A comparison: galactic formation & evolution through semi-analytic and numerical hydrodynamic frameworks in the context of extragalactic astronomy.

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Abstract

In our never-ending cosmic quest to understand the origin of the universe, galactic evolution is profound, as galaxies make up a considerable portion of our universe. Additionally, understanding galactic evolution and the phenomena involved will provide us with the necessary foundation to make predictions about the fate of galaxies and our Milky Way. Although many advances have been made in the field of cosmology, our knowledge of galactic formation and evolution still possesses key gaps. To understand galactic evolution, cosmologists design models of the universe and simulate galactic evolution under the effects of dark matter, dark energy, and baryonic matter. In this article, we mainly discussed two types of frameworks used in designing galactic simulation models: the semi-analytic and numerical hydrodynamic frameworks; we also talked briefly about the N-body and Lamda Cold Dark Matter frameworks. Numerical hydrodynamic simulations provide a tool for investigating the complex and dynamic interactions between numerous physical processes. Meanwhile, semi-analytic models use analytical approximation techniques to handle a range of variables. When choosing a simulation model, the computational complexity of the hydrodynamics framework and the uncertainty of the semi-analytic models prove to be a conundrum. So, we have discussed both frameworks, comparing their advantages and limitations. We concluded that currently both frameworks complete each other's shortcomings, and for a superior understanding of galactic formation and evolution, a more comprehensive framework that combines both approaches is needed.

I. Introduction

There is still a lack of knowledge regarding the mechanisms that led to the formation and evolution of the earliest galaxies, following the Big Bang. Understanding the mechanisms underlying their formation and evolution is crucial to understanding how galaxies will develop in the future. According to previous research [1][2][3][4][5], models have been created to aid in the attempt to comprehend and study the processes of galaxy formation through cosmological simulations. The numerical hydrodynamic simulations and semi-analytic models are derived from these frameworks. Both have widespread use, and each has advantages and disadvantages. Given the enormous number of variables involved, numerical hydrodynamic simulations offer a tool to explore the intricate and dynamic interplay between many physical processes. While semi-analytic models use approximation analytical methods to cope with a variety of variables. The physical processes of galaxy creation and evolution, several models used to represent these processes, numerical hydrodynamics simulations, semi-analytical models, and examples for both models are included in this review article.

II. The Physical Processes of Formation and Evolution of Galaxies

The models used to comprehend and implement the formation and evolution of galaxies mostly include the physical processes covered in this section.

i. Gravity

The first galaxies are thought to begin as small clouds of dust and stars, and as other clouds come near them, gravity ties them together. The cosmological parameters and the characteristics of dark matter affect the shape and magnitude of the primordial power spectrum of density fluctuations. The number of dark matter halos of a particular mass that have collapsed at any given moment can be calculated from this spectrum, which is processed by gravity to determine how quickly these halos expand throughout cosmic time through merging and accretion [6]. It also controls the spatial organization of dark matter halo clusters. According to the conventional theory, each galaxy is born within one of these “shadowy” haloes. Gravitation and dynamical friction progressively drive the orbits to decay until the galaxies combine in halos that each contain their central galaxy. Mergers can have significant impacts on galaxies, including causing bursts of star formation and accretion onto supermassive black holes at the center, as well as changing the structure and appearance of the galaxy [6].

ii. Hydrodynamics and Thermal Evolution

Intense shocks are created during the collapse of an excessively dense province made of gas and dark matter, which raises the entropy of the gas. The gas's ability to reflect thermal energy away and cool down successfully will then decide how the gas evolves in the future. Two-body radiative processes are the main cooling mechanisms important for galaxy formation during most of cosmic history. At a temperature of more than 10than 10^7 Kelvin, gas becomes entirely collisionally ionized and cools mostly through bremsstrahlung (free-free emission) [6]. Collisionally ionized atoms can return to their ground state and electrons can join with ions in the temperature range of 10^4 K to 10^7 K. The collisional excitation/deexcitation of heavy metals (metal line cooling) and molecular cooling are the two processes that cause cooling below 10^4 K. If radiative cooling is ineffective after collapse and shock-heating, a pressure-supported quasi-hydrostatic gaseous halo may develop. Then, in a process that is commonly referred to as a cooling flow, this gas will progressively cool. A different name for this is "hot mode" accretion [6]. The gas will collapse until it is supported by its angular momentum once it cools and loses pressure support. Without ever producing a hot quasi-hydrostatic halo, the gas may accrete straight onto the proto galaxy if the cooling time of the gas is short relative to the dynamical period [7]. According to cosmological hydrodynamic simulations, gas tends to flow along relatively cold, dense filaments during this type of "cold mode" accretion [6].

iii. Star Formation

Once the gas has condensed into the halo's central regions, it may start to self-gravitate or be driven more by its gravity than by dark matter. If cooling processes prevail overheating, then a runaway process can occur in which Giant Molecular Cloud (GMC) complexes form, and eventually some dense cloud cores within these complexes collapse and reach the extreme densities required to ignite nuclear fusion. This is because gas cools more quickly the higher its density, so if cooling processes dominate, then a run-away process can occur [6]. Many aspects of this process are still unclear, though. According to observations [8] [9], 1% of molecular gas turns into stars every period of free fall, which is a practically universal efficiency for star formation [10]. The gas is often transformed into star particles using a probabilistic sampling approach based on a calculated star formation rate [10]. Many cosmological simulations are unable to distinguish between individual cores, much less the scales on which GMC emerges. Therefore, to describe star formation, all current cosmological simulations use empirical sub-grid recipes. Since cold, dense gas eventually gives rise to stars, simulations convert a portion of this gas into collisionless star particles, which reflect coeval, single-metallicity stellar populations that are characterized by an underlying initial stellar mass function [10]. A few simulations additionally take star clusters into account as the primary unit of star formation by enabling the expansion of star particles through accretion from the surrounding medium. This is an alternative to the probabilistic sampling strategy and helps to better mimic the clustered nature of star formation. Modern galaxy formation models track stellar evolution and the mass return of these stars to the gas component after stellar particles have been generated.

iv. Star Formation Feedback

Less than 10% of the current global baryon budget, according to observations, is in the form of stars. We would anticipate that most of the gas would have cooled and generated stars by the present day in Cold Dark Matter (CDM) models without any sort of "feedback" (or suppression of cooling and star formation). This "overcooling problem" was acknowledged even by the forerunners of the earliest models of galaxy formation within a CDM framework, who hypothesized that the energy from supernova explosions may heat gas and possibly blow it out of galaxies, impeding star formation [6]. It is now understood that a variety of processes, like photo-heating, photoionization, and winds, that are connected to massive stars and supernovae may have a role in star formation inefficiency and large-scale winds that lower galaxies' baryon fractions. Again, the majority of cosmological simulations are unable to resolve these physical processes in detail. Therefore, almost all the current models use sub-grid recipes to try to simulate their impact on galaxy scales [6].

v. Black Hole Formation and Growth

As the remains of Population III (metal-free) stars, through the direct collapse of extremely low angular momentum gas or stellar dynamical processes, the first black holes may have formed in the early universe [11]. These black holes can expand by either absorbing gas with very little angular momentum or by generating an accretion disk that drains the gas's angular momentum through viscosity. These processes are modeled via sub-grid recipes since they are, once more, poorly understood and nearly hard to model explicitly in cosmological simulations [6]. The most likely scenario is that the black holes develop at high redshifts as the remains of the first generation of Population III stars have passed their prime. It is still unclear how exactly these first stars formed, but hydrodynamical simulations indicate that they had masses of about a few hundred Solar masses and left behind intermediate-mass black hole remnants [12].

Cosmological black holes have an additional characteristic, angular momentum, in addition to their mass. Essentially, merging with another black hole and material accretion are the two processes that alter a black hole's spin [12].

vi. Active Galactic Nuclei (AGN) Feedback

Strong observational evidence suggests that a supermassive black hole is present in most spheroid-dominated galaxies, which make up most of all big galaxies. A straightforward calculation shows that the energy released in creating these black holes must be greater than the host galaxy's binding energy, indicating that it could have a significant impact on galaxy formation. However, how effectively this energy can couple to the gas in and around galaxies is still unknown [6]. High-velocity winds, which may be expelling the cold interstellar medium from galaxies, and hot bubbles that appear to be produced by enormous radio jets, which may be heating the hot halo gas, are two observational indicators of feedback linked with AGN. In modern cosmological simulations, AGN feedback is also handled with sub-grid recipes [6]. Active galactic nuclei relate to observational phenomena related to accreting supermassive black holes, including electromagnetic radiation, relativistic jets, and less-collimated non-relativistic outflows [10]. Quasar and radio modes, which are used differentially in simulations, are the two most prevalent divisions of this feedback. Some galaxy formation models, however, claim that cosmological simulations lack the resolution necessary to accurately distinguish between the two feedback modes and to keep the number of feedback channels to the minimum necessary to match the observational data. These models do not make this distinction [10]. The radiatively efficient mode of black hole growth is linked to quasar mode feedback, which is frequently implemented through energy or momentum injection under the assumption that the bolometric luminosity corresponds to the accretion rate and that a fixed portion of this luminosity is deposited into the nearby gas [10]. Radio-mode feedback occurs by highly collimated jets of relativistic particles, which are frequently coupled with X-ray bubbles containing enough energy to compensate for cooling losses. This feedback mechanism is therefore thought to be crucial for controlling star formation in large galaxies. As soon as the accretion rate drops below a threshold level, radio-mode feedback is frequently incorporated as a second subresolution feedback channel [10]. The subresolution models for supermassive black holes are still unclear considering that they must cross a gap between real accretion and feedback and the scales that can be defined with simulations [10].

vii. Stellar Populations and Chemical Evolution

Many modelers convolve their predicted star formation histories with straightforward stellar population models that provide the Ultraviolet – Near Infrared Spectral Energy Distribution for stellar populations of a single age and metallicity [13], folding in an assumed stellar Initial Mass Function to directly compare models and observations [6]. In many models nowadays, gas recycling from star mass loss is considered in simulations in a significant way. It is also clear that stars pollute the intergalactic medium out to great distances from galaxies as they develop and undergo supernovae, producing and dispersing heavy metals throughout the gas that surrounds galaxies [6]. Due to several factors, including (1) the highly enhanced cooling rates at intermediate temperatures in metal-enriched gas, (2) the metallicity-sensitive luminosity and color of stellar populations of a given age, and (3) the production of dust by heavy elements, which dims and reddens galaxies in the UV and optical and re-radiates the absorbed energy in the mid-to-far IR, chemical evolution is a crucial component of galaxy formation. The treatment of chemical evolution is currently present in many cosmological models of galaxy formation [6].

viii. Radiative Transfer

Star and AGN radiation can have a significant effect on galaxy formation. Gas can be directly heated by radiation, and it can also change cooling rates by altering the ionization state of the gas (particularly for gas that is metal-enriched) [6].

Additionally, the measured total luminosity, color, and observationally determined morphological and structural properties of galaxies can all be significantly impacted by the transmission of radiation of various wavelengths through and by scattering dust, particularly in the rest-frame UV and optical, which are frequently the only wavelengths available at high redshift. Due to the additional processing cost, most current cosmological simulations that are performed to low redshift do not self-consistently include radiative transfer [6]. To estimate the observed pan-chromatic characteristics of galaxies and their line emission, radiative transfer across a dusty interstellar medium can be calculated in post-processing with a high enough resolution [6].

The effects of radiation in the context of galaxy formation simulations have only been examined in a small number of simulations [10]. This lack of detailed radiation hydrodynamics investigations is mostly due to the difficulty of numerical radiative transfer due to the high dimensionality brought on by the frequency and directional dependence of photon propagation [10].

III. Current Simulation Frameworks

The many advances happening in cosmology over the past decades have enhanced our understanding of galactic formation and evolution. This resulted in a heap of frameworks and models that can simulate galactic evolution to a relatively great extent based on sub-grid recipes. Due to computational limitations, these sub-grids are used and parametrized, and these parameters are tuned based on current observations of galactic properties. Although some of these techniques have been able to reproduce current observations and give us many insights into galactic evolution, their accuracy remains questionable. Three popular, and currently used, frameworks are the Semi-analytic framework, the Numerical Hydrodynamics framework, and the Lambda, Einstein's cosmological constant, Cold Dark Matter (ΛCDM) framework.

It is worth clarifying that the ΛCDM framework is in itself built on the hydrodynamics framework and was considered a hydrodynamic model until it was publicly accepted and used as a framework to build variants of the ΛCDM model. Thus, we will be limiting our discussion to a brief introduction to the ΛCDM framework.

i. The Semi-analytic Framework

The semi-analytic framework, sometimes called the "phenomenological galaxy formation framework," approaches each of the physical processes mentioned above using approximate, analytic techniques. Due to this approximation, semi-analytic models possess a modular framework, which means it is straightforward to revise the implementation of various phenomena to reproduce a more detailed simulation according to current observations [14]. The degree of approximation varies considerably with each model and its desired results based on the complexity of the simulated physical processes. This approximation makes the semi-analytic framework computationally inexpensive. Therefore, it can simulate galactic evolution at a large order of magnitude. However, semi-analytic models involve a large degree of approximation, and the extent to which this approximation affects the simulation's results has not yet been well assessed [12].

ii. The N-body/Numerical Hydrodynamics Framework

The N-body framework (or gravity solvers) is the basic structure for various simulation models (e.g., hydrodynamic models and even semi-analytic models). In N-body models, the simulated portion is divided into a chosen number of particles, or "bodies," hence the name N-body. Then, the forces acting on each particle by the surrounding ones are computed, and the simulation evolves by recomputing the forces in a set time step. Additionally, the boundaries of the simulation volume are comoving and evolve periodically, and the expansion rate of the simulation boundaries is computed using the Friedmann equations (derived from Einstein equations within the context of General Relativity), but the equations are solved using the Newtonian versions since General Relativity corrections are mostly negligible [6].

Hydrodynamic models, which use the N-body technique to simulate dark matter, utilize direct simulation (i.e., the equations of the physical processes are solved for every particle). This increases the level of accuracy of hydrodynamic models over semi-analytic ones, but it also makes them computationally expensive. However, if Moore's law is true, hydrodynamic models will continue to expand as our technology does.

Although hydrodynamic models are not as "flexible" as the semi-analytic ones, they can be modified to suit the required results (i.e., some processes may be approximated or omitted). Many variants of hydrodynamic models exist. For example, GADGET-2 or "GAlaxies with Dark matter and Gas intEracT" relied on smoothed particle hydrodynamics (SPH) to compute the interactions between dark matter and gas clouds [15]. On the other hand, FLASH uses reactive hydrodynamic equations and thermonuclear reaction networks to study the nuclear flashes on the surfaces of white dwarfs and neutron stars [16].

iii. The Lambda Cold Dark Matter (ΛCDM) Framework

Our modern theory of cosmology suggests that the universe mainly consists of dark matter and dark energy, which together account for more than 95% of the energy density of the universe. In the most popular ΛCDM model, dark matter is considered cold (slow-moving), collisionless, and makes up ~25% of the cosmic mass-energy density, and dark energy is represented by a “cosmological constant” Λ, comprising ~70% of the cosmic mass-energy density. The remaining ~4% is baryons (which in the context of this model includes leptons), i.e., ordinary atoms that make up the universe we can see [6]. Although Baryonic Matter only makes up ~4% of the universe, most of the profound problems are with simulating this type of matter as it prompts many complex phenomena.

Numerical N-body techniques have been used to extensively study the growth of structures in dissipationless (dark matter only) ΛCDM simulations. As [6] mentioned, “The gravitationally bound structures that form in these simulations are commonly referred to as dark matter halos, and the abundance, internal structure, shape, clustering, and angular momentum of these halos over cosmic time has been thoroughly quantified.” The ΛCDM paradigm has been thoroughly judged and proved to be successful at explaining and reproducing observations on scales larger than a few kpcs (e.g. [17]). Thus, it provides a framework for shaping models of galactic evolution.

IV. Semi-analytic Models

The approach known as "semi-analytic modeling" or "phenomenological galaxy formation modeling" uses an analytical strategy to tackle the many physical processes related to galaxy formation [12]. The degree of approximation, just like in N-body/hydrodynamic simulations, varies significantly with the complexity of the physics being treated, from precisely calibrated estimates of dark matter merger rates to empirically motivated scaling functions with large parameter uncertainty (for example, in the case of star formation and feedback - just like in N-body/hydrodynamic simulations) [12].

These semi-analytic models monitor things like the amount of gas that accretes onto halos, the amount of hot gas that cools and becomes stars, the removal of cold gas from the galaxy via feedback processes, and the heating of the halo gas. The models are based on the dark matter halo merger history discovered by N-body simulations. Like the output of comprehensive hydrodynamic simulations, the outcome of such a calculation is an anticipated galaxy population that can be contrasted with observable data [10].

When compared to N-body/hydrodynamic simulations, the semi-analytic approach has the main benefit of being computationally less expensive. This enables the quick investigation of parameter space and model space (i.e. the introduction of new physics and evaluation of their impacts) as well as the creation of samples of galaxies that are orders of magnitude larger than those made possible with N-body approaches [12]. Another advantage of semi-analytic models is their efficiency, which allows for a large range of calculations to be performed using multiple model variations [10].

The primary limitation is that they require a higher level of approximation. It has not yet been thoroughly determined how much this matters. Studies comparing semi-analytic and N-body/hydrodynamic calculations have generally found agreement (at least on mass scales well above the resolution limit of the simulation), but they have been restricted to simulations of single galaxies or simplified physics (e.g., hydrodynamics and cooling only) [12]. Semi-analytic models also have the drawback of being less self-consistent than hydrodynamic simulations. Furthermore, because the gas component is not resolved, researching precise gas features, such as circumgalactic gas, is not directly achievable with these models [10].

An example of a semi-analytic model is [18], which simulates the co-evolution of galaxies, black holes, and active galactic nuclei. A fresh semi-analytic model that, within the context of the ΛCDM cosmological framework, self-consistently traces the growth of supermassive black holes (SMBH) and their host galaxies. According to the model, the energy released by accreting black holes controls how big they grow, powers galactic-scale winds that can expel cold gas from galaxies and generates strong jets that heat the hot gas atmospheres around groups and clusters [18]. The new models correctly predict that star formation should be considerably, but not entirely, quenched in huge galaxies at the current time. They also accurately reproduce the exponential cut-off in the stellar mass function and the stellar and cold gas mass densities at redshift z~0. The relationship between SMBH mass and bulge mass that has been found can be naturally reproduced by the model of self-regulated SMBH growth. The models give predictions for the cosmic histories of star formation, stellar mass assembly, cold gas, and metals as they investigate the overall creation history of galaxies and black holes. Models based on the 'concordance' CDM cosmology were shown to overestimate star formation and stellar mass at high redshift [18]. Less small-scale power models anticipate less star formation at high redshift and great agreement with the history of stellar mass assembly as observed, but they may have trouble explaining the cold gas in quasar absorption systems at high redshift [18].

V. Numerical Hydrodynamic Models

Hydrodynamic models are employed to solve the equations of the physics concerned with galactic evolution (e.g., hydrodynamic equations) via direct simulation. In this method, the equations of gravity, hydrodynamics, thermodynamics, and radiative cooling/transfer are solved for a chosen number of points, depending on the available computational power, in a grid (particle-based) or along the flow path of a fluid (mesh-based), or a hybrid of both, depending on the specifics of each model. These three methods are classified, respectively, as Lagrangian methods, Eulerian methods, and arbitrary hybrids of both.

In Lagrangian methods such as the popular Smoothed Particles Hydrodynamics (SPH) model, the particles are treated as programming objects, where each particle carries the information about the fluid and moves freely within it. However, as [6] mentioned “A key drawback is that this method (SPH) does not explicitly conserve energy and entropy in adiabatic flows in the case of variable smoothing lengths.” Eulerian methods divide the fluid into discrete cells and compute the advection of the fluid’s properties through the cell boundaries in the grid. Eulerian methods are superior in handling shocks and surface instabilities. On the other hand, Lagrangian methods are more adaptive and provide more dynamic range per computational expense, and variants such as Entropy-conserving (EC-)SPH have mitigated the flaws in the “Classic” SPH (e.g., [19] and [20]). Then, the Pressure-entropy (PE-)SPH mitigated the flaws in the EC-SPH variant [21]. Although this makes the Lagrangian method superior, the implementation of Adaptive Mesh Refinement (AMR) balanced the scales; AMR provides the adaptivity of the Lagrangian method by subdividing, in real-time, each cell into smaller ones (i.e., increasing the simulation’s resolution). It is worth mentioning the hybrid models that employ both methods, as the gap between the Lagrangian and Eulerian methods is closing. For example, [22], a hydrodynamic simulation that utilizes an arbitrary Lagrangian-Eulerian, has critical advantages over both Lagrangian and Eulerian methods. Because previous models, that employed these methods, have yielded similar results, it is still unclear which one of these three methods is superior [6].

In practice clever techniques (e.g., particle-mesh, tree algorithms, etc.) are used to reduce the computational complexity of the simulation to something manageable by our current technology. Collisionless dark matter can be modelled relatively easily using N-body techniques since it only interacts through gravitational fields [12]. However, baryonic matter must also be computed, which increases the computational complexity of the simulation as more equations must be added to the mix. As more physical phenomena are considered (such as AGN feedback, chemical evolution, star formation feedback, and SMBH formation), the limits of hydrodynamic modelling start to appear. Our current computational capabilities are insufficient to model all these processes in detail, in addition to the current modest numerical understanding of many of these processes, forcing the use of semi-analytic techniques to encompass these processes.

In both the N-body and hydrodynamic frameworks, there is a trade between the details, accuracy, and resolution of the simulation. This can be deduced from Fig. 1. As we move from the “Dark matter only” column, which only needs N-body methods, to the one with baryonic matter added, which uses hydrodynamic methods, we see a drop in the

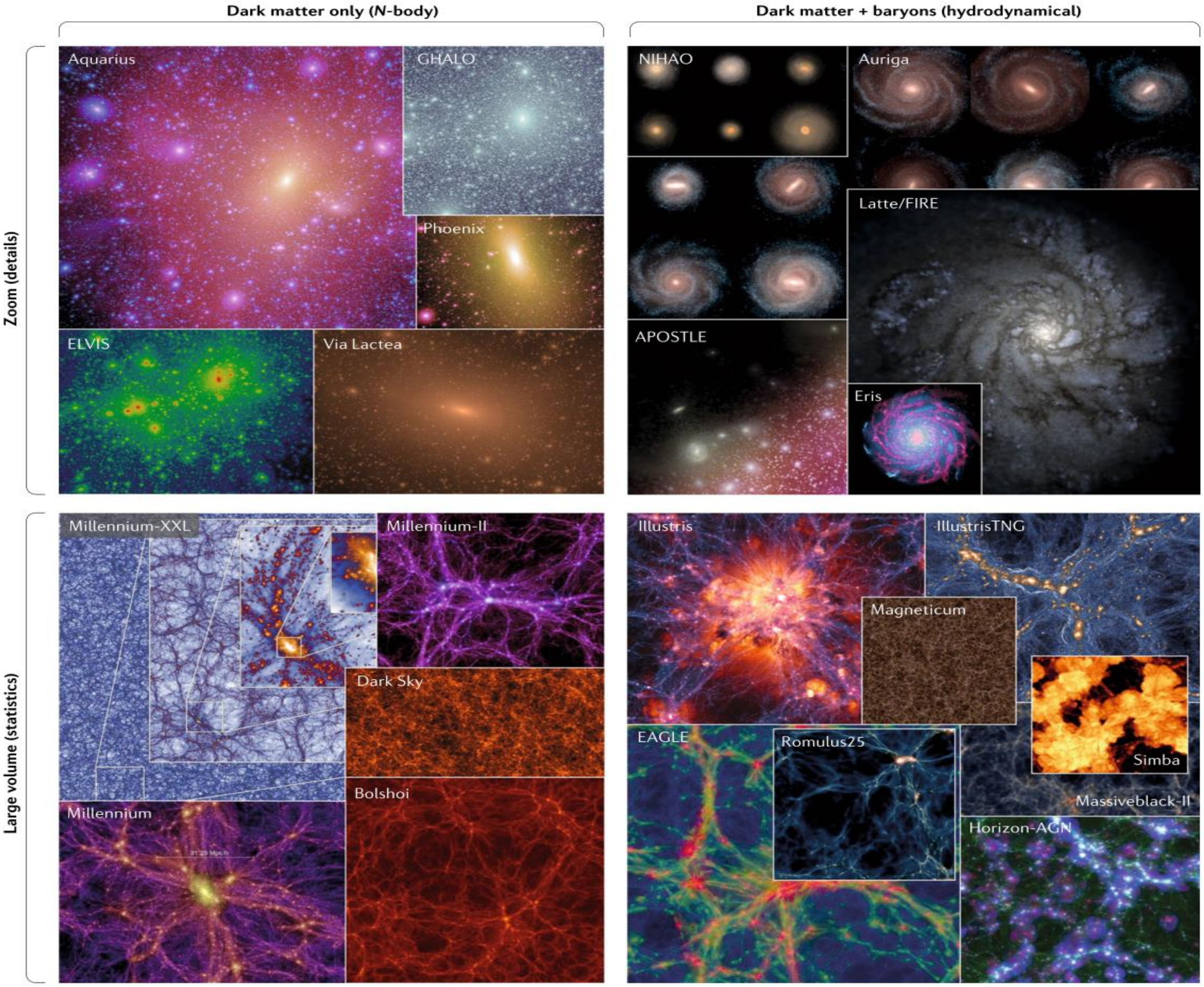

Fig. 1. Visual representations of some selected structures and galaxy formation simulations. In the left column are dark matter simulations, which use the N-body framework. The right column is hydrodynamic simulations, which simulate dark matter using N-body methods and baryonic matter using the hydrodynamic framework. The top row consists of "small" detailed simulations, while the bottom row consists of large-volume simulations that are used to derive global properties. [10]

resolution of the simulation: the Millennium-XXL simulation [24], in the bottom-left corner, is a multi-hundred billion particle simulation, while the Illustris simulation [25], in the bottom-right corner, only reached a particle count of more than 18 billion particles. This is due to the added computational complexity by, also, simulating baryonic matter. The same pattern can be seen in the transition from the "Large volume" statistical row to the "Zoom" detailed one. The particle size decreases from the multi-hundred billion particles in the Millennium-XXL simulation to 1.47 billion particles in the Aquarius simulation [26]; this is caused by the many "detailed" physical phenomena taken into consideration when simulating the "Zoom" row. The "Large volume" row uses some clever methods to approximate the effects of such physical phenomena; this is attributed to the immense number of particles needed to remotely derive the statistical properties of the simulated galaxies.

Although the hydrodynamic framework can provide valuable and accurate insights into galactic evolution, our current computational power limits its capabilities. So, to keep its accuracy, it can be only used on large-scale simulations with undesirable approximations or on small, but comprehensive, simulations (e.g., single galaxies or small clusters).

As mentioned above, when some of the physical processes are simplified or ignored, the number of particles (or size of the mesh depending on the used technique) can be greatly increased by orders of magnitude. For example, the cosmological simulation code GADGET-2 [15], which uses a tree algorithm coupled with SPH, is the largest pure dark matter simulation, containing more than 10 billion particles, since dark matter can be simulated relatively easily without requiring substantial computational power. As a result of [15], many properties of dark matter halos are, now, known to a very high accuracy. Moreover, when radiative cooling and star formation were added to the simulation the number of particles had to be dropped to 250 million. This illustrates how computational complexity can greatly affect the simulation's accuracy and/or resolution, and researchers are forced to either simplify and approximate phenomena or downsize the simulation's resolution.

VI. Methods

We used two inclusion/exclusion criteria to narrow our research down to the focus of this paper. First, we included the research papers related to, and only to, the hydrodynamics and semi-analytic frameworks and the implementation of different physical processes through them. [6], [10], and [12] were the most helpful resources that helped us throughout this research journey. They discussed in detail the cosmological simulations of galaxy formation. Lastly, we excluded all the research concerned with the Milky Way Galaxy only, since this paper focuses on these models in the context of extragalactic astronomy.

VII. Conclusion

From the physical processes, we can conclude that the implementation of star formation as a sub-resolution model with individual stars as its building blocks will still be necessary in future cosmological simulations [10]. In addition to that, it is crucial to comprehend the cosmic evolution of the angular momentum and mass amount of black holes since the spin of a black hole can significantly affect its radiative effectiveness and jet power.

Semi-analytic models' advantage of being computationally inexpensive allows them to be simulated on the scale of galaxy clusters and possibly bigger. Thus, they can, relatively easily, make predictions of galactic properties (e.g., luminosity function and morphology) of various parameter values. However, these results are limited by the uncertain assumptions and approximations used in these models. On the other hand, hydrodynamic models have produced results that are similar to observations, as they have the advantage of following the evolution of baryonic matter and dark matter content of the universe in complete generality

[23]. Despite this advantage, the relatively small resolution size due to the computational complexity of hydrodynamic models limits our ability to derive statistical properties (e.g., luminosity function) and study the effects of varying the simulation parameters. As a result, when hydrodynamic models reach their limit (i.e., the maximum resolution concerning computational power), they result in a semi-analytic technique to simulate the computationally expensive and “chaotic” phenomena (e.g., star formation feedback and AGN).

As it was clearly emphasized, the main problem facing both frameworks is the resolution and accuracy of the model versus the current and available computational power. Logically, as technology keeps advancing, our ability to solve more complex equations and include many more complex phenomena (as we interpret them more intimately) in both simulations will continue to improve considerably.

It may seem that as our computational capabilities increase, the semi-analytic framework will become obsolete. This thought would hold true if we could somehow reach enough computational power to simulate each particle in our current universe, and that is “near” impossible. The two frameworks can be thought of as yin and yang; they complete each other, and only considering one approach is insufficient. Currently, insights are gathered from each framework independently, as models use only one technique. However, to fully understand galactic evolution, a unified model that encompasses both semi-analytic and hydrodynamic techniques into one coherent framework is a necessity.

The agreement in predictions of simulation models that use different techniques suggests that the galactic evolution modelling is headed in the right direction. However, there are still some processes that are not traditionally included in current models such as magnetic fields and cosmic rays, but they have been considered in relatively few research papers (e.g., [27], [28], and [29]).

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