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On the observability of individual Population III stars and their stellar-mass black hole accretion disks through cluster caustic transits

Thematic Areas: • Formation and Evolution of Compact Objects; • Cosmology and Fundamental Physics; • Stars and Stellar Evolution; • Resolved Stellar Populations and their Environments; • Galaxy Evolution; • Multi-Messenger Astronomy and Astrophysics.

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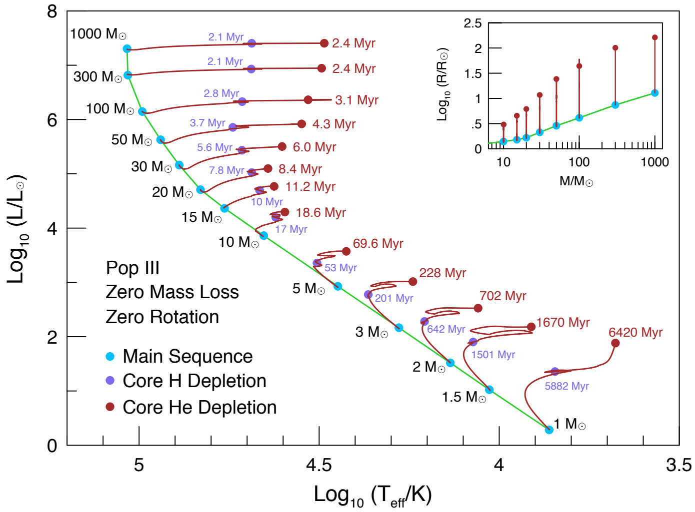
Abstract: Recent near-infrared power-spectra and panchromatic Extragalactic Background Light (EBL) measurements provide upper limits on the integrated near-infrared surface brightness (SB$\gtrsim$31mag arcsec^{-2} at 2μm) that may come from Population III (Pop III) stars and possible accretion disks around resulting stellar-mass black holes (BHs) in the epoch of First Light, broadly taken from z$\simeq$7–17. Physical parameters for zero metallicity Pop III stars at z$\gtrsim$7 can be estimated from `MESA` stellar evolution models through helium-depletion, and for BH accretion disks from quasar microlensing results and multicolor accretion models. Second-generation non-zero metallicity stars can form at higher multiplicity, so that BH accretion disks may be fed by Roche-lobe overflow from lower-mass companions in their AGB stage. The near-infrared SB constraints can be used to calculate the number of caustic transits behind lensing clusters that the James Webb Space Telescope (JWST) and the next generation 25–39 m ground-based telescopes may detect for both Pop III stars and stellar mass BH accretion disks. Because Pop III stars and stellar mass BH accretion disks have sizes of a few$\times10^{-11}$ arcsec at z$\gtrsim$7, typical caustic magnifications can be $\mu\simeq10^4$–10^5, with rise times of hours and decline times of $\lesssim$1 year for cluster transverse velocities of $v_T\lesssim1000$ km s^{-1}. Microlensing by intracluster medium objects can modify transit magnifications, and lengthen visibility times. Depending on BH masses, accretion-disk radii and feeding efficiencies, stellar-mass BH accretion-disk caustic transits could outnumber those from Pop III stars. To observe Pop III caustic transits directly may require monitoring 3–30 lensing clusters to AB$\lesssim$29 mag over a decade or more. *Such a program must be started with JWST at the start of Cycle 1, and — depending on the role of microlensing in the Intra Cluster Light (ICL) — should be continued for decades with the next generation 25–39 m ground-based telescopes, where both JWST and the ground-based facilities each will play a unique and strongly complementary role.*

1. Introduction: In this paper we consider if the James Webb Space Telescope (JWST; Gardner et al. 2006; Rieke et al. 2005; Beichman et al. 2012; Windhorst et al. 2008) can detect First Light objects directly. JWST's Near-InfraRed Camera (NIRCam) is expected to reach medium-deep to deep (AB$\simeq$28.5–29 mag) flux limits routinely, and in ultradeep surveys perhaps as faint as AB$\simeq$30–31 mag. Unlensed Pop III stars or resulting stellar-mass black hole (BH) accretion disks at z$\simeq$7–25 likely have fluxes of AB$\simeq$35–43 mag, and therefore are not directly detectable by JWST, not even via ordinary gravitational lensing (*e.g.*, Rydberg et al. 2013), which gives typical magnifications of $\mu\simeq10$ or $\sim$2.5 mag (*e.g.*, Lotz et al. 2017). However, cluster caustic transits, when a compact restframe UV-source transits a caustic due to the cluster motion in the sky — or due to significant velocity substructure within the cluster — could magnify such compact objects temporarily by factors of $\mu\simeq10^3$–10^5 (*e.g.*, Miralda-Escude 1991; Zackrisson et al. 2015; Kelly et al. 2017, 2018; Diego et al. 2018; Rodney et al. 2018; Windhorst et al. 2018; Chen et al. 2019; Kaurov et al. 2019). This could temporarily boost the brightness of a very compact object by $\mu\simeq$7.5–12.5 mag. Thus if Pop III stars with AB$\simeq$35–41.5 mag at redshifts z$\simeq$7–17 — or accretion disks around their resulting stellar mass BHs — are sufficiently numerous in the sky, they could be detectable for a few months in a a medium-deep or deep (AB$\simeq$28.5–29 mag) monitoring program with JWST of suitable foreground clusters.

2a. Constraints to the Sky-Surface Brightness from Pop III Stars at z$\gtrsim$7: Before we can estimate the number of cluster caustic transits of Pop III objects, we must estimate the maximum possible contribution of Pop III stars and stellar-mass BH accretion disks to the observed near–IR sky surface brightness (the diffuse EBL from z$\gtrsim$7). Based on metallicity arguments, Madau & Silk (2005) suggested that Pop III stars contribute less than a few nW m^{-2} sr^{-1} to the (1–4 μm) InfraRed Background (IRB). Cooray et al. (2012) estimated the Pop III flux to be $\lesssim$0.04 nW m^{-2} sr^{-1} based on a detailed Pop III model for reionization. To confirm these numbers, we estimate the average sky-SB from star-forming objects at z$\simeq$7–8 from the actual HUDF data corrected for incompleteness (Bouwens et al. 2015). To this we need to add the light from the steep faint-end of the galaxy luminosity function (LF) at z$\gtrsim$7 from *inferred but unseen* Pop III objects beyond the detection limit of the deepest HST images, *and* add an estimate of the *maximum* sky-SB from z$\simeq$9 to z$\simeq$17 that is not yet observed. For this, we use the extrapolation of the Madau & Dickinson (2014) cosmic SFR, which is $\sim$0.3 dex above the fits of Finkelstein (2016) and Madau & Fragos (2017) to the most recent WFC3 data at z$\simeq$8–10, resulting in a *most conservative upper limit to the total 2.0 μm sky-SB* from star-forming objects at 7$\lesssim$z$\lesssim$17 down to the luminosity of a single Pop III star: SB$\gtrsim$31 mag arcsec^{-2}.

2b. Diffuse EBL Limits Adopted for Pop III Stellar Mass BH Accretion Disks: Kashlinsky et al. (2012, 2015), Cappelluti et al. (2013), Helgason et al. (2016), and Mitchell-Wynne et al. (2016) provided estimates of the object-free IR-power spectrum. After carefully subtracting all objects in ultradeep Spitzer 3.6 and 4.5 μm images in the GOODS-South field (Grogin et al. 2011; Koekemoer et al. 2011), these papers found a consistent rather uniform *signal* in the power-spectrum on 100–1000$''$ scales with an *r.m.s.* (amplitude)^2 of $\lesssim$0.004 nW^2 m^{-4} sr^{-2}, which is relatively flat on the angular scales where it is well sampled, and is fairly similar between 3.6 and 4.5 μm. This 3.5 μm power spectrum amplitude provides an upper limit to the diffuse 3.5 μm sky-SB that may be generated by objects at z$\gtrsim$7. Cappelluti et al. (2013) cross-correlated the object-subtracted ultradeep Spitzer images with the deepest object-free 0.2–2 keV Chandra images in the same CANDELS field, and found a similar signal on $\gtrsim$10$''$ scales. Cappelluti et al. (2017) fitted the 0.3–7 keV energy spectrum of the X-ray background (XRB) with the redshifted X-ray spectra of known populations, and constrain the fraction of the XRB that can come from unresolved sources — possibly early black holes at z$\gtrsim$6 — as $\lesssim$3% of the peak in the supermassive black hole (SMBH) growth-rate curve at z$\simeq$1–2. If this Spitzer–Chandra cross-correlation signal is real, the implication is that some fraction of it may come from First Light objects at z$\gtrsim$7. This signal has also been modeled with Primordial Black Holes (PBHs; Kohri et al. 2014), Direct Collapse Black Holes (DCBHs; Yue et al. 2013), or Obese Black Holes (OBHs; Natarajan et al. 2017) at z$\gtrsim$7–8. Windhorst et al. (2018, ; hereafter W18) adopt the equivalent sky-SB value of $\gtrsim$30.8 mag arcsec^{-2} at 2.0 μm as the upper limit for BH caustic transit calculations. Note that for caustic transit calculations it does not matter whether the light that comes from z$\gtrsim$7 exists in *faint discrete objects* that have already been detected down to the HUDF limit, or whether this light is fully *unresolved* below the current HUDF object detection limit of AB$\simeq$30 mag. Either way, the maximum 2.0 μm SB of $\sim$31 mag arcsec^{-2} that can be produced at z$\gtrsim$7 may be subject to cluster caustic transits.



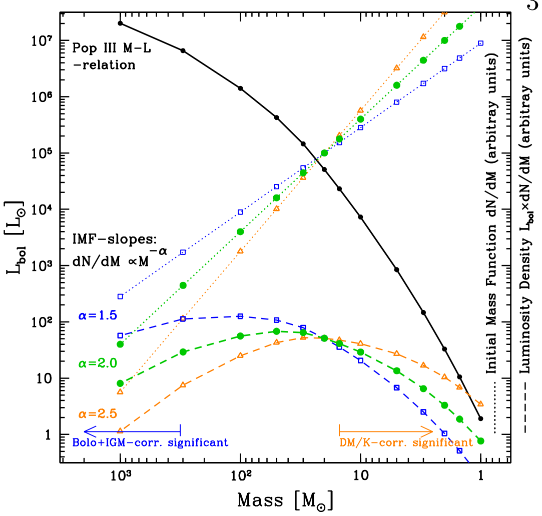


Fig. 1. **(LEFT)** HR diagram for non-rotating, zero mass loss, Z = 0.00 $Z_\odot$ `MESA` models, with evolutionary tracks to core He-depletion shown. Filled circles, labeled by age, correspond to the models in W18. The inset plot shows the mass-radius evolution, with filled circles marking the location of ZAMS and core He-depletion. **Fig. 2 (RIGHT):** The luminosity density (dashed curves) for early star-forming objects inferred from the ZAMS Pop III mass-luminosity relation (solid black line) from W18. The ZAMS Pop III ML-relation is folded with three different IMF slopes (dotted lines), ranging from α=1.5 (top heavy; blue), α=2.0 (normal; green), and α=2.5 (steep IMF; orange). For a Pop III IMF slope of $\alpha\simeq$2, the luminosity density peaks around 30 M$_\odot$, while most of the population's luminosity density is produced between 10–100 M$_\odot$, *i.e.*, the mass range that can produce LIGO-mass BHs!

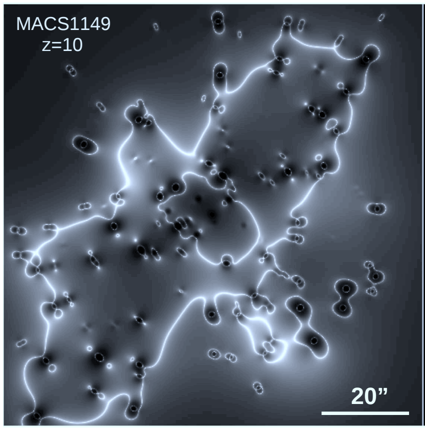
3a. Physical Parameters Adopted for Pop III Stars from `MESA` Models: W18 presented physical properties of Pop III stars from stellar evolution models with HR-diagrams through the hydrogen-depletion and helium-depletion stages, and derived their mass-luminosity relation, bolometric+IGM+K-corrections, and relative contributions to the luminosity density in a faint star-forming object. These non-rotating, zero metallicity, zero mass-loss, single 1–1000 M$_\odot$ star models were calculated using `MESA` (Paxton et al. 2011, 2013, 2015) with physical and numerical parameters the same as those in Farmer et al. (2015), Fields et al. (2016), and Farmer et al. (2016). Fig. 1 shows the zero age main-sequence (ZAMS) in an HR diagram for stellar evolution models with Z = 0.00, and the inset shows their corresponding mass-radius relation. W18 show that Pop III stars with M$\simeq$30–1000 M$_\odot$ have ZAMS photospheric temperatures of 77,000–108,000 K, bolometric luminosities of $L_{\rm bol}\simeq0.16$–20×10^6 $L_\odot$, stellar radii of $R_{\rm MS}$ $\simeq$2–13 R$_\odot$, and main sequence (MS) lifetimes of $\tau_{\rm MS}\simeq$2.1–5.6 Myr. They may therefore be bright enough for occasional caustic transit detections by JWST, as calculated by W18. The MS lifetime τ of the most massive Pop III stars scales roughly as mass/luminosity. Since luminosities are directly proportional to ZAMS mass, the `MESA` models yield MS ages of 5.6–2.1 Myr that are only weakly dependent on ZAMS mass for the mass range of 30–1000 M$_\odot$. Under the assumption that (slightly polluted) massive stars at z$\gtrsim$7 may occur in binary or multiple systems, then for a Salpeter (1955) or flatter IMF, stars with M$\gtrsim$30 M$_\odot$ may have a lower mass companion. Lower mass companion stars with M$\gtrsim$2–5 M$_\odot$ will be in their RGB–AGB stage for $\tau_{\rm GB}$ $\lesssim$30-60 Myr, *i.e.*, much longer than the plausible lifetime of a massive Pop III primary star. They could thus be feeding the LIGO-mass BH leftover from the massive Pop III star after 2.4–6 Myr. As long as the more massive star — during its short giant branch (GB) lifetime — does not transfer the majority of its mass to its companion star, the resulting BH accretion timescale would be driven by the longer GB lifetime of the companion star.

3b. Luminosity Density from Pop III Star Mass-Luminosity Relation and Initial Mass Function: The ZAMS Pop III mass-luminosity relation in Fig. 2 has important implications for the mass range that dominates the luminosity density of a faint star-forming object at z$\gtrsim$7. This is indicated in Fig. 2, where the ZAMS ML-relation is indicated by the solid black line. Three different IMF slopes are indicated in Fig. 2 (dotted curves), ranging from "top-heavy" (α=1.5; blue), "intermediate" (α=2.0; green), and "steep" (α=2.5; orange) which bracket a range of plausible IMFs (*e.g.*, Bastian et al. 2010; Coulter et al. 2017; Scalo 1986). The ZAMS Pop III ML-relation is folded with these three IMF slopes to yield the luminosity density in Fig. 2. For an IMF-slope of $\alpha\simeq$2, most of the *bolometric energy* from faint star-forming objects at z$\gtrsim$7 is thus produced by Pop III stars with masses between 10–100 $M_\odot$, with a smaller contribution from stars with M$\simeq$100–1000 $M_\odot$, and a much smaller contribution from M$\simeq$1–10 $M_\odot$, which is compounded by the significant K-correction for the lowest mass stars (W18). For an IMF slope of $\alpha\simeq2$, the Pop III luminosity density peaks around 30 $M_\odot$ with a broad plateau (green dashed curve in Fig. 2). These are precisely the stars that leave BHs in the mass range observed by LIGO.

4a. Estimates of Cluster Caustic Transits for Pop III stars: To estimate the caustic transit rate and duration for Pop III stars, we first need to evaluate the plausible limits to the transverse velocities of massive lensing clusters, their typical caustic lengths, and the possible effects from microlensing. A Pop III caustic-transit observing program with JWST should select the best lensing clusters with matching prior HST/ACS and WFC3 images, such as the Hubble Frontier Field clusters (HFF; *e.g.*, Lotz et al. 2017; Kawamata et al. 2016; Lagattuta et al. 2017; Acebron et al. 2017; Mahler et al. 2018) or the CLASH clusters (*e.g.*, Postman et al. 2012; Rydberg et al. 2015). Given the significant differences in the allowed v_T-values between the three HFF clusters discussed in W18, we adopt an upper limit of $V_T, s \lesssim 1000$ km s^{-1}. For order-of-magnitude estimates of Pop III object caustic transits at z$\gtrsim$7, we assume average caustic lengths and geometry. Line integration of the lensing models in clusters like Fig. 3b shows that the typical *total* caustic length is $L_{\rm caust} \lesssim 100''$, which we use as upper limit. When a background star crosses a cluster caustic it can be magnified by a factor of up to $\mu\simeq10^5$–10^6 for a short period of time (few weeks–months), depending on the strength of the caustic and the stellar radius, boosting the apparent brightness of the star by ∼12.5–15 mag. Fainter Pop III stars with AB$\simeq$41–43 mag would then be observable with JWST at AB$\lesssim$28.5–29 mag during such caustic crossing events. For the more ubiquitous fold caustics, the magnification near a caustic varies with the distance to the caustic, d, as: $\mu = B_o/\sqrt{d}$, where B_o is a constant that depends on the derivatives of the gravitational potential. For clusters like the HFFs, $B_o\simeq$10–20, while d is expressed in arcseconds (*e.g.*, Miralda-Escude 1991; Diego et al. 2018). Hence, for a Pop III star at z $\gtrsim$7, magnifications of order $\mu\simeq10^3$ can be attained once the star is $\simeq$1 pc away from the caustic (or $d\simeq0''.001$). For an HFF-like cluster with $L_{\rm caust}\simeq100''$, this implies that an area of ∼0.1 arcsec^2 in the source plane can magnify background stars at z$\simeq$12 by $\mu\gtrsim1000$, so that AB$\lesssim$36 mag stars can be lensed to above the detection limit of JWST. Microlensing by ICL can modify transit magnifications, and lengthen visibility times.

4b. Implied Estimates of Cluster Caustic Transits for Pop III Stars: *If* a fraction of the diffuse near-IR background *is* generated by Pop III stars — with a conservative upper limit to their near-IR sky-SB of $\gtrsim$31 mag arcsec^{-2} (§ 2) — then what is the probability that JWST will catch a Pop III star transiting a cluster caustic? We start with the premise that this maximum 1–4 μm sky-SB results from ZAMS Pop III stars with AB$\gtrsim$37.5 mag at z$\gtrsim$7 (§ 2). During their RGB and AGB stages, these Pop III stars may reach AB$\simeq$35 mag at z$\gtrsim$7 (W18). Pop III stars in the mass range of 30$\lesssim$M$\lesssim$1000 $M_\odot$ are the most likely to be detected by JWST at z$\gtrsim$7 at AB$\lesssim$28.5–29 mag *if* the caustic magnifications reach $\mu\gtrsim10^4$–10^5. ZAMS Pop III stars are ∼5.2×10^{-12}–7.78×10^{-11} arcsec across at z$\simeq$12, implying that the brightening time — defined as the time for the magnification to go from zero to its maximum value — is very short (∼0.5–3 hours) when the star transits the caustic *starting* at the "highest-magnification edge". The star would then stay bright for several months to a year, with brightness decaying as $1/\sqrt{t - t_o}$, where $(t - t_o)$ is the time since the stellar disk started the caustic crossing at time t_o. (The reverse transit may of course also be observed).

For an IR background of $\gtrsim$31 mag arcsec^{-2} made up of AB$\simeq$41 mag Pop III stars with M$\simeq$100 $M_\odot$, we estimate that one lensing event can be observed above a flux limit of AB$\simeq$28.5 mag per cluster per ∼2.7 years, or one event when monitoring ∼3 clusters during a year. Because these events should stay detectable at $\mu > \mu$(M=100$M_\odot$) for $t_\mu \simeq 0.4$ years, this implies that ∼ 0.15 such lensed Pop III sources per cluster would be observed above the flux limit at any given time. Thus, for 100 $M_\odot$ Pop III stars, about 6 clusters observed twice about 6 months apart would make the likelihood of observing a lensed Pop III star of order unity, while for more massive stars, detecting a new lensing event (with a time baseline limited to 1 year) would require observation of a larger number of clusters in proportion to the mass M. For lower-mass stars, fewer clusters would need to be observed, as long as they can appear magnified above the detection thresholds of JWST. The *total* transit rates for stars with M$\gtrsim$30 $M_\odot$ that are in principle observable with JWST across the caustics are then predicted to be $\frac{dN_{\rm lens}}{dt}\lesssim0.30$ events per cluster per year. Observing more often when scheduling allows for clusters at higher Zodiacal latitude would be preferred. Since the uncertainty factors



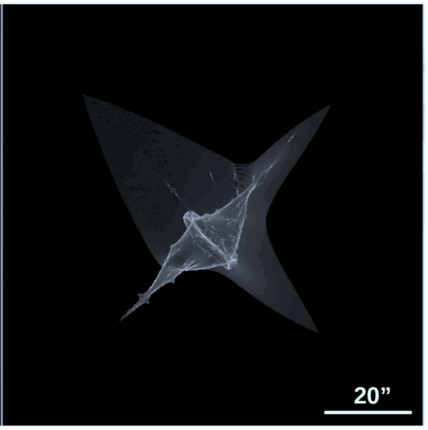


Fig. 3a (LEFT): Lensing magnification map for a galaxy cluster at z$\simeq$0.54 and a source at z=10 (*e.g.*, Lotz et al. 2017). White areas mark the critical curves, where maximum lensing magnification ($\mu \gtrsim$ 10–20) is observed for a source with $r_{\rm hl} \lesssim 0\farcs5$ at z=10. **Fig. 3b [RIGHT]:** Caustic map produced by the cluster mass model for a source at z=10. White indicates where a point source at z=10 produces maximum magnification. The total length of the cluster caustics L$\lesssim$100$''$ is the upper limit used for caustic transits calculations.

in these estimates are ∼0.7 dex, JWST may need to monitor 3–30 clusters during its lifetime. Such a survey would need to be maintained until a sufficient number of Pop III star caustic transits has been detected, so that the actual Pop III star caustic transit rate can be estimated, and the survey strategy updated.

5a. Parameters Adopted for Pop III Star Black Hole Accretion Disks: To address under what conditions JWST could detect the UV accretion disks of Pop III stellar-mass BHs lensed individually through cluster caustic transits at very high magnification, we first need to discuss their plausible range in physical properties, and under what conditions these may be fed from early massive stellar binaries for the expected range in IMF-slope (Fig. 2) and metallicity evolution (Sarmento et al. 2019). For the Pop III ZAMS mass range in our `MESA` models, we adopt similar end-products as in Woosley et al. (2002). The recent LIGO detections of stellar-mass BHs at z$\lesssim$0.1 (Abbott et al. 2016a,c) are very plausibly examples of merging black hole pairs with M$\simeq$29–36 M$_\odot$, 14–21 M$_\odot$, and 19–31 M$_\odot$, respectively, about 1–3 Gyr ago (Abbott et al. 2016b,d,e; Abbott et al. 2017a). For the calculations of Pop III BH accretion disk caustic transits, we assume that Pop III stars with M$\gtrsim$30 M$_\odot$ — with the exception of the mass range of $\sim$100$\lesssim$M$\lesssim$200 M$_\odot$ — can and will produce BHs of roughly 15–70% of the ZAMS Pop III stellar mass, or M$\simeq$5–720 M$_\odot$ (Woosley et al. 2002). The Schwarzschild radii of these Pop III BHs will be in the range $R_{\rm s}$$\simeq$15–2200 km. What matters for the current work is that, while some massive stars with zero or very low metallicity may still exist at z$\simeq$7, at the same time a sufficient fraction of polluted stars (Z$\gtrsim$$10^{-4}$ $Z_\odot$) already exists at z$\simeq$7–17 (Trenti & Stiavelli 2007; Sarmento et al. 2018). The latter are critical, since they likely formed with a significant fraction of binaries, and so play an essential role in BH accretion disk feeding via Roche-lobe overflow during post-main sequence evolution. Any BHs left over after a massive Pop III star's death may accrete from a surrounding lower-mass, low-metallicity star filling its Roche lobe during its post-main sequence evolution, causing a UV-bright accretion disk. The accretion time scales onto these BHs in stellar binaries are not well known, but may have plausibly lasted as long as the GB lifetimes of the less massive star in a binary when it fills its Roche lobe (W18). Blackburne et al. (2011) suggest from their QSO microlensing data that for $M_{\rm BH}$ $\gtrsim$ 10^9M$_\odot$, the accretion disk half-light radii scales as: $r_{\rm hl} \propto M_{\rm BH}{}^{\rho}$. Using $\rho$$\simeq$0.5, we obtain consistent BH UV half-light radii in the range $R_{\rm UV}$ $\simeq$1–16 R$_\odot$ for $M_{\rm BH}$ $\simeq$5–720 M$_\odot$. The bolometric luminosities are $4{\times}10^4$–$6{\times}10^6$ $L_\odot$ for $M_{\rm BH}$ $\simeq$5–720 M$_\odot$. We confirm these results with multi-color thin accretion-disk models, where the temperature increases with radius as $T \propto r^{-3/4}$. Gas on the inner most stable orbit at R$\simeq$3$R_{\rm s}$ has a maximum temperature of about $T_{max}$$\simeq$10 $(\frac{M_{BH}}{100\ M_\odot})^{-\tau}$ keV with $\tau$$\simeq$3/8. At these r$_{hl}$-values, the accretion disks have an effective temperature of $T_{\rm eff}$$\simeq$47,500–48,000 K for M$\simeq$5–720 M$_\odot$. The inner stellar-mass BH accretion disks *will* be significantly hotter than the typical T$\simeq$$10^5$ K temperatures of Pop III stars, plausibly reaching X-ray temperatures at the innermost radii, and reaching $\sim$30,000 K at the outermost radii. UV-bright accretion disks — if unobscured by surrounding dust — have SEDs at $\lambda$$\gtrsim$1216Å that can make it past the neutral IGM at z$\gtrsim$7 with UV radii $\lesssim$40,000 $R_{\rm s}$. Their restframe UV-radii are $R_{\rm UV}$ $\simeq$1–30 R$_\odot$, and their UV-luminosities are at most $3{\times}10^4$–$7{\times}10^6$ $L_\odot$ for M$_{BH}$$\simeq$5–720 M$_\odot$, respectively. Pop III stellar-mass BH accretion disk radii may thus be similar to, or somewhat larger than the 1–13 R$_\odot$ radii of the ZAMS Pop III stars, but no larger than the Pop III RGB- or AGB-star radii in W18. They would fit well within the $\sim$7–55 $R_\odot$ typical Roche lobe sizes seen in massive binaries observed in our own Galaxy, and so are can be fed from a less massive RGB/AGB star in the binary that is filling its Roche lobe.

5b. Estimates of Caustic Transits for Pop III Star Black Hole Accretion Disks: Pop III stars with $30 \lesssim M \lesssim 1000\ M_\odot$ that produce BHs have ZAMS ages of 5.6–2.1 Myr (Fig. 1) with an average of $\sim$3 Myr. Pop III stars of masses $M \simeq 2$–$20\ M_\odot$ live considerably longer than this during their AGB stage, where they could fill their Roche lobes for up to 0.6–60 Myr, with an average GB age of $\sim$6 Myr. Hence, during their AGB stage 2–20 $M_\odot$ stars could feed the BH that is left by a 30–1000 $M_\odot$ star for a maximum duration that is significantly longer than the ZAMS lifetime of that massive Pop III star (Fig. 1). Depending on how steady and efficient BH feeding by a lower mass AGB star in its Roche lobe is, stellar-mass BH accretion disks may be about as likely as Pop III stars at $z \gtrsim 7$ to cause cluster caustic transits that could be observed by JWST, and possibly more likely. Stellar-mass BH accretion disks with a SB$\simeq$31 mag arcsec^{-2} (or $\sim$1 nW m^{-2} sr^{-1}) could produce about one caustic transit per 5 clusters per year, and perhaps as many as one event per 2 clusters per year. A dedicated JWST program that monitors 3 clusters per year for a number of years could thus detect several caustic transits for Pop III stellar-mass BH accretion disks.

6. Possible Observing Programs to Detect Pop III Caustic Transits: To observe caustic transits from First Light objects, a dedicated JWST observing program will be required of at least several, and perhaps up to 30 clusters for a duration of 1–10 years. Depending on their exact contribution to the *diffuse* 1–4 μm sky-SB ($\lesssim$0.01–0.1 nW m^{-2} sr^{-1}), such a JWST observing program to detect individual Pop III stars and/or stellar-mass BH accretion disks at $z \gtrsim 7$ may well require to monitor — in the optimistic case that *most* of the NIR power-spectrum signal comes from $z \gtrsim 7$ — a few suitable galaxy clusters a number of times during a year. All of these cluster observations would require coeval images in four NIRCam filter-pairs and/or four NIRISS filters to constrain the spectral signature and redshift of a Pop III caustic transit candidate. The caustic transits would appear as $z \gtrsim 7$ dropout candidates that vary with time, either increasing rapidly and then slowly fading, or vice versa. The one significant difference between Pop III stellar-mass BH accretion disks and Pop III stars is likely the presence of a hard X-ray component that contributes very significantly at the inner accretion disk radii, and that will *also* have a significant energy tail longwards of Lyα 1216 Å. No such X-ray component would exist for Pop III stars, since their stellar photospheres have nearly uniform temperatures of $T \simeq 10^5$ K (Fig. 1). Hence, Pop III stars will not show chromatic behavior that may be traced during a caustic transit, but BH accretion disks could show such chromaticity if they were detected close to the actual caustic transit.

The next generation 25–40 m ground-based telescopes — the European Extremely Large Telescope (E-ELT), the Giant Magellan Telescope (GMT), and the Thirty Meter Telescope (TMT) — will have much larger collecting area, and narrower PSFs when using Multi-Conjugate (laser-assisted) Adaptive Optics, although perhaps not as stable as JWST's PSFs, and they will have much lower Strehl ratios. They will also have a 1–2 μm sky foreground that is $\gtrsim$7 mag brighter than JWST's in L2. As a consequence, the next generation ground-based telescopes may be able to reach AB$\lesssim$29 mag in integrations of hours at 1–2 μm, but — given their adaptive optics — only over a smaller FOV ($\lesssim 20'' \times 20''$—$1' \times 1'$). Ground-based telescopes will have reduced sensitivity at wavelengths $\lambda \gtrsim 2$–$2.2\ \mu$m because of the strongly increasing thermal foreground. For that reason, JWST will be able to better address any chromatic differences between caustic transits of Pop III stars and their stellar-mass BH accretion-disks, especially those at $z \gtrsim 12$ that require several very sensitive filters at $\lambda \gtrsim 2\ \mu$m, where ground-based telescopes cannot reach AB$\sim$29 mag due to the much brighter thermal foreground. Confirming spectra of caustic transits by Pop III stars or their stellar-mass BH accretion disks could be taken with the JWST NIRISS and NIRSpec spectrographs. In summary, the next generation ground-based telescopes can monitor at 1–2 μm — over a much longer period than JWST — individual Pop III caustic transits that JWST will have detected at 1–5 μm during its lifetime, and also discover new ones on timescales longer than JWST's lifetime. This capability would be particularly useful to follow-up on caustic transits that may be affected by microlensing, and so may stretch out over many decades. In conclusion, unlensed Pop III stars or stellar-mass BH accretion disks may have fluxes of AB$\simeq$35–41.5 mag at $z \simeq 7$–17, and so will *not* be directly detectable by JWST. However, cluster caustic transits with magnifications of $\mu \simeq 10^4$–10^5 may well render them temporarily detectable to JWST in medium-deep to deep observations (AB$\lesssim$28.5–29 mag) on timescales of months to a year, with rise-times less than a few hours.

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