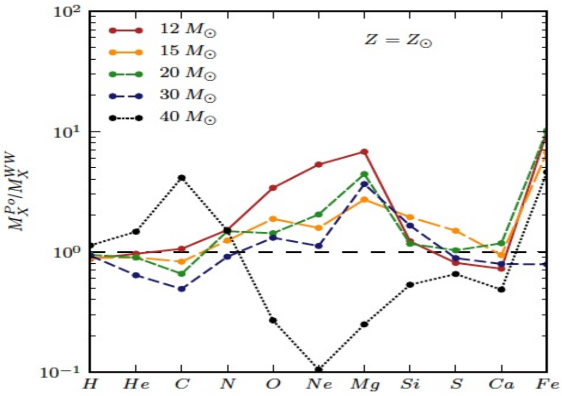



Figure 2. A comparison of the P98 and WW95 sets of chemical yields for SNII, in the case of solar metallicity.

*The implementation of various delay-time-distributions for SNIa*

An important ingredient of chemical enrichment models is the rate of occurrence of SNII, SNIa and AGB stars, which set the amount of progenitor stars determining the total amount of chemical elements being produced and ejected, as well as the time of ejection. While the rates of SNII and AGB stars are easily calculated from the IMF (i.e. amount of stars that are progenitors of SNII and AGB given their mass range), the rate of SNIa is still unknown, as the nature of the progenitors of this type of SN is far less well understood. Observations suggest that SNIa originate from the thermonuclear detonation of CO white dwarfs (WD) near the Chandrasekhar mass, but the mass accretion mechanism is still a topic of considerable debate, with the single and double degenerate scenarios as the two main competing models. Our standard implementation of SNIa used, for simplicity, a simple relation between the SNIa and SNII rates which was a reasonable assumption at the time. However, more recent results show that this is a too simplistic approach. For this reason, we have updated our code assuming an empirical approach to describe the SNIa rates that overcomes the uncertainties in the progenitors of SNIa, and seems to be a better assumption in terms of advances in SNIa studies. In particular, we now parametrize the SNIa rate is terms of an analytic function (Wiersma et al. 2009), the so-called delay-time-distribution (DTD), $\zeta(t)$, which gives the time distribution of the SNIa events, for a single-burst stellar population of a unit stellar mass as a function of time since the starburst. In order to test the dependence of the results to the choice of DTD, our new model is able to adopt 5 different DTDs of different characteristics, namely:

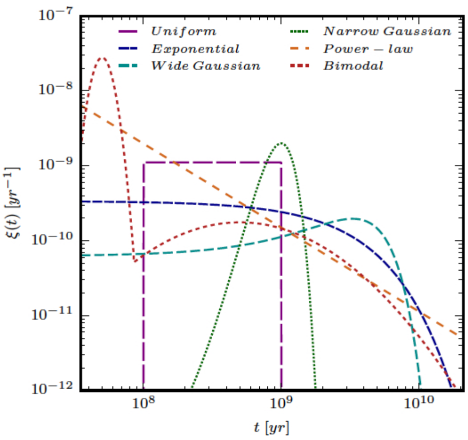



*Figure 3. A comparison of the different DTDs for SNIa allowed in our new model.*

a) power-law: $\zeta(t) \sim \tau^{-1.12}$
b) exponential: $\zeta(t) \sim \exp(-\tau/\tau_{IA})/\tau_{Ia}$
c) bimodal: $\log \zeta(t) \sim 1.4\text{-}50(\log(\tau)-7.7)^2$ for $\tau < \tau_{IA}$
$\log \zeta(t) \sim -0.8\text{-}0.9\,(\log(\tau)-8.7)^2$ for $\tau \geq \tau_{IA}$
d) narrow and wide gaussian: $\zeta(t) \sim \exp[-(\tau-\tau_{IA})^2/(2\sigma^2)]/\sigma$

which assume, respectively, small and large $\sigma$ values. In these equations, $\tau_{IA}$ is a characteristic delay time (assumed to be 1 Gyr and 3 Gyr for the Gaussian and exponential DTDs, respectively, and $\sigma$=0.2$\tau_{IA}$ and 0.5$\tau_{IA}$ for the narrow and wide Gaussian distributions. Finally, the code can also assume a uniform DTD which is the choice of our original model, and we use to compare with previous work.

For each one of the possible DTDs, the number of SNIa can be calculated as:

$$N_{SNIa}(t,t+\Delta t)=A \int f_{WD}(t')\, \zeta(t')\, dt'$$

where the integration goes between $t$ and $t+\Delta t$, $f_{WD}$ is the fraction of white dwarfs and $A$ is a normalization factor. Figure 3 shows a comparison of the various DTDs that are possible choices in our new code, including also the uniform DTD assumed in the standard code.

*The use of a more realistic cooling function*

As a further update to our code we have modified the cooling function. While our standard model included metal-dependent cooling functions tabulated in terms of the iron abundance (Sutherland & Dopita 1993) and assumed collisional ionization equilibrium (CIE), our new implementation uses instead the cooling tables given in Wiersma et al. (2009, W09). W09 provide cooling tables for an optically thin and dust-free gas in ionization equilibrium in the presence of the cosmic microwave background (CMB) radiation and an uniform redshift-dependent UV background radiation field from galaxies, obtained using the photo-ionization package CLOUDY (Ferland et al. 2013), and are a function of the temperature, density, redshift, and the abundances of individual elements. This allows to follow the cooling rate of gas in a more realistic way, particularly in the case of cosmological simulations.

In summary, our new model is now able to use three different IMFs, assumes new chemical yields for SNII, includes the treatment of stars in the AGB phase, and is allowed to chose between different DTDs for SNIa (i.e. different SNIa rates). Furthermore, it introduces a more realistic cooling function. This new model is a step forward in the description of chemical enrichment in the simulations, which on its turn affects the hydrodynamical behaviour of the gas and therefore also influences the star formation process. An important aspect of the new code is that it can properly follow the enrichment of C and N which was not possible before due to the lack of a proper treatment of stars in the AGB phase. Furthermore, the inclusion of more realistic chemical yields for SNII and the possibility to assume different SNIa rates is important in order to produce more robust predictions for the chemical enrichment of galactic systems. Fig. 4 shows a comparison of the SNII, SNIa and AGB stars contributions to the total enrichment in each chemical element, together with the typical time-release scales, in the case of a SSP of 1 $M_\odot$ and solar metallicity ($Z_\odot$), assuming a bimodal DTD, a Chabrier IMF and the new set of chemical yields. The right-hand panel of this figure compares the total relative contribution of the three channels to the production of the different elements.

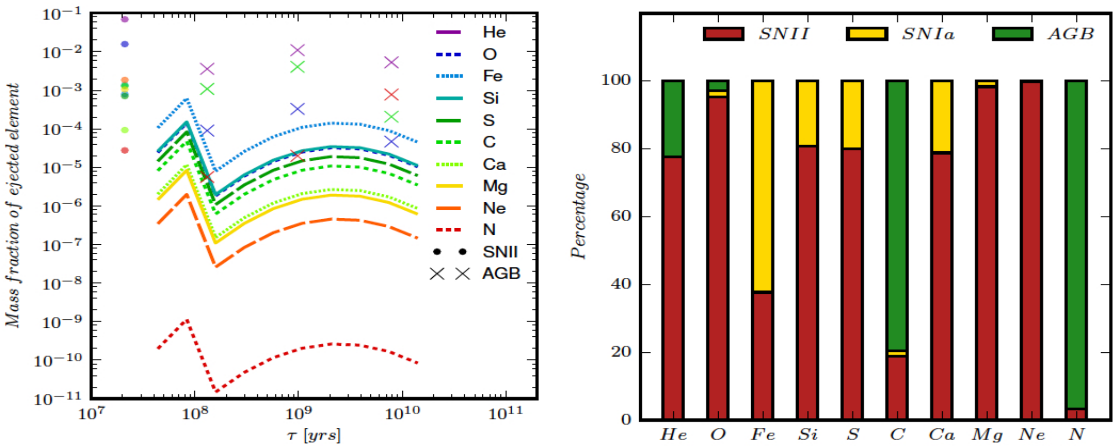



*Figure 4. Left: Mass fraction released by SNII (circles), SNIa (lines) and AGB winds (crosses), for a SSP of 1 $M_\odot$ and $Z_\odot$, assuming a bimodal DTD, a Chabrier IMF and the new chemical yields. Right: A comparison of the mass of various chemical elements ejected by a SSP with $Z_\odot$ via SNII. SNIa and AGBs.*

*New implementation of SN and radiation pressure feedback*

Although not directly related to the work of all members of the group, as part of a separate project Dr. Scannapieco has been involved in the development of a novel model to treat the effects of energy feedback by SNII and to include the description of radiation-pressure from young stars, which are an additional source of feedback. These updates are described in Aumer et. al (2013) and, in some cases, have been used in the works of the group. The main effects of this update is to generate younger galaxies, as the star formation process is more efficiently regulated compared to that obtained considering only feedback from SN. Radiation pressure feedback is particularly important at high redshift, and lead to a significant reduction in early star formation in simulated galaxies.

*(ii) Development of novel tools to properly compare simulations and observations*

An important contribution of our group has been the creation of proper tools to compare simulations and observations in an unbiased manner, which is the only way to constrain our models, select the most likely inputs of the simulations, and better interpret several observational results which suffer from important biases and limitations inherent to the observations. In order to properly compare simulated and observed galaxies, it is necessary to transform the simulation outputs, which give the mass distributions for the gaseous and stellar components, their metallicities and stellar ages, into synthetic observations which provide images and spectra that can be analysed using the exact same techniques that are applied in real observations.

In particular, we have used both Stellar Population Synthesis (SPS) models, with and without the addition of a simple dust law, as well as the radiative transfer Monte Carlo SUNRISE code (Jonsson 2006, Jonsson et al. 2010) in order to create synthetic observations of various of our simulated galaxies. We have then derived the magnitudes and colors, stellar masses, stellar ages, stellar/gas metallicities and star formation rates of the simulated galaxies from their synthetic observations, using a variety of techniques used in large galaxy surveys, and then focused on the techniques applied in the Sloan Digital Sky Survey (SDSS). In this way, it was possible to quantify biases in the observations and identify agreement/disagreement between the simulated and observed galaxies.

*(iii) Simulations of galaxies in different environments and study of stellar components*

As part of our project, we have run a number of simulations of the formation of galaxies in a cosmological context, specifically designed to investigate the effects of environment on the determination of galaxy properties. In particular, we first used the zoom-in initial conditions (ICs) of the Aquarius galaxies (Springel et al. 2008, Scannapieco et al. 2009) which correspond to systems similar in mass to the Milky Way with different formation histories in terms of mass accretion and mergers and that are, at the present time, in relatively quiet environments, having no massive neighbour within a sphere of 2 Mpc. These simulations were used for various of our projects, and will be refereed to as the Aquarius simulations or Aquarius galaxies.

On the other side, an important aspect of the simulations in relation to studies of the formation of galaxies focusing on our Milky Way, is that our Galaxy lives in a rich environment, with Andromeda, another spiral of similar mass, at less than 1 Mpc from it. As is the case for our Aquarius simulations and most studies by other groups, the environment of the Milky Way has been often neglected and assumed to have little impact on the determination of its evolution. In contrast, observational results suggest that galaxy properties can be significantly shaped by environment during their evolution, although the exact effects are still to be understood in detail. Simulations provide a unique tool to study how galaxies evolve in relation to their environment, and for this reason we have run a second set of simulations using the so-called constrained ICs that provide initial conditions which, once evolved until the present time, reproduce the dynamical properties of the Local Group (i.e. Milky Way-Andromeda system) and its surroundings. We have in particular used ICs provided by the CLUES (Constrained Local UniversE Simulations), which allow to follow the formation of a system composed of two main galaxies, candidates for the Milky Way and

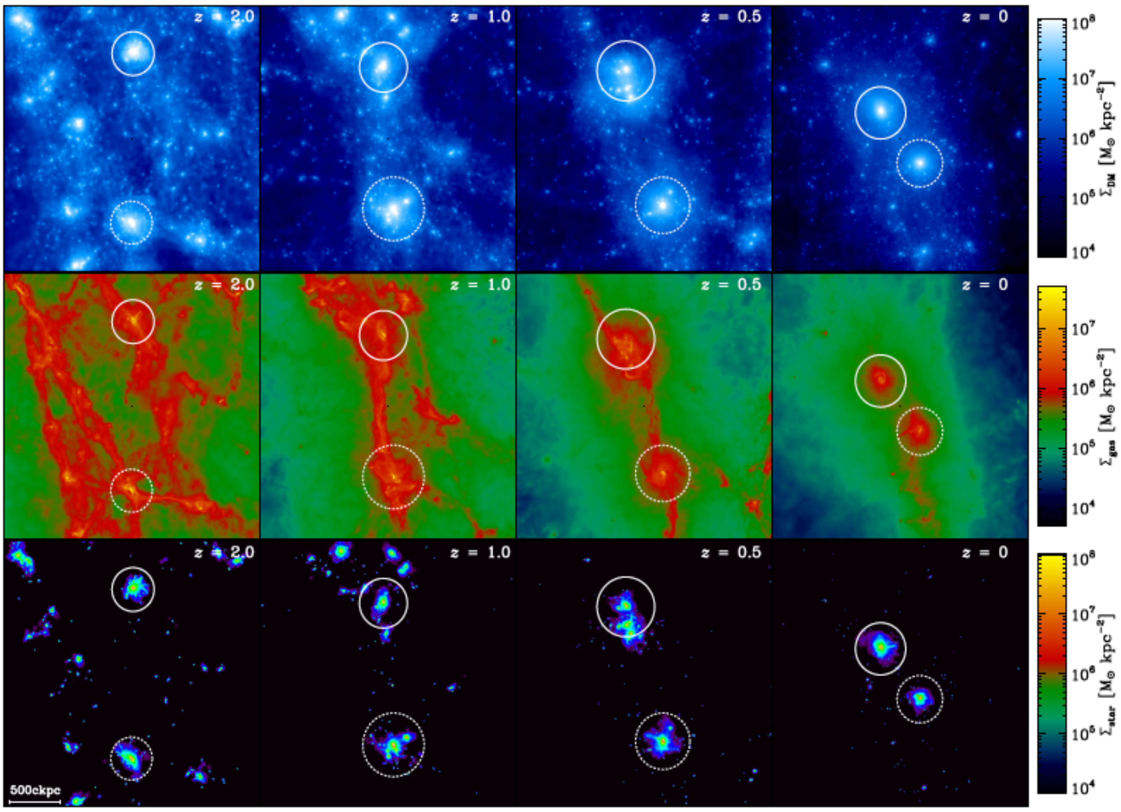



*Figure 5. Projected mass density of dark matter (upper panels), gas (middle panels) and stars (lower panels) for one of our CLUES simulations, for different cosmic times or redshifts.*

Andromeda, and to study possible environmental effects by comparing their predictions to those obtained for the Aquarius galaxies. As an example, we show in Fig. 5 the dark matter, gaseous and stellar distributions for various cosmic times (or redshifts *z*) in a constrained simulation done by our group. Simulations using the constrained simulations will be refereed to as the CLUES simulations.

Our various simulations have also been used to investigate the formation of thick discs and stellar haloes, through various collaboration networks (see publication list).

## Results

The presentation of the results obtained by the group will be done in terms of the three main topics:

a) Effects of environment on the formation of galaxies,
b) Effects of varying the assumptions of the chemical enrichment model on the resulting galaxy properties, and
c) Biases and systematics in the derivation of galaxy properties in observational studies.

We describe these three points in the following.

### *a) Effects of environment on the formation of galaxies*

In Nuza et al. (2014), Creasey et al. (2015) and Scannapieco et al. (2015) we used the CLUES constrained initial conditions to investigate the formation of the Milky Way and Andromeda galaxies in terms of their gas and stars, as well as their joint evolution and the effects of environment on the determination of their properties. Simulations using two different CLUES ICs have been run, one where the high-resolution region has a radius of about 2 Mpc, and a second one where this region is ~7 Mpc. This last simulation allows to have a simulated larger volume and a larger sample of galaxies which inhabit the same large-scale region but have variations in the environmental density. In this part of the project, we have also used the Aquarius galaxies in order to better quantify possible environmental effects of the CLUES simulations. Our main results are as follows.

*(i)* The mass of gas in the different components, namely cold, hot and neutral (HI) in the simulated Milky Way (MW) and Andromeda (M31) is consistent with available observations, and the predictions for the HI distribution are consistent with expectations and HI observations (Fig. 6).

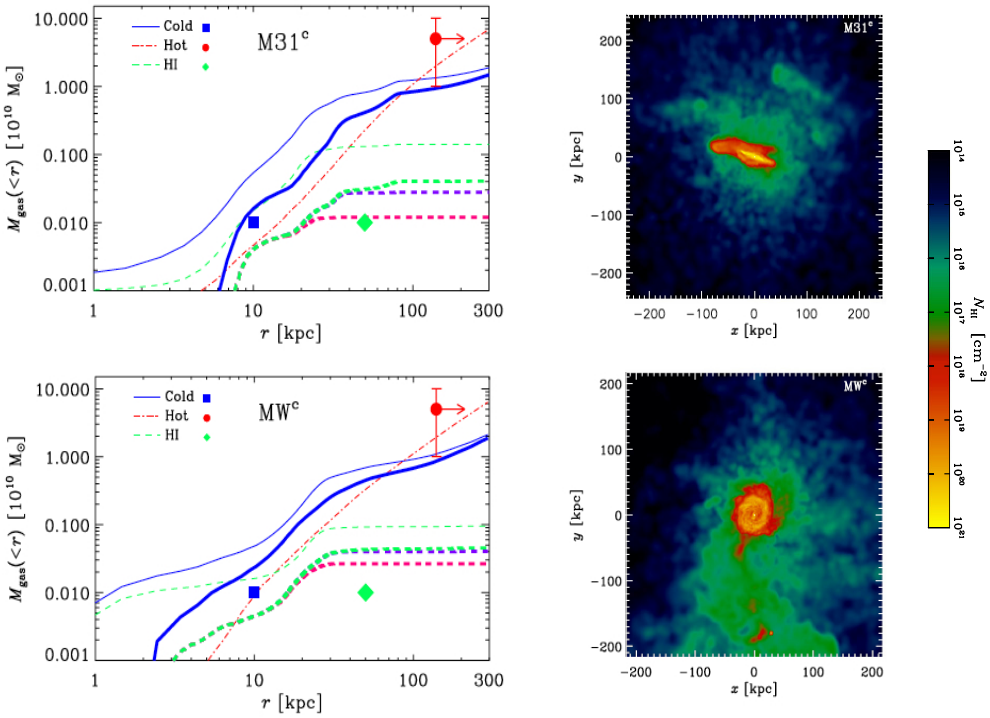



*Figure 6. Left: Cumulative mass profiles of the cold, hot and HI gas components for the MW and M31 simulated galaxies (thin lines). The thick lines show the results corresponding to the exclusion of the gaseous disc, in order to properly compare with observations. The observational data shown here are from Shull et al. (2009), Lehner & Howk (2011), Richter (2012) and Gupta et al. (2012). Right: The distribution of HI gas in the simulated M31, as seen from the MW (upper panel) and the distribution of HI in the simulated MW, as seen from M31 (lower panel). The color scale is also included.*

*(ii)* The predicted HI covering fraction profile for the simulated M31 and the observational estimates of Richter (2012) are in good agreement. The covering fraction profiles for different limits of HI column density are shown in Fig. 7, also for the simulated MW, as well as the regions that are possible for different viewing angles. As in the real MW-M31 system, the latter is approximately edge-on when seen from the MW, and therefore it traces the lower limit of possible covering fractions.

*(iii)* Our simulations predict an excess of gas mass or bridge between the MW and M31 galaxies. This is clear from Fig. 8 where we show the mass profiles from the center of the MW towards M31, for different orientations. When we observe the sky in the direction of M31 we find a significant excess (more than 20$\sigma$) compared to the mean over 50 other random directions. This prediction is consistent with observational results, and is suggestive of possible effects in our Galaxy due to our close neighbour Andromeda.

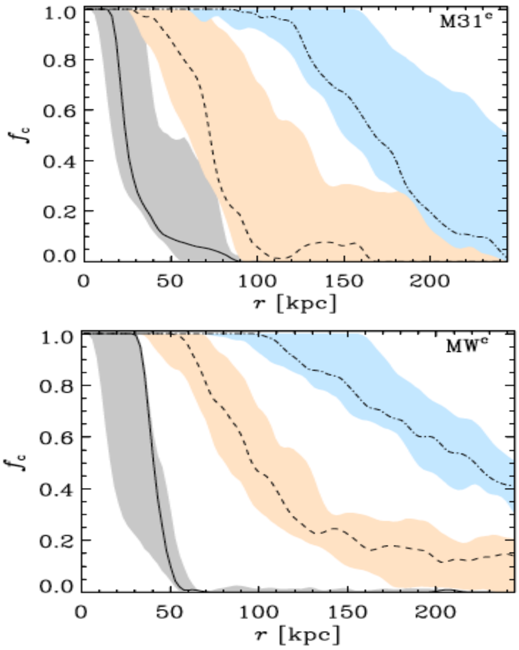



*Figure 7. Covering fraction profiles for the simulated M31 and MW galaxies for different column density limits of $N_{HI}$>$10^{15}$cm$^{-2}$ (dot-dashed lines), $N_{HI}$>$10^{16}$cm$^{-2}$ (dashed lines) and $N_{HI}$>7 $10^{17}$cm$^{-2}$ (solid lines). The shaded areas show the range of possible covering fractions after choosing different viewing angles.*

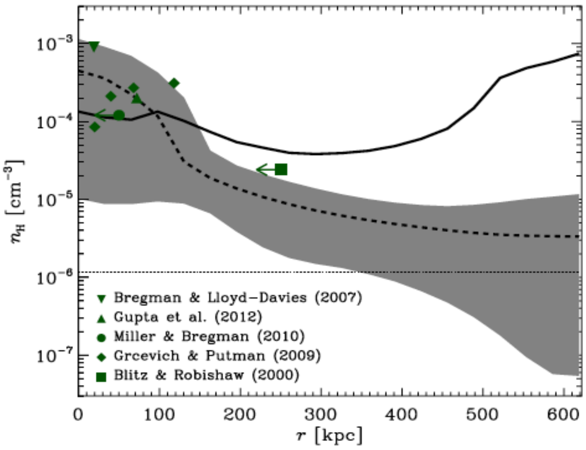



*Figure 8. Hydrogen number density profile as a function of distance to the MW simulated galaxy. The mean value over different (50) random directions is indicated as a dashed line, and the shaded region denotes the standard deviation. Also shown are observational estimations of the electron number densities at different distances from the MW (filled symbols).*

*(iv)* A detailed analysis of the formation and evolution of the stellar components in the simulated MW and M31 showed that the discs have periods of growth and destruction, which can be linked to the occurrence of mergers and of misaligned gas accretion. These results are consistent with those obtained for the discs of the Aquarius galaxies, indicating that, although the MW and M31 live in a richer environment, the very inner regions of the systems where the stellar discs lie have a similar evolution. This suggests that the formation/destruction process of discs is not strongly affected by the large-scale environment. Fig. 9 shows the evolution of the quantity $f_{disc}$, a measure of the disc mass relative to the total stellar mass, for our M31 and MW simulated galaxies, as well as the evolution of the cosine of the angle $\alpha$ between the gaseous and stellar discs. Solid and dotted lines correspond, respectively, to simulations that neglect or include the effects of radiation-pressure feedback that we have run to test the robustness of our results to the feedback strength.

*(v)* Environmental effects can however affect galaxy properties such as the star formation rate (SFR), as galaxies that live in different environments can be subject to different levels of gas accretion. We have quantified the environment of simulated galaxies using the environmental density ($\delta_{1200}$, defined as the overdensity in regions of 1200 comoving kpc around the target galaxies) and studied its relation to various galaxy properties at the present time. In this case we use one of the CLUES simulations with a spherical high-resolution region of 7 Mpc radius, which allowed us to simulate galaxies with different environmental densities. We combined this sample with the Aquarius galaxies that live in general in more quiet environments. Our results show that galaxies in denser environments have systematically higher specific star formation rates (SSFRs) compared to galaxies in quieter regions, as shown in the right-hand panel of Fig. 10.

*(vi)* In order to enlarge the statistical meaning of our results in terms of environmental dependencies, we have studied the evolution of $\delta_{1200}$ for the full sample of simulated galaxies and studied its relation to SSFRs at different times (Fig. 11). We find that

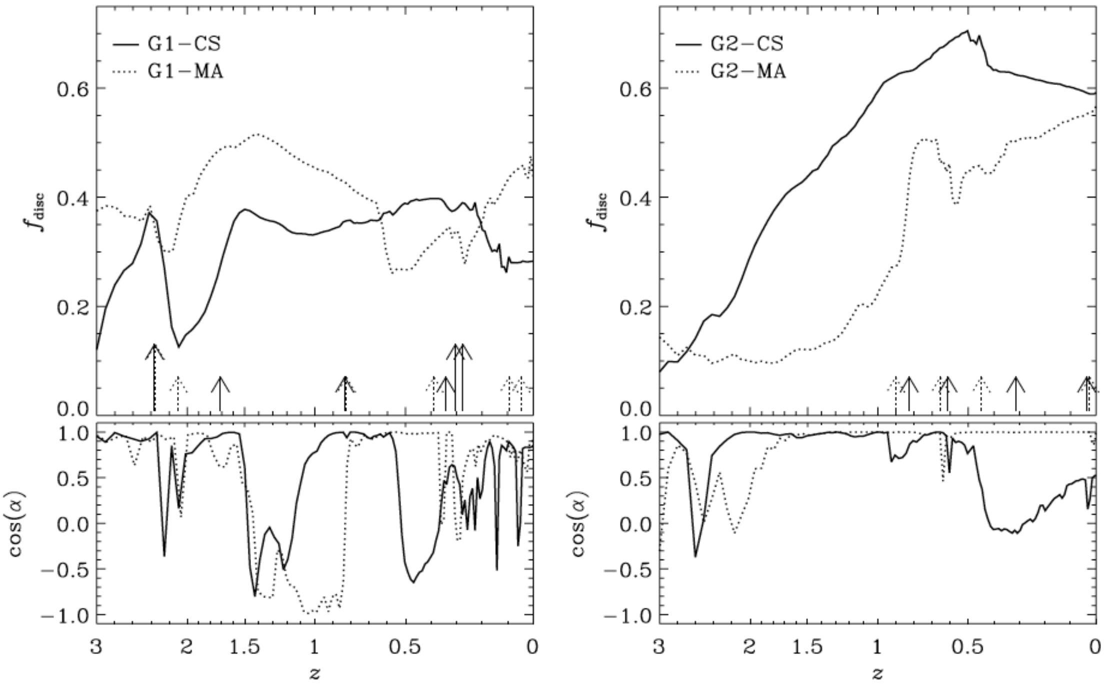



*Figure 9. The evolution of $f_{disc}$, a measure of the stellar mass in the disc to the total stellar mass, and cosine of the angle between the gaseous and stellar discs, for our M31 (left-hand panels) and MW (right-hand panels) simulated galaxies. The solid and dotted lines correspond to the results of simulations that either ignore or include the effects of radiation-pressure feedback. The latter leads to the formation of younger stellar populations, as most notably seen in the case of the simulated MW.*

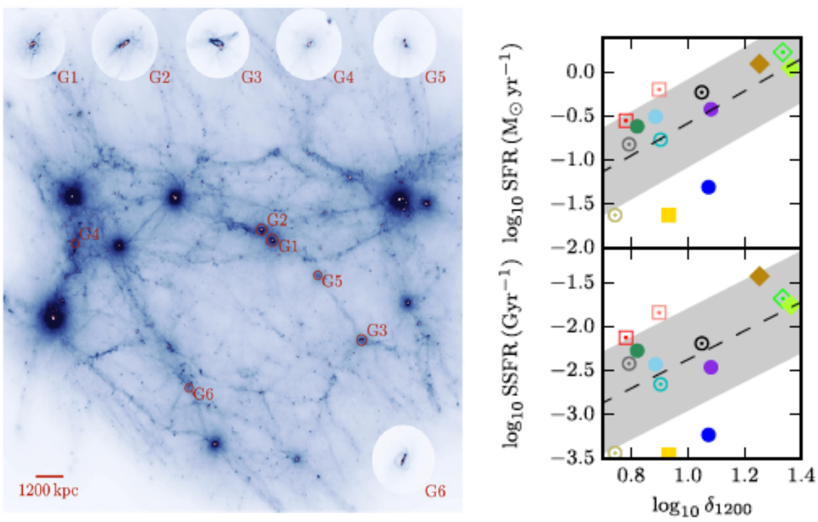
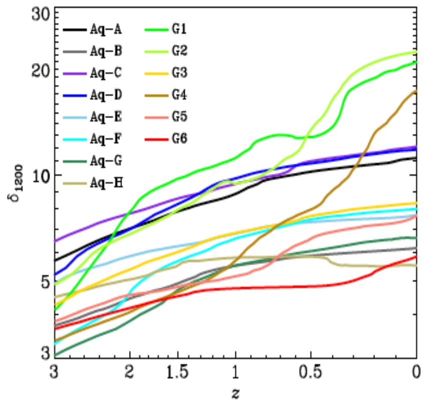



*Figure 10. Left: Map of projected gas density in a constrained simulation of the Local Group using initial conditions of the CLUES project. The simulations covers a large area of approximately 15 Mpc on a side, including the Local Group with MW and M31 candidates, as well as four other galaxies of similar mass and with various environmental densities, defined as the overdensities in spheres of 1200 comoving kpc around the target galaxies. Right: Present-day star formation rate (SFR) and specific star formation rate (SSFR) as a function of (the logarithm of) the environmental density ($\delta_{1200}$) for galaxies in different environments. We detect a statistically significant, positive correlation between SFRs and environmental density.*

differences in SSFRs and $\delta_{1200}$ are correlated, suggesting that our result that galaxies in richer environments could have more significant supply of gas from their surroundings



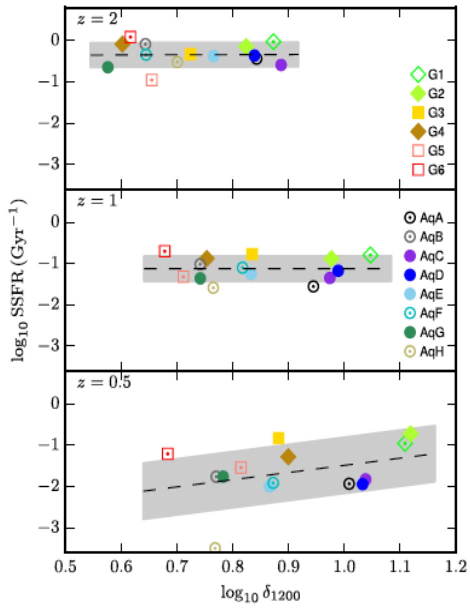




*Figure 11. Left: Evolution of environmental density for simulated galaxies in the CLUES and Aquarius sets. The M31 and MW candidates are detnoted here as G1 and G2. Right: SSFR vs $\delta_{1200}$ for different times for the same simulations.*

enhancing their SFRs is not strongly affected by low statistics, although more work is needed in order to confirm this trend.

*b) Varying the assumptions of the chemical enrichment model and effects on the resulting galaxy properties*

In Poulhazan, Scannapieco & Creasey (in preparation), we present our new model and discuss the implications of varying the different assumptions of the chemical enrichment model. In order to isolate the effects of the different choices we have run two types of simulations, using either idealized initial conditions of isolated galaxies and cosmological initial conditions of one of the Aquarius halos (Aq-C). The main results are described below.

*(i)* The use of various IMFs (Salpeter, Kroupa and Chabrier) have modest effects on the star formation and SNII rates, which are simply a reflection of the different number of stars of different mass and their resulting feedback.

*(ii)* When the chemical yields are varied from WW95 to P98, significant differences are observed in the chemical abundances of the simulated galaxies. In particular, simulations with the P98 yields have in general higher abundance ratios [X/Fe], particularly for O, Ne, N and Mg. In part, these changes are due to the lower Fe levels when we use the P98 yields. Fig. 12 compares the results of isolated galaxy simulations that are identical except for the use of the WW95 or P98 chemical yields.

(*iii)* As expected, large differences in the abundances of C and N appear when AGB stars are included in the models, as AGB are the main contributors of these elements. Fig. 13 compares the evolution of various abundance ratios, for the stars and gas, in idealized simulations of galaxy formation, which either ignore or include a treatment for stars in the AGB phase.

*(iv)* The use of different delay-time-distributions (DTD) for SNIa has an impact on the SNIa rates and resulting metallicities. In order to test the effects of the DTDs on simulated galaxies, we have run simulations of isolated galaxies as well as of galaxies in a cosmological context obtaining similar results. Fig. 14 compares the instantaneous and cumulative SNIa rates for various cosmological simulations with different DTDs, and Fig. 15 shows the normalized integrated DTD which allows to better understand the changes that this choice has on the evolution of SNIa rates and resulting chemical properties, particularly in terms of the absence/presence of prompt SNIa components. Runs with uniform and narrow Gaussian DTDs are the ones where SNIa events appear earlier, with most of them having occurred after 1-2 Gyr of the bulk of star formation activity which peaks at about 0.5 Gyr. In contrast, in the remaining tests only after ~10 Gyr the majority of SNIa events have

happened. Runs with exponential and wide Gaussian DTDs are the ones with larger delay between the star-burst and the SNIa events, with the power-law and bimodal DTD tests appearing as intermediate cases. (Note that the SFRs are not strongly affected by the choice of SNIa DTDs, and therefore these tests have very similar SFRs during the whole evolution).

*(v)* The different behaviors of the SNIa rate when various DTDs are assumed in our simulations lead to variations in the evolution of all chemical elements, and particularly in the iron content, as shown in Fig. 16 (left-hand panel). The most significant differences appear at early time which determine the level of enrichment in the different simulations. At the present-day, these differences might be translated in the observed chemical properties of galaxies, and could in principle be used to decide on the most realistic DTD. The right-hand panel of Fig. 16 compares observations and simulations in terms of the [O/Fe] vs [Fe/H] ratios. All models present a plateau for [Fe/H]≤0 followed by a decrease, although the shape of the "knee" is distinctive of each simulation (and thus of each DTD assumed). The model with uniform DTD lies at an extreme, as the many SNIa events produced early on allow the model to reach a low level of [O/Fe]~0.2 at the plateau. All other models reach a plateau with a higher [O/Fe] level of about 0.4. In particular, simulations assuming a power-law and bimodal DTD exhibit the most abrupt decrease, at the highest [Fe/H] of all runs. As the sharpness of the knee corresponds to the prompt component of the DTD, these two simulations are extreme as they produce so many early SNIa events. The wide Gaussian DTD produces a very soft knee, and at an intermediate behavior we find the runs with exponential and narrow Gaussian DTDs.

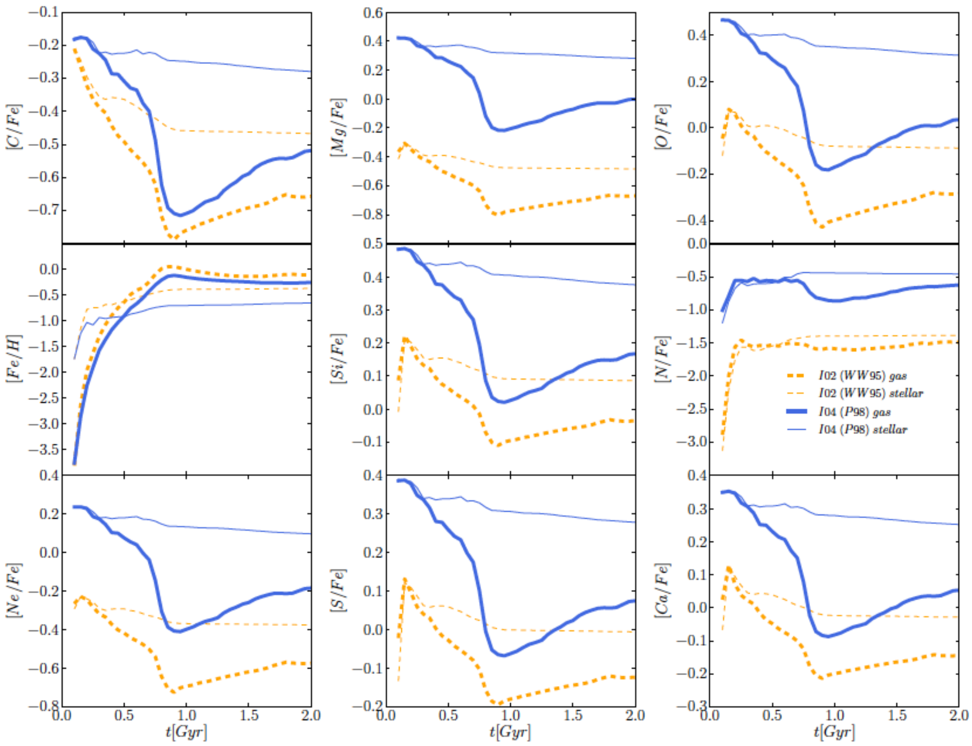



*Figure 12. The effects of varying the chemical yields (WW95 versus P98) on the evolution of the various chemical elements considered in our work, for the stellar and gaseous components in simulations of isolated galaxy formation.*

### *c) Comparing simulations and observations in an unbiased manner*

An important limitation of current studies of galaxy formation is related to the comparison between simulated and observed data. This is however extremely important for simulations – comparisons are used to decide on the successes or failures of the models – and for observations – as the derivation of galaxy properties from observations can suffer

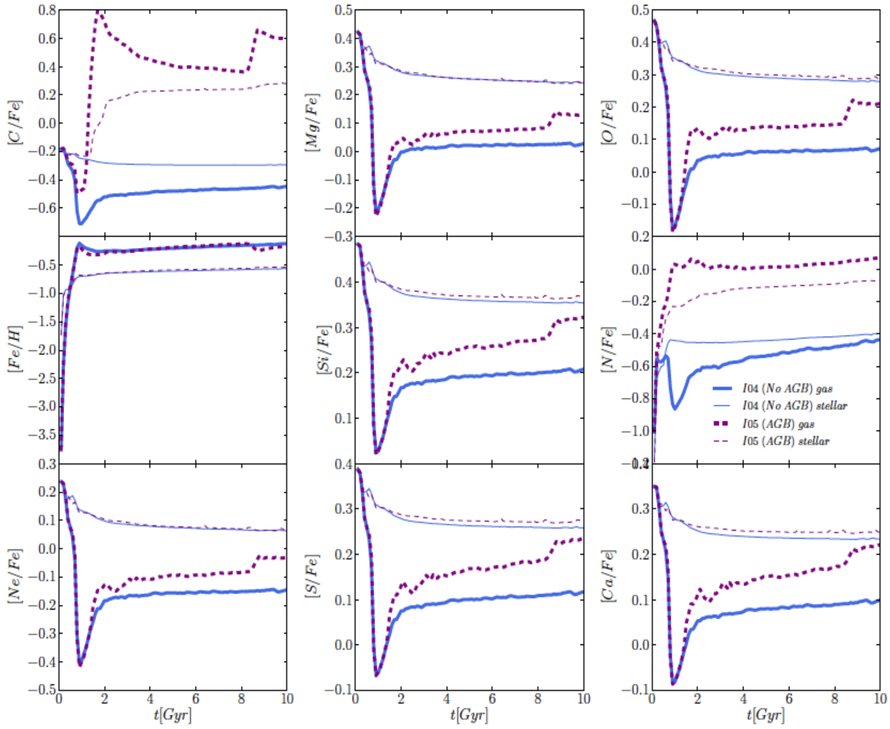



*Figure 13. The effects of including a treatment for stars in the AGB phase on idealized simulations of galaxy formation. The most important changes are, as expected, detected for N and C for which AGB are the main contributors.*

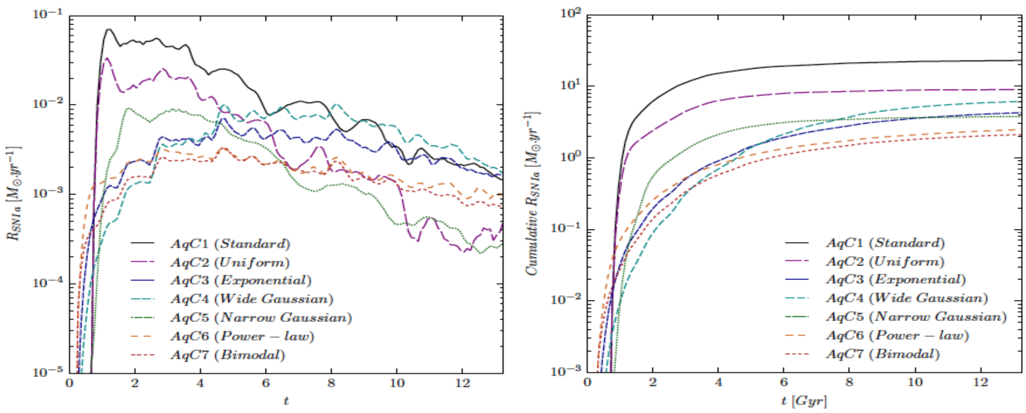



*Figure 14. Instantaneous and cumulative SNIa rates for our cosmological simulations using different DTDs for SNIa.*

from biases and systematics, and the only way to quantify them is using simulations where the real properties to be derived are known in advance. In Guidi et al. (2015, 2016) and Guidi et al., submitted) we explore this problem and create various novel tools to properly compare simulated and observed galaxies, that allow to identify agreement/disagreement between them in a robust way and quantify observational biases. For this purpose, we created synthetic observations of several of our simulated galaxies, and recalculated their properties mimicking the techniques used in various galaxy surveys, focusing in particular on the Sloan Digital Sky Survey (SDSS) and the Calar Alto Legacy Integral Field Area Survey (CALIFA).

In the first part of this study, we have used a set of fifteen simulated galaxies using the Aquarius ICs, comprising a variety of merger, formation and accretion histories, which resulted in a variety of final morphologies, star formation rates, metallicities and gas fractions. As these properties somewhat depend on the modeling of feedback, the same five galaxies were simulated using three different models for chemical enrichment and energy feedback. For the full set of 15 galaxies we have created their present-day synthetic spectra and derived the observables (magnitudes/colors, stellar masses and ages, stellar and gaseous metallicities and star formation rates) in various ways that mimic real observations, and we have compared the results with the direct outputs of the simulations, i.e. the actual properties of the simulated galaxies.

We found that biases and systematics appear at various stages in the process of obtaining the observables from the simulations, due to:

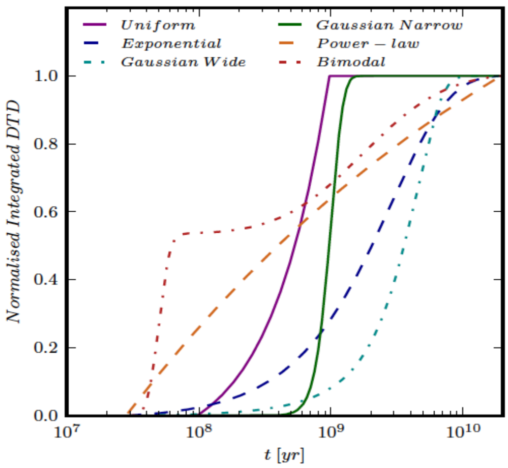



*Figure 15. Normalized integrated DTDs as a function of time for the various DTD choices used in our code.*

*(i)* assumptions/parameters of SPS models,

*(ii)* dust/radiative transfer/projection effects,

*(iii)* weighting with the mass instead of luminosity when calculating mean quantities,

*(iv)* observational biases, e.g. extrapolation to external regions of galaxies where no spectral or photometric data are available,

*(v)* different parametrizations of the star formation history and dust extinction when quantities are derived fitting a pre-constructed grid of models,

*(vi)* in the particular case of gas metallicities and SFRs, the use of different calibrations.

A detailed description of these results and their implications to the derived galaxy properties is presented in Guidi et al. (2015), and synthetic images of our simulations are shown in Fig. 17.

As a second step, we have used our synthetic data to make a detailed comparison between our simulations and SDSS data, and quantified observational biases and systematics. Our results show that, when an unbiased comparison with the SDSS data is performed (see Fig. 18), our simulated galaxies:

*(i)* look photometrically similar to SDSS blue/green valley galaxies,

*(ii)* have concentrations and Sérsic indices mostly in the range of SDSS galaxies, even though the different feedback codes give different results and in some cases outside the observed range,

*(iii)* are in good agreement with SDSS ages, although most of them appear older compared to SDSS spirals,

*(iv)* have stellar metallicities consistent with metal-poor spirals,

*(v)* show good agreement with observations of the gas oxygen abundances, even if they remain slightly more metal-poor,

*(vi)* have SFRs in the region between the SDSS green valley galaxies and the blue cloud, although there are objects with SFRs both in the region of strongly star-forming spirals and in the red cloud of passive ellipticals.

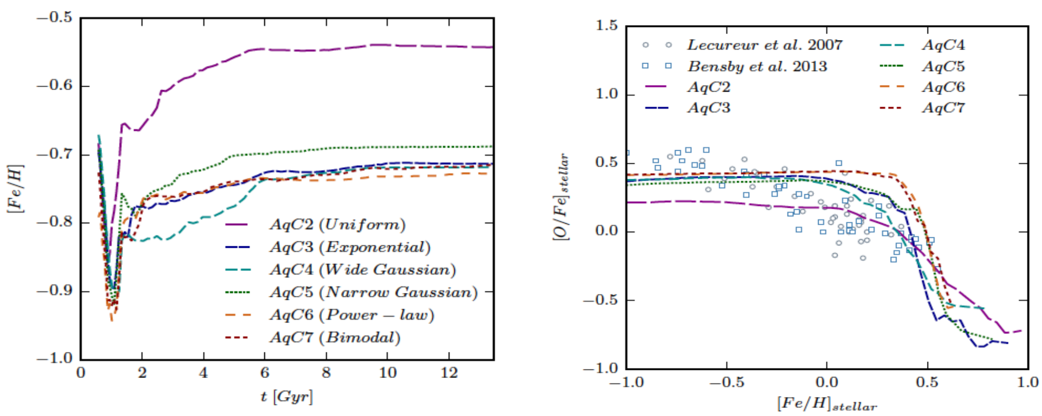



*Figure 16. Left: the evolution of [Fe/H] for our set of cosmological simulations with different DTDs for SNIa. Right: Present-day [O/Fe] vs [Fe/H] for the same simulations, and comparison with observational results.*

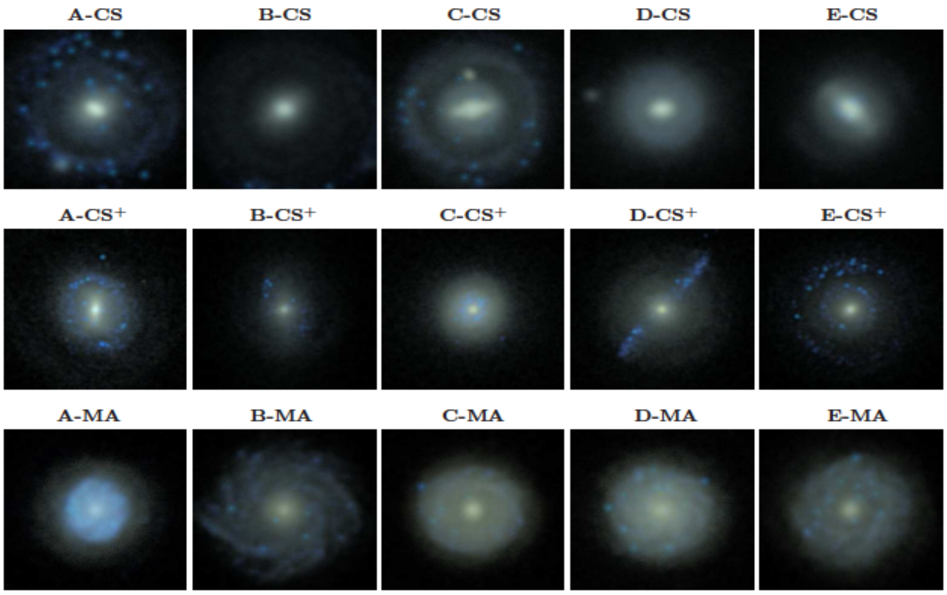



*Figure 17. (u, r, z) multi-bands, face-on images of the 15 simulated galaxies, obtained using the radiative transfer code SUNRISE, for a 60x60 kpc field of view.*

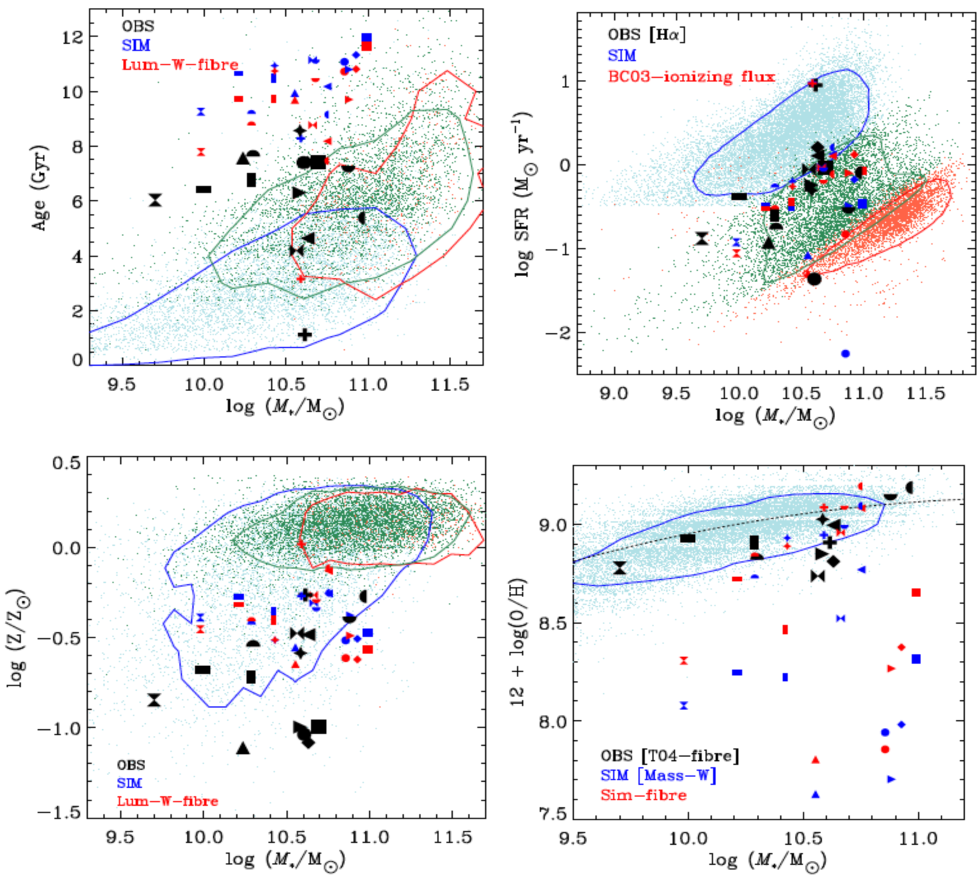



*Figure 18. A comparison of various properties of the simulated galaxies and observations of the SDSS survey, separated into red, green and blue galaxies (points). In each panel we show the results of following observational procedures (OBS, black symbols), the direct result of the simulation (SIM, blue symbols) and an intermediate case with minimum post-processing (red symbols).*

Finally, we have created synthetic datacubes from our simulations mimicking the properties of the Integral Field Spectroscopy (IFS) survey CALIFA. For various simulated galaxies and for different viewing angles, we have obtained the corresponding spatially-resolved spectra, that include stellar and nebular emission, kinematic broadening of the lines, and dust extinction and scattering. For this, we have followed the CALIFA procedures in terms of data format, field of view size, spectral range and sampling.

Fig. 19 shows an example of our synthetic datacubes, which are available to the astronomical community, and provide observers with a powerful benchmark to test the accuracy and calibration of their analysis tools, as we also provide the real properties of the simulated galaxies. In this way, it is possible to quantify biases in the observational procedures, and reliably compare simulations with IFS observations.

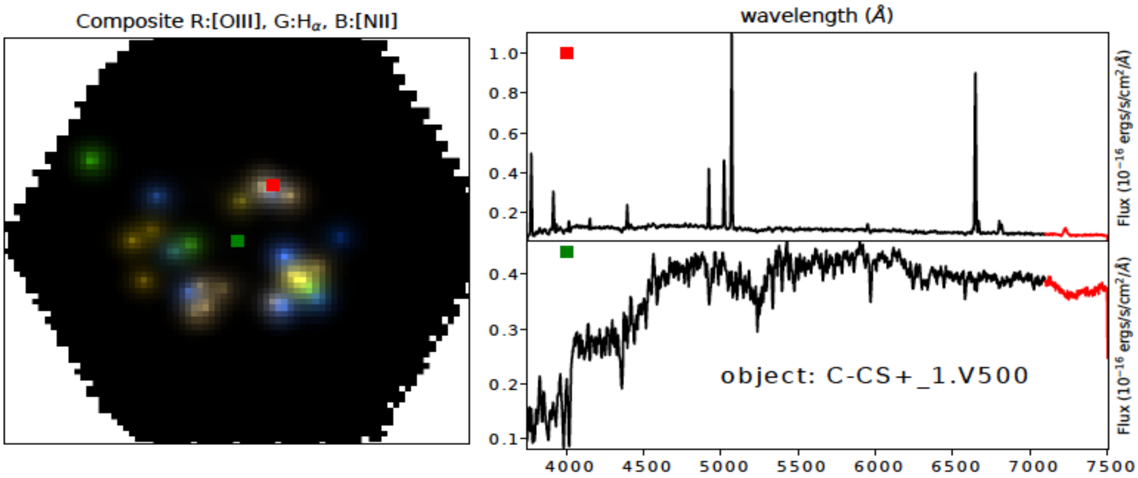



*Figure 19. Left: RGB image of the [OIII]5007, Hα and [NII]6548 emission lines for one of our simulated galaxies. Right: synthetic spectra in two selected spaxels of the RGB image: the upper panel corresponds to the red square in the image and samples a nebular region, while the lower panel shows a V500 spectrum containing only stellar emission, which corresponds to the green square.*

## Cooperation partners which have contributed to the results of the project

Design and analysis of simulations: Sebastián Nuza, Stefan Gottlöber, Matthias Steinmetz, Gustavo Yepes.

Comparisons with SDSS data: C. Jakob Walcher and Anna Gallazzi.

Comparisons with CALIFA: Yago Ascasibar and Javier Casado (and CALIFA collaboration members).

## Qualification work resulting from project

1) Giovanni Guidi, PhD degree, Potsdam University (PU), April 2017.
2) Pierre-Antoine Poulhazan, PhD, Potsdam University, estimated: 2017.

## Open access data

A series of the Local Group simulations performed for this project are publicably available at https://www.clues-project.org/cms/.

The dabacubes created mimicking the CALIFA survey are open and can be found at http://astro.ft.uam.es/selgifs/data_challenge/.

<u>List of publications of the project</u> (Group members are indicated in bold-face)

A – Published papers, directly related to the project

1) **Guidi G.**, **Scannapieco C.,** Walcher C.J., Gallazzi A., 2016, "Physical properties of galaxies: towards a consistent comparison between hydrodynamical simulations and SDSS" , Monthly Notices of the Royal Astronomical Society, 462, 2046.
2) **Guidi G.**, **Scannapieco C.**, Walcher C.J., 2015, "Biases and systematics in the observational derivation of galaxy properties: comparing different techniques on synthetic observations of simulated galaxies", Monthly Notices of the Royal Astronomical Society, 454, 2381.
3) **Scannapieco C.**, **Creasey P.**, Nuza S.E., Yepes G., Gottlöber S., Steinmetz M., 2015, "The Milky Way and Andromeda galaxies in a constrained hydrodynamical simulation: morphological evolution", Astronomy & Astrophysics, 577, 3.
4) **Creasey P.**, **Scannapieco C.**, Nuza S.E., Yepes G., Gottlöber S., Steinmetz M., 2015, "The Effect of Environment On Milky Way-Mass Galaxies in a Constrained Simulation of the Local Group", The Astrophysical Journal, 800, 4.
5) Nuza S.E., Parisi F., **Scannapieco C.**, Richter P., Gottlöber S., Steinmetz M., 2014, "The distribution of gas in the Local Group from constrained cosmological simulations: the case for Andromeda and the Milky Way galaxies", Monthly Notices of the Royal Astronomical Society, 441, 2593.
6) Aumer M., White S.D.M., Naab T., **Scannapieco C.**, 2013, "Towards a more realistic population of bright spiral galaxies in cosmological simulations", Monthly Notices of the Royal Astronomical Society, 434, 3142.
7) **Scannapieco C.**, 2013, "Cosmological simulations of galaxy formation: Successes and challenges in the era of supercomputers. Ludwig Biermann Award Lecture 2012", Astronomische Nachrichten, 334, 499.

B – Further papers of group members related to our project

8) Minchev I., Martig M., Streich D., **Scannapieco C.**, de Jong R.S., Steinmetz M., 2015, ApJ, 804, 9
9) **Creasey P.**, Theuns T., Bower R., 2015, MNRAS, 446, 2125
10) Tissera P.B., **Scannapieco C.**, 2014, MNRAS, 445, 21
11) Tissera P.B., Beers T.C., Carollo D., **Scannapieco C.**, 2014, MNRAS, 439, 3128
12) Piffl T., **Scannapieco C.**, and 23 coauthors, 2014, A&A, 562, 91
13) Minchev I., Chiappini C., Martig M., Steinmetz M., de Jong R.S., Boeche C., **Scannapieco C.**, and 23 coauthors, 2014, ApJ, 781, 20
14) Tissera P.B., **Scannapieco C.**, Beers T.C., Carollo D., 2013, MNRAS, 432, 3391
15) **Creasey P.**, Theuns T., Bower R., 2013, MNRAS, 429, 1922
16) **Scannapieco C.**, Athanassoula E., 2012, MNRAS, 425, 10

C – Submitted papers

17) **Guidi G.**, Casado J., Ascasibar Y., Galbany L., Sánchez-Blázquez P., Sánchez S.F., Rosales-Ortega F.F., **Scannapieco C.**, "The SELGIFS data challenge: generating synthetic observations of CALIFA galaxies from hydrodynamical simulations", Monthly Notices of the Royal Astronomical Society.

D – Papers in preparation

18) **Poulhazan P.-A.**, **Scannapieco C.**, **Creasey P.**, "Chemical enrichment in galaxy formation simulations: the effects of AGB stars and the SNIa delay-time distribution"
19) Ascasibar Y., **Guidi G.**, Casado J., **Scannapieco C.**, Díaz, A. I., "On the nature of diffuse ionized gas in galaxies -- I The contribution of dust scattering to diffuse line emission"

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