The Mysterious Bursts observed by Telescope Array and Axion Quark Nuggets

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Telescope Array (TA) experiment has recorded [1, 2] several short time bursts of air shower like events. These bursts are very distinct from conventional single showers, and are found to be strongly correlated with lightnings. We propose that these bursts represent the direct manifestation of the dark matter annihilation events within the so-called axion quark nugget (AQN) model, which was originally invented for completely different purpose to explain the observed similarity between the dark and the visible components in the Universe, i.e. \( \Omega_{\text{DM}} \sim \Omega_{\text{visible}} \) without any fitting parameters. We support this proposal by demonstrating that the observations [1, 2], including the frequency of appearance, temporal and spatial distributions, intensity, and other related observables are nicely matched the emission features of the AQNs propagating in the atmosphere under thunderstorm. We propose to test these ideas by reanalyzing the existing data by increasing the cutoff time scale \( \Delta t = 1 \) ms for the bursts. We also suggest to test this proposal by analyzing the correlations with proper infrasound and seismic instruments.

I. INTRODUCTION

In this work we discuss two naively unrelated stories. The first one is the study of a specific dark matter (DM) model, the so-called axion quark nugget (AQN) model [3], see a brief overview of this model below. The second deals with the recent puzzling observations [1, 2] by the Telescope Array (TA) experiment of the several short time bursts of air shower like events as recorded by Surface particle Detector (TASD). The bursts are defined as the events when at least three air shower triggers were recorded within 1 ms. Ten bursts have been recorded during five years of the observations (between May 11, 2008 and May 4, 2013). These bursts are very distinct from single showers resulting from conventional ultra high energy cosmic (HECR) events. The unusual features are listed below [1, 2]:

1. Bursts start at much lower altitude than that of conventional HECR showers. All reconstructed air shower fronts for the burst events are much more curved than usual CR air showers;

2. Bursts events do not have sharp edges as conventional HECR normally do;

3. The events are temporally clustered within 1 ms, which would be a highly unlikely occurrence for three consecutive conventional HECR hits in the same area within a radius of approximately 1km;

4. If one tries to fit the observed bursts with conventional code, the energy for HECR events should be in \( 10^{13} \) eV energy range, while the observed bursts correspond to \( (10^{18} - 10^{19}) \) eV energy range as estimated by signal amplitude and distribution. Therefore, the estimated energy from individual events within the bursts is five to six orders of magnitude higher than the energy estimated by event rate;

5. Most of the observed bursts are “synchronized” or “related” with the lightning events, see precise definitions below. Furthermore, all ten recorded bursts occur under thunderstorm;

6. All bursts occur at the same time of lightning or earlier than lightning. Therefore, the bursts are associated with very initial moment of the lightning flashes, and cannot be an outcome nor consequence of the lightning flashes as it would be detected at the later stages of lightning flashes, not initial moment as observed.

7. The total 10 burst events have been observed during 5 years of observations. These bursts are not likely due to chance coincidence between single shower events.

The distinct features as listed above suggest that the bursts are entitled to be considered as very puzzling rare events as they cannot be reconciled with conventional CR, and we coin them as “mysterious bursts”.

* In this work we present the arguments suggesting that these two naively unrelated things (AQN dark matter [3] and the bursts as recorded by TASD [1, 2]) may in fact be intimately linked. In other words, we shall argue that “mysterious bursts” observed by [1, 2] could be a manifestation of the dark matter AQNs traveling in the atmosphere during the thunderstorms. Our arguments are based on analysis of the event rate, the energetics, the flux estimates, the time durations, the spatial distribution and other observables as recorded by [1, 2]. Therefore, we identify the “mysterious bursts” with the AQNs hitting the Earth’s atmosphere under the thunderstorms. We will show that all unusual features as listed in items 1-7 above can be naturally explained within the AQN framework.

Now we are highlighting the basic features of the AQN model which represents the first part of our story, while deferring a more detail overview to Sect. II. The axion quark nugget (AQN) dark matter model [3] was invented long ago with a single motivation to naturally explain the observed similarity between the dark matter and the visible densities in the Universe, i.e. \( \Omega_{\text{DM}} \sim \Omega_{\text{visible}} \) without any fitting parameters. The AQN construction in many respects is similar to the original quark-nugget model suggested by Witten [4], see [5] 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-to-mass ratio, which scales down many observ-
able consequences of an otherwise strongly-interacting
DM candidate.

There are two additional elements in the AQN model
compared to the original models [4–7]. First new element
is the presence of the axion domain walls which are copi-
ously produced during the QCD transition. This domain
wall plays a dual role: first it serves as an additional sta-
bilization factor for the nuggets, which helps to alleviate
a number of problems with the original nugget construc-
tion [4–7]. Secondly, the same axion field generates the
strong CP violation in the entire visible Universe, which
represents a key element of the AQN construction. An-
other feature of the AQN model which plays absolutely
crucial role for the present work is that nuggets can be
made of matter as well as antimatter during the QCD
transition. The direct consequence of this feature along
with coherent CP violation in entire Universe is that
the DM density, Ω_{DM}, and the visible density, Ω_visible,
will automatically assume the same order of magnitude
Ω_{DM} ~ Ω_visible without any fine tuning, see next section
II with more details.

One should emphasize that AQNs are absolutely sta-
ble configurations on cosmological scales. Furthermore,
the antimatter which is hidden in form of the very dense
nuggets is unavailable for annihilation unless the AQNs
hit the stars or the planets. There are also very rare
events of annihilation in the center of the galaxy, which,
in fact, may explain some observed galactic excess emis-
sions in different frequency bands, see next Sect. II
for references. Precisely the AQNs made of antimatter are
capable to release a significant amount of energy when
they enter the Earth’s atmosphere and annihilation pro-
cesses start to occur between antimatter hidden in form
of the AQNs and the atmospheric material. The emission
of positrons from the nuggets made of antimatter is very
common and generic phenomenon as we argue below.

It is important to comment here that the thun-
derclouds play a crucial role in our discussions as they serve
as the triggers which greatly increase the particle emis-
sion rate from the AQNs. This is because the thun-
derclouds are characterized by large preexisting electric field
which serves as a trigger and accelerator of the liberated
positrons. Precisely these features which occur under
thunderclouds explain why all the recorded mysterious
bursts are observed exclusively in the presence of the
thunderclouds. The necessity to have thunderclouds in
the area also explains why the “mysterious bursts” are
so rare events: the AQNs (which are much more fre-
frequent events by themselves, see below) must enter the
area under the thunderclouds to accelerate and intensify
the emission of the positrons which will be eventually
recorded by TASD.

We conclude this Introduction with the following com-
ment. The annihilation events which inevitably occur
when AQN interact with environment lead to many ob-
servable effects due to release of a large amount of energy.

We review the corresponding phenomena when the anni-
hilation events occur in the solar corona and the galactic
center in the following section II. The corresponding an-
nihilation events when AQN enters the Earth atmosphere
lead to the release of energy in the form of the weakly
coupled axions and neutrinos as well as x and γ rays,
electrons, positrons and other particles. It is hard to
observe axions and neutrinos due to their feeble interac-
tions, though the corresponding computations have been
carried out recently. At the same time, the x and γ rays
emitted by AQNs are absorbed over distances ~ 10 m or
so in the atmosphere, and therefore cannot be easily re-
covered for analysis. The characteristic lifetime of free
electrons is also very short and about 10^{-7}s. The liber-
ated positrons, on other hand, can get accelerated under
thundercloud and propagate several kilometers in atmos-
phere at the sea level (and even much more at higher
altitudes).

We propose here that the AQN-induced positrons is
the source of the unusual events observed by TASD
[1, 2]. We should emphasize that the AQN model was
not designed nor invented to explain the “mysterious
bursts”. Rather, the AQN model was constructed for
completely different purposes, to explain the observed
relation: Ω_{DM} ~ Ω_visible without any fine tunings. As
a consequence of the construction (manifested in large
amount of antimatet hidden in form of the AQNs) this
model also predicts a large number of positrons which will
be liberated during the AQN traversing the atmosphere
under the thunderstorm. These energetic positrons can
mimic the CR air-shower, and we identify these unusual
burst events characterized by items 1-7 listed above with
AQN annihilation events in atmosphere. If this identifi-
cation is confirmed by future studies and observations,
the “mysterious bursts” recorded by [1, 2] would be the
first direct (non-gravitation) evidence which reveals the
nature of the dark matter.

Our presentation is organized as follows. In next sec-
tion II we overview the basic ideas of the AQN model
paying special attention to the specific topics relevant for
the present studies. In section III we formulate the basic
ideas of the proposal and make a number of estimates
including the frequency of appearance, the emergence of
clusters identified with bursts, estimate their intensity,
etc. In section IV we confront our proposal with observa-
tions [1, 2] by explaining how the unusual features listed
in items 1-7 naturally emerge in this AQN framework.
Finally, in section V we formulate our basic findings and
suggest possible tests how this proposal can be confirmed
or refute by future studies.

II. THE AQN MODEL.

This section represents a relatively short overview of
the AQN framework where we briefly mention the basic
ideas of the AQN model relevant for the present studies,
especially in subsection II C.
A. The basics. Overview

The original motivation for this model can be explained in two lines as follows. It is commonly assumed that the Universe began in a symmetric state with zero global baryonic charge and later (through some baryon number violating process, non-equilibrium dynamics, and CP violation effects, realizing three famous Sakharov’s criteria) evolved into a state with a net positive baryon number.

We advocate a model in which “baryogenesis” is actually a charge segregation (rather than charge generation) process in which the global baryon number of the universe remains zero at all times. This scenario should be considered as an alternative path which is qualitatively different from conventional baryogenesis. The result of this charge segregation process is two populations of AQN carrying positive and negative baryon number. In other words, the AQN may be formed of either matter or antimatter. However, due to the global CP violating processes associated with \( \theta_0 \neq 0 \) during the early formation stage, the number of nuggets and antinuggets will be different\(^1\). This difference is always an order of one effect irrespectively to the parameters of the theory, the axion mass \( m_a \) or the initial misalignment angle \( \theta_0 \). In this model the AQNs represent the dark matter in the form of dense nuggets of quarks (or antiquarks) and gluons in colour superconducting (CS) phase. We refer to the original papers \([24–27]\) devoted to the specific questions related to the nugget’s formation, generation of the baryon asymmetry, and survival pattern of the nuggets during the evolution in early Universe with its unfriendly environment.

As we already mentioned the strongly interacting AQNs are dark due to the very small cross-section-to-mass ratio. The observable effects do occur when DM and visible matter densities are sufficiently large and rare events of annihilation occur. In particular, the AQN model may explain some excesses of diffuse emission from the galactic center the origin of which remains to be debated, see the original works \([28–33]\) with explicit computations of the galactic radiation excesses for various frequencies, including excesses of the diffuse x- and \( \gamma \)-rays. In all these cases photon emission originates from the outer layer of the nuggets known as the electrosphere, and all intensities in different frequency bands are expressed in terms of a single parameter \( \langle B \rangle \sim 10^{25} \) representing the average baryon charge of the nuggets.

The AQNs may also offer a resolution to some seemingly unrelated puzzles such as the “Solar Corona Mystery” \([34, 35]\), the “Primordial Lithium Puzzle” \([36]\) and the longstanding puzzle with the DAMA/LIBRA observation of the annual modulation at 9.5\( \sigma \) confidence level \([37]\), see \([38]\) for a short overview of the basic results of ref. \([37]\). Furthermore, it may resolve the observed (by XMM-Newton at 11 \( \sigma \) confidence level \([39]\)) puzzling seasonal variation of the X-ray background in the near-Earth environment in the 2-6 keV energy range as suggested in \([40]\). The AQN annihilation events in the Earth’s atmosphere could produce infrasound and seismic acoustic waves as discussed in \([41]\) when the infrasound and seismic acoustic waves have been recorded without any traces of accompanying meteor-like events.

As we mentioned above the single fundamental parameter which essentially determines all the intensities for all 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 \( M_N \sim m_a \langle B \rangle \). The AQNs are macroscopically large nuclear density objects. For the present work we adopt a typical nuclear density of order \( 10^{10} \text{ cm}^{-3} \) such that a nugget with \( |B| \approx 10^{25} \) has a typical radius \( R \approx 2.2 \times 10^{-5} \text{ cm} \) and mass of order 10 g.

It should be contrasted with conventional meteors when an object with mass 10 g. would have a typical size of order 1 cm occupying the volume which would be 15 orders of magnitude larger than the AQN’s volume. This is of course is due to the fact that AQNs have nuclear density which is 15 orders of magnitude higher than the density of a normal matter. One can view an AQN as very small neutron star (NS) with its nuclear density. The difference is that the NS is squeezed by the gravity, while the AQN is squeezed by the axion domain wall pressure.

B. Size distribution. Frequency of appearance.

We now overview the observational constraints on such kind of dense objects which play a key role in our analysis in identification of the “mysterious bursts” recorded by \([1, 2]\) with the AQN annihilation events in atmosphere under the thunderstorm.

The strongest direct detection limit\(^2\) is set by the IceCube Observatory’s, see Appendix A in \([43]\):

\[
\langle B \rangle > 3 \cdot 10^{24} \quad \text{[direct (non)detection constraint], (1)}
\]

There is also upper limit due to the following arguments \([44]\). One can use the Apollo data to constrain the abundance of quark nuggets in the region of 10 kg to one ton.

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\(^1\) The strong \( CP \) violation is related to the fundamental initial parameter \( \theta_0 \). This source of \( CP \) violation is no longer available at the present time due to the axion and its dynamics in early Universe. One should mention that the axion remains the most compelling resolution of the strong \( CP \) problem, see original papers on the axion \([8–14]\), and recent reviews \([15–23]\).

\(^2\) Non-detection of etching tracks in ancient mica gives another indirect constraint on the flux of dark matter nuggets with mass \( M < 55 \text{ g} \) \([42]\). This constraint is based on assumption that all nuggets have the same mass, which is not the case as we discuss below. The nuggets with small masses represent a tiny portion of all nuggets in this model.
The authors of ref. [44] 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 neighbourhood. Assuming that the AQNs do saturate the dark matter, the constraint [44] 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:

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

(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:

$$3 \cdot 10^{24} \lesssim \langle B \rangle \lesssim 10^{28} \text{ [constraints from observations].}$$

(3)

We emphasize that the AQN model within window (3) is consistent with all presently available cosmological, astrophysical, satellite and ground-based constraints. Furthermore, it has been shown that these macroscopical objects can be formed, and the dominant portion of them will survive the dramatic events (such as BBN, galaxy and star formation etc.) during the long evolution of the Universe. This model is very rigid and predictive as there is no much flexibility nor freedom to modify any estimates mentioned above which have been carried out with one and the same set of parameters in drastically different environments when densities and temperatures span many orders in magnitude.

For our interpretation of the “mysterious bursts” [1, 2] in terms of the AQN annihilation events in atmosphere, one needs to know the size distribution and the frequency of appearance of AQNs with a given size. The corresponding AQN flux is proportional to the dark matter number density \(n_{\text{DM}}v_{\text{DM}} \sim (\rho_{\text{DM}}v_{\text{DM}})/\langle B \rangle\). Therefore, the corresponding frequency of appearance at which the AQNs hit the Earth can be estimated as follows [43]:

$$\frac{\langle N \rangle}{4\pi R_{\oplus}^2} \simeq \frac{4 \cdot 10^{-2}}{\text{km}^2 \text{yr}} \left( \frac{\rho_{\text{DM}}}{0.3 \text{ GeV cm}^{-3}} \right) \left( \frac{\langle v_{\text{AQNs}} \rangle}{220 \text{ km s}^{-1}} \right) \left( \frac{10^{25}}{\langle B \rangle} \right),$$

(4)

where we assumed the conventional galactic halo model with the local dark matter density being \(\rho_{\text{DM}} \simeq 0.3 \text{ GeV cm}^{-3}\). The result (4) suggests that the AQNs hit the Earth’s surface with a frequency approximately once a day per \((100 \text{ km})^2\) area. The rate is expressed in terms of the average value \(\langle B \rangle\) as defined below by eq. (5). This rate is suppressed for large sized AQNs when \(B\) is much larger than the mean value \(\langle B \rangle\) and it is enhanced for \(B \lesssim \langle B \rangle\) as we discuss below.

The corresponding size distribution (and corresponding frequency of appearance) is defined as follows: Let \(dN/db\) be the number of AQNs which carry the baryon charge \([B, B+dB]\). The mean value of the baryon charge \(\langle B \rangle\) which enters (4) is defined as follows:

$$\langle B \rangle = \int_{B_{\text{min}}}^{B_{\text{max}}} B \, B f(B), \quad f(B) \propto B^{-\alpha},$$

(5)

where \(f(B)\) is a properly normalized distribution and \(\alpha \simeq (2 - 2.5)\) is the power-law index. One should mention that the parametrization (5) in terms of the distribution function \(f\) was originally introduced by solar physicists to fit the observed extreme UV radiation assuming that the corona heating is saturated by so-called nanoflares (conjectured by Parker many years ago to resolve the “Solar Corona Mystery”). In the original construction function \(f\) describes the energy distribution \(f(E_{\text{nano}})\) for the nanoflares. This scaling was literally adopted in [34, 35], where it was proposed that the nanoflares can be identified with AQN-annihilation events in the solar corona and the energy of the nanoflares \(E_{\text{nano}}\) is related to the baryon charge \(B\) of the AQN as follows: \(E_{\text{nano}} \simeq 2m_{\text{p}}c^2B \simeq (3 \cdot 10^{-3} \text{ erg})B\). As a result the nanoflare energy distribution \(f(E_{\text{nano}})\) and the AQN baryon charge distribution \(f(B)\) is the same (up to proper normalization) function \(f(E_{\text{nano}}) \propto f(B)\) as proposed in [34].

The highly nontrivial element of this identification is that the required energy interval for the nanoflares being in the range \(E_{\text{nano}} \simeq (10^{24} - 10^{30}) \text{ erg}\) as studied by solar physicists largely overlaps with allowed interval for the AQN baryonic charge window (3) derived from drastically different constraints. Furthermore, the observed intensity of the extreme UV emission from the solar corona matches very nicely with the total energy released as a result of the AQN-annihilation events in the transition region [34, 35]. One should emphasize that this “numerical coincidence” is a highly nontrivial self-consistency check of the proposal [34] connecting the conjectured solar nanoflares with AQNs, since the nanoflare properties are constrained by solar corona-heating models, while the intensity of the observed extreme UV due to the AQN annihilation events in the AQN framework is mostly determined by the dark matter density \(\rho_{\text{DM}} \simeq 0.3 \text{ GeV cm}^{-3}\).

C. AQN’s internal temperature \(T\) and the electric charge \(Q\)

Another important element relevant for our interpretation of the “mysterious bursts” [1, 2] in terms of the AQN annihilation events in atmosphere is the internal temperature \(T\) of the nugget and its induced electric charge \(eQ\). The corresponding parameters have been used in our previous applications within AQN framework such as the “Primordial Lithium Puzzle” [36], the solar corona heating puzzle [34, 35] and the seasonal variations observed by XMM-Newton in x-ray frequency bands [40]. In all the previous cases the environment was drastically different from our present application of propagating the AQNs in the Earth’s atmosphere. Nevertheless, the basic concept on structure of the nugget’s core and its electrosphere, including the estimates of the temperature \(T\) and electric charge \(eQ\) remain the same.

In context of the present work the most relevant studies were performed in [41] devoted to the acoustic signals
generated by AQNs propagating in the Earth’s atmosphere. It has been speculated that some mysterious explosions when the infrasound and seismic acoustic waves have been recorded can be identified with very rare large sized AQNs hitting the Earth. The estimations of the parameters $T$ and $Q$ from that analysis \cite{41} can be directly applied to our present studies of the “mysterious bursts” recorded by TASD. The difference is that the paper \cite{41} was focused on x-rays emission (with very short mean free path measured in meters at the sea level) which eventually generates the acoustic waves propagating for much longer distances.

In present studies we will be mostly interested in the AQN’s emission of the positrons which can propagate few kilometers before they reach TASD to be recorded. However, the basic parameters $T$ and $Q$ from \cite{41} relevant for our present studies remain basically the same. We highlight the basic ideas on estimations of the temperature in Appendix A where some specific details relevant for the present work (such as the ionization features of the atmosphere under thunderstorms at relatively high altitude $\sim 10 \text{ km}$) are explicitly taken into account.

Another difference with ref. \cite{41} is that the main focus in the acoustic studies was on very rare and very intense events [which approximately occur once every ten years on $(100 \text{ km})^2$ area]. These rare events are associated with very large nuggets with $B \approx 10^{27}$ which could generate the infrasound signal being sufficiently strong with overpressure on the level of $\delta p \approx 0.3 \text{ Pa}$ above the detector’s sensitivity. Such intense events are very rare ones according to (5). In our present studies we are interested in typical and much more frequent events with $B \approx 10^{25}$ when the event rate is estimated by (4). The long-ranged consequences of the AQN interaction in our present case will be manifested in form of the emitted positrons which can propagate sufficiently long distance as a result of their acceleration by pre-existing electric field commonly present during the thunderstorms.

After an AQN hits the dense region of the Earth’s atmosphere, it acquires an internal temperature of the order $T \approx (10 - 20) \text{ keV}$ as a result of annihilation events in the nugget’s core, see Appendix A for the details. Furthermore, during its journey the AQN’s speed $v_{\text{AQN}} \approx 250 \text{ km/s}$, which is a typical DM value, greatly exceeds the speed of sound $c_s$ by several orders of magnitude such that Mach number $M = v_{\text{AQN}}/c_s \gg 1$. The AQN temperature rise will cause the electrosphere consisting the weakly coupled positrons to expand well beyond the thin layer surrounding the nugget surface. Some of the positrons will stay in close vicinity of the moving, negatively charged nugget core. However, a finite portion of the positrons may leave the system as a result of direct elastic interaction of the weakly coupled positrons with atmospheric molecules and due to the interaction with strong electric field which always present in thunderclouds. The number of weakly bound positrons $Q$ surrounding the nuggets at temperature $T$ can be estimated as follows:

$$Q \approx 4\pi R^2 \int_0^\infty n(z,T)dz \sim \frac{4\pi R^2}{\sqrt{2\pi\alpha}} \left(\frac{T}{m_e}\right)^{1/4}, \tag{6}$$

where $n(z,T)$ is the positron number density in electrosphere, which has been computed in the mean field approximation for the low temperatures \cite{32,33}.

In the equilibrium with small annihilation rate the positrons will occupy very thin layer around the core’s nugget as computed in \cite{32,33}. However, in atmosphere due a large number of non-equilibrium processes such as generation of the shock wave (as a result of large Mach number $M$) and also due to the direct collisions with atmospheric molecules the positron’s cloud is expected to expand well beyond the thin layer around the core’s nugget. Some positrons will be kicked off and leave the system.

How many positrons precisely will leave the system? This question is very hard to answer in any quantitative way, and we will assume that, to first order, that finite portion of them $\sim Q$ may leave the system as a result of shock wave and turbulence, or as a result of direct collisions with atmospheric molecules. The remaining finite portion of them $\sim Q$ will stay in the system and continues its motion with velocity $v_{\text{AQN}}$ surrounding the nugget’s core\cite{3}. In that case, the nugget core acquires a negative electric charge $\sim -|e|Q$ such that the nuggets get partially ionized.

The distance $\rho$ at which the positrons remain attached to the nugget is given by the capture radius $R_{\text{cap}}(T)$, determined by the Coulomb attraction:

$$\frac{aQ(\rho)}{\rho} > \frac{m_e v^2}{2} \approx T \quad \text{for} \quad \rho \lesssim R_{\text{cap}}(T). \tag{7}$$

The capture radius $R_{\text{cap}}(T)$ is many orders of magnitude greater than nugget’s size $R$ due to the long range Coulomb forces. The binding energy represents the difference between Coulomb attraction and kinetic energy and must be obviously negative for the positrons to be tied to the nugget.

We conclude this short overview section with the following comment. The rise of the temperature $T$ and consequently, the electric charge $Q$ as discussed above is very generic feature of the AQN framework when the nuggets propagate in atmosphere and annihilation processes occur in the nugget’s core. The observable effects will be drastically intensified due to the AQN interaction with

\footnotetext[3]{This case should be contrasted with our studies \cite{40} of the seasonal variations observed by XMM-Newton due to the AQN’s emission in x-ray frequency bands. The observations are performed at large distances from Earth $r \approx 7R_\oplus$ in empty space when weakly coupled positrons in electrosphere (6) cannot be kicked off as probability for collisions is very tiny in empty environment. In this case the dominant portion of the positrons $Q$ remains in the system all the time.
pre-existing electric field which always present in thunderclouds. The features expressed by formulae (6) and (7) will play a crucial role in our analysis of the interaction of this positron’s cloud with pre-existing electric field in thunderstorms.

To be more precise, in subsections III C and III D below we argue that the sufficiently strong electric field may liberate and consequently accelerate these positrons to the 10 MeV energy range such that these positrons can easily propagate several kilo-meters before they get annihilated. These energetic positrons can be eventually detected by TASD.

III. “MYSTERIOUS BURSTS” AS THE AQN ANNIHILATION EVENTS

In this section we formulate the basic idea of the proposal on how the “mysterious bursts” recorded by [1, 2] can be interpreted in terms of the AQN annihilation events under thunderstorm. After that we make the estimates supporting every single element of this proposal.

The idea goes as follows [we separated item (a) which is generic and not specific to the atmospheric conditions from item (b) which applies exclusively to the case of the thunderstorm]:

a) The AQN propagates in atmosphere experiences a large number of annihilation events between antimatter quarks hidden in the AQN’s core and surrounding material. The annihilation processes raise the internal temperature of the AQN very much in the same way as discussed in ref. [41]. In the atmosphere the finite portion of the positrons may be kicked off due to the elastic collisions with atmospheric molecules, in which case the positrons may leave the system. However, we expect that the finite portion of the positrons remain bound to the nugget at distances of order $R_{\text{cap}}$, determined by (7).

b) If the AQN hits the area under thundercloud the weakly bound positrons localized far away from the AQN’s core at $R_{\text{cap}}$ may be liberated by preexisting electric field $E \sim \text{kV/cm}$ which is known to exist in thunderclouds. As a result of the strong electric field the positrons will be accelerated to the relativistic velocities and energies of 10 MeV on scales of 100 meters or so. The mean free path for such energetic positrons is several km such that these positrons can reach TASD detectors.

Our proposal is that precisely these energetic positrons generate the “mysterious bursts” recorded by [1, 2]. Below we present the arguments supporting this claim. We shall demonstrate that all highly unusual features listed as items 1-7 in Introduction find very natural explanation within this proposal, which represents the topic of the separate section IV.

A. Frequency of appearance

Here we want to estimate the total number of events which TASD can record within the AQN proposal during 5 years of observations. The starting point is the AQN flux (4) which determines the total number of bursts $N_{\text{bursts}}$ during 5 years of collecting data:

$$N_{\text{bursts}} \simeq \frac{4 \cdot 10^{-2}}{\text{km}^2 \cdot \text{yr}} \cdot (A) \cdot (T) \cdot (F),$$

where $A$ is the effective area, $T$ is the data collection time, and finally factor $F$ describes the fraction of time when the effective area $A$ has been under thunderclouds. We start with the simplest parameter $T \simeq 5$ years according to [1, 2]. Estimation of parameter $F$ is based on compilation of the annual thunderstorm duration from 450 air weather system in USA as described in [45]. The corresponding estimates suggest that on average the thunderstorms last about 1% of time in each given area [45]. We adopt this estimate such that $F \simeq 10^{-2}$.

The last part is the estimation of the effective area $A$. One could naively use the area $A \simeq 680 \text{ km}^2$ covered by the grid array of the SD detectors [1, 2]. However, it would be a strong underestimation for the problem under consideration. The point is that the AQN trajectory very often has large inclination angle. Furthermore, according to [1, 2] the criteria for “related” lightning is that the time difference between burst and lightning is less than 200 ms. This time scale determines the maximal size $L_{\text{thunder}}$ of a thunderstorm system, under which the AQN emits the positrons (which can eventually reach the TASD detectors). The “related” lightning obviously occurs in a different location of the sky, but within the same thunderstorm system. This distance is estimated as follows

$$L_{\text{thunder}} \simeq v_{\text{AQN}} \cdot (200 \text{ ms}) \simeq 250 \text{ km/s} \cdot 0.2s \approx 50 \text{ km},$$

which is a size for a typical thunderstorm system, and few times larger than the size of TASD. This estimate suggests that effective area $A$ within AQN framework can be represented as $A \simeq L_{\text{thunder}}^2 \approx 2.5 \cdot 10^8 \text{ km}^2$.

Collecting all factors together we arrive to our final estimate for frequency of appearance of the burst-like events which TA collaboration could observe during 5 years of collecting data:

$$N_{\text{bursts}} \simeq \frac{4 \cdot 10^{-2}}{\text{km}^2 \cdot \text{yr}} \cdot (2.5 \cdot 10^8 \text{ km}^2)(5\text{yr})(10^{-2}) \approx 5.$$

This estimate (10) should be compared with observed 10 bursts recorded by [1, 2]. We consider a close similarity between these numbers as very encouraging sign as all elements entering (10) come from very different fields which are determined by very different physics (DM and thunderstorms). We also consider this order of magnitude estimate (10) as a highly nontrivial consistency check for the proposal as the basic numerical factor (4) entering (8) depends on the AQN size distribution model.
and can easily deviate by factor 2 or so even for the fixed local dark matter density $\rho_{\text{DM}} \simeq 0.3 \text{GeVcm}^{-3}$ which could also deviate locally from its canonical value\(^4\). However, we shall not elaborate on these specific details in the present work as the main focus of this work is presentation of a big self-consistent picture of the proposal.

In next subsection we discuss the most puzzling observational feature of the bursts when at least three air shower triggers were recorded within 1 ms. We treat these (naively independent) events as a single cluster generated by one and the same AQN traversing the Earth’s atmosphere with typical galactic dark matter velocity $v_{\text{AQN}} \sim 10^{-5}c$.

### B. Mysterious bursts as the clustering events

The crucial parameter for our proposal is the maximal number of particles (positrons) $N^\text{max}_{\text{positrons}}$ which can be emitted by AQN (and which can potentially reach TASD). The total number of positrons which have been accumulated by the AQN at the altitude around 10 km when the internal temperature reaches $T \simeq 10 \text{ keV}$ is determined by formula (6). If a small portion $\eta$ of the weakly coupled positrons will be suddenly liberated\(^5\) by the pre-existing thundercloud electric field the maximal number of particles which can be detected by TASD localized at distance $r$ is estimated as follows:

$$N^\text{max}_{\text{positrons}} \simeq \frac{\eta \cdot Q}{4\pi r^2} \left[507 \cdot 3 \text{m}^2\right] \cdot \langle e^{-\frac{r}{\lambda}} \rangle \quad (11)$$

$$\simeq 10^3 \cdot \left(\frac{\eta(T)}{0.1}\right) \cdot \left(\frac{T}{10 \text{ keV}}\right)^{5/4} \cdot \left(\frac{10 \text{ km}}{r}\right)^2 \cdot \left(\frac{\langle e^{-\frac{r}{\lambda}} \rangle}{0.1}\right),$$

where we substitute the total area of the detector as 507 SDs with area 3 m\(^2\) each. The detected number of particles for a shower-like event within the same cluster (burst) is of order 10\(^3\) or less according to [1, 2], which is consistent with estimate (11).

After the positrons are liberated from the nugget, they will be accelerated to the energies of order 10 MeV by pre-existing electric field with typical scale of order kV/cm, see next subsection III C. In our estimate (11) we assumed that the mean free path $\lambda$ for positrons with few MeV energy is order of kilometer at the sea level and several kilometers at higher altitudes which gives a suppression factor $\langle \exp(-r/\lambda) \rangle \sim 0.1$ for particles with energies in few MeV range. No much suppression occurs for higher energy positrons with energies 10 MeV or higher, which will be often the case as argued in subsection III D.

In (11) we also assumed that $\eta \simeq 0.1$ which describes a portion of the liberated positrons by pre-existing electric field in thunderclouds. The corresponding suppression factor is very hard to estimate on the quantitative level as it is determined by non-equilibrium dynamics as explained in the text above eq. (7). The order of magnitude estimate given in subsection III D is consistent with $\eta \simeq 0.1$. This portion of positrons will be replaced (fast refill) very quickly due to the very fast equilibration processes, see footnote 5.

Next important parameters to consider represent the relevant time scales, which we are about to discuss. First, $\Delta t_{\text{burst}} \lesssim 1 \text{ ms}$ represents a maximum time duration for a single burst which is treated in this work as the cluster of shower-like events from one and the same AQN. Second, each event within the burst does not normally lasts for more than $\Delta t_{\text{event}} \lesssim 10 \mu\text{s}$. These time scales can be represented in terms of the corresponding distances travelled by AQN:

$$L_{\text{burst}} \simeq v_{\text{AQN}} \cdot \Delta t_{\text{burst}} \simeq 250 \text{ m}, \quad L_{\text{event}} \lesssim 2.5 \text{ m}. \quad (12)$$

These time and length scales play an important role in our comparison with temporal and spatial features of pre-existing electric field under thunderstorms, which is the topics of the next subsections III C, III D. In particular, the recorded $\Delta t_{\text{event}}$ measured in $\mu$s will be interpreted in terms of the pre-existing fluctuating electric field which also has a typical time scale measured in $\mu$s, see (15). This interpretation, of course, is very different from conventional analysis of the air shower events which are also characterized by the same $\mu$s time scale, but due to completely different reasons.

### C. Electric field in thunderclouds

In this subsection we overview the properties of the pre-existing electric field which always present in thunderclouds. It represents a short detour from our main topic. However the corresponding parameters play a key role in our arguments in following subsection III D devoted to study of the AQNs under the thunderstorms.

We refer to review papers [46, 47] devoted to study of the lightning where pre-existing electric field plays a crucial role in dynamics of the lightning processes. While there is a consensus on typical parameters of the electric field which are important for the lightning dynamics, the physics of the of the initial moment of lightning remains a matter of debate, and refs [46, 47] represent different views on this matter, see also references [48–50] where some specific elements of existing disagreement have been explicitly formulated and debated.
For our purposes, however, the disputable elements do not play any role in our studies. Important elements for the present work, which are not controversial, are the temporal and spatial characteristics of the electric field and their values under thunderclouds. These parameters are well established and are not part of the debates, and we quote these parameters below.

We start by quoting the so-called critical electric field $E_c$ which must exist in thunderstorms for occurrence of runaway breakdown (RB in terminology [46]) or relativistic runaway electron avalanche (RREA in terminology [47]):

$$E_c = (2.16 - 2.84) \frac{kV}{cm} \exp \left( - \frac{z}{H} \right), \quad h \simeq 8 \text{ km}. \quad (13)$$

Such strong (and even stronger) fields are routinely observed in atmosphere using e.g. balloon measurements. Another important characteristic is the avalanche scale $l_a$ and the corresponding time scale $\tau_a$ for the exponential growth, which are numerically estimated as [46]:

$$l_a \simeq 50 \text{ m}, \quad \tau_a \simeq \frac{l_a}{c} \sim (\text{fraction of}) \ \mu s. \quad (14)$$

The characteristic scale $l_a$ represents the minimum length scale when the exponential growth of runaway avalanche occurs. The spatial scale $L_E$ of a electric field in thunderstorm must substantially exceed the scale $l_a$ for the exponential growth of the avalanche, i.e $L_E \gg l_a$ as argued in [46]. The scale $L_E$ essentially determines the allowed scale of the inhomogeneity and non-uniformity of a fluctuating electric field for the exponential growth to hold.

The electric field obviously shows strong temporal fluctuations (in particular, as a result of spatial inhomogeneities $\sim L_E$ in the system) with time scale $\tau_E$. One can estimate the corresponding parameter $\tau_E$ by proper rescaling $\sim (L_E/l_a)$ in comparison with computed value for $\tau_a$:

$$\tau_E \sim \left( \frac{L_E}{l_a} \right) \tau_a \sim (\text{few}) \ \mu s. \quad (15)$$

To conclude this short detour on lightning processes one should emphasize that it is not our goal to study this complicated physics. Rather, our goal is to overview some characteristics of the electric filed such as $E_c, L_E, \tau_E$ which are known to be present in the atmosphere under the thunderstorm because such phenomenon as lightning obviously exists in nature. In the next subsection we argue that these parameters nicely match the required parameters to explain the observed “mysterious bursts” observed by [1, 2] which are interpreted in this work as the AQN annihilation events under thunderstorm.

D. AQNs under thunderstorm

We are now prepared for the analysis of the AQN weakly coupled positrons (6) under influence of the pre-existing electric field characterized by parameters reviewed in subsection III.C. As previously mentioned we expect that in the atmosphere the finite portion of the positrons may be kicked off due to the elastic collisions with atmospheric molecules but another (also finite) portion of the positrons being also hit by heavy molecules still remain bound to the nugget at distances of order $R_{\text{cap}}$ determined by (7), which can be numerically estimated as:

$$R_{\text{cap}}(T) \simeq \frac{\alpha Q}{T} \sim 2 \text{ cm} \left( \frac{T}{10 \text{ keV}} \right)^{1/4}. \quad (16)$$

At this distance the bound positrons are characterized by potential and kinetic energies (with opposite signs, of course) of order $T$. However, the absolute value of the binding energy $|E_{\text{bound}}| \ll T$ could be much smaller than $T$ as a result of strong cancellation between these two contributions. Therefore, a sudden appearance of strong external electric field (13) along the AQN’s path will inject an additional energy $\Delta E$ estimated as

$$\Delta E \simeq [eE_c \cdot R_{\text{cap}}] \sim 2 \text{ keV} \gg E_{\text{bound}} \text{ at } t = 0. \quad (17)$$

This additional energy injection of order of several keV could liberate the weakly coupled positrons from the nuggets. At this initial moment $t = 0$ the positrons will have kinetic energy of order $\sim$ keV. It is very important that finite portion of the weakly bound positrons (to be estimated below) will be liberated almost instantaneously at the same time $t = 0$ when the AQN enters the region with strong electric field.

These liberated positrons find themselves in the background of strong electric field characterized by typical length scale $L_E \gtrsim 100$ m. This pre-existing field will accelerate them to MeV energies on time scale (15). Indeed,

$$E(\tau_E) \simeq [eE_c \cdot L_E] \sim 10 \text{ MeV at } \tau_E \simeq (\text{few}) \ \mu s. \quad (18)$$

All suddenly released positrons will obviously move in the same direction which is entirely determined by the direction of the electric field. Small angle in the velocity distribution at the exit point is determined by initial energy (17) which implies the presence of transverse component perpendicular to electric field: $v_\perp \simeq \sqrt{2\Delta E/m}$. Therefore, after travelling the distance $r$ the spatially spread range $\Delta r$ is estimated as

$$\Delta r \simeq \left( \frac{v_\perp}{c} \right) r \sim 0.6 \text{ km} \left( \frac{r}{10 \text{ km}} \right). \quad (19)$$

The key element in these estimates is that the fluctuating electric field has sufficient correlation length $L_E$ and strength $E_c$ which allow the positrons to accelerate to very large energies\textsuperscript{6}. Furthermore, this outbreak occurs on the time scale (15) determined by the properties

\textsuperscript{6} It is interesting to note that according to [47] the positrons play a key role in development of the avalanche in RREA framework due to much longer mean free path in comparison with electrons. The nature of positrons in our framework and in ref. [47] is completely different, of course.
of the electric field while the AQN itself remains at the same location as $L_{\text{event}} \ll L_E$ according to (12).

At the same time the scale $L_{\text{burst}} \gg L_{\text{event}}$ determines the number of distinct events which could occur within the same burst during 1 ms. Number of possible events is entirely determined by the features of pre-existing electric field along the AQN’s path. As we discussed above the field strongly fluctuates temporally (with time scale $\tau_E$) and spatially (with scale $L_E$). The event will be recorded by TASD if the electric field points in the direction of the detector within solid angle $\Omega$ subtended at the instant location of the nugget when emission occurs. The solid angle $\Omega \sim 1$ is always sufficiently large for distances $r \sim 10$ km. It remains true even for relatively large zenith angles (skim events).

We now estimate the portion $\eta$ entering eq. (11) of the affected positrons at the instant when the AQN enters the region of strong electric field $\sim E_c$. The idea is to estimate the ratio of the positrons with binding energies smaller than $\Delta E$ in comparison with total number of positrons with binding energy exceeding $\Delta E$ (which could not be liberated by electric field). Assuming the Boltzmann distribution when the typical binding energy is order of $T$ the estimate for $\eta$ reads:

$$\eta \sim \int_0^{\Delta E} \frac{d\epsilon}{d\epsilon} [e^{\epsilon/T}] \exp \left( \frac{-\epsilon}{T} \right) \sim \left( \frac{\Delta E}{T} \right)^{3/2} \sim 0.1 \left( \frac{10\text{keV}}{T} \right)^{3/2}, \quad (20)$$

where $\Delta E$ is proportional to electric field $\sim E_c$ as given by (17).

We conclude this section with the following generic remark. All estimates presented in this section are based on specific features of the electric field which are known to be present in thunderclouds. The same fields are known to be responsible for the lightening processes as well, which of course much more frequent and numerous events. However, the mechanism described above is not literally associated with lightening flashes. In particular, Fig 9 in [1] explicitly shows that some SD events occur earlier than lightning. Furthermore, some events are not related to the lightnings at all. These observations unambiguously imply that the “mysterious bursts” are associated with very initial processes (such as generation of strong electric field under thunderstorms), but not with lightning flashes themselves.

IV. “MYSTERIOUS BURSTS” PROPOSAL III CONFRONTS THE OBSERVATIONS [1, 2]

The goal of this section is to confront the theoretical ideas of the proposal (“Mysterious bursts as the AQN annihilation events” formulated in section III) with observations [1, 2]. We explain how the unusual features from items 1-7 listed in section I can be naturally understood within the AQN framework.

We start our discussions with item 1 from the list. In the AQN framework all positrons are emitted from the typical for thunderstorm altitude around 10 km which is obviously much lower than 30 km altitude when CR air shower normally starts. Furthermore, the events appear to be much more “curved” (see Figs. 3 and 4 in [1]) because the typical time scale (15) is determined by the pre-existing electric field and it could be few times longer than conventional ($1-2\mu$s) time scale typical for the CR air showers.

The same arguments also explain why the observed events do not have sharp edges (see Fig. 6 in [1]) as listed in item 2. The point is that all the liberated positrons have been accelerated on the time scale (15). These processes are not characterized by sharp edges as they are not related to any highly ultra-relativistic particles, in contrast with typical CR air showers.

The AQN traverses the distance $L_{\text{burst}}$ according to (12) during $\Delta t = 1$ ms representing the cluster of events in the AQN framework. This distance never exceeds 1 km. Furthermore, the spatial spread for each individual event within the same cluster also does not exceed 1 km according to (19). These estimates are perfectly consistent with item 3 which is extremely hard to explain in terms of conventional CR air showers.

The item 4 finds a very natural explanation within AQN proposal. Indeed, the intensity of the events within the burst is determined by (11) with the number of particles corresponding to $(10^{18} - 10^{19})$ eV energy range if analyzed in terms of conventional CR air shower event. However, in the AQN framework the number of particles is determined by the different parameters, such as internal temperature$^7$ of the nugget $T$, while the burst is considered to be the cluster of events originated from one and the same AQN traversing very short distance $L_{\text{burst}}$ during 1 ms.

According to item 5 all observed bursts occurred under thunderstorm. It is perfectly consistent with AQN framework because the thunderstorm with its pre-existing electric field (13) plays a crucial role in our mechanism as the electric field instantaneously liberates the positrons and also accelerates them up to 10 MeV energies.

It has been observed that all bursts occur at the same time of lightning or earlier than lightning, according to item 6, see Fig. 9 in [1]. Some bursts are not related to lightning at all. This observation unambiguously implies that the bursts are associated with processes which were present (such as fluctuating electric field) before lightning flashes may (or may not) occur. The AQN mechanism obviously satisfies this requirement as large number of particles (11) have been prepared long before the lightening flashes, and the electric field commonly present in thunderstorm plays role of a trigger liberating the large

$^7$ The corresponding AQN’s properties such as baryon charge $\langle B \rangle$, the temperature $T$ and the $Q$ have been previously computed for completely different purposes in different context. By no means we fitted these parameters to accommodate the observations.
number of the particles when the AQN enters the background electric field under thunderstorm.

The item 7 also finds its natural explanation within AQN proposal. The frequency of appearance of these “mysterious bursts” in our framework is determined by (10) which is perfectly consistent with the observed 10 events [1, 2]. Once again, the parameters which control the frequency of these events are mostly determined by the dark matter flux (4) expressed in terms of the AQN size distribution. These parameters have been fixed long ago for completely different purposes in different context. We did not attempt to fit these parameters to accommodate the observations [1, 2].

Furthermore, the injection energy $\Delta E$ as given by (17) is expressed in terms of thunderstorm parameter $E_c$ and also in terms of $T, Q$ which were computed long ago irrespectively to thunderstorm physics. Nevertheless, the obtained value for $\Delta E$ in keV energy range is precisely what is required to liberate the positrons and consequently accelerate them, see also footnote 7.

To summarize this section: We consider the multiple “numerical coincidences” listed above as strong supporting arguments for this proposal as all recorded features such as frequency of appearance (10), the observed intensity of the events within the bursts (11) as well as required value $\Delta E$ being in keV energy range are all expressed in terms of parameters covering very different fields of physics which span enormous range of scales. These scales include but not limited: the DM density $\rho_{DM}$, thunderstorm electric field $E_c$, microscopical parameter $T$, to name just few. It is very nontrivial self-consistency check that these parameters [from very distinct fields of physics, being fixed by fundamentally different observations] nicely “conspire” to produce very reasonable numerical estimates which are consistent with puzzling features 1-7 as recorded by [1, 2].

V. CONCLUSION

Our basic results can be summarized as follows. We argued that mysterious bursts (with highly unusual features as listed by items 1-7 in Introduction) of shower-like events observed by TASD [1, 2] are naturally interpreted as the cluster events generated by the AQNs propagating in thunderstorm environment. We presented our arguments in section IV where we explained how the puzzling features 1-7, item by item, naturally emerge in the AQN framework. There is no need to repeat these arguments again here in Conclusion, and we refer to the last paragraph of the previous section IV for the summary. Instead, we would like to describe two specific tests of this framework which can confirm, substantiate or refute our proposal.

• First of all, the time scale $\Delta t = 1$ ms as the definition for the burst is obviously an ad hoc parameter. We suggest to reanalyze the existing data to increase this parameter by factor (2-4). We would like to see if more events will be recorded within the same “prolongated burst”, and more new bursts will emerge which previously were not qualified as the bursts (because they had less than three consecutive events).

Our proposal predicts that the answer on both questions should be positive: there should be more events in previously recorded bursts, and it should be more new bursts being recorded if $\Delta t$ to be increased. In fact, it has been mentioned in [1] that there are several two-event bursts and many single events with features similar to the events within bursts. However they were not qualified as the bursts.

One should emphasize that this is a highly nontrivial prediction based on many specific features of our mechanism where the bursts are the cluster events generated by one and the same AQN traversing the thunderclouds in the area with typical DM velocity $\sim 10^{-3}c$. Therefore, its entire trajectory for “prolongated bursts” remains in the same area within the same $L_{burst} \lesssim 1$ km scale as discussed in section IV.

The interpretation in terms of conventional CR would remain very problematic even for larger $\Delta t$ as the chance of coincidence would remain to be very tiny. In fact the corresponding probability (estimated in [1]) could become even smaller as the number of qualified bursts likely to increase for “prolongated bursts” with $\Delta t > 1$ ms.

One should also note that the expansions plans [51] to increase the area up to 3000 km$^2$ to include 500 new SD counters would be a highly beneficial element for the present proposal as it should increase the frequency of appearance of qualified bursts to be observed with new facilities.

• The second test we suggest is to study the correlations with acoustic signals which always accompany the propagation of the AQNs in atmosphere as advocated in [41]. The main topic of that paper was the analysis of the infrasound and seismic acoustic waves which were recorded by Elginfield Infrasound Array (ELFO) and seismic stations near London, Ontario, Canada on July 31st 2008. It was considered as a very mysterious event as it was very different from conventional meteor like events as the synchronized all sky cameras did not observe any activities at that time. It has been shown in [41] that the intensity and the frequency of the infrasound and seismic waves are consistent with observed records if this event is interpreted in terms of the AQN framework. However, the recorded intensity of the infrasound signal corresponds to very large size AQN with $B \simeq 10^{27}$, which are very rare events (once in 10 years). Therefore it has been proposed a detection strategy to search for less intensity signals corresponding to common and typical $B \simeq 10^{25}$ by using Distributed Acoustic Sensing (DAS) instruments. Furthermore, it has been shown that using an amplifier chain one can extend the range of DAS unit to 82 km, while maintaining high signal quality.

The new element we are advocating in the present work is as follows. One can use the existing technology with DAS and install it in the same location where TASD
stands. It would allow to study the correlations between the bursts (interpreted as the cluster events within AQN framework) and small seismic event signals which would be recorded by DAS. An important point here is that DAS can in principle detect not only the intensity and the frequency of the sound wave, but also the direction of the source. This direction can be cross correlated with TASD which is also capable to reconstruct the source of the burst event.

We would like to make few comments on possible relation with some other observations. It has been mentioned in [52] that the observed by TASD gamma ray showers are similar in some respects to bursts [1] interpreted in the present work as the AQN annihilation events. Is there any relation between the two? It is hard to give an unambiguous answer due to a number of reasons: First, some bursts occur earlier than lightning, see item 6 in previous section IV; Secondly, some bursts are not related to lightnings at all. Nevertheless, all the bursts occur under thunderstorm. Therefore, the bursts cannot be literally associated with leader steps during the lightnings, which is precisely the interpretation of the observed TASD gamma ray showers suggested in [52].

In other words, naively these phenomena look differently as observed gamma ray showers [52] are always associated with downward negative lightning leaders during the first 1-2 ms, while some bursts [1] are not related to lightning at all. Still, there is a close similarity in frequency of appearance between the bursts and observed gamma ray showers [52]. This similarity suggests that these two phenomena could be in fact somehow related. However, it requires additional thoughts and analysis to arrive to a more definite conclusion, which is the topic for future studies.

We summarize this Conclusion with the following comment. The estimates of the present work are entirely based on the AQN framework. Why should one take this model seriously? This is because the originally, this model was invented for completely different purposes in order to explain the observed fundamental relation \( \Omega_{\text{DM}} \sim \Omega_{\text{visible}} \), as reviewed in the Introduction. It was not invented to explain the “mysterious bursts” which is the topic of the present work. This model is shown to be consistent with all available cosmological, astrophysical, satellite and ground-based constraints with one and the same set of parameters, see Section II for the references.

Furthermore, the same AQN framework may also explain a number of other (naively unrelated) observed puzzles such as excess of the galactic diffuse emission in different frequency bands, the so-called “Primordial Lithium Puzzle”, “The Solar Corona Mystery”, the DAMA/LIBRA puzzling annual modulation, and some mysterious explosions, see Section II for the references. We also refer to the presentation (four hour talk) [53] for a general overview of the AQN framework during the “Axion Cosmology” program in Munich which was the latest face to face MIAPP meeting, just few weeks before covid-19 restrictions were imposed.

Our present proposal suggests that the bursts with very unusual features as recorded by TASD [1, 2] may be in fact the AQN annihilation events under thunderstorm. If this interpretation is confirmed by future studies it would be the first direct (non-gravitation) evidence which reveals the nature of the DM.

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Appendix A: The AQN internal temperature under thunderstorm

The goal of this Appendix is to overview the basic characteristic of the AQNs, the internal temperature \( T \) which enters several formulae in Section II C in the main text. The corresponding computations have been carried out in [32] in application to the galactic environment with a typical density of surrounding visible baryons of order \( n_{\text{galaxy}} \sim 300 \text{ cm}^{-3} \) in the galactic center. We review these computations with few additional elements which must be implemented for Earth’s atmosphere when typical density of surrounding baryons is much higher \( n_{\text{air}} \sim 30 N_m \sim 10^{21} \text{ cm}^{-3} \), where \( N_m \sim 2.7 \cdot 10^{19} \text{ cm}^{-3} \) is the molecular density in atmosphere when each molecule contains approximately 30 baryons.

The total surface emissivity from electrosphere has been computed in [32] and it is given by

\[
F_{\text{tot}} \simeq \frac{16}{3} \frac{T^4}{\pi} \left( \frac{\alpha}{m} \right)^{3/2} \sqrt{\frac{T}{m}} \tag{A1}
\]

A typical internal temperature of the nuggets can be estimated from the condition that the radiative output of equation (A1) must balanced the flux of energy onto the nugget due to the annihilation events. In this case we may write,

\[
F \simeq \left( 4 \pi R^2 \right) \frac{16}{3} \frac{T^4}{\pi} \left( \frac{\alpha}{m} \right)^{3/2} \sqrt{\frac{T}{m}} + \Delta F_{\text{other}} \tag{A2}
\]

where the left hand side accounts for the total energy radiation from the nuggets’ surface per unit time as given by (A1) plus other processes denoted as \( \Delta F_{\text{other}} \) to be discussed below. The right hand side accounts for the rate of annihilation events when each successful annihilation event of a single baryon charge produces \( \sim 2m_p c^2 \sim 2 \text{ GeV energy} \). In Eq. (A2) we assume that the nugget is characterized by the geometrical cross section \( \pi R^2 \) when it propagates in environment with local density \( n_{\text{air}} \) with velocity \( v_{\text{AQN}} \sim 10^{-3} c \).

The factor \( \kappa \) is introduced to account for the fact that not all matter striking the nugget will annihilate and not
all of the energy released by an annihilation will be thermalized in the nuggets. In particular, some portion of the energy will be released in form of the axions, neutrinos and liberated positrons by the mechanism discussed in the main text of this work. This portion is represented by $\Delta F_{\text{other}}$. The parameter $\kappa$ was estimated for the galactic environment in [32]. This parameter obviously must be different for the earth’s atmosphere. However, for the order of magnitude estimates we ignore this difference.

As such $\kappa$ encodes a large number of complex processes including the probability that not all atoms and molecules are capable to penetrate into the color superconducting phase of the nugget to get annihilated. Furthermore, some positrons can be liberated due to the pre-existing electric field in thunderclouds as discussed in the main text of this work. Furthermore, there is another complication as the AQN moves with supersonic velocity. This generates the shock waves and turbulence in earth’s atmosphere, which makes the computations even more complicated.

In a neutral dilute environment considered previously [32] the value of $\kappa$ cannot exceed $\kappa \lesssim 1$ which would correspond to the total annihilation of all impacting matter into to thermal photons. The high probability of reflection at the sharp quark matter surface lowers the value of $\kappa$. The propagation of an ionized (negatively charged) nugget in a highly ionized plasma (such as solar corona) will increase the effective cross section. As a consequence, the value of $\kappa$ could be very large as discussed in [35] in application to the solar corona heating problem.

The propagation of the AQNs under thunderstorm, which is the topic of the present studies, is an intermediate case between these two previous studies. We shall argue below that ionization effects can be ignored in this case. Furthermore, extra term $\Delta F_{\text{other}}$ related to the positron’s liberation under the thunderstorm (which is a new effect not considered previously) also does not modify our estimates. Therefore, one can estimate a typical internal nugget’s temperature in the Earth atmosphere at altitude $\sim 10$ km as follows:

$$ T \simeq 15\text{ keV} \cdot \left(\frac{N_m}{10^{19}\text{ cm}^{-3}}\right)^{\frac{1}{2}} \left(\frac{\kappa}{0.1}\right)^{\frac{1}{2}}, \quad (A3) $$

which represents a typical internal temperature of the AQNs relevant for the present work. All the uncertainties related to $\kappa$ mentioned above do not modify our qualitative discussions in this work.

In this rest of the Appendix we would like to argue that the ionization features of the nuggets and the environment do not modify our estimates. First, we estimate the kinetic energy of the molecules in the AQN frame:

$$ E_{\text{kinetic}} \simeq \frac{(30\text{ GeV}) \cdot v_{\text{AQN}}^2}{2} \simeq 15\text{ keV}, \quad (A4) $$

which is numerically the same order of magnitude as the internal temperature of the nuggets (A3). Therefore, the typical distance where the positive ions (which always present under the thunderstorm) can modify the annihilation rate assumes the value estimated in (16) and coined as the $R_{\text{cap}}$.

The density of ions $N_i$ under normal conditions is estimated as $N_i \simeq 10^3\text{ cm}^{-3}$ while under RB conditions it could be as high as $N_i \simeq (5 - 8) \cdot 10^4\text{ cm}^{-3}$ according to [46]. Therefore, the extra term due to the ionization features of the environment can be represented as follows

$$ (N_m R^2 + N_i R_{\text{cap}}^2) = N_m R^2 \left[1 + \frac{N_i}{N_m} \left(\frac{R_{\text{cap}}}{R}\right)^2 \right]. \quad (A5) $$

One can check that the correction proportional to $N_i$ numerically is at least 4 orders of magnitude smaller than the main term, and therefore, can be ignored, which a posteriori justifies our approximation.

Now we would like to argue that another assumption we made when we ignored $\Delta F_{\text{other}}$ related to the liberated positrons (due to the presence of electric field during the thunderstorms) is also justified. Indeed, the number of direct collisions of the molecules with AQN per unit time can be estimated as follows:

$$ \frac{dN_{\text{collisions}}}{dt} \simeq (\pi R^2) \cdot N_m \cdot v_{\text{AQN}} \simeq 0.3 \cdot 10^{18} \left(\frac{N_m}{10^{19}\text{ cm}^{-3}}\right) \text{ s}^{-1}. \quad (A6) $$

The dominant portion of these collisions are the elastic scattering processes rather than successful annihilation events suppressed by parameters $\kappa$ as discussed above. Some of these elastic collisions lead to the energy transfer to the positrons from electro-sphere, which also relatively rare events. Some positrons, may even leave the system as a result of the collisions with rate (A6) under influence of the strong electric field as discussed in this work. However, even if one assumes that every single collision event (A6) liberates a positron as a result of electric field lasting a $\mu$s one would get 0.5 MeV energy lost per a single collision, while the annihilation energy gain is 3 orders of magnitude higher as it is proportional $\kappa$ GeV per collision. Therefore, the term $\Delta F_{\text{other}}$ which enters the equation for the energetic balance (A2) and related to the liberated positrons indeed can be ignored. This justifies our approximation a posteriori.

[1] R. Abbasi et al. (Telescope Array Project), Phys. Lett. A 381, 2565 (2017).

[2] T. Okuda, Journal of Physics: Conference Series 1181, 012067 (2019).
