

Primordial-Black-Hole-Based Pathways to Little Red Dots

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The James Webb Space Telescope has uncovered a population of compact, high-redshift sources, the Little Red Dots (LRDs), which may host supermassive black holes (BHs) significantly heavier than their stellar content compared with local scaling relations. These objects challenge standard models of early galaxy formation and may represent an extreme class of early BH hosts. In this Letter, we investigate whether these BHs could have a primordial origin. We first show that the direct formation of these BH masses in the early Universe is excluded by stringent cosmic microwave background μ -distortion limits. We then investigate the assembly of massive BHs from lighter, observationally allowed primordial black holes (PBHs) via hierarchical mergers, finding that, although this channel can operate depending on the merger history, it faces challenges in explaining the observations due to the rarity of the required high-redshift dark matter halos. Finally, we estimate gas accretion onto intermediate-mass PBHs, while jointly tracking metallicity evolution, and identify regions of parameter space in which such growth could reproduce the observed properties of LRDs. As a special case, we focus on the strongly lensed source QSO1, whose extremely low metallicity and large mass provide a stringent test of these formation channels.

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Introduction—Recent observations with the James Webb Space Telescope have revealed a population of compact, optically red sources at high redshifts, commonly referred to as Little Red Dots (LRDs) [1–8]. These objects are characterized by V-shaped rest-frame ultraviolet-optical continua, compact morphologies ($\lesssim 100$ pc), and broad emission features, distinguishing them from typical star-forming galaxies or other previously discovered quasars in

the early Universe [4,9–13]. These characteristics strongly suggest that LRDs are associated with accreting black holes (BHs) at early epochs. Yet, several of their properties remain difficult to reconcile with standard models of early active galactic nuclei (AGN) [2,14,15]. The inferred masses of their putative BHs are on the order of $(10^6\text{--}10^8)M_\odot$, with unusually high BH-to-stellar mass ratios relative to the local $M_{\text{BH}} - M_\star$ relation [1,2,4,16]. LRDs also appear to be abundant, with reported number densities approaching 10%–20% of the galaxy population for an absolute UV magnitude between $M_{\text{UV}} \approx -19$ and $M_{\text{UV}} \approx -22$ [2,9,16]. Moreover, LRDs exhibit weak hot-dust emission and a conspicuous lack of detectable x-ray signatures, which together pose significant challenges to interpretations based solely on AGN templates [17–26]. These nondetections of typical AGN-like features may suggest alternative explanations based on massive and compact galaxies [11,18,27], hierarchical growth within dense environments such as nuclear star clusters [28–30], supermassive stars [31–33], BH stars [34], and direct collapse BH models [35,36]. Notice that a modest fraction of the LRDs observed masses may

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also be attributed to tidal disruption events [30]. It has also been suggested that super-Eddington accretion phases might help explain the lack of x-ray and variability signatures in cases where LRDs are actually AGNs [21,37–40].

An illustrative example is the strongly lensed LRD source QSO1 at redshift $z = 7.04$. Previous studies [41] have reported that QSO1 shows exceptionally low metallicity ($Z \lesssim 0.01Z_\odot$) and hosts an overmassive central BH, with mass $\sim 5 \times 10^7 M_\odot$ and an inferred ratio $M_{\text{BH}}/M_\star > 2$, placing it well above the local $M_{\text{BH}} - M_\star$ relation. More recent analysis [42] has confirmed the BH mass through narrow-line resolved kinematics, strengthening the interpretation that QSO1 contains a rapidly growing BH seed within a compact and metal-poor environment. These properties make QSO1 a benchmark for understanding the diversity of LRDs and the mechanisms that drive extreme BH growth in the early Universe.

A possible interpretation for QSO1, and potentially for the broader population of LRDs, invokes primordial black holes (PBHs) as the initial seeds of their central massive objects [43–46] (see, e.g., Refs. [47–51] for recent reviews). These objects can form from the gravitational collapse of high-redshift large-amplitude perturbations, leading to a possibly wide range of PBH masses (see also Refs. [50,51] for alternative formation scenarios). PBHs are of particular interest because they could also make a significant contribution to dark matter (DM) and potentially account for some of the binary BH mergers observed so far [52–61] by the LIGO-Virgo-KAGRA Collaboration [62–67].

In this Letter, we examine whether QSO1 is consistent with a PBH origin and assess the implications for the broader population of LRDs. Previous studies [41,68,69] suggested that a PBH scenario could naturally account for the low metallicity observed in high-redshift LRDs. Furthermore, PBH seeds provide a pathway that bypasses the formation of stellar mass BH remnants from the first stars, enabling rapid growth into the observed LRD population through efficient gas accretion [70–73]. Here, we explore three primordial-origin scenarios for the BHs powering LRDs: (i) direct PBH formation from high-redshift overdensities, (ii) hierarchical assembly through PBH mergers, and (iii) growth of PBH seeds via gas accretion. We find that direct formation is effectively ruled out by existing constraints; hierarchical mergers face challenges in explaining the inferred number densities of LRDs, whereas accretion onto PBH seeds provides the most viable pathway.

Throughout we use natural units ($\hbar = c = 1$) and assume the Λ CDM cosmology [74].

Direct PBH formation: We examine the possibility that the BHs observed in LRDs could originate from PBHs formed directly with the observed masses in the early Universe, given the existing constraints on the PBH population summarized in Fig. 1. We assume PBH formation proceeds from the collapse of large density

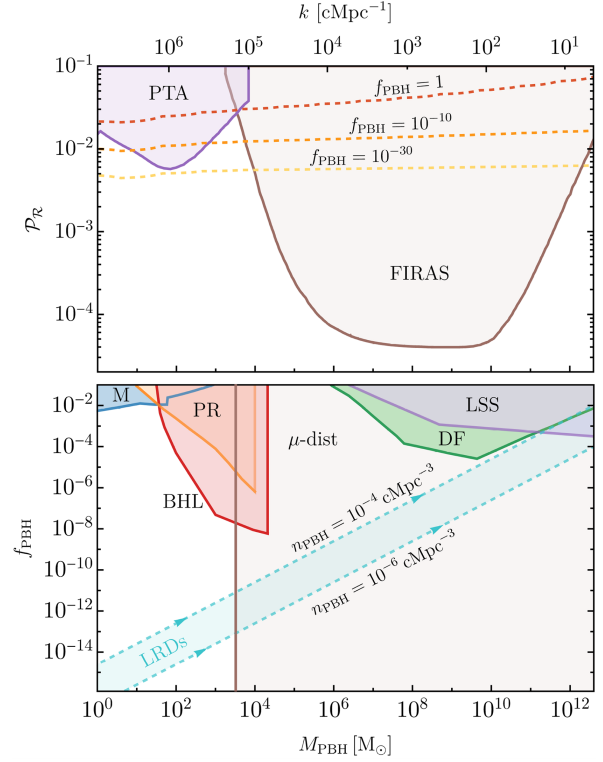


FIG. 1. Constraints on the parameter space of PBH formation. Upper: limits on the amplitude of the primordial power spectrum, in terms of the high-redshift PBH mass M_{PBH} . Lower: the current constraints on the PBH abundance for a monochromatic population (see the main text for a description of the plotted bounds). The colored lines in the upper panel indicate different values of the PBH abundance, while the light blue band in the lower panel shows the number density of observed LRDs associated with an absolute UV magnitude between $M_{\text{UV}} \approx -17$ and $M_{\text{UV}} \approx -22$ [9].

perturbations. This typically requires enhanced curvature perturbations $\mathcal{R}$ on small scales [75–78], which can arise in a variety of early Universe scenarios [79,80], with a primordial power spectrum $\mathcal{P}_{\mathcal{R}}$ reaching $\mathcal{O}(10^{-2})$. Regions exceeding a critical threshold upon Hubble reentry can collapse to form PBHs across a wide range of masses [81–83]. Within this scenario, the PBH mass is related to the corresponding comoving wave number k [84] (see note in Ref. [85]),

$$M_{\text{PBH}} \simeq 44 M_\odot \left(\frac{10^6 \text{ cMpc}^{-1}}{k} \right)^2, \quad (1)$$

showing that directly sourcing PBHs as massive as $M_{\text{PBH}} \sim (10^7 - 10^8) M_\odot$ would require the gravitational collapse of comoving kiloparsec-size perturbations, entering the range of scales constrained by cosmic microwave background (CMB) experiments. In particular, as shown in the upper panel of Fig. 1, the LRD mass range is severely constrained by the FIRAS experiment (brown region), which measures the μ distortions sourced by the energy injection into the

baryon-photon thermal bath from the damping of large-amplitude density perturbations [89]. This implies that PBHs cannot have masses larger than $\sim \mathcal{O}(10^3)M_\odot$ (see Fig. 1), unless the perturbations were extremely non-Gaussian, an (in principle), viable possibility (see, e.g., Refs. [90,91]) that is not easily realized in realistic scenarios [92–97]. Slightly lighter PBHs are also constrained by pulsar timing array (PTA) data (magenta region) [98–107], given that sizable perturbations would source a scalar-induced stochastic background [91,108–110].

The probability $\beta(M_{\text{PBH}})$ to form a PBH of mass M_{PBH} is extremely sensitive to the statistics of rare, large fluctuations in the density field. The probability of collapse dictates the fraction of DM contained in PBHs f_{PBH} as [47]

$$f_{\text{PBH}}(M_{\text{PBH}}) \simeq \left(\frac{\beta(M_{\text{PBH}})}{6 \times 10^{-9}} \right) \left(\frac{M_{\text{PBH}}}{M_\odot} \right)^{-1/2}. \quad (2)$$

In the upper panel of Fig. 1, we show the amplitude of $\mathcal{P}_{\mathcal{R}}$ required to reproduce selected values of f_{PBH} . We follow state-of-the-art modeling of the collapse probability (see, e.g., Ref. [110] and the publicly available code [111]). We conservatively report the computation adopting threshold statistics [112], but acknowledge that systematic uncertainties remain, as peak-theory computations [113] indicate that lower amplitudes are needed and, thus, much weaker bounds [91,110,114,115]. This, however, does not affect our conclusions. For the role of non-Gaussianities in the computation of f_{PBH} , see Refs. [115–124].

Once formed, PBHs are expected to follow a spatial distribution determined by the properties of the underlying density perturbations. For Gaussian fields, PBHs are essentially uncorrelated and their distribution is described by a rare Poisson process [125–128] (in the presence of primordial non-Gaussianity, PBHs can exhibit spatial correlations [129–132], which are, however, difficult to achieve in standard scenarios [133]). The mean comoving number density of a monochromatic PBH population is

$$n_{\text{PBH}} \simeq 3 \left(\frac{f_{\text{PBH}}}{10^{-7}} \right) \left(\frac{M_{\text{PBH}}}{10^3 M_\odot} \right)^{-1} \text{ cMpc}^{-3}. \quad (3)$$

The PBH abundance is constrained by various probes [48]; see lower panel of Fig. 1. Between $\sim 10^{-11}M_\odot$ to a few tens of $M_\odot$, microlensing surveys (M , blue contour) limit PBHs through the nondetection of lensing events [134–137], while around stellar masses, gravitational-wave detections constrain PBHs by comparing observed merger rates with PBH merger predictions [84,138–143] (not shown in the plot to avoid cluttering). Above the solar mass scale, CMB [144–147] (and x-ray backgrounds [148,149]) would be affected by baryonic accretion, depending on the accretion model, e.g., Bondi-Hoyle-Lyttleton (BHL, red contour) [144] or Park-Ricotti (PR, orange contour) [150–154]. For $M_{\text{PBH}} \gtrsim 10^5 M_\odot$,

constraints arise from the disruption of wide binaries, globular cluster stability, dwarf galaxy survival (DF, green contour) [155,156], and large-scale structure formation (LSS, magenta contour) [155,156]. Further constraints dominating at masses $M_{\text{PBH}} \gtrsim 10^9 M_\odot$ arise from CMB bounds on isocurvature perturbations [157], not shown for simplicity. Finally, the brown constraint shows the region excluded by μ distortions discussed above [89].

The combined cosmological constraints shown in Fig. 1 demonstrate that the direct formation of PBHs with masses in the range $\sim (10^4\text{--}10^{11})M_\odot$ is ruled out. Generating PBHs of this size would require a curvature power spectrum amplitude that is incompatible with FIRAS limits on CMB μ distortions. Consequently, the permitted $\mathcal{P}_{\mathcal{R}}$ yields only a negligibly small abundance of PBHs in this mass window (as illustrated by the colored lines in the upper panel of the figure), excluding this proposed interpretation of LRDs. We stress that masses $\sim 10^3 M_\odot$ provide the heaviest seeds allowed by cosmology, for which the power spectrum can reach values $\sim 10^{-2}$, compatible with sizable PBH production. As shown in the lower panel, PBHs with these masses can comprise at most $f_{\text{PBH}} \sim (10^{-4}\text{--}10^{-7})$ of the DM and may only act as seeds to grow into heavier BHs through hierarchical mergers and baryonic accretion, as we discuss below. We stress that the bounds in Fig. 1 are redshift dependent [158] and apply to the initial PBH masses (note that substantial PBH accretion shifts observational bounds to larger masses [159]). This implies that PBHs with initial masses $\sim 10^3 M_\odot$ can, in principle, give rise to a sizable population of LRDs through cosmological growth (following the lines of constant number density, blue arrows), without violating the μ -distortion limits, which are relevant only for larger initial masses.

Assembly via hierarchical mergers: As lighter PBHs remain viable, we now turn to studying the growth of these seeds through hierarchical mergers. These represent a growth mechanism in which PBHs form binaries, merge, and then continue to coalesce with other PBHs in subsequent generations, thus building up mass [160–162]. This growth can proceed through two main channels: a democratic one, in which PBHs of comparable masses merge pairwise at each step, and an oligarchic one, in which the most massive remnants produced in each generation repeatedly merge with lighter seeds [163]. The true scenario is therefore expected to lie between these two limiting cases. A crucial condition for this to work is that the mergers occur within environments dense enough to retain the remnants of each generation. Since these remnants receive recoil kicks [164], only sufficiently deep potential wells can keep them bound, allowing them to participate in the hierarchical growth.

To provide a concrete example, we investigate the possibility of reproducing the properties of the event QSO1. We stress that our methodologies are general and can be applied to any LRDs. Concerning QSO1, given the

low stellar content observed, we expect that the only relevant environment where a hierarchical assembly can be obtained is within DM halos. In these systems, N_{PBH} PBHs are expected to undergo mass segregation and become concentrated within the radius [165]

$$r_{\text{seg}} \simeq \frac{10}{N_{\text{PBH}}^{3/2} \log^{1/3}(0.02 N_{\text{PBH}})} R_{200}, \quad (4)$$

in terms of the radius R_{200} at which the halo mean density is 200 times the critical density of the Universe. For such environments, retaining merger remnants requires kick velocities smaller than the escape velocity, $v_{\text{esc}}(r_{\text{seg}}) = \sqrt{2|\Phi(r_{\text{seg}}) - \Phi(2R_{200})|}$ [166]. Here, Φ describes the DM potential, assumed to follow a Navarro-Frenk-White (NFW) profile [167], with concentration c_{DM} . To reach $\sim(10^7\text{--}10^8)M_{\odot}$, we would need at least $N_{\text{PBH}} \sim 10^4$ PBHs in the DM halo. As shown below, considering a more abundant number of PBHs would require more massive DM halos, which are rare at high redshifts.

We estimate the probability of forming a LRD-like system with mass $10^7 M_{\odot}$ through the runaway mergers of $N_{\text{PBH}} \simeq 10^4$ PBHs with mass $M_{\text{PBH}} \simeq 10^3 M_{\odot}$, by performing simulations as described in Supplemental Material [168]. These simulations determine the probability $\epsilon_{\text{HM}}(v_{\text{esc}})$ of getting a final BH with mass compatible with $10^7 M_{\odot}$ by varying the escape velocity of the DM environment. The efficiency can be fitted as

$$\epsilon_{\text{HM}}(v_{\text{esc}}) = \frac{1}{1 + \exp[-a(\log_{10} v_{\text{esc}} - b)]}, \quad (5)$$

with parameters $a = 9.36(17.00)$ and $b = 2.99(3.29)$, for the oligarchic (democratic) scenario.

By determining v_{esc} in terms of the DM halo mass M_h (obtained by integrating the NFW profile), we provide the probability $\epsilon_{\text{HM}}(M_h)$ that a given DM halo retains the merger remnants and produces a heavier PBH compatible with QSO1. This has to be combined with the abundance of DM halos at a given redshift, captured in the halo mass function $dn(z)/dM_h$ [176]. The number density of environments able to source QSO1-like events reads

$$n(z) = \int dM_h \frac{dn}{dM_h} \epsilon_{\text{HM}}(M_h). \quad (6)$$

Its time evolution is shown in Fig. 2, which summarizes the main predictions for PBH hierarchical mergers. First, one can observe that smaller abundances strongly suppress the probability of sourcing these events. This happens because smaller values of f_{PBH} require heavier DM halos to have at least $N_{\text{PBH}} = 10^4$ objects to undergo the runaway series. Despite the higher escape velocity of these systems (thus retaining each merger remnants), the density of very massive halos decreases at high redshifts, thereby

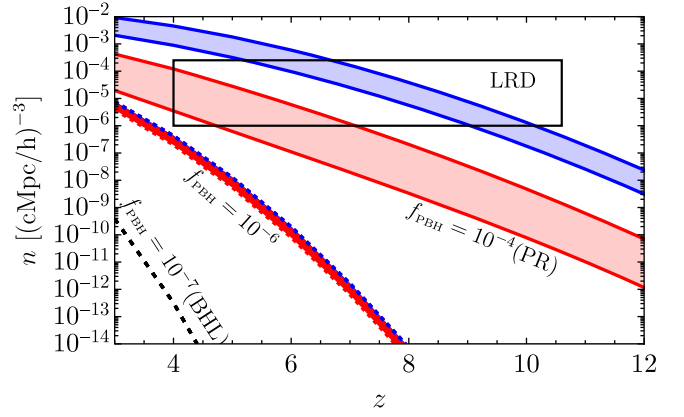


FIG. 2. Number density of environments that are able to form a $10^7 M_{\odot}$ PBH through hierarchical mergers of lighter $10^3 M_{\odot}$ seeds, as a function of redshifts z . Red and blue colors correspond to mergers proceeding through the democratic and oligarchic scenarios, respectively. Solid, dashed, and dotted (shown in black as both cases overlap) lines indicate different values of the PBH abundance f_{PBH} , while the bands consider values of the NFW concentration parameter within the range $c_{\text{DM}} = (0.1\text{--}1)$. The black rectangle indicates the parameter space of the LRDs observed so far [70]. BHL and PR correspond to assuming the maximum abundance allowed by those constraints at the assumed initial mass $10^3 M_{\odot}$, see Fig. 1.

explaining the trends of the plot. Furthermore, by comparing the oligarchic (blue curves) with the democratic (red curves) scenarios, one appreciates that the former gives rise to a larger probability. This is because remnant kicks are suppressed for larger mass ratios, thus reducing the probability of being ejected.

The prediction of our model is comparable with the LRDs observed number density, shown in the black rectangle, only in the oligarchic scenario and for values of the PBH abundance as large as $f_{\text{PBH}} \sim 10^{-4}$, which corresponds to the more optimistic version of the CMB bound (see orange and red contours of Fig. 1), while strongly suppressed otherwise. This implies that explaining the abundance of LRDs and events such as QSO1, using hierarchical mergers alone, is challenging.

Cosmological growth through accretion: The final scenario we consider is one in which the initial PBH seeds with masses $\sim 10^3 M_{\odot}$ grow through baryonic accretion (see also Ref. [177] for a recent review). During their cosmological history, PBHs may efficiently accrete baryons from the surrounding medium, potentially increasing their masses and evolving their spins due to disk formation [57, 178–180], despite several uncertainties related to mechanical and radiative feedback effects [178, 179, 181, 182]. Since baryonic accretion is inherently complex and achieving a complete understanding generally requires sophisticated simulations, in this Letter we take a deliberately simpler route and adopt an accretion model inspired by Refs. [180, 183, 184] (see especially discussion around Fig. 4 of Ref. [185]). As in the previous section, we aim

to reproduce the physical characteristics of QSO1. Nonetheless, the model we consider is general and can be applied to investigate the accretion evolution of PBHs and their ability to reproduce LRDs.

Our starting point is a PBH seed of mass $\sim 10^3 M_\odot$, which begins its accretion evolution at high redshifts ($z \sim 1000$ for definiteness). At higher redshifts, the accretion timescale is larger than the age of the Universe, rendering accretion essentially ineffective [184]. At smaller redshifts, PBHs can accrete baryons from the surrounding medium, potentially changing the metallicity content of its neighborhood due to disk fragmentation and star formation. Considering these phenomena, the PBH accretion rate $\dot{M}_{\text{PBH}}$ is determined through the balance law

$$\dot{M}_{\text{PBH}} = \dot{M}_{\text{inf}} - \dot{M}_* - \dot{M}_{\text{out}} - \dot{M}_g. \quad (7)$$

The contribution $\dot{M}_{\text{inf}}$ accounts for the infall of matter through the PBH Bondi radius, defined as $r_B = GM_h/v_{\text{eff}}^2$ [186]. This radius depends on the effective PBH velocity $v_{\text{eff}} = \sqrt{c_s^2 + v_{\text{rel}}^2}$, expressed in terms of the baryonic sound speed c_s and the PBH-baryon relative velocity v_{rel} [144,178,179,187–190], as well as on the mass enclosed within the surrounding DM minihalo, $M_h = 3M_{\text{PBH}}[1000/(1+z)]$, which embeds heavy PBHs when they constitute only a subdominant DM component [186], as in our case. The infalling rate takes the form

$$\dot{M}_{\text{inf}} = \begin{cases} \dot{M}_B & z \gtrsim z_{\text{B-inst}}, \\ \frac{c_s^3}{G} & z \lesssim z_{\text{B-inst}}. \end{cases} \quad (8)$$

The first term describes the spherically symmetric Bondi accretion rate, $\dot{M}_B = 4\pi\lambda\rho r_B^2 v_{\text{eff}}$ [191,192], onto a mass embedded in a uniform medium with density ρ and effective accretion parameter λ [178,186], which phenomenologically captures the influence of nongravitational effects that reduce the accretion rate, including the Hubble expansion, the coupling of the CMB radiation to the gas through Compton scattering, and the gas viscosity. In what follows, we treat λ as a free parameter and constrain its allowed range by requiring consistency with the observed LRD properties. This contribution provides the flow of matter onto the PBH up to redshift $z_{\text{B-inst}}$, which is set by the Bondi instability time scale [193], at which the gas surrounding the PBHs becomes ionized along the polar axis because of radiation feedback [178,179,182] (at variance with the Park-Ricotti model, where the gas within the Bondi radius is completely ionized [150–154]). At this point, the sound speed within the Bondi radius increases due to ionization, reaching values $c_s \approx 10$ km/s, thus reducing the accretion rate to c_s^3/G [185].

The second contribution in Eq. (7), $\dot{M}_*$, comes from the possibility that, as efficiently accreting PBHs are expected to develop an accretion disk surrounding them [57,180,194], such disks can effectively fragment, inducing

star formation [195]. This process is usually described in terms of the Toomre parameter, $Q \sim \mathcal{O}(1)c_s^3/G\dot{M}_{\text{inf}}$, so that regions with $Q \lesssim 1$ are susceptible to gravitational collapse [196]. This implies that, without rapid inward migration of fragments [197], star formation may already occur at the onset of the Bondi instability, when the density within the Bondi sphere rises significantly. We introduce the effective parameter $f_{\text{frag}} \equiv \dot{M}_*/\dot{M}_{\text{inf}}$ to track the fraction of incoming flow which fragments.

Third, in Eq. (7), we account for the ejection of a fraction of the incoming matter by adding $\dot{M}_{\text{out}} \equiv f_{\text{out}}\dot{M}_{\text{inf}}$.

Finally, we introduce a contribution $\dot{M}_g$ accounting for gas buildup within the Bondi sphere when the system is not in a steady state. This component is expected to be small before the instability [71], when most of the inflowing matter is efficiently accreted by the PBH. However, at $z_{\text{B-inst}}$, we expect a significant gas mass within the region, $M_g \sim M_{\text{PBH}}(z_{\text{B-inst}})$. After the instability time, we assume a steady-state configuration with constant gas mass. While it is theoretically possible to consider a growth in gas mass proportional to the infall rate, $\dot{M}_g \propto \dot{M}_{\text{inf}}$, this effect is degenerate with changes in the ejection fraction f_{out} and thus is omitted in our Letter.

Together with mass evolution, the presence of star formation induces a change in the metallicity Z of the system. Similar to Eq. (7), one can write an effective balance law for this quantity, which leads to [71]

$$\dot{Z} = \frac{1}{M_g} (yf_{\text{frag}} - Z)\dot{M}_{\text{inf}}, \quad (9)$$

in terms of the net metal yield $y \sim \mathcal{O}(10^{-2})$ [198]. As expected, a larger fragmentation parameter would result in a larger metal enrichment of the environment. Notice that our modeling neglects the contribution of heavy elements, associated with the usual structure formation history at later redshifts [198]. In this sense, our results have to be intended as an upper bound on the fragmentation fraction f_{frag} of QSO1-like LRDs (see gray region in Fig. 3).

In Fig. 3, we show the parameter space of our model aimed at reproducing the features of QSO1 [41,42]. The contours indicate that the accretion parameter can span the range $\lambda \in (10^{-3} - 1)$ and effectively account for the mass growth of PBHs from $10^3 M_\odot$ to $10^7 M_\odot$. Notably, increasing the fraction f_{out} of ejected matter (orange contour) effectively corresponds to considering a larger accretion parameter. For the relevant range of λ , we numerically verified that the dimensionless accretion rate $\dot{m} \equiv \dot{M}_{\text{PBH}}/\dot{M}_{\text{Edd}} \lesssim 1$ for $z \gtrsim z_{\text{B-inst}}$, where $\dot{M}_{\text{Edd}} = 10L_{\text{Edd}}$ [199]. For $z \approx z_{\text{B-inst}}$, we enter a super-Eddington phase where $\dot{m}$ reaches values as high as $\sim 10^2$. Depending on the value of λ , the BH may still be in a super-Eddington accretion phase at redshifts $z \approx 7$. Within such a phase, the radiation efficiency is expected to decrease significantly due to the expansion of the trapping radius [200], resulting

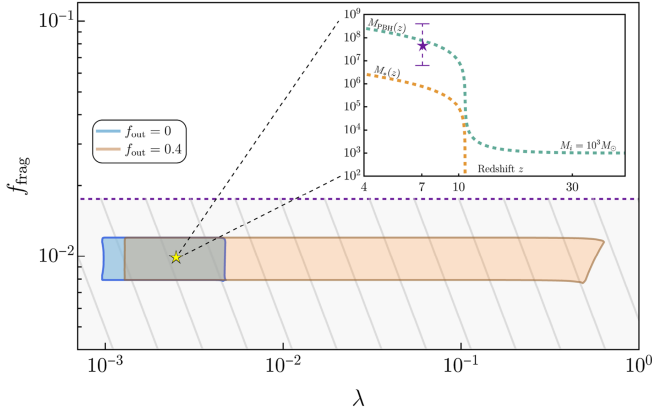


FIG. 3. Parameter space of the accretion-metallicity model, defined by the fragmentation and accretion coefficients, f_{frag} and λ , required to reproduce QSO1 within its 1σ confidence intervals, $M_{\text{QSO1}} = 10^{7.7} M_{\odot}$ and $Z_{\text{QSO1}} = 10^{-2.08} Z_{\odot}$. The orange and blue contours correspond to different choices of the ejection parameter f_{out} . The inset shows the redshift evolution of the PBH and stellar masses corresponding to the yellow star, which marks the central values of the QSO1 parameters. The dashed purple line indicates the maximum f_{frag} allowed within 3σ of the observed metallicity. The gray region shows the parameter space where the metal enrichment from structure formation could contribute to the metallicity of QSO1.

in the absence of x-ray and variability signatures [201,202], as observed for LRDs [37,39,40,203]. Furthermore, the corresponding luminosity is consistent with the observed value, $L_{\text{QSO1}} \simeq 10^{-2} L_{\text{Edd}}$, assuming an accretion efficiency of order $\mathcal{O}(10^{-3}-10^{-4})$. This value aligns closely with predictions from the slim disk model [200,204]. Conversely, the fragmentation coefficient f_{frag} primarily controls the metal content around the PBH. Since QSO1 exhibits exceptionally low metallicity, this sets an upper limit $f_{\text{frag}} \lesssim 10^{-2}$ to avoid overproducing heavy elements. Overall, our model demonstrates that, despite uncertainties in the accretion physics, PBHs could plausibly reproduce the observed properties of QSO1. Our upper limit on f_{frag} implies that the produced stellar mass remains much smaller than the PBH mass, $M_{\star} \lesssim 10^{-2} M_{\text{PBH}}$ (see inset in Fig. 3), consistent with the inferred ratio $M_{\text{BH}}/M_{\star} \gtrsim 2$. Such a large PBH-to-star mass ratio may be a smoking gun of the primordial interpretation for QSO1-like events.

Conclusions—The discovery of LRDs poses a challenge to standard models of early galaxy formation, given their combination of compact sizes, low stellar masses, and potentially massive BHs (we emphasize that measurements of the BH masses based on virial relations may suffer large uncertainties if the observed broad-line widths are dominated by electron scatterings rather than gravitational motions [34,205,206]). In this Letter, we explored whether LRDs could have a primordial origin, focusing on the properties of QSO1 to streamline our analysis. Remarkably, QSO1 is the first LRD with a dynamically

TABLE I. Summary of the primordial scenarios considered in this Letter.

Scenario	Constraint	
(i) Primordial direct collapse	$\times$	μ distortions
(ii) Hierarchical assembly	$\times$	Low number density
(iii) Cosmological accretion	$\checkmark$	Low fragmentation needed

measured BH mass [42] and it exhibits exceptionally low metallicity [41].

We have examined three PBH-based pathways for the origin of the BHs powering LRDs, briefly summarized in Table I. We have shown that the direct formation of such massive objects as PBHs is ruled out by CMB μ -distortion constraints, which severely limit the abundance of very massive PBHs at early times. This implies that scenarios based on PBH seeds as heavy as $10^5 M_{\odot}$, as in Refs. [41,68], are excluded by cosmological bounds. Consequently, viable PBH seeds are restricted to masses $\lesssim 10^3 M_{\odot}$, constituting only a subdominant component of the total DM. Hierarchical mergers of lighter, observationally allowed PBHs provide a possible growth channel, but the efficiency of this channel is highly sensitive to the assembly history and constrained by the typical properties of high-redshift DM halos, making it challenging to reproduce the observed masses. By contrast, gas accretion onto intermediate-mass PBHs, when modeled self-consistently with metallicity evolution, emerges as a more robust pathway, identifying regions of parameter space that can simultaneously reproduce the observed BH masses, stellar-to-BH ratios, and metallicities of LRDs, including the properties of the event QSO1. These conclusions are conservative because PBH growth can happen through a combination of accretion and mergers.

Our Letter can be extended in several directions. One possibility concerns applying this analysis to the full LRD population, assessing whether PBH-based channels can consistently reproduce their observed properties. This could include, among others, the highest-redshift source reported to date [207] or candidate dual LRDs [208]. Moreover, refining the accretion model will be essential to better constrain the parameter space of viable PBH scenarios. Additionally, it would be interesting to consider a mixture scenario in which both accretion and merger contribute to the population evolution. Finally, one may also consider initially clustered PBH formation (e.g., Refs. [132,209]), a scenario which also requires a careful assessment of the CMB bounds as discussed in [130]. We leave these considerations to future work.

Note added—Recently, Ref. [210] appeared, showing that the accretion and metallicity evolution of a heavy PBH seed can result in a QSO1-like LRD when considering both BH and stellar feedback. Unlike in our Letter, the authors

assume the PBH seed to be formed directly with a large observed mass.

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