Morphology of the dark matter contribution to the 511 keV gamma ray sky: constraints from INTEGRAL/SPI observations

Aaron C. Vincent

McGill University (soon Valencia node)

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with **Jim Cline** (McGill)
and **Pierrick Martin** (IPA Grenoble)

The 511 keV signal: our motivation

- A γ-ray signal, strongly peaked around $E_\gamma = 511$ keV, was first observed in balloon-borne experiments by *Johnson et al. (1972)*. This signal is composed of a small **disk** component and a much larger **bulge** component, extending 10-20 degrees away from the galactic plane.

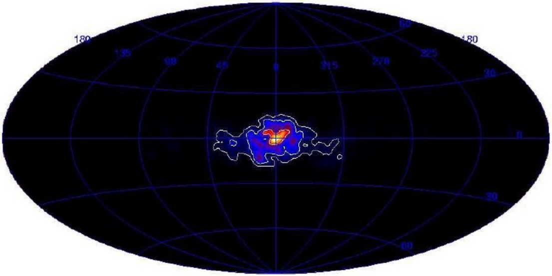


Figure: *Knödlseder et al, 2005 - INTEGRAL/SPI data*

Outline

1. Signatures of positron annihilation
2. Known positron sources
3. Dark Matter to the Rescue
4. Results

1. Signatures of positron annihilation

The signatures of positron annihilation

in-flight annihilation produces two back-to-back 511 keV photons

Positronium formation can occur in two states:

- Singlet state **para-positronium** p-Ps (spins anti-aligned), which decays into two 511 keV photons
- Triplet state **ortho-positronium** o-Ps (spins aligned), which must decay into three photons in order to conserve angular momentum. o-Ps gives a **continuum** spectrum

$$I_{511\mathrm{keV}} \propto 2\left(1 - \frac{3}{4} f_{Ps}\right),$$

where $f_{Ps} = 0.97$ (*Jean et al 2006*) is the measured **positronium formation rate** in the ISM.

Spectrum

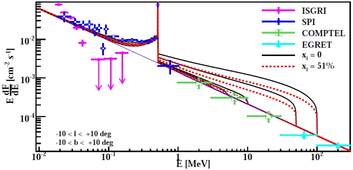


Figure: *Sizun et al. 2006*

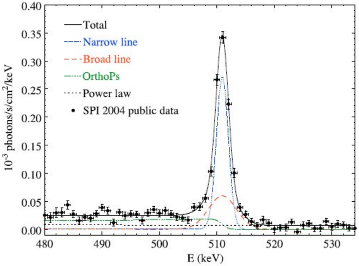


Figure: *Jean et al. 2006*

Gamma ray spectrum around 511 keV tells us:

- the **energy** at which the positrons are injected into the interstellar medium (ISM)
- Key information about the **composition of the ISM** itself (f_{Ps} depends on this, for example)

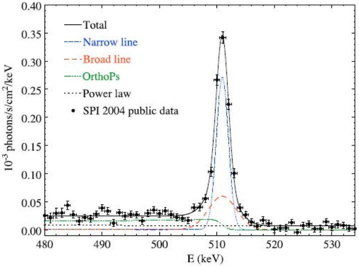
MeV photons: difficult to probe

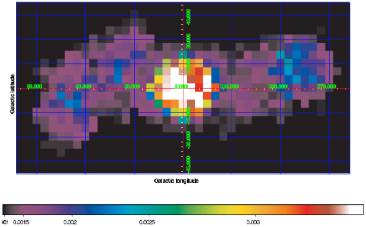
The MeV scale (hard X-ray/ soft γ-ray) is hard to measure

- The atmosphere is opaque at these energies. Must use **balloon**- or **sattelite**- borne detectors.
- Cosmic rays bombarding the instrument produce over 300 gamma-ray lines in the spectrum being probed
- Background is time-dependent
- For these reasons a clear picture did not really begin to form until the late 1990's, with CGRO/OSSE (NASA)

INTEGRAL/SPI and the 511 keV line

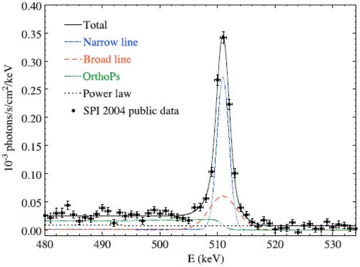
- SPI observes approximately 1.7×10^{-3} 511 keV photons per second
- Implies annihilation of $1.8 \times 10^{43} e^{+} s^{-1}$ in the MW ($3M_{\odot}$ over the lifetime of the MW)
- $B/D > 1.4$
- This observation is not correlated with *any other signal*.





INTEGRAL/SPI: Spectrum

- The positronium continuum and 511 keV line are clearly visible
- The absence of a γ-ray excess above the line implies that the positrons are injected into the ISM at **low energies** (< 3 MeV)
- Line broadening



INTEGRAL/SPI: Morphology

Features

- Mainly: **circular bulge**, extending roughly 10° from the GC
- Since the fourth year of observation, the **disk component** is also clearly present

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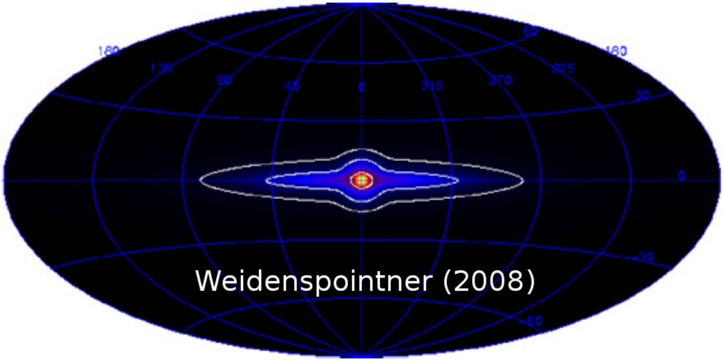
A benchmark empirical fit (Weidenspointner et al. 2008) gives:

- **Two concentric gaussians**, with $FWHM = 3^\circ$ and 11° respectively
- A **thin disk** component, modeled by a young stellar disk
- **8 degrees of freedom** in the fitting procedure
- With the 8-year data maximum log likelihood of $MLR = 2693$. We'll return to this.

Weidenspointner *et al.* fit.



2. Known Positron Sources

Radioactivity

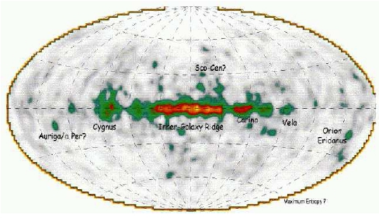
Radioactive β^+ decay produces positrons at the MeV scale

- **Massive stars** produce ^{26}Al ($\tau \sim 500ky$) and ^{44}Ti ($\tau \sim 60y$)
- **Hypernovae** are expected to produce ^{56}Ni. The amount produced is unknown.
- **SNIa** also produce ^{56}Ni. Not clear how many of the decay products wind up escaping.
- **Novae** produce radioactive N and F, but their lifetimes are too short to escape. ^{22}Na does escape, but total production too small

All of these signals are expected to have morphologies correlated with the distribution of stars in the galaxy, however. Present or not, **they do not explain the bulge signal**.

Radioactivity: Aluminium 26

^{26}Al, which is produced in massive stars, is important.



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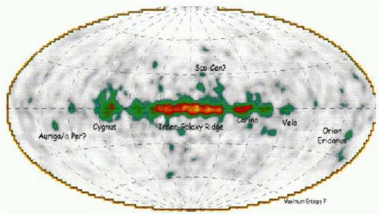


- It is long-lived ($\tau = 7.4 \times 10^5$ years), and produces a gamma-ray line at **1809 keV** during same decay.
- 1809 keV line measured by INTEGRAL/SPI (Diehl et al 2006), giving us a map of the ^{26}Al distribution in the galaxy.
- ^{44}Ti contributions are expected to be of similar magnitude and distribution.

High energy sources

Positrons may be produced by $p - p$ and $\gamma - \gamma$ processes:

- **Cosmic ray collisions** in the ISM;
- **X-Ray Binaries** (XRBs) and **microquasars** ;
- In the high temperature and high B field regions of **pulsars**;
- the **supermassive black hole** at the centre of the Milky Way;

However, these produce **high-energy** positrons (> 30 MeV).

Summary

Source	Intensity	Spectrum	Morphology
Massive stars (^{26}Al)	✓	✓	×
SNe (^{44}Ti)	✓	✓	×
SNIa (^{56}Ni)	× (?)	✓	×
Novae	×	✓	×
Hypernovae/GRBs (^{56}Ni)	?	✓	×
Cosmic ray $p - p$	?	×	×
Pulsars $\gamma - \gamma$	✓	×	×
Central black hole	?	×	✓(?)

(Table adapted from Prantzos et al. 2010)

We need a source, or combination of source with a ✓in all three columns.

3. Dark Matter to the Rescue

Galactic distribution of dark matter

This density distribution can be parametrized with a spherically symmetric **Einasto profile**:

$$\rho_{DM}(r) = \rho_s \exp\left(-\left[\frac{2}{\alpha}\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right);$$

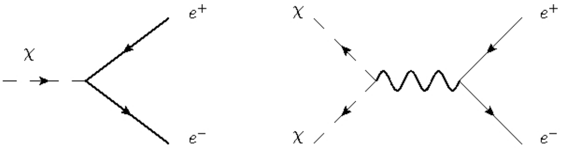
Parameters best fit by the *Via Lactea II* simulation:

$$\alpha = 0.17,$$
$$r_s = 26.\ \mathrm{kpc}$$

The normalization ρ_s can be inferred from indirect measurements of the local dark matter density (e.g. Salucci et al.):

$$\rho_{\odot} \simeq 0.4\ \mathrm{GeVcm}^{-3}$$

Getting positrons from dark matter



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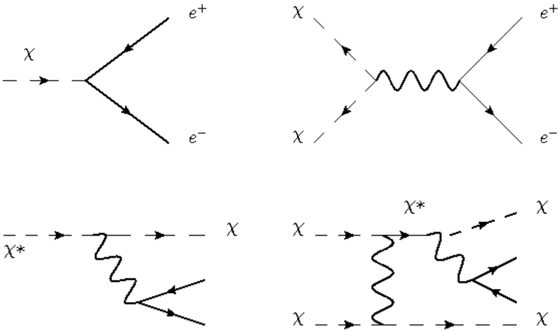


These give the following fluxes:

decay

$$d\Phi \propto \int_{l.o.s.} \frac{\rho(\ell)}{m_\chi \tau} d\ell$$

scattering/annihilation

$$d\Phi \propto \int_{l.o.s.} \frac{\langle \sigma v \rangle \rho^2(\ell)}{m_\chi^2} d\ell$$

Previous results

- Many studies have shown that the rough morphology, intensity and spectrum can be obtained from DM
- Recently, Morris and Weiner (2011) found that the model of Finkbeiner and Weiner can produce the correct intensity
- Ascasibar (2006) studied DM morphology constraints from the one-year INTEGRAL/SPI data
- More recent studies (e.g. Abidin, 2010) compared predictions to empirical fits to the data, rather than to the data itself.
- **Our goal is to use the 8-year data to statistically test the Dark Matter hypothesis**

Hypotheses

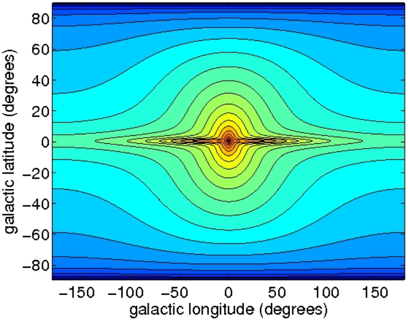
- **Bulge** component of the 511 keV signal is from **DM decay, scattering or annihilation**
- The DM has an **Einasto** (or NFW) profile:

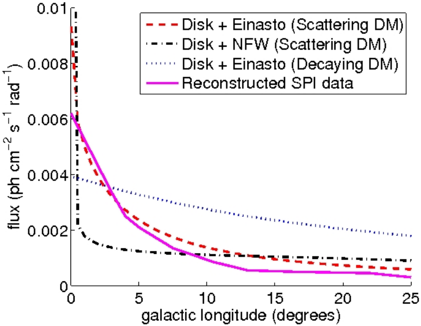
$$\rho_{DM}(r) = \rho_s \exp\left(-\left[\frac{2}{\alpha}\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right);$$

- **Disk** component modeled by **young stellar disk** distribution, with parameters **fixed** by *Diehl et al. 2006* study of the ^{26}Al 1809 keV gamma-ray distribution.
- **No propagation** of e^+ assumed from creation to annihilation.

We **scan** the space of $(\alpha; r_s)$ to determine whether the *Via Lactea II* parameters (0.17; 26 kpc) are a good hypothesis.

The profiles





Results: decaying DM

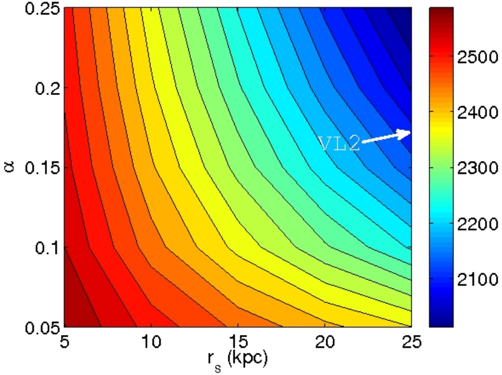


Figure: *Einasto profile + disk*

A very cuspy dark matter profile is needed to correctly describe the morphology of the 511 keV line. *Via Lactea II* results disfavored. MLR = 2194 (c.f. 2693)

Results: scattering DM

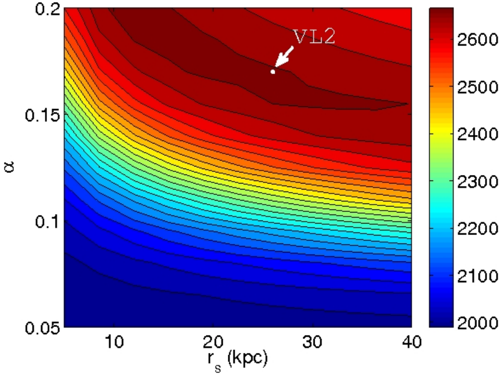


Figure: *Einasto profile + disk*

Best fit point in α-r_s space is statistically identical to the *Via Lactea II* parameters. MLR = 2668 (c.f. 2693); $\chi_p^2 = 1.007$ (c.f. 1.007).

This means that it makes sense to assume that the *Via Lactea II* parameters are the true values.

We are left with only **two degrees of freedom** in our fitting procedure:

- The normalization of the DM component. This specifies $\langle \sigma v \rangle / m_\chi^2$.
- The normalization of the disk component. This tells us the contribution of ^{26}Al and other elements.

Summary of results

Channel	Profile	MLR	Disk flux	DM flux	DM lifetime or cross-section
decay	Einasto only	2139	—	174.5 $\pm$ 3.5	$\tau_\chi = 1.1 \times 10^{26}(\mathrm{GeV}/m_\chi)$
	Einasto + Disk	2194	10.60 $\pm$ 1.42	148.6 $\pm$ 5.1	$\tau_\chi = 1.3 \times 10^{26}(\mathrm{GeV}/m_\chi)$
scattering	Einasto only	2611	—	24.02 $\pm$ 0.47	$\langle\sigma v\rangle_\chi = 5.8 \times 10^{-25}(m_\chi/\mathrm{GeV})^2$
	Einasto + Disk	**2668**	**9.98 $\pm$ 1.32**	**21.16 $\pm$ 0.59**	$\boldsymbol{\langle\sigma v\rangle_\chi = 5.1 \times 10^{-25}(m_\chi/\mathrm{GeV})^2}$
	Einasto (oblate) + Disk	**2669**	**8.74 $\pm$ 1.31**	**21.06 $\pm$ 0.61**	$\boldsymbol{\langle\sigma v\rangle_\chi = 4.9 \times 10^{-25}(m_\chi/\mathrm{GeV})^2}$
	NFW only	1602	—	6.72 $\pm$ 0.17	$\langle\sigma v\rangle_\chi = 8.2 \times 10^{-26}(m_\chi/\mathrm{GeV})^2$
	NFW + Disk	2155	26.45 $\pm$ 1.25	4.90 $\pm$ 0.18	$\langle\sigma v\rangle_\chi = 6.1 \times 10^{-26}(m_\chi/\mathrm{GeV})^2$

Flux units: $10^{-4}\mathrm{ph cm^{-2} s^{-1}}$

- 72% of the disk flux can be attributed to ^{26}Al (consistent with other studies e.g. Knodlseder 2008)
- 10-1000 GeV scattering (XDM) WIMP: $\langle\sigma v\rangle \sim \left[10^{-23}, 10^{-19}\right]$ cm^{3}s^{-1}.
- MeV annihilating WIMP: $\langle\sigma v\rangle \sim 10^{-31}$ cm^{3}s^{-1} : not so great
- adding a degree of **oblateness** does not significantly alter the fits
- Neither does varying the **galactocentric distance** from 8.5 to 8.2 kpc.

Significance of our results

- INTEGRAL anomaly: a $3000 L_\odot$ signal at 511 keV, with no known source at present.
- We have shown, in a quantitative manner, that given its predicted shape, **scattering or annihilating dark matter** can explain the **511 keV signal** just as well as previous phenomenological fits
- we require **six fewer degrees of freedom** (2 vs 8) in our fitting procedure
- we provide a **physical mechanism** for e^+ production

This work shows that from a phenomenological standpoint, the DM hypothesis seems more promising than conventional astrophysical explanations.

Our estimator: the MLR

We use the **maximum likelihood ratio** (MLR) as an estimator for the likelihood of our model, given the INTEGRAL/SPI data. The likelihood L of a model assuming a Poisson distribution of events in each of the N data bins is:

$$L = \prod_{i=1}^{N} \frac{\lambda_i^{n_i} e^{-\lambda_i}}{n_i!}, \quad \text{where} \quad \lambda_i = \sum_k \alpha_k s_i^k + b_i(\beta)$$

- n_i observed counts per bin
- λ_i predicted counts per bin
- s_i^k **source**, convoluted with the instrument response matrix
- b_i background modeled
- α_k, β normalizations: these will be optimized for each set of sources

$$MLR \equiv -2(\ln L_0 - \ln L_1)$$

MLR, continued

$$MLR \equiv -2(\ln L_0 - \ln L_1)$$

- MLR is useful for comparing **nested models**: If parameters $\alpha_{1 \ldots N}$ are fixed to their true value in model **0**, and allowed to vary in model **1**, then MLR is distributed like $\chi^2(MLR, N)$.
- Interpretation: how much better is the **model vs. background only**.
- It can also be used as a **rough comparison with previous fits to different models**.
- A second estimator is the pointing-based χ^2; useful as a secondary statistic only, however.
- benchmark figures from Weidenspointner et al. analysis:

$$MLR = 2693$$

$$\chi^2_p = 1.007$$