INTRODUCTION

DCBHs may be the origins of the first quasars in the universe (e.g., Mortlock et al. 2011; Banados et al. 2018; Matsuoka et al. 2013). They are thought to form in primordial halos immersed in either strong Lyman-Werner ( LW) UV fluxes (Agarwal et al. 2016) or highly supersonic baryon streaming flows (Hirano et al. 2017; Schauer et al. 2017), either of which can prevent them from forming primordial (or Pop III) stars until they reach masses of $10^7 - 10^8 M_\odot$ and virial temperatures of $\sim 10^4$ K that trigger rapid atomic H cooling. Atomic cooling causes gas to collapse at rates of up to $\sim 1 M_\odot$ yr$^{-1}$, forming an accretion disk that builds up a single, supermassive star at its center (Lodato & Natarajan 2006; Regan & Haehnelt 2009; Latif et al. 2013 – although binaries or even small multiples are now thought to be possible; Latif et al. 2020).

Stellar evolution models show that these stars can reach masses of a few $10^5 M_\odot$ before collapsing to DCBHs via the general relativistic instability (Hosokawa et al. 2013; Umeda et al. 2016; Woods et al. 2017; Haeusler et al. 2018b), although a few for which accretion has shut down have been found to explode as highly energetic thermonuclear supernovae (Whalen et al. 2013b; Johnson et al. 2013a).

Chen et al. (2014). DCBHs are currently the leading candidates for the seeds of the first supermassive black holes (SMBHs) because they are born with large masses in high densities in halos that can retain their fuel supply, even when heated by X-rays (Johnson et al. 2013b – see Valiante et al. 2017; Woods et al. 2019 for recent reviews). In contrast, while Pop III star BHs in principle can reach $10^9 M_\odot$ with periodic episodes of super- or hyper-Eddington accretion (Volonteri et al. 2013; Pezzulli et al. 2016), their environments are hostile to such growth (Whalen et al. 2004; Alvarez et al. 2009; Whalen & Fryer 2012; Smith et al. 2018).

What are the prospects for detecting DCBHs, and thus the birth of the first quasars? Using one-dimensional (1D) radiation hydrodynamical models, Pacucci et al. (2013) predicted that DCBHs could be detected by the James Webb Space Telescope (JWST) in the near infrared (NIR) at $z \sim 25$ and by the Advanced Telescope for High-Energy Astrophysics (ATHENA) at $z \sim 15$. Natarajan et al. (2017) used such models to develop criteria for distinguishing the host galaxies of DCBHs from those of other SMBH seeds at $z \sim 10$, showing that JWST can distinguish between seeding mechanisms at this redshift. But these models assume idealized host halos and neglect the cold flows required for the BHs to later become quasars by $z \sim 7$. Like the supermassive stars from which they form, DCBHs are deeply imbedded in these flows, which can heavily reprocess radiation from the BH in ways that could not be considered in previous studies, changing their rest frame spectra and NIR luminosities today.

Here, we calculate NIR AB magnitudes for a DCBH at birth in the flows in which it grows into a quasar by $z \sim 7$. Rather than assuming a grid of accretion rates for the BH, ours are an emergent feature of a cosmological simulation. Our models capture the anisotropy of X-ray breakout into the early intergalactic medium (IGM) and how it affects their detection today. In Section 2 we review our cosmological simulation and how we extract AB magnitudes for the BH from it. DCBH spectra and AB
magnitudes for a variety of JWST, Euclid and WFIRST bands are examined in Section 3, and we conclude in Section 4.

2. NUMERICAL METHOD

We first extract luminosities and H II region profiles for the DCBH from Smidt et al. [2018], which was done with the Enzo adaptive mesh refinement (AMR) cosmology code Bryan et al. [2014]. They are then post processed with Cloudy [Cloudy Collaboration et al. 2017] to obtain rest frame BH spectra. These spectra are then cosmologically redshifted and dimmed, corrected by absorption by the neutral IGM at z > 6, and convolved with telescope filter functions to compute AB magnitudes in a variety of NIR bands as a function of source redshift.

2.1. Enzo Model

Here we briefly review our Enzo simulation. We found a 100 h\(^{-1}\) Mpc box that contains a halo that grows to 1.2 \(\times 10^{12} M_{\odot}\) by z = 7 by accretion rather than by major mergers. We then centered three nested grids on this halo, resimulated it down to z = 19.2, when it reaches a mass of 3 \(\times 10^{8} M_{\odot}\) and begins to atomically cool, placed a 10\(^3\) \(M_{\odot}\) DCBH at its center, and turned on X-rays. Our root grid was 256\(^3\) and the nested grids were 25 \(h^{-1}\) Mpc each for an effective resolution of 2048\(^3\). The initial dark matter and baryon mass resolutions were 8.41 \(\times 10^6 h^{-1} M_{\odot}\) and 1.57 \(\times 10^6 h^{-1} M_{\odot}\), respectively.

We initialized the grid with gaussian primordial density fluctuations at z = 200 with MUSIC [Hahn & Abel 2011], with cosmological parameters from the second-year Planck best fit lowP+lensing+BAO+JLA+H\(_{0}\). \(\Omega_{m} = 0.308, \Omega_{\Lambda} = 0.691, \Omega_{b} = 0.0223, h = 0.677, \sigma_{8} = 0.816, \text{and } n = 0.968\) [Planck Collaboration et al. 2016]. Our maximum refinement level \(l = 10\) produced a maximum resolution of 35 pc (comoving), which was sufficient to resolve the gas flows and radiation transport deep in the halo. Given that only one or two dozen halos per Gpc\(^{-3}\) are expected to reach \(\sim 10^{12} M_{\odot}\) by z = 7 by smooth accretion [Di Matteo et al. 2012, Feng et al. 2014], our 100 \(h^{-1}\) Mpc box was the smallest one that could enclose such a reservoir in a reasonable number of tries. The grid was refined on baryon and dark matter overdensities of 3 \(\times 2^{-0.2i}\) and 3, respectively. The local Jeans length was resolved with 32 zones at all times to avoid artificial fragmentation during collapse.

X-rays from the BH were propagated with the MORAY ray tracing code [Wise & Abel 2011], which is self-consistently coupled to hydrodynamics and nine-species nonequilibrium primordial gas chemistry in Enzo. This physics is key to capturing the onset of SF in the primordial galaxy at later times because free electrons due to secondary ionizations by energetic photoelectrons, which are included in the chemistry and energy equations, catalyze the formation of H\(_2\), which cools gas and creates stars (see, e.g., Machacek et al. 2003). MORAY includes radiation pressure on gas due to photoionizations, and Compton heating by X-rays and primordial gas cooling are included in the energy equation: collisional excitational and ionizational cooling by H and He, recombinational cooling, bremsstrahlung cooling, H\(_2\) cooling, and inverse Compton cooling by the cosmic microwave background.

The BH was represented by a sink particle with a 1 keV X-ray luminosity \(L_x = \epsilon_{x} m_{\text{BH}} c^2\), where \(\epsilon_{x}\), the mean radiative efficiency, is 0.1, and \(m_{\text{BH}}\) is the accretion rate. Because our simulations did not resolve the accretion disk of the BH, we used an alpha disk model to compute \(m_{\text{BH}}\) to approximate the transport of angular momentum out of the disk on subgrid scales. Although stochastic star formation, which includes winds, ionizing UV and supernovae due to stars, was turned on at the same time as X-rays from the BH, no stars formed in the short times we examine the DCBH here so its host halo is still free of metals. We also turned on a uniform LW background due to a global population of primordial stars that evolved with redshift. An image of the H II region of the DCBH at z = 17 is shown in the left panel of Figure 1.

2.2. Cloudy Spectra

To compute DCBH spectra we port spherically-averaged density and temperature profiles of the H II region of the BH from Enzo to Cloudy. They are tabulated in 33 bins that are uniformly partitioned in log radius and extend to the outer layers of the H II region where the temperature of the gas has fallen below 10\(^4\) K (\(\sim 30\) kpc). Each radial bin, or shell, constitutes a single Cloudy model in which densities and temperatures are assumed to be constant. The spectrum emerging from the outer surface of one shell is calculated and then used as the incident spectrum of the next shell. The spectrum emerging from the outermost shell of the H II region is taken to be the rest frame spectrum of the quasar.

The spectrum incident to the lower face of the innermost shell is assumed to be a broken power law \(F_{\nu} \propto \nu^{\alpha}\), where \(\alpha = -2\) for \(h\nu > 50\) keV (2.48 \(\times 10^{-5}\) \(\mu\)m), \(\alpha = -1.6\) for \(50\) keV > \(h\nu > 0.124\) eV (10 \(\mu\)m), and \(\alpha = 5/2\) above 10 \(\mu\)m. It is normalized to the bolometric luminosity of the DCBH. Coronal equilibrium is assumed, in which the gas is collisionally ionized. The rest frame spectrum of the DCBH was calculated at z = 17, when X-rays break out of its host halo. We require Cloudy to use the temperatures Enzo calculates for the H II region instead of inferring them from the spectrum and luminosity of the BH and its surrounding density field because they take into account cooling due to nonequilibrium primordial gas chemistry in cosmological flows. How we compute AB magnitudes from rest frame Cloudy spectra is described in detail in Surace et al. [2018].

3. DETECTING DCBHs

We show rest frame spectra for the DCBH at z = 17 before and after reprocessing by the halo in the right panel of Figure 1. It has a bolometric luminosity of 4.18 \(\times 10^{44}\) erg s\(^{-1}\) corresponding to an accretion rate of 0.85 \(L_{\text{Edd}}\). There is a conspicuous lack of metal lines in the emergent spectrum because X-rays from the BH have not yet triggered star formation. Strong Ly\(\alpha\) absorption is evident at 1216 A as is continuum absorption below 912 A due to the ionization of H. Additional absorption features due to ionization of He I and He II are visible at 504 A and 227 A, respectively. Several prominent He emission lines are superimposed on the continuum absorption below 912 A. There are H\(_{\alpha}\) and weak Paschen series lines at 6560 A and 12800 A. Unlike the spectrum of the cool, red progenitor star [Surace et al. 2018], there
is a lack of continuum absorption above and below 16500 Å due to H$^{-}$ bound-bound and bound-free opacity in the DCBH spectrum because it is destroyed by radiation from the BH.

### 3.1. **NIR Magnitudes**

We show AB magnitudes for the DCBH at $z = 8 - 20$ in *JWST* NIRCam bands at 2.5 - 4.6 μm along with 5σ detection limits for the filters for 100 hr exposures in the top left panel of Figure a. The BH is clearly brighter in the NIR than its progenitor star (see Figures 4 and 3 of Surace et al. 2018, 2019, respectively), with AB magnitudes that are 0.5 - 2.5 brighter depending on filter and wavelength. The magnitudes in all four filters are also more tightly grouped together in consequence of the relatively flat power-law spectrum of the BH. The drop in magnitude at $z = 18$ at 2.5 μm is due to the redshifting of the Lyα absorption feature of the rest frame spectrum into that wavelength. The BH is brightest in the 4.60 μm and 4.44 μm filters over all redshifts, with magnitudes that vary from 27.5 - 30.1 from $z = 8 - 20$. We find that detections in all four NIRCam filters are possible out to $z \sim 19$ with 100 hr exposures and in all the bands redward of 3.56 μm out to $z \sim 25$.

As shown in the upper right panel of Figure b, DCBH magnitudes in the MIRI filters are significantly brighter than in NIRCam, ranging from 24.5 - 27 at 25.5 μm to 27 - 29.8 at 5.6 μm for $z = 8 - 20$. Some of these magnitudes are also much brighter than those of the progenitor star. For example, the magnitudes of a red SMS vary from 31 - 32 at 5.6 μm over the same redshift range (Surace et al. 2018). The ordering of the magnitudes with filter wavelength for the SMS is opposite that of the DCBH, with the shortest wavelengths having the brightest magnitudes. This feature is due to continuum absorption by H$^{-}$ in the envelope of the SMS that is absent from the host halo of the BH. However, while the DCBH magnitudes are brighter in MIRI than NIRCam, the 5σ detection limits for a 100 hour exposure are considerably dimmer, ranging from 24.8 at 18 μm to 28.0 at 5.6 μm. They limit detections of DCBHs to $z = 9$ at 18 μm to $z = 12$ at 5.6 μm. Nevertheless, these AB magnitudes reveal that MIRI could be a powerful instrument for the detection of DCBHs at high redshifts and could discriminate them from SMSs at the same epochs, for which there would be no MIRI signal.

We show DCBH magnitudes in the *Euclid* and WFIRST bands in the lower two panels of Figure 2. Absorption by the neutral IGM at $z \gtrsim 6$ quenches flux in the Y, J and H bands at $z \gtrsim 7$, 10 and 14, respectively, limiting DCBH detections to these redshifts in these filters. Magnitudes vary from 29 - 34 in *Euclid* and 29 - 37 in WFIRST. The AB magnitude limits of 26 and 28 for surveys currently planned for *Euclid* and WFIRST, respectively, would rule out direct detections of DCBHs at $z \gtrsim 6 - 8$.

### 3.2. **DCBH Formation / Detection Rates**

While our synthetic spectrum indicates that DCBHs would be detectable in multiband photometric surveys with *JWST* at $z \sim 8 - 20$, the prospect of actually finding such objects in a given survey depends on their formation rates and the time interval over which a DCBH is likely to display tell-tale spectral or photometric signatures. Wise et al. (2019) and Regan et al. (2019) identified atomically cooling halos at $z \gtrsim 12$ in the Renaissance simulations that could form DCBHs. The 3 DCBH candidate halos that appeared in their 220 cMpc$^{-3}$ average-density region over the $\sim 70$ Myr from $z \sim 14 - 12$ imply a formation rate of $\sim 10^{-10}$ cMpc$^{-3}$ yr$^{-1}$ at these redshifts. While their simulations did not track the subsequent evolution of the gas in these halos, this formation rate can be used to place an upper limit on detections of DCBHs in future *JWST* surveys.

If we adopt a characteristic time scale of $10^{7}$ yr for the validity of our spectrum (set by when star formation likely begins in its host halo) then we expect a comoving density of observable DCBHs of $\sim 10^{-3} f_{\text{DCBH}}$ cMpc$^{-3}$, where $f_{\text{DCBH}}$ is the fraction of candidate halos that produce $\sim 10^{5} M_{\odot}$ BHs. The *JWST* NIRCam...
Fig. 2.—NIR AB magnitudes for the $1.0 \times 10^5 \, M_\odot$ DCBH at birth as it would appear at $z = 8 - 20$ in JWST, Euclid and WFIRST.

Top left: JWST NIRCam bands. The horizontal dashed lines are 5σ AB magnitude detection limits for 100 hour exposures in the filters of corresponding color (2.77 µm: 31.4, 3.56 µm: 31.5, 4.44 µm: 31.0 and 4.60 µm: 29.8). Top right: JWST MIRI bands. The horizontal dashed lines are 5σ AB magnitude detection limits for 100 hour exposures in the filters of corresponding color (5.6 µm: 28.0, 7.7 µm: 27.6, 10.0 µm: 27.0, 15.0 µm: 26.1 and 18.0 µm: 24.7). Bottom left: Euclid. Bottom right: WFIRST. The horizontal dashed lines are detection limits for each instrument (32 for NIRCam, 28 for MIRI assuming a 20 hr exposure, and 26 and 28 for deep-drilling fields in Euclid and WFIRST, respectively.

field of view (9.7 arcmin$^2$) covers $1.3 \times 10^4$ cMpc$^3$ per unit redshift at $z \sim 12$, so one would expect $\sim 10 f_{DCBH}$ detectable DCBHs for each such survey field. With planned medium-deep NIRCam multiband surveys covering $\sim 20$ times this area down to AB mag 29 in the longest-wavelength NIRCam filters (Rieke et al. 2019), the prospects for detecting DCBHs photometrically with JWST would appear to be quite good, even if just some minor fraction ($f_{DCBH} \lesssim 0.01$) of the Regan et al. (2019) candidate halos end up forming them. Another route to detection could be to search the field around an unusually bright $z \sim 15$ galaxy found by some other means, as Wise et al. (2019) and Regan et al. (2019) note that the formation rate of DCBHs may rise by more than an order of magnitude in high-density regions, where the most massive first galaxies are also expected to form.

4. DISCUSSION AND CONCLUSION

With NIRCam AB mag photometry limits of 31 - 32 and NIRSpec limits of $\sim 29$, JWST will be able to detect the birth of the first quasars at $z \gtrsim 20$ and spectroscopically confirm their redshift out to $z \sim 10 - 12$. Our DCBH magnitudes are consistent with simplified 1D calculations in past studies (Pacucci et al. 2015; Natarajan et al. 2017). As shown in the previous section, up to 10 DCBHs could appear in any given JWST survey field from $z = 8 - 20$. But the prospects for discovering them would be better if they could also be found by Euclid and WFIRST because their wide fields would enclose far more of them at high redshifts. Once flagged, DCBH candidates could then be examined with JWST or ground-based extremely large telescopes in greater detail. But, as shown in Figure 2, DCBH magnitudes in the H band magnitudes at $z = 8 - 20$ are dimmer than the detection limits currently envisioned for Euclid and WFIRST (26 and 28, respectively). In principle, these magnitudes could become brighter if accretion rates exceed the Eddington limit but only modestly so because the luminosity rises only logarithmically with such rates, not linearly.

However, this does not mean Euclid and WFIRST cannot find DCBHs at birth because only modest gravi-
tional lensing is required to boost their fluxes above their detection limits. The survey areas of both missions will enclose thousands of galaxy clusters and massive galaxies that could lens flux from background DCBHs, and at \( z \sim 8 - 14 \) magnification factors of only 10 - 100 would be required to reveal them. It is likely that a sufficient fraction of their survey areas will be magnified by \( \sim z - 8 \) magnification factors of only 10 - 100. Even higher magnifications may be realized in future surveys of individual cluster lenses by \( JWST \) but at the cost of smaller lensing volumes (e.g., Whalen et al. 2013; Windhorst et al. 2018).

DCBHs can be distinguished from their SMS progenitors at high redshift because they are brighter and have much higher ratios of flux in the MIRI and NIRCam bands. Also, unlike SMSs and high-z galaxies, they are transients because of variations in cosmological flows onto them on timescales as short as the redshifted light-crossing time of the BH. Periodic dimming and brightening could therefore tag these objects as high-z BHs in transient surveys proposed for \( JWST \) such as FLARE (Wang et al. 2017). Initial redshift cuts can be made for DCBHs because they could appear as dropouts in the NIRCam filters, but more precise determinations would require spectroscopy by instruments such as NIRSpec with \( JWST \) or MOSAIC for the Extremely Large Telescope. Synergies between \( Euclid \) or WFIRST and \( JWST \) or 20+ m ground-based telescopes could open the era of \( z \sim 8 - 20 \) quasar astronomy in the coming decade.

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