


## Ruling Out Initially Clustered Primordial Black Holes as Dark Matter

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Combining constraints from microlensing and Lyman- $\alpha$  forest, we provide a simple argument to show that large spatial clustering of stellar-mass primordial black holes at the time of formation, such as the one induced by the presence of large non-Gaussianities, is ruled out. Therefore, it is not possible to evade existing constraints preventing stellar-mass primordial black holes from being a dominant constituent of the dark matter by boosting their initial clustering.

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*Introduction.*—The physics of primordial black holes (PBHs) has attracted a lot of interest [1–3] thanks to the multiple detections of gravitational waves (GWs) coming from BH binary mergers [4–7] and the suggestion that some of them may be of primordial origin [8–10].

One of the fundamental questions about PBHs is whether they can contribute significantly to the dark matter (DM) abundance. In the LIGO-Virgo-KAGRA (LVK) mass range, the answer seems to be negative. Both microlensing data [2], as well as an otherwise too high merger rate [11–14], impose the fraction  $f_{\text{PBH}}$  of PBHs in DM to be below the percent level. These constraints are derived assuming that PBHs are initially Poisson distributed in space. PBH clustering at the time of formation can, in principle, change the present and past PBH merger rate by both boosting the formation of binaries and increasing the subsequent suppression due to the interaction of binaries in PBH clusters, thus possibly allowing for larger values of  $f_{\text{PBH}}$  [15–20]. Similarly, a sizable initial PBH clustering might relax the microlensing bounds since compact PBH clusters would act as a single lens that is too massive to be probed by microlensing surveys [21–23].

The aim of this Letter is to demonstrate that existing observations do not allow for the totality of DM to consist of stellar-mass PBHs for any amount of initial spatial clustering. The argument is quite simple. To significantly affect constraints stemming from the merger rate of PBH binaries, PBHs must be spatially correlated at the kpc comoving scales which are relevant for the present merger rate. Such PBHs will form compact clusters during radiation domination, which are initially Poisson distributed at larger scales, of the order of Mpc. Thus, existing Lyman- $\alpha$  constraints provide an upper bound on the size of such a PBH correlation. This upper bound is incompatible with the lower bound on the same physical quantity necessary to avoid the microlensing constraints.

We proceed now to summarize our arguments. Technical details are contained in the Supplemental Material [24].

*Modeling PBH clustering.*—PBHs are discrete objects and the two-point correlation function of their density contrast  $\delta_{\text{PBH}}$  takes the general form [25]

$$\langle \delta_{\text{PBH}}(\vec{r}) \delta_{\text{PBH}}(0) \rangle = \frac{1}{\bar{n}_{\text{PBH}}} \delta_D(r) + \xi_{\text{PBH}}(r), \quad (1)$$

where  $r = |\vec{r}|$  is the distance between two PBHs and

$$\bar{n}_{\text{PBH}} \simeq 30 f_{\text{PBH}} \left( \frac{M_{\text{PBH}}}{M_{\odot}} \right)^{-1} \text{ kpc}^{-3} \quad (2)$$

is the average PBH number density per comoving volume. We will assume a monochromatic PBH population with mass  $M_{\text{PBH}}$ . The first term on the right-hand side represents the Poisson term arising from the discrete nature of PBHs. It is present for any distribution of pointlike objects regardless of their clustering. The second term  $\xi_{\text{PBH}}(r)$  is the so-called reduced PBH correlation function.

We will focus on the standard scenario where PBHs form from the collapse of large overdensities when the corresponding wavelengths reenter the horizon [1]. In the absence of primordial non-Gaussianity, PBHs are not correlated and the two-point PBH function is dominated by the Poisson term in the range of initial distances relevant for the calculation of the present merger rate [25,26]. This is because the formation of PBHs is a very rare event. For instance, for a PBH with mass  $M_{\text{PBH}} \sim 10 M_{\odot}$  it happens only in 1 over  $10^8$  Hubble volumes [27]. However, if some non-Gaussianity is present and correlations over distances larger than the horizon arise during formation, sizable spatial correlations between PBHs are possible.

As typically done in the literature, we model initial PBH clustering assuming that the reduced two-point correlator is

approximately constant in space and much larger than unity up to some comoving clustering scale  $r_{\text{cl}}$ ,

$$\xi_{\text{PBH}}(r) \simeq \begin{cases} \xi_0 \gg 1 & \text{for } r \lesssim r_{\text{cl}}, \\ 0 & \text{otherwise,} \end{cases} \quad (3)$$

where  $r_{\text{cl}} \gtrsim 1$  kpc and  $\xi_0 \gtrsim 1$  in order for clustering to be relevant for comoving scales of PBH binaries with typical mass about  $30 M_{\odot}$  that merge today (see, e.g., Refs. [18,28]). At smaller scales, the two-point correlator can be even larger, but with the spatial exclusion condition that  $\xi_{\text{PBH}}(r) \simeq -1$  below approximately the comoving Hubble radius at formation time, as distinct PBHs cannot form arbitrarily close to each other. As we will see, clustered PBHs would induce Poisson perturbations at much larger scales, corresponding to the average cluster distance, well within the Lyman- $\alpha$  range. The relevance of the precise shape of  $\xi_{\text{PBH}}$  is reduced by the fact that the cluster properties after its gravitational collapse are mostly determined by the average overdensity.

Quite generally, the evolution of PBH clustering follows different stages: (i) initially, the cosmological horizon is comparable to the size of PBHs, thus each PBH forms independently (however, this can depend on the formation mechanism). Nevertheless, their formation probability can be heavily modulated, causing them to preferably form in superhorizon patches of comoving size  $r_{\text{cl}}$ . This sets the initial spatial distribution for PBHs. (ii) While the initial PBH density fluctuates due to the initial clustering as well as the discreteness of PBHs, the resulting fluctuations in the total energy density are tiny right after their formation deep in the radiation dominated era. Thus, the PBHs remain coupled to the Hubble expansion. At this stage  $\bar{\rho}_{\text{PBH}} \ll \delta\rho_{\text{PBH}} \ll \rho_{\text{rad}}$  and  $\delta\rho_{\text{PBH}}/\rho_{\text{rad}} \propto a$  (the scale factor) due to the faster dilution of radiation. (iii) When  $\delta\rho_{\text{PBH}} \approx \rho_{\text{rad}}$ , PBHs begin to decouple from the expansion, causing the gravitational collapse and a subsequent violent relaxation of these clusters. Because of the high density contrast, this stage takes place deep in the radiation dominated era [29]. The resulting gravitationally bound clusters have an average mass  $M_{\text{cl}} \simeq M_{\text{PBH}} N_{\text{cl}}$  where  $N_{\text{cl}}$  is the PBH number in the cluster (see the Supplemental Material [24] for more details)

$$N_{\text{cl}} \simeq \bar{n}_{\text{PBH}} \int d^3x \xi_{\text{PBH}} \approx \frac{4\pi}{3} \bar{n}_{\text{PBH}} \xi_0 r_{\text{cl}}^3. \quad (4)$$

In clustered scenarios,  $N_{\text{cl}} \gg 1$  should be assumed. For definiteness, we impose

$$N_{\text{cl}} \gtrsim 3: \quad \xi_0 \gtrsim 2.3 \times 10^{-2} f_{\text{PBH}}^{-1} \left( \frac{M_{\text{PBH}}}{M_{\odot}} \right) \left( \frac{r_{\text{cl}}}{\text{kpc}} \right)^{-3}. \quad (5)$$

(iv) PBH clusters act as pointlike objects at comoving distances  $R_{\text{cl}} \gg r_{\text{cl}}$ , where

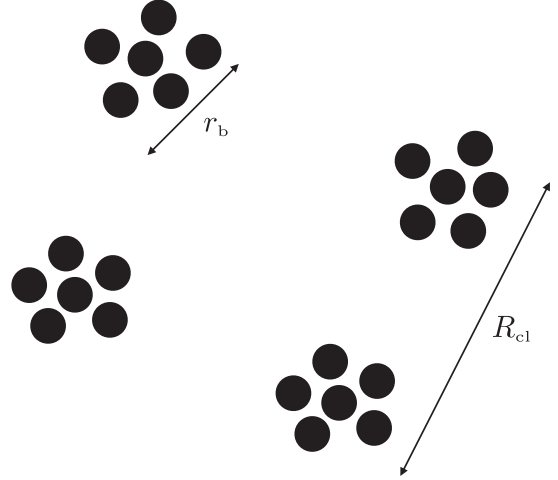


FIG. 1. Pictorial representation of the initially clustered PBHs, along with the relevant scales.

$$R_{\text{cl}} \simeq \frac{1}{\bar{n}_{\text{cl}}^{1/3}} \simeq \left( \frac{\bar{n}_{\text{PBH}}}{N_{\text{cl}}} \right)^{-1/3} \simeq r_{\text{cl}} \xi_0^{1/3}, \quad (6)$$

in terms of the cluster number density  $\bar{n}_{\text{cl}}$ . See Fig. 1 for a pictorial representation. Also, clusters themselves begin to group into bound systems after matter-radiation equality. As they are discrete objects, such PBH clusters follow a Poisson distribution and their subsequent evolution will be similar to the early small scale structure formation of PBHs of mass  $M_{\text{cl}}$  [20,30]. Note that Eq. (6) requires  $\xi_0 \gg 1$  for the initial clusters not to overlap with each other, guaranteeing that their gravitational collapse during radiation domination is clearly separated from the following Poisson clustering evolution.

The physical radius of the cluster is (see the Supplemental Material [24])

$$r_b \simeq 4 \times 10^{-2} \text{ pc} f_{\text{PBH}}^{1/3} \xi_0^{-1} \left( \frac{C}{200} \right)^{-1/3} \left( \frac{r_{\text{cl}}}{\text{kpc}} \right), \quad (7)$$

in terms of their overdensity  $C$  right after decoupling. We require that the cluster does not collapse into a heavy PBH of mass  $\approx M_{\text{cl}}$ , as the latter would correspond to a different (but more typical) scenario in which the DM is composed of Poisson distributed heavy PBHs. Therefore, we demand that the final halo is less compact than a BH, i.e., it must violate the hoop condition  $r_b \lesssim 2GM_{\text{cl}}$  [31]. This is equivalent to demanding that the cluster is much smaller than the cosmological horizon during gravitational collapse or that collapse takes place after the cluster enters the horizon, and translates into

$$\text{Heavy-PBH: } \xi_0 \lesssim 6 \times 10^4 f_{\text{PBH}}^{-1/3} \left( \frac{C}{200} \right)^{-1/6} \left( \frac{r_{\text{cl}}}{\text{kpc}} \right)^{-1}. \quad (8)$$

As these clusters are still very compact, it is easy to check that they are not destroyed by tidal effects coming from interactions with the surrounding environment (see

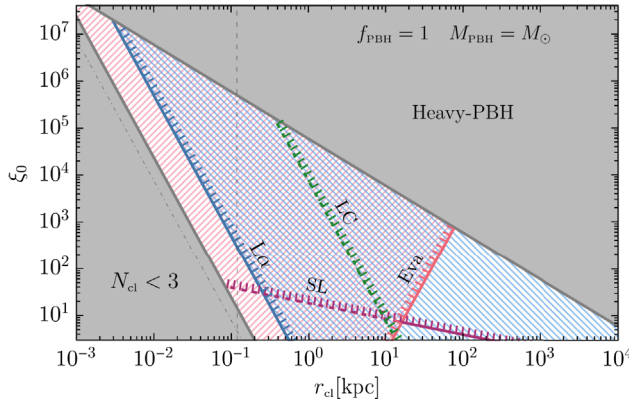


FIG. 2. Constraints on the relevant parameter space for initial PBH clustering, assuming solar-mass PBHs and  $f_{\text{PBH}} = 1$ . In gray we shade out regions where the conditions requiring sufficiently large clusters [ $N_{\text{cl}} \gtrsim 3$ , Eq. (5)] or avoiding heavy PBH formation [Heavy-PBH, Eq. (8)] are not met. The different lines correspond to cluster evaporation [Eva, Eq. (9)], single lens [SL, Eq. (11)] and large clusters limits [LC, Eq. (13)] and Lyman- $\alpha$  constraints [L $\alpha$ , Eq. (16)]. The hatched regions are ruled out by either microlensing (red) and/or Lyman- $\alpha$  (blue) limits, indicating that the combination of these two experiments alone entirely constrains the relevant parameter space. Finally, for reference, we show with the vertical dashed line the PBH average distance if they were Poisson distributed at formation, while the dot-dashed diagonal line refers to condition (17) for coherent accretion.

the Supplemental Material [24] for details). On the other hand, their smaller physical size makes it easier for PBH clusters to dynamically evaporate [32]. The minimal number of PBHs in the cluster to avoid evaporation within the age of the universe can be translated into a constraint on the PBH initial correlation function (see the Supplemental Material [24] for details),

$$\text{Eva: } \xi_0 \lesssim 1.7 \times 10^{-3} f_{\text{PBH}} \left(\frac{200}{C}\right)^{1/2} \left(\frac{M_{\odot}}{M_{\text{PBH}}}\right) \left(\frac{r_{\text{cl}}}{\text{kpc}}\right)^3. \quad (9)$$

This condition, shown as a red solid line in Fig. 2, covers a large parameter space for the initial PBH clustering. Consequently, initial strong clustering  $\xi_0 \gg 1$  enhances cluster evaporation when compared to Poisson initial conditions. More general considerations about PBH clustering modeling can be found in the Supplemental Material [24].

*Microlensing constraints.*—Microlensing surveys provide a powerful probe to constrain PBHs in a wide range of masses. They search for the temporary amplification of distant sources like stars due to the passage of a compact object near the line of sight [33]. Several constraints were set on the abundance of PBHs in the Milky Way halo. Examples are given by observations of M31 using Subaru HSC [34,35], which set a limit on planetary and subplanetary PBH masses, while EROS, MACHO, and OGLE surveys of the Magellanic clouds constrain stellar and planetary PBH masses [36–39]. Overall, stellar microlensing constrains

impose  $f_{\text{PBH}} \lesssim 0.1$  in the mass range  $10^{-10} M_{\odot} \lesssim M_{\text{PBH}} \lesssim 10^3 M_{\odot}$ , thus excluding PBHs for making up all of the DM in this mass range [3].

These limits were derived assuming evenly distributed PBHs. It was suggested that the inevitable clustering of PBHs induced by Poisson initial conditions could significantly relax these bounds [21–23], as they would act as a single lens with a mass much larger than the one relevant for the microlensing surveys. This result was disputed by Refs. [40,41], which found that this criterion can only be satisfied either for very compact PBH clusters that act as a pointlike object, or for noncompact clusters containing a sufficiently large amount of objects, where individual PBHs can be resolved, neither of which are reached in initially Poisson scenarios. On the other hand, initially clustered scenarios may avoid these bounds, provided that PBH clusters remain stable, i.e., satisfy Eq. (9).

The first condition is realized if the Einstein radius of the cluster is larger than its size,  $R_E(M_{\text{cl}}) \gtrsim r_b$ . For surveys of Magellanic clouds, the Einstein radius is [40,41]

$$R_E(M_{\text{cl}}) \simeq 4.8 \times 10^{-5} \text{ pc} \sqrt{\frac{M_{\text{cl}}}{M_{\odot}}}, \quad (10)$$

from which one extracts the condition for compact-enough PBH clusters to act as a single lens,

$$\text{SL: } \xi_0 \gtrsim 18 f_{\text{PBH}}^{-1/9} \left(\frac{C}{200}\right)^{-2/9} \left(\frac{r_{\text{cl}}}{\text{kpc}}\right)^{-1/3}. \quad (11)$$

This condition is shown as a magenta line in Fig. 2, and it is meaningful only in the parameter space where cluster evaporation is not efficient enough (see the transition from the dashed to the solid line in Fig. 2).

On the other hand, clusters which are not compact enough, but have a large amount of PBHs and act as a compilation of spatially correlated individual lenses, can still evade the microlensing limits. This occurs if the number of PBHs in clusters is larger than [41]

$$N_{\text{cl}} \gtrsim 10^6 \left(\frac{M_{\text{PBH}}}{M_{\odot}}\right)^{-1}, \quad (12)$$

which requires

$$\text{LC: } \xi_0 \gtrsim 7.7 \times 10^3 f_{\text{PBH}}^{-1} \left(\frac{r_{\text{cl}}}{\text{kpc}}\right)^{-3}. \quad (13)$$

This bound is depicted in green in Fig. 2. Again, this holds only when PBH clusters do not evaporate efficiently.

*Constraints from Lyman- $\alpha$  observations.*—We now briefly review bounds obtained from the Lyman- $\alpha$  forest and describe how they change if PBHs are initially clustered.

The Lyman- $\alpha$  forest is a series of absorption lines in the spectra of distant galaxies and quasars arising from the

transitions of electrons from the ground state to the first excited state of the neutral hydrogen atom. As the light travels through multiple gas clouds with different redshifts, multiple absorption lines may be formed [42–44].

Assuming that PBHs are initially Poisson distributed, Refs. [45,46] have studied their impact on the Lyman- $\alpha$  observations. The PBH contribution to the matter linear power spectrum would be  $P_{\text{PBH}}(k) = f_{\text{PBH}}^2/\bar{n}_{\text{PBH}}$ , which enhances the standard  $\Lambda$ CDM spectrum producing a small-scale plateau. As the adiabatic contribution evolves as  $k^{-3}$  at large  $k$ , the isocurvature term would be important only at scales relevant for Lyman- $\alpha$  observations. Reference [46] found a  $(2\sigma)$  upper limit of the form

$$f_{\text{PBH}}M_{\text{PBH}} \lesssim 60 M_{\odot}, \quad (14)$$

when a Gaussian prior on the reionization redshift is assumed. For large PBH abundances  $f_{\text{PBH}} = 1$ , these constraints can be interpreted as limits on the PBH mass, while they become weaker for small abundances, up to values  $f_{\text{PBH}} \approx 0.05$  where seed effects could modify the predictions. Following Ref. [46], we do not consider values smaller than  $f_{\text{PBH}} \lesssim 0.05$ .

Crucially, Lyman- $\alpha$  observations concern (at moderate redshifts  $\sim 5$ ), comoving scales between  $\mathcal{O}(10^{-1} \div 1)$  Mpc, which are much larger than the typical cluster scale  $r_{\text{cl}}$ . At such large scales, clustered PBHs can be treated as compact objects with mass  $M_{\text{cl}}$  following a Poisson distribution in space with mean distance  $R_{\text{cl}}$ . This implies that, for strongly clustered PBHs, the Lyman- $\alpha$  bound translates into the condition

$$f_{\text{PBH}}M_{\text{cl}} = f_{\text{PBH}}N_{\text{cl}}M_{\text{PBH}} \lesssim 60 M_{\odot}. \quad (15)$$

It can be rewritten as

$$\text{L}\alpha: \xi_0 \lesssim 0.5 f_{\text{PBH}}^{-2} \left( \frac{r_{\text{cl}}}{\text{kpc}} \right)^{-3}. \quad (16)$$

This is shown as a blue solid line in Fig. 2. The bound is conservative as it does not account for the evolution of initially Poisson distributed PBH clusters under the action of self-gravity before redshift  $z = 199$ , at which Ref. [46] fixed their initial conditions. Including PBH clustering evolution [20,30] would result in a larger power spectrum at scales of interest for the Lyman- $\alpha$  observations and therefore to a bound stronger than Eq. (16).

*Other constraints in the stellar mass range.*—Strong initial PBH clustering affects constraints on  $f_{\text{PBH}}$  also from other independent observables. While a complete analysis of those is beyond the scope of the Letter, we highlight the qualitative effect of clustering on bounds from CMB observations and GW measurements and quantify when these effects are expected to become relevant.

PBHs heavier than the stellar mass are bounded by accretion constraints from Planck data [47,48]. Indeed, soon after the matter-radiation equality, heavy enough PBHs could start accreting baryonic particles from the surrounding medium. The resulting emission of ionizing radiation can alter the opacity of the gas in the period between recombination and reionization, thus affecting the CMB temperature and polarization fluctuations. In the conservative case, Planck data impose roughly  $f_{\text{PBH}} \lesssim (M_{\text{PBH}}/10 M_{\odot})^{-2}$  in the LVK mass range [48].

If PBHs are strongly clustered, these constraints can change. Compact PBH clusters could accrete as a coherent object if the accretion radii of individual PBHs overlap significantly, enhancing the accretion rate by at most a factor of  $N_{\text{cl}}$  when compared to the case where each PBH is an independent accretor [49–51]. This occurs if the average PBH separation in the cluster, i.e.,  $r_b/N_{\text{cl}}^{1/3}$ , is smaller than the individual PBH Bondi radii  $r_{B,\text{PBH}} = GM_{\text{PBH}}/v_{\text{eff}}^2$ , in terms of their effective velocity, which we assume to be dominated by the virial velocity of PBHs in the cluster (see the Supplemental Material [24]), and requires

$$\xi_0 \gtrsim 7.7 \times 10^{-3} f_{\text{PBH}}^{-1} \left( \frac{M_{\text{PBH}}}{M_{\odot}} \right) \left( \frac{r_{\text{cl}}}{\text{kpc}} \right)^{-3}. \quad (17)$$

Strong PBH clustering can tighten bounds coming from accretion at high redshifts in all scenarios with initial clusters characterized by  $N_{\text{cl}} \gtrsim 3$ , as illustrated in Fig. 2. It is conceivable that coherent accretion into PBH clusters alone could close the LVK mass window for clustered PBH-DM, even though a detailed analysis is required.

Although initial PBH clustering enhances the formation of PBH binaries in the early universe [15], even relatively mild clustering can cause nearly all of these binaries to be disrupted [16,19,52]. Nevertheless, disrupted binaries would still result in a merger rate too large to be consistent with LVK observations [4–7], excluding scenarios in which solar mass PBHs make up the entire DM [16]. However, in extreme cases, all PBH binaries formed in the early universe may merge well before the present. In this case, a large number of very compact PBH binaries would be produced in the early universe, but would not contribute to the present merger rate observed by LVK due to their short coalescence times. Nonetheless, they could still give rise to a potentially observable stochastic gravitational wave background. Only binaries forming in the later PBH clusters, likely through three-body interactions [53], would contribute to the present BH-BH merger rate. These effects indicate a very different GW phenomenology of PBH binaries when compared to the Poisson case.

To roughly estimate the minimum value of the initial PBH correlation for such a scenario, consider a circular PBH binary with its initial semimajor axis given by the mean separation in the cluster,  $r_b/N_{\text{cl}}^{1/3}$ , and demand that it coalesces within a Hubble time, that is



$$\xi_0 \gtrsim 5.8 \times 10^3 \left(\frac{C}{200}\right)^{-1/4} \left(\frac{M_{\text{PBH}}}{M_\odot}\right)^{-5/16}. \quad (18)$$

If this condition is met, all initial PBH binaries are expected to have merged before the present day.

*Discussion and conclusions.*—All our simple considerations about initially clustered PBH scenarios induced by a large initial two-point correlation lead to Fig. 2, showing that existing constraints cannot be avoided for  $f_{\text{PBH}} = 1$ . The same conclusion is valid also for  $f_{\text{PBH}} = 0.1$ , as we show in the Supplemental Material [24]. The main reason is simple: too light PBH clusters would evaporate and standard microlensing constraints hold; on the other hand, although sufficiently heavy PBH clusters may be stable and escape microlensing limits, they would inevitably induce large scale perturbations incompatible with the Lyman- $\alpha$  observations.

In more detail, the red region in Fig. 2 covers the parameter space where PBH clusters do not evade the microlensing bounds because of evaporation. In the complementary region, PBH clusters would be stable and may avoid microlensing bounds either by acting as a single lens or by being large enough. However, the blue region indicates that in such parameter space Lyman- $\alpha$  bounds would apply. Therefore, the combination of those constraints alone prevents stellar-mass primordial black holes to be the entirety of the dark matter, even if one considered nonstandard initial conditions with PBHs strongly clustered already at their formation.

We checked that the conclusions summarized in Fig. 2 do not change assuming a different PBH mass in the stellar mass range. While for smaller PBH masses the parameter space bounded by requiring a minimum number of PBHs in the cluster would shift to smaller  $r_{\text{cl}}$ , it is harder for cluster evaporation to occur, thus extending the region where microlensing limits apply. On the other hand, for larger PBH masses, the consistency bound  $N_{\text{cl}} \gtrsim 3$  would shift to the right and evaporation more easily occurs. The bound from Lyman- $\alpha$ , however, does not depend on the  $M_{\text{PBH}}$  explicitly, therefore leaving our results unaffected.

Our conclusions hold independently of the specific form of the two-point correlator on small scales  $r < r_{\text{cl}}$  (which determines the PBH profile inside the clusters) as long as the clusters are approximately Poisson distributed on scales much larger than  $r_{\text{cl}}$ . For the Lyman- $\alpha$  and the single lens condition, a sufficiently compact PBH cluster behaves as a massive compact halo object (MACHO) independently of its composition. Importantly, this implies that our results are independent of the exact distribution of PBH masses making up this object. Finally, although our conclusions are derived assuming a monochromatic spectrum for PBH cluster masses, the case of a wider cluster mass spectrum can be addressed using existing methods for wide PBH mass distributions [54,55] but with PBHs now replaced by compact PBH clusters. In particular, the relevant Lyman- $\alpha$

constraints for extended mass functions were studied in Ref. [46]. In all, we expect our conclusions to withstand reasonable variations of the initial PBH two-point function, the distribution of the masses of PBHs, and their initial clusters.

While our considerations rule out models of PBH formation with initial clustering (see, for instance, Refs. [18,56,57]), we stress that our findings close the window for stellar-mass PBHs as dark matter.

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