Introduction
Figure 1.1 – Time evolution of the (from left to right) full simulation box of 100 Mpc/h, and two regions further zoomed-in around the most massive halo ($M_{\text{FOFhalo}} = 8.2 \times 10^{14} M_\odot$) at the present time ($z = 0$), of 40 and 15 Mpc/h (all in comoving units). From top to bottom: $z = 6$, 2, 1, and 0. Figure from [Boylan-Kolchin et al.][2009].
1.1 Hierarchical structure formation

The large scale structure present in the Universe is thought to have formed in a hierarchical fashion (e.g. Press & Schechter 1974, Rees & Ostriker 1977, White & Rees 1978). Starting from a hot and dense state, the early Universe contained small overdensities, whose traces are seen in the Cosmic Microwave Background. When overdensities contain sufficient mass to counter the expanding Hubble flow of the Universe, they collapse and form self-bound structures, the (dark matter) halos. These halos are often found in sheets, filaments, nodes, and voids, as can be seen from Fig. 1.1. So although modern cosmology is built upon the hypothesis of an isotropic and uniform universe on exceedingly large scales (the cosmological principle), on smaller scales the distribution of matter is highly non-linear.

Of the matter content in our Universe a dominant fraction is thought to be in the form of weakly-interacting particles. Indications of the existence of this “dark matter” are found on a variety of scales, from e.g. rotation curves of individual galaxies (Rubin & Ford 1970, Rubin et al. 1980, Bosma 1978), to clusters of galaxies (the first discovery by Zwicky 1933, 1937), the Universe as a whole (Allen et al. 2003, Komatsu et al. 2011, Planck Collaboration et al. 2014). The search for direct evidence of this dark matter, and the determination of its nature, is strongly being pursued at the moment by astrophysicists as well as particle physicists (e.g. Ackermann et al. 2014, Ajello et al. 2015, Daylan et al. 2016), and the hope is that this mystery will be solved in the coming decade. The $\Lambda$CDM-cosmology is the currently favored cosmological model, where dark energy dominates the energy density of the Universe with $\sim 69\%$ (Planck Collaboration et al. 2014), “cold” dark matter accounts for $\sim 26\%$, and where the last $\sim 5\%$ is in baryons, of which we have observed only a fraction thus far.

Galaxies in the Universe

Galaxies are believed to form and be embedded in dark matter halos (e.g. Freeman & Bland-Hawthorn 2002). While in the early Universe, during the first phases of that formation process, galaxies have very irregular shape and structure, toward the present time different morphologies can be identified (e.g. Conselice 2014). The best known classification scheme identifies two main groups or classes: ellipticals and spirals (the Hubble tuning fork, Hubble 1936; Sandage 1961). Galaxies that do not fit into these defined classes fall into a separate group of “irregular galaxies”.

Elliptical galaxies, as their name suggests, have an elliptical shape and a generally rather smooth brightness profile, following a Sérsic (e.g. Sérsic 1963, Blanton & Moustakas 2009) light profile falling off with $R^{1/n}$ where often for giant elliptical galaxies $n = 4$ (the de Vaucouleurs profile, de Vaucouleurs 1948), while for dwarf elliptical galaxies $n = 1$. Upon closer examination
however, deviations from the smooth profile are apparent in the form of shells and streams in the outer regions and disk-like structures in the inner parts (van Dokkum 2005; Duc et al. 2011; Krajnović et al. 2013). At galaxy masses similar to the Milky Way ellipticals form a relatively small fraction of the galaxy population but toward larger galaxy masses they are increasingly dominant (Conselice 2006; Guo et al. 2011). Central galaxies in clusters are almost always large ellipticals, and the fraction of ellipticals decreases with decreasing galaxy density in the cluster (or group) (the morphology-density relation, Dressler 1980; Postman & Geller 1984; Whitmore et al. 1993; Blanton & Moustakas 2009; Conselice 2014).

Spiral galaxies, of which the Milky Way is one, are the most common galaxy within the intermediate mass range (Conselice 2006; Blanton & Moustakas 2009; Conselice 2014). The disk with its spiral structure is the most striking morphological feature but other components, like bulges and bars are also present, with varying degrees of prominence. The stellar and gas disks are generally described by exponential profiles, morphologically as well as kinematically, with scale radii of a few kpc for Milky Way-like galaxies, although the gas disk can be more extended than the stellar disk. The disk height is generally described by an isothermal profile with disk scale height about \( \lesssim 0.10 \) of the disk scale length for thin disks, and disk scale heights of up to \( \lesssim 0.50 \) (especially for lower mass galaxies, Roychowdhury et al. 2010) of the disk scale length for thick disks. Besides the major components smaller substructure, asymmetries, or deviations from exponential disks, can also be present, like streams, rings, shells, arms, plumes, warps, and lopsidedness. These substructures can be due to internal effects such as disk instabilities or bar formation, or external influences like satellite infall or other tidal disturbances. Irregular galaxies generally lack the regular disk appearance, or are dominated by substructures such as those described above.

Toward lower masses or luminosities disky systems can be seen to become more and more irregular (e.g. Gallagher & Hunter 1984). Such systems are smaller, with disk scale lengths \( R_d \lesssim 1 \text{ kpc} \), and thicker, with velocity dispersions more comparable to the rotational velocities. There are a number of different definitions of what exactly denotes a dwarf galaxy, but one often used is: systems with \( M_V \geq -17 \) and that are more extended than a globular cluster (Tamman 1994; Tolstoy et al. 2009). There is a large number of morphological types within the dwarf galaxy regime. These types have appeared historically and are based on a variety of properties, and depict significant overlap. Some of the most well-known classes are: dwarf spheroidals (dSph), dwarf irregulars (dIrr), dwarf ellipticals (dEll), ultra-faint dwarf galaxies (UFD), blue compact dwarfs (BCD), extremely metal-poor galaxies (XMP), HII galaxies, ultra-compact dwarfs (UCD).

The existence of a lower bound on the mass of galaxies have been questioned already for a few decades, (e.g. Arp 1965). For the last two decades this
question has mostly come up in the context of the so-called “missing satellites” problem as described by Klypin et al. (1999) and Moore et al. (1999), but also in computational efforts that better and better resolve low-mass systems. It appears plausible that observations miss a large set of satellites (and low-mass galaxies in the field) because these systems have formed (almost) no stars for various physical reasons, and so are hard or impossible to observe directly (Klypin et al. 1999). However other alternatives exist, such as a cut-off in the smallest mass halo that can form (driven by the intrinsic nature of dark matter itself). Dwarf galaxies and star-less dark galaxies will be further discussed in Sect. 1.3.

### 1.1.1 Modeling structure formation

For a system where the collisional relaxation timescale is long compared to its characteristic timescale (i.e. the orbital period of stars in a galaxy disk, or of dark matter particles in a dark matter halo), we can consider the constituent particles that almost only interact through gravity as essentially collisionless. Thanks to this and to the dominance of (cold) dark matter, the formation of structure in the Universe can be extensively and successfully studied using large cosmological N-body simulations. This allows for extremely large simulation volumes that model structure on large scales (of 10–1000 Mpc). On the other hand simulations of smaller volumes (< 10 Mpc) with higher resolution can be used to study in detail the formation and evolution, structure and substructure, of individual dark matter halos, and groups of halos. Specific zoom-in (e.g. Aquarius, Springel et al. 2008; NIHAO, Wang et al. 2015; APOSTLE, Sawala et al. 2016a) or constrained (e.g. CLUES, Gottlöber et al. 2010), simulations are often oriented toward simulating the distribution of dark matter in Milky Way-like or Local Group-like environments.

Such N-body simulations determine the gravitational acceleration of one particle from all other particles by solving Poisson’s equation. For a low number of particles, for example in star clusters, this is literally what is done, but for larger numbers of particles direct summation of the forces (which has \(O(N^2)\) time complexity) quickly becomes too computationally expensive. In that case instead of the exact forces of individual particles at large distances, these are approximated by the cumulative force from the center of mass (the hierarchical tree code, Barnes & Hut 1986; Hernquist & Katz 1989). Another approach is to calculate the potential due to the forces of all particles on a grid and moving the particles along gradients of this potential, as in particle-mesh codes (Hockney & Eastwood 1988). In most codes nowadays both these \((O(N\log N))\) approximations are combined in tree-PM codes (Xu 1995) where the short-range forces are calculated using a tree, and long-range forces are approximated using a grid.
The power of dark matter-only simulations lies in tracing the evolution of structure in the Universe, from the very early times until the present day. They allow for the study of the abundance, clustering, internal structure, shape, and angular momentum of the individual dark matter halos that form, as well as of the large scale cosmic web in which they are embedded. The density distributions obtained in \( \Lambda \)CDM cosmological simulations compare very well to those found in large surveys on large scales (e.g. Primack 2005). Another advantage of such N-body simulations is that one can experiment with different dark matter models and monitor the differences in the structure distribution. Modeled alternatives include various “warm” dark matter particles, with larger energies (e.g. CLUES, Zavala et al. 2009; COCO, Bose et al. 2016), and a number of flavors of “self-interacting dark matter” (e.g. Vogelsberger et al. 2012; Rocha et al. 2013), among others.

In most cases to trace the history of a specific halo a series of so-called post processing techniques are used. In the first step, all the halos at each output snapshot of the simulation have to be “found”, or identified. This can be done in different ways, e.g. by defining groups of particles that occupy similar regions in physical and phase space, for example with a Friends-Of-Friends algorithm (FOF, Davis et al. 1985), which is usually combined with a second algorithm to identify objects bound by their self-gravity (e.g. SUBFIND, Springel et al. 2001a). Alternatively, halos can be found as overdensities within the density distribution in physical and/or phase space (e.g. ROCKSTAR, Behroozi et al. 2013b). In the next step halos from different snapshots are connected via a progenitors-descendant-scheme, where each halo has one unique descendant (the halo in the next snapshot with the most particles of the progenitor halo weighted by e.g. a rank based on binding energy), but can have more than one progenitor. In this way merger trees are build up. These trees contain information about the properties of halos at each snapshot as well as its descendant and its progenitors, and so can be used to trace the evolution, including mergers, of halos. Therefore, the halo- and subhalo-catalogs and the merger trees can be used efficiently to study many halo properties from a simulation, without having to inspect the large datasets usually associated with the snapshots with all the particle information. For example, such merger trees are often used as a backbone for semi-analytic modeling of galaxy formation.

As an example Fig. 1.1 shows the formation and evolution of the most massive halo formed in a large cosmological simulation. This most massive halo is comparable to the Coma cluster with a mass of \( M_{\text{FOFhalo}} = 8.2 \times 10^{14} \, M_\odot \), and consists of 119.5 million particles and \( \approx 36000 \) resolved subhalos over nearly 7 orders of magnitude in mass (Boylan-Kolchin et al. 2009).
1.1.2 Modeling galaxy formation and evolution

Including hydrodynamics in the cosmological N-body simulations enables the study of the formation and evolution of galaxies. The dynamics of the gas is mainly modeled with two different methods: mesh-based hydrodynamics (Eulerian; see for a review Teyssier 2015), or smoothed particle hydrodynamics (Lagrangian; see for a review Monaghan 1992, Springel 2010b), but a combined method, moving-mesh hydrodynamics (see for example AREPO, Springel 2010a), is now also used.

In the simulations described in this Thesis we use a smoothed particle hydrodynamics (SPH) approach (e.g. Gingold & Monaghan 1977, Lucy 1977, Monaghan 1992, Springel 2010b). SPH uses particles to trace a fluid and applies kernel smoothing and interpolation to determine the (continuous) fluid quantities. The GADGET simulation code (Springel et al. 2001b, Springel 2005), used in this Thesis, applies a specific implementation in which the thermodynamic state of each fluid particle is defined based on the entropy \( A = \frac{P}{\rho^\gamma} = A(s) \). GADGET uses an adaptive smoothing length based on a given number of neighbors.

Next to gravity and hydrodynamics the physics in simulations is largely governed by the so-called subgrid physics. This essentially means that there is a “resolution” limit present in the simulations based on how detailed the physics in the code is. Processes below this resolution limit, which should be consistent with the mass and length-scale resolution limits in the simulations, are described through prescriptions that mimic the outcome of smaller-scale processes on the resolution scale or empirical relations at the resolution scale.

Main subgrid processes in hydrodynamical codes are related to gas-physics, and are associated to processes such as gas heating and cooling, star formation and feedback, black hole formation and feedback from active galactic nuclei (AGN), stellar populations, and chemical evolution. For example the process of gas cooling is modeled using pre-calculated cooling-functions for a range in gas temperatures, densities, and metallicities. Most of the cooling at \( T_{\text{gas}} \gtrsim 10^4 \) K is done through free-free emission (\( T_{\text{gas}} > 10^7 \) K) and recombination (\( 10^4 \ K < T_{\text{gas}} < 10^7 \) K) in ionized gas (primordial –H and He– gas as well as heavier elements –metal-line cooling). Below this temperature collisional excitation/de-excitation of more heavier elements (metal-line cooling) and molecular cooling can cool the gas further (e.g. Somerville & Davé 2015). Heating on the other hand is mostly due to reionization or feedback effects like photoionization, stellar winds, shocks, and radiative or thermal feedback from stars and AGN.

For the onset of star formation, many codes apply a density threshold, with in addition sometimes other, less stringent criteria, like a convergent gas flow, and an upper limit for the gas temperature. The density threshold for star formation often depends on the level of sophistication of the input physics and the mass and spatial resolution (see e.g. House et al. 2011). In general all
star formation recipes are tuned or shown to reproduce the Kennicutt-Schmidt empirical relation in simulations of isolated disks (e.g. Scannapieco et al. 2012; Somerville & Dave 2015). The amount of star formation then depends on the local (surface or volume) density, and includes a certain stochasticity in the likelihood for star formation to take place. The amount of stars formed is usually assumed to follow a given initial mass function (IMF) and a fixed fraction is assumed to evolve into supernovae (SNe). These SNe (usually TypeII and TypeIa are taken into account), as well as, possibly, stellar winds and radiative feedback, affect the surrounding gas. The SNe feedback is generally dispersed over the neighboring gas particles/cells though thermal feedback, kinetic feedback, or entropy feedback (e.g. Scannapieco et al. 2012; Somerville & Dave 2015).

Another popular way to follow the formation and evolution of galaxies is through semi-analytic modeling (SAM) (e.g. Somerville & Dave 2015). Since galaxies are assumed to be embedded in dark matter halos, many of their properties are computed using information about dark matter halos.
(for example halo merger trees). Dark matter-only simulations or analytic descriptions (see e.g. Press & Schechter 1974) form the skeleton by providing e.g. the number of objects of a given mass at a given time and their evolution in time (through e.g. merger trees). In the semi-analytic model a galaxy consists of a number of different constituents (like stars, hot gas, and cold gas), which hold a certain amount of mass. The mass flow and transformations from one constituent to another is followed with physically or empirically motivated prescriptions. An example of this is given in Fig. 1.2. The prescriptions used in semi-analytic modeling are in essence very similar to the subgrid physics of hydrodynamic simulations, with the exception that for SAMs also the characteristic sizes, densities, concentrations, masses, and radii are determined through prescriptions.

For example in many semi-analytic models the feedback, or ejected gas mass, due to star formation is in total described by $\dot{m}_{\text{ejected}} = \epsilon_w \left( \frac{V_0}{V_c} \right)^{\alpha_w} \dot{m}_*$, where $\dot{m}_*$ is the rate of star formation in the galaxy, $V_c$ is its circular velocity, $V_0$ is an arbitrary normalization parameter, and $\epsilon_w$ and $\alpha_w$ are tunable parameters, where for $\alpha_w = 1, 2$ the ejected mass approximates scalings for feedback through galactic winds from hydrodynamic simulations (Somerville & Davé 2015).

Calibration of the (combination of) unavoidable free parameters in the subgrid and semi-analytical prescriptions is often done using a selection of correlations of galaxy properties and scaling relations, found empirically, that have a small amount of scatter and are well-constrained. Examples of these are, the luminosity function, stellar mass function, the (Baryonic) Tully-Fisher relation, the main sequence of star-forming galaxies, the cold gas–stellar mass relation, the mass–size relation for spiral galaxies, the metallicity–stellar mass relation, and relations between the mass of the central supermassive black hole and galaxy properties (Somerville & Davé 2015, and references therein). Although no existing simulation fits all relations we observe simultaneously, simulations fit a larger subset of these relations increasingly well. Note however that fitting statistical relations does not necessarily imply that individual objects have realistic properties.

\section*{1.1.3 Controlled simulations}

On non-cosmological scales the so-called “controlled” simulations are useful to explore in more detail the evolution of individual halos and galaxies. These simulations have a longer history than the fully cosmological simulations, starting from models of star clusters, with 16 (von Hoerner 1960) and 200 (Aarseth 1963) stellar particles, and galaxies, (Pfleiderer & Siedentopf 1961; Pfleiderer 1963; Tashpulatov 1969, 1970; Yabushita 1971; but see also the work by Holmberg 1941 who modeled a merger between two spiral galaxies by using light bulbs as tracer particles ($N = 37$ per galaxy) and the light intensity as gravitational force). With the growth in computational power, and faster
and more sophisticated algorithms, simulations where galaxies are modeled using millions of particles in the stellar, dark matter, and hot and cold gas components, are the norm now (see e.g. Athanassoula et al. 2016; Vera-Ciro et al. 2014). As similar codes are used as for the cosmological simulation the input physics is also similar.

An important aspect of controlled simulations is the modeling of the initial conditions. This is in contrast partly, to cosmological simulations where the initial conditions are known (to some extent) ab-initio. The character of the research might require for example an initially stable galaxy (for simulating galaxy interactions), or a deliberately, in a particular way, perturbed galaxy (for simulating the development of spiral and bar features e.g. Athanassoula et al. 2013; D’Onghia 2015; Vera-Ciro et al. 2014, see also Chapter 2).

1.2 Galaxy interactions and mergers

Galaxies are often found to be significantly clustered on group, cluster, and larger scales, and sometimes also to be interacting. Many observed irregular features of galaxies, as for example apparent in Arp’s catalog of (large) peculiar galaxies (Arp 1966), can be explained by being due to interactions. According to Toomre (1974) the idea of tidal features being due to interactions between galaxies can be dated back to Chamberlin (1901) (although he discusses the possible formation of spiral nebulae due to interacting gaseous spheres). However, the work by Toomre & Toomre (1972); Toomre (1977) is generally seen as the first numerical simulations that clearly have shown the impact of galaxy mergers, and thereby triggered the interest in this field.

For a long time it was believed that if two similar mass gas-rich disk galaxies merged this would always lead to an elliptical galaxy (e.g. Toomre 1977; Barnes & Hernquist 1992; Cox et al. 2008). In the last few years, however, some groups have shown that two gas-rich disk galaxies merging can also result in a disk galaxy, and that soon after the merger a new thin disk can form (e.g. Springel & Hernquist 2005; Athanassoula et al. 2016), depending on initial conditions. Mass ratio is thus not the only aspect that plays a role in interacting galaxies. For example, Di Matteo et al. (2007, 2008) have shown that while an increase in star formation rates, or even a starburst, often takes place during and/or after a merger (Mihos & Hernquist 1994a,b; Teyssier et al. 2010; Bournaud et al. 2011), and such an increase in star formation is in fact seen in observations (Ellison et al. 2011; Willett et al. 2015; Kaviraj 2014b; Willett et al. 2015), there is not a direct dependence on the merger mass ratio (but see Teyssier et al. 2010). They find that nuclear starbursts are triggered by gas inflow due to non-axisymmetries. As such, direct (prograde) encounters develop more asymmetries and therefore star formation enhancement. However, if more gas is dragged outside the galaxy
by tidal tails, i.e. if the tidal torques are stronger per time interval, the increase in central star formation rate is smaller (Di Matteo et al. 2007, 2008).

Studies into the dynamical effects of minor mergers have mostly focussed on Milky Way-like galaxies. In controlled simulations of systems similar in mass and structure to the Milky Way, minor mergers have been shown to be the source of substructure, like shells, plumes, ripples, X-features (e.g. Quinn & Goodman 1986; Barnes & Hernquist 1992), and more global disturbances as warps, boxy isophotes, disk thickening, and bulge creation or growth (e.g. Schweizer 1990; Toth & Ostriker 1992; Quinn et al. 1993; Walker et al. 1996; Huang & Carlberg 1997; Velazquez & White 1999; Font et al. 2001; Villalobos & Helmi 2008; Hopkins et al. 2008; Purcell et al. 2009; Moster et al. 2010; Qu et al. 2011). Minor mergers are generally harder to observationally identify due to their weaker impact compared to major mergers. On the other hand, this also means that the fractions of bulge-less galaxies and galaxies with really thin disks we observe can be used to constrain the fraction of minor mergers, the longevity of the effects due to minor mergers, or the dependence of the results of minor mergers on properties of the merging halos, galaxies, and the interaction (Toth & Ostriker 1992; Hopkins et al. 2008; Purcell et al. 2009; Moster et al. 2010).

1.3 On the scale of dwarf galaxies

There is a wide variety of dwarf galaxies seen in the Local Universe (e.g. Tolstoy et al. 2009; James et al. 2015). Dwarf galaxies outside of the Local Group came into view in large observing campaigns, that resulted in the Catalogue of galaxies and of clusters of galaxies (Zwicky et al. 1961, 1968), the Catalogue of selected compact galaxies and of post-eruptive galaxies (Zwicky & Zwicky 1971), and the Uppsala General Catalog (Nilson 1973, initiated by E. Holmberg). As small, and fragile, systems dwarf galaxies can be more severely affected by internal and external influences. On the other hand, this also complicates determining the specific processes that are responsible for the variety of observed morphological, structural, and kinematical properties in these systems.

Within a CDM universe the dark matter halo mass function is scale free, and the same subhalo mass function and hence similar merger ratios are expected on all scales (a dependence of the merger fraction on the present day halo mass is almost completely due to a dependence on halo formation redshift \(z_{\text{form}}\) (van den Bosch et al. 2005; van den Bosch & Jiang 2014). Fig. 1.3 shows a cluster-size halo (Gao et al. 2012) and a Milky Way-size halo (Springel et al. 2008) where the distribution of the dark matter substructure in both cases is essentially identical. The dark matter halo properties are found to be the same for dwarf galaxies as for larger mass halos in cosmological N-body simulations.
Figure 1.3 – Two dark matter distributions from two simulations: a cluster-size halo from the Phoenix project (Gao et al. 2012) and a Milky Way-size halo from the Aquarius project (Springel et al. 2008). The dark matter substructure is very similar (see also the discussion in Gao et al. 2012).

Lower mass galaxies are however expected to be strongly influenced by reionization, photoheating, and feedback (e.g. Gnedin 2000; Hoeft et al. 2006; Kaufmann et al. 2007; Okamoto et al. 2008; Gnedin et al. 2009; Li et al. 2010; Sawala et al. 2013). This is thought to have had significant effects on the star formation histories, and present day properties of dwarf galaxies (e.g. Weisz et al. 2014). Moreover, dwarf galaxies can be severely affected when in the neighborhood of larger mass galaxies, due to gas stripping and subsequent star formation quenching (e.g. Sofue 1994; Wetzel et al. 2013), and tidal effects (Mayer et al. 2001b, a, 2006; Sawala et al. 2016b) leading possibly to morphological transformations. Also dwarf–dwarf interactions are expected to be important (e.g. Ashley et al. 2013; Amorisco et al. 2014; Łokas et al. 2014). All these processes are thought to be responsible for the large variety of dwarf galaxies we see. For example Grebel et al. (2003) discuss three very different, but not necessarily independent, formation processes of dwarf spheroidal galaxies (but see also Ricotti & Gnedin 2005; Slater & Bell 2013; Benítez-Llambay et al. 2013), where one depends on more intrinsic properties, and others are due to environmental effects (as described for example in Mayer et al. 2006). Intriguingly however, a small number of dwarf spheroidal galaxies have been found in the field (Makarov et al. 2012; Karachentsev et al. 2015).

New observations seem to indicate that we may not have a fully complete view of the class of dwarf galaxies yet. For example, by using photometric properties of the XMP galaxy Leo P as a proxy, James et al. (2013) found a set of what they call blue diffuse dwarf (BDD) galaxies. Having a low surface brightness main body, and mostly only HII-regions that stand out, these objects would not readily be identified when not specifically searched for. Blue compact dwarf galaxies show similar characteristics, although with a bright center with young stars and a more diffuse older population (e.g.
Gil de Paz et al. (2003) and Paudel et al. (2015). However, BCDs often show irregular morphologies and kinematics (Taylor et al. 1995; Ekta & Chengalur 2010; López-Sánchez 2010; Holwerda et al. 2013; Lelli et al. 2014a; Knapen & Cisternas 2015), in cases without a visible companion (Brosh et al. 2004; Ekta & Chengalur 2010; López-Sánchez 2010; Lelli et al. 2014b). But similar off-center bursts of star formation and kinematic differences between the stellar and gas component have also been observed in XMP galaxies (Filho et al. 2013, 2015). Figure 1.4 shows the Local Group dwarf galaxy IC10, which shows very irregular stellar and gas morphology and kinematics. The cause of these irregular features is still under debate (Nidever et al. 2013; Ashley et al. 2014).

In contrast to the halo mass function, the galaxy mass function is not scale free and sufficiently low-mass halos are expected to be completely devoid of baryons. This might partially be due to reionization and star-formation feedback, but when going to lower mass scales at some point the dark matter halos are too small/light to form any stars (e.g. Verde et al. 2002; Davies et al. 2006; Pustilnik 2008; but see also Taylor & Webster 2005; Warren et al. 2007). This is called a star-less or dark galaxy. Note that gas may be present, although stricter definitions, cold gas-less as well as star-less, are also used (and that is what we assume in the Chapters in this Thesis). Dwarf galaxies that have formed stars in the past but stopped doing so, for example due to reionization, generally called fossils, are not completely devoid of stars as dark galaxies are supposed to be. Nevertheless, as their stellar mass can be too low to be observable, in effect they can be similar to completely dark galaxies.

In general, isolated low-mass halos seem to be gas-rich, with $M_{\text{HI}} > M_\star$, although they might only be able to form a small amount of stars (e.g. Schombert et al. 2001; Zhang et al. 2012; Yaryura et al. 2016). There have been observational efforts to find halos without stars in blind HI-surveys, combined with high resolution optical follow-up (e.g. Adams et al. 2015; Cannon et al. 2015; Janowiecki et al. 2015), but no unambiguous dark galaxies have been found to date. These observations are complicated due to the difficulty in distinguishing between individual systems and HI clouds belonging to other systems, like for example the High Velocity Clouds around the Milky Way (see also the discussion over the extended gas cloud VIRGOHI21, Minchin et al. 2005; Bekki et al. 2005; Davies et al. 2006; Kent et al. 2007). In addition other promising techniques are being developed to find extremely low-mass halos that will likely be dark by purely gravitational effects (e.g. Trentham et al. 2001; Ibata et al. 2002; Johnston et al. 2002; Karachentsev et al. 2006; Vegetti et al. 2010, 2012; Erkal & Belokurov 2015; Nierenberg et al. 2016), and this Thesis may contribute to that group.
Figure 1.4 – The Local Group dwarf galaxy IC10, on the left a composite B, V, Hα image from the Lowell Observatory Local Group Survey (see e.g. Massey et al. 2007), on the right the V-band optical data (grey) embedded in the HI distribution, as observed by the VLA (left and middle panels) and GBT (right panel, with the most extended VLA data overplotted in black), with the colors in the middle and left panel indicating velocities, from Ashley et al. (2014).
In this Thesis we explore the effect that dark subhalos can have on dwarf galaxies. From the expectation of a decreasing stellar mass–halo mass relation toward lower masses and an increasing number of star-less halos below a certain mass scale, and the prediction from ΛCDM that the halo mass function is scale free, we infer two consequences: dwarf galaxies are more sensitive to tidal effects and external perturbers, and a predominant fraction of those perturbers will be dark.

In Chapter 2 and Chapter 3 we test these predictions with a suite of controlled simulations of disky dwarf galaxies in the mass range $M_{\text{vir}} \sim 10^9$–$10^{10}$ $M_\odot$, interacting with dark satellites with as merger mass ratio of $M_{\text{vir, sat}}/M_{\text{vir, host}} = 0.2$. This set-up for the dwarf galaxy is motivated by the idea that star formation mainly takes place in disks, and that this immediately allows us to test the morphological changes induced by the encounter. Chapter 2 describes a set of collisionless simulations where we explore the effects of infalling dark satellites on the morphology, structure, and kinematics of the stellar disk of a dwarf galaxy for a range of disk mass fractions. After carefully setting up the initial conditions, our experiments show that an interaction with a dark satellite can significantly perturb the dwarf galaxy, creating tidal tails and shells, thickening of the disk, and even leading to a spheroidal-like morphology. The effects of the merger are increasingly pronounced for lower disk mass fractions or equivalently, lower baryonic mass fractions. Kinematically the velocity dispersion increases and the rotational velocity decreases. For the lowest disk mass fraction considered, the final dispersion is comparable to the rotational velocity. Therefore, Chapter 2 shows that minor mergers of dwarf galaxies with a dark satellites constitute a novel channel for the formation of dwarf spheroidal galaxies, especially in the field.

Chapter 3 extends the simulations of Chapter 2 to dwarf galaxies with a gas disk. In these hydrodynamic simulations we explore the effect of the minor merger on the dwarf galaxy, and especially on the gas disk and star formation in the dwarf galaxy. We vary structural properties for the dwarf galaxy (the concentration of the dark matter halo, the virial mass and correspondingly the stellar and gas masses, the gas fraction, stellar disk thickness, and extent of the gas disk compared to the stellar disk), the dark satellite (the mass ratio with respect to the host and the concentration of the dark matter halo), and the orbit of the satellite (inclination with respect to the dwarf galaxy stellar disk, and the initial tangential velocity which also controls the eccentricity of the orbit). Our simulations show that the minor mergers can be the cause of short, strong starbursts as well as lead to a significant long-term increase in star formation rate, major tidal tails in the gas as well as in the stellar disk, and that the thickening of the stellar disk discussed in Chapter 2 is also pronounced in the presence of a gas disk. We compare our simulated dwarf galaxies to a large
set of observed irregular dwarf galaxies and blue compact dwarfs, and show that there is important overlap in their general properties. This indicates that interactions between dwarf galaxies and their own (dark) satellites may well contribute to the diversity of the dwarf galaxy population that we see in the Universe around us.

The results of Chapter 2 and Chapter 3 indicate that dwarf galaxies are very susceptible to tidal disturbances due to their own satellites. As we expect these infalling satellites to predominantly be dark, in Chapter 4 we investigate possible methods to characterize the effects on the dwarf galaxy and compare these to observations quantitatively. To this end we gather a number of indicators from the literature that describe structural and kinematical properties of galaxies. We find that although the dwarf galaxies experiencing a merger fill a wide range of the indicators’ parameter space, dwarf galaxies in isolation occupy smaller regions of the space, in particular for parameters describing the asymmetry, concentration, and central surface brightness. Noteworthy differences also occur in the indicators’ parameter spaces describing inconsistent kinematics and orientation between the gas and the stars. This leads us to conclude that specific indicators characterizing the structure and kinematics of dwarfs, can help identifying which systems are experiencing a minor merger with a dark satellite. In particular highly asymmetric, or very concentrated dwarf galaxies, or dwarf galaxies with off-centered star formation, especially in the outskirts, are good candidates to be merging or post-merger systems where the secondary is dark.

A question that remains in the context of dwarf galaxies interacting with their own (dark) satellites is the fraction, for example at the present time, and the frequency of such events. In Chapter 5 we attempt to find an answer to these questions by combining a large, dark matter-only, cosmological simulation (Millennium-II Boylan-Kolchin et al. 2009, see also Fig. 1.1) with a semi-analytic galaxy formation model (see e.g. Starkenburg et al. 2013). We trace back in time the dwarf galaxies with $10^8 \, M_\odot < M_{\text{vir}} < 10^{10} \, M_\odot$ at the present day and $M_\star > 0$, and follow the satellites and their properties. We then compute the fraction of dwarf galaxies that have an infalling, completely dark, satellite above a given mass ratio. Our analysis shows that approximately 10% of the dwarf galaxies have experienced a merger with a dark satellite with a mass ratio large than $1 : 5$ for $z < 0.5$, and 27% for $z < 2$. We conclude that the possible influence of dark satellites on the evolution of dwarf galaxies is substantial and should not be neglected in considering the dwarf galaxy population.

1.5 Future outlook

Dwarf galaxies are the most dark matter-dominated systems known (Tolstoy et al. 2009; Simon et al. 2011). Hence, they provide crucial clues on the nature
of the dark matter itself. Moreover, as fragile systems, they are sensitive and possibly the most direct probes of all the important physical processes driving galaxy evolution, including galaxy interactions, the physics of gas cooling and heating, and star formation and feedback (Simpson et al. 2013; Hu et al. 2016). The relative importance of these processes and how they impact the evolution of low-mass galaxies however, still needs to be determined. This may or may not be related to the huge variety of dwarf galaxies we observe. Possible evolutionary connections between the different dwarf galaxies we see, and the exact role of environment on the formation and evolution of the morphology, structure, and kinematics of dwarf galaxies remain to be established.

Even though resolution in simulations is increasingly higher, there are still many physical processes that we do not precisely understand, as well as their impact on the lower mass scales. For example, both changes in the type of dark matter (e.g. Zavala et al. 2009; Bose et al. 2014; Vogelsberger et al. 2012; Rocha et al. 2013), as well as baryonic processes, like star formation feedback (e.g. Governato et al. 2012;Pontzen & Governato 2012), can impact the structure and internal kinematics of a dwarf galaxy. To pin these down it is necessary to perform, as realistic as possible, hydrodynamical simulations (as dark matter-only simulations seem to predict dark matter halos different in their internal structure and abundance, Sawala et al. 2013; Brooks & Zolotov 2014).

Recent and upcoming multi-wavelength surveys are providing a wealth of unprecedented data on (previously undetected) low-mass systems (e.g., DES, Dark Energy Survey Collaboration; The Dark Energy Survey Collaboration 2005; CALIFA, Sánchez et al. 2012; ALFALFA, Giovanelli et al. 2005; LITTLE THINGS, Hunter et al. 2012; SHIELD, Cannon et al. 2011; WEAVE, Dalton et al. 2014; FOCUS, Lisker et al. 2015). Another interesting development on the dwarf scale is the TiNy Titans project on grouped, paired, and isolated dwarf galaxies (Stierwalt et al. 2015; Pearson et al. 2016), which will provide extremely valuable insights in dwarf galaxy evolution. Furthermore, existing (e.g., ALFALFA, Giovanelli et al. 2005; LITTLE THINGS, Hunter et al. 2012), ongoing (e.g., SHIELD, Cannon et al. 2011) and upcoming HI surveys will provide key insights on the role of the gas in low-mass systems, and increased sensitivity in optical observations will help identify low surface brightness (dwarf) galaxies in the field (see also low surface brightness galaxies in clusters, e.g. Dalcanton et al. 1997; van Dokkum et al. 2015; Roman & Trujillo 2016), as well as features associated to mergers (e.g. Martínez-Delgado et al. 2012; Nidever et al. 2013; Cannon et al. 2014). All these observational efforts will help constrain the model discussed in this Thesis. Additionally, new, and in general more detailed, theoretical efforts are needed to combine this data with predictions from models to test and further develop our understanding of the formation and evolution of the low-mass end of the galaxy spectrum.