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Large-Scale Modulation of the Distribution of Coherent Oscillations of a Primordial Axion Field in the Universe

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Abstract—The spectrum of inhomogeneities generated by archioles, which initially represent nonlinear (with $\delta\rho/\rho > 1$) quasi-one-dimensional percolation structures involving coherent oscillations of the axion field, is found. This spectrum is used to investigate effects that exert influence on the spectrum and quadrupole anisotropy of relic radiation. A model-independent constraint on the scale of axion interaction is obtained. This constraint is consistent with the mixed cool–hot scenarios describing the formation of a large-scale structure in the universe.

1. INTRODUCTION

The modern theory of a large-scale structure of the universe is based on the assumption that this structure is formed as the result of development of gravitational instability from small initial perturbations of density or gravitational potential. As a rule, these perturbations are of a Gaussian character, but some versions of non-Gaussian perturbations have also been considered. The perturbations can be adiabatic, isothermic, and isoentropic and can generally have a rather intricate shape of the spectrum. On the other hand, theories that describe the formation of the structure of the universe imply that these initial perturbations grow for a rather long period dominated by nonrelativistic matter, so that this period falls within the dust stage of expansion. It seems that the consistent scenario of the formation of the large-scale structure that exists in the universe against the background of the observed isotropic relic radiation requires the presence of nonbaryonic dark matter that dominates the density of the universe in the period of structure formation.

At present, the standard model of a hot universe is giving way to inflation cosmology involving baryosynthesis and a nonbaryonic hidden mass. In view of these trends, it can be believed that the physical foundations of this new standard model of a hot universe will also provide a quantitative description of all basic elements of the theory of the structure, such as the origin and spectrum of initial perturbations and the parameters of particles that form dark matter. The model of horizontal unification (MHU) proposed in [1] is a minimal phenomenology of everything, including the physics of inflation, baryosynthesis, and dark matter. One of the solutions based on this model is reduced to the standard axion model of cold dark matter. However, analysis of this solution revealed a problem that concerns a primary inhomogeneity in the distribution of the energy of coherent oscillations of the axion field and which is common to all models of axionic cold dark matter. This problem, referred to as the problem of archioles [2], will be comprehensively analyzed in this study.

Archioles, a formation that represents a replica of the percolation Brownian vacuum structure of axionic walls bounded by strings and which is fixed in the strongly inhomogeneous primary distribution of cold dark matter, seem to appear in all models of an invisible axion as their necessary element. They can have a bearing on interesting alternative scenarios of structure formation that relate the mechanism responsible for structure formation to inhomogeneities of the type of topological singularities that are predicted by some models of elementary particles. Such scenarios differ significantly from those realized in models involving phase transitions at later stages and in models that assume the direct formation of the structure by topological singularities and which can be substantiated only by invoking rather special physical arguments. Therefore, the analysis presented in this study is necessary not only for developing further full cosmological theories on the basis of the MHU, but also for verifying the cosmology of an invisible axion. In particular, consideration of observable effects associated with archioles leads to a new model-independent constraint on the scale of axion interaction.

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2. FORMATION OF THE ARCHIOLE STRUCTURE IN THE EARLY UNIVERSE

In the scenario under study, the evolution of the axion field is determined by cosmological processes that lead to the violation of global Peccei–Quinn symmetry $U(1)_{PQ}$ [3].

The axion is a Nambu–Goldstone boson for the standard $U(1)$ potential

$$V(\varphi) = \frac{\lambda}{2}(\varphi^2 - F_a^2)^2. \quad (1)$$

It is important to note that the axion is massless to the instant of a QCD phase transition in the early universe. However, instanton effects result in the axion mass $m_a = A_c m_\pi f_\pi / F_a$, since $U(1)_{PQ}$ symmetry is not free from an anomaly that is effectively described by the potential [4]

$$V(\theta) = \Lambda_1^4(1 - \cos(\theta N)). \quad (2)$$

In the period of the QCD phase transition, the axion mass depends on temperature as [5, 6]

$$m(T) = 0.1 m_a (\Lambda_{QCD}/T)^{3.7}, \quad (3)$$

until the Compton wavelength of the axion becomes comparable with the horizon scale $m(\tilde{t})\tilde{t} \approx 0.75$, where

$$\tilde{t} \approx 8.8 \times 10^{-7} \Delta^2 \left(\frac{F_a}{10^{12}\ \mathrm{GeV}}\right)^{0.36} \left(\frac{m_a}{6 \times 10^{-6}\ \mathrm{eV}}\right)^{-2} \times \left(\frac{N_{QCD}}{60}\right)^{0.5} \mathrm{s} \quad (4)$$

and

$$\Delta = 10^{\pm 0.5} \left(\frac{m_a}{6 \times 10^{-6}}\right)^{0.82} \left(\frac{\Lambda_{QCD}}{200\ \mathrm{MeV}}\right)^{-0.65} \left(\frac{N_{QCD}}{60}\right)^{-0.41}.$$

Thus, coherent oscillations of the axion field that correspond to an axion condensate with zero momentum and energy density

$$\rho_a = (39.14/2)\left(T_1^2 m_a \frac{1}{M_{Pl}}\right)(T/T_1)^3 \theta^2 F_a^2, \quad (5)$$

where $T_1 = \Lambda_1$ and M_{Pl} is the Planck mass, come into play at the instant $\tilde{t}$. In the cosmology of an invisible axion, it is usually assumed that the energy density of coherent oscillations is distributed uniformly and that it corresponds to the averaged phase value of $\bar{\theta} = 1$. However, the local value of the energy density of coherent oscillations of the axion field depends on the local phase θ that determines the local amplitude of coherent oscillations following axion-mass generation. It was shown in [2] that the initial large-scale inhomogeneity of the distribution of θ must be reflected in the distribution of the energy density of coherent oscillations of the axion field. The large-scale modulation of the distribution of the phase θ is due to the formation of topological singularities in two (Peccei–Quinn and QCD) phase transitions. As soon as the temperature of the universe becomes less than F_a, the field φ acquires the vacuum expectation value $\langle\varphi\rangle = F_a e^{i\theta}$, where θ varies smoothly at the scale F_a^{-1}. The existence of noncontractible closed loops such that circumventions along them change the phase by $2\pi n$ leads to the emergence of axion strings with a linear energy density approximately equal to F_a^2. These strings can be infinite or closed. A numerical simulation of string formation revealed [4] that about 80% of the length of arising strings corresponds to infinite Brownian lines. The remaining 20% of this length is contributed by closed loops. Infinite strings form a random Brownian network with the step

$$L(t) = \lambda t, \quad (6)$$

where $\lambda \simeq 1$. The distribution of loops can be characterized by their concentration $n(R)dR$ in the interval $(R, R + dR)$. According to the concept of scale invariance [4], we have $n(R) \propto R^{-4}$. When the temperature of the universe becomes as low as $T \simeq T_1$, expression (2) makes a significant contribution to the total potential, so that the minimum of energy (at $N = 1$) corresponds to a vacuum with $\theta = 2\pi k$, where k is an integer—for example, $k = 0$. However, the vacuum value of the phase θ cannot be zero everywhere, since the phase must change by $\Delta\theta = 2\pi$ upon a circumvention around a string; hence, we go over from the vacuum with $\theta = 0$ to the vacuum with $\theta = 2\pi$ as the result of such a circumvention. The vacuum value of θ is fixed at all points [4], with the exception of the point $\theta = \pi$. At this point, a transition from one vacuum to another occurs, and the vacuum axion wall is formed.[4)] The width of such a wall bounded by strings is $\delta \simeq m_a^{-1}$. According to [2], the initial value of the phase θ must be close to π near the wall, and the amplitude of coherent oscillations in (4) is determined by the difference of the initial local phase $\theta(x)$ and the vacuum value, which is different from zero only in a narrow region within the wall of thickness m_a^{-1}. With the aid of (4), it can be shown that, in this region, the energy density of coherent oscillations of the axion field is given by

$$\rho^A = \pi^2 \rho_a(\bar{\theta} = 1). \quad (7)$$

Thus, it follows from the above that the distribution of coherent oscillations of the axion field is modulated by nonlinear inhomogeneities in which the relative variations of density are $\delta\rho/\rho > 1$. In [2], such inhomogeneities were referred to as archioles. The scale of this modulation of the density distribution exceeds the cos-

4) The formation of vacuum walls as a consequence of discrete-symmetry breaking was first considered in [7].

mological horizon because of the presence of a 80% infinite component in the structure of axionic strings. In other words, the large-scale structure of archioles replicates the vacuum structure that axionic walls bounded by strings had by the instant $\tilde{t}$, but it is frozen at the radiation-dominated stage and persists following the disappearance of the vacuum structure itself.

The vacuum structure of axionic walls and strings is destroyed comparatively fast for the following reasons. Losses of energy by axionic strings in the period from $t_* \approx 10^{-20}(F_a/(10^{12}\ \mathrm{GeV}))^{-4}$ s to t_W through the emission of axions [8, 9] lead to the disappearance of loops in the cosmological time, while the production of loops by infinite strings results in the rectification of these strings at the scale of the cosmological horizon. Here,

$$t_W \approx 1.7 \times 10^{-6} \Delta^2 \left(\frac{F_a}{10^{12}\ \mathrm{GeV}}\right)^{0.36} \left(\frac{m_a}{6 \times 10^{-6}\ \mathrm{eV}}\right)^{-2} \times \left(\frac{N_{\mathrm{QCD}}}{60}\right)^{0.5} \mathrm{s} \tag{8}$$

is the instant beginning from which the surface tension of axionic walls becomes comparable with the stress of the strings—this is the instant at which $\sigma \approx \mu/t$.

It was shown in [2] that, for $F_a > 10^8$ GeV, the superweak self-interaction of the axion field leads to the splitting of the vacuum structure of archioles and walls bounded by strings. As a result, these two structures evolve independently from this time on. The structure of walls bounded by strings disintegrates rapidly into separate fragments of oscillating walls bounded by loops. In the course of further cosmological evolution, these walls can intersect. Their multiple self-intersections diminish the sizes of such fragments, so that strings regain their dominant role in the dynamics of the vacuum system. From this instant on, the decay of the axionic vacuum system proceeds through the channel of axion emission [10].

The structure of archioles remains frozen at the radiation-dominated stage. On large scales, this structure appears as a random Brownian network formed by quasilinear clusters of dustlike matter and characterized by the step

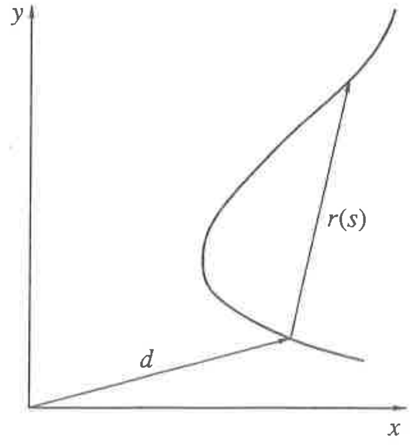
$$L^A(t) = \lambda' \tilde{t}, \tag{9}$$

where $\lambda' \approx 1$. At the instant $\tilde{t}$, the linear density in this network is

$$\mu_A = \pi^2 \rho_a(\bar{\theta} = 1)\tilde{t}\delta. \tag{10}$$

3. INHOMOGENEITIES IN THE DISTRIBUTION OF THE ENERGY DENSITY OF ARCHIOLES

To evaluate the scale of the presumed cosmological effects from archioles, it is necessary to study the spectrum of inhomogeneities that the density develops in response to the large-scale Brownian modulation of the distribution of coherent oscillations of the axion field.



Parametrization of the Brownian network.

The energy density in the network consisting of infinite Brownian lines with linear density (10) has the form

$$\rho(\mathbf{x}) = \sum_i \int ds_i \mu_A \delta(\mathbf{x} - (\mathbf{d}_i + \mathbf{r}_i(s_i))), \tag{11}$$

where the index i runs along the entire infinite line. Here, the point with radius vector $\mathbf{d}_i$ is chosen for each line. The vector $\mathbf{r}_i(s_i)$ is the coordinate parametrized on the corresponding line and measured from the point $\mathbf{d}_i$. In the Fourier representation, we then have

$$\rho(k) = \sum_i \int ds_i \mu_A e^{-i\mathbf{k} \cdot \mathbf{d}_i - i\mathbf{k} \cdot \mathbf{r}_i(s_i)}. \tag{12}$$

Perturbations of the density that are associated with archioles will be described in terms of a two-point autocorrelation function. To evaluate this function for the Brownian network, it is necessary to perform averaging over all lines specified by the radius vectors $\mathbf{d}_i$ and averaging over the Wiener measure that corresponds to the position parameter s_i with radius vector $\mathbf{r}_i(s_i)$. By virtue of the condition of statistical homogeneity and the statistical independence of the points $\mathbf{d}_i$ (see figure), the autocorrelation function $\langle \rho(\mathbf{k})\rho(\mathbf{k}') \rangle$ is contributed only by the diagonal components with $i = j$, the weight of each line being equal to $V^{-1}\delta^3(\mathbf{k} + \mathbf{k}')$. Thus, it follows from the above that

$$\langle \rho(\mathbf{k})\rho(\mathbf{k}') \rangle = NV^{-1}\delta^3(\mathbf{k} + \mathbf{k}')\mu_A^2 \times \int ds ds' \langle e^{-i\mathbf{k} \cdot (\mathbf{r}(s) - \mathbf{r}'(s'))} \rangle_W, \tag{13}$$

where N is the total number of lines. The averaging over the Wiener measure yields

$$\langle e^{-i\mathbf{k} \cdot (\mathbf{r}(s) - \mathbf{r}(s'))} \rangle_W = Z \int \prod_{s''} dr(s'')$$

$$\times \exp(-L^{-1}\int r'^2(s'')ds'')\exp\left(-i\mathbf{k}\cdot\int_{s'}^{s} ds'' r'(s'')\right) \quad (14)$$

$$= \exp(-Lk^2(s-s')/6),$$

where L is the correlation length (9), and Z is the normalization constant. For $s < s'$, the result is analogous to (14) up to the substitution of s' for s. Substituting (14) into (13) for $s > s'$ and $s < s'$ and summing the results, we obtain

$$\langle\rho(\mathbf{k})\rho(\mathbf{k}')\rangle = 12\frac{Nl}{V}\delta^3(\mathbf{k}+\mathbf{k}')L^{-1}\mu_A^2k^{-2}, \quad (15)$$

where l is the total length of each line in the volume V. The total energy density of infinite lines has the form

$$\rho_A = NlV^{-1}\mu_A. \quad (16)$$

Using (9) and (15), we find that the two-point autocorrelation function in the Fourier representation has the form

$$\left\langle\frac{\delta\rho}{\rho_0}(\mathbf{k})\frac{\delta\rho}{\rho_0}(\mathbf{k}')\right\rangle = 12\rho_A\mu_A k^{-2}\delta^3(\mathbf{k}+\mathbf{k}')\tilde{t}^{-1}f^{-2}t^4G^2. \quad (17)$$

The background density ρ_0 is given by

$$\rho_0 = ft^{-2}G^{-1}, \quad (18)$$

where $f = f_{\mathrm{MD}} = 3/(32\pi)$ for the matter-dominated (MD) stage, $f = f_{\mathrm{RD}} = (6\pi)^{-1}$ for the radiation-dominated (RD) stage, and G is the gravitational constant. Since the exponent k in the two-point autocorrelation function (17) falls within the interval $-3 < n < 4$, we can find the mean-square fluctuation of the mass [12]. The result is

$$(\delta M/M)^2(k,t) = k^3\delta^{-3}(\mathbf{k}+\mathbf{k}')\left\langle\frac{\delta\rho}{\rho_0}(\mathbf{k})\frac{\delta\rho}{\rho_0}(\mathbf{k}')\right\rangle. \quad (19)$$

Substituting (17) in (19), we obtain

$$(\delta M/M)^2(k,t) = 12\rho_A\mu_A\tilde{t}^{-1}f^{-2}G^2kt^4. \quad (20)$$

Since the structure of archioles is formed at the instant $\tilde{t}$, we can assume that the total energy density of the lines has the form

$$\rho_A = \frac{\mu_A\tilde{t}}{t^3}(t/\tilde{t})^3 = \left(\frac{\mu_A}{\tilde{t}^2}\right). \quad (21)$$

Let us now consider that the structure of archioles is an initially nonlinear formation, a Brownian network consisting of quasi-one-dimensional lines of dustlike matter. In accordance with this, the evolution of archioles against the background of the general cosmological expansion is reduced to the extension of lines along only one direction characterized by the parameter s. The resulting dependence on the scale factor is $\mu_A \propto \rho_A s \propto a^{-3}\, a \propto a^{-2}$. For $a \propto t^{1/2}$ (g is the number of degrees of freedom), the linear density of archioles at the RD stage varies as

$$\mu'_A = \mu_A(\tilde{t}/t)(g_{*\tilde{t}}/g_{*t})^{1/2}. \quad (22)$$

Replacing μ_A with μ'_A in equation (20), we then have

$$(\delta M/M)^2(k,t) = 12(g_{*\tilde{t}}/g_{*t})\frac{1}{\tilde{t}}f_{\mathrm{RD}}^{-2}(G\mu_A)^2kt^2. \quad (23)$$

Substituting (5) and (10) into (22), we obtain

$$\left(\frac{\delta M}{M}\right)^2(k,t) = 4.6\times10^3\left(\frac{g_{*\tilde{t}}}{g_{*t}}\right)f_{\mathrm{RD}}^{-2}\pi^4\frac{\Lambda_1^4}{M_p^2}\tilde{t}(GF_a^2)^2kt^2. \quad (24)$$

This finally yields

$$\left(\frac{\delta M}{M}\right)^2(k,t) = 2.3\times10^{-24}\left(\frac{F_a}{10^{10}\ \mathrm{GeV}}\right)^4\left(\frac{t}{1\ \mathrm{s}}\right)(kt). \quad (25)$$

It should be noted that the adiabatic perturbation in (25) differs substantially from ordinary adiabatic perturbations that are due to gravitational instability and which grow in proportion to $t^{2/3}$. The growth of the perturbation in (25) is purely geometric; it is associated with the fact that the sizes of successively arising elements of the Brownian network of archioles become smaller than the horizon scale. Such a geometric growth of perturbations is known in some other problems encountered in the physics of random media (see, for example, [13]). The origin of this growth can be explained as follows. At the initial stage of evolution, when the horizon scale is small, fluctuations of a random field that do not exceed, say, two standard deviations can occur within this horizon. Horizons of larger scale can accommodate random-field cells with greater deviations of, say, 2.5σ. This effect is superimposed on the ordinary gravitational instability and eventually leads to a change in the exponent in (24).

Let us now consider two simple cosmological implications of the large-scale structure of archioles.

3.1. Early Energy Release

It was shown in [14] that, to the instant of recombination, the Jeans mass exceeded $10^{18}M_\odot$, where $M_\odot$ is the Sun's mass, and that, in this period, adiabatic perturbations of smaller scale were sound waves. At the stage preceding to recombination, the dissipation of sound-wave energy leads to equalization of density perturbations on the mass scales less than 10^{10}–$10^{12}\ M_\odot$. The scale at which dissipation occurs increases with time in proportion to t^3. In the interval between $z_a \simeq 10^4\Omega_B^{-0.5}$ and $z_b \simeq 5.4\times10^4\Omega_B^{-6/5}$, oscillations associated with masses $M \simeq 3 \times 10^6 \Omega_B^{29/5}$–$4 \times 10^9 \Omega_B^3$ are damped out. The corresponding energy release in the period of recombination is

$$q = \frac{1}{3}\left(\frac{\Delta\rho}{\rho}\right)^2. \tag{26}$$

In accordance with (25), we find the spectrum of density perturbations in the mass region around $10^{11} M_\odot$, which determines the smallest scale of adiabatic perturbations that did not undergo damping in the course of hydrogen recombination at $t_{\rm rec} = 5 \times 10^{11} (\Omega h^2)^{-0.5}$ s. We have

$$\left(\frac{\Delta\rho}{\rho}\right)^2 \simeq \left(\frac{\Delta M}{M}\right)^2_{10^{11} M_\odot} = 1.3 \times 10^{-10}\left(\frac{F_a}{10^{10}\ \text{GeV}}\right)^4. \tag{27}$$

According to (26), the resulting adiabatic perturbation (27) can lead to an early energy release at the level of $q \simeq 4 \times 10^{-11} (F_a/10^{10}\ \text{GeV})^4$. At the same time, the observed spectrum of relic microwave background indicates that this quantity cannot exceed $q_{\rm obs} \le 3 \times 10^{-3}$ [15]. From these two estimates, we can obtain a constraint on the scale of axion interaction. The result is $F_a \le 9 \times 10^{11}$ GeV. The low energy scale of $F_a \simeq 10^6$ GeV (see [17]) is also possible in the model of a hadronic axion [16] and an archion [1]. It is shown in [17] that, in this case, the structure of archioles dissipates because of thermalization of axions that occurs via the reactions $\pi N \longleftrightarrow aN$ in the region $F_a \le 10^8$ GeV after the QCD phase transition.

3.2. *Quadrupole Anisotropy of Relic Radiation*

According to [15], an order-of-magnitude estimate of the anisotropy of relic radiation ($\delta T/T$) can be obtained by considering a domain such that, at instant t, it is characterized by an intrinsic size l and a density fluctuation δ. We then obtain

$$\delta T/T \simeq -\delta(l/t)^2. \tag{28}$$

If $l = t$, we have $|\delta T/T| \simeq |\delta|$; that is, the residual perturbation of relic radiation is on the same order of magnitude as the density fluctuation calculated at the instant when the size of the domain became equal to the distance to the horizon (Sachs–Wolf effect). To estimate the quadrupole anisotropy that is induced in relic radiation by the structure of archioles, we must therefore find the amplitude of perturbations on the scale of the current horizon.

Following recombination, the linear density varies as

$$\mu''_A = \mu_A\left(\frac{\tilde{t}}{t_{\rm RD}}\right)\left(\frac{t_{\rm RD}}{t}\right)^{4/3}\left(\frac{g_{*\tilde{t}}}{g_{*t}}\right)^{0.5}. \tag{29}$$

From (20), we then obtain

$$\left(\frac{\delta M}{M}\right)^2_{\rm MD} = 12\left(\frac{g_{*\tilde{t}}}{g_{*t}}\right)\frac{1}{\tilde{t}}(G\mu_A)^2 f_{\rm MD}^{-2} t_{\rm RD}^{2/3} t^{1/3}(kt), \tag{30}$$

$$\left(\frac{\delta M}{M}\right)^2_{\rm MD} = 2.1 \times 10^{-25}\left(\frac{F_a}{10^{10}\ \text{GeV}}\right)^4 \times \left(\frac{t_{\rm RD}}{1\ \text{s}}\right)^{1/3}\left(\frac{t}{1\ \text{s}}\right)^{2/3}(kt). \tag{31}$$

Substituting $t = t_{\rm rec}$ into (31) and taking into account (28), we arrive at

$$\frac{\delta T}{T} \simeq 2.3 \times 10^{-6}\left(\frac{F_A}{10^{10}\ \text{GeV}}\right)^2. \tag{32}$$

According to COBE data [18], the measured quadrupole anisotropy of relic radiation is at the level of

$$\delta T/T = 5 \times 10^{-6}. \tag{33}$$

Using our expression (32) for the quadrupole anisotropy that is induced in relic radiation by the structure of archioles and taking into account the observational data presented in (33), we can obtain a model-independent constraint on the scale of symmetry breaking in the model of an invisible axion. The result is

$$F_a \le 1.5 \times 10^{10}\ \text{GeV}. \tag{34}$$

The upper limit that we obtained for F_a has an essentially different character than the upper limit in [8, 9] that is close in magnitude, but which was obtained by comparing the density of axions from decays of axionic strings with the critical density. The point is that the density of axions formed in decays of axionic strings depends critically on the assumption about the spectrum of such axions. For example, Davis [8] assumed that axions from decays of strings have a maximum wavelength of $\omega(t) \simeq t^{-1}$ (t is the cosmological time), while Harari and Sikivie [9] deem that the spectrum of such axions is $\propto k^{-1}$. This leads to an uncertainty factor of $\xi \simeq 70$ in the estimate of the density of axions from strings and to the corresponding uncertainty in the estimated upper limit on F_a:

$$F_a \le 2 \times 10^{10} \xi\ \text{GeV}. \tag{35}$$

Here, $\xi = 1$ for the spectrum from [8], and $\xi = 70$ for the spectrum from [9]. Arguments that lead to the constraint presented in (34) are free from these flaws, since they have a model-independent character.

4. CONCLUSION

The results of the above analysis enable us to draw more definitive conclusions about the possible role of archioles in the cosmology of an invisible axion. On one hand, it has been shown that, in contrast to the ideas prevalent in the cosmology of an invisible axion, the averaged effect of inhomogeneities makes a significant contribution to the large-scale distribution of the density of the axion field and plays a noticeable role in the theory that attributes the formation of the large-scale structure in the universe to axionic cold dark matter. In this connection, it is interesting to note that a recent phenomenological analysis that supplemented the perturbation spectrum of the standard model of an invisible axion with a percolation component improved agreement between this model of structure formation and observational data. In the approach developed here, the existence of the percolation component in the form of the network of Brownian lines is explained physically by the phenomenon of archioles.

On the other hand, the constraint that we obtained for the scale of axion interaction is evidence (within the MHU) in favor of the mixed cool–hot scenario that associates the formation of the large-scale structure in the universe with a mixture of axions and massive neutrinos. In the MHU, the scale of the generation-symmetry breaking is chosen by using the full set of cosmological and astrophysical constraints. Such a choice, which determines the scale of archion interaction, tightly fixes the cosmological parameters of the MHU, thereby permitting the construction of the full cosmological model, including inflation, baryosynthesis, and the mixed archion–neutrino (archiole–neutrino) model of nonbaryonic dark matter. Elaboration of such a full scenario that is physically substantiated within the MHU and which describes quantitatively the evolution of the universe from the Planck time to the formation of galaxies will be the subject of a separate study.

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