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Isotropic radio background from quark nugget dark matter

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ABSTRACT

Recent measurements by the ARCADE2 experiment unambiguously show an excess in the isotropic radio background at frequencies below the GHz scale. We argue that this excess may be a natural consequence of the interaction of visible and dark matter in the early universe if the dark matter consists of heavy nuggets of quark matter. Explanation of the observed radio band excess requires the introduction of no new parameters, rather we exploit the same dark matter model and identical normalization parameters to those previously used to explain other excesses of diffuse emission from the centre of our galaxy. These previously observed excesses include the WMAP Haze of GHz radiation, keV X-ray emission and MeV gamma-ray radiation.

1. Introduction

The ARCADE2 experiment has reported an excess in radio emission above the known CMB background at frequencies below the GHz scale [1]. When combined with earlier data [2–5] the ARCADE result implies the existence of a radio background below the CMB peak which results in a measured antenna temperature that grows with a power index of approximately three [6]. This radio excess seems impossible to fit through reasonable modifications to the spectra of known background radio sources [7,8]. Given the lack of a conventional astrophysical source several attempts have been made to explain this excess through a contribution to the radio background from the annihilation of dark matter [9–11]. We argue that this radio excess naturally arises if the dark matter is composed of nuggets of quarks and antiquarks bound in a high density phase. The emission spectrum from these objects as a function of the visible matter density has been previously calculated and, if summed over the history of the universe, this radiation could easily provide the necessary isotropic radio band intensity. This is the main result of the present work.

We should emphasize that the model for dark matter to be used in our estimates below has not been invented to explain the observed excess of radiation in radio bands. Rather, this model had been introduced with a completely different motivation to be discussed below. After it's introduction the model was subsequently used to explain a number of other excesses of diffuse emission from the centre of our galaxy ranging over more than 10 orders of magnitude in energy scale. The present work extends the application of this model from galactic to cosmological scales without changing a single parameter in the model.

After a brief review of the dark matter model in Section 2 we analyze the cosmological evolution of the dark matter nuggets in Section 3. We estimate its potential contribution to the isotropic radio background in Section 4 where we argue that such a contribution could account for the excess observed by the ARCADE2 experiment below the GHz scale.

2. Dark matter as dense quark nuggets

It is known that dark matter dominates over the visible matter of the universe, with which it interacts only weakly, by a factor of approximately five. While the behaviour of dark matter on the scale of galaxies and above is well understood there is no generally accepted model for its microscopic nature. The majority of dark matter models assume the existence of a new fundamental particle whose properties are to be inferred from the behaviour of the dark matter itself. This Letter will consider an alternative model in which the dark matter is composed of nuggets of standard model quarks and antiquarks bound in a high density phase. This class of models (which includes for example Witten's strangelets [12]) is allowed due to the fact that all dark matter detection experiments are sensitive not to the dark matter cross section but to the product of the cross section with the number density. Since only the dark matter mass density, both locally and globally, is experimentally measured this amounts to a limit on the dark matter cross section per mass (σ/M). Consequently, composite strongly interacting objects may be able to constitute the dark matter, despite having a significant interaction cross section, provided their mass is sufficiently large.

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2.1. The model

In this work we will consider a dark matter model presented in [13,14] and reviewed in [15]. The basic idea of this model is that nuggets of dense matter and antimatter form at the same QCD phase transition as conventional baryons (neutrons and protons), providing a natural explanation for the similar scales $\Omega_{\rm DM} \approx 5\Omega_{\rm B}$. Baryogenesis proceeds through a charge separation mechanism: both matter and antimatter nuggets form, but the natural CP violation due to the so-called QCD θ term (which was of order unity $|\theta| \sim 1$ during the QCD phase transition) drives the formation of more antimatter nuggets than matter nuggets, resulting in the leftover baryonic matter that forms the visible matter today. In different words, while the total baryon charge of the universe is zero in this model, different components are not equally distributed between nuggets, antinuggets and the visible matter, i.e. $B_{\rm universe} = B_{\rm nugget} + B_{\rm visible} - \bar{B}_{\rm antinugget} = 0$. It is crucial for this mechanism that CP violation can drive charge separation in the early universe during the QCD phase transition while today the same source of CP violation can be safely neglected. This is a result of the well-known resolution of the so-called strong CP problem with the dynamical axion in which $\theta \sim 1$ during the QCD phase transition becomes $\theta \simeq 0$ at a later epoch, see the original papers [13,14] and review [15] for relevant references and details. Note, that the idea of a charge separation mechanism due to the local violation of CP invariance 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 5.

If this proposal is to explain the both the absence of primordial antimatter in the hadronic phase and the observed visible to dark matter ratio then the matter composition of the universe should be roughly one part visible matter, two parts dark matter in the form of quark nuggets and three parts dark matter in the form of antiquark nuggets. This composition would explain the dominance of visible matter over antimatter and the approximately 1 : 5 visible matter to dark matter ratio, i.e. $\bar{B}_{\rm antinugget} : B_{\rm nugget} : B_{\rm visible} \simeq 3:2:1$. Though this ratio cannot be presently computed exactly, a simple estimate suggests that the three components in this ratio should be order of one as a result of strong dynamics during the QCD phase transition when all parameters, including θ are order of one.

Unlike conventional dark matter candidates, dark-matter/antimatter nuggets are strongly interacting but macroscopically large. They do not contradict any of the many known observational constraints on dark matter or antimatter for three reasons: 1) They carry a huge (anti)baryon charge $|B| \sim 10^{24}$, and so have an extremely tiny number density; 2) The nuggets have nuclear densities, so their effective interaction is small $\sigma/M \sim 10^{-10}$ cm^2/g, well below the typical astrophysical and cosmological limits which are on the order of $\sigma/M < 1$ cm^2/g; 3) They have a large binding energy such that baryon charge in the nuggets is not available to participate in big bang nucleosynthesis (BBN) at $T \approx 1$ MeV. Weakness of the visible-dark matter interaction is achieved in this model due to the small parameter $\sigma/M \sim B^{-1/3}$ rather than due to a weak coupling of a new fundamental field with standard model particles.

While the observable consequences of this model are on average 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. 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 only 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. This includes a number of frequency bands where some excess of emission, which cannot be explained by conventional astrophysical sources have been observed. Here we briefly review the status of several galactic observations which may support the idea of quark nugget dark matter.

2.2. Excess emissions from the galaxy as viewed from the DM model

The model makes unambiguous predictions about the processes ranging over more than 10 orders of magnitude in scale. The basic picture involves the antimatter nuggets – compact cores of nuclear or strange quark matter surrounded by a positron cloud, the "electrosphere" with a profile which can be computed using conventional and well-established physics. Incident matter will annihilate on these nuggets producing radiation at a rate proportional to the annihilation rate, thus scaling as the product $\rho_V(r)\rho_{\rm DM}(r)$ of the local visible and dark matter densities. This will be greatest in the core of the galaxy. To date, we have considered several independent observations of diffuse radiation from the core of our galaxy:

- The annihilation of the positrons of the "electrosphere" with the electrons of the interstellar medium will result in formation of a positronium which consequently decays. The decay will produce a 511 keV line and the associated three photon continuum. Such a spectral feature is in fact observed and has been studied by the SPI INTEGRAL observatory [16]. In our model the properties of the 511 line are naturally explained: The strong peak at the galactic centre and extension into the disk must arise because the intensity follows the distribution $\rho_V(r)\rho_{\rm DM}(r)$ of visible and dark matter densities [17,18]. This should be contrasted with the $\sim \rho_{\rm DM}^2(r)$ scaling which arises in the case of dark matter annihilation or $\sim \rho_{\rm DM}(r)$ in the case of decaying dark matter. A distribution $\sim \rho_V(r)\rho_{\rm DM}(r)$ obviously implies that the predicted emission will be asymmetric, extending into the disk from the galactic centre as it tracks the visible matter. Apparently, such an asymmetry has been observed [19], see also the review paper [20]. The intensity of the emission of the 511 keV line was used to normalize the line of sight integral $\int dr\, \rho_V(r)\rho_{\rm DM}(r)$ in our analysis of all other galactic emissions.
- Positrons closer to the quark matter surface can carry energies up to the nuclear scale. Some galactic electrons are able to penetrate to a sufficiently large depth that they no longer produce the characteristic positronium decay spectrum but a direct $e^-e^+ \to 2\gamma$ emission spectrum [21]. 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 [22]. Observations by the COMPTEL satellite show an excess above the galactic background [23] consistent with our estimates.
- Galactic protons may also annihilate with the antimatter comprising the quark nuggets. The annihilation of a proton within a quark nugget will produce hadronic jets which cascade down into lighter modes of the quark matter. If the energy in one of these jets reaches the quark surface directly it will excite the most weakly bound positron states near the surface. These excited positrons rapidly loose energy to the strong electric field near the quark surface. This process results in the emission of Bremsstrahlung photons at X-ray energies [24]. Observations by the CHANDRA observatory indeed indicate an excess in X-ray emissions from the galactic centre [25] with the intensity and spectrum consistent with our estimates [24].

• The annihilation of visible matter within the nuggets heats them above the background temperature. The thermal spectrum from the nuggets may be predicted based on the emission properties of the electrosphere along with the annihilation rate at various positions within the galaxy [26]. The majority of this thermal energy is emitted at the eV scale where it is very difficult to observe against the galactic background. However the emission spectrum will extend down to the microwave scale where it may be responsible for the "WMAP haze" [27].

2.3. Prospects for ground based detection

While the galactic backgrounds discussed above may offer indirect support for our proposal the possibility of direct detection through earth based observations should also be considered. The corresponding questions have been discussed recently in Refs. [28–30].

The scale of any observable consequences will be determined by the flux of nuggets through the earth. The local dark matter density is roughly 1 GeV/cm^3 and has a velocity around the galactic scale of $v \sim 200$ km/s. Taking these values the mean baryonic charge of the nuggets then sets the flux expected at the earth's surface.

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

Thus, if the baryonic charge is on the order of 10^{25} we should anticipate a flux of one nugget per square kilometer per year with the flux dropping for larger (and thus less abundant) nuggets. This flux is well below the sensitivity of any conventional dark matter searches but, if the energy deposited by such an event is sufficiently large there may still be observational consequences.

A nugget of antimatter crossing the atmosphere will annihilate any atmospheric material which lies in its path. The atmospheric mass involved is substantially smaller than that of the nugget and thus the nugget looses virtually none of its original momentum and charge, and the total energy released is simply proportional to the amount of atmospheric material swept up. We may thus estimate the energy released in such an event as,

$$E_{tot} = 2X_{at}c^2\pi R_n^2 \approx 10^7\ \text{J}\left(\frac{R_n}{10^{-5}\ \text{cm}}\right)^2 \tag{2}$$

where $X_{at} \sim 1$ kg/cm^3 is the atmospheric depth. The majority of this energy will be thermalized inside the nugget however some may be deposited in the atmosphere in an observable form. While the energy scale is similar to that released in a typical meteor event the majority of this energy will be released quiet low in the atmosphere limiting direct visual observation. It has been also argued [28] that only a fraction of all molecules incident on the nugget actually annihilate. Thus, the expression (2) represents a maximum energy available to the shower with the actual value likely to be several orders of magnitude smaller.

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 [28] or through the geosynchrotron emission generated by the large number of secondary particles [29]. It has also been suggested that the ANITA experiment [31] may be sensitive to the radio band thermal emission generated by these objects as they pass through the antarctic ice [30]. These experiments may thus be capable of adding direct detection capability to the indirect evidence discussed above.

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 [31] 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 nuggets' thermal spectrum which may be relevant to direct detection searches arises as the annihilation of atmospheric or ice molecules colliding with the nugget raise its temperature causing it to emit in the radio band. While the density is considerably lower at the same process will result in radio emission from astrophysical regions of relatively high density. A critical aspect of the analysis presented here, as well as that conducted in [26] and [30], is the relative flatness of the nugget emission spectrum with respect to black body radiation. To discuss this further we now turn to a more quantitative description of the thermal spectrum generated by a nugget of quark matter.

3. Nugget thermodynamics

As discussed above thermal emission from the nuggets may provide a component of the WMAP haze. In investigating this proposal the thermal emission spectrum of a nugget of quark matter was worked out in [26] where the spectrum was found to be,

$$\frac{dE}{dt\,dA\,d\nu} = \frac{4}{45}\cdot\frac{T_N^3\alpha^{5/2}}{\pi}\cdot\sqrt[4]{\frac{T_N}{m_e}}\left(1+\frac{h\nu}{T_N}\right)e^{-h\nu/T_N}f\left(\frac{h\nu}{T_N}\right) \tag{3}$$

where T_N is the temperature of the quark nuggets and the function $f(x)$ is defined to be,

$$\begin{aligned} f(x) &\equiv 17 - 12\ln(x/2) \quad x<1 \\ &\equiv 17 + 12\ln(2) \quad x>1 \end{aligned} \tag{4}$$

It should be noted that the leading order dependence of this spectrum on frequency is relatively weak resulting in a near flat spectrum at energies below the nugget temperature.

The basic proposal presented here is that while the nuggets make a contribution to the isotropic background which is much smaller than that of the CMB at its peak (~ 160 GHz) the thermal spectrum of the CMB falls as $\sim \nu^3$ below peak while the nugget contribution remains essentially constant coming to dominate at low energies and resulting in an observed isotropic background temperature that seems to grow with the third power of frequency.

To expand on this basic idea we must estimate the temperature evolution of the nuggets over the history of the universe. To do this we compare the rate at which thermal energy is emitted with the rate at which visible matter deposits energy in the nugget through annihilations. The integrated thermal radiation from a nugget is given by,

$$\frac{dE}{dt} = 4\pi R_N^2\frac{16}{3\pi}\alpha^{5/2}T_N^4\sqrt[4]{\frac{T_N}{m_e}} \tag{5}$$

This rate should be proportional to the flux of visible matter onto the quark nugget.

$$\Phi_{vis} = \rho_{vis}c^2 v\pi R_N^2 \tag{6}$$

The velocity of visible matter drops proportional to the scale factor while the visible matter density falls as a^{-3}.

$$\Phi_{vis}(z) = \rho_0 c^2 v_0\pi R_N^2(1+z)^4 \tag{7}$$

As only a fraction of the energy released through annihilations is actually thermalized in the nugget expressions (5) and (6) are equal up to some multiplicative constant less than one. While other mechanisms for energy loss exist (such as those leading to the various galactic sources described in (Section 2.2)) thermal emission is expected to be the dominant cooling mechanism. This is due to the fact that the approximately 2 GeV released by the annihilation of a proton within the quark matter rapidly cascades down to many low energy excitations of the light modes of the quark matter. By the time this energy is transported to the quark surface the individual excitations do not have sufficient energy to overcome the nuclear scale binding energy of the quark matter and produce significant levels of particle emission. The same strong binding force prevents the anti-baryon charge to escape the system.

The numerical coefficient relating the annihilation rate and thermal emission is not a free parameter and it can, in principle, be computed, the details of such a computation will be commented upon below. This procedure results in a thermal evolution of the form

$$T(z) = T_{LS}\left(\frac{1+z}{1+z_{LS}}\right)^{17/4} \tag{8}$$

Here the parameter T_{LS} is the effective radiating temperature of the nuggets (as it appears in expression (3)) at the time of last scattering (i.e. during CMB formation). This temperature is calculable in principle, but is dependent on the fraction of visible matter which is converted to thermal energy in the nuggets after its annihilation. Rather than attempting a direct calculation of this temperature we shall simply treat it as a phenomenological parameter to be fit by the data. It should be noted that a very similar calculation was carried out in [26] where it was estimated that, to provide the observed WMAP galactic haze the nuggets must have a temperature at the eV scale in the galactic centre. As we estimate below, the present density of the visible matter at the centre of galaxy and the corresponding density at the time of the last scattering are about the same. Consequently, T_{LS} is expected to be at the same eV scale estimated in [26]. As mentioned above, we opted to treat T_{LS} as a fitting parameter which we expect to be in eV scale range.

To get a basic idea of the scale at which we may expect the isotropic radio background we may compare it to the foreground galactic emission which we claim is visible as the WMAP haze. In the environment of the galactic centre with the nuggets carrying a typical galactic velocity the matter flux onto the nugget scales as

$$\rho_{vis} v \approx 300\ \frac{\text{GeV}}{\text{cm}^3}\cdot 2\cdot 10^7\ \frac{\text{cm}}{\text{s}} = 6\cdot 10^9\ \frac{\text{GeV}}{\text{cm}^2\,\text{s}} \tag{9}$$

where we use the average numerical values adopted in [26]. A similar calculation at the time of last scattering gives

$$\rho_{vis} v = \rho_c \Omega_{vis}\sqrt{\frac{2T}{m_e}}c(1+z)^3 \approx 10^{10}\ \frac{\text{GeV}}{\text{cm}^2\,\text{s}} \tag{10}$$

The similarity of these scales (9) and (10) indicate that the initial intensity of this cosmological background should have been similar to that of the present day galactic spectrum. As the universe expands and cools the nugget's contribution to the isotropic background falls off quickly and photons produced at early times redshift to lower energies. This process means that, at the present day CMB peak the nugget background contribution to the spectrum is vanishingly small. However, at frequencies below the CMB peak the flatness of the nugget spectrum causes the background to eventually emerge as the dominant isotropic radio source.

4. Emission spectrum

Having established the temperature evolution of the nuggets as well as their thermal spectrum we may now determine the present day radio background due to the presence of quark matter nuggets over the history of the universe. This is accomplished by integrating the source density over all redshifts correcting for the redshifting of photon frequency after emission.

$$I(\nu) = \frac{c}{H_0}\int \frac{dz}{(1+z)h(z)}\frac{\rho_{\rm DM}}{M_N}\frac{dE}{d\nu\,dt}\big[\nu(1+z), T(z)\big] \tag{11}$$

For simplicity this analysis we will ignore the reheating of matter during structure formation at late times. Obviously a full treatment would involve the clustering of dark matter into the structure observed in the universe today as was done in [11] and [9]. However these considerations go beyond the scope of this Letter which seeks only to demonstrate the feasibility of this mechanism of producing an isotropic radio background. In this simplification we are aided by the fact that the density of visible matter must be quite strongly enhanced before the nuggets begin to again contribute to the radio background. By this time the visible matter in the galaxies will also be generating radiation at these bands and much of the radio signal will be lost as a "haze" contribution to the host galaxies.

Numerical we may estimate the impact of late time reheating by considering modifications of the thermal dependence given in (8). For example suppose that at redshift less than $z = 10$ we allow one tenth of the dark matter to reheat to a temperature of 1 eV (the present day value in the galactic centre). This will give produce two terms in the integrand of (11) one with a temperature falling as before and the other fixed at 1 eV below $z = 10$. The contribution of this second term does not strongly impact the value of the total integral which is heavily weighted towards early times. Numerically this procedure is found to introduces variations in the predicted antenna temperature on the order of a few percent across the frequency range considered here. Such a variation is considerably smaller than the uncertainty in the initial nugget temperature T_{LS}. Including structure formation would of course produce a more precise result, and would allow for the consideration of small anisotropies in the resulting radio background but the present estimate will be taken as sufficient for the purposes of this work.

With this simplifying assumption the integral (11) may be performed using the nugget temperature dependence given in (8). The results of this integration are plotted in Fig. 1 for a range of initial nugget temperatures along with the data point from several relevant experiments. From Fig. 1 it can be seen that the nuggets make little contribution at frequencies near the CMB peak (associated with photons emitted at ~ 0.3 eV at the time of last scattering) but, due to the relative flatness of the nugget emission spectrum (3), come to dominate below GHz frequencies where the thermal spectrum of the CMB photons fall as $\sim \nu^3$. This behaviour naturally explains the spectral index of $\gamma \sim 3$ described in [6].

5. Conclusion

The main result of this work can be formulated as follows. If the dark matter consists of heavy nuggets of quark matter in a high density phase then these objects may have a more complex thermal history than dark matter consisting of a new fundamental particle. We have estimated the thermal evolution of quark matter nuggets from the time the universe first becomes transparent and determined the impact of this additional source of diffuse radio emission on the present day background. This analysis finds that at energies near the CMB peak the nugget contribution to the

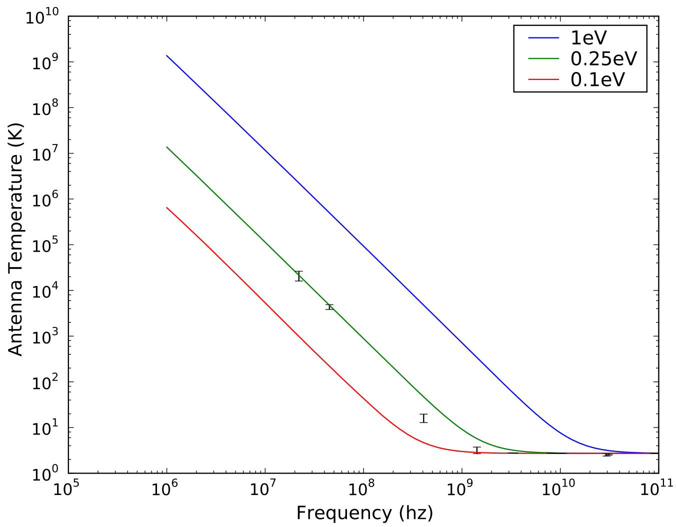

Fig. 1. Predicted antenna temperature assuming that the quark nuggets have a temperature of 0.1 eV, 0.25 eV and 1 eV at the time of CMB formation. Also plotted are the data points from the radio band observations cited in the text.

radio background is several orders of magnitude below that of the thermal CMB spectrum. However the CMB spectrum falls of at frequencies below peak much faster than that of the nuggets such that, at frequencies below roughly a GHz, they come to give the dominant contribution to 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.

We emphasize that the only fitting parameter, T_{LS} entering the final result presented in Fig. 1 is not really a free parameter, and in principle can be computed as it is determined by the conventional well-established physics. We presented the order of magnitude estimate $T_{LS} \sim 1$ eV, and the fit plotted in Fig. 1 is consistent with this estimate. One should add that this dark matter proposal may explain a number of "apparently unrelated" puzzles. All these puzzles strongly suggest (independently) the presence of some source of excess diffuse radiation in different bands ranging over 13 orders of magnitude in frequency. The new element which we advocate in this Letter is that the same dark matter model which offers a source for these previously discussed excesses of diffuse emission can also explain that observed by ARCADE2 in radio bands. In this case the emission originates primarily from very early times with $z \sim 10^3$ in contrast with our previous applications which have analyzed only present day galactic emissions.

Finally, what is perhaps more remarkable is the fact that the key assumption of this dark matter model, the charge separation effect reviewed in Section 2.1, 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. [32] for the details. In particular, the local violation of the $\mathcal{CP}$ invariance observed at RHIC (Relativistic Heavy Ion Collider) [33] and LHC (Large Hadron Collider) [34] have been interpreted in [32,35,36] 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.

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