Stringent neutrino flux constraints on antiquark nugget dark matter

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Strongly interacting matter in the form of nuggets of nuclear-density material is not currently excluded as a dark matter candidate in the ten gram to hundreds of kilogram mass range. A recent variation on quark nugget dark matter models postulates that a first-order imbalance between matter and antimatter at the quark-gluon phase transition in the early Universe could lead to most of the dark matter bound into heavy (baryon number $B \sim 10^{25}$) antiquark nuggets in the current epoch, explaining both the dark matter preponderance and the matter-antimatter asymmetry. Interactions of these massive objects with normal matter in the Earth and Sun lead to annihilation and an associated neutrino flux in the ∼30 MeV range. We calculate these fluxes for antiquark nuggets of sufficient flux to account for the dark matter and find that current neutrino flux limits from Super-Kamiokande (SuperK) exclude these objects as major dark matter candidates at a high confidence level. Antiquark nuggets in the previously allowed mass range cannot account for more than ∼15% of the dark matter flux.

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Baryons in the form of normal matter are tightly constrained as dark matter candidates under standard models of light element synthesis in the early Universe [1], but a hypothesis originally proposed by Witten [2] provides for production of stable composite strange quark matter, also known as *nuclearites* or *strangelets*, prior to nucleosynthesis, effectively removing this baryonic material from interaction during later phases [3]. In the decades since this proposal, it has undergone much scrutiny and refinement [4–7], and still remains as a viable hypothesis [8]. With the tightening constraints on beyond-standard model particle candidates, alternative scenarios such as stable quark nuggets also deserve renewed attention as dark matter candidates. Although such objects might seem to be excluded as dark matter candidates because of their strong interactions, it is in fact the cross section per gram of candidate material σ/M that is astrophysically important for the viability of dark matter candidates. The current best estimate of this constraint is $\sigma/M \lesssim 0.1$–$1\ \mathrm{cm}^2\,\mathrm{g}^{-1}$ [9,10]. This bound is easily evaded by massive quark nuggets, for the simple reason that they are rare enough that their interactions with any other objects exceed normal time scales for observation.

Mass regions from baryon number $B \sim 10^3 - 10^{25}$ are already largely constrained [11–14] to values well below the dark matter flux. Above this range the flux in quark nuggets is too low to be constrained by normal detectors, and indirect methods must be employed, for example, limits on seismic events for objects in the hundreds to thousands of kg range. In most scenarios, quark nuggets of normal matter, rather than antimatter, are considered, and their interactions with other massive bodies are primarily through collisional heating via their kinetic energy, since their mean velocity in the solar neighborhood should be of order $250\ \mathrm{km\,s^{-1}}$, consistent with the galactic virial dispersion.

Because the nuggets are formed at a very early epoch, both normal quark and antiquark matter are allowed, and in fact a nearly equal mix is possible. Recent work has emphasized the possibility that a moderate asymmetry in these objects during their production, and subsequent "drop-out" from normal matter interactions, could naturally explain both the dark matter and the current matter-antimatter asymmetry, without a need for fine-tuning [14,15]. This scenario would require a large population of antiquark nuggets (AQN) as well as normal quark nuggets, and the former objects would have very different phenomenology of their interactions with normal matter, with antimatter annihilation dominating over kinetic energy deposition. In this report, we consider a proposed model where antiquark nuggets dominate the dark matter [16–18]. Matter-anitmatter annihilations from those AQNs entering the Sun lead to a detectable MeV neutrino flux from pion and muon decay, over a very wide range of quark nugget masses. The current bounds from SuperK [19] then provide constraints that, under standard parameters for these objects, exclude them as dark matter candidates.

To model AQN interactions in the Sun, we developed a Monte Carlo code which starts with an isotropic flux of AQN at 30 AU, using a Maxwellian velocity distribution,

$$f(v)dv = \frac{4}{\sqrt{\pi}}\left(\frac{3}{2}\right)^{3/2}\frac{v^2}{v_{rms}^3}\exp\left(\frac{-3v^2}{2v_{rms}^2}\right)dv \qquad (1)$$

where v is the AQN speed, and $v_{rms} \sim 270\ \mathrm{km\,s^{-1}}$ is the galactic velocity dispersion. At 30 AU, the solar escape velocity is about $5\ \mathrm{km\,s^{-1}}$, around 2% of the mean speed of the particles; thus the phase space is only slightly biased by the solar potential. The relevant average inward flux of dark matter particles through a spherical surface, based on the assumed average local dark matter density $\bar{\rho}_{\mathrm{DM}} = 0.3\,\mathrm{GeV\,cm^{-3}}$, is given by $\Phi = \bar{n}\,\bar{v}\,/2$, where $\bar{n} = \bar{\rho}_{\mathrm{DM}}/m$

for AQN mass m; we show the derivation of the flux normalization in Supplemental Material.

Once their speed and impact parameter are known, the impact parameter for capture is given by

$$b_{\mathrm{cap}} = R_{\odot}\sqrt{1+\frac{2GM_{\odot}}{R_{\odot}v^2}} \tag{2}$$

where G is the gravitational constant, and $R_{\odot}, M_{\odot}$ are the solar radius and mass, respectively. Those AQN that intersect the solar disk are then propagated into the inner Solar System using a fourth-order Runge-Kutta integrator.

Upon entering the solar interior, AQN begin to collide with and annihilate with normal matter, which is encountered both through their in-fall speed and cross section, and through the rapid rise in the thermal acoustic velocity of the solar interior. For the former accretion mechanism, the AQN speed and cross section are used, and for the latter, the acoustic speed vs solar radius combined with the area of the (presumed) spherical AQN is used. The kinetic energy loss by ram pressure for either quark or antiquark nuggets was first derived in the analysis of de Rujula and Glashow [20],

$$\frac{dE}{dx} = -\sigma_n \rho(s) v^2 \tag{3}$$

where σ_n is the cross-sectional area of the nugget, and $\rho(s)$ is the density along the track s. These results apply in the case of isotropic emission (and thus isotropic recoil) of the resulting radiation, which is consistent with the original AQN emission model proposed. Any significant anisotropy in the emission pattern requires a thermal gradient across the surface of the AQN; such a thermal gradient does not seem consistent with the high thermal conductivity implied for the AQN model at the nonrelativistic speeds considered here.

For normal quark matter, the mass remains constant throughout the interaction, but for AQN, matter annihilation at some fractional efficiency ϵ_a causes it to lose mass during its transit of the solar interior. The efficiency factor is due to reflection of incoming nuclei by the surface of the quark nugget; typical estimates of the efficiency are $\epsilon_a \sim 0.05$. Thus the complete equation of motion for AQN is modified both by the mass loss and the efficiency.

$$m(t)\frac{d\vec{v}}{dt} = -(1-\epsilon_a)\sigma_n(m)\rho(r)v^2\hat{v} - \frac{Gm(t)M_{\mathrm{int}}(r)}{|r^3|}\vec{r} \tag{4}$$

where $M_{\mathrm{int}}(r)$ is the solar mass interior to radial distance r. The variable AQN mass term $m(t)$ appears in this form here since we have assumed that the energy of annihilation is radiated isotropically from the AQN surface, a reasonable assumption, since the emission is treated as effective blackbody radiation from the AGN surface as it thermalizes the annihilated material.

The cross-sectional area of the nugget is given by

$$\sigma_n(m) = \pi\left(\frac{3m(t)}{4\pi\rho_N}\right)^{2/3} \tag{5}$$

where $\rho_N = 3.5\times 10^{17}\ \mathrm{kg\,m^{-3}}$ is the nuclear density of the nuggets. The mass loss function $m(t)$ is determined by

$$\frac{dm}{dt} = \frac{dm}{ds}\frac{ds}{dt} = v\frac{dm}{ds} = F(v, c_s) \tag{6}$$

where the function $F(v, c_s)$ accounts for the two accretion regimes with respect to the solar acoustic velocity $c_s(r)$. For $v > c_s$, the speed of the AQN is supersonic and cross-sectional capture of material dominates; for subsonic speeds $v < c_s$, the capture becomes spherical, dominated by the acoustic speed of the surrounding gas,

$$F(v>c_s) \simeq v\sigma_n\rho(r), \quad F(v<c_s) \simeq c_s(r)A_n\rho r \tag{7}$$

where $A_n = 4\sigma_n$ is the AQN total area. For the solar acoustic speed and density, we use standard solar model data [21]. With this equation of motion and mass loss function, the total number of nuclear interactions per AQN is determined.

Recent calculations by Rott, Siegal-Gaskins, and Beacom (RSB) [22] of annihilation of weakly interactive massive particle (WIMP) dark matter candidates have looked specifically at the neutrino production through WIMP annihilation in the Sun. Despite the fact that the propagation and annihilation of a WIMP and an AQN are dissimilar, once annihilation takes place in pions, the resulting decay chains are commensurate and may be accurately used to estimate neutrino production for AQNs as well once the number of pions and muons is estimated. These calculations involved detailed simulations of the hadronic interactions in the high-density solar interior, with a specific goal of yielding the number of neutrinos produced per annihilation. While these calculations included some uncertainty in the efficiency of producing final hadronic states from WIMP annihilation, they otherwise apply directly to annihilation of AQN in the sun, a process in which hadronic final states are completely dominant.

For the average number N_ν of neutrinos per annihilation, RSB found $N_\nu \sim 1$–10, depending on details of the hadronic fraction of the annihilation products. While π^- form Coulombic atoms and are eventually absorbed, the positive pions decay leading to three neutrinos, $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$, with energies up to about 53 MeV. Underground neutrino detectors such as SuperK and SNO have their highest signal-to-noise ratio in the energy range from 20–50 MeV for electron antineutrinos and neutrinos, respectively. Electron neutrinos comprise about $1/3$ of the total, and the matter-enhanced oscillation probability $P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 1/6$, yielding about $1/18$ of the total neutrino flux in electron antineutrinos at Earth [22]. Despite its small fraction of the total, the $\bar{\nu}_e$ component of the neutrino flux provides the most stringent limit, because of the high sensitivity of terrestrial neutrino detectors to this flavor channel. However, it is important to note that Super-K limits also constrain neutrino fluxes down to about 11 MeV [19], with bounds that are about a factor of 4 weaker than those at higher energies, but still significant.

We simulate the AQN mass range from 1 gram to 10^8 kg, and we use the low end of the range given by RSB, 1 neutrino per nucleon annihilation, to estimate the resulting neutrino flux vs AQN mass. Beyond 10^8 kg, we find that the interval between individual AQN captures by the Sun begins to significantly exceed the time it takes for an AQN of this mass to deposit its energy in the Sun. Since the neutrino emission is no longer continuous in this case, the Sun is effectively too small to probe mass ranges beyond 10^8 kg.

We note in passing that the typical total annihilation power produced in the Sun by AQNs of all masses at the dark matter flux level is of order 10^{27} ergs s^{-1}, less than 10^{-6} of the solar luminosity; thus the energy deposited by AQN in the Sun is of no consequence in constraining their flux.

Results for the total and $\bar{\nu}_e$ flux at Earth are shown in Fig. 1. SuperK electron antineutrino flux limits [19] are plotted along with the expected all-neutrino and electron antineutrino fluxes for an AQN flux equal to the expected dark matter flux. The resulting electron antineutrino fluxes exceed the limit by a factor of 10 at the low end, and a factor of 6.5 at the high end of the mass range. The neutrino fluxes from AQN interactions decrease only slowly with AQN mass, primarily due to the increased probability that AQNs of larger masses may cross the Sun on an unbound transit chord, and survive to escape without depositing all of their mass energy.

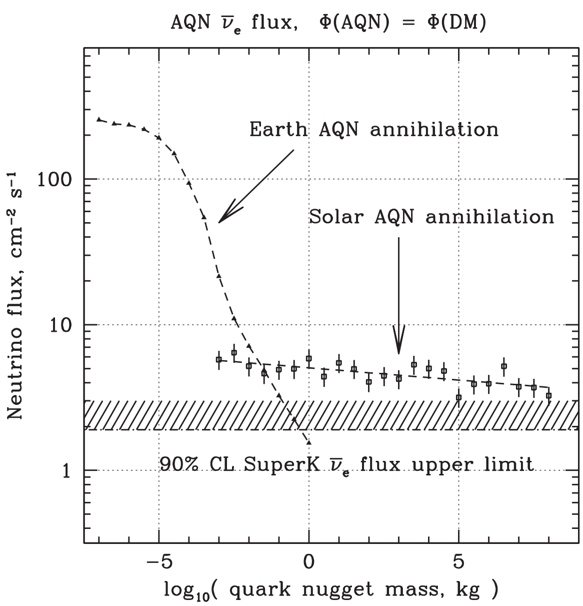

FIG. 1. Neutrino fluxes from the Sun resulting from AQN annihilation when the AQN flux equals the local dark matter flux for $\rho_{DM} = 0.3$ GeV cm^{-3}. The upper set of points is the total neutrino flux (with the flavors at the source indicated) and the lower set of points (=1/18 upper) is the expected electron antineutrino fluxes. Limits from SuperK for the >20 MeV antineutrino flux are also shown.

Since the results for Fig. 1 are computed for an assumed flux of AQNs equal to the dark matter flux at a mean three-dimensional velocity of 250 km s^{-1} and a density of 0.3 GeV cm^{-3}, the Super-K limits from antielectron neutrinos translate directly to monomass limits of no more than 10%–15% of the dark matter flux as shown in Fig. 2. The plot shows also the equivalent differential dark matter flux for these masses, along with constraints on normal-matter quark nuggets which apply to AQN as well in this case. The curves in each case (and the data points where shown) are monomass limits, treating the quark nugget spectrum as a delta function in mass. Integral limits involving (perhaps) more realistic spectra with a distribution of masses would of course be more restrictive, and the limits shown are thus conservative. The dark matter flux is thus also expressed as a pure differential flux density of monomass objects at each given baryon number.

Prior limits (typically at the 90% CL where stated) from the absence of observations of fast meteors [23,24], appropriate tracks in samples of the mineral Mica [13], and seismic limits from the Apollo-11 Lunar lander [25–27] already provide constraints below the dark matter flux for all strange quark nuggets of baryon numbers from $\sim 10^{19-25}$ from the terrestrial observations, and for a smaller window from 50–1000 kg based on the Lunar seismic limits. Our results, which range from AQN masses of 1 gram up to 10^8 kg, eliminate

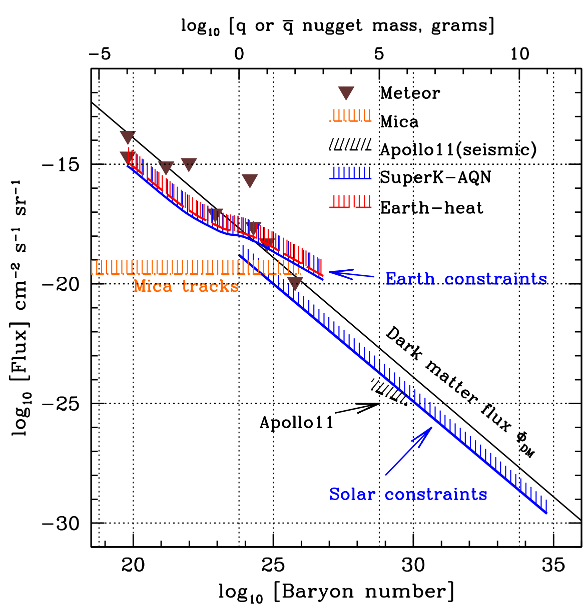

FIG. 2. Constraints on normal-matter quark nuggets from prior work as shown, compared to constraints from this work on antiquark nuggets. The constraints from normal-matter quark nuggets also apply.

antiquark nuggets over a wide mass range from $B = 10^{20-35}$, with no more than 10%–15% of the dark matter flux allowed in AQN. Our constraints do not of course work in reverse for normal-matter quark nuggets; their phenomenology does not include neutrino production in the same manner as AQN.

Our limits have virtually no dependence on the assumed 5% AQN-nucleon capture efficiency, at least within an order of magnitude. This is because the great majority of deposited energy by AQN in the Sun comes from objects whose orbits rapidly decay in the interior of the Sun after they enter it, whether or not they were tightly bound to begin with. Capture efficiencies even an order of magnitude lower than the expected 5% result in a redistribution of the deposited energy, but the bound remains essentially unaffected. At the lower masses, most of the AQN are found to fully annihilate outside the solar core; lower nucleon capture efficiencies result in their energy being deposited closer to the core, but do not allow them to escape. The expected capture efficiency would have to be several orders of magnitude below expected values [15] in order to begin to relax these bounds.

If the AQN exist in a color-superconducting phase [14] the output spectrum of neutrinos can be significantly modified, leading to a lower energy component which might evade this bound, but could result in much higher neutrino fluxes at lower energies. However, lower-energy neutrino fluxes would still be subject to the weaker low-energy bound above 11 MeV noted above, and depending on the predicted low-energy neutrino fluxes, the resulting AQN flux bound might even be more stringent. In addition, the model that motivated this study [17,18] predicted specific muon fluxes that would result from color-superconducting AQN transiting normal matter, and thus regardless of the internal baryonic states, the resulting muons would lead to a neutrino excess comparable to what we model in this study. In this case, our bound can be also interpreted as a stringent constraint on the muon production efficiency proposed in Refs. [17,18].

In summary, while antiquark nuggets of masses in the kg to the 100 Kton range may be stable and could still provide a component of the current closure density of the Universe, their interactions in the Sun are a strong source of neutrino fluxes at Earth, and preclude their number density to a fraction of no more than 10%–15% of the dark matter density. For ρ_{DM} we have assumed a value at the low end of current estimates [28,29]; values could be several times higher than our estimate, and would lower the allowed AQN fraction of the dark matter accordingly. We have also assumed a neutrino-per-$q\bar{q}$ annihilation ratio of unity; this value is at the extreme low end of the estimated range [22], and midrange values would further tighten the bound.

Our results are also robust to assumptions regarding the annihilation efficiency of AQN; those entering the Sun are found to be unlikely to escape complete destruction even at efficiencies an order of magnitude below expectations. It is rather striking that while the excess of deposited energy by a dark matter flux of AQN is found to have negligible effects on the solar luminosity, neutrino fluxes from the Sun are remarkably sensitive to these objects, yielding robust and stringent constraints.

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