Solar Wind Bremsstrahlung off DM in our Solar System

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We consider the possibility that the solar wind emits photons via bremsstrahlung when colliding with dark matter (DM) particles within the solar system. To this effect, we calculate the bremsstrahlung spectrum a proton would emit when colliding with a neutral spin-1/2 particle through the exchange of a scalar neutral particle. We assume a speed of 600 km/sec for the solar wind and assume that the speed of the dark matter halo is due to the motion of the sun through our galaxy, which we take as 300 km/sec. We assume a DM density of 0.3 GeV/cm³ and a solar wind composed primarily of protons with a total rate of ejection mass set at 10³ kg/sec. We use a Monte Carlo technique to let this interaction take place within the solar system and calculate the photon rate an observer would detect on Earth or at the edge of the solar system as a function of photon energy. We find that the rates are in general very small but could be observable in some scenarios at wavelengths in the mm or cm range.

Introduction

About one year ago, Xenon1T reported a clean signal above known backgrounds [1]. This measurement triggered a flurry of activity aiming at explaining this signal in the context of Dark Matter (DM)[2-5] or others [6,7]. Xenon1T is one of several direct detection cryogenic detectors [8-13] where the DM particle interacts directly with the nucleus of the detector and one records its recoil [14,15,16]. There are also direct detectors where the energy deposited by the DM particles causes the explosion of a superheated droplet embedded in a gel and one simply records the sound wave [17-20]. The direct detection approach suffers from a mass threshold: when the mass of the DM particle becomes small, it becomes very difficult for the DM particle to deposit enough energy in the nucleus to produce a detectable signal. In order to overcome this low mass threshold, new mechanisms based on the Migdal effect use the effect of the recoil of the nucleus on the electronic cloud [21-30]. Another avenue is to explore the possibility that the DM particles be upscattered by more energetic particles such as cosmic rays.[31,32]

The indirect detection approach relies on the gravitational pull of massive bodies that could lead to the accumulation of DM particles in their core, be they the Earth, the sun or the galaxy. This increase in density will lead to an enhanced probability of annihilation DM-particle-antiparticle which would then produce standard particles that could be detected on Earth.[33] The presence of DM inside the sun would have an effect on its behaviour and some interesting limits on axion-photon couplings have been obtained from a global fit to solar data, including helioseismology [34]. Allowing both the accumulation of DM particles inside the sun and their interaction with electrons would lead to DM upscattering off the electrons and possibly interesting rates on Earth of DM energetic enough to produce a signal in the direct detection experiments [35]. A similar accumulation could take place within exoplanets and would affect their evolution [36].

The presence of DM in the early universe will also have an effect on its early evolution [37] and could produce a distortion in the cosmic microwave background at recombination [38] as well as affecting the evolution of galaxies and their satellites later on [39].

Recently, an Earth-scale detector called GNOME [40] reported a first null result from a relatively short operation time aiming at measuring a topological defect due to an axion-like particle field propagating through space [41]. The signal from such a field as the Earth crosses it would be a slight perturbation in high precision/sensitivity instruments such as atomic clocks occurring at slightly different instants.

DM particles could also be produced at high energy colliders such as the LHC [42,43].

In this paper, we calculate the bremsstrahlung photon flux one would receive from the collision between a proton from the solar wind and a DM particle in the vicinity of the solar system. We consider space itself as a collider whose collision angle and luminosity will vary throughout the solar system. We neglect cosmic magnetic fields and assume that the solar wind travels in straight line at a speed of 600 km/sec ($\beta_M = 0.002$). We consider that protons constitute most of the solar wind and the ejection mass rate from the sun is set at $10^9$ kg/sec = $R_{sw}$. We assume that the dark matter has a density of 0.3 GeV/cm³ [44,45,46] and that it is at rest in our part of the galaxy; its relative motion is due to the motion of the sun, which we take as 300 km/sec ($\beta_{DM} = 0.001$).

In the following sections, we describe some technical points before presenting our results and conclusions.

Procedure

The process we are interested in is

$$p(p) + q(q) \rightarrow p(p) + q(q) + \gamma(k)$$  (1)
where \( p \) is the proton, \( q \) is the DM particle and \( \gamma \) is the photon. As it is a three-body final state, we will use a Monte Carlo technique to calculate this spectrum.

Bremsstrahlung has been studied by Bethe and Heitler in the context of a charged particle colliding with a much more massive particle; for example, a proton impinging on a heavy nucleus [47, 48] This process is still of interest as higher corrections are added to the original work [49-54] Processes where a hard photon is produced through the interaction of a particle with a DM particle have been studied recently [55,56], but the bremsstrahlung we study here is a little different in that it is due to the exchange of a light neutral particle. When a proton collides with an atom, it does not feel an important positive charge until it is well inside the electronic cloud and feels the full nuclear electric charge when it is inside the innermost electronic shell. This takes place at a distance that is less than 0.053 nm since the average value of \( r \) is \( \frac{\alpha}{2\pi} (3n^2 - l(l+1)) \). With DM, it does not see the object until it is within the range of the messengers scalar, which is about \( 2 \times 10^{-15} \) m for a messenger of 0.1 GeV.

In order to calculate the photon flux, we will proceed as follows:
- using a Monte Carlo technique based on the matrix element of the process at hand, we build the distribution \( d^2\sigma/dE_\gamma d\cos \theta_\gamma \) for several collision angles between the proton and the DM particle
- we pick an observation point with an observation cone of a given opening angle and orientation: we will consider 2 observation points and 4 orientations.
- using a Monte Carlo technique, we scan the observation cone in a random and uniform way. Each observation point within this cone defines completely all angles and distances of the collision.
- since we have calculated \( d^2\sigma/dE_\gamma d\cos \theta_\gamma \) for that given colliding angle and outgoing photon angle, we select \( \sigma \) at random within the distribution and read the corresponding \( E_\gamma \) for this event.
- multiplying this partial cross-section by the luminosity, \( \mathcal{L} \) at that position and different geometrical parameters that take into account the fact that the photon can be emitted anywhere on a cone of angle \( \theta_\gamma \) and will not necessarily reach the Earth, we obtain \( \Phi_\gamma \) and \( E_\gamma \) for this event.
- averaging the distribution produced within the cone and multiplying by the number of independant colliders in the cone, given by \( V_{\text{cone}}/V_{\text{accelerator}} \) will give the desired flux.

We set our axes such that the sun is at the origin, the Earth is along the positive y-axis and its rotation around the sun is from the positive-x to the positive-y axes.

Matrix Element

We consider a relatively simple, generic model where a proton scatters off a neutral spin-1/2 DM particle through the exchange of a scalar neutral DM particle. We set the mass of the proton at 1 GeV. The DM masses are free and the couplings are also free: \( p - p - DM_{\text{exchange}} = \lambda \) and \( DM_{\text{colide}} - DM_{\text{colide}} - DM_{\text{exchange}} = \Lambda \), where \( DM_{\text{colide}} \) is the DM particle that collides with the proton and \( DM_{\text{exchange}} \) is the DM particle exchanged between the proton and the DM_{\text{colide}} particle. Since we do not take into account the spin of the proton, the only angles that can be defined in the process are with respect to \( \beta_{DM} \): \( \theta_{DM} \), the angle between the incoming proton and the DM particle, and \( \theta_{\gamma} \), the angle of the outgoing photon with respect to the incoming proton are the relevant angles of the process since we do not observe nor the proton nor the DM particle after the collision.

As the speeds of the colliding particles are small, we have a non relativistic problem where the maximum energy of the photon is

\[
E^\gamma_{\text{max}} = \frac{(1/2)(M_M M_{DM})(\beta_{DM} - \beta_{DM}^\prime)^2}{M_M + M_{DM}}
\]

where \( M \) as a subscript stands for matter or proton in our case.

We are mostly interested in the low energy part of the photon spectrum: the eV and sub-eV scale. As is well known, [57,58,59] bremsstrahlung processes tend to diverge if we let the energy of the photon go to 0, the divergencies being cancelled by the higher order corrections. In our case, we set the minimal energy of the photon at \( 10^{-10} \) GeV. The null mass of the photon is potentially a numerical problem; in order to avoid numerically negative photon masses and instabilities, we give a mass to the photon \( k^2 = m_\gamma^2 \) and include the extra terms in the matrix element that come with this mass: the summation over polarisation states is \( (g^{\mu\nu} - k^\mu k^\nu/m_\gamma^2) \). We have verified that masses between \( 10^{-13} \) GeV and \( 10^{-16} \) GeV give identical results but a mass of \( 10^{-11} \) GeV does not; we worked with \( 10^{-14} \) GeV.

At this point, when considering a head-on collision process and varying the incoming energies of the colliding particles, we observe the usual behaviour of bremsstrahlung photons as having a slightly enhanced emission probability at right angle at low energy and peaking more and more in the forward direction at higher energies.

Monte Carlo

Clearly, in the process that we want to study, the solar wind will not be in a head on collision with the DM. We then modify the boost factor of our center of mass system (CM) to take into account the angle of incidence of the DM. [48,60,61] In every collision, the motion of the solar wind particle defines our positive \( z' \)-axis. The angle between the matter particle and the DM particle, \( \theta_{DM} \) is defined such that a head-on collision corresponds to \( \theta_{DM} = 0 \) and collinear collision corresponds to \( \theta_{DM} = 180 \). We then consider a boost factor at a given angle \( \theta_{DM} \):

\[
\beta_{CM} = (-q_{z'}, -q_{y'}, p_{z'} - q_{z'}/(p^0 + q^0)
\]
and
\[
\gamma_{CM} = (1/2) \log((1 + \beta_{CM})/(1 - \beta_{CM}))
\]  
where \( \chi \) is the rapidity factor of the process. The Mandelstam variable \( s \equiv (p + q)^2 \) becomes
\[
s = M^2 + M^2_{DM} - 2M M_{DM} \gamma_{DM} (1 + \beta_{DM} \cos(\theta_{DM}))
\]  
where \( \gamma_{DM} \) and \( \gamma_{DM} \) are the usual relativistic parameters.

Taking these into account, we use a Monte Carlo technique to build the different distributions. The distributions are \( d\sigma/d\cos(\theta_{i}) \), \( d\sigma/dE_{\gamma} \), and \( d^2\sigma/dcos(\theta_{i}) dE_{\gamma} \); where \( E_{\gamma} \) is the energy of the emitted photon and \( \theta_{i} \) is the photon angle with respect to the positive \( z' \)-axis, \( i \) the incoming matter particle. The energy distribution converges very smoothly, but the angular distribution, due to the three-body final state, is slower to converge and required \( 2 \times 10^9 \) events to reach a relatively clean distribution. There was still a fairly large spread in the amplitude of the angular distributions and we used a fifth-order smoothing algorithm [62]:
\[
y_i = \frac{1}{35} (-3y_{i-2} + 12y_{i-1} + 17y_i + 12y_{i+1} - 3y_{i+2})
\]  
After 150 iterations, the spread is reduced by about a factor 5 and keeps the general features of the original distribution as can be seen on figure 1 where the narrow band is the final distribution.

The doubly differentiated distribution \( d^2\sigma/dcos(\theta_{i}) dE_{\gamma} \) is the most important in what follows. In order to study the interaction of the solar wind with the DM halo, we built this distribution for collision angles \( (\theta_{DM}) \) from 0 to 180 degrees by increments of 10 degrees; we have then 19 distributions.

**Scanning the solar system**

Once we have these distributions, we let the solar wind scatter off the DM in the solar system and beyond. We first pick an observation point from which originates an observation cone of a given opening angle \( (\delta_{C}) \), length and orientation; all photons observed must be produced within this cone. Once we have picked a collision point at random within the cone, all angles and distances are well defined: \( \theta_{DM} \), \( \theta_{\gamma} \), \( \vec{R} \) (the vector from the observation point to the collision point) and \( \vec{D} \) (the vector from the sun to the collision point).

We build the photon flux \( (\Phi) \) in \( 1/m^2 \ sec \) as
\[
\frac{d\Phi}{dE_{\gamma}} = \frac{1}{N} \langle \frac{d\Phi}{dE_{\gamma}} \rangle \left( \frac{V_{cone}}{V_{collider}} \right)
\]  
where
\[
\langle \frac{d\Phi}{dE_{\gamma}} \rangle = \left( \sum_{i=1}^{N} \frac{d^2\sigma}{d\cos(\theta_{i}) dE_{\gamma}} \cdot G_i \right)_{\cos(\theta_{Earth})} \bigg| \vec{R}_{i} \in \text{cone}
\]  
and
\[
G_i = \frac{(\Delta \cos(\theta_{i})) \cdot L_i}{2\pi (R \sin(\theta_{i})) (R \Delta \theta_{i})}
\]  
\( L_i \) is the luminosity at the colliding point, \( \vec{R} \) is a unit vector from the observation point to the colliding point, \( \Delta \cos(\theta_{i}) \) is the width of the bin previously defined, and \( \Delta \theta_{i} \) is the angular width of the band that we consider at the Earth. \( G_i \) takes into account the fact that the photon is emitted on a cone of angle \( (\theta_{i}) \) and will not necessarily reach the Earth. Once the cone has been sampled and averaged, we multiply by the number of independent accelerators that we have in our cone.

The sun is at the origin of our coordinate system and our observation point is along the positive \( y \) axis; this is \( \vec{R}_0 \). We define the elevation angle of the observation apparatus as \( \theta \) above the ecliptic plane and \( \phi \) from the positive \( y \)-axis towards the positive \( x \)-axis. The aperture of the observing apparatus defines the opening angle of the observing cone; \( \delta_{C} \) such that the total angle of the cone is \( 2\delta_{C} \). We will use \( \delta_{C} = 40^\circ \).

In order to sample the cone in a uniform and random manner, we embed the cone in a cube \((x'',y'',z'')\) tailored to the cone and produce random numbers within each axis of the cube. We keep the events that fall within the cone and do not take into account those that lay outside of our cone. Due to the \( 1/D^2 \) behaviour of the solar flux that will appear later in the luminosity and the \( 1/2\pi R \sin\theta_{\gamma} R \Delta\theta_{\gamma} \) behaviour of the area of the ring where the photon can be emitted, one expects that the contribution of very far away colliders will decrease and therefore, when building our distributions, we should reach a plateau, a maximum photon flux once the length of our cone of integration reaches a certain value. Numerically, we should even observe a decrease in the amplitude of the distributions if we increase the length of the cone since integration up to very far distances would take a very large number of events in order to scan properly the regions that contribute most. We observe this behaviour in our distributions. We should also observe an increase in the number of photons when we increase the opening angle of the observational cone; this relation is not so straightforward though as the emission of the bremsstrahlung photon is not uniform in the collision process and some regions of the observation cone might be better at producing photons than others. We also observe this behaviour in our distributions.

In order to scan the cone, we proceed as follows: our observation point is at the origin of our \( x'' - y'' - z'' \) frame where we generate coordinates at random. This frame has the same orientation as our observation cone and its \( x'' \)-axis corresponds to our \( x \)-axis (we set \( \phi = 0 \)). The cone is simply rotated by a certain angle around its \( x'' \)-axis. Once the \((x'',y'',z'')\) coordinates are generated at random, we have \( \vec{R} \), the vector from the observation point to the colliding point. It is then straightforward to define the vectors that define the position of the observation point and the collision point. We consider four
such rotations:
A- 45 degrees: we look 45 degrees above the ecliptic with our back to the the sun
B- 90 degrees: we look 90 degrees above the ecliptic plane
C- 135 degrees: we look 45 degrees above the ecliptic plane and partly toward the sun
D- 180 degrees: we look directly at the sun but we exclude a cone of 2 degrees full angle in order to exclude the sun itself.

The relevant vectors are then:
\[ \vec{R}_o = (0, R_o, 0) \quad \vec{D} = \vec{R}_o + \vec{R} \]
\[ \vec{V}_{DM} = \beta_{DM}(0, -1, 0) \quad \vec{V}_M = \beta_M(D_x, D_y, D_z)/|\vec{D}| \]

In this work, we assume that the DM is incoming along the \(-y\) axis; the motion of the sun is in the direction of the ecliptic plane towards the Earth. The angles \(\theta_{DM}\) and \(\theta_s\) are obtained from the scalar products
\[ \cos(\psi) = \frac{\vec{D} \cdot \vec{V}_{DM}}{D \cdot V_{DM}} \quad \text{and} \quad \cos(\eta) = \frac{\vec{D} \cdot \vec{R}}{D \cdot R} \]

From these definitions we have \(\theta_{DM} = \pi - \psi\) and \(\theta_s = \pi - \eta\).

**Probability for the outgoing photon to be ejected with a given energy**

Once these angles are determined we go back to the distributions we built previously and pick the one that corresponds to the correct value of \(\theta_{DM}\); i.e. the \(d^2\sigma/d\cos(\theta_s)dE\gamma\) that corresponds to our value of \(\theta_{DM}\).

Within this distribution, we pick the specific row that corresponds to the correct value of \(\theta_s\). This row represents the distribution \(d\sigma/dE\gamma\) for \(\theta_{DM}\) and \(\theta_s\), fixed by the position of the collision point. Within this distribution, we consider the highest possible value of the differential cross-section and pick a number at random between 0 and 1 to multiply it with. Since the cross-section (differential or total) represents the probability that a given process takes place, multiplying this maximum value by a random number between 0 and 1 will give the probability that the wanted process take place. We then read the corresponding value of the photon-energy. We now have the cross-section (or probability) that a photon be produced at a given angle with a given energy when a proton of a given energy collides with a DM particle of a given energy at a given incoming angle.

**Luminosity**

The luminosity \((1/m^2 \text{ sec})\) depends on the densities and velocities of the colliding particles and also on the colliding angle. [63,64] We assume a uniform density of the dark matter cloud within our region of the galaxy and set it at 0.3 GeV/cm^3. Regarding the solar wind, we assume that the sun emits a certain amount of material in space every second: we set it at \(10^9\) kg/sec and assume that it is mostly protons. We also include the usual \(1/D^2\) behaviour of the solar flux, which leads to a decreasing density of the solar wind but we assume that this density is constant over the 600 km that our solar wind travels in one second. Essentially, we consider a beam of uniform density over 600 km in length and 1 meter in cross-section. Since the interaction rate is rather small, we do not take into account the depletion of the solar wind flux as it travels through space. In these conditions, the required kinematical factor is given by

\[ K = \sqrt{((\tilde{\beta}_M - \tilde{\beta}_{DM})^2 - (\tilde{\beta}_M \times \tilde{\beta}_{DM})^2)} \] (10)

so that the luminosity is given by

\[ L = \rho_M \rho_{DM} L_x L_y v_M v_{DM} \Delta t \ast K \] (11)

where \(L_x\) and \(L_y\) are the transverse sections of the beam, which we take as 1 m, and \(\Delta t\) is the time scale of the collision, which we take as 1 second. \(\rho_M\) is the density of matter (protons) at the collision point, given by

\[ \rho_M = \frac{R_{sw}/m_{\text{proton}}}{4\pi D^2 v_M} \]

and \(\rho_{DM}\) is the density of dark matter particles at the collision point in \(1/m^3\).

In order to get the final spectrum from this observation cone, we divide the distribution that we just built by the number of events used (which gives us the average spectrum) and then multiply by the number of independent accelerators within this cone: \(V_{cone}/V_{collider}\). We take \(V_{collider} = (600000 + 300000)m^3\). This procedure is justified since the distances travelled by our particles in 1 second are very much smaller than the distances at hand: we would need to consider \(\sim 10^{28}\) collision points for our colliders to begin to overlap within the cone. This procedure is also symmetric both from the point of view of the matter and from the point of view of the DM particle. We neglect the effect encountered when \(\theta_{DM} = 180\), in which case the two volumes would overlap.

**Free parameters**

There are 5 free elements in this scenario: 2 DM masses, 2 DM-couplings and the density of DM particles in the galaxy. Clearly, the couplings and the density of the DM particles in the solar system simply factor out as \(\rho_{DM}\) and \(\lambda^2 A^2\). The mass of the DM particle exchanged in the process also factors out as \(1/m^3\) since we have a t-channel process and the photon energies involved are much smaller than the masses. Regarding the mass of the incoming DM particle, it does not factor out and we find that the maximum bremsstrahlung occurs when its mass is about twice that of the proton so that the proton and the colliding DM particle have about the same momentum. The angle of the observation cone also factors out, but one has to be careful because the production volume might depend on the orientation when this angle becomes small. Therefore, our results can be scaled up or
down by multiplying them by the following expression:

\[
\frac{\left(\lambda^2 \Lambda^2\right) \cdot \left(\rho_{DM} \rho^0_{DM} / \rho^0_{DM}\right) \cdot \left(R_{sw} R^0_{sw}\right) \cdot \left(\tan(\delta_C) / \tan(\delta^0_C)\right)^2}{(M_{exchange}/0.1GeV)^4}
\]

where \(R_{sw} = 10^9 \text{kg/sec}, \rho_{DM} = 0.3 \text{GeV/cm}^3, \delta_C = 40^\circ\).

**Results**

We consider two observation points: one at 1 au (the Earth) and another at the edge of the solar system, at 50 au (Note that when looking directly at the sun from 50 au, reducing the exclusion cone from 1 degree, it was at 1 au to 1/50 degree has very little effect). We also consider two scenarios: in the first one (scenario A), the colliding DM particle has a mass of 2 GeV and the exchange particle has a mass 0.1 GeV. Such scenarios have been considered as *secluded WIMP dark matter* and some models allow excited state. [65,66,67]. In the second scenario (scenario B), the colliding particle and the exchange particle have the same mass. In scenario A, we use the mass of the colliding particle to calculate the density of DM particles (\(\rho_{DM}\)). We also considered several lengths and opening angles of the observational cone and verified that our distributions behaved as expected.

The result is figures 2, 3, 4, and 5, which represent \(\Phi(E)\) vs \(E\), where \(\Phi(E)\) is in \(1/m^2 \text{sec eV}\) and \(E\) is in eV; recall that the visible spectrum is from 1.6 eV to 3.2 eV.

One notes that:

- All curves exhibit a straight line at low photon energy but show some noise at higher energy; the higher energy part of the spectrum converges more slowly.
- The rate at 45 degrees is substantially smaller than the rates at 90, 135 and 180 degrees.
- The rates at 90, 135 and 180 degrees are very similar.
- All slopes at 1 au are very similar, at about -3.2 \(1/m^2 \text{sec eV}^2\), for both scenarios.
- The slopes at a distance of 50 au are also very similar to those at 1 au.
- The rate at 50 au when looking at the sun is similar to the rate at 1 au and 45 degrees with a behaviour similar to that of 1 ua when the observation angle changes.

The straight lines indicate that:

\[
d\Phi(E_{\gamma})/dE_{\gamma} = \phi_0 \left(E_{\gamma}/E_{\gamma}^0\right)^{-\alpha} \rightarrow (12)
\]

\[
\Phi_{E_{\gamma}^{max}}^{E_{\gamma}^{min}} = \frac{\phi_0 (E_{\gamma}^0)^{\alpha}}{\alpha - 1} \left\{ \frac{1}{(E_{\gamma}^{min})^{\alpha - 1}} - \frac{1}{(E_{\gamma}^{max})^{\alpha - 1}} \right\} (13)
\]

where \(\phi_0 (1/m^2 \text{sec eV})\) and \(E_{\gamma}^0\) is some reference point.

From figures 2, 3, 4, and 5, we can extrapolate safely to 0.01 eV and with caution somewhat below. Using these different parameters, we obtain Table I, where we give the photon flux \((1/m^2 \text{sec})\) for different scenarios and photon energy bands. As we have already covered the whole observation cone, taking into account its opening angle of 40°, we could say that our units are \(1/m^2 \text{sec} (0.47 \pi \text{sr})\).

One has to be careful in scaling because opening or closing the observation cone at different observation angles might not give the same result as the productive zones may vary in size at different observation angles. From Table I, we can see that the rates are very small over the whole range with the parameters used here but could become interesting at wavelengths of mm or cm (with energies in the meV range) in scenario B. Clearly, if we reduce the mass of the exchange particle by a factor of 10, we gain a factor \(10^4\) in the rates and these become interesting in the microns range, as long as we remain in scenario B. In a model where several DM particles can coexist with very different masses and interact with each other and with the proton, the scenario that we consider here would be the dominant one: a heavier exchange particle would reduce the t-channel amplitude and a lighter colliding particle would reduce the bremsstrahlung. Of course, a complete calculation with all diagrams involved would be necessary.

Our results indicate also that the excess luminosity observed recently by the New Horizon probe [68] cannot come from this process, at least not with reasonable parameters. One would need far higher energy protons (or other charged particles) or far higher density in order to produce the excess in the visible range; likely, such particles would have been observed in other ways.

Reversing the situation, a scenario where the heavier DM particle could couple to lighter dark particles would lead to their production through bremsstrahlung off the DM particle as it scatters off the solar wind, thereby increasing their presence in our solar system. This effect would be larger in close proximity of the sun. Similarly, in a model similar to the one considered here, a proton could emit via bremsstrahlung a light dark matter particle.[69]

There is also the interesting possibility that an electron could interact with the DM; such couplings have been considered before in the context of the 0.511 MeV emission from the center of the galaxy [70,71] and the possibility of DM upscattering in the sun [35]. This process should lead to results similar to what we have here and opens up the possibility of sensitivity to very small masses in the DM spectrum since the bremsstrahlung seems to be maximum when the colliding particles have about the same momentum and the electrons in the solar wind have a speed similar to that of the sun in the galaxy.

A proposed future MeV gamma-ray telescope is expected to probe the MeV or sub-MeV DM mass range.[72]

We have neglected cosmic magnetic fields, which would bend the solar wind and modify the colliding angles within the observation cone. Evaluating the effects of these fields on the spectrum would be interesting, but it is unlikely this could make the signal observable in the visible, for example. We have also neglected the effect of the solar wind on the density of the DM. It is likely that the presence of the wind would increase the density of the DM particles in its vicinity and as most of the spectrum is produced relatively close to the sun, this would tend to
increase the counting rate observed, but likely not enough to
gain several orders of magnitude. When considering
the spectrum at longer wavelengths however (in the mm
or cm range) and assuming that the spectrum keeps a
slope similar to what we have calculated here, then
these effects could make a difference in the observable spec-
trum. We have assumed that the sun moves towards the
Earth (or the observation points) in its motion around
the galaxy. Taking the real motion of the sun into ac-
count could have a small effect on our results and bring
some proidicty to our signal. A more precise calculation
(finer angular and energy bins and finer sampling mesh) is necessary in order to assess the importance of
these effect at very low photon energy as well as a precise
modeling of the cosmos in this regime. [73]

Conclusions
We have considered the scattering of the solar wind off
DM particles that might be populating our solar sys-
tem. We allowed the scattered proton to emit a photon
through bremstrahlung and calculated the spectrum
that one would observe either at 1 au or at 50 au from
the sun. We have assumed a uniform DM density in our
region of the galaxy and neglected the effects of cosmic
magnetic fields on the solar wind. We have found that
the rates are very small in general and could not explain
the excess luminosity observed recently by the New Horizon
probe with reasonable parameters. Extrapolating our re-
sults down to 0.01 eV is reasonable and indicates that the
rates are still very small with the parameters we used.
Reducing the mass of the exchange particle to 0.01 GeV
could produce a few hundred counts/sec in the 0.01-0.05
eV window (25-150 microns). Extrapolating our results
to lower energy photons, there could be a measurable
photon rate in the mm or cm range where one could ex-
pect a few hundred to a few thousands photons/m$^2$ sec in
the scenario where the exchange DM particle has a mass
of 0.1 GeV. A more precise numerical calculation would
be required to confirm this behaviour of the photon flux
down to very low photon energies.

The scenario that we have considered and appears to
be the most promising is that of a DM particle whose
mass is about 2 $m_{proton}$ interacting with a proton via
the exchange of a much lighter DM. This opens up the
possibility of bremstrahlung of the lighter DM particle
off the heavier DM particle as the latter scatters off a
proton; thereby increasing the abundance of the lighter
DM particle.

Considering bremsstrahlung emission from the scatter-
ing of electrons off DM particles also opens up the pos-
sibility of exploring small mass regime in the DM sector
since the bremsstrahlung seems to be maximum when the
momentum of the colliding particles are about the same
and the solar wind has a speed similar to that of the sun
in the galaxy.

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computers.

References
1- E.Aprile et als, Phys.Rev.D102(2020)072004; hep-ex:2006.09721
2- H.An, M.Pospelov, J.Praderl, A.Ritz, Phys.Rev.
D102(2020)115022; hep-ph:2006.13929
and references therein.
3- S.Vagnozzi, L.Visinelli, P.Brax, A.-C.Davis,J.Sakstein,
hep-ph:2103.15834 and references therein
4- M.Dutta,S.Mahapatra,D.Borah,N.Sahu,
hep-ph:2101.06472 and references therein
5- J.Billard,M.Boulay,S.Cebrian,L.Covi, APPEC Com-
mittee Report; hep-ex:2104.07634 and references therein
6- M.Szydagis,C.Levy,G.M.Blockinger,A.Kamah,N.
Parveen,G.R.C.Rischbieter, Phys.Rev.D103(2021)
012002; hep-ex:2007.00528
7- A.E.Robinson, hep-ex:2006.13278
8- E.Aprile,et als, XENON-Collaboration, JCAP11
(2020)03;physics.ins-det:2007.08076
9- D.S.Akerib, et als, LUX-Collaboration,
Phys. Rev. D101(2020)052002; astro-ph.IM:1802.06039
10- A.H. Abdelhameed, et als, CRESST-Collaboration,
Phys.Rev.D100(2019)102002; astro-ph.CO:1904-00498
11- H.Kluck, CRESST-Collaboration, J.Phys.Conf.
Serv.1468(2020)012038
12- X.Ren, et als,PANDA-Collaboration,
Phys.Rev.Lett.121(2018)021304 hep-ex:1802.06912
13- J.Yang, et als, PANDA-Collaboration; hep-
ex:2104.14724
14- H.An., M.Pospelov, J.Pradler, A.Ritz,
Phys.Lett.B747(2015)331-338; hep-ph:1412.8378
15- G.Prézeau, A.Kurylov, M.Kamionsky, P.Vogel,
Phys.Rev.Lett.91(2003)231301; astro-ph:0309115
16- D. Hooper, S.M. McDermott, Phys.Rev.D97
(2018)115006; hep-ph:1802.03025
17- E.Behnke, et als, PICASSO-Collaboration,
Astropart.Phys.90(2017)85-92; hep-ex:1611:01499
18- M.Lafrenière, Thèse de Doctorat, Dépt. de Physique,
U.de Montréal, Déc. 2016; and references therein.
19- C.Amole, et als, PICO-Collaboration,
Phys.Rev.D100(2019)022001; astro-ph.CO:1902.04031
20- C.B. Krauss, PICO-Collaboration,
J.Phys.Ser.1468(2020)012043
21- R. Bernabei, et als, Int.J.Mod.Phys.A22(2007)3155-
3168;astro-ph:0706.1421
22- M.Ibe, W.Nakano, Y.Shoji, K.Suzuki,
JHEP03(2018),194; hep-ph:1707.07258
23- N.F.Bell,J.B.Dent,J.L.Newstead,S.Sabharwal,T.J.Weiler,
Phys.Rev.D101(2020)015012; hep-ph:1905.00046
24- V.S.Flambaum, L.Su, L.Wu, B.Zhu;
hep-ph:2012.09751
25- J.A.Dror, G.Elor, R.McGehee, T.-T.Yu,
Phys.Rev.D103(2021)035001; hep-ph:2011.01940
26- C.Kouvaris, J.Praderl, Phys.Rev.Lett.118(2017)
03180; hep-ph:1607.01789
27.- M.J. Dolan, F. Kahlhoefer, C. McCabe, Phys.Rev.Lett.121(2018),101801; hep-ph:1711.09906
28. - R. Essig, J. Mardon, T. Volansky, JHEP05(2016)046; hep-ph:1108.5383
29. - B.V. Lehmann, S. Profumo, Phys.Rev.D102(2020)023938; hep-ph:2002.07809
30. - G.D. Starkman, D.N. Spergel, Phys.Rev.Lett.74(1995)623-2625; hep-ph:9409275
31. - T. Bringmann, M. Pospelov, Phys.Rev.Lett.122(2019)171801; hep-ph:1810.10543
32. - J. Alvey, M. Campos, M. Fairbairn, T. You, Phys.Rev.Lett.123(2019)261802; hep-ph:1905.05776
33. - M. Klasen, M. Pohl, G. Sigi, Prog.in Part. and Nucl. Phys.85(2015)1-32; hep-ph:1507.03800
34. - N. Vinyoles, A. Serenelli, F. L. Villante, S. Basu, J. Redondo, J. Isen, JCAP10(2015),015;
    astro-ph:SR:1501.01639
35. - H. An, M. Pospelov, J. Pradler, A. Ritz, Phys.Rev.Lett.120(2018)141801; hep-ph:1708.03642
36. - R.K. Leane, J. Smirnov, Phys.Rev.Lett.126(2021)161101; hep-ph:2001.00015
37. - V. Gluscevic, K. K. Boddy, Phys.Rev.Lett.121(2018)011301; astro-ph:CO:1712.07133
38. - Y. Ali-Haïmoud, J. Chuba, M. Kamionkowski, Phys.Rev.Lett.115071304; astro-ph:CO:1506.04745
39. - K. Maamani, V. Gluscevic, K. K. Boddy, E.O. Nadler, R.H. Wechsler, Astrophys.J.Lett.,907(2021)2,L46;
    astro-ph:CO:2010.02936
40. - S. Afach, et als., astro-ph:CO:21021379
41. - A. Derevianko, M. Pospelov, Nature,Physics 10(2014)933; physics.atom-ph:1311.1244
42. - M. Bauer, M. Heiles, M. Neubert, A. Thamm, Eur.Phys.J.C79(2019)74;
43. - H. Mies, C. Schreiber, P. Schwall, JHEP04(2021)049; hep-ph:2100.1399
44. - J. I. Read, J.Phys.G41(2014)063101; astro-ph:GA:1404.1938
45. - C. J. Copi, L. M. Krauss, Phys.Rev.D63(2001),043507; astro-ph:0009467
46. - P. Salucci, F. Nesti, G. Gentile, C. F. Martins, Astron.Astrophysics,523(2010)A83
47. - H. Bethe, W. Heitler, Proc.Roy.Soc.146(1934)83
48. - Classical Electrodynamics, J. D. Jackson; Wiley, New York, 2nd Edition, 1975
49. - P. Talukdar, F. Myhrer, U. Raha, Eur.Phys.J.A54(2018)11,195; nucl-th:1712.09963
50. - U. Eichmann, W. Greiner, J.Phys.G23(1997)L65-L76; nucl-th:9706044
51. - T. S. Biro, K. Nita, A. L. de Paoli, W. Bauer, W. Cassing, U. Mosel, Nucl.Phys.A475(1987)579-597
52. - G. Baur, A. Leuschner, Eur.Phys.J.C18(1999)631-635; hep-ph:9902245
53. - W. Zhun, Nucl.Phys.B693(2020)114958, hep-ph:1909.03053
54. - M. Cirelli, P. D. Serpico, G. Zaharijas, JCAP11(2013)035; astro-ph:HE:1307.7152
55. - J. B. Dent, B. Dutta, J. L. Newstead, A. Rodriguez, I. M. Shoemaker, Z. Tabrizi; hep-ph:2012.07930
56. - L. Su, L. Wu, and B. Zhu; hep-ph:2105.06326
57. - Relativistic Quantum Mechanics, Bjorken J.D. and S.D. Drell; Vol. 1, McGraw-Hill, New York, 1964
58. - An Introduction to Quantum Field Theory, Peskin, M.E. and D. V. Schroeder; Addison Wesley, New York, 1995
59. - Relativistic Quantum Mechanics and Field Theory, Gross, F., Wiley Interscience, New York, 1993
60. - Relativistic Kinematics, R. Hagedorn; Benjamin/Cummings, London, 1963
61. - Collider Physics, Barger, V. D. and R.J.N. Phillips, Addison Wesley, New York, 1987
62. - A. Savitzky, M. J. E. Golay, Analyt.Chem.8(1964)1627-1639
63. - W. Herr, B. Muratori, CERN Acc. School and DESY Zeuthen: Accelerator Physics, (2003)361-377
64. - H. Burkhardt, P. Graefstrom, LHC Project Report 1019 (2007)
65. - M. Pospelov, A. Ritz, M. Voloshin, Phys.Lett.B662(2008)53-61; hep-ph:0711.4866
66. - K. Schutz, T. R. Stayer, JCAP01(2015),21; hep-ph:1409.2867
67. - A. Dedes, I. Giomataris, K. Suxho, J. D. Vergados, Nucl.Phys.B826(2010)148-177; hep-ph:0907.0758
68. - T. R. Lauer, et als., Astrophys.J.96(2021)2,77; astro-ph:GA:2011.03052
69. - N. F. Bell, Y. Cai, J. H. Dent, R. K. Leane, T. Weiler, Phys.Rev.D96(2017),023011; hep-ph:1705.01105
70. - R. Bernabei, et als., Phys.Rev.D77(2008)023506; hep-ph:0712.0562
71. - J. F. Beacom, N. F. Bell, G. Bertone, Phys.Rev.Lett.94(2005)171301; astro-ph:0409403
72. - A. Coogan, A. Moiseev, L. Morrison, S. Profumo, astro-ph:HE:2101.10370
73. - D. Gaggero, M. Valli, Adv.in High Energy Phys.2018(2018)3010514; astro-ph:HE:1802.00636

Table 1

| Integrated expected photon fluxes for the two scenarios considered, for different observation angles, and for different energy bands. In scenario A, the colliding particle has a mass of 2 GeV while the exchange particle has a mass of 0.1 GeV, while both have a mass of 0.1 GeV in scenario B. A-180-01 means: scenario A, observation angle of 180 degrees (directly at the sun) and observation point at 1 au from the sun. The fluxes are in $1/m^2sec$. If one takes into account that the opening angle of the observation cone is 40°, then our units for the flux are $1/m^2sec(0.47 \pi sr)$ |
FIG. 1. Angular distribution before and after smoothing

FIG. 2. Photon flux (1/m² sec eV) vs photon energy (eV) for 1au-180 degrees (+), 1au-45 degrees (x), and 50au-180 degrees (o) in scenario A

FIG. 3. Photon flux (1/m² sec eV) vs photon energy (eV) for 1au-90 degrees (+), and 1au-135 (x) in scenario A

FIG. 4. Photon flux (1/m² sec eV) vs photon energy (eV) for 1au-180 degrees (+), 1au-45 degrees (x) and 50au-180 degrees (o) in scenario B
FIG. 5. Photon flux (1/m² sec eV) vs photon energy (eV) for 1au-90 degrees (+), and 1au-135 degrees (x) in scenario B

Table I

| scenario | slope  | 1.6-3.2 eV | 0.5-1.0 eV | 0.1-0.5 eV | 10-50 meV | 1-5 meV | 0.1-0.5 meV |
|----------|--------|------------|------------|------------|-----------|---------|------------|
| A-180-01 | -3.38  | 9.5 × 10⁻⁸ | 1.5 × 10⁻⁶ | 8.4 × 10⁻⁵ | 0.021     | 5.1     | 1200       |
| A-135-01 | -3.50  | 1.4 × 10⁻⁷ | 2.6 × 10⁻⁶ | 1.7 × 10⁻⁴ | 0.053     | 17      | 5400       |
| A-90-01  | -3.10  | 1.0 × 10⁻⁷ | 1.14 × 10⁻⁶| 4.2 × 10⁻⁵ | 5.4 × 10⁻³| 0.68    | 86         |
| A-45-01  | -2.99  | 8.4 × 10⁻⁹ | 8.6 × 10⁻⁸ | 2.7 × 10⁻⁶ | 2.6 × 10⁻⁴| 0.026   | 2.6        |
| A-180-50 | -3.28  | 4.5 × 10⁻⁹ | 6.3 × 10⁻⁸ | 3.0 × 10⁻⁶ | 5.9 × 10⁻⁴| 0.11    | 22         |
| B-180-01 | -3.17  | 1.2 × 10⁻¹⁰| 1.5 × 10⁻⁹ | 6.2 × 10⁻⁸ | 9.1 × 10⁻⁶| 1.4 × 10⁻³| 0.20       |
| B-135-01 | -3.16  | 1.5 × 10⁻¹⁰| 1.8 × 10⁻⁹ | 7.2 × 10⁻⁸ | 1.0 × 10⁻⁵| 1.5 × 10⁻³| 0.21       |
| B-90-01  | -3.10  | 8.5 × 10⁻¹¹| 9.7 × 10⁻¹⁰| 3.6 × 10⁻⁸ | 4.6 × 10⁻⁶| 5.7 × 10⁻⁴| 0.072      |
| B-45-01  | -2.96  | 8.9 × 10⁻¹²| 8.7 × 10⁻¹¹| 2.6 × 10⁻⁹ | 2.4 × 10⁻⁷| 2.2 × 10⁻⁵| 0.002      |
| B-180-50 | -3.13  | 3.4 × 10⁻¹²| 4.1 × 10⁻¹¹| 1.6 × 10⁻⁹ | 2.1 × 10⁻⁷| 2.9 × 10⁻⁵| 0.004      |