Galaxy catalogs from the S\textsc{a}ge Semi-Analytic Model calibrated on The Three Hundred hydrodynamical simulations: A method to push the limits toward lower mass galaxies in dark matter only clusters simulations

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Abstract. The new generation of upcoming deep photometric and spectroscopic surveys will allow us to measure the astrophysical properties of faint galaxies in massive clusters. This would demand to produce simulations of galaxy clusters with better mass resolution than the ones available today if we want to make comparisons between the upcoming observations and predictions of cosmological models. But producing full-physics hydrodynamical simulations of the most massive clusters is not an easy task. This would involve billions of computational elements to reliably resolve low mass galaxies similar to those measured in observations. On the other hand, dark matter only simulations of cluster size halos can be done with much larger mass resolution but at the cost of having to apply a model that populate galaxies within each of the subhalos in these simulations. In this paper we present the results of a new set of dark matter only simulations with different mass resolutions within the Three Hundred project. We have generated catalogs of galaxies with stellar and luminosity properties by applying the S\textsc{a}ge Semi-Analytical Model of galaxy formation. To obtain the catalogs consistent with the results from hydrodynamical simulations, the internal physical parameters of S\textsc{a}ge were calibrated with the Particle Swarm Optimization method using a subset of full-physics runs with the same mass resolution than the dark matter only ones.

1 Introduction

The new generation of upcoming deep surveys like Euclid [1], 4MOST [2] and Weave [3], will detect galaxies within clusters down to very faint magnitudes. This will help to understand the physics of galaxy formation and evolution in these high density environments and will also allow to derive more accurate mass estimates of the total mass of clusters from their galaxy content, which is key to be able to put constrains on the cosmological parameters of the Universe. But, at the same time, it will also demand new methods to perform cosmological simulations of cluster size objects with better mass resolutions to be able to
contrast the predictions from the theoretical models with those observed by the new surveys. The full-physics hydrodynamical simulations of massive clusters generated by the ‘zoom-in’ technique adopted in The Three Hundred\cite{1} project offer the perfect laboratory for a comparison with current surveys but they have a mass resolution not enough to resolve dark matter sub haloes with $10^{11} h^{-1} M_\odot$ and below. Their hosted galaxies have magnitudes that are fainter than those coming from upcoming (e.g. Euclid will reach magnitudes $m_H \sim 24$) surveys. For this reason, a new generation of hydrodynamical simulations with higher mass resolution of The Three Hundred clusters is being carried out but given the high computational cost, only 5 zoomed regions, out of a total of 324 regions, have been completed so far. On the other hand, dark matter only versions of the full data set at high resolution have already been completed using much less computational resources. Therefore, we can make an efficient use of these simulations if we can emulate the observational properties of the galaxies within each of the dark subhalos that mimic those coming from the full-physics hydrodynamical simulations at our disposal. To do this, we use as an emulator the publicly available SAGE Semi-Analytic Model (SAM)\cite{5} of galaxy formation, and calibrate their free parameters against observables from the hydrodynamical simulations.

### Table 1. The Three Hundred simulations.

<table>
<thead>
<tr>
<th>Name</th>
<th>N particles</th>
<th>DM particle mass $[h^{-1} M_\odot]$</th>
<th>DM halo resolution (100p$^*$) $[h^{-1} M_\odot]$</th>
<th>N regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>3K-DMO</td>
<td>3840$^3$</td>
<td>$1.5 \times 10^9$</td>
<td>$10^{11}$</td>
<td>324</td>
</tr>
<tr>
<td>3K-GIZMO</td>
<td>3840$^3$</td>
<td>$1.5 \times 10^9$</td>
<td>$10^{11}$</td>
<td>324</td>
</tr>
<tr>
<td>7K-DMO</td>
<td>7680$^3$</td>
<td>$1.8 \times 10^8$</td>
<td>$10^{10}$</td>
<td>324</td>
</tr>
<tr>
<td>7K-GIZMO</td>
<td>7680$^3$</td>
<td>$1.8 \times 10^8$</td>
<td>$10^{10}$</td>
<td>5</td>
</tr>
<tr>
<td>15K-DMO</td>
<td>15360$^3$</td>
<td>$2.3 \times 10^7$</td>
<td>$10^9$</td>
<td>3</td>
</tr>
</tbody>
</table>

* : 100 dark matter particles to form a halo.

## 2 Data

### 2.1 The Three Hundred dataset

Our data set is based on the 324 zoomed regions simulated within The Three Hundred project with different physics flavours, including the newest runs with dark matter only. They were created starting from the Dark Matter Only (DM-Only) MultiDark Simulation\cite{6} (MDPL2), which consist of a $1 \times 10^9 h^{-1} \text{Gpc}$ cube containing 3840$^3$ dark matter particles (DM) each with a mass of $1.5 \times 10^9 h^{-1} M_\odot$. The initial conditions were generated by identifying the Lagrangian regions of all the particles lying within a spherical region of $15 h^{-1} \text{Mpc}$ centred around each of the 324 most massive clusters of MDPL2 at $z = 0$. Within this Lagrangian region, high resolution dark matter and gas particles were populated while dark matter particles of increasing mass levels fill the full box outside the zoomed area, describing the global gravitational field. The Three Hundred Collaboration performed these simulations in five different variants based on the GIZMO-SIMBA\cite{7} code, which can generate both DM-Only and hydrodynamical simulations. Depending mainly on the physics and resolutions, the five variants of The Three Hundred Simulations we are using in this work are: 1) **3K-GIZMO**: Full-physics hydrodynamics zoomed simulations of 324 regions with a DM particle resolution of $1.5 \times 10^9 h^{-1} M_\odot$, 2) **3K-DMO**: DM-only simulations at the same resolution as the 3K-GIZMO simulations and 324 regions are available, 3) **7K-GIZMO**: Physics as 3K-GIZMO but at high resolution which contain 7680$^3$ DM particles (twice particles per dimension than 3K-DMO or 3K-GIZMO) with a DM particle mass of $1.8 \times 10^8 h^{-1} M_\odot$. For these, we only have 5 available regions given its high computational cost, 4) **7K-DMO**: DM-only simulations at high

1\url{https://www.the300-project.org}
resolution as \textbf{7K-gizmo} and 324 regions are available, 5) \textbf{15K-dmo}: DM-only simulations as \textbf{7K-dmo} but at very high resolution which contain 15360$^3$ DM particles (twice particles per dimension than \textbf{7K-dmo} or \textbf{7K-gizmo}) with a DM particle mass of $2.3 \times 10^7 \ h^{-1} M_\odot$. For these simulations we only have 3 regions at the moment. For a global summary of the \textbf{The Three Hundred} simulations see Table 1.

2.2 Semi-Analytic Model of Galaxy formation and Evolution: \textbf{SAGE}

In this work we use the \textbf{SAGE} SAM [5] which has 14 internal parameters to model the physical process of the galaxies through merger trees of DM haloes. All these parameter values can be tuned to calibrate the \textbf{SAGE} galaxy properties with respect to different (observed or simulated) constrains. Considering that we have the whole 324 regions in \textbf{7K-dmo} simulations, we will apply the \textbf{SAGE} model on them (\textbf{7K-SAGE}) for calibrating the parameters of the model in order to obtain results as close as possible to the 5 \textbf{7K-gizmo} available regions. Once the \textbf{SAGE} model is calibrated we then apply it to the full \textbf{7K-dmo} dataset to obtain the galaxy properties of all the halos and subhalos in these simulations.

2.3 \textbf{SAGE} calibration with Particle Swarm Optimization

To calibrate \textbf{SAGE} we use the \textbf{Particle swarm optimization} (PSO) [9] method (see [8] for its first use to calibrate a SAM) which varies the internal parameters of \textbf{7K-SAGE} efficiently and finds the optimal values that minimize the difference between galaxy properties between \textbf{7K-SAGE} and \textbf{7K-gizmo}. PSO is a computational optimization technique in multi-dimensional spaces that is based on the movement of particles represented by their positions in the parameter space. In our case, each PSO particle correspond to given values of the parameters of a \textbf{SAGE} run. Using several of these particles, PSO works like birds moving in a swarm, hence the name. They can profit from the common experience of all members of the swarm when looking for food. This search method is at least 30 times faster than the standard Monte Carlo minimization techniques (see [10] and [11]).

In this work, we take as calibrators, the average cumulative stellar mass function ($<\text{CSMF}>$) and the z-band and U-band average cumulative luminosity function ($<\text{CLF}>$) of galaxies within all clusters more massive than at least $10^{14} \ h^{-1} M_\odot$. We compute these observable from the 5 available regions of \textbf{7K-gizmo}-simulations and compute them also in their corresponding DM only version \textbf{7K-dmo} simulations using \textbf{SAGE}. The galaxy luminosities were calculated by the Stellar Population Synthesis model \textbf{STARDUST} [12] for both \textbf{7K-SAGE} and \textbf{7K-gizmo}. We calibrate these 3 galaxy properties at 4 different redshifts: $z = 0,$ $z = 0.1,$ $z = 0.5,$ and $z = 1$ because we want to be able to reproduce the star formation history from hydrodynamical simulations. Finally, the \textbf{7K-SAGE} calibration was done considering simultaneously the 3 galaxy properties at 4 different redshifts (between 0 and 1) in order to have a consistent evolution of these properties with respect to the hydrodynamical results. In Fig 1 we show the final \textbf{7K-SAGE} calibration considering a minimum stellar mass and maximum luminosity limit when we calibrate with PSO because there are not enough haloes in the \textbf{7K-dmo} simulations compared to \textbf{7K-gizmo} since in hydrodynamical simulations of galaxy clusters there are more low mass subhalos because baryonic matter helps them to survive [13].

3 Results

Considering the above mentioned calibration of \textbf{SAGE} parameters in Section 2.3, we can then apply the model on the other DM-Only simulation at different resolutions: \textbf{3K-dmo} (low
Figure 1. Average cumulative stellar mass functions ($<\text{CSMF}>$; top panels), average cumulative luminosity functions for the $z$-band ($<\text{CL}_zF>$; panels in the second row), and average cumulative luminosity functions for the $U$-band ($<\text{CL}_UF>$; bottom panels) at 4 redshifts: $z = 0$, $z = 0.1$, $z = 0.5$, and $z = 1$ (left to right panels). These cumulative functions have been used to calibrate $7\text{k-SAGE}$ (blue line) with respect to $7\text{k-GIZMO}$ (red line) with PSO using all clusters with $M_{\text{halo}} > 10^{14} h^{-1} M_\odot$ in the 5 coincident regions of $7\text{k-DMO}$ and $7\text{k-GIZMO}$. The filled color regions correspond to the 1-$\sigma$ error and the vertical blue line represents the limit used in the calibration procedure (minimum limit for stellar mass and maximum limit for luminosity). For each panel, the ratio of the average cumulative functions over that from $7\text{k-GIZMO}$ is shown at the bottom.

resolution) and $15\text{k-DMO}$ (very high resolution). Thus we can check whether the galaxy properties obtained from the calibrated SAGE are sensitive to the resolution of the dark matter halos. In the $<\text{CSMF}>$ of Fig. 2-left we show all the versions of the simulations that we have considered (see Table 1 to see all data), where it seems that the application of the $7\text{k-SAGE}$ calibration on different resolution DM-Only simulations, such as $3\text{k-DMO}$ and $15\text{k-DMO}$, is consistent before the minimum of the stellar mass limit. In addition, in the stellar mass - halo mass relationship of Fig. 2-right we can see the consistency between the hydrodynamical simulations and the results of SAGE calibrated on DM-Only simulation. Finally, with this calibration we can reach smaller galaxies by applying it in the DM-Only simulation at $15\text{k-DMO}$. As we can see in Fig. 3, CSMF considering all the complete regions available in $3\text{k-GIZMO}$, $3\text{k-SAGE}$, $7\text{k-GIZMO}$ and $7\text{k-SAGE}$, this calibration opens the possibility to have new galaxy catalogs. We generated a catalog of 10 million galaxies from the SAGE emulator from the 324 regions of $7\text{k-DMO}$ simulations, and 1 million galaxies through SAGE from only 3 regions of $15\text{k-DMO}$ simulations. These catalogs have a large number of galaxies because we have a large number of dark matter merger trees from all the host halos and their substructures.
4 Conclusions

A galaxy emulator has been developed by S\textsc{age} SAM applied to The Three Hundred DM-Only simulations to reproduce results from 7\textsc{k-gizmo} simulations such as stellar and luminosity properties of haloes at several redshifts (0 to 1). Given the low computational cost of DM-Only simulations + SAMs compared to hydrodynamical simulations we are able to push the limit towards lower mass galaxies in clusters simulations that can be very useful to make predictions for upcoming deep surveys like EUCLID, 4MOST and WEAVE.

In addition, the S\textsc{age} calibration seems not to be sensitive to the resolution of the DM-Only simulation, so the calibration at 7\textsc{k-dmo} resolution can be safely applied in the 15\textsc{k-dmo} higher resolution simulations. This emulator is amazingly flexible because we can add more galaxy properties and more redshifts to the calibration procedure with a modest increase in computational time. Thus, this opens up the possibility of studying properties such as gas or supermassive black holes at $z > 5$, bringing us closer to the early universe of hydrodynamical simulations. Finally, a mock catalog of galaxies from the calibrated S\textsc{age} is now ready to be used within The Three Hundred Collaboration.

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References

Figure 3. Cumulative stellar mass functions (CSMF) at redshift $z = 0$ for $3k$-GIZMO (dashed red line), $7k$-SAGE calibrated (solid blue line), $3k$-SAGE (dashed blue line) with the parameters obtained in the $7k$-SAGE calibration using all available regions (see Table 1). Vertical blue line corresponds to the minimum for stellar mass limit used in the calibration.