# The changing relationship between galaxy stellar mass and dark matter halo mass since z = 2


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## Introduction

**Relating galaxy properties to those of their dark matter halos**

If we wish to understand galaxy formation in a cosmological context it is crucial that we observationally relate the properties of galaxies to those of the dark matter halos in which they reside. This has been done very effectively in the local universe (e.g. Li et al. 2006, Zhehavi et al. 2011) and even up to z = 1 (e.g. Zheng et al. 2007), but little is known at z > 1 where the star formation rate is peaking and massive galaxies seem to be forming most of their mass.

**Galaxy clustering**

One highly effective means of relating galaxies to their parent dark matter halos is through an analysis of their clustering. The more massive a halo the more strongly it clusters; thus, since the dark matter is dominating the mass distribution one can infer that a more clustered galaxy population lives in more massive halos.

**Halo occupation distributions**

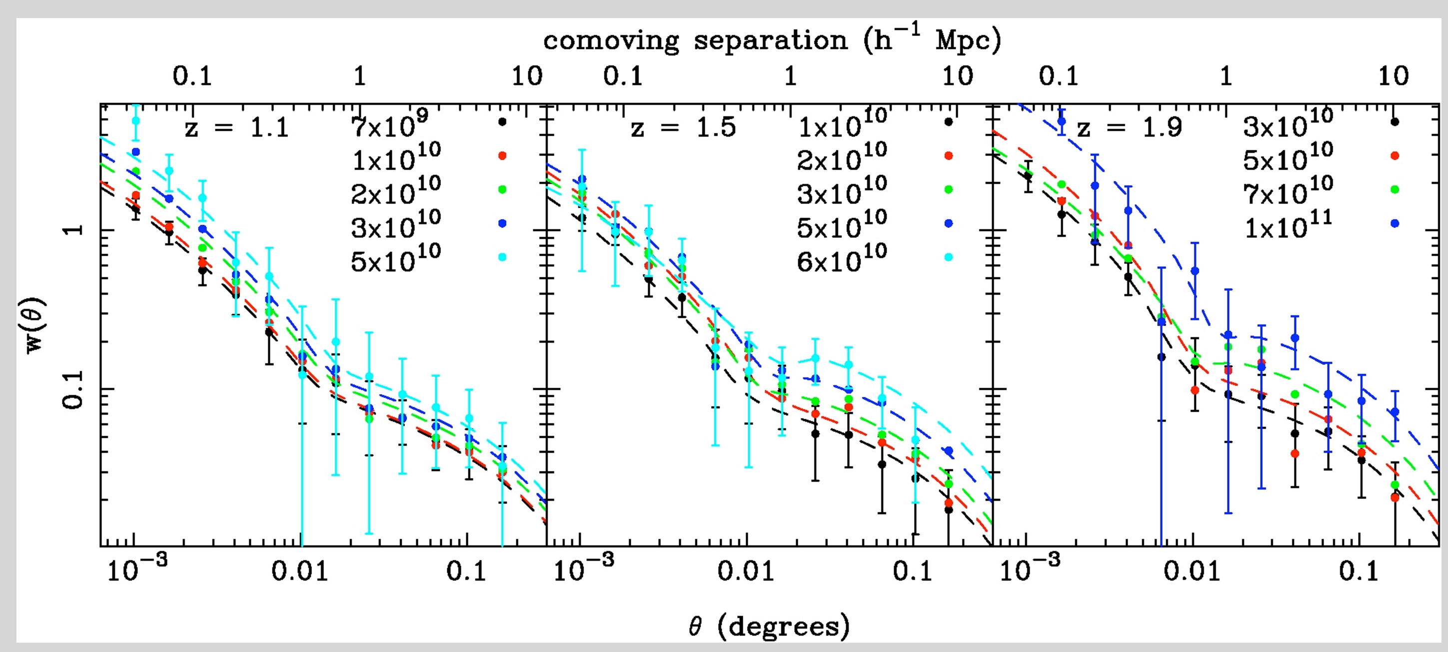
It is possible to accurately model the clustering and space density of galaxies by placing galaxies in dark matter halos following a simple yet flexible analytic form that depends on the mass of the halo. These analytic forms are known as halo occupation distributions (e.g. Cooray & Sheth 2003). It is assumed that galaxies in halos are either centrals or satellites with different mass thresholds determining when halos begin to host a central or satellite galaxies.


We have measured the stellar mass dependent clustering of massive galaxies at 1 < z < 2 demonstrating that the trend whereby the clustering amplitude increases as the stellar mass increases extends to these early times. By fitting halo models to these clustering measurements, along with similar measurements at z~0.1, we are able to determine how the relationship between galaxy stellar mass and dark matter halo mass evolves from z = 2 to the present. Using these relationships we demonstrate that the most efficient halo mass for forming stars increases at higher redshift (`halo downsizing') and that there exists a strong dependence of the stellar mass growth rate of galaxies on both their stellar and halo masses.


## Stellar mass dependent clustering at 1 < z < 2

**Angular 2 point correlation function**

The clustering amplitude increases as the stellar mass threshold increases in each of the redshift intervals. The amplitude is significantly higher on both large and small scales.

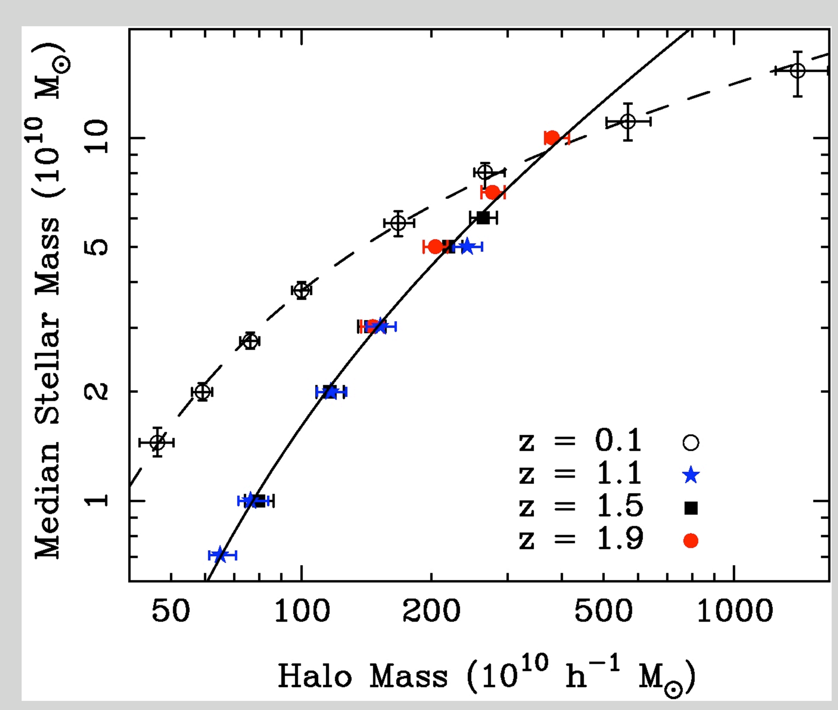



**Halo model fits**

The dashed lines in the plot above show the best fitting halo model to each of the clustering measurements.

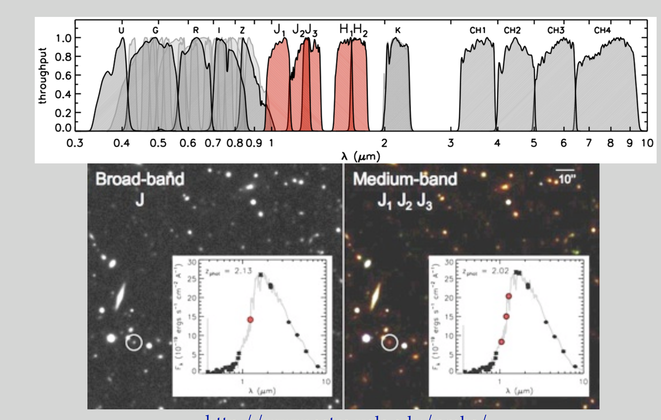
**Stellar mass - dark matter halo mass relation**

The best fitting halo occupation distributions, fit to both the clustering and space density of our mass limited samples, allow us to easily determine how the stellar mass of central galaxies depends on the mass of the halos in which they reside. The plot shows this relation derived from the fits to the 1 < z < 2 clustering measurements from the NMBS. Also shown is the same relation derived from fits to the clustering of galaxies in the SDSS at different stellar mass thresholds.




## Data

### Newfirm Medium Band Survey




The NEWFIRM Medium Band Survey (NMBS) (Whitaker et al., 2011) includes medium-band NIR (J1,J2,J3,H1,H2,K), optical broad (ugriz) and medium bands, IRAC imaging and MIPS 24μm data over 4.4 deg$^2$ in the COSMOS and AEGIS fields. The inclusion of the NIR medium band filters greatly increases the photometric redshift accuracy at 1.3 < z < 3 by a factor of ~4 to $\sigma_z/(1+z) < 0.02$.

**Photo-z and SED fitting**

Photometric redshifts for all galaxies were calculated using the EAZY code (Brammer, van Dokkum, & Coppi 2008). Stellar masses were computed using FAST (Kriek et al. 2009), from Bruzual & Charlot (2003) models with Solar metallicity and a Chabrier (2003) IMF, closely matching the stellar mass determination for the SDSS samples.

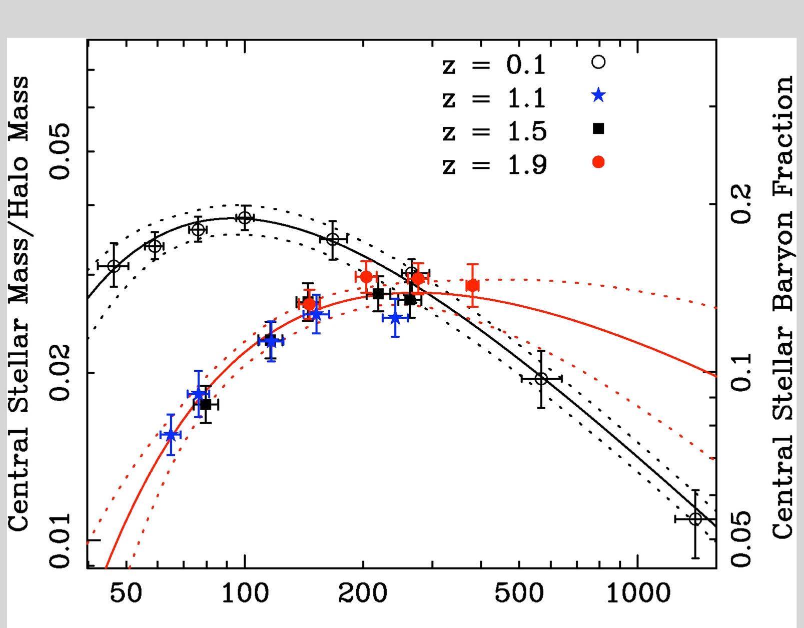
**Mass limited samples**

We defined three volume limited samples, complete in stellar mass, with mean redshifts 1.1, 1.5 and 1.9 and stellar mass > $7\times10^9$, $1\times10^{10}$, and $3\times10^{10}$ M⊙ respectively. These samples were split further at differing stellar mass limits.

### Local Galaxies -- SDSS

For a local reference sample we use publicly available catalogs from the SDSS DR7 (Abazajian et al. 2009). We define several volume limited samples complete in stellar mass including galaxies from 0.04 < z < 0.115. These samples are derived from the large scale structure samples of the NYU-Value Added Galaxy Catalogue (Blanton et al. 2005). Stellar masses are taken from the catalog provided by the MPA-JHU group (http://www.mpa-garching.mpg.de/SDSS/DR7/), which used of the Bruzual and Charlot (2003) SPS models.

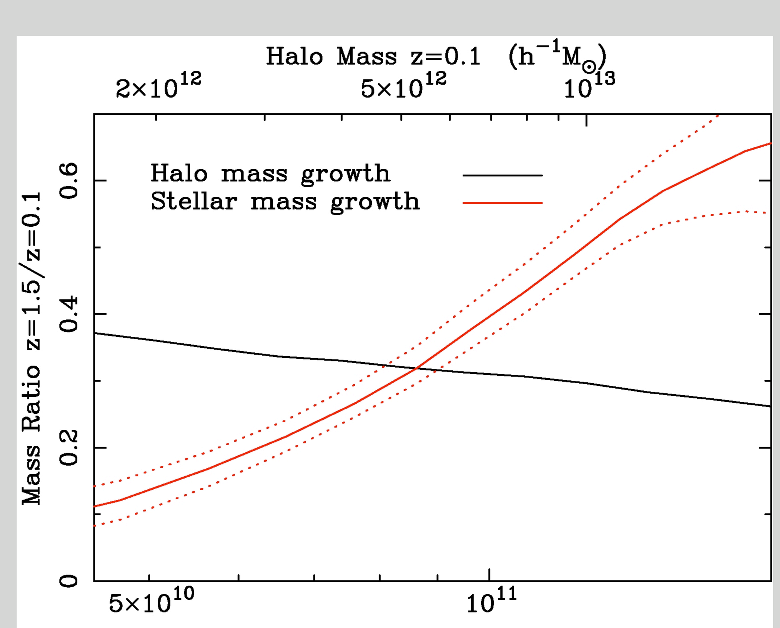
## The dependence of star formation efficiency on dark matter halo mass




**Star formation efficiency and halo downsizing**

If the fraction of baryons is constant then the ratio between the median central galaxy stellar mass and halo mass reveals the fraction of baryons which have been converted into stars in the central galaxy. This star formation efficiency peaks in higher mass halos at z~1.5 (~3 x $10^{12}$ $h^{-1}$ M⊙) than in the local universe (~9x$10^{11}$ $h^{-1}$ M⊙). This is an example of halo downsizing, whereby the halos which are forming stars most efficiently move to lower masses at lower redshifts.

## The dependence of stellar mass growth on stellar and dark matter halo mass




The fraction of stellar mass in place in galaxies at z~1.5 decreases from over 50% for galaxies with masses >$10^{11}$ M⊙ at z=0.1 to just over 10% for galaxies with masses < 5x$10^{10}$ M⊙ at z=0.1. At the same time the halos in which the galaxies reside at z=0.1 have between 25 and 35% of their mass in place at z=1.5 with the lowest mass halos growing the least over this time.

**Linking galaxies from high to low redshift**

By combining the measured relationships between the median stellar mass of central galaxies and halo mass at redshifts 0.1 and 1.5 we can estimate the typical stellar mass growth and how it depends on both halo and stellar mass (Zheng et al. 2007). For a halo of a given mass at z = 0.1 we use the halo merger tree algorithm of Parkinson et al. (2008) to determine the median halo mass of it's most massive progenitor halo at z = 1.5. We can then compare the typical stellar mass of a central galaxy in the halo at z = 0.1 with the stellar mass of a central in its most massive progenitor halo. In an average sense we can then determine how the mass has changed from z = 1.5 to the present day.

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