A NEW MODEL FOR DARK MATTER HALOS HOSTING QUASARS

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ABSTRACT

A new model for quasar-hosting dark matter halos, meeting two physical conditions, is put forth. First, significant interactions are taken into consideration to trigger quasar activities. Second, satellites in very massive halos at low redshift are removed from consideration due to their deficiency in cold gas. We analyze the Millennium Simulation to find halos that meet these two conditions and simultaneously match two-point auto-correlation functions of quasars and cross-correlation functions between quasars and galaxies at \(z = 0.5–3.2\). The masses of the quasar hosts found decrease with decreasing redshift, with the mass thresholds being \([2–5] \times 10^{12}, (2–5) \times 10^{11}, (1–3) \times 10^{11}\) \(M_\odot\) for median luminosities of \([10^{46}, 10^{46}, 10^{45}]\) erg s\(^{-1}\) at \(z = (3.2, 1.4, 0.53)\), respectively, an order of magnitude lower than those inferred based on halo occupation distribution modeling. In this model, quasar hosts are primarily massive central halos at \(z \geq 2–3\) but increasingly dominated by lower mass satellite halos experiencing major interactions toward lower redshift. However, below \(z = 1\), satellite halos in groups more massive than \(\sim 2 \times 10^{13} M_\odot\) do not host quasars. Whether for central or satellite halos, imposing the condition of significant interactions substantially boosts the clustering strength compared to the total population with the same mass cut. The inferred lifetimes of quasars at \(z = 0.5–3.2\) of 3–30 Myr are in agreement with observations. Quasars at \(z \approx 2\) would be hosted by halos of mass \(\sim 5 \times 10^{11} M_\odot\) in this model, compared to \(\sim 3 \times 10^{12} M_\odot\) previously thought, which would help reconcile with the observed, otherwise puzzling high covering fractions for Lyman limit systems around quasars.

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

1. INTRODUCTION

Masses of dark matter halos hosting quasars are not directly measured. They are inferred by indirect methods, such as via their clustering properties (i.e., auto-correlation function (ACF) or cross-correlation function (CCF)). Using ACF or CCF can yield solutions on the (lower) threshold halo masses. The solution on halo mass based on such a method is not unique, which will be illustrated by a simple example. Let us suppose a sample composed of halos of large mass \(M\) and an equal number of small halos of mass \(m\), coming in tight pairs of \(M\) and \(m\) with a separation much smaller than the scale for the correlation function of interest. For such a sample, the ACF of halos of mass \(M\) is essentially identical to that of \(m\) or a cross-correlation between \(M\) and \(m\). Although dark matter halos in the standard hierarchical cold dark matter model are less simple, the feature that small mass halos tend to cluster around massive halos is generic. This example suggests that alternative solutions of dark matter halos hosting quasars exist. It would then be of interest to find models that are based on our understanding of the thermal dynamic evolution of gas in halos and other physical considerations, which is the purpose of this Letter.

2. SIMULATIONS AND ANALYSIS METHOD

We utilize the Millennium Simulation (Springel et al. 2005) to perform the analysis, whose properties meet our requirements, including a large box of 500 \(h^{-1}\) Mpc, a mass resolution with dark matter particles of mass \(8.6 \times 10^8 h^{-1} M_\odot\), and a spatial resolution of 5 \(h^{-1}\) kpc comoving. Halos are found using a friends-of-friends (FOF) algorithm. Satellite halos are separated out using the 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 \(n = 1\), and \(H_0 = 100 h\) km s\(^{-1}\) Mpc\(^{-1}\) with \(h = 0.73\).

Given the periodic box, we compute the two-point ACF \(\xi(r_p, \pi)\) of a halo sample by

\[
\xi(r_p, \pi) = \frac{DD}{RR} - 1,
\]

where \(r_p\) and \(\pi\) are the pair separation in the sky plane and along the line of sight, respectively, as in observations. The CCF is similarly computed:

\[
\xi(r_p, \pi) = \frac{D_1 D_2}{R_1 R_2} - 1,
\]

where \(D_1\) and \(D_2\) correspond to galaxies and quasars, \(R_1\) and \(R_2\) correspond to randomly distributed galaxies and quasars that are computed analytically.

The projected two-point correlation function \(w_p(r_p)\) is:

\[
w_p(r_p) = 2 \int_0^\infty d\pi \xi_s(r_p, \pi).
\]

In practice, the integration is up to \(\pi_{\text{max}}\). We use \(\pi_{\text{max}} = (100, 80, 70) h^{-1}\) Mpc comoving at \(z = (3.2, 1.4, 0.5)\), respectively, as in observations.

3. A NEW MODEL FOR QSO-HOSTING

DARK MATTER HALOS AT \(Z = 0.5–3.2\)

Our physical modeling is motivated by insights on cosmic gas evolution from cosmological hydrodynamic simulations and
observations. Simulations show four significant trends. First, cosmological structures collapse to form sheet, filaments, and halos, and shock-heat the gas to progressively higher temperatures with decreasing redshift (e.g., Cen & Ostriker 1999). Second, overdense regions where larger halos are preferentially located begin to be heated earlier and have higher temperatures than lower density regions at any given time, causing specific star formation rates of larger galaxies to fall below the general dimming trend at higher redshift than less massive galaxies and galaxies with high sSFR to gradually shift to lower density environments at lower redshift. This physical process of differential gravitational heating with respect to redshift is able to explain the apparent cosmic downsizing phenomenon (e.g., Cowie et al. 1996), the cosmic star formation history (e.g., Hopkins & Beacom 2006), and galaxy color migration (Cen 2011, 2014). Third, quasars appear to occur in congested environments, as evidenced by high bias inferred based on their strong clustering, with the apparent merger fraction of bright QSOs (L > \(10^{46}\) erg s\(^{-1}\)) approaching unity (e.g., Hickox et al. 2014). Finally, a quasar host galaxy presumably channels a significant amount of gas into its central black hole, which we interpret as the galaxy being rich in cold gas. This requirement would exclude satellite halos of high-mass halos at lower redshift when the latter become hot-gas-dominated (e.g., Feldmann et al. 2011; Cen 2014). These physical considerations provide the basis for the construction of the new model detailed in the steps below. First, for \(z > 1\).

(1) All—central and satellite—halos with virial mass \(> m_{h,0}\) constitute the baseline sample, denoted as SA.

(2) Each halo in SA is then selected with the following probability, PDF(DR), computed as follows. For a halo \(X\) of mass \(m_h\), we make a neighbor list of all neighbor halos with mass \(\geq m_h/2\). For each neighbor halo on the neighbor list, we compute \(\Delta r = d_n/r_{p,n}\), where \(d_n\) is the distance from \(X\) to, and \(r_p\) is the virial radius of, the neighbor in question. We then find the minimum of all \(\Delta r_n\)’s, calling it DR for halo X. PDF(DR) is defined as

\[
\text{PDF}(\text{DR}) = 1 \quad \text{for} \quad \text{DR} < \text{DR}_0; \quad \text{PDF}(\text{DR}) = (\text{DR}_0/\text{DR})^3 \quad \text{for} \quad \text{DR} \geq \text{DR}_0.
\]

(4) Our choice of the specific PDF is somewhat arbitrary but serves to reflect our assertion that the probability of dark matter halos hosting quasars decreases if the degree of interactions decreases, when \(\text{DR} > \text{DR}_0\). The results remain little changed, for example, had we used a steeper power law of 4 instead of 3. At \(z < 1\), when the mean SFR in the universe starts a steep drop (Hopkins & Beacom 2006), we impose an additional criterion (3) to account for the gravitational heating.

(3) Those halos that are within the virial radius of massive halos \(> m_{h,0}\) are removed for \(z < 1\).

In essence, we model the quasar hosts at \(z > 1\) with two parameters, \(m_{h,0}\) and \(\text{DR}_0\), and at \(z < 1\) with three parameters, \(m_{h,0}\), \(\text{DR}_0\), and \(M_{\text{cen}}\).

We present results in the order of decreasing redshift. Figure 1 shows the ACF of quasar hosts at \(z = 3.2\) for three cases: \((m_{h,0}, \text{DR}_0) = (2 \times 10^{12} M_\odot, 3), (5 \times 10^{12} M_\odot, 3),\) and \((2 \times 10^{12} M_\odot, 1)\). Based on halo occupation distribution (HOD) modeling, Richardson et al. (2012) infer the median mass of quasar host halos at \(z \sim 3.2\) of \(M_{\text{cen}} = 14.1^{+5.8}_{-6.9} \times 10^{12} h^{-1} M_\odot\), consistent with the threshold mass case with \(M_h = 10^{13} M_\odot\). All model ACFs fall below the observed data at \(r_p \geq 30\) Mpc due to simulation box size. The ACF amplitude is seen to increase with increasing \(m_{h,0}\). The ACF with a smaller value of \(\text{DR}_0\) steepens at a smaller \(r_p\) and rises further toward lower \(r_p\). This behavior is understandable, since a lower \(\text{DR}_0\) overweight pairs at smaller separations. The extant observations do not allow useful constraints on \(\text{DR}_0\) at \(z = 3.2\). We see from visual examination that \(m_{h,0} = (2-5) \times 10^{12} M_\odot\) provides an excellent fit to the observed ACF for \(r_p = 2-30 h^{-1}\) Mpc.

Figure 2 shows the ACF of quasar hosts at \(z = 1.4\) for three cases: \((m_{h,0}, \text{DR}_0) = (2 \times 10^{11} M_\odot, 0.5), (5 \times 10^{11} M_\odot, 0.5),\)
Anderson et al. (2012) is from the Baryon Oscillation Spectroscopic Survey (Schlegel et al. 2009; Dawson et al. 2013). The sample of 8198 quasars at \( z \sim 0.53 \) (shown in both the left and right panels), respectively, at \( (2–5) \times 10^{13} M_\odot \) provides excellent fits to the observed ACF for \( r_p = 1–40 h^{-1} \text{Mpc} \). The observed ACF extends down to about 20 \( h^{-1} \text{kpc} \), which allows us to constrain \( \Delta R_0. \) We see that, varying \( \Delta R_0 \) from 1.0 to 0.5, the amplitude of the ACF at \( r_p \leq 1 h^{-1} \text{Mpc} \) increases, with \( \Delta R_0 = 0.5 \) providing a good match. The physical implication is that quasar activities at \( z = 1.4 \) seem to be triggered when a halo of mass \( \gtrsim (2–5) \times 10^{11} M_\odot \) interacts significantly with another halo of comparable mass, in contrast to the \( z = 3.2 \) quasars that are primarily hosted by central galaxies with no major companions.

Finally, Figure 3 shows the results at \( z = 0.51 \). The left panel shows the ACF of halos with masses above the threshold \( 10^{13} h^{-1} M_\odot \)—mock CMASS galaxies—provides a good match to the observed ACF of CMASS galaxies. Consistent with previous analysis, we see that the CCF between halos with masses above the threshold \( 3.5 \times 10^{12} M_\odot \) and mock CMASS galaxies match the observed counterpart. The right panel of Figure 3 shows the mock quasar-CMASS galaxy CCF at \( z = 0.51 \) for four cases with \( (m_{h,0}, M_{h,0}, \Delta R_0) = (2 \times 10^{11} M_\odot, 2 \times 10^{13} M_\odot, 0.5) \) (solid red diamonds), \( (2 \times 10^{11} M_\odot, 2 \times 10^{13} M_\odot, 1.0) \) (solid green hexagons), \( (5 \times 10^{10} M_\odot, 2 \times 10^{13} M_\odot, 1.0) \) (open blue squares), and \( (2 \times 10^{11} M_\odot, 1 \times 10^{13} M_\odot, 1.0) \) (open yellow stars).

and \( (2 \times 10^{11} M_\odot, 1.0) \). The threshold mass case with \( M_{h,0} = 6 \times 10^{12} M_\odot \) provides a good match to the observational data for \( r_p = 1–30 h^{-1} \text{Mpc} \), consistent with HOD modeling by Richardson et al. (2012), who constrain the median mass of the central host halos to be \( M_{\text{cen}} = 4.1^{+0.4}_{-0.3} \times 10^{12} h^{-1} M_\odot \). We see that \( m_{h,0} = (2–5) \times 10^{11} M_\odot \) provides excellent fits to the observed ACF for \( r_p = 1–40 h^{-1} \text{Mpc} \). The observed ACF extends down to about 20 \( h^{-1} \text{kpc} \), which allows us to constrain \( \Delta R_0. \) We see that, varying \( \Delta R_0 \) from 1.0 to 0.5, the amplitude of the ACF at \( r_p \leq 1 h^{-1} \text{Mpc} \) increases, with \( \Delta R_0 = 0.5 \) providing a good match. The physical implication is that quasar activities at \( z = 1.4 \) seem to be triggered when a halo of mass \( \gtrsim (2–5) \times 10^{11} M_\odot \) interacts significantly with another halo of comparable mass, in contrast to the \( z = 3.2 \) quasars that are primarily hosted by central galaxies with no major companions.

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consistent with the fact that the red CMASS galaxies are red due to the same environment effects and hence have about the same halo mass \( M_{h,0} = 10^{13} h^{-1} M_\odot \).

4. Predictions and Tests of Our Model

We have demonstrated that our physically based model can account for the observed clustering of quasars at \( z = 3.2, 1.4, 0.53 \). Figure 4 contrasts the sharp differences between our model and the conventional HOD based modeling; the halo masses in our model are an order of magnitude lower than those inferred from HOD modeling. Our model gives quasar-hosting halo mass threshold of \( (2–5) \times 10^{12}, (2–5) \times 10^{11}, (1–3) \times 10^{11} \) at \( z = (3.2, 1.4, 0.53) \), respectively.
median mass of \((14.1^{+5.8}_{-6.9} \times 10^{12}, 4.1^{+0.3}_{-0.4} \times 10^{12}, 4.0 \times 10^{12}) h^{-1} M_\odot\) based on HOD modeling (Richardson et al. 2012; Shen et al. 2013). Although we have not made fitting for quasars at redshifts higher than \(z = 3.2\), we anticipate that the quasars at higher redshifts that have comparable luminosities as those at \(z = 3.2\) will primarily be hosted by central galaxies of mass \((2–5) \times 10^{12} M_\odot\). We note that the median luminosity of the observed quasars decreases from \(~10^{46}\) erg s\(^{-1}\) at \(z \geq 1.4\) to \(~10^{45}\) erg s\(^{-1}\) at \(z = 0.53\), which reflects the known downsizing scenario and is in accord with the decreasing halo mass with decreasing redshift inferred in our model. Our results and detailed comparisons with HOD based modeling are also tabulated in Table 1, along with inferred quasar duty cycles and lifetimes.

Can we differentiate between these two models? Trainor & Steidel (2012) cross correlate 1558 galaxies with spectroscopic redshifts with 15 of the most luminous (\(\geq 10^{44} L_\odot, M_{1450} \approx 30\)) quasars at \(z \approx 2.7\). Even for these hyperluminous quasars (HLQSOs), they infer a host halo mass of \(\log(M_{h}/M_\odot) = 12.3 \pm 0.5\), which is in very good agreement with our model \(\log(M_{h}/M_\odot) = 2–5 \times 10^{12} M_\odot\) but much smaller than inferred from HOD modeling. They also find that, on average, the HLQSOs lie within significant galaxy over-densities, characterized by a velocity dispersion \(\sigma_v \approx 200\) km s\(^{-1}\) and a transverse angular scale of \(~25' \approx 200\) physical kpc, which they argue correspond to small groups with \(\log(M_{h}/M_\odot) \approx 13\). The rare HLQSOs are apparently not hosted by rare dark matter halos. This is fully consistent with our suggestion that dark matter halo mass is not the sole determining factor of quasar luminosities and that interactions may be instrumental to triggering quasar activities.

Another independent method to infer halo masses of quasar hosts is to measure their cold gas content. Prochaska et al. (2013) detect about 60%–70% covering fraction of Lyman limit systems within the virial radius of \(z = 2\) quasars, using the binary quasar sample (Hennawi et al. 2006). This has created significant tension: hydrodynamic simulations of the cold dark matter model yield less than 20% covering fraction for halos of mass \(~3 \times 10^{12} M_\odot\) (Paucher-Giguere et al. 2014); halos of still higher mass have still lower covering fractions. On the other hand, the simulations show a \(~60%\) covering fraction if the mass of quasar-hosting halos is \(~3 \times 10^{11} M_\odot\). This indicates that the lower halo masses for quasar hosts in our model can explain the high content of neutral gas in \(z \sim 2\) quasars.

The mean quasar lifetime may be estimated by equating \(t_f \times f_q\), where \(t_f\) is the Hubble time at the redshift in question and \(f_q\) the duty cycle of quasar hosting halos. Existing observational constraints provide useful range for \(t_f\) for quasars at \(z \sim 3\). Lifetimes based on halo abundances from clustering analyses of quasars have been given by many authors (e.g., Martini & Weinberg 2001; Porciani et al. 2004; Shen et al. 2007); in our case, this is a degenerate derivation. Thus, it is useful to have a survey of quasar lifetimes based on other independent methods. Jakobsen et al. (2003) derive \(t_f > 10\) Myr, Worseck et al. (2007) give \(t_f > 25\) Myr, Gonçalves et al. (2008) yield \(t_f = 16–33\) Myr, and McQuinn & Worseck (2014) yield \(t_f \geq 10\) Myr for quasars at \(z \sim 2–3\), all based on the method of the quasar proximity effect. Bolton et al. (2012) obtain \(t_f > 3\) Myr using the line-of-sight thermal proximity effect. Trainor & Steidel (2013), using a novel method of Ly\(\alpha\) emitters (LAEs) exhibiting fluorescent emission via the reprocessing of ionizing radiation from nearby hyperluminous QSOs, find 1 Myr \(\leq t_f \leq 20\) Myr at \(z = 2.5–2.9\). We see that all these estimates are consistent with our model. As a comparison, the inferred \(t_f^{HOD} \approx 400\) Myr at \(z = 3.2\) from HOD modeling.

Finally, self-consistently reproducing the quasar luminosity functions (e.g., Wyithe & Loeb 2002, 2003; Shen 2009; Conroy & White 2013) will provide another test, which we defer to a separate study.

5. CONCLUSIONS

We put forth a new model for dark matter halos that host quasars. Our model is substantially different from previous models based on simple lower mass threshold or HOD based lower mass threshold. Instead, we impose two conditions that are physically based. The first condition is that significant interactions with other halos are a necessary ingredient to trigger quasar activities. Second, satellite halos within the virial radius of large halos above certain mass at low redshift are removed from consideration since they are hot-gas-dominated.

| (1) \(z\) | (2) \(L_{bol}\) \(\log(a^{bol}_{gal})\) \times10^{-7} | (3) \(n_{obs}\) | (4) \(n_{sim}\) | (5) \(m_{h,0}\) \(\times10^{12}\) | (6) \(m_{h,0}\) \(\times10^{-3}\) | (7) \(t_q\) (Myr) | (8) \(f_q^{HOD}\) \(\times10^{12}\) | (9) \(f_q^{HOD}\) \(\times10^{-3}\) | (10) \(t_q^{HOD}\) (Myr) |
|---|---|---|---|---|---|---|---|---|
| 3.2 | 46.3 | 2.5 | 0.2–0.9 | 2–5 | 3–13 | 5–26 | 20 | 215 | 425 |
| 1.4 | 46.1 | 30 | 9–44 | 0.2–0.5 | 0.6–3 | 3–15 | 5.8 | 1.8 | 7.5 |
| 0.53 | 45.1 | 50 | 29–85 | 0.1–0.3 | 0.6–2 | 5–15 | 5.7 | 1.3 | 10 |

Notes. Bold entries indicate values from our model. Column 1: \(z_{med}\) is the median redshift of the sample that is analyzed. Column 2: \(L_{bol}\) is the bolometric luminosity of the observed quasar sample obtained using conversions in Richards et al. (2006) and Runnoe et al. (2012). Column 3: \(n_{obs}\) is the number density of the observed quasar sample (Shen & Kelly 2012) in \([\text{Mpc}^{-3} h^{-1}]\). Column 4: \(n_{sim}\) is the number density of the dark matter halos with mass \(> m_{h,0}\) in \([\text{Mpc}^{-3} h^{-3}]\). Column 6: \(f_q^{HOD}\) is the duty cycle of the quasars in our model. Column 7: \(t_q\) is the mean quasar lifetime in our model defined as \(t_f \times f_q\), where \(t_f\) is the Hubble time at the redshift in question. Column 8: \(M_{HOD}^{q}\) is the derived host halo mass of the observed population of quasars derived from HOD modeling (Richardson et al. 2012; Shen et al. 2013) in \([M_\odot]\). Column 9: \(f_q^{HOD}\) is the duty cycle of the observed population of quasars based on HOD modeling, using the type II quasars-corrected abundance in Column 3. Column 10: \(t_q^{HOD}\) is the life time of the quasars based on \(f_q^{HOD}\) in Column 9.
We investigate this model utilizing halo catalogs from the Millennium Simulation. By requiring that halos simultaneously meet these two conditions and match two-point auto-correlation functions of quasars and cross-correlation functions between quasars and galaxies, we are able to identify quasar-hosting halos. The resulting host halos are distinctly different from other models. Quasar hosts are less massive, by an order of magnitude, than inferred based on either simple halo mass threshold or HOD models. Quasar hosts are less massive, by an order of magnitude, than inferred based on either simple halo mass threshold or HOD models. The resulting host halos are distinctly different from other models. Quasar hosts are less massive, by an order of magnitude, than inferred based on either simple halo mass threshold or HOD models.

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