The Halo Occupation Distribution of Obscured Quasars: Revisiting the Unification Model

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1 INTRODUCTION

There is now a great deal of evidence linking galaxy evolution to the growth of supermassive black holes (SMBH; e.g., Richstone et al. 1998; Gebhardt et al. 2000; Merritt & Ferrarese 2001; Tremaine et al. 2002; Graham et al. 2011). The cold dark matter paradigm of galaxy formation implies that galaxies form in the potential wells of massive dark matter (DM) halos (e.g., White & Rees 1978; White & Frenk 1991; Kauffmann et al. 1993; Navarro et al. 1995; Mo & White 1996; Kauffmann et al. 1999; Hopkins et al. 2010; Conroy & White 2013; Conselice 2014; Shankar et al. 2015). So, a complete assessment of galaxy evolution requires an understanding of the connection between the growth and formation of SMBH and the dark matter halos they inhabit.

Galaxies that emit particularly strongly from the region near the SMBH that they harbor are called active galactic nuclei (AGN). AGN have been used to study the interplay between dark matter halos, and the galaxies and SMBHs they host, which is often referred to as “AGN/SMBH co-evolution” (e.g., Kauffmann & Haehnelt 2000; Wyithe & Loeb 2003; Marconi et al. 2004; Cattaneo et al. 2006; Croton et al. 2006; Hopkins et al. 2006; Lapi et al. 2006; Shankar et al. 2004; Di Matteo et al. 2008; Booth & Schaye 2009; Volonteri et al. 2011; Conroy & White 2013; Caplar et al. 2015; Oogi et al. 2016).

A key observational probe of the relation between SMBHs and their host DM halos is AGN clustering, which is frequently measured via the two-point-correlation function (2PCF; e.g., Arp 1970). Clustering measurements of different types of AGN have been carried out by several groups employing data from multiple surveys in the optical waveband (e.g., Croom et al. 2004; Porciani et al. 2004; Croom et al. 2005; Gilli et al. 2005; Myers et al. 2006; Myers et al. 2007a; Coil et al. 2007; Shen et al. 2007; Wake et al. 2008; Shen et al. 2009; Ross et al. 2009; Coil et al. 2009; Hickox et al. 2009, 2011; Allevato et al. 2011; Donoso et al. 2012, 2013; Krumpe et al. 2012; Cappelluti et al. 2012, 2013; White et al. 2012; Shen et al. 2013; Krumpe et al. 2012, 2013; Mountrichas et al. 2013; Koutoulidis et al. 2013; Krumpe et al. 2015; Elkefkarzadeh et al. 2015, 2017).

The majority of these studies involve measurement of the 2PCF of a certain kind of AGN, namely optically bright quasars. Due to their high luminosity, quasars are detected to high redshifts (as high as z ∼ 7, e.g., Mortlock et al. 2011), making them powerful probes of structure formation over a wide redshift range. In addition, the large sample sizes of quasars and the availability of reliable redshifts make them excellent candidates for studying how SMBHs co-evolve with cosmic structure. However, quasars have broad spectral-energy distributions and quasar emission at different wavelengths may be characteristic of quite different physical pro-

ABSTRACT

We model the projected angular two-point correlation function (2PCF) of obscured and unobscured quasars selected using the Wide-field Infrared Survey Explorer (WISE), at a median redshift of z ∼ 1 using a five parameter Halo Occupation Distribution (HOD) parameterization, derived from a cosmological hydrodynamic simulation by Chatterjee et al. The HOD parameterization was previously used to model the 2PCF of optically selected quasars and X-ray bright active galactic nuclei (AGN) at z ∼ 1. The current work shows that a single HOD parameterization can be used to model the population of different kinds of AGN in dark matter halos suggesting the universality of the relation between AGN and their host dark matter halos. Our results show that the median halo mass of central quasar hosts increases from optically selected (4.1±0.3 × 10^{12} M_{\odot}) and infra-red (IR) bright unobscured populations (6.3^{+0.2}_{-0.3} × 10^{12} h^{-1} M_{\odot}) to obscured quasars (10.0^{+2.6}_{-3.7} × 10^{12} h^{-1} M_{\odot}), signifying an increase in the degree of clustering. The projected satellite fractions also increase from optically bright to obscured quasars and tend to disfavor a simple ‘orientation only’ theory of active galactic nuclei unification. Our results also show that future measurements of the small scale clustering of obscured quasars can constrain current theories of galaxy evolution where quasars evolve from an IR- bright obscured phase to the optically bright unobscured phase.
cesses in the accretion disc and adjacent structures surrounding the central engine. Studies of quasar clustering have therefore moved beyond the optical waveband spanning the entire electromagnetic spectrum to test how large scale structures influence the properties of quasars (e.g., Shen et al. 2003; Donoso et al. 2010; Hickox et al. 2011; DiPompeo et al. 2014; Mendez et al. 2016; DiPompeo et al. 2016).

In this work, we employ the halo occupation distribution (HOD) formalism (e.g., Ma & Fry 2004; Seljak 2000; Berlind & Weinberg 2002; Zheng et al. 2005; Zheng & Weinberg 2007; Wake et al. 2008; Shen et al. 2010; Miyaji et al. 2011; Starikova et al. 2011; Allevato et al. 2011; Richardson et al. 2012; Kavo & Oguri 2012; Shen et al. 2012; Richardson et al. 2013; Allevato et al. 2014; Cen & Safarzadeh 2015) to derive the host dark matter halo properties of the quasars studied by DiPompeo et al. (2016, hereafter D16).

The HOD technique has been successfully used in the context of galaxy evolution in the recent past (e.g., Zehavi et al. 2005; Zheng et al. 2007; Zheng & Weinberg 2007). Currently, large multi-wavelength datasets of AGN have provided the tools to carry out the HOD analysis of AGN/quasar clustering in a statistically robust manner. Recently (Richardson et al. 2012; R12 hereafter and Richardson et al. 2013; R13 hereafter) use optically selected quasars and X-ray bright AGN at $z \sim 1$ to perform a comparison study of the HOD using the measured 2PCF of these two classes of AGN.

The results show that a universal parameterization of the AGN HOD is applicable for these two classes of AGN suggesting a universality in the relationship between AGN and their host dark matter halos. The results favor a scenario in which SMBH are believed to evolve from a bright quasar phase to an X-ray phase to a radio-loud phase along with the growth and evolution of their host dark matter halos. This scenario was proposed by Hickox et al. (2009) using multi-wavelength samples of low redshift AGN. The HOD technique is hence emerging as a successful tool to study quasar/AGN co-evolution in the way it allowed us to understand galaxy evolution with large scale structure in the Universe.

Recently D16 measured the 2PCF of $z \sim 1.0$ quasars, selected using infrared imaging from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010), and characterized as obscured or unobscured using an optical-IR color cut with optical imaging data (Hickox et al. 2007) from Data Release 8 (DR8) of the Sloan Digital Sky Survey (SDSS; York et al. 2000). Our work is in the vein of R12 and R13 where we try to test for the universality of the AGN HOD using obscured quasars and assess the role of the obscured phase in light of our previous work with optical and X-ray bright sample.

We compare the HOD properties of the WISE-selected quasars with the optical sample to test for similarities and/or differences in the large scale (and intra-halo) environments of these two classes of quasars. According to the simplest AGN unification theory, the central SMBH and accretion disk of a quasar are surrounded by an optically thick dusty torus, and the obscuration of the central broad-line-region and the accretion disk by the torus occurs at certain inclination angles as the torus intercepts the line of sight (Urry & Padovani 1995). In this paradigm, it is expected that different population of quasars would have identical host halo properties as the distinction is only an orientational effect. Our work is directed toward examining the validity of this prediction via a robust, HOD-based approach.

The paper is organized as follows. In §2 and §3, we briefly describe our data sets, the parameterization of the quasar HOD, and the theoretical modeling of the 2PCF. We present the results of our HOD modeling in §4. Finally, we discuss the implications of our results and summarize them in §5. Throughout this work we assume a spatially flat, ΛCDM cosmology (Spergel et al. 2007): $\Omega_m = 0.26, \Omega_L = 0.74, \Omega_k = 0.0435, n_s = 0.96, \sigma_8 = 0.78$, and $h = 0.71$. We quote all distances in comoving $h^{-1}$ Mpc and masses in units of $h^{-1} M_\odot$ unless otherwise stated.

2 DATASETS

The projected 2PCF of quasars that we use in this work is constructed from the clustering sample first measured in DiPompeo et al. (2014) (henceforth referred to as D14) and updated in D16. For calculating the 2PCF, D16 uses the Landy & Szalay estimator, given as (Landy & Szalay 1993)

$$\xi(\theta) = \frac{DD(\theta) - 2DR(\theta) + RR(\theta)}{RR(\theta)},$$

where $DD(\theta), RR(\theta)$ and $DR(\theta)$ are defined as, respectively, the number of pairs of points separated by an angle $\theta$ in the (projected) sky, the number of pairs of points similarly separated in a random distribution, and the number of cross-pairs of points between the data and the random distributions. We refer the reader to D16 for a detailed description of the observations and datasets. Here we describe the main features of the data.

The clustering sample has been selected from both the all-sky and the all-WISE catalogs of the WISE survey. WISE has mapped the sky in four wavebands at 3.4 $\mu$m, 4.6 $\mu$m, 12 $\mu$m and 22 $\mu$m, referred to as W1, W2, W3 and W4. A notable feature of the D16 sample is that it satisfies the selections of both the all-sky and the all-WISE catalogs. Both obscured and unobscured quasars are observable with WISE as the hot dust in quasars is responsible for an increasing power-law spectrum in the mid-IR (e.g., Lacy et al. 2004; Stern et al. 2005; Donley et al. 2007; Lacy et al. 2013).

A simple color cut at $W1 - W2 > 0.8$ for objects with $W2 < 15.05$ is used for selecting 225,303 quasar candidates from the all-sky, all-WISE data in the region $135^\circ < RA < 226^\circ$ and $1^\circ < DEC < 54^\circ$. This region is chosen since it is far from the Galactic plane, and hence suffers from less foreground contamination. For details of the masking techniques, we refer the reader to D14 and D16. After the removal of various contaminants, the sample contains 175,911 quasars over an area of 3422 deg$^2$. We note that given the contamination and the lack of spectroscopy, the objects we refer as quasars are actually better termed as ‘quasar candidates’ in the truest sense.

The initial WISE-selected sample is then matched to SDSS $r$-band data, and the SDSS “bad field” and “bright star” masks are applied. The resulting sample consists of 173,834 WISE-selected quasars over an area of 3387 deg$^2$. Obscured and unobscured quasars are then separated by applying an optical-IR color-cut of $r - W2 > 6$ (e.g., Hickox et al. 2007). In addition, any WISE-selected quasars that have no SDSS counterparts in $r$-band are designated to be obscured quasars. The ultimate sample comprises 62,715 obscured and 88,834 unobscured quasars over an area of 3250 deg$^2$. The median redshifts of the unobscured and obscured quasars in the sample are $z \sim 1.04$ (with a standard deviation of 0.58) and $z \sim 0.90$ (with a standard deviation of 0.54), respectively. The entire sample of quasars covers a redshift range of $z \sim 0.1$ to 3.0.

To compute the number density of quasars we calculate the comoving volume in the shell between $z \sim 0.1$ and $z \sim 3.0$. We
find an average number density of $2.0 \times 10^{-6} \ (h^{-1} \text{Mpc})^{-3}$ and $2.9 \times 10^{-6} \ (h^{-1} \text{Mpc})^{-3}$ for obscured and unobscured quasars, respectively. We also adopted a different method for calculating the number densities, by considering all quasars to lie in the shell between comoving radii corresponding to median $z - \sigma_z$ and median $z + \sigma_z$. We find that the results are weakly sensitive to the method of choice. While performing our HOD modeling we adopted a 15% error on our estimate of the number densities, to account for uncertainties in the redshift distributions of the quasars.

### 3 METHODOLOGY

For a given cosmology the characteristic host masses of quasars are typically obtained via bias measurements (e.g., Jing 1998, Sheth et al 2001). However, those bias estimates do not incorporate the full halo distribution of quasars, and make no distinction between central and satellite populations. The HOD formalism, instead, allows us to extract the full distribution of the host dark matter halos of quasars from the 2PCF, which provides a more complete understanding of the relationship between quasars and their host halos. In this section, we introduce our HOD parameterization and describe the methodology by which we use the HOD to model the 2PCF.

#### 3.1 Halo Occupation Distribution of Quasars

The HOD of quasars is characterized by $P(N|M)$ which signifies the conditional probability that a halo of mass $M$ contains $N$ quasars combined with the spatial and velocity distributions of quasars within halos. In principle, $P(N|M)$ could be fully constructed by determining all its moments from the clustering data (e.g., Zheng et al 2007). For our purpose of modeling the 2PCF, we need the first two moments of the distribution namely, $⟨N(M)⟩$ and $⟨N(N-1)⟩_M$ (Berlind & Weinberg 2002). The HOD is assumed to be dependent only on the halo mass since the assembly bias effect is assumed to be small for the massive halos that typically host quasars (e.g., Bond et al 1999, Gao et al 2003).

The Mean Occupation Function (MOF), or the first moment of the probability distribution, is defined as the average number of quasars in dark matter halos as a function of halo mass. We adopt
Figure 2. Top Left: The projected 2PCF of WISE-selected unobscured quasars (median redshift $z \sim 1$). The blue line is the best-fit model for the 2PCF. Top Right: The MOF, as a function of halo mass. The magenta solid line and blue dashed line are the MOFs of the central and satellite unobscured quasars, respectively. Bottom Left: The distribution of central (magenta solid) and satellite (blue dashed, scaled by a factor of forty for visualization purpose) unobscured quasars in dark matter halos as a function of halo mass. Bottom Right: The probability distributions of the median mass scales of central (magenta solid) and satellite (blue dashed) quasars.

a form for the MOF that consists of the sum of a softened step function for central quasars and a modified power-law for satellite quasars (Chatterjee et al. 2012, C12 hereafter). The MOF is then given by

$$\langle N(M) \rangle_{\text{cen}} = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{\log M - \log M_{\text{min}}}{\sigma_{\log M}} \right) \right],$$

$$\langle N(M) \rangle_{\text{sat}} = \left( \frac{M}{M_1} \right)^\alpha \exp \left( \frac{-M_{\text{cut}}}{M} \right),$$

$$\langle N(M) \rangle = \langle N(M) \rangle_{\text{cen}} + \langle N(M) \rangle_{\text{sat}},$$

where $M_{\text{min}}$ is the host halo mass at which the average number of quasars per halo is 0.5, $\sigma_{\log M}$ is the transition width of the softened step function, $M_1$ refers to the mass scale at which the satellite fraction is unity, $\alpha$ is the power-law index, and $M_{\text{cut}}$ is the lower mass range at which the number of satellite quasars in simulations falls off exponentially. In order to perform a more constrained fit, we excluded $M_{\text{cut}}$ and conducted a four-parameter modeling of the MOF. For a given halo mass, satellite quasars in simulations are found to follow an approximate Poisson distribution (e.g., C12 Degraf et al. 2011). Thus, for simplicity, we assume a Poisson distribution and a nearest integer distribution for the satellite and central quasar occupation numbers, respectively. Following R12, we assume that the occupation fractions of central and satellite quasars are uncorrelated with each other.

This HOD model used in this work was developed from a cosmological simulation which included SMBH growth and AGN feedback (Di Matteo et al. 2008). The HOD was derived based on a black hole mass based selection (Degraf et al. 2011) and a luminosity based selection (C12) and the results showed that they differ significantly due to the scatter in the correlation between black hole mass and AGN luminosity (see C12 for discussion). Here we use the luminosity based HOD model which better represents our observed samples. In this model the central occupation asymptotically reaches its maximum value one (i.e., when every halo hosts a quasar within a luminosity threshold) while the satellite occupation increases with increasing mass. It is believed that the satellite quasars are formed mostly through secondary processes (processes that are less sensitive to the gravitational potential of the dark matter halo) such as halo mergers and hence the quasar number scales as halo mass to the first order. The parameter $M_{\text{cut}}$ signifies a mass scale below which such secondary processes and satellite occupation thereof are exponentially suppressed. As mentioned before, in this study we noted that our modeling stays weakly sensitive to
$M_{\text{cut}}$ since it is lower than the typical halo mass scales of quasars. We thus did a four parameter fit to our model.

We, however, note that the HOD was derived based on a low luminosity sample, due to the small volume ($34h^{-1}$ Mpc box) of the Di Matteo et al. (2008) simulations. R12 extrapolated this HOD model to explain the clustering of bright quasars. Similarly to R13 used the same HOD model to derive the host halos of X-ray selected AGN (Allevato et al. 2011). R12 discuss the effect of theoretical bias (choice of HOD model) on derived physical parameters and the degeneracy of HOD models to current 2PCF measurements. To address this degeneracy Chatterjee et al. (2013) developed a direct measurement technique using the MaxBCG cluster sample along with SDSS quasars which revealed that at low redshift the quasar fraction tends to increase with host halo mass supporting the C12 parameterization. Following previous work, we thus assume that the AGN HOD has a universal form which we use for interpreting the clustering measurements of WISE selected quasars. See §5 for further discussion on the HOD parameterization.

To obtain the host dark matter halo population of quasars we convolve the MOF with the halo mass function (HMF). We use the HMF of Jenkins et al. (2001) in our current model. We note that our modeling is weakly sensitive to the choice of the HMF (R12, R13). We model the radial distribution of satellite quasars within halos as a Navarro, Frenk & White profile (NFW, Navarro et al. 1997) with the concentration relation from Bullock et al. (2001).

\[
c(M, z) = \frac{c_0}{1 + \frac{M}{M_c}}^\beta,
\]

where $M_c$ is the nonlinear mass for collapse at $z = 0$, and $\beta = -0.13$. R12 verified that the model is weakly sensitive to the choice of $c_0$ and hence, following R12, we adopt $c_0 = 32$.

### 3.2 Calculation of the 2-point Correlation Function

The quasar 2PCF, $\xi_q(r)$, is the excess probability of finding quasar pairs separated by a spatial distance $r$ as compared to a random distribution (Peebles 1980). It can be decoupled into contributions from intra-halo pairs, $\xi_{1h}(r)$, and inter-halo pairs, $\xi_{2h}(r)$. The intra- or two-halo term can be approximated as (Berlind & Weinberg 2002).

\[
\xi_{2h}(r) \approx \left[ n_q^{-1} \int_0^\infty dM \frac{dn}{dM} (N(M)) b_h(M) \right]^2 \xi_m(r),
\]

where $n_q$ represents the number density of quasars, $dn/dM$ is the differential halo mass function, $b_h(M)$ is the halo bias factor, and $\xi_m(r)$ is the 2PCF of underlying dark matter. The term in square brackets corresponds to the quasar linear bias factor, $b_q$. The one-halo term can be modeled as

\[
1 + \xi_{1h}(r) \approx \frac{1}{4\pi \sigma_q^2} \int_0^\infty dM \frac{dn}{dM} (N(N-1)) b_h(M) F_M(r),
\]

where $F_M(r)$ is the average fraction of same-halo pairs at separations $\leq r$. The calculation accounts for the differences in the distributions of the central-satellite and satellite-satellite pairs (Zehavi et al. 2005).

The projected 2PCF can be defined from the line-of-sight integral of the 3D correlation function $\xi(r)$ as (Davis & Peebles 1983).

\[
w_p(r_p) = 2 \int_0^{r_{\text{max}}} \xi(r) dr_p,
\]

where $r_p$ is the projected comoving transverse separation and $r_{\parallel}$ is the line of sight distance such that $r = \sqrt{r_p^2 + r_{\parallel}^2}$. Eq. 8 is obtained by using the box-function as the filter functions (since we are not smoothening out spatial fluctuations over our clustering scales) in the Limber approximation equation (see Eq. 13 of Simon 2007).

Rather than working in configuration space, D16 measured the angular correlation function due to the unavailability of reliable redshifts for their entire sample. If $0$ is the angular separation of quasar pairs, corresponding to a comoving transverse separation $r_p$, then the number of pairs ($N(r_p)$) with separation between $r_p$ and $(r_p + dr_p)$ can be obtained from the angular 2PCF ($w(\theta)$) via

\[
N(r_p) dr_p = N \times \sigma \times [1 + w(\theta)] \times 2\pi r_p dr_p,
\]

where $N$ is the total number of objects and $\sigma$ is the surface density of quasars.

We consider a volume of length $L$ and cross-sectional area $A$. If the actual number and the surface density (projected over the full size $L$) of quasars are $n$ and $\sigma$ respectively, we have: total number of quasars in that box $= A \times L \times n = A \times \sigma$, where $\sigma$ is the surface density when all the quasars are projected on the surface perpendicular to the line of sight. Hence we can approximately write, $\sigma \approx n \times L$. Then, from Eq. 9 we have

\[
N(r_p) dr_p = N \times n \times L \times [1 + w(\theta)] \times 2\pi r_p dr_p.
\]

The pair count can also be computed from the 3D correlation function $\xi \left( \sqrt{r_p^2 + r_{\parallel}^2} \right)$. We reserve $r_1$ for denoting the line-of-sight distance between quasar pairs. The number of pairs between $r_1$ and $r_1 + dr_1$ contributed from a layer chosen along the line of sight $y$ to $y + dy$ is

\[
N(r_1) dr_1 dy = \frac{N}{L} dy \int_{-y}^{L-y} n 2\pi r_p dr_p \left[ 1 + \xi \left( \sqrt{r_p^2 + r_{\parallel}^2} \right) \right] dr_p,
\]

where $n$ is the number density of quasars. $\frac{N}{L} dy$ is number of quasars in the mentioned layer. Hence, the total number of pairs having projected separation $r_1$ is

\[
N(r_1) dr_1 = \int_0^L \frac{N}{L} dy \int_{-y}^{L-y} n 2\pi r_p dr_p \left[ 1 + \xi \left( \sqrt{r_p^2 + r_{\parallel}^2} \right) \right] dr_p.
\]

Now comparing Equations 10 and 11,

\[
w(\theta) = \int_0^L \frac{dy}{L} \times \frac{1}{L} \int_{-y}^{L-y} \xi \left( \sqrt{r_p^2 + r_{\parallel}^2} \right) dr_p.
\]

Due to large-scale homogeneity, if we assume the quasar distribution to be periodic, then $[(-y) \rightarrow (L - y)]$ integration can be equated to that over $[0 \rightarrow L]$. Then we have

\[
w(\theta) = \int_0^L \frac{dy}{L} \times \frac{1}{L} \int_0^L \xi \left( \sqrt{r_p^2 + r_{\parallel}^2} \right) dr_p = \frac{1}{L} \int_0^L \xi \left( \sqrt{r_p^2 + r_{\parallel}^2} \right) dr_p.
\]

therefore, using Eq. 8 we get:

\[
w(x) = \frac{1}{L} \int_0^L \xi \left( \sqrt{r_p^2 + r_{\parallel}^2} \right) dr_p = \frac{1}{2\pi \sigma_{\parallel}^2} w_p(r_p)
\]

where $L = r_{\parallel\text{max}}$ is the depth of the survey.

Thus, we can approximately write the angular to spatial 2PCF conversion as $w(\theta) \times 2\pi r_{\parallel\text{max}} = w_p(r_p)$. We use $r_{\parallel\text{max}} = 2.88 \ Gpc$ for obscured quasars, and $2.87 \ Gpc$ for unobscured sample — which are, respectively, the comoving distances corresponding to the thickness of the shell : median $z \pm \sigma_z$ (which are $z \approx 0.90 \pm 0.54$ for obscured and $z \approx 1.04 \pm 0.58$ unobscured).

We would like to note that this particular method of conversion from angular to spatial coordinates has a caveat. The given
Figure 3. Comparison of host halo mass scales for three populations of quasars: The red solid curve and blue dotted curve show the distributions for the central populations of obscured and unobscured WISE-selected quasars, respectively. The black dashed curve shows the central distribution of SDSS DR7 quasars from R12. The difference in the central mass scales between obscured D16 population and R12 is significant (1.6σ). See Table 1 for comparison with D16 typical halo mass scales obtained from the bias measurements of quasars. Right : Similar plot showing the distribution of satellite populations. The vertical lines with corresponding blue and red shaded regions show the one sigma errors on the medians of the central and satellite distributions. The differences in the satellite host mass scales are modest.

The code populates a virtual sky with halos, and the halos with quasars following the C12 MOF (Eqns. 1 and 2). Following the prescription of R13 we calculate the $\chi^2$ value of each point in the parameter space using the diagonal elements of the covariance matrix (see Myers et al. 2007a). Each calculated $\chi^2$ accounts for the combined uncertainties of the 2PCF values and the number density of quasars. In our calculation, dark matter halos are defined as objects with a mean density of 200 times that of the background density (for further details about the routine see R12; Zheng et al. 2007). The MCMC contains 100,000 points in the HOD parameter space, and the set of parameters with the minimum $\chi^2$ value provides the best-fit theoretical model. The error on each of the individual parameters is obtained from the procedure followed by R12. The $\chi^2$ values are arranged in ascending order starting from the minimum $\chi^2$. The envelope (of parameter values) corresponding to the 68% of the values from the minimum is used to quantify the error on the best-fit parameters.

Table 1. Halo Mass Scales of Obscured and Unobscured quasars

| Sample            | log$(M_{\text{cent}}/h^{-1}M_\odot)$ | log$(M_{\text{typical}}/h^{-1}M_\odot)$ |
|-------------------|-------------------------------------|------------------------------------------|
| D16 obscured      | 13.0$^{+0.1}_{-0.2}$                 | 13.0$^{+0.14}_{-0.16}$                   |
| D16 unobscured    | 12.8$^{+0.3}_{-0.2}$                 | 12.72$^{+0.13}_{-0.15}$                  |
| R12               | 12.6$^{+0.04}_{-0.03}$               |                                          |

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4.1 WISE-selected Obscured Quasars

In the top-left panel of Fig. 1, we show our four-parameter HOD fit to the 2PCF of WISE-selected obscured quasars, at a median redshift of $z \sim 0.9$. The best-fit parameters are: $\log(M_{\text{min}}/(h^{-1}M_\odot)) = 15.26^{+0.48}_{-0.42}$, $\sigma_{\log M} = 1.25^{+0.36}_{-0.20}$, $\log(M_1/(h^{-1}M_\odot)) = 14.56^{+0.14}_{-0.02}$, and $\alpha = 3.99^{+0.01}_{-0.03}$. The best-fit set of parameters correspond to a reduced $\chi^2 = 1.12$ (with eight degrees of freedom). In the top-right panel of Fig. 1 we show the MOF from the best-fit HOD model, decomposed into its central and satellite components. The shaded regions depict the uncertainties in our estimate of the MOF.
In the bottom-left panel of Fig. 1, we show the host halo mass distribution of WISE-selected obscured quasars for the central and satellite populations. We have magnified the satellite distribution by a factor of 15 for visualization purposes. The peak of the satellite distribution is much lower than that of the central distribution, which is expected since the probability of finding two bright quasars in a single DM halo is minimal. The central population peaks at a halo mass of \(\log(M/(h^{-1}M_\odot)) = 13.0^{+0.1}_{-0.2}\). The satellite population peaks at \(\log(M/(h^{-1}M_\odot)) = 14.4^{+0.1}_{-0.6}\). In the bottom-right panel of Fig. 1 we show the probability distributions of the median halo mass scales (obtained by multiplying the MOF with the HMF) of central and satellite quasars.

### 4.2 WISE-selected Unobscured Quasars

In the top-left panel of Fig. 2, we show the best-fit HOD of the observed 2PCF of WISE-selected unobscured quasars, at a median redshift of \(z \sim 1.04\). The best-fit parameters are: \(\log(M_{\text{min}}/(h^{-1}M_\odot)) = 15.75^{+0.75}_{-0.84}\), \(\sigma_{\log M} = 1.49^{+0.33}_{-0.35}\), \(\log(M_1/(h^{-1}M_\odot)) = 15.14^{+3.53}_{-0.37}\), and \(\alpha = 2.59^{+1.41}_{-1.27}\). The minimum \(\chi^2\) of the best-fit, given 6 degrees of freedom, corresponds to a reduced \(\chi^2 = 0.44\). In the top-right panel of Fig. 2 we show the MOF from the best-fit HOD model, decomposed into its central and satellite components. In the bottom-left panel of Fig. 2 we show the host halo mass distributions of central and satellite quasars. The satellite distribution has been magnified by a factor of 40 to make it visible. The central population peaks at a DM halo mass of \(\log(M/(h^{-1}M_\odot)) = 12.8^{+0.3}_{-0.2}\). The satellite population peaks at \(\log(M/(h^{-1}M_\odot)) = 14.0^{+0.5}_{-0.9}\). In the bottom-right panel of Fig. 2 we show the probability distribution of the median mass scales (obtained by multiplying the MOF with the HMF).

### 4.3 Comparison with Optically Selected Quasars

The comparison between the distributions of obscured and unobscured quasars obtained from our four-parameter model and the same from R12 are shown in Fig. 3. In R12 the median halo masses of central and satellite quasars lie in the range \(M_{\text{cen}} = 4.1^{+0.3}_{-0.5} \times 10^{12} h^{-1} M_\odot\) and \(M_{\text{sat}} = 3.6^{+0.8}_{-1.0} \times 10^{14} h^{-1} M_\odot\), respectively. The central distribution of R12 is in agreement with that of unobscured D16 quasars, \(M_{\text{cen}} = 6.3^{+0.7}_{-2.3} \times 10^{12} h^{-1} M_\odot\). The median halo mass of D16 obscured quasars is higher \(M_{\text{cen}} = 10.0^{+3.6}_{-3.7} \times 10^{12} h^{-1} M_\odot\) than the halo masses of the R12 SDSS-selected unobscured population (at a level of 1.6 \(\sigma\)). Our statistical significances are quoted in the sense that the lower bound on the measurement of one is consistent with the upper bound on the measurement of the other.

The typical halo mass scales of obscured and unobscured quasars as measured by D16 (via bias evolution) are shown in Table 1 for comparison with the current work. We note that our results are consistent with D16. D16 report a slight difference in the host halo mass scales of their obscured and unobscured populations. DiPompeo et al. (2017) combines clustering and cosmic microwave background lensing measurements over a larger area and reported a difference of higher significance in the typical halo mass scales of obscured and unobscured quasars. Our results on full HOD analysis tend to favor their findings. We do not observe any significant difference in those two populations, but the differences in central host mass scales of R12 (optically selected unobscured population) and D16 obscured quasars are significant (as discussed above). Our HOD results for the D16 samples are also in agreement with that of Mendez et al. (2016) who do not find any significant differences between the clustering of obscured and unobscured populations. However, we do observe a difference in the host mass scales of R12 and D16 obscured quasars.

This implies that typically obscured quasars tend to prefer higher mass halos than their unobscured counterparts. We would like to emphasize that although simple bias based techniques can provide constraints on host halos it is essential to exploit the full HOD prescription to truly quantify the statistical significance of the derived host halo masses from 2PCF analyses. As noted before, the HOD provides the full halo mass distribution which in turn can provide additional constraints on observed results. For example, in this work the inferred halo masses of the WISE selected obscured and unobscured quasars are similar despite being slightly different in bias-based measurements in D16. Allevato et al. (2014) use X-ray selected AGN to infer the host masses of obscured and unobscured populations. Their results show that unobscured quasars inhabit higher-mass halos compared to the obscured population. We want to emphasise that in Richardson et al. (2013) we have done a comparison of the HOD of optically bright quasars with that of X-ray selected AGN. We do see that at similar redshifts X-ray AGN have higher mass hosts compared to optical quasars favoring the Hickox picture that was proposed for lower redshift AGN. We thus note that a comparison of X-ray-selected and IR-selected samples merits consideration. In Richardson et al. (2013), we argue that AGN follow an evolutionary sequence from optically bright quasar phase to X-ray phase to and radio phase while their host dark matter halos grow with time. Our aim in the current paper is to examine the role of the obscured phase in this evolutionary sequence.

At face value, there is a difference in the satellite distribution and the satellite fractions for the three populations of quasars. For R12 the satellite fraction is \(f_{\text{sat}} = (7.4 \pm 1.4) \times 10^{-4}\). For D16 the satellite fraction for unobscured quasars is higher, \(f_{\text{sat}} = (1.9^{+3.6}_{-1.8}) \times 10^{-3}\). The D16 WISE-selected obscured population has even an order of magnitude higher satellite fraction, \(f_{\text{sat}} = (4.9^{+1.8}_{-1.4}) \times 10^{-2}\), as compared to their WISE-selected unobscured counterparts. We do observe a \(\sim 16\) difference in the satellite fractions between R12 and the D16 obscured population which we consider as statistically insignificant.

R12 combined their large scale 2PCF measurements with the small scale clustering measurements of binary quasars from Hennawi et al. (2008). In the case of D16 samples we do not have such small scale measurements with WISE and hence our halo mass constraint essentially came from the two-halo term. The lack of pairs on small scales arises due to effects discussed in D14. The WISE PSF, and artifacts in WISE that have to be masked, made it difficult to measure the autocorrelation function on small scales (see D14 for details). However we note that if future surveys if we do have more information on the small scale clustering of obscured quasars, we can improve our constraints on the satellite HOD. To illustrate this fact, we repeated our HOD analysis replacing the WISE-selected quasars with a mock data set in which the error bars on the 2PCF were reduced to an optimistic 10% of their measured values.

Fig. 4 shows the distribution of the host halo masses and the satellite fractions of the mock data. With these reduced error bars, the HOD formalism would show a significant difference between the HOD parameters for different populations of quasars. Although it is unlikely that the difference that we see in satellite fractions in the projected samples of D16 and R12 (based on the current obser-
vations) will solely be due to selection bias we still consider that as a possibility in explaining the observed difference. Future datasets can truly shed light on this issue. It is important to note, however, that greatly improved precision in clustering measurements for these populations would not yield a highly significant improvement in estimates of host halo masses for central quasars, compared to the current work. Recently [Jiang et al. (2016)] measured the small scale environments (within 100 kpc) of low redshift Seyfert samples. They found that at low redshift type 2 AGN are more strongly clustered on small scales than type 1s and that the two types have similar amplitudes on large scales. This is similar to our finding but we note that our results are drawn for a high redshift quasar sample with scales greater than 100 kpc.

The WISE-selected quasar samples from D16 span a wide range of redshift, from $z \sim 0.1$ to 3.0. As discussed in §3, we interpret our derived HOD to be the true HOD at the median redshift of the D16 samples ($z \sim 1$). Essentially, we assume that any redshift evolution is incorporated within general statistical uncertainties in measurements of the clustering of quasars from D16. Were the measurement precision for the 2PCF of WISE-selected quasars to improve, such an assumption might no longer be valid. Thus, improved 2PCF measurements for WISE-selected quasars will require better modeling of the redshift evolution of the HOD in order for our formalism to yield robust conclusions regarding the mass scales of different populations of quasars. This also applies to the calculation of number densities as well as other approximations (e.g., angular to spatial conversion) adopted in this formalism. We further discuss these issues in §5.

As discussed in §3.2, converting from spatial to angular scales introduces some uncertainty in our modeling. We emphasize that the effect of this uncertainty in our results is insignificant. This is further justified by the fact that the arbitrariness in conversion alters only the normalization of the projected 2PCF, by a small numerical constant of the order of unity. To test this effect of 2PCF normalization on our results, we repeated the entire analysis by increasing the normalization by a factor of two. This change produced a slight difference in the peak masses of the central quasars, which is well within the error range shown in the bottom panels of Fig. 1 and Fig. 2. The satellite halo occupation distributions remained unchanged.

5 DISCUSSION AND CONCLUSIONS

According to the simplest AGN unification theory, the central SMBH and accretion disk of a quasar are surrounded by an optically thick ‘dusty torus,’ and the obscuration of the central broad-line-region by the torus occurs at certain inclination angles as the torus intercepts the line of sight (Urry & Padovani [1995]). In this paradigm, it would be expected that all three populations of quasars that we study in this paper should have identical host halo mass distribution.\footnote{modular the possibility that the samples have very different luminosities (see, e.g., D16 and DiPompeo et al. [2017] for further discussion).} It is possible that the simplest orientation-based unified model of AGN may be inadequate, however (see Netzer [2015] for a review). Within the last few decades, there have been attempts to address the nature of quasars using modified formalisms that build on the unification-through-orientation paradigm. One such formalism, the “evolutionary theory” of quasars (e.g., Sanders et al. [1988], Hopkins et al. [2005, 2008], Hickox et al. [2009]) explains the origin of different types of quasars from the perspective of galaxy evolution (see Mitra [2016] and DiPompeo et al. [2017] for discussion).

In a pioneering work, Sanders et al. [1988] proposed that ultraluminous infrared galaxies (ULIRGs) are the initial, heavily obscured, stages of a quasar, which, after shedding surrounding dust, is revealed in the optical as an unobscured quasar. Hopkins et al. [2006] proposed a merger-driven unification model in which quasar activity is triggered by galaxy mergers. Such mergers provide abundant matter, both for near-Eddington accretion on to central SMBHs and to trigger bursts of star formation in galaxies (e.g., Cavaliere & Vittorini [2000], Hopkins et al. [2006, 2008]). At the same time, galaxy mergers could initially enshroud central SMBHs with optically thick dust, producing an IR-bright obscured phase for quasars. As an example of evidence for this framework, Chen et al. [2013, 2015] find that galaxy mergers are more strongly correlated with star-formation in obscured quasars than in unobscured quasars. As accretion onto the central SMBH increases, the evolutionary paradigm suggests that, ultimately, feedback sets in (e.g., Ciotti & Ostriker [2001], Wyithe & Loeb [2003], Croton et al. [2006], Di Matteo et al. [2005], Sijacki et al. [2007], Somerville et al. [2008], Ostriker et al. [2010], Novak et al. [2011]), driving away the gas and dust around the central quasar. As the dust is blown away, the central quasar becomes visible in the optical and enters an unobscured phase (Hopkins et al. [2005]).

In the context of feedback-driven evolutionary theory the satellite fractions of obscured and unobscured quasars can be dif-

Figure 4. The projected HOD satellite constraints with reduced errors (∼10% of current) on the measured 2PCF. The top panel depicts the distribution of the median mass scales while the bottom panel shows the constraints on the satellite fractions. See discussions in §4 and §5.
different as not all of the initially obscured quasars in a halo, triggered by mergers, are expected to go to the unobscured phase; since feedback from a newly formed bright unobscured quasar could blow away gas from neighboring region. By starving the other obscured satellite AGNs, of food for accretion, it could inhibit the formation of another unobscured quasar in the same halo (e.g., Ostriker et al. 2010; Chatterjee et al. 2013; Mitra 2016). This could result in a decrement of satellite fraction while going from the obscured to the unobscured phase.

It is interesting to evaluate our work under both the “evolutionary” and the “orientation” frameworks. We note that there is a difference in the distributions of the host masses of central quasars (see Fig. 3) of R12 and the WISE-selected obscured population, although at a lower significance (1.6σ). This implies that the large-scale distributions of SDSS-only-selected (R12) unobscured quasars, and the WISE-selected obscured quasars (D16), cannot be fully explained by the simple unification-by-orientation scheme although that model is still consistent with our results owing to the modest statistical significance of the difference in halo masses. However, it is important to note that even in the evolutionary picture, the host halo masses of obscured and unobscured quasars can be similar if the transition time from obscured to unobscured phase is much lower than the typical halo evolution timescales. We observe that the median redshifts of R12 and D16 are 1.4 and 0.9 respectively. So in the evolutionary paradigm, the unobscured population of R12 should be coming from a higher redshift obscured population and the observed differences in host halo mass could as well reflect the overall redshift evolution of DM halos.

A recent work by Hopkins et al. (2016) throws light on this issue of timescales. Using a detailed simulation in the vicinity of the SMBH, they predict a typical transition timescale of Myr, much smaller than the halo evolution time scales. Thus in this paradigm, one should not expect any difference in mass scales of host dark matter halos of quasars. However, satellite AGNs in a given halo might still be inhibited from going into bright unobscured phase, causing a difference in satellite fraction. So it could as well be likely that the ∼ 1.6σ difference we found in median halo masses between R12 and D16 obscured is due to the evolution of halo mass function itself from z ∼ 1.4 to z ∼ 0.9 (median redshifts of the two samples). Moreover, the picture drawn by Hopkins et al. (2016) is not purely evolutionary, it does include the orientational picture of dusty torus formation self-consistently as a result of AGN feedback, at a later stage of its evolution. So those with their torus in line-of-sight will also contribute to the obscured population, hence nullifying the halo difference even more. This is in phase with our result of statistically consistent halo mass scales of D16 obscured and unobscured populations.

Since satellite population differences might still be present, this also suggests that in future HOD work, studying satellite fraction with more tighter constraints could be a better way, than just looking at halo mass scales, to distinguish between different stages of AGN evolution. We, however, note that there are significant differences in scenarios simulated and the one drawn in our HOD work. Starbursts, stellar outflow from galactic bulge and its coupling with the interstellar medium has a notable role to play in the duty-cycles of AGN mentioned by Hopkins et al. (2016). Moreover the halo masses considered in the simulation are $2 \times 10^{12} M_\odot$ and feedback timescales might be different in more massive halos where we have the possibility of having satellite quasars. Their study did not consider greater than 100 pc outflow, whereas large scale (beyond galaxy scale) quasar feedback is a well-observed phenomenon.

In this work, we have shown that the C12 model derived from a cosmological hydrodynamic simulation of AGN feedback adequately explains the clustering properties of infra-red selected quasars suggesting a universal relationship between AGN activity and their host dark matter halos. We show that the HOD formalism provides more robust constraint on competing theories describing the classification of obscured and unobscured quasars and provide the very first constraint on satellite fractions of obscured quasars. In addition to that, we have for the first time proposed a technique on performing HOD modeling of angular correlation functions which are often observables in surveys where reliable spectroscopic redshifts are not available. However, we note that despite the potential statistical power of future quasar/AGN surveys and the success of HOD modeling, one of the limitations in using the HOD to model quasar/AGN clustering is the theoretical understanding of the HOD itself.

As mentioned previously the C12 model adopted in this work was constructed from a small volume cosmological simulation of low-luminosity AGN. Moreover, the model relies on a simplified subgrid-model of AGN population and AGN feedback (see C12 for discussion). We emphasize that theoretical models based on semi-analytic or numerical simulations do require extensive comparison with observations in proving their validity. The current work along with R12 and R13 do provide justification for the C12 model to be a valid HOD prescription for studying AGN co-evolution. A similar sub-grid model of AGN growth and feedback has been recently used in a large volume cosmological simulation by Feng et al. (2015) which would further enable us to extend our HOD work to higher luminosity AGN and particularly to the population that shines as bright quasars.

Another caveat of the current HOD parameterization lies in the redshift evolution of the HOD itself. C12 noted that the HOD parameters of the current model evolved with redshift for the low-luminosity sources, but at minor significance. There have not been any definitive studies apropos the redshift evolution of the HOD of quasars. So, in this, and in previous works, the derived HODs for quasar clustering measurements have been interpreted as the “true” HOD at the median redshift of the studied quasar populations (with other approximations such as number density estimates in accordance with this interpretation). This interpretation relies on the assumption that the redshift evolution of the HOD produces effects that are smaller than the statistical uncertainties of quasar/AGN 2PCF measurements. Once the statistical power of quasar/AGN clustering measurements increases, we might enter a regime where such assumptions are no longer appropriate.

We propose to perform a study on redshift evolution of the quasar HOD with the recently run Feng et al. (2015) simulation. We also like to refer to DiPompeo et al. (2017) for discussion on redshifts of the quasar sample. D16 did not have redshifts for all of their studied samples, notably the obscured sources. Hence even observationally it was not possible to split the sample into redshift bins for studying the redshift evolution. We plan to do a newer and deeper optical survey for carrying out the redshift analysis. That would allow us to compare our theoretical study of the redshift evolution with that of observations.

The understanding of quasar/AGN HOD is absolutely important in interpreting other observations (e.g., Sunyaev Zeldovich: SZ effect from quasar feedback: Ruan et al. 2015; Verdier et al. 2016; Crichton et al. 2016; Dutta Chowdhury & Chatterjee 2017). Recently Dutta Chowdhury & Chatterjee (2017) showed that the uncertainty in the high halo mass tail of the mean occupation function of quasars as well as the lack of knowledge of the red-
shift evolution of the quasar HOD leaves the SZ detection from quasar feedback in cosmic microwave background experiments to be inconclusive. Hence the scope of the HOD work in unraveling the physical scenarios of AGN-co-evolution is extremely promising. Ultimately, a better understanding of the theoretical aspects of quasar/AGN HODs will be required in order to confidently interpret future quasar clustering measurements as well as measurements where quasars/AGN are probes of the high redshift Universe.

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