Solar Corona Heating by the Axion Quark Nugget Dark Matter

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Abstract. Astrophysics faces two 80-year-old mysteries: the nature of dark matter, and the high temperature of the million degree solar corona, radiating an extreme ultraviolet (EUV) excess of $10^{27}$ erg/s. The current paradigm is that the corona is heated by hypothetical nanoflares of unknown origin. Recently, in ref. [1] it was suggested that the nanoflares can be identified with the nuggets from the Axion Quark Nugget (AQN) dark matter model. This model was invented as an explanation of the observed ratio $\Omega_{\text{dark}} \sim \Omega_{\text{visible}}$, and has no free parameter other than the Axion mass. It is proposed that the AQN particles moving through the coronal plasma (and annihilating) can both explain the EUV excess and drastic changes of the temperature in the Transition Region. To test this proposal, we performed detailed numerical simulations with a realistic AQN particle distribution and physical environment. Remarkably, our calculations predict the correct energy budget for the solar corona, and an energy injection altitude in agreement with the temperature and mass density profile of the solar atmosphere. Therefore, we propose that the two 80-year-old mysteries could be two sides of the same coin. We make several predictions based on this proposal that can be tested by the upcoming NASA mission the Parker Solar Probe.
1 Introduction

The nature of dark matter remains entirely mysterious, 80 years after the first evidence \[2\] supporting its existence, and despite numerous direct and indirect searches. At a completely different scale and for different physics, the measured temperature of the solar corona is another 80 years old puzzle \[3\], which still does not have a satisfactory solution. Indeed, the solar corona is a very peculiar environment \[4\] as it seems to defy basic thermodynamics. Starting at an altitude of 1000 km and above of the photosphere, the highly ionized iron lines show that the plasma temperature must exceed \(10^6\) K. The total energy radiated away by the corona is of the order of \(L_{\text{corona}} \approx 10^{27}\) erg s\(^{-1}\), which is about \(10^{-6} - 10^{-7}\) of the total energy radiated by the photosphere. Most of the energy is radiated at the extreme ultra violet (EUV) and soft X-ray wavelengths. The corona is the only solar atmospheric layer which emits thermally in X-ray. However, it is not in thermal equilibrium with its environment, since it is much hotter than the 5800 K black body of the photosphere. As shown in figure 1, there is a very sharp transition region located in the upper chromosphere where the temperature suddenly jumps to \(10^6\) K. This transition layer appears to be very thin, 200 km at most. This apparent violation of the second principle of thermodynamics can only be resolved if there is some non-thermal injection of energy that heats up the corona, located significantly above the photosphere. The source should be able to sustain a power of the order of \(10^{27}\) erg s\(^{-1}\). We want to emphasize that the problem we are discussing here concerns the so-called quiet Sun, that is regions of the Sun away from active spots and coronal holes. In these active regions, it is known that magnetic reconnection gives rise to powerful
Figure 1. Left: The temperature distribution of the inner and outer Sun. The drastic changes occur in vicinity of 2000km. Right: the unexpected deviation from the thermal distribution in the extreme ultraviolet (EUV) and soft x-rays in the solar spectrum constitutes the celebrated solar corona problem. This EUV and x-ray radiation is originated from chromosphere, transition and corona regions. The total EUV intensity represents a small \( \sim (10^{-7} - 10^{-6}) \) portion of the solar irradiance. The plots are taken from [5].

solar flares, but the energy injection provided by these spectacular events have a negligible contribution to the overall heating of the corona and can be ignored.

As a solution to the quiet Sun corona heating problem, [6] proposed that “nanoflares” could provide the fundamental input unit of electromagnetic energy needed. Nanoflares were described originally as miniature version of their giant flares counterparts, but the actual mechanism as to how nanoflares would be triggered remains unclear. At first, there appear to be a connection between nanoflares \((10^{24} - 10^{26} \text{ erg})\), microflares \((10^{26} - 10^{29} \text{ erg})\) and flares \((10^{29} - 10^{32} \text{ erg})\) because, over seven orders of magnitude, they exhibit similar energy count power law with slope \( a \approx -1.8 \). The occurrence rate of nanoflares is still controversial because similar statistical studies using SOHO/EIT [7] and TRACE [8, 9] data report different slopes, varying from -1.35 to -2.6. The occurrence rate of nanoflares is particularly important to know, because slopes shallower than -2 cannot meet the heat source requirement needed to explain the Solar corona EUV excess. High resolution observations of micro and unresolved nanoflares with TRACE suggest that the currently observed rate of nano and micro flares remains insufficient to heat the corona, even if the count rate is extrapolated to an hypothetical picoflare regime [10].

Figure 1 shows that the sharp increase in temperature of the corona coincides with a sharp decline of the mass density, suggesting that the two quantities are, somehow, related. Qualitatively, this peculiar behavior of the Sun atmosphere is suggesting for some external irradiation (pressure) acting continuously on the whole Sun. Interestingly, also transient heating events, including the concepts of “micro-events”, “micro-flares” and “nanoflares” [6], have been previously considered to be of potential interest for understanding the coronal
heating mechanism because they may give rise to a basal background heating near the solar surface, see original papers [11–18] and reviews [19–21].

Another indication of a possible external agent is a recent study showing a significant correlation between the M and X flare activity on the Sun and the heliocentric longitude of inner planets in the solar system [22]. In fact, the Sun is not the only star with a hot corona; most stars, if not all, are also surrounded by hot coronae emitting in X-ray [23], which suggests that the same problem is encountered in other stars.

The time variability and spatial distribution of nanoflare are also important clues about the nature of non-thermal processes happening in the chromosphere. Recent RHESSI observations demonstrate clearly that nanoflares and microflares are different physical phenomena [15]. Microflares are well resolved and similar to a miniature version of the solar flares, appearing preferentially in active regions, with a higher temperature and emission measure. Nanoflares however tend to appear uniformly on the Sun and have very distinct energetics compared to microflares.

In the present work we follow [1, 24] and advocate a drastically different scenario where the energy deposition is originated from outside the system, in contrast with previously considered proposals when the energy is originated from the deep dense regions of the sun. We want to argue that the observed peculiar behaviour might be intimately related to this fundamentally distinct scenario when the extra source of the energy is associated with the dark matter nuggets continuously entering the sun from outer space. A large amount of energy is available in the proposal [1] as result of huge energy deposition of such dark matter constituents (represented in the model by the quark nuggets made of matter and antimatter) before being disintegrated as described below.

The basic assumption of [1] is that the nanoflares (including sub-resolution events with very low energies) can be identified with annihilation events of the nuggets representing the dark matter particles in this framework. The main goal of the present work is to justify this assumption by explicit numerical simulations. We shall see that, indeed, the dominant portion of the internal energy of the nuggets will be deposited in corona, before entering the dense regions of the photosphere. Furthermore, as we shall see the annihilation processes of the nuggets with the solar material start effectively at the altitude around 2000 km. It is precisely in this region that most of the energy deposition occurs. We conjecture that the drastic changes in the transition region occur as a result of these annihilation events, which we argue are responsible for the resolution of the solar corona puzzle. Furthermore, as we shall see, the energy radiated in corona assumes the observed value $10^{27}$ erg s$^{-1}$ without adjusting any parameters of the model. This intensity is mostly determined by the dark matter density in the solar system where $\rho_{DM} \simeq 0.3$ GeV/cm$^3$. We consider this numerical coincidence as a strong evidence supporting our arguments.

This proposal offers an explicit resolution of a long standing puzzle on the heating mechanisms in drastically different way in comparison with the standard paradigm: the energy deposit comes from outer space, rather than from dense internal regions of the Sun. This proposal also offers a number of “smoking gun” predictions which can be in principle tested with high resolution instruments (such as upcoming NASA mission the Parker solar probe) to be discussed in concluding section 8.

The presentation is organized as follows. First, in section 2 we overview the basic properties of the nanoflares. Then, in section 3 we overview the basic features of the AQN dark matter model. In section 4 we highlight the basic ideas of the proposal [1] where we identify these two entities, the nanoflares from section 2 and the nuggets from section
Section 5 follows with formulations for the interaction cross-section of the AQN in the solar atmosphere. Finally, in section 6 we describe the setup for the numerical simulations performed to test our proposal. The main results of our numerical analysis are then presented in section 7.

2 Overview of the nanoflares

The term “nanoflare” was introduced by Parker in 1983 [6]. Later on this term has been used in series of papers by Benz and coauthors [11–15] and many others to advocate the idea that precisely these small “micro-events” might be responsible for the heating of the quiet solar corona. It is not the goal of this work to review different aspects and different analyses related to the nanoflares and the heating mechanisms. Instead, we just want to mention a few relatively recent studies [16–19] and reviews [20, 21] which support the basic claim of early works that the nanoflares play the dominant role in heating of solar corona. Some disagreement still remains between different groups on spectral properties of the nanoflares (see some details below).

In most studies the term “nanoflare” describes a generic event for any impulsive energy release on a small scale, without specifying its cause. In other words, the hydrodynamic consequences of impulsive heating (due to the nanoflares) have been used without discussing their nature, see review papers [20, 21]. The definition suggested in [15] is essentially equivalent to the definition adopted in [20, 21] and refers to nanoflares as the “micro-events” in quiet regions of the corona, to be contrasted with “microflares” which are significantly larger in scale and observed in active regions.

First of all, according to ref. [13] to reproduce the measured radiation loss, the observed range of nanoflares needs to be extrapolated from sub-resolution events with energy $\sim 10^{21}$ erg to the observed events interpolating between $(3.1 \cdot 10^{24} - 1.3 \cdot 10^{26})$ erg. As we will discuss in section 3, this energy window corresponds to the (anti)baryon charge of the nugget which largely overlaps with allowed window for AQNs.

According to ref. [15] the nanoflares are distributed very uniformly in quiet regions, in contrast with micro-flares and flares which are much more energetic and occur exclusively in active areas. It is perfectly consistent with our identification of the nanoflares as the annihilation events because the AQNs must be present in all areas irrespectively to the active region distribution in the Sun. At the same time the micro-flares and flares are originated in the active zones, and therefore cannot be uniformly distributed.

Our next comment is related to the observation of the large Doppler shift with a typical velocities (250-310) km/s, see figure 5 in ref. [11]. Furthermore, the observed line width in OV of $\pm 140$ km/s far exceeds the thermal ion velocity which is around 11 km/s [11]. As we discuss in section 3 these observed features can be easily understood within the AQN framework as the typical velocities of the nuggets entering the solar corona is about $\sim 300$ km/s. Therefore, it is perfectly consistent with observations of the very large Doppler shifts and related broadenings of the line widths. Typical time-scales of the nanoflare events, of order of $(10^{1} - 10^{2})$ sec. are also consistent with estimates [1].

One should also remark here that the energy output observed by EIT on the SoHO satellite is of order of 10% of the total radiative output in the same region [14]. The interpretation of this “apparent deficiency” is also obvious within our our identification of the nanoflares as the AQN annihilation events. Indeed, only a small portion of the AQNs are sufficiently large to produce the events with the energies above the instrumental threshold which can be
recorded. Smaller events must also occur and must contribute to the total solar radiative output, but they are not recorded due to insufficient resolution of the current instruments.

Our next comment in this short overview is related to nanoflare frequency distribution as a function of its energy. The corresponding function can be formally expressed as follows

\[
dN \sim B^{-\alpha_{\text{nano}}}dB \sim W^{-\alpha_{\text{nano}}}dW, \quad \text{for} \quad W \simeq (4 \cdot 10^{20} - 10^{26}) \text{ erg} \tag{2.1}
\]

where \(dN\) is the number of the nanoflares (including the sub-resolution events) per unit time with energy between \(W\) and \(W + dW\). We identify these nanoflare events with annihilation events of the AQN carrying the baryon charges between \(B\) and \(B + dB\). These two distributions are tightly linked as these two entities are identically the same in our framework. The energy of the events \(W\) in this distribution can be always expressed in terms of the baryon charges \(B\) of the AQNs because they are intimately linked: \(W \simeq 2m_pc^2B\) as the annihilation event of a single baryon charge from the AQN deposits a huge amount of energy to the corona equivalent to \(2m_pc^2\).

Our final comment in this short overview is as follows. Some nanoflares are sufficiently energetic (above the instrumental threshold) and, therefore, can be observed as tiny jets, see e.g. review [28]. In fact such jets indeed have been observed [29]. Furthermore, it has been claimed that the observed “anemone jets outside of sunspots...” are very typical and common events with the following typical characteristics [29]:

\[
L \sim (2000 - 5000) \text{ km long}, \quad R \sim (150 - 300) \text{ km wide.} \tag{2.2}
\]

This topology of the jets is perfectly consistent with our identification of the nanoflares with the annihilation events of the nuggets with the solar material because the nuggets entering the solar corona have velocities exceeding the speed of sound, which inevitably produce the shock waves [24] with typical the parameters (2.2).

3 Overview of the Axion Quark Nugget (AQN) dark matter model

The AQN model in the title of this section stands for the axion quark nugget model, see original work [30] and short overview [31] with large number of references on the original results reflecting different aspects of the AQN 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 quark nuggets [32], strangelets [33], nuclearities [34], see also review [35] with large number of references on the original results. In the models [32–35] the presence of strange quark stabilizes the quark matter at sufficiently high densities allowing strangelets being formed in the early universe to remain stable over cosmological timescales.

The original motivation [30] of this model was based on the observation that the visible and dark matter densities in the Universe are of the same order of magnitude. This feature is automatically realized in the AQN model

\[
\Omega_{\text{dark}} \sim \Omega_{\text{visible}} \tag{3.1}
\]

as they are both proportional to the same fundamental \(\Lambda_{\text{QCD}}\) scale, and they both are originated at the same QCD epoch. If these processes are not fundamentally related the two components \(\Omega_{\text{dark}}\) and \(\Omega_{\text{visible}}\) could easily exist at vastly different scales.
In comparison with many other similar proposals \cite{32–35} the AQN dark matter model has two unique features:

1. There is an additional stabilization factor in the AQN model provided by the axion domain walls which are copiously produced during the QCD transition in early Universe;

2. The AQNs could be made of matter as well as antimatter in this framework as a result of separation of the baryon charges.

The most important astrophysical implication of these new aspects relevant for the present studies is that quark nuggets made of antimatter store a huge amount of energy which can be released when the anti-nuggets hit the Sun from outer space and get annihilated. This feature of the AQN model is unique and is not shared by any other dark matter models because the dark matter in AQN model is made of the same quarks and antiquarks of the standard model (SM) of particle physics. One should also remark here that the annihilation events of the anti-nuggets with visible matter may produce a number of other observable effects in different circumstances such as rare events of annihilation of anti-nuggets with visible matter in the centre of galaxy, or in the Earth atmosphere, see some references on the original computations for different frequency bands in short review \cite{31}.

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 when 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 colour superconducting (CS) phase. The formation of the nuggets made of matter and antimatter occurs through the dynamics of shrinking axion domain walls, see original papers \cite{36–38} with many technical details.

Thenuggets, after they formed, can be viewed as the strongly interacting and macroscopically large objects with a typical nuclear density and with 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 \( 10^{-6} \text{eV} \leq m_a \leq 10^{-2} \text{eV} \). This axion window corresponds to the range of the nugget’s baryon charge \( B \) which largely overlaps with all presently available and independent constraints on such kind of dark matter masses and baryon charges, see e.g. \cite{31, 39} for review,

\[
10^{23} \leq |B| \leq 10^{28}, \quad \mathcal{M} \sim m_p B \tag{3.2}
\]

where \( \mathcal{M} \) is the mass of the nugget and \( m_p \) is the proton mass. This model is perfectly consistent with all known astrophysical, cosmological, satellite and ground based constraints within the parametrical range for the mass \( \mathcal{M} \) and the baryon charge \( B \) mentioned above (3.2). It is also consistent with known constraints from the axion search experiments.

Furthermore, it is known that the galactic spectrum contains several excesses of diffuse emission of uncertain origin, the best known example being the strong galactic 511 keV line. If the nuggets have the average baryon number in the \( \langle B \rangle \sim 10^{25} \) range they 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). For further details see the original works \cite{40–45} with specific computations in different frequency bands in galactic radiation, and a short overview \cite{31}.
Finally we want to mention that the recent EDGES observation of a stronger than anticipated 21 cm absorption \cite{46} can find very natural explanation within the AQN framework as recently advocated in \cite{47}. The basic idea is that the extra thermal emission from AQN dark matter at early times produces precisely the required intensity (without adjusting of any parameters) to explain the recent EDGES observation.

The AQN model does not contradict any of the many known observational constraints on dark matter or antimatter in the Universe due to the following main reason \cite{48}: the nuggets carry very large baryon charge $|B| \gtrsim 10^{23}$, 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 qualify as DM candidates.

4 The AQN annihilation events as nanoflares

We want to overview here the basic results of ref. \cite{1} suggesting that the heating of the chromosphere and corona is due to the annihilation events of the AQN with the solar material. Indeed, the impact parameter for capture of the nuggets by the Sun can be estimated as follows:

$$b_{\text{cap}} \simeq R_\odot \sqrt{1 + \gamma_\odot}, \quad \gamma_\odot \equiv \frac{2GM_\odot}{R_\odot v^2}, \tag{4.1}$$

where $v \simeq 10^{-3}c$ is a typical velocity of the nuggets. Assuming that $\rho_{\text{DM}} \sim 0.3 \text{ GeV cm}^{-3}$ and using the capture impact parameter (4.1), one can estimate the total energy flux due to the complete annihilation of the nuggets,

$$L_\odot (\text{AQN}) \sim 4\pi b_{\text{cap}}^2 \cdot v \cdot \rho_{\text{DM}} \simeq 3 \cdot 10^{30} \cdot \frac{\text{GeV}}{s} \simeq 4.8 \cdot 10^{27} \cdot \frac{\text{erg}}{s}, \tag{4.2}$$

where we substitute constant $v \simeq 10^{-3}c$ to simplify numerical analysis. This estimate is very suggestive as it roughly coincides with the observed total EUV energy output from the corona which is hard to explain in terms of conventional astrophysical sources as highlighted in the Introduction. Precisely this “accidental numerical coincidence” was the main motivation to put forward the idea \cite{1} that (4.2) represents a new source of energy feeding the EUV and soft x-ray radiation.

The main assumption made in \cite{1} is that a finite portion of annihilation events have occurred before the anti-nuggets entered the dense regions of the Sun. The main goal of the present work is to test and explore this assumption: that only these annihilation events supply the energy source of the observed EUV and x-ray radiation from the corona and the chromosphere. The key argument made in \cite{1} is that, even though the total energy due to the annihilation of the anti-nuggets is very small ($\sim 10^{-7}$ fraction of the solar luminosity), the anti-nuggets produce the EUV and x-ray spectrum characterized by a temperature $T \sim 10^6 \text{ K}$. Such spectrum observed in corona and the chromosphere is hard to explain by any conventional astrophysical processes as mentioned in the Introduction.

One should emphasize that the estimates (4.2) for the radiated power as well as the estimate for a typical temperature $T \sim 10^6 \text{ K}$ are not very sensitive to the size distribution of the nuggets. This is because the estimate (4.2) represents the total energy input due to the complete nugget’s annihilation, while their total baryon charge is determined by the dark matter density $\rho_{\text{DM}} \sim 0.3 \text{ GeV cm}^{-3}$ surrounding the Sun.
In addition to the energy argument we have just made, it should be noted that the energy distribution window given by eq. (2.1) for the nanoflare largely overlaps with the baryonic charge window given by eq. (3.2) allowed for the AQNs. Indeed, the annihilation of a single baryon charge produces an energy of about 2 GeV which is convenient to express in terms of the conventional erg units as follows,

\[ 1 \text{ GeV} = 1.6 \cdot 10^{-10} \text{ J} = 1.6 \cdot 10^{-3} \text{ erg}, \]

which implies that the nanoflare energy window (2.1) largely overlaps with the baryon charge window (3.2) of the nuggets which are capable of releasing this energy as a result of annihilation events. One should emphasize that this overlap is a highly nontrivial self-consistency check of this proposal as the nanoflare window (2.1) was established by studying the solar corona heating models, while the nugget’s baryon charge window (3.2) represents a large number of constraints based on cosmological, astrophysical, satellite and ground based observations and experiments, including the axion search experiments.

The following comment will also be useful for the rest of the paper: the authors of ref. [16] claim that the the data prefer a nanoflare energy distribution \( \alpha_{\text{nano}} \approx 2.5 \), while numerous attempts to reproduce the data with \( \alpha_{\text{nano}} < 2 \) were unsuccessful. This is consistent with previous analysis [14] with \( \alpha_{\text{nano}} \approx 2.3 \). It should be contrasted with another analysis [18] which suggests that \( \alpha_{\text{nano}} \approx 1.2 \) for events below \( W \leq 10^{24} \text{ erg} \), and \( \alpha_{\text{nano}} \approx 2.5 \) for events above \( W \geq 10^{24} \text{ erg} \). Analysis [18] also suggests that the change of the scaling (the position of the knee) occurs at energies close to \( \langle W \rangle \approx 10^{24} \text{ erg} \), which roughly coincides with the maximum of the energy distribution, see figure 7 in [18].

5 Formulation of the interaction cross section

In this section we highlight and further develop the basic ideas from [1] with estimations of the rate of ionization of the nuggets (and anti-nuggets) as a result of their high supersonic speed in the corona. The corresponding estimates will play an important role in our discussions which follow as these estimates provide an effective cross section for the nugget-plasma interaction, which in turn essentially determines the altitude where the heat will be mostly deposited.

We start with estimation of the electrical charge of the AQN when they enter the solar corona. The basic idea of the estimate is as follows. The total neutrality of the nuggets in the model is supported by the electrosphere made of leptons (electrons for nuggets and the positrons for the anti-nuggets). For non-zero intrinsic nugget’s temperature \( T \neq 0 \) a small portion of the loose positrons will be stripped off from the AQNs, such that the nuggets will be ionized at \( T \neq 0 \). As a result the nuggets will acquire a non-vanishing positive charge, while anti-nuggets will acquire a non vanishing negative electric charge \( Q \). To estimate this charge \( Q \) one can use the electro-sphere density profile function \( n(r) \) by removing the contribution of the region of loosely bounded positrons with low momentum \( p^2 \leq 2m_eT \). The corresponding computation leads to the following estimate for \( Q \), see [1]:

\[ Q \approx 4\pi R^2 \int_{\sqrt{2m_eT}}^{\infty} n(z) dz \sim \frac{4\pi R^2}{2\pi} \cdot \left( T \sqrt{2m_eT} \right). \]

If we assume a typical AQN size \( R \sim 10^{-5} \text{ cm} \) and \( T \sim 100 \text{ eV} \) corresponding to the temperature of the surrounding plasma in the corona we arrive at the estimate \( Q \sim 10^8 \) which represents a very tiny portion in comparison with a typical baryon charge \( B \sim 10^{25} \) hidden in
the AQNs, i.e. \( (Q/B) \ll 1 \). One should emphasize that our estimate \( T \sim 100 \, \text{eV} \) is actually a lower limit for an estimation of the charge \( Q \), because the corresponding temperature entering eq. (5.1) should be identified with the internal thermal temperature \( T_I \) of the nuggets (and anti-nuggets), to be contrasted with the surrounding plasma temperature \( T_P \) measured far away from the nuggets. The \( T_I \) could be many orders of magnitude higher than the average plasma temperature \( T_P \sim 100 \, \text{eV} \), and so the charge \( Q \sim T_{3/2}^I \) could also be drastically different in magnitude. It is worth noting that we could also expect the internal local temperatures for the nuggets versus the antinuggets to be drastically different, because heating from the proposed annihilation events occur exclusively inside the antinuggets, while the nuggets are heated exclusively as a result of the supersonic motion in the surrounding plasma. The estimates and arguments for the effective cross section formulated in the following paragraphs, which attempt to account for the internal and plasma temperature differences \( T_I \) and \( T_P \) due to supersonic motion, are then only lower limits for the antinuggets (for they do not account for the annihilation heating).

In our numerical simulations that follow, it is important that we have formulations for the calculation of the effective interaction sizes of the nuggets and antinuggets. The simplest and very rough way to estimate the corresponding parameter \( R_{\text{eff}} \) (effective radius of the spherical AQN) is to approximate an effective Coulomb cross section between the nuggets carrying the charge \( Q \) and the plasma of the electrons and protons by assuming that a typical momentum transfer is order of the temperature of the surrounding plasma, \( |q| \sim T_P \), i.e.

\[
\pi R_{\text{eff}}^2 \sim \frac{Q^2 \alpha^2}{q^2} \sim \frac{Q^2 \alpha^2}{T_P^2}.
\]  

(5.2)

So now we can estimate \( R_{\text{eff}} \) using the ionization charges determined by eq. (5.1):

\[
\left( \frac{R_{\text{eff}}}{R} \right)^2 \simeq \frac{8 (m_e T_P) R^2}{\pi} \left( \frac{T_I}{T_P} \right)^3.
\]  

(5.3)

Or equivalently, we define for the purposes of our simulations:

\[
\left( \frac{R_{\text{eff}}}{R} \right) = \epsilon_1 \left( \frac{T_I}{T_P} \right)^{3/2}, \quad \epsilon_1 \equiv \sqrt{\frac{8 (m_e T_P) R^2}{\pi}}
\]  

(5.4)

Where \( \epsilon_1 \) is defined to be understood as a dimensionless enhancement factor for the nugget interaction radius. If we ignore the difference between the temperatures \( T_I \) and \( T_P \) we arrive at an estimate for \( R_{\text{eff}} \) (from \( \epsilon_1 \), which then effectively determines the size of the system) as

\[
\left( \frac{R_{\text{eff}}}{R} \right) \simeq 10^4 \Rightarrow R_{\text{eff}} \sim 0.1 \, \text{cm} \quad \text{for} \quad Q \sim 10^8 \quad \text{and} \quad T_P \sim 10^6 \, \text{K}.
\]  

(5.5)

Precisely this value \( R_{\text{eff}} \sim 0.1 \, \text{cm} \) has been used in an order of magnitude estimate in [1].

The effective radius \( R_{\text{eff}} \) of the AQNs can be interpreted as an effective size of the nuggets due to the ionization characterized by the nugget’s charge \( Q \). It can also be thought of as a typical radius of a sphere which can accommodate \( \sim n_{\text{sun}}(l) R_{\text{eff}}(l) \) number of particles from plasma. Precisely these particles effectively participate in the processes of annihilation and energy transfer from the antinugget to the surrounding solar plasma. The corresponding value of \( R_{\text{eff}}(l) \) obviously depends on the environmental parameters such as density \( n_{\text{sun}}(l) \) and the temperature \( T_P(l) \) of the plasma. This feature is reflected by dependence of the internal temperature on the altitude \( l \).
To account for the physics related to the difference between internal temperature $T_I$ and plasma temperature $T_P$ we first define the corresponding dimensionless parameter:

$$\epsilon_2 \equiv \left( \frac{T_I}{T_P} \right)^{3/2} \Rightarrow \left( \frac{R_{\text{eff}}}{R} \right) = \epsilon_1 \epsilon_2$$  \hspace{1cm} (5.6)

So that in what follows $\epsilon_1$ and $\epsilon_2$ are treated as the phenomenological enhancement parameters.

An estimation of the internal thermal temperature $T_I$ (or what is the same $\epsilon_2$) is a highly nontrivial and complicated problem and requires an understanding of how the heat (due to the friction and the annihilation events continuously occurring inside the antinuggets) will be transferred to the surrounding plasma from a body moving with supersonic speed with Mach number $M \equiv v/c_s > 1$. The efficiency of this heat transfer eventually determines the internal thermal temperature of a nugget and the corresponding charge $Q$. The corresponding energy transfer efficiency depends on the number of many body plasma phenomena, including turbulence in the vicinity of the nugget’s surface. Such an estimate of the internal temperature $T_I$ is well beyond the scope of the present work. As we mentioned, in what follows we treat $\epsilon_2$ as a phenomenological parameter. However, one could get a rough estimate on the magnitude of $T_I$ using simple thermodynamical arguments which go as follows.

It has been argued in [24] that the nuggets in the corona will inevitably generate shock waves due to their very large Mach number, which was estimated as $M \simeq (1.5-15)$ depending on the typical velocities of the nuggets. It is known that a shock wave generates a discontinuity in temperature, which for large Mach numbers $M \gg 1$ can be approximated as follows [24, 49]

$$\frac{T_2}{T_1} \simeq M^2 \cdot \frac{2 \gamma (\gamma - 1)}{(\gamma + 1)^2}, \quad \gamma \simeq 5/3.$$ \hspace{1cm} (5.7)

In this formula we identify the temperature $T_1 \simeq T_P$ with the temperature of the surrounding unperturbed plasma, while the high temperature $T_2$ occurs as a result of the shock wave. If one assumes that the turbulence (which normally develops around a body moving with supersonic speed) will efficiently equalize the internal temperature of the nuggets $T_I$ with $T_2$ one can estimate from eq. (5.7) that $T_I/T_P \sim M^2$, which could be very large as the factor $M \sim 10$ could be very large. This effect obviously applies to both types of the AQNs: nuggets and antinuggets. However, we note again that we expect $T_I$ for the antinuggets could actually be much larger than $T_I$ for the nuggets once the antinuggets start to annihilate in the Sun and have an additional internal heat generated as a result. In any case, these estimates suggest that $\epsilon_2$ could be numerically very large as it scales with the internal temperature as $T^{3/2}$. The important result for our work, then, is that the parameter $\epsilon_2$ scales with and is determined by the Mach number as follows:

$$\epsilon_2 \equiv \left( \frac{T_I}{T_P} \right)^{3/2} \sim M^3.$$ \hspace{1cm} (5.8)

Therefore, the parameters $\epsilon_1$ and $\epsilon_2$ depend on altitude as well as on the AQN velocity at each given point, as the AQN velocity obviously changes with time as a result of friction and annihilation events. The corresponding modifications of the parameters $\epsilon_1$ and $\epsilon_2$ when time evolves, and thus the evolution of the effective interaction cross section, will be explicitly accounted for in our numerical studies in the next section.
6 Numerical simulations setup

The main aim of this work was to investigate the feasibility and accuracy of the proposed model of the AQN dark matter particles being the source of the heating of the corona through nanoflare-type events. To do this, we performed detailed numerical simulations of the entire proposed process, paying particular attention to the solar environment. We divided our simulations into three main steps: in the first step we generated the dark matter particles in the solar neighborhood and calculated their trajectories, in the second step we identified these particles as AQN and assigned masses to them, and in the third step we solved the equations for annihilation of these AQN in the solar atmosphere.

6.1 DM particles in the solar neighborhood

For the initial set-up, we first populated the solar neighborhood with a large sample of particles with randomly assigned positions and velocities from known probability distributions, i.e. a Monte Carlo sampling. The Sun rotational velocity is \( V_c \simeq 220 \text{ km/s} \) relative to the galactic center, and at the Sun location. We are assuming that the dark matter halo is not rotating relative to the galactic center; [25] showed that the halo rotation speed is of the order of \( 10 \text{ km/s} \), which is negligible compared to \( V_c \). In the halo frame, the dark matter particles follow a NFW density profile with an isotropic velocity distribution given by a three dimensional Maxwellian distribution. The velocity dispersion per component \( \sigma_{v_i} \) must be calculated from the Jeans equation, at the Sun location, which is \( 0.04 r_{\text{vir}} \), where \( r_{\text{vir}} \simeq 200 \text{ kpc} \) is the Virial radius of the Milky-Way. Considering a Milky-Way mass of approximately \( 10^{12} \text{ M}_\odot \), the velocity dispersion per component is \( \sigma_{v_i} \simeq 100 \text{ km/s} \) at the Sun location [26, 27], where we have assumed a spherical dark matter halo. Consequently, the full velocity distribution of AQN particles is given by a three dimensional Maxwellian distribution shifted in one direction, given by the equation:

\[
 f_v(v_x, v_y, v_z) = \frac{1}{\sqrt{2\pi} \sigma_{v_i}} \exp \left[ -\frac{(v_x - v_\odot)^2 + v_y^2 + v_z^2}{2\sigma_{v_i}^2} \right]. \tag{6.1}
\]

The positions of the particles are such that a spherical annulus of radii \( R_{\text{max}} = 10 \text{ AU}, R_{\text{min}} = R_\odot \) around the Sun is populated uniformly (i.e. the probability of finding a particle in a volume element \( dV \) is constant throughout the entire volume). To generate the uniform distribution of particle positions, we used the following coordinate equations:

\[
 r = \left[ \left( R_{\text{max}}^3 - R_{\text{min}}^3 \right) u + R_{\text{min}}^3 \right]^{1/3} \tag{6.2}
\]

\[
 \theta = \cos^{-1} (2v - 1), \quad \phi = 2\pi w, \quad u, v, w \sim \text{Unif}(0, 1)
\]

We can then generate the Monte Carlo sampled 3D positions and velocities for each particle. We generated \( 2 \times 10^{10} \) such sample particles, and let them move according to Newton’s law of gravity. Note that this number is not the true number of DM particles that exist in the solar neighborhood, but only a small representative fraction, chosen due to computational limitations. A rescaling procedure to match the actual number density of dark matter particles will be given in Section 6.2.

Once we have the position and velocity for each particle, we calculated the trajectory for each particle using classical two-body orbital dynamics and determine whether it is captured
Figure 2. Probability density distributions of the trajectory conditions for the 36,123 impacting AQN dark matter particles. It can be seen that the probability of impact is distance independent, while the impact parameter scales linearly, where \( b_{\text{max}} \equiv R_\odot \sqrt{1 + \left(\frac{2GM_\odot}{R_\odot v_i^2}\right)} \) (\( v_i \) being the initial velocity drawn from eq. (6.1)). The window of time approximately between 0.25 and 1.25 months, where the ‘time to impact’ distribution is constant (i.e. the AQN flux becomes constant), is used to extrapolate the total impact rate and the total luminosity from those impacts.

by the Sun, i.e. if the perihelion of the hyperbolic trajectory is less than \( R_\odot \). Particles that are determined to have a path intersecting the solar surface are then saved for the next step of the simulation. From our original analyzed sample of \( 2 \times 10^{10} \), we find that only approximately \( 3.6 \times 10^4 \) particles have the initial conditions that will eventually lead to a successful capture. As expected, only a very small fraction of dark matter particles in the solar neighborhood are actually incident upon the Sun. It is important to keep in mind that this fraction does not represent the true impact rate; calculating the true rate requires an exact measure of time duration of AQN accretion in addition to the number density rescaling. This calculation is ultimately addressed in the following sub-section (see in particular eqs. 6.3 and 6.4). What is important about these 36000 particles is that they provide us with a set of particles whose initial conditions sample exactly the true parameter space of particles captured by the Sun. Trajectory and impact properties are calculated for these particles, the distributions of which are given in figure 2.
6.2 AQN mass relations

In order to solve the annihilation equations of the third step, and to calculate the true rate of impact events, we have to provide the dark matter particles with a realistic mass distribution. As discussed in section 3, we propose that the dark matter particles are represented by AQNs, and the AQN annihilation events are identified with nanoflares (4). The direct consequence of this identification is that the nanoflare energy distribution (2.1) coincides with the AQN mass distribution as advocated in [1, 24]. This identification also implies that we can adopt a variety of models for nanoflare energy distribution which have been previously discussed in order to fit the observations. To be more specific, we use the following nanoflare models [14, 16, 18] with a range of different power-law index $\alpha$ and different lower limits of extrapolation for the nanoflare energy distribution. These models have been reviewed in Section 4. For the convenience of the readers we plotted the energy distributions on Fig. 3 where we expressed the corresponding energy scale in terms of the baryon charge $B$ of the AQNs according to (4.3).

In our work we then explore the results of each of these distributions represented on Fig. 3 and originally introduced in [14, 16, 18] as reviewed in Section 4. In particular, depending on the model, the index $\alpha$ takes values of 2.5, 2.0, and a broken power-law of 1.2 below $B_{\text{threshold}} \simeq 3 \times 10^{26}$ ($W_{\text{threshold}} \simeq 10^{24}$ erg), and 2.5 above. $B_{\text{min}}$ is taken to be either $10^{23}$ or $3 \times 10^{24}$ ($W_{\text{min}} \simeq 3 \times 10^{20}$ erg or $10^{22}$ erg). As with the velocity, random draws of baryon charges are made from these distributions and assigned to the $3.6 \times 10^4$ impacting AQN. We shall argue below that our main results are not very sensitive to the specific features of these different distributions.

One important consequence of varying the baryon charge distribution for our purposes is in determining the true number density of the dark matter particles in the solar neighborhood, which in turn determines the AQN impact rate on the solar surface and thus the proposed luminosity from these impacts. For our work, we use the current estimate for the local dark matter density of $\rho_{\text{DM}} \sim 0.3$ GeV cm$^{-3}$. Under the AQN DM model, approximately $\sim 3/5$ of the mass density is in the form of the anti-nuggets (which are the ones that are proposed...
to annihilate)\[31\]. Only some portion of this DM component (\(\sim 2/3\)) contributes to the annihilation processes in the solar atmosphere, while the remaining part (\(\sim 1/3\)) will be radiated as free propagating axions \[38\] which is an interesting phenomenon by itself, but not the topic of the present study. These factors are taken into account in the following calculations. For each baryon distribution case, we can then calculate a scaling factor \(f_S\) by which our results of simulating only \(2 \times 10^{10}\) particles can be multiplied by to get the extrapolated true values. We have:

\[
\langle B \rangle = \int_{B_{\text{min}}}^{B_{\text{max}}} B \cdot f(B) \, dB, \quad f(B) \propto B^{-\alpha}
\]

\[\bar{n}_{\text{AQN}} \simeq \left( \frac{2}{3} \cdot \frac{3}{5} \cdot 0.3 \text{ GeVcm}^{-3} \right) \frac{1}{m_p(B)}, \]

\[f_S \equiv \frac{\frac{4}{3} \pi (R_{\text{max}}^3 - R_{\text{min}}^3)}{2 \times 10^{10}} \bar{n}_{\text{AQN}}, \quad R_{\text{max}} = 10 \text{ AU}, \quad R_{\text{min}} = R_\odot \quad (6.3)\]

The notation \(\bar{n}_{\text{AQN}}\) is introduced to describe the true number density of the anti-matter AQNs. Put another way, the factor \(f_S\) would be 1 if we populated our simulation space with the true total number of AQN in the \(R_{\text{max}}\) sphere instead of \(2 \times 10^{10}\). The true rate of impacts of the AQN can then be approximated by considering the number of impacts \(N(\Delta t_{\text{imp}})\) in our sample that occur in some time window \(\Delta t_{\text{imp}}\), where \(t_{\text{imp}}\) is the time it takes for a DM particle to travel from its initial position to the solar surface. This time window cannot be chosen arbitrarily, but motivated by the finite-size effects of our simulation space. Consider the particles that initially lie on the edge of our volume, at \(R_{\text{max}} = 10\) AU. From eq. 6.1, the maximum initial velocity that these particles can have is \(\sim 600 \text{ km.s}^{-1}\), and if they are on a straight radial trajectory towards the Sun (the shortest path), the time it would take them to reach and impact the Sun would be \(\sim 10 \text{ AU}/600 \text{ km.s}^{-1} \sim 1 \text{ month}\). Thus our time window to count the number of impacts cannot exceed \(\sim 1 \text{ month}\). If it did, then particles that actually exist beyond 10 AU would not be correctly accounted for in our simulation space and time. This whole argument and motivation is readily apparent in the bottom-left sub-plot of figure 2, where we see as expected that the number of impacts starts to decrease beyond \(t_{\text{imp}} \sim 1 \text{ month}\), whereas before that the impact flux is constant (except for in the very beginning, where it is slightly higher due to some initial simulation effects). We thus select the precise time window which starts at \(t_{\text{imp}} = 0.25\) months and ends at \(t_{\text{imp}} = 1.25\) months. Our extrapolated true impact rate calculation then follows:

\[
\frac{dN_{\text{imp}}}{dt} \simeq \frac{N(\Delta t_{\text{imp}})}{\Delta t_{\text{imp}}} \cdot f_S, \quad t_{\text{imp}} \in [0.25, 1.25] \text{ months} \quad (6.4)
\]

For the different mass distributions that we explore, this final extrapolated impact rate varies from \(\sim 10^6 \text{ s}^{-1}\) to \(\sim 10^3 \text{ s}^{-1}\) for the mean baryon charges of \(\langle B \rangle \sim 10^{25} - 10^{26}\) (see figure 8).

### 6.3 AQN annihilation in the sun

We now have all the dark matter parameters assigned in order to simulate the annihilation of the AQN in the solar atmosphere. Two first order differential equations have to be solved: one that describes the kinetic energy loss of the AQN due to friction as it collides with particles in the atmosphere (ram pressure), and the other that describes the mass loss of the AQN due to the annihilation of the anti-baryons of the nugget with the baryons in the atmosphere.
The energy lost is assumed to radiate isotropically from the nugget surface. The equations to solve are constructed as follows:

We follow the conventional idea first formulated by A. De Rujula and S. Glashow in a 1984 paper [34] regarding the collision of quark nuggets with the Earth. The energy loss is:

\[ \frac{dE}{ds} = -\sigma \rho v^2 \]  \hspace{1cm} (6.5)

where \( s \) is the path distance, \( \sigma \) is the effective cross sectional area of the nugget, \( \rho \) is the density of the environment and \( v \) is the nugget velocity. Re-formulating as a time derivative:

\[ \frac{dE}{dt} = \frac{dE}{ds} \cdot \frac{ds}{dt} = -\sigma \rho v^2 = -\pi R_{\text{eff}}^2 \rho v^2, \]  \hspace{1cm} (6.6)

where we introduce the effective cross section in terms of the effective size of the nugget \( R_{\text{eff}} \), to be identified in what follows with \( R_{\text{eff}} \) from previous section. Now, we also have:

\[ E = \frac{1}{2} m v^2 \implies \frac{dE}{dt} = mv \cdot \frac{dv}{dt} + \frac{1}{2} v^2 \cdot \frac{dm}{dt} \]  \hspace{1cm} (6.7)

And the rate of mass loss of the AQN is given by:

\[ \frac{dm}{dt} = -\sigma \rho v = -\pi R_{\text{eff}}^2 \rho v. \]  \hspace{1cm} (6.8)

Equating eqs. (6.6) (6.7), and substituting eq. (6.8) we arrive to the following relation describing the variation of the velocity \( v(t) \) of the nugget of mass \( m(t) \) in the environment characterized by density \( \rho \) which also varies as the nugget propagates from high latitude with low densities to lower altitude with much higher densities,

\[ m \cdot \frac{dv}{dt} = -\pi R_{\text{eff}}^2 \rho v^2. \]  \hspace{1cm} (6.9)

In vector form the complete dynamical equation of motion is then:

\[ m(t) \cdot \frac{d\vec{v}}{dt} = -\frac{\pi}{2} R_{\text{eff}}^2(t)\rho(t)v^2(t)\vec{\hat{v}} - \frac{GM_{\odot}m(t)}{r^2(t)}\vec{\hat{r}} \]  \hspace{1cm} (6.10)

In order to numerically solve this equation, we must break it down into its component equations. We naturally use the circular coordinates \((r, \theta)\) (i.e. radial and tangential velocity components), and after taking into account the kinematic terms arising from our choice of coordinates, end up with the coupled differential equations:

\[ \frac{dv_r}{dt} = -\frac{v_r}{v} v - \frac{GM_{\odot}}{r^2} + \frac{v_\theta^2}{r}, \quad \frac{dr}{dt} = v_r \]

\[ \frac{dv_\theta}{dt} = -\frac{v_\theta - v_r v_\theta}{v}, \quad \frac{dm}{dt} = \frac{2ma}{v} \]

with \( a \equiv \frac{\pi R_{\text{eff}}^2 \rho v^2}{2m} \), \( v \equiv \sqrt{\frac{v_r^2 + v_\theta^2}{r}} \)  \hspace{1cm} (6.11)

Finally, combined with the solar density and temperature profiles from figure 1, and following the arguments laid out in section 5, we deal with the computation of the effective radius \( R_{\text{eff}} \) in our numerical analysis. We treat \( m, v \) as the dynamical variables of the AQN, while \( \rho, T \) as the external parameters describing the solar atmosphere (which also depend on time \( t \) as
the nuggets traverse through the solar atmosphere). The resulting equations are solved for each time step with environment dependent dimensionless parameters \( \epsilon_1, \epsilon_2, M \) (defined in section 5) calculated as follows:

\[
M = \frac{v}{c} \left( \frac{3 \gamma T}{m_p} \right)^{-1/2} \simeq 4.9 \left( \frac{v}{\text{km} \cdot \text{s}^{-1}} \right) \left( \frac{T}{\text{K}} \right)^{-1/2}
\]

\[
\epsilon_1 = R \left( \frac{8 m_e T}{\pi} \right)^{1/2} \simeq 4.7 \left( \frac{m}{\text{g}} \right)^{1/3} \left( \frac{T}{\text{K}} \right)^{1/2}
\]

\[
\epsilon_2 = \left( \frac{(5 M^2 - 1)(M^2 + 3)}{16 M^2} \right)^{3/2}
\]

\[
R_{\text{eff}} = \epsilon_1 \epsilon_2 R = \epsilon_1 \epsilon_2 \left( \frac{3 m}{4 \pi \rho_n} \right)^{1/3}, \quad \rho_n = 3.5 \times 10^{17} \text{ kg.m}^{-3}, \tag{6.12}
\]

where \( \rho_n \) is the typical nuclear density which enters the computations of the AQN masses. It describes the energy density per unit baryon charge.

These parameters (6.12) play precisely the key role in our analysis as they determine the effective interaction of the AQNs with the solar material \( \sigma = \pi R_{\text{eff}}^2 \). This interaction obviously depends on the velocities of the AQNs because the effective coupling is proportional to the Mach number \( M = v/c_s \). The effective interaction is highly sensitive to the temperature of the environment \( T \) because the ionized charge of the nugget is determined by the surrounding temperature.

We use a 4th order Runge-Kutta numerical integrator (from the scipy.integrate package in Python) to solve the system of ODEs (6.11) with parameters (6.12) determined by the environment. Looking at figure 1, it is clear that the solar density is extremely low beyond a height of about 3000 km, and so there will be virtually no energy loss for the AQN before it reaches this height. Thus we start our numerical solver at a height of 3000 km for each nugget as it heads towards the solar surface. The initial radial and tangential velocities, as well as the initial masses of the nuggets are known at this height from the first two steps described in this section. The solver is allowed to run until one of two pre-defined termination events occur: i) the nugget reaches zero height i.e. hits the photosphere, or ii) the nugget loses 99.9\% of its initial mass i.e. virtually all its mass. To minimize numerical error, the maximum time step allowed is 0.01 seconds, which is on top of the in-built error tolerances of the solver, which keeps the local error estimate for \( \frac{dx}{dt} \) below \( 10^{-3} x + 10^{-6} \) (for any variable \( x \)).

7 Simulation results

• The time (and height) dependent solution for a typical AQN trajectory as it annihilates in the solar atmosphere is shown in figure 4. The same parameters as a function of the height above the photosphere are shown at the bottom row in figure 4. There are two key observations here. The first is that the nugget loses virtually all its mass before reaching the photosphere as shown on the bottom right panel figure 4, thus confirming the original assumption [1] and fully consistent with our present proposal. Furthermore, we find an even more profound feature: the AQN starts to lose energy to the environment at a height of about 2000 km, which is where the solar Transition Region is. What is most remarkable about this feature is that it is a very robust property of the system, and not very sensitive to the specific details of the model. Indeed, if we vary the masses of the AQNs, we still get the same starting height around 2000 km, and similar profiles overall, as seen in figure 5.
Figure 4. Evolution of the properties of a typical AQN as it annihilates in the solar atmosphere. In the first row the x-axis is time and in the second row it is the height. Particularly important for our proposal is the bottom-right sub-plot showing the mass lost to the environment as a function of height above the surface.

Figure 5. The mass loss profiles for the entire range of AQN masses that we explore. It can be seen that the profile shape does not change considerably. In particular, all the AQN start to lose their mass at a height of $\sim 2000 \text{ km}$, and all have effectively lost their entire mass by the time they hit the photosphere.
Figure 6. The distributions of some annihilation observables that we get from simulating the evolution of all AQN as they travel through the solar atmosphere. The different colors correspond to the different mass distributions we explore as given in figure 3. What is important is not the slight differences between distributions, but the narrow range of values that the results cover over the entire parameter space.

- We then check whether these features are indeed very robust consequences of the entire system, not being too sensitive to the details of the nanoflare energy distributions listed in figure 3, nor to the range of initial conditions for the impacting AQN. With this goal in mind, we solve for the evolution of the AQN in the solar atmosphere for all the $\sim 36000$ DM particles, and repeat this exercise for the 6 different mass distribution models. The results of this analysis is shown in figure 6. Three important features stand out:
  a) All nuggets, regardless of initial mass, velocity or impact parameter, annihilate and lose more than 97% of their total mass to the environment before hitting the surface;
  b) The timescale for this loss is on the order of 10 seconds, which is completely consistent with the time-scales expected for nanoflare events (of order $10^1 - 10^2$ s). For our analysis we have defined the annihilation starting time to be when the AQN has lost 0.5% of its initial mass, and the ending time to be when it hits the surface (or has only 0.5% of its initial mass left);
  c) All nuggets start annihilating between 2000-2200 km, almost exactly overlapping with the Transition Region. The same feature can be represented in a different way by plotting the probability distribution in percentage as a function of the height, shown in figure 7. For illustrative purposes we only show a particular mass distribution, but this generic feature holds for other distributions as well.

- The next important result is that of the AQN impact rate, which is by definition the number of annihilation events per second that happen over the entire solar surface as a result of AQNs impacting the Sun (see eq. 6.4). The corresponding plot is presented in figure 8. The rate depends on the AQN mass distribution model, which are shown in figure 3. As shown in figure 8, the less massive the nugget, the higher the impact rate.

- Following the previous result, we want to compute the total injected energy per unit time per unit length for a given altitude over the entire solar surface. We want to quantify the AQN energy deposition as a function of height (i.e. the annihilation luminosity density). The result is presented in figure 9 for a typical nanoflare distribution. The corresponding behavior
Figure 7. An easy to read plot for the distribution of the annihilation starting height, which is defined to be the altitude at which the AQN has lost 0.5% of its initial mass.

Figure 8. The extrapolated true impact rate for the different mass distributions presented in figure 3, and calculated according to eq. (6.4). In the framework of our proposal, this is the same as the nanoflare event frequency.

is striking: it is strongly peaked at a height around 2000 km, in close vicinity of the Transition Region. This profile shape is robust and holds for all nanoflare distributions listed in figure 3.

The technical reason for this behaviour to emerge is related to the drastic changes that occur in the interaction rate of the AQN with the solar material. The corresponding effective interaction cross section depends on the temperature, density and the Mach number, and all these parameters rise (or fall) sharply in the Transition Region. We speculate that this
Figure 9. The total deposited energy profile for a particular mass distribution. Here the total energy injection is calculated by multiplying the mean annihilation energy profile for the AQNs by the extrapolated total impact rate. The luminosity peak seen at $\sim$2000 km serves to suggest a natural explanation within our model for the temperature rise in the Transition Region. Local very fast and efficient deposition of energy is a key element in solving the Transition Region puzzle with its dramatic variation of all thermodynamical parameters on a small scale (measured in $10^2$ km rather than in $10^3$ km), as shown in figure 1.

- Our final comment relates to the computational result for the total annihilation energy injected in the solar atmosphere per unit time (the annihilation luminosity). It is calculated as $L_{tot} = \langle \Delta m_{AQN} \rangle \cdot dN_{imp}/dt$, where $\Delta m_{AQN}$ is the total mass lost by an AQN in its trajectory through the solar atmosphere. Essentially it represents the integral over the energy distribution as a function of height shown in figure 9 (indeed both methods are self-consistent). The result of this calculation for 6 different nanoflare distributions is shown in figure 10. The most profound feature of this plot is that the total luminosity (energy injection) is almost constant, and is not sensitive to the nanoflare models. Furthermore, it is amazingly close to the observed luminosity $\sim 10^{27}$ erg s$^{-1}$ in EUV and soft x-rays radiation. This “numerical coincidence” was, in fact, the main motivation in [1] to advocate this proposal. The intuitive explanation that the total luminosity is not sensitive to the AQN mass (nanoflare) distribution can be understood from the fact that our basic normalization is determined by the dark matter density $0.3$ GeV cm$^{-3}$. Different distributions would generate different number densities (and impact rates) of the nuggets as shown in figure 8. However, the total mass available in the solar neighborhood to annihilate is fixed, and since we have already shown that the individual mass loss fraction for nuggets is not particularly sensitive to the initial mass distribution, thus the total injected annihilation energy remains (almost) the same as well.

Figure 10 also demonstrates the self-consistency of our numerical computational scheme. Indeed, we started with a very large number of particles distributed over a 10 AU radius.
Figure 10. The extrapolated total luminosity for the different mass distributions, that are a result of our simulations. Remarkably, without any fine-tuning of parameters, the total luminosity is $\approx 1 \times 10^{27} \text{ erg s}^{-1}$ across distributions, in agreement with the observed quiet Sun EUV and soft x-ray flux.

sphere. Nevertheless, we ended up (after a large number of pure computational steps, not related with the underlying physics of the AQN dark matter proposal) with proper number of AQNs entering the solar atmosphere and generating the luminosity of order $\sim 10^{27} \text{ erg s}^{-1}$.

This is a remarkable result because this energy is mostly emitted from the region around 2000 km (as shown in figure 9) which is characterized by high temperature $T \sim 10^6$ K. Therefore, it is quite natural to expect that most of the emission will be in the form of EUV and soft x-rays, in full agreement with observations. These results provide strong numerical support for the assumption made in [1] that the luminosity generated by the AQN annihilation events will be mostly radiated in the EUV and soft x-ray bands of the spectrum.

8 Conclusion

Our conclusion is separated in three parts: the first part presents the basic results of the proposal, the second part describes the possible tests, and the third part presents our thoughts on possible future directions along the lines advocated by this proposal.

8.1 Basic results of the proposal

We have shown that the AQN dark matter model (which was originally invented as a natural explanation of the observed ratio (3.1) between the dark and visible components in our Universe) could account for most, if not all, of the EUV radiation excess of the Solar corona. It is useful to remind the main conventional ideas proposed to explain the “hot” corona, and see how it compares to our model. There are essentially two major current approaches:

1) the first is based on Alfven waves which are capable of carrying energy up to coronal heights. Alfven waves cannot compress the plasma, therefore some additional process is needed in order to explain how the wave energy is transfered to the plasma; several models
have been developed including turbulence-based mechanisms. In this type of model, the energy is transported from the photosphere up to the corona through the chromosphere.

2) the other approach is based on magnetic reconnection, where energy is injected via small “bursts” associated with reconnecting magnetic loops. In this model, the energy is generally injected in situ. Nanoflares belong to this category since they are (originally) thought to be miniature versions of big Solar flares, which are known to be associated with magnetic reconnection phenomena.

Unfortunately, there is still no consensus on which mechanism is responsible for heating the corona, but recent observations suggest that Alfven waves cannot provide a sufficient heat source [10, 50]. One should emphasize that we are dealing with the quiet Sun (well outside of the active regions), where a typical magnetic field is around 1 Gauss. It is highly unlikely that the magnetic phenomena may play a prominent role in such circumstances. In fact, all heating models advocated so far seem to require the existence of unobserved (i.e. unresolved with current instrumentation) source of energy injection [51]. Furthermore, in most recent studies such as MHD simulations, the term “nanoflare” describes a generic event for any impulsive energy release on a small scale, without specifying its cause and their nature, see review papers [20, 21].

Our proposal fills this gap and identifies these previously considered generic events coined as the “nanoflares” with the AQN annihilation events [1, 24]. This identification uniquely specifies the nature of the energy source. An external source for the “hot” corona circumvents many of the issues discussed in decades of papers on this topic. Of course it does not mean that Alfven waves do not happen in the solar atmosphere, but they are not the main heating mechanism. Moreover, these mechanisms are known to be important for other reasons, such as being related to the extraction processes of the Solar wind. Our comment here is that this identification essentially provides the initial configurations which can be used by MHD practitioners to study consequent time and spatial evolution of these energetic disturbances (the AQN annihilation events ⇔ nanoflares) in solar atmosphere.

It is important to emphasize that the AQN model was initially designed to address cosmological issues expressed by eq. (3.1) and has absolutely nothing to do with Solar physics. In particular, the model has only one tunable parameter, the axion mass scale $m_a$ because the baryon charge $B$ of the nuggets is determined by the axion mass $m_a$ as reviewed in section 3. An important point relevant for the present study is that this model has no tunning parameters associated to the physics of the Sun. Its implication for the heating of the Solar corona are direct consequences of the original model without any alterations. The key parameter in the calculation is the dark matter mass density, which is known to be about 0.3 GeV/cm$^3$ in the Solar System. As shown in section 7 the energy injected in the corona is directly proportional to this quantity. Once the number density of dark matter particle is fixed, the physical mechanism driving how many dark matter particles are falling on the Sun every second is pure classical Newtonian gravity. It is quite remarkable and shocking at the same time that the amount of energy released in the corona turns out to match the observed value, since there is a priori no reason for the dark matter mass density and Newtonian physics to conspire to give the correct result.

To conclude this subsection, the most important results are expressed by two plots. First, figure 9 shows that the dominant portion of the energy is injected in the region close to 2000 km where $T \simeq 10^6$ K, and therefore the radiation is expected to be in form of the EUV and soft x-rays. Secondly, figure 10 shows that this EUV radiation is very close to the observed value $\approx 10^{27}$ erg·s$^{-1}$ which is very robust consequence of the model mostly
determined by the dark matter density 0.3 GeV/cm$^3$ in the Solar System.

8.2 Possible tests of the proposal

The results of the present work are consequences of an extraordinary idea: essentially we claim that the resolution of the 80 years old "corona heating mystery" is due to the incident dark matter particles which continuously hit the solar atmosphere. The resolution of the puzzle comes from outside, not inside the system! In order to be accepted by the community, this fundamentally novel paradigm must pass multiple tests in the future.

NASA is launching a mission in July 2018 designed to explore the Solar corona and its heating mechanisms: the Parker Solar Probe (PSP)\textsuperscript{1}. PSP will be capable of performing high resolution imaging of the lower Solar atmosphere and detailed studies of its magnetic environment. We believe that PSP will be able to test our model, by looking at some specific features:

1- The so-called "nanoflare" sites will be observed as burst of energy, but they should not be associated with any unusual local magnetic activity, including quiet regions during the solar minima. Since the source of energy injection comes from a random direction from space, it can happen anywhere and not specifically in active regions where the magnetic field is strong.

2- The energy injection should be confined to the top of the chromosphere, in the transition region. It is sometimes advocated that the top chromosphere high temperature is a problem even more serious than the "hot" corona because the chromosphere is much denser and therefore harder to heat. In our model the heating of the chromosphere arises naturally as one can see from figure 9 describing the altitude distribution of the energy deposition.

3- The altitude of energy injection should be the same everywhere, and not depend on the location on the Sun, more specifically it should not depend whether or not we are looking at a quiet or active region of the Sun. It is still not understood how prominences can form in the much hotter and rarefied coronal regions. In our model, prominences and coronal heating are completely different phenomena.

4- The reheating process should happen all over the Sun steadily, relatively constant in time and relatively homogeneous in space.

5- The energy injection in our model can be thought as a local event which lasts about 10 seconds with typical linear spatial extension of order 1000 km. Conventional MHD should be used to describe consequent time and spatial evolution of these energetic disturbances which should be treated as the initial configurations of the system.

6- It is possible that high resolution imaging could reveal shock wave fronts caused by the AQNs moving at velocities much larger than speed of sound. The observation of these small jet-like events with typical nanoflare energies, lasting for about 10 seconds outside the active regions will be a strong evidence supporting our proposal.

7- As we mentioned in section 3 a finite portion (about 1/3 of its mass) of the AQNs will be disintegrated in form of the propagating axions. Therefore, the total intensity of the emitted axions can be estimated as 1/2 of the EUV emission computed in this work (and plotted on figure 10), i.e. $0.5 \cdot 10^{27}$ erg⋅s$^{-1}$. These axions will be mostly emitted with relativistic velocities $v \sim 0.5c$. Therefore, these axions will have very distinct spectral properties in comparison with galactic axions (characterized by $v \sim 10^{-3}c$) and conventional solar axions which are produced through the Primakoff effect in the central regions of the Sun.

\textsuperscript{1}https://www.nasa.gov/content/goddard/parker-solar-probe
and therefore have typical energies $E_a \sim 4$ keV. These new type of the solar axions can be, in principle, discovered with upgraded CAST (CERN Axion Search Telescope) type instruments as argued in [52].

8- As we discussed above the radiation from AQNs is expected to be mostly in the form of EUV and soft x-rays because the major portion of the energy is injected in the region close to 2000 km where $T \simeq 10^6$ K. Rare events of production of highly energetic γ rays (in MeV or even in GeV range) are possible as a result of annihilation events. However, the most likely outcome of such emissions is the thermalization of these energetic γ rays in turbulent transferring of the energy from AQNs to the surrounding plasma. The probability that such energetic γ rays can leave the system unaffected is small as the nuggets are very dense objects. However, the observation of such energetic γ rays from injection site would be another spectacular event supporting our proposal because there is no known conventional physical process that can generate such energetic photons from the non-active regions in quiet non-flaring Sun.

8.3 Future directions

Our model is still incomplete. There are extensions of this work which will emerge naturally in future studies:

• AQN impacts distribution asymmetry: The solar system is moving along a nearly circular orbit around the galactic center at a speed of approximately 220 km/s. The rotation axis of the Sun is pointing 30 degrees above (galactic north) the galactic plane, oriented towards the solar apex. On the other hand, it is known that the galactic Dark Matter halo is not rotating with the disk, at least in the context of Cold Dark Matter simulations. Consequently, the flux of AQN particles captured by the Sun should be stronger on the solar apex side than the opposite side. Given that the rotation axis of the Sun is pointing only 30 degrees above the solar apex, the location of AQN impacts is not completely randomized by the Sun rotation, and we should see an asymmetry in the solar corona temperature relative to distance from the apex. As a matter of fact, there are reports of anomalous north-south asymmetry, but how strongly the effect will mingle with the solar cycle remains to be determined.

• Heat transfer: once the AQN has deposited the energy locally, a thermalization process takes place, which is not discussed in this work. Our model predicts that the energy is released in the upper chromosphere, and the strong mass density gradient forces the heat to diffuse at higher altitude rather than sinking down to in the Chromosphere. The fundamental question is therefore to find out if the actual temperature profile is stable against thermalization in the context of AQN energy injection. Future modeling including thermodynamics will provide the answer. This future work will likely involve MHD simulations of low density plasma. It should be noted that conventional MHD simulations have been used to model the time and spatial evolution of these energetic disturbances in the context of the “nanoflares” model. The difference with previous “nanoflare” studies is that, for the AQN model, we know precisely the nature of these disturbances\(^2\). In particular, we know the altitude dependence, velocity loss with time, energy injection rate with time, etc. In other words, the AQN annihilation events (injection sites) should be treated as the initial configurations of the system, and conventional MHD codes can be used to study the evolution of the system afterwards.

• It is expected that a similar EUV and soft x-ray radiation discussed in the present work must be present in all other stars with dense coronal atmospheres. Such a radiation indeed

\(^{2}\text{It should be contrasted with conventional definition of a nanoflare as a “generic event for any impulsive energy release on a small scale, without specifying its cause and their nature”, see reviews [20, 21].}\)
has been observed in many systems, see ref. [53] for a review. We think that a detailed study of the EUV and x-ray radiation (specifically in quiet stellar regions) in different types of stars is highly desirable as it will shed light on the different types of energy sources responsible for the corona heating for variety of stars. The intensity and spectral properties of the radiation must obviously depend on internal structure of a star under study, as well as the outer dark matter density $\rho_{DM}(r)$ which itself strongly depends on distance of the star from the galactic center. Indeed, in our proposal, the EUV and x-ray radiation from stars is sensitive to the surrounding dark matter density $\rho_{DM}(r)$ which is drastically different for stars close to the center of a galaxy from stars which are far away from the center.

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