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STUDYING GALAXY AND HOT GAS INTERACTIONS THROUGH CROSS-CORRELATIONS OF THE THERMAL SUNYAEV-ZELDOVICH EFFECT AND GALAXY SURVEYS

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Abstract. In addition to dark matter, massive halos also contain galaxies and hot gas. These latter two components interact and influence each other. On the one hand, galaxies and stars therein form from gas, cooling towards the halo center. On the other hand, galaxies also influence the gas dynamics through a number of feedback processes, including stellar radiation, supernovae, and AGN feedback. In order to study these feedback processes and to understand the effect of the environment (mainly the gas thermodynamics) on the galaxy stellar population, it is useful to measure the joint distribution of galaxies and hot gas. In our study, we cross-correlate the thermal Sunyaev-Zeldovich (tSZ) map provided by the Planck satellite with the CMASS galaxy sample from BOSS. Binning galaxies on stellar mass, we can more finely study the interactions between gas and galaxies. Making use of the halo model formalism, we model the gas distribution inside galaxy halos and determine how its pressure depends on galaxy stellar mass. We find a hint that the gas pressure decreases slightly in the vicinity of the most massive galaxies, which could help to constrain feedback models.

Keywords: cosmology, Sunyaev-Zeldovich, galaxies, gas, cosmic microwave background

1 Introduction

The large-scale structure of the Universe is organized through a set of halos and filaments which form through the gravitational collapse of dark matter. The gas distribution then follows the underlying dark matter field, as do galaxies, which form in dark matter halos. The galaxy and gas distributions are closely linked to each other since galaxies (and their stellar populations) form from the cooling of gas in the dark matter halos. Moreover, after a galaxy has formed, there are many interactions between the stars and the gas therein, so that the gas dynamics is also affected by the processes occurring in the galaxy. Those processes are referred to as "feedback" effects and include gas ionization and ejection due to stellar radiation, supernovae and Active Galactic Nuclei (AGN) feedback. In our study, we aim at probing the joint distribution of galaxies and gas and at providing clues about whether the gas dynamics depends on the host galaxy's stellar population. We study galaxy and hot gas interactions through the cross-correlation of the thermal Sunyaev-Zeldovich (tSZ) effect and a galaxy survey. Section 2 presents the data that we use and how the measurements are performed. We then describe our modeling in Sect. 3. Finally, we present and discuss the results in Sect. 4.

2 Data and Measurements

2.1 *The galaxy catalog*

We use the CMASS galaxy sample (Alam et al. 2015), which is a subsample of the BOSS survey and released in the Sloan Digital Sky Survey's data release 12. In order to study the impact of stellar population on the galaxy and gas distributions, we define four subsamples from CMASS defined by stellar mass thresholds: $\log M_*/M_\odot > 10.8$, $\log M_*/M_\odot > 11.1$, $\log M_*/M_\odot > 11.25$, and $\log M_*/M_\odot > 11.4$. Note that these are all very high stellar masses, as CMASS was constructed with approximately constant (and actually high) stellar

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masses. The stellar masses estimates that we use come from the Portsmouth stellar population synthesis code (Maraston et al. 2013), which fits the observed galaxy spectral energy distributions.

The catalogs are then turned into *HEALPix*[*] (Górski et al. 2005; Zonca et al. 2019) maps, applying weights to take into account a number of observational effects, as described in Anderson et al. (2014).

2.2 The tSZ map

The hot gas distribution can be studied thanks to the tSZ effect, which is a distortion of the CMB spectrum due to the interaction of CMB photons with energetic electrons in the hot, ionized intra-halo gas (circumgalactic medium, or CGM). In this study, we use the Compton-y parameter map provided by Planck Collaboration et al. (2016) in the 2015 *Planck* data release.

2.3 Power spectra estimation

For each galaxy subsample, we estimate its power spectrum and its cross-spectrum with the Compton-y map. In the case of full sky coverage, the cross-correlation of two maps a and a' can be estimated using,

$$C_\ell^{aa'} = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m} a'^{*}_{\ell m}, \tag{2.1}$$

where $a_{\ell m}$ denotes the coefficients of the spherical harmonic decomposition of map a and the asterisk indicates complex conjugation. However, in practice we do not observe the full sky, which introduces a mixing between the multipoles. This is taken into account by the *NaMaster*[†] code from Alonso et al. (2019), that we use for the estimation of the auto and cross-correlation power spectra.

Finally, we subtract the shot noise from the galaxy power spectra (no noise needs to be removed for the cross-correlations since the noise in the galaxy and Compton-y maps is not correlated), correct for the cosmic infrared background contamination, and estimate a Gaussian covariance matrix, all as described in more detail in Kou & Bartlett (2023).

3 Modeling

3.1 Line-of-sight projection

Using the Limber approximation (Limber 1953), the angular power spectra can be modeled as line-of-sight integrals over redshift, z:

$$C_\ell^{AB} = \int \frac{dz}{c} \frac{H(z)}{\chi(z)^2} W_A(z) W_B(z) P^{AB}\left(k = \frac{\ell}{\chi(z)}, z\right), \tag{3.1}$$

where H is the Hubble function, c is the speed of light, χ is the comoving distance, P^{AB} is the three-dimensional power spectrum of tracers A and B, and W_A and W_B are the kernels for the different probes. For the galaxies and the Compton-y parameter, those kernels are,

$$W_g(z) = \frac{1}{n_{\rm tot}} \frac{dn}{dz} \tag{3.2}$$

$$W_y(z) = \frac{1}{1+z}, \tag{3.3}$$

with $\frac{dn}{dz}$ the galaxy redshift distribution and $n_{\rm tot}$ the total number of galaxies in the sample.

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[*] http://healpix.sf.net

[†] https://github.com/LSSTDESC/NaMaster

3.2 Halo model

The three-dimensional power spectrum, P^{AB}, is modeled using the halo model formalism (for a review, see Cooray & Sheth 2002). In this model, all matter, galaxies and gas are assumed to reside in dark matter halos. The dark matter distribution is then described by two main quantities: the halo mass function and the halo bias, for which we use functions derived from numerical simulations (Tinker et al. 2008, 2010). Once the dark matter distribution is (statistically) fixed, we need to describe how galaxies and gas populate the halos.

3.2.1 Halo Occupation Distribution (HOD)

We split galaxies between centrals and satellites and use the following HOD modeling (Zheng et al. 2005),

$$\langle N_{\rm c}|M\rangle = \frac{1}{2}\left[1+\mathrm{erf}\left(\frac{\log M - \log M_{\rm min}}{\sigma_{\log M}}\right)\right] f_{\rm inc}(M) \tag{3.4}$$

$$\langle N_{\rm s}|M\rangle = \langle N_{\rm c}|M\rangle \left(\frac{M-M_0}{M_1}\right)^{\alpha_g} \mathcal{H}(M>M_0), \tag{3.5}$$

where $\langle N_{\rm c}|M\rangle$ (resp. $\langle N_{\rm s}|M\rangle$) is the number of central (resp. satellite) galaxies in a halo of mass M, $\mathcal{H}$ and erf are the Heaviside and the error functions, M_0, M_1, $M_{\rm min}$, $\sigma_{\log M}$, α_g are free parameters, and $f_{\rm inc}$ is a function introduced by More et al. (2015) to take into account the fact that CMASS is incomplete at low stellar mass. In practice, M_0 and α_g are fixed to reduce degeneracies, and only M_1, $M_{\rm min}$ and $\sigma_{\log M}$ are varied (see Kou & Bartlett 2023, for more detail).

3.2.2 Gas distribution profile

As for the galaxies, we need to describe how the gas is distributed inside a halo. We therefore use the pressure profile $P_{\rm e}(r|M)$ from Arnaud et al. (2010) with the parameters from Planck Collaboration et al. (2013),

$$P_{\rm e}(r|M) = 1.65(h/0.7)^2\,{\rm eV\,cm^{-3}}E^{8/3}(z)\left(\frac{(1-b_{\rm h})M_{500c}}{3\times10^{14}(0.7/h)M_\odot}\right)^{2/3+\alpha_p} p[r|(1-b_{\rm h})M_{500c}], \tag{3.6}$$

where h is the reduced Hubble constant, $E(z)=H(z)/H_0$, $\alpha_p=0.12$, M_{500c} is the mass of a halo defined such that the halo is a spherical region with average density equal to 500 times the critical density of the Universe. Finally, p is the gas distribution profile, taken as a generalized Navarro-Frenk-White profile (Navarro et al. 1997), and $b_{\rm h}$ is the so-called hydrostatic mass bias. This latter parameter probes the amplitude of the pressure profile and it is the only one that we leave free in our fits.

4 Results and Discussion

For each stellar mass bin, we run a MCMC analysis using the *emcee*[‡] (Foreman-Mackey et al. 2013) sampler to fit our model to the observations.

We constrain the hydrostatic mass bias and find that it is either constant or slightly increasing ($1-b_h$ decreases) with galaxy stellar mass (see the blue curve in Fig. 1). Since we use this bias parameter as a proxy to study the gas dynamics, we also show directly the inferred halo-bias weighted thermal pressure as the orange curve in Fig. 1. Similarly, we find a hint that the gas pressure is slightly lower around high stellar-mass galaxies. This could suggest that these galaxies have exhausted their supply of gas through the formation of stars, or that strong feedback has ejected the gas out of the halos. This kind of measurement can therefore be used to test galaxy evolution and feedback models. More results, especially about how galaxies populate their halos depending on the stellar mass of the observed galaxies, can be found in Kou & Bartlett (2023).

5 Conclusion

The distributions of galaxies and gas are strongly correlated due to the way galaxies form and to the interactions between the stellar population of galaxies and gas, known as feedback effects. Using the cross-correlation of

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[‡] https://emcee.readthedocs.io/

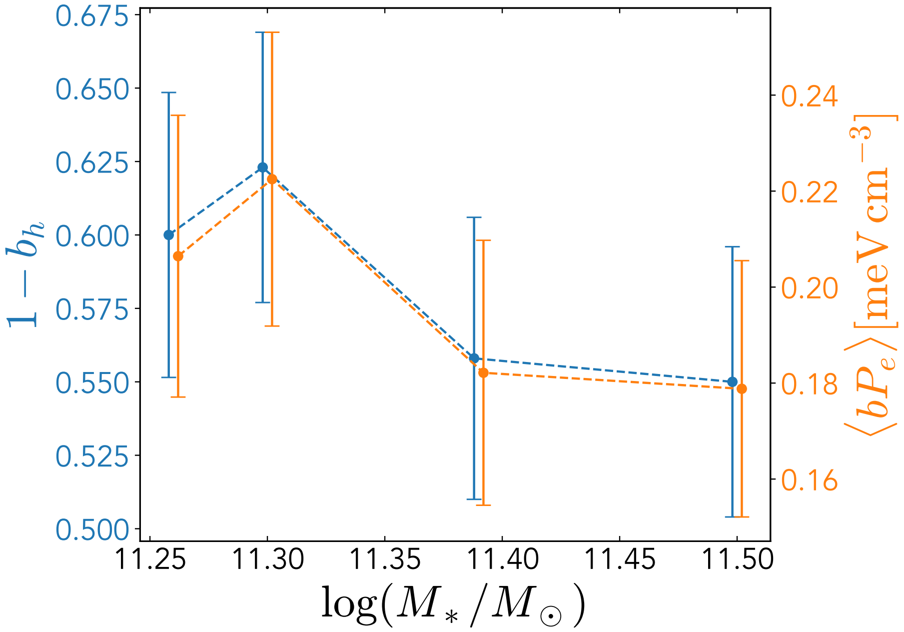

Fig. 1. Hydrostatic mass bias (blue) and halo-bias weighted thermal pressure (orange) as a function of galaxy median stellar mass. The two sets of error bars are shifted along the x-axis for visualization.

CMASS galaxies and the tSZ effect map provided by the *Planck* collaboration, we studied the joint distribution of gas and galaxies. Binning the galaxies by stellar mass, we find that the gas pressure decreases slightly in the vicinity of galaxies with the highest stellar mass. Reproducing this kind of study with the next generation surveys will make it possible to test more precisely galaxy formation, evolution and feedback processes.

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