TESTING DARK MATTER HALO MODELS OF QUASARS
WITH THERMAL SUNYAEV–ZELDOVICH EFFECT

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ABSTRACT

A statistical analysis of stacked Compton-y maps of quasar hosts with a median redshift of 1.5 using Millennium Simulation is performed to address two issues: one on the feedback energy from quasars and the other on testing dark matter halo models for quasar hosts. While the first step revealed that the resolution of FWHM = 10 arcmin obtained by Planck data, the observed thermal Sunyaev–Zeldovich (tSZ) effect can be entirely accounted for and explained by the thermal energy of halos sourced by the gravitational collapse of halos, without a need to invoke additional, large energy sources, such as quasar or stellar feedback. Allowing for uncertainties of dust temperature in the calibration of observed Compton-y maps, the maximum additional feedback energy is ~25% of that previously suggested. Second, we show that with an FWHM = 1 arcmin beam, tSZ measurements will provide a potentially powerful test of quasar-hosting dark matter halo models, limited only by possible observational systematic uncertainties, not by statistical ones, even in the presence of possible quasar feedback.

Key words: dark matter – large-scale structure of universe – galaxies: luminosity function, mass function – quasars: general – quasars: supermassive black holes

1. INTRODUCTION

The nature of the dark matter halos hosting quasars remains debatable. There are primarily two competing models. One is the traditional, popular halo occupation distribution (HOD) model, which is based on assigning a probability function to quasars that reside in a halo of a given mass in order to match the observed quasar clustering strength (Zheng et al. 2005, 2007; Shen et al. 2013). The other model is a physically motivated model recently put forth (Cen & Safarzadeh 2015, “CS model” hereafter).

While the CS model, like the HOD-based model, matches the observed clustering of quasars, the masses of the dark matter halos in the CS model are very different from those of the HOD-based model. For example, at $z \approx 0.5–2$, the host halos in the CS model have masses of $\sim 10^{11}–10^{12} M_{\odot}$, compared to $(0.5–2) \times 10^{13} M_{\odot}$ in the HOD model. This then offers a critical differentiator between the CS and HOD models, namely, the cold gas content in quasars host galaxies. Specifically, because of the large halo mass required in the HOD model, quasar hosts have a much lower content of cold gas than in the CS model. Cen & Safarzadeh (2015) have shown that the CS model is in excellent agreement with the observed covering fraction of 60%–70% for Lyman limit systems within the virial radius of $z \sim 2$ quasars (Prochaska et al. 2013). On the other hand, the HOD model is inconsistent with observations of the high covering fraction of Lyman limit systems in quasar host galaxies. Given the fundamental importance of the nature of dark matter halos hosting quasars, in this Letter, we present another potentially powerful test to distinguish between these two competing models. We show that upcoming measurements of the thermal Sunyaev–Zeldovich (tSZ) effect at arcminute resolution (or better) should be able to differentiate between them with high confidence.

2. SIMULATIONS AND ANALYSIS METHOD

We utilize the Millennium Simulation (Springel et al. 2005) to perform the analysis. A set of properties of this simulation that meet our requirements include a large box of 500$h^{-1}$ Mpc, a relatively good mass resolution with dark matter particles of mass $8.6 \times 10^9 h^{-1} M_{\odot}$, and a spatial resolution of $5 h^{-1}$ kpc comoving. The mass and spatial resolutions are adequate for capturing halos of masses greater than $10^{13} M_{\odot}$, which are resolved by at least about 100 particles and 40 spatial resolution elements for the virial diameter. Dark matter halos are found through a friends-of-friends algorithm. Satellite halos orbiting within each virialized halo are identified by applying a SUBFIND algorithm (Springel et al. 2001). The adopted $\Lambda$CDM cosmology parameters are $\Omega_m = 0.25$, $\Omega_b = 0.045$, $\Omega_k = 0.75$, $\sigma_8 = 0.9$, and $n = 1$, where the Hubble constant is $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$ with $h = 0.73$. We do not expect that our results strongly depend on the choice of cosmological parameters within reasonable ranges, such as those from Komatsu et al. (2011).

The steps taken to construct the tSZ maps are as follows. For each (either CS or HOD) quasar model, we sample the quasar host dark matter halos at each redshift, $z = 0.5, 1.4, and 3.2$. For each quasar host, we select all halos within a projected radius of 80 arcmin centered at the quasar in a cylinder with the depth equal to the length of the simulation box in a given direction. The thermal energy of a halo of mass $M_h$ is calculated using

$$E_{\text{th}} = \frac{3 \Omega_b}{2 \Omega_m} M_h \sigma^2$$

where $M_h$ is the halo mass and $\sigma$ the 1D velocity dispersion computed as

$$\sigma = 0.01 \times \left( \frac{M_h}{M_\odot} \right)^{1/3} \left[ \frac{\Omega_m(z = 0)}{\Omega_m(z)} \right]^{1/6} (1 + z)^{1/2} [\text{km s}^{-1}]$$

(2)
The energy of each halo is then distributed uniformly in a projected area inside its virial radius $r_v$. To construct SZ maps, we project the energy of each halo using a cloud-in-cell technique in 2D. We obtain the Compton-$y$ parameter corresponding to total projected thermal energy $E_{th}/A$ at each pixel with

$$y = 0.88 \times 0.588 \times \frac{2 \sigma_T E_{th}}{3m_e c^2 A}$$  \hspace{1cm} (3)$$

where $A$ is the area of the pixel, $\sigma_T$ the Thomson scattering cross section, $m_e$ the electron mass, $c$ the speed of light, and 0.88 and 0.58 account for electron density and molecular weight, respectively. We limit the dark matter halos that contribute to the $y$ calculation to the mass range $[3 \times 10^{12}, 5.5 \times 10^{14}] M_\odot$ at $z = 0.5$ and $[3 \times 10^{12}, 6.5 \times 10^{14}] M_\odot$ at both $z = 1.4$ and 3.2. The upper mass limits are used in order to enable comparisons to the observations, accounting for the fact that in the Planck observation generated $y$-maps, the clusters more massive than these indicated upper limits are masked out (Planck Collaboration et al. 2014). The lower-mass limits reflect the fact that less massive halos would be cold stream dominated instead of virial shock heated and gas dominated; changing the lower-mass limit from $3 \times 10^{12} M_\odot$ to $1 \times 10^{12} M_\odot$ only slightly increases the computed $y$-parameter.

To enable comparison with the observed Compton-$y$ maps stacked over a range of redshift $z \sim 0.1$--3.0 with median redshift of $z_{med} \sim 1.5$ (Ruan et al. 2015), we appropriately assign weightings of (36%, 51%, 13%) for $z = (0.5, 1.4, 3.2)$ maps, respectively, and sum up the contributions from the three redshifts. These weightings are adopted to mimic the redshift distribution of stacked quasars used in the observational analysis. To compute the variance of the $y$-parameter, we make nine maps each averaged over 10,000 such individual maps. In addition, we construct isolated quasar-host-only $y$-maps with only the quasar host halo’s energy contributing to the final $y$-map. In other words, in those isolated quasar $y$-maps, we exclude effects from projected, clustered neighboring halos.

3. VALIDATING QUASAR MODELS WITH PLANCK tSZ EFFECT MAPS

We first validate the quasar models by comparing them to Planck observations. Figure 1 shows Compton-$y$ maps for five randomly selected quasar maps at $z = 1.4$ (including the projection effects) in the five panels other than the top left panel and the average over 10,000 such individual maps is shown in the top left panel. Each individual map is centered on the quasar halo from the CS model. Halos that contribute to the signal are in the mass range we describe above, and in some cases, the quasar halo itself does not contribute to the signal if its mass falls outside the mass range.

The left panel of Figure 2 shows the Compton-$y$ radial profile obtained by sampling of the CS (blue shaded region) and HOD (purple shaded region) models, respectively. Overplotted is the result obtained by stacking the Planck tSZ maps for quasars in the redshift range $[0.1, 3.0]$ with a median redshift of 1.5 (green shaded region, Ruan et al. 2015). To compare with Planck tSZ maps, we smooth our synthetic maps with a beam of FWHM = 10 arcmin. We see that at the resolution of Planck of FWHM = 10 arcmin, both the CS and HOD models are consistent with the observed level of tSZ being contributed entirely by shock heated, virialized gas within massive halos. Given our generous mass limit of contributing halos and neglect of gravitationally shock heated gas outside the virial radius, it is likely that the estimates for CS and HOD models shown in the left panel of Figure 2 are somewhat underestimated. Thus, in disagreement with Ruan et al. (2015) with respect to feedback energy from other non-gravitational sources, we see little evidence of a need for a large contribution to the tSZ from non-gravitational energy sources, including quasars or stars.

To better understand this discrepancy, we show in the right panel of Figure 2 the Compton-$y$ profile in the HOD model, when only the quasar-hosting halo contributes to the thermal energy in the map, neglecting the contribution from clustered neighboring halos. We see that the isolated quasar map yields a tSZ signal peaked around $y \sim 1.4 \times 10^{-8}$ (black curve with shaded area) versus $y \sim 3.0 \times 10^{-7}$ as seen in the left panel where all neighboring halos are included. It is hence very clear that the overall Compton-$y$ parameter reflects the collective thermal energy contribution of halos clustered around the quasar-hosting halos in both the CS and HOD models. The collective effect exceeds that of the quasar host halo by more than an order of magnitude. We attribute the suggested need of additional quasar feedback energy in order to account for the observed tSZ effect proposed by Ruan et al. (2015) to the fact that projection effects due to clustered halos are not taken into account in their analysis. In the right panel of Figure 2, we also show the mean tSZ signals for quasars at three different redshifts separately. Since in this case no projected structures are included, the results are commensurate with the quasar halo masses in the models that increase with increasing redshift. In the (HOD, CS) models (Cen & Safarzadeh 2015), the lower-mass threshold of quasar hosts is $[2 \times 10^{13}, (2-5) \times 10^{12}] M_\odot$ at $z = 3.2$, $[5.8 \times 10^{12}, (2-5) \times 10^{11}] M_\odot$ at $z = 1.4$, and $[5.7 \times 10^{12}, (1-3) \times 10^{11}] M_\odot$ at $z = 0.5$. It is also worth noting that in the absence of projection effects, the quasar tSZ signal in the CS model is about a factor of 5 at $(z = 3.2)$ to 25 (at $z = 0.5$) lower than in the HOD model, due to differences in the quasar host halo masses in the two models.

It should be made clear that the projection effects are present at all redshifts. In the middle panel of Figure 2, we show the average Compton-$y$ profile per quasar for the CS (solid curves) and HOD (dashed curves) models separately at $z = 0.5$ (blue), $z = 1.4$ (green), and $z = 3.2$ (red), including projection effects. Two trends are seen and fully understandable. First, overall, the tSZ signal per quasar, with projected structures, increases with decreasing redshift in the range from $z = 0.5$ to $z = 3.2$. This is expected due to continued growth of cosmic structure with time. We note that if we had not removed the most massive clusters in our tSZ maps (to account for the masking-out of massive clusters in Planck maps (Planck Collaboration et al. 2014), the increase with decreasing redshift would be stronger. Second, the ratio of a tSZ signal with projection effects to that without projection effects increases strongly with decreasing redshift due to the combined effect of decreasing
quasar host halo mass and increasing clustering around massive halos with decreasing redshift.

In the left panel of Figure 2, the observed $y$-map values are not dust corrected. The correction amplitude for dust effect with the procedure used by Ruan et al. (2015), by applying the channel weights from the Hill & Spergel (2014) $y$-map construction to dust-like (modified blackbody) spectra, depends sensitively on dust temperature assumed. J. P. Greco & J. C. Hill (2015, private communication) show that for a dust temperature of 34 K used in Ruan et al. (2015), the $y$-map response is indeed negative over the entire redshift range of the quasar sample, resulting in an increase in total thermal energy in the $y$-map by about 37%; for lower dust temperatures, the $y$-map response becomes less negative and could go positive below some temperatures for all redshifts; for a dust temperature of 20 K, the $y$-map response is very slightly negative at $z < 1.4$ but significantly positive at $z > 1.4$, with the net $y$-map response for the quasar sample slightly positive. With regard to dust temperature, observational evidence is varied, but data suggesting lower temperatures are widespread. For example, Schlegel et al. (1998) indicate dust temperatures of 17–21 K in our own Galaxy; Kashiwagi & Suto (2015) suggest a dust temperature of 18 K for dust around galaxies from far-infrared image stacking analysis; Greco et al. (2015)

Figure 1. Top left panel shows the average Compton-$y$ map of 10,000 individual maps centered on the quasar host sampled from the CS model at $z = 1.4$. The other five panels show five randomly selected individual maps for five quasar halos. The pixel size is 0.034 arcmin.
suggest an overall dust temperature of 200 K in modeling the cosmic infrared background. Thus, the contribution of dust emission itself to the $y$-map depends significantly on the dust temperature, and the exact temperature of dust is uncertain at best and the actual $y$-map response is thus uncertain. Even if we take the dust-corrected $y$-map from Ruan et al. (2015), given our results that the dust-uncorrected $y$-values can be explained solely by gravitational energy of halos hosting QSOs and neighboring ones, the QSO contribution is at most about one-fourth of what is inferred in Ruan et al. (2015).

4. TESTING COMPETING QUASAR MODELS WITH ARC Minute-Resolution $t$SZ EFFECT MAPS

Having validated both the CS and HOD models by the Planck $t$SZ data on 10 arcmin scales in the previous section, here, we propose a test to differentiate between them. Figure 3 shows the stacked $t$SZ map of quasars with a median redshift of 1.5 smoothed with an FWHM = 1 arcmin in the CS model. Right panel shows the same for the HOD model.
versus \((0.55 \pm 0.03) \times 10^{-6}\) in the CS model. This is a large difference and can be easily tested.

Before quantifying how the two models may be differentiated, it is useful to understand the distribution of contributions from individual y-maps to the averaged y-map. Figure 5 shows the probability distribution function (PDF) of the y-parameter of the central region of radius 1 arcmin of 10,000 individual quasar-hosting halos (including projection effects) smoothed with FWHM = 1 arcmin (red histogram) and smoothed with FWHM = 10 arcmin (blue histogram). It is evident that the distribution of log\(y\) in both cases is close to Gaussian, hence the distribution of \(y\) is approximately lognormal. This indicates that the overall contribution to the stacked maps is skewed to the high end of the y-distribution. We find that 7.8\%, 12.1\%, and 22.5\% of high \(y\) quasar halos contribute to 25\%, 50\%, and 75\% of the overall y-value in the case with FWHM = 1 arcmin and 6.3\%, 9.6\%, and 18.4\% in the case with FWHM = 10 arcmin. Given the non-Gaussian nature, we apply the statistical technique of bootstrap resampling to estimate errors on the mean y-value. We find that the fractional error on the mean, computed by bootstrap sampling from our 10,000 samples, is 3.7\% and 3.2\% for FWHM = 10 arcmin and 1 arcmin cases, respectively. Thus, with a sample of 26,000 quasars as in Ruan et al. (2015), the fractional error on the mean would be 2\% for the FWHM = 1 arcmin case. Since the fractional difference between the HOD \(\langle y_{\text{central}} \rangle = (1.0 \pm 0.05) \times 10^{-6}\) and the CS \(\langle y_{\text{central}} \rangle = (0.55 \pm 0.03) \times 10^{-6}\) is 60\%, this means that the HOD and CS models can be distinguished at the \(\sim 3\sigma\) level, if statistical uncertainties are the only uncertainties. It is thus likely that the significance of differentiating the two models using the arcminute-scale tSZ effect around quasars will be limited by systematic uncertainties.

As stated in Section 3, there is a possibility that a significant fraction (\(\sim 25\%\)) of the observed thermal energy based on y-maps may be due to non-gravitational heating, such as quasar feedback suggested by Ruan et al. (2015). Under the reasonable assumption that the energy from quasar feedback accumulates over time, say via episodic high-energy radio jets, the quasar feedback energy would be proportional to the galaxy stellar mass or approximately the halo mass, given the observed correlation between supermassive black hole mass and the bulge stellar mass or velocity dispersion (e.g., Magorrian et al. 1998; Richstone et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002). If we further assume that the radial profile of the deposited energy from quasar feedback is the same as that of thermal energy sourced by gravitational energy, it follows that the central y-value of the (HOD, CS) models would be boosted from \([1.0 \pm 0.05) \times 10^{-6}, (0.55 \pm 0.03) \times 10^{-6}\]\(\) shown in Figure 4 to \([1.4 \pm 0.07) \times 10^{-6}, (0.77 \pm 0.04) \times 10^{-6}\]\(\). With the inclusion of this systematic uncertainty on quasar feedback energy, the expected central y-value ranges would become \([1.0 - 1.4) \times 10^{-6}, (0.55 - 0.77) \times 10^{-6}\], respectively, for the (HOD, CS) models, which remain strongly testable with arcminute-resolution tSZ observations.

5. CONCLUSIONS

We perform a statistical analysis of stacked y-maps of quasar hosts using Millennium Simulation. Two significant findings may be summarized. First, at the available resolution of FWHM = 10 arcmin obtained by Planck data, the observed tSZ effect can be entirely accounted for and explained by thermal energy of halos sourced by gravitational collapse. No additional energy source is required at this juncture. It must be noted that at FWHM = 10 arcmin projection effects are an important contribution to the y-parameter of clustered halos with the \(\sim 10\) arcmin scale dominating over the host halos themselves by an order of magnitude. Considering uncertainties of dust temperature in the calibration of observed y-maps, the maximum quasar feedback energy is about 25\% of that suggested (Ruan et al. 2015).

Second, we show that at the FWHM = 1 arcmin beam, the central value of the y-parameter is \((1.0 \pm 0.05) \times 10^{-6}\) and \((0.55 \pm 0.03) \times 10^{-6}\) in the HOD and CS models, respectively, because of the significant differences in the masses of quasar-hosting halos in the two models. At \(\approx 0.5 - 2\), the host halos in the CS model have masses of \(\sim 10^{11} - 10^{12} M_\odot\), compared to \((0.5 - 2) \times 10^{13} M_\odot\) in the HOD model. With an
observational sample of 26,000 quasars, one will be able to
distinguish between the HOD and CS models at a very high
confidence level statistically, indicating that the signifi-
cance level will only be limited by systematic uncertainties.
With possible quasar feedback, the expected central y-value
uncertainty ranges would be enlarged to become 
\[(1.0–1.4) \times 10^{-6}, (0.55–0.77) \times 10^{-6}\], respectively, for the
(HOD, CS) models, which remain strongly testable with
arcminute-resolution tSZ observations. Upcoming observa-
tions, such as Advanced ACT (Calabrese et al. 2014), may
be able to provide a definitive test.

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REFERENCES

Calabrese, E., Hložek, R., Battaglia, N., et al. 2014, JCAP, 08, 010
Cen, R., & Safarzadeh, M. 2015, ApJL, 798, L38
Ferrarese, L., & Merritt, D. 2000, ApJL, 539, L19
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJL, 539, L13
Greco, J. P., Hill, J. C., Spergel, D. N., & Battaglia, N. 2015, ApJ, 808, 151
Hill, J. C., & Spergel, D. N. 2014, JCAP, 2, 30
Kashiwagi, T., & Suto, Y. 2015, MNRAS, 451, 4162
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285
Planck Collaboration., Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, A29
Prochaska, J. X., Hennawi, J. F., & Simcoe, R. A. 2013, ApJL, 762, L19
Richstone, D., Ajhar, E. A., Bender, R., et al. 1998, Natur, 395, A14
Ruan, J. J., McQuinn, M., & Anderson, S. F. 2015, ApJ, 802, 135
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Shen, Y., McBride, C. K., White, M., et al. 2013, ApJ, 778, 98
Springel, V., White, S. D. M., Jenkins, A., et al. 2005, Natur, 435, 629
Springel, V., White, S. D. M., Tormen, G., & Kauffmann, G. 2001, MNRAS, 328, 726
Tremaine, S., Gebhardt, K., Bender, R., et al. 2002, ApJ, 574, 740
Zheng, X. Z., Bell, E. F., Papovich, C., et al. 2007, ApJ, 667, 760
Zheng, Z., Berlind, A. A., Weinberg, D. H., et al. 2005, ApJ, 633, 791