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HI mock-observations of simulated low-mass galaxies in a
multi-phase ISM model

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Zusammenfassung

Die Entwicklung von Galaxien wird durch ein Zusammenspiel verschiedener physikalischer Prozesse vorangetrieben. Zwerggalaxien nehmen in der Erforschung dieser Prozesse eine bedeutende Rolle ein, da sich einzelne Effekte aufgrund des geringen Gravitationspotentials besonders auf ihre Struktur und innere Dynamik auswirken. Auch in der Kosmologie spielen Zwerggalaxien eine wichtige Rolle, da sie als die kosmologischen Grundbausteine angesehen werden. Das Standardmodell der Kosmologie (Λ CDM) trifft für diese Grundbausteine bestimmte Vorhersagen, welche mittels Vergleich zwischen Simulationen und Beobachtungen überprüft werden können. Auf großen, kosmologischen Skalen ist die Übereinstimmung zwischen Modell und Beobachtung bemerkenswert. Jedoch auf kleinen Skalen, im Bereich der Zwerggalaxien, treten einige Unstimmigkeiten auf. Aufmerksamkeit erregt hat in den vergangenen Jahren etwa die große Diversität an Rotationskurven-Formen, welche Galaxien im niedrigen Masse-Bereich aufweisen. Diese wird im Λ CDM-Paradigma nicht erwartet, da die Massenverteilung innerhalb der Galaxien als einheitlich angenommen wird. Ähnliche Spannungen konnten in der Vergangenheit durch Fortschritte in den Simulationsmethoden gelöst werden, insbesondere durch die Implementierung baryonischer Prozesse. Bisher konnte die Rotationskurven-Diversität jedoch nicht durch solche Effekte erklärt werden. Untersuchungen deuten darauf hin, dass die Rekonstruktion der Rotationskurven aus Beobachtungsdaten mittels gängiger Methoden an sich problematisch ist. Im Hinblick auf diese Überlegungen wurden in diesem Projekt die HI-Rotationskurven massearmer Galaxien aus kosmologischen Simulationen analysiert. Zur Verfügung gestellt wurden die Daten von sechs Test-Durchläufen von COLIBRE, eines Vorreiter-Projekts, welches kosmologische Simulationen mit einem mehrphasigen Modell für das interstellare Medium verwirklicht. Dazu wurden simulierte Beobachtungen durchgeführt und die Rotationskurven mittels der etablierten „Tilted-Ring-Methode“ rekonstruiert. Diese gemessenen Rotationskurven wurden mit den Rotationskurven verglichen, die direkt aus den Simulationsdaten erhoben wurden. Die Ergebnisse deuten darauf hin, dass die Ableitung des Masseprofils von Galaxien aus deren gemessenen Rotationskurven problematisch sein kann, da sowohl Störungen der Gasrotation als auch beobachtungsspezifische Effekte auf die gemessenen Kurven Einfluss haben können. Dieses Phänomen verstärkt sich bei Galaxien, die nur schwach rotationsgestützt sind.

Abstract

Low-mass galaxies play a profound role in our understanding of galaxy formation and evolution. They are shaped by various physical processes, to which their shallow gravitational potential makes them particularly sensitive. Also an interplay between baryonic processes and the dark matter halo becomes apparent in simulations of low-mass galaxies. In the cosmological context, dwarf galaxies are seen as the building blocks of larger systems, for which the standard model of cosmology (Λ CDM) predicts specific properties. Hence, dwarf galaxies have become valuable laboratories to test not only our understanding of galactic physics but also that of dark matter and cosmology. As such, they have been in the focus of studies addressing tensions between the modelled and the observed Universe. One such tension that has gained attention in recent years is the observed rotation curve shape diversity of low-mass galaxies, which is not predicted by simulations within Λ CDM. A number of similar small-scale challenges to the Λ CDM model have been alleviated by more accurate models of baryonic processes. However, regarding the rotation curve diversity, recent studies suggest that tensions may arise from the methods used to reconstruct observed rotation curves. In light of this, the H I rotation curves of low-mass galaxies from cosmological volumes simulated with state-of-the-art baryonic models were analysed. Provided were six test runs from the COLIBRE project, which is one of the pioneering cosmological simulation projects to explicitly model the multi-phase interstellar medium. Mock-observations were used to recover the rotation curves with the standard method of tilted-ring modelling. The mock-observed curves are compared to the true particle velocity curves and particle mass distributions to assess the reliability of observed rotation curves as tracers of the underlying matter profile. While the radial mass distributions are generally in agreement with the profiles expected in the Λ CDM paradigm, the rotation curve of the gas particles and the mock-observed rotation curves deviate in most cases and exhibit a diversity in shapes that is comparable to that of observed galaxies. The effect tends to be stronger in galaxies with weaker rotational support. The results imply that measured galaxy rotation curves are impacted by gas perturbations as well as observational effects.

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1. Introduction

In the endeavour to fathom the complexities of galaxy formation and evolution, a number of valuable clues can be found at the low-mass end of the galaxy population. Due to their low gravitational potential, dwarf galaxies are particularly sensitive to the processes that drive galaxy evolution, such as mergers, feedback mechanisms, winds, gas accretion, and environmental effects. Their morphological and kinematic structures thus provide important insight into the contributions from the respective mechanisms. Also in our understanding of cosmology, dwarf galaxies play a fundamental role, namely that of the cosmological building blocks of larger systems. In both aspects, cosmological simulations provide a valuable tool to advance our understanding. Not only do models of galaxy formation help us comprehend the relevant processes at play, simulations also provide a possibility to directly track the evolution of galaxies and the large-scale structure over cosmological time scales. At the same time, the underlying cosmological model can be tested by comparing the simulated Universe with the observed.

The current standard model of cosmology is the Λ -cold dark matter (Λ CDM) model. In brief, this model assumes that General Relativity is valid, that dark energy (represented by the letter Λ) drives the expansion of the Universe, and that, apart from a very small portion of visible baryonic matter, the matter in the Universe is primarily dark, cold and collisionless, i.e. its motions are non-relativistic and it interacts only gravitationally with visible matter. This model has been very successful in describing the formation of the large-scale structure of the Universe and is supported by observational evidence provided by the cosmic microwave background (CMB, [Aghanim et al., 2020](#)). Yet, several tensions between the model and observations have been identified.

On small (galactic) scales, it has been the dwarf galaxy population in particular, which has challenged the prevailing Λ CDM model. Mismatches were reported concerning e.g. the abundance and distribution of satellite galaxies or the internal mass distribution of low-mass galaxies in general. For example, the Λ CDM model makes clear predictions about the number of subhalos (building blocks) of a halo of given mass. However, the number of satellite galaxies surrounding the Milky Way (MW) was reported to be lower than predicted. This issue has been widely discussed as the ‘*missing satellites problem*’ ([Klypin et al., 1999](#)). Moreover, the model robustly predicts the mass distribution among the subhalos. However, the most massive predicted subhalos for a MW-mass galaxy could not be matched to the brightest observed MW satellite galaxies, although it is not expected that such massive subhalos would fail to form stars. This issue has thus been termed the ‘*too-big-to-fail problem*’ ([Boylan-Kolchin et al., 2011](#)). Furthermore, the model predicts a widely isotropic spatial distribution of subhalos around a host halo. This is contradicted by the observed orbital alignments of the MW satellites, hence, the ‘*planes of satellites problem*’ ([Pawlowski 2018](#)).

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Regarding the internal density structure, the Λ CDM model predicts that dark matter (DM) halos are self-similar at all scales and described by a Navarro-Frenk-White (NFW, Navarro et al. 1997) density profile with a central density ‘cusp’. However, observations have revealed low-mass galaxies with flat density ‘cores’, creating the ‘*cusp-core problem*’ (de Blok, 2010).

These early works comparing simulations to observations used dark-matter-only (DMO) simulations, which can be a legitimate approximation for certain purposes, given the predominance of dark matter. However, especially on the small scales, where gravitational potentials are small, baryonic processes do matter. Indeed, some of the above-mentioned tensions could be alleviated as simulations became more advanced, taking baryonic processes into account (see Sales et al. 2022). For instance, it has been shown that baryonic feedback mechanisms can impact the distribution of dark matter by altering the gravitational potential via mass outflows, transforming ‘cusps’ into ‘cores’ (Pontzen & Governato, 2012).

In the focus of this project is the ‘*rotation curve diversity problem*’ (Oman et al. 2015), which has gained attention in recent years. Observed late-type dwarf galaxies show a large diversity from slowly to steeply rising rotation curves, even at fixed mass. Assuming that the rotation curve traces the underlying mass distribution, this implies a diversity in the inner density structures, which is not expected in Λ CDM cosmology. The implementation of baryonic processes alone, which provided an explanation for the ‘cusp-core’ problem, does not suffice to reproduce the observed diversity. Different prescriptions for star formation and feedback in various large-scale cosmological simulations have lead to either cuspy or cored density profiles of low-mass galaxies, but failed to capture the full diversity (see Santos-Santos et al. 2020). Thus, while feedback mechanisms are capable of transforming desity cusps into cores within the Λ CDM paradigm, they cannot explain why galaxies at fixed mass can be either cuspy or cored. Such discrepancies can be highly informative, as they highlight gaps in current understanding and help identify the relevant questions to address.

The Λ CDM small-scale challenges have motivated research to explore alternative dark matter models, such as warm dark matter (WDM) or self-interacting dark matter (SIDM) or Modified Newtonian Dynamics (MOND). However, a mismatch between observations and predictions by simulations may not necessarily mean a failure of the underlying cosmological model, but could also arise from the limitations of observational and computational methods. From the computational side, a valid comparison to observations and a test of any cosmological model require that the *known* physics are modelled as accurately as possible.

In this respect, cosmological simulations have progressed considerably. Over the past decades, large efforts have been made to account for complex baryonic processes. Along with increasing resolution, the models describing star formation, feedback mechanisms, gas heating and cooling and chemical evolution have become more and more refined. One recent advancement is the multi-phase realisation of the interstellar medium (ISM). Modern hydrodynamic cosmological simulations projects(such as e.g. EAGLE, ‘Evolution ans Assembly of GaLaxies and their Environment’ Schaye et al. 2015), have previously

used a simplified ISM model, which did not capture the cold atomic and molecular gas phases directly. Instead, they imposed an artificial pressure floor, which should prevent gas clumps from collapsing below the resolved scales. However, such a model tends to result in too smooth disks with too large scale heights (see Crain & van de Voort 2023). In the endeavour of simulating realistic galaxies, the ISM structure is not irrelevant, since the different gas phases trace different stellar and interstellar processes and conditions and, therefore, follow different kinematics and vertical distributions within the galaxy. The COLIBRE (‘COLd ISM Better REsolution’ Schaye et al. 2025) simulation project, which provided the data for this project, is a successor project of EAGLE. The COLIBRE model incorporates the complexities of the ISM directly, representing the state of the art of cosmological simulations.

On the observational side, the approach to constrain structure of dark matter halos is to derive the mass profiles of galaxies from their rotation curves. For gas-rich disk galaxies, neutral atomic hydrogen (H I) and the corresponding 21-cm signal serves as a favourable tracer, due to its high abundance and large extent across the galaxy disk. Also here, mismatches between observations and simulations can be caused. On the one hand, there are instrumental limitations. Regarding rotation curve measurements, the effect of beam smearing is a relevant issue. Limited spatial resolution can smear velocity gradients, mainly affecting the inner part of the rotation curve (Bosma 1978). This effect thus leads to a damping of the measured inner rotation velocity and to an apparent cored rotation profile. The effect of beam smearing can be mitigated if the data is well-resolved, or if the effect is accounted for in the reconstruction of the rotation curves. As technical possibilities advance, issues related to spatial resolution or noise can be largely mitigated.

On the other hand, problems may arise from simplified assumptions made in the reconstruction of the rotation curves. The standard method to fit observed H I rotation curves is to use a tilted-ring model, which decomposes the rotating gas disk into concentric rings, which are described by the relation

$$V_{los} = V_{sys} + V_{rot} \sin(i) \cos(\theta), \quad (1.1)$$

where V_{los} is the measured line-of-sight velocity, V_{sys} is the systemic velocity, i is the inclination of the ring and θ is the position angle of the projected ellipse. This is an accurate description only for razor-thin disks with perfect circular motion. For real galaxies, this approximation may suffer from the presence of non-circular motions and degeneracies between disk thickness and inclination (Di Teodoro & Fraternali 2015). Non-circular motions of the H I gas can be a cumbersome issue in the recovery of rotation curves. They can be caused by stellar bars, spiral arms, triaxial halo potentials or bursty star formation and can be expected to occur frequently in dwarf irregular galaxies. Oman et al. (2019) showed that non-circular motions lead to a strong dependence of the measured rotation curve on the viewing angle under which the galaxy is observed. This leads to deviations of the recovered rotation curve from the bulk rotation, depending on the alignment between the velocity pattern and the line of sight. Oman et al. (2019) also demonstrated that lower-velocity extra-planar gas in thick gas disks biases the deviations due to this

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effect towards more slowly rising rotation profiles, which additionally complicates the reconstruction of the circular velocity curves of low-mass galaxies.

Another assumption that is usually made when deriving the mass distributions from observed rotation curves is that the observed rotation velocity equals the circular velocity, which is directly related to the enclosed mass

$$V_{\text{circ}} = \sqrt{\frac{G m(< r)}{r}}, \quad (1.2)$$

where G is the gravitational constant and $m(< r)$ is the mass enclosed within radius r . However, [Downing & Oman \(2023\)](#) showed that H I rotation curves might not be reliable tracers of the circular velocity curves, as there may be perturbations of the gas motions that are not readily identifiable by the observer. The authors identified galaxy interactions, vertical or radial bulk motions, strong warps, galactic winds and triaxial DM halo potentials as the most common causes of such perturbations in simulated galaxies from the APOSTLE [\(Fattahi et al. 2016\)](#) zoom-in simulation project.

Recent studies suggest that these complications in the kinematic modelling could be the dominant cause for the observed rotation curve diversity (see e.g. [Roper et al. 2023](#) [Sands et al. 2024](#)).

The aim of this project is to examine the diversity of rotation curves of simulated galaxies from a set of test runs provided by COLIBRE, a state-of-the-art cosmological simulation project. Mock observations of atomic hydrogen are used for a valid comparison between the simulations and observed data. In addition, the mock-observed rotation curves are compared to the mass distribution and particle velocities obtained from the simulation data, in order to explore the impact of systematic observational effects.

2. Methods

2.1. The simulations

The analysis of the simulated galaxies was conducted on a series of test runs from the recent cosmological simulation project COLIBRE (Schaye et al., 2025). COLIBRE is a successor project of EAGLE and stands for ‘COLd Ism Better REsolution’. In addition to realising a high spatial and mass resolution, which is needed to follow the evolution of low-mass galaxies, COLIBRE incorporates an explicit model of the multi-phase ISM, capturing also the cold and dense gas phases, which has previously not been standard in large-scale cosmological simulations such as EAGLE. In order to achieve this, a number of processes need to be modelled, which govern the interaction between gas, dust and radiation. These include radiative cooling, self-shielding, dust and chemical evolution and corresponding cooling mechanisms, star formation, ionisation and recombination, stellar feedback and radiation pressure. The description of these processes is complex and requires adequate sub-grid representations. The computational effort is made feasible with the used code SWIFT (Schaller et al., 2024). The main aspects of the code design of SWIFT and the simulation configurations are described in the following.

2.1.1. The SWIFT code

The code used is the publically available smoothed particle hydrodynamics (SPH) code SWIFT. The abbreviation stands for SPH With Inter-dependent Fine-grained Tasking, which hints at the procedural principles of the code. In SPH, the hydrodynamical fluid is sampled by discrete Lagrangian particles, i.e. parcels following the fluid flow. Ensuring continuity within the fluid, the physical properties are interpolated between the discrete particles. This is realised by convolving the particle-carried quantities, such as mass, thermal energy, etc., with a smoothing kernel. The basic working principle of SPH is illustrated in Fig. 2.1. The smoothing length h of a particle determines the radius of influence within which the kernel operates. h itself depends on the local particle number density to ensure adequate sampling. The exact weighting of the contribution from a neighbouring particle j at a distance r_j depends on the shape of the kernel. In this framework, the hydrodynamical equations of motion are solved and the internal energies evolved.

Dark matter is represented by its own particle type, which, on the ground of Λ CDM cosmology, interacts only gravitationally with other particles. The gravitational force between particles is softened in order to avoid unphysical behaviour when particles come spatially close to one another. The particles are, therefore, assigned a gravitational softening length ϵ_{dm} for dark matter and ϵ_{bar} for baryonic particles. SWIFT uses a

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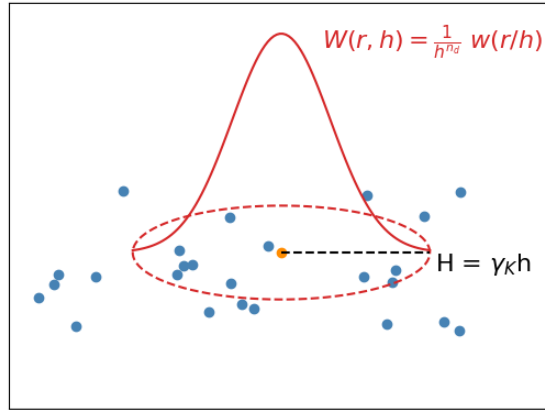


Figure 2.1.: Schematic 2D-representation of the basic working principles of SPH. The kernel function $W(r, h)$ and the kernel support radius H are determined by the smoothing length h . n_d is the number of spatial dimensions. Via convolution with the smoothing kernel, the quantities describing the particle of interest (orange) are influenced by the neighbouring particles, i.e. particles that are within a radius $r \leq H$ from the particle of interest. The weighting of the influence depends on the distance r_j of the respective particle with index j and on the kernel shape $w(r/h)$. The factor γ_K is specific to the smoothing kernel used (see Dehnen & Aly 2012).

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Wendland C2 (Wendland 1995) kernel for softening on particle distances below 3ϵ . Above this scale, gravity is Newtonian.

As a gravity solver, the code implements a fast-multipole method, where the long-range gravitational interactions are approximated by interactions between the centers of mass of particle groups. This grouping is achieved by constructing a hierarchical tree structure. One characteristic trait of SWIFT is its ‘hydrodynamics first’ approach, i.e. the structure of the tree is based upon the distribution of the SPH neighbourhoods.

For a given particle, the neighbourhood is the set of surrounding particles within the kernel’s radius of influence. Since the properties of the given particle are connected to its neighbourhood, the basis of SPH interactions is layed by the distribution of neighbours. The performance gain of SWIFT with respect to other codes is largely based on the neighbour-finding algorithm used. Classically, SPH codes have performed the search for neighbouring particles using tree-walks, which are time-consuming and hinder efficient parallelisation of tasks. In the EAGLE simulations, for example, over 65% of the computation time was consumed by the neighbour-finding algorithm which relied on a tree-walk (Schaller et al. 2024). SWIFT, instead, uses a nested grid, which defines the cells in which neighbouring particles can be found. The structure of the grid follows the pattern of an oct-tree, as the cells are split into eight children, whereby the size of the cells reflects the local particle density of the neighbourhood. However, no walks up and down the tree have to be performed in the hydrodynamic scheme. All information about possible interaction pathways lies in the structure of the grid and corresponding calculations need to be performed only for particles within one grid cell and for particles in adjacent cells.

This neighbour-finding algorithm, together with the task-based parallelisation scheme, is the procedural basis of the SWIFT code. The task-based parallelism ensures that the workload is balanced among the computing threads and computing time is thus used efficiently. The classical parallelisation approach used in most cosmological simulation codes is to assign the computing cores to different patches of the simulated volume. This, however, means an inhomogeneous distribution of workload, as some volumes might be computationally more demanding than others. Since this approach requires global synchronisation points, it leads to a substantial amount of unused computation time that is spent waiting for all units to finish a specific task. By grouping the particles into grid cells that define which particles can interact with each other, operations on independent cells can be performed simultaneously. Making use of this advantage, SWIFT distributes the workload on a task-based basis. In principle, all tasks are queued (once potential dependencies are fulfilled) and can be fetched and executed by any available computing thread. This enables the code to tap the potential of modern architectures of high-performance computers and comply with the high computational demand of high-resolution cosmological simulations.

The specific parameter configurations used to run the COLIBRE test simulations are summarized in the next section.

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Version	Name	Description
2022/02	chemtab_ESN_2p0	pre-tabulated chemical rates, fixed SNII energy of $2.5 \cdot 10^{51}$ erg
2023/03	chimes_ESN_var	chemical rates calculated by CHIMES, varying SNII energies applied
2023/08	chimes_ESN_var_hmin	decreased $h_{min, ratio}$ wrt. previous runs
2023/08 shield 0.5	shield_0p5	broadly like <code>chimes_ESN_var_hmin</code> , slight changes in feedback energy and temperature ranges
2023/08 shield 1.0	shield_1p0	identical to <code>shield_0p5</code> except for shielding length factor
2023/08 LR	lowres	low-resolution run; else broadly like <code>chimes_ESN_var_hmin</code>

Table 2.1.: Overview of the main differences between the simulation test runs. ‘Version’ refers to the date (year/month) and, where required, specification of the test runs conducted by the COLIBRE team. ‘Name’ refers the name given to the respective runs in the present thesis text.

2.1.2. The simulation runs

During the course of this work, the COLIBRE project was still under development. Provided were the snapshots at redshift $z = 0$ of six simulation test runs that differed in resolution or in specific parameters used to describe the baryonic sub-resolution models. For all runs, the models were calibrated to reproduce the observed galaxy stellar mass function and stellar mass vs. half mass radius relation at redshift $z = 0$. For illustration, Figure 2.2 shows the projected gas density maps of the simulated volumes at $z = 0$. The following is a basic overview of the simulation configurations, highlighting the relevant differences between the various runs. Short descriptions are listed in Table 2.1

Numerical resolution

Table 2.2 lists the parameters describing the mass resolution and the gravitational and hydrodynamic force resolutions realised in the different simulation runs. All except the low-resolution run used the same initial particle mass of $2.26 \times 10^5 M_\odot$ for gas particles and $3.03 \times 10^5 M_\odot$ for dark matter particles. The low-resolution simulation used an initial mass of $1.8 \times 10^6 M_\odot$ for gas and $2.42 \times 10^6 M_\odot$ for dark matter particles, respectively. The hydrodynamic and gravitational force softening lengths of gas and DM particles in the low-resolution run are twice the softening lengths in the high-resolution runs. The parameter $h_{min, ratio} = \gamma_K h_{min} / 3\epsilon$ describes the resolution of the hydrodynamic forces (given by the minimum smoothing length h_{min}) in terms of the gravitational force resolution ϵ_{bar} . Ploekinger et al. (2024) showed that this resolution parameter is critical for the numerical stability of simulations that model the cold ISM explicitly. In the provided test

2.1. The simulations

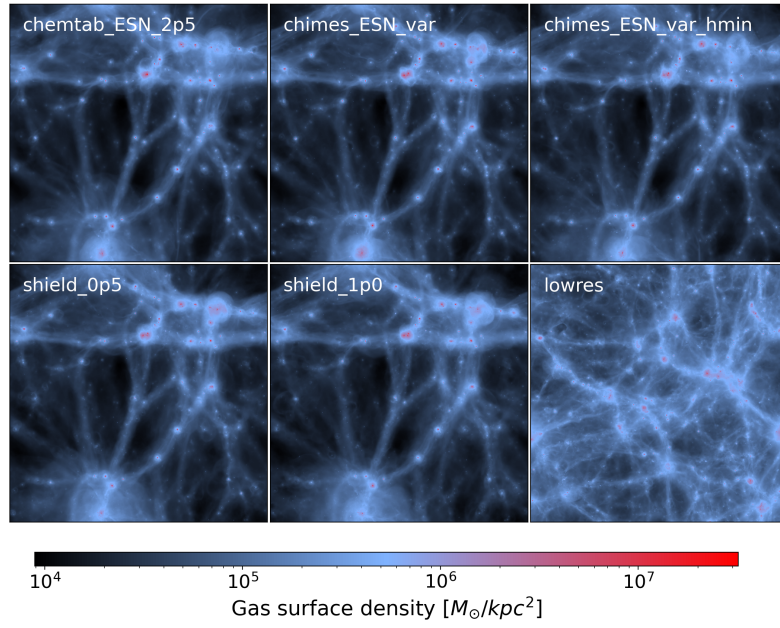


Figure 2.2.: Gas surface density maps of the simulated volume. As reflected by the similarity of the five high-resolution boxes, these simulation runs share the same initial conditions. The visible differences between these maps arise from a combination of parameter variations and the stochastic nature of the sub-grid models (see [Borrow et al., 2023](#)). The low-resolution run (bottom right panel) used a larger box size (see Table [2.2](#)) and different initial conditions.

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Simulation run	L (cMpc)	N	m_{gas} ($M_{\odot}$)	m_{dm} ($M_{\odot}$)	ϵ_{bar} (pkpc)	ϵ_{dm} (pkpc)	$h_{\text{min, ratio}}$
chemtab_ESN_2p5	12.5	376^3	2.26×10^5	3.03×10^5	0.35	0.41	0.01
chimes_ESN_var	12.5	376^3	2.26×10^5	3.03×10^5	0.35	0.4095	0.01
chimes_ESN_var_hmin	12.5	376^3	2.26×10^5	3.03×10^5	0.35	0.4095	1e-8
shield_0p5	12.5	376^3	2.26×10^5	3.03×10^5	0.35	0.4095	1e-8
shield_1p0	12.5	376^3	2.26×10^5	3.03×10^5	0.35	0.4095	1e-8
lowres	25	376^3	1.8×10^6	2.42×10^6	0.7	0.819	1e-8

Table 2.2.: Resolution parameters of the various simulation runs. Columns from left to right: name of simulation run, comoving cube length L , particle number N in cube, initial mass of gas particle m_{gas} , average mass of dark matter particle m_{dm} , baryonic gravitational force softening length η_{bar} , dark matter gravitational force softening length η_{dm} , SPH resolution parameter $h_{\text{min, ratio}}$

	chemtab_ESN_2p5	all other runs
Ω_b	0.0482518	0.0486
Ω_{CDM}	0.2587481	0.256011
Ω_{Λ}	0.693	0.693922
Ω_r	0	7.79180471e-5
h	0.6777	0.681

Table 2.3.: Cosmological parameters used in the simulation test runs

runs $h_{\text{min, ratio}}$ varies between the small values 0.01 and 10^{-8} . For comparison, EAGLE used an $h_{\text{min, ratio}}$ of 0.1.

Cosmological framework

All simulations were performed within the cosmological framework of Λ CDM. The chemtab_ESN_2p5 run differed from the subsequent runs in the cosmological parameters used, which are listed in Table 2.3. Furthermore, neutrinos were only considered in the subsequent runs, which is, however, more relevant for the large-scale structure of the simulated Universe than on the scales of low-mass galaxies (see e.g. Abazajian & Kaplinghat, 2016). All simulations started at redshift $z=127$ and used the multi-scale Gaussian white-noise field Panphasia (Jenkins, 2013) to set the initial conditions.

Gas cooling

Gas cooling was implemented directly, allowing the gas to transition from the ionised phase to the cold atomic and molecular phases. This has not been standard in large-scale simulations (e.g. EAGLE), which impose an artificial pressure floor in order to avoid numerical instabilities at high densities. Figure 2.3 illustrates the effect of such a pressure floor on the temperature-density distribution of the ISM. Gas that would naturally cool

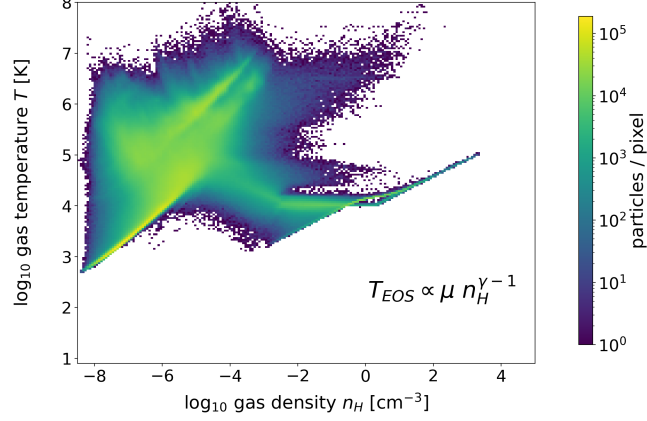


Figure 2.3.: Temperature-density diagram of hydrogen gas from the `chemtab_ESN_2p5` simulation re-run with a temperature floor T_{EOS} corresponding to an effective equation of state $P_{EOS} \propto \rho^\gamma$ with $\gamma = 4/3$.

below a certain temperature is forced to follow an effective equation of state of the form $P \propto \rho^\gamma$ (or $T \propto \mu \rho^{\gamma-1}$), where P and T are the pressure and temperature, respectively, ρ is the density, μ is the mean molecular weight and γ is the adiabatic index.

COLIBRE does not use such a pressure floor. Instead, the underlying physical conditions are allowed to govern the evolution of the ISM, also in the cold and dense regions. Figure 2.4 shows the temperature-density diagrams of the total gas in the six simulation test runs. Figure 2.5 shows the part of gas that is inside the low-mass galaxies. The horizontal branch in the temperature-density diagrams at $T \sim 10^4$ K corresponds to H II regions, i.e. ionised regions surrounding young massive stars. This is the warm ionised medium (WIM). Above this temperature and at lower densities there is gas that has been heated by supernova (SN) events or active galactic nuclei (AGN). The warm neutral medium (WNM) and the cold neutral medium (CNM) reside in the thermally stable regions at around 10^4 and 10^2 K, respectively. The density at which the medium transitions between the two regimes depends on the gas metallicity. The exact shape of the branches also registers non-equilibrium heating and cooling rates.

Overall, the WNM extends from $n_H \sim 10^{-3} \text{ cm}^{-3}$ up to densities of $n \sim 10 \text{ cm}^{-3}$. The enhanced particle concentration in the CNM branch emerges around $n \sim 10^{-1} \text{ cm}^{-3}$ and extends to densities $n_H \gtrsim 10^2 \text{ cm}^{-3}$. Molecular clouds are found at the cold and dense end of the CNM, typically with temperatures below 30 K and with densities $n_H \gtrsim 10^2 \text{ cm}^{-3}$.

The heating and cooling rates within the interstellar gas are determined by the radiation field which the gas is exposed to, the shielding column density, which determines how much of the radiation is felt by the gas at what depth, and the chemical composition, which affects the absorbing and emitting properties of the medium. Dust, which has very

2. Methods

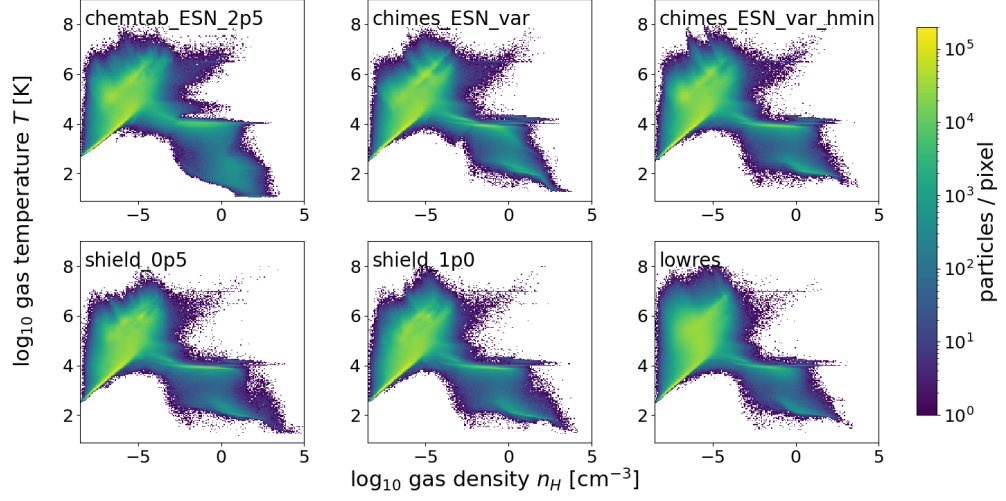


Figure 2.4.: Temperature-density diagrams of hydrogen gas of the different simulation runs.

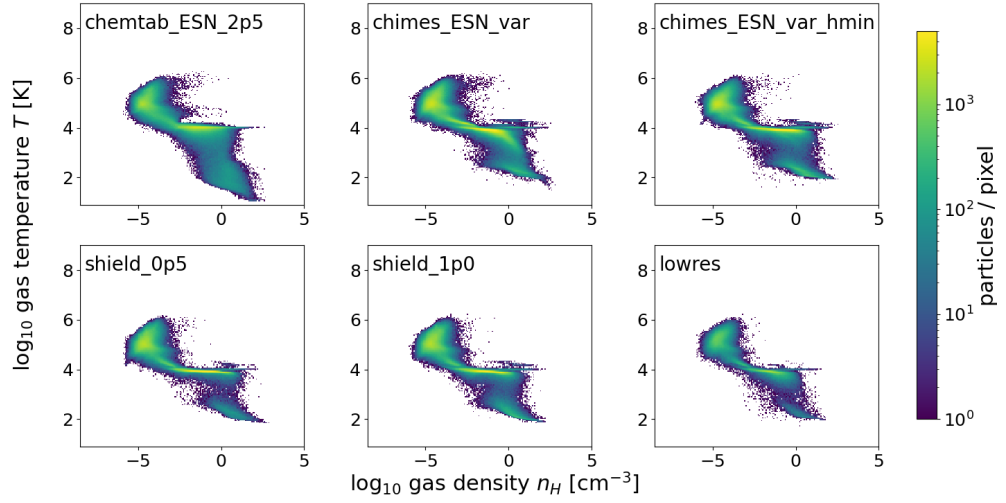


Figure 2.5.: Same as [2.4](#), but limited to the low-mass galaxies considered in this project.

characteristic cooling and heating properties, also plays an important role as a catalyst for molecular hydrogen formation. Cosmic rays, on the other hand, provide a heating source while ionising atoms and destroying molecules via photodissociation. Thus, a wealth of heating and cooling channels and complex chemical networks have to be accounted for in order to realistically model the ISM. This requires fine-tuning of a multitude of parameters.

Between most runs, several parameters were varied simultaneously, which makes it difficult to assess the impact of the individual parameters. One important change regarding the cooling prescriptions occurred between the early simulation run `chemtab_ESN_2p5` and the subsequent runs. In the former, the pre-tabulated cooling and heating rates from Ploeckinger & Schaye (2020) were used. These rates were calculated assuming an ISM in chemical and ionisation equilibrium. In the subsequent runs, the non-equilibrium network CHIMES (Richings et al. 2014a,b) was employed to calculate the chemical reactions of hydrogen and helium including their ionisation states and the corresponding cooling and heating rates for every time step. This allows for a more accurate treatment of these abundant species, as changes in the ISM typically occur on time scales smaller than those needed for the gas to settle to chemical equilibrium. Pre-tabulated rates were still used for heavier elements because of the high computational expense of such real-time calculations. The temperature-density diagram of the `chemtab_ESN_2p5` run stands out from that of the other runs in terms of a smoother distribution of gas below $T \sim 10^4$ K, which may, at least in part, be attributed to the distinct method to calculate the cooling and heating rates. The relatively warm lower end of the other runs can likely be attributed to the used model for the interstellar radiation field (ISRF).

Another important component of the ISM model is the parameterisation of the shielding properties of the gas. For the cold ISM the shielding column density is associated with the local Jeans (1902) length of a self-gravitating gas cloud, based on the density and temperature of the gas. The corresponding column density is multiplied by a shielding length factor, which is an input parameter that determines how much gas is effectively shielded and thus has an influence on the cooling process.

The two simulation runs `shield_0p5` and `shield_1p0` differed merely in the used shielding length factor and were otherwise identical. The shielding length factors 0.5 and 1.0 correspond to a shielding into the centre of the gas cloud or shielding by the whole cloud, respectively (see Ploeckinger et al. 2025). The temperature-density diagrams in Figure 2.5 show that the larger shielding length factor leads to an enhancement of the CNM branch.

Dust

Dust plays an important role in the chemical evolution and radiative transfer within the ISM. The grains are produced in the ejecta of stars and are subject to various growth and destruction processes. The dust evolution in the ISM is realised via metal diffusion in order to account for mixing between the discrete gas particles or resolution elements.

The most important change in the treatment of dust in the different simulation runs

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occurred between `chemtab_ESN_2p5`, where the pre-tabulated cooling rates used a fixed dust-to-metal ratio, and subsequent runs, where the dust evolution is connected to CHIMES and therefore directly affects the chemical evolution and heating and cooling rates in the ISM. The latter simulation runs also use a dust model with two different grain sizes (‘small’ and ‘large’, see [Trayford et al., 2025](#)).

Star formation

The star formation prescriptions are the same for all simulation runs considered here, using the fiducial model of [Nobels et al. \(2024\)](#). The adopted star formation law is a [Schmidt \(1959\)](#) law

$$\dot{\rho}_\star = \epsilon_{SF} \frac{\rho}{t_{ff}}, \quad (2.1)$$

where the star formation rate density $\dot{\rho}_\star$ depends on the star formation efficiency ϵ_{SF} , the gas density ρ and the density-dependent free-fall time $t_{ff} = \sqrt{3\pi/32G\rho}$. The star formation efficiency is a free parameter and is set to 1% per free-fall time. Since the numerical time steps are typically small compared to the gas consumption timescale needed to convert an entire gas particle into a star particle, the star formation law is implemented stochastically with a probability depending on the ratio between the two time scales. Which gas particles are eligible for star formation is defined by a gravitational instability criterion, which takes into account the thermal and turbulent velocity support. Another requirement for the conversion into a star is that the gas has an over-density of 100 with respect to the cosmic mean. This is relevant for high redshifts, where stars might otherwise form outside of halos due to the overall higher cosmic mean density.

Stellar feedback

The prescriptions for supernova (SN) feedback are based on the model of [Chaikin et al. \(2023\)](#). Energy from core-collapse (type II) supernovae is injected stochastically into the neighbouring gas particles via a thermal and a kinetic channel. The stochastic approach is necessary because the neighbouring gas particles are resolution elements with masses of order $10^5 M_\odot$, which means that the total mass of gas within the kernel of the star particle is much larger than the mass of the simple stellar population represented by the star particle. Uniform distribution of the thermal energy among the SPH neighbours would thus lead to the individual gas particles receiving only small changes in temperature that could not reproduce a realistic supernova surrounding. The amount of energy ΔE_{SN} released via supernovae in one time step depends on the initial mass $m_\star$ and age t of the star particle as well as on f_E , the energy of a single supernova in units of 10^{51} erg.

$$\Delta E_{SN}(t, \Delta t, m_\star, f_E) = 10^{51} \text{ erg } f_E m_\star \int_{m_d(t+\Delta t)}^{m_d(t)} \Phi(m) dm, \quad (2.2)$$

where $\Phi(m)$ is the initial mass function (IMF) of the simple stellar population represented by the star particle and $m_d(t)$ is the zero-age main-sequence mass of stars that die at age

2.1. The simulations

t. 10^{51} erg is the canonical energy released by one supernova event. f_E can be viewed as the fraction of the supernova energy that is applied to the surrounding gas particles. The value of f_E can be greater than unity to compensate for numerical energy losses due to the finite resolution or smaller than unity to account for an underestimate of physical radiative losses due to the stochastic treatment of thermal feedback.

The `chemtab_ESN_2p5` run assumed a higher energy per SN event (E_{SN}) than the canonical 10^{51} erg, while keeping f_E fixed to unity. For clarity and consistency with the parameters in Table 2.4, equation 2.3 can be re-written as

$$\Delta E_{SN}(t, \Delta t, m_*, f_E) = E_{SN} f_E m_* \int_{m_d(t+\Delta t)}^{m_d(t)} \Phi(m) dm. \quad (2.3)$$

A fraction of the liberated energy $f_{kin} \cdot \Delta E_{SN}$ is injected via the kinetic channel. The energy released via the thermal channel is $(1 - f_{kin}) \cdot \Delta E_{SN}$. The probability that a gas particle gets heated by ΔT in one time step is a function of the supernova energy ΔE_{SN} , the fraction f_{kin} , the injected temperature change ΔT and the total mass of the neighbouring gas particles. f_E , f_{kin} and ΔT are free parameters specified in the simulations. Also the number of feedback events a star particle produces in its lifetime depends on them. The applied supernova energies f_E and the desired temperature change ΔT vary between the different simulation runs. If the gas particles do not receive enough heat, their cooling time-scales are short, which leads to the effect of over-cooling. On the other hand, if the energy change per feedback event is very large, this is balanced by a decrease in the number of feedback events. As an optimal value to minimise over-cooling losses while adequately sampling the number of feedback events, the EAGLE simulations used a fixed value $\Delta T = 10^{7.5}$ while supernova energy fraction per unit stellar mass varied with density. In the COLIBRE test runs the injected temperature change ΔT was itself allowed to vary with density between $10^{6.5}$ and 10^8 K, or between 10^7 and 10^8 K, respectively. In all runs except `chemtab_ESN_2p5` f_E was also allowed to vary, namely with the pressure of the gas out of which the star particle formed. The values of the feedback energy parameters used in the different simulation runs are listed in Table 2.4. Not listed are the yield factors of the chemical elements, which also differed between the simulation runs.

The kinetic feedback channel follows the same principles as the thermal channel, only that the gas particles receiving kinetic feedback gain energy in the form of a small change in velocity Δv by 50 km/s instead of temperature. To ensure momentum conversion, the kick is exerted on two particles at a time that lie in opposite direction.

While supernovae return mass and energy to the ISM when stars reach the end of their lifetimes, feedback also occurs in the early phases of the stellar evolution in the form of ionising radiation from young massive stars, stellar winds and radiation pressure.

The amount of gas that gets ionised by the radiation from massive stars is limited to the Strömgren sphere. The mass of the Strömgren sphere depends on the mass and age of the star particle, the number density of the hydrogen gas and the ionisation rate. Since the neighbouring gas particles are elements of $10^5 M_\odot$, not all neighbours can be ionised at

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once. Instead, ionisation occurs stochastically with a probability $P_{H\text{II}} = M_S/M_{ngb}$, where M_S is the mass of the Strömgren sphere and M_{ngb} is the total mass of the neighbouring gas particles. A particle that has been tagged as ionised is prevented from cooling and recombining for 2 Myr. This is realised by introducing a temperature floor of $T = 10^4 K$ below which the particle cannot cool. This default time-scale should ensure that the distribution of the ionised hydrogen gas is well-sampled, also capturing relative motions of ionised particles.

Radiation pressure is included in the form of radial kicks that are given stochastically to the surrounding gas particles. The probability that a neighbouring gas particle receives kinetic energy from radiation pressure is determined by the flux from the star particle $F(\lambda)$ and the fraction of absorbed radiation f_{abs} , which in turn depends on the density, temperature and chemical composition of the gas. The simulation runs solved for the absorption fractions using CHIMES, except for the `chemtab_ESN_2p5` run, where the tabulated values from Ploekinger & Schaye (2020) were used. The stellar fluxes relevant for the radiation pressure and ionisation were calculated on the basis of the stellar evolution models from BPASS (Stanway & Eldridge, 2018) using a Chabrier (2003) IMF.

2.1.3. The data sets

The snapshots were provided along with the corresponding halo catalogues that had been established using the halo finder VELOCiraptor (Elahi et al., 2019). VELOCiraptor links particle groups based on spatial and velocity information. This 6D Friends-of-Friends (FoF) algorithm allows it to identify bound structures and substructures, as well as tidally disrupted systems. The output catalogues indicate the levels in the substructure hierarchy and contain information about the different particle types *gas*, *stars*, *black holes* and *dark matter* and overall galaxy properties related to mass and radius, position and velocity, rotation velocity and angular momentum, energy, and halo shape, as well as aperture quantities such as average gas metallicity and star formation rate. Identification (ID) numbers of galaxies shown in the Results section are the halo IDs of the corresponding halo catalogues.

2.2. Software used to read and analyse the data

2.2.1. SWIFTsimIO

SWIFTsimIO (Borrow & Borrisov, 2020) is a `python` tool to read and analyse SWIFT simulation data. The object-oriented application programming interface (API) allows to dynamically read and load data from the simulation snapshot as needed. Particle properties of interest can be accessed via a tree of objects and sub-objects. For example, to visualise the temperature-density phase distribution (Fig. 2.4) in the simulation snapshot, the relevant data is retrieved via a `python` script as follows:

```
import swiftsimio
data = swiftsimio.load('snapshotfile.hdf5')
```

2.2. Software used to read and analyse the data

Feedback parameter	Units	<i>chemtab_ESII_2p5</i>	<i>chimes_ESII_var</i>	<i>chimes_ESII_var_hmin</i>	<i>shield_0p5</i>	<i>shield_1p0</i>	<i>lowres</i>
$t_{\text{delay},\text{SNII}}$	Gyr	0.02	-	-	-	-	-
E_{SNII}	10^{51} erg	2.5	1.0	1.0	1.0	1.0	1.0
f_E		1.0	var	var	var	var	var
f_E min		-	0.1	0.1	0.5	0.5	0.1
f_E max		-	3.5	3.5	4.0	4.0	4.0
f_E pivot P_0	K/cm ³	-	$8 \cdot 10^3$	$8 \cdot 10^3$	$3 \cdot 10^4$	$3 \cdot 10^4$	$1.5 \cdot 10^4$
ΔT_{SNII}	log K	var	var	var	var	var	var
ΔT_{SNII} min	log K	6.5	6.5	6.5	7.0	7.0	7.0
ΔT_{SNII} max	log K	8.0	8.0	8.0	8.0	8.0	8.0
ΔT_{SNII} pivot n_0	H/cm ³	0.25	0.40	0.30	0.50	0.50	0.80
ΔT_{SNIa}	log K	7.5	var	var	var	var	var
ΔT_{SNIa} min	log K	-	6.5	6.5	7.0	7.0	7.0
ΔT_{SNIa} max	log K	-	8.0	8.0	8.0	8.0	8.0
ΔT_{SNIa} pivot n_0	H/cm ³	-	0.40	0.30	0.50	0.50	0.80

Table 2.4.: Parameters determining the energies and temperature changes induced by supernovae (core-collapse and type Ia). $t_{\text{delay},\text{SNII}}$ is the delay time of thermal feedback for SNII. E_{SN} and f_E are the energy produced in one SN event and the fraction of that energy that is effectively applied to neighbouring particles. ΔT_{SN} is the temperature change that a particle receives in the feedback process. A value ‘var’ indicates that the respective feedback parameter varies with the conditions in the ISM out of which the star particles are born, here pressure P_0 and density n_0 , respectively. The dependence is characterised by the given minimum and maximum values and pivot points.

```
gas_temperature = data.gas.temperatures
gas_density = data.gas.densities
```

Also the halo catalogue corresponding to the simulation snapshot can be accessed by SWIFTsimIO via the velociraptor library. The following code snippet shows how information about galaxies, as output by the halo finder VELOCIRaptor, can be obtained.

```
from velociraptor import load as load_catlogue
halos = load_catlogue(catalogue_files[‘properties’])

virial_radius = halos.radii.rvir
maximum_rotation_velocity = halos.velocities.vmax
mHI_within_5kpc = halos.gas_hydrogen_species_masses.HI_mass_5_kpc
```

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SWIFTsimIO was mainly used to collect global galaxy properties such as gas fractions or the maximum rotation velocities which served as criterion in the sample selection. For the more detailed analyses, which involved operations on the galaxy particles, SWIFTGalaxy was the main tool used.

2.2.2. SWIFTGalaxy

The SWIFTGalaxy (Oman, 2025) package, a module extending SWIFTsimIO, provides a convenient way to mask particles associated with a halo and re-center the coordinate system on the center of the galaxy of interest. In this respect SWIFTGalaxy is more efficient than SWIFTsimIO and greatly facilitates the investigation of the individual galaxies and operations on them, such as e.g. coordinate rotations. SWIFTGalaxy was thus used as the main instrument to handle the galaxies in the simulation snapshots.

Below is an example of how a SWIFTGalaxy object is created, where the halo index i is the i -th entry in the halo catalogue. Throughout the following analyses ‘minpot’ was used as centre type, defining the centre of the galaxies as the point where the potential is minimal. As an extra mask ‘bound_only’ was chosen so that only gravitationally bound particles would be considered.

```
sg = SWIFTGalaxy(
    snapshotfile ,
    Velociraptor(
        velociraptor_files = catalogue_files ,
        halo_index = i ,
        centre_type = 'minpot' ,
        extramask = 'bound_only' ,
    ) ,
)
```

2.2.3. MARTINI

MARTINI (Mock Array Radio Telescope Interferometry of the Neutral ISM) by Oman (2019) is a modular open-source software package built to mimic realistic radio observations. It allows the user to build the desired observation setup from separate modules that define the source, data cube, beam, noise, spectral model, and SPH kernel, respectively. In principle, the procedure, as was used for this project, can be outlined as follows: The simulated galaxy of interest is passed as source to the source module, where distance, position, inclination, and peculiar velocity can be defined. Next, a data cube is constructed, defining the image size in pixel number, pixel scale in arcseconds and velocity resolution given by the number and width of the velocity channels. The runtime of the program is significantly impacted by the size of the output image, ranging from a few minutes for images with 128x128 pixels to several hours for images with 1024x1024 pixels¹, for

¹see examples section in MARTINI GitHub repository, <https://github.com/kyleoman/MARTINI> accessed 9 November 2025

2.2. Software used to read and analyse the data

instance. Determining the angular resolution of the mock observation, a telescope beam is defined by the corresponding module where the size and form of the beam are set. To avoid undersampling of the beam, its FWHM should span approximately 3 pixels. Mimicking observations, noise is added to the data. Furthermore, a spectral model is defined which is used to process the H I data from the simulation into measured spectral lines. Last but not least, the user chooses an SPH kernel, preferably the same as that used in the simulation code. An adaptive kernel can be used to achieve high accuracy in high-resolution regions while ensuring stability over regions with small smoothing lengths compared to the pixel size. Having configured the observational setup, the mock-observation is then executed via the following steps: The configuration is passed to MARTINI, the source is inserted in the data cube, the noise is added, and a convolution with the beam is applied. The resulting data cube is output in FITS (Wells et al., 1981) or hdf5 (Koranne, 2011) format. The information stored in this cube can be used, for instance, to produce maps of the 0th, 1st and 2nd velocity moment, i.e. intensity, velocity, and velocity dispersion, respectively. Furthermore, the output files can be passed to a fitting routine to model the rotation curves of the mock-observed galaxies.

2.2.4. 3D-BAROLO

To fit the rotation curves to the simulated observations, the publicly available software 3D-BAROLO (3D-Based Analysis of Rotating Objects from Line Observations) by Di Teodoro & Fraternali (2015) was used. 3D-BAROLO applies a ‘tilted-ring model’ fitting routine, where the gas disks are broken down into a number of concentric rings, each of which is modelled separately.

The fitting procedure is outlined as follows: Starting at the innermost ring, a model is produced by randomly populating the ring with gas clouds in a Monte-Carlo-based manner. 3D-Barolo then generates a data cube as if simulating an observation of the model, which is then projected into the data cube of the observed galaxy. Before comparing the model to the input data, it is smoothed to the same spatial resolution as the data via a convolution with a 2D-Gaussian corresponding to the beam of the observation. If the model reproduces the data well, the algorithm moves on to the next ring and the process is repeated.

The resulting fitted rotation curve depends on the combination of input parameters which the user can specify in a parameter file. The input parameters describing the rings are the central coordinates (XPOS, YPOS) and systemic velocity of the galaxy (VSY), the inclination (INC) with respect to the observer, the position angle (PA) of the major axis with respect to the North direction on the sky, the rotation velocity (VROT) and velocity dispersion (VDISP) of the gas, the disk scale height (Z0) and gas surface density (DENS). While 3D-Barolo is capable of extracting initial guesses for these parameters from the data, the user is advised to provide reasonable initial values. The rotation velocity determined for one ring depends sensitively on the geometric parameters, such as inclination, position angle, and centre coordinates. Optionally, the model can be normalized to the observed 0th moment map which corresponds to the surface density of the galaxy. In this way, the surface density can be neglected, which would otherwise have

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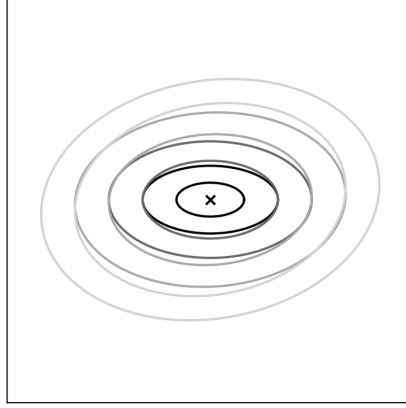


Figure 2.6.: Illustration of the tilted-ring model. The model describes the galaxy as a composition of concentric rotating rings. Each ring is fitted separately, taking into account inclination and position angle.

to be fitted along with the other parameters describing the ring. The user can choose between azimuthally averaged and pixel-by-pixel normalization. The latter option is more suitable for fitting galaxies with morphological peculiarities such as holes or pronounced clumps.

Furthermore, the user can specify how the fitting routine should proceed, e.g. which parameters are fixed and which are allowed to vary, or whether only one side of the velocity map (receding or approaching) is used for the fit or both. Also, there is an option of a two-stage fitting process, which is relevant if the inclination and position angle are allowed to vary between the fitted rings. To avoid unphysical discontinuities the geometric parameters are thus regularised after the first stage and kept fixed in the second stage where only the kinematic parameters are fitted. The user can set which type of regularisation function is used. The options are a bezier function, the median, or polynomial of n^{th} degree.

Further refinements can be made by specifying the type of residual and weighting which influence the minimisation process. Whether the model generated by 3D-Barolo reproduces the data sufficiently well is determined by the number F , with

$$F = \frac{1}{n} \sum_{i=1}^n \Delta r_i w(\theta_i), \quad (2.4)$$

where Δr_i are the residuals from the pixel-by-pixel comparison between model and data and $w(\theta)$ is a weighting function. The default residual is the absolute difference between model and data

2.2. Software used to read and analyse the data

$$\Delta r = |mod - obs| \quad (2.5)$$

and the default weighting function is

$$w(\theta) = \cos(\theta)^2, \quad (2.6)$$

which gives most weight to the pixels along the major axis where most of the velocity information lies, as θ is the azimuthal angle measured from the major axis.

Parameter	Value	Units	Description
RADSEP	9	arcsec	Equivalent to beam width
XPOS	Npix/2 - 0.5	pixels	The centroid of the velocity map, here the center of the image
YPOS			
VSYS	612.9	km s ⁻¹	Determined by the Hubble flow H ₀ D
VROT	30	km s ⁻¹	Initial guess for rotation velocity
VDISP	8	km s ⁻¹	Initial guess for velocity dispersion
INC	60	deg	Inclination
PA	90	deg	Position angle
Z0	2	arcsec	Disk scale height
DELTAINC	15	deg	Allowed variation of the inclination
DELTAPA	20	deg	Allowed variation of the position angle
FREE	VROT	-	These parameters are allowed to vary during the fitting process
	VDISP		
	INC		
	PA		
FTYPE	2	-	The function to be minimised is $ mod - obs $
WFUNC	1	-	The weighting function is $ \cos(\theta) $
LTYPE	1	-	Layer type along z is gaussian.
SIDE	B	-	Both sides of the velocity map (approaching and receding) are fitted
MASK	SMOOTH	-	Convolves channel maps with a Gaussian corresponding to the beam
BLANKCUT	2.5	-	Smoothed mask is built from region where S/N > BLANKCUT
NORM	LOCAL	-	Model is normalised pixel by pixel
TWOSTAGE	TRUE	-	INC, PA regularised before second fitting stage where VROT, VDISP are fitted
REGTYPE	bezier	-	Function used to regularise INC, PA
LINEAR	0.425	channels	Instrumental broadening (standard deviation)
ADRIFT	TRUE	-	Asymmetric drift correction is calculated

Table 2.5.: Input parameters used with the fitting tool 3D-Barolo

2. Methods

2.3. Sample selection

Since the objects of interest are low-mass disk galaxies, only galaxies in a V_{max} range between 60 and 120 km/s were studied, following the selection criteria of [Oman et al. \(2019\)](#). The upper limit is to restrict the sample to low-mass galaxies and the lower limit is to ensure that the H I distribution in the galaxies is well sampled in terms of gas particle number. Furthermore, satellite galaxies were excluded in order to isolate the analysis of the internal galaxy dynamics from possible influences of a host halo potential or other environmental effects. To select the subsamples from the simulation snapshots according to the above criteria, the halo finder (**Velociraptor**) information was used. The sizes of the parent samples fulfilling the selection criteria in each of the simulation snapshots are listed in Table [2.6](#). At this point, no assessment is made whether or not a galaxy might be undergoing interactions or be otherwise ill-suited for rotation curve analysis. The final selection follows after a more detailed inspection of the galaxies (see Section [2.8](#)). The reduced sizes of the *selected* samples are also listed in Table [2.6](#).

simulation run name	parent sample size	selected sample size
chemtab_ESN_2p5	48	17
chimes_ESN_var	49	26
chimes_ESN_var_hmin	49	27
shield_0p5	49	26
shield_1p0	50	24
lowres	307	55

Table 2.6.: Sizes of parent samples that fulfill the basic selection criteria (isolated galaxies with $60 < V_{max}/km\ s^{-1} < 120$) and final *selected* sample sizes following a more detailed inspection (see Sec. [2.8](#)).

2.4. Obtaining global galaxy properties

2.4.1. H I mass

The H I mass of the galaxies was read from the simulation data as well as determined from the mock observations. Following the procedure of [Hunter et al. \(2012\)](#) applied for the galaxies in the LITTLE THINGS survey, the H I mass was derived from the H I column density. Using the relation between flux density S and brightness temperature T

$$S(Jy\ beam^{-1}) = 1.65 \cdot 10^{-6} \Delta\alpha\Delta\delta\ T(K), \quad (2.7)$$

the column density

$$N_{H\text{I}}(atoms\ cm^{-2}) = 1.823 \cdot 10^{18} \sum T(K)\Delta V(km\ s^{-1}), \quad (2.8)$$

can be expressed as

$$N_{H\text{I}}(atoms\ cm^{-2}) = \frac{1.1048 \cdot 10^{24}}{\Delta\alpha\Delta\delta} \sum S(Jy\ beam^{-1})\Delta V(km\ s^{-1}), \quad (2.9)$$

2.4. Obtaining global galaxy properties

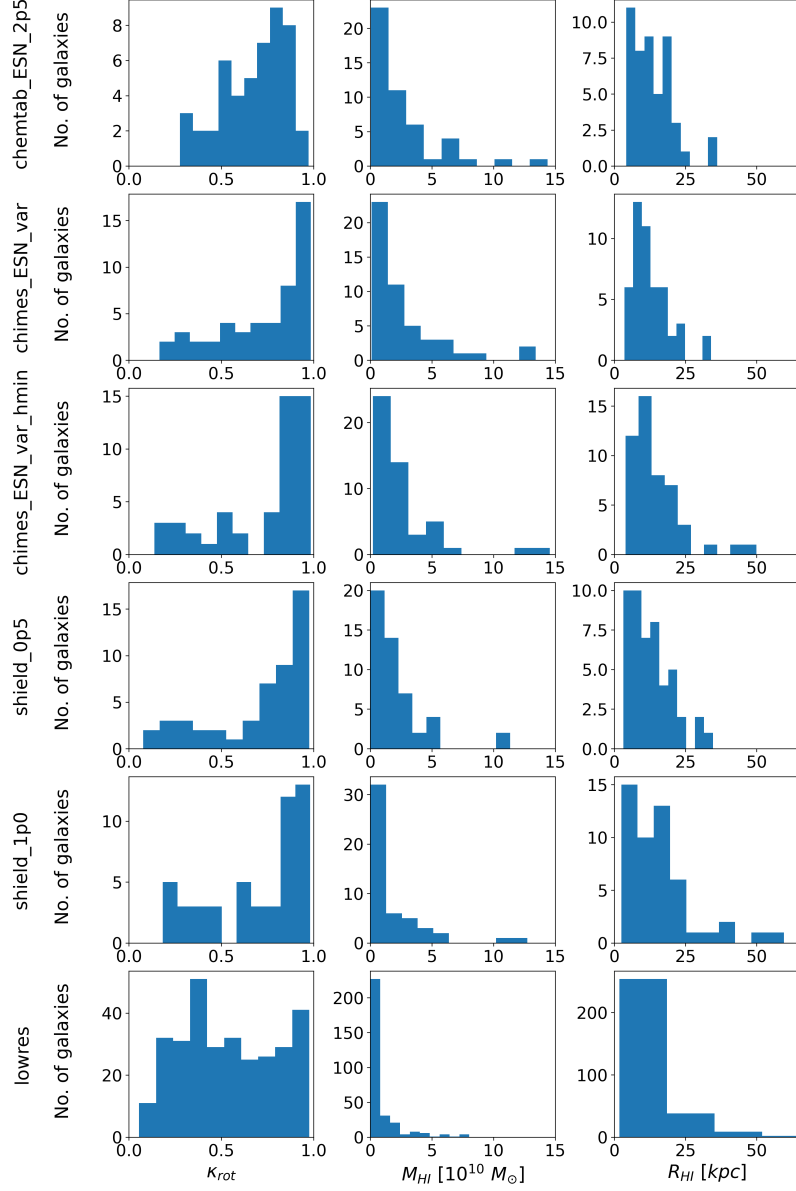


Figure 2.7.: Structural properties of all isolated DGs with $60 < V_{max}/\text{km s}^{-1} < 120$ in each simulation run. Columns from left to right show the rotational support parameter κ_{rot} , the H I mass, and the H I disk radius, defined as the radius of the sphere enclosing 90% of the H I mass. The values shown were obtained from the particle data. Histograms correspond to 10 bins per data sample.

2. Methods

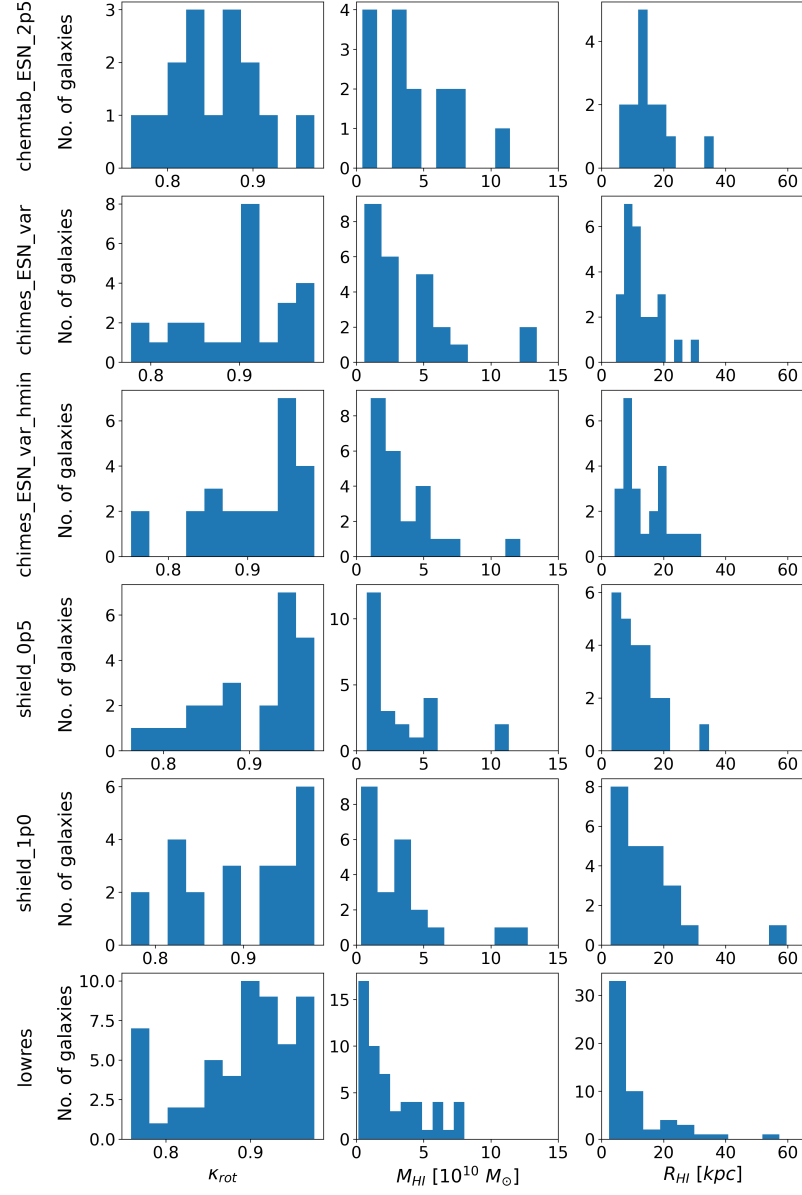


Figure 2.8.: Structural properties (same as in Figure 2.7) of the *selected* samples, i.e. after excluding galaxies ill-suited for the rotation curve analyses (see section 2.8).

2.4. Obtaining global galaxy properties

where the flux cube is integrated along the velocity axis and $\Delta\alpha$ and $\Delta\delta$ are the major and minor axis of the beam FWHM. Converting the column density in atoms per cm^2 to atoms per pixel at the distance of the galaxy and summing over all pixels of the column density map yields the total H I mass

$$M_{\text{HI}}(M_{\odot}) = m_{\text{HI}}(M_{\odot}) \cdot N_{\text{HI}}(\text{atoms cm}^{-2}) \cdot \left(D(\text{cm}) a \frac{\pi}{180 \cdot 3600} \right)^2. \quad (2.10)$$

2.4.2. Disk size

The radius of the galaxies' H I disks was defined as the radius enclosing 90% of the H I mass, R_{90} . This is analogous to the radius used in similar studies of simulated galaxies (e.g. Roper et al. 2023; Downing & Oman 2023) as well as the radius derived for the galaxies in the LITTLE THINGS survey (Hunter et al. 2021). Computationally, R_{90} was obtained by sorting the gas particles in the SWIFTGalaxy by radial distance to the galaxy centre. R_{90} is then the distance from the galaxy centre at which the cumulative H I mass is 90% of the total H I mass.

R_{90} was also estimated from the mock-observed data, for comparison. This was done by masking ellipses on the H I surface density maps and calculating the H I mass enclosed within, as described in Section 2.4.1. The ellipses correspond to disks inclined by 60° . R_{90} was now defined as the semi-major axis of the ellipse enclosing 90% of the total H I mass.

2.4.3. Disk thickness

The thickness of the H I disks was defined as the half-width half-maximum (HWHM) of the vertical density distribution (HWHM_z). To obtain the radial profiles of the disk heights, HWHM_z was computed in equally-spaced radial bins out to R_{90} . The cylindrical annuli were chosen to have a width of 0.4 kpc, which corresponds to the beam size of the mock observations at the assumed distance of the galaxies (see section 2.6.1). Each annulus was divided into vertical bins of 100 pc height. The density was obtained by dividing the H I mass in each ring layer by the corresponding volume. To facilitate the computation, the galaxies were first rotated to an edge-on orientation (i.e. with their angular momentum vector aligned with the z-axis of the global coordinates). The vertical distances were then simply the distances along the z-axis. The resulting vertical density profile in each ring was fit with a Gaussian curve. The HWHM_z which quantifies the height of the disk, was defined as the Gaussian HWHM.

2.4.4. Morphology

The H I morphology of the simulated galaxies was studied making use of visualisations. As will be explained in section 2.6.1 the data obtained in the mock-observations is a cube of dimension $N_{\text{pix}} \times N_{\text{pix}} \times N_{\text{vch}}$, where N_{pix} is the number of pixels per image axis and N_{vch} is the number of velocity channels. The data cube stores the galaxy's flux per pixel per velocity channel as would be observed if the simulated galaxy was projected on

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the sky. From this flux cube, maps of the 0th and 1st moment, i.e. integrated intensity and line-of-sight velocity, were created. The maps were created by calculating

$$m_0(x_{i,j}) = \sum_n^{N_{\text{vch}}} F(x_{i,j}, n) \quad (2.11)$$

and

$$m_1(x_{i,j}) = \frac{\sum_n^{N_{\text{vch}}} v(n) F(x_{i,j}, n)}{m_0}, \quad (2.12)$$

respectively, where $F(x_{i,j}, n)$ is the flux in the velocity channel n at the pixel position $x_{i,j}$ and $v(n)$ is the velocity in channel n . The maps were visualised using the python plotting tool `matplotlib.pyplot` and examined for the overall H I structure of the galaxies as well as for peculiarities. Complementary to the visual inspection of these maps, a computational approach was used to reveal the dynamical structure of the galaxies, as described in the following paragraph.

2.4.5. Rotational support

The rotational support of the H I disk was quantified, using the definition of (Sales 2010)

$$\kappa_{\text{rot}} = \frac{\sum_i \frac{1}{2} m_i \left(\frac{j_{z,i}}{r_i} \right)^2}{\sum_i \frac{1}{2} m_i v_i^2}, \quad (2.13)$$

which measures the amount of kinetic energy that is on ordered rotation with respect to the total kinetic energy. j_z is the z-component of the specific angular momentum, where

$$j_z = \left(\frac{\vec{r} \times m \vec{v}_{\text{azi}}}{m} \right)_z = r v_{\text{azi}} \quad (2.14)$$

and therefore equation 2.13 can be written as

$$\kappa_{\text{rot}} = \frac{\sum_i m_i v_{\text{azi},i}^2}{\sum_i m_i v_i^2}, \quad (2.15)$$

where m_i is the mass of the particle at radial distance r_i from the galaxy's center and $v_{\text{azi},i}$ and v_i the azimuthal and total velocity of the gas particle with index i , respectively. A step-by-step description how v_{azi} was obtained is given in section 2.5.2

2.5. Obtaining rotation curves from simulation data

Simulations provide a unique opportunity to study certain aspects of galaxy dynamics in a way that is inaccessible to observers. For instance, the relative contributions from the different types of matter, such as stars, gas and dark matter, can be isolated in the case of simulations, whereas observers need to derive the distribution of the total mass and dark matter content of galaxies from the dynamics of the stars and gas. Moreover, simulations allow the viewer to rotate the galaxies in any arbitrary way, that is, a galaxy

2.5. Obtaining rotation curves from simulation data

can be viewed from any point of view at any desired inclination, whereas observers have no control over inclination and viewing angle.

As described in the following paragraphs, the rotation curves of the galaxies were obtained via three different methods, targeting different underlying problems.

2.5.1. Circular velocity

The circular velocity is the most direct tracer of the mass distribution. Assuming a spherical halo and balance between gravitational and centrifugal force, the circular velocity is related to the mass via

$$v_{\text{circ}} = \sqrt{\frac{G M(< r)}{r}}, \quad (2.16)$$

where G is the gravitational constant, r is the radial distance from the galactic centre and $M(< r)$ is the mass enclosed within r . In order to obtain the circular velocity curves for the galaxies in the simulation snapshots, the contributions from the different particle types (stars, gas, and dark matter) were first calculated individually and then added together to yield the total circular velocity profiles. Black holes were not included, since the masses of individual black holes in the galaxy samples are comparable to or smaller than that of a single gas particle.

2.5.2. Median azimuthal H I gas velocity

In an unperturbed galaxy the rotational velocity of the H I gas is governed by the underlying total mass distribution. Therefore, the former is widely used as a tracer for the latter. However, the gas may be perturbed by processes that might not be obvious to observers (Oman et al. 2023). In that case the mass distribution derived from the H I rotation curve might be incorrect. Since the H I rotation velocities can be read directly from the particle data and compared to the circular velocities, the effect of such gas perturbations can be isolated from any additional uncertainties that observations entail.

In order to obtain the true H I rotation curves, the galaxies were rotated to lie face-on in the y-z plane. The rotation was performed using the `L_align` function from the MARTINI submodule `martini.sources.L_align`. This function calculates the angular momentum vector from an enclosed mass fraction defined by the user and outputs a rotation matrix to align the obtained angular momentum vector of the galaxy with the desired axis of the global coordinate system, which is here the x-axis in the case of face-on orientation. Following Downing & Oman (2023), the angular momentum vector was calculated from the inner 30% of the H I mass, in order to minimize the impact of potential warps in the outer disk. Again following the definition of Downing & Oman (2023) for H I-bearing particles (see Table 2.7), particles with small H I fractions were ignored in this step, in order to capture the motion of the atomic gas component.

To correct for possible peculiar motions of the galaxies, the velocities were re-centered on the mean velocity of the innermost 500 particles. The azimuthal direction was then

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defined as the cross product between the unit angular momentum vector and the position vector of the respective gas particle, i.e.

$$\vec{a}_{azi} = \hat{L} \times \vec{x}. \quad (2.17)$$

The velocity of the gas particle in azimuthal direction is then given by the projection of the cartesian velocity $\vec{v}$ onto the azimuthal unit vector,

$$v_{azi} = \vec{v} \cdot \hat{a}_{azi}. \quad (2.18)$$

The radial profile of the H I rotation velocity was obtained by taking the median of the azimuthal velocities of particles within concentric bins of 0.4 kpc width out to the radius enclosing 90% of the H I mass. The bin width was chosen to match the beam size of the mock-observations. The definition of the center, peculiar velocity center and radius were the same as those used for the mock-observations and are summarised in Table 2.7

2.6. Obtaining rotation curves from H I mock-observations

2.6.1. Simulating an observation

The mock observations were conducted using the MARTINI package (Oman 2019). For each halo in the sample of interest, a SWIFTGalaxy object was created and passed to MARTINI as source. When setting the parameters relevant for the observational setup, two key factors were considered: (a) the resolution in physical space should be comparable to that of modern observations targeting low-mass galaxies, such as the THINGS (Walter et al. 2008) and LITTLE THINGS (Hunter et al. 2012) surveys and (b) the image size needed to cover the H I disks of the galaxies should be kept below 512 pixels per axis in order to limit the computation time to $\lesssim 30$ minutes per galaxy. It was verified that the choice of image size did not affect the results.

Distance, angular and physical resolution are related via

$$\tan(\alpha) = \frac{l}{D}, \quad (2.19)$$

where α is the angular resolution in radian and l is the physical length of a structure resolved at distance D . For angular resolutions of a few arcseconds and with $[\text{rad}] = [\text{deg}] \frac{\pi}{180}$ equation 2.19 can be transformed to

$$l = D \cdot \alpha["] \frac{\pi}{180} \frac{1}{3600}. \quad (2.20)$$

The technical setup of the THINGS and LITTLE THINGS surveys, which targeted nearby galaxies, achieved an angular resolution of 6", which corresponds to a physical resolution ranging from 26 to 500 pc, depending on the distances of the galaxies. This provides one of the key guiding principals to set the beam size α and distance D for the mock-observation. The linear resolution should not be lower than 500 pc. The second guidance principal is the image size that should be able accommodate the larger

2.6. Obtaining rotation curves from HI mock-observations

galaxies within 512x512 pixels where the pixel size is $\frac{1}{3}$ of the beam size. For small and intermediate disks pixel numbers of 128x128 and 256x256 were used, respectively. The galaxies should thus be placed at a distance far enough to make the larger galaxies fit into the limited image size and small enough to resolve structures of < 500 pc. According to these considerations, the beam size was set to 9" for a distance $D = 9$ Mpc which yields a physical resolution of 393 pc and thus forms a compromise between resolution and image size (i.e. runtime).

All sources were placed at the same distance D and rotated to an inclination of 60° . To account for peculiar motions, the velocities were recentered on the mean velocity of the innermost 500 HI-bearing particles, setting the peculiar velocity of the galaxy to zero. As for the calculation of v_{azi} , particles with small HI fractions were rejected in this step to ensure that the velocity centre truly reflects the motion of the HI gas without contamination from ionised or molecular gas. After recentering, the velocity center of the mock-observed galaxy is solely given by Hubble flow, i.e. the systemic velocity is the same for each galaxy, namely H_0 times the distance, which, for $H_0 = 68.1 \text{ km s}^{-1} \text{ Mpc}^{-1}$, results in 612.9 km s^{-1} .

The number and width of the velocity channels were set to match the medium velocity resolution used in the THINGS survey, namely 128 channels with $\Delta v = 2.6 \text{ km s}^{-1}$.

A Gaussian noise with seed=0 was added with an rms value of $3 \cdot 10^{-8} \text{ Jy/arcsec}^2$. This is much lower than the noise level in real observations. The THINGS observations have a median rms noise of 0.6 mJ/beam, which for a beam size of 9" would correspond to $9 \cdot 10^{-6} \text{ Jy/arcsec}^2$. In order not to lose information at this point, the mock-observation was made with the low noise level. The effect of a higher noise level on the obtained rotation curves will be discussed in Section 4.2.4.

To model the HI lines, the thermal spectral model was chosen, which estimates the line width from the particle properties in the simulation.

For the SPH smoothing kernel, the adaptive kernel option was chosen, with the Wendland C2 kernel as first choice. As alternative kernels to use in regions of small and intermediate smoothing lengths compared to the pixel scale, the Dirac-Delta kernel and Gaussian kernel were used, respectively.

For each galaxy the mock-observation was repeated as if viewed along the axis perpendicular to the original line of sight. This was achieved by rotating the galaxies by 90° around their rotation axis. The purpose of this was to illustrate the effect of the viewing angle on the measured rotation curves, an effect that cannot be controlled in observations of real galaxies. All definitions and settings defining the mock observation setup are summarised in Table 2.7.

To visualise the galaxies as they would appear to an observer, intensity and velocity maps were produced from the MARTINI data cubes. These maps were used to identify interacting or disturbed galaxies that would not serve to probe the intrinsic profiles of the rotating mass. Relevant features were obvious double-peak intensities, tidal features, turbulent, asymmetric velocity maps, or an unexpected orientation of the velocity field. The latter indicates that something is disturbing the angular momentum calculation. These galaxies were not discarded at this point, however. Their velocity curves were fitted

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Galaxy structure definitions	
Galaxy centre	minimum potential
Peculiar velocity centre	mean velocity of 500 innermost H I-bearing particles
H I-bearing	$m_{\text{H I}} / m_{\text{H I, max}} > 0.3$
Radius (R_{90})	radius enclosing 90% of the total H I mass

Mock observation settings	
Distance	9 Mpc
Inclination	60°
Viewing angle	0° and 90°
Pixel scale	3 arcsec
Npix	128, 256 or 512 so that at least $2 \cdot R_{90}$ is enclosed
N velocity channels	128
Velocity channel width	2.6 km s^{-1}
Velocity centre	$H_0 [\text{km s}^{-1} \text{ Mpc}^{-1}] \cdot \text{Distance} [\text{Mpc}]$
Beam	9 arcsec, circular Gaussian
Noise	$3.0\text{e-}8 \text{ Jy arcsec}^{-2}$
Spectral model	thermal
SPH kernel	adaptive: WendlandC2, Gaussian (truncate=6), Dirac-Delta

Table 2.7.: Definitions and settings of relevant parameters

nonetheless, in order to examine how they relate to the observed features.

2.6.2. Rotation curve fitting

The rotation curve fitting was done using the software 3D-BAROLO. An overview of the used input parameters is provided in Table 2.5. During the fitting process, not only the rotation velocity and velocity dispersion were allowed to vary from ring to ring, but also the geometrical parameters INC (inclination) and PA (position angle), in order to account for warps and twists. The separation between the rings (RADSEP) was chosen to match the beam width of the mock observations. The spatial centre of the velocity map was set as the central pixel of the image, which is here by construction the point of the galactic potential minimum. In observed galaxies, the peak of the stellar light distribution is often used to define the coordinates of the centre, which can be expected to coincide with the potential minimum (see Oman, 2017). Since the pixel count in 3D-BAROLO starts at 0, the central position on the x- and y-axis is thus $\text{Npix}/2 - 0.5$, where Npix is the number of pixels per image axis. The velocity center around which the rings rotate is given by the systemic velocity (VSY). Since the galaxies have been re-centred on their peculiar velocities, the systemic velocity is fully determined by the Hubble flow, i.e. by their distance times H_0 . An asymmetric drift correction is provided by 3D-BAROLO. Since some of the fits exhibit unrealistic inflexions in the outermost, low-signal regions of the galaxies, all curves were cut off at R_{90} .

2.7. Analysis of rotation curves

2.7.1. Quantifying the agreement between rotation curves from different methods

In order to measure the agreement or disagreement between the rotation curves obtained from the different methods quantitatively, an agreement parameter was defined. The parameter measuring the agreement between V_{circ} and V_{azi} is

$$A_{vcirc,vazi} = med(1 - v_{azi,r_i}/v_{circ,r_i}). \quad (2.21)$$

$v_{azi,r_i}/v_{circ,r_i}$ is the fractional difference between the two velocities measured at the radii r_i . The median is used as a summary statistic to describe the overall agreement over all radii. Perfect agreement would yield $A_{vcirc,vazi} = 0$. If V_{azi} significantly underestimates V_{circ} the value of the agreement parameter converges to 1. Negative values indicate that V_{azi} overestimates V_{circ} .

Analogously, the agreement between the rotation curves obtained via mock observations from different viewing angles is defined as

$$A_{\Phi_0,\Phi_{90}} = med(1 - v_{obs,\Phi=0,r_i}/v_{obs,\Phi=90,r_i}). \quad (2.22)$$

The latter parameter describes how the viewing angle impacts the shape of the rotation curves, whereas the former parameter indicates if the mass distribution of the galaxy can at all be reliably traced by the H I rotation curve.

These parameters were used to determine, for each simulation run, the statistics regarding the classification of galaxies into the cases described below. Concerning the agreement between V_{azi} and V_{circ} the rotation curves were grouped into the following broad categories:

- Excellent: V_{azi} is an excellent tracer of V_{circ} , i.e. the gas rotates widely unperturbed in a well-defined disk.
Criterion: $A_{vcirc,vazi} \leq 0.03$
- Fair: V_{azi} is a fair tracer of V_{circ} , i.e. V_{azi} shows some deviations from V_{circ} but widely follows the overall shape.
Criterion: $0.03 \leq A_{vcirc,vazi} \leq 0.1$
- Poor: V_{azi} is a poor tracer of V_{circ} , i.e. the gas is not following the expected circular motion. This indicates that the H I rotation is experiencing significant perturbations.
Criterion: $A_{vcirc,vazi} \geq 0.1$

The impact of the viewing angle on the observed rotation curves was captured in the category

- Large Φ -dependence: $V_{obs,\Phi=0}$ and $V_{obs,\Phi=90}$ are significantly different, i.e. the viewing angle significantly impacts the observed rotation curve.
Criterion: $A_{\Phi_0,\Phi_{90}} \geq 0.1$

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The criteria to draw the line between ‘excellent’, ‘fair’, and ‘poor’ agreement were guided by visual inspection of the rotation curve plots. Those V_{azi} curves that show excellent agreement with V_{circ} with not more than minor oscillations around V_{circ} correspond to an agreement parameter $A < 0.03$. For agreement parameters larger than that, the oscillations grow larger but the global rotation curve shape is still widely preserved up to values of 0.1. For $A > 0.1$, the shape of V_{azi} becomes noticeably different from that of V_{circ} . To classify the agreement between the mock-observed rotation curves, only one critical value, namely $A = 0.1$ was used. Considering that the observed rotation curves $V_{obs, \Phi=0}$ and $V_{obs, \Phi=90}$ tend to show more fluctuations than V_{azi} , this value is large enough to allow for some oscillations in rotation curves that still classify as ‘fair tracers’ of V_{azi} or ‘in fair agreement’ with each other. The agreement parameters of observed rotation curves that do not trace V_{azi} span a wide range of values larger than 0.1, the degree of disagreement is, however, irrelevant here since the purpose of this evaluation is only to assess whether or not there are dominant observational effects influencing the rotation curve measurements.

A more detailed evaluation was to reveal the relative importance of perturbed gas motions and observational effects as drivers of the deviations of the observed rotation curves from circular velocity. This is reflected in the statistics of the following cases:

- Obs. main: V_{azi} is an excellent or fair tracer of V_{circ} but either of the V_{obs} disagree, i.e. observational effects are the main driver of the differences between observed rotation curves and V_{circ} .
Criterion: $A_{vcirc, vazi} \leq 0.1$ & $A_{vazi, vobs} > 0.1$
- Obs. main (excel): Observational effects as main driver in the case of excellent agreement between V_{azi} and V_{circ} .
Criterion: $A_{vcirc, vazi} \leq 0.03$ & $A_{vazi, vobs} > 0.1$
- Gas main: Both V_{obs} agree with V_{azi} but V_{azi} does not trace V_{circ} excellently well, i.e. gas perturbations are the main driver.
Criterion: $A_{vazi, vobs} < 0.1$ & $A_{vcirc, vazi} > 0.03$
- Gas main (poor): gas perturbations as the main driver in the case of poor agreement between V_{azi} and V_{circ} .
Criterion: $A_{vazi, vobs} < 0.1$ & $A_{vcirc, vazi} > 0.1$
- All agree: All curves agree well, i.e. the gas is widely unperturbed and there are no additional observational effects that impact the observed rotation curve.
Criterion: $A_{vcirc, vazi} \leq 0.03$ & $A_{vazi, vobs} < 0.1$
- All disagree: All curves disagree, i.e. the gas is undergoing perturbations and observational effects additionally impact the observed rotation curves.
Criterion: $A_{vcirc, vazi} \geq 0.03$ & $A_{vazi, vobs} > 0.1$

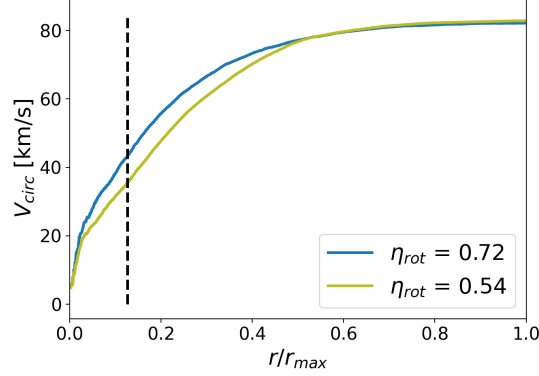


Figure 2.9.: Illustration of the shape parameter η_{rot} . The blue and green curves represent two galaxies with equal V_{max} values. The vertical dashed line marks the fiducial radius r_{fid} . The shape of the rotation curves is quantified by the rotation velocity V_{fid} at r_{fid} . The more steeply rising profile (blue) has a higher value of V_{fid} . The ratio between V_{fid} and V_{max} gives the normalised shape parameter η_{rot} .

2.7.2. Parameterisation of rotation curve shapes

When analysing the rotation curves of galaxies in hindsight of their mass distributions, the inner regions are of particular interest. The Λ CDM cosmology predicts cuspy inner density profiles, i.e. velocity curves that rise steeply in the inner region. The shape of the rotation curve can thus be quantified by the rotation velocity at a fiducial inner radius. Here the definition of the fiducial radius from Santos-Santos et al. (2020) was adopted:

$$r_{fid} = 2 \cdot \frac{V_{max}}{70 \text{ km/s}} \text{ kpc} \quad (2.23)$$

The rotation velocity V_{fid} at this fiducial radius is a measure of the shape of the velocity profile. High rotation velocities at this radius indicate steeply rising rotation curves, i.e. cuspy density profiles, whereas low values of V_{fid} are associated with cored density profiles. Division by the galaxy's maximum rotation velocity yields the normalised shape parameter

$$\eta_{rot} = \frac{V_{fid}}{V_{max}}, \quad (2.24)$$

used by Santos-Santos et al. (2020). Values of η_{rot} close to 1 indicate a steeply rising rotation curve that reaches maximum velocity near the fiducial inner radius.

The scaling of r_{fid} with V_{max} ensures that the probed inner portion of the rotation curve is independent of the galaxy mass. This, however, also means that the measurement of the shape parameters can potentially be affected by individual peaks in the rotation

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curves. Since some of the fitted curves as well as some of the computed V_{azi} curves exhibit such peaks due to their oscillating behaviour, the rotation curves were first smoothed using the `scipy.gaussian_filter1d` function with $\sigma = 1$. It was verified that the smoothing reduces sharp spikes in the velocity profiles while conserving dips and bumps that might be associated with the galaxy’s H I distribution.

Furthermore, the baryonic contribution at r_{fid} was investigated. Following Santos-Santos et al. (2020) the baryonic importance was defined as

$$\eta_{bar} = (V_{bar,fid}/V_{fid})^2, \quad (2.25)$$

where $V_{bar,fid}$ is the rotation velocity at r_{fid} contributed by the baryonic mass. With equation 2.16 this simplifies to

$$\eta_{bar} = M_{bar,fid}/M_{tot,fid}. \quad (2.26)$$

In the case of the V_{circ} curves, the masses of the stellar and gaseous components were read directly from the simulation data. The mock observations, mimicking radio observations, capture only the natural hydrogen, but neither the stellar component nor molecular or ionised gas. The baryonic mass at r_{fid} was therefore also taken from the simulation data, assuming that the gas and stellar mass could be reliably determined by observations. The total mass at r_{fid} was estimated as the mass an observer would derive assuming that the measured rotation curve followed the circular velocity curve (see relation 2.16), yielding

$$M_{tot,fid} = \frac{V_{obs,fid}^2 r_{fid}}{G}. \quad (2.27)$$

2.8. Identifying ill-suited galaxies

Not all galaxies are equally suitable for analysis with the methods described above. The sample was therefore divided into galaxies for which the methods are expected to be adequate and galaxies that are likely ill-suited. In the following, the two samples are referred to as ‘*selected*’ and ‘*unselected*’ sample, respectively. Examining the two samples separately should yield insight into the challenges that observers may encounter when studying rotation curves of low-mass galaxies. The *selected* sample should be limited to well-defined disk galaxies. This is to reveal the more subtle effects that can influence the observed rotation curves of galaxies, even when they are expected to be well-described by a tilted-ring model. The *unselected* sample may contain galaxies whose observed rotation curves can be expected to be inaccurate for various reasons. It should be noted that different authors may use different selection criteria, as discussed in Section 4.2.2. While the primary focus of this analysis lies on the *selected* sample, the *unselected* sample is therefore included for comparison. In order to evaluate which galaxies qualify for the *selected* sample, the following criteria were considered: (a) the H I content, (b) the rotational support, (c) morphological features indicating interactions and (d) the stability of the angular momentum vector within the inner region of the galaxy. Additionally, it

2.8. Identifying ill-suited galaxies

was verified that r_{fid} , used to quantify the rotation curve shape, is compatible with the numerical convergence scale of the galactic halos (see [Power et al. \(2003\)](#)).

H I content

Since the mock observations simulate radio observations of the neutral hydrogen, it is important that the galaxies to be analysed contain enough H I to trace the rotation of the galaxy well. While the H I content was not directly restricted a priori, it was verified that the galaxies in the samples hold a substantial amount of H I. Indeed, in all samples, the galaxies have H I masses $> 10^7 M_{\odot}$. An exception is the low-resolution run, which did produce a number of field galaxies in the V_{max} range of interest with small or minimal H I content. These were, however, effectively filtered out by the rotational support criterion or, in the case of two galaxies, based on visual inspection.

Rotational support

The primary assumption of the tilted-ring model is that the galaxy to be modelled is rotationally supported. While 3D-BAROLO takes the local gas velocity dispersion into account, breaking the galaxy down into concentric rotating rings is not reasonable if the global kinematics of the emitting gas are dominated by random motions.

The rotational support of the simulated galaxies was quantified through the parameter κ_{rot} (see equation [2.13](#)). As [Sales et al. \(2010\)](#) have shown, well defined rotating disks are described by $\kappa_{rot} > 0.75$. This value was adopted as the primary criterion to select the galaxies from which the most reliable results are to be expected.

Interactions

H I rotation curves of galaxies can only be used as tracers of their density profile if the motions of the gas are governed by their internal mass distribution. Often, however, the kinematics are influenced by external processes such as galaxy interactions. Mimicking real observations, the intensity and velocity maps from MARTINI were inspected for obvious peculiarities. If features indicative of ongoing or recent interactions such as tidal tails, warps, peculiar elongations, ring structures, or large asymmetries in the velocity maps were detected, the galaxy was unselected.

Angular momentum stability

The last criterion is perhaps the most subtle, but can have a large impact on the analyses of rotation curves undertaken here. Much of the analysis described here relies on the control over the galaxies' orientation. The mock observations use a fixed inclination of 60° for all galaxies, which poses a large advantage compared to observations of real galaxies, where the inclination needs to be inferred from the data. To align the simulated galaxies in the desired way, the angular momentum vector is used, which is calculated from the masses and motions of gas particles in the central regions. The reliability of the galaxies' orientation is therefore dictated by the reliability of the calculated angular momentum.

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However, the mass fraction from which to calculate the angular momentum should be calculated is not inherently defined. The choice of the inner 30% of the total H I mass was made to exclude the outer regions of the disk, which could be potentially affected by warps, while still including a large number of particles for robust statistics. Yet, in some cases the particle motions in the inner regions might be disturbed by e.g. an in-falling mass or bursty star formation, which could have an effect on the reliability of the angular momentum vector and therefore on all results that record the galaxy’s orientation. Figure 2.10 schematically illustrates how the choice of enclosed mass fraction may influence the resulting angular momentum vector. Figure 2.11 shows the 0th and 1st moment maps of an example galaxy with angular momentum vectors calculated from different mass fractions to demonstrate this effect. Depending on the mass fraction used to calculate the angular momentum vector, this galaxy is viewed under slightly different inclination and position angles. Figure 2.12 plots the V_{azi} curves resulting from slightly varying orientations due to unstable angular momentum vectors for three example galaxies. As can be seen, the calculation of V_{azi} is robust against slight variations of the angular momentum vector. The mock-observed rotation curves, on the other hand, are sensitive to it, as can be seen in Figure 2.13, which shows the rotation curve fits for the same three example galaxies. In order to minimise uncertainties resulting from this effect, only galaxies with stable angular momentum vectors were selected. For each galaxy, the stability of the angular momentum vector was assessed by varying the mass fraction from which the angular momentum is calculated. To quantify the variation along the shells enclosing different mass fractions, namely 20, 30, and 40% of the total H I mass, the parameter L_{var} was defined as

$$L_{var} = \sqrt{\frac{1}{N_{\text{dim}}} \sum_{\text{dim}=x,y,z} \left(\sigma_{\hat{L},\text{dim}} \right)^2}. \quad (2.28)$$

The above expression is the root-mean-square of the standard deviations $\sigma_{\hat{L},\text{dim}}$ of the angular momentum unit vectors $\hat{L}$, that were computed across the different mass shells for each spatial dimension and averaged over the number of dimensions N_{dim} . L_{var} does not reflect an angular difference, which is typically associated with warped disks, but instead captures the variability of $\hat{L}$ across the mass shells due to any form of perturbation.

The angular momentum vector is considered stable if $L_{var} < 0.1$. This choice was guided by visual comparison of the rotation curve fits corresponding to the variations.

With the goal to verify the validity of the exclusion criteria, the H I content, κ_{rot} , and L_{var} were checked in parallel to the appearance of the velocity maps and furthermore to the agreement between the rotation curves obtained via the different methods. This was supposed to reveal the most significant exclusion criterion as well as potential dependencies between the critical parameters and, thus, enable to establish a pattern based on which the evaluation could be run automatically without the need to visually inspect all velocity maps. The latter point is aimed at an easy applicability of the analyses on various and in particular large datasets, such as the snapshot of the low-resolution run.

The comparison of the critical parameters with the visual appearance of the velocity maps revealed κ_{rot} and L_{var} as the most robust criteria. All galaxies that would be

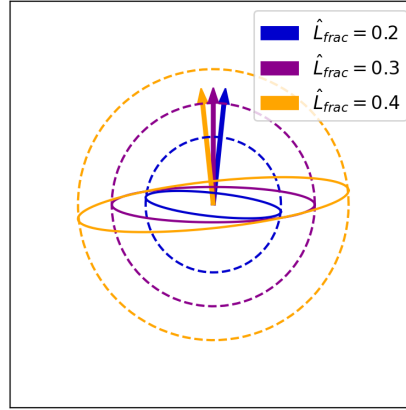


Figure 2.10.: Schematic illustration of how the choice of H I mass fraction can affect the angular momentum vector. The unit vector $\hat{L}$ may change direction, depending on the motions of particles enclosed within the spherical shells corresponding to different mass fractions. The labeled values correspond to 20, 30, and 40% of the total H I mass of the galaxy.

2. Methods

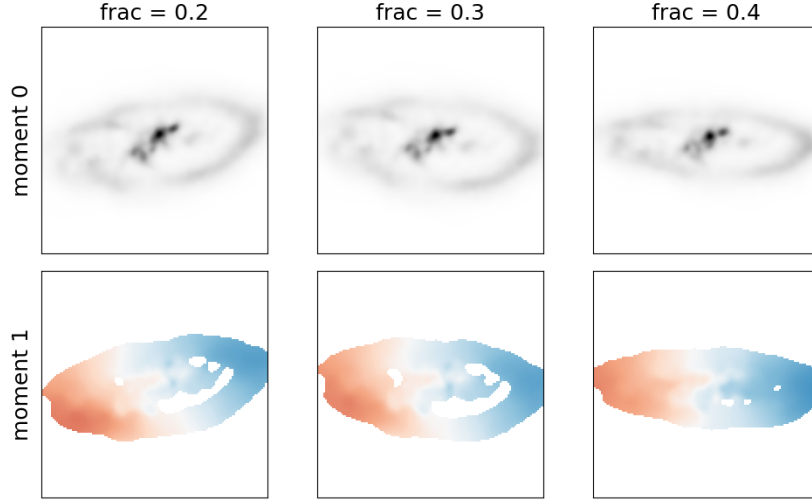


Figure 2.11.: 0th and 1st moment maps of an example galaxy (Halo ID: 54) from `chimes_ESN_var`. The galaxy’s angular momentum vector which controls its orientation was calculated using the inner 20, 30, and 40 per cent of the total H I mass, respectively. These different mass fractions (denoted by ‘frac’) result in slightly different orientations of the angular momentum vector and therefore in differences in the inclination and position angle.

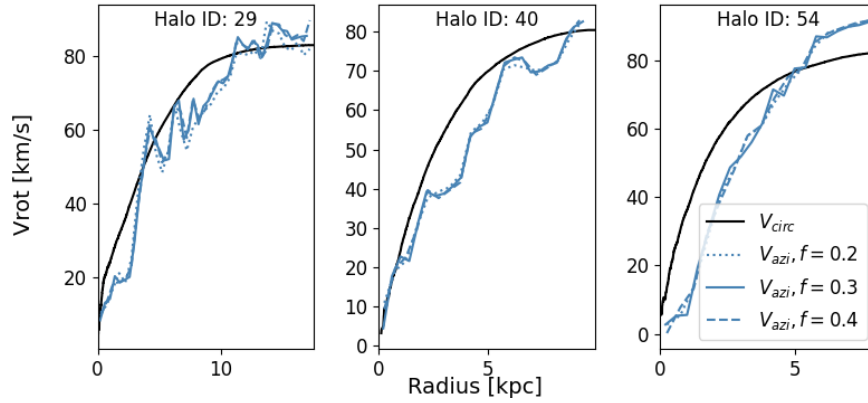


Figure 2.12.: `chimes_ESN_var`: Median azimuthal H I particle velocity (V_{azi}) curves of three example galaxies with uncertain inclination. f denotes the fraction of the H I mass used to calculate the angular momentum vector by which the galaxies were oriented.

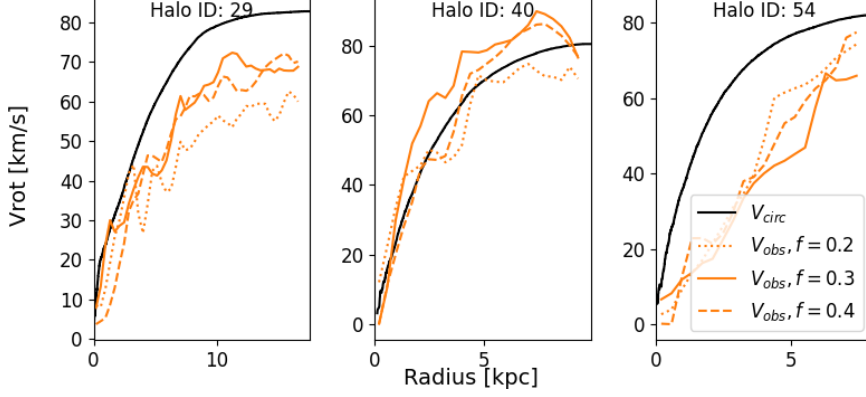


Figure 2.13.: `chimes_ESN_var`: Rotation curve fits (V_{obs}) from mock observations of three example galaxies with uncertain inclination. f denotes the fraction of the H I mass used to calculate the angular momentum vector by which the galaxies were oriented.

excluded based on visual inspection of the mock-observed data also exhibit large L_{var} or small κ_{rot} values. In many cases, large angular momentum variation coincides with weak rotational support, but not in all. In some cases, the otherwise well-defined disk seems to be disturbed in the center. As explained above, this limits the accuracy of the inclination, which can in turn impact the modelled rotation curve and should thus be avoided. Figure 2.14 illustrates the sample selection based on κ_{rot} and L_{var} and the correlation of these parameters with the agreement between V_{circ} and V_{azi} .

Convergence radius

Power et al. (2003) have defined a convergence radius for dark-matter halos in cosmological simulations, based on the enclosed number of particles and corresponding two-body relaxation time scale. They found that convergence within radius R is achieved on scales where the average two-body relaxation time scale t_{relax} becomes comparable to the age of the Universe t_0 , i.e. $t_{relax} > 0.6 t_0$. The condition for convergence is, therefore,

$$0.6 < \frac{t_{relax}}{t_0} = \frac{\sqrt{200}}{8} \frac{N}{\ln N} \sqrt{\frac{\rho_{crit}}{\bar{\rho}}}, \quad (2.29)$$

where $\rho_{crit} = \frac{3H_0^2}{8\pi G}$ is the critical density of the Universe and $\bar{\rho}$ is the mean density within a radius R_{conv} , which relates the convergence condition to the numerical resolution, as

$$\bar{\rho} = \frac{3 M_{encl}}{4\pi R_{conv}^3} \quad (2.30)$$

2. Methods

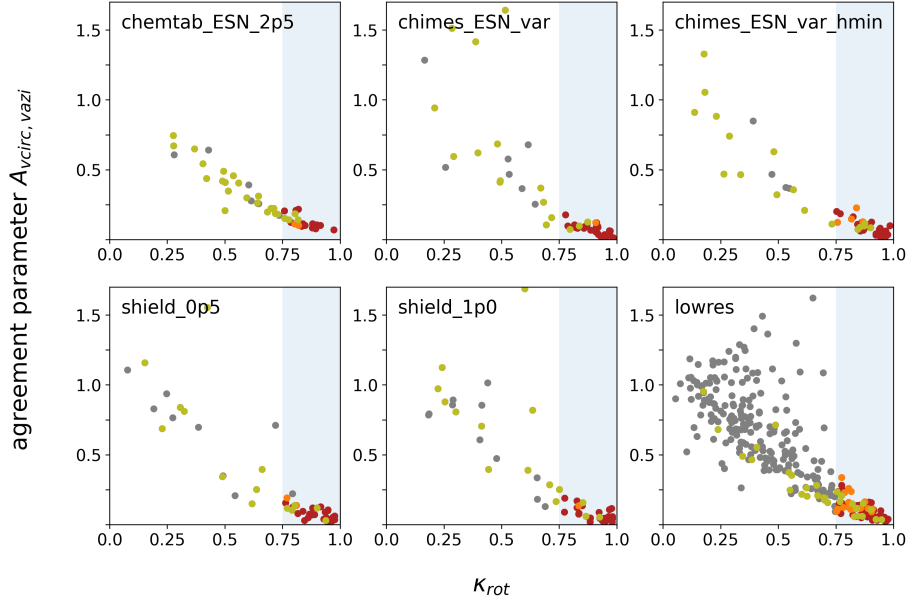


Figure 2.14.: Correlation of the agreement parameter $A_{vcirc,vazi}$ with the rotational support parameter κ_{rot} . Perfect agreement between V_{circ} and V_{azi} corresponds to $A_{vcirc,vazi} = 0$. The shaded region indicates the selection criterion $\kappa_{rot} \geq 0.75$. Galaxies with lower κ_{rot} values are *unselected*. Green dots mark the galaxies with angular momentum variation $L_{var} \geq 0.1$. Galaxies which fulfill the κ_{rot} criterion but not the L_{var} criterion are also *unselected*. Orange dots mark the remaining galaxies that were excluded based on visual inspection of the velocity moment maps. The final *selected* samples used for the following analyses are indicated by the red dots.

2.8. Identifying ill-suited galaxies

and

$$M_{encl} = N \cdot m_{dm}, \quad (2.31)$$

where N is the enclosed number of particles and m_{dm} is the particle mass. The convergence radius R_{conv} is the minimum scale on which the simulation produces reliable results. It should be noted that the criterion $\frac{t_{relax}}{t_0} > 0.6$ defined by Power et al. (2003) is suited for DMO simulations. Schaller et al. (2015) showed that for the EAGLE simulations the criterion could be relaxed to $\frac{t_{relax}}{t_0} > 0.33$ and still yield a conservative estimate of R_{conv} . For the present analysis the criterion of Schaller et al. (2015) was adopted. Galaxies were not selected or unselected based on this criterion, but the measurements of the rotation curve parameters are considered robust only for galaxies where $r_{fid} \geq R_{conv}$.

3. Results

3.1. Global galaxy properties

3.1.1. Disk size and H I content

Figure 3.1 shows the H I mass-size relation of the simulated galaxies in the six snapshots. Blue dots indicate the values obtained from the particle data, cyan circles mark the values obtained from mock-observed data for comparison. For completeness, also the *unselected* samples are shown, indicated by open circles. The dashed line marks the fit

$$\log(R_{H\text{I}}) = 0.506 * \log(M_{H\text{I}}) - 3.293. \quad (3.1)$$

obtained by Wang et al. (2016) for observed galaxies. The shaded band indicates the observed 3σ scatter with $\sigma = 0.06$ dex. The *selected* simulated galaxies are generally in good agreement with the observed relation, albeit exhibiting a slightly larger scatter than that observed. The galaxies from the low-resolution run have preferentially larger H I disks at fixed H I mass than observed galaxies.

3.1.2. H I disk thickness

The disk heights, as defined by the half-width-half-maximum of the vertical H I density distribution (HWHM_z), obtained for the six galaxy samples are plotted as a function of radius in Figure 3.2. Figure 3.3 shows a zoom-in on the central regions of the disks. In all samples the H I disks show a flaring trend where the HWHM_z increases with radius. The red solid lines in the plots mark the median HWHM_z profiles of the galaxy samples from the respective simulation runs. The `chemtab_ESN_2p5` run (top left panel) produced on average the thickest H I disks, especially in the central regions. In this simulation run, the median HWHM_z reaches values above 500 pc within a radius of 2 kpc and grows to ~ 1 kpc at a radius of 5 kpc. In the other simulation runs, the disk height grows more slowly with the median HWHM_z reaching 500 pc at a radial distance of ~ 5 kpc and a thickness of ~ 1 kpc at radii of ~ 10 kpc.

The H I disk heights produced by the COLIBRE test runs are generally consistent with those measured in observed dwarf galaxies, with the exception of the `chemtab_ESN_2p5` run, in which the H I disks tend to be thicker. It should be noted that a direct comparison between results should be made with caution, as different authors use different methodologies. Patra (2020) studied the disk heights of dwarf galaxies from the LITTLE THINGS survey by modelling the disks ring by ring and solving for the hydrostatic equilibrium equation. Their methodology involved assumptions about the underlying dark-matter halo structure and knowledge about the distribution of stars, which is not considered in

3. Results

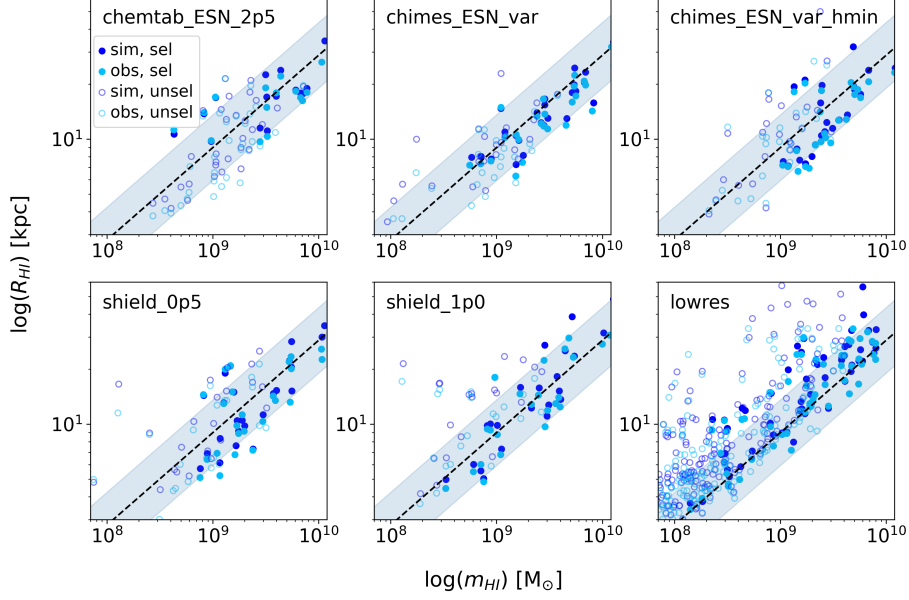


Figure 3.1.: H I mass - size relation of the galaxy samples from the six simulation snapshots. The H I disk radius $R_{H\text{I}}$ is defined as the radius enclosing 90% of the H I mass. The dashed line marks the fit by Wang et al. (2016) for observed galaxies. Blue symbols indicate values obtained from the simulation data. Cyan symbols indicate values obtained from mock observations. Dots represent the *selected* samples. Open circles mark the *unselected* samples.

the analysis conducted here. Yet, their resulting HWHM_z values are comparable to those obtained here. Those galaxies from the LITTLE THINGS sample which fall into the V_{max} range studied here, namely DDO 47, DDO 52, DDO 87, DDO 101, DDO 168, NGC 3738 and Haro 36, have HWHM_z values of ~ 200 pc at radii around 2 kpc and (where data exist at larger radii) ~ 400 pc at 5 kpc. These H I disk height profiles are reproduced in the COLIBRE test runs (except for `chemtab_ESN_2p5`), though they tend to fall towards the lower end of the thickness range spanned by the simulated galaxies. O'Brien et al. (2010) analysed a sample of eight edge-on dwarf galaxies, seven of which fall within the V_{max} range that is of interest here. The measured HWHM_z values of these galaxies range between 200 pc and 1 kpc at a radius of 5 kpc, which is in good agreement with the simulation runs apart from `chemtab_ESN_2p5`. The particular differences between the individual runs will be discussed in Section 4

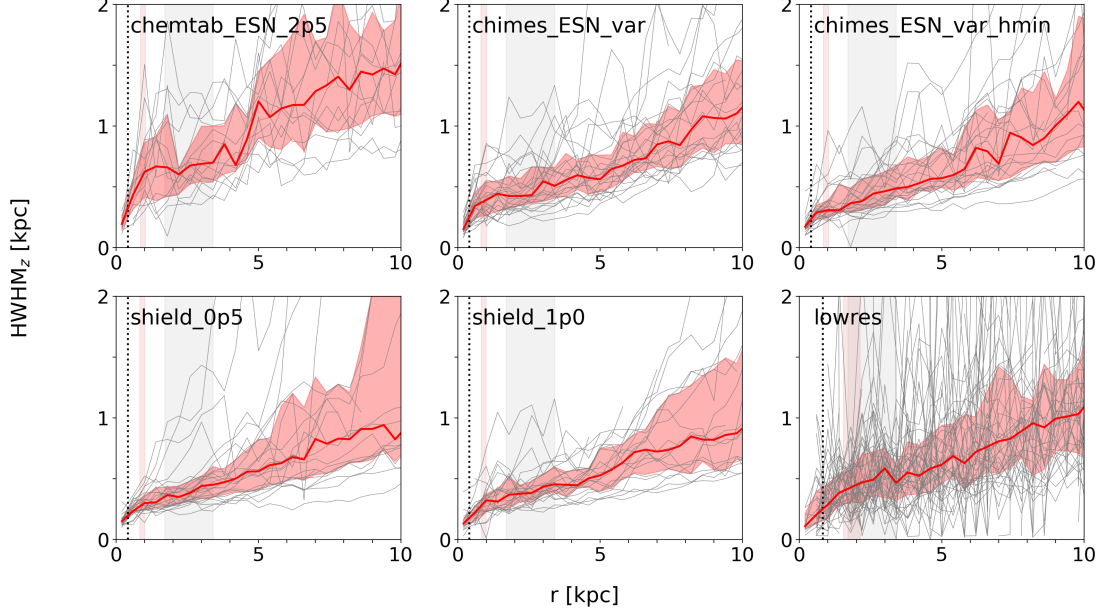


Figure 3.2.: H I disk thickness profiles of the *selected* galaxy samples. The solid red line represents the median, the shaded region marks the range between the 25th and 75th percentiles. The vertical shaded bands indicate the range of convergence radii R_{conv} (red) and fiducial radii r_{fid} (grey) of the galaxies in the respective samples. The vertical black dotted line indicates the gravitational softening length ϵ_{dm} .

3.1.3. H I morphology and dynamical structure

The simulated galaxies show a variety of morphologies as seen in their mock-observed H I distribution, including well-defined disks as well as highly irregular systems. The disks exhibit intricate structures, featuring H I patterns that are often web-like, some are indicative of arm-like structures. Others show no clear disk, indicating that the gas dynamics are dominated by random or turbulent motions. Several galaxies show features of past interactions, such as warps, elongations, or ring structures. The majority of the studied galaxies exhibit holes in their H I distribution. Such holes are typical for dwarf irregular galaxies and are associated with stellar feedback (see e.g. [Hunter et al., 2024](#)). Furthermore, H I feedback bubbles have been shown to be relevant for rotation curve studies, as they can push the gas rotation out of equilibrium (see [Read et al., 2016](#)). In terms of the H I distribution, the galaxies produced in the simulations discussed here are more realistic than those produced in the EAGLE simulations, H I morphologies were

3. Results

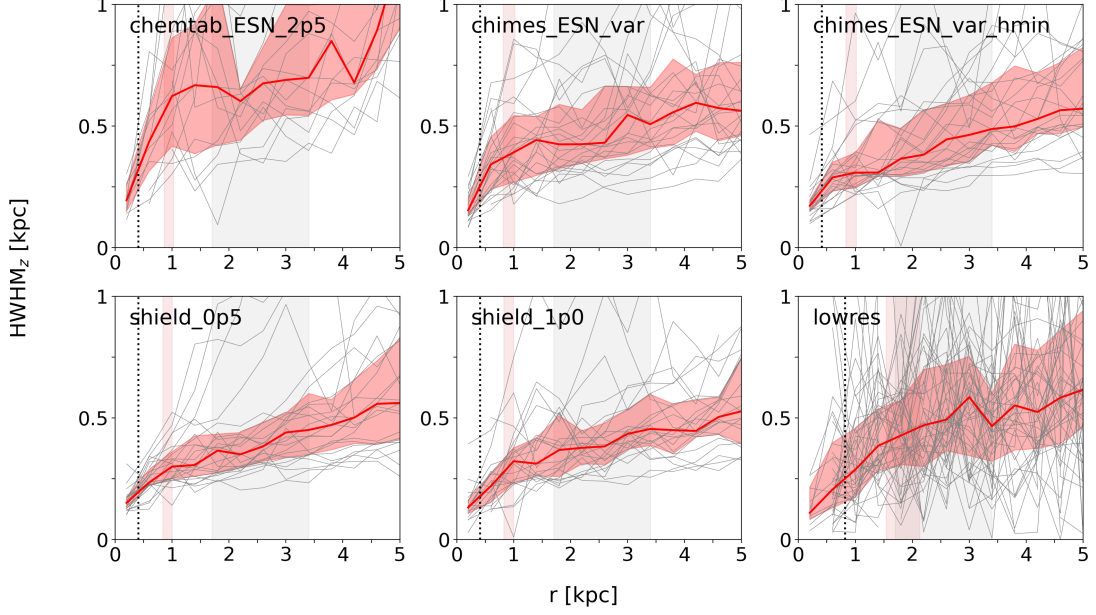


Figure 3.3.: Same as Figure 3.2, but zoomed in to show the inner 5 kpc.

generally lacking intricate structure and whose H I holes were unrealistically large (Bahé et al. 2016). Figure 3.4 shows some representative examples of the various mock-observed H I morphologies. Images of the full samples can be found in Appendix A.

3.2. Agreement between rotation curves

In order to assess whether V_{azi} and V_{obs} serve as a tracer of the V_{circ} , i.e. the underlying mass profiles, the agreement between these rotation curves was evaluated. The figures 3.2 - 3.8 show the rotation curves of galaxies representative of the different cases described in Section 2.7.1 as well as the corresponding intensity and velocity maps as mock-observed from the different viewing angles. The black curves in the top panels of figures 3.2 - 3.8 are the circular velocity curves V_{circ} that were computed from the total mass distribution of the respective galaxies. The blue curves are the median azimuthal velocity curves V_{azi} of the H I gas, as calculated directly from the particle velocities. The solid and dashed orange curves are the rotation curves obtained via mock observations from the two different viewing angles.

The cases labelled are:

- excel: excellent agreement between V_{circ} and V_{azi} ; azimuthal H I rotation curve traces

3.2. Agreement between rotation curves

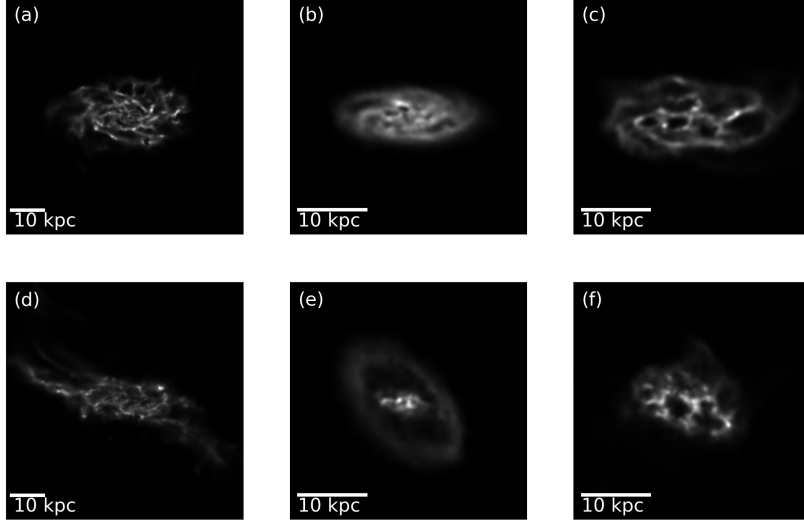


Figure 3.4.: Selection of representative examples of the simulated galaxies' morphologies. The horizontal bars mark the scale of 10 kpc for reference. Intricate structure is clearly visible in all examples. Galaxies (a), (b), and (c) represent well-defined disk galaxies. Galaxies (d) and (e) show features that are indicative of recent interaction (a strong warp and an inclined ring structure, respectively) and were therefore *unselected*. Galaxy (f) is an example of a *selected* galaxy at the limit of the κ_{rot} selection criterion.

the circular velocity, deviating only by mild oscillations.

- fair: fair agreement between V_{circ} and V_{azi} ; azimuthal H I rotation curve may show some deviations from the circular velocity curve but follows the overall shape
- poor: poor agreement between V_{circ} and V_{azi} , azimuthal H I rotation curve shape deviates significantly from the circular velocity curve
- Φ -dep.: the rotation curves obtained via mock-observations depend significantly on the viewing angle
- gas main: V_{azi} deviates from V_{circ} but the mock-observed curves reproduce V_{azi} ; gas perturbations are the main driver of the observed deviations from V_{circ} .
- obs. main: excellent or fair agreement between v_{circ} and V_{azi} but at least one of

3. Results

	<i>chemtab_ESN_2p5</i>	<i>chimes_ESN_var</i>	<i>chimes_ESN_var_hmin</i>	<i>shield_0p5</i>	<i>shield_1p0</i>	<i>lowres</i>
#	15/48	25/49	25/49	24/49	23/50	55/307
excel	0.00	0.16	0.16	0.08	0.17	0.05
fair	0.27	0.68	0.48	0.67	0.52	0.60
poor	0.73	0.16	0.36	0.25	0.34	0.35
Φ -dep.	0.73	0.76	0.80	0.63	0.65	0.56
gas main	0.33	0.16	0.20	0.33	0.26	0.29
gas main (poor)	0.07	0.00	0.00	0.04	0.09	0.00
obs. main	0.00	0.52	0.32	0.46	0.39	0.39
obs. main (excel)	0.00	0.00	0.04	0.08	0.04	0.00
all agree	0.00	0.16	0.12	0.00	0.13	0.06
all disagree	0.27	0.03	0.24	0.33	0.22	0.42

Table 3.1.: Relative frequency of the agreement cases defined in Section 2.7.1 within the *selected* samples of the simulation test runs. The first row indicates the size of the selected samples with respect to the parent samples.

the mock-observed rotation curves deviates significantly from V_{azi} ; observational effects are the main driver of the deviation from the circular velocity curve

These representative examples highlight some interesting observations made in the course of the analyses of the galaxies' rotation curves.

The trend is that deviations from circular velocity increase for smaller disk sizes as morphologies become more and more irregular. One morphological characteristic that seems to play an important role in shaping the rotation curves is the presence of large holes or feedback bubbles. While bubbles are also present in some of the galaxies in the 'excellent tracer' category, the increase in frequency and size of the bubbles is accompanied by a weaker agreement between the different rotation curves.

On the one hand these bubbles can contribute a substantial amount of non-circular motions, driving V_{azi} away from V_{circ} . On the other hand, also the fitting process could be affected if they coincide with the galaxy's projected major axis where most of the velocity information lies.

Table 3.1 shows the fraction of the galaxies from the *selected* samples falling in the categories defined above. The exact numbers may vary depending on the definition of the agreement parameters and the choice of critical values used to distinguish between different cases. However, the statistics highlight several interesting points:

3.2. Agreement between rotation curves

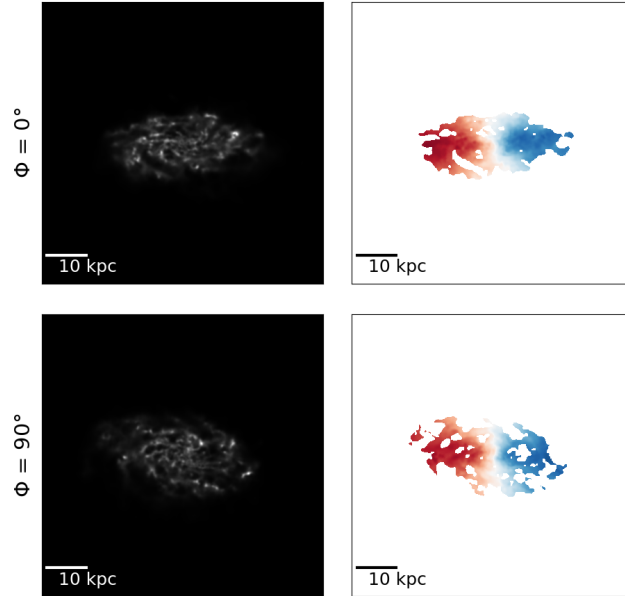
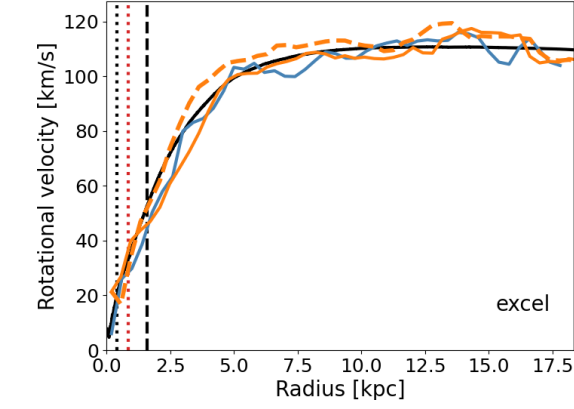


Figure 3.5.: Example of a galaxy with excellent agreement between circular velocity curve (black line) and azimuthal velocity curve (blue line). The orange lines are the rotation curves that an observer would measure from a viewing angle $\Phi = 0$ (solid line) or $\Phi = 90$ (dashed line), respectively. Vertical dotted lines indicate the smoothing length ϵ_{dm} (black) and convergence radius R_{conv} (red). The black dashed line indicates the fiducial radius r_{fid} .

3. Results

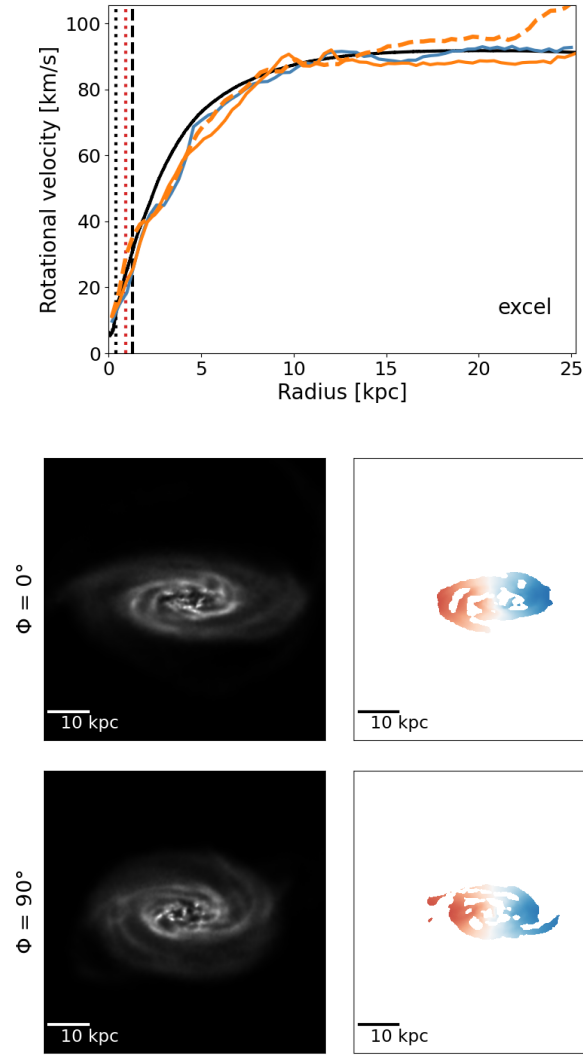


Figure 3.6.: Same as Figure 3.2

3.2. Agreement between rotation curves

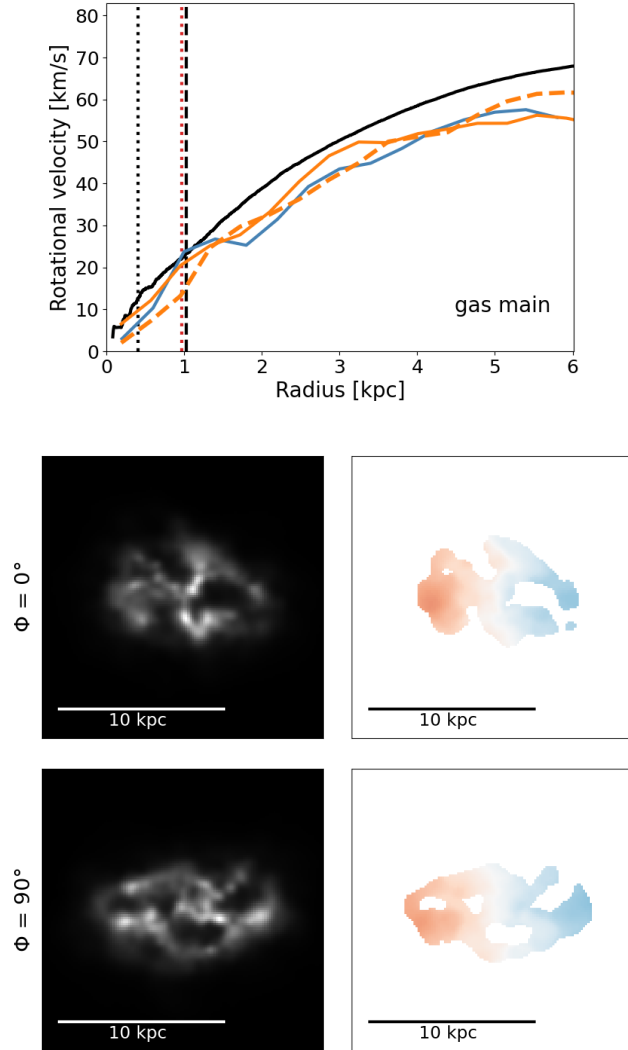


Figure 3.7.: Same as Figure [3.2](#) but for a representative example of the case ‘*gas main*’.

3. Results

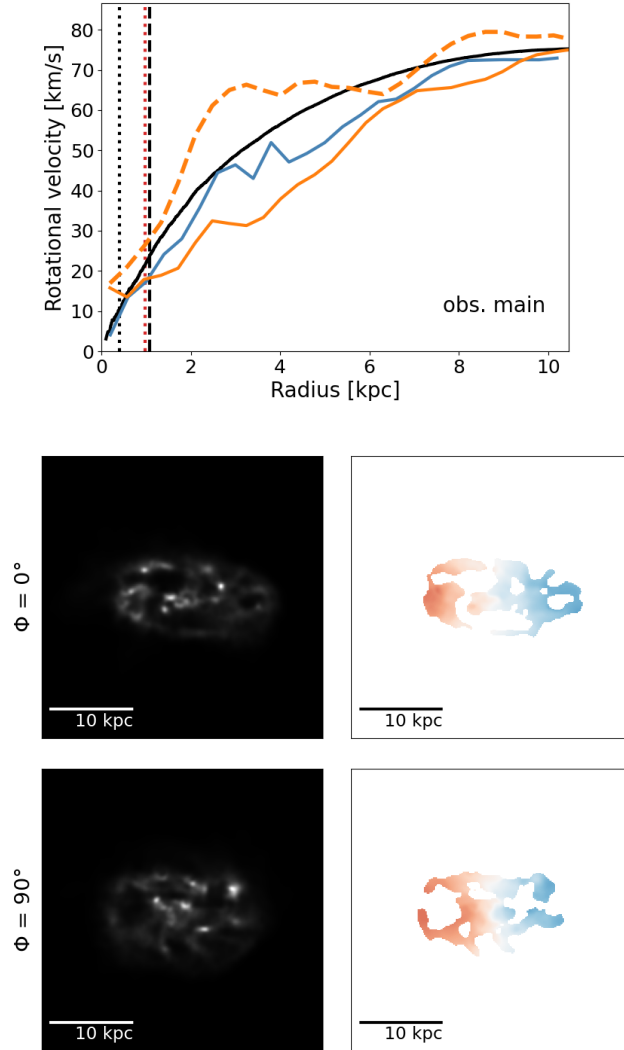


Figure 3.8.: Same as Figure 3.2 but for a representative example of the case ‘*obs main*’.

3.3. Rotation curve diversity

1. Having excluded ill-suited galaxies, the remaining samples still contain substantial fractions of galaxies whose median azimuthal H I velocity curve does not trace the circular velocity well. In most simulation runs, the poor tracers constitute a smaller fraction than the fair tracers, with the exception of the chemtab_ESN_2p5 run. Excellent tracers constitute the smallest fraction.
2. The majority of observed rotation curves show a large dependence on the viewing angle in all simulation runs.
3. Larger fractions are found in the case that v_{obs} deviates from V_{azi} while V_{azi} is a fair tracer of V_{circ} than in the case that V_{obs} traces V_{azi} accurately while V_{azi} is a fair or poor tracer of V_{circ} . This suggests that observational effects were often the stronger influencer of the measured rotation curves than the gas perturbations alone.
4. None or few galaxies where observational effects are strong are in the category with V_{azi} as excellent tracer of V_{circ} . Analogously, galaxies where gas perturbations are the main driver in shaping the measured rotation curves are hardly found in the category where V_{azi} is a bad tracer of V_{circ} . This underscores that the effects of gas perturbation and observational uncertainties are not independent. It rather seems that the deviations due to observational effects increase if V_{azi} is already affected by gas perturbations.

3.3. Rotation curve diversity

Figure 3.9 shows the rotation curve shape parameter V_{fid} of the circular velocity curves as a function of V_{max} for galaxies of the *selected* samples from the different simulation snapshots.

The grey dots indicate observational data collected by Santos-Santos et al. (2020) for comparison. These include datasets from THINGS (de Blok et al. 2008), LITTLE THINGS (Oh et al. 2015), SPARC (Lelli et al. 2016), Adams et al. (2014), and Relatores et al. (2019). Two lines are drawn to guide the eye: the black dotted line marks the 1:1 relation between V_{fid} and V_{max} . Points that lie close to this line indicate very steeply rising velocity profiles. The solid grey line marks the relation expected for NFW profiles with the halo concentration parameters calculated according to Correa et al. (2015). The shaded band indicates the region of ± 0.1 dex from the NFW expectation. The vertical dashed lines indicate the V_{max} limits based on which the samples were originally selected.

The circular velocity curve shapes, which directly trace the underlying mass distribution, are widely compatible with NFW profiles, as most of the data points lie within the grey shaded area. Figure 3.10 emphasizes the trends of the V_{circ} shapes relative to the NFW expectation by normalising the data to the NFW values. In general, galaxies with lower V_{max} values tend to lie below the NFW line, i.e. they tend towards more cored profiles, while galaxies with higher V_{max} values lie preferentially above the NFW line, tending towards more cuspy profiles. The particular differences between the various simulation runs are discussed in Section 4

3. Results

The rotation curve diversity of V_{circ} , i.e. the scatter in V_{fid} at fixed V_{max} , is smaller than that of the observed rotation curves from the literature, as can be seen in Figure 3.9.

The rotation curves obtained via mock-observations exhibit a significantly larger scatter in V_{fid} as shown in Figure 3.11. Also, some of the measured V_{max} values are scattered beyond the original selection limits in the case of the mock observations. Figure 3.12 shows again the normalisation of the data to the NFW expectation. The rotation curve shapes obtained from mock observations agree remarkably well with the observed data points. Note that the sample sizes of the mock-observed galaxies (blue ‘+’ symbols) are doubled in Figures 3.11 and 3.12 by plotting the results for each galaxy as observed from both viewing angles. Yet, the *selected* galaxy samples shown in these figures do not cover the full diversity. The extremely cuspy profiles on the lower V_{max} -end that would lie above the grey band are not reproduced in any of the test runs.

Figure 3.13 illustrates how the circular velocity profile relates to the baryonic importance in the inner regions. The parameter

$$\eta_{bar} = (V_{bar,fid}/V_{fid})^2 \quad (3.2)$$

from Santos-Santos et al. (2020) indicates the contribution of baryonic matter to the rotation velocity at the fiducial radius r_{fid} . Observations have shown that nearby low-mass galaxies with cuspy profiles (as indicated by high values of η_{rot}) span a wide range in η_{bar} , ranging from $\eta_{bar} \lesssim 0.1$ to $\eta_{bar} \sim 1$ and galaxies with high baryonic importance (as indicated by large η_{bar}) span a wide range in η_{rot} . The observed data are indicated by the grey dots in Figure 3.13. The upper-right corner of the plots is populated by the higher-mass galaxies, for which it is not unexpected that the accumulation of baryonic matter in the central region supports a cuspy rotation profile. Somewhat counter-intuitive is the presence of galaxies with little baryonic importance and steeply rising rotation profiles and the presence of cored profiles with high baryonic importance. Indeed, the galaxies with the most cored profiles show the highest baryonic importance, and the profiles with the least baryonic importance are the most cuspy ones. As has been pointed out by Santos-Santos et al. (2020), the mechanism that reproduces the observed rotation curve diversity in simulated low-mass galaxies must also reproduce this distribution in the η_{rot} - η_{bar} plane.

Figure 3.14 shows the distribution η_{rot} vs. η_{bar} as measured from the mock-observed rotation curves. Again, the samples are now doubled because the data obtained from both viewing angles are plotted. The data points corresponding to V_{obs} are more scattered than those corresponding to V_{circ} and widely agree with the observed data (grey dots). In particular, the lower wing of the observed distribution (slowly rising profiles with large baryonic importance) is covered. Since the inner circular velocity curves are preferentially underestimated by the observed rotation curves while the measure of the baryonic mass is not affected, a large portion of galaxies now appear centrally baryon-dominated. The other end of the distribution (steeply rising profiles with minor baryonic importance) remains less populated, except in the chemtab_ESN_2p5 sample. Here, the data points spread

3.3. Rotation curve diversity

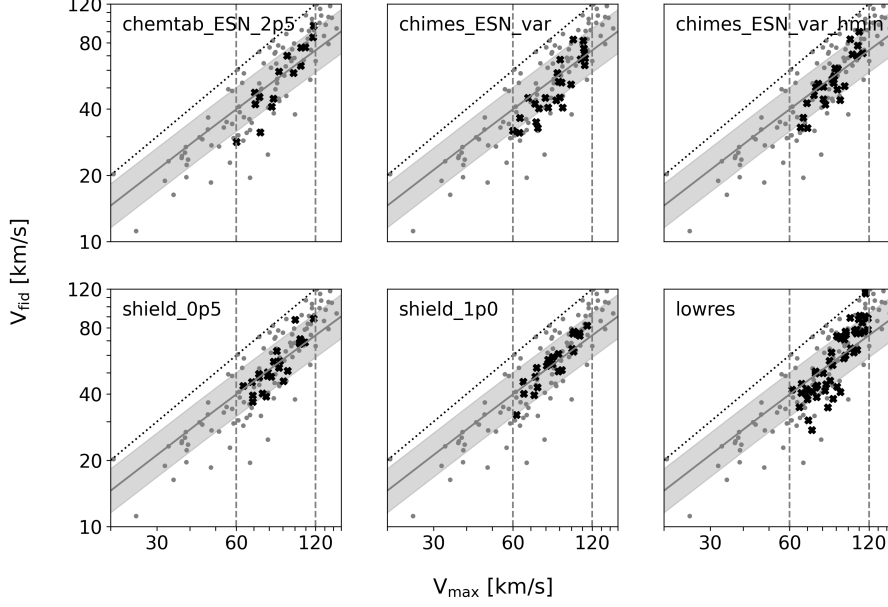


Figure 3.9.: *Rotation curve shapes.* Black bold crosses represent the circular velocity curves V_{circ} of the *selected* samples, grey dots indicate the observed data sample from Santos-Santos et al. (2020). The grey solid line indicates the V_{fid} values expected for NFW profiles at given V_{max} and with a halo concentration calculated according to Correa et al. (2015). The shaded band spans ± 0.1 dex. The black dotted line indicates the 1:1 relation between V_{fid} and V_{max} . Rotation profiles that rise very steeply lie close to this line. The more slowly rising a rotation curve is, the lower is its V_{fid} value at fixed V_{max} . The circular velocity profiles are generally in good agreement with the NFW expectation.

across the entire panel. The differences between the results of the different simulation runs are addressed in the next section.

3. Results

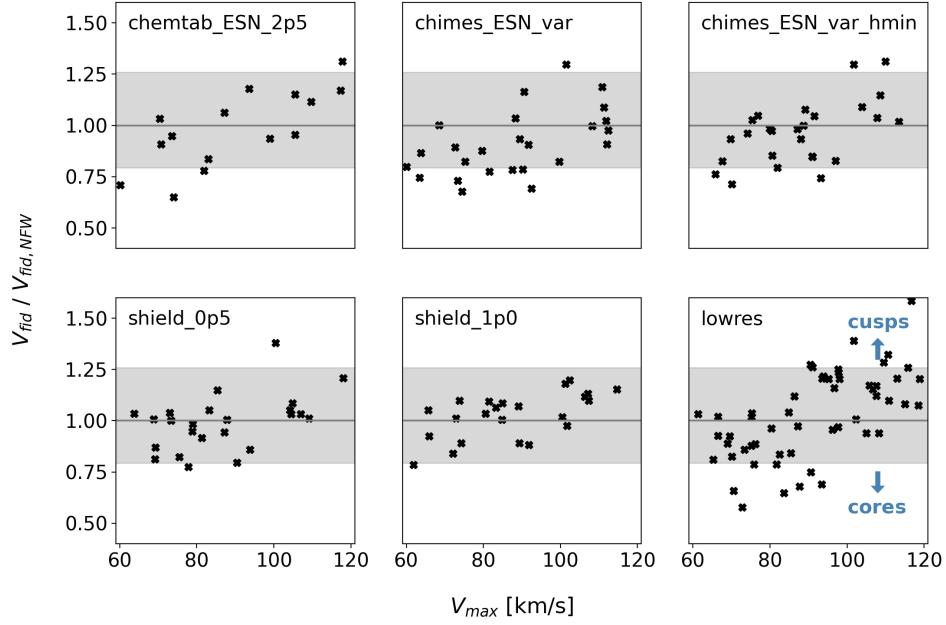


Figure 3.10.: This figure shows the V_{fid} values of the *selected* circular velocity curves normalised to the NFW expectation (grey solid line, as in Figure 3.9). Rotation curves that lie above the grey line are more steeply rising, corresponding to ‘cuspy’ density profiles, whereas galaxies that lie below the grey line represent more ‘cored’ density profiles. While overall consistent with NFW profiles, galaxies with lower V_{max} lie preferentially below the grey line and galaxies with higher V_{max} tend to lie above.

3.3. Rotation curve diversity

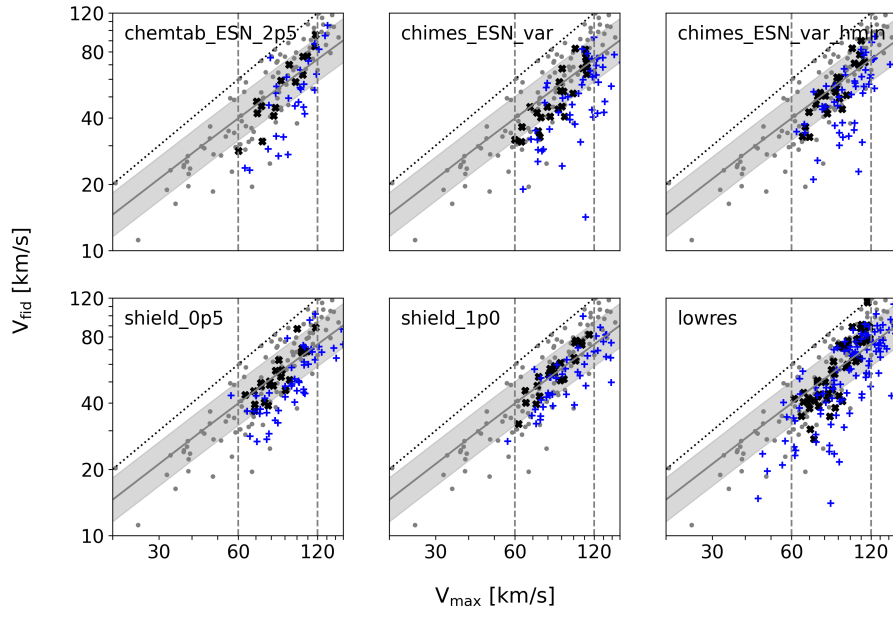


Figure 3.11.: Same as in Figure 3.9, but including the data from the mock observations (blue ‘+’ symbols). Data obtained from both viewing angles ($\Phi = 0$ and $\Phi = 90$) are plotted. Mock-observed rotation curves exhibit a larger scatter in V_{fid} than the circular velocity curves, bearing resemblance to the observed data.

3. Results

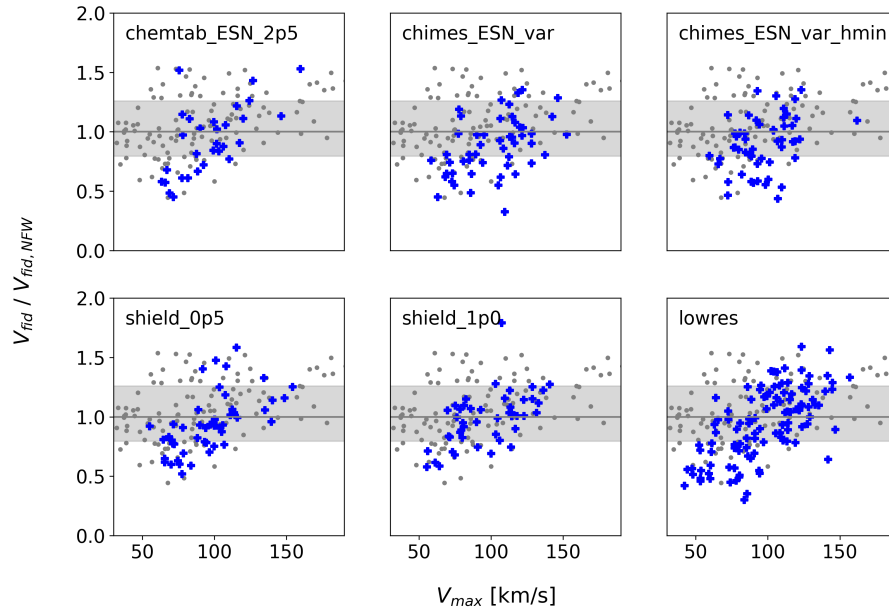


Figure 3.12.: Same as in Figure 3.10 but for data from the mock observations (bold blue ‘+’ symbols), as well as from the literature (grey dots, Santos-Santos et al. 2020) for comparison. Data obtained from both viewing angles ($\Phi = 0$ and $\Phi = 90$) are plotted. Mock-observed rotation curves exhibit a larger scatter in V_{fid} than the circular velocity curves, bearing resemblance to the observed data.

3.3. Rotation curve diversity

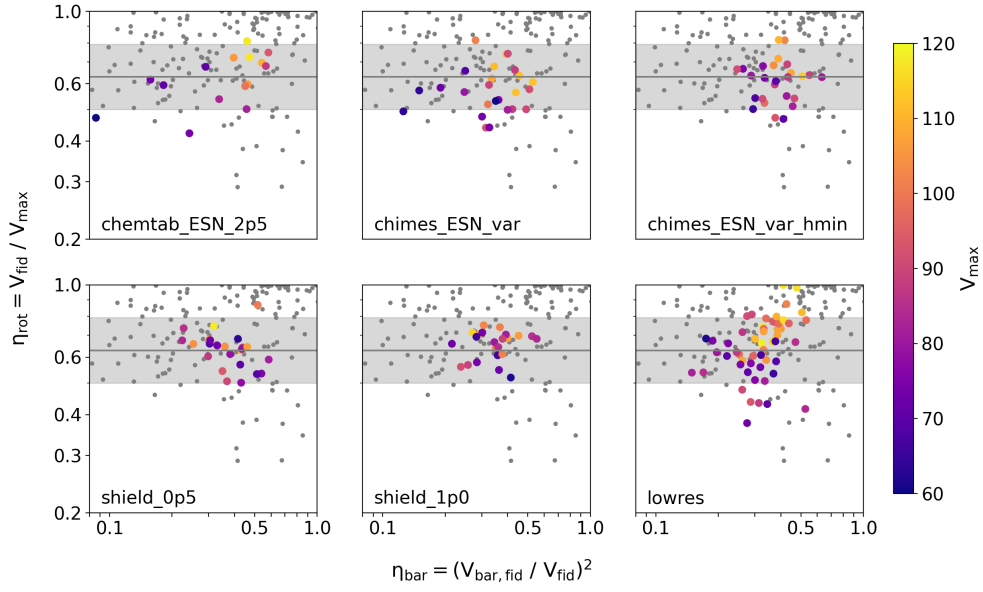


Figure 3.13.: *Rotation curve shape vs. central baryonic importance of the circular velocity curves.* Coloured data points indicate the *selected* samples and are colour-coded by the galaxies' V_{max} values. Grey dots indicate observed data from Santos-Santos et al. (2020) for comparison. The horizontal line indicates the mean η_{rot} value expected for NFW profiles in the selected V_{max} range and with halo concentration parameters calculated according to Correa et al. (2015).

3. Results

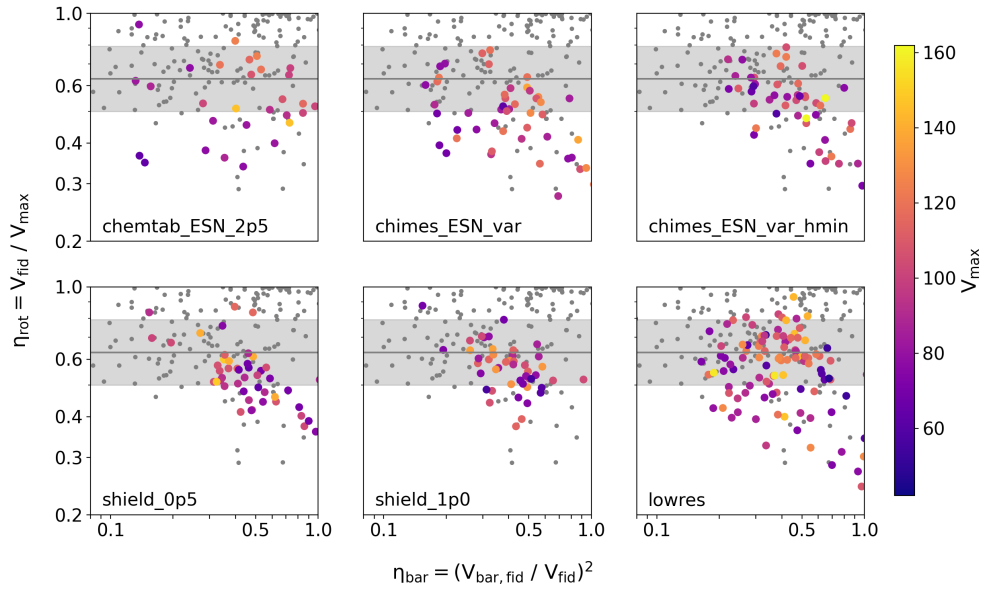


Figure 3.14.: Same as in Figure 3.13 but for the mock-observed rotation curves. Data obtained from both viewing angles ($\Phi = 0$ and $\Phi = 90$) are plotted.

4. Discussion

4.1. Effect of parameter variations

The comparison of the results from the various simulation runs reveals the sensitivity to or robustness against the variation of the parameters tested here. The following sections examine the effect of parameter variations on the results obtained directly from the simulation data and the results obtained from mock observations. The former should reveal the direct effect of the parameter variations on the galaxies' structural properties including the total mass distribution as reflected in the circular velocity profile. The latter is to reveal whether potential differences between the various galaxy samples would also be visible to an observer or outweighed by observational effects. Furthermore, combining an observer's perspective with the additional information available here can help to constrain what drives the observational effects and whether this correlates with properties sensitive to parameter variations in the simulation runs.

The `lowres` simulation run produced some peculiar results that indicate that the galaxies in the studied mass range were not resolved sufficiently to represent a realistic dwarf galaxy population. On the one hand, the excess of isolated low-mass galaxies with weak rotational support and little H I hints at the sample not being representative. On the other hand, the H I mass-size relation is offset from the observed relation. Furthermore, the fiducial radii used to quantify the rotation curve shapes are smaller than the convergence radius of this simulation run, due to the larger particle masses. Although [Schaye et al. \(2015\)](#) have shown that the convergence radius defined by [Power et al. \(2003\)](#) is a conservative upper limit and the results of the low-resolution run are qualitatively similar to the high-resolution variants, the detailed discussion focuses on the results from the high-resolution runs only.

4.1.1. Results obtained from simulation data

Structural properties

The H I mass-size relation of the simulated galaxy populations is largely unaffected by variations of the simulation parameters, as can be seen in figure [3.1](#).

The disk thickness, on the other hand, seems to be more sensitive to the specific implementation of baryonic processes. Figures [3.3](#) and [3.2](#) show that the `chemtab_ESN_2p5` run produced, on average, the thickest H I disks, followed by the low-resolution run. The lowest median of HWHM_z profiles was found in the `shield_1p0` run. This difference in median disk thickness of the galaxy samples is most pronounced in the central regions. The major differences between `chemtab_ESN_2p5` and the other simulation runs were the

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use of tabulated chemical reactions and gas cooling and heating rates and the employed supernova feedback. Feedback mechanisms are known to impact the structure of low-mass galaxies, as they are associated with the redistribution of matter and details of the implementation may control e.g. the strength of outflows or the height above the disk at which gas gets deposited (see Bahé et al., 2016). The simulation run `chemtab_ESN_2p5` differed from the subsequent runs in the assumption of a SNII energy of $2.5 \cdot 10^{51}$ erg and a fixed fraction of 1.0 of that energy applied in one SNII event. The other runs assumed SNII energies of 10^{51} erg and let the applied fractions vary, depending on the birth pressure of the star particle. These simulation runs used fractions ranging from 0.1 to 3.5, from 0.1 to 4.0 or from 0.5 to 4.0, respectively (see table 2.4). Another difference between `chemtab_ESN_2p5` and the other simulation runs was the fixed temperature change $\Delta T = 10^{7.5}$ which a neighbouring gas particle receives from supernovae of type Ia. In the subsequent runs this temperature was allowed to vary, depending on the birth density of the star particle. But since all runs, including `chemtab_ESN_2p5`, also had varying ΔT for SNII events and the same minimum and maximum ΔT was used in `chemtab_ESN_2p5`, `chimes_ESN_var` and `chimes_ESN_var_hmin`, the variations in the allowed range of temperature change are likely not the major driver of the systematically thicker HI disks in the `chemtab_ESN_2p5`. From the parameters tested here, the HI disk thickness thus seems to be most sensitive to the applied supernova energies.

The most straight-forward comparison can be made between the two simulation runs `shield_0.5` and `shield_1p0`, which differ in only one parameter, namely the shielding length factor. This pre-factor controls the shielding column density and is thus relevant for gas cooling. While the `shield_0p5` run differed from `chimes_ESN_var_hmin` in the details of the pressure dependence of the applied SNII energy and maximal dust boost factor, the HWHM_z profiles of the galaxy population from these runs are similar. The distribution of HWHM_z profiles in the `shield_1p0`, however, is notably different, as it lacks HWHM_z values exceeding 1 kpc out to radii of ~ 6 kpc. This could be interpreted as a consequence of the larger shielding column density, as, due to the more efficient gas cooling, the gas may stay confined to thinner disks, especially in the inner regions. A larger galaxy sample would be desirable to confirm this effect.

Rotation curve shapes

The distribution of circular velocity curve (V_{circ}) shapes, corresponding to the underlying mass profiles, do not seem to be very sensitive to the tested parameter variations. The circular velocity curve shapes, as quantified by V_{fid} are generally in good agreement with NFW density profiles, although the lower-mass galaxies tend to lie below the NFW line with lower values of V_{fid} and the higher-mass galaxies preferentially have more cuspy profiles with higher V_{fid} values. Slight differences could be discerned in the actual trends of V_{fid} vs. V_{max} between the different simulation runs (see Fig. 3.10), although larger galaxy samples would be needed to draw firm conclusions. In all runs except for `chemtab_ESN_2p5` the lower-mass end of the galaxy population parallels the NFW prediction, preferentially below the NFW line, while there is an upward trend towards higher V_{fid} for galaxies with V_{max} values above 100 km/s. This is not unexpected, as

4.1. Effect of parameter variations

higher-mass galaxies accumulate more baryonic matter, which acts gravitationally on the DM halo, enhancing the density in the centre (see Schaller et al., 2015). In the panel representing the `chemtab_ESN_2p5` run, this upturn is not seen. Instead, $V_{fid}/V_{fid,NFW}$ seems to rise linearly from lower to higher V_{max} values. A possible interpretation of this would be that the SNII energies that give rise to thicker H I disks also change the gravitational potential via mass outflows in a way that supports density core formation on the low-mass end. Also in the `shield_1p0` run, the distribution of galaxy shapes is slightly distinct. Here, the lower-mass end is slightly raised in terms of V_{fid} so that more low-mass galaxies lie above the NFW line than in the other simulation runs. The higher-mass end, on the other hand, stays bound within the NFW band, i.e. central density cusps are less pronounced with respect to the other simulation runs. A possible interpretation of this is that efficient cooling promoted the accumulation of baryonic matter and therefore enhanced central densities at the lower-mass end. At the higher-mass end this enhancement could be counteracted by starbursts.

Since the mentioned differences in the distributions of circular velocity curve shapes are small, they could be attributed to the small sample numbers in the simulation runs. Yet, it is interesting to note that they appear in those simulation runs, which already stood out in terms of the galaxies' vertical structures.

Also, the trend of rotation curve shape with baryonic importance bears some differences between the various simulation runs. The most noticeable variation can again be seen in the trend of the `chemtab_ESN_2p5` galaxies (see figure 3.13). In most simulation runs, the galaxy sample is concentrated in a small region $0.3 \lesssim \eta_{bar} \lesssim 0.6$ centered at $\eta_{rot} = 0.63$, which corresponds to the mean value expected for NFW profiles in the selected V_{max} range. The `chemtab_ESN_2p5` sample, on the other hand, shows a clear trend from low-mass galaxies with slowly rising velocity profiles and small baryonic importance to galaxies with higher mass, more steeply rising velocity profiles, and greater baryonic importance. This trend is likely a consequence of baryonic outflows driven by the relatively high thermal energies of type II supernovae, which are particularly efficient at the lower end of the considered mass range. Also, the `chimes_ESN_var` sample contains individual galaxies with low η_{bar} values but does not exhibit such a clear trend. A distinct trend can here also be seen in the rotation curve shapes of the `shield_0p5` galaxies. These galaxies seem to exhibit an anti-correlation between η_{rot} and η_{bar} where the cuspiest density profiles correspond to smaller baryonic importance. At fixed η_{rot} , the lowest-mass galaxies (as indicated by the lowest V_{max} values) tend to have higher values of η_{bar} than higher-mass galaxies. This is in contrast to the other simulation runs where the lower-mass galaxies preferentially show lower baryonic importance at fixed η_{rot} . This simulation run was largely based on the configurations of the `chimes_ESN_var_hmin` run but differed in the details of the prescriptions for supernova feedback. The range of energy fractions applied per SNII event as well as the pivot point of the birth pressure dependence of the energy fraction are shifted towards higher values for `shield_0p5` with respect to `chimes_ESN_var_hmin`. For SNII as well as SNIa events the applied temperature change has a higher minimum value and density pivot. Interestingly, the η_{rot} vs. η_{bar} distribution of galaxies from the `shield_1p0` run is more similar to the distribution from the `chimes`

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ESN_var_hmin run, although the two simulation runs `shield_0p5` and `shield_1p0` are identical apart from the shielding length factor. This implies that either the differences in the distributions are merely an effect of the small galaxy sample sizes or the changes that may be induced by an increased feedback efficiency are counteracted by the more efficient shielding of the ISM.

4.1.2. Results obtained from mock-observations

An observer's perspective

As can be seen in figure 3.1 observers of the galaxy samples analysed here would find H I masses and sizes similar to those obtained from the particle data. However, the rotation curves they would measure for these galaxies often deviate from the calculated circular velocity curves, as can be seen in Figures A.6 - A.14

An observer would find an appreciable scatter in rotation curve shapes with $V_{fid} - V_{max}$ values comparable to those reported in the literature (see Figures 3.11 and 3.12). This is true for all galaxy samples analysed with no clear differences between the various simulation runs. However, in comparison to the literature, the lower-mass galaxies with steeply rising rotation curves are missing in the *selected* galaxy samples analysed here. For maximum rotation velocities below ~ 100 kpc, the region above the grey NFW band remains largely empty in all panels in figures 3.11 and 3.12

The galaxy samples from the different simulation runs do appear different to the observer in terms of their distributions of the rotation curve shape parameter η_{rot} vs. the baryonic importance parameter η_{bar} (see Figure 3.14). The distribution of the sample from `chemtab_ESN_2p5` spreads almost evenly across the entire panel, with galaxies of low V_{max} found preferentially at lower baryonic importance. The other galaxy samples exhibit a weak to moderate anticorrelation between η_{rot} and η_{bar} . This anticorrelation is strongest in the `shield_0p5` sample. This sample also follows a peculiar trend where galaxies with the lowest V_{max} values are the most centrally baryon-dominated galaxies. Galaxies with such properties are also reported in the literature (e.g. Santos-Santos et al., 2020), although the observed low-mass galaxies show a larger scatter in baryonic importance per V_{max} bin, similar to the samples from `chimes_ESN_var_hmin` and `shield_1p0`. These samples are most compatible with the literature data in terms of baryonic importance. Note, however, that the mock observations do not include information on the stellar component. Therefore the observed η_{bar} was calculated using the true baryonic mass read from the simulation data.

A mock observer's privilege

The direct comparison between the observed rotation curve V_{obs} , the true H I rotation curve V_{azi} calculated from the particle velocities and the expected circular velocity calculated from the particle masses V_{circ} is a privilege of the mock-observer. This allows the mock observer to test the validity of the observed results and identify potential problems with their interpretation.

4.1. Effect of parameter variations

The rotation curve plots (Figures A.6 - A.14) show that the rotation curves that an observer would measure preferentially underestimate the circular velocity curves calculated from the mass distributions, especially in the inner regions of the galaxies. Overestimates of the inner curves also occur, but less frequently. The outermost parts of the V_{circ} curves are often overestimated by the mock-observed rotation velocities. This leads to a shift in the rotation curve shapes towards preferentially more slowly rising profiles in an expanded V_{max} range with respect to the circular velocity curves (see Figures 3.11 and 3.12).

Comparing V_{circ} and V_{obs} to V_{azi} sheds light on the origin of the discrepancies. Deviations of V_{azi} from V_{circ} indicate that the H I gas motions are perturbed. If the observed rotation curve V_{obs} agrees with V_{azi} , this means that the fit recovered the H I rotation well but the inferred mass profile may still be incorrect. Conversely it is possible that V_{azi} traces V_{circ} but V_{obs} deviates, indicating that the discrepancy is mainly driven by observational effects such as the alignment of the line of sight with the rotation pattern or limitations of the fitting procedure. In many cases of the studied galaxies, an interplay between these effects is apparent.

Figures 3.2 - 3.8 show rotation curve plots representative of the cases

- excel: V_{circ} , V_{azi} and V_{obs} observed from both viewing angles are in excellent agreement
- gas main: V_{azi} deviates from V_{circ} but is traced well by V_{obs} , i.e. the gas perturbations are the main cause of the deviation of V_{obs} from V_{circ} .
- obs main: V_{azi} is an excellent or fair tracer of V_{circ} but the V_{obs} curves deviate, i.e. the H I rotation follows the underlying mass distribution but observational effects drive the deviation of V_{obs} from V_{circ} .
- poor: V_{azi} is a poor tracer of V_{circ} . In most of these cases V_{obs} is then also an unreliable tracer of V_{azi} .

As can be seen in Table 3.1, the parameter variations between the different simulation runs had little effect on the case statistics. The one simulation run that stands out in terms of the agreement parameter distribution is `chemtab_ESN_2p5`, where no galaxies meet the criteria for the *excel* case. Instead, the majority of galaxies in this sample show poor agreement between V_{circ} and V_{azi} . In view of this simulation run's distinct treatment of supernova feedback, this suggests that vertical bulk flows may be the cause of the distorted H I rotation curves of this galaxy sample, an effect that has been investigated by Downing & Oman (2023). This is also in line with the larger median disk thickness of this galaxy sample, compared to the simulation runs that used variable supernova energies. In all simulation runs, including `chemtab_ESN_2p5`, the majority of the observed rotation curves exhibit a clear dependence on the viewing angle Φ , which highlights the importance of observational effects. Inspection of the plots of V_{circ} , V_{azi} and V_{obs} and the case statistics reveals that gas perturbations and observational effects occur independently in some cases, but are generally not unrelated. The discrepancies between the rotation

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curves observed from the different viewing angles appear to preferentially increase as the agreement between V_{azi} and V_{circ} decreases. Comparing the rotation curve plots to the H I morphologies (see Figures A.1 - A.5) of the galaxies suggests that H I holes play a role in the cause of the discrepancies. This is not surprising, as Read et al. (2016) have demonstrated the impact of feedback holes on measured rotation curves. Yet, the link between H I holes and the discrepancies is not straight forward, as holes are also present in galaxies with good agreement between the rotation curves. However, the results suggest that large H I holes might be an indicator that the observed rotation should be interpreted with caution.

On the whole, the differences between the galaxy samples from the various simulation runs are subtle. The higher supernova energies in `chemtab_ESN_2p5` are likely reflected in the thicker gas disks and poorer agreement of V_{azi} with V_{circ} . The higher shielding length factor in `shield_1p0` may give rise to thinner gas disks. However, a combination of gas perturbations and observational effects increases the scatter in the measured rotation curve shapes in a way that outweighs possible differences due to underlying structural properties.

4.2. Discussion of methods

4.2.1. Automated procedures

The analyses of the galaxy samples involved a combination of visual inspection and automated processes. In particular, the rotation curve fitting routine of 3D-BAROLO was run automatically on all galaxies using the same input parameters. This means that the fits did not receive any fine-tuning, except for changing the regularisation function to a 3rd-order polynomial in cases where the Bezier function did not yield a result. The produced fits are adequate for the questions addressed in this project, but the procedural approach might differ in this respect from observations, which usually aim at producing the most accurate results for individual galaxies and thus involve a more detailed assessment of the observed velocity field, e.g. in view of the radial trends of the inclination or the position angle, prior to setting the corresponding parameters and deciding on the type of regularisation (see e.g. Iorio et al., 2017) on a galaxy-by-galaxy basis. However, this should not affect the results presented here, as it has been shown that the program 3D-BAROLO is, in principle, capable of producing reliable fits without specific fine-tuning of the input parameters, as long as reasonable initial guesses are provided (see Di Teodoro & Fraternali, 2015). In the course of the automated fitting procedure, also the same velocity centre value was passed to the fitting algorithm for all galaxies. It should be noted that the simulation run `chemtab_ESN_2p5` used slightly different cosmological parameters than the other simulation runs, which affects the Hubble flow determining the systemic velocities of the galaxies. The velocity centre of the galaxies from this run is thus offset by 2.97 km/s. However, given the velocity channel width $\Delta v_{ch} = 2.6$ km/s set in the mock-observations, this should not have an effect on the fitted rotation curves.

4.2.2. Selection criteria

The primary selection criterion was based on the maximum rotational velocity as retrieved from the VELOCIRaptor information. This is equivalent to studying dwarf galaxies in the corresponding mass range. Further selection criteria were then applied in order to ensure that the sample consists of well-defined, rotation-supported disk galaxies. The purpose of this was to explore the impact of observational effects on the rotation curve analysis. Dispersion-dominated systems can be expected to be less well described by a tilted-ring model. Unselecting those galaxies should highlight the more subtle effects that might occur even in observations of well-defined disk galaxies.

The definition of a well-defined disk was based on the rotational support parameter κ_{rot} introduced by Sales et al. (2010). It was calculated using the particle velocities retrieved from the simulation data. This information is not directly available to observers. Observationally, the evaluation of rotational support also often relies on the ratio between rotational velocity and velocity dispersion (see e.g. Foster et al. 2018) but the observational and simulation-based methods are not directly comparable. Moreover, different studies of rotation curves of low-mass galaxies may adopt different selection criteria. For example, Oh et al. (2015) selected 26 out of 41 LITTLE THINGS galaxies based on their regular rotation pattern, while Iorio et al. (2017) found only 17 dIrr galaxies from LITTLE THINGS suitable for their rotation curve analysis, excluding dIrrs with low inclination angles and blue compact dwarfs (BCD). Lelli et al. (2016) restricted their rotation curve analysis of SPARC galaxies based on inclination angle and quality of rotation curves, excluding galaxies with significant asymmetries, strong non-circular motions, or offsets between gas and stellar distributions. While the sample selections of the mentioned studies are all intended to ensure a reliable rotation curve analysis, the particular criteria are not consistent and not directly comparable to those adopted here. This has to be kept in mind when comparing the results presented above with observed results from the literature. The sample studied by Santos-Santos et al. (2020), indicated by gray data points in the diversity plots, includes highly irregular galaxies and BCDs and likely contains galaxies that would have been *unselected* based on the selection process applied in this project.

Figure 4.1 shows the rotation curve diversity of the full samples of isolated galaxies selected by their V_{max} values. In this case, the scatter of the rotation curve shapes becomes considerably larger than that of the *selected* sample. In some cases, the cuspy profiles in the V_{max} range between 60 and 100 km/s are reproduced. A notable portion of the samples also exhibit V_{fid} values that are much lower than the range covered by the observed data (grey dots in Figure 4.1). Furthermore, the galaxies now appear to populate the lower V_{max} region well outside the selected range. The region of lowest V_{max} and V_{fid} is dominated by systems with lowest κ_{rot} values. Inspection of the corresponding rotation curves reveals many cases of likely unphysical wiggles, little H I signal, or no clear rotation. For further discussion of the *unselected* samples, such galaxies were again excluded. The V_{max} and V_{fid} values found in the `shield_1p0` sample resemble the most to the distribution presented by Santos-Santos et al. (2020). In particular, this simulation run produced observed velocity curve shapes in the region above the grey NFW band

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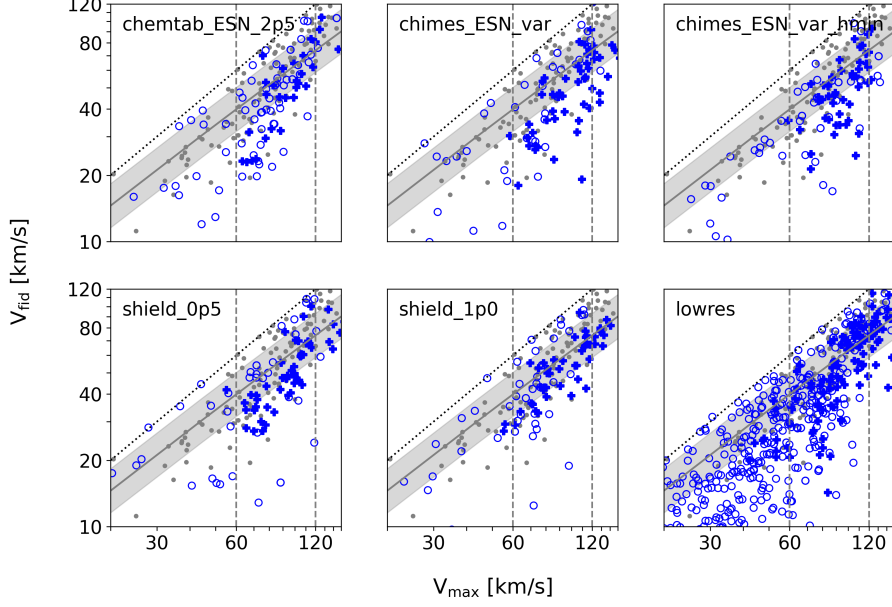


Figure 4.1.: Rotation curve diversity obtained from mock observations of the *selected* (bold ‘+’ symbols) and the *unselected* (open circles) samples. The reference lines are the same as in Figure 3.11

in the V_{max} range between 60 and 100 km/s. The following paragraphs examine these galaxies in more detail.

Figure 4.2 illustrates the diversity of a subset of the *unselected* galaxies with reasonable V_{obs} curves and highlights two galaxies (indicated by the letters A and B) with steeply rising mock-observed rotation curves in the V_{max} range between 60 and 100 km/s. Figure 4.3 shows the corresponding mock images, velocity maps and rotation curves of these galaxies.

Galaxy A has an irregular morphology and a κ_{rot} value of 0.65, i.e., although it is dominated by rotational motions, there is a significant contribution from random motions. This galaxy has a steeply rising circular velocity curve V_{circ} (black cross in figure 4.2) with a maximum of 89 km/s. The rotation curve shape observed from one viewing angle ($\Phi = 0$ deg) is slightly higher than that of V_{circ} , whereas from the other viewing angle ($\Phi = 90$) it has a lower maximum velocity and slightly lower V_{fid} .

Galaxy B has a κ_{rot} value of 0.25 and an azimuthal H I velocity (blue line) indicative of a system that is not rotationally supported. The fitted rotation curve from a viewing angle $\Phi = 0$ agrees with this, however, from a viewing angle $\Phi = 90$, clear rotation is observed. It should be noted that this galaxy also has an unstable angular momentum

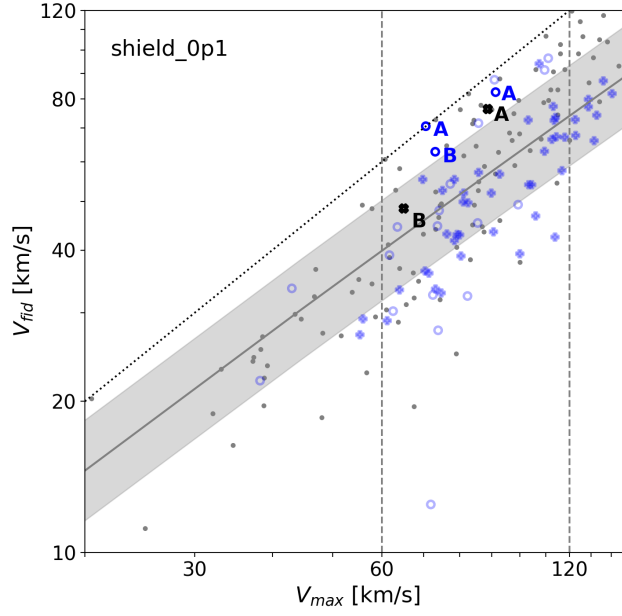


Figure 4.2.: *Rotation curve diversity in the `shield_1p0` simulation run.* Two galaxies A and B from *unselected* sample are highlighted. Black crosses correspond to their circular velocity (V_{circ}) curves, blue open circles indicate the values obtained via mock observations from the viewing angles $\Phi = 0$ and $\Phi = 90$. Note that galaxy B shows no rotation if observed with $\Phi = 0$ and is therefore shown with only one blue data point. Transparent symbols indicate the remaining galaxies in the snapshot, where bold ‘+’ symbols represent the *selected* sample and open circles represent a subset of the *unselected* sample. Reference lines and literature data points (grey dots) are the same as in Figure 3.9.

4. Discussion

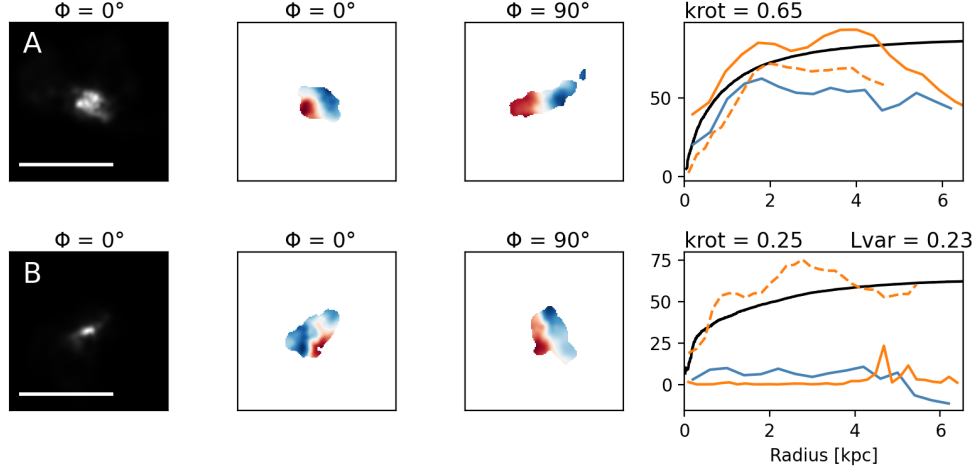


Figure 4.3.: *Morphologies and rotation curves of galaxies A and B from Figure 4.2* Columns from left to right represent the integrated H I intensity (moment 0) maps with a scale of 10 kpc indicated by the horizontal reference bar, the line-of-sight velocity (moment 1) maps observed from the viewing angles $\Phi = 0$ and $\Phi = 90$, and the corresponding rotation curves. The rotation curve plots show the circular velocity curve V_{circ} (solid black line), the azimuthal particle velocity curve V_{azi} (solid blue line) and the fitted rotation curves V_{obs} an observer would obtain from the viewing angles $\Phi = 0$ (solid orange line) and $\Phi = 90$ (dashed orange line). The rotational support parameters κ_{rot} and, where relevant, the angular momentum variation L_{var} of the galaxies are indicated.

vector, as indicated by the value $L_{var} = 0.23$, likely due to the unordered motions visible in the velocity map observed from a viewing angle $\Phi = 0$. As discussed in section 2.8 this can impact the orientation of the galaxy and may therefore also influence the calculation of κ_{rot} , which relates the total kinetic energy to the kinetic energy that is in ordered motion around the axis described by the angular momentum vector. The maximum velocity of this galaxy observed at $\Phi = 90$ is higher than that of the calculated circular velocity curve, placing the observed galaxy above the NFW band in the V_{fid} vs. V_{max} plot.

Interestingly, galaxies A and B occupy the same positions in the plot as the SPARC galaxies NGC 1705 and UGC 07151, which are classified into numerical Hubble types 11 and 6, respectively (see Lelli et al. 2016 Table 1), which further underscores the observed diversity: Not only do late-type dwarf galaxies of similar mass have diverse rotation curve shapes, but also can similar rotation profiles occur in dwarf galaxies of diverse morphological stages. In the case of the two mentioned mock-observed galaxies A and B, the underlying circular velocity curves are quite different from each other, however

they are observed with similar shapes due to observational effects.

Relaxing the selection criteria based on κ_{rot} and L_{var} not only increases the scatter in V_{fid} but also alters the distribution of the observed maximum velocities, primarily towards lower values. Figure 4.4 highlights two galaxies, C and D, that are observed at lower maximum velocities than would be allowed by the primary selection criterion $60 \leq V_{max,circ} \leq 120$. Their underlying circular velocity curves place them in the region between ~ 70 and ~ 80 km/s, within the shaded NFW band. Figure 4.5 again shows the corresponding H I intensity and velocity maps and rotation curves. Galaxies C and D are comparable to galaxy A in terms of H I morphology and gas kinematics. They have irregular morphologies and are dominated by rotational motions. In both cases, the fitted rotation curves strongly depend on the viewing angle of the observer, shifting one of the respective $V_{obs,\Phi}$ curves towards lower observed V_{max} and V_{fid} .

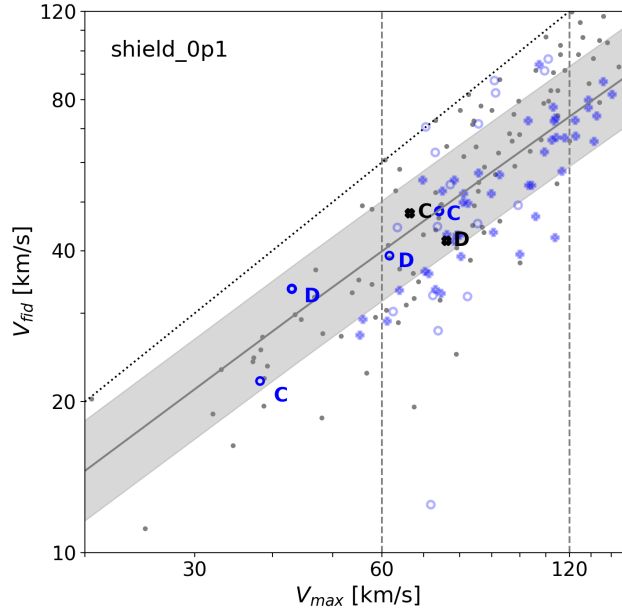


Figure 4.4.: As in Figure 4.2 but highlighting galaxies C and D.

4.2.3. Sources of uncertainties

The determination of a galaxy's rotation curve from an observed data cube, comprises several sources of uncertainties. Instrumental limitations such as noise and resolution were

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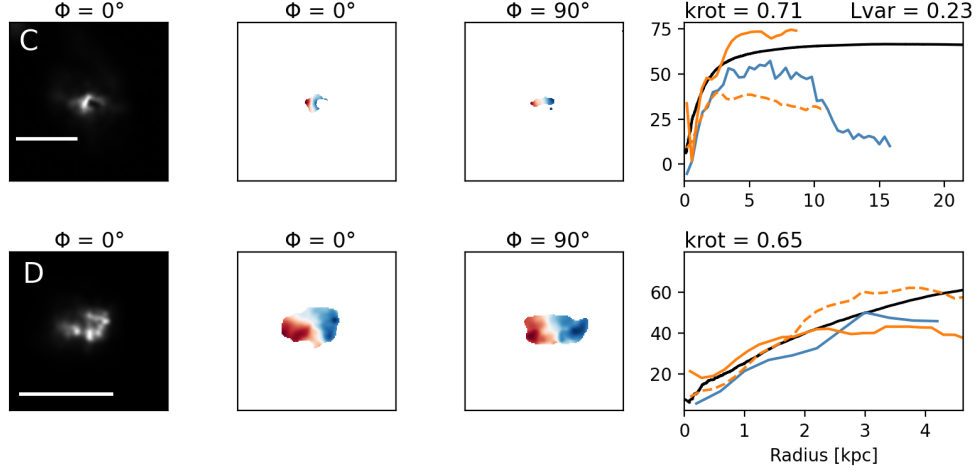


Figure 4.5.: As in Figure 4.3, but for galaxies C and D from Figure 4.4

mimicked in the mock observations. Initially, the mock observations were conducted with a low noise level of $3 \cdot 10^{-8}$ Jy/arcsec² and a spatial resolution of ~ 390 pc. To verify that the results do not depend on this particular choice, the mock observation was repeated with altered observational conditions for one of the simulation runs, as is discussed in more detail in Sec. 4.2.4. In general, lower spatial resolution is associated with the effect of beam smearing, which can damp the rotation curves, especially in the inner galactic regions, when fitted with a 2D tilted-ring approach. The choice of 3D-BAROLO as a 3D fitting method accounts for this effect by convolving the modeled data cube with the beam, making the resulting rotation curve largely independent of the spatial resolution, as demonstrated by Di Teodoro & Fraternali (2015).

Critical for any tilted-ring model technique are the geometrical parameters describing the rings. These are the spatial position of the rotational center, the systemic velocity, the inclination of the disk, and the position angle of the projected ellipses. Observers need to derive these quantities from the data and their accuracy is critical, as errors propagate into the fitted rotation curve.

In the mock observations, these parameters were defined when creating the observational setup in MARTINI. The systemic velocity and center position are therefore known in this case. Also the inclination of the galaxies with respect to the virtual observer was set in MARTINI. However, the orientation of the galaxies required the calculation of the angular momentum vector, which depends on the specific mass fraction used, as explained in section 2.8. The actual inclination and position angle might therefore deviate slightly from the nominal input values. Uncertainties related to this issue were minimised by verifying the stability of the angular momentum vector along concentric shells containing the inner 20, 30, and 40 per cent of the total H I mass and excluding galaxies with large

angular momentum variations and therefore uncertain inclinations.

Another potential source of uncertainty are the assumptions made in the modelling procedure. The tilted-ring model assumes that the gas is in circular motion in a rotation-dominated, thin disk. This representation may be over-simplified in many cases of dwarf irregular galaxies. To reduce the impact of over-simplified assumptions, the *selected* sample was limited to well-defined, rotationally supported disks. However, non-circular motions may still be present and on top of that the rotation curve fits are affected by the thickness of the disks. Currently, fitting algorithms including 3D-BAROLO struggle to handle thick disks, as emission from different heights as well as from neighboring rings contribute to the measured velocity (Iorio et al. 2017). Furthermore, the disk thickness is degenerate with the disk inclination (Di Teodoro & Fraternali 2015), which may further complicate the reconstruction of the rotation curves. These issues are particularly relevant for dwarf galaxies, which typically have relatively thick disks (see Patra 2020), but are inevitable with standard modeling techniques.

4.2.4. Noise and resolution

The mock observations were made with an added noise level of $3 \cdot 10^{-8}$ Jy/arcsec², which is considerably lower than the noise level achieved in real observations. For comparison, the mock observation of the `chimes_ESN_var_hmin` galaxies was re-run with a more realistic noise level of 10^{-5} Jy/arcsec², which corresponds to the order of magnitude of the noise level of the majority of the LITTLE THINGS observations. Furthermore, the effect of an increased spatial resolution was tested by repeating the mock-observations at a distance of 3.7 Mpc, which corresponds to the median distance of the LITTLE THINGS sample, and with a beam FWHM of 6". The increased spatial resolution observation was run with the higher noise level to mimic the conditions found at the LITTLE THINGS survey. Figures 4.6 and 4.7 show the H I intensity, velocity and velocity dispersion maps of three example galaxies from mock observations conducted under different observational conditions.

In the following, the effect of noise on the observed rotation curve shapes is examined separately for those galaxies that were selected based on the parameters κ_{rot} and L_{var} and those that were excluded based on these criteria or on visual inspection.

Figure 4.8 shows the rotation curves of the *selected* sample fitted to the mock observations with the two different noise levels and spatial resolutions. The curves are plotted out to R_{90} , the calculated radius enclosing 90% of the H I mass. The curves generally agree very well with each other in the inner regions of the galaxies. However, in many cases the fits to the data with higher noise level (green and pink dashed lines) stop at smaller radii than those with the lower noise level (solid orange line). This illustrates that the information available to observers may be limited, especially in the outskirts of the H I disk. Figure 4.6 shows the velocity moment maps of a galaxy where all three curves are in excellent agreement. Figure 4.7 plots the maps of a galaxy which is an example of disagreeing curves. As can be seen in the velocity moment maps, information from the outer parts of this galaxy is lost in the observations with higher noise level.

In any case, the fits of the inner rotation curves, which are of interest when deriving the central mass profile, can be considered robust in most cases, as they are in excellent

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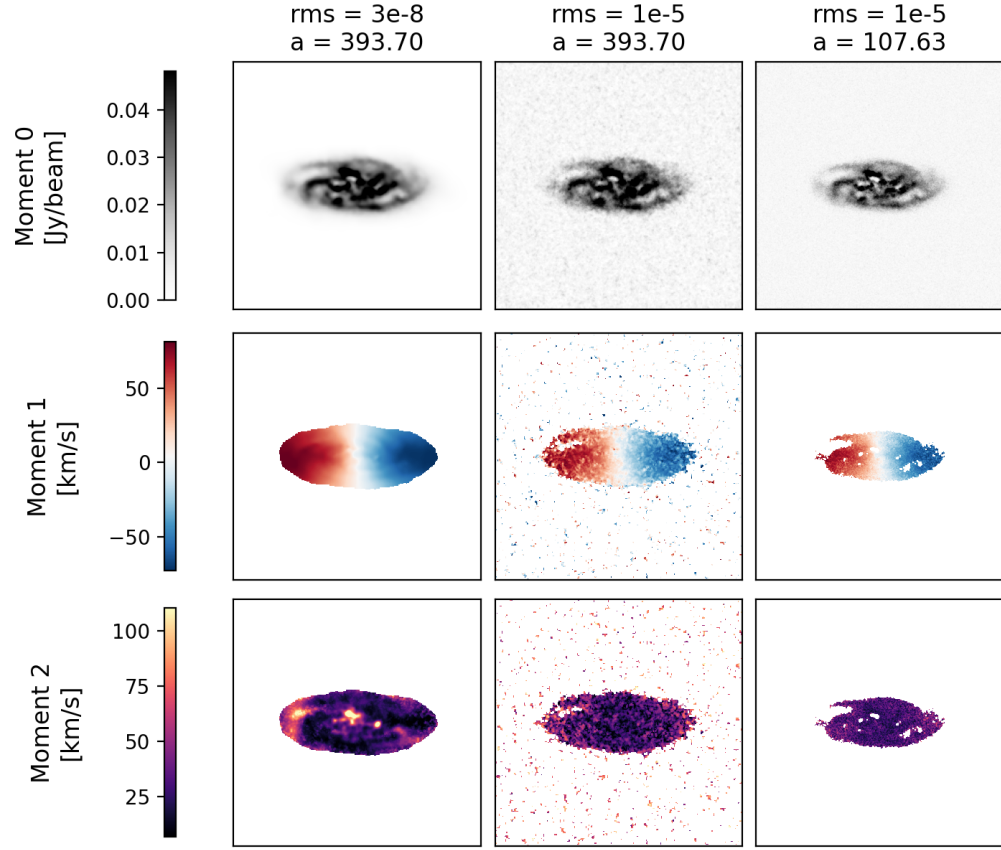


Figure 4.6.: Example galaxy (Halo ID 97594) from `chimes_ESN_var_hmin` mock-observed with different noise and resolution settings. This galaxy is a representative example for excellent agreement between observed and expected rotation curves (see Section 2.7.1). Rows from top to bottom show the integrated H I intensity (moment 0) maps, the line-of-sight velocity (moment 1) maps and the line-of-sight velocity dispersion (moment 2) maps, respectively. Column labels indicate the rms noise in Jy/arcsec^2 and spatial resolution a in pc. Note that the relation between distance and image size was different in the setup with higher spatial resolution, which makes the galaxy appear smaller in the third column.

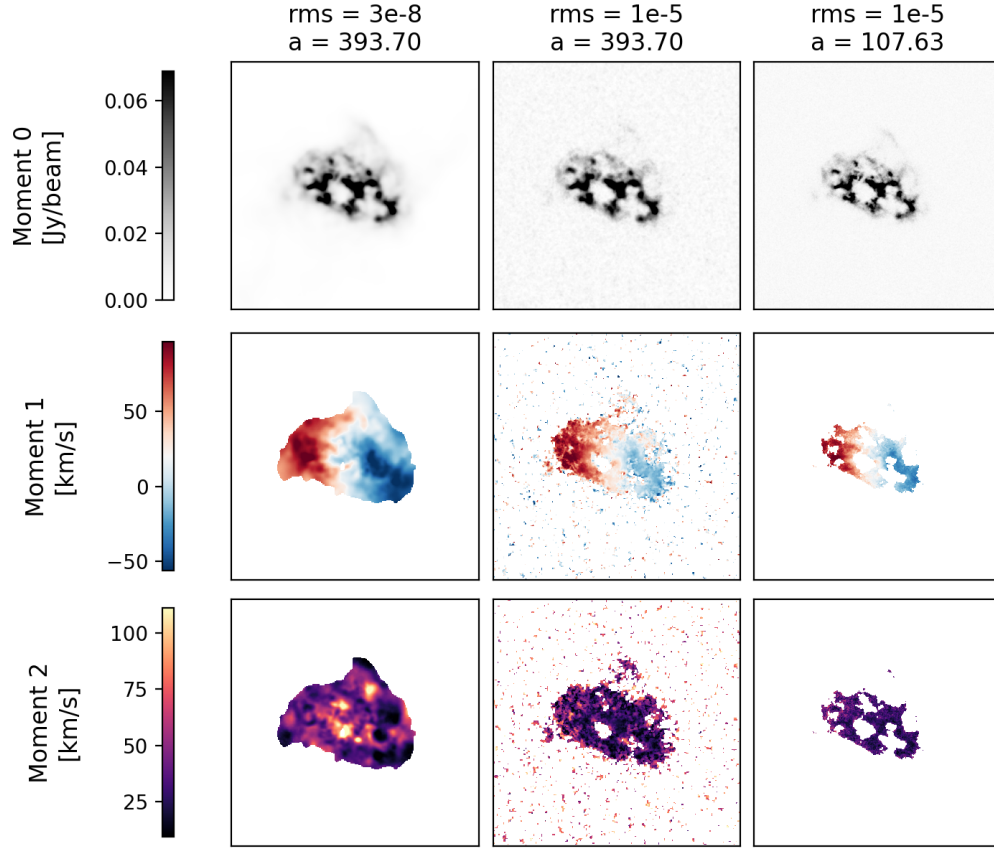


Figure 4.7.: As in Figure 4.6 but for Galaxy 20016 from `chimes_ESN_var_hmin`. This galaxy is a representative example of poor agreement between observed and expected rotation curves (see Section 2.7.1).

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agreement under the varied observational conditions. However, the observed maximum velocities are less accurate as they occur at larger radii where the signal may be low and some of the fitted rotation curves diverge. Since the rotation velocity V_{fid} at the fiducial radius r_{fid} is used to quantify the steepness of the inner rotation curve and r_{fid} scales with V_{max} , a shift in the maximum velocity also affects the parameter V_{fid} . However, the results do not change significantly, as can be seen in figure 4.9. Due to the definition of the rotation curve shape parameter and its dependence on V_{max} the exact position of the galaxies shifts in the $V_{fid} - V_{max}$ diagram under altered observational conditions. The shapes themselves and the trend with v_{max} , however, are widely preserved as the shift occurs parallel to the NFW line.

Analogous to Figures 4.8 and 4.9, Figures 4.10 and 4.11 compare the fitted rotation curves and corresponding rotation curve shape parameters resulting from the mock observations with the different noise levels and spatial resolutions, this time for the *unselected*, i.e. kinematically more complex, sample. Figure 4.10 shows that the rotation curves of this sample are generally rather bad tracers of the circular velocity curves. In addition, the rotation curves observed at different noise levels and spatial resolutions deviate from each other in many cases. Figure 4.11 compares the resulting rotation curve shape parameters V_{fid} and $\eta_{rot} = V_{fid}/V_{max}$. Note that galaxies with no clear rotation, strong wiggles in the rotation curve fits or low signal in the higher-noise mocks were excluded from this plot. In the case of the resulting subset of the *unselected* sample, the higher noise levels (green and pink circles) not only yield preferentially lower observed V_{max} but also increased values of V_{fid} and η_{rot} with respect to the lower noise level (blue circles). While the blue circles are mostly found below the NFW line, the green and pink circles corresponding to the higher noise level also populate the region above the NFW line, especially at low maximum velocities. Thus, for the more irregular types of galaxies with less rotationally supported kinematics, for which the observed rotation curves are generally less reliable tracers of the circular velocity curves, the noise level does have an influence on the observed rotation curve shapes. The increased spatial resolution (pink circles) had no significant impact on the rotation curve shapes.

With the higher noise level, two galaxies are found in the V_{max} region between 60 and 100 km/s and η_{rot} values above the gray NFW band, which is avoided by galaxies mock-observed at the lower noise level. These are indicated by the letters E and F in figure 4.12. Galaxy E was unselected from the original sample based on visual inspection. It exhibits an inclined ring structure, which likely affects the rotation curve fit.

For galaxy F, the shapes of the inner rotation curves obtained with different noise levels agree with each other. However the curves with the higher noise level do not reach the radii where the velocity is maximal. Therefore the galaxy retains its cuspy shape but is shifted towards lower V_{max} into the said region.

4.3. Implications for Observers

The results presented here underscore the potential issues with dwarf galaxy mass profiles inferred from observed rotation curves.

4.3. Implications for Observers

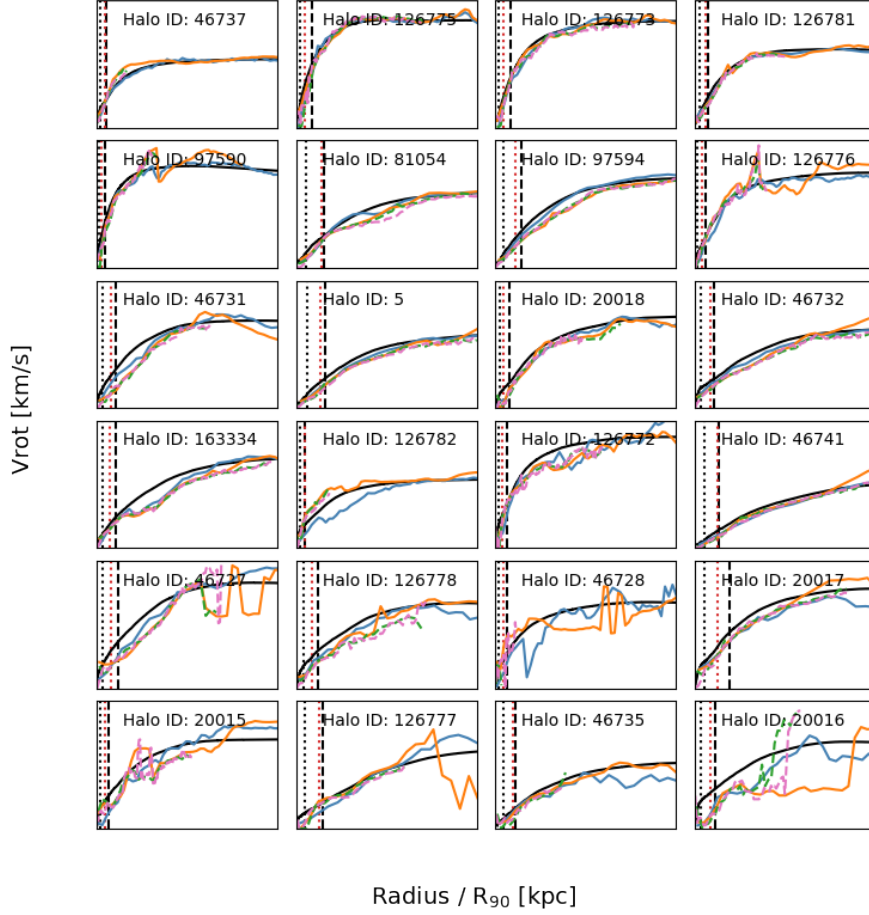


Figure 4.8.: Rotation curves of the `chimes_ESN_var_hmin_selected` sample. The solid black line indicates the calculated circular velocity curve. The solid orange line indicates the fitted rotation curve for a mock observation with a noise level of $3 \cdot 10^{-8}$ Jy/arcsec². The dashed green line indicates the fitted rotation curve for a mock observation with a noise level of 10^{-5} Jy/arcsec².

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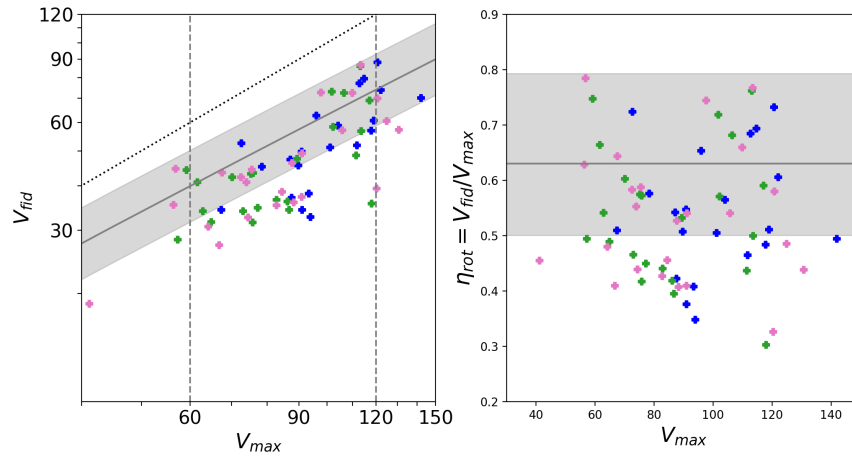


Figure 4.9.: Rotation curve diversity in the `chimes_ESN_var_hmin_selected` sample as indicated by V_{fid} vs. V_{max} (left panel) and η_{rot} vs. V_{max} for different noise and resolution settings. Blue symbols correspond to the primarily adopted setting, i.e a noise level $rms = 3 \cdot 10^{-8}$ Jy/arcsec² and spatial resolution scale $a = 392.70$ pc. Green symbols correspond to an increased noise level of $rms = 10^{-5}$ Jy/arcsec² at the original spatial resolution. Pink symbols correspond to the same increased noise level of $rms = 10^{-5}$ Jy/arcsec² at an increased spatial resolution scale $a = 107.63$. The reference lines and shaded band are the same as in Figures 3.9 and 3.13 respectively.

4.3. Implications for Observers

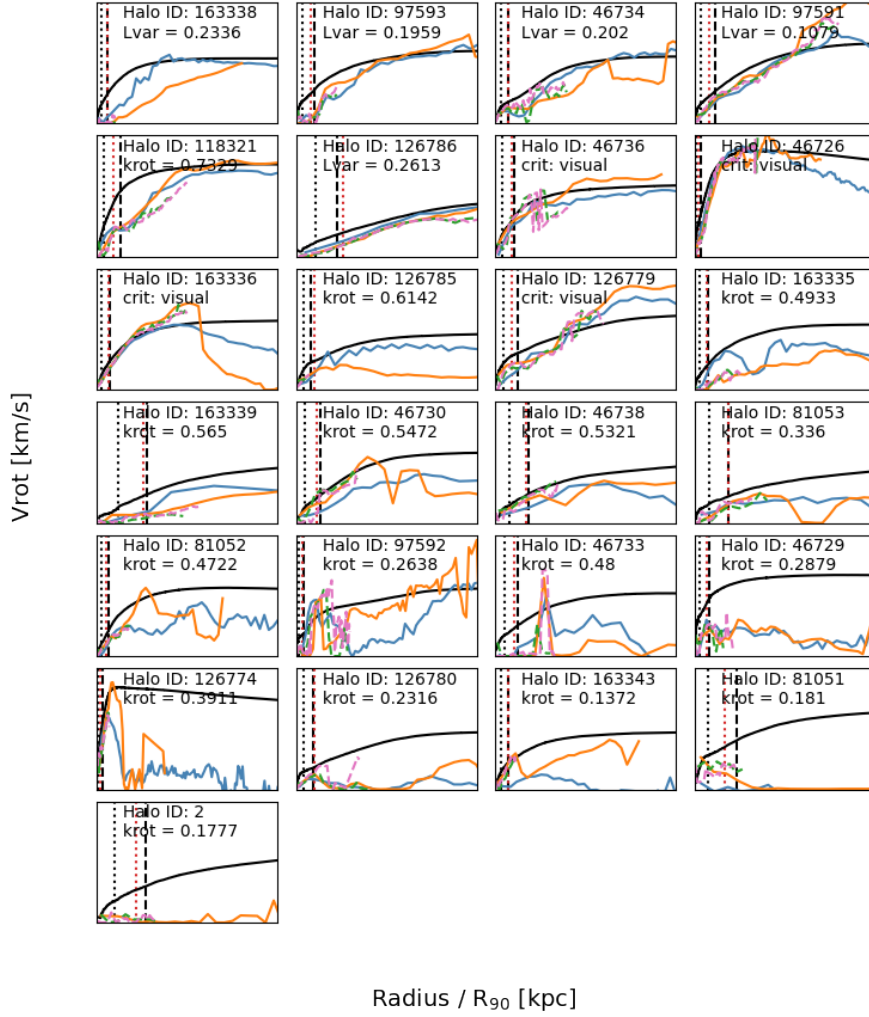


Figure 4.10.: Rotation curves of the *chimes_ESN_var_hmin_unselected* sample. The solid black line indicates the calculated circular velocity curve. The solid orange line indicates the fitted rotation curve for a mock observation with a noise level of $3 \cdot 10^{-8}$ Jy/arcsec². The dashed green line indicates the fitted rotation curve for a mock observation with a noise level of 10^{-5} Jy/arcsec².

4. Discussion

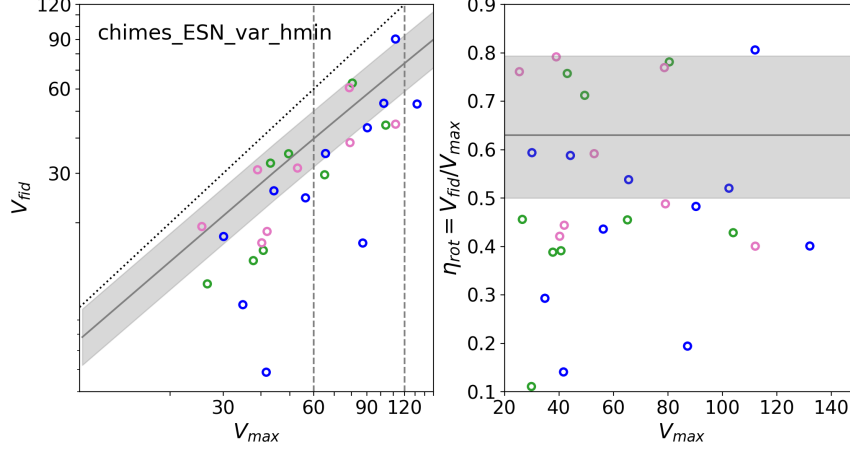


Figure 4.11.: As in Figure 4.9 but for the *unselected* sample.

The comparison of V_{azi} to V_{circ} shows that HI rotation is often an unreliable tracer of the underlying mass distribution, as was already demonstrated by [Downing & Oman \(2023\)](#). For observers this means that even if the HI rotation can be measured and fitted with high accuracy, the mass profile derived under the customary assumptions might still be incorrect. The comparison between V_{azi} and V_{obs} gained from mock observations reveals that, in addition to perturbations of the gas rotation itself, further discrepancies are introduced by systematic observational effects. This is underscored in the *obs main* cases where such effects appeared to be the main driver of the deviations of the observed rotation curves from the expected circular velocity curves.

Observers are therefore facing a two-fold challenge: to distinguish perturbed gas motions from the true underlying matter structure and to distinguish perturbed gas motions from observational effects. The latter are largely related to the assumptions made in the construction of the rotation curve. The widely used tilted-ring model assumes that the gas is orbiting in circular motions in a rotationally dominated, thin disk, which might in many cases fail to represent late-type dwarf galaxies correctly.

In this respect, the separate analyses of the *selected* samples consisting of well-defined, rotationally supported disks and galaxies that did not meet the selection criteria revealed some interesting points: The measured rotation curves of the *selected* samples of all simulation runs preferentially underestimated the inner circular velocity curves, resulting in predominantly cored profiles observed at the lower-mass end, which is in line with an interplay between non-circular gas motions and non-negligible disk thickness, as described by [Oman et al. \(2019\)](#). Rotation curves with V_{fid} values above the expected NFW values, which would indicate highly cuspy density profiles, are only observed in the lower-mass sector when galaxies from the *unselected* sample with weaker rotational support are taken

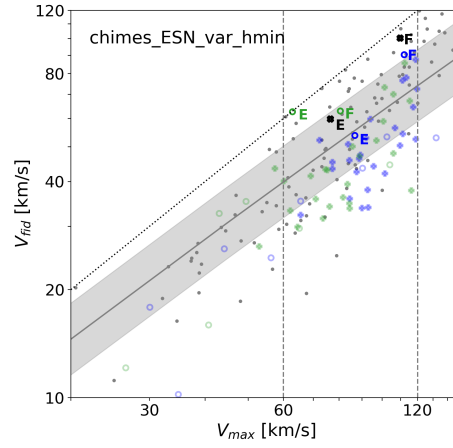


Figure 4.12.: *Rotation curve diversity in the `chimes_ESN_var_hmin` simulation run.* Two galaxies E and F from *unselected* sample are highlighted. Black crosses correspond to their circular velocity (V_{circ}) curves, blue open circles indicate the values obtained via mock observations with a noise level $rms = 3 \cdot 10^{-8}$ Jy/arcsec² and green open circles indicate the values obtained with a noise level of $3 \cdot 10^{-8}$ Jy/arcsec². Here, observations from only one viewing angle ($\Phi = 0$) are shown. Transparent symbols indicate the remaining galaxies in the snapshot, where ‘+’ symbols represent the *selected* sample and open circles represent a subset of the *unselected* sample. Reference lines and literature data points (grey dots) are the same as in Figure 3.9.

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into account. This hints at the systematically different effects arising from the different assumptions made in the process of the rotation curve fitting. Disentangling these effects is challenging, as multiple assumptions may be violated at the same time.

In any case, observed rotation curves have to be interpreted with caution. To date, there is no straight-forward way for observers to assess the reliability of the measured rotation curves. This poses a severe issue to observational research of the (dark) matter distribution in dwarf galaxies.

The results of this project and previous work suggest that a careful analyses of the observed velocity fields, together with rotation curve fitting methods that take into account non-circular motions, disk thickness and pressure support will be necessary to better constrain the mass distribution in dwarf galaxies.

4.4. Implications for the rotation curve diversity problem

The analyses of galaxies in the tested simulation runs, which realise a state-of-the-art treatment of the gas phases and high resolution, confirm previous results from studies of dwarf galaxies in simulations with lower resolution and more simplified ISM models: Systematic observational effects introduce a significant scatter in the observed rotation curve shapes of low-mass galaxies, which could explain the observed rotation curve diversity. These effects have a stronger impact on the observed rotation curves than the fine-tuned details of the sub-grid prescriptions. While it has been shown that sub-grid models, in particular those for star formation and feedback, have a strong impact on the true matter distribution in low-mass galaxies and the corresponding circular velocity curves, the observed rotation curves are rather insensitive to the underlying variations. As demonstrated in this project and previous work, the shape of the circular velocity curve corresponding to the underlying mass distribution can be dramatically different to the rotation curve shape an observer might measure.

This may alleviate the tension of the observed rotation curve diversity in low-mass galaxies with the Λ CDM cosmology. On the other hand, it marks the limitations of observational small-scale tests of cosmological models.

4.5. Limitations

The main limitation of this project was the small sample sizes that resulted from the small box sizes of the simulation test runs. The data of the final COLIBRE simulation are becoming available as this project is being finished. In order to confirm the trends observed here, it would be desirable to repeat the analysis on the larger dataset.

5. Conclusion

In this project, mock observations were used to analyse the H I rotation curves of simulated low-mass galaxies. Provided were the snapshots at $z = 0$ of six different test runs of the COLIBRE project, a state-of-the-art cosmological simulation project with high resolution and a multi-phase model of the ISM. The rotation curves were fitted using a 3D tilted-ring model approach.

The rotation curves were studied particularly with regard to the observed rotation curve diversity problem, addressing the impact of the model variations on the structural properties of the galaxies and the discrepancies between the circular velocity curves expected from the resulting mass distributions and the corresponding rotation curves that would be measured by an observer.

The main findings can be summarised as follows:

- The tested parameter variations appear to have a mild influence on the H I disk thickness of the galaxies. The impact on the circular velocity curves, as calculated from the mass profiles, is subtle. It would be interesting to confirm the trends with larger galaxy sample sizes. Overall, the circular velocity curves are in good agreement with NFW density profiles, whose central density cusps are preferentially slightly flattened at the lower end of the studied mass range and slightly enhanced at the higher-mass end.
- The rotation curves obtained from mock observations are severely affected by (i) perturbations of the gas rotation and (ii) systematic observational effects. These effects can occur independently, but are not generally unrelated. The resulting scatter in observed rotation curve shapes overrides the distribution in circular velocity curve shapes. Thus it does not directly reflect the underlying sub-grid models.
- Limiting the samples to well-defined, rotationally supported disks results in observed rotation curves that systematically underestimate the inner circular velocity curves. Rotation curves with enhanced cusps are only reproduced when galaxies with non-negligible pressure support are included, which potentially relates the systematic effects to the underlying model assumptions.

The results are in line with previous studies of dwarf galaxies in cosmological simulations, which have proposed observational effects as a potential solution to the rotation curve diversity problem. The fact that the observed rotation curve shapes of low-mass galaxies do not reflect the true underlying mass distributions may alleviate the tension of the observed rotation curve diversity with the Λ CDM cosmology. On the other hand, it has

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sobering implications that are far-reaching. The results imply that mass estimates derived from observed rotation curves may not be reliable, which deprives the research of the primary observational access to dark matter in dwarf galaxies to date. This marks the limit of observational tests of cosmology on small scales. Over the past decades, cosmological simulations have become increasingly sophisticated, incorporating the complexities of baryonic physics. In the endeavour of testing cosmological models, it appears at this point that the way forward is a refinement of the observational approaches, including methods to account for non-circular motions in thick, dispersion-dominated gas disks.

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A. Appendix

A. Appendix

Halo ID	Action	Comments on H I morphology
10	x	uncertain inclination
16	-	large bubble
26	-	irregular disk
28	-	large holes
30	-	irregular disk with holes
31	x	long filamentary arms, uncertain inclination
32	-	holes, turbulences in velocity map
36	-	large holes, turbulences in velocity map
37	-	large holes, turbulences in velocity map
48	-	large holes, turbulences in velocity map
51	-	diffuse arm structure
56	-	irregular arm structure
57	-	highly irregular structure

Table A.1.: `chemtab_ESN_2p5`. This table lists the galaxies that fulfill the selection criteria based on κ_{rot} and L_{var} but show poor agreement between V_{circ} and V_{azi} , which indicates a disturbed H I rotation. Column (1) indicates the galaxies' halo ID, as assigned by the halo finder, column (2) indicates the action taken: 'x' indicates that the galaxy was excluded based on observable features in the intensity and velocity maps, '-' indicates that no action was taken and the galaxy was left in the *selected* sample. Column (3) gives short comments on the H I morphologies.

Halo ID	Action	Comments on H I morphology
23	-	long filamentary arms following rotation of main body, explains dip in rotation curve
33	-	irregular morph., turbulent velocity map. likely due to feedback bubbles
34	x	inclination uncertain, large holes
50	-	loosely wound irregular arms
66	-	highly irregular morphology

Table A.2.: Same as Table A.1 but for the `chimes_ESN_var` simulation snapshot.

Halo ID	Action	Comments on H I morphology
20016	-	large holes, turbulent velocity map
20017	-	clear, smooth rotation, filament visible from $\Phi = 90^\circ$
46726	x	strong warp
46727	-	slightly asymmetric velocity map, only visible from $\Phi = 0^\circ$
46728	-	lose, fragmented arms, feedback bubbles in inner region
46735	-	highly irregular, large holes
46736	x	inclined ring structure
126777	-	large holes, turbulent velocity map
126778	-	large holes
126779	-	asymmetric velocity map, obvious only from $\Phi = 0^\circ$
163336	-	clear rotation, smooth velocity map faint features indicating infall or tidal interaction only visible from one viewing angle ($\Phi = 90^\circ$)

Table A.3.: Same as Table [A.1](#) but for the `chimes_ESN_var_hmin` simulation snapshot.

Halo ID	Action	Comments on H I morphology
3	-	large holes, turbulent velocity map
19473	x	tidal features
46839	-	irregular arm structure
46843	x	no clear disk
46847	-	irregular morphology, large hole/loop
127025	-	smooth but slightly asymmetric rotation
127026	-	irregular morphology, likely impacted by feedback bubbles
164371	-	ring structures aligned in well-defined disk

Table A.4.: Same as Table [A.1](#) but for the `shield_0p5` simulation snapshot.

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Halo ID	Action	Comments on H I morphology
19194	-	well-defined disk with prominent bubbles
46289	-	irregular disk with holes
80468	-	irregular disk with bubbles
96959	-	very large bubbles
126226	-	clear disk, some prominent bubbles
126235	-	open ring shape
126237	-	well-defined disk, smooth rotation, small size
163399	x	merging pair

Table A.5.: Same as Table A.1 but for the `shield_1p0` simulation snapshot.

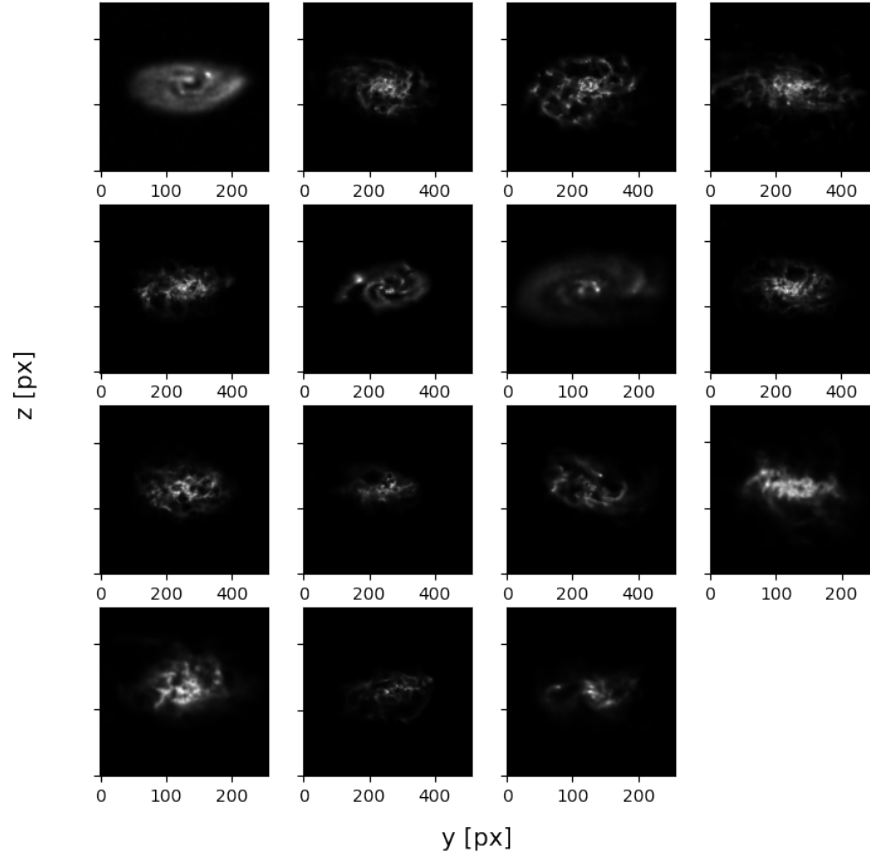


Figure A.1.: H I morphologies of the *selected* `chemtab_ESN_2p5` galaxies, sorted by increasing disagreement between V_{circ} and V_{azi} . The pixel scale is 130.9 pc.

Halo ID	Action	Comments on H I morphology
19	x	tidal features, warped disk
21	-	irregular
18606	x	no clear rotation
18619	x	likely a merger
36611	x	likely tidal features
36622	-	irregular arms with holes, opened arms only visible from viewing angle $\Phi = 90^\circ$
36626	x	no clear disc, little H I
36642	x	irregularities could be tidal features
36645	x	irregularity could be tidal feature or infalling stream
67183	-	irregular disk with holes
67194	-	irregular
67198	x	tidal features
97633	x	large filaments, not a well-defined disk
97647	x	likely tidal features
97649	x	uncertain inclination
97650	x	possibly a merger
97673	-	irregular
124792	-	lose, fragmented arms
124800	-	irregular disk
124802	-	irregular, large holes
124805	x	inclined ring structure
124808	-	irregular disk
124812	-	small irregular
124820	x	no clear disk, little H I
153287	-	well defined disk with large holes
153290	-	highly irregular structure
153293	x	small body, large spurs, likely a merger remnant
153296	x	uncertain inclination
153318	-	irregular
153320	x	large lopsided filament, could indicate recent interaction
153322	-	small irregular
153344	-	irregular with loop/filament

Table A.6.: Same as Table [A.1](#) but for the **lowres** simulation snapshot.

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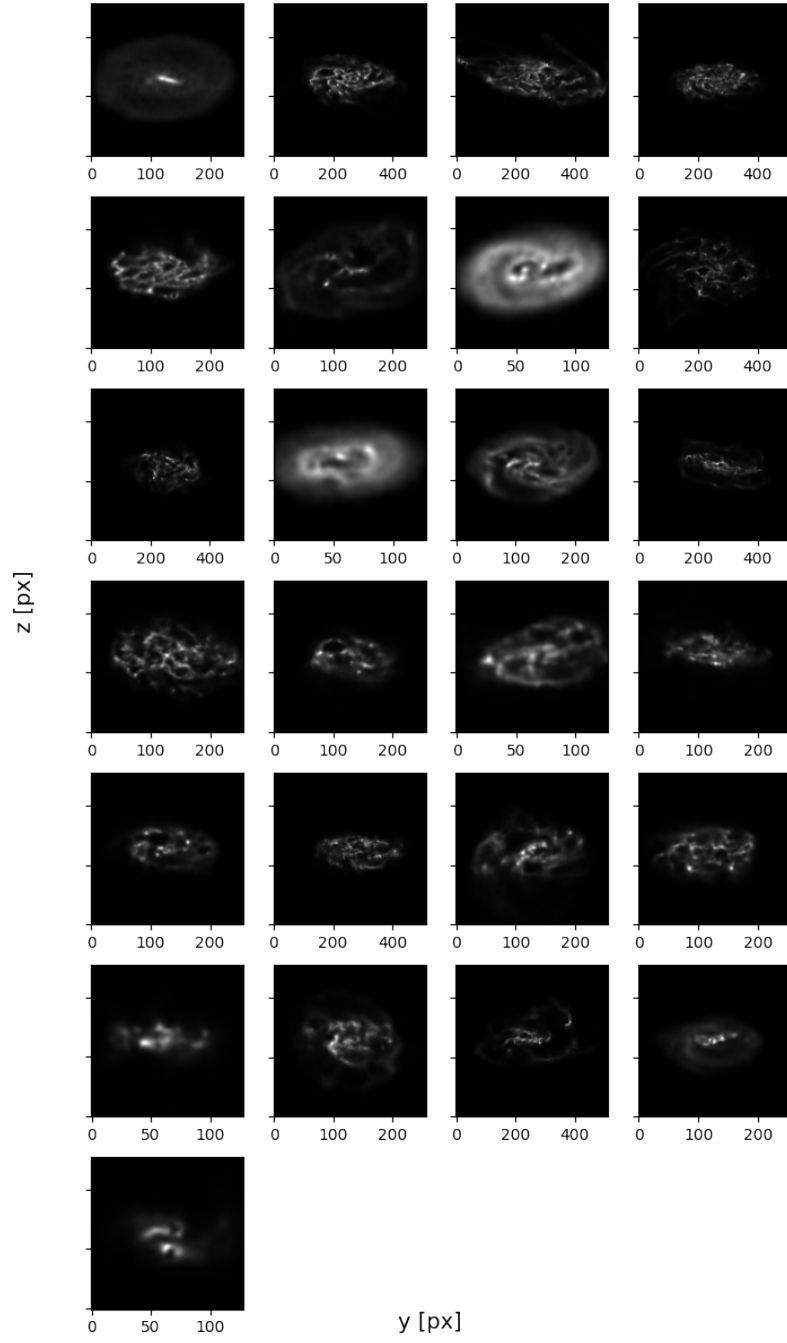


Figure A.2.: Same as Figure [A.1](#) but for the *selected* `chimes_ESN_var` galaxies.

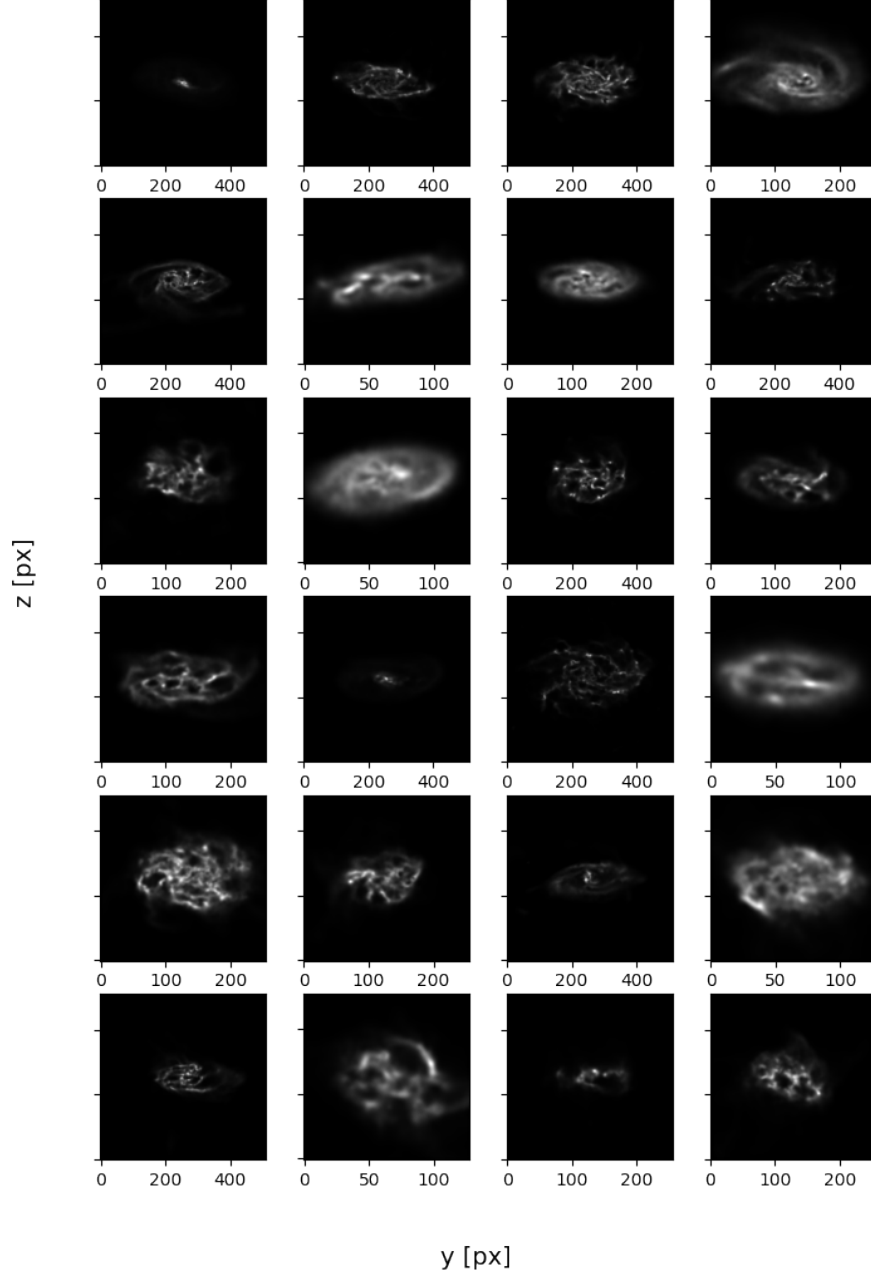


Figure A.3.: Same as Figure [A.1](#) but for the *selected* `chimes_ESN_var_hmin` galaxies.

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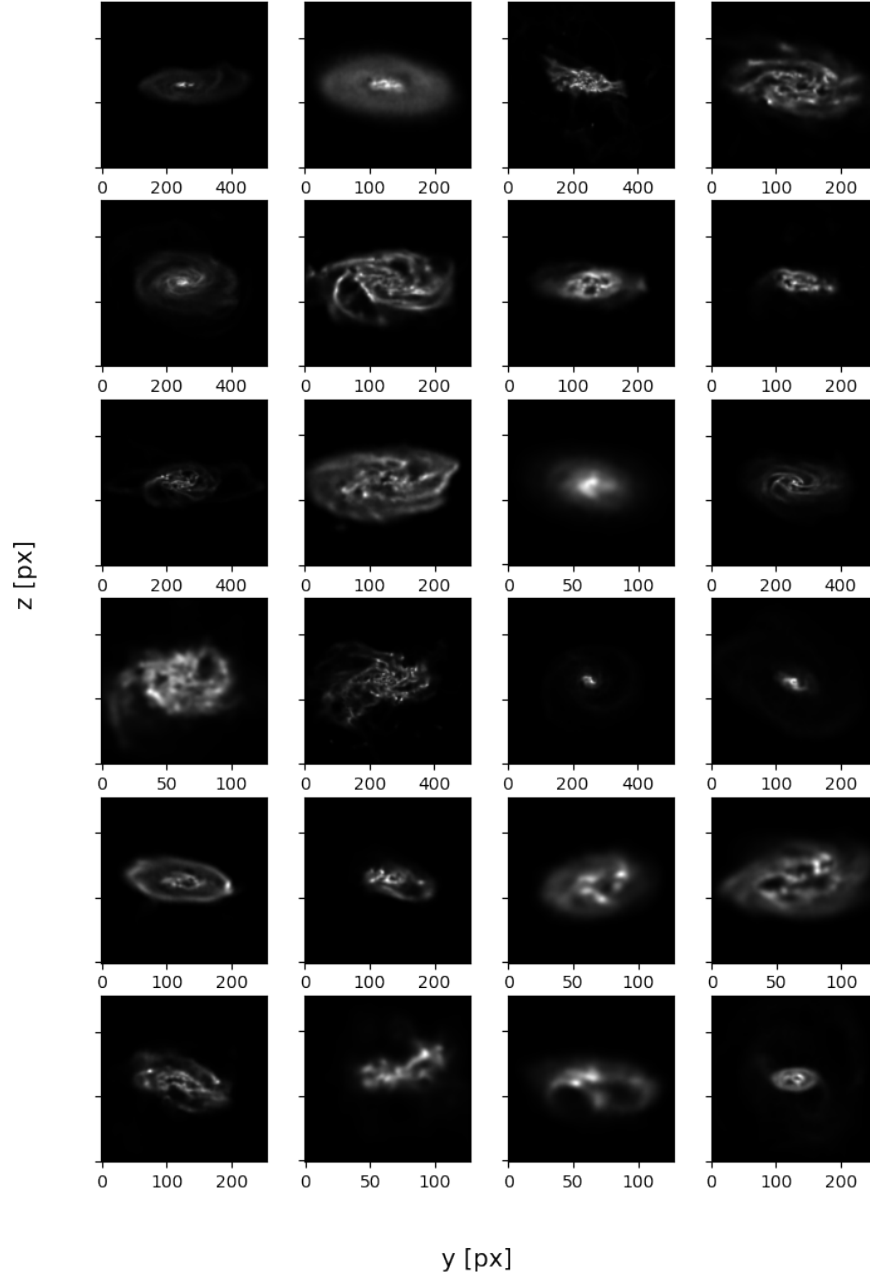


Figure A.4.: Same as Figure [A.1](#), but for the *selected shield_0p5* galaxies.

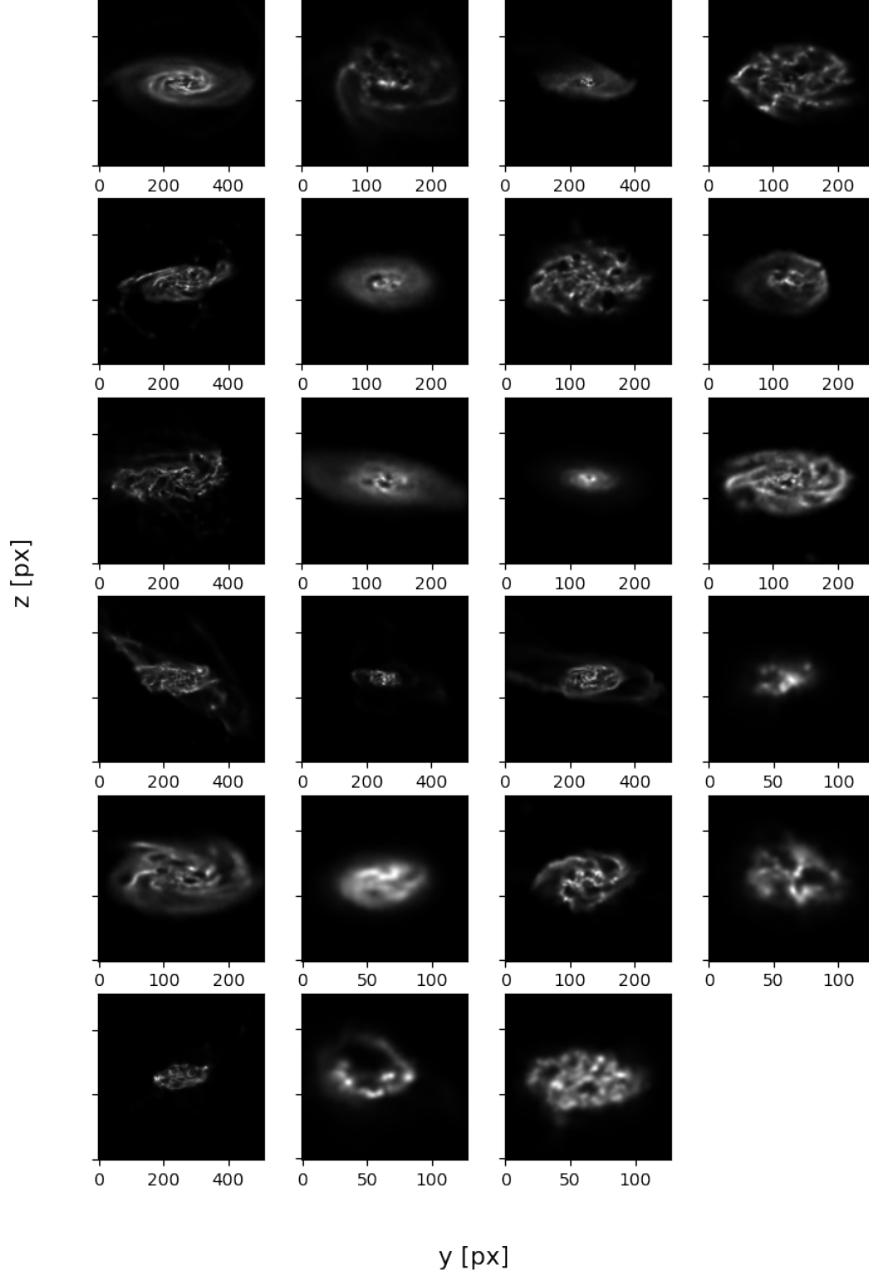


Figure A.5.: Same as Figure [A.1](#) but for the *selected shield_1p0* galaxies.

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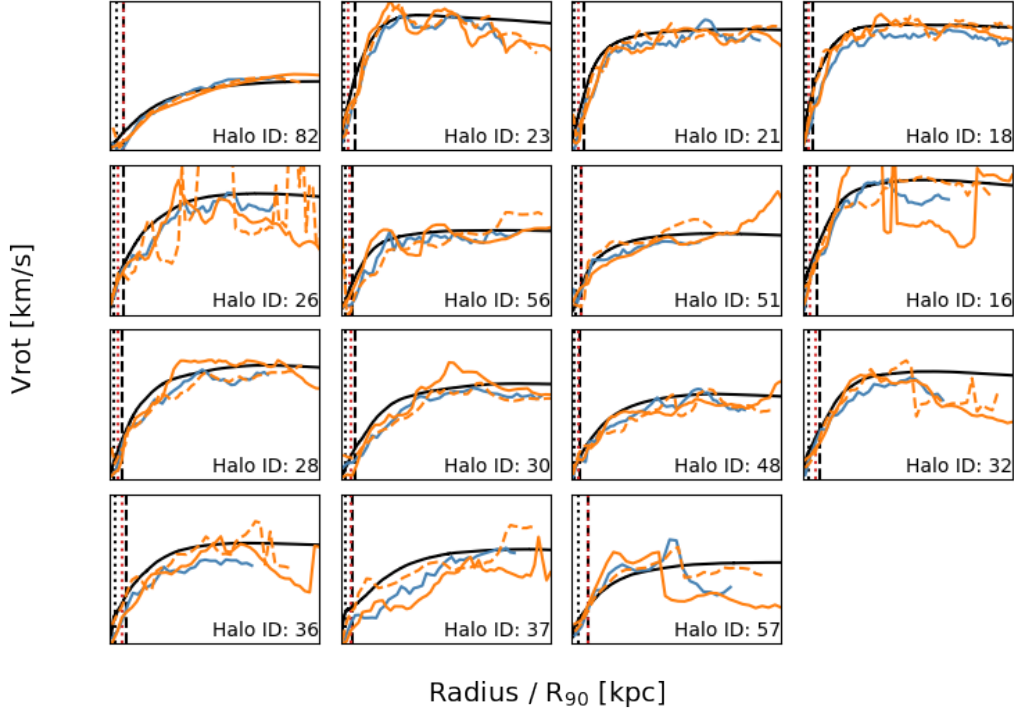


Figure A.6.: Rotation curves of the *selected* `chemtab_ESN_2p5` galaxies, sorted by increasing disagreement between V_{circ} and V_{azi} . Plotted are the circular velocity curves V_{circ} (black solid lines), the median azimuthal particle velocity curves V_{azi} (blue solid lines) and the mock-observed rotation curves V_{obs} obtained from two viewing angles $\Phi = 0$ (solid orange lines) and $\Phi = 90$ (dashed orange lines). Vertical lines indicate the gravitational softening length ϵ_{dm} (black dotted line), the convergence radius R_{conv} (red dotted line) and the fiducial radius r_{fid} (black dashed line). The y-axis limits are $[0, 130]$ km/s in all panels.

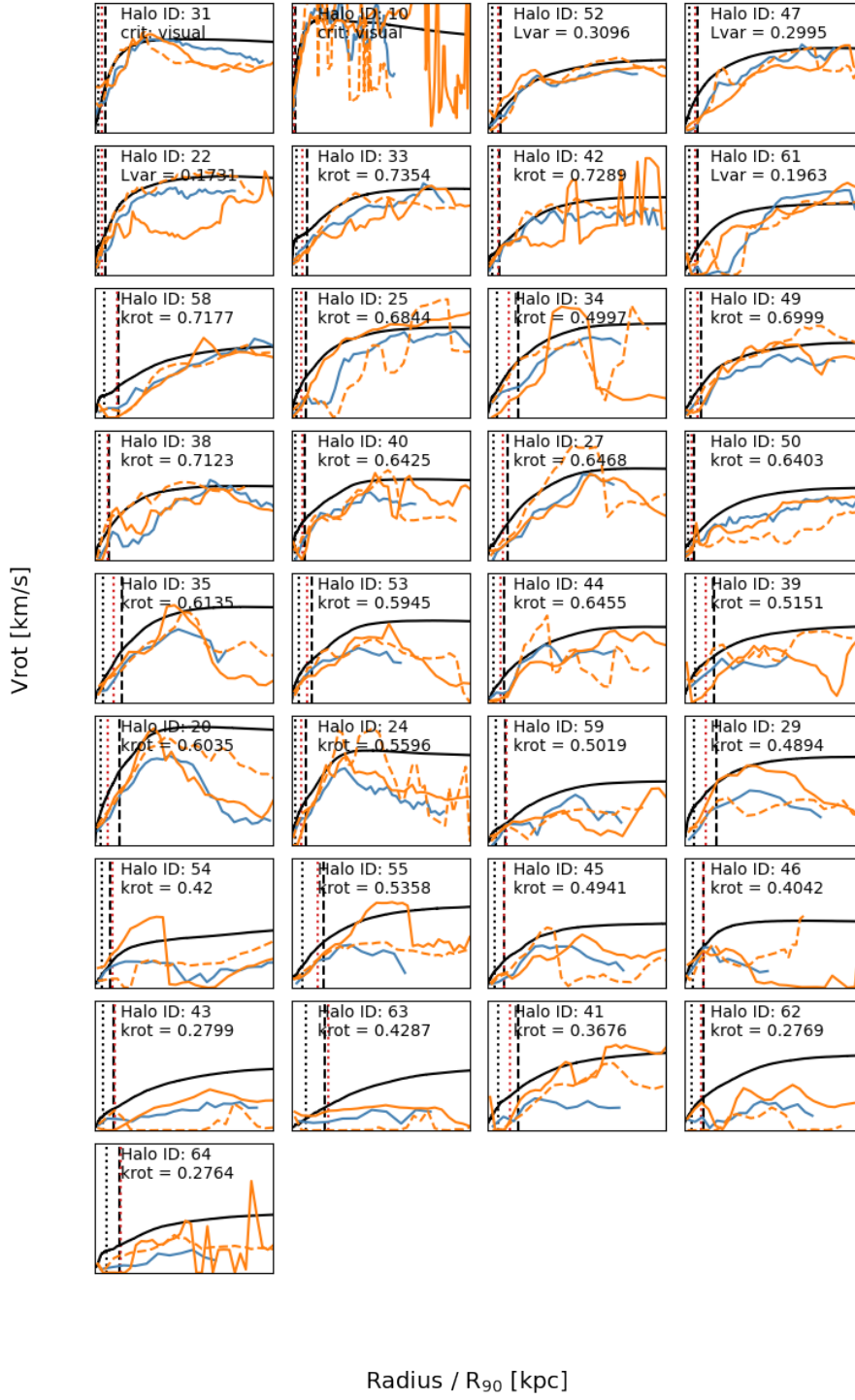


Figure A.7.: Same as in Figure A.6, but for the *unselected* galaxies of chemtab_ESN_2p5

A. Appendix

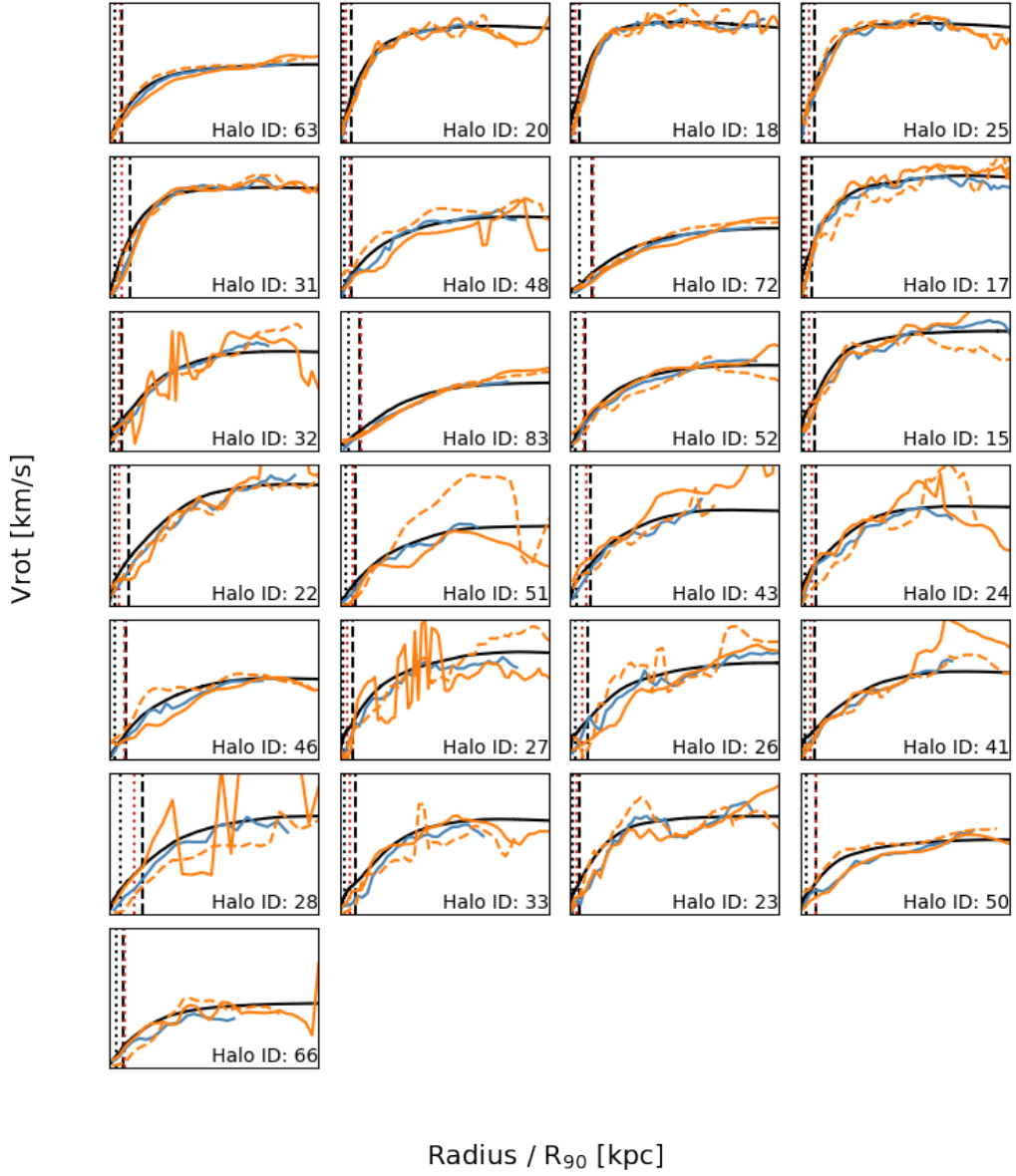


Figure A.8.: Same as in Figure A.6, but for the *selected* galaxies of `chimes_ESN_var`

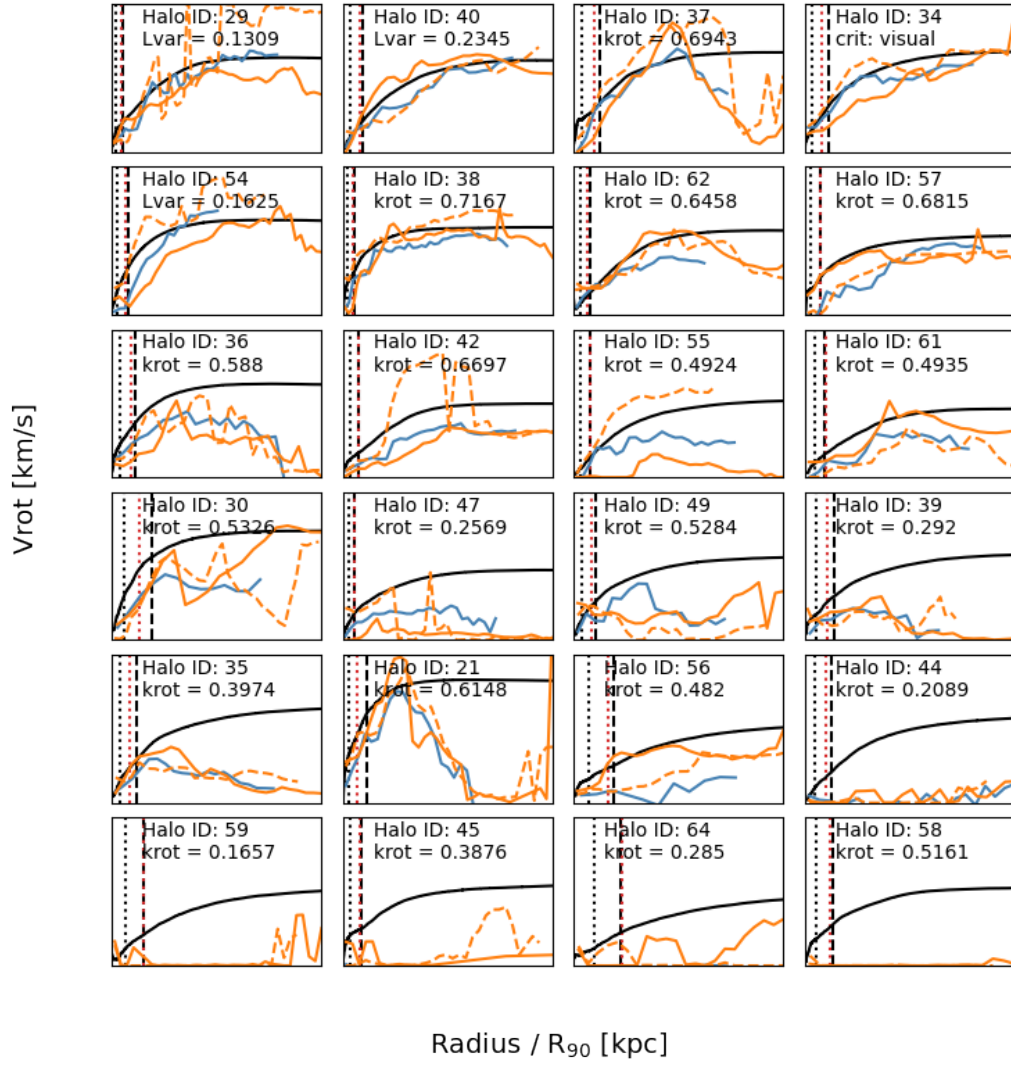


Figure A.9.: Same as in Figure A.6 but for the *unselected* galaxies of `chimes_ESN_var`.

A. Appendix

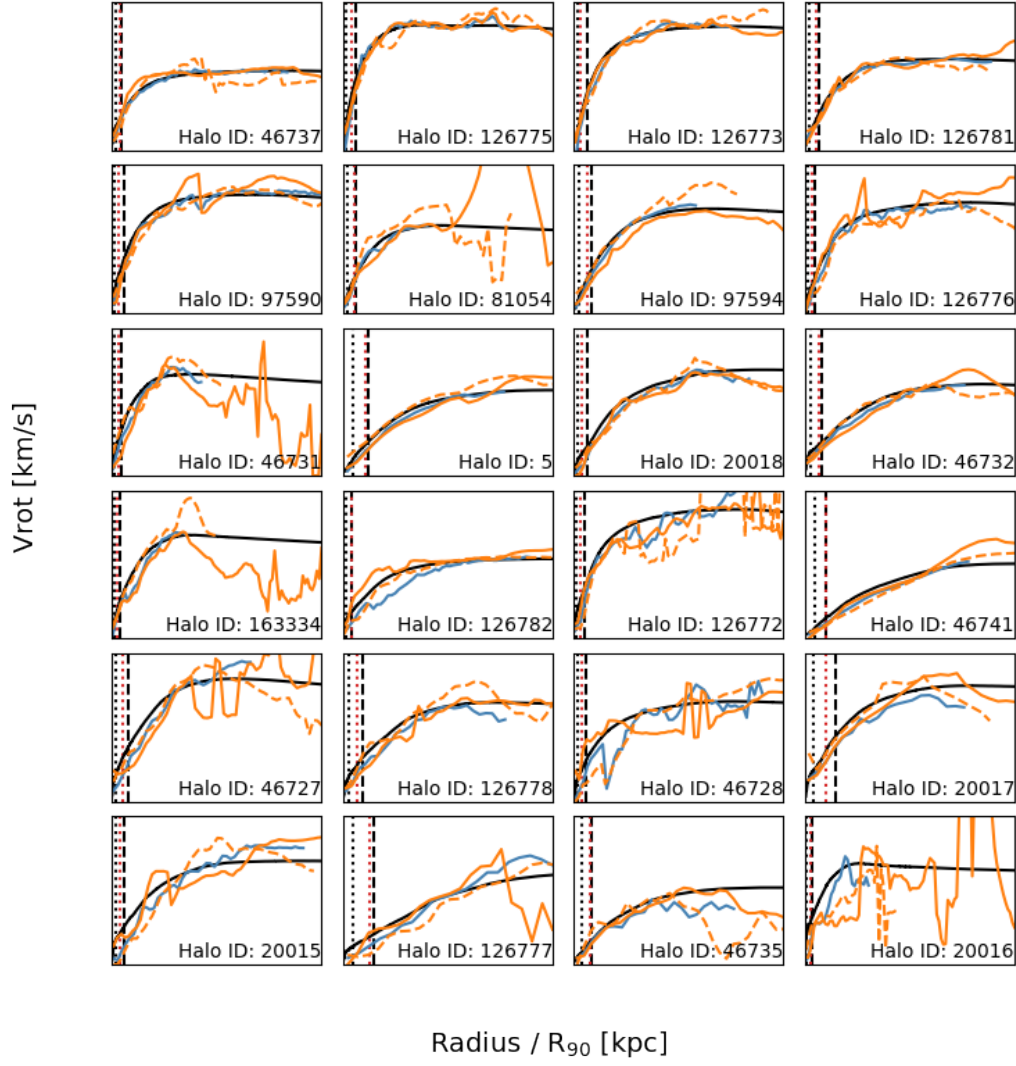


Figure A.10.: Same as in Figure [A.6](#) but for the *selected* galaxies of `chimes_ESN_var_hmin`.

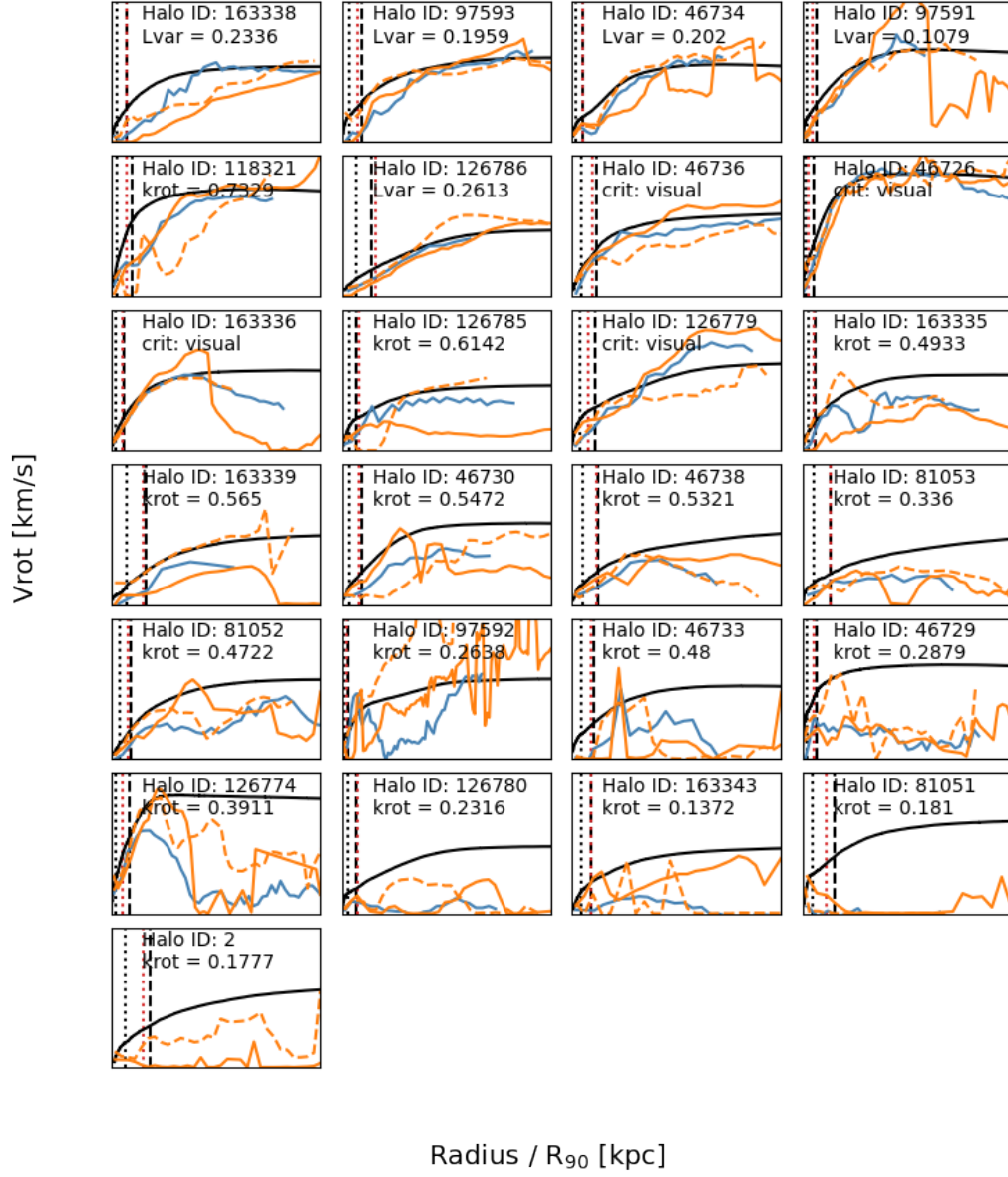


Figure A.11.: Same as in Figure A.6, but for the *unselected* galaxies of `chimes_ESN_var_hmin`.

A. Appendix

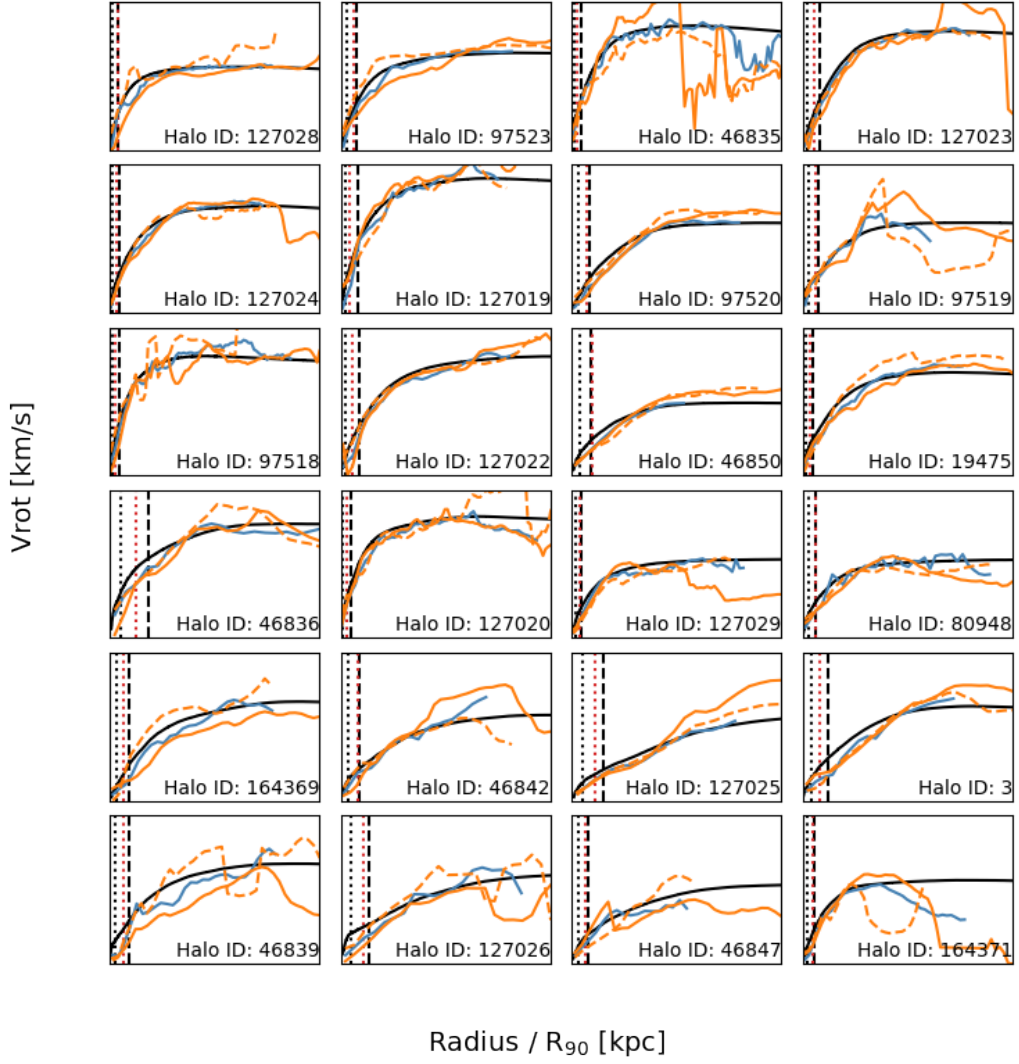


Figure A.12.: Same as in Figure A.6, but for the *selected* galaxies of shield_0p5.

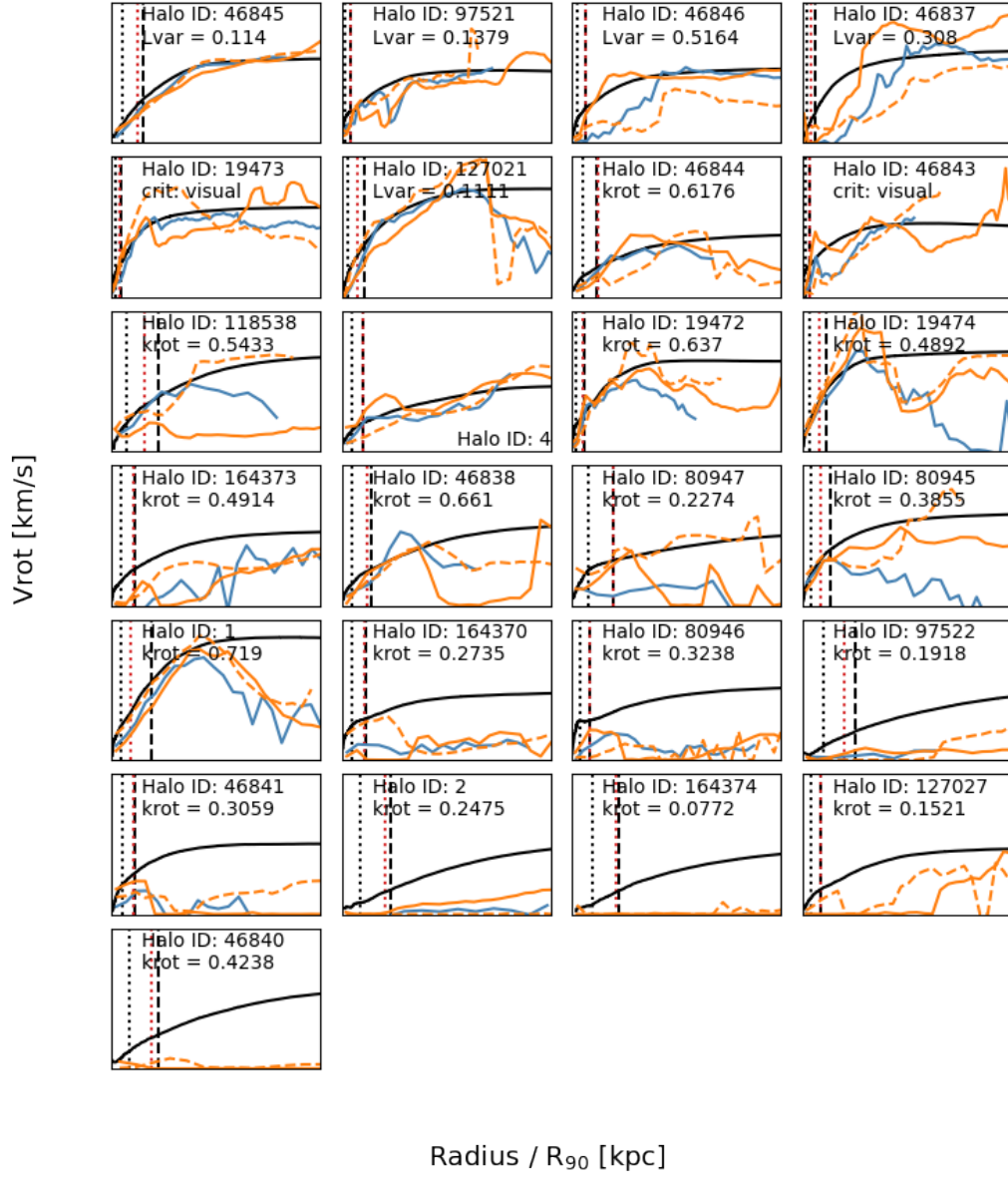


Figure A.13.: Same as in Figure A.6 but for the *unselected* galaxies of *shield_0p5*.

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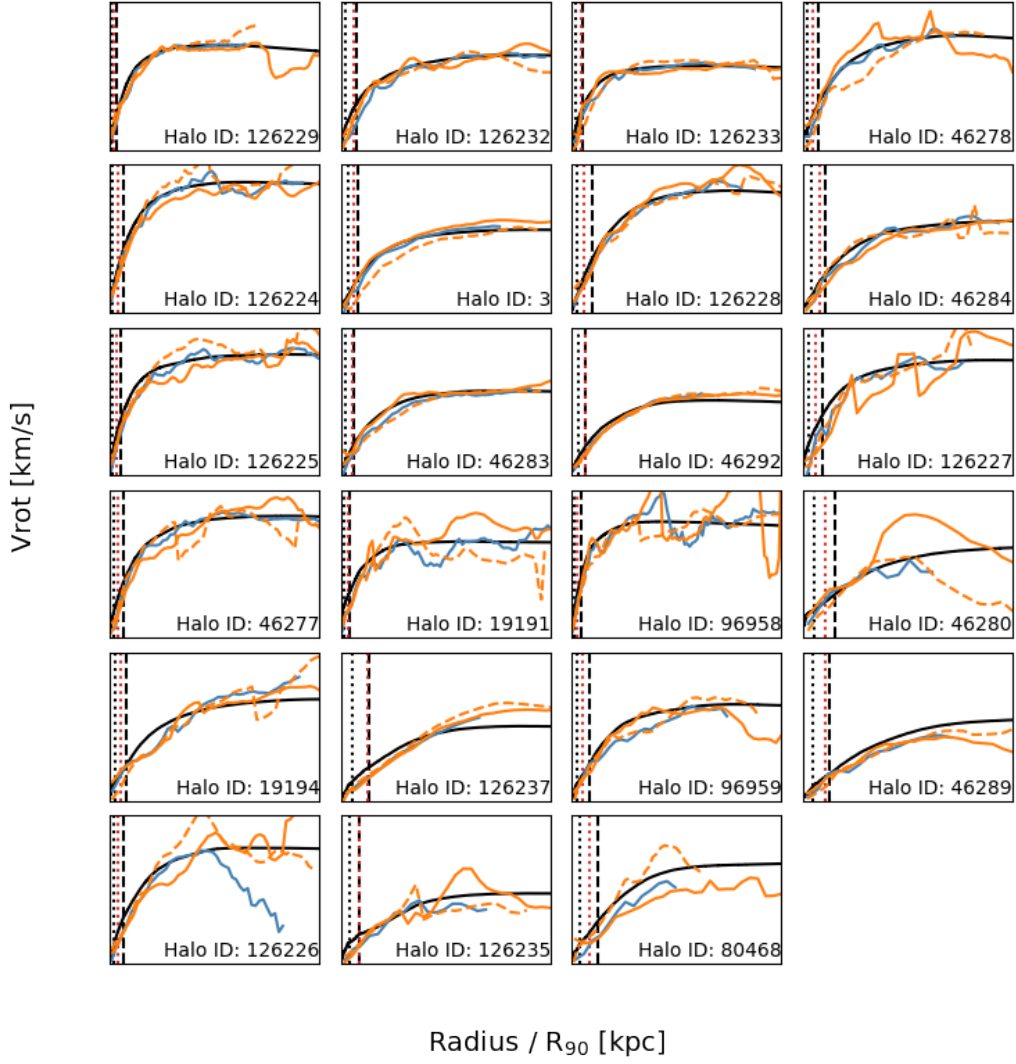


Figure A.14.: Same as in Figure A.6, but for the *selected* galaxies of `shield_1p0`.

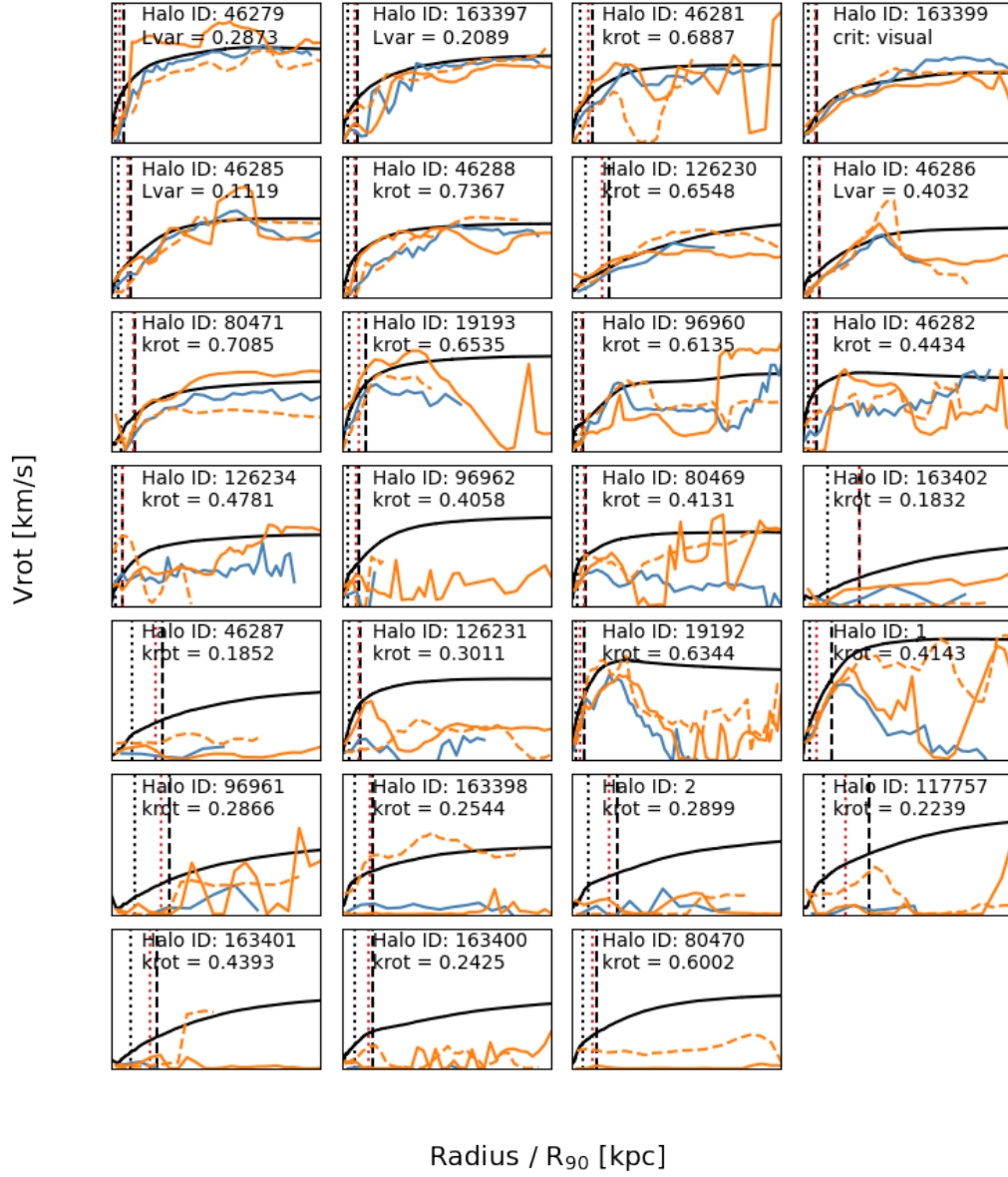


Figure A.15.: Same as in Figure A.6 but for the *unselected* galaxies of *shield_1p0*.