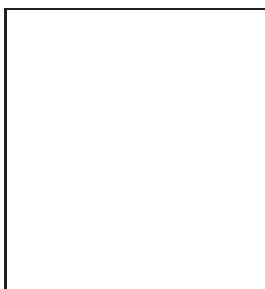# Could a γ Line Betray the Mass of Light Dark Matter?

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We [1] compute the pair annihilation cross section of light dark matter scalar particles into two photons, and discuss the detectability of the monochromatic line associated with these annihilations.

1 Introduction

The need for Cold Dark Matter (DM) to describe and understand how structures in the universe hold together, has become increasingly pressing with the impressive amout of observational data collected in the last ten years. Alternatives to DM, like modifications of gravity, are being put to critical and maybe fatal test by recording maps of gravitational lensing. Indeed, the separation recently observed in colliding clusters between the (maybe modified) gravitational deviation of light and the normal matter that causes it, seems very contrived with modified gravity, and very natural if collisionless DM is the main source of gravity. Questions about the nature of DM and its non-gravitational detection are therefore more relevant than ever.

In this context, the precise determination by INTEGRAL/SPI [2] of the characteristics of the 511 keV line emitted in our galaxy is intriguing. Indeed, it implies wihtout any doubt that the central bulge of our galaxy is a strong source of positrons. Astrophysical sources like Low Mass X-ray Binaries (LMXB) and Type 1a Supernovae (SN1A) [3] cannot naturally explain why this source is at the same time steady, extended and absent in the disk. On the contrary, production of positrons through DM annihilation is naturally steady and concentrated in the bulge where the DM density increases: a fit of the needed DM density profile can even be attempted [4], yielding a reasonable NFW profile $\rho(r) \sim r^{-1}$ for DM annihilation at rest, in opposition to a less reasonable $\rho \sim r^{-2}$ for DM decay.

In order to maximize the electron-positron annihilation channel, such DM must be light (LDM) [5,6], at least below muon pair threshold: $m_{dm} < 100\,\text{MeV}$. More constraining upper bounds can be obtained by a careful study of final state radiation processes (dm dm$^\star \to e^+ e^- \gamma$) and positron anihilation in flight, both producing continuous gamma ray spectra which increase with m_{dm}. From the first, $m_{dm} < 35$ MeV is obtained [7], and $m_{dm} < 20$ MeV from comparing the second with error bars on the measured spectra. On the other hand, m_{dm} should be higher than 2 MeV to avoid spoiling nucleosynthesis [8], and higher than 10 MeV if there is a significant coupling to neutrinos which can alter supernova explosions [9], but such is not necessarily the case.

A fairly unique viable model satisfying all the above constraints contains scalar DM particles with $m_{dm} \sim 10\,\text{MeV}$, annihilating at rest in the galactic bulge into e^+e^- pairs via t-channel exchange of heavy ($> 100\,\text{GeV}$) fermions F_e. Given the large local DM abundance inferred from the rotation curve, the annihilation cross-section yielding the observed positron source is however too small to explain a correct relic density inferred e.g. from cosmic microwave background measurements. A further light vector particle can then be invoked to mediate an s-channel annihilation process: being velocity dependent, this process becomes dominant in the early universe and can independently be adjusted to the relic density.

If correct, such a model [5] would profoundly alter the road to unification in particle physics. It therefore seems important to look for other experimental cross-checks. The simplest and most convincing one would be the discovery of another gamma ray line, from the process dm dm$^\star \to \gamma\gamma$. In the following, we show [1] this line is anavoidable in such a model, estimate its intensity, and discuss its observability.

2   Dark matter annihilation cross section into two photons

The model considered is specified by the Lagrangian $\mathcal{L} = \bar{\psi}_{F_e}(c_r P_L + c_l P_R)\psi_e \phi_{dm} + h.c$ where $P_{R,L}$ are the chiral projectors $(1 \pm \gamma_5)/2$. The relevant annihilation diagrams are box-diagrams containing 1, 2 or 3 heavy fermions F_e. Assuming that $dm \neq dm^\star$ (which fixes the circulation of arrows), there are 6 diagrams, taking into account permutation of the 2 photon external legs.

From naive power counting, each box is logarithmically divergent. However, gauge invariance dictates a result proportional to $F_{\mu\nu}^2$ rather than A_μ^2. This requires 2 powers of external momenta, so that the integrand must in fact converge like d^4k/k^6 for large loop momenta k. In the limit $m_{F_e} \gg m_{e,dm}$ (relevant due to LEP and other collider/accelerator constraints), the contribution of momenta larger than m_{F_e} is $\sim 1/m_{F_e}^2$. The leading $1/m_{F_e}$ term can thus be safely obtained by expanding the integrand in powers of $1/m_{F_e}$ and keeping only the first term.

$$\approx \quad \text{[diagram]} \quad + \ O(\tfrac{1}{m_F^2}) \qquad \Leftrightarrow \qquad \mathcal{L}_{eff} = \frac{1}{m_{F_e}}\phi_{dm}^*\phi_{dm}\bar{\psi}_e(a + ib\gamma_5)\psi_e$$

This corresponds to "pinching" the box with one F_e into a triangle involving only electrons and an effective dm-dm-e-e coupling given bywith the real couplings a, b given by $a + ib = c_l^* c_r$. For this set-up, computing the cross-section is a loop-textbook exercise for which we find:

$$\sigma_{\gamma\gamma} v_r = \frac{\alpha^2}{(2\pi)^3 \, m_{F_e}^2} \frac{m_e^2}{m_{dm}^2} \times \left[b^2 |2C_0 m_{dm}^2|^2 + a^2 |1 + 2C_0(m_e^2 - m_{dm}^2)|^2 \right].$$

C_0 is a function of m_e and m_{dm} given by the Passarino-Veltman scalar integral. For $m_{dm} > m_e$, this function develops an imaginary part corresponding to the formation of a real $e^+ e^-$ pair subsequently annihilating into 2 photons, and giving the largest contribution for masses above 1 MeV.

For $m_{dm} \ll m_e$, C_0 behaves as $[-1/(2m_e^2) + m_{dm}^2/(3m_e^4)]$, so that both terms of the cross section behave as $m_{dm}^2/(m_e m_{F_e})^2$. This limit is relevant to estimate the effect of heavier particles than the electron in the loop. For example, the contribution of the τ lepton could be significant if the corresponding couplings (a_τ, b_τ) are larger than $\approx (m_\tau/m_{dm}) \times (a_e, b_e) \times (m_{F_\tau}/m_{F_e})$ (with $m_{\rm dm} < m_\tau$), i.e. if they scale at least like usual Yukawa couplings. Since an independent detailed analysis is required to check whether or not such couplings can pass particle physics constraints, we prefer giving a conservative estimate based on the electron contribution only. The latter cannot be turned off without losing the 511 keV line signal. It therefore constitutes a safe lower bound for assessing the detectability of the line at $E_\gamma = m_{dm}$.

Within the pinch approximation, the cross-section relevant for the origin of the 511 keV emission is:

$$\sigma_{511} v_r = \frac{\beta_e}{4\pi m_{F_e}^2} \left(a^2 \beta_e^2 + b^2 \right)$$

with $\beta_e = \sqrt{1 - m_e^2/m_{dm}^2}$, which indeed for $b = 0$ reduces to the expression used[4] for large m_{F_e}. After careful comparison with SPI data, Ascasibar et al.[4] found

$$\sigma_{511} v_r = 2.6 \, 10^{-30} \left(\frac{m_{dm}}{\rm MeV} \right)^2 \rm cm^3/s.$$

The $\gamma\gamma$ annihilation cross-section is then also determined by this measurement in terms of the ratio of annihilation branching ratios:

$$\eta \doteq \frac{\sigma_{\gamma\gamma}}{\sigma_{511}} = \frac{\alpha^2}{2\pi^2 \, \beta_e} \frac{m_e^2}{m_{dm}^2} \frac{a^2 |1 + 2(m_e^2 - m_{dm}^2)C_0|^2 + b^2 |2m_{dm}^2 C_0|^2}{a^2 \beta_e^2 + b^2} \qquad (1)$$

As announced, this ratio cannot vanish, whatever the value of a/b, so that a minimum $\gamma\gamma$ flux is guaranteed. As m_{dm} approaches m_e from above, the ratio increases like β_e^{-3} for a pure scalar coupling ($b = 0$) and like β_e^{-1} for an axial one ($a = 0$). The ratio decreases almost linearly with the dark mater mass for $m_{\rm dm} > 1$ MeV. In the table below, we give typical values of the ratio η for the most conservative case (i.e. $a = 0$, β_e^{-1}):

m_{dm}(MeV) :	0.52	1	5	20
$\eta(a = 0)$:	$8.8 \, 10^{-5}$	$1.4 \, 10^{-5}$	$3.6 \, 10^{-6}$	$8.1 \, 10^{-7}$

Notice that the simple guess[10] applied to the case of decaying DM

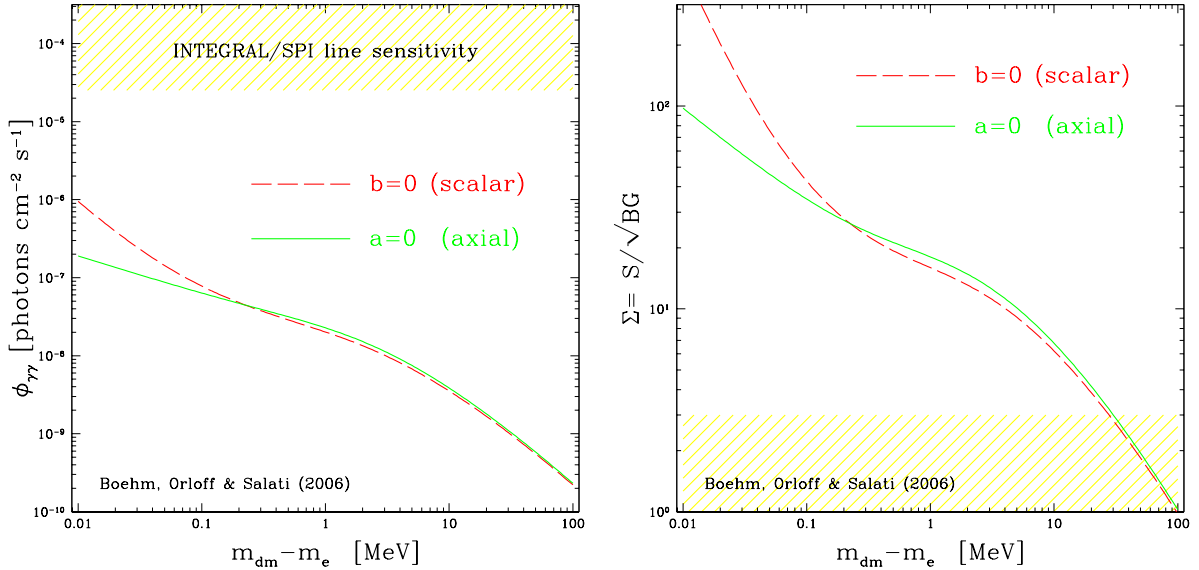$$\eta_{guess} \approx \frac{\alpha^2 m_{dm}^2}{2\pi^2 m_e^2 \beta_e^3}$$

Figure 1: Left: flux of the monochromatic $E_\gamma = m_{dm}$ line from a 8 degree cone around the galactic center. Right: significance of the monochromatic $E_\gamma = m_{dm}$ line above the continuum background for one year of observation with an ideal detector of 1 m^2 and a 10^{-3} energy resolution.

increases instead of decreasing with m_{dm}. For a typical mass of 10 MeV, this guess overestimates the monochromatic flux by a factor 635 with respect to our result (Eq.1). As we will see in the next section, such a factor is crucial to the line observability.

3 Detectability of the monochromatic line

A few experiments have already scanned the energy range above the electron mass. The instruments on board of INTEGRAL for example have been designed to survey point-like objects as well as extended sources over an energy range between 15 keV-10 MeV. The instrument INTEGRAL/SPI itself is a spectrometer designed to monitor the 20 keV-8 MeV range with excellent energy resolution. Therefore a legitimate question is whether or not the line $E_\gamma = m_{dm}$ could have been (or could be) detected by the same instrument that has unveiled the 511 keV signal. This essentially depends on the ratio η as given above, and on the background.

The 511 keV emission has been measured with a $\sim 10\%$ precision [11] to be

$$\langle I_{511} \rangle = 6.62 \times 10^{-3} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

inside a region that extends over $350° < l < 10°$ in longitude and $|b| < 10°$ in latitude. If this emission originates from a NFW distribution of LDM species around the galactic center with a characteristic halo radius of 16.7 kpc, the signal from the inner 5° is found [4] to be

$$\langle I_{511}(5°) \rangle = 1.8 \times 10^{-2} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad,$$

once the SPI response function is taken into account and the instrumental background is properly modeled. If the positron propagation is negligible, then the map of the 511 keV emission should correspond to that of the LDM annihilations.

Within this approximation, we expect the spatial distributions of both the 511 keV and the two-gamma ray lines to be identical and their intensities to be related by the ratio η:

$$\langle I_{\gamma\gamma}(\theta_{\gamma\gamma})\rangle = \eta \; \frac{\theta_{511}}{\theta_{\gamma\gamma}} \; \frac{\langle I_{511}(\theta_{511})\rangle}{(1 - 3f/4)} \quad .$$

This expression is approximately valid as long as the angular radii $\theta_{\gamma\gamma}$ and θ_{511} of the regions monitored by the gamma-ray spectrometer are small. In what follows, the fraction f of positrons forming positronium has been taken [4] equal to 93%. This is in perfect agreement with the positronium fraction later derived [12], i.e. $f_{Ps} = 0.92 \pm 0.09$. The monochromatic line flux

$$\phi_{\gamma\gamma}(< \theta_{\gamma\gamma}) = \pi \, \theta_{\gamma\gamma}^2 \; \langle I_{\gamma\gamma}(\theta_{\gamma\gamma})\rangle$$

has been plotted in Fig. 1 in the case of the LDM model with F exchange and assuming a NFW profile. The angular radius $\theta_{\gamma\gamma} = 8°$ corresponds to the field of view of the satellite. For typical LDM masses in the MeV range, the expected flux is about three orders of magnitude below the claimed INTEGRAL/SPI line sensitivity [13] (which is about 2.5×10^{-5} ph cm^{-2} s^{-1} after 10^6 seconds). An unrealistic exposure of 30,000 years would thus be required in order to detect the $E = m_{\rm dm}$ line. When the LDM species is degenerate in mass with the electron, the flux is only a factor of 25 below the SPI detection limit (assuming a pure scalar coupling b=0). As long as the mass difference $m_{dm} - m_e$ does not exceed 0.1 MeV, it is roughly comparable with the expected 478 keV line signal emitted by Novae [14], that is about $\sim 10^{-7}$ ph cm^{-2} s^{-1}.

SPI sensitivity is limited by the instrumental background that arises mostly from cosmic rays impinging on the apparatus and activating the BGO scintillator. On the contrary, the absolute sensitivity of an ideal instrument is purely limited by the gamma-ray continuum background. This emission has been recently estimated [11]

$$I_{BG}(E) = 1.15 \times 10^{-2} \, E^{-1.82} \text{ ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1} \quad,$$

inside the central region that extends over $350° < l < 10°$ in longitude and $|b| < 10°$ in latitude. The energy E is expressed in units of MeV.

We thus estimate the significance $\Sigma \equiv \text{signal}/\sqrt{\text{background}}$ for the LDM line to emerge above this background (assuming it is isotropic) to be

$$\Sigma = \sqrt{\pi} \; \theta_{511} \; \frac{\langle I_{511}(\theta_{511})\rangle}{(1 - 3f/4)} \; \eta \; \sqrt{\frac{S_0 \, T_0}{I_{BG} \, \Delta E_0}} \quad,$$

with S_0 the surface of the detector, T_0 the exposure time, I_{BG} the above-mentionned continuum background intensity and ΔE_0 the energy resolution. The significance Σ (displayed as a function of the dark particle mass in Fig. 1 for a surface of 1 m^2, an exposure duration of $T_0 = 1$ year and an energy resolution of 0.1%) indicates that those values would theoretically allow to extract the minimal guaranteed signal computed at 3 standard deviations above background for all relevant LDM masses below 30 MeV.

There is nothing to be gained by narrowing the angular aperture $\theta_{\gamma\gamma}$ because, for the assumed NFW profile, the signal increases linearly with this angular radius, as does the square root of an isotropic background.

In contrast, note that the monochromatic line should be extremely narrow: its width is expected to be about a few eV which experimentally is very challenging if one compares

it with the present SPI sensitivity that is about 10^{-3} at MeV energies. At lower energies, there are nevertheless instruments, e.g. X-ray CCD, bolometers, Bragg spectrometers which are able to resolve eV widths. A significant improvement on the resolution ΔE_0 at higher energies would probably be necessary in order to reach a large enough significance and ensure detection. Indeed, an effective surface of $1m^2$ might be hard to attain in space.

Next generation instruments such as AGILE/(super AGILE) or GLAST, which in principle could be more promising, will probably be limited by the energy range that they are able to investigate. Future instruments might nevertheless be able to see this line if their energy resolution and sensitivity are improved by a large factor with respect to SPI present characteristics.

Maybe a better chance to detect this line is to do observations at a high latitude and a longitude slightly off the galactic centre. In this case, indeed, the background should drop significantly (the density of dark clouds has been measured recently [15]) but the line flux may decrease by a smaller factor.

Acknowledgement

1. C. Boehm, J. Orloff, and P. Salati. *Phys. Lett.*, B641:247–253, 2006.
2. P. Jean et al. *Astron. Astrophys.*, 407:L55, 2003.
3. J. Knodlseder et al. *Astron. Astrophys.*, 441:513–532, 2005.
4. Y. Ascasibar, P. Jean, C. Boehm, and J. Knoedlseder. *Mon. Not. Roy. Astron. Soc.*, 368:1695–1705, 2006.
5. C. Boehm and P. Fayet. *Nucl. Phys.*, B683:219–263, 2004.
6. C. Boehm, T. A. Ensslin, and J. Silk. *J. Phys.*, G30:279–286, 2004.
7. C. Boehm and P. Uwer. 0600.
8. Pasquale Dario Serpico and Georg G. Raffelt. *Phys. Rev.*, D70:043526, 2004.
9. P. Fayet, D. Hooper, and G. Sigl. *Phys. Rev. Lett.*, 96:211302, 2006.
10. S. Kasuya and M. Kawasaki. *Phys. Rev.*, D73:063007, 2006.
11. Andrew W. Strong et al. *Astron. Astrophys.*, 444:495, 2005.
12. Georg Weidenspointner et al. 0100.
13. J. P. Roques et al. 1000.
14. B. J. Teegarden and K. Watanabe. *Astrophys. J.*, 646:965–981, 2006.
15. J.-M. Casandjian I.A. Grenier and R. Terrier. *Science*, 307:1292, 2005.