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

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The 511 keV signal: our motivation

- The $E_\gamma = 511$ keV gamma-ray line observed by INTEGRAL/SPI. This signal is composed of a small **disk** component and a much larger **bulge** component, extending $\sim$10 degrees away from the galactic plane. As we heard on Tuesday (talk by N. Prantzos), such B/D > 1.4 is not seen in any other region of the EM spectrum.

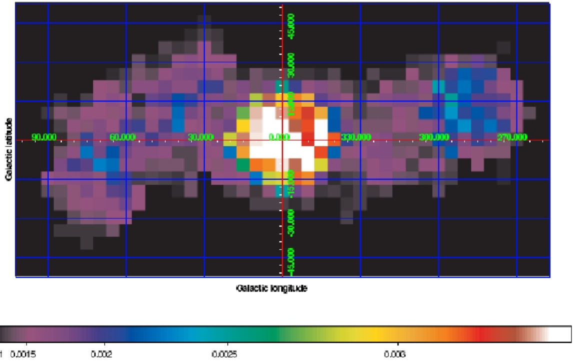


Figure: *Bouchet et al. 2010 - INTEGRAL/SPI data*

Outline

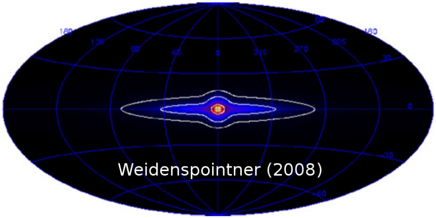
1. Positrons in the Milky Way

INTEGRAL/SPI — current observations

After 8 years of observation, we have the following picture of the 511 keV sky:

- SPI observes approximately 1.7×10^{-3} 511 keV photons per second — about $10^3 L_\odot$
- this is consistent with the **annihilation** of $1.5 \times 10^{43} e^+ s^{-1}$ in the bulge, and $0.3 \times 10^{43} e^+ s^{-1}$ in the disk. (about 3 $m_\odot$ over the lifetime of the Galaxy)
- if a **steady state** is assumed, that means the **creation** of $\sim 1.8 \times 10^{43}$ positrons per second in the Galaxy.
- 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** ($\lesssim 3 MeV$)

INTEGRAL/SPI — current observations: Morphology



- Mainly: **circular bulge**, extending roughly 10° from the GC
- Since the fourth year of observation, the **disk component** is also clearly present
- A benchmark empirical fit to this signal was done by Weidenspointner et al. (2008):
  - **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.

Known sources of positrons in the MW

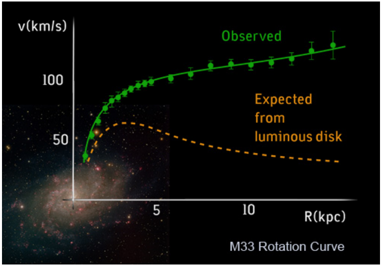
Source	Intensity	Spectrum	Morphology
Massive stars (^{26}Al)	✓	✓	×
SNe (^{44}Ti)	✓	✓	×
SNIa (^{56}Ni)	× (?)	✓	×
Novae	×	✓	×
Hypernovae/GRBs (^{56}Ni)	?	✓	×
Cosmic ray $p - p$	?	×	×
Pulsars $\gamma - \gamma$	✓	×	×
Central black hole	?	×	✓(?)

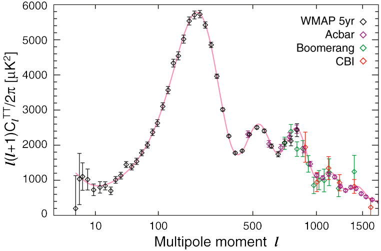
(Table adapted from Prantzos et al. 2010)

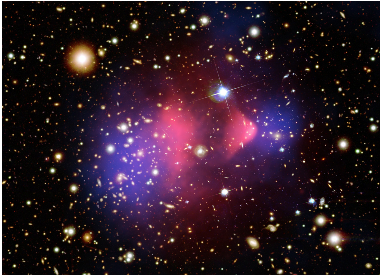
We need a source, or combination of source with a ✓in all three columns.

3. Dark Matter to the Rescue

Obligatory dark matter slide







- 85 % of matter
- Explains observations on many scales
- non-gravitational sector unknown

Images: Andromeda:Harvard-Smithsonian center for Astrophysics; Bullet cluster: NASA

What's known about the particle nature of dark matter

- It is **cold**: must be non-relativistic enough to allow structure to collapse at early enough times;
- It is **dark** enough not to radiate away energy efficiently
- It must behave like **matter** to have the correct equation of state, and to give the right dynamics on galactic and cluster scales.

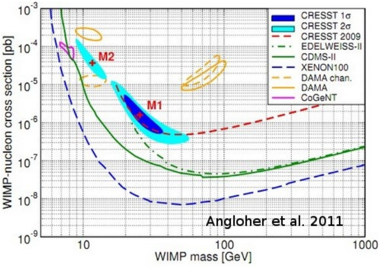
This leads to the Cold Dark Matter (**CDM**) paradigm. Within this is the WIMP scenario (or **WIMP miracle**). If dark matter was produced thermally in the early universe, the **self-annihilation cross-section** required to produce the correct abundance of DM today must be:

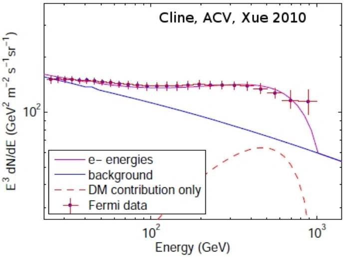
$$\langle \sigma v \rangle_{ann} = 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}, \tag{1}$$

which is pretty close to a typical weak-scale cross-section. It would be very nice for a DM model to conserve this WIMPiness, then.

What about the mass?

Not much to go on...





$\sim$ few **GeV** if you would like to believe recent claimed direct detection results (**DAMA/LIBRA, CoGeNT, ...**)

...or a **TeV** if you're wanting to explain other cosmic ray anomalies, such as the high-energy positron bump seen by **Fermi** and **PAMELA**.

Galactic distribution of dark matter

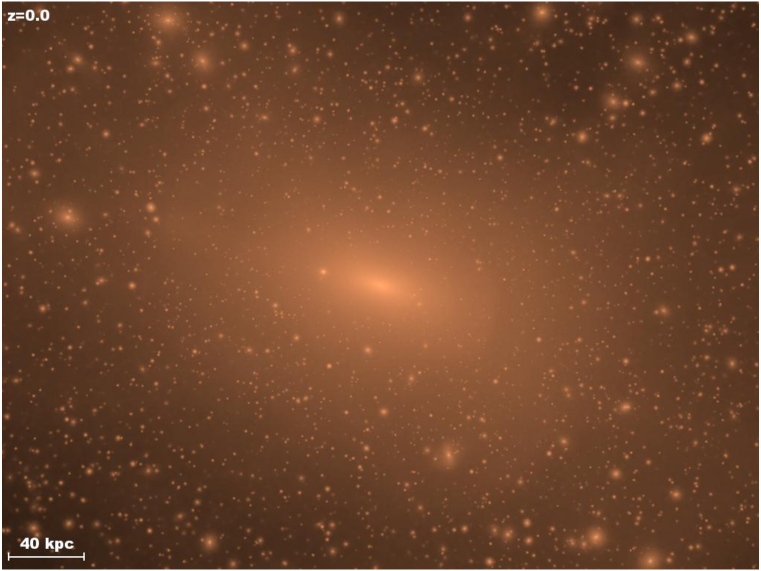


Figure: *Via Lactea II*

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:

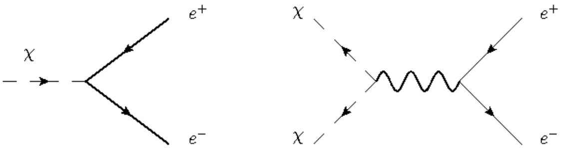
$$\alpha = 0.17,$$
$$r_s = 26.\ \mathrm{kpc}$$

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

$$\rho_{Sun} \simeq 0.4\ \mathrm{GeV cm}^{-3}$$

Getting positrons from dark matter

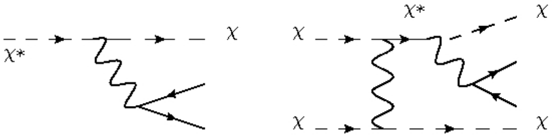
Most obvious possibilities: Decay or annihilation of a $\sim$ MeV WIMP:



...but there's another, more attractive option: **multi-state DM**(Finkbeiner and Weiner 2007, then many others including Chen et al 2009, Cline et al. 2010). Also called Excited Dark Matter (**XDM**)

- e.g. 2 states: χ and $\chi*$
- $\Delta m_\chi \simeq 2m_e$
- **DM mass becomes a free parameter** again.

Morphology



1) Long-lived metastable state looks like a **decay**:

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

2) Short-lived metastable state, produced by **scattering**, looks like an 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, with parameters from **Via Lactea II** simulation:

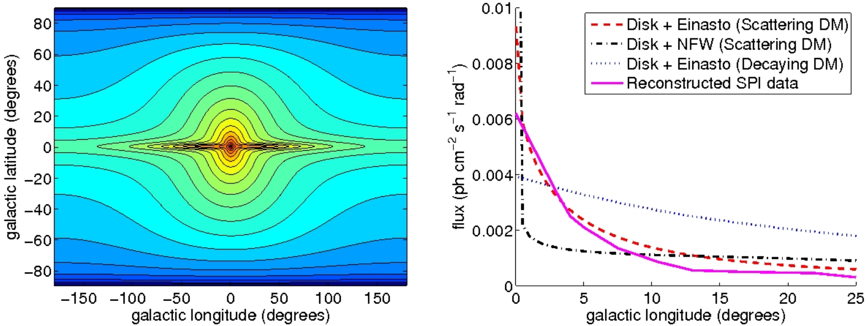
$$\rho_{DM}(r) = \rho_s \exp\left(-\left[\frac{2}{\alpha}\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right); \alpha = 0.17,\ r_s = 26\ \mathrm{kpc} \quad (2)$$

- **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:

$$\dot{n}_{YD}(x, y, z) = \dot{n}_0 \left[e^{-\left(\frac{a}{R_0}\right)^2} - e^{-\left(\frac{a}{R_i}\right)^2} \right], \quad (3)$$

- we compare to 8 years of INTEGRAL/SPI observation, looking at a bin of 5 keV width, centered at 511 keV,
- **No propagation** of e^+ assumed from creation to annihilation.

The profiles



Estimator: Maximum log-Likelihood Ratio (MLR)

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

- 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;
- benchmark figures from Weidenspointner et al. analysis:

$$MLR = 2693$$
$$\chi^2_p = 1.007$$

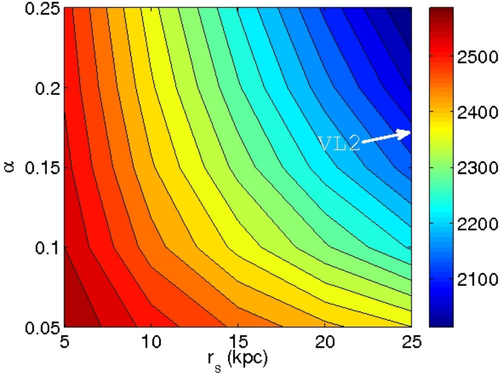


Figure: *Einasto profile + disk*

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

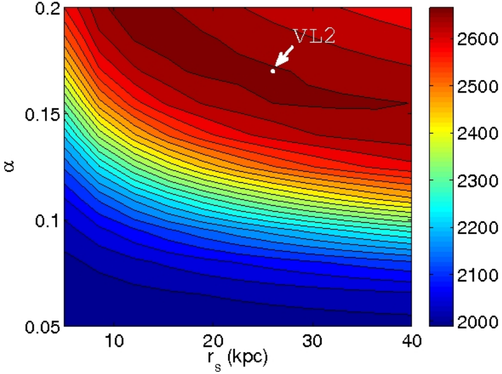


Figure: *Einasto profile + disk*

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. This leaves us 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 how much ^{26}Al and other elements are present in the model.

Summary of results (1)

Channel	Profile	MLR	Disk flux	DM flux	DM lifetime or cross-section
decay	Einasto only	2139	—	174.5 ± 3.5	$\tau_\chi = 1.1 \times 10^{26} (\mathrm{GeV}/m_\chi)$
	Einasto + Disk	2194	10.60 ± 1.42	148.6 ± 5.1	$\tau_\chi = 1.3 \times 10^{26} (\mathrm{GeV}/m_\chi)$
scattering	Einasto only	2611	—	24.02 ± 0.47	$\langle \sigma v \rangle_\chi = 5.8 \times 10^{-25} (m_\chi/\mathrm{GeV})^2$
	Einasto + Disk	**2668**	**9.98 ± 1.32**	**21.16 ± 0.59**	$\boldsymbol{\langle \sigma v \rangle_\chi = 5.1 \times 10^{-25} (m_\chi/\mathrm{GeV})^2}$
	Einasto (oblate) + Disk	**2669**	**8.74 ± 1.31**	**21.06 ± 0.61**	$\boldsymbol{\langle \sigma v \rangle_\chi = 4.9 \times 10^{-25} (m_\chi/\mathrm{GeV})^2}$
	NFW only	1602	—	6.72 ± 0.17	$\langle \sigma v \rangle_\chi = 8.2 \times 10^{-26} (m_\chi/\mathrm{GeV})^2$
	NFW + Disk	2155	26.45 ± 1.25	4.90 ± 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 great for simple models, but viable if $\exists$ other stronger annihilation channels;
- adding a degree of **oblateness** does not significantly alter the fits;
- Neither does varying the **galactocentric distance** from 8.5 to 8.2 kpc.

Summary of results (2)

Source	Intensity	Spectrum	Morphology
Decaying Dark Matter	✓	✓	×
Scattering Dark Matter (+ ^{26}Al)	✓	✓	✓

Caveat

Some element that could significantly affect our results:

- The **propagation** of e^+ from its sources
- The influence of baryons on halo formation

Conclusions

- 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 ($1.9 < B/D < 2.4$)
- we require **six fewer degrees of freedom** (2 vs 8) in our fitting procedure
- we provide a **physical mechanism** for e^+ production and its morphology
- 72% of the **disk flux** can be attributed to ^{26}**Al**
- consistent with thermal relic density cross-sections