Axion quark nuggets and how a global network can discover them

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We advocate an idea that the presence of the daily and annual modulations of the axion flux on the Earth's surface may dramatically change the strategy of the axion searches. Our computations are based on the so-called axion quark nugget (AQN) dark-matter model which was originally put forward to explain the similarity of the dark and visible cosmological matter densities $\Omega_{dark} \sim \Omega_{visible}$. In our framework, the population of galactic axions with mass 10^{-6} eV $\leq m_a \leq 10^{-3}$ eV and velocity $\langle v_a \rangle \sim 10^{-3}c$ will be always accompanied by the axions with typical velocities $\langle v_a \rangle \sim 0.6c$ emitted by AQNs. We formulate the broadband detection strategy to search for such relativistic axions by studying the daily and annual modulations. We describe several tests which could effectively discriminate a true signal from noise. These AQN-originated axions can be observed as correlated events which could be recorded by synchronized stations in the global network. The correlations can be effectively studied if the detectors are positioned at distances shorter than a few hundred kilometers.

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I. INTRODUCTION

The Peccei-Quinn mechanism, accompanied by axions, remains the most compelling resolution of the strong *CP* problem, see original papers [1–7] and recent reviews [8–18]. The conventional idea for production of the dark-matter (DM) axions is either by the misalignment mechanism when the cosmological field $\theta(t)$ oscillates and emits cold axions before it settles at a minimum, or via the decay of topological objects, see recent reviews [8–18].

In addition to these well-established mechanisms, a fundamentally novel mechanism for axion production was studied in recent papers [19–22]. This mechanism is rooted in the so-called axion quark nugget (AQN) dark-matter model [23]. The AQN construction in many respects

is similar to the original quark-nugget model suggested by Witten [24], see [25] for a review. This type of DM is "cosmologically dark" not because of the weakness of the AQN interactions, but due to their small cross-section-tomass ratio, which scales down many observable consequences of an otherwise strongly interacting DM candidate.

There are two additional elements in the AQN model compared to the original proposal [24,25]. First, there is an additional stabilization factor for the nuggets provided by the axion domain walls which are copiously produced during the QCD transition which help to alleviate a number of problems with the original [24,25] nugget model.¹ Another feature of AQNs is that nuggets can be made of

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¹In particular, a first-order phase transition is not a required feature for the nuggets' formation as the axion domain wall (with internal QCD substructure) plays the role of the squeezer. Another problem with [24,25] is that nuggets likely evaporate on a Hubble timescale. For the AQN model this is not applicable because the vacuum-ground-state energies inside (the color-superconducting phase) and outside (the hadronic phase) the nugget are drastically different. Therefore, these two systems can coexist only in the presence of an external pressure, provided by the axion domain wall. This should be contrasted with the original model [24,25], which must be stable at zero external pressure.

matter as well as *antimatter* during the QCD transition. The direct consequence of this feature is that DM density, Ω_{DM} , and the baryonic matter density, $\Omega_{visible}$, will automatically assume the same order of magnitude $\Omega_{DM} \sim \Omega_{visible}$ without any fine tuning. This is because they have the same QCD origin and are both proportional to the same fundamental dimensional parameter Λ_{QCD} which ensures that the relation $\Omega_{DM} \sim \Omega_{visible}$ always holds irrespective of the parameters of the model such as the axion mass m_a or misalignment angle θ_0 .

The existence of both AQN species explains the observed asymmetry between matter and antimatter as a result of separation of the baryon charge and generation of the disparity between matter and antimatter nuggets as a result of strong CP violation during the QCD epoch. Both AQNs with matter and antimatter serve as dark matter in this framework. In particular, if the number of antinuggets is larger than the number of nuggets by a factor of 3/2 at the end of the formation, the ratio between visible and darkmatter components assumes its observed value $\Omega_{DM} \simeq$ $5\Omega_{visible}$, while the total baryon charge of the Universe (including the nuggets, antinuggets and the visible baryons) remains zero at all times. This should be contrasted with the conventional baryogenesis paradigm where extra baryons (1 part in 10^{10}) must be produced during the early stages of the evolution of the Universe to match the observations.

We refer the reader to the original papers [26-29]devoted to the specific questions related to the nugget formation, generation of the baryon asymmetry, and how the nuggets survive the "unfriendly" environment of the early Universe. Here we would like to make several generic comments relevant for the present studies. First, the AQN framework resolves two fundamental problems simultaneously: the nature of dark matter and the asymmetry between matter and antimatter. Second, the AQNs are composite objects consisting of axion field and quarks and gluons in the color-superconducting (CS) phase, squeezed by the axion domain wall (DW). This represents an absolutely stable system on cosmological timescales as it assumes the lowest-energy configuration for a given baryon charge. Third, while the model was originally invented to explain the observed relation $\Omega_{DM} \sim \Omega_{visible}$ as mentioned above, it may also explain a number of other (naively unrelated, but observed) phenomena, see below.

The AQNs may also offer a resolution to the so-called "primordial lithium puzzle" [30], the "solar corona mystery" [31,32], and may also explain the recent EDGES observation [33], which is in some tension with the standard cosmological model. Furthermore, it may resolve [34] the longstanding puzzle with the DAMA/LIBRA observation [35] of the annual modulation at 9.5 σ confidence level, which is in direct conflict with other DM experiments if interpreted in terms of WIMP-nuclei interaction. In the present studies we adopt the same set of physical parameters of the model which were used in explanation of the aforementioned phenomena.

The key parameter which essentially determines all the intensities for the effects mentioned above is the average baryon charge $\langle B \rangle$ of the AQNs. There is a number of constraints on this parameter which are reviewed below. One should also mention that the AQNs masses related to their baryon charge by $M_N \simeq m_p |B|$, where we ignore small differences between the energy per baryon charge in CS and hadronic confined phases. The resulting AQN are macroscopically large objects with a typical size of $R \simeq 10^{-5}$ cm and roughly nuclear density resulting in masses roughly 10 g. For the present work we adopt a typical nuclear density of order 10^{40} cm⁻³ such that a nugget with $|B| \simeq 10^{25}$ has a typical radius $R \simeq 10^{-5}$ cm.

The strongest direct detection limit is set by the IceCube Observatory's nondetection of a nonrelativistic magnetic monopole [36]. While the magnetic monopoles and the AQNs interact with material of the detector differently, in both cases the interaction leads to electromagnetic and hadronic cascades along the trajectory of AQN (or magnetic monopole) which must be observed by the detector if such an event occurs. A nonobservation of any such cascades puts the following limit on the flux of heavy nonrelativistic particles passing through the detector, see Appendix A in [21]:

$$\langle B \rangle > 3 \times 10^{24}$$
 [direct (non) detection constraint]. (1)

Similar limits are also obtained from the Antarctic Impulsive Transient Antenna [37]. In the same work the author also derives the constraint arising from a potential contribution of the AQN annihilation events to the Earth's energy budget requiring $|B| > 2.6 \times 10^{24}$ [37], which is consistent with (1). There is also a constraint on the flux of heavy dark matter with mass M < 55 g based on the nondetection of etching tracks in ancient mica [38]. It slightly touches the lower bound (1), but does not strongly constrain the entire window (3).

The authors of [39] use the Apollo data to constrain the abundance of quark nuggets in the region of 10 kg to one ton. It has been argued that the contribution of such heavy nuggets must be at least an order of magnitude less than would saturate the dark matter in the solar neighborhood [39]. Assuming that the AQNs do saturate the dark matter, the constraint [39] can be reinterpreted that at least 90% of the AQNs must have masses below 10 kg. This constraint can be approximately expressed in terms of the baryon charge:

$$\langle B \rangle \lesssim 10^{28}$$
 [Apollo constraint]. (2)

Therefore, indirect observational constraints (1) and (2) suggest that if the AQNs exist and saturate the dark-matter density today, the dominant portion of them must reside in the window:

$$3 \times 10^{24} \lesssim \langle B \rangle \lesssim 10^{28}$$
 [constraints from observations]. (3)

Completely different and independent observations also suggest that the galactic spectrum contains several excesses of diffuse emission the origin of which is not well established, and remains to be debated. The best-known example is the strong galactic 511 keV line. If the nuggets have a baryon number in the $\langle B \rangle \sim 10^{25}$ range they could offer a potential explanation for several of these diffuse components. It is a nontrivial consistency check that the required $\langle B \rangle$ to explain these excesses of the galactic diffuse emission belongs to the same mass range as stated above. For further details see the original works [40–45] with explicit computations of the galactic radiation excesses for various frequencies, including the observed excesses of the diffuse x and γ rays. In all these cases the intensity of the photon emission is expressed in terms of a single parameter $\langle B \rangle$ such that all relative intensities are unambiguously fixed because they are determined by the Standard Model physics.

Yet another AQN-related effect might be intimately linked to the so-called "solar corona heating mystery". The renowned (since 1939) puzzle is that the corona has a temperature $T \simeq 10^6$ K which is 100 times hotter than the surface temperature of the Sun, and conventional astrophysical sources fail to explain the extreme UV and soft x-ray radiation from the corona 2000 km above the photosphere. Our comment here is that this puzzle might find its natural resolution with the same baryon charge $\langle B \rangle$ from window (3) which was constrained from drastically different systems as reviewed above.

We emphasize that the AQN model within window (3) is consistent with all presently available cosmological, astrophysical, satellite and ground-based constraints. This model is very rigid and predictive as there is not much flexibility nor freedom to modify any estimates in different systems as reviewed in this Introduction. In particular, the AQN-induced flux (4) which plays a key role in the present studies cannot change its numerical value for more than a factor of 2, depending on the size distribution within the window (3). The same comment also applies to all other observables such as modulation parameters $\kappa_{(a)}$ and $\kappa_{(d)}$ and amplification factor A(t) to be discussed in the present work.

II. AQN-INDUCED AXION FLUX ON EARTH

Relevant for the present studies consequence of the construction is that the axion portion of the energy contributes to about 1/3 of the total AQN's mass in the form of the axion DW surrounding the nugget's core. This system represents a time-independent configuration which kinematically cannot convert its axion related energy (generated at earlier times during the QCD formation

epoch) to freely propagating time-dependent axions. However, any time-dependent perturbation, such as passage of the AQN through the Earth's interior, inevitably results [20] in emission of real propagating relativistic axions with typical velocities $\langle v_a \rangle \sim 0.6c$ (*c* is the speed of light), liberating the initially stored axion energy. The energy flux of the AQN-induced axions on the Earth surface was computed in [22] using full-scale Monte Carlo simulations accounting for all possible AQN trajectories traversing the Earth:

$$\langle E_a \rangle \Phi_a^{\text{AQN}} \simeq 10^{14} \left[\frac{\text{eV}}{\text{cm}^2 \,\text{s}} \right], \qquad \langle E_a \rangle \simeq 1.3 m_a, \quad (4)$$

where E_a is the axion energy and Φ_a^{AQN} is the AQN flux. The rate (4) includes all types of AQN trajectories inside the Earth's interior: trajectories where AONs hit the surface with incident angles close to 0° (in which case the AQN crosses the Earth core and exits at the opposite side of the Earth) as well as trajectories where AQNs just touch the surface with incident angles close to 90°, in which case AQNs leave without much annihilation in the deep underground. The result of the summation over all these trajectories can be expressed in terms of the average mass (energy) loss $\langle \Delta m_{\rm AON} \rangle$ per AQN. The same information can also be expressed in terms of the average baryon-charge loss per nugget $\langle \Delta B \rangle$ as these two are directly related: $\langle \Delta m_{AON} \rangle \approx$ $m_p \langle \Delta B \rangle$, see [22] for details. Let us repeat again: the expression (4) represents the average flux accounting for different trajectories and AQN size distributions averaged over times much greater than a year.

For the purposes of the present work, it is important to consider the time-dependent modulation and amplifications effects which can be represented as follows:

$$\langle E_a \rangle \Phi_a^{AQN}(t) \simeq 10^{14} A(t) \left[\frac{\text{eV}}{\text{cm}^2 \text{ s}} \right], \qquad \langle E_a \rangle \simeq 1.3 m_a, \quad (5)$$

where A(t) is the modulation/amplification time-dependent factor. The factor A for the daily and annual modulations is discussed in Sec. IV below and is given by Eqs. (9) and (10), correspondingly. In both cases, the factor A does not deviate from the average value by more than 10%. However, sometimes the factor A can be numerically large for rare burstlike events, the so-called "local flashes" in the terminology of Ref. [22]. These short bursts (with a duration time of the order of a second for $A \simeq 10^2$ [22]) result from the interaction of the AQN hitting the Earth in a close vicinity of a detector. Another feature of the AQNinduced axions distinguishing them from conventional galactic axions is that the typical velocities of the AQNinduced axions are relativistic with $\langle v_a \rangle \sim 0.6c$, in contrast to the galactic axions with $\langle v_a \rangle \sim 10^{-3}c$.

It is instructive to compare the AQN-induced flux (5) with the flux computed from assumption that the galactic

axions saturate the DM density $\rho_{\rm DM} \sim 0.3 \ {\rm GeV} \cdot {\rm cm}^{-3}$ today. This assumption cannot be satisfied in the entire window of $10^{-6} \text{ eV} \lesssim m_a \lesssim 10^{-3} \text{ eV}$ as the conventional contribution is highly sensitive to m_a as $\rho_{\rm DM} \sim m_a^{-7/6}$ and may saturate the DM density at $m_a \lesssim 10^{-5}$ eV, depending on additional assumptions on production mechanism. It should be contrasted with the AQN framework where $\Omega_{\rm DM} \sim \Omega_{\rm visible}$ always holds irrespective of the parameters of the model such as the axion mass m_a or misalignment angle θ_0 . This, in particular, implies that for $m_a \gtrsim 10^{-4}$ eV the conventional galactic axions contribute very little to Ω_{DM} while the AQNs are the dominant contributor to the DM density. Nevertheless, in what follows we need a point of normalization with conventional picture and conventional estimates. With this purpose in mind, here and in what follows we compare the AQN-induced flux (5) with A = 1 with conventional galactic axion flux computed with the assumption formulated above. In this case the numerical value for the flux (5) is approximately 2 orders of magnitude below the value computed for the conventional galactic axions.

The cavity-type experiments such as ADMX are to date the only ones to probe the parameter space of the conventional QCD axions with $\langle v_a \rangle \sim 10^{-3}c$, while we are interested in detection of the relativistic axions with $\langle v_a \rangle \sim 0.6c$. This requires a different type of instrument and drastically different search strategies. We argue below that the daily and annual modulations (9) and (10) as well as the short burstlike amplifications with $A \simeq 10^2$ might be the key elements in formulating a novel detection strategy to observe these effects, which is precisely the topic of the present work.

Let us reiterate that the goal of the present work is not to design a specific instrument which would be capable of detecting the axions being emitted by AQNs and would be the sensing element of the synchronized stations assembled in a global network. For example, the presently operating Global Network of Optical Magnetometers for Exotic physics searches (GNOME) [46,47] is sensitive to frequencies of up the kHz range, while the preferred value for the axion mass for the AQN dark matter is $m_a \simeq 10^{-4}$ eV corresponding to 24 GHz.

The present work is devoted to a completely different question. We wish to develop a strategy which would provide a future framework to study the axions emitted by AQNs. While there are no presently available instruments operating in the interesting window: $10^{-6} \text{ eV} \leq m_a \leq 10^{-3} \text{ eV}$ we do not see any fundamental obstacles which would prevent designing and building the required instruments in future. In what follows we *assume* that the axion-search detectors sensitive to 24 GHz can be designed and built, for example using single-photon detectors for the GHz range [48,49].

There are several key ingredients in our proposal. First of all, as already mentioned, the secondary axions emitted by AQNs are relativistic with $\langle v_a \rangle \sim 0.6c$, in contrast to conventional galactic axions with $\langle v_a \rangle \sim 10^{-3}c$. This has an important implication for the proposed search because the axion is broadband with $\Delta \nu / \nu \sim 1$, in contrast with conventional narrow-line galactic axions with $\Delta \nu / \nu \lesssim$ 10^{-6} , searched for with the cavity-type detectors. Second, we *assume* that a GNOME-like network sensitive to the required frequencies and spectral features can be built in the future. The strategy for detecting broadband axions is formulated in Sec. IV.

III. BASIC IDEA, NOTATIONS AND DEFINITIONS

The starting point of our analysis is the Hamiltonian describing the coupling of the spin operator (for electrons or nucleons) with the gradient of the axion field. The same coupling was discussed for the CASPEr experiment [50–52] in the case of nucleons and for QUAX [53] in the case of electrons. This coupling is analogous to the Zeeman effect (the basis of magnetometry [54]) with the gradient of the pseudoscalar $\nabla a(\mathbf{r}, t)$ being a pseudovector analogous to magnetic field:

$$H_{\rm spin} \simeq g_{\rm a} \boldsymbol{\sigma} \cdot \boldsymbol{\nabla} a(\mathbf{r}, t), \qquad g_{\rm a} \propto f_a^{-1}.$$
 (6)

Here, the coupling constant g_a assumes the value $g_a \equiv g_{aee}$ for electrons or $g_a \equiv g_{aNN}$ for nucleons in notations of Ref. [50] and f_a is the so-called axion decay constant. The coupling (6) describes the interaction of the spins of a material with an oscillating pseudomagnetic field $\mathbf{B}_a \propto$ $\nabla a(\mathbf{r}, t)$ generated by the gradient of the propagating axion $a(\mathbf{r}, t) = a_0 \exp(-iE_a t + i\mathbf{p}_a \cdot \mathbf{r})$, where the normalization constant a_0 can be expressed in terms of the AQN-induced flux (5) computed on the Earth's surface, see below. The maximum magnitude of the perturbation due to the coupling (6) can be estimated as

$$\Delta E \simeq g_{\mathrm{a}} m_a a_0 (\boldsymbol{\sigma} \cdot \mathbf{v}_a) \sim 10^{-8} \sqrt{A} \, \mathrm{s}^{-1} \left(\frac{g_{\mathrm{a}}}{10^{-9} \, \mathrm{GeV}^{-1}} \right), \quad (7)$$

where we estimated normalization factor a_0 using AQN-induced flux (5). In conventional energy units, $\Delta E \simeq 6 \times 10^{-24} \sqrt{A}$ eV. The strength of the interaction (6) is normally expressed in terms of the pseudomagnetic field B_a which for nucleon and electron systems assumes the following values:

$$B_a^N \equiv \frac{\Delta E}{\mu_N} \simeq 2 \times 10^{-16} \sqrt{A} \left(\frac{g_{aNN}}{10^{-9} \text{ GeV}^{-1}} \right) \text{ T},$$
$$B_a^e \equiv \frac{\Delta E}{\mu_e} \simeq 10^{-19} \sqrt{A} \left(\frac{g_{aee}}{10^{-9} \text{ GeV}^{-1}} \right) \text{ T}.$$
(8)

It is instructive to compare our estimate (7) for the AQNinduced axions with similar estimate for the conventional galactic axions saturating the galactic-DM density. As one can see from (7) the numerical value for ΔE [and correspondingly for B_a given by (8)] is approximately 3 times larger for the AQN-induced axions (in comparison with corresponding estimate of Ref. [50] for galactic axions) even without amplification due to two effects working in opposite direction. The AQN-induced axion flux is 2 orders of magnitude smaller than the galactic axion flux. As typical axion galactic velocities are 10^{-3} c, while the AQN-induced axions are relativistic with $\langle v_a \rangle \simeq 0.6c$, the corresponding AQN-induced axion density is 5 orders of magnitude smaller than the galactic axion density. As ΔE depends on the axion density as $\sqrt{n_a}$ this gives a suppression factor $\sqrt{10^{-5}} \sim 3 \times 10^{-3}$ in comparison with estimates for the galactic axions. However, the velocities of the AQN-induced axions are relativistic with $v_a \sim c$ which provides the enhancement factor 10^3 as velocity linearly enters (7), which explains why ΔE given by (7) is 3 times of the corresponding estimate [50]. The amplification factor A makes this enhancement even stronger.

A few comments are in order. First of all, the observable (7) as well as the pseudomagnetic field (8) depend on the amplitude of the axion field a_0 , not on its intensity $n_a \sim |a_0|^2$. This implies that the signal will show the oscillating features with the frequency determined by m_a .

Second, the axion field $a(\mathbf{r}, t)$ can be treated as a classical field because the number of the AQN-induced axions (5) accommodated by a single de Broglie volume is large in spite of the fact that the de Broglie wavelength λ for relativistic AQN-induced axions is much shorter than for galactic axions:

$$n_a^{\rm AQN} \lambda^3 \sim \frac{\Phi_a^{\rm AQN}}{v_a} \cdot \left(\frac{\hbar}{m_a v_a}\right)^3 \sim 10^6 \left(\frac{10^{-4}~{\rm eV}}{m_a}\right)^4 \gg 1. \label{eq:alpha_a$$

We emphasize that the wavelength λ of the emitted axions is short, measured in centimeters, while the distance ΔR (relevant for detecting a correlation) between the network stations is measured in hundred kilometers. To reiterate: we are suggesting to study the *correlation* between the transient signals which could be detected by different network stations. It should be contrasted with a proposal to study the *coherent* signal when the amplitude $a_{\rm ALP}$ of axion light particles (ALPs) with very small mass $m_{\rm ALP} \simeq$ $[10^{-12} - 10^{-14}]$ eV has a coherence length scale $\lambda_{\rm ALP} \equiv$ $m_{\rm ALP}^{-1} \simeq [10^2 - 10^4]$ kilometers. The study of these ALPs is not a topic of the present work as the axions being discussed here are exclusively conventional QCD axions with a mass range of $(10^{-6} \text{ eV} \leq m_a \leq 10^{-3} \text{ eV})$ with short wavelength measured in centimeters.

The final and most important for this work comment is as follows. If there is a global network (GN) of axion-search detectors, there will be a correlated signal which can be detected with several synchronized GN stations due to the local flash from *one and the same* AQN traversing in close

vicinity of these stations. The corresponding correlations discussed in Sec. V play a key role in the formulation of our novel detection strategy because these correlations can unambiguously remove "fake" signals from the AQN-related events.

The presence of the daily and annual modulations [22] of the axion flux on the Earth's surface along with the large average velocities $\langle v_a \rangle \simeq 0.6c$ of the emitted axions by AQNs dramatically changes entire strategy of axion searches, the topic discussed in Sec. IV. After we explain the broadband detection strategy, we turn to Sec. V where we present the arguments suggesting that the most efficient configuration for our purposes is the presence of a subset of several GN stations which are positioned in close vicinity of each other with $\Delta R \sim 10^2$ km or less.

IV. DETECTION OF BROADBAND AXIONS

As the axions emitted by AQN have relativistic velocities with a large dispersion [20], the corresponding signal is expected to be spectrally broad. It should be contrasted with the conventional galactic axions searched for, for instance, in experiments based on tuning of the resonant frequency of a cavity to match the microwave photons produced by the axions in the presence of a strong magnetic field. In the latter, one assumes that the galactic-DM axion velocities and their dispersion are small $\delta v/c \sim \langle v_a \rangle/c \sim 10^{-3}$. The cavity-type experiments such as ADMX, ADMX-HF [55], HAYSTAC [56], and the experiments at CAPP reviewed in [57] are to date the only experiments to probe the particularly interesting region of parameter space corresponding to standard QCD axion models with $10^{-6} \text{ eV} \lesssim$ $m_a \lesssim 10^{-3}$ eV. The galactic axions generate a narrow microwave resonance with $\Delta \nu / \nu \sim (\delta v / c)^2 \sim 10^{-6}$ such that the cavity-type experiments are designed to search for such a narrow line.

Since the photons produced by the axions from AQNs are broadband, with $\Delta\nu/\nu \sim 1$, one needs to use a correspondingly broadband detector and the conventional cavity detectors which are designed to search for narrow lines should be replaced with broadband instruments such as ABRACADABRA [58], LC Circuit [59], see also [60], which detect axion-induced magnetic fields and can be operated in a broadband mode. The search strategy has to be correspondingly adapted for AQN-induced axions.

An important specific feature of the spectrum of the AQN-induced axions that can be used for discriminating against spurious signals is that it has a peak around $v_a \ge 0.6c$ with a sharp cutoff at higher velocities around $v_a \ge 0.8c$ and a strong suppression at low velocities $v_a \le 0.2c$, see Fig. 1(a) in [20]. These features correspond to the axion frequency band as follows: $m_a \le \omega_a \le 1.8m_a$.

While there are presently no broadband experiments operating in the interesting window: $10^{-6} \text{ eV} \lesssim m_a \lesssim 10^{-3} \text{ eV}$ we do not see any fundamental obstacles which

would prevent one from designing and building a required instrument in the future. In what follows we *assume* that detectors sensitive to broadband axions can be designed and built.

With this assumption in mind, a strategy to probe the QCD axion can be formulated as follows. It has been known since [61] that the DM flux shows annual modulation due to the differences in relative orientations of the DM wind and the direction of the Earth's motion around the Sun. The corresponding effect for AQN-induced axions was computed in [22]. The daily modulation which is a feature for the AQN model was also computed in the same paper.² The broadband strategy is to separate a large frequency band into a number of smaller frequency bins with the width $\Delta \nu \sim \nu$ according to the axion dispersion relation as discussed above.

The time-dependent signal in each frequency bin Δv_i has to be fitted according to the expected modulation pattern, daily, or annual. For example, the annual modulation should be fitted according to the following formula:

$$A_{(a)}(t) \equiv [1 + \kappa_{(a)} \cos \Omega_a(t - t_0)],$$
 (9)

where $\Omega_a = 2\pi \text{ yr}^{-1} \approx 2\pi \cdot 32 \text{ nHz}$ is the angular frequency of the annual modulation and label "a" in Ω_a stands for annual. The $\Omega_a t_0$ is the phase shift corresponding to the maximum on June 1 and minimum on December 1 for the standard galactic-DM distribution, see [61,63].

The same procedure should be repeated for all frequency bins "*i*". Let us assume that the modulation has been recorded in a specific bin \overline{i} . The modulation coefficient $\kappa_{(a)}^{\overline{i}}$ for a specific \overline{i} could be as large as 10%. The parameters Ω_a , $\kappa_{(a)}^{\overline{i}}$ and t_0 are to be extracted from the fitting analysis and compared with theoretical predictions.

A test that it is not a spurious signal is a relatively simple procedure: one should check that no modulations appear in all other bins (except to possible neighbours to \overline{i} bin). A more powerful test to exclude spurious signals is described in Sec. V. One should comment here that precisely this strategy has been used by the DAMA/ LIBRA Collaboration which has been observing the annual modulation for 20 years.³ It is considered as a strong evidence of the dark-matter origin of the modulation for recoil energy in bins $E_{\text{recoil}} \simeq (1-6)$ keV, while the modulation vanishes outside this range, see the latest results in [35] and an explanation within AQN framework in [34].

A similar procedure can be applied for the daily modulations and can be described as follows [22]:

$$A_{\rm (d)}(t) \equiv [1 + \kappa_{\rm (d)} \cos(\Omega_d t - \phi_0)], \tag{10}$$

where $\Omega_d = 2\pi \text{ day}^{-1} \approx 2\pi \cdot 11.6 \ \mu\text{Hz}$ is the angular frequency of the daily modulation, while ϕ_0 is the phase shift similar to $\Omega_a t_0$ in (9). It can be assumed to be constant on the scale of days. However, it actually slowly changes with time due to the variation of the direction of DM wind with respect to the Earth.

In summary, the axions characterized by broad distribution with $m_a \leq \omega_a \leq 1.8 m_a$ as discussed above will produce nonzero modulation coefficients $\kappa_{(a)}$ and $\kappa_{(d)}$ in one frequency bin \bar{i} (or perhaps two neighbouring bins). It is a nontrivial consistency test that the modulation occurs in one and the same frequency bin \bar{i} for two drastically different analyses: the fittings for (9) and (10), correspondingly. A further consistency check is see whether the modulation is observed in other frequency bins. A more sophisticated, but at the same time, more powerful test is described below. The next section should be considered as a powerful tool which discriminates the true signal contributing to (9) and (10) from a spurious noise background.

V. TIME DELAYS AND DURATIONS

In this section we describe a test which would unambiguously suggest if the observed modulations is due to the noise and/or systematic errors, or it represents a truly DM signal. The test is based on analysis of local flashes which are burstlike events.

The mechanism of a local flash is the following: the flux of AQN-induced axions gains a large amplification factor A in an instant when a moving AQN is sufficiently close to the detector, namely [22]

$$A(d) \simeq \left(\frac{0.2R_{\oplus}}{d}\right)^2 = \left(\frac{1.27 \times 10^3 \text{ km}}{d}\right)^2, \quad (11)$$

where *d* is the shortest distance from the AQN to the detector, while R_{\oplus} is the Earth's radius. The time duration of the local flash is by definition:

$$\Delta \tau \equiv \frac{d}{v_{\rm AQN}} \simeq 4.25 A^{-1/2} \ s \left(\frac{300 \ \rm km \ s^{-1}}{v_{\rm AQN}}\right).$$
(12)

Therefore, for amplification $A \gtrsim 10^2$ the required distance from the detector to AQN is $d \lesssim 10^2$ km. Consequently, for two nearby GN stations located 10^2 km (or less) apart there is a large chance to detect a correlated signal amplified by $A \sim 10^2$ from *one and the same* AQN.

²Daily modulations are also present in galactic-axion "wind" experiments such as those of Refs. [51,52,62].

³DAMA/LIBRA Collaboration claims [35] the observation for an annual modulation in the (1–6) keV energy range at 9.5 σ C.L. The C.L. is even higher (12.9 σ) for (2–6) keV energy range when DAMA/NaI and DL-phase1 are combined with DL-phase2 results. The measured period (0.999 ± 0.001) year and phase corresponding to $t_0 = 145 \pm 5$ days corresponding to the maximum of the signal around June 1.



FIG. 1. The two stations located at **R** and **R'** on the surface of Earth respectively. Each station has a distance **d** (and **d'**) from the AQN trajectory $\mathbf{r}(t) = \mathbf{v}_{AON}t + \mathbf{r}_{0}$.

To assess the time delay of a correlated signal, consider two stations located at \mathbf{R} and \mathbf{R}' on the surface of the Earth respectively, see Fig. 1. Now the first station detects a local flash when an AQN passes nearby. The trajectory of the AQN is linear [21,22] and can be described as

$$\mathbf{r}(t) = \mathbf{v}_{\mathrm{AQN}}t + \mathbf{r}_0,\tag{13}$$

where \mathbf{v}_{AQN} can be approximated as a constant within the short time of correlated local flash ~1 s, \mathbf{r}_0 is the intercept at the plane spanned by \mathbf{R} and \mathbf{R}' . The distances from the stations to the AQN trajectory are denoted as \mathbf{d} and \mathbf{d}' respectively.

By imposing the orthogonal condition of **d** (and **d**') to \mathbf{v}_{AQN} , we solve for the moment t_* (and t'_*) when a peak signal of the local flash is detected in each station:

$$0 = \mathbf{d} \cdot \mathbf{v}_{AQN} = [\mathbf{r}(t_*) - \mathbf{R}] \cdot \mathbf{v}_{AQN},$$

$$0 = \mathbf{d}' \cdot \mathbf{v}_{AQN} = [\mathbf{r}(t_*') - \mathbf{R}'] \cdot \mathbf{v}_{AQN}.$$
 (14)

The solutions give the time delay between two stations

$$\Delta t \equiv |t'_* - t_*| = \frac{\Delta R}{v_{\rm AQN}} \delta, \qquad \delta \equiv |\Delta \hat{\mathbf{R}} \cdot \hat{\mathbf{v}}|, \quad (15)$$

where $\Delta \mathbf{R} = \mathbf{R}' - \mathbf{R}$ is the separation distance between the two stations, as presented in Fig. 1. In practice, $\delta \in (-1, 1)$ will be a free tuning parameter because the incident direction $\hat{\mathbf{v}}$ of the AQN trajectory is unknown. Assuming $\Delta R \sim 10^2$ km and $v_{AQN} \sim 300$ km s⁻¹, we expect Δt is no greater than ~1 s. For smaller ΔR the time delay Δt decreases correspondingly. In particular, two detectors localized in the same building must show the synchronized pulses with zero time delay.

One important relation in what follows can be derived from Eqs. (14) and (15):

$$\mathbf{d}' = \mathbf{d} + \mathbf{v}_{\mathrm{AQN}} \Delta t - \Delta \mathbf{R}, \qquad (16a)$$

$$d' \equiv |\mathbf{d}'| \le d + \Delta R(1+\delta). \tag{16b}$$

Here Eq. (16a) can be also understood directly from the vector configuration in Fig. 1, and Eq. (16b) is based on the inequality $|\mathbf{a} + \mathbf{b}| \le |\mathbf{a}| + |\mathbf{b}|$.

To ensure a correlated signal distinguishable from background noise, amplifications received in both stations need to be sufficiently large. Assuming a local flash is detected in the first station with amplification A(d), the constraint to the second station is clearly $d' \leq d$ or, according to Eqs. (11) and (16b):

$$\Delta R \lesssim \frac{d}{1+\delta} \simeq 85 \, \mathrm{km} \left(\frac{1.5}{1+\delta}\right) \left(\frac{10^2}{A}\right)^{1/2}, \qquad (17)$$

where $A \equiv A(d)$ for brevity of notation, and $\delta \simeq 0.5$ is estimated by assuming a uniform distribution of AQN flux. Hence, to observe a correlated signal from two nearby stations with amplification $A \gtrsim 10^2$, the separation distance should be 85 km or less.

Lastly, we estimate the event rate of a correlated signal for a given amplification A. The event rate for a single station has been estimated in Ref. [22]. The correlated event rate (CER) is the single event rate multiplied by an additional suppression factor (as presented in square bracket below):

CER ~ 0.29
$$A^{-3/2} \min^{-1} \left[\frac{\frac{1}{2} \pi d^2}{2 \pi \Delta R^2} \right]$$

 $\gtrsim 0.23 \ \text{day}^{-1} \left(\frac{1+\delta}{1.5} \right)^2 \left(\frac{10^2}{A} \right)^{3/2}.$ (18)

Comparing to the single event rate calculated in Ref. [22], the CER is suppressed by roughly one half for two nearby stations subject to constraint (17).

TABLE I. Estimations of local flashes for different *A* as defined by (5). The corresponding event rate and the time duration τ depend on factor *A*, which itself is determined by the shortest distance from the nugget's trajectory to the detector. The table is adopted from [22].

A	τ (Time span)	Event rate
1	10 s	0.3 min^{-1}
10	3 s	$0.5 hr^{-1}$
10 ²	1 s	$0.4 day^{-1}$
10 ³	0.3 s	$5 yr^{-1}$
104	0.1 s	0.2 yr^{-1}

We conclude this section with the following remark. The AQN model unambiguously predicts the intensity of the flux (5) with well-defined amplification parameters *A* listed in Table I. As mentioned above, there is no specific instrument at this time that is sensitive to the relevant frequency band and which could effectively use the broadband detection strategy as described in this paper. Therefore, we cannot estimate the relevant sensitivity of an instrument at this point. However, such estimations can be performed in the future as the basic physics parameters such as the flux (5) and the modulation parameters (9) and (10) are unambiguously fixed in this framework, and there is no room nor flexibility to modify them.

VI. CONCLUSION

The presence of the daily (10) and annual (9) modulations of the axion flux on the Earth's surface along with the large average velocities of the axions emitted by AQNs dictates the search strategy for such axions. We suggest broadband detection to attack this problem as described in Sec. IV. We also suggest several tests to discriminate the DM signal from spurious signal. A sophisticated and powerful test is described in Sec. V. It requires a global network of sensors with individual stations sensitive to axions with the frequency determined by m_a . It also requires the network to be configured in such a way that it contains two or more nearby stations with a distance of ~ 100 km or less between them. We argue that such stations should observe correlated amplified signals with an event rate of ~ 0.2 /day and with a time delay (15) on the order of a second or less (depending on the actual distance separation between stations). The presence of such correlation may be a decisive tool in discriminating the signal from the noise background.

The estimates are based on the AQN model. Why should one take this model seriously? A simple answer is as follows. Originally, this model was invented to explain the observed relation $\Omega_{\rm DM} \sim \Omega_{\rm visible}$ where the "baryogenesis" framework is replaced with a "charge-separation" paradigm, as reviewed in the Introduction. This model is shown

to be consistent with all available cosmological, astrophysical, satellite and ground-based constraints, where AQNs could leave a detectable electromagnetic signature as reviewed in the Introduction, with one and the *same set* of parameters. The AQN-induced flux (5) is unambiguously predicted using the same set of physical parameters. The use of the modulations (9) and (10) and time delays (15) discussed in this work may reveal the traces of the AQN *directly*, in contrast with *indirect* observations mentioned in the Introduction.

Finally, we note that in this work we considered detecting the AQNs via the axions that they emit interacting with the Earth. Considering that AQNs also produce considerable amount of energy from the annihilation with the Earth's baryons, it will likely be easier to detect the AQN via the associated energy deposition, for instance, acoustic, signatures.⁴ An important point is that the network and modulation approaches discussed above will be helpful in this case as well. We leave this topic for future studies.

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⁴Electromagnetic signatures in the form of x rays or γ rays will be absorbed in the atmosphere and underground, which makes it hard to detect them. It would be also difficult to discriminate the AQN-induced photons from the background of radiation on the Earth's surface.

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