The 21cm Absorption Line and Axion Quark Nugget Dark Matter Model.

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We argue that dark matter in the form of macroscopically large nuggets of standard model quarks and antiquarks can help to alleviate the tension between standard model cosmology and the recent EDGES observation of a stronger than anticipated 21 cm absorption feature. The effect occurs as a result of the thermal emission from quark nugget dark matter at early times and at energies well below the peak of the CMB. Similar radiation at early times may also contribute a fraction of the GHz range excess observed by ARCADE2.

I. INTRODUCTION

Redshifted 21 cm emission serves as a tracer of baryonic physics in the early universe and at cosmic dawn. Recent observations by the low-band antenna of the Experiment to Detect the Global EoR Signal (EDGES) of a strong 21 cm absorption feature pose a challenge to our standard picture of the early universe [1]. This signal suggests a larger than expected difference between the radiation temperature and the spin temperature of the absorbing hydrogen gas. In particular it has been suggested that a stronger than expected radio background present before $z > 17$ may be capable of producing the EDGES result [2]. The possibility of a low energy excess was also indicated by the earlier observations of ARCADE2 in the GHz range [3].

The EDGES result has sparked a number of proposals designed to alleviate its tension with the standard framework. In particular, it has been suggested that the dark matter (DM) may act as a heat sink cooling the neutral gas relative to the CMB [4–6]. However this idea seems to be subject to very strong constraints [7–9].

Another direction to ease the tension with the conventional model is to introduce an additional source of soft radiation at large $z$ as suggested in the recent paper [10] using DM particles [11, 12] or intermediate mass black holes as suggested in [13]. However, these proposals in which dark matter or black holes modify the soft photon spectrum generally also modify the hard photon spectrum, which is strongly constrained by independent observations [14]. Therefore, any model introduced to explain the EDGES result must produce emission which is strongly suppressed at energies above the radio band.

Here we present a proposal capable of producing soft photon emission above the observed CMB. The arguments are based on the Axion Quark Nugget (AQN) dark matter model. This model was designed to alleviate its tension with the standard framework. In particular, it has been suggested that a stronger than expected radio background present before $z > 17$ may be capable of producing the EDGES result [2].

The AQN model was invented long ago [15], though a specific formation mechanism for the nuggets was developed in the much more recent papers [16–18]. It was proposed independently of the recent EDGES observations [1] and, in contrast with recent activities in the field, the AQN model was not invented to explain the EDGES result. Rather, this model was invented as a natural explanation of the observed ratio of dark matter to baryon ratio of expression (1). The similarity between dark matter $\Omega_{\text{dark}}$ and the visible matter $\Omega_{\text{visible}}$ strongly suggests that both types of matter formed during the same cosmological epoch. For the baryon density this is obviously the QCD transition as the baryon mass $m_B$ is obviously proportional to $\Lambda_{\text{QCD}}$ while the electroweak contribution proportional to the quark masses $\sim m_q$ represents only a minor contribution to the proton mass.

The second comment we would like to make in this Introduction is as follows. We already mentioned that the earlier observations of ARCADE2 in the GHz range [3] hinted at a possible excess of diffuse radiation. In the recent work [2] the authors argue that just $\sim 1\%$ of this excess is needed to explain the EDGES result.

We have argued in [19] that the AQN model will necessarily contribute to the radio background across a broad range from the MHz up to the GHz scale. As such it offers a possible mechanism to generate the soft photon background assumed to be present in [2] and capable of producing the EDGES result.

Our presentation is organized as follows. In Section II we provide an overview of the AQN dark matter model with emphasis on cosmological and astrophysical applications. In section III we discuss some specific features of the spectrum radiated by the nuggets at large $z$. In Section IV we compute the resulting sky temperature to argue that recent EDGES observations can be naturally understood within the AQN framework.

II. AXION QUARK NUGGET DARK MATTER MODEL

The idea that the dark matter may take the form of composite objects of standard model quarks in a novel phase goes back to the quark nugget model [20]. The axion quark nugget (AQN) model [15] differs from earlier
models in the essential role of the axion field in its construction and in that the AQN could be made of matter as well as antimatter in this framework as the result of a charge separation process to be discussed below. Precisely this feature plays a key role in the context of the present work.

The basic idea of the AQN proposal can be explained 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, the so-called baryogenesis) 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 in the form of dense nuggets of quarks and antiquarks in a colour superconducting (CS) phase. The formation of the nuggets made of matter and antimatter occurs through the dynamics of shrinking axion domain walls. For technical details of the formation process see the recent original papers [16–18].

Once formed the nuggets are strongly interacting and macroscopically large objects with nuclear scale density and a typical size $R \sim (10^{-5} - 10^{-4})\, \text{cm}$ determined by the axion mass $m_a$ as these two parameters are linked, $R \sim m_a^{-1}$. It is important to emphasize that there are strong constraints on the allowed window for the axion mass, which can be represented as follows $10^{-6}\, \text{eV} \leq m_a \leq 10^{-2}\, \text{eV}$, see recent reviews [21–29] on the subject. The Compton wavelength of the axion represents the largest scale in the AQN formation process and consequently sets a maximum baryon number for the nuggets $B^{1/3} \lesssim m_a^{-4}$. [18] strongly limiting the parameter space in which the AQN model may comprise the dark matter.

The allowed mass of the AQN is constrained by a variety of direct and indirect observational constraints. As the AQN are strongly interacting searches constrain their number density rather than interaction strength, consequently they impose constraints on

$$n_N = \frac{\rho_{DM}}{\langle M \rangle} \approx \frac{\rho_{DM}}{m_p (B)}$$

where $\langle M \rangle$ is the average mass of the nuggets and $\langle B \rangle$ is their average baryon number, not to be confused with the baryon number $B$ of individual nuggets, see (6) below. The low mass regime is strongly constrained by a variety of direct searches [30, 31] requiring

$$\langle M \rangle \gtrsim 10^{-2}\, \text{kg}, \quad |\langle B \rangle| \gtrsim 10^{25}.$$  \tag{3}

Lensing constraints apply at higher masses but only above the region favoured by the axion mass [30]. Lunar seismology also limits the fraction of the nugget population that falls in the mass range $10^9$ kg - $10^9$ kg ($10^{28} \lesssim |B| \lesssim 10^{30}$) to account for less than 10% of the local dark matter flux [32]. This result is however sensitive to the efficiency with which the nuggets couple to long wavelength seismic waves.

This model is perfectly consistent with all known astrophysical, cosmological, satellite and ground based constraints within the parametrical range for the mass $M$ and the baryon charge $B$ given by (3). It is also consistent with known constraints from the axion search experiments. Furthermore, there are a number of frequency bands where some excess of emission was observed, but not fully explained by conventional astrophysical sources. Our comment here is that this model may explain some portion, or even the entire excess of the observed radiation in these frequency bands, see the short review [31] and additional references at the end of this section.

Another key element of this model is the coherent axion field $\theta$ which is assumed to be non-zero during the QCD transition in early Universe. As a result of these $CP$ violating processes the number of nuggets and antinuggets formed will be different. This difference is always an order one effect [16–18] irrespective of the parameters of the theory, the axion mass $m_a$ or the initial misalignment angle $\theta_0$. As a result of this disparity between nugget and anti-nugget formation a similar disparity would also emerge between visible quarks and antiquarks. This is precisely the reason why the resulting visible and dark matter densities must be the same order of magnitude they are both proportional to the same fundamental $\Lambda_{QCD}$ scale, and they both are originated at the same QCD epoch resulting in the relation in expression (1). If these processes are not fundamentally related the two components $\Omega_{\text{dark}}$ and $\Omega_{\text{visible}}$ could easily exist at vastly different scales.

If we assume that the quark nuggets explain the entirety of both the baryon asymmetry and the dark matter then the matter component of the universe consists of antiquark nuggets with mass density $\rho_N$, quark nuggets with mass density $\rho_N$ and free baryons with mass density $\rho_B$ in the ratio

$$\rho_N : \rho_N : \rho_B \simeq 3 : 2 : 1,$$  \tag{4}

which corresponds to a zero total baryon charge of the Universe, while the ratio of the visible to DM densities takes the observed value of $n_B/(n_N + n_N) \sim 1/5$. For a more quantitative treatment of this problem accounting for slight differences between energy densities in the hadronic (for baryons) and CS (for nuggets) phases and the presence of the propagating dark matter axions see [18].

Unlike conventional dark matter candidates, such as Weakly interacting Massive Particles (WIMPs) the dark-matter/antimatter nuggets are strongly interacting and macroscopically large objects. However, they do not contradict the many known observational constraints on dark matter or antimatter in the Universe due to the following main reasons [33]: They carry very large baryon charge $\langle B \rangle \gtrsim 10^{25}$, and so their number density is very small $\sim B^{-1}$. As a result of this unique feature, their interaction with visible matter is highly inefficient, and therefore, the nuggets are perfectly qualified as dark matter candidates. Furthermore, the quark nuggets have a
very large binding energy due to the large gap \( \Delta \sim 100 \) MeV in CS phases. Therefore, the baryon charge is so strongly bound in the core of the nugget that it is not available to participate in big bang nucleosynthesis at \( T \approx 1 \) MeV, long after the nuggets had been formed.

It should be noted that the galactic spectrum contains several excesses of diffuse emission the origin of which is unknown, the best known example being the strong galactic 511 keV line. The rare annihilation events of the anti-baryon charge with visible matter could offer a potential explanation for several of these diffuse components (including 511 keV line and accompanied continuum of \( \gamma \) rays in 100 keV and few MeV ranges, as well as x-rays, and radio frequency bands). It is important to emphasize that all these emissions at drastically different frequencies are expressed in terms of a single fundamental parameter of the model, the average baryon charge of the nugget \( (B) \), or what is the same, the axion mass \( m_a \). This is because the rate of annihilation events is proportional to one and the same product of the local visible and DM distributions at the annihilation site defined as

\[
\Phi \sim 4 \pi R^2 \int d\Omega d[l_{\text{visible}}(l) \cdot n_{\text{DM}}(l)],
\]

where \( R^2 \sim B^{2/3} \) is the effective cross section \( \sigma \) of interaction between DM and visible matter. As \( n_{\text{DM}} \sim M^{-1} \sim B^{-1} \) the effective interaction (5) is strongly suppressed \( \sim B^{-1/3} \ll 1 \). Precisely this small geometrical factor replaces the conventional WIMPs requirement for weakness of the dark-visible coupling. The AQNs achieved this weakness not as a result of a new fundamental weak coupling constant but rather through suppression as a result of large baryon number \( B \) constrained by eq. (3).

To conclude this review section devoted to the AQN model we would like to mention the recent claim that the AQNs might be responsible for the resolution of the renowned (since 1939) “solar corona heating mystery”. The puzzle is that the corona has a temperature \( T \sim 10^6 \)K which is 100 times hotter than the surface temperature of the Sun, and conventional astrophysical sources fail to explain the extreme UV (EUV) and soft x-ray intensities. This estimate is derived exclusively in terms of known dark matter density \( \rho_{\text{DM}} \sim 0.3 \) GeVcm\(^{-3}\) and dark matter velocity \( v_{\text{DM}} \sim 10^{-3}c \) surrounding the Sun without adjusting any parameters of the model.

In context of the present studies it is important to emphasize that this picture when the AQNs are responsible for the resolution of the “solar corona heating mystery” is consistent with old idea advocated by Parker [42] suggesting that there must be small, sub-resolution events, the so-called “nanoflares”, which uniformly heat the corona. In most studies the term “nanoflares” describes a generic burst-like event for any impulsive energy release on a small scale, without specifying its cause. In other words, in most studies the hydrodynamic consequences of impulsive heating (due to the nanoflares) have been used without discussing their nature, see recent review papers [43, 44]. The AQN framework offers a specific realization of these nanoflares in form of the AQN annihilation events, see [40, 41] with details and references on the original literature on observations supporting this identification.

The identification implies that a baryon number distribution must be in the range

\[
10^{23} \leq |B| \leq 10^{28}.
\]

It is a highly nontrivial consistency check for the proposal [40, 41] that the required window (6) is consistent with the range of mean baryon number allowed by the axion and dark matter search constraints (3) as these come from a number of different and independent constraints extracted from astrophysical, cosmological, satellite and ground based observations. The window (6) will be used in our estimates of the sky temperature in Section IV.

### III. THERMAL RADIATION FROM NUGGETS

The antiquark nuggets are heated through interactions with the surrounding visible matter as a result of annihilation events in their interior. This heating results in radiation which depends on environment: a denser environment leads to a higher temperature and, therefore, stronger radiation from the AQNs. Of particular importance is the fact that the nuggets emit a non-black body spectrum which will distort the low energy CMB spectrum. The spectrum of nuggets at low temperatures was analyzed in [39] and was found to be

\[
\frac{dE}{d\nu \, dA} = \frac{32 \pi^2}{45} \frac{\alpha^{5/2} (k_B T_N)^3}{(h\nu)^2} \sqrt{\frac{k_B T_N}{m_e c^2}} \times \left( 1 + \frac{h\nu}{k_B T_N} \right) e^{-h\nu/k_B T_N} F\left( \frac{h\nu}{k_B T_N} \right)
\]

where \( T_N \) is the nuggets’ internal effective temperature, \( m_e \) is the electron mass and we have defined the function

\[
F(x) = \begin{cases} 17 - 12 \ln \left( \frac{x}{2} \right) & x < 1, \\ 17 + 12 \ln(2) & x > 1 \end{cases}
\]

to simplify the numerical analysis. The spectrum (7) is very hard at low frequencies \( \nu \ll T_N \) relative to black body radiation which will play an important role in our analysis.

The total energy emitted by the nugget per unit time per unit area \( dA \) is given by integrating expression (7)
over all emission frequencies to obtain,
\[
\frac{dE}{dt \, dA} = \frac{128\pi^2}{3} \frac{e^{5/2}(k_B T_N)^4}{h^3c^2} \sqrt{\frac{k_B T_N}{m_e c^2}}. \tag{9}
\]
The radiating temperature is then determined by balancing this emission rate with the rate at which energy is deposited on the nugget by the annihilation of incident baryonic matter.

The flux of visible matter onto a single antiquark nugget results in annihilation events with an energy injection rate per unit area \(dA\) of the nugget’s surface of,
\[
\frac{dE}{dt \, dA} = 2c^2 \chi \rho_{\text{vis}} v \tag{10}
\]
where \(\chi\) is the annihilation efficiency, \(\rho_{\text{vis}}\) is the visible matter density surrounding the anti-nugget, \(v\) is the relative velocity, and the factor of \(2c^2\) appears in front of (10) because a single annihilation event of a unit baryon charge \(B = 1\) leads to release of energy \(\sim 2m_p c^2\), while \(\rho_{\text{vis}}\) can be well approximated as \(\rho_{\text{vis}} \simeq m_p n_{\text{vis}}\).

A smaller heating contribution is made by collisions with visible matter that do not result in annihilation but may be assumed negligible in the following calculations (collisional heating will determine the much lower temperature scale of the matter nuggets whose contribution to the radio background is well below that of the antimatter nuggets.)

Equating the power radiated from expression (9) with the heating processes in equation (10) allows us to estimate the internal temperature of the nuggets throughout their evolution. However a precise thermal history will depend on details of the nuggets’ thermodynamics beyond the scope of this paper which instead takes a more phenomenological approach. We assume that the temperature evolution with redshift follows a power law of the form,
\[
T(z) = T_{\text{rec}} \left( \frac{1 + z}{1 + z_{\text{rec}}} \right)^\beta \tag{11}
\]
where \(z_{\text{rec}} \approx 1100\) is the redshift at recombination and \(T_{\text{rec}}\) is the nuggets’ average radiative temperature at that time\(^1\). We may estimate the power law exponent \(\beta\) by noting that the total thermal emission in expression (9) scales as \(T_N^{17/4}\). If the heating is annihilation dominated then the energy input follows equation (10) which scales as \((1 + z)^{3.5}\) if the matter is thermally coupled to the CMB or as \((1 + z)^4\) if it is cooling adiabatically. These two possible scaling laws would imply either \(\beta \approx \frac{17}{14}\) or \(\beta \approx \frac{16}{17}\). It should be noted that emission is strongly dominated by the contribution from large \(z\) so that the observable spectrum is largely insensitive to the precise value of \(\beta\). More important is the nuggets’ effective radiating temperature at the time the universe becomes transparent to low energy radiation.

The annihilation efficiency \(\chi\) for galactic environment was estimated in [39] to be \(\chi \approx 0.1\) leading to an estimation of the nugget’s radiative temperature in the galactic environment to be \(T \sim 1\) eV. There are two factors which suggest that \(T_{\text{rec}}\) must be somewhat lower in comparison with galactic environment. The first factor is that the average density and temperature at \(z_{\text{rec}} = 1100\) are somewhat lower than at the galactic centre. Second, and much more important, is that the annihilation efficiency at \(z_{\text{rec}}\) (when the gas hydrogen is mostly neutral) must be smaller than in the highly ionized galactic media. This is because the anti-nuggets carry a relatively small negative charge (due to the positron’s ionization from outside at \(T \neq 0\)). Therefore, these negatively charged antiquark nuggets attract protons from visible matter, but not the neutral hydrogen atoms present before reionization.

One should comment here that all processes responsible for heating the nuggets and for the consequent photon emission from the nuggets are based exclusively on conventional physics, mostly QED, atomic and nuclear physics. Nevertheless, computation of the parameter \(\chi\) from first principles remains a hard technical problem. Therefore, for the purpose of this paper we will use \(T_{\text{rec}}\) as a fitting parameter and simply demonstrate that the value required to reproduce the observed EDGES result is consistent with our order of magnitude \(T_{\text{rec}} \lesssim 1\) eV estimate.

\section{IV. SOFT PHOTON EXCESS FROM AQN DARK MATTER}

As was claimed in [2] a stronger than predicted radiation background present before \(z \sim 20\) may produce the strong 21 cm absorption feature observed by EDGES. This results from the larger misalignment between the radiation temperature and the spin temperature of neutral hydrogen with the strength of this feature scaling as,
\[
\delta T \sim x_{HI} \left( 1 - \frac{T_r}{T_s} \right) \tag{12}
\]
where \(x_{HI}\) is the fraction of neutral hydrogen and \(T_r\) and \(T_s\) are the radiation and gas spin temperatures respectively.

In what follows we will demonstrate that the radiation background produced by the nuggets mimics that
required to produce the 21 cm absorption strength according to the computations of ref. [2]. To be more specific, we want to reproduce the power law spectrum observed today

\[ T(\nu) = T_{\text{CMB}} + \xi T_R \left( \frac{\nu}{\nu_0} \right)^\beta \]  

(13)

with the parameters \( T_{\text{CMB}} = 2.729\,\text{K}, \ \xi \approx 0.01, \ T_R = 1.19\,\text{K}, \ \nu_0 = 1\,\text{GHz}, \ \beta = -2.62 \) which [2] claims will reproduce the EDGES result.

In order to estimate the present day background contribution from the nuggets we need to integrate their contribution over all redshifts from recombination down to \( z \approx 20 \). While the nuggets will continue to produce radiation below \( z = 20 \) it is only their large \( z \) contribution which contributes to 21 cm absorption and should be compared to the spectrum in expression (13). This contribution was previously estimated in [19] and is given by the integral,

\[ I(\nu) = \int_{20}^{1100} \frac{2c dz}{3H(z)(1+z)} \rho_{\text{DM}} \langle \frac{\sigma}{\mathcal{M}} \rangle \frac{dE}{d\nu \ dA} \]  

(14)

where \( \langle \frac{\sigma}{\mathcal{M}} \rangle \approx \langle B \rangle^{-1/3} \) is the average cross-section to mass ratio of the nuggets and \( \frac{dE}{d\nu \ dA} \) is the emission spectrum given in equation (7) evaluated at the redshift corrected frequency \( \nu(1+z) \). The factor of 2/3 accounts for the fact that only the antiquark nuggets from (4) will be sufficiently heated to contribute to the spectrum at MHz frequencies. Note that the resulting expression scales with the nuggets’ average cross-section to mass ratio and is thus suppressed at large baryon number as \( B^{-1/3} \). This relatively weak dependence on baryon number means that the required value of \( T_{\text{rec}} \) remains at the eV scale within the allowed window (3).

The evolution of best fit \( T_{\text{rec}} \) as a function of baryon number is shown in figure 1 and falls in the sub eV range across a wide range of nugget sizes.

The spectrum which results from performing the integration of expression (14) is shown in figure 2 with the temperature \( T_{\text{rec}} \approx 0.3\,\text{eV} \) chosen to match the required sky temperature at \( \nu = 75\,\text{MHz} \). The key observation here is that the spectrum (7) is almost constant for small frequencies at \( \nu \ll T_{\text{rec}} \), while the CMB has conventional black-body suppression at small \( \nu \). This is the technical explanation why the spectrum (7) scales similarly to (13) when expressed in terms of the sky temperature.

A few comments are in order. First of all, while an additional large redshift source of radio band emission may ease the tension between present cosmological models and the EDGES result the same result limits the ionizing radiation contribution of any such source. As may be seen from the scaling in expression (12) the absorption feature will be strengthened only if the increase in radiation temperature is not accompanied by a similar increase in the ionization fraction or gas temperature. In Appendix A we present simple arguments suggesting that composite dark matter models (such as the AQN model advocated in the present work) are uniquely able to provide a radiation background of this type due to the necessary presence of dark matter at early times and the ability of composite objects to thermalize any energy produced. In conventional dark matter models (formulated in terms of local weakly interacting fields) the dark matter particles typically produce high energy photons or other ionizing particles which can generate a radio band signal only through subsequent interactions with the sur-

FIG. 1. Nugget temperature required to produce 1% of the ARCADE2 excess as measured at \( \nu = 75\,\text{MHz} \) as a function of the nuggets mean baryon number.

FIG. 2. Sky Temperature as a function of frequency across the EDGES low-band frequency range (50-100MHz). The approximate temperature profile required to reproduce the observed 21 cm absorption feature is shown in black as is the contribution from nuggets of size \( B = 10^{26} \) with the initial temperature \( T_{\text{LS}} \approx 0.3\,\text{eV} \) chosen to match the the required temperature excess 75MHz. The analysis of ref. [2] was based on formula (13) which may be reproduced by the AQN model with accuracy better than 15% across the entire relevant region.
rounding visible matter and which may significantly alter the ionization fraction.

Another question which may also occur is how the internal temperature of the nuggets $T_{\text{rec}} \sim (0.3 - 0.4) \, \text{eV}$ could be much lower than the temperature of the environment $T \sim 1 \, \text{eV}$. The answer is that the photons which dominate the thermodynamics cannot be easily absorbed by the nuggets to increase their temperature. This is due to the internal structure of the nuggets: the plasma frequency $\omega_p \simeq 6 \, \text{eV}$ of the electrosphere is sufficiently large [39] to prevent the CMB photons from penetrating the nuggets, such that the low energy photons are elastically reflected rather than absorbed by the AQNs.

As may be seen in figure 2 the spectrum of the nuggets can closely match the required radio excess with a suitable choice of initial temperature for any given average baryon number within the window (3). This is the main result of the present work. Essentially, by explicit computations within the AQN framework, we support the claim made in ref.[2] that $\sim 1\%$ contribution to ARCADE2 excess from radiation at earlier times may explain the EDGES result.

V. CONCLUSION

We have argued that AQN dark matter will produce an excess of soft photons at early times. If these photons sufficiently increase the radiation temperature at long wavelengths they may produce a larger than anticipated difference between the radiation temperature and the spin temperature of the neutral hydrogen gas. This in turn, as argued in [2], will account for the stronger than anticipated 21 cm absorption feature centred at $z \approx 17$ observed by EDGES. Our explicit computations in the AQN model should be considered as an explicit realization of the idea formulated in ref.[2] that a $\sim 1\%$ contribution to ARCADE2 excess from radiation at earlier times may explain the EDGES result.

Our claim is that the AQN dark matter model is well suited to providing such a soft photon excess as the nuggets have a large number of low energy excitation levels (associated with positrons far from the nugget’s surface) which will dominate their emission spectrum. In this sense the EDGES result, if confirmed, would seem to favour composite dark matter models in which any energy release may be thermalized down to the lowest available emission modes. The same composite structure of the nuggets prevents equilibration of the CMB photons with the internal temperature of the nuggets.

We reiterate that this AQN model was invented as the natural explanation of the observed ratio (1), suggesting that the dark matter $\Omega_{\text{dark}}$ and the visible matter $\Omega_{\text{visible}}$ formed at the same cosmic epoch. Some of the history of this model is traced in Section II and the references therein. This should be contrasted with a large number of recently introduced models specifically designed to explain the EDGES result.

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Appendix A: Higher Energy Radiation

In this Appendix we argue that the high energy radiation which necessarily accompanies the radio band emission is negligible in the framework of the AQN dark matter model.

In particular the major portion of the energy resulting from the annihilation of a nucleus in the bulk of an AQN will be thermalized while roughly half of the near surface electron annihilations will result in the emission of a $\gamma$-ray with energy of order $m_e$. We may thus estimate the relative strength of thermal emission to ionizing high energy radiation as $m_p/m_e \approx 2000$.

An order of magnitude estimate of the HI ionization fraction resulting due to $\gamma$-ray emission from the nuggets demonstrates their minimal impact on gas dynamics. If we assume that every collision of an atom with an antiquark nugget results in the emission of a $\gamma$ ray of average energy $E \sim m_e c^2$ then the maximum rate at which a nugget can ionize the surrounding gas is,

$$\frac{dn_{\text{ion}}}{dt} \simeq \frac{m_e^2 v_B \sigma_N}{I_{\text{HI}}} \rho_B$$

where $I_{\text{HI}} = 13.6 \, \text{eV}$ is the ionization energy of hydrogen. Note that, as discussed in the case of nuclear annihilations, it is likely that only a fraction of all collisions will result in an electron annihilation. This estimate is therefore an upper bound on ionizing radiation assuming all incident atoms result in a high energy photon being emitted. Scaling this expression by the antiquark nugget to hydrogen ratio,

$$\frac{n_N}{n_{\text{H1}}} = \frac{\Omega_{\text{DM}} m_p}{\Omega_{\text{B}} M_p} \approx (A2)$$

gives the rate of change of the ionization fraction,

$$\frac{dx_{\text{HI}}}{dt} \simeq \frac{\Omega_{\text{DM}} m_e c^2}{\Omega_{\text{B}} M_p I_{\text{HI}}} \rho_B v_B \sigma_N. \quad (A3)$$

Finally noting that $t \approx H^{-1}$ allows us to integrate this expression over redshift.

$$\Delta x_{\text{HI}} = \int dz \frac{dx_{\text{HI}}}{dz} \frac{dt}{dz} \approx \frac{\rho_0 \Omega_{\text{DM}} m_e c^2}{H_0 \sqrt{\Omega_{\text{M}}} I_{\text{HI}}} v_0 \frac{\sigma_N}{M_p} (1 + z_{LS})^2 \quad (A4)$$

where $v_0 \sim 150 \, \text{m/s}$ is the hydrogen atom velocity scale at $T_{\text{CBM}}$ and we have used the fact that emission is strongly peaked at early times when the universe is matter dominated. Finally, we may formulate this in terms of the
average baryon number of the nuggets,
\[
\Delta x_{HI} \approx 3 \times 10^{-10} \left( \frac{10^{26}}{B} \right)^{1/3}.
\]  

(A5)

Which is a negligibly small change in the ionization fraction.

Emission from the nuggets at energies \(E \sim m_e c^2\) produced at \(z = 1100\) will be redshifted down to the keV scale and are thus sensitive to the limits from the *Chandra* x-ray background observations [45]. However the majority of these photons are absorbed and ionize the neutral hydrogen as discussed above and the remaining x-rays are well below the observed backgrounds.

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