Axion Quark Nuggets and how a Global Network can discover them

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We advocate the idea that a global network of the synchronized axion detectors can greatly enhance the discovery potential of the QCD axions. Our computations are based on the so-called Axion Quark Nugget (AQN) dark matter model which was originally invented to explain the similarity of the dark and visible cosmological matter densities ΩDM ≈ Ωvisible. In our framework the conventional population of the galactic axions will be always accompanied by the axions emitted by AQNs. These AQN-originated axions with mass 10−6 eV ≲ ma ≲ 10−3 eV can be observed as correlated events with synchronized detectors assembled in a global network. The correlations can be effectively observed if the individual axion detectors are positioned at distances shorter than a few hundred kilometres.

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 θ(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 has been 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 model is “cosmologically dark”, not because of the weakness of their interactions, but due to their small cross-section-to-mass 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 old 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 model1. Another feature of AQNs is that nuggets can be made of matter as well as antimatter during the QCD transition. The direct consequence of this feature is that DM density, ΩDM, and the baryonic matter density, Ωvisible, will automatically assume the same order of magnitude ΩDM ≈ Ωvisible without any fine tunings. This is because they have the same QCD origin and are both proportional to the same fundamental dimensional parameter ΛQCD which ensures that the relation ΩDM ≈ Ωvisible always holds irrespectively to the parameters of the model such as the axion mass ma or initial misalignment angle θ0.

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 made of matter and antimatter serve as dark matter in this framework. It should be contrasted with the conventional baryogenesis paradigm when extra baryons (1 part in 1010) 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’s formation, generation of the baryon asymmetry, and survival pattern of the nuggets. Here we would like to make

1 In particular, a first-order phase transition is not required feature for the nugget’s formation as the axion domain wall (with internal QCD substructure) plays the role of the squeezer. Another problem with [24, 25] is that nuggets will likely evaporate on a Hubble time-scale. For the AQN model this argument is not applicable because the vacuum-ground-state energies inside (color-superconducting phase) and outside (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.
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. Secondly, the AQNs are composite objects made out of axion field and quarks and gluons in the color superconducting (CS) phase, squeezed by the axion domain wall (DW). It represents an absolutely stable system on cosmological time scales as it assumes the lowest energy configuration for a given baryon charge. Third, while the model was originally invented to explain the observed relation $\Omega_{DM} \sim \Omega_{\text{visible}}$, as mentioned above, it may also explain a number of other (naively unrelated, but observed) phenomena, such as the excess of diffuse galactic emission in different frequency bands, including the 511 keV line.

The AQNs may also offer a resolution to the so-called “Primordial Lithium Puzzle” [30], the “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] a longstanding puzzle with Dama-Libra observation of the annual modulation at 9.5$\sigma$ confidence level, which is in direct conflict with all other DM experiments, if interpreted in terms of WIMP-nuclei interaction. We emphasize that the AQN model is consistent with all presently available cosmological, astrophysical, satellite and ground-based constraints. In the present studies we adopt the same set of physical parameters of the model which were used in explanation of the aforementioned phenomena.

Our final comment relevant for the present work goes as follows: 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 static 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 in the emission of real propagating relativistic axions with typical velocities $\langle v_a \rangle \sim 0.6c$, liberating the initially stored axion energy. In fact, the energy flux of the AQN-induced axions on the Earth surface has been computed in [22] using full scale Monte Carlo simulations accounting for all possible AQN trajectories traversing the earth:

$$\langle E_a \rangle \Phi_a^{\text{AQN}} \sim 10^{14} A \frac{\text{eV}}{\text{cm}^2 \text{s}}, \quad \langle E_a \rangle \simeq 1.3 m_a,$$

where $A$ is the amplification factor which could be numerically very large for short spark-like amplifications (the so-called “local flashes” in the terminology of Ref[22]). We emphasize that these “local flashes” are time bursts (with a duration order of a second for $A \sim 10^2$ [22]) resulting from interaction of the AQN hitting the Earth in a close vicinity of a detector. In the case of $A \simeq 1$ the flux (1) is, on average, approximately two orders of magnitude smaller than the conventional galactic axion flux. The possible observation of these AQN-induced propagating axions (1) using a global network such as GNOME (Global Network of Optical Magnetometers to search for Exotic physics) [35, 36] when the amplification factor is large $A \geq 10^2$ is the topic of the present work.

We do not discuss in present work any specific requirements related to the frequency characteristics of the detectors. The corresponding features are entirely determined by the properties of the synchronized stations assembled in a global network. For example, the presently operating GNOME [35, 36] is sensitive to the frequencies in the kHz band or lower, while our preferred value for the axion mass $m_a \simeq 10^{-4}\text{eV}$ corresponds to 24 GHz. The key ingredient of the proposal is the presence of a network, similar to GNOME. Therefore, we assume that the updated GNOME or a new GNOME-like network sensitive to the required frequencies can be built in future.

The axion production mechanism in the AQN framework has been developed in [19–21]. Therefore, to avoid any repetition of the background material we refer to that papers regarding the computations of the spectrum and intensity. We refer to [22] devoted to specific questions related to the time modulations and amplifications which always accompany the passage of the AQNs through the Earth. This part of the analysis represents the key element for the present proposal to observe these “local flashes” using a global network such as GNOME when amplification factor $A \sim (10^2 - 10^4)$ is large.

Basic Idea, notations and definitions. The starting point of our analysis is the Hamiltonian describing the coupling of the spin operator (electrons or nucleons) with the gradient of the axion field. The same coupling has been discussed for CASPEr proposal [37] in the case of nucleons and for QUAX proposal [38] in case of electrons. This interaction represents the basic coupling for the field of optical magnetometry [39]:

$$H_{\text{spin}} \simeq g_a \sigma \cdot \nabla a(r,t), \quad g_a \propto f_a^{-1}. \quad (2)$$

In formula (2) we use, for generality, a single parameter $g_a$ which may assume the value $g_a \equiv g_{ae}$ for electrons or $g_a \equiv g_{aNN}$ for nucleons in notations of Ref.[40]. The coupling (2) describes the interaction of the spins of a material with an oscillating “pseudo-magnetic” field $B_a \propto \nabla a(r,t)$ generated by the gradient of the propagating axion $a(r,t) = a_0 \exp(-i E_a t + ip_a \cdot r)$, where the normalization constant $a_0$ can be expressed in terms of the AQN-induced flux (1) computed on the Earth’s surface, see below. The maximum magnitude of the perturbation due to the coupling (2) can be estimated as

$$\Delta E \simeq g_a m_a a_0 (\sigma \cdot v_a) \sim 10^{-8} \sqrt{A} \text{s}^{-1} \left( \frac{g_a}{10^{-9} \text{ GeV}^{-1}} \right). \quad (3)$$
where we estimated normalization factor $a_0$ using AQN-induced flux (1). In conventional energy units $\Delta E \approx 6 \cdot 10^{-24} \sqrt{A} \text{ eV}$. The strength of the interaction (2) is normally expressed in terms of the “pseudo-magnetic” field $B_\alpha$ which for nucleon and electron systems assume the following values

$$B_\alpha^N \equiv \frac{\Delta E}{\mu_N} \approx 2 \cdot 10^{-16} \sqrt{A} \left( \frac{g_{\alpha NN}}{10^{-9} \text{ GeV}^{-1}} \right) \text{T},$$

$$B_\alpha^e \equiv \frac{\Delta E}{\mu_e} \approx 10^{-19} \sqrt{A} \left( \frac{g_{\alpha ee}}{10^{-9} \text{ GeV}^{-1}} \right) \text{T}. \quad (4)$$

It is instructive to compare our estimate (3) for the AQN-induced axions with similar estimate for the conventional galactic axions. As one can see from (3) the numerical value for $\Delta E$ (and correspondingly for $B_\alpha$ given by (4)) is approximately 3 times larger for the AQN-induced axions (in comparison with corresponding estimate of Ref. [40] for galactic axions) even without amplification due to two effects working in opposite direction. The AQN-induced axion flux is two 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 $v_a \simeq 0.6c$, the corresponding AQN-induced axion density is 5 orders of magnitude smaller than the galactic axion density. As $\Delta E$ depends on the axion density as $\sqrt{n_a}$ this gives a suppression factor $\sqrt{10^{-5}} \approx 3 \cdot 10^{-3}$ 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 (3), which explains why $\Delta E$ given by (3) is three times of the corresponding estimate [40]. The amplification factor $A$ makes this enhancement even stronger.

A few comments are in order. First of all, the observable (3) as well as “pseudo-magnetic” field (4) depend on amplitude of the axion field $a_0$, not on its intensity $n_a \sim |a|^2$. This implies that the signal will show the oscillating features with the frequency determined by $m_a$.

Secondly, the axion field $a(r, t)$ can be treated as a classical field because the number of the AQN-induced axions (1) accommodated by a single de-Broglie volume is very large in spite of the fact that the de-Broglie wavelength $\lambda$ for relativistic AQN-induced axions is much shorter than for galactic axions,

$$n_a^{\text{AQN}} \lambda^3 \sim \Phi^{\text{AQN}} \frac{\hbar}{v_a m_a} \left( \frac{\hbar}{m_a v_a} \right)^3 \sim 10^6 \left( \frac{10^{-4} \text{eV}}{m_a} \right)^4 \gg 1.$$

Finally and the 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. We emphasize that the wavelength $\lambda$ of the emitted axions is short, measured in centimetres, while the distance $\Delta R$ (relevant for the detecting of a correlation) between GN stations is measured in hundreds kilometres. To reiterate: we are suggesting to study the correlation between the transient signals which could be detected by different GN stations. It should be contrasted with a proposal to study the coherent signal when the amplitude $a_{\text{ALP}}$ of ultra light particles has a coherence length scale $(10^2-10^4)$ kilometres.

In the next section 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 from each other with $\Delta R \sim 10^2$ km. This is because this subset of the GN stations will be the subject of the amplification factor $A \sim (10^2 - 10^4)$ produced by a single AQN traversing in close vicinity of these stations. Amplification factor $A \sim 10^2$ is expected to occur once a day in every point on the earth surface, while stronger amplifications are relatively rare events [22]. In this case the correlated signal can be observed by this subset of the GN stations with time delays $\Delta t \sim \Delta R/v_{\text{AQN}} \sim 1 \text{s}$ where $v_{\text{AQN}} \sim 10^{-3} c$ is a typical velocity for DM particles. The time duration of the AQN-induced burst will assume a similar magnitude $\Delta \tau \sim 1 \text{s}$, see next section with relevant estimates.

**Time delays and durations.** 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]

$$A(d) \approx \left( \frac{0.2 R_\oplus}{d} \right)^2 = \left( \frac{1.27 \times 10^3 \text{km}}{d} \right)^2,$$  \quad (5)

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:

$$\Delta \tau = \frac{d}{v_{\text{AQN}}} \approx 4.25 A^{-1/2} \left( \frac{300 \text{km s}^{-1}}{v_{\text{AQN}}} \right).$$  \quad (6)

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 about $10^2$ km apart there is a large chance to detect a correlated signal amplified by $A \sim 10^2$ from one and the same AQN.

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 approximated as a constant within the short time of correlated local flash $\sim 1$ s, $r_0$ is the intercept at the plane spanned by $\mathbf{R}$ and $\mathbf{R}'$. The distances
FIG. 1: The two stations located at \( \mathbf{R} \) and \( \mathbf{R}' \) on the surface of Earth respectively. Each station has a distance \( \mathbf{d} \) (and \( \mathbf{d}' \)) from the AQN trajectory \( \mathbf{r}(t) = v_{AQN} t + \mathbf{r}_0 \). from the stations to the AQN trajectory are denoted as \( \mathbf{d} \) and \( \mathbf{d}' \) respectively.

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

\[
0 = \mathbf{d} \cdot v_{AQN} = \left[ \mathbf{r}(t_*) - \mathbf{R} \right] \cdot v_{AQN},
0 = \mathbf{d}' \cdot v_{AQN} = \left[ \mathbf{r}(t'_*) - \mathbf{R}' \right] \cdot v_{AQN}.
\tag{8}
\]

The solutions give the time delay between two stations

\[
\Delta t \equiv |t'_* - t_*| = \frac{\Delta R}{v_{AQN}}, \quad \delta \equiv |\mathbf{\hat{R}} \cdot \mathbf{\hat{v}}|,
\tag{9}
\]

where \( \Delta R = \mathbf{R}' - \mathbf{R} \) 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 \( \mathbf{\hat{v}} \) of the AQN trajectory is unknown. Assuming \( \Delta R \sim 10^2 \) km and \( v_{AQN} \sim 300 \) km s\(^{-1}\), we expect \( \Delta t \) is no greater than \( \sim 1 \) s.

One important relation in what follows can be derived from Eqs. (8) and (9):

\[
\mathbf{d}' = \mathbf{d} + v_{AQN} \Delta t - \Delta \mathbf{R},
\tag{10a}
\]

\[
\mathbf{d}' \equiv |\mathbf{d}'| \leq d + \Delta R(1 + \delta) \tag{10b}.
\]

Here Eq. (10a) can be also understood directly from the vector configuration in Fig. 1, and Eq. (10b) is based on the inequality \( |\mathbf{a} + \mathbf{b}| \leq |\mathbf{a}| + |\mathbf{b}| \).

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 \( d' \lesssim d \) or, according to Eqs. (5) and (10b):

\[
\Delta R \lesssim \frac{d}{1 + \delta} \approx 85 \text{ km}\left(\frac{1.5}{1 + \delta}\right)\left(\frac{10^2}{A}\right)^{1/2} ,
\tag{11}
\]

where \( A \equiv A(d) \) for brevity of notation, and \( \delta \approx 0.5 \) 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 optimal separation distance is about 85 km.

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):

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

\[
\gtrsim 0.23 \text{ day}^{-1} \left( \frac{1 + \delta}{1.5} \right)^2 \left( \frac{10^2}{A} \right)^{3/2} .
\tag{12}
\]

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 (11).

**Conclusion.** The key element of our proposal is the presence of a GN when the individual stations are sensitive to required frequency determined by \( m_\chi \). We also require that the network is configured in such a way that it contains two or more nearby stations with the distance \( \sim 10^2 \) km between them. In this case we argued that these stations should observe correlated amplified signals with event rate \( \sim 0.2 \) day and with time delay \( \Delta t \) on order of a second. The presence of such correlation may play a pivotal role in discovery of the axion signal as the correlation with well defined time delay (9) may be a decisive tool in discriminating the signal from the noise background.

The estimates are based on the AQN model. Why should we take this model seriously? A simple answer is as follows. Originally, this model was invented to explain a number of other (naively unrelated) observed phenomena such as excess of the galactic diffuse emission in different frequency bands, the so-called “Primordial Lithium Puzzle”, “The Solar Corona Mystery”, and
the Dama-Libra puzzling annual modulation, see Introduction for the references. A GN suggested in this work is capable to detect the traces of the AQN directly by measuring the correlations, in contrast with indirect observations mentioned above.

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[1] V. V. Flambaum and A. R. Zhitnitsky, Phys. Rev. D99, 023017 (2019), arXiv:1811.01965 [hep-ph].

[2] A. Ringwald, in Proceedings of the Neutrino Oscillation Workshop (NOW2016). 4 - 11 September, 2016. Otranto (Lecce, Italy) (2016) p. 81, arXiv:1612.08933 [hep-ph].

[3] R. Battesti et al., Phys. Rept. 765-766, 1 (2018), arXiv:1803.07547 [physics.ins-det].

[4] I. G. Iastorza and J. Redondo, Prog. Part. Nucl. Phys. 102, 89 (2018), arXiv:1801.08127 [hep-ph].

[5] H. Fischer, X. Liang, Y. Semertzidis, A. Zhitnitsky, and K. Zioutas, Phys. Rev. D99, 043013 (2018), arXiv:1805.05184 [hep-ph].

[6] X. Liang and A. Zhitnitsky, Phys. Rev. D99, 023015 (2019), arXiv:1810.00673 [hep-ph].

[7] K. Lawson, X. Liang, A. Mead, M. S. R. Siddiqui, L. Van Waerbeke, and A. Zhitnitsky, Phys. Rev. D100, 043531 (2019), arXiv:1905.00022 [astro-ph.CO].

[8] X. Liang, A. Mead, M. S. R. Siddiqui, L. Van Waerbeke, and A. Zhitnitsky, (2019), arXiv:1908.04675 [astro-ph.CO].

[9] A. R. Zhitnitsky, JCAP 10, 010 (2003), hep-ph/0202161.

[10] E. Witten, Phys. Rev. D30, 272 (1984).

[11] J. Madsen, Hadrons in dense matter and hadrosynthesis. Proceedings, 11th Chris Engelbrecht Summer School, Cape Town, South Africa, February 4-13, 1998, Lect. Notes Phys. 516, 162 (1999), [162(1998)], arXiv:astro-ph/9809032 [astro-ph].

[12] X. Liang and A. Zhitnitsky, Phys. Rev. D 94, 083502 (2016), arXiv:1606.00435 [hep-ph].

[13] S. Ge, X. Liang, and A. Zhitnitsky, Phys. Rev. D 96, 063514 (2017), arXiv:1702.04354 [hep-ph].

[14] S. Ge, X. Liang, and A. Zhitnitsky, Phys. Rev. D 97, 043008 (2018), arXiv:1711.06271 [hep-ph].

[15] S. Ge, K. Lawson, and A. Zhitnitsky, Phys. Rev. D99, 116017 (2019), arXiv:1903.05000 [hep-ph].

[16] V. V. Flambaum and A. R. Zhitnitsky, Phys. Rev. D99, 023517 (2019), arXiv:1811.01965 [hep-ph].

[17] A. Zhitnitsky, JCAP 10, 050 (2017), arXiv:1707.03400 [astro-ph,SR].

[18] N. Raza, L. Van Waerbeke, and A. Zhitnitsky, Phys. Rev. D 98, 103527 (2018), arXiv:1805.01897 [astro-ph,SR].

[19] K. Lawson and A. R. Zhitnitsky, Phys. Dark Univ. 24, 100295 (2019), arXiv:1804.07340 [hep-ph].

[20] A. Zhitnitsky, (2019), arXiv:1909.05320 [hep-ph].

[21] S. Pustelny, D. F. J. Kimball, C. Pankow, M. P. Ledbetter, A. Lombardi, A. Ortolan, R. Pengo, G. Ruoso, and A. Ringwald, in Proceedings of the Neutrino Oscillation Workshop (NOW2016). 4 - 11 September, 2016. Otranto (Lecce, Italy) (2016) p. 81, arXiv:1612.08933 [hep-ph].

[22] P. Sikivie, in Axions, Lecture Notes in Physics, Berlin Springer Verlag, Vol. 741, edited by M. Kuster, G. Raffelt, and B. Beltrán (2008) p. 19, astro-ph/0610440.

[23] G. G. Raffelt, in Axions, Lecture Notes in Physics, Berlin Springer Verlag, Vol. 741, edited by M. Kuster, G. Raffelt, and B. Beltrán (2008) p. 51, hep-ph/0611350.

[24] P. Sikivie, International Journal of Modern Physics A 25, 554 (2010), arXiv:0909.0949 [hep-ph].

[25] L. J. Rosenberg, Proceedings of the National Academy of Science 112, 12278 (2015).

[26] D. J. E. Marsh, Physics Reports 643, 1 (2016), arXiv:1510.07633.

[27] P. W. Graham and S. Rajendran, Phys. Rev. D88, 035023 (2013), arXiv:1306.6088 [hep-ph].