# 1

# Introduction

Galaxy formation has undergone fast development in the past few decades, both theoretically and observationally. The number of observed galaxies is expanding rapidly and observations are pushing to lower masses and higher redshifts. Diffuse gas has been observed in absorption against bright background objects and in emission around galaxies. Simulations predict that the spatial distribution of the intergalactic medium, the cosmic web, has a profound impact on the evolution of galaxies. Gas accretion provides the fuel for star formation, which is inhibited by outflows powered by supernova explosions and active galactic nuclei (AGN). Star formation and feedback produce and distribute metals in the surrounding medium, which aids the process of galaxy formation. To understand the assembly of galaxies, we need to understand how they are fuelled.

## 1.1 Structure formation in the Universe

More than thirteen billion years ago the Universe was almost completely homogeneous. Tiny gas density fluctuations of the order $10^{-5}$ grew into everything we can see today. Structure on the largest scales is completely governed by gravity. The matter is concentrated in a 'cosmic web' of sheets and filaments that are determined by the original fluctuations and the cosmological parameters, principally $\Omega_{\rm m}$, $\Omega_\Lambda$, $h$, $\sigma_8$, and $n$. The values of these parameters can be derived from accurate observations of the cosmic microwave background, the radiation emitted by recombining protons and electrons and redshifted by a factor of about 1100, and of the large-scale distribution of matter (e.g. Spergel et al., 2003; Komatsu et al., 2011).

The distribution of matter is not spherically symmetric, so the collapse will be different in different directions. First collapse happens in one dimension, forming sheets. When collapse happens in two dimenions, filaments form. In the end, collapse occurs in three dimension and haloes are formed. An illustration of the gas distribution in the present-day Universe is shown in Figure 1.1. Assuming spherical collapse, the internal density for collapsed haloes is $\rho_{\rm coll} \approx 18\pi^2 \langle \rho_{\rm m} \rangle$ (Padmanabhan, 2002), where $\langle \rho_{\rm m} \rangle$ is the cosmic mean matter density:

$$\langle \rho_{\rm m} \rangle = \Omega_{\rm m} \rho_{\rm crit} = \Omega_{\rm m} (1+z)^3 \rho_{\rm crit,0} = \Omega_{\rm m} (1+z)^3 \frac{3H_0^2}{8\pi G}, \tag{1.1}$$

where $H_0$ is the $z = 0$ value of the Hubble parameter and $G$ is the gravitational constant. The mass of this object then is $M_{\rm halo} = \frac{4}{3}\pi \rho_{\rm coll} R_{\rm vir}^3$, from which we can derive an expression for the virial radius:

$$R_{\rm vir} \approx \left( \frac{2GM_{\rm halo}}{H_0^2 \Omega_{\rm m} 18\pi^2} \right)^{1/3} \frac{1}{1+z} \tag{1.2}$$

or

$$R_{\rm vir} \approx 3.4 \cdot 10^2 \text{ kpc} \left( \frac{M}{10^{12}\,{\rm M}_\odot} \right)^{1/3} \left( \frac{\Omega_{\rm m} H_0^2}{1.3 \times 10^{-36}\, s^{-2}} \right)^{-1/3} \frac{1}{1+z}. \tag{1.3}$$

Galaxies form inside their much larger haloes in the highest density peaks and are dominated by baryons, because gas is able to cool, whereas dark matter can only lose energy due to gravitational interactions, e.g. dynamical friction. Galaxy properties therefore depend on other things than just gravity. The gas behaves like an ideal gas. Its pressure increases when its volume decreases or its temperature increases. It can move supersonically and it can therefore experience shocks, converting its kinetic energy into thermal energy.

While the collapse of dark matter halts as it reaches virial equilibrium in haloes, baryons can radiate away their binding energy, allowing them to collapse

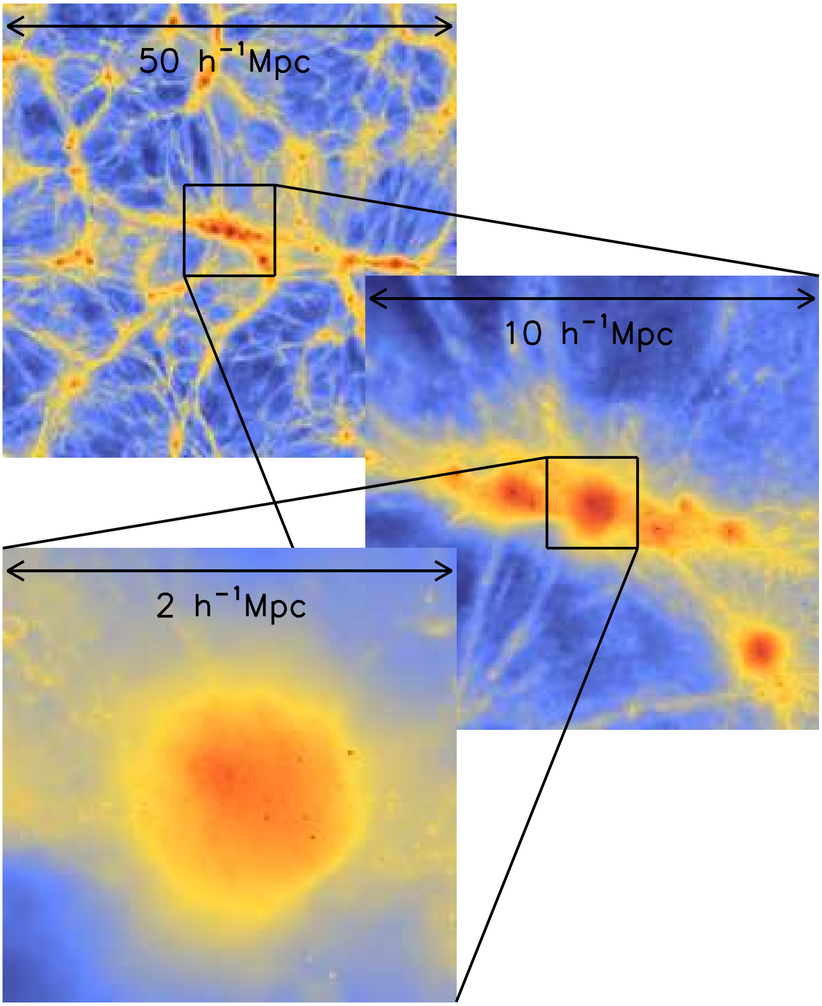


**Figure 1.1:** Zoom-in from 50 $h^{-1}$Mpc to 10 $h^{-1}$Mpc to 2 $h^{-1}$Mpc of the gas density in a 2 $h^{-1}$Mpc slice of the Universe at $z = 0$, centred on a massive halo ($M_{\rm halo} = 10^{13.5}$ $M_{\odot}$), showing the filaments of the cosmic web and the haloes embedded within them. The colour bar is logarithmic, the same in all panels, and runs from the mean cosmic density (blue) to $10^4$ times the mean density of the Universe (red). The simulation used is the reference simulation in a (50 $h^{-1}$Mpc)$^3$ volume from the OWLS project (Schaye et al., 2010).

further and fragment into smaller structures, such as stars and galaxies. The cooling time can be defined as the ratio of the thermal energy density of the gas and the cooling rate, which depends on the density, temperature, and metallicity of the gas, because it may be dominated by metal-line emission.

After virialization, a gas cloud can be in one of three regimes. If the characteristic cooling time exceeds the Hubble time-scale, the gas will not be able to radiate away the thermal energy that supports it and will therefore not collapse. If, on the other hand, the cooling time is smaller than the Hubble time, but larger than the dynamical time-scale, then the cloud can adjust its density and temperature quasi-statically. It will increase both its density and its temperature while maintaining hydrostatic equilibrium. Finally, if the cooling time is shorter than the dynamical time, the cloud will cool faster than it can collapse, lowering the Jeans mass and possibly leading to fragmentation. This is the regime in which galaxies are thought to form (Rees & Ostriker, 1977; Silk, 1977).

We can divide the gas in the Universe into a couple of different phases in temperature-density space. Their relative importance at $z = 4$, 2, and 0 is shown in Figure 1.2. Gas with densities up to $\sim 10^2$ times the cosmic average density represents the intergalactic medium (IGM). In the beginning, there was no structure and all gas had densities very close to the cosmic mean and therefore all gas started out in the IGM. At later times, a significant fraction of this gas resides in filamentary structures. The gas can be heated to temperatures above $10^5$ K when kinetic energy, generated by gravitational infall or galactic winds, is converted into thermal energy. We refer to this tenuous, shock-heated gas as the warm-hot intergalactic medium (WHIM). The WHIM also includes denser halo gas. The intracluster medium is the very hot $T > 10^7$ K gas located in galaxy groups and clusters. Gas at overdensities $\rho/\langle\rho\rangle > 10^2$, but at much lower temperature ($T < 10^5$ K), resides mostly in the densest parts of filaments and low-mass haloes. Gas at very high densities $n_{\rm H} > 0.1$ cm$^{-3}$ is located inside galaxies, in the interstellar medium (ISM).

Although the IGM completely dominates the mass budget at high redshift, by $z = 0$ the WHIM carries about the same amount of mass (Davé et al., 2001). The ICM is never very important, because the highest-mass objects are rare (e.g. Shull et al., 2011). The amount of gas in the ISM and in low-temperature halo gas peaks at $z = 3 - 2$ and declines thereafter (e.g. van de Voort et al., 2011b)

In the low-density IGM, the dominant cooling process is the expansion of the Universe. As the gas reaches higher densities, radiative cooling becomes more important. The cooling time $t_{\rm cool}$ is shorter at higher redshift, because the density, $\rho$, is higher and $t_{\rm cool} \propto \rho^{-1}$. The Hubble time $t_{\rm H}$ is also shorter, but with a weaker dependence, $t_{\rm H} \propto \rho^{1/2}$. Hence, galaxy formation will depend on redshift. The so-called cooling radius is the radius, from the halo centre, where $t_{\rm cool}$ equals $t_{\rm H}$. If the cooling radius lies well inside the halo, which is the case for high-mass haloes, a quasi-static, hot atmosphere will form. Accretion onto the galaxy is then regulated by the cooling function. If, on the other hand, this

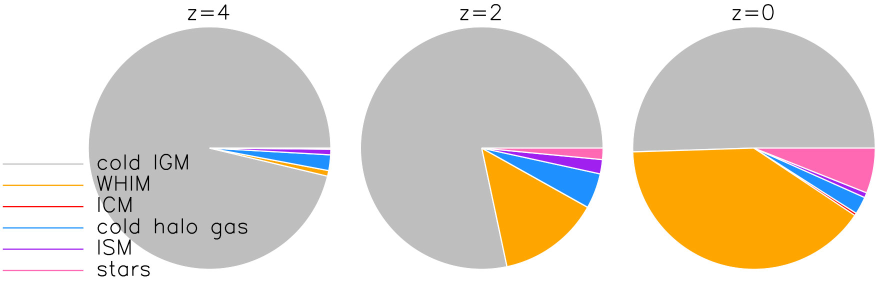


**Figure 1.2:** Distribution of baryonic matter amongst the different gas phases and stars. The cold IGM (grey) dominates, but becomes less important towards lower redshift. The WHIM (orange) becomes more important towards lower redshift. The ICM (red) is never very important. The amount of cold halo gas (blue) and ISM (purple) is largest at $z \approx 2$. The stellar mass keeps building up down to $z = 0$. The simulation used is the reference simulation in a $(50\ h^{-1}\mathrm{Mpc})^3$ volume from the OWLS project (Schaye et al., 2010).

radius is larger than the virial radius, then there will be no hot halo and the gas will not go through an accretion shock at the virial radius. The rapid cooling of gas in low-mass haloes was already shown by Rees & Ostriker (1977) and White & Rees (1978). The accretion rate onto the central galaxy then depends on the infall rate, but not on the cooling rate (White & Frenk, 1991).

Because haloes are not spherical, the cooling radius will not be the same for the entire halo. Gas can accrete onto a halo from the low-density IGM or along filaments of the cosmic web. The different gas densities will impact the temperature of the gas. As mentioned before, the gas needs to radiate away its energy to reach higher densities and thus to be able to enter a galaxy. Metal-line emission dominates the cooling function for metallicities $Z/Z_{\odot} \gtrsim 0.1$, which peaks at $T \approx 10^{5-5.5}$ K (Wiersma et al., 2009a). Gas at much higher temperatures will cool slowly. This gives rise to a bimodal temperature distribution for gas that accretes onto a massive halo (Kereš et al., 2005; Dekel & Birnboim, 2006).

Star formation in galaxies is fuelled by the accretion of gas from their haloes. Haloes replenish their gas reservoir by accreting from the IGM. When gas accretes onto a halo it can be shock-heated to the virial temperature of that halo and reach a quasi-static equilibrium supported by the pressure of the hot gas. We call this form of gas accretion 'hot-mode accretion' (Katz et al., 2003; Kereš et al., 2005). Because gas accreted onto high-mass haloes along filaments of the cosmic web or in clumps, or onto low-mass haloes, may not experience an accretion shock at the virial radius and will therefore remain cold until it accretes onto the central galaxy or is hit by an outflow, we refer to this mode of accretion as 'cold-mode accretion' (Katz et al., 2003; Kereš et al., 2005). Both modes can coexist. Especially at high redshift, cold streams penetrate the hot, virialized haloes of massive galaxies (Kereš et al., 2005; Dekel & Birnboim, 2006; Ocvirk et al., 2008; Dekel et al., 2009a; Kereš et al., 2009a; van de Voort et al., 2011a; Powell et al., 2011).

After gas has become part of the multiphase ISM of a galaxy, stars can form out of it. Star formation in galaxies is observed to follow a close relation between the gas surface density and the star formation rate surface density (Kennicutt, 1998). The gas surface density can be related to the gas volume density and both are a function of the total thermal pressure (Schaye & Dalla Vecchia, 2008). The observed gas consumption time-scale, i.e. the gas mass divided by the star formation rate, is of the order of a Gyr.

In the absence of any feedback mechanism, gas accretion and star formation happen too efficiently and the amount of baryons in stars would greatly exceed the observed amount. Outflows are routinely detected in the form of blueshifted interstellar absorption lines in the spectra of star-forming galaxies (e.g. Steidel et al., 2010; Rubin et al., 2010; Rakic et al., 2011a), in X-ray emission and in hydrogen Balmer-$\alpha$ line emission (e.g. Lehnert et al., 1999; Cecil et al., 2001; Veilleux et al., 2005). Single supernova explosions can temporarily outshine their host galaxy. The material from the star that is expelled at high velocity, sweeps up material in front of it, thus evacuating a bubble of hot gas around the original star. When many supernovae occur in the same region, the bubbles can overlap and form superbubbles, which can lead to large-scale galactic outflows (e.g. Weaver et al., 1977; Mac Low & Ferrara, 1999).

Supermassive black holes are present in all massive galaxies (e.g. Kormendy & Richstone, 1995; Ferrarese & Merritt, 2000). Material accreting onto these black holes is thought to release some of its rest mass energy to power active galactic nuclei (AGN) (Salpeter, 1964). AGN are invoked as a mechanism powerful enough to quench star formation in the most massive galaxies by driving gas out at high velocities.

Stars produce heavy elements, which can be distributed in their surroundings by stellar winds and supernova explosions. These metals are ejected from the galaxy by galactic winds driven by supernovae or AGN and enrich the halo gas as well as part of the IGM (e.g. Wiersma et al., 2011). The enrichment enhances the cooling rate of the gas and previously ejected gas can be reaccreted by the same object or a different one (Oppenheimer et al., 2010). Because of large-scale outflows, the IGM, haloes, and galaxies are intimately connected and the cycle of baryons becomes complicated as outflows and inflows interact.

Even though there is plenty of observational evidence for galactic outflows, inflows are not commonly seen. It is, however, quite possible that the inflowing material has such small cross-sections that the signal is completely swamped by outflowing material (e.g. Faucher-Giguère & Kereš, 2011; Stewart et al., 2011a). Hot, hydrostatic halo gas is routinely studied using X-ray observations of galaxy groups and clusters and has perhaps even been detected around individual galaxies (e.g. Crain et al., 2010a,b; Anderson & Bregman, 2011). As of yet, there is no direct evidence of cold-mode accretion, although there are some possible detections in emission (Rauch et al., 2011) and absorption (Ribaudo et al., 2011; Giavalisco et al., 2011).

Diffuse gas can be detected in absorption using a bright background source. UV and X-ray absorption line studies have revealed cold, neutral gas and the WHIM. Their interpretation is not easy, as there is only information along the line of sight and no information about the spatial extent of the absorbing cloud and often the location of the nearest galaxy is unknown. The neutral hydrogen column density distribution has been measured over ten orders of magnitude in $N_{\mathrm{H\,I}}$ (e.g. Tytler, 1987; Kim et al., 2002; Péroux et al., 2005; O'Meara et al., 2007; Prochaska & Wolfe, 2009; Noterdaeme et al., 2009; Prochaska et al., 2010). Low column density ($N_{\mathrm{H\,I}} < 10^{17.2}$ cm$^2$) material is known as the Lyman-$\alpha$ forest and originates mostly in the photo-ionized IGM (e.g. Bi et al., 1992; Cen et al., 1994; Hernquist et al., 1996; Theuns et al., 1998; Schaye, 2001a). Higher column density systems originate from gas in haloes and galaxies. By correlating the H I absorption in the spectra of background quasars with both the transverse and line of sight separations from foreground galaxies, Rakic et al. (2011b) have recently detected strong evidence for infall of cold gas on scales of $\sim 1.4 - 2.0$ proper Mpc at $z \approx 2.4$.

The gas emissivity in X-ray and UV scales with the square of the density. The signal is thus dominated by high-density regions. In this way, emission line studies complement the absorption line studies. They have the added advantage of providing a two-dimensional image, in addition to the third dimension provided by the redshift of the emission line, allowing us to study the three-dimensional spatial distribution. The interpretation of emitting gas would therefore be easier, but because the emission is very faint, detecting it is still a challenge.

How all processes occurring in galaxy formation interact is a field of active research. One can use numerical simulations as a tool to study this interplay and to predict the observational consequences.

## 1.2 Cosmological simulations

Because the time-scales involved in galaxy formation are generally very long compared to a human life time, numerical simulations are an excellent tool to study structure formation dynamically. Additionally it is possible to study a particular process by running two simulations, one with and one without it. The complex, non-linear behaviour of the density perturbations necessitates the use of supercomputers to perform the calculations. Numerical simulations have significantly improved our understanding of the large-scale structure in the Universe. Even though we know very little about the physical nature of dark matter and dark energy, the standard cosmological constant or vacuum-dominated cold dark matter ($\Lambda$CDM) model reproduces the observed large-scale structure and clustering of galaxies really well (Weinberg et al., 2004; Springel et al., 2005a).

Despite its many successes, this model is not sufficient to explain the properties of galaxies. Baryonic processes, that are not all well understood, are essential ingredients. Through feedback they can even impact the dark matter distribution, a process that one should take into account when doing precision cosmology (van Daalen et al., 2011; Semboloni et al., 2011).

Most cosmological simulations, i.e. simulations of structure formation in a representative part of the universe, use particles to discretize the mass, because of the superior spatial resolution to grid-based codes. The spatial resolution is automatically higher in denser regions, where galaxies form. Little time is spent on calculations in low density regions, where properties do not change rapidly anyway. Another advantage of particle-based simulations is that there is no preferred spatial direction and the resolution is increased continuously from low- to high-density regions. An advantage that is particularly important for this thesis is that we can trace the mass back in time to investigate its history.

The advantage of grid-based codes is that they are superior in resolving discontinuities, such as shocks. Turbulence and instabilities are also more easily resolved. An added advantage is that one can choose a different property than density as a refinement criterion and achieve high resolution in any region of interest.

The expansion of the universe is dealt with by using comoving coordinates. In physical space every volume element expands by an equal amount, set by the cosmological parameters. To deal with the thermodynamic property of baryons, smoothed particle hydrodynamics (SPH) can be used, in which some properties of particles, e.g. density and metallicity, are smoothed over space by a spline kernel function. Unfortunately, in SPH simulations shocks are not resolved as true discontinuities, but they are smeared out over a few smoothing lengths, leading to in-shock cooling (Hutchings & Thomas, 2000). This problem can be avoided by using a sufficiently high resolution (Creasey et al., 2011).

Although cosmological simulations can provide sufficiently accurate calculations for diffuse gas, once the gas reaches high densities, that are characteristic of the ISM, the multiphase medium cannot be resolved. The formation of individual stars from molecular clouds is not (yet) possible in cosmological simulations. The effect that stars have, through e.g. ionizing photons, metal production, stellar winds, and supernova explosions, has to be modelled with subgrid prescriptions. Subgrid models are also needed for radiative cooling, because it happens on the atomic level, and for accretion onto black holes, because the scale of the accretion disc is not resolved.

The goal of developing subgrid models is that, even though the small-scale physics is dealt with in an approximate, global sense, its effect is the same on scales that are resolved. Unfortunately it is not always clear what the large-scale effect should be and there is a lot of (unwanted) freedom in the subgrid modelling. The OverWhelmingly Large Simulations (Schaye et al., 2010, OWLS) project contains a suite of more than fifty cosmological, hydrodynamical simulations. There is a reference model and all other simulations are variations on this model, in the sense that only one parameter or one model was varied at a time. Even though there are certainly uncertainties associated with these simulations, their importance can be quantified by comparing simulations with different resolution and different subgrid physics. In this thesis we use a subset of the OWLS runs and will focus on the properties of gas accretion and their consequences, the effect of feedback, and the observational signature of diffuse gas outside galaxies.

## 1.3 This thesis

Numerical studies of the nature of gas accretion have revealed a bimodality, at least for massive haloes. The temperature of gas accretion onto haloes is either $\lesssim 10^5$ K or close to the virial temperature of the halo (Kereš et al., 2005; Dekel & Birnboim, 2006; Ocvirk et al., 2008; Dekel et al., 2009a; Kereš et al., 2009a; van de Voort et al., 2011a; Powell et al., 2011). Even though dividing accreting gas into two modes does not change the problem simulations have with reproducing observations, it can shed light on the physical mechanism behind it. In this thesis the following open questions will be addressed:

1. What are the properties of accreting gas? How do the properties of gas accretion onto haloes affect the accretion onto galaxies and subsequently the star formation rates of the galaxies?

2. What is the impact of realistic outflows on the inflowing gas? Is star formation quenched by ejecting gas from the ISM or by preventing it from accreting? Which processes set the global star formation rate?

3. Has cold-mode accretion already been observed as H I absorption systems? If so, in what kind of objects is it found? Is the cold-mode gas accreting for the first time or reaccreting?

4. Can we observe halo gas in emission in the near future? If so, which metal lines would be most promising and what do they tell us about the physical state of the gas?

A brief summary of the contents of this thesis is given below.

**Chapter 2: Gas accretion onto galaxies and haloes**

We found that gas accretion is mostly smooth, with mergers only becoming important for groups and clusters. Without supernova or AGN feedback the gas accretion rate onto haloes scales like the dark matter accretion rate. The same is not true for gas accretion onto galaxies, because the gas has to cool before it can enter the ISM of the galaxy. Including feedback from supernovae or AGN reduces the halo accretion rate by factors of a few and galaxy accretion rates by up to an order of magnitude, because outflowing gas prevents the inflowing gas from accreting. Galactic winds increase the halo mass at which the central galaxies grow most efficiently by about two orders of magnitude to $M_{\rm halo} \approx 10^{12}$ $M_\odot$.

Gas accretion is bimodal, with maximum past temperatures either of the order of the virial temperature or $\lesssim 10^5$ K. We define cold-mode (hot-mode) accretion as gas that is accreted and whose temperature did not exceed (did exceed) $10^{5.5}$ K before it accreted onto a galaxy. The fraction of the gas accreted onto haloes in the hot mode is insensitive to feedback and metal-line cooling. It increases with decreasing redshift, but is mostly determined by the halo mass. In contrast, for accretion onto galaxies, the cold mode is always significant and the relative contributions of the two accretion modes are more sensitive to feedback and metal-line cooling. (This work has been completed and published, van de Voort et al. 2011a.)

**Chapter 3: The drop in the cosmic SFR below redshift 2**

Given that hot- and cold-mode accretion vary with redshift and halo mass, we determine their roles in shaping the global star formation rate density. Including feedback processes is essential to match observations of the global star formation rate density, because it reduces the star formation rate in low- and high-mass galaxies. The cosmic star formation rate is observed to drop sharply after $z = 2$. We find that the drop in the star formation rate follows a corresponding decline in the global cold-mode accretion rate density onto haloes, but with a delay of the order of the gas consumption time-scale in the interstellar medium.

In contrast to cold-mode accretion, which peaks at $z \approx 3$, the hot mode continues to increase to $z \approx 1$ and remains roughly constant thereafter. By $z = 0$, the hot mode strongly dominates the global accretion rate onto haloes, but most of the hot halo gas never accretes onto galaxies. AGN feedback plays a crucial role by preferentially preventing the gas that entered haloes in the hot mode from accreting onto their central galaxies. Consequently, in the absence of AGN feedback, gas accreted in the hot mode would become the dominant source of fuel for star formation and the drop-off in the cosmic star formation rate would be much less steep. (This work has been completed and published, van de Voort et al. 2011b.)

**Chapter 4: Gas properties in and around haloes**

We study the properties of gas inside and around galaxy haloes as a function of radius and halo mass. The properties of cold- and hot-mode gas are clearly distinguishable in the outer parts of massive haloes. The cold-mode gas is mostly confined to clumpy filaments that are in pressure equilibrium with the diffuse, hot-mode gas. Besides being colder and denser, cold-mode gas typically has a much lower metallicity and is much more likely to be infalling. However, the spread in the properties of the gas is large. Due to a strong cooling flow near the central galaxy, the properties of gas accreted through the cold and hot modes in the inner halo are indistinguishable. Stronger feedback results in larger outflow velocities and pushes hot-mode gas to larger radii. The differences between cold- and hot-mode gas resemble those between inflowing and outflowing gas, although they are somewhat smaller. The gas properties evolve as expected from virial arguments, which can also account for the dependence of many gas properties on halo mass. (This work has been completed and submitted, van de Voort & Schaye 2012.)

**Chapter 5: Cold flows as H I absorption systems**

We use the OWLS reference simulation that has been post-processed with radiative transfer to study the contribution of cold flows to the observed $z = 3$ column density distribution of neutral hydrogen, which our simulation reproduces. We have found that nearly all of the H I absorption arises in gas that has remained colder than $10^{5.5}$ K, at least while it was extragalactic. In addition, the majority of the H I is rapidly falling towards a nearby galaxy, with non-negligible contributions from outflowing and static gas. Above a column density of $N_{\rm H\,I} = 10^{17}$ cm$^{-2}$, most of the absorbers reside inside haloes, but the interstellar medium only dominates for $N_{\rm H\,I} > 10^{21}$ cm$^{-2}$. Haloes with total mass below $10^{10}$ M$_\odot$ dominate the absorption for $10^{17} < N_{\rm H\,I} < 10^{21}$ cm$^{-2}$, but the average halo mass increases sharply for higher column densities.

Systems with $N_{\rm H\,I} > 10^{17}$ cm$^{-2}$ are closely related to star formation: most of their H I either will become part of the interstellar medium before $z = 2$ or has been ejected from a galaxy at $z > 3$. Cold accretion flows are critical for the success of our simulation in reproducing the observed rate of incidence of damped Lyman-$\alpha$ and particularly that of Lyman limit systems. We therefore conclude that cold accretion flows exist and have already been detected in the form of high column density H I absorbers. (This work has been completed and is in press, van de Voort et al. 2012.)

**Chapter 6: Metal-line emission from galaxy haloes**

The gas outside of galaxies is diffuse and therefore faint. With current and upcoming instruments we may be able to detect the halo gas in emission, even if only in a statistical sense. We calculate the expected metal-line emission as a function of radius from the central galaxy and compare it to the capabilities of current and future facilities. We found that detecting metal-line emission in the UV from halo gas at high redshift will be a challenge for upcoming instruments. When stacking galaxies to reduce the noise, it is in principle possible to observe C III, C IV, O VI, Si III, and Si IV out to $10 - 20$ per cent of the virial radius in haloes larger than $10^{11}$ M$_\odot$. These lines are somewhat brighter in haloes at low redshift, but future UV missions should aim to achieve a flux limit of $10^{-19}$ ergs s$^{-1}$cm$^2$ arcsec$^2$. At low redshift, proposed X-ray telescopes can detect O VIII emission out to the virial radius of groups and clusters. C VI, N VII, and O VII can also be detected to smaller radii, $0.1 - 0.5$R$_{\rm vir}$. Actually observing this gas would enable us to confirm or revise what we have learned from simulations. (This work is in an advanced stage of preparation and will be submitted soon.)

## 1.4 Outlook

Research will never truly be finished, because there will always be new questions that arise. Significant progress will be made in the near future in the study of galaxy formation, both observationally and theoretically. As observations improve, simulations will have to improve as well. Higher spatial resolution and time resolution will lead to improvements, especially when it goes hand in hand with the development of more advanced subgrid models.

Although we can quantify the uncertainties with the suite of simulations used for this thesis, many of the observed properties of galaxies are not reproduced by a single simulation. The Evolution and Assembly of GaLaxies and their Environments (EAGLE) project will be the largest SPH simulation down to $z = 0$ as of yet, with a resolution high enough to resolve the Jeans scale up to the star formation threshold and a volume large enough to contain a significant amount of massive haloes. The strategy is to tune the feedback parameters to match the observed stellar mass function and the stellar mass-halo mass relation. This will result in a large sample of relatively realistic, well-resolved massive galaxies and will therefore be well-suited for comparing to observations.

Radiative transfer is usually not taken into account in cosmological simulations. Instead, all the gas is assumed to be optically thin and is exposed to the same ionizing UV background radiation. In reality, inhomogeneous ionizing radiation from local sources and self-shielding of the gas can change the temperature and density of gas in haloes and in the IGM, so it should be included. Recent progress in radiative transfer modelling will make this feasible.

Numerical simulations help us investigate what is happening outside of galaxies, but we need to observe the material to confirm our ideas. Future instruments that have been designed for the detection of UV and X-ray emission will certainly aid our understanding. In particular, next year MUSE, an integral field spectrograph, will be installed on the VLT, which is expected to detect many sources, in emission and absorption (Bacon et al., 2010). Additionally, proposed X-ray missions would be ideal for detecting metal-line emission from the WHIM in the centres and outskirts of massive haloes and studying the gas properties (e.g. den Herder et al., 2011).

Lyman-$\alpha$ radiation is an important tool for observing the distant Universe, because it is much brighter than metal-line emission. Its interpretation is still a challenge, because the Lyman-$\alpha$ line is a resonant line and photons scatter many times before escaping, which strongly affects the line profile. Lyman-$\alpha$ radiative transfer simulations will allow us to disentangle radiative transfer effects from the kinematics of the gas in a statistically meaningful sample and help to interpret observations.