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Simulating Galaxy Structure within ΛCDM

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Understanding the origin of galaxy morphologies is one of the foremost questions yet to be answered in the studies of galaxy formation. The leading paradigm in galaxy formation within ΛCDM provides a viable model to explain the main components of galaxies like bulges, disks, stellar and gaseous halos. However, it requires a delicate fine-tuning of mass accretion, star formation and feedback to recreate realistic galaxies in simulations. Does the Universe require such balancing acts or are we excluding relevant physics that resolves this fine-tuning problem? I will review the current status of numerical simulations in galaxy formation with special emphasis on the recent progress made in our understanding of the origin of galaxy morphologies. I will conclude by identifying the remaining challenges and most promising avenues to make progress in the field.

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1. Introduction

Galaxies are fascinating objects due to their complexity and beauty. They can display a large variety of shapes and components, from round dispersion dominated spheroids to thin and cold rotationally supported disks; bars, shells and tidal bridges are quite common, creating a spectacular zoo of observed morphologies in the sky. Understanding how these galaxies formed and evolved to their present day shapes is the essence of what could be called the "Galaxy-Formation Problem".

The most challenging aspect of studying galaxies is the wide range of scales involved; understanding galaxy formation requires a model that explains the coupling between cosmological scales –order of several Mpc– with those typical of the interstellar medium (ISM) –several AU or single pc. Galaxies are shaped by their environment, mass accretion, cooling/heating of gas, turbulence injection, star formation and, ultimately, how all these processes impact the conditions of the ISM from where further populations of stars will be born. Unfortunately, these processes cannot be studied individually, as they are strongly interconnected and modify each other. The coupling between these processes at all scales is what makes galaxy formation a very complex, yet extremely exciting, field of research.

Within the ΛCDM scenario, galaxies form at the bottom of the potential wells of halos that grow hierarchically in mass until they acquire the properties that we observe today [1]. The morphology of galaxies is believed to be a transient phenomena responding to the mass assembly process of the halo and baryons within them [2, 3]. Disk-dominated galaxies are believed to be formed from smooth accretion of gas that settles into a rotationally supported disk component [4 – 7] whereas spheroidal galaxies form mainly by mergers between systems of comparable mass [8 – 12]. Secular processes triggered by the presence of a bar have also been shown to help building dispersion-dominated systems [13 – 16].

Because of the non-linearity of the processes involved in galaxy formation, hydrodynamical numerical simulations represent the main tool to study galaxy morphology. For example, an early study presented in Steinmetz & Navarro (2002) [17] provided validity to the theories about evolution of galaxy morphology by showing a single galaxy transiting several morphological types throughout its evolution within the CDM cosmological scenario.

Despite several early successes, simulating realistic galaxies (i.e. that simultaneously follow the observed scaling relations, color distributions, star formation histories, etc.) has proven to be extremely challenging. The factors responsible for the difficulties range from the requirement of very high resolution simulations and natural limitations imposed by the hydrodynamical techniques, to the lack of understanding of how stellar and black-hole feedback operate on the scale of galaxies. I review in what follows some of the most important strides to understand galaxy morphology in the field of cosmological numerical simulations.

2. Simulating Galaxy Morphology: Past & Present

There has been enormous progress in the field of simulating galaxy structure. Arguable, the first reports of realistic simulated galaxies within the cosmological context appeared at the break of the century, for both, disks [18 – 20] as well as spheroidal galaxies [21]. However, all simulated disk galaxies had a significant bulge component, comparable to observed S0 or Sa type galaxies,

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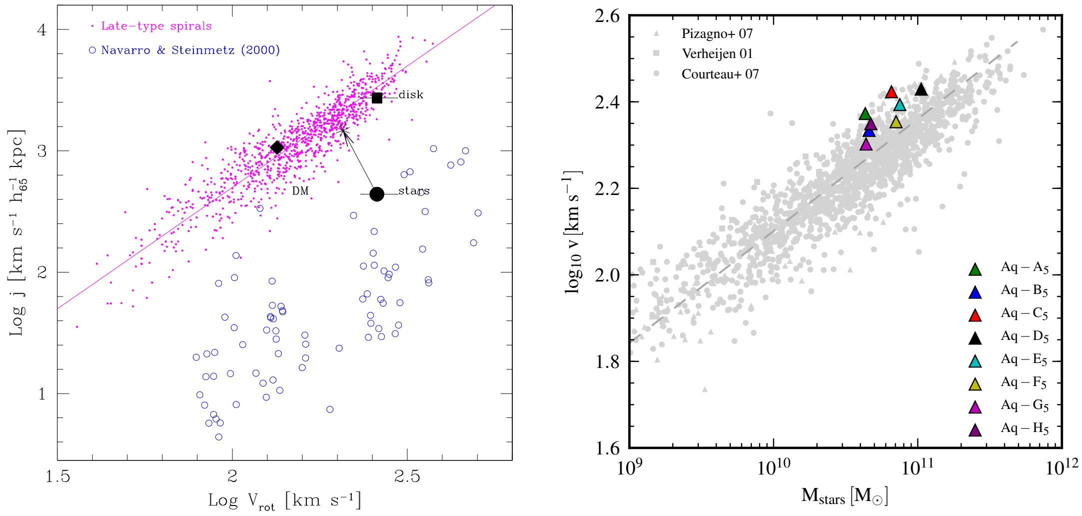

Figure 1: Angular momentum content of observed galaxies compared with past (left) and state-of-the-art (right) simulated galaxies. *Left:* earlier simulations (circles) show a significant lack of specific angular momentum j compared to observed galaxies (magenta dots). The agreement improves if only the disk component is considered (black square). *Right:* example of a recent set of cosmological simulations of disk galaxies that show similar content of angular momentum than observed ones (gray dots) at a given stellar mass. Figures taken from Abadi et al. 2003a and Marinacci et al. 2014.

and no effort was able to reproduce the properties of late type disks such as our own Galaxy nor fully bulgeless objects like, for instance, NGC6503.

On these early attempts, simulated galaxies were typically more concentrated and had less angular momentum than observed ones, a problem referred to as the "angular momentum problem" (see [22]). The left panel in Figure 1 (originally presented in Abadi et al. 2003a) shows the specific angular momentum at a given circular velocity (a common proxy for mass) for observed disk galaxies (magenta dots) and simulated objects (blue/black circles). The simulations are downshifted from the observed relation, indicating that simulated galaxies had less angular momentum than observed ones with comparable mass. Encouragingly, considering only the disk component of a simulated galaxy (identified by decomposing the object into a disk and a spheroid component) the agreement was considerably better (black square).

In the vanilla-model for disk formation presented by [7], disks are linked to the properties of the dark matter halo, and their sizes are determined by the spin of the halo and the ratio m_d/j_d, where m_d represents the fraction of baryons they accumulate compared to the total available mass (i.e. the Universal baryon fraction) and j_d is the fraction of the angular momentum that those baryons are able to bring to the center compared to the total within the virialized halo. From this point of view, disk formation is an extremely tough problem: to match the abundance of galaxies requires that only a *small fraction* of the available baryons is turned into stars –$\sim$ 20% for galaxies like the Milky Way [23, 24]– but reproducing the scaling relations is only possible when *all* of the available angular momentum is captured by those stars [7, 25]. Notice that, because the angular momentum scales linearly with distance, the baryons located originally in the outskirts of the halos are those carrying most of the angular momentum content. Forming disks, therefore, requires a mechanism able to form the galaxies out of a small fraction of the *external* baryons while simultaneously preventing the cooling and star formation from the cold and dense gas located close to the centers of halos.

In the last decade, several arguments were presented to show that this re-distribution of mass and spin needed to build disks can be achieved through stellar feedback. This is the process by which the energy and momentum from stellar winds and supernova explosions change the conditions of the surrounding gas, preventing the formation of new stars and presumably driving significant amounts of gas outside of the central regions of galaxies. Major progress was made in the area of simulated disk galaxies by including efficient treatments for this feedback process and, starting from the formation of a bulgeless dwarf galaxy [26], the success spread to the formation of disk galaxies comparable to that of the Milky Way [27 – 30]. Several state-of-the-art cosmological zoom-in simulations are able to recreate the properties of observed disk-dominated galaxies, including their angular momentum content, as shown by the right panel in Fig. 1 (originally included in Marinacci et al. 2014).

However, a close inspection of the recent work in formation of disk galaxies suggests a poor agreement about the reason for the improved match to observations. Authors attribute the success to widely different (and sometimes, contradicting) factors: *i*) low star formation efficiency combined with mass return from stars (Agertz et al.), *ii*) high threshold for star formation and the need of very high numerical resolution (Guedes et al.), *iii*) inclusion of radiation pressure (Aumer et al.) or *iv*) an improved hydrodynamic scheme and a relatively simple ISM model, with results independent of resolution (Marinacci et al). The poor consensus is partially a reflection of the great impact that feedback has in galaxy structure [31 – 33] as well as a reminder of the large uncertainties currently present in the coupling between the stellar feedback and the dynamics of the surrounding gas.

Improving our understanding of galaxy morphology requires close comparisons between models and observations. Notice, however, that observations tightly constrain the properties of galaxy *populations* and not *individual* objects. Although, from the numerical point of view the advantages of focusing on single objects – or zoom-in technique where all computational power is invested in simulating to great detail a given halo/galaxy– are obvious, from the observational side we are unable to say with certainty the kind of galaxy that should populate a given single halo. On the contrary, observations place strong constraints on the properties of galaxy populations, with exquisite statistical measurements such as the correlation function, mass function, gas-to-mass ratios, color bimodality, star formation sequence, etc.

A proper comparison with observations therefore calls for a very large set of simulated galaxies, which can be achieved by using cosmological simulations of representative volumes of the universe. Such an approach sacrifices numerical resolution to gain statistical power in the number of objects simulated, and thus can be seen as a complementary methodology to that of zoom-ins described above. In what follows, I discuss what can be learned by taking such an approach.

3. Understanding the Origin of Galaxy Morphology with Large Volume Simulations

The idea of simulating large volumes of the Universe is not new, with several examples of

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numerical simulations with cosmological box sizes ~ 100 and above (see e.g. [34 – 37]). However, due to numerical limitations in the number of particles and simulation techniques, most of these efforts were devoted to dark-matter only simulations; or, if baryons were included, the numerical resolution was insufficient to resolve the galaxies and their structure. Fortunately, in the last couple of years there has been a significant progress in this area, with a few large-scale baryonic simulations currently available in the literature [38 – 41].

In Sales et al. 2012 [42], we used the suite of cosmological hydrodynamical simulations "Galaxies-Intergalactic Medium Interaction Calculation", GIMIC [38], as they are to-date the only simulations with resolution high enough to study galaxy structure at redshift $z = 0$. These simulations follow the evolution of five nearly spherical volumes of the universe with radius $\sim 20-25h^{-1}$Mpc each and selected from the larger box (N-body only runs) *Millennium simulations* [34]. These regions sample different environments that deviate $(-2,-1,\ 0,+1,+2)\sigma$ from the mean cosmic overdensity, where σ is the *rms* mass fluctuation on scales $\sim 20h^{-1}$Mpc. All the runs assume a ΛCDM cosmology consistent with WMAP-1 results ($\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $\Omega_b = 0.045$, $n_s = 1$, $H = 100h$ km s^{-1} Mpc^{-1}, $h = 0.73$). At the highest resolution available, the softening scale is always better than $\varepsilon = 0.5h^{-1}$kpc (physical), and the mass per particle is $m_p =\sim 10^6 h^{-1}\mathrm{M}_\odot$ and $m_p = 6.6h^{-1}\mathrm{M}_\odot$ for the baryons and dark matter, respectively.

We select all galaxies with total mass comparable to that of the Milky Way, $M_{\rm vir} = [0.5\text{-}1.5] \times 10^{12}h^{-1}\mathrm{M}_\odot$[1]; resulting in a sample of 100 galaxies with varied morphologies. Objects were identified using the SUBFIND algorithm [43, 44] and we considered only central (i.e. no satellite) objects. Our sample is a statistically significant – and so far, the largest– set of simulated galaxies sampling without biases different environments, assembly histories, halo structure, etc.; representing the ideal data to study the origin of galaxy morphology within ΛCDM.

In what follows, we quantify the (stellar) morphology of our galaxies by using the kinematics of the stars. Following [45] we use the fraction of the kinetic energy in ordered rotation, $\kappa_{\rm rot}$, defined as:

$$\kappa_{\rm rot} = K_{\rm rot}/K; \quad \text{with} \quad \mathrm{K_{rot}} = \sum(1/2)\mathrm{m}(\mathrm{j_z/R})^2 \tag{3.1}$$

where m is the mass of a star particle; j_z is the z-component of the specific angular momentum, assuming that the z-axis coincides with the angular momentum vector of the galaxy; and R is the (cylindrical) distance to the z-axis. For idealized conditions, $\kappa_{\rm rot}$ varies between zero and unity for rotation-free to perfect disks, respectively. In practice, simulated objects span the range $\sim [0.2, 0.8]$, with $\kappa_{\rm rot}$ correlating well with morphologies assigned via the widely used "dynamical decomposition" method proposed in [19].

Fig. 2 shows a snapshot view of some of our galaxies ordered, from left to right, with an increasing value of rotational support. This samples approximately the full morphology diversity, from spheroid- ($\kappa_{\rm rot} < 0.3$) to disk-dominated objects ($\kappa_{\rm rot} > 0.7$); a highly encouraging first result for a

[1]Virial quantities throughout this paper are defined at the radius enclosing 200 times the critical density of the Universe.

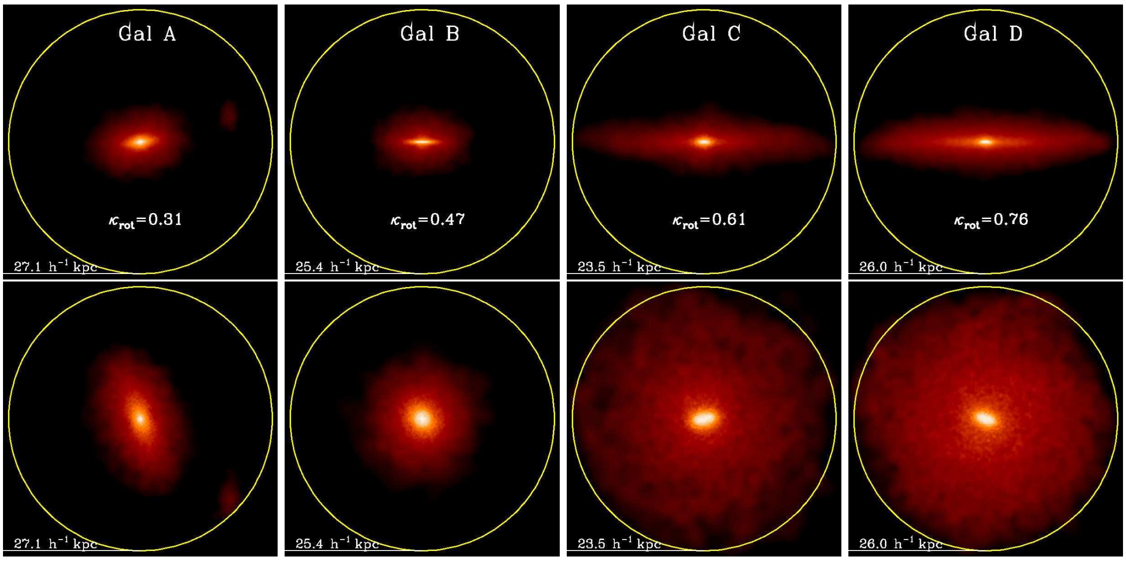

Figure 2: Stellar structure of four galaxies in our sample ordered with increasing degree of rotational support (left to right). The first and second rows show edge-on and face-on projections of the stellar distribution. The yellow circle marks the radius, $r_{\rm gal} = 0.15\,r_{200}$, used to define the galaxy. (Figure taken from Sales et al. 2012.)

sample of galaxies selected only in terms of virial mass. We can then move to the next question: What makes these galaxies look so different?

As discussed in Sec. 2, disks are expected to form in halos with high angular momentum and a quiet accretion history. The lack of recent major mergers means that halos tend to form earlier, such that stellar disks should preferentially inhabit halos with early formation times.

The left panels in Fig. 3 show that morphology is roughly independent of these halo properties, despite the intuition generated by the models. We find no correlation between $\kappa_{\rm rot}$ and halo formation time $t_{50\%}$ –defined as the time when the progenitor reaches half its final mass– (top panel), the relative mass fraction in the largest major merger (middle) or the halo spin (bottom panel).

Similarly, Fig. 3 also shows that the fraction of baryons locked into galaxies (related to m_d in the Mo et al. formalism) does not play a major role in determining morphology (bottom right panel), nor does the fraction of stars accreted (middle). Our results indicate that several of the spheroid-dominated galaxies experienced no mergers during their evolution, forming all their stars *in-situ*. The origin of these “merger-free” spheroids is puzzling and will be addressed later in Fig. 6. An interesting clue comes from the contribution of the hot versus the cold modes of gas accretion. The upper right panel of Fig. 3 shows a significant correlation between morphology and $f_{\rm hot}$, defined as the fraction of stars born from gas accreted in the hot phase. We use the maximum temperature ever reached by gas particles as a discriminant of the accretion mode; with a fixed threshold $T = 10^{5.5}$ °K to separate between them. We find that disks have a significantly larger fraction of hot accretion than the spheroids; and is therefore the accretion from the hot corona –not the “cold-flows”– the ones favoring disk formation.

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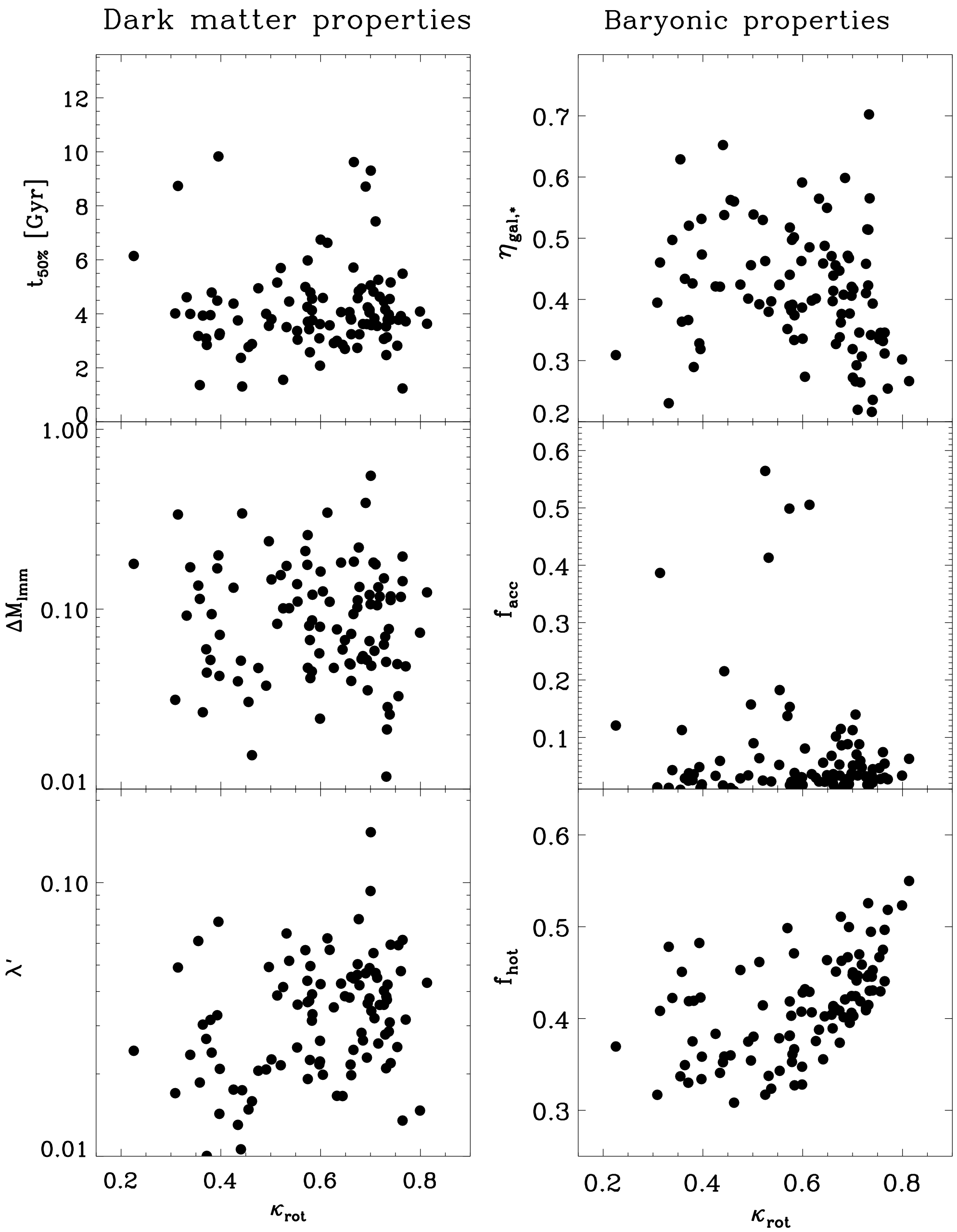

Figure 3: Correlations between morphology, as measured by $\kappa_{\rm rot}$, and a number of parameters characterizing the assembly history of each galaxy and its halo. On the left, from top to bottom, $t_{50\%}$ is the half-mass halo formation time, in Gyrs; $\Delta M_{\rm lmm}$ is the maximum fraction of the final halo mass assembled in the single largest merger event after $z = 3$; and λ' is the dimensionless rotation parameter. On the right, the galaxy formation "efficiency", $\eta_{\rm gal,*} = M_{\rm gal}/(f_{\rm bar}M_{200})$; $f_{\rm acc}$ is the fraction of *accreted* stars (i.e., stars formed in galaxy progenitors other than the main one) and $f_{\rm hot}$ is the fraction of stars born out of gas that went through the "hot phase" (i.e., $T_{\rm max} > 10^{5.5}$ °K). Statistically significant correlations are found only for $f_{\rm hot}$. (Figure taken from Sales et al. 2012.)

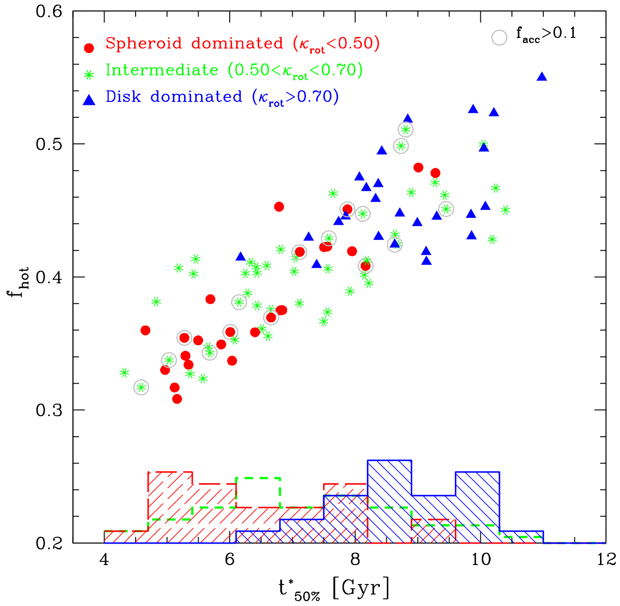

Figure 4: The fraction of stars born from "hot accretion" versus the median formation time of stars in the galaxy, $t^*_{50\%,}$. Symbols are colored according to morphology as indicated in the label. Bottom histograms show the distribution of median formation time for each morphology bin. The good correlation between $f_{\rm hot}$ and $t^*_{50\%}$ suggests that gas accreted from the "hot phase" takes longer to accrete and to be transformed into stars that gas accreted through cold flows. Late gas accretion favors the assembly of stellar disks. (Figure taken from Sales et al. 2012.)

Fig. 4 helps to better understand this trend by showing that the average formation time of the stars in galaxies, $t^*_{50\%}$, increases the larger the $f_{\rm hot}$. This means that heating gas to a hot corona before cooling delays its accretion and favors the late assembly of a galaxy: the larger $f_{\rm hot}$ the later stars form. Recent star formation promotes the formation and survivability of disks. However, the picture is still incomplete; Fig. 4 shows that several spheroid-dominated systems form despite late $t^*_{50\%}$, a high $f_{\rm hot}$ and without a significant merger activity. We turn our attention to them.

We gain further intuition about the origin of galaxy morphology by looking into the angular momentum content of these galaxies. Within the current paradigm of structure formation, the angular momentum of the baryons (as well as that of the dark matter) is imprinted early on in the proto-galactic material at the "time of turnaround", $t_{\rm ta}$, when decoupling from the general expansion takes place. The system later evolves by baryons dissipating their energy and flowing to the center of dark matter potentials conserving their angular momentum initially imprinted at turnaround.

It is therefore natural to look at the distribution of angular momentum of the baryons at the time when is acquired, i.e. at $t_{\rm ta}$. For each galaxy, we identify their turnaround time and study the spatial distribution of the angular momentum of the baryons that end up within $r_{\rm gal}$ at $z = 0$. Fig. 5 shows the projection of the angular momentum within spheres containing 20%, 50% and 95% of these particles in a system oriented such that the total angular momentum is pointing in the vertical

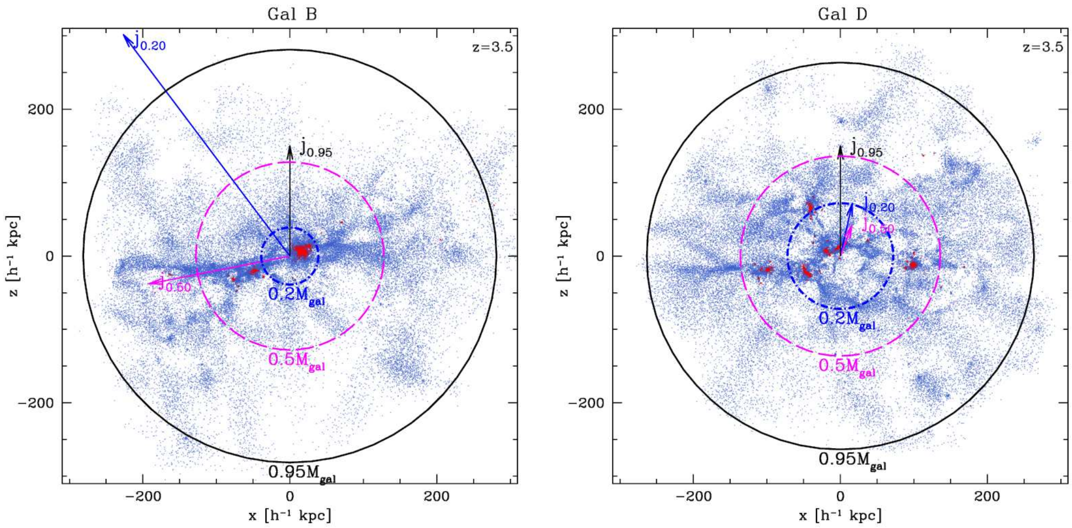

Figure 5: Projected particle distribution near turnaround time, $z = 3.5$, of baryons that collapse to form, at $z = 0$, a spheroid- (left) and a disk- (right) dominated galaxy. Red and blue correspond to already formed stars and gas, respectively. Box sizes are in physical units. Concentric circles enclose 20%, 50%, and 95% of the mass, and arrows indicate the angular momentum of all material enclosed within each radius. Arrow lengths are normalized to the total value in each panel, which defines the z axis of the projection. Note the misalignment of the angular momentum of various parts of the system for the spheroid-dominated (left). Angular momentum is more coherently acquired in the case of the disk-dominated galaxy. (Figure taken from Sales et al. 2012.)

direction (black arrow). We do this exercise for a spheroid- (left) and a disk-dominated (right) galaxy. This figure shows that the situation is quite different according to morphology: the galaxy that will end up as an spheroid at $z = 0$ has its angular momentum pointing to different directions for different mass shells whereas for the disk-dominated galaxy, the arrows align nicely indicating coherence in the distribution of the baryonic spin.

Fig. 6 shows clearly that this behavior is characteristic of the whole sample and is not a specific feature of the two galaxies displayed in Fig. 5. Fig. 6 shows, for galaxies with a given morphology (different $\kappa_{\rm rot}$ bin) the median cosine of the angle θ as a function of enclosed mass, where θ is defined as the angle between the angular momentum at a given enclosed mass $m/m_{\rm tot}$ and the total angular momentum of the system. By definition, all curves must pass through $x = y = 1$. The main panel of Fig. 6 suggests that the spins of the baryons that end up forming disk galaxies are more coherently aligned than those objects forming spheroid-dominated galaxies. This trend also applies to individual objects: the inset panel shows the spin alignment averaged over all mass shells of the same object as a function of $\kappa_{\rm rot}$. The progenitors of disk dominated objects show mostly $< cos(\theta) >$ larger than 0.5, whereas for spheroids the self-alignment is significantly worse.

This analysis adds another clue into the formation of spheroids versus disks: for the former case, different regions of the same system have, at turnaround, large misalignments in their acquired spin; often times with inner regions completely counter-rotating with respect to the outer material. When mass accretion proceeds after the turnaround, the spin of consecutive misaligned shells adds up and mixes, resulting in an overall cancellation of the rotation, leaving behind a

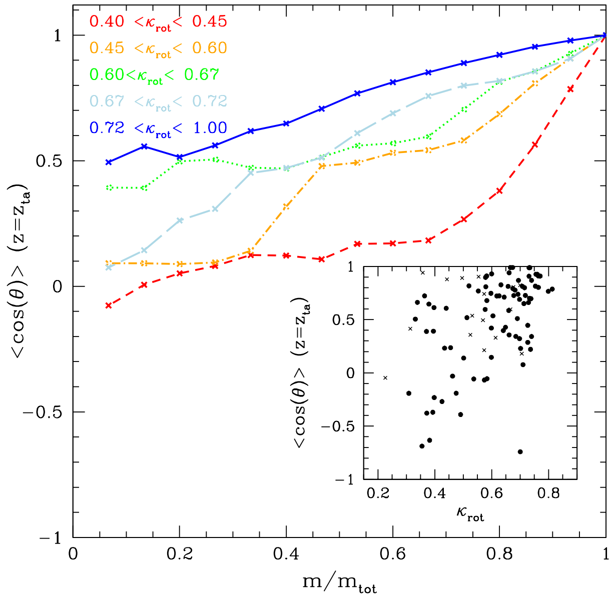

Figure 6: Angle between the angular momentum enclosed within a given mass fraction, $m/m_{\rm tot}$, and the total spin of the system measured at the time of maximum expansion (turnaround). Lines indicate the average value considering all halos within a given $\kappa_{\rm rot}$ bin, as labeled. Notice that disk-dominated galaxies show a distribution of angular momentum more coherently aligned. The inset panel shows, for individual objects, the mean angle (measured at timearound) averaged over all shells as a function of $\kappa_{\rm rot}$. Notice that several spheroid-dominated systems have negative $\langle\cos(\theta)\rangle$, indicating that a large fraction of their mass is actually counter-rotating with respect to the total spin. (Figure taken from Sales et al. 2012.)

spheroid-dominated object. This explains the formation of spheroids in absence of mergers highlighted in the discussion of Fig. 3.

Summarizing, the study of simulated galaxies selected from large volume simulations is a promising avenue to help unravel the origin of galaxy morphologies, mostly because it allows a direct comparison to the observable properties of galaxy populations. Our results indicate, for objects like the Milky Way, a very poor correlation between morphology and the properties of the dark matter halo. On the other hand, we find that disk formation is promoted in halos with a large fraction of gas accretion from the hot-mode as well as a coherent distribution of angular momentum at the time of the turn around. Spheroid-dominated galaxies can also form in absence of mergers by direct filamentary accretion of cold gas, especially if accompanied by substantial spin misalignments.

4. Future Challenges

Although the scenario described above is compelling, there are still several open questions and points where the model for the origin of galaxy morphologies shall be tested. We highlight some of them below:

- Redshift Evolution of Galaxy Structure:
  There seems to be convincing evidence supporting a strong galaxy morphology evolution with redshift. Observational data suggest that the fraction of galaxies that are disks increases sharply with redshift, at least for the massive end, where completeness can be achieved [46, 47]. Simulations provide the ideal tool to contrast these observations with galaxy formation models, pinning down the reason for the large abundance of disks at high redshift and their consequent transformation into dispersion dominated systems at the present time.

- Diffuse Stellar Components:
  Thick disks, stellar halos, shells and streams can encode valuable information about the assembly history of galaxies. What in the past was restricted only to studies of our own Galaxy, targeting the faint and diffuse stellar components of external objects is becoming achievable, with several studies and surveys dedicated to such goal (PAndAS [48], GHOSTS [49], and deep optical imaging of individual galaxies [50, 51], among others). Because the assembly of these faint components is believed to be intimately linked to the formation of the central galaxies, joint analysis of morphology and distribution and properties of the diffuse stellar structure represent a fundamental test for any cosmological model of galaxy formation.

- Metals and HI in the CGM:
  Similar to the point above, the distribution of gas and metals around galaxies is one of the most novel constraints for galaxy formation models available today. Strongly related to the cooling/heating processes as well as to the phase-space (density and temperature) and accretion of the gas, studies of the circumgalactic medium (CGM) have the potential to revolutionize our understanding of galaxy formation. Several observational efforts are already ongoing [52 – 56], and some early theoretical studies in numerical simulations are showing promising results [57 – 60]. Encouragingly, CGM studies in tandem with analysis of the overall efficiency of galaxy formation to turn gas into stars can place strong constraints on the relatively poorly understood feedback processes, offering an exciting avenue to make progress in the field.

- Missing Physics of the ISM:
  In current cosmological simulations, the theoretical modeling of the baryonic physics at the sub-parsec scale is still rather crude, although the situation is starting to improve substantially since the last couple of years. There are several potential sources of feedback identified so far; such as supernova explosions, radiation pressure and ionization from massive stars [61 – 66], magnetic fields [67 – 69], cosmic ray pressure [70 – 73], blazar heating [74], black hole feedback, etc; but the effectiveness with which they couple to the dynamics of the gas is still a mater of active debate. Numerical simulations aimed at targeting the gap between the star-formation scales and those of whole galaxies are needed to achieve a comprehensive understanding of how feedback works and shapes the morphology of the galaxies we observe in our skies.

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