A full pipeline for modelling low surface brightness galaxies

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Image Credit: Tech Times

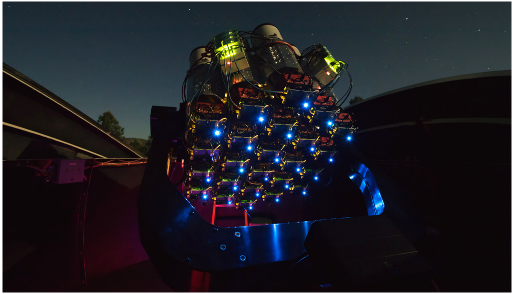
Outline

Introduction

- The existence of galaxies, as faint as the night sky, is known since nearly 3 decades (Bothun et al. 1987; Impey et al. 1988; Schombert & Bothun 1988)
- New measurements allow to investigate these galaxies in more detail
- The formation history of LSB-objects remains largely undetermined
- Besides new measurements also numerical studies are an interesting approach to study these galaxies and make predictions based on the simulations
- The way that LSBGs form in voids should, in principle, offer an observable tracer for the dynamics of voids and maybe help distinguish between FLRW and inhomogeneous modelling of voids.

- In the literature there exists a difference between **L**ow **S**urface **B**rightness **G**alaxies and **U**ltra **D**iffuse **G**alaxies
- Both are characterized by their low surface brightness. UDGs have the typical mass of a dwarf galaxy and are large as normal $L_\star$ galaxies
- It is not clear weather "classical" LSBGs and UDGs share a similar formation scenario or not

The Dragonfly Telescope



Van Dokkum

- Recent measurements of a huge abundance of UDGs in the coma cluster (van Dokkum 2015) shifted this kind of galaxies back into the focus of modern research
- These galaxies now have also been detected in the Virgo, Fornax and other low-z clusters
- Although we expect these galaxies to form in voids as well, to measurement their distances in such an environment is very difficult
- More and more of these galaxies are recently detected; A possible solution for the missing satellite problem?

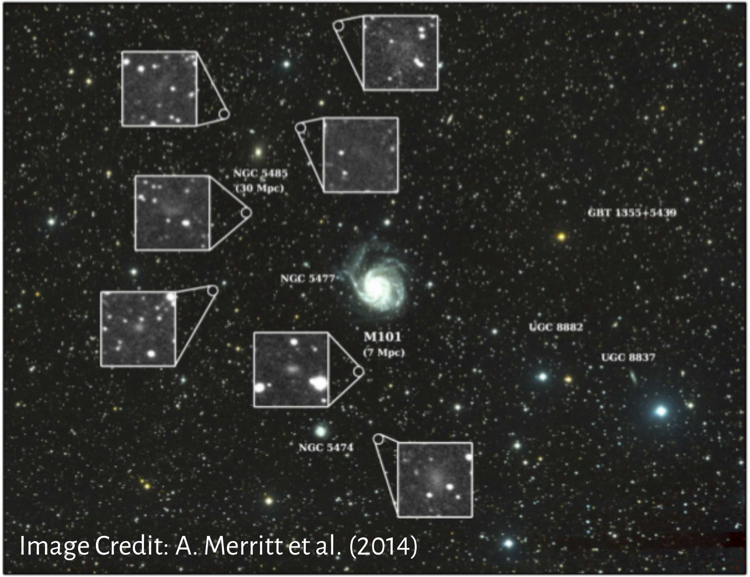
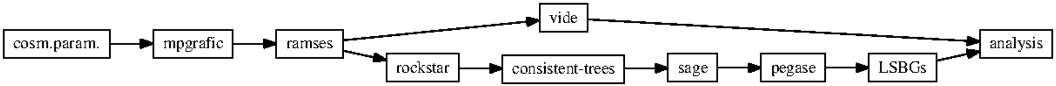


Image Credit: A. Merritt et al. (2014)

- There exists a variety of hypothesized formation scenarios. It is possible that these galaxies are failed $L_\star$ galaxies, diffuse dwarfs that have undergone a phase of quenching or that these galaxies form in high spin host halos
- First measurements indicated that these galaxies are rather red but newer measurements show that they can also be blue and can have huge HI reservoirs
- There exist numerical studies for all three hypotheses (Di Cintio et al. 2016; Yu Rong et al. 2017; Fangzhou Jiang et al. 2018)

- Our work aims at increasing our understanding of low surface brightness galaxies in general
- We are constructing a full pipeline in order to simulate and analyze LSBGs

Code	Purpose
MPGRAFIC	create initial conditions
RAMSES	*N*-body simulation
VIDE	search for voids in the simulation
ROCKSTAR	search for halos
CONSISTENT-TREES	generate a halo merger tree
SAGE	semi analytical galaxy evolution tool to populate the halos
PÉGASE	Stellar synthesis code to estimate magnitudes



Our approach is to connect several well tested numerical tools in order to create a full pipeline to simulate and analyze galaxies.

MPGRAFIC - S. Prunet et al. 2008

- First generates a white noise with constant power spectrum $\langle |n_1(k)|^2 \rangle = 1$
- Second step is to convolve the white noise to the power spectrum to construct the initial fluctuation field as $\delta(k) = n_1(k)A(k)$ where $A(k) = \sqrt{P(k)}$
- It is easy to see that $\langle |\delta(k)|^2 \rangle = P(k)$ - construct it like this to obtain the correct power spectrum
- From the continuity equation one can recover

$$\frac{1}{aH}\nabla_x u = -f(\Omega_m, \Omega_\Lambda)\delta(x) \tag{1}$$

where $f(\Omega_m, \Omega_\Lambda) = \frac{\mathrm{dlog}D}{\mathrm{dlog}a}$. u is comoving velocity, x comoving position and D is the density contrast.

- The particles are displaced from their regular grid and with the last equation we can compute their velocity $\Rightarrow$ compute initial conditions

RAMSES - R. Teyssier 2002

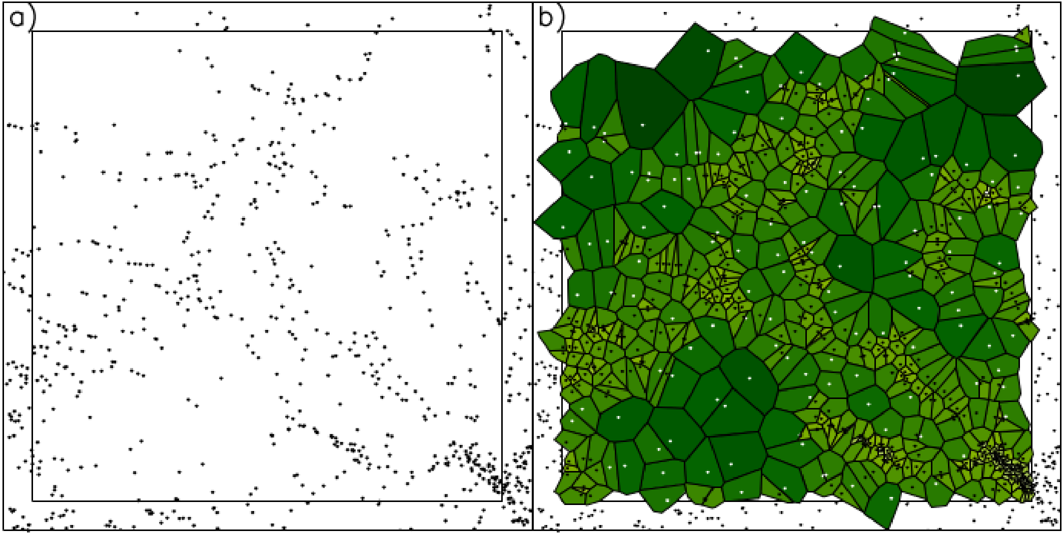
- RAMSES is an adaptive mash code. It uses the initial conditions derived with MPGRAFIC
- At the moment we are only running a pure dark matter simulation, the essential equations are

$$\frac{\mathrm{d}x_p}{\mathrm{d}t} = v_p \ , \ \frac{\mathrm{d}v_p}{\mathrm{d}t} = -\nabla_x \phi \ , \ \Delta\phi = 4\pi G\rho \tag{2}$$

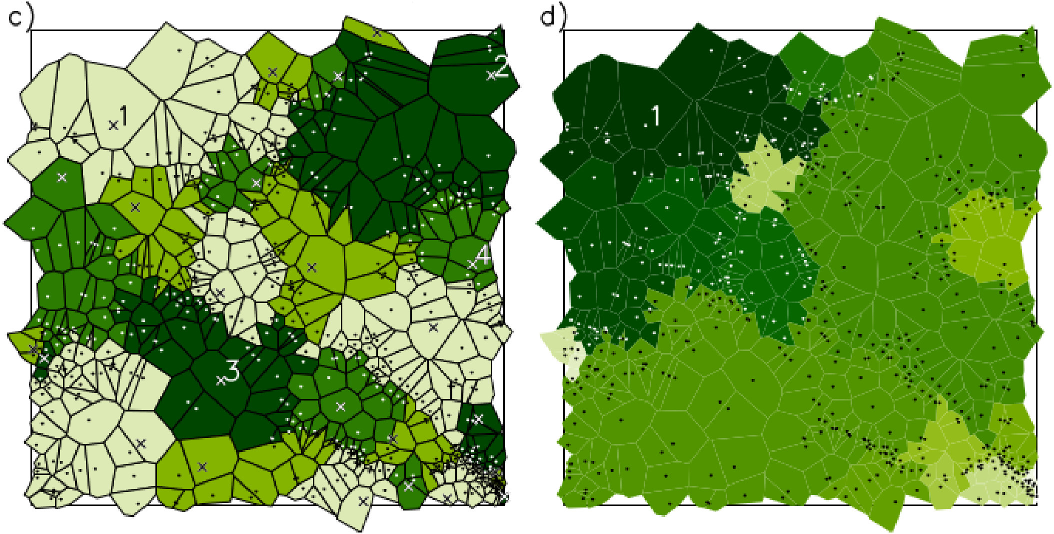
- Solving these equations over time gives us the position and velocity of each particle
- The mass of a single particle is computed via

$$m = \frac{3}{8\pi G}\Omega_m V H(t) \tag{3}$$

VIDE/ZOBOV - P. M. Sutter et al. 2014 and M. C. Neyrinck 2007



VIDE/ZOBOV



ROCKSTAR - P. S. Behroozi et al. 2011

- ROCKSTAR is a 7 dim FoF halo finder, the first step is to identify spatial FoF groups
- In a second step ROCKSTAR identifies substructures by using the velocity of each particle via

$$d(p_1, p_2) = \left(\frac{|\vec{x_1} - \vec{x_2}|^2}{\sigma_x^2} + \frac{|\vec{v_1} - \vec{v_2}|^2}{\sigma_v^2} \right)^{1/2} \tag{4}$$

- The length is chosen by the algorithm such that a constant fraction f of particles is linked
- In each of these substructures the code generates an seed-halo, these halos are then merged to generate the final halo catalog

CONSISTENT-TREES - P. S. Behroozi et al. 2013

This code takes the output from ROCKSTAR and generates the halo-merger-tree. The merger-tree is the input for SAGE and contains all essential information about the temporal evolution of halos, e.g. their progenitors, their descendants and their satellites.

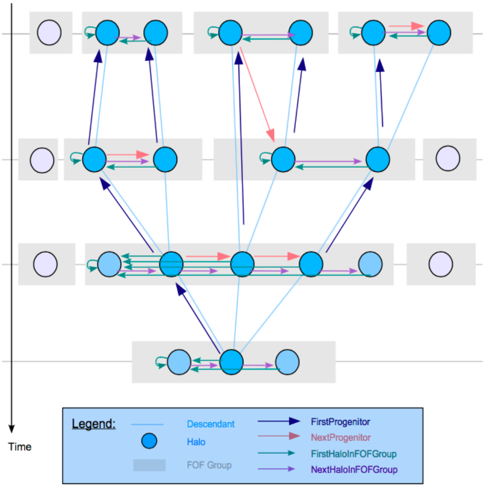


Image Credit: M. Sinha, LHaloTreeReader

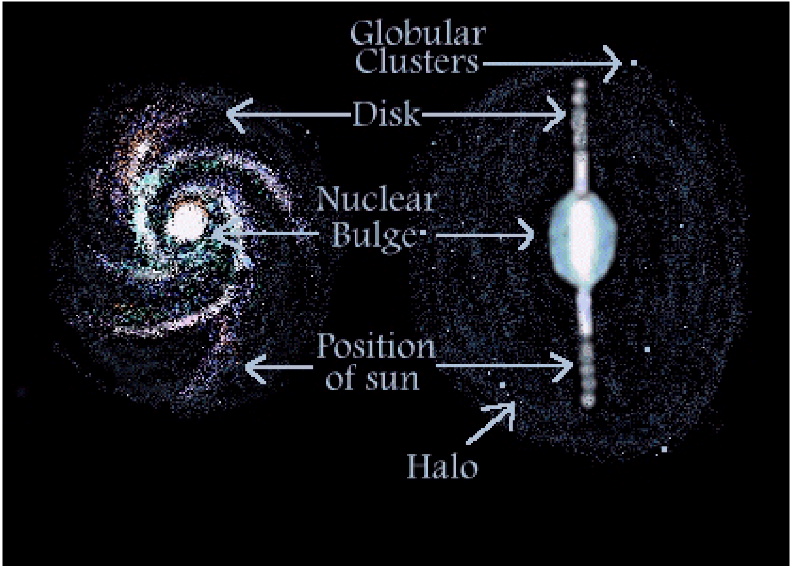


Image Credit: cornell.edu

SAGE - D. J. Croton 2016

Semi-**A**nalytical **G**alaxy **E**volution

This code is remarkable since it is designed to work on any *N*-body simulation as long as the input is given in the correct format (we use a converter).

Gas Infall

The virialized mass and radius of the dark matter halo are generated by RAMSES and estimated by ROCKSTAR. SAGE estimates the baryonic mass in a galaxy corresponding to the dark matter mass via the baryonic fraction f_b. New gas is added as hot gas and ejected gas is first taken from the hot reservoir.

Reionization

The baryonic growth of low mass halos is suppressed by photoionization heating of the IGM by feedback of the first stars.

Hot Gas Halo

Every galaxy is surrounded by a halo of hot gas, the cooling time can be approximated by

$$t_{\rm cool} = \frac{3}{2}\frac{\bar{\mu} m_p k T_{\rm vir}}{\rho_g(r)\Lambda(T_{\rm vir}, Z)}, \tag{5}$$

where $\bar{\mu} m_p$ is the mean particle mass , $\rho_g(r)$ is the density of hot gas and $\Lambda(T_{\rm vir}, Z)$ is the cooling function.

Star Formation

The cold gas is concentrated in a disk in the center of the galaxy. Cold gas above the critical surface density

$$m_{\rm crit} = 3.8 \times 10^9 \left(\frac{V_{\rm Vir}}{200{\rm kms}^{-1}}\right)\left(\frac{r_{\rm disk}}{10{\rm kpc}}\right) M_\odot \tag{6}$$

can form stars. The stellar mass is described via

$$\dot{m}_\star = \alpha_{\rm SF}\frac{(m_{\rm cold} - m_{\rm crit})}{t_{\rm dyn}} \tag{7}$$

Supernova Feedback
Supermassive stars will form with a given rate ϵ and eventually end in a supernova, reheating cold gas and stripping hot gas out of the galaxy. Gas that was stripped away can fall back into the galaxy if the galaxy is massive enough.

AGN Feedback

- Radio mode: Depended on the cold gas that is accreted by the black hole SAGE computes a radio luminosity for the black hole. Additionally SAGE introduces a heating radius around the black hole in which gas never cools down again.
- Quasar mode: Triggered by mergers the black hole accretes mass very fast and thus emittes a lot of energy.

Starbursts
Starbursts occur after mergers or if the disk is instable. After a merger, stars proportionally to the cold gas of both galaxies, are formed and if the disk is unstable, stars proportionally to the cold gas added to the bulge, are formed.

PÉGASE - M. Fioc & B. Rocca-Volmerange 2019

We now have access to a variety of information including the stellar masses, the star formation rate of galaxies and many more but we have no information about the brightness of the galaxy. To calculate the brightness we use a stellar synthesis code. The basic steps are

1. Compute a single stellar population (SSP) (set of stars with the same initial chemical composition, created instantaneously) for various metallicities

$$L_\lambda^{\mathrm{SSP}}(t, \{\chi_0\}) = \int L_\lambda^{\mathrm{star}}(m, t, \{\chi_0\})\phi(m)\mathrm{d}(\ln m) \tag{8}$$

2. Use stellar evolutionary tracks to evolve the SSPs. They provide information about the evolution of the bolometric luminosity of a star
3. A galaxy consists of various SSPs with various ages and metallicities. The monochromatic luminosity of a galaxy can be computed via

$$L_\lambda^\star(t) = \int_{t'=0}^{t} \psi(t-t')L_\lambda^{\mathrm{SSP}}(t', Z[t-t'])\mathrm{d}t' \tag{9}$$

Pros

Simple Physics

Fast - we can run everything on one device so we have full information about every step in the simulation

On large scales and for a large enough amount of galaxies a simpler approach should still give us the right trends

Well understood methods

Cons

Simple Physics

Oversimplified physics, maybe we miss the essential processes to form LSBGs

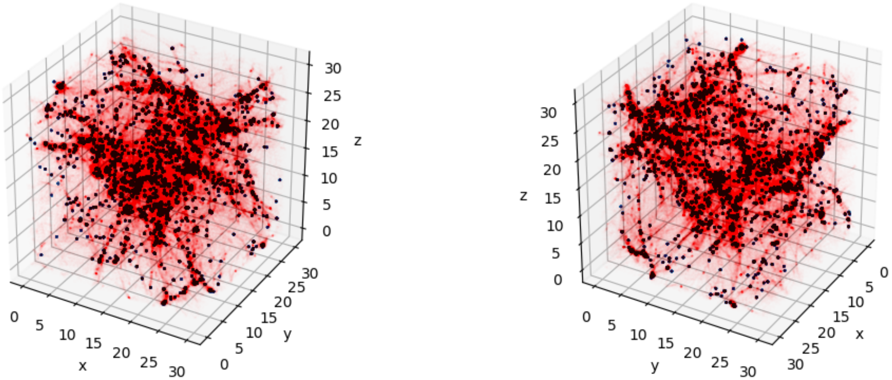
Our simulation is only based on dark matter, hydrodynamical simulations yield more realistic scenarios

BUT: We are able to include important processes into our pipeline
If needed we can exchanges codes in our pipeline

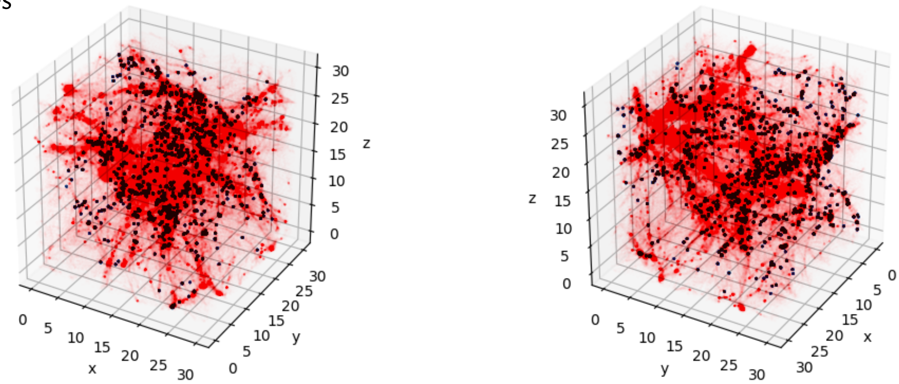
We presented a full pipeline to simulate galaxies and their environment. The huge advantage is that we are able to interact at any stage of the code and check what is happening in full detail. The following, preliminary results are derived from a simulation with following parameter

N	128^3
L	$30\,\frac{\mathrm{Mpc}}{\mathrm{h}}$
H_0	$75\,\frac{\mathrm{km}}{\mathrm{Mpc\ s}}$
Ω_m	0.3
Ω_λ	0.7

red: DM particles
Circles: Galaxies

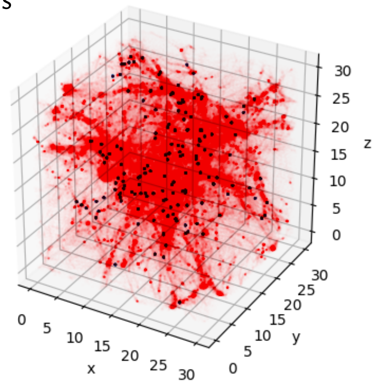


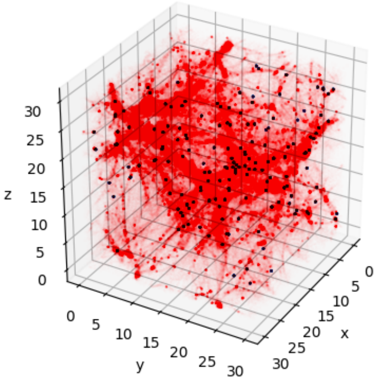
red: DM particles
Circles: void-galaxies

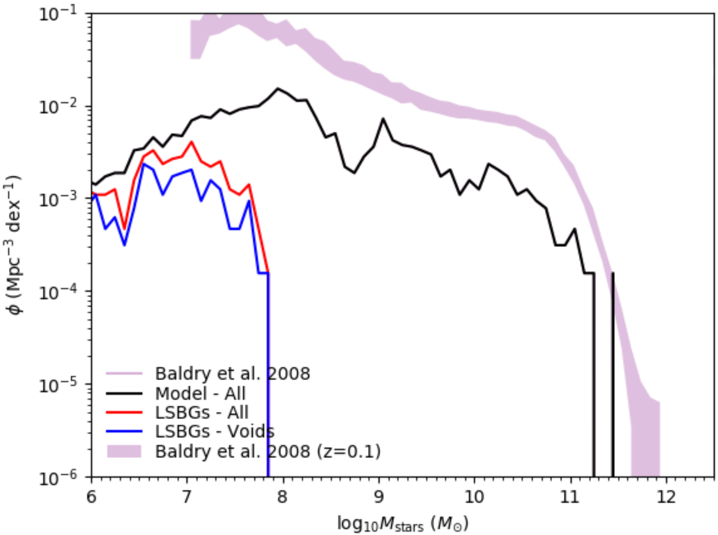


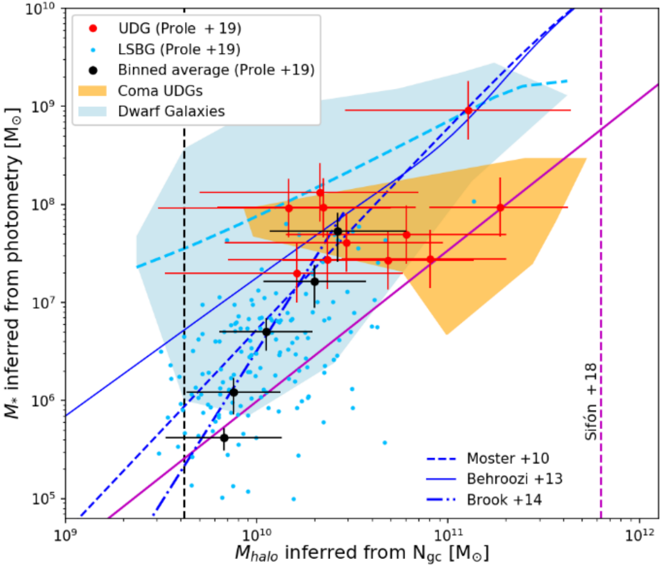
red: DM particles

Circles: void-LSBGs

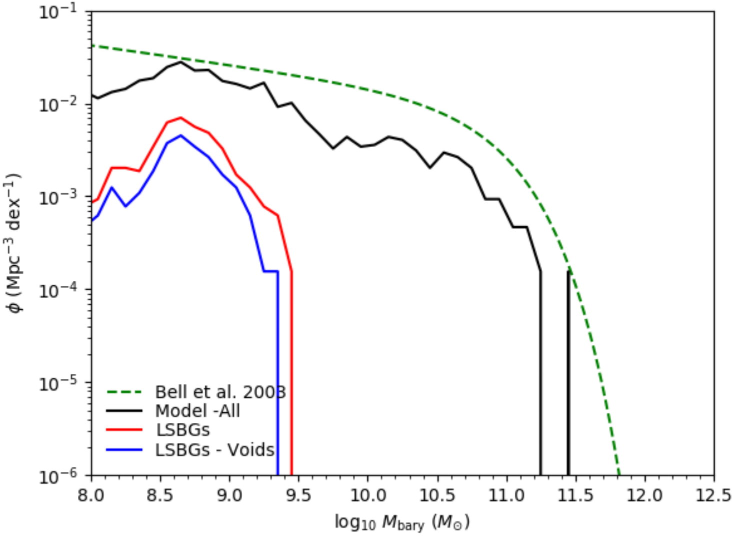


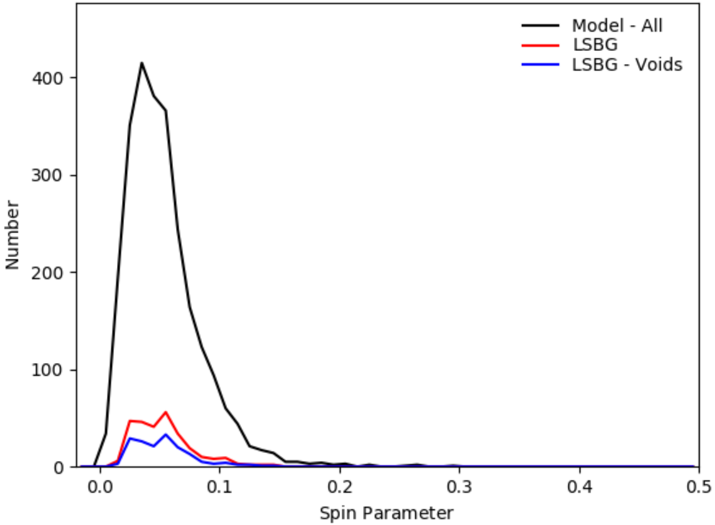


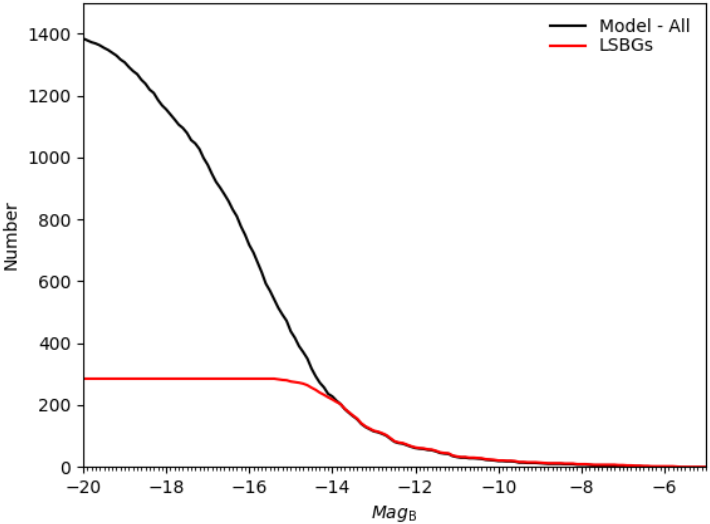

10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ϕ (Mpc^{-3} dex^{-1})
6
7
8
9
10
11
12
$\log_{10} M_{\rm stars}$ ($M_\odot$)
Baldry et al. 2008
Model - All
LSBGs - All
LSBGs - Voids
Baldry et al. 2008 (z=0.1)



D. J. et al. Prole 2019


10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ϕ (Mpc^{-3} dex^{-1})
8.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5
12.0
12.5
$\log_{10} M_{\rm bary}$ ($M_\odot$)
Bell et al. 2003
Model -All
LSBGs
LSBGs - Voids


Model - All
LSBG
LSBG - Voids
Number
400
300
200
100
0
0.0
0.1
0.2
0.3
0.4
0.5
Spin Parameter


Model - All
LSBGs
Number
1400
1200
1000
800
600
400
200
0
−20
−18
−16
−14
−12
−10
−8
−6
Mag_B

Conclusion

- We find 1563 galaxies, 285 of them are LSBGs. The criterion to identify a LSBG is $\mu_g \geq 22 \frac{\mathrm{mag}}{\mathrm{arcsec}^2}$
- 910 galaxies in our simulation are in a void for $z = 0$. Out of these void-galaxies 163 are LSBGs.
- In total we find 2522 halos, we see that only a about $2/3$ of these halos are able to hold galaxies.
- Even if our results are very preliminary right now they so far look reasonable.

Outlook

- We still need a lot of work to set up the pipeline properly and test it, especially the void finder seems to not work properly
- Once the pipeline is set up and all parameter are set properly it will be a useful tool to rapidly generate and analyze galaxy populations
- We have a huge amount of information that is accessible at every timestep of the simulation which allows to recover the galaxy formation history in a convenient way
- Our analysis is not restricted to search for LSBGs, it should be possible to analyze arbitrary galaxy populations
- Future work: using GR *N*-body simulations (e.g. GEVOLUTION or GRAMSES), we will improve our analysis to be much more realistic

Thanks for your attention!