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Effects of dark atoms in structure formation.

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Effect of Dark Atom in structure Formation.

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Abstract

The origin and evolution of large scale structure is today the outstanding problem in cosmology. This is the most fundamental question we can ask about the universe whose solution should help us to better understand problems as the epoch of galaxy formation, the clustering in the galaxy distribution, the amplitude and form of anisotropies in the microwave background radiation. Several has been the approaches and models trying to solve this problem: no one has given a final answer. The leading idea of all structure formation theories is that structures was born from small perturbations in the otherwise uniform distribution of matter in the early Universe, which is supposed to be, in great part, dark (matter not detectable through light emission). In Matter,electron is absolutely stable owing to the conservation of electric charge, while the stability of proton is conditioned by the conservation of baryon charge. The stability of ordinary matter is thus protected by the conservation of electric and baryon charges, and its properties reflect the fundamental physical scales of electroweak and strong interactions. Similarly, a component of the dark matter could consist of two darkly charged particles with a large mass ratio and a massless force carrier. This 'atomic' dark sector could behave much like the baryonic sector, cooling and fragmenting down to stellar-mass or smaller scales. Past studies have shown that cosmic microwave background and large-scale structure constraints rule out $\geq 5\%$ of the dark matter to behave in this manner. However, theories show that, even with percent level mass fractions, a dark atomic sector could affect some extragalactic and galactic observables. We track the cooling and merger history of an atomic dark component for much of the interesting parameter space. Unlike the baryons, where stellar feedback (driven by nuclear physics) delays the formation and growth of galaxies, cooling dark atomic gas typically results in disks forming earlier, leaving more time for their destruction via mergers. Rather than disks in Milky Way sized halos, we find the end product is typically spheroidal structures on galactic scales or dark atom fragments distributed on halo scales. This result contrasts with previous studies, which had assumed that the dark atoms would result in dark disks. Furthermore the dark atoms condense into dense clumps, analogous to how the baryons fragment on solar-mass scales. We estimate the size of these dark clumps, and use these estimates to show that viable atomic dark matter parameter space is ruled out by stellar microlensing, by the half-light radii of ultra-faint dwarf galaxies, and by Milky Way mass-to-light inferences.

1 Introduction

The standard theory of cosmology is the Hot Big Bang, according to which the early universe was hot, dense, very nearly homogeneous, and expanding adiabatically according to the laws of general relativity (GR). This theory nicely accounts for the cosmic background radiation, and is at least roughly consistent with the abundances of the lightest nuclides. It is probably even true, as far as it goes; at least, I will assume so here. But as a fundamental theory of cosmology, the standard theory is seriously incomplete. One way of putting this is to say that it describes the middle of the story, but leaves us guessing about both the beginning and the end.

Galaxies and clusters of galaxies are the largest bound systems, and the filamentary or wall-like superclusters and the voids between them are the largest scale structures visible in the universe, but their origins are not yet entirely understood. Moreover, within the framework of the standard theory of gravity, there is compelling observational evidence that most of the mass detected gravitationally in galaxies and clusters, and especially on larger scales, is "dark" - that is, visible neither in absorption nor emission of any frequency of electromagnetic radiation. But we still do not know what this dark matter is.

Explaining the rich variety and correlations of galaxy and cluster morphology will require filling in much more of the history of the universe:

- Beginnings, in order to understand the origin of the fluctuations that eventually collapse gravitationally to form galaxies and large scale structure. This is a mystery in the standard hot big bang universe, because the matter that comprises a typical galaxy, for example, first came into causal contact about a year after the Big Bang. It is hard to see how galaxy-size fluctuations could have formed after that, but even harder to see how they could have formed earlier. The best solution to this problem yet discovered, and the one emphasized here, is cosmic inflation. The main alternative, discussed in less detail here, is cosmic topological defects.

- Denouement, since even given appropriate initial fluctuations, we are far from understanding the evolution of galaxies, clusters, and large scale structure - or even the origins of stars and the stellar initial mass function.

- And the dark matter is probably the key to unravelling the plot since it appears to be gravitationally dominant on all scales larger than the cores of galaxies. The dark matter is therefore crucial for understanding the evolution and present structure of galaxies, clusters, superclusters and voids. We will concentrate on the period after the first three minutes, during which the universe expands by a factor of $\sim 10^8$ to its present size, and all the observed structures form. This is now an area undergoing intense development in astrophysics, both observationally and theoretically. It is likely that the present decade will see the construction at last of a fundamental theory of cosmology, with perhaps profound implications for particle physics - and possibly even for broader areas of modern culture.

The current controversy over the amount of matter in the universe will be emphasized, discussing especially the two leading alternatives: a critical-density universe, i.e. with $\Omega_0 \equiv \bar{\rho}_0/\rho_c = 1$ (see Table 1.1), vs. a low-density universe having $\Omega_0 \approx 0.3$ with a positive cosmological constant $\Lambda > 0$ such that $\Omega_\Lambda \equiv \Lambda/\left(3H_0^2\right) = 1 - \Omega_0$ supplying the additional density required for the flatness predicted by the simplest inflationary models. (The significance of the cosmological parameters Ω_0, H_0, t_0, and Λ is discussed in § 1.2.) $\Omega = 1$ requires that the expansion rate of the universe, the Hubble parameter $H_0 \equiv 100h$ km s^{-1}Mpc^{-1} $\equiv 50h_{50}$ km s^{-1}Mpc^{-1}, be relatively low, $h0.6$, in order that the age of the universe t_0 be as large as the minimum estimate of the age of the stars in the oldest globular clusters. If the expansion rate turns out to be larger than this, we will see that GR then requires that $\Omega_0 < 1$, with a positive cosmological constant giving a larger age for any value of Ω_0.

Although theoeies concentrate on the implications of CDM and alternative theories of dark matter for the development of galaxies and large scale structure in the relatively "recent" universe, we can hardly avoid recalling some of the earlier parts of the story. Inflation or cosmic defects will be important in this context for the nearly constant curvature spectrum of primordial fluctuations and as plausible solutions to the problem of generating these large scale fluctuations without violating causality; and primordial nucleosynthesis will be important as a source of information on the amount of ordinary ("baryonic") matter in the universe. The fact that the observational lower bound on $\Omega_0 -$ namely $0.3\Omega_0$ - exceeds the most conservative upper limit on baryonic mass $\Omega_b 0.03h^{-2}$ from Big Bang Nucleosynthesis is the main evidence that there must be such nonbaryonic dark matter particles.

Of special concern will be evidence and arguments bearing on the astrophysical properties of the dark matter, which can also help to constrain possible particle physics candidates. The most popular of these are few-eV neutrinos (the "hot" dark matter candidate), heavy stable particles such as ~ 100GeV photinos (or whatever neutralino is the lightest supersymmetric partner particle) or $10^{-6} - 10^{-3}$eV "invisible" axions (these remain the favorite "cold" dark matter candidates), and various more exotic ideas such as keV gravitinos ("warm" dark matter) or primordial black holes (BH).

2 Dark Matter Candidates

Here we are using the usual astrophysical classification of the dark matter candidates into hot, warm, or cold, depending on their thermal velocity in the early universe. Hot dark matter, such as few-eV neutrinos, is still relativistic when galaxy-size masses $\left(\sim 10^{12} M_\odot\right)$ are first encompassed within the horizon. Warm dark matter is just becoming nonrelativistic then. Cold dark matter, such as axions or massive photinos, is nonrelativistic when even globular cluster masses $\left(\sim 10^{6} M_\odot\right)$ come within the horizon. As a consequence, fluctuations on galaxy scales are wiped out by the "free streaming" of the hot dark matter particles which are moving at nearly the speed of light. But galaxy-size fluctuations are preserved with warm dark matter, and all cosmologically relevant fluctuations survive in a universe dominated by the sluggishly moving cold dark matter.

The first possibility for nonbaryonic dark matter that was examined in detail was massive neutrinos, assumed to have mass $\sim 25\mathrm{eV}-$ both because that mass corresponds to closure density for $h \approx 0.5$, and because in the late 1970s the Moscow tritium β-decay experiment provided evidence (subsequently contradicted by other experiments) that the electron neutrino has that mass. Although this picture leads to superclusters and voids of roughly the size seen, superclusters are the first structures to collapse in this theory since smaller size fluctuations do not survive. The theory foundered on this point, however, since galaxies are almost certainly older than superclusters. The standard (adiabatic) form of this theory has recently been ruled out by the COBE data: if the amplitude of the fluctuation spectrum is small enough for consistency with the COBE fluctuations, superclusters would just be beginning to form at the present epoch, and hardly any smaller-scale structures, including galaxies, could have formed by the present epoch.

A currently popular possibility is that the dark matter is cold. After Peebles (1982), we were among those who first proposed and worked out the consequences of the Cold Dark Matter (CDM) model (Primack & Blumenthal 1983, 1984; Blumenthal et al. 1984). Its virtues include an account of galaxy and cluster formation that at first sight appeared to be very attractive. Its defects took longer to uncover, partly because uncertainty about how to normalize the CDM fluctuation amplitude allowed for a certain amount of fudging, at least until COBE measured the fluctuation amplitude. The most serious problem with CDM is probably the mismatch between supercluster-scale and galaxy-scale structures and velocities, which suggests that the CDM fluctuation spectrum is not quite the right shape - which can perhaps be remedied if the dark matter content is a mixture of hot and cold, or if there is less than a critical density of cold dark matter.

Table 1.1. Physical Constants for Cosmology

parsec	pc	$= 3.09 \times 10^{18}$ cm $= 3.26$ light years (lyr)
Newton's const.	G	$= 6.67 \times 10^{-8} \mathrm{dynecm}^2 \ \mathrm{g}^{-2}$
Hubble parameter	H_0	$= 100h \ \mathrm{km\ s}^{-1} \mathrm{Mpc}^{-1}, 1/2h1$
Hubble time	H_0^{-1}	$= h^{-1} 9.78 \mathrm{Gyr}$
Hubble radius	R_H	$= cH^{-1} = 3.00 h^{-1} \mathrm{Gpc}$
critical density	ρ_c	$= 3H^2/8\pi G = 1.88 \times 10^{-29} h^2 \ \mathrm{g\ cm}^{-3}$
		$= 10.5 h^2 \mathrm{keVcm}^{-3} = 2.78 \times 10^{11} h^2 M_\odot \mathrm{Mpc}^{-3}$
speed of light	c	$= 3.00 \times 10^{10} \ \mathrm{cm\ s}^{-1} = 306 \mathrm{MpcGyr}^{-1}$
solar mass	$M_\odot$	$= 1.99 \times 10^{33}$ g
solar luminosity	$L_\odot$	$= 3.85 \times 10^{33} \mathrm{ergs}^{-1}$
Planck's const.	$\hbar$	$= 1.05 \times 10 \times 27 \mathrm{ergs} = 6.58 \times 10^{-16} \mathrm{eVs}$
Planck mass	$m_{P\ell}$	$= (\hbar c/G)^{1/2} = 2.18 \times 10^{-5}$ g $= 1.22 \times 10^{19} \mathrm{GeV}$

The basic theoretical framework for cosmology is reviewed first, followed by a discussion of the current knowledge about the fundamental cosmological parameters.

Table 1.1 lists the values of the most important physical constants used in this chapter (cf. Barnett et al. 1996). The distance to distant galaxies is deduced from their redshifts; consequently, the parameter h appears in many formulas where the distance matters.

3 Dark Atom

Observations of the cosmic microwave background (CMB) and the large-scale distribution of galaxies indicate that only 20% of the matter in the cosmos is baryonic and that the rest is some other substance, termed dark matter. The baryonic sector is highly collisional and efficient at radiating energy, resulting in complex dynamics. Atomic and bremsstrahlung emission allow the baryons to cool and form a disk within Milky Way-sized halos. Further cooling, often by molecules, allows the baryons to lose pressure support and fragment all the way down to stellar masses, with this mass scale determined by how far sound waves are able to travel within a collapse time. Dark matter, on the other hand, is typically imagined to only weakly interact (with itself or the baryonic sector). As a result, the densest bound structures that dark matter forms, dark matter halos, are a factor of ~ 100 more extended than the galaxy disks that reside within them.

This scenario of diffuse, non-interacting dark matter has met with tremendous success at explaining the largescale structure of the cosmos , the distribution of matter in galaxy groups and clusters, and limits on the interaction cross section in astrophysical systems. However, studies have claimed that this vanilla dark matter model may not explain certain anomalies on < 100kpc scales . Motivated by the fact that the baryonic sector is so physically rich, a multitude of studies have imagined a more complex dark sector. Dark matter models with a new dark force that enhances annihilations , large self interactions, and interactions with baryons 8 have been considered in detail. Several studies have considered the possibility that of 'atomic' dark matter, where a component of the dark matter consists of charged particles with an MeV-mass dark 'electron'. This scenario leads to complex cooling physics analogous to the baryonic sector argued that the "dark atoms" would cool into a dark disk, leading to a new set of observables. Such observables include signatures of additional dissipation in observations of galaxy cluster mergers and an unexpected velocity distribution function in direct dark matter detection experiments.

Various observables have been used to constrain the fraction of the dark matter that could be atomic. Diffuse, darkly charged dark matter is constrained by selfinteraction limits from the Bullet Cluster to be $< 30\%$ of the dark matter. However, if this matter had cooled and fragmented into dense nuggets, the atomic dark matter would behave collisionlessly, avoiding this bound. A more robust bound comes from the early Universe. If the dark atoms were coupled to the thermal bath at any time in the early universe, there would also be a dark

CMB. The dark CMB with a temperature today of T_{d0} would drag around the dark atoms, damping the growth of their overdensities and generating acoustic oscillations in their clustering. CMB and galaxy clustering observations show no evidence for such damping or oscillations. If 100% of the dark matter were atomic, the only viable parameter space has a dark CMB temperature of 0.3 Kelvin or a dark electron that is more massive than the Standard Model electron. However, almost all atomic dark matter parameter space is allowed if 5% of the dark matter were atomic, as considered here.

This study develops more physical models for the structure formation and astrophysics of dark atoms. These models show that the assumption of previous studies that dark atoms end up in galaxy-scale disks is rarely justified and, hence, neither are the constraints derived from this assumption. We do find that such modeling predicts the dark atoms to clump on certain characteristic scales, opening up new avenues for constraining the atomic dark matter parameter space. We show that observations of dwarf galaxies, galaxy rotation curves, and stellar microlensing may allow percent-level constraints on the fraction of dark matter in some parts of atomic dark matter parameter space.

The atomic dark matter models we consider have the following properties

- The "dark proton" is much heavier than the "dark electron". We consider dark proton masses of $1\mathrm{GeV} < \mathrm{m_X} < 10\mathrm{GeV}$, and dark electron masses of $10^{-2}\mathrm{GeV} < \mathrm{m_C} < 10^{-5}\mathrm{GeV}$. The subscript c stands for 'coolant' as a light dark electron is critical for cooling. The 'dark proton' and 'dark electron' only have dark electromagnetic interactions through a massless dark photon γ_D with the dark fine structure constant α_X in the range $10^{-3} - 10^{-1}$. We show that these ranges for m_c, m_X, and α_X cover much of the interesting parameter space where energy exchange and cooling is possible.

- Dark atoms comprise $\epsilon = 5\%$ percent of the dark matter. We do not expect our qualitative conclusions to change for order of magnitude larger or smaller values.

- The ratio of temperature of dark CMB photons to standard model (SM) CMB photons, $\xi \equiv \frac{T_{d0}}{T_{\gamma 0}} = 0.5$. Current CMB measurements of the effective relativistic degrees of freedom require $\xi \leq 0.51$. and the constraints from large-scale structure are somewhat more stringent 25 . Our conclusions are unchanged if instead $\xi \ll 0.5$, except in the relatively small part of parameter space where Compton cooling is the primary coolant.

1 The upper bound on α_X is chosen to keep dark electromagnetic interactions weak, allowing us to use standard results for atomic processes.

2 The cooling times scale as $\propto \epsilon^{-1}$, often quite a bit smaller than the lifetime of the halo. Changing ϵ would change slightly the regions of our parameter space that can cool efficiently, it would not affect our qualitative conclusions regarding galaxy morphology significantly. - Finally, we adopt a minimalist model for the dark sector in which there is no feedback on the distribution of dark atoms. This largely means that there are no dark 'supernovae' or something of the like (which would likely be the case if there is no nuclear physics in the dark sector).

4 DARK GALAXY FORMATION

Many work on atomic dark matter has argued that, if this component of the dark matter cools, it naturally forms a galaxy-scale disk . This conclusion is not obvious. Newly accreted atomic dark matter 'gas' tends to shock heat and smoothly populate the entire halo that surrounds a galaxy (which is more than an order of magnitude larger than the size of a galaxy). Cooling then leads to the gas condensing, since it has lost pressure support. Since free fall to the center of halo takes a somewhat smaller amount of time than collapse, as the gas cools it condenses into the center of the halo, forming a disk whose size is determined largely by angular momentum conservation. Finally, the likely end result of cooling is compact gas fragments that behave collisionlessly, analogous to how baryonic matter fragments into stars. Over the cosmic history, halos are continually merging and growing. The central disks inside merging halos often merge themselves, disrupting the disks and making them more spheroidal in shape. Such disruption is the reason why more massive galaxies than the Milky Way tend to not be risky but instead more spheroidal.

Astrophysicists have developed fast semi-analytic methods to follow the formation of galactic structures without running expensive numerical simulations. Running such cosmological simulations that cover the large parameter space of atomic dark matter would be prohibitive, and so these fast methods are crucial for this study. We describe a basic semi-analytic implementation below, and use it to understand the distribution of atomic dark matter within dark matter halos.

4.1 Formalism

Structure formation in our universe has a bottom-up hierarchy. Smaller dark matter halos form earlier, and these halos go on to merge with others, growing into larger ones. Thus, the material that constitutes a $z = 0$ Milky Way-sized halo, at earlier times resided in smaller.

The time to fall to the center is shorter by a factor of $\sim \epsilon^{1/2}$ than the condensation time. For this reason, cooling is not insitu on the scale of a halo, but instead pressure and viscous forces result into the gas condensing into the halo center. In addition, the large-scale tidal field is responsible for torquing halos and imparting angular momentum. The amount of angular momentum per unit binding energy only varies by a factor of a few, so all disks and bulges have roughly the same size relative to the halo virial radius . halos. The extended Press-Schechter formalism provides an analytic method to follow a halo's merger history. This formalism reproduces the statistics of halo merger histories seen in fully cosmological simulations.

In the extended Press-Schechter formalism, a halo with mass $M_{\text{halo}} = M$ is considered to have formed at a redshift of z if the $z = 0$ linear overdensity averaged over a spherical region of mass scale M, δ_M, exceeds

$$\omega(z) = 1.69/D(z)$$

where $D(z)$ is the linear growth factor for the matter overdensity and $\omega(z)$ is the critical linear theory overdensity 2.6[6] (Note that this model is defined in Lagrangian space, where there is a one-to-one relation between M and the region's Lagrangian radius.) The largest mass scale for which $\delta_M > \omega(z)$ sets the halo's mass in this model. At higher redshifts, $D(z)$ is smaller and, hence, $\delta_M > \omega(z)$ for the same region is likely to be satisfied at smaller M (as the RMS of δ_M decreases monotonically with M), reproducing the bottom-up hierarchy of structure formation. This algorithm allows one to associate a halo of mass M with the halos that constituted it at an earlier time. Note that the statistics of δ_M are Gaussian, which allows for straightforward analytic formula in terms of the RMS of δ_M.

While the merger tree provides the history of the collisionless component of the dark matter, to understand the condensation of the atomic dark matter, the rules governing this component are followed on top of the merger tree. In astrophysics, similar calculations are done to follow galaxy formation, and they are called 'semi-analytic galaxy formation models'. The exact algorithm used for this computation is described in detail in Appendix Here we briefly sketch the approach. To add galaxy formation to this tree, we start at the end branches and descend towards the trunk. 7 Every time a merger occurs, we determine whether the atomic dark matter in the merged halo can cool by comparing its cooling time, dynamical time, and equilibrium time ($t_{\text{cool}}, t_{\text{dyn}}$ and t_{equil}) to the halo lifetime (t_{halo})[8], defined as the time for the current halo mass to double through subsequent mergers and accretion. If $t_{\text{cool}}, t_{\text{dyn}}, t_{\text{equil}} < t_{\text{halo}}$, we consider the entire reservoir of dark baryons to have cooled. When the gas within a halo cools, it forms a central disk (because of angular momentum conservation).

4.2 Merger tree evaluation for SM parameters

To develop some intuition, first consider the case where the dark atoms have Standard Model (SM) parameters: $\alpha_X = 1/137, m_c = 5 \times 10^{-4}\text{GeV}, m_X = 1\text{GeV}$. The halo mass resolution we adopt in our merger tree for these and subsequent calculations is $M_{\text{res}} = 3\times10^7 M_\odot$, well below the $10^{12} M_\odot$ mass of the Milky Way. Our results do not change appreciably if we take $M_{\text{res}} = 10^8 M_\odot$. The top panels in Fig. 2 show the mass and the virial temperature of the main progenitor (MP) as a function of redshift. The bottom-left panel shows the mass fraction of gas that has cooled as a function of redshift, showing that $\sim 70\%$ of the gas has cooled by the present.

At $z = 0$, most of the baryons form a bulge component and there is a negligible fraction in the disk. Following the history of the MP, its cools to form a disk at $z \approx 10$, but then undergoes a major merger at $z \approx 4$ destroying its disk component. Subsequent mergers then contribute mostly to the bulge (except for gas that cools which contributes to the disk). As smaller systems merge with the MP, most of their atomic dark matter ends up in the virialized halo because the dynamical friction time is not short enough to reach the center of the MP.

It may seem contradictory that the dark baryons with SM parameters do not form a disk since SM baryons do end up forming a disk for Milky Way-like halos. However, we note that the SM case for dark atoms should not reproduce the properties of observed galaxies because our dark atoms do not have nuclear physics that feedback in the form of additional radiation and supernovae. Such feedback plays a significant role in recycling baryonic gas that make it into a galactic disk back into the diffuse dark matter halo. For example, even though the cooling times are less than the age of the Universe, only 20% of SM baryons associated with the Milky Way halo condense into the Galaxy, and this fraction is even less in both smaller and larger halos than the Milky Way's halo 34 .

5 Scanning over the parameter space

Now that we have considered the specific case of SM parameters, let us consider a broader range of m_c, α_X, m_X, focusing approximately on the interesting range where cooling can happen. For the proton masses we consider, $m_X = 1\text{GeV}$ and 10GeV. For dark electron masses we consider $m_c \subset \left[10^{-2}\text{GeV}, 10^{-5}\text{GeV}\right]$ and fine structure constants of $\alpha_X \subset \left[10^{-1}, 10^{-3}\right]$. The upper bound on α_X has been selected for the electron to remain non-relativistic in dark atoms, while the upper bound on m_c is chosen because above this value the gas never becomes ionized for the virial temperatures associated with our choices of m_X and, hence, likely cannot cool. Values of m_c lower than 10^{-5}GeV result in the gas being photoionized by the dark CMB radiation today, which complicates our calculations (as it eliminates atomic cooling, makes Compton processes heat the gas for $T < T_{d0}$, and adds additional photoheating).

6 MASS OF DARK STARS

This section estimates the characteristic mass of dark atom fragments, which we use in the next section to constrain dark atom models. These fragments are the end product of cooling, analogous to stars in the baryonic sector. Assuming the dark proton and electron are fermions, these fragments are likely to be the dark analog of white dwarfs (although the timescale to radiate energy and reach this limit could be long), or, if they are above the dark atom's Chandrasekhar mass of $\approx 1.4 \left(\text{GeV}/m_X\right)^{1/2} M_\odot$, they are are likely to be black holes.

In the baryonic sector, observations show that stars show a characteristic mass of a couple tenths that of the Sun, with most of the total mass in stars within a factor of few of this scale, and with a power-law tail in number density to higher masses with index.Mass distribution holds over environments enriched with a broad range of metallicities, although it is believed that stars that form in unenriched regions were more massive. Explaining the characteristic mass of stars is a topic of ongoing theoretical and numerical work, but there is a basic picture for how the characteristic mass of stars comes about . The picture is of gas fragmenting on smaller and smaller scales as it cools, loses pressure support, and condenses. Namely, diffuse cooling gas tends to stay isothermal, and as isothermal gas gets denser, sound waves can communicate over increasingly less massive regions in a gravitational collapse time (t_{dyn}). The length and mass scale over which sound waves can travel in a dynamical time is called the Jeans radius and Jeans mass and given respectively by

$$R_J = \left(\frac{15T}{4\pi G m_X^2 n_X}\right)^{1/2} \qquad \text{and} \qquad M_J = \frac{4\pi}{3} m_X n_X R_J^3$$

where n_X is the dark proton density. Eventually, the gas becomes dense enough that it is no longer able to radiate its energy sufficiently and heats up, halting fragmentation. The stellar mass scale arises from evaluating Eq. 8 at the applicable temperatures and densities.

Theoretical calculations for the size of these cores in metal enriched environments tend to be somewhat smaller than the characteristic mass of stars 13 Calculations show that these cores are larger with $M_J \sim 500M_\odot$ 42 in environments unenriched by stellar nucleosynthesis because the gas radiates less efficiently and, hence, does not reach as low temperatures. For more massive protostars, stellar radiation likely halts accretion: For unenriched environments, calculations predict that this occurs at somewhat smaller masses than the Jeans mass, $M \sim 100M_\odot$42. However, without fusion power - the limit that we assume applies for atomic dark matter - the characteristic mass of 'dark clumps' would likely be closer to M_J. (Since our atomic matter does not have nuclear physics, we do not call the clumps 'stars'.

Our approach is similar to that developed for baryons. We will evaluate the Jeans Mass, at the temperature and density where gas cannot cool efficiently. For these calculations, we assume that the cooling radiation of dark fragments is insufficient to affect surrounding gas and its fragmentation; such feedback does happen for standard baryons. However, because of nuclear fusion, radiation is much more important for baryons than if they were powered solely by gravitational energy: For a solar mass star, there is more than a hundred times more energy to fuse the hydrogen into helium than the gravitational energy to collapse to a degeneracy pressure supported white dwarf. Thus, it is likely that radiative feedback can be neglected, particularly in the parameter space where the dark clumps are less massive than stars. In addition, whether dark fragments even radiate ionizing and dissociating photons depends on the temperature of their atmospheres and how it compares to the binding energy of dark atoms, $\alpha_X^2 m_c$. With no internal energy generation, it is likely that a dark fragment's surface has a low temperature as it collapses.

For the baryonic gas in our universe, deuterium burning and dust formation can complicate this simple picture, wrinkles that do not apply to our atomic dark matter fragments.

Small protostars may continue to accrete an $\mathcal{O}(10)$ factor in gas because the acoustic contact at an earlier time was over a larger region such that the gas was able to self organize over larger masses than the minimum fragmentation mass.

Even if there were some internal energy generation, such as from dark matter annihilations, the unimportance of radiation backgrounds likely still holds for much of our parameter space. For baryonic matter, Carter 44 notes that it is even a conspiracy that stars like the Sun exist and slightly smaller α would result in all stars being dominated by convective energy transport and hence red. In addition, even if the dark clumps radiate ionizing photons, photoionization tends to be a relatively weak form of feedback that has trouble halting ionized gas from cooling.

6.1 Dark atomic cooling

Let us begin by assuming that the gas can cool only via atomic cooling and that there are no molecules present. We discuss the case with molecules in the next section. In the case of atomic cooling, we expect regions where gas can cool efficiently at halo densities will allow the gas to cool to $T \sim 0.1 B_X$, reminding you that B_X is the binding energy of dark hydrogen. Both bremsstrahlung and atomic cooling become increasingly efficient with decreasing temperature, driving the gas to lower and lower temperatures. However, below $T \sim 0.1 B_X$, their are insufficient dark electrons in the Maxwellian tail to excite line cooling and also the gas starts to become neutral, which further shuts off all cooling processes. The exact temperature the gas cools to depends on n, m_c, and α_X, but the prefactor of 0.1 is rather generic owing the strong exponential dependence both of the ionized fraction and collisional cooling on temperature.

One of the ways cooling can become inefficient is if the gas reaches thermal equilibrium. However, it is difficult for the lowest allowed atomic transitions in the gas to reach thermal equilibrium because the transition times are short, with atomic hydrogen's spontaneous transition rate from the $2p$ to $1s$ being roughly $A_{21} \sim 10^9 \text{ s}^{-1}$, scaling as $\alpha_X^5 m_c$. The number density at which collisional excitations become equal to spontaneous decays so that dark atomic transitions go into thermal equilibrium is

$$n_{\rm TE} = 3 \times 10^{19} \text{ cm}^{-3} \times \left(\frac{\alpha_X}{\alpha}\right)^6 \left(\frac{m_c}{m_e}\right)^3$$

where we have assumed a collision rate of $\Gamma_{\rm coll} = n_X \pi \alpha_X a_0^2 f$ at a temperature of $T = \frac{B_X}{10}$, where a_0 is the 'Bohr radius'. Here $f \sim 10^{-3}$ is the exponentially small fraction of electrons in the Maxwellian tail that can collisionally excite transitions. We find that $n_{\rm TE}$ is not achieved in any of our parameter space. When transitions are not in thermal equilibrium, the gas continues to cool, condense and fragment, unless the gas becomes optically thick to a process that destroys cooling lines. The absorption process that is most likely to set the opacity is free-free absorption (the inverse process of bremsstrahlung). For the free free optical depth to be unity for a cloud of size the Jeans radius (Eq. 8 at the Ly$\alpha lineforhydrogen - themajoratomiccoolinglinewefind$

$$n_{\rm ff} = 7 \times 10^9 \text{ cm}^{-3} \left(\frac{\alpha_X}{\alpha}\right)^2 \left(\frac{m_c}{m_e}\right)^3 \left(\frac{m_X}{m_p}\right)^{2/3}$$

where we have assumed a temperature of $T = 0.1 B_X{}^{15}$ This gives us the scaling of the Jeans mass due to final

15 If we evaluated at $\nu \sim T$ characteristic of free-free emission, we would find two orders of magnitude lower densities (and one density set by free-free opacity as

$$M_J^{\rm ff} \simeq 1800 M_\odot \times \left(\frac{\alpha_X}{\alpha}\right)^2 \left(\frac{m_X}{m_p}\right)^{-7/3}$$

For values of α_X larger than the fine structure constant, it is possible that Compton and double Compton scatterings destroy the alpha line more efficiently (for smaller densities) than free free absorption. However it is not obvious whether thermalization proceeds efficiently at these densities. We ignore this possibility here.

Finally, we ignore two other thermalization processes: bound-free absorption and H$^-$absorption. Both of these processes are extremely temperature dependent and so their effects on opacity are difficult to calculate. Boundfree needs to be from electrons in the $n = 2$ state, which are suppressed by density (with fraction equaling $n/n_{\rm crit}\ \exp[-\Delta E/T]$) and by ionization. Furthermore, unlike free-free, both processes tends to be narrow band owing to the photoionization cross sections generically scaling as ν^{-3}; this allows the gas to cool at other wavelengths or, if such cooling is sufficiently blocked, to heat up and collisionally ionize these absorbers. Furthermore, these absorbers are more sensitive to dissociating ionizing backgrounds.

Figure 4 shows the estimated mass of stars, estimated using M_J for $T = \alpha_X^2 m_c/10$ and evaluated for when cooling becomes inefficient owing to free-free absorption, $n_{\rm ff}$. With the m_c dependence of M_J^{ff} in Eq. 11 Jeans mass only depends on α_X^2 and the higher the α_X the higher the mass. The Jeans mass also decreases with increasing m_X.

6.2 Dark molecular cooling

Dark molecules, a bound state between two dark hydrogen atoms, could potentially form and enable to gas to cool to much lower temperatures than atomic cooling. Furthermore, molecules reach thermal equilibrium at much lower densities owing to their smaller spontaneous emission coefficient relative to atoms. These differences result in a gas of dark molecules fragmenting on different scales than one of atoms.

However, it is very difficult to predict whether dark molecules will form. In our Universe, molecular hydrogen formation is typically highly out of thermal equilibrium. (At low redshifts, most forms on the surface of dust grains.) Solving the rate equations for dark hydrogen formation to determine whether it can cool the gas is complex. Additionally, dark hydrogen is easily destroyed by radiation backgrounds with energies of $0.4\alpha_x^2 m_c$ (and order of magnitude lower dark clump masses). However, free free emission is much more likely to be in thermal equilibrium and, hence, surface emission because equilibrium is established by the sea of Coulomb interactions. its catalyst $\mathrm{H}^{-}$is destroyed by $0.05\alpha_x^2 m_c$ ones). Indeed, once a very small number of baryonic stars formed in the Universe owing to molecular hydrogen cooling, the dissociating background from these stars is thought to destroy all molecular hydrogen in unenriched environments 45 . 46. Here we will consider the cases where molecules can cool the gas for all of our dark parameter space, noting that the case where they cannot was treated in the previous atomic cooling section.

In analogy to atomic gas, molecules can cool to $\sim \alpha_x^2 m_c^2 / m_X$ if it can cool via rotational transitions and till $\sim \alpha_X^2 m_c^{3/2} / m_X^{1/2}$ through roto-vibrational transitions. We assume the $\sim$ are equality for ensuing calculations. Rotational transitions are forbidden dipole transitions, whereas they are allowed at quadropole order. The rate is given by $\Gamma_{\text{quad}} = \alpha^7 m_X^{-5} m_c^6$. Roto-vibrational transitions can proceed through dipole radiation with the rate given by $\Gamma_{\text{dipole}} = \alpha^5 m_X^{-3/2} m_c^{5/2}$. Not all the parameter space can cool via rotational transitions because the spontaneous emission timescale can become longer than the dynamical time.

7 CONSTRAINTS ON DARK BARYONS

In the previous sections, we calculated the mass of dark clumps assuming both atomic and molecular cooling. Since the Jeans mass sets the scale of fragmentation of the gas, we can assume that the mass of the dark clusters is approximately the minimum Jeans mass over its condensation history. We note that it would be unsurprising for our characteristic mass to misestimate the actual mass by an order of magnitude. We again take solace in that the large parameter space of models means that an order of magnitude shift in characteristic clump mass often shifts the ruled-out regions marginally. In addition, one of our most stringent constraints turns out not to depend on the masses of the dark clumps.

This class of constraints is simpler as it does not depend on the additional step of estimating the mass of the dark clumps. Astronomers understand how to map stellar luminosity of a galaxy to its mass in stars at the factor of two level from studies that have modeled in detail populations of stars. The factor of two estimated error stems from the amount the mass-to-light ratio vary between different models 47 . Thus, we can observe the light of galaxies and use this to estimate the mass in stars. These mass estimates can be compared with modeling that determines the enclosed mass, either by observing galactic rotation curves or by using strong gravitational lensing (and on scales where standard dark matter should be a small contribution to the density). Unlike the massto-light estimates, these other mass estimates are sensitive to the enclosed mass in atomic dark matter. Thus, atomic dark matter in a bulge or disk cannot contribute more than the mass already in stars, as the mass in stars is approximately the error on mass-to-light inferences. Let us first examine the case of the Milky Way. Since only two percent of the Milky Way halo's mass is in the Milky Way galaxy itself, this constrains

$$\epsilon \times \left\{ f_{\text{bulge}} \left(\left. \frac{r_{\text{MW}}}{r_{\text{s}}} \right|_{\text{bulge}} \right)^3 + f_{\text{disk}} \left(\left. \frac{r_{\text{MW}}}{r_{\text{s}}} \right|_{\text{disk}} \right)^2 \right\} 0.02$$

where r_{MW} is the Milky Way stellar radius and r_{s} is the dark atom radius, either in the bulge or disk. We take $r_{\text{MW}} = 3\text{kpc}$. Our calculations show that the region of our parameter space where a disk forms has $r_{\text{s}} \approx 2 r_{\text{MW}}$, although the difference from equality may owe to simplifications in our semi-analytic model (the assumed isothermal potential model overestimates the disk size and we did not model the distribution of halo spin parameters rather assuming the mean). However, in most of the remaining parameter space where a disk does not form and the cooling is efficient $r_{\text{s}} < r_{\text{MW}}$, leading to stronger constraints on ϵ.

An equivalent constraint was published recently which constrained the surface mass density Σ_{MW} (and hence the galaxy mass) of our Milky Way disk by using stellar velocity data from Gaia sattelite 48 . However this study assumed that the entire parameter space of dark baryons that can cool forms a dark disk and contributes directly to Σ_{MW}. Since this assumption is not valid for most of our parameter space we do not use this constraint.

In more massive halos than the Milky Way, the anal- ogous constraint may be even stronger as the stellar-tohalo mass fraction is found to decrease with halo mass as $M_{\text{stars}} / M_{\text{DM}} \approx 0.02 \left(M_{\text{DM}} / \left[10^{12} M_{\odot} \right] \right)^{-0.5}$ [34]. Sonnenfeld et al. 49 and Posacki et al. 150 have constrained the masses in galaxies in the range of $10^{13} - 10^{14.5} M_{\odot}$ from dynamical modeling combined with strong lensing mass estimates. We expect these measurements to be extremely constraining as, for example, the mass of a galaxy in a $10^{14} M_{\odot}$ halo is 2×10^{-3} its halo mass, so naively a disk or bulge of 2×10^{-3} in atomic dark matter would be ruled out. However, deriving bounds from these more massive halos requires simulating a $10^{14} M_{\odot}$ merger tree to calculate bulge sizes, as in some parameter space a small fraction of the dark matter may reside in a bulge.

8 Constraints from ultra-faint dwarf galaxies

Dynamical friction is a gravitational effect in which a heavier object deflects lighter ones, leaving a wake in its path, and the mass in this wake causes it to lose momentum and spiral towards the center of the potential. The momentum lost by the heavier object is then gained by lighter objects, 'heating' them and causing their distribution to become more extended. In the parameter space in which dark clumps are considerably heavier than (baryonic) stars, dynamical friction acting on the dark clumps would increase the size of star clusters until they 'dissolve' in their host galaxy. Similarly, the stars in the galaxy themselves would experience the same 'heating, potentially increasing their half-light radius.

Such constraints from dynamical friction heating are the strongest for the ultra-faint dwarf galaxies, satellites of Milky Way and Andromeda with halo masses of $\sim 10^{10} M_{\odot}$ - the smallest galaxies and halos that are known. Ultra-faint dwarf galaxies are the most dark matter-dominated systems in the Universe. In particular, we can translate the MACHO and primordial black hole constraints from over to our dark baryons parameter space, which yields

$$\epsilon \times f_{\rm cooled} \times M_{\rm ADM} \geq 10 M_\odot$$

where $M_{\rm ADM}$ is the mass of atomic dark matter clumps and $f_{\rm cooled}$ is the fraction of gas cooled. The above bound comes from assuming the time to increase in half-light radii of the ultra-faint dwarf galaxies from 2 pc to 30pc is larger than 10 Gyr (see Fig. 3 in [51])

We did a merger tree simulation for $10^{10} M_\odot$ to estimate the parameter space where the 'dark atoms' can cool and form dark clumps. We have not included the fact that in parts of the parameter space with large spheroid fractions the dark clumps will be much more

Stronger bounds can be derived from the same paper using the evaporation of stellar clusters in the Eri II galaxy. concentrated near the center of dwarf galaxy increasing (by a huge factor) the rate of 'heating' caused by their dynamic friction. Nevertheless, even with this extremely conservative assumption, much of the parameter space in which $M_{\rm ADM} > 200 M_\odot$ is ruled out.

9 Microlensing constraints

The dark clumps will act as gravitational lenses to stars, leading to enhancements in flux of these stars that are of the order one when the star passes in projection within the Einstein radius of a lens, R_E. The timescale for this enhancement is $t_{\rm ml} \sim R_E/v$, which corresponds to of the order 100 days for a solar mass star, assuming that the the relative velocity of the star with respect to the lens is a Milky Way-like $v = 200$ km s^{-1}.

On a halo scale, the MACHO survey offers the best constraints on dark clumps 52 . This survey searched for stellar lensing events towards the Large Magellanic Clouds. MACHO constrains dark clumps distributed like an NFW halo to be $< 10\%$ of the dark matter for masses in the range $10^{-7} - 10^{-3} M_\odot$[53], and $< 40\%$ of the dark matter for $M_\odot = 1 - 30$[49, 50], and somewhat weaker constraints between these ranges (although there are also more lenses than expected in this range, allowing for tens of percent of the dark matter). Unfortunately, because we consider $\epsilon < 0.05$ and in most of our cooling scenarios the dark clumps are more concentrated than the halo dark matter, which suppresses the lensing efficiency by the fractional distance to the lens relative to a lens at half the source distance (for us a factor of > 10), halo-scale microlensing does not constrain viable parameter space for atomic dark matter.

Galactic microlensing surveys, which instead use source stars within the Milky Way, provide more of a constraint on our model. The OGLE survey detects thousands of lensing events, with the histogram of event durations peaking at 30 days, as expected for stars - few tenths of solar mass objects. Less than a tenth of events that occur have 3 day timescale, which would correspond to $M_{\rm ADM} \sim 10^{-3} M_\odot$. Thus, the number of solar mass objects relative to stars should be $\rho_{\mathrm{ADM}} = 0.1\left(\left[0.1 M_{\odot}\right]/M_{\mathrm{ADM}}\right)^{1/2}\rho_{*}$, where the factor in parentheses accounts for the higher rate of lower mass lenses and ρ_{*} is the number density in stars and we have taken their characteristic mass to be $0.1 M_{\odot}$. Thus, for $M_{\mathrm{ADM}} \sim 10^{-3} M_{\odot}, \rho_{\mathrm{ADM}} < \rho_{*}$. Finally, note that the mass in stars in Milky Way-like galaxy is estimated to be $\approx 0.02 M_{\mathrm{DM}}$ from galaxy-halo abundance matching [34]. Thus, if all the dark clumps are in a disk, using that $\rho_{*} \propto 0.02 M_{\mathrm{DM}}/\left[0.1 M_{\odot}\right]$ and using $\epsilon = 0.05$ we get

$$f_{\mathrm{disk}} 4 \times 10^{-3} \quad \text{for} \quad M_{\mathrm{ADM}} \sim 10^{-3} M_{\odot}$$

The constraints are less stringent on the case where the lensing is from a bulge, where since a bulge is more extended, within the plane of the galaxy $l_{\mathrm{disk}}/R_{\mathrm{bulge}} \sim 0.1$!

$$f_{\mathrm{bulge}}\, 4 \times 10^{-2} \quad \text{for} \quad M_{\mathrm{ADM}} \sim 10^{-3} M_{\odot}$$

This neglects that some source stars that have been surveyed are bulge stars, which will be more sensitive to bulge atomic dark matter.

These constraints are extremely powerful and are likely to rule out much of the dark atom parameter space for $m_X = 10\mathrm{GeV}$ in the the molecular cooling scenario, where we find $M_{\mathrm{ADM}} \sim 10^{-3} M_{\odot}$ (and roto-vibrational cooling is dominant). However, it does not rule out any of our dark atom parameter space for $m_X = 1\mathrm{GeV}$, since the characteristic mass scale there is $> 10^{-1} M_{\odot}$.

The above estimates are mostly for illustration, and we do not include the microlensing constraints in 6 In order to derive proper constraints one would need to take into account the correct spheroidal radius of our 'dark galaxy', which can change the distances between lens and source and the correct modeling of the spread in the lensing timescales.

Future shorter cadence microlensing surveys should be powerful for constraining the sub-solar mass atomic dark matter parameter space, such as the upcoming NASA mission WFIRST 17 WFIRST will be sensitive to lenses with masses as small as $10^{-8} M_{\odot}$[55], providing extremely sensitive constraints on ϵ in our models, especially in the regions where roto-vibrational molecular cooling sets the mass of stars. The limitation for such constraints comes from not knowing how much mass resides in planets and asteroids in the Galaxy. Models predict planet/asteroid mass densities that are at least two orders of magnitude down from the mass in stars (and their masses are concentrated at certain scales). Thus, future microlensing surveys will dramatically constrain ϵ for our parameter space with $M_{\mathrm{ADM}} 10^{-3} M_{\odot}$.

10 CONCLUSIONS

We tried explore the constraints on a fraction of the dark matter being two darkly charged particles with a large mass ratio and a massless force carrier. In such models, the dark matter can cool and exhibit interesting dynamics. Studies assumed that, in parameter space where the dark matter can cool, it would form a disk. The dark world might even be as diverse and interesting as the visible world but the interactions between dark protons and dark electrons could make them lose energy over time. As such, they might slow down enough to clump into flat disks around galaxies, just like regular matter does. In contrast, most dark matter apparently forms roughly spherical haloes around galaxies, stars and planets. This concept means galaxies would have two disks, one made of regular atoms and one of dark atoms, which is why the investigators call their idea the double-disk dark matter model. The double-disk dark matter idea is a novel twist on an intriguing concept — that the physics of dark matter might be as complicated and interesting as the physics of ordinary matter is known to be. The basic possibility of a dark force very similar to electromagnetism — a long-range force with positive and negative charges, Such a model implies dark radiation, dark magnetic fields, and a host of other interesting phenomena. But we only had one kind of dark-matter particle in our model; to go to the world of dark atoms and dark chemistry requires more kinds of particles. That's the direction the new papers are taking. The gravitational effects of a dark atom disk on stars in galaxies could eventually be detectable via the European Space Agency's Gaia space observatory which aims to map the movement of approximately 1 billion stars in the Milky Way. This can be how we might first detect this dark disk, Moreover, since this novel form of dark matter is expected to be much slower on average than regular dark matter, it should be more susceptible for capture by the Earth, by the sun, or other heavy celestial objects. Annihilation of this dark matter captured by the sun can result in neutrino fluxes, which can be measured directly by the IceCube Neutrino Observatory on the South Pole. In addition, the dark electrons and dark protons the scientists propose might also have antimatter counterparts — dark anti-electrons and dark anti-protons. When these particles collide with their counterparts, they would release gamma rays, the most energetic form of light, which telescopes should be able to spot. Furthermore, dark atoms might also have formed clouds of dark plasma, ripples in which might have influenced the formation of the early universe and thus have visible effects on large-scale cosmic structures that exist nowadays.

11 References

[1]A.G.Doroshkevich, Ya.B.Zeldovich, R.A.Sunyaev and M.Yu.Khlopov. Astronomical consequences of neutrino rest mass. II. Spectrum of density fluctuations and fluctuations of microwave background.

[2]Pis'ma Astron. Zh. (1980) V. 6, PP. 452-464. Reprinted in: Ya.B.Zeldovich.Selected Works. Particles, Nuclei, Universe. Ed. Yu.B.Khariton, Moscow, Nauka, 1985, PP. 358-365. [English translation: Sov. Astron. Lett. (1980) V. 6, PP.252-256]

[3]A.G.Doroshkevich, Ya.B.Zeldovich, R.A.Sunyaev and M.Yu.Khlopov. Astronomical consequences of neutrino rest mass. III. Nonlinear stage of theevolution of perturbations and dark matter. Pis'ma Astron. Zh. (1380) V. 6,PP.465-470. Reprinted in: Ya.B.Zeldovich. Selected Works. Particles, Nuclei,Universe.

Ed. Yu.B.Khariton, Moscow, Nauka, 1985, PP. 166-370. [English translation: Sov. Astron. Lett. (1980) V. 6, P. 257]

[4]A.G.Doroshkevich and M.Yu.Khlopov.The Development of Structure in a Neutrino Universe. Astron. Zh. (1981), V.58,PP. 913-924. [English translation: Sov. Astron. (1981) V. 25, P. 521]

[5]A.G.Doroshkevich, Ya.B.Zeldovich, A.S.Szalay, R.A.Sunyaev and M.Yu.Khlopov. Cosmological impact of the neutrino rest mass. Ann.N.Y.Acad.Sci.(1981), V.397, PP. 32-41.

[6]V.F.Shvartsman, V.B.Braginskii, S.S.Gershtein, Ya.B.Zeldovich and M.Yu.Khlopov.Possibility of detecting relict massive neutrinos. Pis'ma v ZhETF (1982),V.36, PP. 224-226. [English translation: JETP Lett. (1982) V.36, PP.277-279].

[7]S.I.Blinnikov and M.Yu.Khlopov.On the possible signatures of mirror particles. Yadernaya Fizika (1982) V. 36,PP. 809-811. [English translation: Sov.J.Nucl.Phys. (1982) V.36, PP.472-474]

[8]S.I.Blinnikov and M.Yu.Khlopov.On the possible astronomical effects of "mirror' particles. Astron. Zh.(1983), V. 50, PP. 632-639. [English translation: Sov. Astron. (1983) V. 27,PP. 371-355]

[9]M.Yu.Khlopov, G.M.Beskin, N.G.Bochkarev, L.A.Pustilnik and S.A.Pustilnik Observational physics of mirror world. Astron. Zh. (1991), V. 69, PP. 121-130.[English translation: Sov.Astron. (1991) V.35, PP.21-30].

[8]A.G.Doroshkevich and M.Yu.Khlopov.On the physical nature of dark matter of the Universe. Yadernaya Fizika (1984) V. 39, PP. 869-870. [English translation: Sov.J.Nucl.Phys. (1984) V.39,PP.551-553]

[9]A.G.Doroshkevich and M.Yu.Khlopov.Formation of structure in the Universe with unstable neutrinos. Mon. Not. Roy.astr. Soc. (1984) V. 211, PP. 279-282.

[10]A.G.Doroshkevich, M.Yu.Khlopov and A.A.Klypin.Large-scale structure formation by decaying massive neutrinos.Mon.Not.Roy.astr.soc. (1989) V.239, PP. 923-938.

[11]Z.G.Berezhiani and M.Yu.Khlopov.Physics of cosmological dark matter in the theory of broken family symmetry.Yadernaya Fizika (1990) V. 52, PP. 96-103. [English translation:Sov.J.Nucl.Phys. (1990) V.52, PP.60-64]

[12]Z.G.Berezhiani and M.Yu.Khlopov.Cosmology of spontaneously broken gauge family symmetry with axion solution of strong CP-problem. Z.Phys.C-Particles and Fields (1991), V. 49, PP. 73-78.

[13]A.S.Sakharov and M.Yu.Khlopov.Horizontal unification as the phenomenology of the theory of "everything".Yadernaya Fizika (1994) V. 57, PP. 690-697. [English translation: Phys.Atom.Nucl. (1994) V. 57, PP. 651-658]

[14]M.Yu.Khlopov.Physical arguments, favouring multicomponent dark matter. In: Dark matter in cosmology, clocks and tests of fundamental laws. Eds.B.Guiderdoni et al.Editions Frontieres, 1995. PP. 133-138.

[15]A.S.Sakharov and M.Yu.Khlopov.The nonhomogeneity problem for the primordial axion field. Yadernaya Fizika(1994) V. 57, PP. 514- 516. [English translation: Phys.Atom.Nucl. (1994) V.57, PP. 485-487]

[16]M.Yu.Khlopov, A.S.Sakharov and D.D.Sokoloff.The nonlinear modulation of the density distribution in standard axionic CDM and its cosmological

impact. Nucl.Phys. B (Proc. Suppl.) (1999) V. 72,105-109.

[17]S.Sakharov (Zurich, ETH), Maxim Yu. Khlopov (Moscow Phys. Eng. Inst. COSMION,Moscow Moscow, IPM). Feb 2001. 9pp. Published in J.Exp.Theor.Phys.91:921-929,2001,J.Exp.Theor.Phys.92:921-929,2001.e-Print Archive: hep-ph/0106187