Accelerating early galaxy formation with primordial black holes

BOUYAN LIU \(^1,2\) and VOLKER BROMM \(^2\)

\(^1\)Department of Astronomy, University of Texas at Austin, 2515 Speedway, Austin, TX 78712, USA
\(^2\)Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK

Submitted to ApJL

ABSTRACT

Recent observations with JWST have identified several bright galaxy candidates at \(z \gtrsim 10\), some of which appear unusually massive (up to \(\sim 10^{11} \, M_\odot\)). Such early formation of massive galaxies is difficult to reconcile with standard ΛCDM predictions, demanding very high star formation efficiency (SFE), possibly even in excess of the cosmic baryon mass budget in collapsed structures. With an idealized analysis based on linear perturbation theory and the Press-Schechter formalism, we show that the observed massive galaxy candidates can be explained with lower SFE than required in ΛCDM, if structure formation is accelerated by massive (\(\gtrsim 10^9 \, M_\odot\)) primordial black holes (PBHs) that enhance primordial density fluctuations. We identify the region of PBH parameter space, allowed by existing empirical constraints, that can produce the most massive galaxy candidates observed by JWST, and discuss the general signatures of PBH cosmologies in the JWST era.

Keywords: galaxies: abundances — galaxies: high-redshift — black hole physics — dark matter

1. INTRODUCTION

Understanding the onset of star and galaxy formation at the end of the cosmic dark ages, a few 100 million years after the Big Bang, is one of the key goals of modern cosmology (e.g., Barkana & Loeb 2001; Bromm & Yoshida 2011). With the successful launch of the James Webb Space Telescope (JWST), this formative period of cosmic history is now becoming accessible to direct observations, thus finally testing the theoretical framework of early structure formation. The latter extends the ΛCDM model, which is highly successful in accounting for galaxy formation and evolution following the epoch of reionization (Springel et al. 2006; Mo et al. 2010), to the first billion years after the Big Bang.

The initial JWST imaging via the Cosmic Evolution Early Release Science (CEERS) survey has discovered a population of surprisingly massive galaxy candidates at \(z \gtrsim 10\), with inferred stellar masses of \(\gtrsim 10^9 \, M_\odot\) (Atek et al. 2022; Finkelstein et al. 2022; Harikane et al. 2022; Naidu et al. 2022; Yan et al. 2022). The current record among these photometric detections reaches out to \(z \approx 16.7\) (Donnan et al. 2022). Such massive sources so early in cosmic history would be difficult to reconcile with the expectation from standard ΛCDM (Boylan-Kolchin 2022; Inayoshi et al. 2022; Lovell et al. 2022), and this includes similarly over-massive (up to \(\sim 10^{11} \, M_\odot\)) galaxy candidates detected at \(z \approx 10\) (Labbé et al. 2022). An important caveat here is that the early release JWST candidate galaxies are based on photometry only, rendering their redshift and spectral energy distribution (SED) fits uncertain (Steinhardt et al. 2022), until spectroscopic follow-up will become available. Part of the seeming discrepancy may also be alleviated by the absence of dust in sources at the highest redshifts, thus boosting their rest-frame UV luminosities (e.g., Jaacks et al. 2018; Ferrara et al. 2022).

It is a long-standing question in cosmology when the first galaxies emerged, and how massive they were, going back to the idea that globular clusters formed at the Jeans scale under the conditions immediately following recombination (Peebles & Dicke 1968). The modern view of early structure formation, based on the dominant role of cold dark matter (CDM), posits initial building blocks for galaxy formation that are low-mass, of order \(10^6 \, M_\odot\), virializing at \(z \approx 20 – 30\) (Couchman & Rees 1986; Haiman et al. 1996).
Numerous models have been proposed to suppress small-scale fluctuations, thus delaying the onset of galaxy formation to later times, in response to empirical hints for the lack or absence of low-mass objects that are otherwise predicted by CDM models (Bullock & Boylan-Kolchin 2017). An extreme scenario here is the fuzzy dark matter (FDM) model, assuming ultra-light axion-like dark matter particles with corresponding de Broglie wavelengths of $\sim 1\, \text{kpc}$ (Hui et al. 2017). Quantum pressure would thus prevent the collapse of structure on the scale of dwarf galaxies (e.g., Sullivan et al. 2018).

The opposite effect, deriving models to accelerate early structure formation, beyond the $\Lambda$CDM baseline prediction, as may be required to explain the massive JWST galaxy candidates, is much more challenging. One recent study invokes the presence of an early dark energy (EDE) component, resulting in such an accelerated formation of high-redshifts structures (Klypin et al. 2021). We here explore a different possibility of boosting the emergence of massive galaxies in early cosmic history, based on the presence of primordial black hole (PBH) dark matter and the corresponding isocurvature (Poisson) perturbations that increase the power of density fluctuations in addition to the standard $\Lambda$CDM adiabatic mode (Carr & Kühnel 2020; Liu et al. 2022).

2. PBH STRUCTURE FORMATION

For simplicity, we adopt a monochromatic mass function\(^1\) for PBHs, such that a PBH model is specified by the BH mass $m_{\text{PBH}}$ and fraction $f_{\text{PBH}}$ of dark matter in the form of PBHs. We assume that PBHs produce isocurvature perturbations in the primordial density field on top of the standard adiabatic mode due to the random distribution of PBHs at small scales (i.e., the ‘Poisson’ effect, Carr & Silk 2018). These isocurvature perturbations only grow in the matter-dominated era\(^2\). The linear power spectrum (extrapolated to $a = 1$) of dark matter density fluctuations can be written as (Afshordi et al. 2003; Carr & Silk 2018; Inman & Ali-Haïmoud 2019; Liu et al. 2022)

$$P(k) = P_{\text{ad}}(k) + P_{\text{iso}}(k),$$

$$P_{\text{iso}}(k) \simeq f_{\text{PBH}} D_0^2/\bar{n}_{\text{PBH}}, \quad (1)$$

where $P_{\text{ad}}(k)$ is the standard adiabatic mode in $\Lambda$CDM cosmology\(^3\), $\bar{n}_{\text{PBH}} = f_{\text{PBH}} 3H_0^2/(\Omega_{\text{m}} - \Omega_{\text{b}})/m_{\text{PBH}}$ is the cosmic (co-moving) number density of PBHs, and $D_0$ is the growth factor of isocurvature perturbations evaluated at $a = 1$, given by (Inman & Ali-Haïmoud 2019)

$$D(a) \simeq \left(1 + \frac{3\gamma a}{2a_- s}\right)^{a_-} - 1, \quad s = \frac{a}{a_{\text{eq}}},$$

$$\gamma = \frac{\Omega_{\text{m}} - \Omega_{\text{b}}}{\Omega_{\text{m}}}, \quad a_- = \frac{1}{4} \left(\sqrt{1 + 24\gamma} - 1\right), \quad (2)$$

where $a_{\text{eq}} = 1/(1 + z_{\text{eq}})$ is the scale factor at matter-radiation equality with $z_{\text{eq}} \simeq 3400$. In this work, we ignore the higher-order (non-linear) ‘seed’ effect (Carr & Silk 2018) and mode mixing\(^4\), lacking a self-consistent linear perturbation theory that can take them into account. Such effects tend to enhance the perturbations induced by PBHs and further accelerate formation of (massive) structures, so that our results can be regarded as conservative estimates. Note that without these higher-order terms, $P_{\text{iso}}(k) \propto m_{\text{PBH}} f_{\text{PBH}}$, so that the effect of PBHs is governed by a single parameter $m_{\text{PBH}} f_{\text{PBH}}$. For examples, Fig. 1 shows the power spectra with $m_{\text{PBH}} f_{\text{PBH}} = 90$, 10,000 and $10^6\, M_\odot$.

---

\(^1\) See, e.g., Carr & Silk (2018); Tada & Yokoyama (2019); Carr & Kühnel (2019); Carr et al. (2021a) for discussion of the PBH mass spectrum.

\(^2\) Perturbations induced by PBHs enter the horizon earlier than matter-radiation equality at all scales relevant here.

\(^3\) We use the $\Lambda$CDM power spectrum (for the adiabatic mode) measured by Planck Collaboration et al. (2020) with $\Omega_{\text{m}} = 0.3153$, $\Omega_{\text{b}} = 0.0493$, $h = 0.6736$, $\sigma_8 = 0.8111$ and $n_s = 0.9649$ from the PYTHON package colossus (Diemer 2018).

\(^4\) At early stages when overdensities are very small, the isocurvature mode and adiabatic mode are uncorrelated. However, at later stages (e.g., $z \sim 10 \sim 20$, when the first galaxies form), the two modes can be mixed as PBHs follow the large-scale adiabatic mode to fall into larger structures and meanwhile induce/disrupt DM structures around themselves on small scales (Liu et al. 2022).
Once $P(k)$ is known, we use the Press-Schechter (PS) formalism (Press & Schechter 1974; Mo et al. 2010) with a Gaussian window function to calculate the halo mass function (HMF), $dn(M, z)/dM$, including corrections for ellipsoidal dynamics (Sheth & Tormen 1999). Following Boylan-Kolchin (2022), given the star formation efficiency (SFE), $\epsilon = M_\star / (f_b m_{\text{halo}})$, we then derive the (co-moving) cumulative stellar mass density contained within galaxies above a certain stellar mass $M_\star$ as

$$\rho_\star (M_\star, z) = \epsilon f_b \rho (M_{\text{halo}}, z) = \epsilon f_b \int_{M_{\text{halo}}}^{\infty} M \frac{dn(M, z)}{dM} dM,$$

where $f_b = \Omega_b / \Omega_m$ is the cosmic average baryon fraction. Exploring whether PBH scenarios can explain the massive galaxy candidates reported by Labbé et al. (2022), in the following sections we compare the $\rho_\star (M_\star, z)$ predicted by our PBH models with observations, and discuss the general signatures of PBHs observable by JWST.

3. PBH SIGNATURES IN THE JWST ERA

Based on 14 galaxy candidates with masses $\sim 10^9 - 10^{11} M_\odot$ at $7 < z < 11$, identified in the JWST CEERS program, Labbé et al. (2022, see their fig. 4) derive the cumulative stellar mass density at $z = 8$ and 10 for $M_\star \gtrsim 10^{10} M_\odot$. In particular, they find $\rho_\star (\gtrsim 10^{10} M_\odot) \sim 1.3^{+1.1}_{-0.6} \times 10^6 M_\odot \text{ Mpc}^{-3}$ and $\rho_\star (\gtrsim 10^{10.5} M_\odot) \sim 9^{+11}_{-6} \times 10^5 M_\odot \text{ Mpc}^{-3}$ at $z \sim 10$, higher than the maximum achievable in ΛCDM (with $\epsilon = 1$) by up to a factor of $\sim 50$. Using the formalism described in the previous section (Eqs. 1-3), we find the PBH parameters that can reproduce these results for SFE values $\epsilon = 1$ and 0.1, comparing with existing observational constraints in the $f_{PBH}$-$m_{PBH}$ space, as shown in Fig. 2.

It turns out that to explain the observational data at $M_\star \sim 10^{10.5}$ ($10^9$) $M_\odot$, we must have $m_{PBH} \gtrsim 1.8 \times 10^5$ ($2.4 \times 10^5$) $M_\odot$ for $\epsilon < 1$ and $m_{PBH} \gtrsim 6.1 \times 10^5$ ($1.8 \times 10^6$) $M_\odot$ for $\epsilon < 0.1$. Since $f_{PBH} \lesssim 1$, this indicates that we need relatively massive PBHs with $m_{PBH} \gtrsim 10^5 M_\odot$ to form the observed massive galaxies. Such PBH models are strongly constrained by observations of $\mu$-distortion in the cosmic microwave background (CMB), if primordial density fluctuations are Gaussian (Carr et al. 2021b, see their figs. 10 and 16). Nevertheless, the constraints can be weaker when the Gaussian assumption is relaxed (e.g., Nakama et al. 2018). For instance, with the long-dashed curve in Fig. 2 we show a particular case of the phenomenological non-Gaussian model in Nakama et al. (2016) with $p = 0.5$, where $p$ is the non-Gaussianity parameter ($p = 2$ means Gaussian). In this case, PBHs with $m_{PBH} \gtrsim 10^{11} M_\odot$

![Figure 2](image-url)

**Figure 2.** The PBH parameters required to explain the cumulative stellar mass density at $z \sim 10$, measured by JWST (Labbé et al. 2022). The PBH models consistent with JWST observations are shown with the solid and dashed lines for $\epsilon = 1$ and 0.1, respectively. In each case, the upper (lower) line corresponds to the data point at the limiting mass $M_\star \sim 10^{10.5}$ ($10^{10}$). We also show the (conservative) constraint from the FIRAS CMB $\mu$-distortion limit with a non-Gaussianity parameter $p = 0.5$ (Nakama et al. 2018, long-dashed), and the combined constraint from X-ray binaries (XB, Inoue & Kusenko 2017), dynamical friction (DF, Carr & Sakellariadou 1999) and large-scale structures (LSS, Carr & Silk 2018), compiled by Carr et al. (2021b, dashed-dotted). Four sample models are labeled with triangles (see Table 1), among which the big (small) triangles can (not) explain the Labbé et al. (2022) results. The darker triangles (M1 and M4) satisfy both observational constraints while the fainter triangles (M2 and M3) only satisfy the XB+DF+LSS constraint.

can still have large enough $f_{PBH} (\gtrsim 10^{-5})$ to explain both JWST observations and the CMB $\mu$-distortion limit (Nakama et al. 2018), as measured by the COBE Far Infrared Absolute Spectrophotometer (FIRAS). Besides, the CMB $\mu$-distortion constraint can be evaded, if PBHs grow significantly between the $\mu$-distortion epoch ($7 \times 10^6 s < t < 3 \times 10^9 s$) and matter-radiation equality (Carr et al. 2021b).

Beyond the CMB constraint, PBHs with $m_{PBH} \gtrsim 10^9 M_\odot$ are also constrained by X-ray binaries (XB, Inoue & Kusenko 2017), infall of PBHs into the Galactic center by dynamical friction (DF, Carr & Sakellariadou 1999), and large-scale structure statistics (LSS, Carr & Silk 2018), which together require $f_{PBH} \lesssim 10^{-4} - 10^{-2}$ for $m_{PBH} \sim 10^9 - 10^{12} M_\odot$ (see the dashed-dotted curve in Fig. 2). Such constraints are generally weaker than that from CMB $\mu$-distortion, allowing a PBH abundance for $m_{PBH} \gtrsim 10^9 M_\odot$ sufficient to produce the high stellar mass density in massive galaxies at $z \sim 10$, inferred by JWST (Labbé et al. 2022).
Table 1. Representative PBH models.

| Model | $m_{PBH}$ [$M_\odot$] | $f_{PBH}$ | $m_{PBH}/M_\odot$ |
|-------|------------------------|-----------|-------------------|
| M1    | $3 \times 10^3$        | $3 \times 10^{-4}$ | 90 |
| M2    | $10^9$                 | $10^{-5}$  | 10000            |
| M3    | $10^{10}$              | $10^{-4}$  | $10^6$           |
| M4    | $10^{11}$              | $10^{-5}$  | $10^6$           |

To further demonstrate the effects of PBHs in high-$z$ galaxy/structure formation potentially observable by JWST, we focus on 4 models representative for typical regions in the PBH parameter space (Fig. 2), as listed in Table 1. Here M1 and M4 satisfy all observational constraints considered above, while M2 and M3 only satisfy the XB+DF+LSS combined constraint. On the other hand, M3 and M4 are consistent with the recent JWST results in Labbè et al. (2022) with $\epsilon \sim 0.1 - 1$, while M1 and M2 cannot reproduce the observations even with $\epsilon = 1$. Note that M3 and M4 are identical in terms of structure formation in our formalism as they both have $m_{PBH}/f_{PBH} = 10^6 M_\odot$, and we use the label M3/4 to denote either of them. Although M4 is less constrained by CMB $\mu$ distortion, M3 is favored by observations of quasars, which find a few tens of BHs with $\sim 10^{11} M_\odot$, but no candidate reaching $10^{11} M_\odot$ (except for Phoenix A, Brockamp et al. 2016).

In Fig. 3, we present the results for $\rho_*(> M_*)$ in standard ΛCDM (solid), M1 (dashed), M2 (dashed-dotted) and M3/4 (dotted) for $\epsilon = 1$ (thin) and 0.1 (thick) at $z = 10, 15$ and 20. We also plot the lower mass limits of galaxies detectable by JWST CEERS NIRCam LW imaging (for an exposure time of $\sim 2000$ s) in Fig. 3, considering a magnitude limit $m_{F444W} \sim 28$ for the filter F444W with a signal-to-noise ratio (SNR) $\gtrsim 5$, derived from the JWST Exposure Time Calculator\(^5\). We calculate the stellar mass limit as the total mass of stars formed in a star formation event whose peak luminosity matches the magnitude limit according to the stellar population synthesis code YGGDRASIL (Zackrisson et al. 2011). For Population III (Pop III) stars we adopt their (instantaneous-burst) Pop III.1 model with an extremely top-heavy Salpeter initial mass function (IMF) in the range of $50 - 500 M_\odot$, based on Schaerer (2002), while for Population II (Pop II) stars we use their $Z = 0.0004$ model from Starburst99 (Leitherer et al. 1999; Vázquez & Leitherer 2005) with a universal Kroupa (2001) IMF in the interval $0.1 - 100 M_\odot$. For both Pop III and II, we consider a nebula covering fraction of $f_{cov} = 0.5$ and no Lyman-α transmission. Note that these limits will be reduced by about one order of magnitude.

\(^5\) https://jwst.etc.stsci.edu/
Early galaxy formation with PBHs

4. SUMMARY AND CONCLUSIONS

The recent detection of surprisingly massive ($\sim 10^{10} - 10^{11} \, M_\odot$) galaxy candidates at $z \sim 10$ by JWST (Labbé et al. 2022), if confirmed, brings new challenges to ΛCDM (and a broad range of dynamical dark energy models) which cannot provide enough baryonic matter in collapsed structures for such early massive galaxy formation (Boylan-Kolchin 2022; Lovell et al. 2022; Menci et al. 2022). Note that the source properties derived from photometry are sensitive to the underlying SED fitting templates, such that the stellar masses can be lower by up to 1.6 dex than reported in Labbé et al. (2022), if other templates with improved physical justification are adopted, removing the tension with ΛCDM (Steinhardt et al. 2022, see their fig. 3). However, currently no template can satisfactorily match the observed photometry self-consistently, and follow-up spectroscopic observations are needed to robustly pin down the properties of these galaxy candidates.

Assuming that the results in Labbé et al. (2022) are true, we use a simple analytical model based on linear perturbation theory and the PS formalism (Sec. 2) to show that such early formation of massive galaxies is possible if PBHs make up part of dark matter with $m_{PBH} f_{PBH} \gtrsim 6 \times 10^6 \, (2 \times 10^5) \, M_\odot$ for SFE $\epsilon < 0.1 \, (1)$. Although such massive PBHs are mostly ruled out by observations of the CMB $\mu$-distortion, this strong constraint relies on the assumptions that primordial density fluctuations are Gaussian and that PBHs hardly grow during the radiation-dominated era. With such assumptions relaxed and the CMB $\mu$-distortion constraint weakened/evaded (see e.g., Nakama et al. 2018; Carr et al. 2021b), the other constraints from X-ray binaries (Inayoshi et al. 2022), dynamical friction (Carr & Sakellariadou 1999) and large-scale structures (Carr & Silk 2018) allow a substantial region in the PBH parameter space with $m_{PBH} \sim 10^9 - 10^{11} \, M_\odot$ and $f_{PBH} \sim 10^{-5} - 10^{-3}$ that is consistent with the recent JWST observations (and no detection of BHs above $10^{11} \, M_\odot$). If the stellar masses measured by Labbé et al. (2022) are over-estimated, less extreme PBH models would be able to explain them for the same value of $\epsilon$, and the same PBH model could allow lower values of $\epsilon$. For instance, if the inferred stellar masses were indeed reduced by 1.6 dex in follow-up observations, we would only need $m_{PBH} f_{PBH} \gtrsim 2 \times 10^5 \, M_\odot$ to form the observed galaxies with $\epsilon < 0.025$ at $z \sim 10$.

We also find that the effects of PBHs are stronger at higher $z$, implying that stronger signatures of PBHs may be found in future wider and deeper surveys by JWST. Actually, if the object CEERS-1749 reported in Naidu et al. (2022) is a galaxy at $z \sim 17$, its large mass ($\sim 5 \times 10^9 \, M_\odot$) is also in $> 3\sigma$ tension with ΛCDM (Lovell et al. 2022, see their fig. 6). Even if follow-up studies do not find such excess of very massive galaxies at higher $z$, this may not necessarily rule out our PBH models, since the SFE can evolve rapidly with redshift at cosmic dawn ($z \sim 6 - 30$) due to metal enrichment, the build-up of radiation backgrounds and the transition in dominant stellar population (see e.g., Fialkov & Barkana 2019; Mirocha & Furlanetto 2019; Schauer et al. 2019; Liu et al. 2020). Note that our exploratory work focuses on structure formation with PBHs and does not cover other important aspects, such as BH accretion and feedback. Follow-up studies with more detailed modeling of the interactions between PBHs, baryons and (non-PBH) dark matter are required to fully understand the roles played by massive ($\gtrsim 10^5 \, M_\odot$) PBHs in structure/galaxy/star formation and their observational signatures, similar to what has been done for stellar-mass PBHs (e.g., Kashlinsky 2016; Gong & Kitajima 2017;...
In general, the recent discovery of potentially very early massive galaxy formation by JWST (Labbé et al. 2022) hints at faster structure formation in the high-z universe, above the ΛCDM baseline, which can be achieved if part of dark matter is composed of massive (∼10^9 M_⊙) PBHs. A similar trend is also seen in observations of (proto-) galaxy clusters that show an excess of strong-lensing sources (Meneghetti et al. 2020, 2022) and of star formation (Remus et al. 2022) that are difficult to explain in ΛCDM. Strikingly, this trend for accelerated structure formation at high-z goes in the opposite direction of invoking the suppression of fluctuations to account for the well-known small-scale problems of ΛCDM. Together with other hints for PBHs (see e.g., Clesse & García-Bellido 2018), these findings imply that the nature of dark matter may be more complex than our standard expectation, e.g., involving important sub-components such as PBHs. This challenge calls for the thorough theoretical exploration of the alternatives to ΛCDM, in conjunction with advanced observational campaigns to probe the high-redshift universe. Here, we are entering an exciting period of discovery, with frontier facilities, such as JWST, Euclid, the Square Kilometre Array (SKA), as well as the Einstein Telescope (ET) and Laser Interferometer Space Antenna (LISA) gravitational wave observatories.

REFERENCES

Afshordi, N., McDonald, P., & Spergel, D. N. 2003, ApJ, 594, L71
Atek, H., Shuntov, M., Furtak, L. J., et al. 2022, arXiv e-prints, arXiv:2207.12338
Barkana, R., & Loeb, A. 2001, Phys. Rep., 349, 125
Bhatawdekar, R., & Conselice, C. J. 2021, ApJ, 909, 144
Boylan-Kolchin, M. 2022, arXiv e-prints, arXiv:2208.01611
Brockamp, M., Baumgardt, H., Britzen, S., & Zensus, A. 2016, A&A, 585, A153
Bromm, V., & Yoshida, N. 2011, ARA&A, 49, 373
Bullock, J. S., & Boylan-Kolchin, M. 2017, ARA&A, 55, 343
Cappelluti, N., Hasinger, G., & Natarajan, P. 2022, ApJ, 926, 205
Carr, B., Clesse, S., & García-Bellido, J. 2021a, MNRAS, 501, 1426
Carr, B., Kohri, K., Sendouda, Y., & Yokoyama, J. 2021b, Reports on Progress in Physics, 84, 116902
Carr, B., & Kühnel, F. 2019, Phys. Rev. D, 99, 103535
—. 2020, Annual Review of Nuclear and Particle Science, 70, 355
Carr, B., & Silk, J. 2018, MNRAS, 478, 3756
Carr, B. J., & Sakellariadou, M. 1999, ApJ, 516, 195
Clesse, S., & García-Bellido, J. 2018, Physics of the Dark Universe, 22, 137
Couchman, H. M. P., & Rees, M. J. 1986, MNRAS, 221, 53
Diemer, B. 2018, ApJS, 239, 35
Donnan, C. T., McLeod, D. J., Dunlop, J. S., et al. 2022, arXiv e-prints, arXiv:2207.12356
Ferrara, A., Pallottini, A., & Dayal, P. 2022, arXiv e-prints, arXiv:2208.0720
Fialkov, A., & Barkana, R. 2019, MNRAS, 486, 1763
Finkelstein, S. L., Bagley, M. B., Arrabal Haro, P., et al. 2022, arXiv e-prints, arXiv:2207.12474
Gong, J.-O., & Kitajima, N. 2017, Journal of Cosmology and Astroparticle Physics, 2017, 017
Haiman, Z., Thoul, A. A., & Loeb, A. 1996, ApJ, 464, 523
Harikane, Y., Ouchi, M., Oguri, M., et al. 2022, arXiv e-prints, arXiv:2208.01612
Hui, L., Ostriker, J. P., Tremaine, S., & Witten, E. 2017, Phys. Rev. D, 95, 043541
Inayoshi, K., Harikane, Y., Inoue, A. K., Li, W., & Ho, L. C. 2022, arXiv e-prints, arXiv:2208.06872
Inman, D., & Ali-Haïmoud, Y. 2019, Phys. Rev. D, 100, 083528
Inoue, Y., & Kusenko, A. 2017, J. Cosmology Astropart. Phys., 2017, 034
Jaacks, J., Finkelstein, S. L., & Bromm, V. 2018, MNRAS, 475, 3883
Kashlinsky, A. 2016, ApJ, 823, L25
Klypin, A., Poulin, V., Prada, F., et al. 2021, MNRAS, 504, 769
Kroupa, P. 2001, MNRAS, 322, 231
Labbé, I., van Dokkum, P., Nelson, E., et al. 2022, arXiv e-prints, arXiv:2207.12446
Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, ApJS, 123, 3
Liu, B., Schauer, A. T. P., & Bromm, V. 2020, MNRAS, 495, 1700
Liu, B., Zhang, S., & Bromm, V. 2022, MNRAS, 514, 2376
Lovell, C. C., Harrison, I., Harikane, Y., Tacchella, S., & Wilkins, S. M. 2022, arXiv e-prints, arXiv:2208.10479
Menci, N., Castellano, M., Santini, P., et al. 2022, arXiv e-prints, arXiv:2208.11471
Meneghetti, M., Davoli, G., Bergamini, P., et al. 2020, Science, 369, 1347
Meneghetti, M., Ragagnin, A., Borgani, S., et al. 2022, arXiv e-prints, arXiv:2204.09065
Mirocha, J., & Furlanetto, S. R. 2019, MNRAS, 483, 1980
Mo, H., Van den Bosch, F., & White, S. 2010, Galaxy formation and evolution (Cambridge University Press)
Naidu, R. P., Oesch, P. A., Setton, D. J., et al. 2022, arXiv e-prints, arXiv:2208.02794
Nakama, T., Carr, B., & Silk, J. 2018, Phys. Rev. D, 97, 043525
Nakama, T., Suyama, T., & Yokoyama, J. 2016, Phys. Rev. D, 94, 103522
Peebles, P. J. E., & Dicke, R. H. 1968, ApJ, 154, 891
Planck Collaboration, Aghanim, N., Akrami, Y., et al. 2020, A&A, 641, A6
Press, W. H., & Schechter, P. 1974, ApJ, 187, 425
Remus, R.-S., Dolag, K., & Dannerbauer, H. 2022, arXiv e-prints, arXiv:2208.01053
Schaefer, D. 2002, A&A, 382, 28
Schauer, A. T. P., Liu, B., & Bromm, V. 2019, ApJ, 877, L5
Sheth, R. K., & Tormen, G. 1999, MNRAS, 308, 119
Springel, V., Frenk, C. S., & White, S. D. M. 2006, Nature, 440, 1137
Steinhardt, C. L., Kokorev, V., Rusakov, V., Garcia, E., & Sneppen, A. 2022, arXiv e-prints, arXiv:2208.07879
Sullivan, J. M., Hirano, S., & Bromm, V. 2018, MNRAS, 481, L69
Tada, Y., & Yokoyama, S. 2019, Phys. Rev. D, 100, 023537
Vázquez, G. A., & Leitherer, C. 2005, ApJ, 621, 695
Yajima, H., & Khochfar, S. 2017, MNRAS, 467, L51
Yan, H., Ma, Z., Ling, C., et al. 2022, arXiv e-prints, arXiv:2207.11558
Zackrisson, E., Rydberg, C.-E., Schaefer, D., Östlin, G., & Tuli, M. 2011, ApJ, 740, 13
Zackrisson, E., Zitrin, A., Trenti, M., et al. 2012, MNRAS, 427, 2212