

Diffuse cosmic gamma-rays at 1-20 MeV: A trace of the dark matter?

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Abstract. Several independent observations of the galactic core suggest hitherto unexplained sources of energy. The most well known case is the 511 keV line which has proven very difficult to explain with conventional astrophysical positron sources. A similar, but less well known mystery is the excess of gamma-ray photons detected by COMPTEL across a broad energy range $\sim 1 - 20$ MeV. Such photons are found to be very difficult to produce via known astrophysical sources. We show in this work that dark matter in the form of dense antimatter droplets provides a natural explanation for the observed flux of gamma-rays in the $\sim 1 - 20$ MeV range. We argue that such photons must always accompany the 511 keV line as they are produced by the same mechanism within our framework. We calculate the spectrum and intensity of the $\sim 1 - 20$ MeV gamma-rays, and find it to be consistent with the COMPTEL data.

1. Introduction

Recent observations of the galactic centre have presented a number of puzzles for our current understanding of galactic structure and astrophysical processes. In particular a series of independent observations have detected an excess flux of photons across a broad range of energies. In particular, these observations include:

- SPI/INTEGRAL observations of the galactic centre have detected an excess of 511 keV gamma rays resulting from low momentum electron-positron annihilations. The observed intensity is a mystery. After accounting for known positron sources, only a small fraction of the emission may be explained [1, 2, 3, 4, 5, 6].

- Detection by the CHANDRA satellite of diffuse X-ray emission from across the galactic bulge provides a puzzling picture: after subtracting known X-ray sources one finds a residual diffuse thermal X-ray emission consistent with a two-temperature plasma with the hot component close to $T \simeq 8 \text{ keV}$. According to [7] the hot component is very difficult to understand within the standard picture. Such a plasma would be too hot to be bound to the galactic center. The authors of ref. [7] also remark that the energy required to sustain a plasma of this temperature corresponds to the entire kinetic energy of one supernova every 3000 yr, which is unreasonably high.

- The flux of gamma rays in the 1-20 MeV range measured by COMPTEL represents yet another mystery. As discussed in [8] the best fit models for diffuse galactic γ rays fit the observed spectrum well for a very broad range of energies, 20 MeV- 100 GeV. It also gives a good representation of the latitude distribution of the emission from the plane to the poles, and of the longitudinal distribution. However, the model fails to explain the excess in the 1-20 MeV range observed by COMPTEL in the inner part of the galaxy ($l = 330^\circ - 30^\circ$, $|b| = 0^\circ - 5^\circ$), see figure 1. As claimed in [8] some additional γ ray sources are required to explain this energy region.

These data, when taken together, suggest the existence of an energy source beyond currently established astrophysical phenomenon. The main goal of this paper is to argue that these (seemingly unrelated) observations may be explained by a single mechanism. The origin of both the 511 keV radiation and broad $1 \text{ MeV} \leq k \leq 20 \text{ MeV}$ emission can be naturally explained by the idea that dark matter (DM) consists of Compact Composite Objects (CCOs) made of matter and antimatter [9, 10, 11], similar to Witten's dense strangelets [12]. Dark antimatter nuggets would provide an unlimited source of positrons (e^+) within this framework as suggested in [13, 14]. The resonance formation of positronium between impinging galactic electrons (e^-) and positrons (e^+) from the DM nuggets, and their subsequent decay, lead to the 511 keV line. Non-resonance direct $e^+e^- \rightarrow 2\gamma$ annihilation would produce a broad spectrum at $1 \text{ MeV} \leq k \leq 20 \text{ MeV}$ which we identify with the excess observed by COMPTEL. This continuum emission must always accompany the 511 keV line and the two must be spatially correlated, as argued earlier [11]. Available observational data suggest that the intensity of the 511 keV line is concentrated in the bulge of the galaxy (80% of the photons come from a circle of a half-angle 6°). The **excess** flux in the 1-20 MeV

range observed by COMPTEL is also detected only within the inner part of the galaxy ($l = 330^\circ - 30^\circ$, $|b| = 0^\circ - 5^\circ$). These observations are consistent with our proposal that both phenomena have common origin.

We stress here that COMPTEL does indeed measure significant emissions across the 1-20 MeV range from throughout the galactic disc. However the majority of this radiation may be attributed to well known astrophysical processes, see[8]. It is only once the contributions from processes such as pion decays, and inverse Compton or bremsstrahlung scattering of cosmic rays have been subtracted that the excess emissions from the galactic centre become apparent. Whereas we assume that the 511 keV line is dominated by annihilation events involving a dark matter nugget in the case of MeV emission a detailed subtraction of all contributions to the observed emissions is critical. Visually, the morphology of 511 keV line and 1-20 MeV continuum look very different, and naively, there could be no correlation between the two. This conclusion comes from the fact that the continuum 1-20 MeV photons are observed everywhere while the 511 keV line is strongly concentrated in the bulge. As mentioned above, the majority of 1-20 MeV radiation from the galactic disc may be explained by well known astrophysical processes with some excess from the bulge, while the 511 keV line does not include such a background contribution in the galactic disk. Both further modeling of the contributing processes and more detailed observations in the two different bands will be required to confirm or rule out the validity of our proposal that the two emissions originate from the same physics.

It has been argued that in the soft energy regime, below a few 100s of keV, total emissions are dominated by the point source contribution which provides a good match to observations (with the exception of the 511 keV line and associated positronium continuum[15].) On the other hand at large energies, above 100 MeV, interstellar processes dominate and again the observational data is well matched by theoretical models[8]. The COMPTEL data in the 1-20MeV range falls between there two separate regimes. It has proven difficult to explain by any conventional process. This is however precisely the energy range in which our proposed dark matter model has observational consequences.

In the present paper we estimate the intensity and the photon spectrum in the $1 \text{ MeV} \leq k \leq 20 \text{ MeV}$ energy range. Assuming dark antimatter to be the common source for the 511 keV line as well as the $1 \text{ MeV} \leq k \leq 20 \text{ MeV}$ emission we extract some phenomenological parameters describing their properties.

It is quite remarkable that another (also naively unrelated) puzzle, the diffuse X-ray emission observed by CHANDRA [7], may also have a common origin with the 511 keV line and excess MeV radiation as argued in [16]. We show below that dark matter in form of CCOs is consistent with all of the COMPTEL data, and that it may in fact fully explain the missing sources of emission. If our proposal turns out to be correct, there should be spatial correlations between the various emissions (511 keV line measured by SPI/INTEGRAL and $1 \text{ MeV} \leq k \leq 20 \text{ MeV}$ measured by COMPTEL as well as the diffuse X-ray emission with $T \sim 8 \text{ keV}$ measured by CHANDRA). This should allow

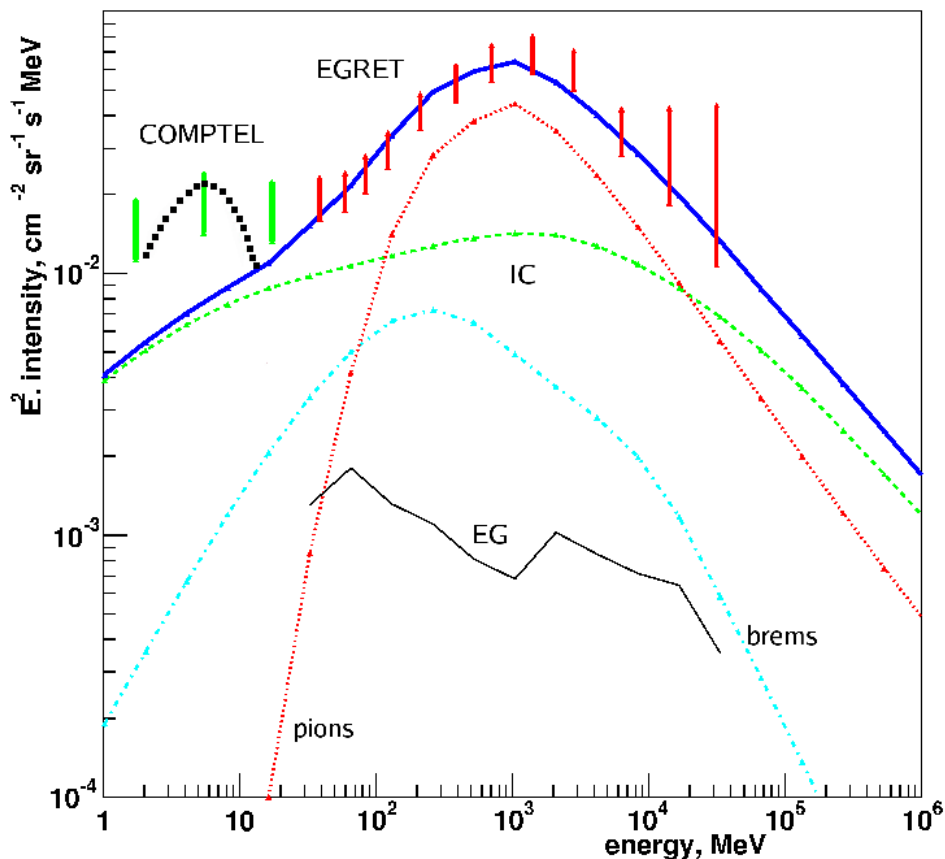


Figure 1. γ ray spectrum of inner galaxy for optimized model[24]. Green vertical bars: COMPTEL data. Heavy solid line: total calculated flux for optimized model. Heavy black dots: Calculated emission spectrum from electron-nugget annihilation processes, see appendix for details. Combination of the blue solid line(optimized model [24]) plus heavy black dots (present work) should be compared with COMPTEL data.

our proposal to be verified or ruled out by future, more precise measurements.

2. Dark Matter as Compact Composite Objects (CCOs).

Unlike conventional dark matter candidates, dark matter/antimatter nuggets are strongly interacting, macroscopically large objects. Such a seemingly counterintuitive proposal does not contradict any of the many known observational constraints on dark matter or antimatter in our universe for three main reasons: 1) the nuggets carry a huge (anti)baryon charge $|B| \approx 10^{20} - 10^{33}$, so they have a macroscopic size and a tiny number density. 2) They have nuclear densities in the bulk, so their interaction cross-section per unit mass is small $\sigma/M \approx 10^{-13} - 10^{-9} \text{ cm}^2/\text{g}$. This small factor effectively replaces a condition on weakness of interaction of conventional dark matter candidates such as WIMPs. 3) They have a large binding energy (gap $\Delta \approx 100 \text{ MeV}$) such that baryons in the nuggets are not available to participate in big bang nucleosynthesis

(BBN) at $T \approx 1$ MeV. On large scales, the CCOs are sufficiently dilute that they behave as standard collisionless cold dark matter (CCDM). However, when the number densities of both dark and visible matter become sufficiently high, dark-antimatter-visible-matter collisions may release significant radiation and energy. This obviously alters the standard prediction of CCDM on galactic scales. Hopefully, this radiation can be detected and identified which would provide strong evidence for “non-baryonic DM” which nevertheless carry huge baryon charge in the form of dense nuggets.

The basic proposal was originally intended to explain the order of magnitude similarity in the energy densities of visible and dark matter, $\Omega_{DM} \approx 5\Omega_B$. Such a similarity has no simple explanation if dark matter represents a fundamentally different field than normal matter. If however, both visible and dark matter have their origins at the QCD phase transition of the early universe they would naturally be expected to have similar scales [10].

This paper seeks specifically to explain the COMPTEL detection of excess photons in the 1-20 MeV range and relate this excess to other radiation puzzles mentioned above. In particular, as both resonance positronium formation and direct $e^+e^- \rightarrow 2\gamma$ photon production have a common source, the general normalization which depends on DM and visible matter distributions does not bring any additional uncertainties in our estimates which follow.

In this paper we adopt a simple model for nugget structure in which all quarks form one of the color superconducting (CS) phases with densities a few times typical nuclear density, while the electrons in the bulk of the nuggets can be treated as a noninteracting Fermi gas with density $n_e \simeq \frac{(\mu^2 - m_e^2)^{3/2}}{3\pi^2}$, with μ being the electron chemical potential. A precise numerical estimation of μ depends on the specific details of the CS phase under consideration, and on the structure of the surface of the nuggets. Generally it may take physical values from a few MeV up to tens of MeV [17], [18]. In this paper we will treat μ as an effective parameter of our model which varies in the range $\text{MeV} \leq \mu \leq \text{tens MeV}$. Some features of the nuggets which will be relevant for our calculations are discussed in Appendix.

3. Spectrum Calculation

As suggested previously in refs [13], [14] the 511 keV line can be naturally explained as a result of positronium formation when a non-relativistic electron (e^-) hits the antimatter nugget surrounded by positrons (e^+) with chemical potential μ . A certain fraction of galactic electrons incident on the CCO will annihilate directly $e^+e^- \rightarrow 2\gamma$ (rather than participate in resonance positronium formation) resulting in the creation of photons of energy greater than 511keV with a maximum energy up to $\simeq \mu$. The corresponding fraction of electrons obviously depends on lepton’s chemical potential μ and on specific properties of the nugget’s surface structure and the resulting distribution of positrons. It is not the goal of the present paper to calculate the corresponding fraction based on a specific model. Instead, we shall introduce this ratio as theoretically unknown

phenomenological parameter which will be fixed to match the observational data.

It will be demonstrated that radiation arising from this DM model can account for the broad spectrum across the 1-20 MeV range observed by COMPTEL. Anticipating this conclusion, we should mention here, that it is quite remarkable that the maximum energy where the excess has been observed by COMPTEL (~ 20 MeV) coincides with a typical estimation for μ in quark matter [17], [18]. As we shall see below, the maximum photon energy within our mechanism exactly coincides with the lepton chemical potential in the nugget $\mu \sim 20$ MeV. We stress here that this energy scale arises naturally from the properties of quark matter and has not been introduced in order to fit with the COMPTEL observations. This is very robust prediction of our mechanism which is not sensitive to the specific details of the nugget's structure nor to DM and visible matter distributions.

As mentioned above, we treat the positrons at the CCO surface as a non-interacting Fermi gas of chemical potential μ . The density of states in the momentum range p to $p + dp$ is then given by, $dn(p) = \frac{2d^3p}{(2\pi)^3}$ so that the rate of direct electron-positron annihilation resulting in a photon of momentum k and involving a positron of momentum p is given by,

$$\frac{dI(k, \mu)}{dkdt} = \int dn(p)v(p)\frac{d\sigma(p, k)}{dk} = \int \frac{2d^3(p)}{(2\pi)^3} \frac{p}{E} \frac{d\sigma(p, k)}{dk}, \quad (1)$$

where $\frac{d\sigma(p, k)}{dk}$ is the electron rest frame cross section for direct electron-positron annihilation resulting in a photon of momentum k . In this formula we assume that incoming electron has a velocity v_e well below that of a typical positron ($v(p)$) Within the nugget. Therefore, calculations are carried out in the rest frame of the incident electron, i.e. $v_e = 0$.

The required cross-section may be obtained from a simple QED calculation, at tree level it is given by

$$\begin{aligned} \frac{d\sigma(p)}{dk} &= \frac{\pi\alpha^2}{mp^2} \left[\frac{-(3m + E)(m + E)}{(m + E - k)^2} - 2 \right] \\ &+ \frac{\pi\alpha^2}{mp^2} \left[\frac{\frac{1}{k}(3m + E)(m + E)^2 - (\frac{m}{k})^2(m + E)^2}{(m + E - k)^2} \right], \end{aligned} \quad (2)$$

see for example[4]. In this expression E represents the energy of a Fermi gas positron. The net production rate of photons of momentum k is then given by integrating this expression over all allowed momentum states of the Fermi gas

$$\begin{aligned} \frac{dI(k, \mu)}{dkdt} &= \int \frac{8\pi dE}{(2\pi)^2} \frac{\pi\alpha^2}{m} \left[\frac{-(3m + E)(m + E)}{(m + E - k)^2} - 2 \right] \\ &+ \int \frac{8\pi dE}{(2\pi)^2} \frac{\pi\alpha^2}{m} \left[\frac{\frac{1}{k}(3m + E)(m + E)^2 - (\frac{m}{k})^2(m + E)^2}{(m + E - k)^2} \right], \end{aligned} \quad (3)$$

where we have integrated over all solid angles. In deriving this expression we have taken into account that the upper and lower limits of integration are set by the chemical potential and the threshold for photon production respectively. As maximum

photon energy occurs for emission along the direction of initial positron momentum the threshold momentum is the value for which such a configuration results in a photon of energy k . Evaluating this expression gives the probability of annihilation per unit time dt for emitted photon energies from k to $k + dk$ when a single electron hits the nugget,

$$\begin{aligned} \frac{dI(k, \mu)}{dkdt} = & \frac{\alpha^2}{\pi m k^2} \left[k(k^2 + 2mk - 2m^2) \ln \left(\frac{(2k - m)(\mu + m - k)}{mk} \right) \right. \\ & - \frac{3}{2}k^3 - (\mu + 5m)k^2 + \left(\frac{1}{2}\mu^2 + 3\mu m + \frac{9}{2}m^2 \right)k - m^2(\mu + m) \\ & \left. + \frac{k^2 m^2}{\mu + m - k} + (8k^4 - 8mk^3 - \frac{5}{2}m^2 k^2 + 4m^3 k - m^4) \frac{k}{(2k - m)^2} \right] \end{aligned} \quad (4)$$

In the next section, based on this spectrum, we will evaluate the expected flux of photons in the 1-20 MeV range resulting from the direct $e^+e^- \rightarrow 2\gamma$ annihilation by normalizing the corresponding flux to 511 keV line measured by INTEGRAL. For normalization purposes in what follows we also need the total flux integrated over all photon energies. For large $\mu \gg m$ the corresponding expression is given by

$$\frac{dI(\mu)}{dt} = \int \frac{dI(k, \mu)}{dkdt} dk \simeq \frac{\alpha^2 m}{2\pi} \left(\frac{\mu}{m} \right)^2 \ln \left(\frac{\mu}{m} \right) \quad (5)$$

This approximation is found to be fully adequate for our present purposes.

4. Normalization to 511 keV Line

The original proposal [13] on formation of the 511 keV line assumes that almost all galactic electrons incident on the DM anti-nuggets will form an intermediate state positronium. About a quarter of the positronium decays (from the 1S_0 state) release back-to-back 511 keV photons, while three quarters (from the 3S_1 state) will lead to continuum emission with energy $k \leq 511$ keV, also observed by the INTEGRAL. In addition, as originally suggested in [11] and as was mentioned above, a certain fraction of galactic electrons incident on the anti nuggets will annihilate directly $e^+e^- \rightarrow 2\gamma$ avoiding resonance positronium formation. This direct annihilation results in the creation of photons with a maximum energy up to $\simeq \mu$ which, by definition, is the maximum energy of positrons in the nuggets. The corresponding spectrum for a single event was calculated above and is given by eq.(4). Our goal here is to present the corresponding expression for the flux accounting for all annihilation processes happening along the line of sight towards the galactic centre. This flux will depend on the number of electrons along the line of sight which is roughly determined by the number density of protons, $n_{e^-} \simeq n_B \sim \rho_B(r)/m_p$ while the number density of DM particles is determined by the DM distribution, $n_{DM} \sim \rho_{DM}(r)(Bm_p)$.

4.1. Spectral flux in 1-20 MeV range from the galactic center.

By comparing the flux for the 511 keV line with the flux in the 1-20 MeV range, one may remove the dependence on the dark and visible matter distributions because, provided

they have a common origin, the radiation for both fluxes should be integrated along almost the same line of sight from the earth to the core of the galaxy. As a result, direct comparisons between the data provides non-trivial insight into the properties of the nuggets, independent of the matter distributions. Therefore, we can avoid the corresponding uncertainties related to $\rho_{DM}(r)$, $\rho_B(r)$ as well as uncertainties related to typical sizes of the nuggets, their size-distribution etc by normalizing the spectrum of these 1-20 MeV photons using the well-measured intensity of the 511 keV line with an average flux observed to be $\frac{d\Phi}{d\Omega} \simeq 0.025$ photons $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ coming from a circle of half angle 6° [2] from the inner part of the galaxy. This region strongly overlaps with the region of interests where COMPTEL data are available, ($l = 330^\circ - 30^\circ$, $|b| = 0^\circ - 5^\circ$). In what follows we neglect any differences resulting from the slightly different lines of sight for measurements by INTEGRAL and COMPTEL.

In addition, we introduce the coefficient χ as the ratio of electrons which experience direct $e^+e^- \rightarrow 2\gamma$ annihilation in comparison with the number of electrons which experience resonance positronium formation. Now the spectrum obtained in (4) may be normalized using the high energy approximation (5) and then scaled by the observed flux of 511 keV photons (A more extensive description of this flux calculation may be found in [13]). Following this procedure one arrives at an expression for the flux of 1-20 MeV photons from the bulge of the galaxy normalized to the 511 keV line as described above,

$$\begin{aligned} \frac{d\Phi(k)}{d\Omega dk} &= 0.025 \cdot \frac{4\chi}{\text{MeV} \cdot \text{s} \cdot \text{cm}^2 \cdot \text{sr}} \cdot \left(\frac{2}{k^2 \mu^2 \ln\left(\frac{\mu}{m}\right)} \right) \\ &\times \left[k(k^2 + 2mk - 2m^2) \ln\left(\frac{(2k-m)(\mu+m-k)}{mk}\right) \right. \\ &- \frac{3}{2}k^3 - (\mu + 5m)k^2 + \left(\frac{1}{2}\mu^2 + 3\mu m + \frac{9}{2}m^2\right)k - m^2(\mu + m) \\ &\left. + \frac{k^2 m^2}{\mu + m - k} + (8k^4 - 8mk^3 - \frac{5}{2}m^2 k^2 + 4m^3 k - m^4) \frac{k}{(2k-m)^2} \right] \end{aligned} \quad (6)$$

where we have taken into account that the total number of positroniums formed is 4 times the number of positroniums in the 1S_0 state emitting 511 keV photons with the flux $\frac{d\Phi}{d\Omega} \simeq 0.025$ photons $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. We also took into account the normalization (5) for the direct annihilation $e^+e^- \rightarrow 2\gamma$ for large μ . In eq.(6) mass, m , photon energy, k and chemical potential, μ are all measured in MeV units.

This normalization allows us to analyze the MeV spectra without a precise model of dark matter /visible matter distributions within the galactic bulge, assuming of course that both emissions (511 keV line and 1-20 MeV photons) come from the same source, the antimatter nuggets. As we shall see in the next subsection, our mechanism can easily explain a large spectral flux measured by COMPTEL if the values of μ within the physically relevant range of tens of MeV and parameter $\chi \sim 0.1$, see below \ddagger .

\ddagger roughly speaking, the parameter χ describes the survival rate of electrons after they enter the nugget's electrosphere and experience the resonance positronium formation.

4.2. Discussion of results

The COMPTEL observations, figure 1, suggest that a typical spectral flux in the tens of MeV region is, $k^2 \frac{d\Phi(k)}{d\Omega dk} \sim 10^{-2} (\text{MeV} \cdot \text{s}^{-1} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1})$. Such a magnitude can be easily accommodated by our mechanism with a survival rate of $\chi \sim 0.1$ as can be seen from the general normalization of eq. (6). We do not attempt in this work to make a precise fitting to the measured spectrum. Such a fitting would require, for example, the subtraction of all contributions from background emission processes, such as those due to cosmic rays[8], or other background astrophysical processes, see [19] and references to the original literature therein.

On the theoretical side, it is expected that the spectrum may be considerably changed when the surface details of the nuggets are taken into account. This is due to the fact that $\mu(r)$ depends on the distance from the nugget's surface. In this "transition region" the lepton chemical potential slowly interpolates between μ in the bulk and zero in the vacuum [17]. The implications of this transition region for the predicted spectrum are discussed briefly in the appendix below.

However, we do not expect the general normalization factor χ as estimated above to experience any considerable changes when all these (and many other) unaccounted effects are considered.

As argued in [14], a typical time scale for a formation of the positronium is simply a typical atomic time if an electron is surrounded by positrons with atomic densities. In our case one expects $\tau_{Ps} \sim \nu^{-1}$ where $\hbar\nu \simeq m_e\alpha^2$ is a typical energy scale for the positronium. Therefore, the vast majority of incident electrons will form positronium. Only a very small portion of the electrons may be expected to avoid positronium formation, and reach surface where the local chemical potential is large and $e^+e^- \rightarrow 2\gamma$ annihilation events producing 1-20 MeV photons dominate. Precise estimation of the fraction χ of electrons which are able to reach the surface strongly depends on a number of factors, such as typical velocities of electrons in the galactic bulge, specific features of the transition region (which itself depends on μ in the bulk, the temperature of the surface and many other parameters). It is not our goal of this paper to estimate the parameter χ using some model dependent calculations, instead our goal is to constrain the properties of the antimatter nuggets using the observational data available. We are quite satisfied with the result $\chi \ll 1$ which is a natural value for all types of antimatter nuggets with any type of color superconductivity in the bulk. In the Appendix we sketch the procedure of calculating the spectrum by using a very simplified model for the nugget's structure. The results of a representative calculation are presented on Fig.1 where we use numerical coefficient $\chi \sim 0.2$.

5. Conclusion.

The discussions in this paper have been motivated by the observation that the 511 keV line and excess of the diffuse γ -rays in 1-20 MeV range—two apparently unrelated

puzzles of modern astrophysics—might in fact have a common origin. It is remarkable that both of these observations can be naturally explained within a model which was invented to explain a completely different puzzle—the similarities between dark matter and visible baryonic matter densities in the universe, $\Omega_{DM} \sim \Omega_B$, rather than having been designed to specifically explain either 511 keV or 1-20 MeV γ -ray emissions §. In this respect our proposal is very different from a large number of other suggestions which were specifically invented to resolve 511 keV puzzle, see [20] for an almost complete set of references on the subject.

Another motivation is to bring to the attention of the astrophysics community the possibility that these two independent observations may have a common origin. Evidence for similar morphologies might already be present in the existing data as discussed in the introduction— 511 keV emission as well as excess of the continuum 1-20 MeV emission (after subtracting contributions from well known astrophysical processes) are concentrated around the galactic center while no considerable excess flux is observed outside this region.

If such a morphological correlation between the 511 keV line and the excess of the diffuse γ -rays at 1-20 MeV is confirmed by future, more precise measurements, it would give a strong evidence that the diffuse γ -rays in the 1-20 MeV range are due to e^+e^- annihilation (511 keV line obviously is a result of e^+e^- annihilation via the positronium formation). At the same time, the required energetic positrons produced as a result of the annihilation of ~ 20 MeV dark matter particles (suggested, e.g. in[3],[21]) seem ruled out [4, 5, 6]. The only option which remains is to lock energetic positrons ~ 20 MeV in some form for which the in-flight annihilation with electrons from the interstellar medium is limited to satisfy the necessary constraints [4, 6] (see however ref.[22] with another suggestion). Our model with antimatter nuggets offers precisely this kind of structure for the confinement of positrons while still allowing energetic annihilations when electrons from the interstellar medium hit the nuggets. It is quite remarkable that typical values of the estimated lepton chemical potential for quark matter fall in the range of tens of MeV which is precisely where an excess of diffuse γ -rays is observed by COMPTEL. We have to stress again, we have not introduced this parameter in order to explain the COMPTEL γ excess, rather this range of $\mu \sim$ tens MeV was calculated long ago for a quark matter surface[17].

If our testable prediction of spatial correlations between the 511 keV and the excess of the diffuse γ -ray emission in 1-20 MeV range is verified by new observational data||, this would be of fundamental physical interest, irrespective of any model specific details.

§ It is also quite remarkable that another naively unrelated puzzle of modern astrophysics, diffuse X ray emission, may also find its natural explanation within the same model [16].

|| In particular, while the GLAST main instrument, the Large Area Telescope (LAT), will provide unprecedented sensitivity to gamma rays in the energy range of about 20 MeV to about 300 GeV, the GLAST Burst Monitor (GBM) will be sensitive to X-rays and gamma rays with energies between 8 keV and 25 MeV which in principle overlaps with the region of interests. However, it is not clear whether GBM sensitivity will be sufficient to establish the correlation between 511 keV line and excess of the diffuse 1-20 MeV continuum as we advocating in the present work.

It would unambiguously imply that the positrons are hidden in some form of antimatter nuggets. The point of this paper is to argue that this model should be seriously investigated because such a correlation might unlock several important cosmological and astrophysical mysteries.

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Appendix A. Dark Matter Anti-Nuggets and their Interactions with In-falling Visible Electrons

In order to present a representative spectrum resulting from the interactions between a dark matter CCO and incident galactic electrons it will be necessary to detail some features of the transition region discussed above. While a full treatment is beyond the scope of this paper some simple calculations should suffice to demonstrate the general effects of including a non-trivial distribution of lepton chemical potentials.

While the quark matter surface is relatively sharp, with a scale set by strong force interactions, the surrounding leptons are bound electromagnetically and take the form of an extended electrosphere. In what follows we shall denote the lepton chemical potential at the quark matter surface as μ_0 , it is this value which is expected to fall in the \sim tens MeV range. Above the surface the local value of μ must fall off such that $\mu(r \rightarrow \infty) \sim 1/r$ as a consequence of Maxwell's equations and the requirement of chemical equilibrium [17]. For present purposes we consider the ultra relativistic case in which the local positron chemical potential is much larger than m and varies with distance z from the surface as

$$\mu_{e^+}(z) = \sqrt{\frac{3\pi}{2\alpha}} \frac{1}{(z+z_0)}, \quad z_0 = \sqrt{\frac{3\pi}{2\alpha}} \frac{1}{\mu_0}, \quad n_{e^+}(z) \simeq \frac{\mu_{e^+}^3(z)}{3\pi^2} \quad (\text{A.1})$$

where z_0 can be interpreted as a characteristic thickness of the electrosphere [17],[23]. Such a behavior (A.1) is a result of mean field calculations similar to the Thomas-Fermi approximation in atomic physics. This model has previously been applied in the context of quark stars[17],[23].

At a given height the flux of incident electrons will undergo an exponential extinction with an annihilation rate $\frac{dI(z)}{dt}$ as given in equation (5). Consequently the number of electrons surviving at height z satisfies,

$$\left(\frac{dN_{e^-}(z)}{dt} \right) = N_{e^-}(z) \left(\frac{dI(z)}{dt} \right) \quad (\text{A.2})$$

In principle, if we knew the precise structure of the electrosphere at all heights, from small to very large densities, we could calculate the survival rate χ as well as the number of electrons $N_{e^-}(z)$ available for annihilation with the nugget's positrons in

the dense region closest to the quark matter surface. As we mentioned above, a full treatment of this problem is beyond the scope of the present work. Instead, we introduce a phenomenological parameter χ which describes the fraction of electrons which survive resonance formation and reach the dense inner region where direct annihilation events dominate. We model the dense region by introducing a parameter z_{max} such the relevant region satisfies the following condition, $z \leq z_{max}$. We will choose z_{max} such that $\mu(z_{max}) \gg m_e$ thus the ultra relativistic approximation holds within this region and eq. (A.1) can be trusted.

For large $\mu_{e^+}(z) \gg m$ one can approximately integrate equation (A.2) using the expression (A.1) for $\mu_{e^+}(z)$ and approximate expression (5) for $\left(\frac{dI(z)}{dt}\right)$ at large μ . The obtained result is

$$N_{e^-}(z) = N_{e^-}(z_{max})e^{-\left[\frac{3\alpha}{4mv_e}\left(\frac{1}{(z+z_0)} - \frac{1}{(z_{max}+z_0)}\right)\ln\left(\frac{\mu_0}{m}\right)\right]}, \quad z \leq z_{max}, \quad (\text{A.3})$$

where v_e is the z - component of the in-falling electron's velocity. In order to obtain the complete resultant spectrum we average expression (6), calculated based on annihilation at a specific $\mu_{e^+}(z)$ value, over all heights weighted by the remaining electron density at point z above the nugget's surface,

$$\frac{d\Phi(k)_{net}}{d\Omega dk} \sim \int_0^{z_{max}} dz N_{e^-}(z) \frac{d\Phi(k, \mu(z))}{d\Omega dk}. \quad (\text{A.4})$$

As is to be expected accounting for the distribution of $\mu(z)$ values with height z produces an E^2I curve which is considerably flatter than the single μ valued spectrum given in (6). The result of this procedure is shown in Fig 1 with representative values of $\chi = 0.2, \mu_0 = 60, z_{max} = 28z_0$ chosen.

We stress that we do not attempt in the present work to make a perfect fit to the observations by exploring a variety of possible models for the electrospheres of the nuggets. Instead, the main goal of this appendix is to present an idea of how a calculation of the complete spectrum resulting from our mechanism would proceed in a simple-minded model. We have not attempted to consider the effects of a range of incident electron velocities, and have limited our calculations to the relativistic limit so that the resultant spectrum is unreliable below $E \sim$ few MeV. However, the generic features of the spectrum will remain the same. These features are: from eq. (6) it is clear that for a given $\mu(z)$ the flux times k^2 is strongly peaked at maximum possible momenta $k \leq \mu(z)$. At the same time electron density $N_{e^-}(z)$ is decreasing when electron moves to the region of the larger positron densities as eq. (A.3) suggests. These two effects strongly compensate for each other such that $E^2\Phi$ is almost flat in the region of interests, varying by only a factor of two over an order of magnitude in energy. Detail analysis of the spectrum as well as its model dependence and sensitivity to phenomenological parameters will be presented in our future work. However, we should remark here that the resulting spectrum shown in Fig 1 is not meant to fit the COMPTEL measurements. Rather, it is meant to describe the **excess** between the measurements and the contributions accounted by other known astrophysical processes[8] which we

treat as a background in the present work. In particular, for the photon's energy $k \sim (20 - 30)\text{MeV}$ the excess almost vanishes according to analysis[8], and the spectrum above this region could be nicely fitted. Our model automatically has this feature as a generic consequence of the exponential suppression of the electron density $N_{e-}(z)$ when electrons are approaching the very dense region with large μ close to the nugget's surface, see eq. (A.3). Indeed, superposition of the γ ray background calculated in [24] (blue solid line in 1) and the γ ray contribution due to the annihilation mechanism with nuggets (heavy black dots) falls almost to the central value of the COMPTEL data at the highest energy about 20 MeV (green vertical bar at the right side). As we mentioned above, in few MeV region our calculations are not valid due to some assumptions we have made to simplify our estimates such as cut off at z_{max} where chemical potential $\mu(z_{max})$ is in few MeV range. Therefore, we interpret the obtained results as consistent with the COMPTEL data.

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