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THE ENVIRONMENTAL DEPENDENCE OF STRUCTURES FOR MASSIVE GALAXIES FROM THE HYPER SUPRIME-CAM SURVEY

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ABSTRACT

TODO: Place holder; This is the abstract used for giving a talk.
Under the most popular formation scenario, the structures of massive central galaxies depend on environment at fixed stellar mass due to different assembly histories shaped by their host halos. Yet, clear evidence of such effect is still lacking. Using deep, multi-band images for a large sample of massive galaxies at 0.2 < z < 0.5 from the Hyper Suprime-Cam (HSC) survey, we discover subtle, but systematic structural difference for massive galaxies in low and high mass haloes. The differences are consistent with richer merger history in more massive halos. We show that the average profiles of mass, shape, and color, along with relations among masses within different radius (as proxy of mass assembled at different time) can help us gain more insights of their assembly history, and the weak lensing analysis enabled by HSC survey further helps us connect the differences we find to the average halo properties.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: photometry — galaxies: structure — galaxies: surveys

1. INTRODUCTION

Scientific Background

- Massive galaxies are important cosmic probe and unique labs to study galaxy evolution.
- Briefly explain why massive early-type galaxies are important through the difficulties of stellar-halo mass relation and stellar mass function at the high-mass end.
- Brief summary of the current understanding of their cosmic assembly history.
- Explain why we should care about the environment, and why we expect to see some environemtnal dependence in the structure and other properties of massive galaxies.
- Brief review of the current observations. It is still not clear whether there is a clear environmental dependence.

Observational difficulties (a.k.a Why we need HSC)

- Explain why it is important to study the mass distribution of massive galaxies out to large physical radius; and, given their unique light profiles, why it is more difficult to study them compared to late-type galaxies.
- Very brief summary of past observational efforts, and why they are not good enough (Not enough number of really massive galaxy; Shallow images; Background subtraction issue; and stacking analysis can be dangerous as while)

Basica idea of this work

- Here we take advantages of the ambitious Hyper-Suprime camera survey....

The paper is organized as follows. Section 2 gives a brief overview of the HSC observation and data reduction. We will also summarize the process of sample selection. In Section 3, we will describe the method for deriving the stellar mass surface density profile. The main results are summarized in Section 4. Section 5 provides discussions of the assumptions used in this work, the potentially interesting physical implications, and several future improvements, ending with a summary in Section 6.

All the magnitudes used here are in AB system (REF). Within this work, we assume $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. OBSERVATIONS AND SAMPLE SELECTION

2.1. *The Hyper Suprime-Cam Survey*

The Subaru Strategic Program (SSP, REF) makes use of the new prime-focus camera, the Hyper Suprime-Cam (HSC; REF: Miyazaki et al. 2012), on the 8.2-m Subaru telescope at Mauna Kea. Taking advantage of the large field of view (FoV; 1.5 deg in diameter) of HSC, this ambitious multi-layer photometric survey will cover $\sim$ 1400 deg^2 of sky in 5 broad bands (g r i z Y) to the depth of $r \sim 26$ mag in the `WIDE` part in the next few years. This work is based on the internal data release `S15B`, which covers $\sim$ 100 square of degree of sky in all 5-band to the required depth of `WIDE` survey. The regions covered by this release are overlapped with several previous spectroscopic survey (e.g. SDSS/BOSS REF; GAMA REF).

The data are processed with `hscPipe 4.0.1`, a derivative of the Large Synoptic Survey Telescope (LSST) pipeline (REF: Ivezic et al. 2008, Axelrod et al. 2010), modified for use with Suprime-Cam and Hyper Suprime-Cam. `hscPipe` first bias subtract, flat field, model background, and perform object detection and measurement on the single exposure data. Then,

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different exposures are warped onto a common World Coordinate System (WCS) and combined into final images with improved signal-to-noise ratio (SNR) after astrometric and photometric calibration. The pixel scale of the combined images is 0.168″. The photometric calibration is based on data obtained from the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) 1 imaging survey (REF: Schlafly et al. 2012, Tonry et al. 2012, Magnier et al. 2013). To achieve consistent deblending and photometry across all bands, the `hscPipe` will perform multi-band post-processing on the combined images. The footprints and peaks of detected sources on each band will be merged into a single catalog. This consistent set of peaks and footprints is used as starting point for deblend and measure objects on the combined images of each band. These measurements are then merged into a reference catalog. After fixing the centroids, shape, and other non-amplitude parameters of every object in this catalog, `hscPipe` will derive forced photometry measurements at each band. Details of `hscPipe` and the multi-band processing method will be presented in REF(Bosch et al. 2017?).

In Figure 1, we compare the false color (`gri`) images of three nearby massive ETGs from both SDSS and HSC surveys. The images are generated using similar scaling and color schemes, and clearly demonstrate HSC's capability to reach to low surface brightness domain. In *i*-band (ignoring the slight difference in filter response curve), the HSC `WIDE` image is 2.5-3.0 magnitude deeper than SDSS on average. This gives us huge advantage in exploring the outskirt of massive ETGs given their extended, shallow outer surface brightness profiles.

Motivated by the requirement of weak lensing analysis, the *i*-band data typically has the best seeing in all five bands (the median seeing is around FWHM$\sim 0.8''$). Therefore, we will mostly use the *i*-band images to study the structure of galaxies.

2.2. *Massive central galaxies in different environments*

The main scientific goal of this work is to investigate mass assembly history of massive, central ETGs, and its dependence on environments (or host dark halo mass) through their the spatial distribution of stellar mass.

To achieve this goal, we will select $\log(M_{\star}/M_{\odot})> 11.5$ massive central galaxies within host halo mass larger and smaller than $\log(M_{\rm Halo}/M_{\odot})= 14.0$ at $0.2 < z < 0.5$. As both $M_{\star}$-$M_{\rm Halo}$ relation and stellar mass function are still quite uncertain at $\log(M_{\star}/M_{\odot})> 11.5$, it is of great interest to investigate the structure of galaxies in this region carefully. And, this stellar mass cut can greatly reduce the contamination of satellites (e.g. REF: van Uitert et al. 2016). Meanwhile, under the adopted cosmology, $1''$ equals 3.3 and 6.1 kpc at redshit 0.2 and 0.5. Hence, our redshift bin enables us to reliable measure the total stellar mass within the inner 5 to 10 kpc (where the "in-situ" component should still dominates) of massive galaxies at the high redshift end assuming the typical seeing of data. At the same time, the depth of the data still allows to study the very outskirt (~ 100 kpc) of these galaxies at $z\sim 0.5$. Also, such limits on mass and redshift ensure us a sizable sample while let us safely ignore any significant structural evolution (no star formation, lower merger rate et al. . e.g. REF).

Based on recent constraints of $M_{\star}$-$M_{\rm Halo}$ relation (e.g. REF), above $\log(M_{\star}/M_{\odot})= 11.5$, there is a large scatter of halo mass at fixed stellar mass. At $\log(M_{\rm Halo}/M_{\odot})< 14.0$, these massive galaxies are mostly the centrals of small groups; while at $\log(M_{\rm Halo}/M_{\odot})> 14.0$, they start to become the centrals of very massive groups and galaxy clusters. Limited by the sample size and the capability of measureing halo mass for individual central galaxy, we will simply separate the sample into two broad halo mass bins with the help of the `redMaPPer` cluster catalog [5] (`v5.10`, e.g. REF: Rykoff et al. 2014; Rozo et al. 2015b). These clusters are selected from the SDSS DR8 photometric data using overdensity of red-sequence galaxies. For each cluster, the catalog provides robust estimations of photometric redshift z_{Λ} and richness Λ, along with the best candidate of the central galaxy (the one with the highest central probability `P_CEN`). Information about the identified member candidates is also provided separately. Please see Rozo et al. (2014, 2015a, 2015b) for more details about the performance of the `redMaPPer` cluster catalog. Several works (e.g. Li et al. 2015; Saro et al. 2015; Farahi et al. 2016; Simet et al. 2016) have tried to calibrate the $M_{200c}-\Lambda$ relation using different methods. Despite the slightly different calibrations derived, it is safe to assume that most clusters identified by `redMaPPer` ($\Lambda > 20$) have $\log(M_{200c}/M_{\odot}) \geq 14.0$. Considering the typical uncertainty of richness, and the fact that `redMaPPer` catalog starts to become incomplete toward low richness ($\Lambda < 40$) end at $z > 0.33$, we will focus on the $\Lambda > 30$ clusters in this work. Based on the calibrations from Farahi et al. (2016) or Simet et al. (2016), such richness cut gives us haloes with $M_{200c} \geq 1.56\pm0.35\times10^{14}M_{\odot}$ or $M_{200c} \geq 1.60\pm0.11\times10^{14}M_{\odot}$. Therefore, `redMaPPer` can provide us a sample of massive central galaxies in $\log(M_{\rm Halo}/M_{\odot})\geq 14.0$ haloes. And, we assume that, in the same footprints and redshift range, the $\log(M_{\star}/M_{\odot})\geq 11.5$ galaxies outside `redMaPPer` clusters are most likely to be the central of $\log(M_{\rm Halo}/M_{\odot})< 14.0$ haloes.

According to Leauthaud et al. (2016), all $0.2 < z < 0.5$ and $\log(M_{\star}/M_{\odot})\geq 11.5$ galaxies should have $i_{\rm SDSS,cModel} \leq 21.0$ mag. Ignoring the tiny difference in response curves between SDSS and HSC *i*-band filters, we started by selecting all galaxies with $i_{\rm HSC,cModel} \leq 21.5$ in the regions that are covered in all five filters, and have already reached the expected depth of `WIDE` survey. The details of the HSC `cModel` photometry, and its performence will be described in Bosch et al. in. prep. It is quite similar to the SDSS `cModel` in principle as it also fits the total flux of an object using a combination of de Vaucouleur and exponential components after the PSF convolution is considered. In our selection, we require well defined centroids and `cModel` magnitude in all five bands. **[Song: Should we discuss the impact of failed cModel photometry?]** A series of quality control cuts are applied to remove objects that are affected by saturation, cosmic ray, other optical artefacts. After these cuts, a total number of N1 galaxies left in the sample () **TODO: Finish this part** (This sample will be referred as `phoAll`).

We match this sample with the central galaxies of `redMaPPer` catalogs using a $2.0''$ radius, and it results in N2 galaxies. A small fraction of `redMaPPer` centrals in the our footprints do not have matched object in our sample due to severe contamination from optical artefacts or bleeding trails from saturated objects. And slight change of the mathcing radius has no impact of this sample. For galaxy in this sample (will be referred as `redBCG`), the photometric redshift of the cluster is available for each of them; while for of them, the spectroscopic redshift from SDSS DR8 is also provided by `redMaPPer` catalog when available.

[5] See: http://risa.stanford.edu/redmapper/

For the vast majority of galaxies that are not the centrals of very massive haloes, we need other sources for their redshfit estimations. Although there has been many efforts for deriving photometric redshift (photo-z) using HSC five-band photometry, it is still a working progress now, and its performence at $z \leq 0.5$ is expected to be less satisfying due to the lack of information at the shorter wavelength side of the 4000 break. Therefore, we will only rely on external spectroscopic redshifts (spec-z) for this work. The HSC database compiles a catalog of external spec-z for this data release by matching the detected objects with public data of several spectroscopic surveys (e.g. SDSS/BOSS REF; GAMA REF; PRIMUS REF; et al.). Duplicated matches from different sources are merged through interal matching using 0.5″ radius.

We match the `phoAll` sample with this external spec-z catalog using a 1.0″ radius, and it leads to N3 results. There are N4 objects at $0.2 \leq z \leq 0.5$. The `redBCG` sample is also matched in the same way. For ... **TODO: Finish it...**

Selection of the `PHOTO` sample

- `PRIMARY` detection: In the inner region of the `Tract` and Patch; has no `CHILD`.
- Require the galaxy to be detected in all 5-band
- For *i*-band detection, we require the object is covered by at least 4 `Visit`.
- Has useful `cModel` photometry in all 5-band
- *i*-band `cModel` magnitude brigther than 21.0 mag (justify this later
- Has to be extended object.
- Has reliable central position and shape using SDSS algorithm
- Typical quality cuts in *griz*-band.

Selection of the `SPECZ` sample

- Brief summary of the HSC spec-z catalog.
- Internal catalog match results in 121998 galaxies
- Brief break down of the spec-z sample; Most of the spectroscopic redshift come from SDSS/BOSS and GAMA survey
- Only keep objects at $z < 0.6$ **TODO: Justify this later**

2.3. *Central galaxies of $\Lambda > 20$ haloes using the `redMaPPer` clusters*

To select the central galaxies of cluster-level dark matter haloes, we make use of the `redMaPPer` cluster catalog [6].

Match to the `redMaPPer` catalog

- For this work, we use the `redMaPPer` catalog based on SDSS DR8 photometry. **TODO: Need some explanation**
- Match with the `PHOTO` sample using a 1.0″ matching radius, results in 704 clusters. (Justify this matching radius)
- Select the `redMaPPer` clusters at $z < 0.6$.
- There is a small population of central galaxies from `redMaPPer` that are within the HSC footprint, but does not have matched photometry, briefly explain them

2.4. *Galaxies in $\Lambda < 20$ haloes*

- Remove the galaxy that is close to any `redMaPPer` cluster
- Remove the galaxy that is close to any bright star **TODO: Justify why we do not do this to the `redMaPPer` central sample**

3. DATA REDUCTION

3.1. *1-D surface brightness profile*

Basica ideas

- Briefly explain that 1-D surface brightness profile is a very old fashion, but robust and straightforward way to describe the light or mass distribution of a galaxy. Although it is not exactly "model-independent", it indeed has the advantages of not easily affected by complex substrctures within the galaxy comparing with the more popular 2-D modelling method.
- Due to the uniquely extended nature of the light distributions of these massive ETGs, it is still unclear which is the most appropriate 2-D model for them (Can not be well described by 1-Sérsic model).

Step by step description

- Generation of cutout image in multiple bands:
  1. Choice of image size: make sure that the cutout covers out to at least 500 kpc from the center of the galaxy.
  2. Also generate the bad pixel masks, and the reconstructed PSF model for the galaxy center.
- Generation of object masks:
  1. Briefly explain why we need to our own photometry instead of just using the cModel results from the HSC pipeline.
  2. We need two kinds of masks: mask of all objects that will be used to measure the sky value; mask of objects expect for the central galaxy we want to derive surface brightness profile. Briefly describe their requirements.
  3. Object detection using `SEP` Python library.
- **Re-measurement and correction of sky background**:

3.2. *Average mass-to-light ratio*

- Briefly explain the method to convert surface brightness profiles into mass density profile, focusing on the key assumptions.
- Describe the SED fitting process.
- Briefly discuss the impact of choices of SSP model, IMF, priors of parameters for SED fitting

[6] See: http://risa.stanford.edu/redmapper/

3.3. *Basic properties of the sample*

- Compare stellar mass from integration of 1-D profile and the `cModel` photometry
- Stellar mass, redshift, K-corrected color distributions.
- Red sequence properties
- Potential "contaminations" from disc galaxies

TODO: Justify why we can assume most very massive galaxies in $\Lambda < 30$haloes are central galaxies

4. RESULTS

4.1. *Impact of deep photometry on the luminosity and stellar mass function*

4.2. *Comparison of stellar mass density profiles*

Brief summary of the process of sample matching

4.2.1. *Using stellar mass derived from the GAMA survey*

4.2.2. *Using stellar mass within 10 kpc aperture*

4.2.3. *Using stellar mass within 100 kpc aperture*

4.3. *Relations between stellar mass within different physical apertures*

4.4. $M_* - R_{50}$ *relation*

5. DISCUSSION

5.1. *Implications on assembly history of massive galaxies*

Comparison of mass profiles with previous studies at high redsfhit

5.2. *Ellipticity profiles*

5.3. *The impact of M/L gradient*

5.4. *Massive satellites of the $\Lambda > 20$ haloes*

[Song: TBD: optional]

5.5. *Connection and difference with the Intra-Cluster Light*

5.6. *Future improvements*

1. Improvements of HSC data reduction: better sky modelling; `redMaPPer` clusters using HSC photometry.
2. Comparison with 2-D image modelling method.
3. "Correct" the PSF smeearing effect at the center with the help of residual correct 2-D model.

6. SUMMARY

The Hyper Suprime-Cam (HSC) collaboration includes the astronomical communities of Japan and Taiwan, and Princeton University. The HSC instrumentation and software were developed by the National Astronomical Observatory of Japan (NAOJ), the Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), the University of Tokyo, the High Energy Accelerator Research Organization (KEK), the Academia Sinica Institute for Astronomy and Astrophysics in Taiwan (ASIAA), and Princeton University. Funding was contributed by the FIRST program from Japanese Cabinet Office, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Japan Society for the Promotion of Science (JSPS), Japan Science and Technology Agency (JST), the Toray Science Foundation, NAOJ, Kavli IPMU, KEK, ASIAA, and Princeton University.

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy. The SDSS-III web site is http://www.sdss3.org. SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, University of Cambridge, University of Florida, the French Participation Group, the German Participation Group, the Instituto de Astrofisica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

TODO: Full acknowledgement

- Acknowledgements for Kevin and Alexie's funding
- Acknowledgements for the Python libraries

APPENDIX

A. EXTRACTION OF 1-D SURFACE BRIGHTNESS PROFILE

B. DERIVE AVERAGE MASS-TO-LIGHT RATIO USING `ISEDFIT`

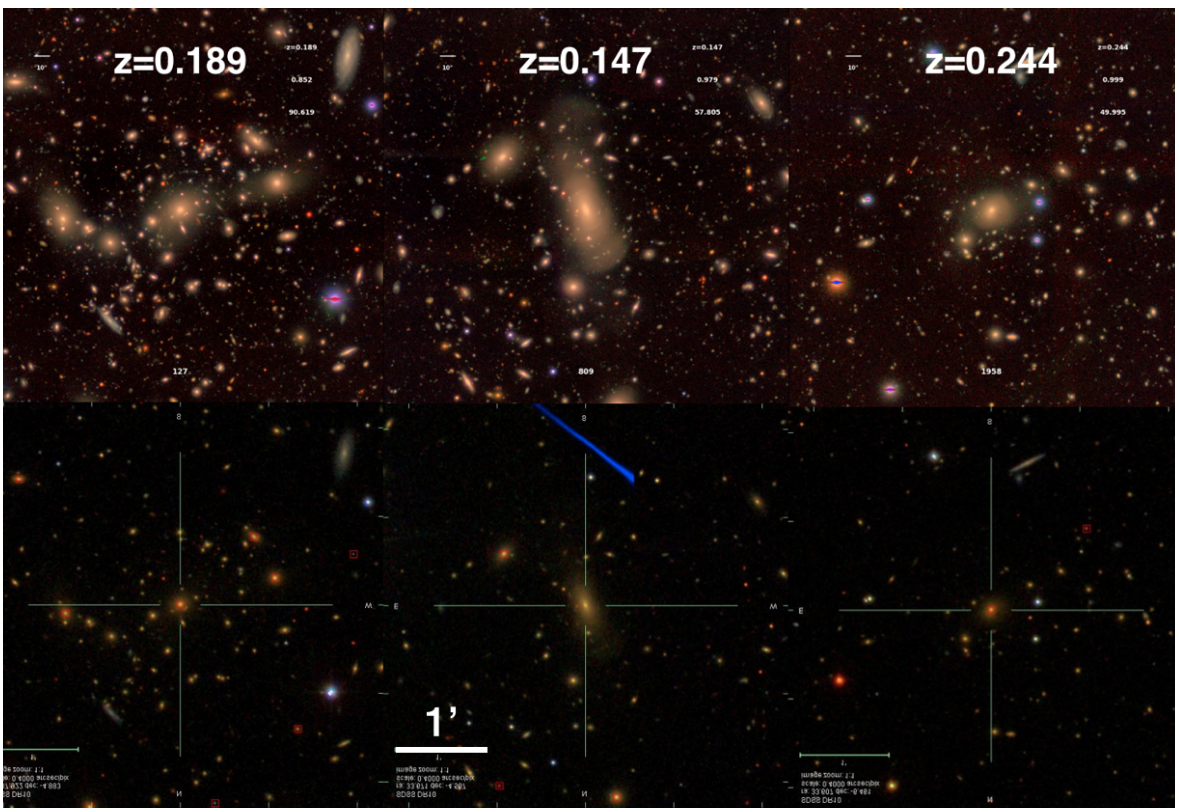

FIG. 1.— Figure.1**TODO: Caption**

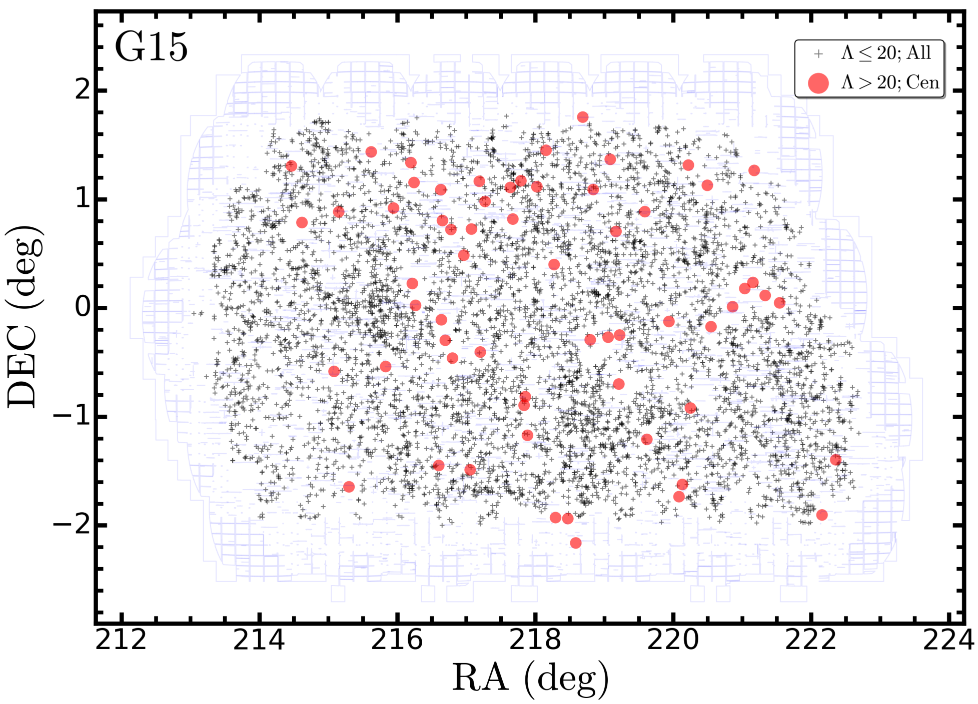

FIG. 2.— Figure.2**TODO: Caption**

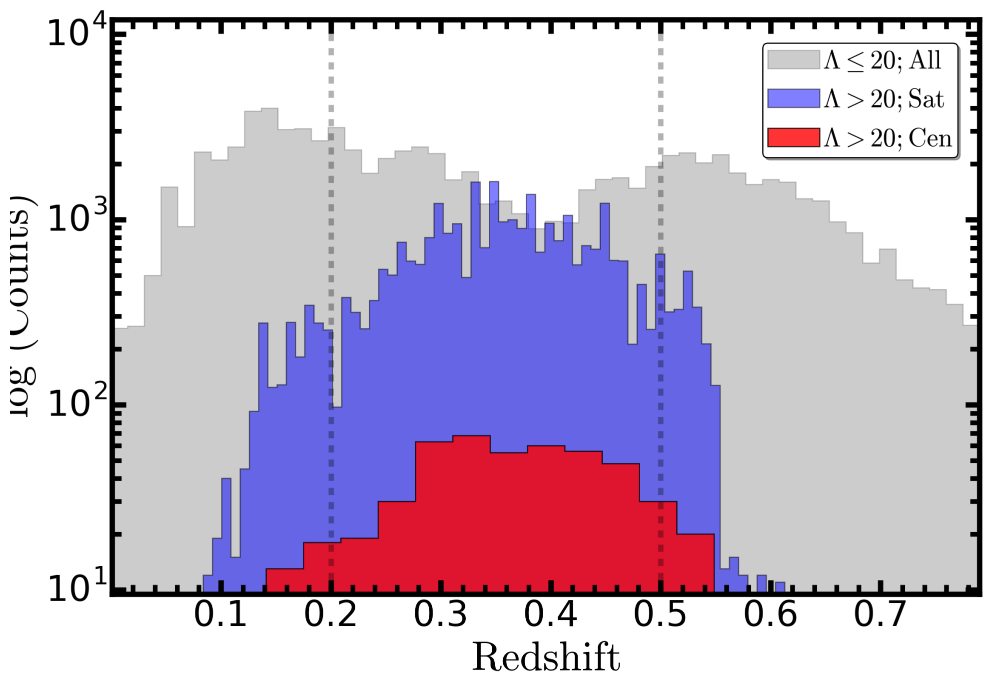

FIG. 3.— Figure.3**TODO: Caption**

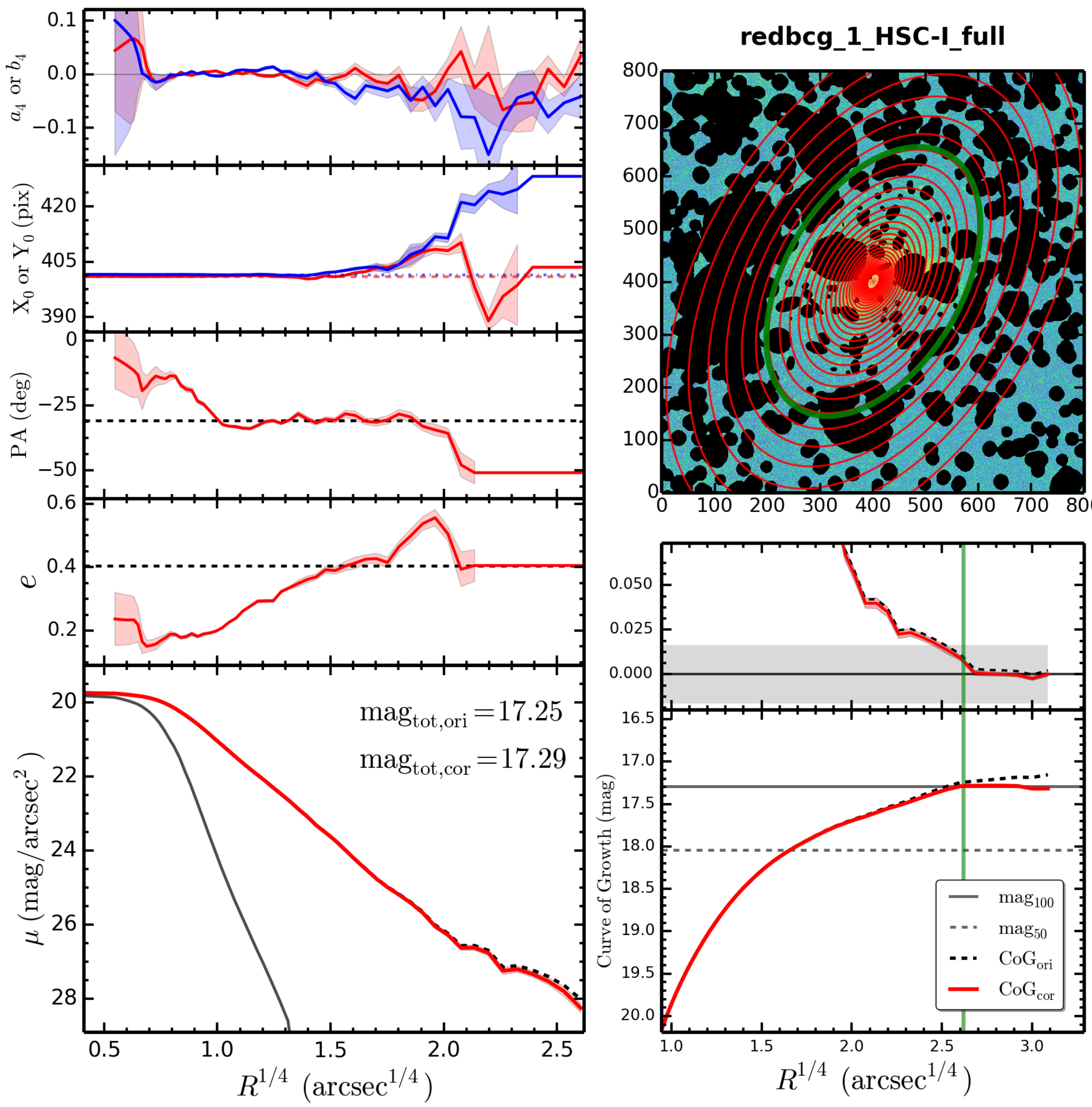

FIG. 4.— Figure.4**TODO: Caption**

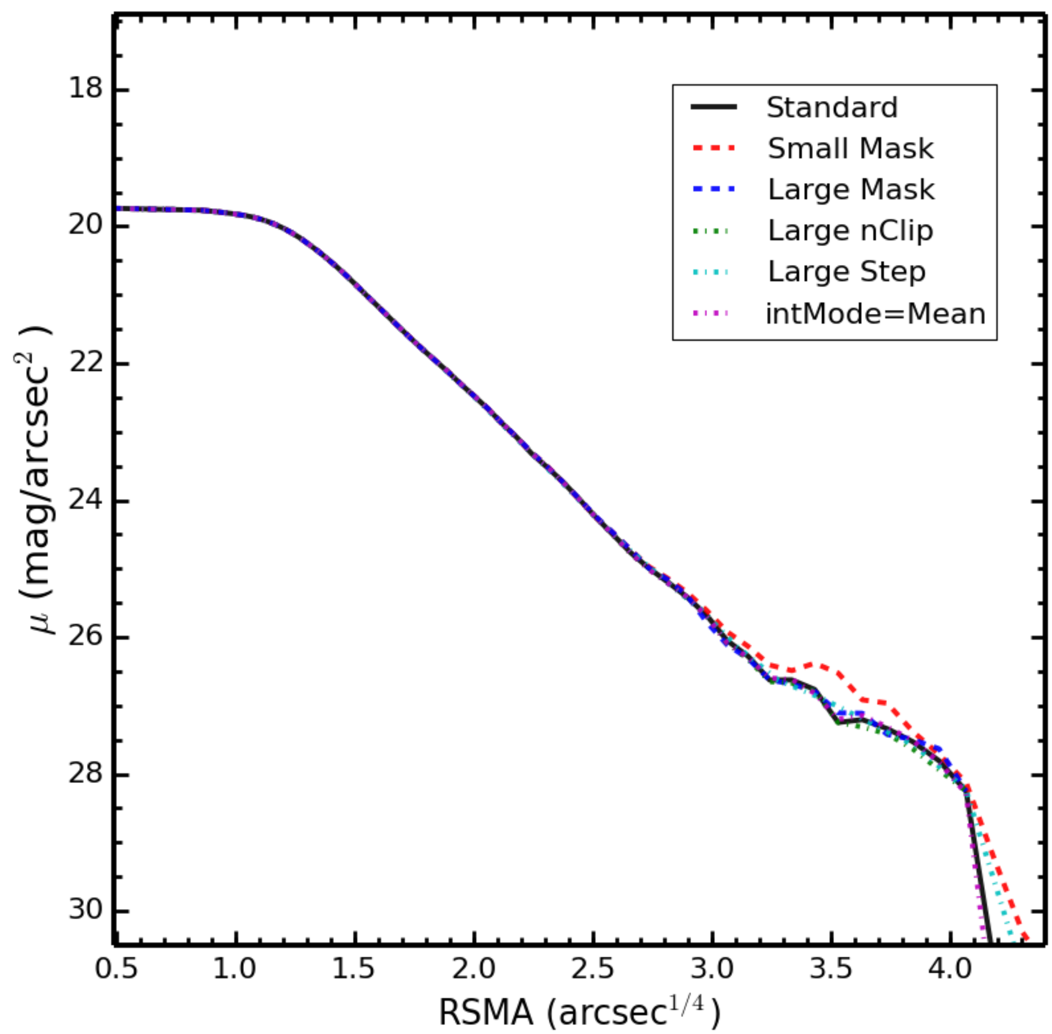

FIG. 5.— Figure.5**TODO: Caption**