Unveiling Dark Forces with Measurements of the Large Scale Structure of the Universe

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Cosmology offers opportunities to test dark matter independently of its interactions with the standard model. We study the imprints of long-range forces acting solely in the dark sector on the distribution of galaxies, the so-called large scale structure (LSS). We derive the strongest constraint on such forces from a combination of Planck and BOSS data. Along the way we consistently develop, for the first time, the effective field theory of LSS in the presence of new dynamics in the dark sector. We forecast that future surveys will improve the current bound by an order of magnitude.

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Introduction.—The overwhelming experimental evidence for dark matter (DM) arises purely from its gravitational interactions, which might hide an elaborate dark sector. At the same time, the observed complexity of the interactions of visible matter could suggest that a similar multifaceted dynamics is at work in the dark sector, with new particle species interacting at different length scales.

Moreover, the large number of DM production mechanisms [1–5] that do not require any nongravitational portals leaves open the possibility that the dark and visible sectors interact purely through gravity. Under this reasonable (though undesirable) circumstance, precision cosmology and astrophysical probes might be the only tools capable of testing the dynamics of the dark sector.

It is thus of utmost importance to ask how much the nature of the dark sector can be explored through cosmological precision observables *independently* of its nongravitational portals with the standard model.

Specifically, the question we address in this Letter is whether DM possesses self-interactions affecting cosmological scales. We focus on interactions with range λ_φ larger than, or comparable to, the size of the Universe today ($\lambda_\varphi > H_0^{-1}$, where H_0 is the Hubble constant), with the goal of understanding how strongly present and future cosmological data will test the interaction strength of these long-range dark forces.

We expect the n-point correlation functions of galaxies, as measured by ongoing redshift surveys like DESI [6] and Euclid [7], to be the most suitable observables to test dark forces, since they provide direct information about the behavior of the matter fluctuations. These surveys will collect 1 order of magnitude more data than the current generation, e.g., the BOSS survey [8], providing new measurements at an unprecedented precision. An important phenomenological question is thus how much these upcoming datasets will help unveil the hidden dynamics of the dark sector.

To obtain the theoretical predictions for the galaxy correlators beyond linear perturbation theory (PT), we extend the effective field theory of large scale structure (EFTofLSS) [9–22] to include the presence of a dark force acting on DM (see also related studies in the context of modified gravity theories [23–25]). To our knowledge this is the first consistent perturbative calculation, beyond the linear regime, of the effects of dark sector dynamics on LSS n-point functions.

We find that combining the galaxy power spectrum with the cosmic microwave background (CMB) greatly improves the sensitivity to dark forces. Our results are summarized in Fig. 1. In particular, our analysis of the two-point correlation function of BOSS data strengthens the constraint from CMB Planck data alone derived in Ref. [26] by a factor of 2. Our forecast for Euclid anticipates an improvement by a factor of 5, leaving open the possibility of finding interesting deviations from ΛCDM.

This improvement stems from the distinctive dynamics of dark forces, which leave most of their imprints in the matter power spectrum. From this perspective, our Letter can be viewed as a novel example of dark sector dynamics that will be uniquely tested by future LSS data, going beyond the present knowledge from Planck measurements of the CMB (see Refs. [27,28] for previous approaches). To correctly take into account the interplay between the different observables we find it crucial to employ a particle physics description of the dark sector, which consistently incorporates corrections to both the cosmological background and the fluctuations, thus capturing effects that would be missed by approaches where the two are studied separately.

Finally, our consistent treatment of the EFTofLSS allows us to estimate that further extending the precision of the calculations of the galaxy power spectrum and bispectrum has the potential to improve the reach on dark forces. This observation strongly motivates new theoretical efforts to unleash the full discovery potential of future galaxy surveys.

Setup.—Physically, a long-range dark force can be mediated by an ultralight scalar field with mass $m_\varphi = \lambda_\varphi^{-1} < H_0 \approx 10^{-33}$ eV and trilinear coupling to the DM field χ, $\mathcal{L}_{\rm int} = -\kappa\varphi\chi^2$ [29–32]. Introducing the dimensionless field $s = G_s^{1/2}\varphi$, with effective constant $G_s \equiv \kappa^2/m_\chi^4$, the model Lagrangian becomes

$$-2\mathcal{L} \supset (\partial\chi)^2 + m_\chi^2(s)\chi^2 + \left[(\partial s)^2 + m_\varphi^2 s^2\right]/G_s, \quad (1)$$

where we neglected self-interactions of s and its nonminimal coupling to gravity, which arise at $\mathcal{O}(G_s^{-2})$ and $\mathcal{O}(G_s^{-1}G_N^{-1})$, respectively. The effect of the long-range scalar force can thus be reabsorbed in a space-time dependent mass for DM, $m_\chi(s) = m_\chi(1+2s)^{1/2}$.

Radiative corrections induced by DM loops make m_φ directly sensitive to the DM mass, so that requiring $m_\varphi \lesssim H_0$ bounds the DM mass from above, $m_\chi \lesssim (16\pi^2 M_{\rm Pl}^2 H_0^2/\beta)^{1/4}$, where we defined

$$\beta \equiv G_s/(4\pi G_N) \quad (2)$$

as the strength of the new force normalized to gravity. In the range of β of interest for this Letter the bound reads $m_\chi \lesssim 10^{-2}$ eV, favoring a bosonic nature for DM, which we assume to be a scalar for the remainder of this Letter. In light of the current constraint on β from the CMB, $\beta \lesssim 0.01$ [26], our analytical results are systematically derived at leading order in the small β expansion.

In this framework the DM can still be described as a collisionless fluid, with geodesics affected by the dark force. Assuming χ to be pressureless up to nonlinear dynamics, its evolution is governed by continuity and Euler equations with metric perturbations expanded to linear order, whereas the first three moments of the χ phase space distribution are retained fully nonlinearly [9,10].

In turn, the dynamics of the scalar field is dictated by the DM energy density, as discussed in Ref. [26]. At the background level, the Klein-Gordon equation during matter domination has the solution $\bar{s} - \bar{s}_{\rm eq} \simeq -\beta\tilde{m}_s f_\chi \log a/a_{\rm eq}$, where a is the scale factor, $\tilde{m}_s \equiv d\log m_\chi(s)/ds = (1+2\bar{s})^{-1}$, $f_\chi \equiv \bar{\rho}_\chi/\bar{\rho}_m$ is the interacting fraction of the total matter, and $\bar{s}_{\rm eq}$ is the value of the scalar field at matter-radiation equality, which is found to be practically identical to its initial displacement $\bar{s}_{\rm ini}$ by solving the evolution in radiation domination.

Throughout cosmic history the light scalar is dominated by kinetic energy, $w_s \simeq +1$, and makes up a subleading fraction of the total energy density. However, the scalar profile modifies the redshift of the DM energy density, accelerating it from a^{-3} to $a^{-(3+\varepsilon)}a_{\rm eq}^{\varepsilon}$, which in turn modifies cosmological distances according to

$$\frac{H}{H_{\rm CDM}} \simeq 1 - \frac{1}{2}\varepsilon f_\chi \log\frac{a}{a_{\rm eq}}, \quad \text{with} \quad \varepsilon \equiv \beta\tilde{m}_s^2 f_\chi, \quad (3)$$

as discussed in Supplemental Material A [33]. We assume that the scalar has negligible initial displacement, $\bar{s}_{\rm ini} \simeq 0$, yielding $\tilde{m}_s \simeq 1$ and $\varepsilon \simeq \beta f_\chi$ at leading order in β. We further assume that all of DM couples to the long-range force, though we comment in the Outlook section on scenarios where only a fraction of the DM energy density is interacting.

Signatures in cosmological correlators.—The presence of a scalar long-range force modifies the subhorizon dynamics in two ways: (i) it enhances the growth of the total matter fluctuations; (ii) it sources relative density and velocity fluctuations between DM and baryons. In this section we demonstrate why the first effect dominates in scenarios where the dark force interacts with the totality of DM (i.e., $f_\chi \simeq 1$). We leave a discussion of scenarios with $f_\chi \ll 1$ for a companion study [34].

The observables measured in redshift surveys are correlation functions of the galaxy number density perturbation $\delta_g \equiv n_g/\bar{n}_g - 1$, which, at long wavelengths, can be expanded in terms of the matter fields as [35–37]

$$\delta_g = b_1\delta_m + b_r\delta_r + b_\theta\theta_r + \text{nonlinear terms}, \quad (4)$$

where $\theta \equiv \nabla_i v^i$. In the above we defined the density contrasts $\delta_x \equiv \rho_x/\bar{\rho}_x - 1$ for $x = \chi, b$, the total and relative matter perturbations

$$\delta_m = f_\chi\delta_\chi + (1-f_\chi)\delta_b, \qquad \delta_r = \delta_\chi - \delta_b, \quad (5)$$

and similarly for the velocity fields $\mathbf{v}_m$ and $\mathbf{v}_r$.

Enhanced growth: In the subhorizon limit $k \gg aH$ and deep in matter domination, the evolution equations for the total matter perturbations maintain the same structure of the CDM ones. This follows from the absence of new scales in scenarios with long-range dark forces. At the linear level we find $\delta_m^{(1)}(\mathbf{k}, a) = D_{1m}\delta_0(\mathbf{k})$, with a linear growth factor

$$D_{1m} \simeq \left[1 + \frac{6}{5}\varepsilon f_\chi \left(\log\frac{a}{a_{\rm eq}} - \frac{181}{90}\right)\right] D_{1m}^{\rm CDM}, \qquad (6)$$

where $D_{1m}^{\rm CDM} = a$ and $\delta_0(\mathbf{k})$ is related to the value of the fluctuation at matter-radiation equality. The overall growth gets enhanced compared to the CDM case at $\mathcal{O}(\beta)$, with a large logarithm boosting this effect even further. This logarithm has the same origin of the one that appeared in Eq. (3) and it is connected to the dark force being long-range throughout the evolution of the Universe.

At the nonlinear level we find a remarkably simple structure for the solutions at order $n \geq 2$,

$$\delta_m^{(n)}(\mathbf{k}, a) = (D_{1m})^n \int_{\mathbf{k}} \mathrm{d}k_{1\ldots n}[F_n + \varepsilon f_\chi \Delta F_n](\mathbf{k}_1, \ldots, \mathbf{k}_n), \qquad (7)$$

where F_n is a standard CDM kernel [38] and $\int_{\mathbf{k}} \mathrm{d}k_{1\ldots n} \equiv \int[(\mathrm{d}^3k_1\ldots\mathrm{d}^3k_n)/(2\pi)^{3(n-1)}]\delta^{(3)}(\mathbf{k}-\sum_{i=1}^n \mathbf{k}_i)\delta_0(\mathbf{k}_1)\ldots\delta_0(\mathbf{k}_n)$. Modulo non-log-enhanced subleading terms, the time dependence is fully encapsulated by the linear growth factor, as in ΛCDM. Furthermore, the new nonlinearities induced by the dark force, ΔF_n, do not introduce any additional spatial structure and do not change the infrared (IR) behavior of the solution (explicit expressions can be found in parts A and B of the Supplemental Material [33], which includes Refs. [39–51]).

The form of Eq. (7) greatly simplifies the evaluation of the nonlinear dynamics, allowing us to model the effects of new physics on cosmological correlators at $\mathcal{O}(\varepsilon f_\chi \log a/a_{\rm eq})$. In this approximation, $\delta_0(\mathbf{k})$ is related to the inflationary perturbation through the ΛCDM transfer function [52].

With this model at hand, we can easily derive a one-dimensional Fisher forecast on the dark force coupling, which estimates the idealized Euclid reach (see Supplemental Material D and E for details [33]). At 95% confidence level (CL) from the real space power spectrum we find $(\varepsilon f_\chi)_{P_g} < 1.5 \times 10^{-4}$ for $k_{\rm max} = 0.27\ h\,\mathrm{Mpc}^{-1}$. Realistic bounds in redshift space from BOSS and forecasts accounting for degeneracies will be presented in the section on Constraints and discussion.

Relative densities and velocities: The relative perturbations are proportional to $\varepsilon\delta_m$ at linear order, and their growth is not enhanced by large logs at $\mathcal{O}(\beta)$: $\delta_r^{(1)} = -\theta_r^{(1)}/(aH) = 5\varepsilon\delta_m^{(1)}/3$. This remains true nonlinearly, where

$$\delta_r^{(n)}(\mathbf{k}, a) = \varepsilon(D_{1m}^{\rm CDM})^n \int_{\mathbf{k}} \mathrm{d}k_{1\ldots n} F_{nr}(\mathbf{k}_1, \ldots, \mathbf{k}_n). \qquad (8)$$

Therefore, to account for the leading log-enhanced effects when $f_\chi \simeq 1$ it is sufficient to retain only the total matter perturbations in the bias expansion of Eq. (4). The relative error associated to this approximation is of order $10\%/f_\chi$.

Nevertheless, the presence of large scale relative perturbations effectively breaks the equivalence principle (EP) and can be tested by looking at the breakdown of the consistency relations which constrain the IR structure of cosmological correlation functions in ΛCDM [53–65].

At the level of the galaxy power spectrum P_g, the EP ensures that bulk flows do not contribute to shifts in the position of the BAO scale [66–68], which will be measured down to few permille by future surveys. New operators in the galaxy bias expansion [37,69–71] can in general cause a shift, but their effect is suppressed in our model because the relative matter fluctuations follow the total matter ones at linear level: $\delta_r^{(1)} \propto \beta\delta_m^{(1)}$ and $\mathbf{v}_r^{(1)} \propto \beta\mathbf{v}_m^{(1)}$.

At higher order in the EFT, and in the presence of an EP violation, one would naively expect $\mathcal{O}(\beta)$ shifts of the BAO position. However, as shown in Supplemental Material C [33], at the power spectrum level relative motions only enter as $\mathbf{v}_r^2 \sim \mathcal{O}(\beta^2)$ and are therefore negligible, given the CMB constraint on $\beta \lesssim 0.01$ [72]. We explicitly checked the cancellation of bulk flows at one loop and $\mathcal{O}(\beta)$ in the matter and galaxy power spectra [73]. The same logic applies to higher-order bias parameters in the relative velocities and densities.

Beyond the two-point function, EP violation can reveal itself in the form of a $1/p$ pole in the squeezed limit of the bispectrum B_g, where p is the long wavelength mode [23,24,53–59]. For fluctuations of two different tracers, δ_g^A and δ_g^B, and using the bias expansion in Eq. (4), the squeezed limit of the bispectrum reads

$$\left.\frac{B_g^{AAB}(\mathbf{p}, \mathbf{p}_1, \mathbf{p}_2)}{P_{m,L}^{\rm CDM}(p) P_{m,L}^{\rm CDM}(p_1)}\right|_{\mathbf{p}\to 0} \simeq \varepsilon \frac{\mathbf{p}\cdot\mathbf{p}_1}{p^2} \frac{7b_1^A}{6} \Delta b^{AB}, \qquad (9)$$

where $\Delta b^{AB} \equiv b_1^A \bar{b}_r^B - b_1^B \bar{b}_r^A$ and $\bar{b}_r \equiv b_r - 4\mathcal{H}b_\theta/7$ up to nonlinear terms discussed in Supplemental Material A [33]. For a single tracer, $A = B$, the pole vanishes due to the symmetry under exchange of the two short modes. The above expression generalizes the results of Refs. [55,59], by consistently including the modifications to the cosmological background and all the relevant bias operators.

Analytical and numerical estimates of relative bias parameters [36,74] indicate that, in a ΛCDM model, $b_r, \mathcal{H}b_\theta \sim \mathcal{O}(1)$. A one-dimensional Fisher forecast gives at 95% CL $(\varepsilon f_\chi^{1/2})_{B_g^{AAB}} < 9.4 \times 10^{-3}\big(b_1/(\bar{b}_r^A - \bar{b}_r^B)\big)^{1/2}$ for $b_1^A = b_1^B = b_1$ and $k_{\rm max} = 0.11\ h\,\mathrm{Mpc}^{-1}$. Even an optimistic reach for maximally different tracers is much weaker than the sensitivity of the power spectrum, although with a different scaling with f_χ (see Supplemental Material D [33] for a detailed derivation).

We therefore conclude that, for $f_\chi \simeq 1$, the impact of dark forces on the galaxy power spectrum and bispectrum

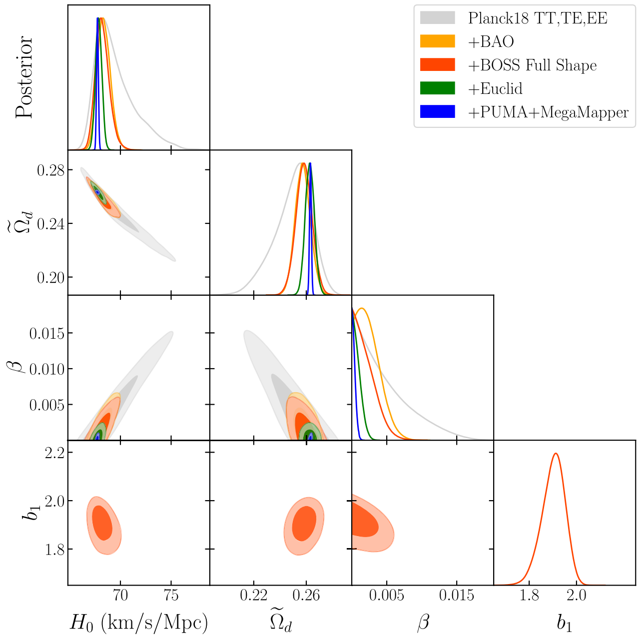

FIG. 1. Present constraints and forecasted reach on the dark force parameter space, obtained from the analysis of the redshift space galaxy power spectrum using the EFTofLSS. β is the strength of the dark force normalized to gravity, as defined in Eq. (2). $\tilde{\Omega}_d$ serves as a proxy for Ω_χ^0, see the main text for details. b_1 is the linear bias parameter for BOSS galaxies with $z_{\rm eff} = 0.57$ and in the north galactic cap. Gray (orange) contours show the constraints from Planck (Planck + BAO), previously obtained in Ref. [26]. Red contours show the constraints after including the analysis of the full shape of the BOSS power spectrum [8]. Green contours correspond to our forecast for the ongoing Euclid survey, while blue contours include the proposed PUMA and MegaMapper surveys.

is dominated by the log-enhanced growth of structure discussed previously. We focus on this effect from now on.

Constraints and discussion.—Given the results discussed in the previous sections, we are now in the position to search for long-range interactions in the dark sector with galaxy survey data. In this Letter we make use of the BOSS data release 12 [8]. This contains approximately 1×10^6 galaxies, divided in two redshift bins, with $z_{\rm eff} = 0.32$ and 0.57, and in two patches, above and below the galactic hemisphere. We include measurements of the position of the reconstructed BAO from BOSS [8] and other surveys [75–77], and Planck measurements of the CMB power spectra, including lensing [78]. The theoretical model for the power spectrum is evaluated with the PYBIRD code [79,80] and compared to the data up to $k_{\rm max} = 0.20(0.23)\ h\,{\rm Mpc}^{-1}$ for the lower (higher) redshift bin. We sample the posterior of the cosmological and nuisance parameters with MONTEPYTHON [81,82]. The final constraint on β is always marginalized over the 6 standard cosmological parameters and 8 nuisance parameters in the galaxy power spectrum analysis, per redshift bin and galactic cap, to account for nonlinear galaxy bias, shot noise, and the counterterms of the EFT.

A summary of the bounds is shown in Fig. 1, where we plot the four-dimensional parameter space of β, the Hubble constant H_0, the parameter $\tilde{\Omega}_d$, serving as a proxy for Ω_χ^0 and defined as the fractional energy density the interacting DM χ would have today had it evolved like a^{-3} [26], and the linear bias of the high-redshift bin for the north galactic cap. At 95% CL we obtain $\beta < 0.012$ from Planck data (gray contours), which improves to $\beta < 0.0048$ including BOSS full shape information on top of all the present BAO data (red contours).

The degeneracy between H_0 and β moves along the direction that keeps the angular size of the sound horizon at recombination constant: increasing β reduces the amount of matter at late times and can be compensated by a larger H_0 (or, equivalently, smaller $\tilde{\Omega}_d$). The addition of the full shape of the BOSS galaxy power spectrum does not significantly improve over the Planck + BAO constraint presented in Ref. [26]. This was expected, since the dominant effect of the new force is an approximately constant upward shift of the amplitude of the matter power spectrum, which can be compensated by decreasing the linear bias b_1, defined in Eq. (4). Given the bound from Planck + BAO on β, and the statistical errors of the BOSS data, the uncertainty on the linear bias is too large to provide significant additional constraining power. In other words, the modification of the background evolution induced by the dark force, as probed by CMB and BAO data, trumps the enhanced growth of structure at late times, which at the power spectrum level is highly contaminated by the nuisance parameters (see Supplemental Material E [33] for the complete results).

We then use our theoretical model to forecast the reach of future spectroscopic surveys and 21 cm instruments, such as the ongoing DESI and Euclid, and the proposed MegaMapper [83] and PUMA [84]. Our forecasts are based on the 1-loop modeling of the redshift space galaxy power spectrum presented in Ref. [85] and implemented in the Fisher forecasting code FishLSS [86,87]. The green lines in Fig. 1 show the improvement in the bound on β brought by adding the Euclid spectroscopic sample to the Planck and BOSS datasets, while the blue line corresponds to the further inclusion of MegaMapper and PUMA. We find that future surveys, thanks to their large volume, could dramatically improve current bounds and reach $\beta < 0.002(0.0008)$ at 95% CL for Euclid (PUMA + MegaMapper), even after marginalizing over all the nuisance parameters of the nonlinear modeling.

As we detailed above, the strong degeneracy between galaxy bias and β limits the ultimate reach of a power spectrum analysis. It is thus interesting to see to what extent higher order correlation functions such as the bispectrum, which is known to help break degeneracies between cosmological and nuisance parameters [88–91], can tame this effect and provide stronger bounds on DM long-range interactions.

As a proof of concept we can forecast the constraining power of a joint analysis for the Euclid survey [92], combining the real space power spectrum at one loop with the real space bispectrum at tree level. For the latter we include all triangular configurations up to $k_{\max} = 0.11\ h\,\mathrm{Mpc}^{-1}$, independently of redshift. We find that the limited k range imposed by our tree-level calculation prevents the bispectrum from helping significantly in breaking parameter degeneracies, once priors derived from current data are imposed. From a single-parameter Fisher forecast we find at 95% CL $(\varepsilon f_\chi)_{B_g} < 7.3 \times 10^{-4}(0.11\ h\,\mathrm{Mpc}^{-1}/k_{\max})^{2.2}$ for the bispectrum alone (see Supplemental Material D and E for further details [33]). The dependence of the bispectrum reach on $k_{\max}$ shows that extrapolating to $\approx 0.2\ h\,\mathrm{Mpc}^{-1}$ could yield a comparable sensitivity to the power spectrum one presented in the section on Enhanced growth. We view this as a strong indication that unleashing the power of higher order correlators to constrain dark forces requires a 1-loop modeling of the bispectrum, and possibly the inclusion of the trispectrum [23,24,93,94].

As the uncertainty on β decreases, higher order terms in the perturbative series for ΛCDM, e.g., 2-loop corrections to the power spectrum, can become comparable in size to new physics effects. Using estimates based on available results [95] we find that constraints on β down to $\mathcal{O}(10^{-3})$ are still insensitive to the theory error. This issue is however more pressing for the bispectrum and could even affect future analyses of the power spectrum, if $\beta \sim \mathcal{O}(10^{-4})$ sensitivity will be achieved.

Outlook.—In this Letter we derived the first constraints on long-range forces acting on DM from the LSS of the Universe. We showed that including the galaxy power spectrum as currently measured by BOSS improves the constraint on the dark force strength by a factor of 2 with respect to the CMB alone, reaching $\beta < 0.0048$ at 95% CL This is the strongest bound to date on long-range interactions in the dark sector from cosmological data (see Refs. [96,97] for constraints from galactic dynamics). A further tightening is forecasted with upcoming measurements from larger surveys, for example $\beta < 0.002$ for Euclid.

This Letter can be expanded in several directions. A pressing one is to extend the perturbative modeling of higher-point correlators in the presence of dark forces. In particular, we found that the galaxy bispectrum may reach the same level of sensitivity of the power spectrum. Beyond galaxy n-point functions, probing directly the galaxy velocity field, e.g., with peculiar velocity surveys [98–100], could enable auxiliary constraints and help isolate the non-log-enhanced EP violations.

In addition, other regions of the parameter space of dark forces can be probed using the results presented here. First, if only a small fraction of DM is self-interacting (i.e., $f_\chi \ll 1$) the contributions to galaxy correlators of relative perturbations, proportional to βf_χ, can overcome the log-enhanced corrections, which scale as $\beta f_\chi^2 \log a/a_{\mathrm{eq}}$. The interplay of these effects in testing the $f_\chi \ll 1$ scenario will be discussed in a forthcoming publication [34]. Second, one is naturally led to consider heavier mediators, $m_\varphi \gtrsim H_0$, corresponding to a shorter range for the dark force. In this regime, the evolution of the cosmological background is modified, as the mediator itself is expected to constitute a fraction of DM today. Addressing these questions will allow us to form a complete picture of what LSS can teach us about DM self-interactions.

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