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The Structure of Massive Galaxies and Its Dependence on Dark Matter Halo Mass

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ABSTRACT

[Song: Placeholder] Using deep images from the Hyper Suprime–Cam (HSC) Survey, we show that the massive central galaxies in less and more massive dark matter halos have different stellar mass distributions. In this work, we use weak lensing (WL) analysis based on HSC images to further investigate the connection between stellar mass distribution and the dark matter halo properties in massive galaxies. We detect a significant dependence that suggest XXXXXXX. We also find similar trends in hydrodynamic simulations and semi-empirical models. With the help from the recent `UniverseMachine` semi-empirical model, we forward modeling the observed stellar mass functions (SMF) for different aperture masses and the WL profiles across the $M_{\star,\rm Tot}$-$M_{\star,10\ \rm kpc}$ plane at the same time. This model provides us a new window to look into the connection between the assembly of massive galaxies and their dark matter haloes. We find XXXXX (put the amazing results here).

Key words: galaxies: evolution – galaxies: haloes – dark matter – surveys

1 INTRODUCTION

Scientific background on galaxy-halo connection for massive galaxies and why it is important

Motivation: We find that central galaxies in more or less massive dark matter haloes could have different stellar mass distributions. This result has many exciting implications about the assembly of massive galaxies and their galaxy–halo connection. Here we use the stellar mass distributions of z 0.4 massive galaxies and their weak lensing signals to further study how exactly the dark matter halo masses connect to the stellar mass within different regions of massive galaxies.

[Song: Placeholder] This paper is organized as follows. §2 presents our data and our sample selection. §3 describes the `UniverseMachine` model and how we use it to study the dark matter halo mass across the $M_{\star,\rm Tot}$-$M_{\star,10\ \rm kpc}$ plane. Our main results are presented in §4 and discussed in §5. §6 presents our summary and conclusions.

Magnitudes use the AB system (Oke & Gunn 1983), and are corrected for Galactic extinction using calibrations from Schlafly & Finkbeiner (2011). In this work, we assume $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_{\rm m} = 0.3$, and $\Omega_\Lambda = 0.7$. Stellar mass is noted $M_\star$ and has been derived using a Chabrier Initial Mass Function (IMF; Chabrier 2003). $M_{\rm halo}$ denotes halo mass in general whereas $M_{\rm 200b}$ is explicitly defined as $M_{\rm 200b} \equiv M(< r_{\rm 200b}) = 200\bar{\rho}\times\frac{4}{3}\pi r^3_{\rm 200b}$ where $r_{\rm 200b}$ is the radius at which the mean interior density is equal to 200 times the mean matter density ($\bar{\rho}$).

2 MASSIVE GALAXIES OBSERVED BY HYPER SUPRIME-CAM SURVEY

2.1 Sample selection

[Song: Placeholder] The Subaru Strategic Program (SSP, Miyazaki et al. prep) makes use of the new prime-focus camera, the Hyper Suprime-Cam (HSC; Miyazaki et al. 2012), on the 8.2-m Subaru telescope at Mauna Kea. The ambitious multi-layer HSC survey takes advantage of the large field of view (FoV; 1.5 deg in diameter) of this camera and will cover ∼ 1400 deg^2 in 5 broad bands ($grizY$) to a limiting depth of $r \sim 26$ mag in the `WIDE` layer. This work is based on the internal data release `S15B`, which covers ∼ 100 deg^2

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in all 5-band to full `WIDE` depth. The regions covered by this release overlap with a number of spectroscopic surveys (e.g. SDSS/BOSS: Eisenstein et al. 2011, ?; GAMA: Driver et al. 2011, Liske et al. 2015).

The HSC `WIDE` survey is about 3.0-4.0 magnitudes deeper in the i-band than SDSS. Combined with the excellent imaging resolution (the median i-band seeing is 0.6"), and the wide area, the HSC survey represents a tremendous data set to perform a large statistical study of the surface brightness profiles of ETGs out to large radii. Fig **??** illustrates the quality of HSC imaging compared to SDSS for three low redshift ETGs, and shows that HSC survey data are well suited for mapping the stellar distribution of massive galaxies out to large radii.

HSC i-band images typically have the best seeing compared to other bands because of strict requirements driven by weak lensing science. We will therefore use the i-band images to measure the stellar distributions of massive galaxies.

2.2 Surface mass density profiles and aperture masses

Briefly explain how 1-D mass density profiles are extracted and how aperture masses are measured.

2.3 Weak lensing analysis around massive galaxies

Briefly explain how weak lensing density profiles are measured using HSC images.

3 MODEL

3.1 `UniverseMachine` Model

Briefly explain the `UniverseMachine` semi-empirical model.

3.2 Old Model: the $M_{\star,\rm Tot}$–$M_{\star,10\ \rm kpc}$ plane

Need a lot of edits!

Physical motivation of this model is based on the finding in simulations that the stellar mass of *all* galaxies in the halo correlates the best with the halo mass.

Here we describe the basic structure of the model. The physical parameters used here are:

- $M_{\rm halo}$: Mass of the dark matter halo.
- $M_{\star,\rm All}$: Simulated/modelled stellar mass of all galaxies in the halo.
- $M_{\star,\rm BCG}$: Simulated/modelled stellar mass of the central part of the galaxy.
- $M_{\star,\rm ICL}$: Simulated/modelled stellar mass of the intra-cluster light of a halo.
- $M_{\star,\rm Cen}$: Simulated/modelled total stellar mass of the central galaxies. Equals to $M_{\star,\rm BCG}$+$M_{\star,\rm ICL}$.
- $M_{\star,\rm Tot}$: Observed stellar mass within a 100 kpc elliptical aperture.
- $M_{\star,10\ \rm kpc}$: Observed stellar mass within a 10 kpc elliptical aperture.

Using the UniverseMachine model based on the MultiDark simulation (referred to as the `UniverseMachine` model), we assume there is a simple log–linear relation between $M_{\rm halo}$ and $M_{\star,\rm All}$:

$$\log M_{\star,\ \rm All} = a \times \log M_{\rm Halo} + b \tag{1}$$

The above relation has a log–normal scatter. The scatter varies with $M_{\rm halo}$, and follows a simple form:

$$\sigma_{M_{\star,\ \rm All}} = c \times \log M_{\rm Halo} + d \tag{2}$$

And, the slopes and normalizations of these two simple relations (a, b, c, d) are the four free parameters in this model.

The other aspects of this model, including the predictions of stellar masses within different radius, are simply inherited from the `UniverseMachine` model. We will "remap" the distributions of parameters using conditional abundance matching method (provided by the `UniverseMachine` software). The original parameters from the UM2 model will be labelled with Ori, while the "remapped" ones will be labelled as Remap.

To compare with observations, we make the assumption that, after the "remapping", we can use the $M_{\star,\ \rm Cen,\ Remap}$ and $M_{\star,\ \rm BCG,\ Remap}$ to match the observed $M_{\star,\rm Tot}$ and $M_{\star,10\ \rm kpc}$.

The "remapped" $M_{\star,\ \rm Cen,\ Remap}$ and $M_{\star,\ \rm BCG,\ Remap}$ are from:

$$M_{\star,\ \rm Cen,\ Remap} = M_{\star,\ \rm All,\ Remap} * (M_{\star,\ \rm Cen,\ Ori}/M_{\star,\ \rm All,\ Ori}) \tag{3}$$

$$M_{\star,\ \rm BCG,\ Remap} = M_{\star,\ \rm Cen,\ Remap} * (M_{\star,\ \rm BCG,\ Ori}/M_{\star,\ \rm Cen,\ Ori}) \tag{4}$$

Here:

- $M_{\star,\ \rm Cen,\ Ori}/M_{\star,\ \rm All,\ Ori}$: is the fraction of the stellar mass within a halo stored in the central galaxy and the ICL components. $M_{\star,\ \rm Cen,\ Ori}/M_{\star,\ \rm All,\ Ori}\sim 1.0$ means that central galaxy dominates the stellar mass of the halo, and satellites make little contribution.
- $M_{\star,\ \rm BCG,\ Ori}/M_{\star,\ \rm Cen,\ Ori}$: if we assume that the $M_{\star,\rm Cen}$ is the "true" total stellar mass of the central galaxy system, $M_{\star,\ \rm BCG,\ Ori}/M_{\star,\ \rm Cen,\ Ori}$ is the fraction of the stellar mass stored in the inner region of the central galaxy.

Describe the choices of models and how we perform the modelling (e.g., details about the MCMC run).

3.3 New Model: the $M_{\star,ins}$–$M_{\star,exs}$ plane

[Song: For discussion, we keep descriptions for both old and new models here. Directly mapping the $M_{\star,\rm BCG}$ and $M_{\star,\rm Cen}$ to our $M_{\star,10\ \rm kpc}$ and $M_{\star,\rm Tot}$ turns out to be problematic. As show in the Figure D2, the fraction of $M_{\star,\rm BCG}$ in $M_{\star,\rm Cen}$ from the `UniverseMachine` model shows a very different distribution compared to the fraction of $M_{\star,10\ \rm kpc}$ in $M_{\star,\rm Tot}$ from HSC observations. Too many `UniverseMachine` massive galaxies have very high $M_{\star,\rm BCG}$ fraction that will significantly mislead the model. `UniverseMachine` model now uses a very simple model to determine the fraction of stars that go into the ICL component after merger.

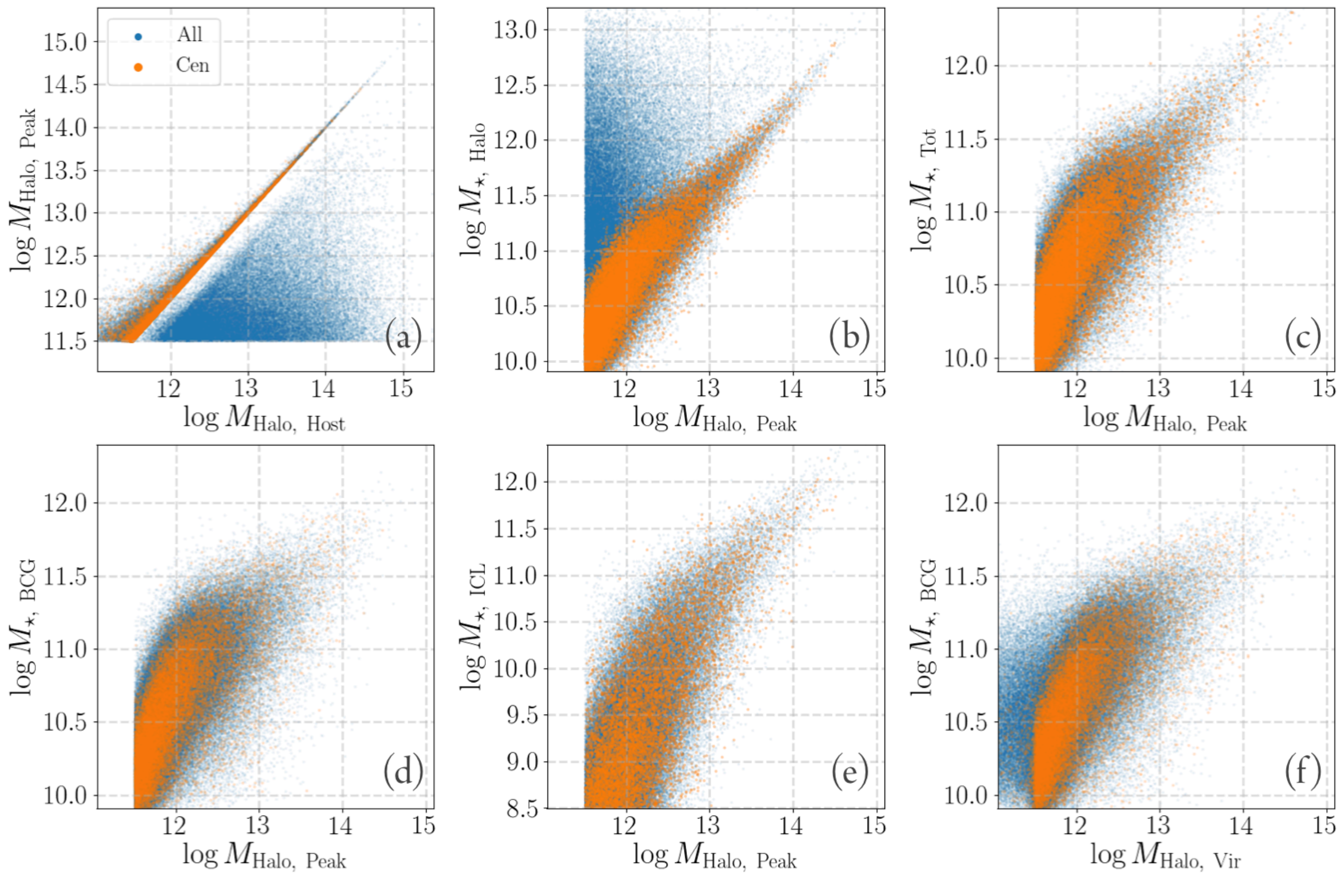

Figure 1. Basic properties of the UniverseMachine model. (a): The relationship between the host halo mass and the peak halo mass. (b): Relation between peak halo mass and the stellar mass of all galaxies within the halo; (c): Relation between the peak halo mass and the total stellar mass of the central galaxy system (BCG+ICL); (d): Relation between peak halo mass and the BCG stellar mass; (e): Relation between the peak halo mass and the ICL stellar mass; (f): Relation between the Virial mass of the halo and the BCG stellar mass. Central galaxies are highlighted using orange color.

So it is not surprising that there is mismatch with observation.]

Here we describe the basic structure of the model. The physical parameters used here are:

- $M_{\rm halo}$: Dark matter halo mass.
- $M_{\star,\rm All}$: Total stellar mass of all galaxies (central and satellites) in the dark matter halo.
- $M_{\star,ins}$: The stellar mass of the *in situ* component, which is the stars formed in the dark matter halo of the main progenitor.
- $M_{\star,exs}$: The stellar mass of the *ex situ* component, which is the stars accreted from merging with galaxies in other dark matter haloes.
- $M_{\star,\rm Gal}$: The total stellar mass of the galaxy, which is $M_{\star,ins}$+$M_{\star,exs}$.
- $M_{\star,\rm Tot}$: Observed stellar mass within a 100 kpc elliptical aperture.
- $M_{\star,10\ \rm kpc}$: Observed stellar mass within a 10 kpc elliptical aperture.

Using the `UniverseMachine` model based on the MultiDark simulation (referred to as the `UniverseMachine` model), we assume there is a simple log–linear relation between $M_{\rm halo}$ and $M_{\star,\rm All}$:

$$\log M_{\star,\rm All} = a \times \log M_{\rm Halo} + b. \tag{5}$$

The above relation has a log–normal scatter. The scatter varies with $M_{\rm halo}$, and follows a simple form:

$$\sigma_{\log M_{\star,\rm All}} = c \times \log M_{\rm Halo} + d. \tag{6}$$

The slopes and normalizations of these two relations (a, b, c, d) will be modelled as free parameters in our model. Using these assumptions, now we can 'remap' the `UniverseMachine` model to predict the observed aperture stellar masses using conditional abundance matching method. This process makes use of two mass fractions from the `UniverseMachine` model:

- $f_{\rm Cen,\ UM} = M_{\star,\ \rm Cen,\ Ori}/M_{\star,\ \rm All,\ Ori}$: is the fraction of stellar mass of the central galaxy to the total stellar mass within the halo. $f_{\rm Cen,\ UM} \sim 1.0$ means that central galaxy dominates the stellar mass budget of the halo.
- $M_{\star,\ \rm BCG,\ Ori}/M_{\star,\ \rm Cen,\ Ori}$: if we assume that the $M_{\star,\rm Cen}$ is the "true" total stellar mass of the central galaxy system,

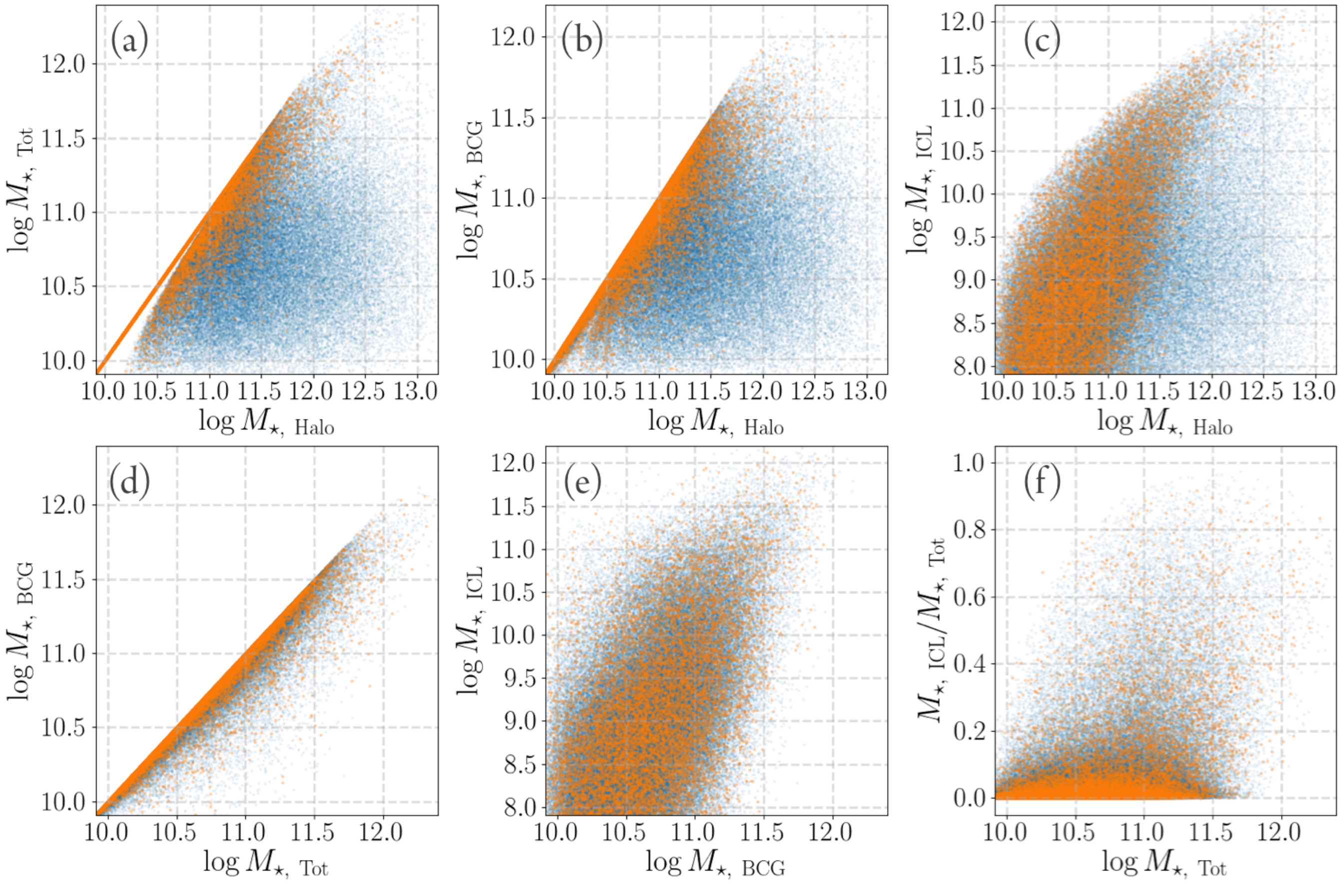

Figure 2. Relationships between different stellar masses in UniverseMachine mock catalogs. (a): All stellar masses in a halo and the total stellar mass of the central galaxy system (BCG+ICL); (b): All stellar mass in a halo and the stellar mass of the BCG; (c): All stellar mass in a halo and the stellar mass of the ICL component; (d): Total stellar mass of the central galaxy system and the BCG stellar mass; (e): BCG stellar mass and the mass of the ICL component; (f): Total stellar mass of the central galaxy system and the fraction of ICL mass. Central galaxies are highlighted using orange color.

$M_{\star,\ \rm BCG,\ Ori}/M_{\star,\ \rm Cen,\ Ori}$ is the fraction of the stellar mass stored in the inner region of the central galaxy.

In addition, we assume empirical relations between the modeled and observed stellar masses.

In the simplest form, we assume the observed $M_{\star,10\ \rm kpc}$ represent a constant fraction of the *in situ* component, and $M_{\star,\rm Tot}$ represents the total stellar mass of the galaxy:

$$\begin{aligned} M_{\star,10\ \rm kpc} &= f_{in-situ} \times M_{\star,in-situ}, \\ M_{\star,100\ \rm kpc} &= M_{\star,\ in-situ} + M_{\star,ex-situ}. \end{aligned} \tag{7}$$

We will "remap" the distributions of parameters using conditional abundance matching method. The original parameters from the `UniverseMachine` model will be labelled with Ori, while the "remapped" ones will be labelled as Remap.

To compare with observations, we make the assumption that, after the "remapping", we can use the $M_{\star,\ \rm Cen,\ Remap}$ and $M_{\star,\ \rm BCG,\ Remap}$ to match the observed $M_{\star,\rm Tot}$ and $M_{\star,10\ \rm kpc}$.

The "remapped" $M_{\star,\ \rm Cen,\ Remap}$ and $M_{\star,\ \rm BCG,\ Remap}$ are from:

$$M_{\star,\ \rm Cen,\ Remap} = M_{\star,\ \rm All,\ Remap} * (M_{\star,\ \rm Cen,\ Ori}/M_{\star,\ \rm All,\ Ori}) \tag{8}$$

$$M_{\star,\ \rm BCG,\ Remap} = M_{\star,\ \rm Cen,\ Remap} * (M_{\star,\ \rm BCG,\ Ori}/M_{\star,\ \rm Cen,\ Ori}) \tag{9}$$

4 RESULTS

4.1 Halo mass across the $M_{\star,\rm Tot}$-$M_{\star,10\ \rm kpc}$ plane

Key results: describe how does halo mass change across the $M_{\star,\rm Tot}$-$M_{\star,10\ \rm kpc}$ plane using the weak lensing signals.

Show similar trends in MassiveBlack-II simulation and in the `UniverseMachine` model.

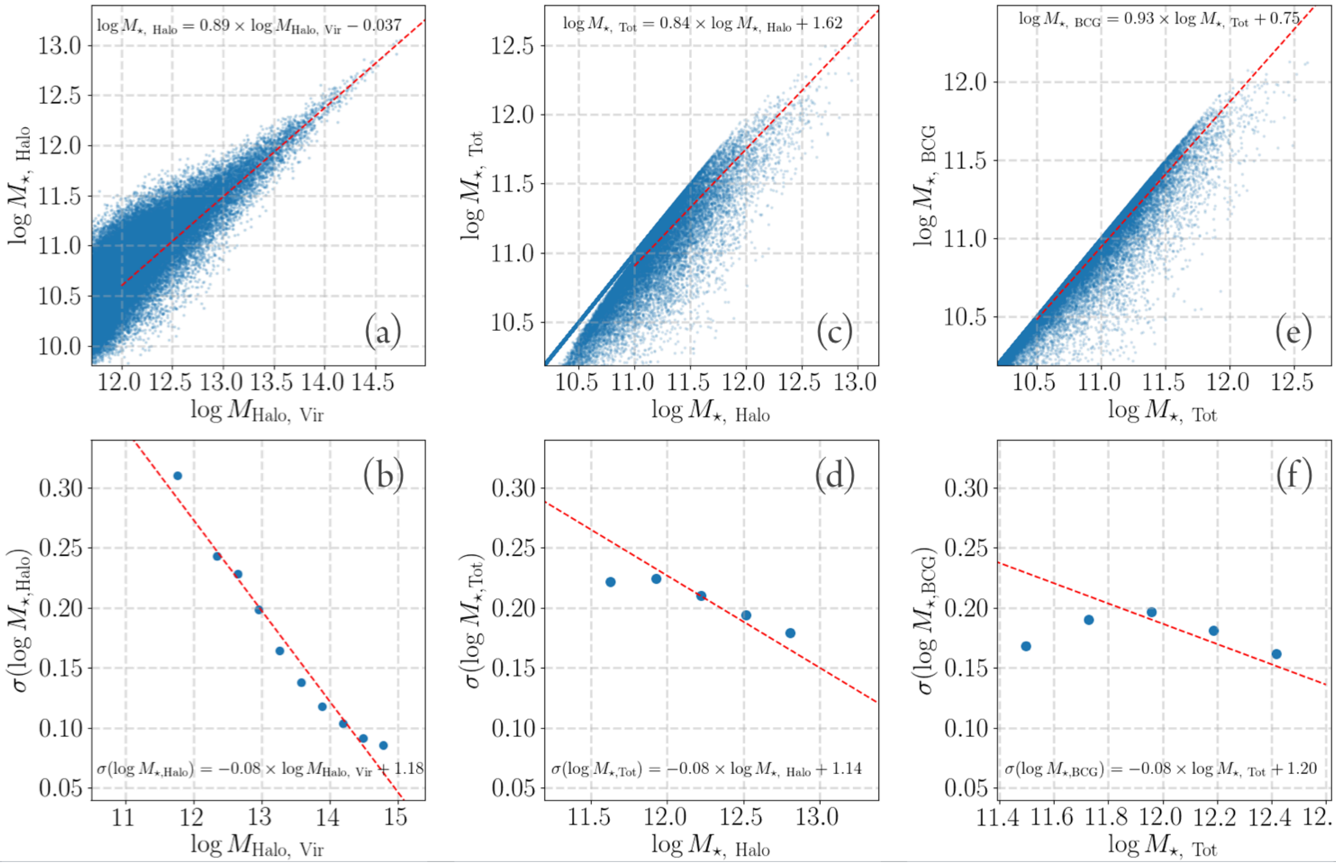

Figure 3. Simple log–log linear fit to some scaling relations in `UniverseMachine` mock catalogs. These relations are for central galaxies only. (a): Relation between the Virial halo mass and all stellar mass within a halo; (b) the scatters of total stellar mass in the halo in different halo mass bins. (c): Relation between all stellar mass in a halo and the total stellar mass of the central galaxy system (BGC+ICL); (d): the scatter of the total mass of the central galaxy. (e): Relation between the total stellar mass of central galaxy system and the BCG stellar mass; (f): scatter of BCG stellar mass in different total stellar mass bins. The red dashed-lines show the best–fit log–log linear relation. The functional forms of these best–fit relations are also displayed. The best–fit relations in panel (a) and (b) will be used as initial guesses in our fit.

4.2 Results from forward modelling method

Key results: describe how well the model can fit the stellar mass functions and weak lensing signals at the same time, and what can we learn from the best fit model.

5 DISCUSSION

- Caveats and limitations of this model
- Implications on selecting galaxies using their central properties
- Other scientific applications of this model

6 SUMMARY AND CONCLUSIONS

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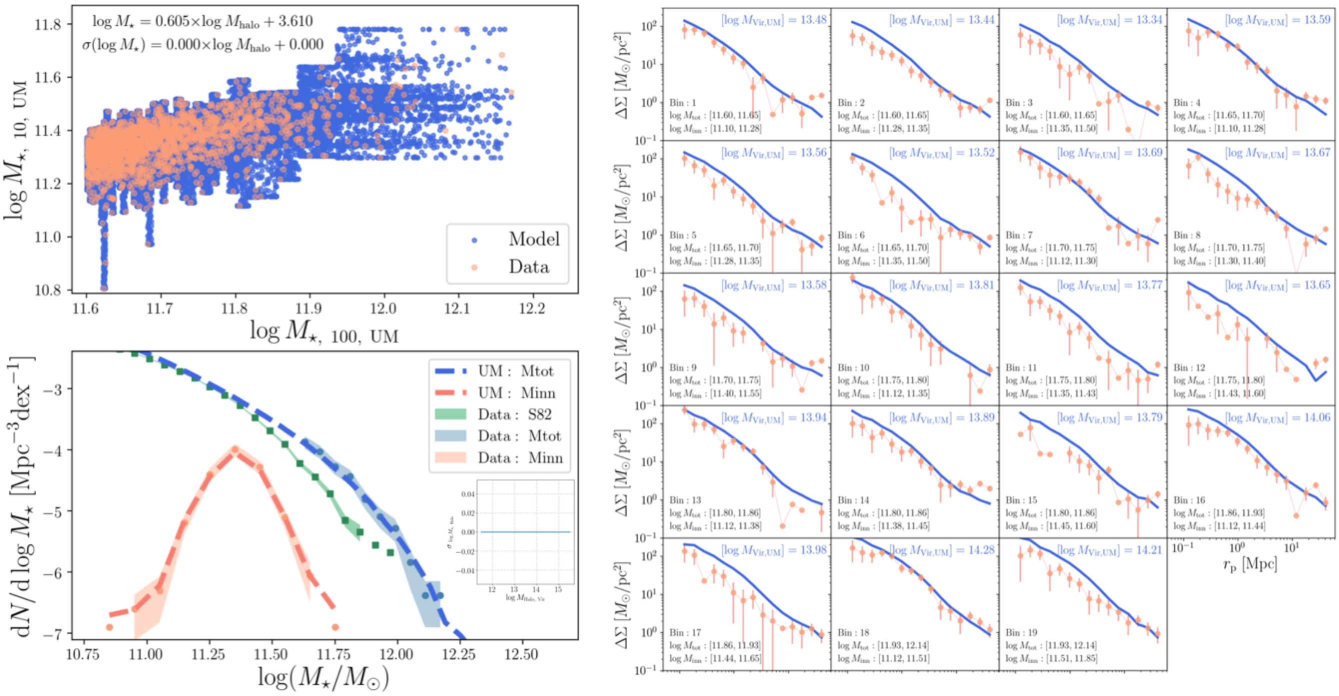

Figure 4. Overview of Model A (Left): Distributions of the predicted stellar mass within 100 and 10 kpc, and comparisons with the observed stellar mass functions. (Right): Comparisons between the predicted weak lensing mass density profiles in different stellar mass bins and the observed ones in the same bin.

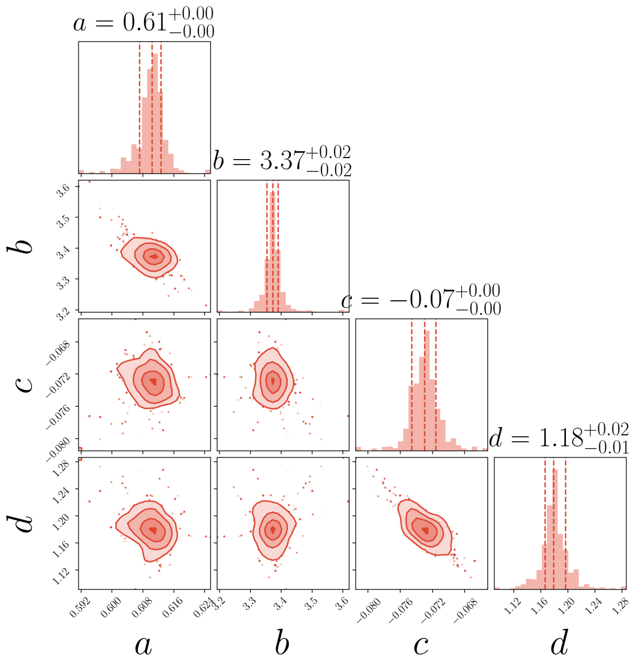

Figure 5. Corner plot for the best–fit parameters from the MCMC modelling.

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2-D plotting library for Python (Hunter 2007); `Astropy`, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013); `scikit-learn`, a machine-learning library in Python (Pedregosa et al. 2011); `astroML`, a machine learning library for astrophysics (Vanderplas et al. 2012); `IPython`, an interactive computing system for Python (Pérez & Granger 2007); `sep` Source Extraction and Photometry in Python (Barbary et al. 2015); `palettable`, color palettes for Python; `emcee`, Seriously Kick-Ass MCMC in Python; `Colossus`, COsmology, haLO and large-Scale StrUcture toolS (Diemer 2015).

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APPENDIX A: DETAILS ABOUT SAMPLE SELECTION

APPENDIX B: DETAILS ABOUT SED FITTING

APPENDIX C: DETAILS ABOUT APERTURE MASS ESTIMATES

APPENDIX D: DETAILS ABOUT THE `UniverseMachine` MODEL

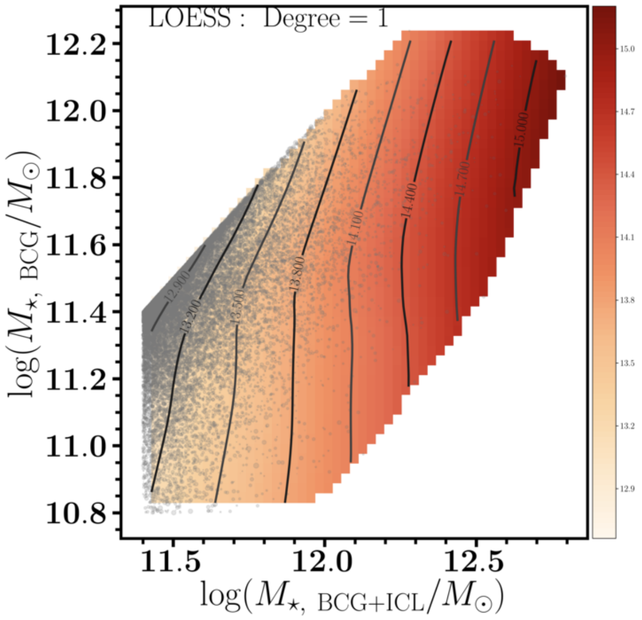

Figure D1. The relationship between the total stellar mass of the central galaxies and the BCG stellar masses from the `UniverseMachine` mock catalogs. The continuous color surface shows the smooth maps of halo mass using degree= 1 `LOESS` method (Locally Weighted Regression, Cleveland 1979, Cleveland & Devlin 1988, Cappellari et al. 2013). The 'iso–M_{halo}' curves are overlaid as well.

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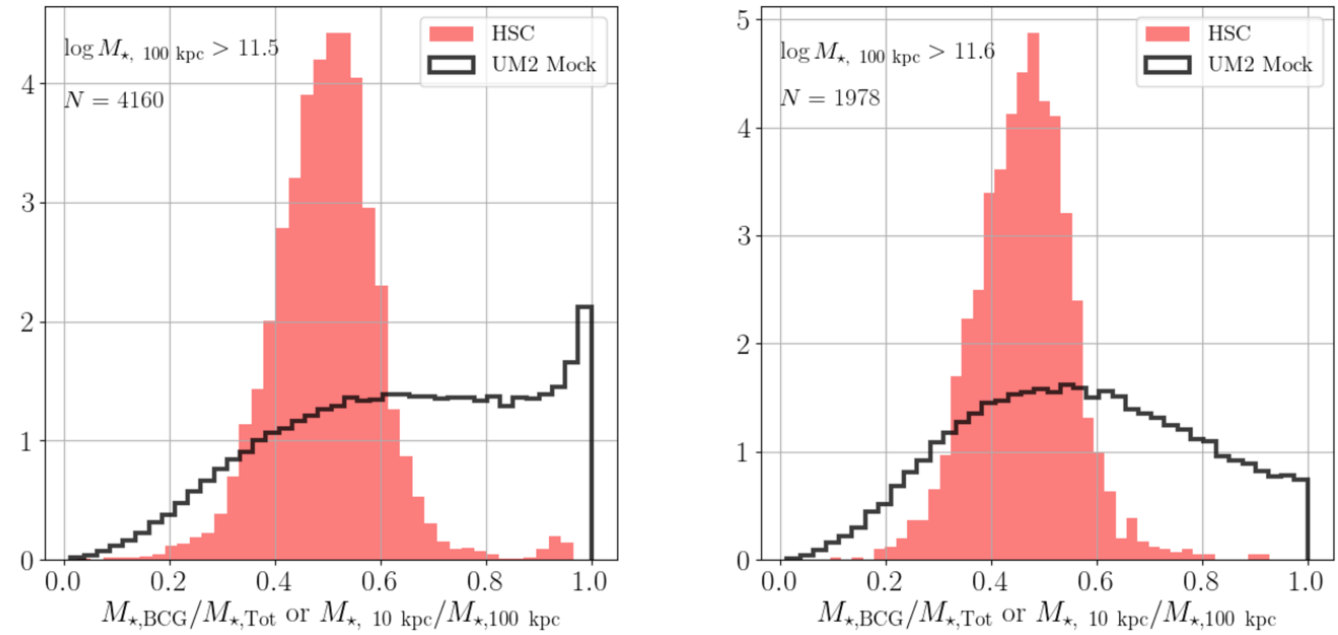

Figure D2. Comparisons between the fraction of BCG stellar mass in the BCG+ICL central galaxy system from UniverseMachine mock catalog and the fractional ratio between stellar mass within 10 and 100 kpc from HSC observations. The HSC data are at $0.3 < z < 0.5$. We pick two subsamples with the stellar mass within 100 kpc apertures larger than $10^{11.5} M_{\odot}$ (Left panel, 4160 galaxies) and $10^{11.6}$ (Right panel, 1978 galaxies) solar mass. We pick massive galaxies from the `UniverseMachine` mock catalogs above the same volume density. We can see that the two distributions are quite different. The `UniverseMachine` distributions have a higher average fraction and much larger scatter. And there appears to be a population of central galaxies in `UniverseMachine` with no ICL component at all, especially in the left sample.