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Late forming dark matter in theories of neutrino dark energy

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We study the possibility of late forming dark matter, where a scalar field, previously trapped in a metastable state by thermal or finite density effects, goes through a phase transition near the era matter-radiation equality and begins to oscillate about its true minimum. Such a theory is motivated generally if the dark energy is of a similar form, but has not yet made the transition to dark matter, and, in particular, arises automatically in recently considered theories of neutrino dark energy. If such a field comprises the present dark matter, the matter power spectrum typically shows a sharp break at small, presently nonlinear scales, below which power is highly suppressed and previously contained acoustic oscillations. If, instead, such a field forms a subdominant component of the total dark matter, such acoustic oscillations may imprint themselves in the linear regime.

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I. INTRODUCTION

The increasingly significant evidence for the dark universe has established a strong paradigm in cosmology, in which the dynamics of the universe at the largest scales are governed by two components of energy which, up to this point, have only been observed by their gravitational consequences [1–6]. These two, dark matter and dark energy, appear to behave in fundamentally different ways, with dark matter clustering into galaxies and diluting as the universe expands, while dark energy appears to remain smooth and dilutes either slowly or not at all, with equation of state near $w = -1$.

In spite of this, there is great effort to explore whether or not these substances might somehow be related. The strongest motivation for this is the similarity of the energy densities of ρ_{DM} and ρ_{DE} at the present epoch. Such attempts to connect these substances inevitably must confront the above differences, and attempts to unify them into one fluid often lead to dramatic observational consequences (see, for example, [7]).

There is a slightly more restrained approach, however. Rather than viewing these substances as necessarily the same fluid, we might instead view them of a similar type. That is, dark matter may be a substance which, at some time in the past, behaved as dark energy, and dark energy may, in the future, behave as dark matter. The fact that physics in the standard model has a generational structure, with repeated fields at different mass scales, especially motivates such duplication. In particular, in theories where the dark energy is connected to a new neutrino force as recently explored in [8–10], such generational structure is expected in the dark energy sector. It is inspiring to note that recent results from MiniBoone experiments [11] as well as reanalysis of big bang nucleosynthesis and CMB data [12] might be giving us hints for the existence of light eV sterile states which are essential components of this kind of neutrino dark energy model.

Such a consideration immediately raises the question: for how long must dark matter have behaved as dark matter? Certainly, at least since matter-radiation equality dark matter has been clustering and diluting more or less as a^{-3}. However, even at eras earlier than this, the clustering behavior of the dark matter can be observed in the power spectrum, at least to scales of $0.1h^{-1}$ Mpc, where the matter power spectrum becomes nonlinear.

It is quite natural to consider a scalar field which at some point in the history of the universe transitions to a dark matter state. Chaotic inflation [13,14], for instance, ends when the slow-roll condition ends, and, for a suitable potential, begins to evolve as dark matter. A very familiar example of such dark matter is the axion [15–17], which acquires a (relatively) large mass after the QCD phase transition, at which point it begins to behave as dark matter. A conversion to dark matter is the natural final state of numerous quintessence theories [18–20]

Our focus here will be on a transition that occurs much later in the universe, in order to make connections to theories of dark energy. In fact, we shall see that this transition naturally occurs near the era of matter-radiation equality. With such a late-time transition, effects on the cold dark matter (CDM) power spectrum are possible. This ''late forming dark matter'' (LFDM) arises simply from a scalar field coupled to a thermal bath, initially sitting in a metastable state, behaving like a cosmological constant. When the thermal bath dilutes, the scalar transitions near matter-radiation equality (MRE) to dark matter, yielding interesting observable consequences.

The layout of this paper is as follows: in Sec. II, we will lay out the basic structure of a general theory. In Sec. III we will explore the effects of such a scenario on the power spectrum of dark matter. In Sec. IV we will see how this sort of dark matter naturally arises in theories of neutrino dark energy. In Sec. VI we will review what experimental studies constrain this scenario, and may test it in the future. Finally, in Sec. VII we will conclude.

II. LATE FORMING DARK MATTER

Let us consider a single scalar field ϕ coupled to some other relativistic particle ψ which is in thermal equilibrium. For simplicity, we will assume that ϕ is at zero temperature (i.e., its couplings to ψ are sufficiently small that it is not thermalized). At zero temperature for ψ, we assume a potential of the form

$$V(\phi) = V_0 - \frac{m^2}{2}\phi^2 - \epsilon\phi^3 + \frac{\lambda}{4}\phi^4, \tag{1}$$

where V_0 is a constant which sets the true cosmological constant to zero. We assume the presence of the thermal ψ contributes a term to the potential

$$\delta V = DT^2\phi^2, \tag{2}$$

where D is a coefficient determined by the spin, coupling, and number of degrees of freedom in ψ.

The behavior of this system is simple to understand. At high temperature, there is a thermal mass for ϕ which will confine it to the origin. At

$$T = \sqrt{\frac{\lambda m^2 + 2\epsilon^2}{2D\lambda}} \tag{3}$$

a new minimum appears at energy lower than at $\phi = 0$. However, because of the thermal mass, ϕ remains trapped at the origin.

At a temperature

$$T_{\rm tach} = \frac{m}{\sqrt{2D}} \tag{4}$$

ϕ becomes tachyonic about the origin, and will begin to oscillate about what then evolves into its true minimum. These oscillations then behave as dark matter. Note that the energy in the dark matter is set by the depth of the global minimum relative to $\phi = 0$ at $T_{\rm tach}$, in this case $O(\epsilon^4/\lambda^3)$. If all the dimensionful parameters are of the same order (i.e., $\epsilon \sim m$), then the temperature at which dark matter is formed is soon followed by matter-radiation equality. Such correlation leaves a strong imprint on the power spectrum which we will discuss in Sec. III.

The above gives an extremely simple example of a model in which, for most of the history of the universe, ϕ acted as a cosmological constant and only at very late times does ϕ begin to behave as conventional dark matter. Such a form of dark matter is very natural when similar structures explain the existence of dark energy, for instance, in neutrino theories of dark energy.

III. COSMOLOGICAL CONSEQUENCES

Unlike weak-scale dark matter, which necessitates some interactions with ordinary matter which may be tested at underground experiments, and unlike axions, which require a coupling to photons giving again an experimental test, LFDM theories need not have strong couplings to standard model fields. Even within theories of neutrino dark energy, where LFDM is motivated, direct tests are difficult, if not impossible.

The best hope of detection for such a scenario is cosmological. Because we expect $z_{\rm tach}$ naturally to lie near $z_{\rm MRE}$, we expect deviations in the power spectrum of dark matter at small ($k \gtrsim h$ Mpc^{-1}) scales. In this section we will discuss the signatures of LFDM and the predictions it makes for cosmological experiments.

In general, for our scenario, effects on the CMB are negligible. We will return to this issue later. As LFDM behaves as ordinary CDM after $z_{\rm tach}$, we should not expect visible consequences on scales $k < k_{\rm tach}$, where $k_{\rm tach}$ is the scale of the horizon at $z_{\rm tach}$.

A. Power spectra

Let us consider the power spectrum for dark matter near $z_{\rm tach}$. Since this is when CDM is formed, after this point we can evolve it quite simply. The relevant quantity for the local density of dark matter is the redshift when it formed. Since all dark matter forms with the same initial energy density, regions where it forms earlier will have diluted more at later times, and regions where it forms later will have diluted less.

Dark matter forms at $z_{\rm tach} = \bar{z}_{\rm tach} + \delta z_{\rm tach}(x)$. By definition $z_{\rm tach}$ is the redshift when $T(z_{\rm tach}, x) = T_{\rm tach}$. We can reexpress the local temperature as

$$T(\bar{z}_{\rm tach} + \delta z(x)) = \bar{T}(\bar{z}_{\rm tach} + \delta z) + \delta T(\bar{z}_{\rm tach} + \delta z, x) \tag{5}$$

$$= (\bar{T}(\bar{z}_{\rm tach}) + \delta T(\bar{z}_{\rm tach}, x)) \times \frac{(1 + \bar{z}_{\rm tach})}{(1 + \bar{z}_{\rm tach} + \delta z)}. \tag{6}$$

The last equality is clearly true only for regions over which sound waves cannot propagate between $\bar{z}_{\rm tach}$ and $\bar{z}_{\rm tach} + \delta z_{\rm tach}$. Since this will be at scales of order 10^5 smaller than the horizon size, we can neglect it for our purposes. By definition, $T_{\rm tach} = T(\bar{z}_{\rm tach} + \delta z_{\rm tach}, x) = \bar{T}(\bar{z}_{\rm tach})$, and thus we can easily find that

$$\delta T(\bar{z}_{\rm tach}, x)/\bar{T}(\bar{z}_{\rm tach}) = \delta z_{\rm tach}/(1 + \bar{z}_{\rm tach}). \tag{7}$$

Similarly, $\rho(z,x)/\bar{\rho}(z) = (1 + \bar{z}_{\rm tach})^3/(1 + \bar{z}_{\rm tach} + \delta z(x))^3$, from which we can find

$$\delta\rho(\bar{z}_{\rm tach}, x)/\bar{\rho}(\bar{z}_{\rm tach}) = 3\delta z_{\rm tach}(x)/(1 + \bar{z}_{\rm tach}) = 3\delta T(\bar{z}_{\rm tach}, x)/T(\bar{z}_{\rm tach}). \tag{8}$$

Thus, at $z = z_{\rm tach}$ the CDM power spectrum is proportional to the ψ temperature power spectrum at $z_{\rm tach}$. From this point, the density perturbations will grow as CDM, so determining the power spectrum of CDM today is tantamount to determining the ψ-temperature power spectrum at $z_{\rm tach}$.

We will ultimately want to identify ψ with a more conventional particle-physics candidate, and, in particular, the neutrino. In general, the neutrino is highly relativistic at the time of its decoupling, after which it free-streams until it becomes nonrelativistic, yielding a suppression of its power at scales $k > k_{\rm fs} = 0.018\ \Omega^{1/2}(\frac{m_\nu}{\rm eV})^{1/2}\ {\rm Mpc}^{-1}$. However, in models of neutrino dark energy, there are additional neutrino interactions, and these may serve to keep the neutrino tightly coupled until $z_{\rm tach}$. If this is the case, this should be imprinted on the CDM power spectrum. Similar studies have been performed for scenarios where the neutrino was significantly heavier, and such strong interactions were proposed in order to retain neutrinos as dark matter [21]. More recently, the implications of such neutrino interactions for cosmology have been studied [22–25].

B. Calculation of power spectra for LFDM

We will consider LFDM with both an interacting and a noninteracting coupled bath. As described above, we will compute the power spectrum of the relativistic fluid, and match that to the initial power spectrum of the CDM at $z = z_{\rm tach}$. The noninteracting case is straightforward. The interacting case can be got by considering earlier studies of the evolution of density perturbations for interacting neutrinos [26,27], where the interaction makes different components behave as a single tightly coupled fluid. Under this assumption, the shear or anisotropic stress in the perturbation is negligible. The evolution is characterized by density and velocity perturbations only, and we can truncate all the higher order moments. The evolution of density and velocity perturbations is given by [28]

$$\dot{\delta} = -(1 + w)(\theta + \dot{h}/2) - 3\frac{\dot{a}}{a}(c_s^2 - w)\delta, \qquad (9)$$

$$\dot{\theta} = -\frac{\dot{a}}{a}(1 - 3w)\theta - \frac{\dot{w}}{1 + w}\theta + \frac{c_s^2}{1 + w}k^2\delta. \qquad (10)$$

We are interested in the case where the thermal bath is made of essentially massless particles, so the equation of state and sound speed are given by $w = 1/3 = c_s^2$. To get the amplitude of the perturbation at any redshift, the above two equations need to be solved with the background equations of motion for the metric perturbations. We have modified the publicly available CAMB and CMBFAST to solve and get the power spectra at $z_{\rm tach}$.

After $z_{\rm tach}$, LFDM follows the same evolution equation as CDM, and it is straightforward to grow the perturbations to today. We are principally interested in situations where LFDM makes up all or nearly all of the dark matter, but we can also consider situations where it is only some fraction. As we see in Fig. 1, there is a suppression of power at small scales, and the possibility of acoustic oscillations imprinted on the power spectrum. For comparison, we also include the power spectrum for ΛCDM with a 0.75 eV massive neutrino, near the experimental limit [29–31]. Though both LFDM and a massive neutrino give suppression in power, there is a distinct difference in power spectra between the two. The suppression of power for a massive neutrino turns on much more gradually than the abrupt suppression for LFDM.

As we make $z_{\rm tach}$ smaller (larger), we move the break to larger (smaller) scales. At scales much smaller than $k_{\rm tach}$ we would expect the acoustic oscillations to be damped out (which is not captured by our tightly coupled approximation). If LFDM is merely a fraction of the dark matter, the observability of such oscillations would depend on how

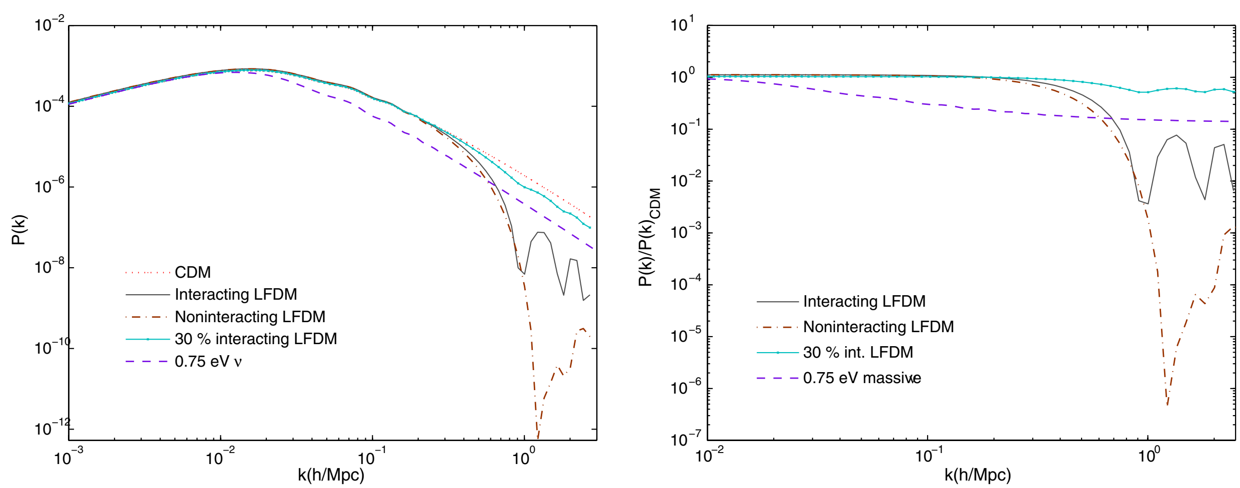

FIG. 1 (color online). Power spectra (left) and power compared to CDM (right) for CDM, LFDM (with different fractions, interacting and free-streaming), and a 0.75 eV free-streaming neutrino for $z_{\rm tach} = 50\,000$.

much LFDM existed. If LFDM is all or nearly all of the dark matter, the oscillations are already severely constrained, and must lie in the nonlinear regime [32].

It is important to point out here, though we get a large suppression beyond $k \approx 0.01h$ Mpc^{-1}, we cannot compare it directly to the linear power spectra of standard ΛCDM cosmology in this regime as the nonlinear effects in structure formations [34,35] become very important for $k \gtrsim 0.15h$ Mpc^{-1}. We return to this issue in Sec. VI. Only if LFDM forms later in time ($z_{\rm tach} \ll 15\,000$) does the power get suppressed in the linear regime. In this case a rigorous statistical analysis would be needed to place legitimate constraints on this scenario, which is beyond the scope of this paper.

IV. MODELS OF LFDM IN THEORIES OF NEUTRINO DARK ENERGY

The idea of LFDM is appealing, largely because it offers to make a connection to theories of dark energy. If the dark energy is associated with a scalar field trapped at a false minimum in its potential due to thermal effects, then, quite likely, "copies" of such physics may have existed earlier. If so, the energy stored there would now behave as dark matter.

Remarkably, there is already a class of models that fit these criteria, specifically the recently discussed "hybrid" models of neutrino dark energy [10]. There has been a long motivation to make a connection between neutrino masses and dark energy [8,9,36–38]. In these most recent models, the generational structure of the neutrinos is copied in the dark energy sector. The finite density of relic neutrinos modifies the potential and stabilizes a scalar field at a false minimum. These hybrid models arise naturally when mass-varying neutrino models are promoted to a supersymmetric theory (see [39–41] for other supersymmetric extensions).

The natural extension to LFDM comes in these supersymmetric theories. We refer readers to [10] for details, and only briefly summarize here. Because there are three neutrinos, these theories contain three singlet neutrinos N_i. Each one of these is associated by supersymmetry with a scalar field. Arguments related to naturalness suggest the lightest of the three neutrinos is associated with the dark energy today. Energy previously trapped in the other scalar neutrinos would appear as dark matter today, and it is this that we consider.

We shall now present a simple model of LFDM within the context of neutrino dark energy theories. It is not intended to be representative of all such models, but merely a simple example of one with the relevant phenomenology.

Consider the fermion fields $\psi_{2,3}$, and scalars $n_{2,3}$, with a Lagrangian

$$\mathcal{L} = \lambda n_2 \psi_3^2 + 2\lambda n_2 \psi_2 \psi_3 + m_3 \psi_3 \nu_3 + m_2 \psi_2 \nu_2 + V_{\rm susy} + V_{\rm soft} + V_\epsilon, \tag{11}$$

where

$$V_{\rm susy} = 4\lambda^2 |n_2|^2 |n_3|^2 + \lambda^2 |n_3|^4, \tag{12}$$

$$V_{\rm soft} = \tilde{m}_2^2 |n_2|^2 - \tilde{m}_3^2 |n_3|^2 + (\tilde{a}_3 n_3^3 + {\rm H.c.}), \tag{13}$$

and

$$V_\epsilon = 4\lambda\epsilon(n_3^* n_2^3 + n_3^3 n_2^* + {\rm H.c.}) + \epsilon^2(|n_2|^4 + 4|n_3|^2|n_2|^2). \tag{14}$$

Such a Lagrangian can easily be constructed supersymmetrically with soft terms of their natural size. The terms in V_ϵ are included in order to generate a Majorana mass for the neutrino in the vacuum. We also expect couplings to the "acceleron" (again, see [8,10]), which is directly tied to the stability of dark energy today. Both these couplings as well as V_ϵ do not influence our discussion here. It has been demonstrated that the vacuum expectation values of such fields do not spoil the success of the dark energy theory in these hybrid models [42].

The natural size of each soft term is of the order of the associated Dirac mass (i.e., $\tilde{a}_3 \sim \tilde{m}_3 \sim m_3$ which is expected to be of order 0.1 eV), assuming the dark energy sector has no approximate R symmetry.

If n_2 has a large expectation value, it generates a Majorana mass for ψ_3 of order $m_3^2/\lambda n_2$. The presence of the relic neutrinos affects the dynamics of n_2, in particular, by driving it to larger values. Assuming that the relic neutrinos are in the light mass eigenstate (see [43]), the relic neutrinos contribute a term to the effective potential for n_2,

$$V_{\rm eff} = \frac{T^2 m_3^4}{24\lambda^2 n_2^2}, \tag{15}$$

which is minimized for large n_2, competing with the n_2 mass term which is minimized at $n_2 = 0$. The competition drives an expectation value $\langle \lambda n_2 \rangle \sim m_3\sqrt{\lambda T/m_2}$. (We should note all temperatures here refer to neutrino temperature, which is slightly lower than the CMB temperature.) The nonzero value of n_2 creates a positive value for the mass squared of n_3, stabilizing it in the false vacuum with an effective cosmological constant. Such a model is analogous to hybrid inflation models, with n_2 playing the role of the slow-roll field, and n_3 playing the role of the waterfall field.

The temperature where n_3 becomes tachyonic is $T_{\rm tach} = \sqrt{3/2} m_2 \tilde{m}_3^2/\lambda m_3^2$, and the energy converted to dark matter at that time is $\rho_{\rm LFDM} \sim 10^{-3} \tilde{a}_3^4/\lambda^6$. The time of matter-radiation equality is $T_{\rm MRE} = 3\sqrt{3/2}\tilde{a}_3^4 m_3^6/64\lambda^3 m_2^3 \tilde{m}_3^6$. Because of the high powers of parameters, each uncertain by factors of order one, there is a high uncertainty in $T_{\rm MRE}$. Simply varying the mass parameters in the ranges $10^{-1.5}$ eV $< \tilde{m}_3$, $\tilde{a}_3$, $m_3 < 10^{-.5}$, 10^{-2} eV$<$ $m_2 < 10^{-1}$ eV and the parameter $10^{-2} < \lambda < 1$, we find 10^{-3} eV $\lesssim T_{\rm MRE} \lesssim 10^7$ eV. Similarly, we find

$10 - 1 \lesssim T_{\mathrm{MRE}}/T_{\mathrm{DMDE}} \lesssim 10^{13}$. Hence, the solution to the coincidence problem is present in that such a crossing should occur relatively soon after matter-radiation equality. However, the precise value is clearly uncertain, so the success is limited.

Given that we can set λ by fixing T_{MRE}, we can more precisely determine T_{tach}, even with the uncertainties of parameters. Thus, using the same ranges above, and requiring $\lambda < 1$, one finds that $1\ \mathrm{eV} \lesssim T_{\mathrm{tach}} \lesssim 10^3\ \mathrm{eV}$ and thus $2 \times 10^{-2} h\ \mathrm{Mpc}^{-1} \lesssim k_{\mathrm{tach}} 20 h\ \mathrm{Mpc}^{-1}$. Such limits are certainly model dependent, but clearly there is a strong expectation of a break in the power spectrum in the observable range.

V. DISCUSSION: POSSIBILITY OF LFDM DECAY

As seen from our phenomenological model, the LFDM scalar might have a coupling to a sterile neutrino, opening the possibility of dark matter decay into light sterile states. If the coupling is considerably strong, the decay process may lead to interesting phenomenology through late-time integrated Sachs-Wolfe effects [44]. However, in this paper, our goal is to mainly capture the effect of a unique and a late phase transition and thus we are interested in the regime where the coupling responsible for LFDM decay into sterile neutrino is negligible. We will soon see that for a considerable range of parameter space in our theory, this is quite natural. Now, we would like to make a few comments about the work [44] where an oscillating sub-eV scalar acting as dark matter decays into light fermions (neutrinos). First of all, we would like to point out that there is a fundamental difference in the cosmology presented in that work compared to ours, though both the scenarios can emerge in the context of neutrino dark energy. The main difference is that no late phase transition has been considered in [44] unlike ours; rather the main focus of their work is on the parametric decay of an oscillating scalar, behaving as dark matter since long back (few orders of redshift earlier than us) in the history of the universe. In contrast, in our case the coherent oscillation starts pretty late—near $T \sim \mathrm{eV}$.

As an obvious consequence, the matter spectra in their work does not show a sharp break; rather they got a modification in the CMB spectra through the integrated Sachs-Wolfe effect as slowly decaying dark matter gives a time variation of gravitational potential during structure formation. Though the goal of that work [44] is to emphasize a different cosmological aspect (dark matter decay), as a theoretical motivation, our model of LFDM has been referred there. In fact, for a certain choice of model parameters in the supersymmetric theories of neutrino dark energy and LFDM, late phase transition can be absent and the cosmology described in [44] could be achieved. This happens when one can push the phase transition to a very high redshift (deep in the radiation dominated era).

As derived in the previous section, the temperature of the phase transition is given by $T_{\mathrm{tach}} = \sqrt{3/2} m_2 \tilde{m}_3^2 / \lambda m_3^2$. Because of higher powers of parameter, each uncertainty by a factor of order one would result in high uncertainty in T_{tach}. After simple calculation and substituting T_{MRE} we get $T_{\mathrm{tach}}^3 \simeq \frac{\tilde{a}^4}{T_{\mathrm{MRE}} \lambda^6}$. For a reasonable choice of parameters and relatively small coupling, one can easily obtain $T_{\mathrm{tach}} \gg 10^3 T_{\mathrm{MRE}}$, and if we allow a few percent fine-tuning, T_{tach} can be even pushed near the big bang nucleosynthesis era. For this early phase transition, where the scalar is behaving as dark matter since long back in cosmic history, one would not expect to see a sharp cutoff in matter power spectra as $k_{\mathrm{tach}} \gg 10^3\ \mathrm{Mpc}^{-1}$ is pushed to a much smaller scale (far beyond the linear regime). This is the reason why in [44] no such effect in matter power spectra has been reported. So the effect on CMB and matter power spectra found in [44] is mainly due to the decay of the scalar into light neutrinos. In contrast, the effect on matter power spectra we have studied is mainly due to a late phase transition. The main purpose of our work is to investigate how late a viable dark matter can be formed in the universe and to study its unique signature on structure formation. Thus we have assumed dark matter decay to be negligible to capture the effect of the late formation of dark matter on structure formation.

VI. EXPERIMENTS

A great deal of data already would constrain such a scenario. For instance, one immediate concern would be from the CMB. In general, neutrinos are not free-streaming at recombination, which affects the gravitational potential well which boosts the first peak of the CMB. Such constraints have been considered [23,45], but one interacting neutrino seems acceptable ($3.46 \leq N_{\mathrm{eff}}^{\nu} \leq 5.2$) (95% CL), [12,46]. One also must consider the constraint on the total number of free-streaming neutrinos during decoupling because having extra radiation degrees of freedom could delay the matter-radiation equality resulting in the early integrated Sachs-Wolfe effect[47–50]. Structure formation is where LFDM is most likely to be tested. Many experiments such as the 2dF Galaxy Redshift Survey [1,51], Sloan Digital Sky Survey (SDSS) [52], Ly-α forest [53–57], and weak gravitational lensing [58] have measured the matter power spectrum over a wide range of scales. Though these experiments are in good agreement with the ΛCDM model, small scales remain an open question, with possible modifications seen in Lyman-α systems [35], as well as some studies of dwarf galaxies [59].

The studies most promising to test this scenario in the future would include Ly-α data, but one still needs nonlinear simulations to extract the linear power spectra information on these length scales. Future weak lensing experiments [60] will measure the power at higher z

when the relevant scales would be more linear. Other experiments like 21 cm tomography [61] will also measure power in very small scales (sub-Mpc) and may find signatures of LFDM. As discussed before, to compare LFDM power spectra with experiments in this range we need detailed N-body simulation which includes the nonlinear hydrodynamical effects of gravitational clustering.

VII. CONCLUSIONS

We have considered the scenario of LFDM in which a scalar field converts the energy of a metastable point to dark matter at times late in the history of the universe, near the era of matter-radiation equality. Such effects arise when the potential of the scalar field is strongly affected by finite temperature effects from some additional thermal species. These theories arise naturally in hybrid models of neutrino dark energy, in which new scalar fields arise in association with neutrinos.

The power spectrum of such theories naturally has a sharp cutoff near the scale of the horizion at matter-radiation equality, due to the streaming of the thermal species. The presence of strong scattering of these particles can modify the depth of the break, and the presence of acoustic oscillations.

Within the context of theories of neutrino dark energy, the scale of dark energy is controlled by the scale of neutrino masses, and, similarly, the amount of dark matter, and the redshift at which it forms, $z_{\rm tach}$, are also determined by the neutrino masses. In these simple theories, consistency requires a sharp break in the CDM power spectrum in the approximate range $10^2 h$ Mpc$^{-1} \gtrsim k_{\rm tach} \gtrsim 10^{-3} h$ Mpc^{-1}. Future studies at small scales, such as of Lyman-α systems, gravitational lensing, or 21 cm absorption may be able to test these theories.

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