



HAL
open science

Could a Gamma Line Betray the Mass of Light Dark Matter?

Jean Orloff

► **To cite this version:**

Jean Orloff. Could a Gamma Line Betray the Mass of Light Dark Matter?. Electroweak Interactions and Unified Theories, Mar 2007, La Thuile, Italy. pp.263. hal-00164293

HAL Id: hal-00164293

<https://hal.science/hal-00164293>

Submitted on 19 Jul 2007

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

J. Orloff

LPC, Université Blaise Pascal, 63177 Aubière Cedex, France

We¹ 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 amount 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/SPI² of the characteristics of the 511 keV line emitted in our galaxy is intriguing. Indeed, it implies without 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 attempted⁴, 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: $m_{dm} < 100$ MeV. More constraining upper bounds can be obtained by a careful study of final state radiation processes ($dm dm^* \rightarrow e^+ e^- \gamma$) and positron annihilation in flight, both producing continuous gamma ray spectra which increase with m_{dm} . From the first, $m_{dm} < 35$ MeV is obtained⁷, 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 nucleosynthesis⁸, and higher than 10 MeV if there is a significant coupling to neutrinos which can alter supernova explosions⁹, but such is not necessarily the case.

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 $m_{dm} < m_\tau$), 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:

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

with $\beta_e = \sqrt{1 - m_e^2/m_{dm}^2}$, which indeed for $b = 0$ reduces to the expression used⁴ for large m_{F_e} . After careful comparison with SPI data, Ascasibar et al.⁴ found

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

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

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

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 matter mass for $m_{dm} > 1$ 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}):

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

Notice that the simple guess¹⁰ applied to the case of decaying DM

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

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

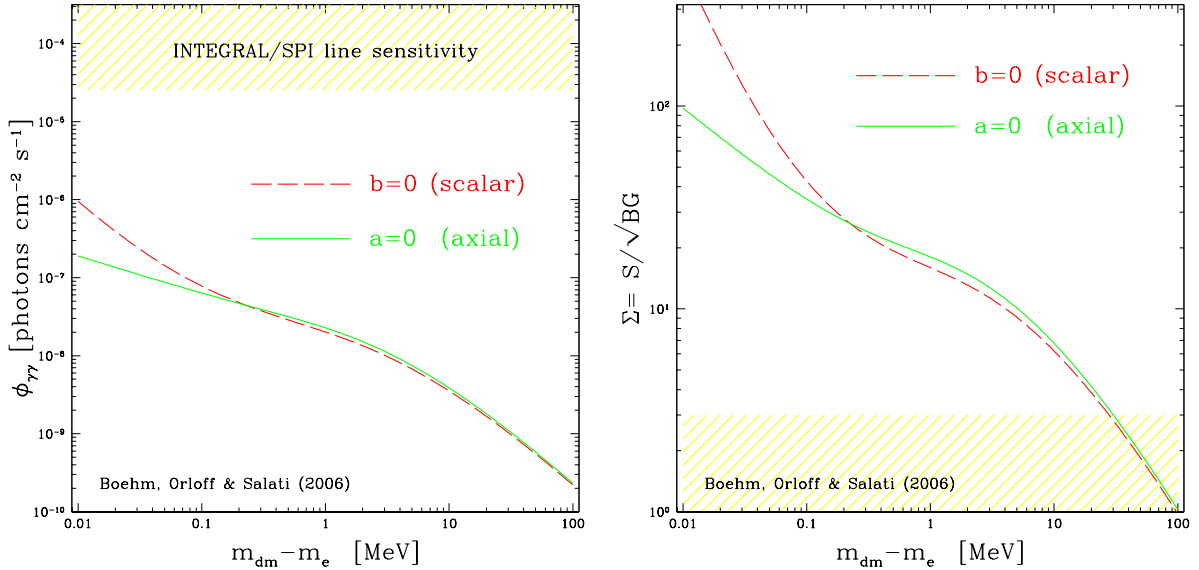


Figure 1: Left: flux of the monochromatic $E_\gamma = m_{dm}$ line from a 8 degree cone around the galactic center. Right: significance of the monochromatic $E_\gamma = m_{dm}$ line above the continuum background for one year of observation with an ideal detector of 1 m² and a 10⁻³ energy resolution.

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 $\sim 10\%$ precision¹¹ 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 $350^\circ < l < 10^\circ$ in longitude and $|b| < 10^\circ$ 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 found⁴ to be

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

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 :

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

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 taken⁴ equal to 93%. This is in perfect

agreement with the positronium fraction later derived¹², 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 $\theta_{\gamma\gamma} = 8^\circ$ 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 sensitivity¹³ (which is about 2.5×10^{-5} ph cm⁻² s⁻¹ after 10⁶ seconds). An unrealistic exposure of 30,000 years would thus be required in order to detect the $E = m_{dm}$ 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 Novae¹⁴, 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 estimated¹¹

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

inside the central region that extends over $350^\circ < l < 10^\circ$ in longitude and $|b| < 10^\circ$ 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

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

with S_0 the surface of the detector, T_0 the exposure time, I_{BG} the above-mentioned 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 m², 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 1m² 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 recently¹⁵) but the line flux may decrease by a smaller factor.

Acknowledgement

It is a pleasure to thank the organisers for the most enjoyable and stimulating conference.

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. Teggarden and K. Watanabe. *Astrophys. J.*, 646:965–981, 2006.
15. J.-M. Casandjian I.A. Grenier and R. Terrier. *Science*, 307:1292, 2005.