2.1 Terminology

Universe: In general terms, the universe can be defined as all of time and space and all forms of matter and energy it includes. Whenever we refer to the term universe after this section, we talk about the part of the universe that has been simulated in the context of a specific simulation.

Baryonic and non-baryonic matter: There exist two types of matter within the universe: Baryonic and non-baryonic matter. Strictly speaking, baryonic matter consists of only baryon particles, like protons and neutrons. In practice, the term baryonic matter simply refers to everything that is made out of normal atomic matter. This group therefore contains objects like stars, planets and gas clouds. Non baryonic matter is everything that does not belong to the group of baryonic matter. This group includes dark matter and particles of type electron or neutrino.

Galaxy: Galaxies are defined as a system of stars, dust, gas and dark-matter that is held together by gravity. They usually contain millions to trillions of stars. Smaller accumulations of stars are simply called clusters. Since the currently available computational power does not suffice to simulate such enormous amounts of particles, we will use the term galaxy for every star cluster.
It is generally assumed that galaxies form due to density fluctuations caused by small gravitational instabillities that were present at the very beginning of the universe.

Active Galactic Nucleus: Some galaxies have an extremely bright and compact region at their center, called Active Galactic Nucleus (AGN). Galaxies containing such a region are also called active galaxies.

2.2 Cosmology Simulations

Often, cosmology simulations are done using the so called N-body simulations, in which the interaction of N particles is computed by numerically solving the equation of motions [TH08] [Bag04].

Dolag et al. [DBS+08] described some more advanced techniques to solve N-body systems. They further explained how Eulerian grid methods and variants of Lagrangian smoothed particle hydrodynamics can be used to simulate large scale structures. In a more recent paper, C. Llinares reviewed existing techniques that can handle simulations with modified gravity [Lli18], which is necessary whenever a simulation includes dark matter.

In order to simulate cosmic structures efficently on diverse computing architectures, including every current supercomputer, scientists from the National Argonne Labratory developed a N-body code framework called Hardware/Hybrid Accelerated Cosmology Code (HACC). Lately, they extended it to allow simulations that include baryonic matter and AGN [HPF+16]. The data used in this thesis is the result of a simulation executed with HACC. It was released in the context of the IEEE Scientific Visualization Contest 2019 and is further described in the next section.

2.3 Simulation Data

The simulation was executed with a total of 524,289 particles placed in a $[0, 64]^3 Mpc/h$, bounding box, where $h = 0.71$ is a scale factor. The simulation covers a time span of 5 million years. 50% of particles are categorized as baryons, the other 50% as non-baryons. Over time, baryons can transition back and forth between four different subcategories; "not-categorized" baryon, star, star-forming or wind. Non-baryons only have two subcategories, namely "not-categorized" non-baryon and AGN. At timestep zero, all particles are positioned on a uniform grid where every other particle is either of type "not-categorized" baryon or "not-categorized" non-baryon.

The simulation evolves from $z = 200$ (universe is 5 million years old) to $z = 0$ (today) where z is the redshift. Each of the 625 timesteps are sampled linearly in terms of the cosmological scale factor a, where:

$$a = \frac{1}{1+z} \tag{2.1}$$

The resulting data set contains information about the type of each particle, its positions, velocity, internal energy and other attributes at each time step. The different attributes are further described in Table 2.1.

2.4 Scientific Visualizations

Many visualizations based on cosmology data have already been made. In 2015, Rizzi et al. showed that large datasets, like cosmology datasets, can be rendered efficently using point sprites. They argued that direct point rendering avoids loss of dynamic range and memory sparsity, while also being fast due to hardware accelerated point rendering. They implemented their solution into vl3. vl3 is a volume rendering framework for visualization of large datasets [RHI+15].

Habib et al. [AEB+18] showed how to use a SPH-Kernel to interpolate point data by first generating a chaining mesh. Interpolation has the advantage that one gets a continous value map in the end, rather than a discrete one. However, it is necessary to first map the particles onto a chain mesh. The same paper also discussed the possibility of visualizing data with help of Paraview [Par], vl3 and by utilizing a virtual reality environment.

Another important aspect of cosmology simulations is the possibility of gaining knowledge about the evolution of dark matter particle clusters, called Halos. Preston et al. [PGX+16] used interactive merger trees to visualize how these clusters merge together over time.

Name	*Abbrev.*	*Unit*	*Description*
Position	x,y,z	$[Mpc/h]$	Position of the particle
Velocity	vx,vy,vz	$[km/s]$	Velocity of the particle
Internal Energy	uu	$[km^2/s^2]$	Energy of a particle, excluding kinetic energy
SPH Smoothing Length	hh	$[Mpc/h]$	Describes the radius of a sphere encompassing 270 particles centered on the particle. The smoothing length is small in high density regions and large in low density regions.
Molecular weight	mu	[1]	This will be a constant number except in simulations with star formation
Density	rho	$[\frac{h^2 \cdot m_{sol}}{Mpc^3}]$	Density of the particle
Gravitational Potential	phi	$[ICU]$	The gravitational potential is the potential a particle posesses due to its position in a gravitational field.
Mass	mass	$[ICU]$	Mass of the particle
ID	ID	[1]	ID of the particle. Identifies a particle. Due to the way particles are buffered in the simulation, particle id's can disappear or suddenly exist twice within one timestep. According to the HACC-Team, this happens on such a small scale, that it can be ignored.
mask	mask	[1]	The mask describes what type a particle belongs to. 2nd bit: Denotes whether a particle is dark matter (0) or a baryon(1) 6th bit: Denotes if a baryon particle is also a star particle 7th bit: Denotes if a baryon particle is also a wind particle 8th bit: Denotes if a baryon particle is also a star forming gas particle 9th bit: Denotes if a dark matter particle has been flagged as an AGN

Table 2.1: *An overview of the different attributes associated with a particle in the given data set. m_{sol} stands for the mass of the sun and $h = 0.71$. All fields except the id and the mask are given with float precision (4 Bytes). The id is a int64_t (8 Bytes) and the mask is a uint16_t (2 Bytes). ICU stands for internal code units.*