What Regulates Galaxy Evolution?
Open Questions in our Understanding of Galaxy Formation and Evolution.

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Abstract

In April 2013, a workshop entitled “What Regulates Galaxy Evolution” was held at the Lorentz Center. The aim of the workshop was to bring together the observational and theoretical community working on galaxy evolution, and to discuss in depth of the current problems in the subject, as well as to review the most recent observational constraints. A total of 42 astrophysicists attended the workshop. A significant fraction of the time was devoted to identifying the most interesting “open questions” in the field, and to discuss how progress can be made. This review discusses the four questions (one for each day of the workshop) that, in our opinion, were the focus of the most intense debate. We present each question in its context, and close with a discussion of what future directions should be pursued in order to make progress on these problems.

Keywords: Galaxy Evolution; Physical Properties of Galaxies; Theoretical models of Galaxy Formation and Evolution; Groups and Clusters of Galaxies; Environmental Processes.

1. Introduction

In the last decade, a number of observational tests of the standard cosmological paradigm have ushered in a new era of “precision cosmology”. Our current standard model for structure formation is able to reproduce simultaneously a number of important observational constraints, ranging from the temperature fluctuations in the cosmic microwave background, the power spectrum of low redshift galaxies, to the acceleration of the cosmic expansion inferred from supernovae explosions. While the cosmological paradigm appears to be firmly established, a theory of galaxy formation continues to be elusive, and our understanding of the physical processes that determine the observed variety of
galaxies is at best rudimentary. Although much progress has been made, both on the theoretical and observational side, understanding how galaxies form and evolve remains one of the most outstanding questions of modern astrophysics. In addition to being an interesting question on its own right, galaxy formation also has important implications for cosmological studies. Indeed, at least some cosmological probes use galaxies as tracers (e.g. those based on measurements of galaxy clustering). A better understanding of the galaxy formation process is therefore crucial in order to improve our knowledge of the mass-energy content of the Universe.

These are exciting times to study galaxy formation: a wealth of new data are expected from ongoing and planned photometric and spectroscopic surveys of the local and more distant Universe, at different wavelengths. In parallel, the field of computational astrophysics has progressed rapidly thanks to increasing computational power and to the development of more sophisticated numerical algorithms.

In April 2013, the authors of this paper organized a workshop at the Lorentz Center\footnote{http://www.lorentzcenter.nl/lc/web/2013/528/info.php3?wsid=528} to bring together the observational and theoretical community and discuss in depth of the current problems in galaxy formation, as well as to review the most recent observational constraints. A total of 42 astronomers participated in the workshop, including theorists and observers working on a wide range of topics in galaxy formation, from dwarf galaxies, to massive galaxies, isolated galaxies and cluster galaxies, from very high to very low redshift. A significant portion of the workshop was devoted to identifying the most interesting open questions in galaxy evolution, and how progress can be made on these problems. Many interesting questions were debated. Below, we provide a summary of the four questions (one for each day of the workshop) that, in our opinion, were the focus of the most intense debate. We will discuss those four questions in their context, and close with an outlook on what areas in galaxy formation we believe are especially promising to help making progress on the identified problems. In particular, the four questions selected are: (i) Are we reaching a fundamental limit in our ability to measure properties such as stellar mass and star formation rates? (ii) What is the star formation and assembly history of galaxies with mass below $10^9 \, M_\odot$? (iii) Does the central-satellite division provide the right framework to study galaxy evolution? (iv) We understand which processes affect galaxies in different environments. Do the details matter?

Since they were selected simply based on the interest they generated, the four questions are quite different in nature: (i) and (iii) are technical, (iv) a somewhat philosophical one, and (ii) is more a standard science question.
2. Question 1 - Are we reaching a fundamental limit in our ability to measure properties such as stellar mass and star formation rates?

Two of the most fundamental parameters that describe a galaxy are its total mass in stars, and the rate at which stellar mass grows via star formation, the star formation rate (SFR). Measuring the evolution of stellar masses and SFRs both for individual galaxies and for the Universe as a whole occupies a substantial fraction of the observational resources devoted to the study of galaxy formation [see for example 1, 2, 3, 4, 5, 6, just to mention a few]. Given their important role for assessing the success of theoretical models [e.g. 7, 8, 9], increasing the precision with which stellar masses and SFRs are measured, over a wide range of redshifts and halo masses, continues to be a major goal of the observational community.

Over the last two decades, incredible progress has been made in obtaining high-quality data for this purpose. In particular, the Sloan Digital Sky Survey (SDSS) has provided high-quality photometry and spectroscopy which have allowed the measurement of stellar masses and SFRs for millions of galaxies [1, 2, 10]. While no survey complementary to the SDSS exists for the high-redshift Universe yet, the coming of wide-field NIR and MIR cameras, the WFC3 camera on HST, as well as significant improvements in photometric redshift techniques have opened up studies of the stellar masses of samples of up to hundreds of thousands of galaxies, up to as far as $z \sim 8$ [e.g., 11, 12, 6, 13]. Likewise, access to the FIR and Sub-mm from Spitzer, Herschel, and now ALMA have allowed us to study dusty star formation up to $z \sim 6$ [e.g., 14, 15, 16], and GALEX has made the study of SFRs from the rest-frame UV available in the local Universe [e.g., 17, 18, 3].

With this extraordinary increase in the sample sizes and data quality for distant galaxies, it has become increasingly clear that the dominant source of uncertainty is provided by systematics in the conversion of the photons we observe, into physical quantities [19]. Without an improvement in our understanding of these systematic uncertainties, it is unclear whether we will be able to take advantage of the nearly overwhelming samples of galaxies that will be available for study from surveys with upcoming telescopes such as LSST, Euclid, and WFIRST. Can we really develop techniques to reduce systematic uncertainties in deriving key quantities such as stellar mass and SFRs, or are we truly reaching a fundamental limit in our ability to do so?

Stellar masses are typically determined for galaxies by fitting their spectral energy distributions (SEDs) measured from either spectra, or broadband photometry to synthetic spectra derived from stellar population synthesis (SPS) codes. A thorough discussion of this process, and the inherent challenges with it can be found in the recent review by [19]. In brief, SPS models encode the current state-of-the-art knowledge of stellar evolution both on and off the main-sequence, and use isochrones combined with both real and synthetic spectra for stars to produce composite SEDs that the data can be fit to. Not all SPS models are alike, with each employing slightly different isochrones and/or treatment of the various phases of stellar evolution. Therefore, for identical raw observational
Figure 1: Left panel: The effect of varying assumptions in SED fitting on the derived stellar mass of individual galaxies at $z \sim 2$ compared to the default model (see text) from [20]. All galaxies have 13 band photometry and spectroscopic redshifts. EL and NEL denote galaxies with and without emission lines (effectively quiescent or star-forming galaxies). The largest systematic uncertainties come from the choice of SPS model. Right panel: The effect of varying assumptions in SED fitting on the stellar mass function of galaxies at $z \sim 1.7$ from [11]. Other than unusual IMFs, again the largest systematic uncertainty is from the choice of SPS model.

data, different stellar masses are derived using different SPS codes. The difference between SPS codes was recently highlighted by the various treatments of the thermally-pulsating asymptotic branch phase (TP-AGB) of stellar evolution (see Section 6.2). This is challenging to model, yet can have a large effect on derived synthetic SEDs. Because of the TP-AGB phase, and other differences between the codes, most recent observational studies have concluded that the largest systematic uncertainty in deriving stellar masses currently is the uncertainty in how to treat stellar evolution (i.e., the SPS codes themselves).

This is illustrated in the left panel of Figure 1 (from [20]) that shows the effect of varying assumptions parameters in the SED fitting to determine the systematic differences in the derived stellar mass of individual massive galaxies at $z \sim 2$. Parameters were varied relative to a default template set: Bruzual & Charlot (2003) SPS models, the Calzetti dust law, and solar metallicity. Figure 1 shows that the largest systematic uncertainty in the determination of stellar masses for individual galaxies is the choice of SPS model, and this difference is a factor of $\sim 1.6$. The right panel of Figure 1 (from [11]) shows the same approach but this time the effect on the full stellar mass function at $z \sim 1.7$. The most extreme effect on the stellar mass function is the use of bottom light initial mass functions (IMFs). Thereafter, the next largest effect is the choice of the SPS model. Note that a bottom light IMF is disfavoured by more recent data [e.g. 21, 22, and references therein].

Our understanding of stellar evolution is not the only limitation in deriving stellar masses. When using SPS models, additional free parameters determine the output synthetic spectra such as the metallicity of the stellar population, the IMF, the star formation history (SFH), the dust attenuation law, and the
dust geometry. In the case of fitting broad band photometry, which is not capable of constraining these properties, usually a single metallicity (typical solar), a single IMF (frequently Kroupa or Chabrier), a single dust law (frequently Calzetti or the Milky Way), and a single dust geometry (homogeneous screen) are assumed. The SFH is now one parameter that is commonly fit for, although most frequently it is assumed to have simple functional forms such as declining exponentials \( \text{SFR} \propto e^{-t/\tau} \), the so-called “\( \tau \)-models”. More recently it has been pointed out that \textit{increasing} \( \tau \)-models (i.e., \( \text{SFR} \propto e^{t/\tau} \)) may be more appropriate for star-forming galaxies \cite{23, 24}, and this has been adopted for some stellar mass determinations \cite{23}. It is clear that these myriad assumptions will underlie significant systematic uncertainties in the stellar mass determinations as it is well-known that galaxies have a range of metallicities, IMFs, SFHs, and dust geometries.

These issues are well known and have been for some time; however, it is not clear how large the systematic uncertainties truly are because there is no sample of galaxies for which we accurately know the stellar mass from an independent method (e.g., star counts). Therefore, other than globular clusters, there are few populations that can be used as benchmarks for methods of stellar mass determination. Studies have tried varying as many of the parameters in SED fitting as possible in order to make estimates of the current level of systematic uncertainties using both real \cite[e.g., 26, 27, 20, 11]{26, 27, 20, 11} and simulated galaxies \cite[e.g., 28, 29, 30]{28, 29, 30}. However, these are simply varying the so-called “known unknowns” and so realistically provide only a lower-limit on the size of systematic uncertainties given that there are certainly still “unknown unknowns” in the process (e.g. if unusual IMFs or strange dust laws exist, the effect of these on deriving stellar masses has not been tested).

At the Lorentz workshop as part of one of the discussion sections, M. Franx conducted a “poll” of the attendees asking what they felt the current level of systematic uncertainties were in deriving stellar masses. Put another way, they were asked what they felt a “safe” error bar (random + systematic) would be for the stellar mass of a typical galaxy. While there were a range of opinions, the majority felt that uncertainties were \( \sim 0.5 \) dex for galaxies at \( z \sim 0 \), using SDSS spectra, and \( \sim 1.0 \) dex for galaxies at \( z \sim 2 \), using standard broadband techniques. This is substantially larger than the systematic uncertainties derived from varying the “known unknowns” above, but astronomers are cautious and well aware of potential unknown unknowns.

A notable dissenter was C. Conroy, who suggested that uncertainties were smaller, probably more like \( 0.3 \) dex locally, and \( \sim 0.5 \) dex at higher redshift. He pointed out that evidence for this is the fact that there exist scaling relations between the stellar mass of galaxies and other properties such as their size, dynamical mass, and SFR. These parameters are determined in independent ways, and so if the systematic uncertainties in stellar masses truly were \( 1.0 \) dex, it is unlikely (although not impossible) that tight scaling relations would exist.

To return more directly to the question at hand, which is, are we reaching a fundamental limit in our ability to measure stellar masses? The answer to the question has to be twofold, depending on how we phrase exactly the question.
above. If the question is: are we reaching a limit in our ability to improve our understanding of galaxy formation using stellar masses determined from standard techniques? Then, the answer must be “yes”. Other than a few unprobed areas of parameter space for the stellar mass function, such as very high redshift \((z > 4)\), or very low masses \((\log(M_{\text{star}}/M_\odot) < 9.5 \text{ at } z > 1)\), the statistics and quality of photometric data compared to that already in hand are unlikely to improve substantially in the future. More photometry cannot solve our problems.

In the most direct form of the question, which is are we truly reaching a “fundamental limit” (due to physical reasons) in our ability to measure stellar masses, the answer has to be emphatically “no”. We should hope so too, because if the uncertainties truly are 0.5 – 1.0 dex as the attendees suggested, then as a community we would like to think we could improve on such a dismal situation! We will come back to this in Section 6 below.

3. Question 2 - What is the star formation and assembly history of galaxies with mass below \(10^9 M_\odot\)?

Galaxies with stellar mass below \(10^9 M_\odot\) exhibit a variety of physical properties, from dwarf spheroidals (dSph) that are gas poor and tend to be concentrated around more massive galaxies, to dwarf irregulars (dIrr) whose gas fraction can vary from zero to one, and tend to be more isolated than dSphs. The star formation histories of both types of galaxies are very stochastic, but they all contain a certain fraction of old stars [31]. A relatively tight mass-metallicity relation is in place which, together with information from gas masses, provide strong evidence for significant metal and mass losses. Outflows from low-mass galaxies are likely metal-enriched (i.e. the outflows contain more metals per unit mass than the average interstellar medium) [32, 33, 34]. Galaxies in this mass regime provide very strong constraints to galaxy formation models, both in terms of their total number density, and with respect to their physical properties.

In fact, from the theoretical point of view, recent studies have pointed out the existence of a fundamental problem with the evolution of low mass galaxies in hierarchical galaxy formation models, as well as in the state-of-the-art hydrodynamical simulations [see [3, and references therein]. This problem manifests itself in different forms: a dramatic difference is found between the observed number density of low mass galaxies and that predicted by galaxy formation models. When including a strong feedback from supernovae, models are able to reproduce the observed galaxy stellar mass function in the local Universe, but they consistently over-produce the number density of sub-M* galaxies at higher redshift [33, 11, 36]. These same studies also indicate that low-mass galaxies tend to be too old and passive compared with observational measurements. Models also fail to reproduce the observed anti-correlation between specific star formation rates and stellar mass [37, 38]. Finally, models typically under-predict the observed specific star formation rates at \(z < 2\), while over-predicting the same quantities at \(z > 3\) [39, 40].
Early attempts to address these problems focused on the simplified treatment of satellite galaxies as the main problem responsible for (at least some of) the disagreements mentioned. It is usually assumed that when a galaxy is accreted onto a larger structure (i.e. when it becomes a satellite galaxy) its reservoir of hot gas is stripped and therefore cannot replenish the galaxy with new fuel for star formation [this is the ‘strangulation’ process discussed in 41]. Until a few years back, the common assumption was that the stripping was happening instantaneously. This induced a very rapid decline of the star formation histories of satellite galaxies, creating an excess of red and passive galaxies with respect to the observations [e.g. 42, 43]. The exhaustion of star formation occurs over a very short time-scale also because these models usually include a very efficient stellar feedback, that removes any residual gas from the galaxy adding it either to the hot component associated with the corresponding central galaxy, or ejecting it outside the halo. In more recent studies, a more gradual stripping of the hot gas reservoir has been assumed [44, 45, 46, 36]. Albeit improved, the agreement with observational measurements is far from satisfactory.

[35] showed that the over-production of galaxies at intermediate and low mass in the models is not solely due to an incorrect treatment of the evolution of satellite galaxies. Rather, this is mainly driven by an over-efficient formation of central galaxies at high redshift, in haloes with circular velocities \( \sim 100 - 200 \text{ km s}^{-1} \). Therefore, mechanisms that only affect satellite galaxies (such as strangulation or ram-pressure stripping) or mechanisms that only affect low-mass haloes (such as photoionizations) do not provide viable solutions. Suppressing the formation of galaxies in small but compact haloes at high redshift is not trivial: the density of the haloes is too high and their potential wells are too deep to suppress star formation with heating from an external UV background. Galactic winds certainly play an important role, but they should not destroy galaxies of the same circular velocity at lower redshift. As pointed out by H. Mo at the workshop, it should also be noted that one cannot ‘hide’ the mass ejected from low-mass galaxies, because also the slope of the HI mass function is very shallow. Indeed, attempts to solve the overabundance of low-mass galaxies by reducing the star formation efficiency lead to a dramatic over-prediction of the cold gas content of galaxies [47].

At the time of writing, the consensus is that the discrepancies discussed above require a critical revision of the feedback (and recycling) schemes that are currently implemented in hierarchical galaxy formation models. In particular, what appears to be needed is a mechanism that is able to decouple the growth of low-mass galaxies (that occurs late) from that of their hosts (that, in contrast, occurs early). As pointed out by [9], the feedback schemes currently adopted in galaxy formation models are unable to achieve this because of their dependence on halo mass and cosmic time. The same authors stressed that a potentially important mechanism is that of gas recycling. In current models, this is parametrized in a way that its efficiency increases at higher redshift so that the net outflow rates are low at early cosmic times and increase at lower redshift. Recent hydrodynamical simulations suggest the evolution with cosmic time should be weaker [48]. In a recent study, [49] modified the recycling scheme...
making gas re-incorporation time scales dependent on halo mass and independent on redshift. This modification appears to move model predictions closer to the observational data for the galaxy stellar mass function at different redshift. The predicted passive fraction of low mass dwarfs remains, however, too high with respect to observational measurements. Alternative scenarios that invoke suppression of gas accretion in low mass haloes can alleviate significantly the problem \[50, 51\]. Unfortunately, however, these scenarios appears to be ‘ad hoc’, and the exact mechanism remains unclear.

It is interesting to note that the excess of low and intermediate mass galaxies is connected to a long-standing problem in the framework of hydrodynamical simulations: gas cooling is very efficient at high redshift and in small and compact haloes. Thus, baryons condense early in clumps that then fall into larger haloes and merge via dynamical friction. This produces a net and significant transfer of angular momentum from the baryons to the dark matter, resulting in spiral galaxies with large bulges and compact disks (this is the so called ‘angular momentum catastrophe’). The formation of a realistic rotationally supported disk galaxy in a fully cosmological simulation is still an open problem. Recent numerical work shows that it is in part due to limited resolution, and related numerical effects that cause artificial angular momentum loss and spurious bulge formation (for a detailed discussion, see \[52\]). Feedback driven by supernovae explosions represents a crucial ingredient to regulate the assembly of galaxies and avoid catastrophic losses of angular momentum. Despite much progress, however, the formation of thin and high angular momentum stellar disks remains a challenge \[53\] and references therein. As in semi-analytic studies, some form of ‘early feedback’ seems to be required in order to suppress excessive formation of stars at high redshift \[54\].

But how well do we know the star formation and assembly histories of these low-mass galaxies?

As discussed in the previous section, a galaxy star formation history can be constrained comparing its spectral energy distribution (SED) to a model spectra obtained convolving different simple stellar populations with a library of SFHs. This requires a number of assumptions on e.g. the IMF, stellar evolution, dust extinction, and chemical evolution. All these ingredients contribute to making the uncertainty on SED derived star formation histories very large (with the largest contribution coming from the assumed stellar evolutionary tracks). For local galaxies, the star formation history can be independently constrained from the colour-magnitude diagram (CMD). A figure shown at the workshop by J. Dalcanton received much attention, and was the subject of much discussion: Figure 2 compares estimates of star formation histories obtained from a SED fitting method, and the CMD diagram. In particular, the left panel shows the cumulative star formation fraction obtained using an approach (the ‘Main Sequence Integration’ method) that is found to be consistent with SED-fitting estimates after accounting for age uncertainties. The trends shown in the figure are extrapolations down to the mass range corresponding to the dIrr for which CMD-based estimates are available. These are shown as black symbols with error bars in the figure. The right panel shows SED-fitting estimates for galaxies
in different mass bins, compared to the CMD estimates by [31]. The figure shows that estimates based on the CMD are largely inconsistent with those obtained extrapolating results based on SED-fitting techniques. These results are confirmed by recent full spectrum fits of high signal-to-noise data in the central regions of nearby disk galaxies [56], as well as by a detailed analysis of the star formation and chemical enrichment histories based on very deep data for isolated Local Group galaxies [57]. Therefore, CMD estimates (that are likely more accurate than those based on SED-fitting techniques) suggest that dwarf galaxies form large fractions of their stars at $z > 1$, as massive galaxies do. The right panel of Figure 2 shows that this makes the trends with galaxy stellar mass non-monotonic, unless there are other systematics in the modelling not yet under control. In the extreme case that all SED-fitting estimates need to be corrected, this could even cancel any trend with galaxy stellar mass, and possibly remove some of the problems discussed above!

Given the strong constraining power of these observables, a better understanding of age uncertainties in this mass range is clearly needed.

4. Question 3 - Does the central-satellite division provide the right framework to study galaxy evolution?

The classification of galaxies into central and satellites provides an intuitive framework to study the effects of large scale environment on the evolution of galaxies. The framework assumes that all galaxies form at the center of dark matter halos. Galaxies that are located at the center of the most massive,
dominant halo are defined as “central” galaxies, and those that are in bound subhalos of more massive halos are defined as “satellite” galaxies. In principle, the framework allows us to determine whether it is the galaxy’s own halo, or the halo of another galaxy that plays the dominant role in its evolution.

In simulations, the distinction between a dominant halo and the other bound substructures is clear at all mass scales (the right panel of Figure 3 shows a snapshot at \( z = 0 \) of a Milky Way-like halo - it is well known that, in a hierarchical universe, galaxies are scaled versions of galaxy clusters \([58]\)). In addition, in all theoretical models of galaxy formation and evolution, central galaxies are bound to be “special”: these are the only galaxies onto which gas that is shock heated to the virial temperature of dark matter haloes cools radiatively. Therefore, it is undoubtedly useful to split observed galaxy samples into central and satellite galaxies. But how accurately can we correctly identify galaxies as either centrals or satellites?

In rich galaxy clusters (see e.g. Figure 3 left panel), the brightest galaxies are typically located at the centre of a distribution of lower luminosity satellite galaxies. The identification of the ‘brightest cluster galaxy’ (BCG) is relatively straightforward in most of the cases, but not always: Coma has two very bright members located in the proximity of the peak of the X-ray emission.

As highlighted by P. van Dokkum at the Lorentz meeting, while the framework is undoubtedly an intuitive way to approach the question of large scale environment, and there are clearly scales on which the framework seems to make sense (e.g. the scale of rich galaxy clusters), there may also be scales where it
Figure 4: From left to right, HST images of Hickson Compact Groups 44, 92, and 79. Unlike the examples in Figure 3 where it is unambiguous which galaxies are centrals and which are satellites, it is not clear which galaxies of these groups should be considered the centrals and which should be considered the satellites. This is because there is not a particular galaxy that is clearly the most massive and at the center of the overall distribution. The Hickson groups are more spatially compact than most groups so are useful for illustration; however, most galaxies do live in groups of similar total numbers of galaxies as the Hickson groups. Therefore, it is not clear that the central/satellite framework is appropriate for the study of most galaxies.

may be less functional.

For example, Figure 4 shows images of three Hickson compact groups [60]. While these are clearly bound groups, it is not at all clear which galaxy should be designated the “central”, and which should be the “satellites”. It is worth noting that groups as compact as the Hickson groups are rare, and that many groups have clear dominant central galaxies such as seen in galaxy clusters. However, the existence of the Hickson groups, as well other groups with similar mass ratios of galaxies, but less compact distribution, do show that the central/satellite framework will clearly have limitations in certain cases.

Along the same lines, Figure 5 shows a schematic layout of galaxies in the Local Group. While it seems intuitive that the Milky Way and M31 should both be considered centrals of a large population of their own satellites, it is likely given the distance and relatively low peculiar velocity between the two that they would be considered to belong to the same halo in many satellite/central group finders. If so, then which of the Milky Way or M31 should be considered the central in the Local Group, and which the satellite? M31 is a more massive galaxy, so likely it would be designated as the central; however, from Figure 5 it is quite clear that the relationship of M31 to its nearest satellites must be quite different than its relationship to the Milky Way. Likewise for the relationship of Milky Way and its satellites. We have to consider that the relationship of the Milky Way to M31 cannot be the considered on the same grounds as the relationship of galaxies such as the LMC and SMC to it. The situation would be worse if the Milky Way is assigned as a satellite of M31. Then, all of the Milky Way’s satellites would also be assigned to be satellites of M31. Herein lies a potentially significant problem, as it is clear that the evolution of the LMC and SMC must be more governed by the halo of the Milky Way, not M31, and
this is lost in the central/satellite framework.

Configurations such as the Local Group, with two massive galaxies in close proximity may not be the most common type of group in most group catalogs; however, the Local Group is a useful illustration of two potential issues with the central/satellite framework. The first is that every bound system can have only one central galaxy, with the rest of the galaxies being satellites of that central. The concern here is that we may be losing our ability to understanding the physics of galaxy evolution in systems similar to the Local Group if we are assigning the SMC and LMC satellites of M31, a galaxy that clearly does not dominate their future evolution.

One of the current challenges is that at present, the data are not deep enough to be able to resolve the finer structure in satellites, such as in the Local Group configuration. For example, in the well-used \cite{61} catalog, $\sim 85\%$ of galaxies that live in groups of at least 2 galaxies, have only 2 galaxies in the “group”. This is because the absolute magnitude limit is $M_r = -19.5$, which is only about 1 magnitude fainter than the characteristic magnitude at this redshift, $M_*^r = -20.7$. \cite{62}. At this depth, the Milky Way and M31 system would appear as a group of two galaxies using this group finder. Therefore it is possible that the central/satellite framework may be failing to capture the interesting effects of environment on the evolution of many galaxies. If so, then it clearly demands an answer to the question of if the central/satellite division provides the right framework to study galaxy evolution?

It is not an easy question to answer. One study that attempted to quantify what information is gained or lost using the framework is by \cite{63}. They compared the fractions of red satellite galaxies as a function of both local density estimators, and with the central/satellite group catalog of \cite{61}. They found that at high densities and high halo masses the results generally converged; however, at lower densities and lower halo masses they did not. They attributed this difference to the challenges of assigning galaxies as either centrals or satellites when halo masses are low.

Speculating, it would seem that the framework does make sense when the mass ratio between the central and the satellites is large, and we resolve much lower mass satellites. That works with the current data in systems such as massive galaxy clusters, where the central is very massive, but the satellites are still massive enough that many are detected down to the limit of the SDSS. Where it seems to be non-intuitive is when the mass ratio of the central and any of the satellites approach unity, and we cannot detect the fainter satellite population. The Local Group is a good example of this. Things are also problematic when there is no galaxy that is clearly central spatially in a group, such as the Hickson compact groups. The question that needs to be answered in a quantitative way is, what information are we really loosing by forcing systems like the Local Group into the central/satellite division? How can we know what information is lost? What is the most important information?

While some attempts have been made, clearly more work is needed to address these questions. Whatever the answer, it is likely that the framework will remain popular for many types of analysis for the foreseeable future. The advantage
Figure 5: Schematic layout of the Local Group (Credit: Richard Powell). Both the Milky Way and M31 are centrals of a system of smaller satellites. However, many of the typical central/satellite algorithms when applied to the system would likely classify M31 as the central, and the Milky Way (and its satellites) as satellites of M31. It is possible may cause erroneous conclusions to be drawn, as galaxies such as the LMC and SMC cannot be influenced by their “central” in the same way that M32 is.
of the satellite/central framework is that it is a tool that allows simulations and data to be put in a similar classification scheme, which thereby allows us to make testable predictions of environmental effects on galaxy evolution using simulations. This utility likely outweighs many of the possible issues, and therefore it is likely to remain for lack of better alternatives. Furthermore, deeper surveys such as GAMA are coming online, and they will permit a more robust definition of central/satellite than can be done with the current SDSS catalogs.

As pointed out by S. McGee at the meeting, the use of light cones built from simulations or semi-analytic models allows a direct comparison between model predictions and observational data to be carried out. In fact, an increasing number of studies are taking advantage of “mock catalogues” to interpret data in the framework of theoretical models [64, 65, 66]. In principle, these comparisons can circumvent the need to utilize the central/satellite framework. In practice, however, this division is still used when interpreting the observational data in the framework of the models.

5. Question 4 - We understand which processes affect galaxies in different environments. Do the details matter?

It has been known for a long time that the local and large scale environment play an important role in determining many galaxy properties. The milestone paper in the subject is probably that of [67]. Theoretical studies on this topic started early on and indicated the existence of a plethora of physical processes that can influence the evolution of galaxies in different environments [68, and references therein]. The efficiency and influence of each of these processes has been studied in detail using dedicated numerical experiments. In the real Universe, however, physical processes act in a complex network of actions, back-reactions and self-regulations that makes their relative importance difficult to quantify. So, while we can say (citing M. Balogh at the Lorentz meeting) that we know which processes affect the evolution of satellite galaxies (ram-pressure, harassment, strangulation, tidal stripping, and assembly bias are all at work), we certainly do not understand how these processes combine to establish the detailed trends we observe. Therefore, the obvious answer to this question is: yes, the details do matter because, in order to understand how galaxies evolve in different environments, we need to quantify the relative role of different physical processes.

The completion of large spectroscopic surveys both in the local Universe and at higher redshift has allowed a detailed quantification of the physical properties of satellite galaxies in a multi-dimensional space (stellar mass, halo mass, redshift, radial distance from the cluster centre). As mentioned in the previous section, many key results concerning the evolution of galaxies as a function of the environment have come from the application of the central/satellite framework to SDSS data. These studies have highlighted that satellite galaxies are on average redder and less frequently star-forming than their centrals, regardless of the central halo mass and the satellite stellar mass [e.g., 69, 70, 71].
The central/satellite framework also revealed the puzzling issue of the “galaxy conformity” [69], which is that satellites tend to somehow know about the star formation properties of their centrals. Star-forming centrals have a significantly higher fraction of late-type satellites than haloes with an early-type central galaxy. As of yet, the reason for the galaxy conformity is not well understood. It has been speculated that it may arise from an assembly bias, with quiescent centrals having accreted their satellites earlier, hence they have been affected by environmental processes longer [72]. It has also been suggested that quiescent centrals inhabit more massive halos than star-forming centrals of similar stellar mass [73]. It is also possible that some of the conformity may occur because of the misclassification of some satellites as centrals [74].

One recent result on the evolution of satellite galaxies that was heavily discussed at the Lorentz meeting is shown in Figure 6 from [75]. The figure shows how the star formation rates of star forming galaxies from the SDSS depend on galaxy stellar mass, in low (left panel) and high (right panel) density regions. Assuming that high density regions mainly contain satellite galaxies, the figure shows that active satellite galaxies form stars at a rate that is very similar to that of central galaxies of the same mass, suggesting that the transition from active to passive must be very rapid. Considering group catalogues based on SDSS Data Release 7, [76] have studied the specific star formation rate distribution of satellite galaxies and its dependence on various physical properties. All galaxies (both centrals and satellites) exhibit a similar bimodal distribution of specific star formation rates. The distribution, and in particular its minimum (corresponding to the so-called ‘green valley’), appear not to depend strongly on stellar mass, halo mass, and distance from the halo centre. This puts important
constraints on the efficiency and time-scales of the processes affecting the evolution of satellite galaxies. In particular, (1) satellite galaxies must have evolved as central galaxies (forming stars at very similar rate) for several Gyrs; (2) once ‘quenching’ of star formation begins, this must occur on a rapid timescale in order to avoid an excess of galaxies at intermediate values of sSFR; (3) there is no minimum halo mass for satellite-specific processes. Several other studies have argued for relatively long time-scale for the suppression of the star formation rates in satellite galaxies [for example 77, 78, 79, and references therein]. This turns out to be a very tough constraint for theoretical models.

As discussed above, the basic working hypothesis of modern theories of galaxy formation is that, when a galaxy is accreted onto a larger halo, the cold gas supply can no longer be replenished by cooling, because of the stripping of the hot gas reservoir [41]. This leads to the exhaustion of star formation in the galaxy, on a time-scale that depends on how fast the stripping of the hot gas associated with the infalling galaxy is, how efficient the stellar feedback is, and what is the fate of the reheated and ejected gas. For all of these processes, our understanding is incomplete (this is especially true for what concerns the stellar feedback), and current implementations all induce a very rapid decline of the star formation histories of satellite galaxies, contributing to create the excess of red and passive galaxies discussed above (see Question 2). A more gradual stripping, that follows the stripping of the dark matter substructures or simple models inspired by numerical simulations, does not provide yet a satisfactory agreement with observational data. It remains unclear how satellite galaxies can sustain significant levels of star formation for several Gyrs, and if this can be achieved by simply relaxing the assumption of instantaneous stripping of the hot gas reservoir associated with galaxies when they are accreted. In addition, it should be considered that at least part of the problems with satellite evolution might be related to the fact that current models could predict the wrong properties for central galaxies at the time of accretion.

In general, a detailed quantification of the influence of different environmental physical processes is complicated by the fact that one cannot easily separate “nature” from “nurture”. According to the current paradigm for structure formation, dark matter collapses into haloes in a bottom-up fashion: small systems form first and subsequently merge to form progressively larger systems. As structure grows, galaxies join more and more massive systems, therefore experiencing a variety of environments during their lifetime. In this context, the nature-nurture debate appears to be ill posed, as these two elements of galaxy evolution are inevitably and heavily intertwined [72].

6. Ways forward

In the previous sections we have highlighted four open questions related to the broad subject of galaxy evolution. What can be done in order to make progress on these questions? Below we discuss what we believe are the main steps to be taken in order to make progress on the questions discussed above.
6.1. Future Improvements in Data for Stellar Mass Determination

One of the fundamental parameters needed to measure the stellar mass of a galaxy is the redshift. For distant galaxies, where spectroscopic redshifts are currently few, usually the broadband SED is used simultaneously for redshift determination and for fitting of the stellar mass. Clearly if there are large systematic errors in determining the photometric redshifts (either from the method, or template set), then the stellar masses will also be incorrect. We know this happens at some level for all samples, as even the very best sets of photometric redshifts determined at high redshift [e.g., 80, 81, 13, 82] typically have catastrophic outlier fractions (when compared against even very limited sets of spectroscopic redshifts) of 1% – 5%. Therefore it is clear that obtaining spectroscopic redshifts for large samples of distant galaxies is a very straightforward and tractable way of improving our current measurements of stellar masses.

Large optical spectroscopic redshift surveys of the distant Universe have been done (e.g., DEEP2, zCOSMOS, GOODS, VVDS, PRIMUS), and even new ones are coming online (e.g., VIPERS, VUDS). These have been extremely useful for verifying photometric redshifts (and thereby stellar masses). They have, however, all selected targets based on optical selection criteria. As far as the authors are aware, a spectroscopic redshift survey which aims to be complete in stellar mass (this would require a selection in the rest-frame optical) up to a given redshift does not yet exist, and could be very useful for a determination of the stellar mass function that is robust to photometric redshift uncertainties.

The 8m class telescopes are now commissioning, or have already commissioned their NIR multi-object spectrographs (e.g., FMOS, MOSFIRE, KMOS, MMIRS, FLAMINGOS2). Spectroscopic redshift surveys from these will no doubt help us push to higher redshift, and allow us to more easily access spectroscopic redshifts for the most intrinsically red galaxies.

Spectra will also be invaluable for better determining stellar masses via fitting of the spectra. As shown by [e.g., 83] with SDSS data, more information about the star formation history can be determined from spectra than broadband photometry alone, and much of it can be done in a way that is independent of dust, a significant complicating factor in the determination of mass-to-light ratios. Rest-frame optical spectra with high signal-to-noise (S/N) can also be used to determine stellar metallicities [e.g., 84, 85, 86], thus removing an additional assumption that must be made in the case of broadband photometry. In the case of very high S/N spectroscopy, dynamical masses can be determined from the widths of the absorption lines. While these suffer from the fact that they must be corrected to a fixed physical size, and measure the total enclosed mass (dark, stellar, and gas), they do provide extremely valuable upper limits of what the total mass can be.

Another fundamental limitation in our modelling of stellar masses is the correct dust attenuation law to use. Only a few have been measured directly, such as the LMC, SMC, Milky Way, and the Calzetti law for starburst galaxies. These are notably different from each other, and given they are determined locally, it is unclear whether they apply in the distant Universe where star forming regions
are likely quite different, and metallicity is lower. Efforts have been made to empirically determine new dust laws from galaxies [e.g., 57], quasars [e.g., 88, 89] and from the power-law SEDs of gamma ray bursts [e.g., 90, 91]. Additional empirical determinations of the dust attenuation law for distant galaxies of various classes and stellar masses would be extremely valuable for determining better masses, and is also potentially tractable in the future.

Lastly, one approach that has only begun to be exploited is to model the stellar masses of galaxies in a spatially resolved way. This could be extremely valuable for removing both the universal “dust screen” assumption, where the dust obscures the entire stellar population (young and old) in the same manner, and for removing the need for the entire galaxy to be fit to a single parametric SFH. Efforts to do this both locally [e.g., 92, 93] and in the distant Universe [e.g., 94, 95, 96] have shown that this is only modestly different than standard assumptions for most galaxies, but does substantially change the stellar masses for small subsets of the population. Overall, this would be a positive step forward, and the upcoming CALIFA [97] and MANGA surveys will provide high-quality data for this type of modelling for hundreds to thousands of galaxies.

6.2. Future Improvements in Models for Stellar Mass Determination

It is well documented that most of the well-used SPS models [e.g., 98, 99, 100] produce different stellar masses with the same observational data. This is clearly problematic and underlies the uncertainties in the process of SPS. Here we discuss some straightforward improvements that could be made. Much of this discussion has been influenced by the review paper by [19], and we refer the reader to that paper for a more in-depth discussion of the topic.

Currently, one of the most heavily debated issues in the SPS community is the treatment of the TP-AGB phase of stellar evolution. It was pointed out by [99] that at that time, models may not treat this short-lived but bright phase of stellar evolution correctly, and [99] provided a new set of models with an updated treatment of TP-AGB evolution. Later studies pointed out that this treatment might not be ideal as it over-predicts the amount of rest-frame NIR flux for post-starburst galaxies [101, 102]. [100, 103] include the strength of the TP-AGB as a variable as part of their SPS models, and [104] continue to update their models to reflect the best-possible treatment. It is now clear that convergence on the treatment of this phase of stellar evolution is a mandatory ingredient for reducing the systematic uncertainties in deriving stellar masses.

Several other obvious aspects of stellar evolution are also missing from current codes, and their implementation would also be useful. These include rotation of the stars (that has the effect of lengthening the main-sequence lifetime of stars by \( \sim 25\% \) [105]), and binary star evolution. As suggested by [19], one of the most obvious elements missing from the most-used SPS models (PEGASE excepted) is the inclusion of emission lines in the synthetic spectra. Emission lines contribute to the broad band flux of galaxies, and because of the short

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2See http://www.sdss3.org/future/manga.php
timescales of star formation they probe (compared to the UV), they give valuable information on the SFH. Contamination of broad band fluxes from emission lines is not a significant issue in the local Universe, where the typical equivalent widths (EWs) of galaxies are of order of a few to tens. However, recent work has shown that strong emission lines, with EWs up to $\sim 1000\AA$ can be seen for very young galaxies at $z > 4$ [e.g., 106, 107, 108, 109], and this can lead to a significant overestimation of their stellar masses. It has also been shown by [110, 111] that dwarf galaxies at $z \sim 2$ have extreme EWs, up to $\sim 1000\AA$.

Finally, dust remains a major issue. One clear way forward in this regard is to produce SPS codes that simultaneously take account of the emission from stars and its subsequent absorption and re-emission at longer wavelengths by dust. If FIR data is available, then dust absorption and emission can be accounted for in a self-consistent way. In particular, this could be very helpful in improving on our understanding of dust geometry and attenuation law on a galaxy-by-galaxy basis. Some such codes have been developed such as MAGPHYS [112] and CIGALE [113] and their refinement is clearly an avenue forward in terms of improving our ability to model stellar masses.

The last consideration that has not been discussed significantly in this article (neither at the meeting) is the IMF, that can vary [e.g. 114, 115, 116]. Given the challenges of determining the IMF for any galaxies other than locally, the IMF may prove to be a fundamental limitation in our ability to measure stellar masses.

6.3. Future improvements in Theoretical Models of Galaxy Evolution

The last decade has witnessed enormous progress in our ability to model the formation and the evolution of galaxies in a cosmological context. The advent of more and more powerful computers, and the development of more sophisticated algorithms has allowed us to carry out simulations with increasing resolution, and including sophisticated modelling of various physical processes. Dark matter substructures are nowadays routinely identified and their history robustly tracked. These “merger trees” can be used to construct halo occupation and abundance matching models, as well as a basis for semi-analytic models of galaxy formation. Parallel effort with hydrodynamical simulations has allowed us to understand, at least qualitatively, the role of different physical processes and their importance at different scales.

Despite progress, however, some persistent problems have been identified. In particular, all models over-predict the number densities of low to intermediate stellar mass galaxies and under-predict the fraction of active satellite galaxies. As discussed above, these two failures might well be different manifestations of the same problem. The current wisdom is that the solution of the problem lies in a physical process that is able to break the parallelism between mass growth and halo growth. It remains to be seen if this can be achieved by modifying the stellar feedback scheme. Likely, it is the modelling of the “self-regulation” between the star formation and the stellar feedback that should be improved, in particular for low-mass galaxies. In fact, dwarf galaxies in the Local Group appear to have had “bursty” and stochastic star formation histories [117] - a
constraint that is very difficult to reproduce in the framework of available simulations and galaxy formation models. In this framework, gas recycling and the differential ejection of metals and gas are important processes to understand. Both detailed numerical simulations and dedicated observations are required to this end. Parallel effort in developing self-consistent phenomenological models of galaxy evolution [e.g. 118, 119], as well as in testing non-standard dark matter models and/or cosmologies [120, 121, 122] will be important to understand what is required as an addition to our current theory of galaxy formation and evolution.

From the numerical point of view, published work on the role of environment on galaxy evolution is still largely focused on massive galaxy clusters (simulations of ram-pressure stripping in poor groups have been carried out by [123] and by [124]; the effects of both tides and ram-pressure have been analysed for the specific case of the Local Group by [125]). Yet, as discussed above, groups likely represent the most common environment that galaxies experience. The situation is slowly improving [see e.g. 126], but additional work on detailed controlled numerical experiments (including the evolution of the gaseous components) is needed in order to quantify the importance of different physical processes, at the typical velocity dispersions of galaxy groups. This will also help us understanding to what degree the problem with satellite galaxies is related to a poor treatment of environmental processes.

In order to keep up with the imminent observational revolution that will happen in the next future, models need to be further extended: MANGA is scheduled to begin in the Fall of 2014, and it will ultimately allow resolved spectral measurements for about 10,000 galaxies in the nearby Universe. SKA (and its precursors) will measure the abundance of HI in the Universe and its evolution, while ALMA will soon begin to probe the molecular gas contents in high-redshift galaxies. In order to make the best use possible of the overwhelming amount of data that will come in the next future, our theoretical tools need to be updated including an explicit treatment of the transition from atomic to molecular gas, and (possibly) an explicit modelling of spatially resolved physical properties. Work has started in this direction [127, 128, 129].

Finally, as pointed out in the final discussion session at the Lorentz meeting by C. Conroy, metals (including detailed abundance ratios) still represent a underutilized, yet very powerful constraint to models of galaxy formation and evolution [see e.g. 130, 131]. Therefore, the new generations of galaxy formation models and simulations should all include an explicit and detailed treatment of the chemical evolution of different species.

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3How much time galaxies spend in a “group” environment will depend on the galaxy stellar mass and on the actual definition of galaxy group [see e.g. 74].
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