

Quark (Anti)Nugget Dark Matter

Kyle Lawson and Ariel R. Zhitnitsky

Department of Physics & Astronomy, University of British Columbia, Vancouver, B.C. V6T 1Z1, Canada

We review a testable dark matter model outside of the standard WIMP paradigm in which the observed ratio $\Omega_{\text{dark}} \simeq 5 \cdot \Omega_{\text{visible}}$ for visible and dark matter densities finds its natural explanation as a result of their common QCD origin. Special emphasis is placed on the observational consequences of this model and on the detection prospects for present or planned experiments. In particular, we argue that the relative intensities for a number of observed excesses of emission (covering more than 11 orders of magnitude) can be explained by this model without any new fundamental parameters as all relative intensities for these emissions are determined by standard and well established physics.

I. QCD AS A SINGLE SOURCE FOR DARK MATTER AND VISIBLE BARYONS

In this proposal we argue that two of the largest open questions in cosmology, the origin of the matter/antimatter asymmetry and the nature of the dark matter (DM), may have their origin within a single theoretical framework. Furthermore, both effects may originate at the same cosmological epoch from one and the same QCD physics.

It is generally assumed that the universe began in a symmetric state with zero global baryonic charge and later, through some baryon number violating process, evolved into a state with a net positive baryon number. As an alternative to this scenario we advocate a model in which “baryogenesis” is actually a charge separation process in which the global baryon number of the universe remains zero. In this model the unobserved antibaryons come to comprise the dark matter. A connection between dark matter and baryogenesis is made particularly compelling by the similar energy densities of the visible and dark matter with $\Omega_{\text{dark}} \simeq 5 \cdot \Omega_{\text{visible}}$. If these processes are not fundamentally related the two components could exist at vastly different scales.

In this model baryogenesis occurs at the QCD phase transition. Both quarks and antiquarks are thermally abundant in the primordial plasma but, in addition to forming conventional baryons, some fraction of them are bound into heavy nuggets of quark matter in a colour superconducting phase. Nuggets of both matter and antimatter are formed as a result of the dynamics of the axion domain walls [1, 2], some details of this process will be discussed in section II. Were CP symmetry to be exactly preserved an equal number of matter and antimatter nuggets would form resulting in no net “baryogenesis”. However, CP violating processes associated with the axion θ term in QCD result in the preferential formation of antinuggets¹. At the phase transition $\theta \sim 1$ and

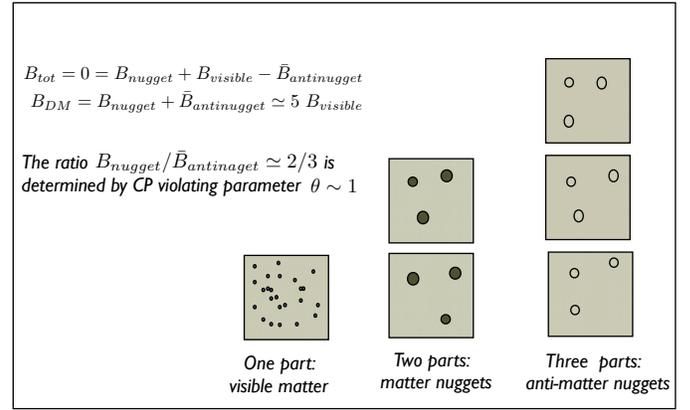


FIG. 1. Matter in the Universe. A model which explains both the matter -antimatter asymmetry and the observed ratio of visible matter and DM

all asymmetry effects would have been order one while during the present epoch, long after the phase transition, this source of CP violation is no longer available. The remaining antibaryons in the plasma then annihilate away leaving only the baryons whose antimatter counterparts are bound in the excess of antinuggets and thus unavailable to annihilate. The observed matter to dark matter ratio results if the number of antinuggets is larger than number of nuggets by a factor of $\sim 3/2$ at the end of nugget formation. This would result in a matter content with baryons, quark nuggets and antiquark nuggets in an approximate ratio

$$B_{\text{visible}} : B_{\text{nuggets}} : B_{\text{antinuggets}} \simeq 1 : 2 : 3, \quad (1)$$

and no net baryonic charge, as sketched on Fig.1.

Unlike conventional dark matter candidates, dark-matter/antimatter nuggets are strongly interacting but

¹ This preference is essentially determined by the sign of θ . Note, that the idea of a charge separation mechanism resulting from local violation of CP invariance through an induced θ_{ind} can be experimentally tested at the Relativistic Heavy Ion Collider (RHIC) and the LHC. We include a few comments and relevant

references, including some references to recent experimental results supporting the basic idea, in section V.

macroscopically large. They do not contradict the many known observational constraints on dark matter or anti-matter for three main reasons [3]:

- They carry a huge (anti)baryon charge $|B| \gtrsim 10^{25}$, and so have an extremely tiny number density;
- The nuggets have nuclear densities, so their effective interaction is small $\sigma/M \sim 10^{-10} \text{ cm}^2/\text{g}$, well below the typical astrophysical and cosmological limits which are on the order of $\sigma/M < 1 \text{ cm}^2/\text{g}$;
- They have a large binding energy such that the baryon charge in the nuggets is not available to participate in big bang nucleosynthesis (BBN) at $T \approx 1 \text{ MeV}$.

To reiterate: the weakness of the visible-dark matter interaction in this model due to the small geometrical parameter $\sigma/M \sim B^{-1/3}$ rather than due to the weak coupling of a new fundamental field to standard model particles. It is this small effective interaction $\sim \sigma/M \sim B^{-1/3}$ which replaces the conventional requirement of sufficiently weak interactions for WIMPs.

An fundamental measure of the scale of baryogenesis is the baryon to entropy ratio at the present time

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq \frac{n_B}{n_\gamma} \sim 10^{-10}. \quad (2)$$

If the nuggets were not present after the phase transition the conventional baryons and anti-baryons would continue to annihilate each other until the temperature reaches $T \simeq 22 \text{ MeV}$ when density would be 9 orders of magnitude smaller than observed. This annihilation catastrophe, normally thought to be resolved as a result of ‘‘baryogenesis,’’ is avoided in our proposal because more anti-baryons than baryons are hidden in the form of the macroscopical nuggets and thus no longer available for annihilation. Only the visible baryons (not anti-baryons) remain in the system after nugget formation is fully completed.

In our proposal (in contrast with conventional models) the ratio η is determined by the formation temperature T_{form} at which the nuggets and anti-nuggets basically have competed their formation and below which annihilation with surrounding matter becomes negligible. This temperature is determined by many factors: transmission/reflection coefficients, evolution of the nuggets, expansion of the universe, cooling rates, evaporation rates, the dynamics of the axion domain wall network, etc. In general, all of these effects will contribute equally to determining T_{form} at the QCD scale. Technically, the corresponding effects are hard to compute as even basic properties of the QCD phase diagram at nonzero θ are still unknown. However, an approximate estimate of T_{form} is quite simple as it must be expressed in terms of the gap $\Delta \sim 100 \text{ MeV}$ when the colour superconducting phase sets in inside the nuggets. The observed ratio (2) corresponds to $T_{\text{form}} \simeq 41 \text{ MeV}$ which is indeed a typical QCD scale slightly below the critical

temperature $T_c \simeq 0.6\Delta$ when colour superconductivity sets in.

In different words, in this proposal the ratio (2) emerges as a result of the QCD dynamics when process of charge separation stops at $T_{\text{form}} \simeq 41 \text{ MeV}$, rather than a result of baryogenesis when a net baryonic charge is produced.

II. QUARK (ANTI)NUGGETS AS DARK MATTER

The majority of dark matter models assume the existence of a new fundamental field coupled only weakly to the standard model particles, these models may then be tuned to match the observed dark matter properties. We take a different perspective and consider the possibility that the dark matter is in fact composed of well known quarks and antiquarks but in a new high density phase, similar to the Witten’s strangelets [4]. The only new crucial element in comparison with previous studies based on Witten’s droplets [4] is that the nuggets could be made of matter as well as antimatter in our framework, and the stability of the DM nuggets is provided by the axion domain walls [1].

Though the QCD phase diagram at $\theta \neq 0$ is not known, it is well understood that θ is in fact the angular variable, and therefore supports various types of the domain walls, including the so-called $N = 1$ domain walls when θ interpolates between one and the same physical vacuum state $\theta \rightarrow \theta + 2\pi$. While such domain walls are formally unstable, their life time could be much longer than life time of the universe. Furthermore, it is expected that closed bubbles made of these $N = 1$ axion domain walls are also produced during the QCD phase transition with a typical correlation length $\sim m_a^{-1}$ where m_a is the axion mass. The $N = 1$ axion domain walls are unique in a sense that they might be formed even in case of inflation which normally prevents the generation of any other types of topological defects.

The collapse of these closed bubbles is halted due to the fermi pressure acting inside of the bubbles as sketched on Fig. 2. The equilibrium of the obtained system has been analyzed in [1] for a specific axion domain wall with tension $\sigma_a \simeq 1.8 \cdot 10^8 \text{ GeV}^3$ which corresponds to $m_a \sim 10^{-6} \text{ eV}$. For these axion parameters it has been found that a typical baryon charge of the nugget is $B \sim 10^{32}$ while a typical size of the nugget is $R \sim 10^{-3} \text{ cm}$. Using the dimensional arguments one can easily infer that these parameters scale with the axion mass as follows

$$\sigma_a \sim m_a^{-1}, \quad R \sim \sigma_a, \quad B \sim \sigma_a^3. \quad (3)$$

Therefore, when the axion mass m_a varies within the observationally allowed window $10^{-6} \text{ eV} \leq m_a \leq 10^{-3} \text{ eV}$, see e.g. reviews [6, 7], the corresponding nuggets parameters also vary as follows

$$10^{-6} \text{ cm} \lesssim R \lesssim 10^{-3} \text{ cm}, \quad 10^{23} \lesssim B \lesssim 10^{32}. \quad (4)$$

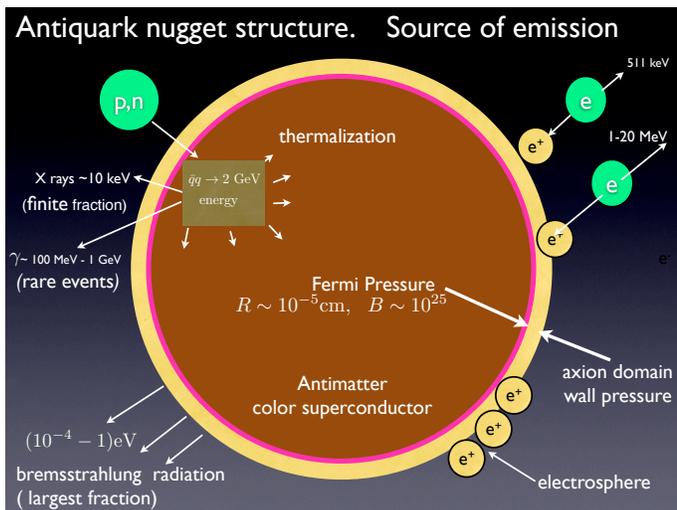


FIG. 2. (Anti)nugget internal structure and sources of emission from the core of the galaxy.

The corresponding allowed region is essentially uncovered by present experiments, see Fig.5 from section IV.

While the observable consequences of this model are strongly suppressed by the low number density of the quark nuggets the interaction of these objects with the visible matter of the galaxy will necessarily produce observable effects. Any such consequences will be largest where the densities of both visible and dark matter are largest such as in the core of galaxies or the early universe. The nuggets essentially behave as conventional cold DM in an environment where the surrounding density is small, while in environments of sufficiently large density they begin interacting and emitting radiation (i.e. effectively become visible matter) when they are placed in an environment of sufficiently large density².

We emphasize that the phenomenologically relevant features of the nuggets are determined by properties of the surface layer of electrons (or positrons in the case of an antimatter nugget) known as the electrosphere as sketched on lower right corner of Fig.2. These proper-

² In this short review we concentrate on the phenomenological consequences of anti-nuggets which can act as additional radiation sources as a result of rare annihilation events, see sections III, IV for some details. Matter nuggets may also be phenomenologically interesting as they will occasionally be captured by astronomical objects. Captured matter nuggets will behave very differently from strangelets [4] because the nuggets do not convert the entire surrounding object into strange matter. Rather, the high density regions inside any object will remain a finite size (4) with the quark matter extending to eventually become normal nuclear matter at lower densities, as in studies of possible colour superconducting cores of neutron stars. The possibility that standard astronomical objects may have a small quark matter core implies that some objects may be observed to have a much higher density than typically assumed, see e.g. [5] and the many references therein on some observational consequences of high density objects dressed by a normal matter.

ties are in principle, calculable from first principles using only the well established rules of QCD and QED. As such the model contains no tunable fundamental parameters, except for a single mean baryon number $\langle B \rangle$ which is hard to compute theoretically as it depends on all complications mentioned above such as QCD phase diagram at $\theta \neq 0$, formation and evolution of the nuggets, etc. This parameter $\langle B \rangle \sim 10^{25}$ is fixed in our proposal assuming that anti-nuggets saturate the observed 511 keV line from the centre of galaxy, see next section III.

III. ASTROPHYSICAL OBSERVATIONS

A comparison between different observations of emission from the centre of galaxy is possible because the rate of annihilation events is proportional to $n_{\text{visible}}(r)n_{\text{DM}}(r)$ -the product of the local visible and DM distributions at the annihilation site. The observed fluxes for different emissions thus depend on one and the same line-of-sight integral

$$\Phi \propto R^2 \int d\Omega dl [n_{\text{visible}}(l) \cdot n_{\text{DM}}(l)], \quad (5)$$

where $R \sim B^{1/3}$ is a typical size of the nugget which determines the effective cross section of interaction between DM and visible matter. As $n_{\text{DM}} \sim B^{-1}$ the effective interaction is strongly suppressed $\sim B^{-1/3}$ as we already mention in section I. The average baryonic charge B of the nuggets is the only unknown parameter of the model. It is determined by the properties of the axion as reviewed in section II. In what follows we fix Φ from (5) for all galactic emissions considered below by assuming that our mechanism saturates 511 keV line as discussed below. It corresponds to an average baryon charge $B \sim 10^{25}$ for a typical density distributions $n_{\text{visible}}(r), n_{\text{DM}}(r)$ entering (5). Other emissions from different bands are expressed in terms of the same integral (5), and therefore, the relative intensities are completely determined by the internal structure of the nuggets which is described by conventional nuclear physics and basic QED.

We emphasize that this proposal makes a very non-trivial prediction: the morphology of all the different diffuse emission sources discussed below must be very strongly correlated. Furthermore, in this framework all emissions from different bands are proportional to $\int dl [n_{\text{visible}}(l) \cdot n_{\text{DM}}(l)]$, which should be contrasted with many other DM models in which the intensities of predicted emissions are proportional to $\int dl n_{\text{DM}}^2(l)$ for annihilating DM models or $\int dl n_{\text{DM}}(l)$ for decaying DM models.

There are a number of frequency bands in which an excess of emission, not easily explained by conventional astrophysical sources has been observed. These include:

a) The SPI/INTEGRAL observatory detects a stronger than expected 511 keV line associated with the galactic centre [8].

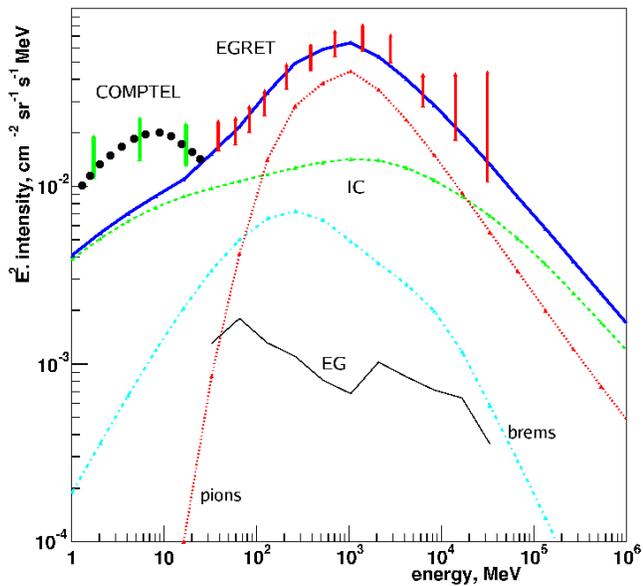


FIG. 3. γ ray spectrum of inner galaxy. Green vertical bars: COMPTEL data. Solid blue line: expected total emission due to a combination of conventional astrophysical sources. Heavy black dots: calculated emission spectrum from electron-nugget annihilation processes, taken from [15].

b) The COMPTEL satellite observes an excess in 1-30 MeV γ -rays [9], see green vertical bars on Fig.3.

c) In the x-ray range CHANDRA observed a ~ 10 keV plasma associated with the galactic centre. This plasma has no clear heating mechanism and is too energetic to remain bound to the galaxy [10].

d) In the microwave range WMAP observes a “haze” associated with the foreground galaxy [11].

e) At temperatures below the CMB peak ARCADE2 has measured a sharp rise in the isotropic radio background suggesting an additional source of radiation present in the universe before the formation of large scale structure [12], see data points on Fig.4.

The interaction between the nuggets and their environment is governed by well known nuclear physics and basic QED. As such their observable properties contain relatively few tunable parameters allowing several strong tests of the model to be made based on galactic observations. It is found that the presence of quark nugget dark matter is not merely allowed by present observations but that the overall fit to the diffuse galactic emission spectrum across many orders of magnitude in energy may be improved by their inclusion. To be more specific, in our proposal the excesses of emissions are explained as follows:

a) The galactic electrons incident on an antiquark nugget annihilate with the surrounding positron layer through resonance positronium (Ps) formation. This results in the 511 keV line with a typical width of order \sim few keV accompanied by the conventional continuum

due to 3γ decay [13, 14], sketched on right upper corner on Fig.2. The distribution $[n_{\text{visible}} \cdot n_{DM}]$ from eq. (5) implies that the predicted emission will be asymmetric, with extension into the disk from the galactic center as it tracks the visible matter. There appears to be evidence for an asymmetry of this form [8].

b) Some galactic electrons are able to penetrate to a sufficiently large depth as shown on right upper corner on Fig.2. Positrons closer to the quark matter surface can carry energies up to the nuclear scale. These events no longer produce the characteristic positronium decay spectrum but a direct non-resonance $e^-e^+ \rightarrow 2\gamma$ emission spectrum [15]. The transition between these two regimes is determined by conventional physics and allows us to compute the strength and spectrum of the MeV scale emissions relative to that of the 511 keV line [16]. Observations by the COMPTEL satellite indeed show an excess above the galactic background [9] consistent with our estimates, see heavy black dots on Fig. 3. We emphasize that the ratio between these two emissions is determined by well established physics. This ratio is highly sensitive to the positron density in electrosphere (shown on right lower corner on Fig.2) which has highly nontrivial behaviour. It was computed using Thomas-Fermi approximation [16] to estimate the spectrum in MeV band shown on Fig.3.

c) Galactic protons incident on the nugget will penetrate some distance into the quark matter before annihilating into hadronic jets sketched on left upper corner on Fig.2. This process results in the emission of Bremsstrahlung photons at x-ray energies [17]. Observations by the CHANDRA observatory indeed indicate an excess in x-ray emissions from the galactic centre [10] with the intensity and spectrum consistent with our estimates [17].

d) Hadronic jets produced deeper in the nugget or emitted in the downward direction will be completely absorbed. They eventually emit thermal photons with radio frequencies contributing to the WMAP haze sketched on left lower corner on Fig.2. Again the relative scales of these emissions may be estimated and is found to be in agreement with their observed levels, see [18] for the details.

e) The source of the emission discussed above with radio frequencies contributing to the WMAP haze sketched on left lower corner on Fig.2 is also quite active at earlier times at $z \sim 10^3$ when the densities of the particles are about the same order of magnitude as in the center of galaxy at present time. The analysis [19] finds that at energies near the CMB peak the nugget contribution to the radio background is several orders of magnitude below that of the thermal CMB spectrum. However the CMB spectrum falls off at frequencies below peak much faster than that of the nuggets such that, at frequencies below roughly a GHz, they come to dominate the isotropic radio background. As such the presence of dark matter in the form of quark nuggets offers a potential explanation of the radio excess observed by ARCADE2, as shown on

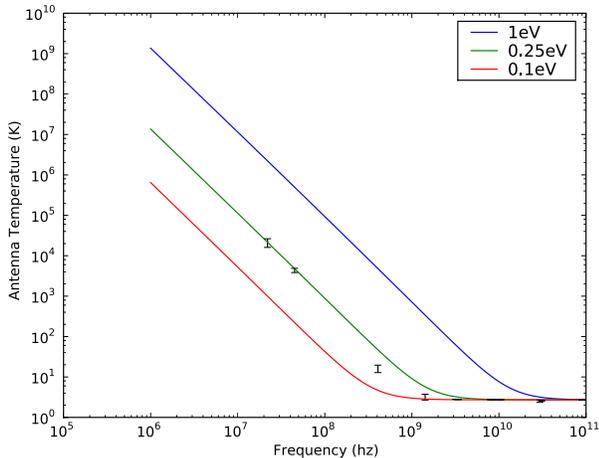


FIG. 4. Predicted antenna temperature assuming that the quark nuggets have a temperature of 0.1eV, 0.25eV and 1eV at the time of CMB formation. Also plotted are the data points from the radio band observations. Taken from [19]

Fig. 4.

These apparent excess emission sources have been cited as possible support for a number of dark matter models as well as other exotic astrophysical phenomenon. At present however they remain open matters for investigation and, given the uncertainties in the galactic spectrum and the wide variety of proposed explanations are unlikely to provide clear evidence in the near future. Therefore, we turn to direct detection prospects of such objects.

IV. DIRECT DETECTION PROSPECTS

Given the uncertainties associated with galactic backgrounds a complementary direct detection approach is necessary. While direct searches for weakly interacting dark matter require large sensitivity a search for high mass dark matter requires large area detectors. If the dark matter consists of quark nuggets at the $B \sim 10^{25}$ scale they will have a flux of

$$\frac{dN}{dA dt} = nv \approx \left(\frac{10^{25}}{B} \right) \text{km}^{-2} \text{yr}^{-1} \quad (6)$$

While this flux is far below the sensitivity of conventional dark matter searches it is similar to the flux of cosmic rays near the GZK limit. As such present and future experiments investigating ultrahigh energy cosmic rays may also serve as search platforms for dark matter of this type.

A nugget of dark matter impacting the earth's atmosphere will annihilate the line of atmospheric molecules in it's path heating the nugget and depositing energy in the atmosphere. For a nugget with a radius of 10^{-5}cm

the annihilation of all molecules along it's path would result in the annihilation of 10^{-10}kg of matter and generate $\sim 10^7 J$ substantially more than a conventional UHECR though much of this energy is actually thermalized within the nugget. The majority of this energy is produced by nuclear annihilations occurring within the nugget, the hadronic components released in these events remain bound to the quark matter and thermalize within it before they are able to escape into the atmosphere. While they are less strongly bound electrons are unable to escape through the dense positron layer at the nugget surface and are also thermalized. As such the emission from the nuggets is dominated by relativistic muons and thermal photons.

Recent work has considered the possibility that large scale cosmic ray detectors may be capable of observing quark nuggets passing through the earth's atmosphere either through the extensive air shower such an event would trigger [20] or through the geosynchrotron emission generated by the large number of secondary particles [21]. It has also been suggested that the ANITA experiment may be sensitive to the radio band thermal emission generated by these objects as they pass through the antarctic ice [22]. These experiments may thus be capable of adding direct detection capability to the indirect evidence discussed above in section III.

On entering the earth's crust the nugget will continue to deposit energy along its path, however this energy is dissipated in the surrounding rock and is unlikely to be directly observable. Generally the nuggets carry sufficient momentum to travel directly through the earth and emerge from the opposite side however a small fraction may be captured and deposit all their energy. In [22] the possible contribution of energy deposited by quark nuggets to the earth's thermal budget was estimated and found to be consistent with observations.

The muonic component of the shower is particularly important as it drives an extensive air shower surrounding the quark nugget. This shower will be similar to those initiated by an ultrahigh energy proton or nucleus, as both arise from a large number of hadronic cascades, but with some important distinctions. The most important distinction arises from the fact that the quark nugget remains intact as it traverses the atmosphere and continues to produce new secondary particles all the way to the surface. This introduces a fundamentally new timescale into the air shower as the nuggets move significantly slower than the speed of light. For nuggets with typical galactic scale velocities this implies a slower duration on the millisecond scale a thousand times longer than that of a standard cosmic ray event.

As with air showers initiated by a single ultra high energy primary these showers may be detected through atmospheric fluorescence, surface particle detectors or the emission of geosynchrotron radiation in the radio band. For a more extensive discussion of the phenomenology of quark matter induced shower see [20], [21]. Both the Pierre Auger Observatory and Telescope Array should, in

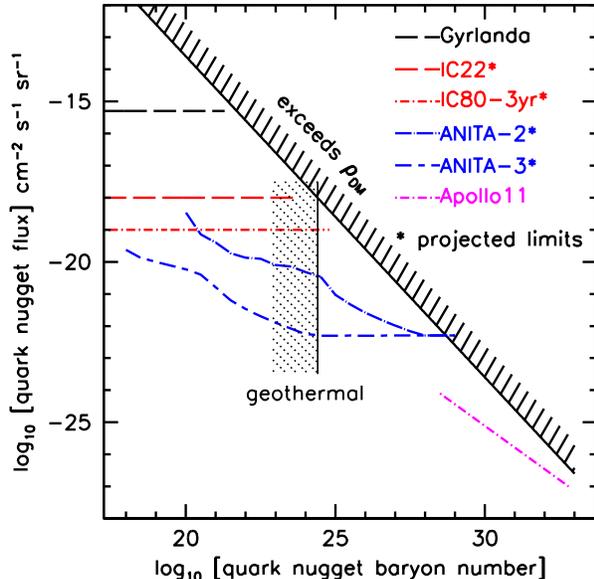


FIG. 5. Limits on quark nugget mass and density based on current constraints and ANITA data currently under analysis. Taken from [22].

principle, be capable of placing significant constraints on the flux of quark nuggets as will the JEM-EUSO experiment when it begins taking data. In all cases sensitivity to these events will require the analysis of data for events with millisecond scale durations.

A second important differentiating feature of the air shower initiated by a quark nugget is the fact that it will contain a thermal component emitted from the nugget surface. This temperature will rise with the surrounding density and be emitted uniformly in all directions. This distinctly contrasts with the highly beamed Cherenkov and geosynchrotron radiation associated with traditional cosmic ray showers and extending over a much wider frequency range than atmospheric fluorescence. At large surrounding densities the nugget temperature can easily reach the keV scale and contribute significantly to the total emission. In particular the signal from a nugget moving through the radio transparent antarctic ice will be dominantly thermal. The ANITA experiment is sensitive to this radio component and the analysis of presently collected data should be able to constrain the presence of quark nugget dark matter across a significant section of parameter space [22] as shown in Fig. 5.

V. CONCLUSION

The model which is advocated in the present review was originally invented as a simple and natural expla-

nation of the observed relation: $\Omega_{\text{dark}} \simeq 5 \cdot \Omega_{\text{visible}}$ by postulating that both elements originated from one and the same QCD scale. The immediate consequence of this proposal is the presence of antimatter in a form of macroscopically large anti-nuggets. An equal portion of matter and antimatter in our universe does not contradict the conventional and naive arguments on the near absence of antimatter observed in our universe as explained in section I.

It turns out that this dark matter proposal as a byproduct of baryogenesis may explain a number of apparently unrelated puzzles relating to diffuse emission observed in many bands as reviewed in section III. All these puzzles strongly suggest (independently) the presence of some source of excess diffuse radiation from the centre of galaxy in bands ranging over 11 orders of magnitude in frequency. Furthermore, the same dark matter model can also explain the isotropic background observed by ARCADE2 in the radio bands. In this case the emission originates primarily from very early times with $z \sim 10^3$ in contrast with our previous applications to the excess in galactic emissions. It should be emphasized that all relative intensities of diffuse radiation in this proposal are fixed as they are determined by conventional physics. The absolute normalization is expressed in terms of a single unknown parameter: the average size of the nugget, or identically, the average baryon charge $B \sim 10^{25}$, which itself is determined by the axion parameters as explained in section II.

Observation of any morphological correlations between the different excesses in diffuse emission mentioned in section III would strongly support this proposal as it is difficult to imagine how such a correlation may emerge in any other model (which are typically designed to explain an excess of emission in a single specific frequency band).

In addition to this type of indirect observational support this model is also amenable to direct observational tests. As outlined in section IV several large scale experiments both, active and planned, have the ability to observe the small but non-zero flux of antimatter through the earth. In particular large scale cosmic ray detectors intended to study the cosmic rays near the GZK scale are currently probing a flux scale comparable to that of quark antinuggets. The passage of an antinugget through the atmosphere will produce both electromagnetic radiation and a secondary particle shower that should be observable to a range of cosmic ray detectors. The detection and identification of these event will require the analysis of data over the millisecond scale typical of a nugget crossing the atmosphere (or other large targets such as the antarctic ice).

Finally, what is perhaps more remarkable is the fact that the key assumption of this dark matter model, the charge separation effect reviewed in sections I and II, can be experimentally tested in heavy ion collisions, where a similar \mathcal{CP} odd environment with $\theta \sim 1$ can be achieved, see section IV in ref.[23] for the details. In particular, the local violation of the \mathcal{CP} invariance observed at RHIC

(Relativistic Heavy Ion Collider)[24] and LHC (Large Hadron Collider)[25] have been interpreted in [23, 26, 27] as an outcome of a charge separation mechanism in the presence of the induced $\theta \sim 1$ resulting from a collision. The difference is of course that \mathcal{CP} odd term with $\theta \sim 1$ discussed in cosmology describes a theory on the horizon scale, while $\theta \sim 1$ in heavy ion collisions is correlated on a size of the colliding nuclei.

ACKNOWLEDGEMENTS

We are thankful to participants of the Cosmic Frontier Workshop (CF3 and CF6 groups), SLAC, March 2013,

at which this proposal was presented, for their numerous questions and useful discussions. This research was supported in part by the Natural Sciences and Engineering Research Council of Canada.

-
- [1] A. R. Zhitnitsky, JCAP **0310**, 010 (2003) [hep-ph/0202161].
- [2] D. H. Oaknin and A. Zhitnitsky, Phys. Rev. D **71**, 023519 (2005) [hep-ph/0309086].
- [3] A. Zhitnitsky, Phys. Rev. D **74**, 043515 (2006) [astro-ph/0603064].
- [4] E. Witten, Phys. Rev. D **30**, 272 (1984).
- [5] L. Labun, J. Birrell and J. Rafelski, Phys. Rev. Lett. **110**, 111102 (2013) [arXiv:1104.4572 [astro-ph.EP]].
- [6] S. J. Asztalos, L. J. Rosenberg, K. van Bibber, P. Sikivie, K. Zioutas, Ann. Rev. Nucl. Part. Sci. **56**, 293-326 (2006).
- [7] P. Sikivie, Int. J. Mod. Phys. A **25**, 554 (2010) [arXiv:0909.0949 [hep-ph]].
- [8] N. Prantzos, C. Boehm, A. M. Bykov, R. Diehl, K. Ferriere, N. Guessoum, P. Jean and J. Knoedlseder *et al.*, Rev. Mod. Phys. **83**, 1001 (2011), arXiv:1009.4620 [astro-ph.HE].
- [9] A. W. Strong, I. V. Moskalenko, and O. Reimer, Astrophys. J. **613**, 962 (2004), arXiv:astro-ph/0406254.
- [10] M. P. Muno *et al.*, Astrophys. J. **613**, 326 (2004), arXiv:astro-ph/0402087.
- [11] D. P. Finkbeiner, Astrophys. J. **614**, 186 (2004), arXiv:astro-ph/0311547.
- [12] D. Fixsen *et al.*, The Astrophysical Journal **734** (2011).
- [13] D. H. Oaknin and A. R. Zhitnitsky, Phys. Rev. Lett. **94**, 101301 (2005), arXiv:hep-ph/0406146.
- [14] A. Zhitnitsky, Phys. Rev. D **76**, 103518 (2007), arXiv:astro-ph/0607361.
- [15] K. Lawson and A. R. Zhitnitsky, JCAP **0801**, 022 (2008), arXiv:0704.3064 [astro-ph].
- [16] M. M. Forbes, K. Lawson and A. R. Zhitnitsky, Phys. Rev. D **82**, 083510 (2010) [arXiv:0910.4541 [astro-ph.GA]].
- [17] M. M. Forbes and A. R. Zhitnitsky, JCAP **0801**, 023 (2008) [astro-ph/0611506].
- [18] M. M. Forbes and A. R. Zhitnitsky, Phys. Rev. D **78**, 083505 (2008) [arXiv:0802.3830 [astro-ph]].
- [19] K. Lawson and A. R. Zhitnitsky, Phys. Lett. B **724**, pp. 17 (2013) [arXiv:1210.2400 [astro-ph.CO]].
- [20] K. Lawson, Phys. Rev. D **83**, 103520 (2011).
- [21] K. Lawson, Phys. Rev. D **88**, 043519 (2013) [arXiv:1208.0042 [astro-ph.HE]].
- [22] Gorham, Peter.W., Phys. Rev. D **86**, 123005 (2012).
- [23] D. Kharzeev and A. Zhitnitsky, Nucl. Phys. A **797**, 67 (2007) [arXiv:0706.1026 [hep-ph]].
- [24] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **81**, 054908 (2010) [arXiv:0909.1717 [nucl-ex]].
- [25] B. Abelev *et al.* [ALICE Collaboration], Phys. Rev. Lett. **110**, 012301 (2013) [arXiv:1207.0900 [nucl-ex]].
- [26] A. R. Zhitnitsky, Nucl. Phys. A **853**, 135 (2011) [arXiv:1008.3598 [nucl-th]].
- [27] A. R. Zhitnitsky, Nucl. Phys. A **886**, 17 (2012) [arXiv:1201.2665 [hep-ph]].