Chapter 6

Conclusions and future perspectives

In this Ph.D. Thesis, we have investigated the properties and dynamics of the cool circumgalactic medium (CGM) of low-redshift galaxies. This is a gas at $T \sim 10^4$ K, which has been extensively observed, mainly through absorption studies, in the halos of galaxies at $z < 1$, up to their virial radius (see Section 1.2.2). The aim of this work has been to address some of the open questions regarding this medium, outlined in the Introduction (see Section 1.5). To date, there are, indeed, several uncertainties related to the physical properties (like its density or metallicity) of the cool CGM and, most importantly, to its formation mechanisms. Whether this cool medium originates primarily from accretion of the intergalactic medium (IGM) into the galaxy halos, from feedback from the central galaxy, or from a combination of the two, is still unclear. Moreover, it is unknown how much the interaction with the hot phase of the CGM (also called corona) influences the properties and dynamics of the cool gas and whether the latter is able to feed the central galaxy’s star formation or, instead, evaporates into the surrounding environment. With this Thesis, using state-of-the-art observational constraints, coupled with original semi-analytical modeling and insight from high-resolution hydrodynamical simulations, we have investigated
these problems and we have been able to draw clear conclusions about the origin and fate of the cool CGM.

Below, we explain the main methods utilized in this Thesis and we summarize the results of the previous Chapters (Section 6.1), we list the implications that the findings of this work entail (Section 6.2) and, finally, we outline some of the possible future developments (Section 6.3).

6.1 Summary of the Thesis

Throughout this work, we have described the circumgalactic medium as composed of two distinct phases, with cool gas at $T \sim 10^4$ K in pressure equilibrium with a volume-filling hot ($T \sim 10^6-7$ K) medium, or corona. The hot gas is in hydrostatic equilibrium with the dark matter (DM) gravitational potential and generally accounts for 20% of the total amount of baryons associated with the halo\(^1\). This representation of the CGM is justified by several observational constraints, both for the cool (see Tumlinson et al. 2017, and references therein) and the hot (e.g. O’Sullivan et al. 2007; Miller & Bregman 2015; Bregman et al. 2018; Li et al. 2018) phase of this medium. The interactions with the hot corona, including pressure confinement, ram pressure (also called drag), hydrodynamical (e.g. Kelvin-Helmholtz and Rayleigh-Taylor) instabilities and thermal conduction, are crucial in determining the dynamics and most of the properties of the cool clouds. In Chapters 2, 3 and 4, we have developed and used semi-analytic parametric models to describe the CGM system, while in Chapter 5 we have made use of high-resolution hydrodynamical simulations. All the results of this study are based on the comparison of our theoretical predictions with state-of-the-art observations of the cool CGM around both early- and late-type galaxies in the local Universe.

In Chapter 2, we have described the cool CGM around massive early-type galaxies (ETGs) as a radial infall of clouds accreted from the IGM, at a rate comparable to the one predicted by cosmological models (Fakhouri et al. 2010). We have compared our model predictions with the kinematics inferred by the COS-LRG survey (Chen et al. 2018; Zahedy et al. 2019) and, through a Bayesian analysis, we have found that our models can successfully reproduce the data, with the drag force of the hot corona being fundamental in slowing down the cool clouds, bringing them to velocities similar to the observed ones. We also found that, in order to reproduce the observations, the clouds need to evaporate into the hot gas and are therefore not feeding the central galaxy’s star-formation, in agreement with the quiescent nature of ETGs.

In Chapter 3, we have moved our focus on star-forming galaxies. In this case, we have tested a popular model in which the cool CGM clouds are part of biconical outflows, powered by the supernova (SN) explosions in the disk. Similar to Chapter 2, we used a Bayesian analysis to compare our model pre-

\(^1\)In Chapters 3 and 4, we also explored models with a corona with a mass equal to, respectively, 2% and 40% of the total baryonic mass, finding similar results to the ones reported below.
dictions with real data, in this case given by the detections of the cool CGM around a sample of \( \sim 40 \) star-forming galaxies, from the surveys of COS-Halos (Werk et al. 2013) and COS-GASS (Borthakur et al. 2015). Given that the cool CGM is detected up to the virial radii of these galaxies, in order to overcome the gravitational attraction and the drag force of the hot gas, the outflows need very high velocities and mass loading factors. As a consequence, we have found that, to power such outflows, the efficiency with which the energy of supernova explosions is transferred to the kinetic energy of the outflowing gas needs to be of the order of 250%, which is unphysical. Such efficiencies are also in strong disagreement with theoretical expectations, where most of the energy is radiated away and the efficiency is of the order of 10% (e.g. McKee & Ostriker 1977; Kim & Ostriker 2015). We concluded that SN feedback alone cannot be the origin of most of the cool CGM around star-forming nearby galaxies.

In Chapter 4, we have adopted a similar approach to the one used in the previous Chapters, in order to explain the properties of the cool CGM of M31, which has been recently characterized in detail by the project AMIGA (Lehner et al. 2020), piercing the halo of M31 with more than 40 sightlines. Mapping the cool CGM of one single galaxy across its entire halo, this survey provides then an unprecedented amount of information. In this case, we compared models of both inflow and outflow for the cool clouds. We assumed, in accordance with theoretical arguments (e.g. Pezzulli et al. 2017) and observational constraints (Hodges-Kluck et al. 2016), that the hot corona is rotating, with a total angular momentum that is consistent with the cosmological expectations (see Cimatti et al. 2019) for the halo of M31. We calibrated our models on the AMIGA data. We have found that, similar to the other star-forming galaxies, SN feedback is not a viable way to reproduce the cool CGM around M31, given that the outflows require SN efficiencies of the order of 700%. On the other hand, we found that the inflow of low-metallicity (\( Z \approx 0.05 Z_\odot \)) gas, consistent with the accretion from the IGM, can nicely reproduce the observations. The total mass accretion of the cool medium is similar to the predictions from cosmological models (Correa et al. 2015a,b) and its angular momentum, due to the drag force of the hot gas, is consistent with the one of the corona.

Finally, in Chapter 5, we have utilized high-resolution hydrodynamical simulations, using the software PLUTO (Mignone et al. 2007, 2012), to better describe the interactions between the cool and hot phases of the CGM, focusing in particular on the gas populating the halo of M31. This allowed us to study the fate of the cool CGM clouds, which could not be determined with the semi-analytical models of Chapter 4. We have followed the infall of a single cloud, starting from the virial radius, including the effects of radiative cooling, thermal conduction and the DM halo gravitational potential. We have used the results of Chapter 4 as initial conditions for our numerical experiments. We have found that, in our simulations, the cool clouds are not able to survive their journey and to reach the galactic disk, evaporating instead into the hot corona, at distances larger than 150 kpc from the central galaxy.
6.2 Main implications for the cool CGM

6.2.1 The predominance of accretion

The main conclusion of this work is that the cool CGM is part of the accretion of gas into the halos of galaxies from the intergalactic medium (IGM). This is evident from the results of Chapters 2 and 4, where we have shown that models of gas accretion can successfully reproduce the observational data of COS-LRG (e.g. Chen et al. 2018) and AMIGA (Lehner et al. 2020). Moreover, it is also a natural implication of Chapter 3, where the accretion from the IGM represents the most likely origin of the cool gas, given that we exclude the scenario of SN feedback as a possible formation mechanism (see also below).

We found an accretion rate that is consistent with (although slightly higher than) the estimates of cosmological models based on dark-matter-only simulations (Fakhouri et al. 2010; Correa et al. 2015a,b). Moreover, from Chapter 4, we have found that this medium has low metallicity, with values that are not far from the typical estimates for the IGM (e.g. Danforth & Shull 2008). Therefore, the accretion from the IGM, in addition to successfully reproduce the observed cool CGM properties, represents also a physically motivated and self-consistent scenario. We conclude that this constitutes the main formation mechanism of the cool gas in the halos of both early- and late-type galaxies in the local Universe.

Based on the results from cosmological hydrodynamical models and simulations, the presence of cool accreting gas in the halos of galaxies at least as massive as our Milky Way is not obvious. In the cold/hot mode accretion scenario (e.g. Birnboim & Dekel 2003; Kereš et al. 2009, see Chapter 1), galaxies of this mass, at redshifts close to zero, are expected to be surrounded mainly by a hot gas atmosphere, while cool gas filaments should be able to penetrate in less massive halos (e.g. Dekel et al. 2009). The value of the mass threshold between these two types of accretion is, however, still debated. Moreover, when present, in cosmological simulations the cold accretion is composed by filaments that penetrate into the halos with large infall velocities (e.g. Nelson et al. 2016), while we found that, in our models, the cool clouds start at the virial radius with velocities of about 10 km s\(^{-1}\). We argued that these clouds are originated by the fragmentation of the streams entering the halo and interacting with the hot pre-existing CGM. The absence of cool gas clouds in large-scale hydrodynamical simulations might, instead, be due to the lack of resolution (see van de Voort et al. 2019). With this Thesis, we have demonstrated that the presence of cool gas clouds, accreted from the IGM and that account for a total amount of baryons comparable to the mass of the stellar component, is a common feature of low-redshift galaxies.

Finally, we note that, both in Chapter 2 and 4, we found an accretion rate that is slightly (1.5 times) higher than the theoretical expectations at the present time. This may be due to the fact that the gas accretion was larger in the past (3-4 Gyr ago, consistent with the cloud infall time in our models). However,
Main implications for the cool CGM

this result may also suggest that part of the cool CGM might form from different processes, among which we proposed satellite stripping (e.g. Greveich & Putman 2009; Marasco et al. 2016; Johnson et al. 2018) or thermal instabilities of the hot gas (e.g. Sharma et al. 2012; Sormani & Sobacchi 2019). Analyzing the details of these processes and their relation with the cool circumgalactic gas is however left for future work.

The (minor) role of SN feedback

One of the goals of this Thesis has been to investigate whether or not there is a connection between the star formation of the host galaxy and its circumgalactic medium. In particular, we explored whether the feedback from supernova explosions in the disk can be one of the main formation mechanisms of the cool CGM. We have seen indeed, in Chapter 1, that a large amount of cool ionized gas is observed both around passive and star-forming galaxies (e.g. Thom et al. 2012; Tumlinson et al. 2013; Huang et al. 2021) and the relation between the star-formation in the galaxy and the cool CGM is, to date, not clear.

While we do not expect strong galactic outflows in quiescent ETGs, many authors have proposed, both from a theoretical and an observational point of view, that in star-forming galaxies, a crucial role in the formation of the cool CGM is played by the SN feedback (e.g. Ford et al. 2014; Schroetter et al. 2019). We have explored this scenario in Chapters 3 and 4, where we have clearly shown, instead, that SN feedback is not able to impact the cool gas at a distance \( \geq 50 \) kpc from the galactic disk, since the energy requirements to bring these cool clouds up to these very large distances are too high. We conclude, therefore, that SN outflows may be important to determine the properties of the extraplanar gas (see Section 1.2.1), the inner region of the CGM, at the interface with the central galaxy, while the vast majority of the outer cool CGM can be, instead, explained with the accretion from the IGM.

6.2.2 Fate of the cool CGM

Understanding the fate of the cool CGM is crucial to infer the role of this medium in galaxy evolution. If some of this cool gas accretes on the central galaxy, it would join the galaxy’s reservoir of HI, which can fuel the formation of new stars at a rate that depends on the star formation efficiency. Observed properties of galaxies can be used to put limits of the amount of cold gas accretion that reaches the disk. If excessive accretion onto the disk takes place, galaxies would have either a gas fraction or a star formation rate (SFR) much higher than what we observe. As an example, in our study of the CGM of M31 (Chapter 4) we have inferred a rate of gas accretion, from the IGM into the CGM, of \( 15 \) \( M_\odot \) yr\(^{-1}\). If all of this gas reached the central galaxy, it would either double the mass of HI in less than 1 Gyr, or result in a star formation rate more than one order of magnitude larger than observed (\( \sim 1 \) \( M_\odot \) yr\(^{-1}\); Rahmani et al. 2016). The situation is even more puzzling for ETGs, which currently have a star formation rate close to zero and very small fractions of neutral hydrogen,
despite a gas accretion rate at the virial radius of hundreds of $M_\odot \text{ yr}^{-1}$ (see Chapter 2). Therefore, in Chapter 1 we argued that some mechanism must halt the flow of cool CGM from reaching the central galaxies. With the work presented in this Thesis, especially in Chapters 2 and 5, we have found that this mechanism is the evaporation of the cool clouds into the hot corona.

In Chapter 2, we attributed the evaporation of the clouds to the development of hydrodynamical instabilities and to thermal conduction, which is likely very efficient in the very hot gaseous halos of massive ellipticals ($T \lesssim 10^7$ K), approximating the cloud destruction with a constant evaporation rate. We have seen, in particular, that the cloud destruction is necessary to reproduce the observational data. In Chapter 5, we have found a similar result (the evaporation of the clouds) for star-forming galaxies (M31 in particular), where the temperature of the hot gas is lower ($T \sim 10^6$ K) with respect to the coronae of massive ETGs. In this case, we directly solved the system of ideal hydrodynamical equations, with the use of high-resolution numerical simulations. Our semi-analytical models and hydrodynamical simulations, therefore, suggest that, both in massive ETGs and in star-forming $L^*$ galaxies, the fate of the vast majority of the infalling cool CGM is to evaporate into the hot coronal gas (see also Section 6.3.3) and not to feed the central galaxy star formation, which is instead likely regulated by the processes happening in the inner gas layers of the halo (e.g. Marasco et al. 2012; Pezzulli & Fraternali 2016; Fraternali 2017), a problem whose investigation is outside the scope of this Thesis.

Furthermore, we have found that the majority of this cool gas is likely segregated in the external regions (intrinsic galactocentric distances $> 100$ kpc) of the halos and that the detections of this gas at impact parameters of a few tens of kpc are mainly due to projection effects.

### 6.3 Future prospects

#### 6.3.1 New observational constraints

All the findings of this Thesis are based on observational data, that we have used to calibrate our theoretical models. While the total sample used throughout this work is still limited, with a collection of only about 60 galaxies, recent and future surveys can provide numerous observational constraints that can potentially be interpreted by similar models. Combining surveys like MEGAFLOW (Schroetter et al. 2016), CGM$^2$ (Wilde et al. 2020) and CUBS (Chen et al. 2020a) can lead to a sample of up to several hundreds of objects, providing a more complete statistical view on the cool CGM of galaxies at redshift $\lesssim 1$ (and potentially also at higher redshift). Moreover, explaining the data of the cool gas around specific types of galaxies, going from dwarfs to galaxies with active galactic nuclei (AGN) and starburst galaxies, is also one of the future directions of this investigation and it can be achieved with the data currently available in the literature (e.g. Bordoloi et al. 2014; Heckman et al. 2017; Berg et al. 2018).

While building large statistical samples is very important, we have seen,
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In Chapter 4, how studying the CGM of a single galaxy halo can also be extremely useful in order to draw conclusions about the origin and dynamics of this medium. Extended maps of the cool CGM of single galaxies (like those available from the tomography of gravitational arcs, see for example Lopez et al. 2018; Tejos et al. 2021) can be crucial to improve our understanding of this gas and our models have the potential to interpret also this kind of data. Finally, by directly implementing in our models a self-consistent photo-ionization mechanism (using for example softwares like CLOUDY, Ferland et al. 2013), we could self-consistently reproduce, at the same time, the observed column densities of different ions. This might allow us to separate the properties of ions with low (e.g. Mg II) and high (e.g. O VI) ionization potentials and to, therefore, investigate separately the cool ($T \sim 10^4$ K) and warm ($T \gtrsim 10^5$ K) phases of the CGM.

In addition to the observations of the cool CGM, the launch within the next 15 years of several X-ray missions like ATHENA, Lynx, AXIS or XRISM (see for example Nandra et al. 2013; The Lynx Team 2018; Mushotzky et al. 2019; XRISM Science Team 2020; Simionescu et al. 2021), with a great improvement of both the spatial and spectral resolution of X-ray observations, will open a new window on the properties of the hot coronae surrounding low-redshift galaxies. Given the importance that the hot CGM has on the dynamics and fate of the cool circumgalactic clouds (see Section 6.2.2), a better characterization of this gas will be very useful in improving the accuracy of any model of the CGM.

### 6.3.2 Improving numerical simulations of the CGM

Hydrodynamical simulations are key to our understanding of the interactions between the different phases of the CGM. While large-scale, cosmological simulations have still an insufficient resolution (e.g. van de Voort et al. 2019), idealized, high-resolution simulations have extensively been used to study the properties of the cool gas and its survival in a hot ambient medium (e.g. Mariucci et al. 2010b; Armillotta et al. 2016; Schneider et al. 2018; Grønnow et al. 2018). However, the external regions of the halos, where we believe most of the cool CGM resides, have rarely been explored with this type of simulations (e.g. Armillotta et al. 2017).

In Chapter 5, we have shown a variety of results focused on the cool gas in the halo of M31. The analysis of these high-resolution hydrodynamical simulations has provided insight on the evolution of the mass, velocity and shape of the cool clouds, results that can be used to improve our semi-analytical models, as we also discuss in the next Section. Before doing so, however, a more thorough analysis is necessary. We plan, indeed, to implement additional physical effects, like the presence of an ionizing extragalactic UV background (e.g. Haardt & Madau 2012) or of the magnetic field (e.g. Kooij et al. 2021, although at these large galactocentric distances the magnetic field has likely only a secondary role in the cool gas evolution) and to further improve the study on the convergence of these simulations with the resolution. Finally, it is crucial to
investigate different initial conditions, in order to have a more complete view of the CGM of galaxies with different properties and to take into account the various uncertainties on the values of parameters including the hot gas temperature, the cloud masses and sizes and the metallicity of both phases of the circumgalactic gas.

6.3.3 Refining models of the CGM

Refining and generalizing the semi-analytic models of Chapters 2, 3 and 4 represents the main goal of this investigation in the near future. This can be done in different ways, some of which have already been discussed throughout this Thesis. As mentioned in Section 6.3.2, a fundamental step will be to incorporate the results of high-resolution simulations into our models, possibly describing the mass loss and size evolution of the clouds with physically motivated analytical prescriptions, which can be directly fit to the observational constraints. We have made a first attempt in this direction in Chapter 5, showing the potential of this approach in explaining the physics and the properties of the CGM.

Another possible improvement of our models is to include the variation of the cosmological accretion rate with time (e.g. Correa et al. 2015b). Furthermore, it would be important to model the mass increase of the hot gas: indeed, we have found that the fate of the cool gas is to evaporate into the hot corona, and given that the masses of the two phases are comparable with each other, the mass of the hot CGM should significantly increase with time. This problem has been briefly discussed throughout this Thesis, but we plan in the future to self-consistently implement this effect in our models. Finally, alternative scenarios to those investigated in this Thesis might also be relevant for the formation of the cool CGM. In particular, future possible studies include the modeling, as an origin of the cool gas, of gas stripping from satellite galaxies, condensation of the hot corona due to thermal instabilities (this scenario has partially been explored in Chapter 2), or of outflows due to AGN. The implementation of these effects will allow us to build a more complete description of the cool gas around galaxies.

Through the interplay between new observational data, results from hydrodynamical simulations and analytical modeling, the investigation started with this Thesis has the aim of improving our knowledge of the circumgalactic medium of galaxies. By understanding the dynamics, origin and fate of this gas, we can indeed take a fundamental step in our comprehension of how galaxies form and evolve in the Universe.