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Astrophysical Sciences

Supermassive black holes and the cosmological formation of massive early-type galaxies (title not final)

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- Haven't really thought about the contents of this chapter yet

3.1 Overview of GADGET-3

3.2 Smoothed Particle Hydrodynamics

3.3 Gas cooling?

3.4 Feedback?

3.5 KETJU

4. Creating initial conditions for the cosmological simulations

This chapter focuses on the methods used to create the necessary configuration files for the high resolution cosmological simulations. First, we discuss the so-called 'zoom-in' method, which allows us to have spatially large simulation boxes with high resolution regions. After this, we discuss the code MUSIC (MUlti-Scale initial conditions), which used to create a spatial volume with highly accurate velocity and density perturbations, with the root-mean square (RMS) relative error being of the order 10^{-4} Hahn & Abel (2011). The created initial conditions (ICs) file is used for the performed GADGET-3 simulations. As the runs performed with GADGET-3 are the main focus of this thesis, the section for MUSIC is not as in-depth as the GADGET-3 discussion in chapter 3. The last part of this chaper focuses on the setup of the cosmological setup of the simulations, and on the preliminary low resolution run needed for the higher resolution simulations.

4.1 Zoom-in technique

To study galaxy formation and evolution in a proper cosmological context, our simulation box must have a large volume. To resolve the gravitational effects of a smaller scale structure, it is also required to have a high resolution, i.e. a large amount of particles with relatively low mass. Having a sufficient resolution on the whole simulation volume would result in a unreasonably large computational workload. Thus it is more sensible to implement a method, which has a high resolution in a single region of interest, surrounded by a large volume with a smaller resolution. This nowadays so-called 'zoom-in' technique has been in use for multiple decades. One of the first simulations with a region of interest surrounded by low resolution background was performed by Navarro & White (1994), and later implementations have been used by e.g. Power et al. (2003) and Marinacci et al. (2014). Modern

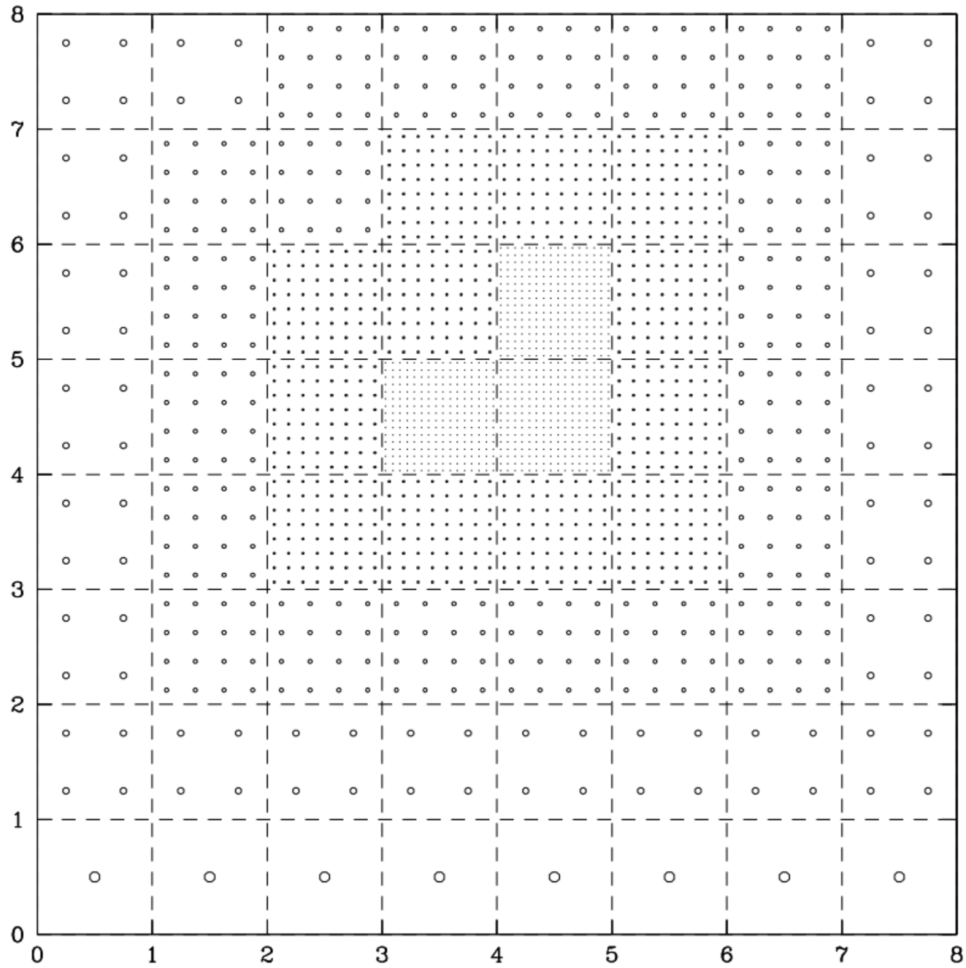

Figure 4.1: An example of a multiple scale mesh grid (Klypin et al., 2001). THIS CAPTION IS NOT FINISHED

implementations, such as the one used in this thesis, use zoom regions with multiple levels of smaller scale particles, as shown in Figure 4.1.

To locate the regions of intetrest, we need to first perform a computationally light simulation without a high resolution volume (discussed in SECTION REFERENCE HERE), and then choose the zoom-in region and perform the simulation again. The initial conditions (ICs) must also portray a realistic case, i.e. the fluctuations at a very high redshift must match the expected structure from theory. Fortunately, we can use a single program to create good ICs, with zoom-in box included.

4.2 MUSIC

4.2.1 Basic properties of MUSIC

4.2.2 Algorithms of MUSIC

- Short section on how MUSIC generates initial particle positions, velocity fields and so on (basically summary of the first few sections of the MUSIC paper)

4.2.3 Creating an IC-file with a zoom-in box

- Step by step explanation of creating the IC file with a zoom-in region

4.3 GADGET-3 setup for the zoom-in -simulations

4.3.1 Cosmological setup

4.3.2 Low-resolution run

4.3.3 Choosing the zoom-in regions

- FoF -algorithm
- Conditions of the chosen halos
- Figure showing the zoom-in regions from the low res run

4.3.4 Initial conditions

h_0	Ω_m	Ω_b	Ω_Λ	σ_8	ρ_{crit}
70.3	0.276	0.045	0.724	0.811	9.28×10^{-27} kg/m^3

Table 4.1: Cosmological parameters used for the simulations. If a simulation doesn't include baryons, the dark matter density parameter Ω_{DM} is equal to the matter density parameter Ω_{m}. If baryons are included, $\Omega_{\mathrm{DM}} = \Omega_{\mathrm{m}} - \Omega_{\mathrm{b}}$.

- Information from GADGET3 config files

5. Cosmological GADGET-3 simulations

5.1 Computational load of the simulations

- Quick overview: CPUs used, time elapsed, where simulations were run

5.2 Locating galaxy centers: the shrinking sphere -method

5.3 Properties of the galaxies

Simulation	r_{vir} (kpc)	M_* ($M_\odot$)	M_{V} (mag)	$M_{*,\mathrm{gal}}/M_{\mathrm{vir}}$	M_{bh} ($M_\odot$)
Med res, A	517	3.98×10^{11}	-22.4	0.025	5.82×10^{9}
Med res, B	574	5.16×10^{11}	-22.7	0.024	6.23×10^{9}
Med res, C	400	2.56×10^{11}	-22.0	0.035	3.96×10^{9}
High res, A	526	5.31×10^{11}	-22.6	0.032	3.64×10^{9}
High res, B	578	6.38×10^{11}	-22.8	0.029	4.54×10^{9}
High res, C	400	3.46×10^{11}	-22.2	0.047	2.80×10^{9}

Table 5.1: Properties of the zoomed-in galaxies at redshift $z = 0$.

5.3.1 Rotation curves

- Med res galaxy A simulation is performed with single precision, I'm currently doing the simulation in double precision
- Rotation curves do not have the same limits on the y-axis

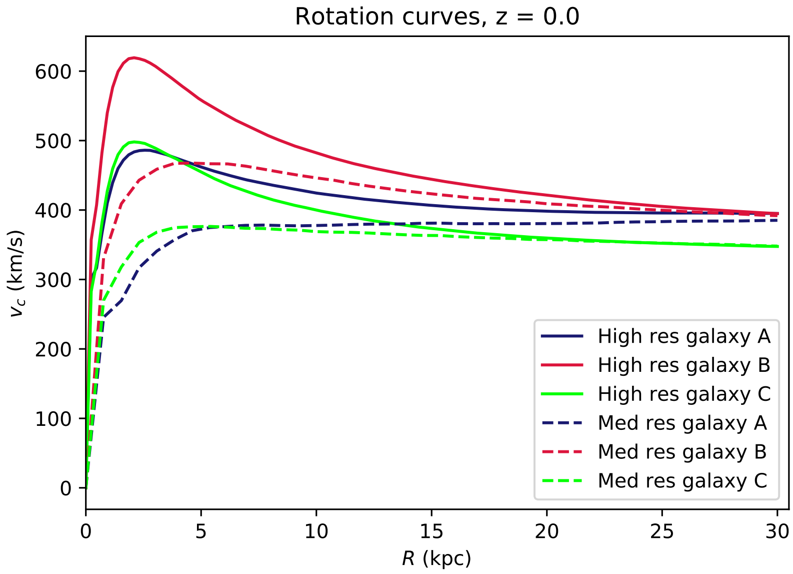

Figure 5.1: Rotation curves for each galaxy including baryons, at redshift 0. The continuous lines represent the high resolution simulations and the dasheld lines represent the medium resolution simulations.

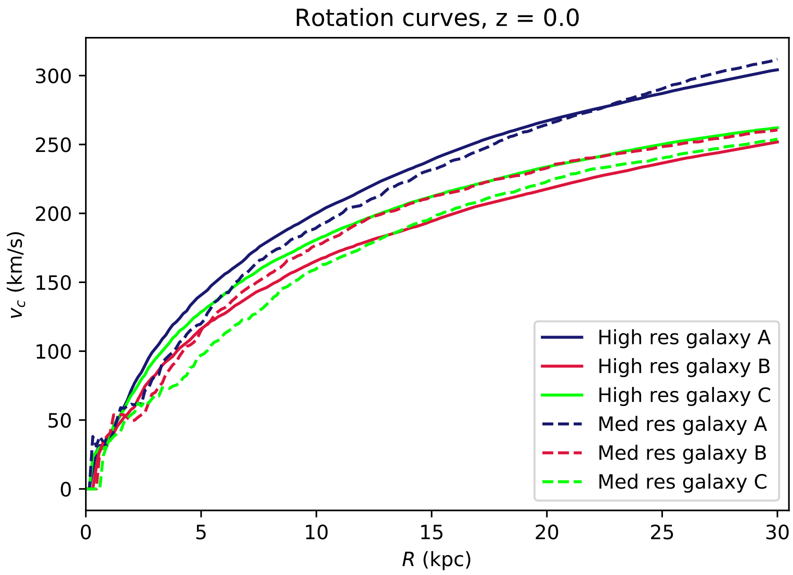

Figure 5.2: Rotation curves for each galaxy including only dark matter, at redshift 0. The continuous lines represent the high resolution simulations and the dasheld lines represent the medium resolution simulations.

5.3.2 Star formation history

- The stellar mass evolution plot is not yet done for high res simulations.

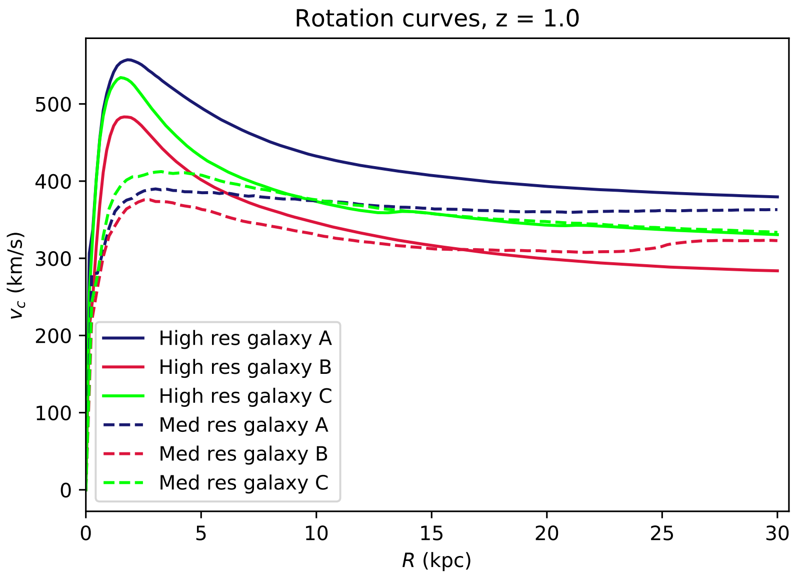

Figure 5.3: Rotation curves for each galaxy including baryons, at redshift 1. The continuous lines represent the high resolution simulations and the dasheld lines represent the medium resolution simulations.

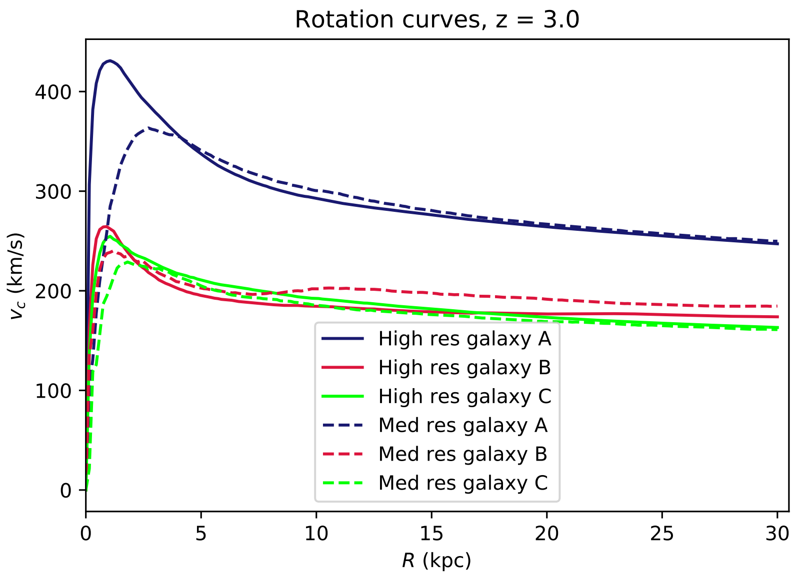

Figure 5.4: Rotation curves for each galaxy including baryons, at redshift 3. The continuous lines represent the high resolution simulations and the dasheld lines represent the medium resolution simulations.

- Redshifts missing from the stellar mass evolution plot
- SFRs, also histograms?

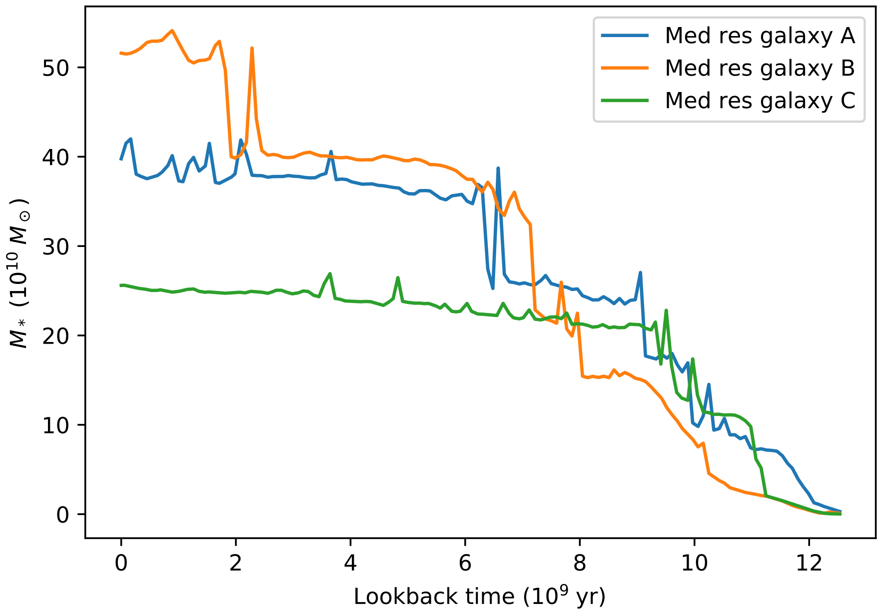

Figure 5.5: Stellar mass evolution for the medium resolution galaxies. The calculated stellar mass is the stellar mass within $r_{\rm gal} = r_{\rm vir}/10$.

- Again, med res A results will probably change a bit when double precision run is finished.
- Formation efficiencies, comparing to the cosmological parameter

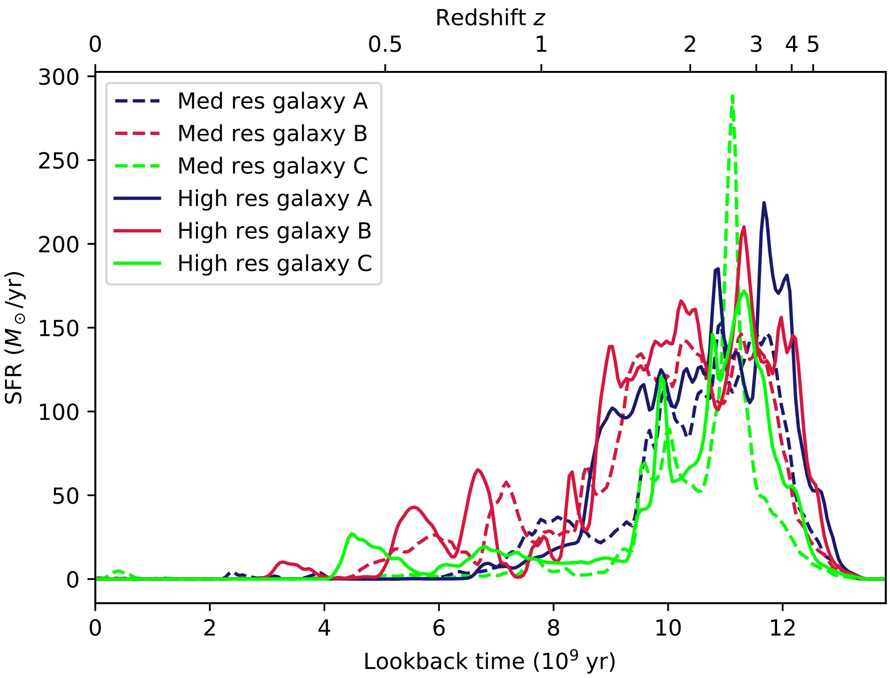

Figure 5.6: Stellar for mation rates for each zoomed-in galaxy, plottes ad a function of lookback time. The lines are created from histograms having a length of 5 Myr, which are then smoothed. The continuous lines represent the high resolution simulations and the dasheld lines represent the medium resolution simulations.

5.3.3 Colors and magnitudes

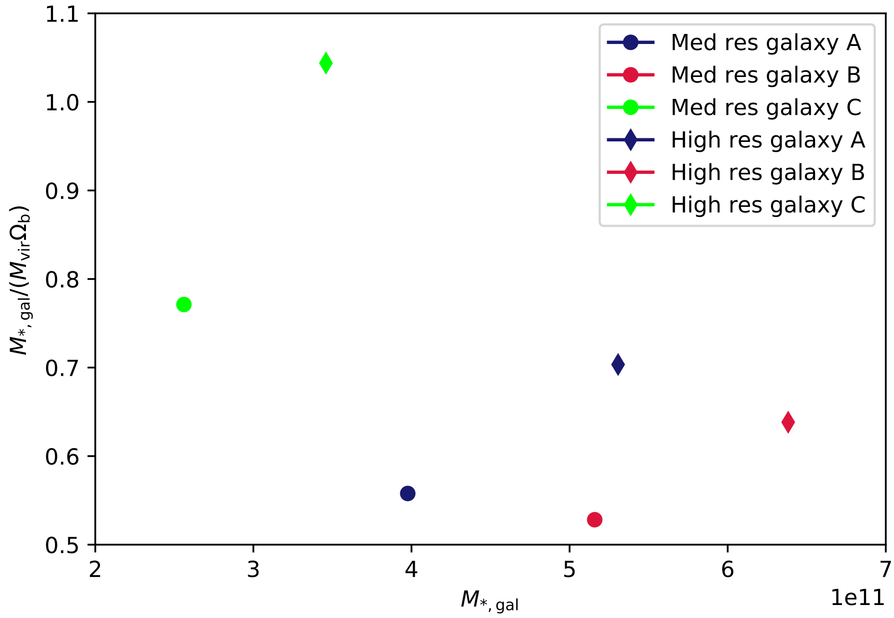

Figure 5.7: Galaxy formation efficiencies for each galaxy, plotted with their stellar masses. The cosmological baryon density Ω_{b} is set to 0.045 in the simulations. The diamond and circular markers show the results of the high resolution and the medium resolution zoom-in simulations, respectively.

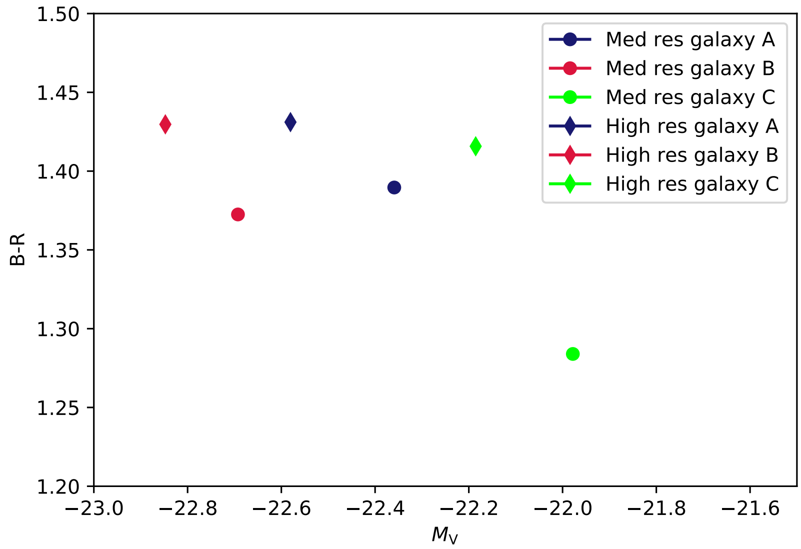

Figure 5.8: B-R colors for each simulated galaxy, plotted with each galaxy's absolute magnitude in the V-band. The diamond and circular markers show the results of the high resolution and the medium resolution zoom-in simulations, respectively.

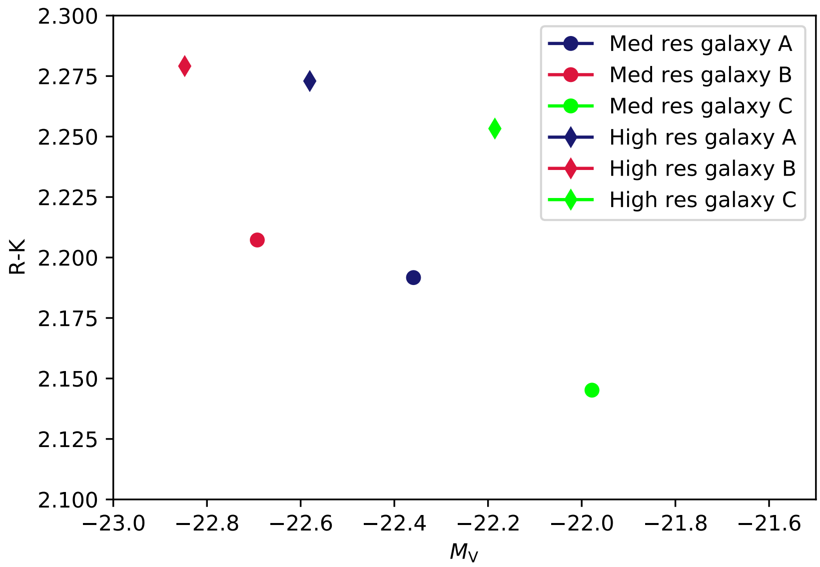

Figure 5.9: R-K colors for each simulated galaxy, plotted with each galaxy's absolute magnitude in the V-band. The diamond and circular markers show the results of the high resolution and the medium resolution zoom-in simulations, respectively.

6. Simulations with KETJU

7. Conclusions

- recap on what was written/studied
- more own thoughts on results
- future missions
- how could the simulations be more realistic (higher resolution, more feedback stuff?)

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