

Effective Field Theory Constraints on Primordial Black Holes from the High-Redshift Lyman- α Forest

Mikhail M. Ivanov^{1,2,*} and Sokratis Trifinopoulos^{1,3,4,†}

¹*Center for Theoretical Physics—A Leinweber Institute, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

²*The NSF AI Institute for Artificial Intelligence and Fundamental Interactions, Cambridge, Massachusetts 02139, USA*

³*Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*

⁴*Physik-Institut, Universität Zürich, 8057 Zürich, Switzerland*



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We present updated constraints on the abundance of primordial black hole (PBH) dark matter from the high-redshift Lyman- α forest data from MIKE/HIRES experiments. Our analysis leverages an effective field theory (EFT) description of the 1D flux power spectrum, allowing us to analytically predict the Lyman- α fluctuations on quasilinear scales from first principles. Our EFT-based likelihood enables robust inference across redshifts $z = 4.2\text{--}5.4$ and down to scales of 100 kpc, within previously unexplored regions of parameter space for this dataset. We derive new bounds on the PBH fraction with respect to the total dark matter f_{PBH} , excluding populations with $f_{\text{PBH}} \gtrsim 10^{-3}$ for masses $M_{\text{PBH}} \sim 10^4\text{--}10^{16} M_{\odot}$. This offers the leading constraint for PBHs heavier than $10^9 M_{\odot}$ and highlights the Lyman- α forest as a uniquely sensitive probe of new physics models that modify the structure formation history of our Universe.

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Introduction—The large-scale structure (LSS) of the Universe is rapidly becoming a leading observational pillar of modern cosmology. It captures the evolution of tiny primordial fluctuations—visible at the time of photon decoupling in the cosmic microwave background (CMB)—into the web of galaxies and matter that we observe today [1]. Measurements of the matter distribution inferred by LSS observations enable robust tests of the standard cosmological model, while constraining a range of nonstandard scenarios for the formation and growth of cosmic structure.

LSS probes such as Galactic observations [2–4] and CMB measurements [5–8], may constrain the matter-power spectrum at the permill level, at larger spatial scales but they lose sensitivity at wave numbers above 0.5 Mpc^{-1} . On the other hand, the Lyman- α forest [9] and ultraviolet luminosity functions [10], while not achieving the same level of precision, can extend cosmological constraints to higher redshifts and smaller scales with wave numbers up to $k \sim 10 \text{ Mpc}^{-1}$. A striking feature of these probes is their sensitivity to the small scale matter power spectrum which may contain contributions from beyond the standard matter components. Such perturbations arise in certain new

physics models including axionlike particles [11–20], and primordial black holes (PBHs) [21–27].

In this Letter, we focus on Lyman- α constraints on PBHs [28] with masses in the range $10^4\text{--}10^{10} M_{\odot}$. Even as a subpercent component of dark matter, PBHs in this mass window can leave rich cosmological signatures [29]. On the lighter end they could grow into the supermassive black holes found in Galactic Centers today via accretion and mergers [30–35], or they may have formed already supermassive from the collapse of large primordial fluctuations [36,37]. In the latter case, they would be present at the onset of matter domination, inducing a scale-invariant “isocurvature” component in the power spectrum and acting as seeds for accelerated galaxy formation via the *Poisson effect* [21–23,38,39]. Binaries formed from such PBHs could also produce distinctive gravitational-wave signatures in the nHz frequency band [26,40–42]. For even larger masses, $M_{\text{PBH}} \gtrsim 10^{12} M_{\odot}$, *stupendously large PBHs* (SLABs) may exist as rare relics roaming the intergalactic medium [43].

The Lyman- α forest, observed through absorption features in quasar spectra, probes the distribution of neutral hydrogen in the redshift range $2 < z < 5$. The presence of PBHs can lead to a significant enhancement of the transmitted flux power relative to the standard Λ CDM prediction. The state-of-the-art constraints on the PBH parameter space from the Lyman- α forest are given in Ref. [24], where a suite of hydrodynamic simulations was performed with the isocurvature perturbations incorporated into the initial conditions at $z = 199$. The obtained 2σ upper bound is of the form $f_{\text{PBH}} < (M_{\text{PBH}}/60 M_{\odot})^{-1}$. However, their analysis applies for PBH populations with $f_{\text{PBH}} \lesssim 0.05$, and because

*Contact author: ivanov99@mit.edu

†Contact author: sokratis.trifinopoulos@cern.ch

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no simulations were performed for $f_{\text{PBH}} M_{\text{PBH}} > 10^4$, the bound cannot be directly extrapolated to the superheavy regime $M_{\text{PBH}} \gtrsim 10^5 M_\odot$ [29,43].

Our approach takes advantage of the effective field theory (EFT) of the Lyman- α forest developed originally in [44] (see also Refs. [45–53]). This framework offers a perturbative and systematically controlled description of the flux power spectrum, expressed in terms of large-scale cosmological observables and local bias operators. It accounts for nonlinear gravitational evolution and redshift-space distortions in a consistent bottom-up way [54–56]. Crucially, EFT enables analytic predictions in the regimes where hydrodynamical simulations have not been applied, thereby probing regions of the PBH parameter space that have not been tested before. As such, EFT provides an important complementary framework for modeling the Lyman- α forest.

Supermassive primordial black holes—Even though on sufficiently large scales the PBH fluctuations are adiabatic, at smaller scales the fact that PBHs are discrete compact objects becomes important. Assuming no particular initial clustering at the epoch of PBH formation, their locations are random, and thus their spatial distribution adheres to Poissonian statistics. As a result, a shot noise is generated in the total energy density which corresponds to isocurvature perturbations [22]. The perturbations remain frozen during the radiation-dominated era [57] but evolve linearly right afterward (i.e., $z < z_{\text{eq}} \approx 3400$).

For simplicity, we assume a monochromatic mass function, and the PBH populations are characterized by their mass, M_{PBH} , and the fractional abundance f_{PBH} . The matter power spectrum today is modified by the addition of a scale-independent component P_{iso} [21,23]:

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

$$P_{\text{iso}} \simeq \begin{cases} (f_{\text{PBH}} D_+(0))^2 / \bar{n}_{\text{PBH}}, & \text{if } k \leq k_{\text{cut}} \\ 0, & \text{otherwise} \end{cases}, \quad (1)$$

where $P_{\text{ad}}(k)$ is the adiabatic mode in Λ CDM, $\bar{n}_{\text{PBH}} = f_{\text{PBH}} \rho_{\text{crit},0} \Omega_{\text{DM}} / M_{\text{PBH}}$ is the comoving average number density of PBHs, and $D_+(z)$ is the isocurvature transfer function [23].

Phenomenologically, the isocurvature contribution is truncated at a scale k_{cut} , which parametrizes the regime where a Gaussian and perturbative description of PBH-induced fluctuations ceases to be reliable due to PBH discreteness and sparsity effects. In the absence of a reliable description of the transition between the linear and the nonlinear regimes, the cut-off scale is chosen to be the inverse mean separation between PBHs, $\bar{k}_{\text{PBH}} = (2\pi^2 \bar{n}_{\text{PBH}})^{1/3}$ [16,23,58]. Additionally, we stress that strong nonlinear dynamics around the PBHs develop when the PBHs are very rare and they effectively evolve in isolation. This situation is known as the *seed effect* [22] and becomes

dominant in the regime $f_{\text{PBH}} \lesssim (1 + z_{\text{coll}})/z_{\text{eq}}$, where z_{coll} is the redshift of the collapse of the nonlinear structure that embeds PBHs. Therefore, we restrict our discussion within the range of validity of the Poisson effect, which for the relevant redshifts corresponds to $f_{\text{PBH}} \gtrsim 10^{-3}$.

Analysis details—

The dataset: The Lyman- α forest probes the spatial fluctuations in the transmitted flux $F = e^{-\tau}$ of high-redshift quasar spectra, where τ is the optical depth due to absorption by neutral hydrogen in the intergalactic medium (IGM).

The key observable is the one-dimensional (1D) flux power spectrum $P_F(k_{\parallel}, z)$, which quantifies correlations of flux fluctuations along the line-of-sight (LOS) direction in redshift space. This observable indirectly traces the matter distribution while encoding additional astrophysical effects such as redshift-space distortions (RSD).

For this Letter we focus on high-redshift Lyman- α data, probing the linear matter power spectrum on scales smaller than other experiments, which is advantageous for PBH constraints. We use the MIKE and HIRES spectrograph data [59,60] in redshift bins $z = 4.2, 4.6, 5.0, 5.4$ covering the wave numbers $k/([\text{km/s}]^{-1}) = 0.01\text{--}0.08$, corresponding to the comoving wave numbers $(0.64\text{--}11.2) \, h \, \text{Mpc}^{-1}$. We combine overlapping MIKE/HIRES redshift bins in a single data vector using inverse covariance weights as detailed in the Supplemental Material [61,62].

EFT of the Lyman- α forest: To disentangle cosmological information from small-scale baryonic physics, we employ the EFT of the Lyman- α forest [44]. This framework constructs the most general perturbative expansion of the flux field in terms of long-wavelength operators consistent with the symmetries of the problem, and is valid up to the scale where the nonlinear effects become strong. Typically, this is where the density field becomes fully nonlinear. In a Λ CDM cosmology at redshift $z \sim 5$, this happens only at very small wave numbers, $k_{\text{NL}} \sim 100 \, h \, \text{Mpc}^{-1}$, by virtue of the approximate scale invariance of the primordial power spectrum. In this setup, the relevant nonlinear scale will be set by the Lyman- α forest gas scale $k_J \gtrsim 20 \, h \, \text{Mpc}^{-1}$ [63].

The above suggests that the EFT is applicable to the entire range of scales probed by MIKE/HIRES data. Inhomogeneities in the ionizing background, and patchy reionization can introduce new scales relevant for the EFT. In the perturbative regime, these effects are captured by our gradient expansion counterterms. If these effects were large, they would lead to large measured values of counterterms, which we do not find in the actual data analysis, validating our scale counting. This is consistent with the simulation study [64] that found the effect of inhomogeneous ionization on the 1D power spectrum to be relatively small.

EFT is the most conservative description of the Lyman- α forest, which is based only on symmetries and dimensional

analysis. EFT builds on two factors: (i) the SO(2) rotational symmetry implies that the only allowed operators are scalars and gradients along the LOS (denoted by $\parallel$), with the most important component being the matter overdensity field δ_m , and the gradient of peculiar velocity $\eta \equiv \partial_{\parallel} v_{\parallel}/(aH)$, respectively, and (ii) the equivalence principle dictates that the higher-order terms (and counterterms) can depend only on velocity gradients and tidal fields.

We define the flux contrast field as

$$\delta_F(\mathbf{x}) \equiv \frac{F(\mathbf{x})}{\langle F \rangle} - 1, \quad (2)$$

and in the rest frame of a neutral hydrogen cloud the expansion reads as

$$\delta_F(\mathbf{x}) = b_1 \delta_m(\mathbf{x}) + b_{\eta} \eta(\mathbf{x}) + \sum_i b_{\mathcal{O}_i} \mathcal{O}_i(\mathbf{x}) \quad (3)$$

$$+ \delta_{\text{ctr}}(\mathbf{x}) + \epsilon(\mathbf{x}), \quad (4)$$

where $\mathcal{O}_i$ denote the higher-order composite operators, and ϵ encodes stochastic noise [52]. The expression (3) is transferred in the observer's frame using the RSD mapping [54]. The observable 1D flux power spectrum is obtained then by integrating the 3D flux power spectrum over hard momenta along the LOS,

$$P_F^{\text{1D}}(k_{\parallel}, z) = \frac{1}{2\pi} \int_{k_{\parallel}}^{\infty} dk k P_F^{\text{3D}}(k, k_{\parallel}, z), \quad (5)$$

where $P_F^{\text{3D}}(k, k_{\parallel}, z)$ is given by Fourier transform of the two-point correlation function of the field δ_F . At tree level it can be expressed as a generalization of the Kaiser formula for galaxies [65]:

$$P_{\text{tree}}(k, z) = \left(b_1 - b_{\eta} \mu^2 \frac{d \ln D_+(z)}{d \ln a} \right)^2 P(k), \quad (6)$$

where $\mu = k_{\parallel}/k$ and D_+ is the growth factor, while at the one-loop level we have additional contributions from the operators $\mathcal{O}_i$ in Eq. (3) computed in Ref. [48]. $\delta_{\text{ctr}} \sim \nabla^2 \delta_{\text{lin}}$ captures higher derivative bias, baryonic effects, Doppler broadening, and gas smoothing. The 1D projection integral introduces additional sensitivity to small scales which physically corresponds to additional stochastic corrections of the form $P_{\text{1D, stoch}}(k_{\parallel}) = \mathcal{C}_0 + \mathcal{C}_1 k_{\parallel}^2 + \mathcal{C}_2 k_{\parallel}^4 + \dots$, which absorb corrections originating from small-scale effects.

In total, our EFT model introduces 19 nuisance parameters for each redshift bin. This corresponds to the most general line-of-sight tracer of the matter field. To reduce the freedom in the fit, we impose a simulation-based relationship between parameters following [48, 49]. We use precision EFT parameter measurements from the state of the art ACCEL² simulation [66] to extract relationships (priors)

on the nonlinear EFT bias parameters $b_{\mathcal{O}_i}(b_1)$ as functions of the linear bias [49]. This approach was previously validated on various simulations: ACCEL² [49], Sherwood [48], and Abacus FGPA mocks [67], giving consistent results across different microscopic models [52], suggesting its robustness in light of simulation uncertainties and variations.

In order to be more conservative and avoid extrapolation errors, we only use the $z = 4, 5$ ACCEL² EFT parameter measurements which cover the range of redshifts relevant for the MIKE/HIRES data. Note that in this approach b_1 controls both the scale-independent and scale-independent bias $b_{\mathcal{O}_i}$ via the simulation-based priors. While this modeling approach produces an excellent fit to MIKE/HIRES data without any additional calibrations, we also marginalize over the 1D stochastic counterterms in order to be more conservative.

Physically, the EFT parameter marginalization is equivalent to integrating over a broad range of astrophysical uncertainties, including thermal broadening, mean temperature, adiabatic index, etc. Specifically, we marginalize the stochastic parameters over a Gaussian distribution that is centered at the ACCEL² prior $\mathcal{C}_n(b_1)$ and has a width estimated from the small-scale sensitivity of the EFT fit to the simulation data, as is standard in particle physics. This results in a highly flexible conservative model which has four independent free parameters ($b_1, \mathcal{C}_0, \mathcal{C}_1, \mathcal{C}_2$) in each redshift bin. Details of our theory model are provided in the Supplemental Material [61, 62], where we demonstrate that it produces an excellent fit to the data, which validates our modeling choices.

Finally, we include the effect of PBHs by feeding the modified linear matter power spectrum in Eq. (1) to the tree-level and loop EFT calculations.

Analysis: We perform our parameter inference using a MontePython [68, 69] Markov chain Monte Carlo (MCMC) engine, interfaced with a modified version of the EFT code CLASS-PT [70]. We fix the six standard cosmological parameters $\{\omega_b, \omega_{\text{DM}}, 100\theta_s, \tau_{\text{reio}}, \ln(10^{10} A_s), n_s\}$ to their Planck CMB best-fit values.

Results—Focusing on the new physics, we vary the constant term P_{iso} for different fixed choices of $k_{\text{cut}}/(h\text{Mpc}^{-1})$,

$$\{0.06, 0.13, 0.28, 0.60, 1.3, 2.8, 6.0, 13\}, \quad (7)$$

and later map the constraints on the PBH parameter space via Eq. (1), e.g., the wave numbers in Eq. (7) correspond to the PBH masses $\log 10(\{13, 12, 11, 10, 9, 8, 7, 6\})M_{\odot}$ for $f_{\text{PBH}} = 10^{-2}$. The marginalized 95% upper limits on $P_{\text{iso}}/(h^{-1}\text{Mpc})^3$ for the corresponding k_{cut} read as

$$\{1000, 660, 350, 20, 7.8, 1.6, 7.9 \times 10^{-2}, 3.4 \times 10^{-2}\}, \quad (8)$$

which can be readily converted into strong limits on the combination $f_{\text{PBH}} M_{\text{PBH}}$. We stress that the results of our

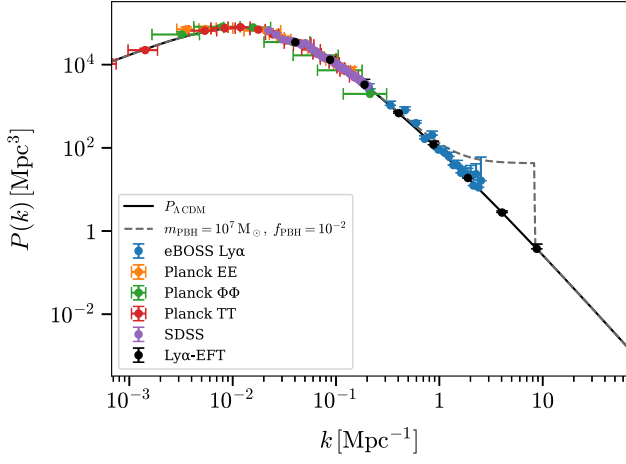


FIG. 1. The linear matter power spectrum at $z = 0$ is shown for Λ CDM (black), and for a PBH model with $f_{\text{PBH}} = 10^{-2}$ and $M_{\text{PBH}} = 10^7 M_{\odot}$ (gray dashed). The black dots (and corresponding error bars) denote the 95% C.L. constraints on overfluctuations from the high-redshift Lyman- α data from MIKE/HIRES, that are derived in this Letter. The blue dots denote the Lyman- α from eBOSS DR14 [9,71]. The rest of the error bars correspond to observations of luminous red galaxies (purple) by Sloan Digital Sky Survey Data Release 7 (SDSS DR7) [2] (purple) and the *Planck* 2018 [6] CMB temperature (red), polarization (orange), and lensing (green) power spectra.

analysis can be readily applied to any model that predicts such a scale-invariant enhancement of the power spectrum at the scales of interest. Our analysis constrains such departures from the Λ CDM matter power spectrum for $0.6 \lesssim k/(h\text{Mpc}^{-1}) \lesssim 13$ at the $\lesssim 10\%$ level as can be seen in Fig. 1.

We stress that the data points shown in Fig. 1 are correlated, which is particularly important for $k < 0.6 h\text{Mpc}^{-1}$ outside of the MIKE/HIRES range. The constraints on these wave numbers come entirely from the EFT mode coupling, which is an indirect effect, resulting in the abrupt deterioration of our constraints for $k_{\text{cut}} < 0.6 h\text{Mpc}^{-1}$. Note that the parameter space $k_{\text{cut}} \lesssim 0.3 h\text{Mpc}^{-1}$ should be better constrained by full-shape galaxy clustering data from DESI [72,73].

In Fig. 2, we show how those constraints translate on the $M_{\text{PBH}} - f_{\text{PBH}}$ plane together with all the other relevant constraints discussed in the literature. The constraint (red line) takes the shape of a trapezoid between $f_{\text{PBH}} = 1$ and the limit of the Poisson effect $f_{\text{PBH}} \gtrsim \mathcal{O}(10^{-3})$ spanning a wide range of masses, i.e., between $10^5 M_{\odot}$ and $10^{13} M_{\odot}$. The right side is determined by a lower bin of k_{cut} in Eq. (7). Evidently, it becomes the leading constraint on the regime above $\mathcal{O}(10^9 M_{\odot})$ [74] stretching up to $10^{16} M_{\odot}$, deep into

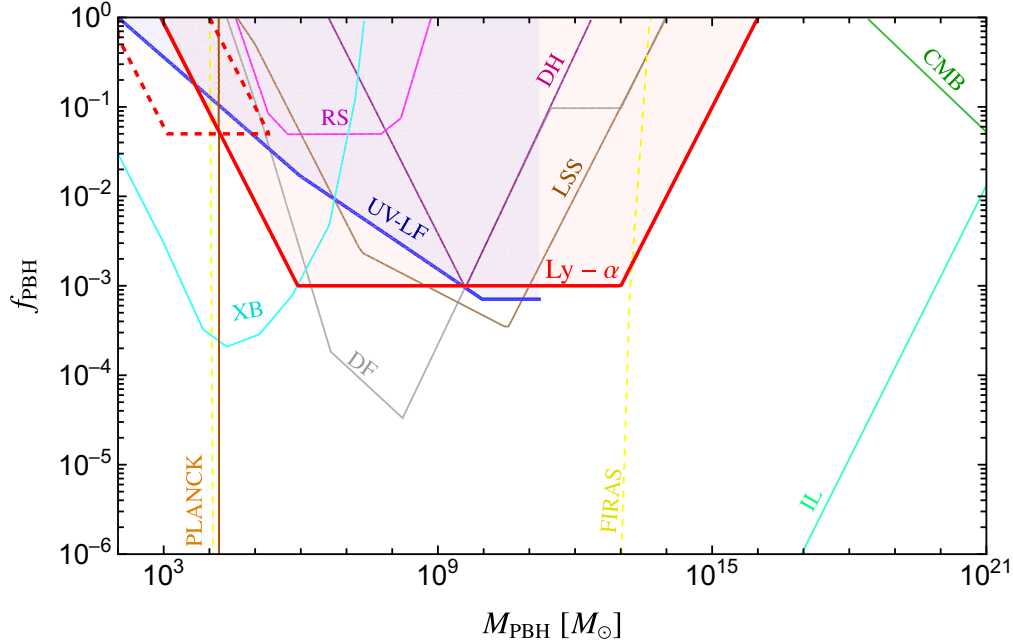


FIG. 2. Constraints on the parameter space of supermassive and stupendously large primordial black holes at 95% C.L. The red shaded region denotes the region excluded due to Lyman- α MIKES/HIRES data derived in this Letter. We also show the Lyman- α constraints from the simulation-based study of Ref. [24] (dashed red). Limits arise also due to CMB anisotropies produced by accreting PBHs measured by *Planck* [35] (PLANCK, yellow), x-ray flux induced by accretion [75] (XB, cyan), millilensing of radio sources [76] (magenta), dynamical friction causing halo objects to fall in the nucleus of the Milky Way [77] (DF, grey), overheating of stars in the galactic disk [77] (DH, purple), high-redshift formation of large-scale structures [22] (LSS, brown), the Hubble Space Telescope ultraviolet luminosity function [26,78] (UVLF, blue), and the CMB dipole anisotropy [29] (CMB, green). The region on the left side of the yellow dashed line is constrained by CMB spectral μ distortion measured by COBE/FIRAS surveys [79] in the Gaussian limit [74]. The right side of the light green line denotes the incredulity limit (IL), which corresponds to one black hole per Hubble volume.

the region of SLABs. The left side corresponds to the P_{iso} upper limit at $k_{\text{cut}} = 13 \text{ hMpc}^{-1}$ as all PBH populations with $k_{\text{cut}} > 13 \text{ hMpc}^{-1}$ have shot noise contributions extending at least up to $k_{\text{cut}} = 13 \text{ hMpc}^{-1}$. In principle, we can get stronger constraints for $k_{\text{cut}} > 13 \text{ hMpc}^{-1}$ as EFT has sensitivity to these scales (outside of the MIKE/HIRES direct range) due to mode coupling, but we conservatively do not use this information here in order to be more agnostic with respect to small-scale dynamics.

We also show for comparison the previous state-of-the-art bound using the same dataset from Ref. [24]. A first observation is that the two bounds are probing complementary parts of the parameter space and feature different shapes. As expected, the simulation-driven analysis is capable of constraining the parameter space in the fully nonlinear regime $k \gg k_{\text{NL}}$, where the EFT description breaks down, and its shape is determined by the Poisson condition at the onset of the simulations $f_{\text{PBH}} \gtrsim 0.05$. However, as explained in the Introduction, the reach of the bound for PBHs with masses above $10^5 M_{\odot}$ is restricted by computational limitations. On the other hand, the EFT is applied at much lower redshifts, where the Poisson condition allows for smaller f_{PBH} values and successfully constrains scales that correspond to much heavier PBHs.

Conclusions—We have shown that the high-redshift Lyman- α forest data, interpreted through the EFT framework, can place stringent limits on new physics that enhances power at subhalo scales by isocurvature fluctuations. EFT enables the efficient and computationally tractable analytic exploration of parameter spaces of such a model. As we argue here, a significant fraction of the Lyman- α forest data at high redshift is approximately perturbative, and hence can be efficiently analyzed with EFT. Focusing on the scenario of PBHs, we derived constraints on f_{PBH} in a regime previously unassessed from the state-of-the-art simulation-based studies. In particular, supermassive PBHs and SLABs with per mill abundances with respect to dark matter, are decisively excluded.

Ongoing and upcoming high-resolution spectroscopy of distant quasars and galaxies, e.g., the Lyman- α data from DESI [80] and Spec-S5 [81], are poised to grow the Lyman- α forest in the near future, providing more precision data to constrain small-scale cosmological physics at high redshifts. In addition, the galaxy clustering data from DESI analyzed with EFT can be used to set limits on an uncharted part of the parameter space of supermassive black holes. These datasets together with other future galactic surveys, such as Euclid [82], the Rubin Observatory LSST [83], as well as the 21-cm signal [84] and even deep-field instruments like the James Webb Space Telescope (JWST) [85,86] will sharpen our understanding of the LSS structure in the early Universe. These forthcoming observations offer thus a golden opportunity to go beyond not only the Λ CDM paradigm but also the Standard Model of particle physics.

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Data availability—The data are not publicly available. The data are available from the authors upon reasonable request.

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