Indirect Searches of Dark Matter

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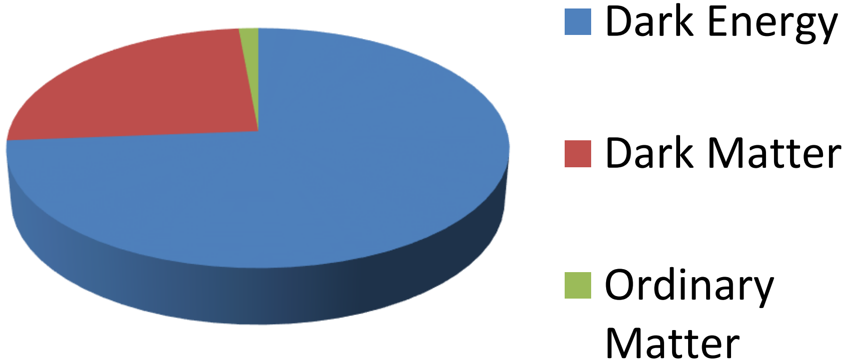
- Introduction
    - Dark Matter detection
- Indirect searches
    - Gamma rays
    - Neutrinos
    - Charged cosmic rays: positrons, antiprotons,...
- Conclusions

Dark Matter

- The success of the Standard Model of cosmology: Λ-Cold Dark Matter (ΛCDM) is based on the existence of non standard particles:

  - Dark Matter

Cosmological Composition



ΛCDM

Dark Matter

- The success of the Standard Model of cosmology: Λ-Cold Dark Matter (ΛCDM) is based on the existence of non standard particles:

  - Dark Matter

    - Any other interaction than gravitational is negligible.
    - Its velocity or pressure is negligible.

Dark Matter

- The success of the Standard Model of cosmology: Λ-Cold Dark Matter (ΛCDM) is based on the existence of non standard particles:

  - Dark Matter

    - Theoretical Physics: The DM is the main interest of many models and theories.
    - Experimental Physics: Many experiments are motivated totally or partially by DM.

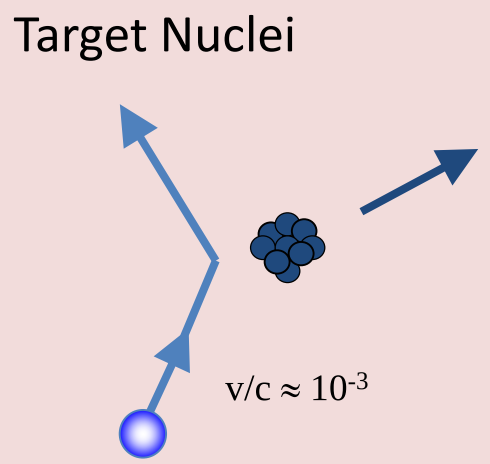
Dark Searches

Direct Detection

Indirect Detection

Dark Searches

Direct Detection

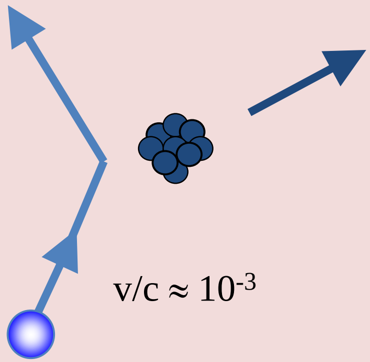


Indirect Detection

Dark Searches

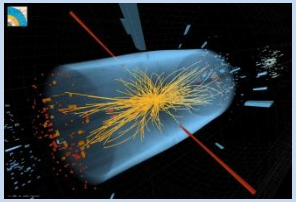
Direct Detection

Target Nuclei



Indirect Detection

DM Production
at Colliders
(Missing Energy)



Dark Searches

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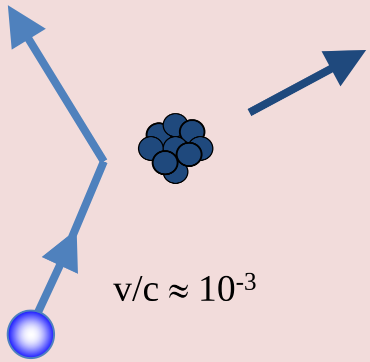
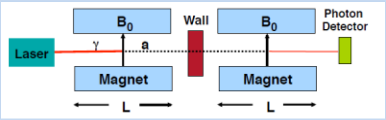


Indirect Detection

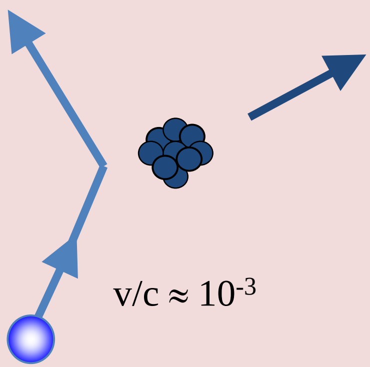
DM Production at “photon regeneration”



Dark Searches

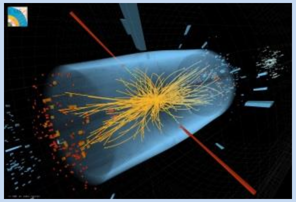
Direct Detection

Target Nuclei



Indirect Detection

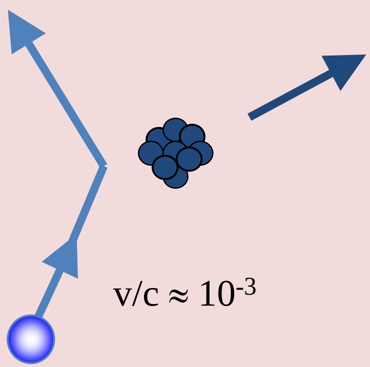
DM Production



Dark Searches

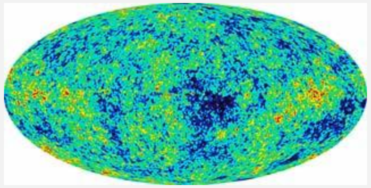
Direct Detection

Target Nuclei

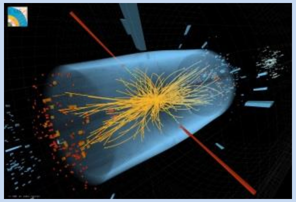


Indirect Detection

Cosmological Measurements



DM Production



Dark Searches

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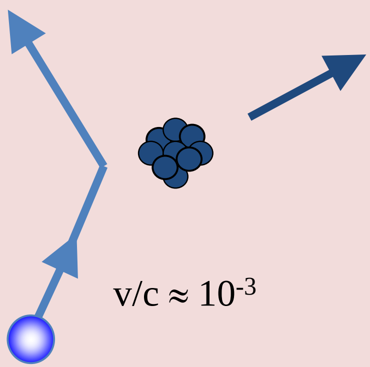
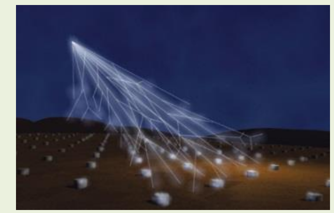
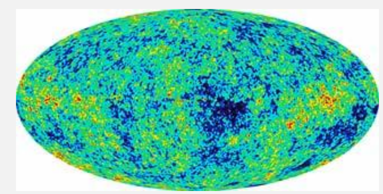


Indirect Detection

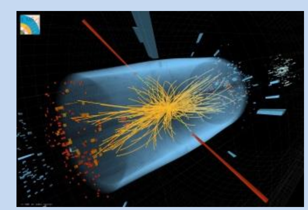
Cosmic Rays



Cosmological Measurements



DM Production



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Direct Detection

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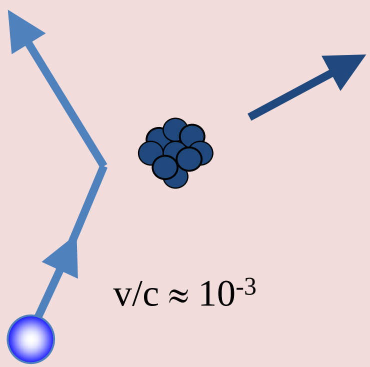
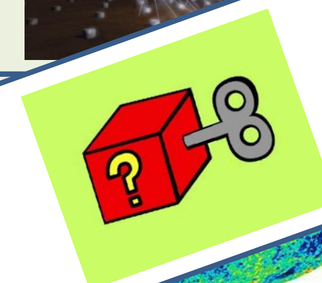


Indirect Detection

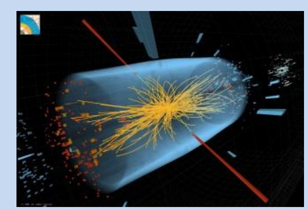
Cosmic Rays

Cos

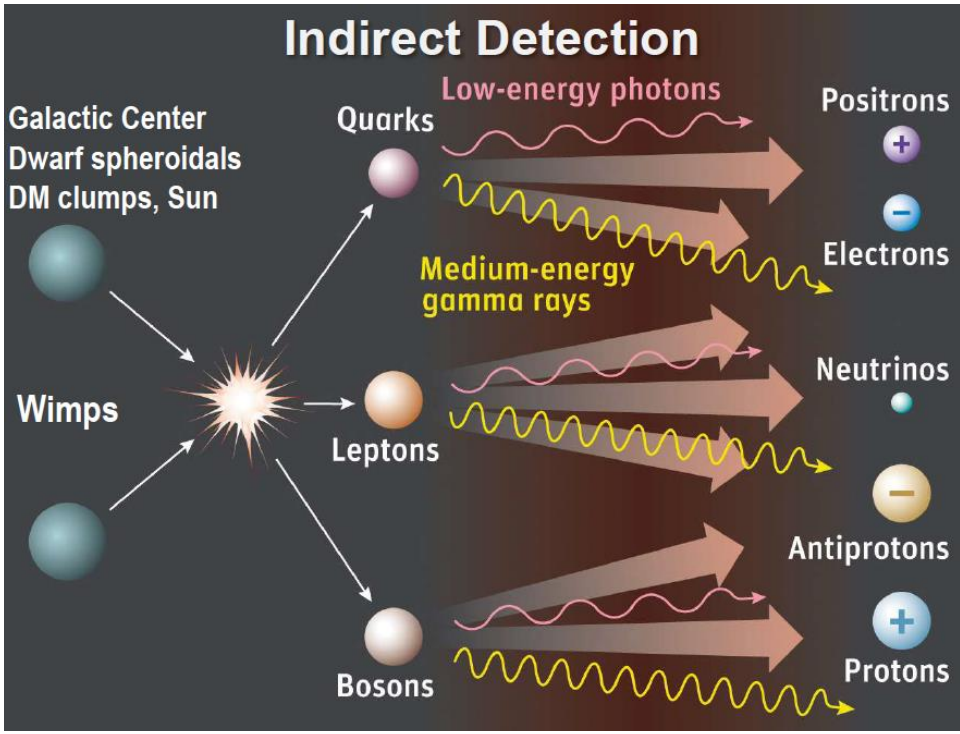
Anything?

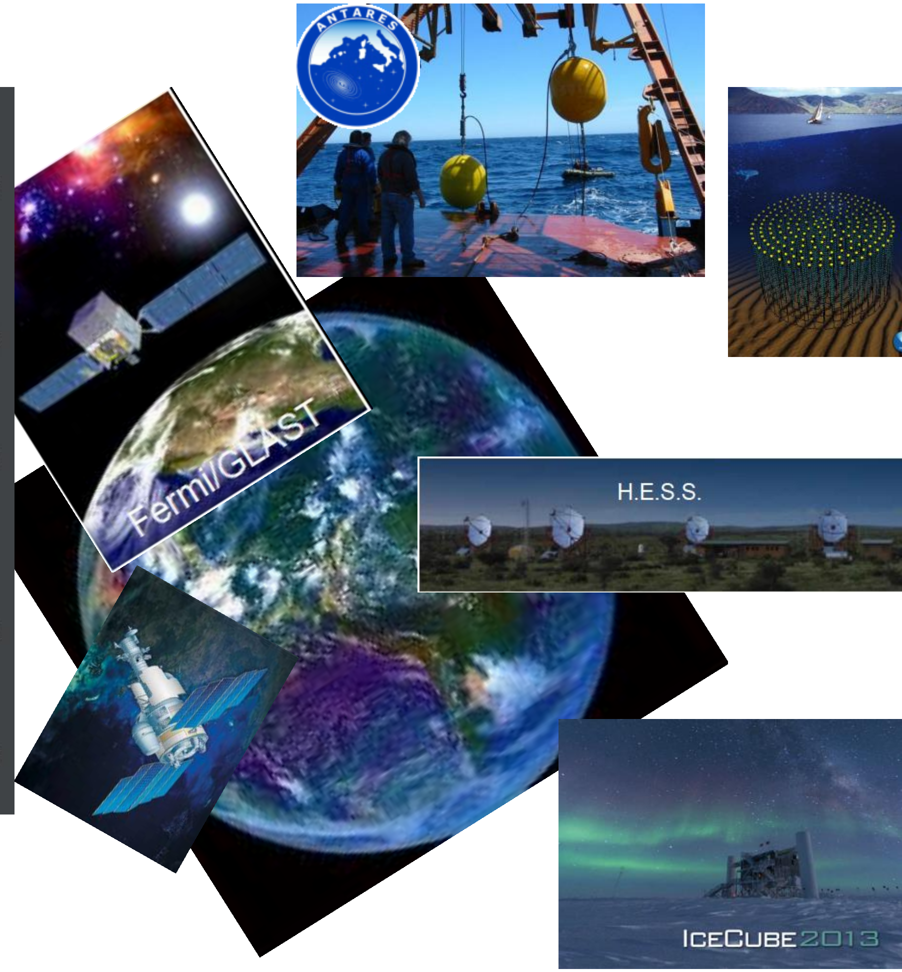


DM Production



Indirect Searches: Cosmic rays





Gamma ray Anomalies

Lines Anomalies:

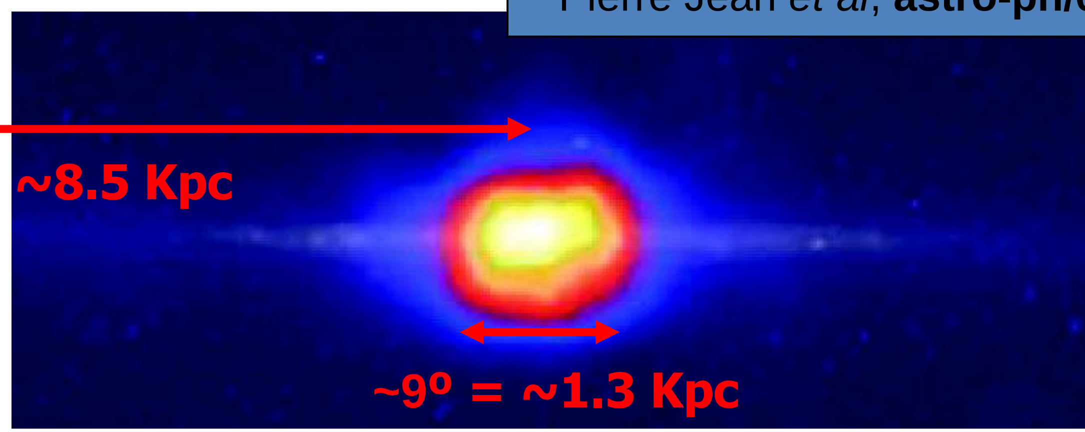
1. 511 keV from Galactic Bulge (HEAO-3,… SPI): 1980-2003

511 keV line from the Galactic Bulge

We have had observations of 511 photons coming form the center of the galaxy for the last 30 years with different instruments.

instrument	year	flux $[10^{-3}\ ph\ cm^{-2}\ s^{-1}]$	centroid $[keV]$	width (FWHM) $[keV]$	references
HEAO-3[a]	1979 – 1980	1.13 ± 0.13	510.92 ± 0.23	$1.6^{+0.9}_{-1.6}$	Mahoney et al. 1994
GRIS[b]	1988 *and* 1992	0.88 ± 0.07		2.5 ± 0.4	Leventhal et al. 1993
HEXAGONE[b]	1989	1.00 ± 0.24	511.33 ± 0.41	$2.90^{+1.10}_{-1.01}$	Smith et al. 1993
TGRS[c]	1995 – 1997	1.07 ± 0.05	510.98 ± 0.10	1.81 ± 0.54	Harris et al. 1998
SPI	2003	$0.99^{+0.47}_{-0.21}$	$511.06^{+0.17}_{-0.19}$	$2.95^{+0.45}_{-0.51}$	

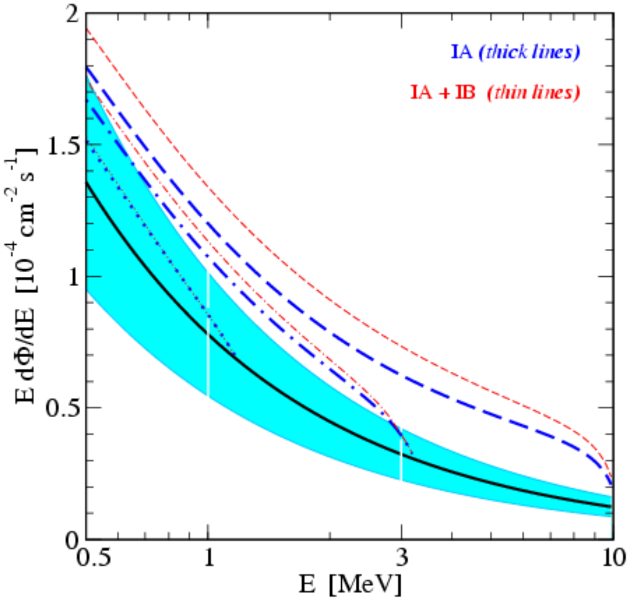
Pierre Jean *et al*, **astro-ph/0309484**



511 keV signal by SPectromètre Integral

511 keV line from the Galactic Bulge

The signal comes from $e^+e^- \to \gamma\gamma$ **, but it is difficult to find a source of 10^43 positrons per second inside the bulge with kinetic energies smaller than ~ 4 MeV and as it is required.**



J.F. Beacom and H. Yuksel , **astro-ph/0512411**

Proposed sources of positrons

1. Supernovas Type II, Ia and Ic
2. Wolf-Rayet Stars
3. Neutron stars, pulsars
4. Cosmic rays
5. Black holes
6. Dark Matter:
    6.1. Annihilating DM
    6.2. Decaying DM

511 keV line from the Galactic Bulge

Several authors have studied this signal with inside different decaying Dark Matter models:

1. Sterile neutrinos
2. Axinos
3. Moduli
4. WIMPs
5. Branons

C. Picciotto and M. Pospelov , hep-ph/0402178
D. Hooper and L.T. Wang, hep-ph/0402220
S. Kasuya and M. Kawasaki, astro-ph/0602296
M. Pospelov and A. Ritz, hep-ph/0703128
J. Cembranos [illegible] ari, 0801.0630[astro-ph]

C. Boehm, D. Hooper, J. Silk, M. Casse, and J. Paul, Phys. Rev. Lett. 92, 101301 (2004), astro-ph/0309686.

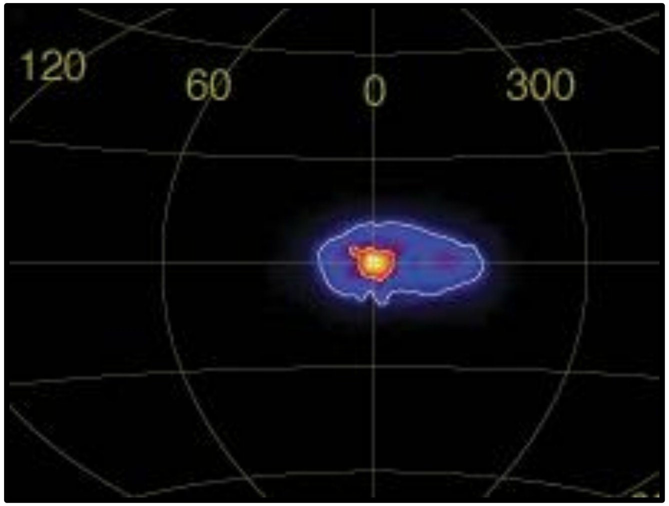
To account for th[illegible] find the condition[illegible] total DM abundance):

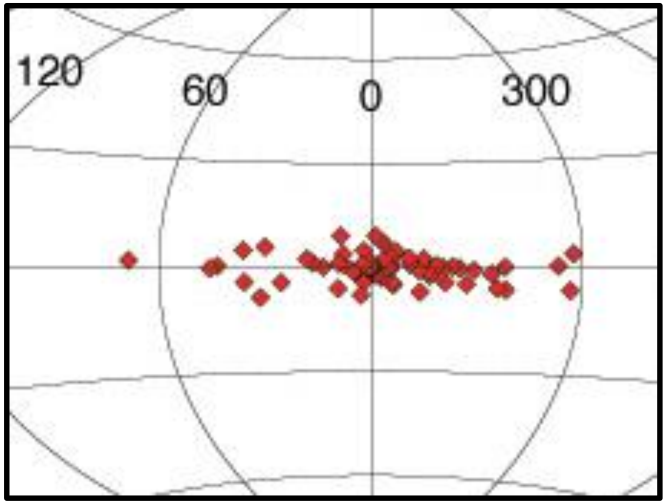
$$M \text{ (or } \Delta M) \sim 1 \text{ MeV}$$

$$\tau \sim 10\text{^}26 \text{ sec } / M \text{ (MeV)}$$

511 keV line from the Galactic Bulge

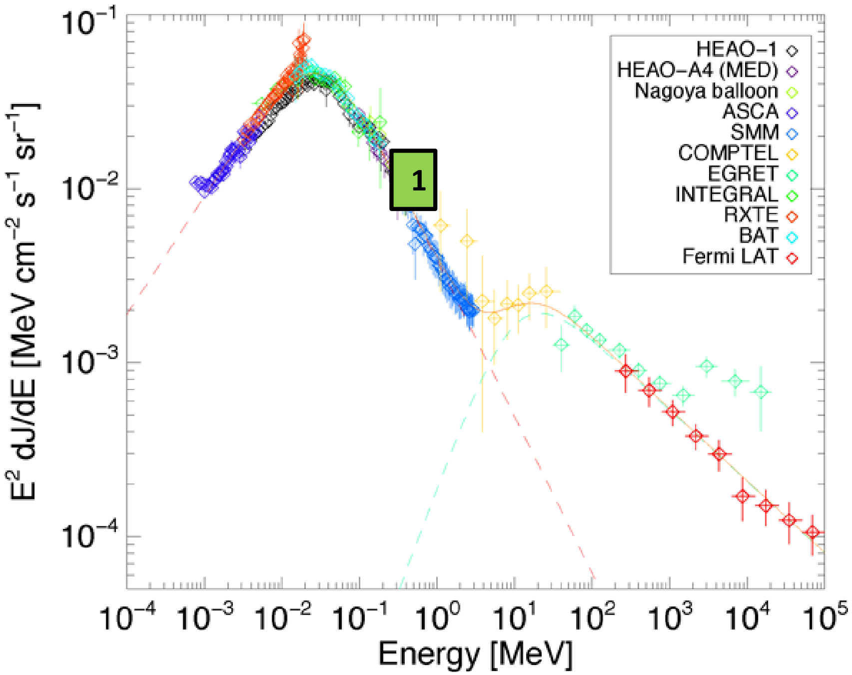
Recent observations by INTEGRAL shows asymmetric morphology of the signal, may be correlated with the distribution of low-mass X-ray binaries





Gamma ray Anomalies and DM

Monochromatic (#) and continuous (#) anomalies related to DM in the literature:



Gamma ray Anomalies

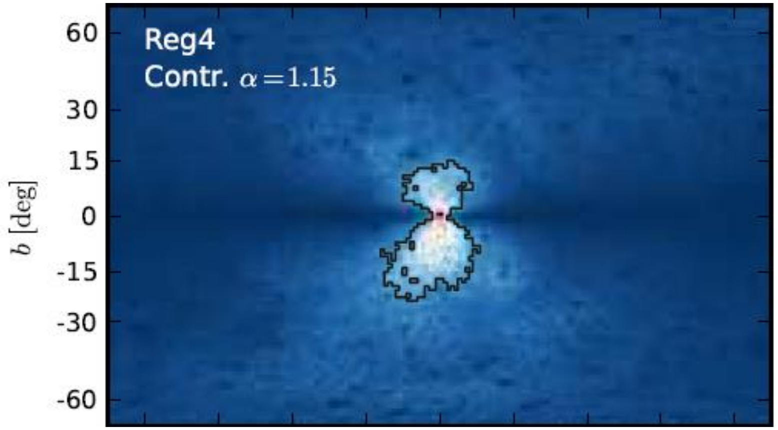
Lines Anomalies:

1. 511 keV from Galactic Bulge (HEAO-3,… SPI): 1980-2003

2. 130 GeV from the Galactic Center (Fermi): 2012-2012

130 GeV line from the Galactic Center

Significant evidence for a line around 130 GeV in the Fermi-LAT data. The morphology was consistent with annihilating dark matter in the Milky Way's halo into γγ, γZ, γh or other exotic states.



C. Weniger, **JCAP 1208 (2012) 007, arXiv:1204.2797**

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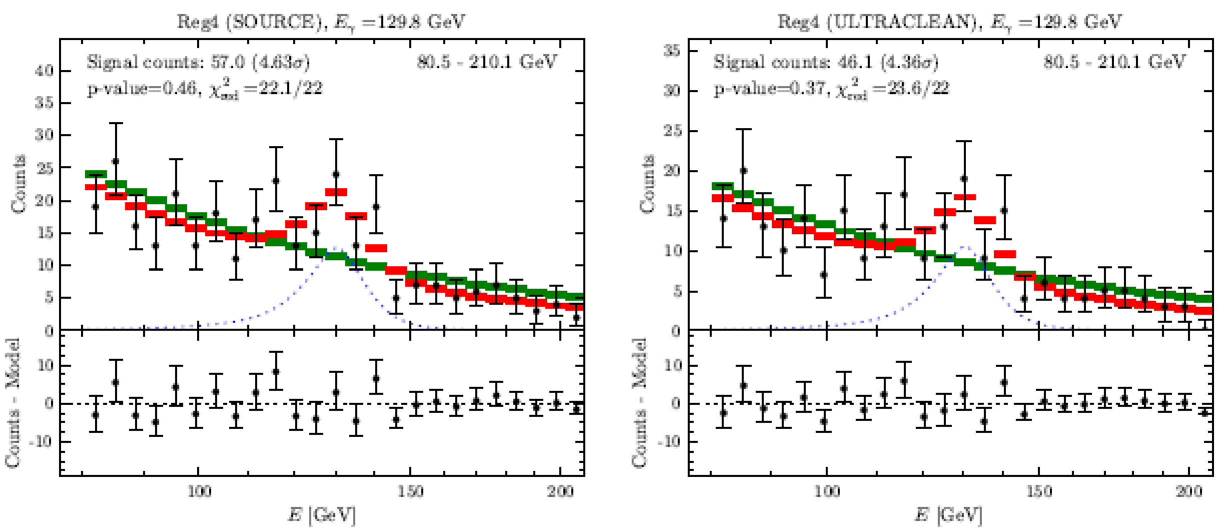

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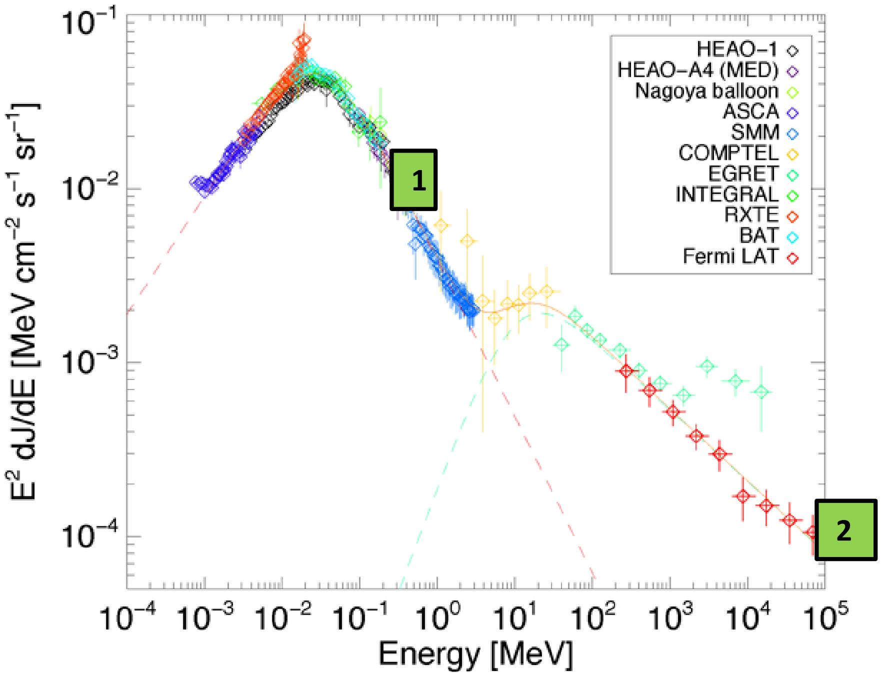


Gamma ray Anomalies

Lines Anomalies:

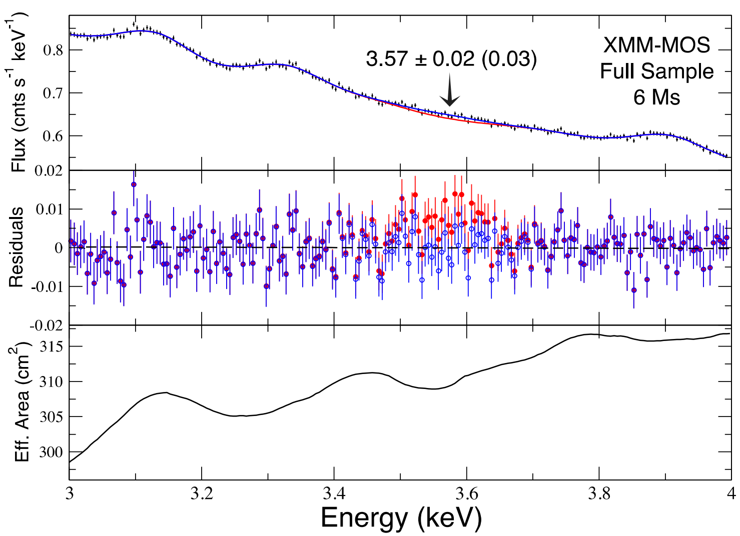
1. 511 keV from Galactic Bulge (HEAO-3,… SPI): 1980-2003

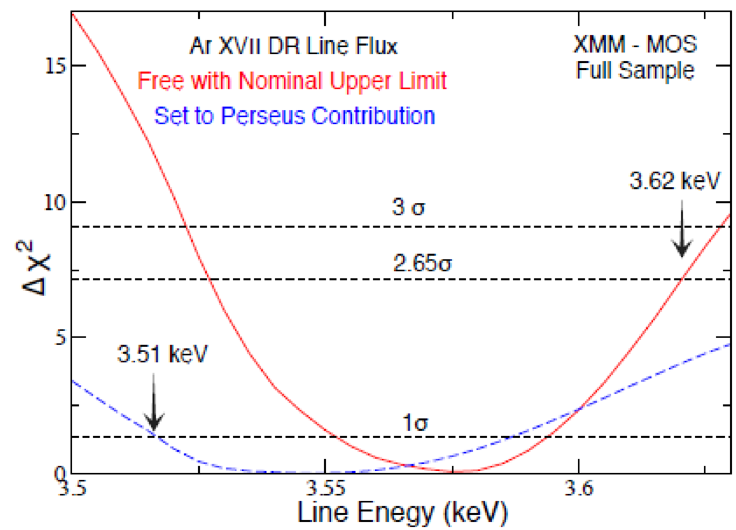
2. 130 GeV from the Galactic Center (Fermi): 2012-2012

3. 3.56 KeV from Galaxy Clusters and Galactic Center (XMM-Newton and Chandra): 2014-2014

3.56 keV line

In 2014, XMM-Newton reported a potential detection of an X-ray line at 3.56 keV from a combination of clusters, with a particularly bright signal from Perseus. A similar analysis by Chandra found a line at the same energy from Perseus and Andromeda.





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E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, et al. (2014), 1402.2301.
A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, and J. Franse (2014), 1402.4119.

Recently, XMM-Newton has found evidence of the line from the galactic center of the Milky Way.

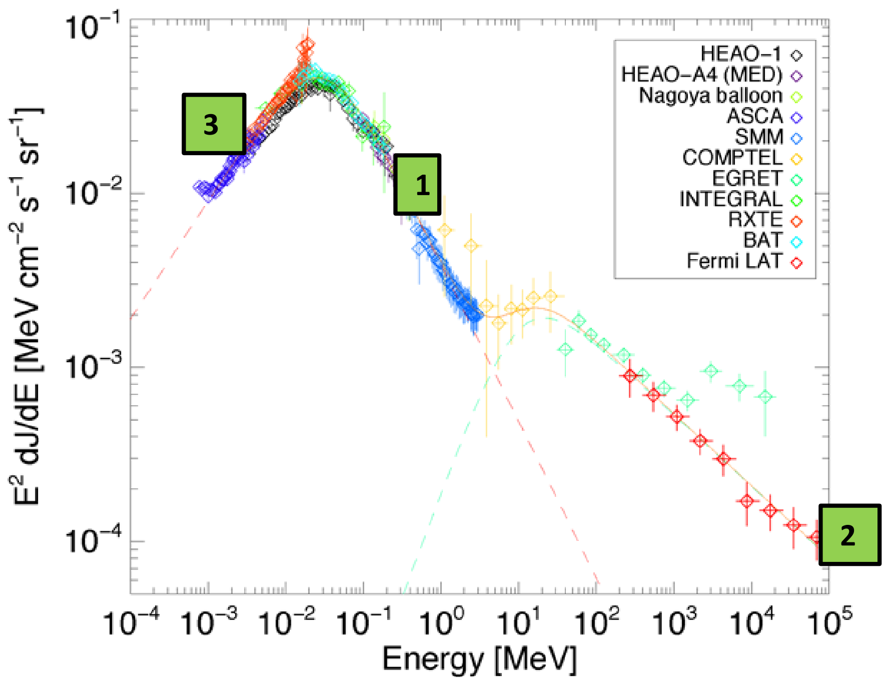
A. Boyarsky, J. Franse, D. Iakubovskyi and O.Ruchayskiy, arXiv:1408.2503 [astro-ph.CO].

Few days after the first references, many manuscripts speculated with the possibility of a DM origin. E.g.:

D. P. Finkbeiner and N. Weiner, arXiv:1402.6671 [hep-ph].

Gamma ray Anomalies and DM

Monochromatic (#) and continuous (#) anomalies related to DM in the literature:



Gamma ray Anomalies

Continuous Anomalies:

4. GeV emission from the Dark Halo (EGRET): 1997-2004

GeV Emission from the 'double doughnut halo'

The spectral shape of the gamma ray sky was measured in the 1990s by the Egret experiment in the energy range of 0.1-10 GeV, where an excess over expected background was reported for E>1 GeV.

P. Sreekumar et al. [EGRET Collaboration], Astrophys. J. 494, 523 (1998) [arXiv:astro-ph/9709257].

More than 6 years later, this excess was claimed to be consistent with a 50-70 GeV neutralino annihilation into mainly bb pairs, in a DM Halo involving two rings of dark matter at 4 and 13 kpc.

W. de Boer, M. Herold, C. Sander, V. Zhukov, A. V. Gladyshev and D. I. Kazakov, arXiv:astro-ph/0408272.
W. de Boer, C. Sander, V. Zhukov, A. V. Gladyshev and D. I. Kazakov, Astron. Astrophys. 444, 51 (2005) [arXiv:astro-ph/0508617].

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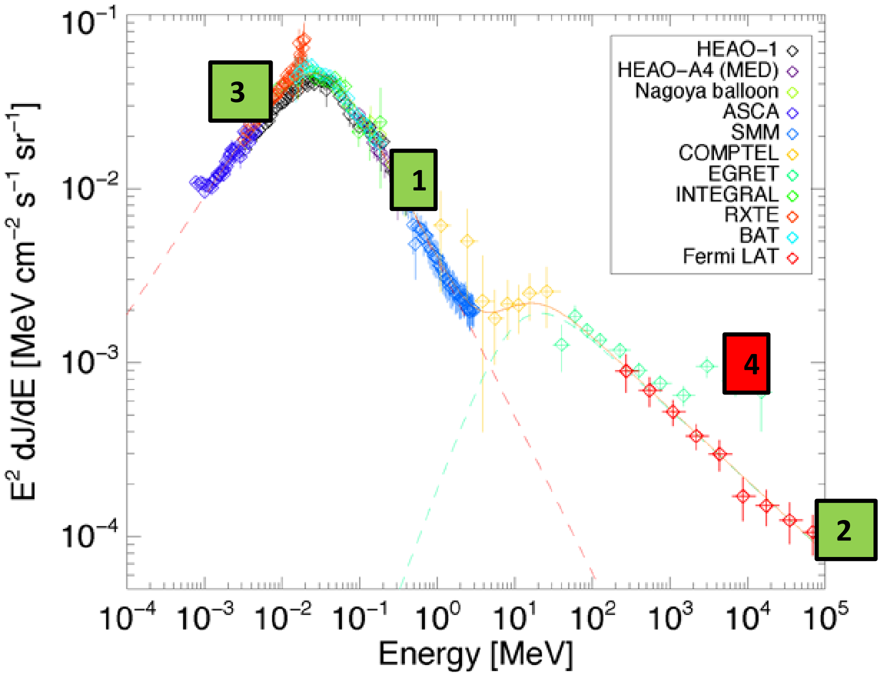


Gamma ray Anomalies

Continuous Anomalies:

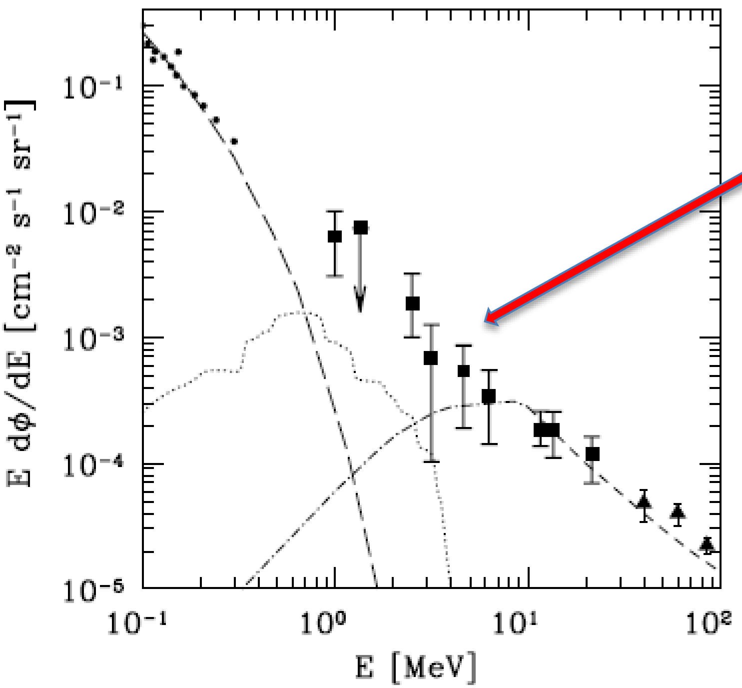
4. GeV emission from the Dark Halo (EGRET): 1997-2004

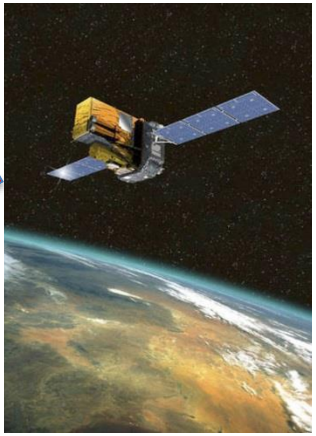
5. MeV isotropic emission (COMPTEL): 2000-2005

MeV COMPTEL Isotropic excess

The cosmic gamma ray background is reasonably well-modeled by thermal emission form AGN (for E<1 MeV) and beamed AGN and Blazars (for E>10 MeV).

But it has been claimed that no standard astrophysical source can account for the gamma rays in between.





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Published COMPTEL data:

G. Weidenspointner et al., American Institute of Physics Conference Series 510, 467 (2000).

First DM interpretation:

K. Ahn and E. Komatsu, Phys. Rev. D 72, 061301 (2005), arXiv:astro-ph/0506520

Gamma ray Anomalies and DM

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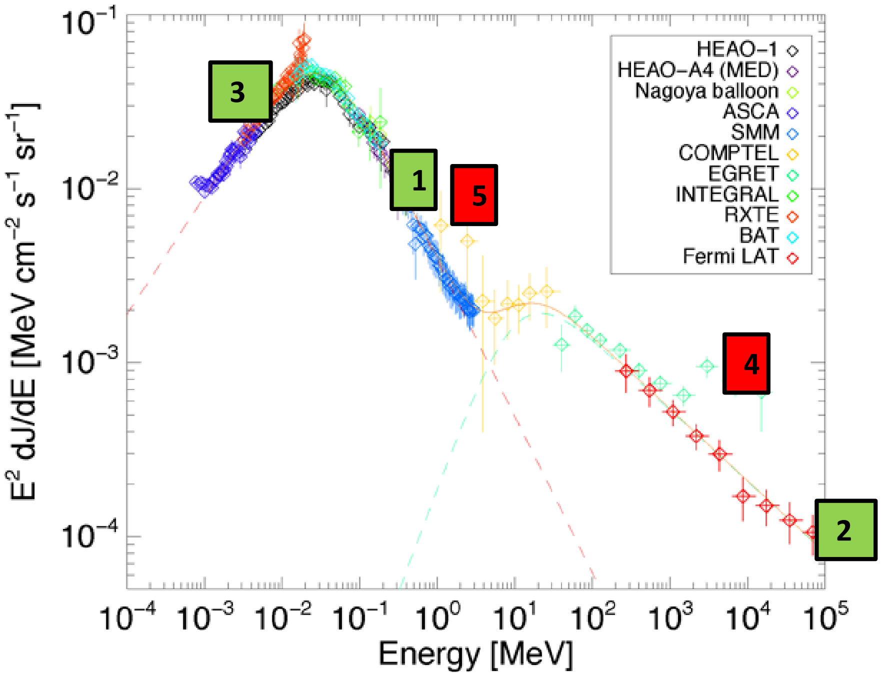

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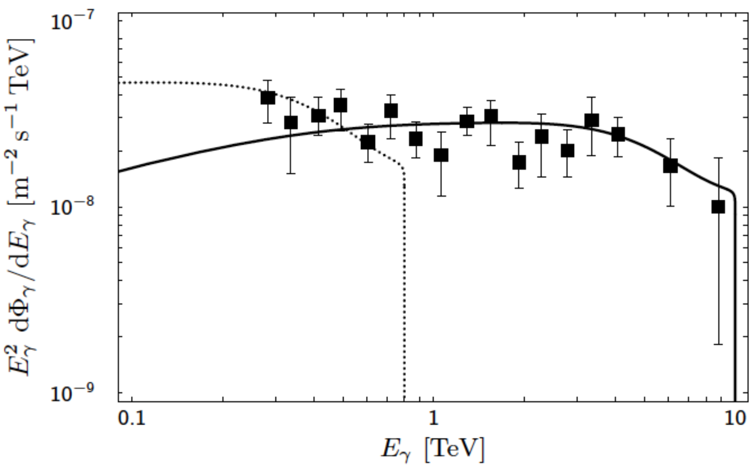
6. TeV emission from the Galactic Center (HESS): 2004-2004

TeV Emission from the Galactic Center

An excess in very high energy gamma rays from the galactic centerwas reported by HESS in 2004.

H.E.S.S. Collaboration, F. Aharonian et al., Astron. Astrophys. 425, L13 (2004), astro-ph/0408145.

Few months later, it was claimed that KK DM models provide a good fit to the data.



L. Bergstöm et al. arXiv:astro-ph/0410359v2(2005)

Gamma ray Anomalies and DM

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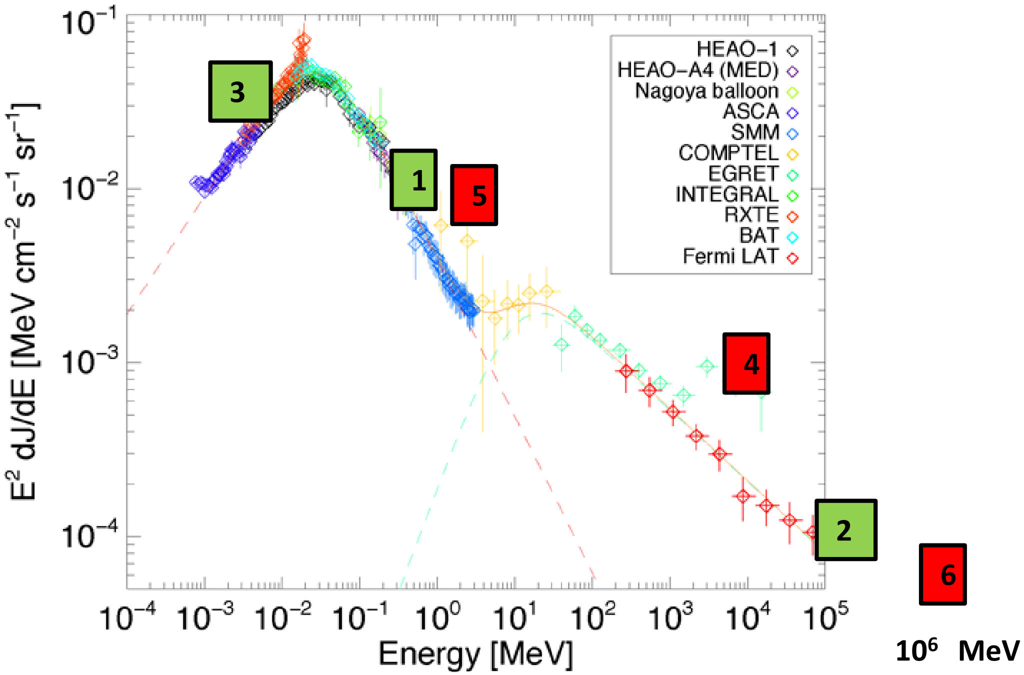

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7. GeV emission from the Galactic Center (Fermi): 2009-2009

GeV Emission from the Galactic Center

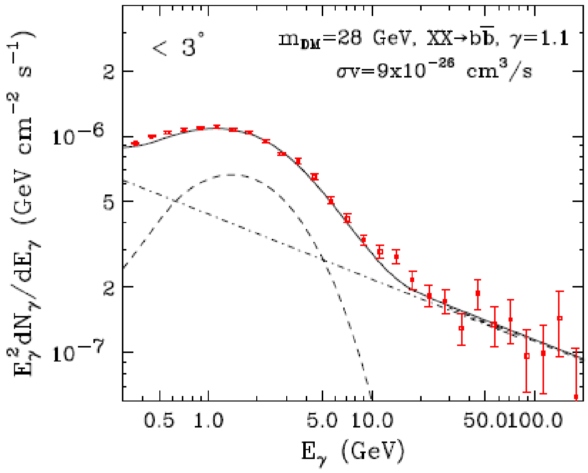
Significant evidence for an excess around 1-3 GeV in the Fermi-LAT data from the Galactic Center.

The morphology was consistent with annihilating 20-40 dark matter in a cuspy halo ($\rho_{DM} \sim r^{-1.25}$).

Intensity is consistent with a thermal cross section:

$\sigma v \sim 2 \times 10^{-26}$ cm^3/s is ($\rho_{local} = 0.3$ GeV/cm^3)

L. Goodenough, D. Hooper, arXiv:0910.2998



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L. Goodenough, D. Hooper, arXiv:0910.2998

Data was available some months before:

V. Vitale [FERMI-LAT Collaboration], AIP Conf. Proc. 1112, 164 (2009);
C. Meurer [Fermi LAT Collaboration], AIP Conf. Proc. 1085, 719 (2009);
T. Ylinen, Y. Edmonds, E. D. Bloom and J. Conrad [FERMI-LAT Collaboration], arXiv:0812.2853 [astro-ph].

Gamma ray Anomalies and DM

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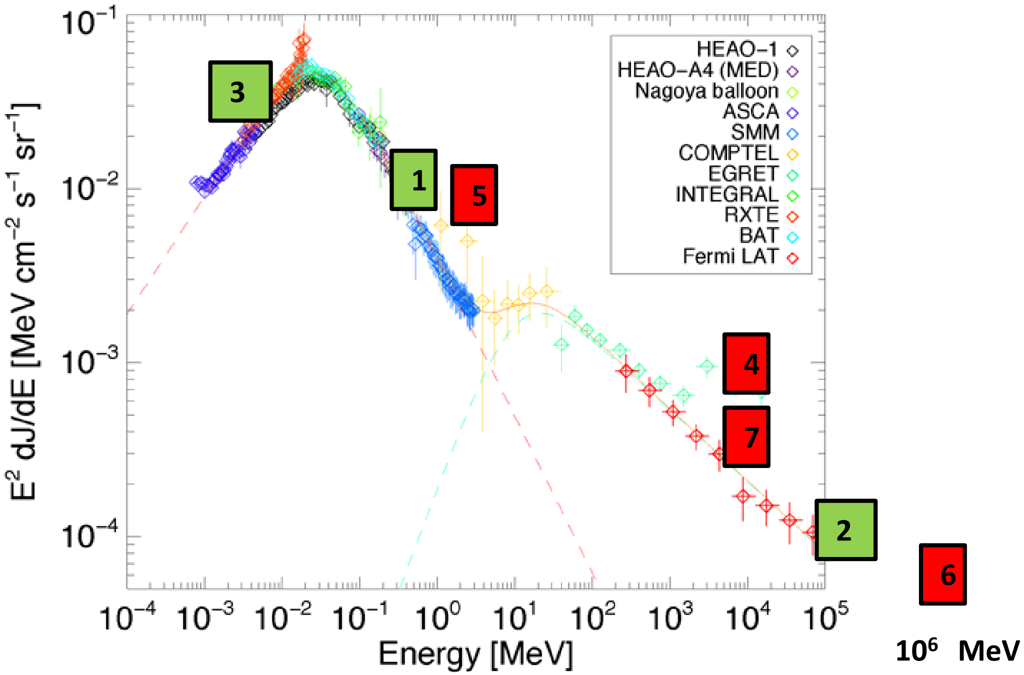

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8. Isotropic radio emission (ARCADE 2): 2011-2011

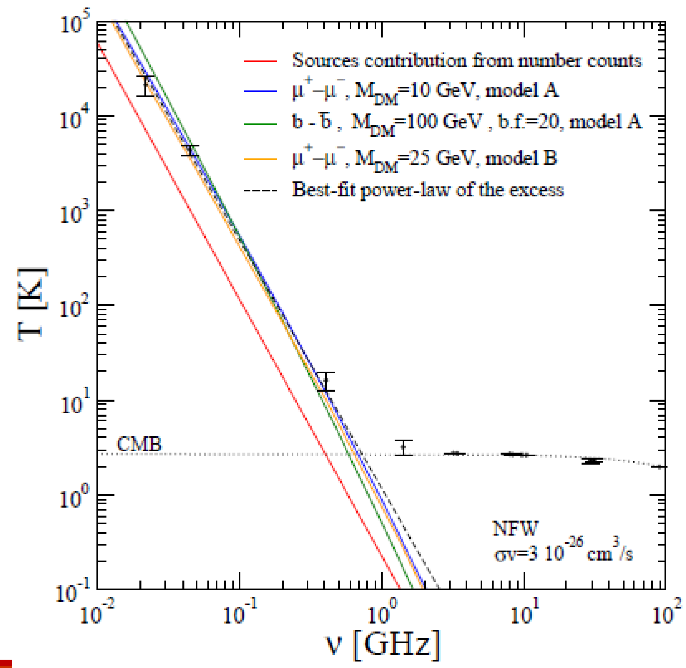
Isotropic Radio Emission

In 2011, ARCADE 2 reported an isotropic background that is 5-6 times higher than predicted from astrophysical sources.

J. Singal et al., Astrophys. J. 730 (2011) 138.
A. Kogut et al., Astrophys. J. 734 (2011) 4.

Few months later, it was analyzed as due to the synchrotron emission from dark matter annihilation products.

Fornengo, N., Lineros, R., Regis, M., & Taoso, M. 2011, Physical Review Letters, 107, A261302



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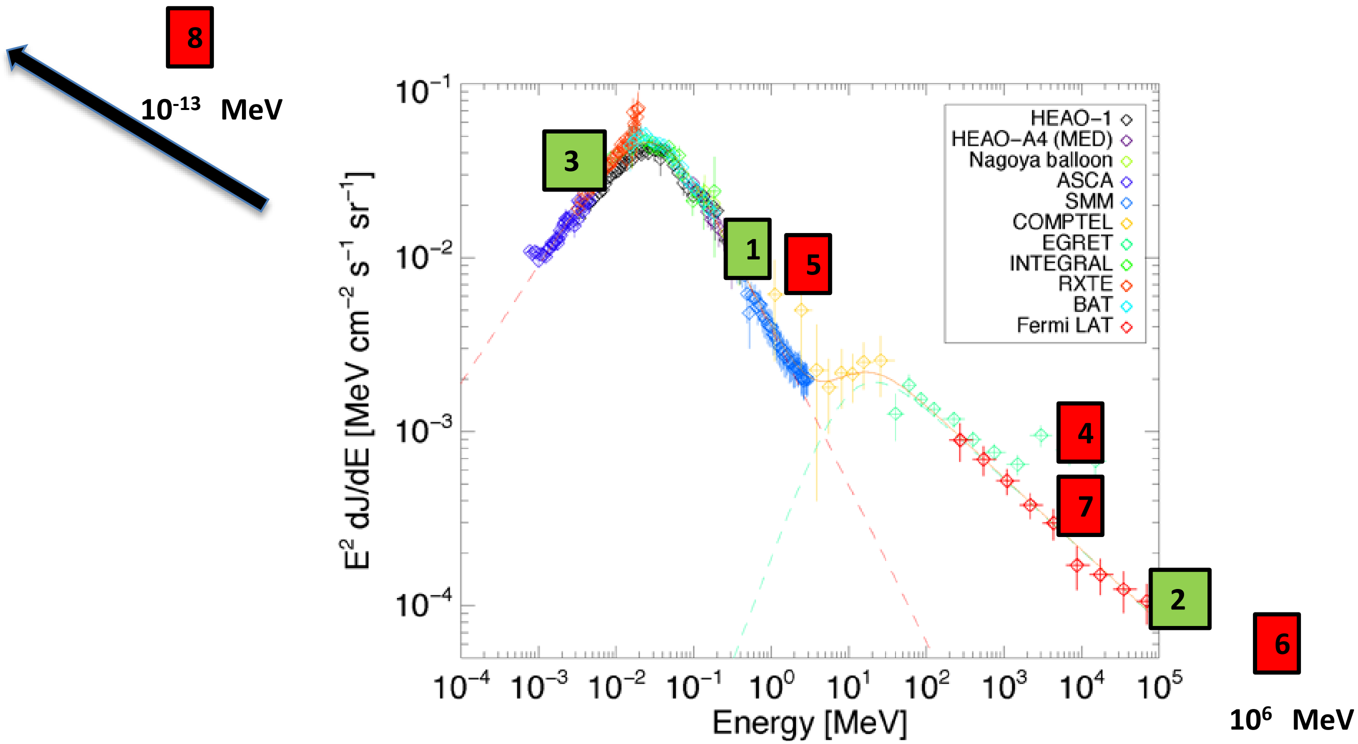

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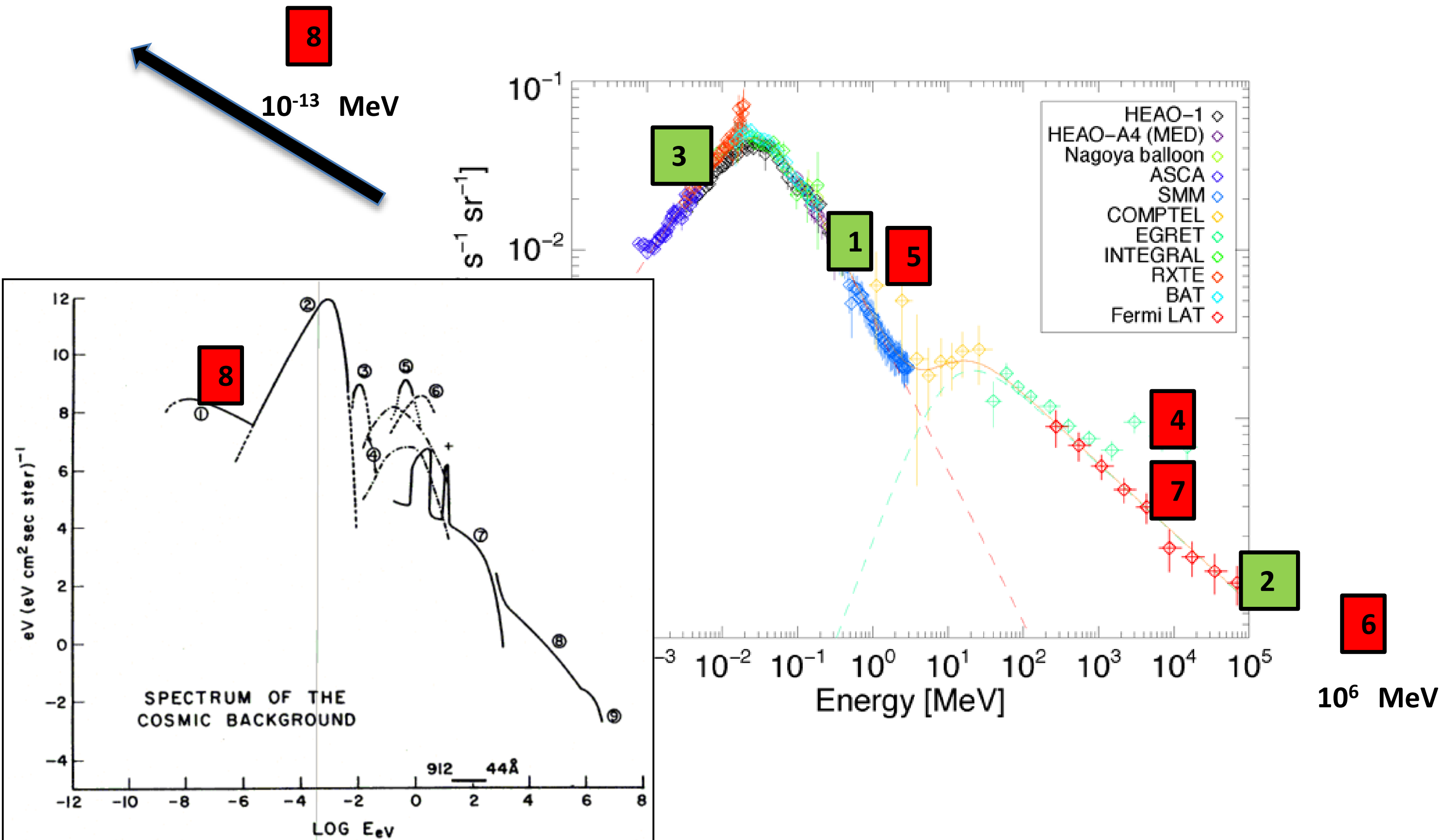

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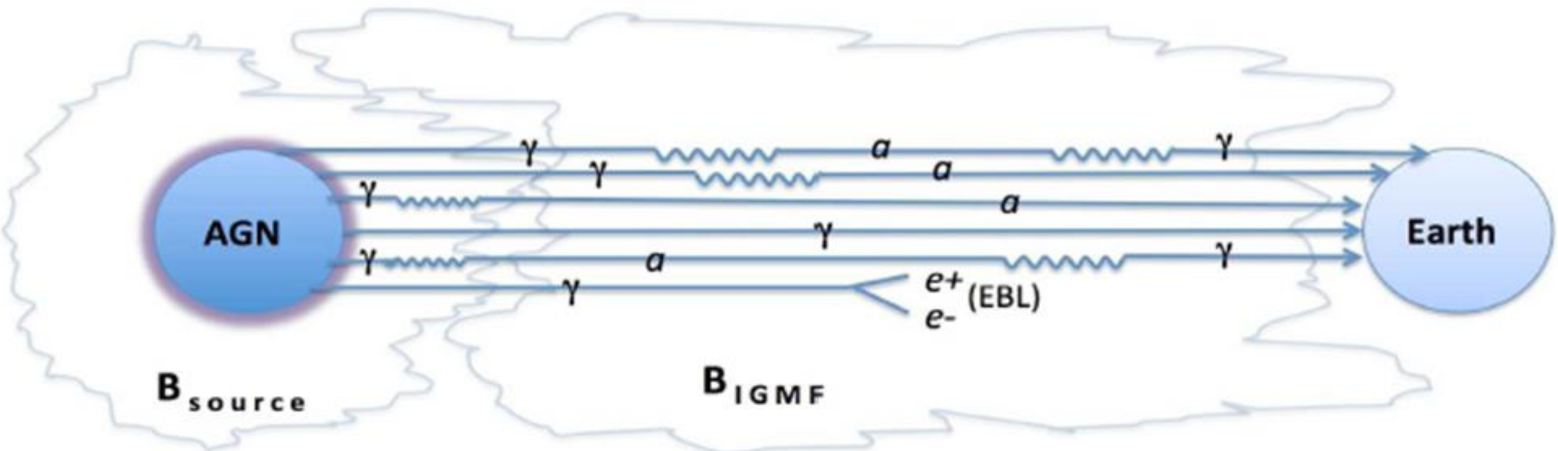
9. Extra Galactic Background Light (EGL) anomaly (VERITAS, MAGIC,…): 1998/2009-2009

Extragalactic Background Light Anomaly

Very high-energy (VHE, E > 100 GeV) gamma rays from extragalactic sources interact with photons of the Extragalactic Background Light (EBL). It implies a exponential suppression of the photon flux with the optical depth, that increases with distance and energy.



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This suppression has not been observed as predicted:

Neshpor Y. I., Stepanyan A. A., Kalekin O. P., Fomin, V. P., Chalenko N. N. & Shitov V. G. 1998, Astron. Lett., 24, 134

Stepanyan A. A., Neshpor Y. I., Andreeva N. A., Kalekin, O. P., Zhogolev N. A., Fomin V. P.& Shitov V. G., 2002, Astron. Rep., 46, 634

Aliu et al., 2008, submitted to ApJL, astro-ph/0810.4712

Krennrich, Dwek and Imran, 2008, submitted to ApJ, astro-ph/0810.2522

Acciari V. A., 2009, ApJL, accepted, astro-ph/0901.4527

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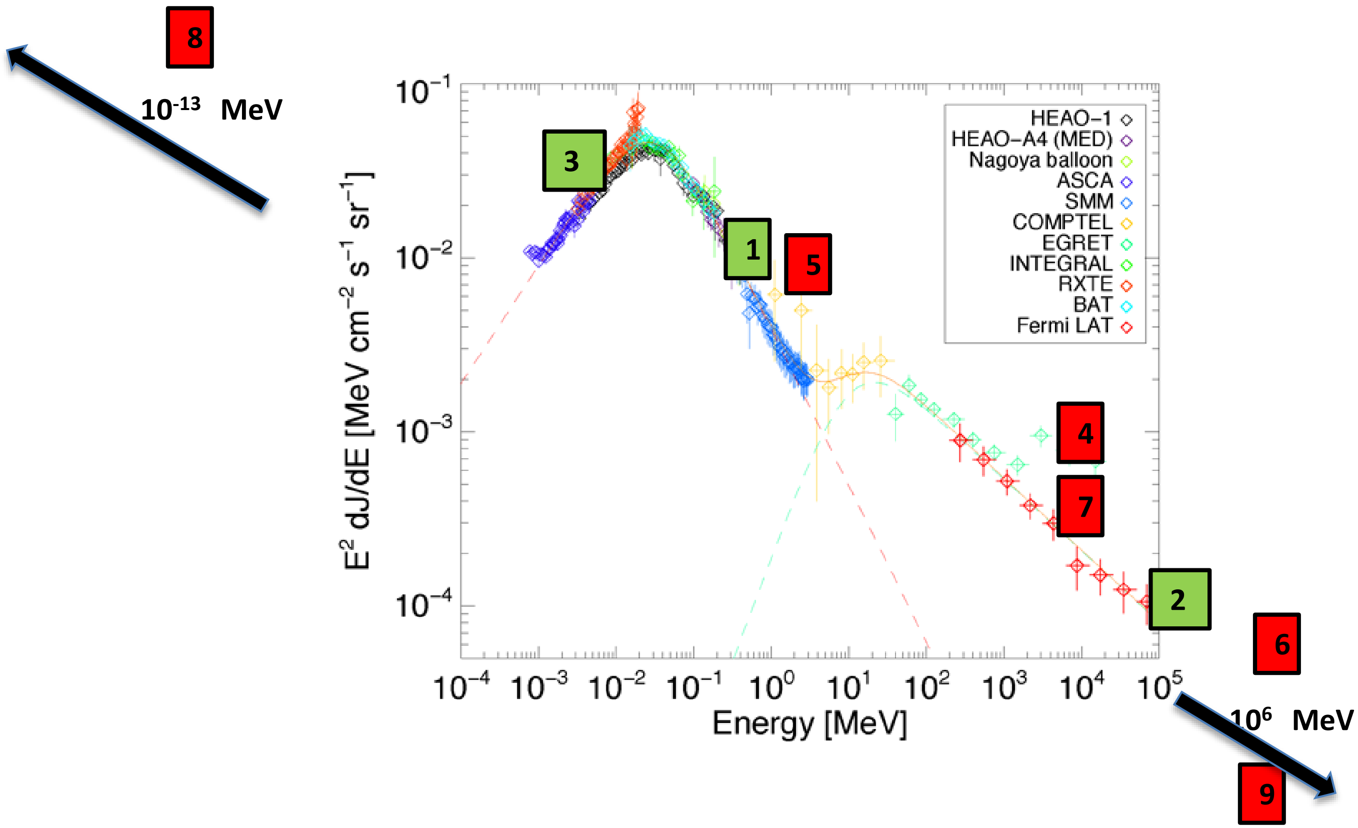
This suppression has not been observed as predicted.

One of the explanations to such difference between observations and theory, it is the possible oscillation of photons into DM particles such as axion-like-particles:

M. A. Sanchez-Conde, D. Paneque, E. Bloom, F. Prada and A. Dominguez, Phys. Rev. D 79 (2009) 123511 [arXiv:0905.3270 [astro-ph.CO]].

Gamma ray Anomalies and DM

Monochromatic (#) and continuous (#) anomalies related to DM in the literature:



Gamma ray Anomalies

Continuous Anomalies:

4. GeV emission from the Dark Halo (EGRET): 1997-2004

5. MeV isotropic emission (COMPTEL): 2000-2005

6. TeV emission from the Galactic Center (HESS): 2004-2004

7. GeV emission from the Galactic Center (Fermi): 2009-2009

8. Isotropic radio emission (ARCADE 2): 2011-2011

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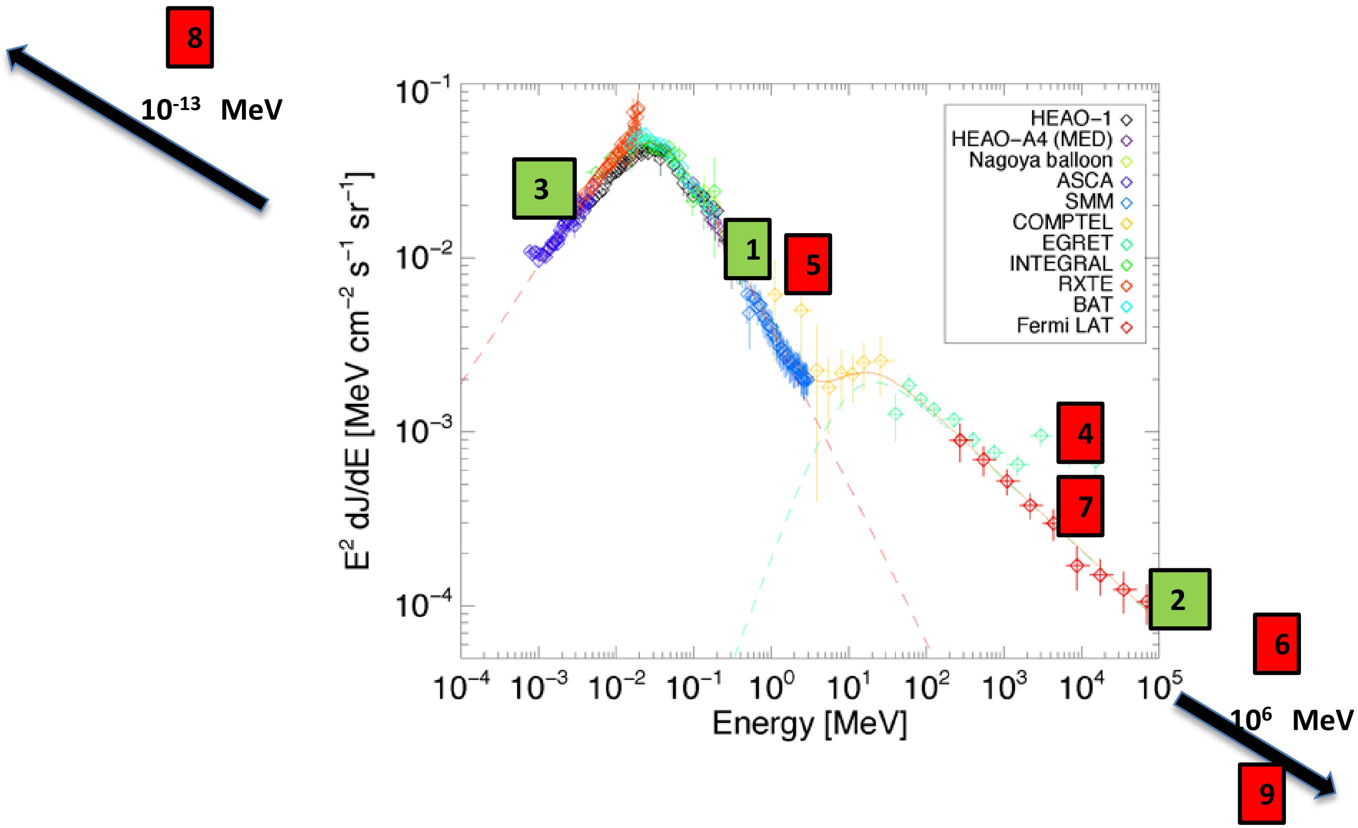

‘Natural solutions’ to any Gamma ray Anomalies

DM provides ‘natural solutions’ to any observation.

‘Natural solutions’ to any Gamma ray Anomalies

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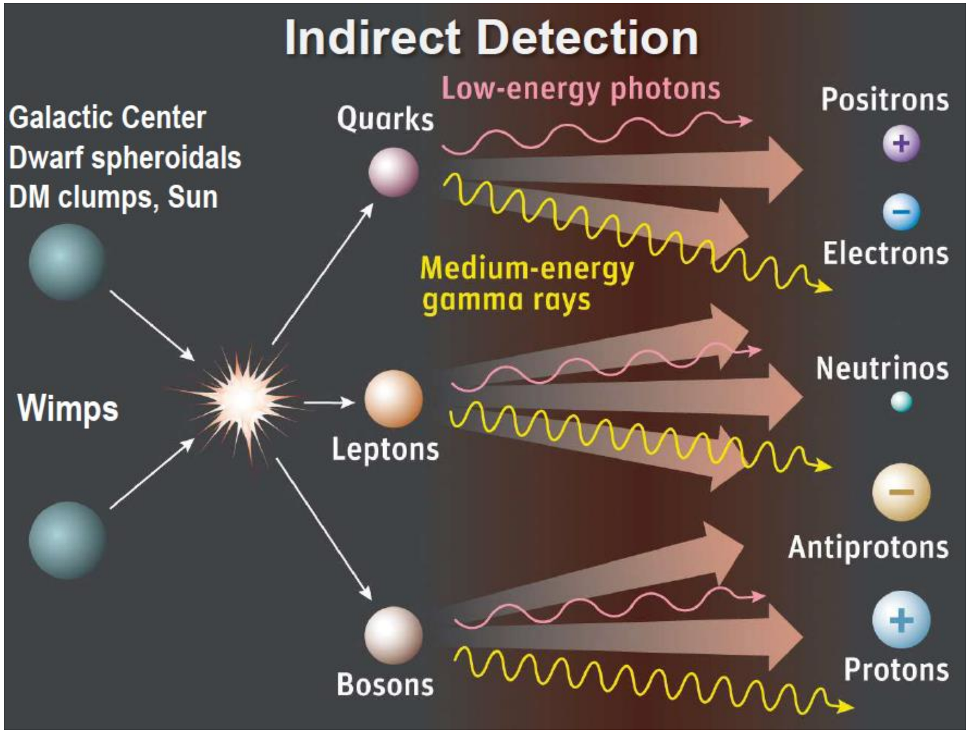
‘Natural solutions’ to any Gamma ray Anomalies

DM provides ‘natural solutions’ to any observation.

But also, standard astrophysical sources seem to be able to fit any observation.

Indirect Searches: Cosmic rays



Indirect Searches: Cosmic rays

Cosmic-ray fluxes at the Earth from DM annihilating or decay in Galactic sources depend by the Standard Model (SM) secondary particle of interest.

Gamma rays:

$$\frac{d\Phi_\gamma}{dE} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \cdot \frac{dN_i^{(\gamma)}}{dE} \cdot \frac{\Delta\Omega \left\langle J_{(a)} \right\rangle_{\Delta\Omega}}{4\pi M^a}$$

Neutrinos:

$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3} \sum_{a=1}^{2} \sum_{i}^{\text{channels}} P_{fp} \cdot \frac{\zeta_i^{(a,\nu_p)}}{a} \frac{dN_i^{(\nu_p)}}{dE} \cdot \frac{\Delta\Omega \left\langle J_{(a)} \right\rangle_{\Delta\Omega}}{4\pi M^a}$$

Antimatter:
(antiprotons)

$$\frac{\mathrm{d}\Phi_{\bar{p}}}{\mathrm{d}E_{\bar{p}}} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \frac{\mathrm{d}N_i^{(\bar{p})}}{\mathrm{d}E_{\bar{p}}} \cdot \frac{v_{\bar{p}}}{4\pi} \left(\frac{\rho_\odot}{M}\right)^a R_{(a)}(E_{\bar{p}})$$

DM annihilation vs Decay

a=1 $\zeta^{(1)} = \Gamma$

a=2 $\zeta^{(2)} = \langle\sigma v\rangle$

They depend on the DM model.

For annihilation, it is standard to fix the value $\zeta^{(2)}$ around thermal one :

$$\langle \sigma v \rangle = 3 \cdot 10^{-26}\ \mathrm{cm^3 s^{-1}}$$

The final flux has a different dependence with the DM mass and the density distribution in these cases.

simulated by Monte Carlo events

or HERWIG.

$$\frac{\zeta_i^{(a)}}{a} \cdot \frac{dN_i^{(\gamma)}}{dE} \cdot \frac{\Delta\Omega \langle J_{(a)} \rangle_{\Delta\Omega}}{4\pi M^a}$$

nnels

$$\sum_i P_{fp} \cdot \frac{\zeta_i^{(a,\nu_p)}}{a} \frac{dN_i^{(\nu_p)}}{dE} \cdot \frac{\Delta\Omega \langle J_{(a)} \rangle_{\Delta\Omega}}{4\pi M^a}$$

$$\frac{\zeta_i^{(a)}}{a} \frac{\mathrm{d}N_i^{(\bar{p})}}{\mathrm{d}E_{\bar{p}}} \cdot \frac{v_{\bar{p}}}{4\pi} \left(\frac{\rho_\odot}{M}\right)^a R_{(a)}(E_{\bar{p}})$$

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DM density distribuion

Astrophysical factor encode the physics of DM distribution and particles propagation.

For gamma-rays and neutrinos:

$$\langle J_{(a)} \rangle = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \mathrm{d}\Omega \int_0^{l_{max}(\Psi)} \rho^a[r(l)] dl(\Psi)$$

depends by the DM distribution and the devise angular resolution and effective area.

For antimatter:

Is the solution of the diffusion equation that depends by the DM distribution and diffusion model.

$$\frac{\Delta\Omega \langle J_{(a)} \rangle_{\Delta\Omega}}{4\pi M^a}$$

$$\frac{dN_i^{(\nu_p)}}{dE} \cdot \frac{\Delta\Omega \langle J_{(a)} \rangle_{\Delta\Omega}}{4\pi M^a}$$

$$\left(\frac{\rho_\odot}{M}\right)^a R_{(a)}(E_{\bar{p}})$$

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Antiprotons:

$$\frac{\mathrm{d}\Phi_{\bar{p}}}{\mathrm{d}E_{\bar{p}}} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \frac{\mathrm{d}N_i^{(\bar{p})}}{\mathrm{d}E_{\bar{p}}} \cdot \frac{v_{\bar{p}}}{4\pi} \left(\frac{\rho_\odot}{M}\right)^a R_{(a)}(E_{\bar{p}})$$

Indirect Searches: Simulations

Secondary particle fluxes are simulated by Monte Carlo events generator software such as PYTHIA or HERWIG.

Gamma-rays:

$$\frac{d\Phi_\gamma}{dE} = \sum_{a=1}^{2} \sum_{i}^{\text{channels}} \frac{\zeta_i^{(a)}}{a} \cdot \frac{dN_i^{(\gamma)}}{dE} \cdot \frac{\Delta\Omega \left\langle J_{(a)} \right\rangle_{\Delta\Omega}}{4\pi M^a}$$

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Gamma rays

- Gamma ray fitting functions
  - HESS data from the Galactic Center
- Comparison of Monte Carlo event generators
  - PYTHIA 6.418 (Fortran)
  - HERWIG 6.5.10 (Fortran)
  - PYTHIA 8.165 (C++)
  - HERWIG 2.6.1 (C++)

Gamma Ray Fitting Functions

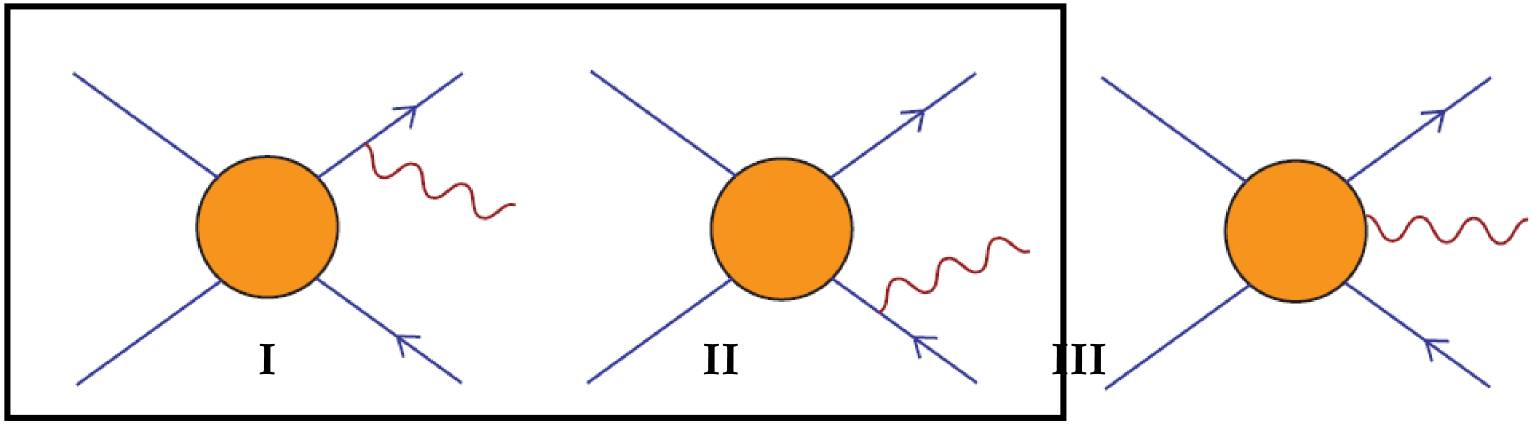
- Gamma-ray spectra do not depend on DM model or DM model except for small particular tuned regions of the parameter space:

- Fitting functions for particle-antiparticle channels.

JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

Internal Bremsstrahlung



Bringmann, Bergström and Edsjö **JHEP 0801:049,2008**.

✓ bremsstrahlung contributions **I** and **II** are included in the performed simulations.

✓ Model dependent contribution **III** is negligible except for very particular region of models with degenerate spectrum

Cannoni, Gómez, Sánchez-Conde, Prada & Panella **PRD 81 : 107303, 2010.**

Gamma Ray Fitting Functions

- Physical process to get gamma rays from WIMPs:

Firstly: Annihilation of WIMPs (mainly by pairs) in SM particles.

Secondly: Those unstable SM products decay and/or hadronize.

$$E_{\rm CM} = 2\, M \quad \text{Center of mass frame}$$

- Simulate E_{CM} ⇔ Simulate different WIMP masses.

- Package **PYTHIA 6.418** version was used.

- Variable $x \equiv E_\gamma / M$ in the interval [0, 1].

Energy bins:

$$[10^{-5},\, 10^{-3}]\ [10^{-3},\, 0.2]\ [0.2,\, 0.5]\ [0.5,\, 0.8]\ [0.8,\, 1.0]$$

Gamma Ray Fitting Functions

I. Leptons and quarks (except *top* quark)

$$x^{1.5}\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = a_1 \mathrm{exp}\left(-b_1 x^{n_1} - b_2 x^{n_2} - \frac{c_1}{x^{d_1}} + \frac{c_2}{x^{d_2}}\right) + q\, x^{1.5} \ln\left[p(1-x)\right] \frac{x^2 - 2x + 2}{x}$$

II. *W* and *Z* gauge bosons

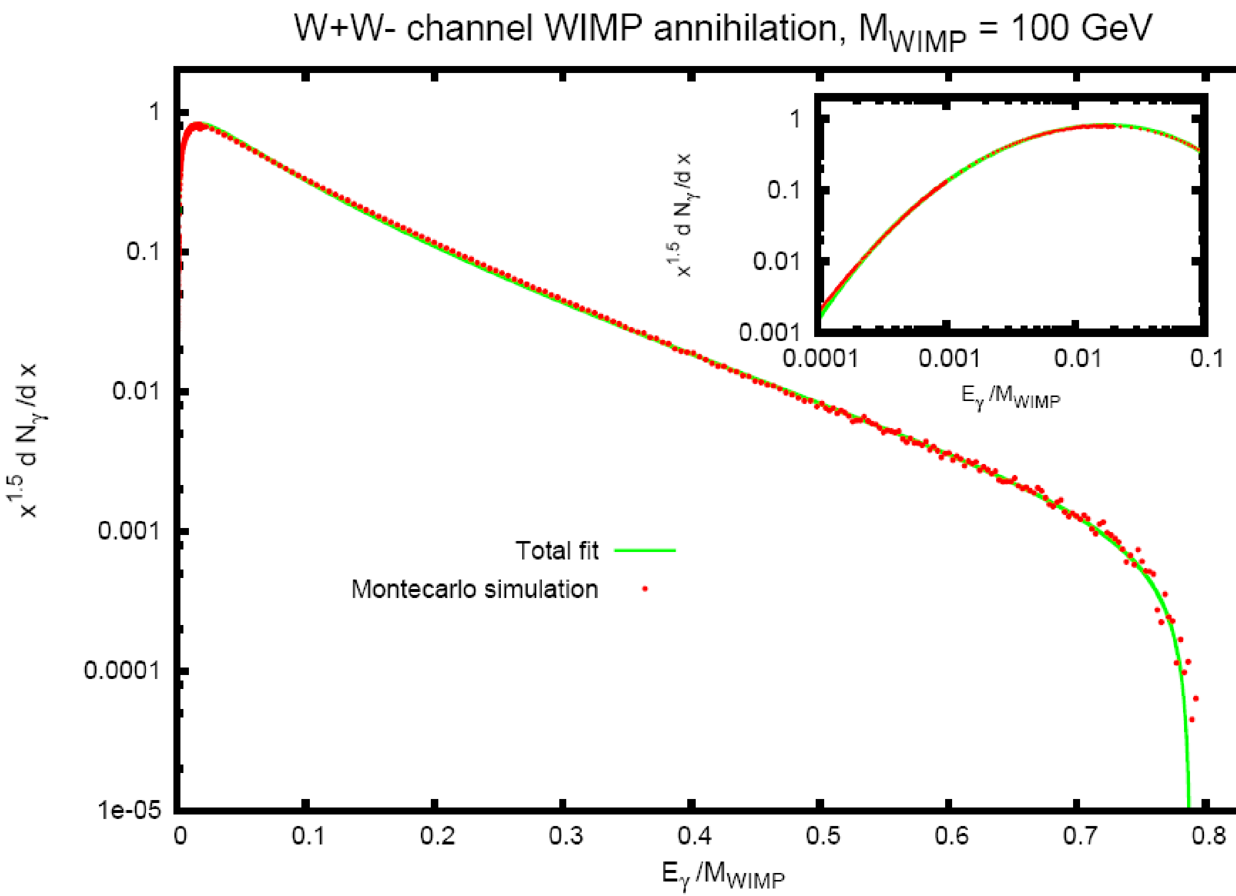
$$x^{1.5}\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = a_1 \exp\left(-b_1\, x^{n_1} - \frac{c_1}{x^{d_1}}\right)\left\{\frac{\ln[p(j-x)]}{\ln p}\right\}^q$$

$$x \equiv E_\gamma / M$$

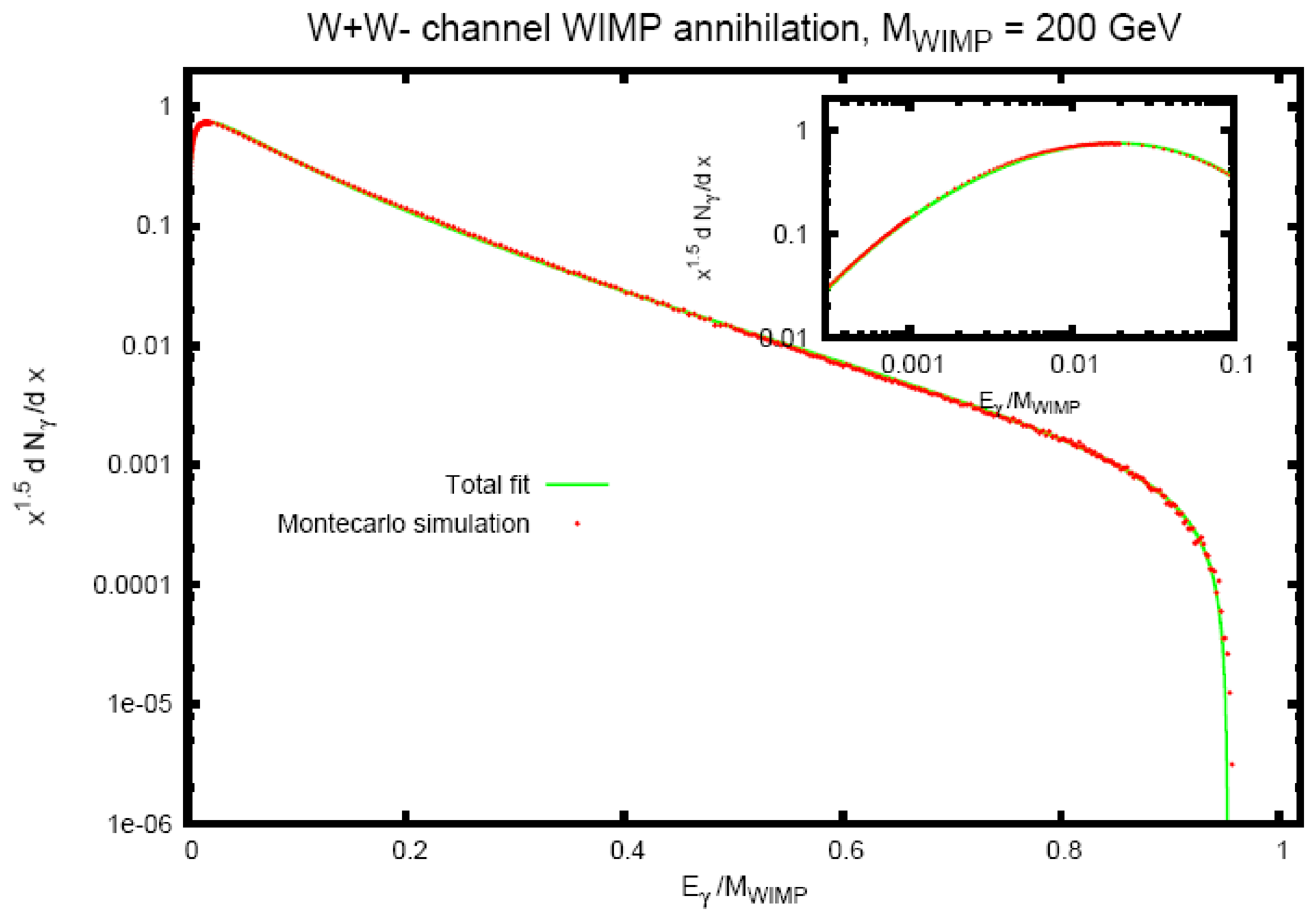
III. Top quark

$$x^{1.5}\frac{\mathrm{d}N_\gamma}{\mathrm{d}x} = a_1 \exp\left(-b_1\, x^{n_1} - \frac{c_1}{x^{d_1}} - \frac{c_2}{x^{d_2}}\right)\left\{\frac{\ln[p(1-x^l)]}{\ln p}\right\}^q$$

W+W- channel Fitting Function



W+W- channel Fitting Function



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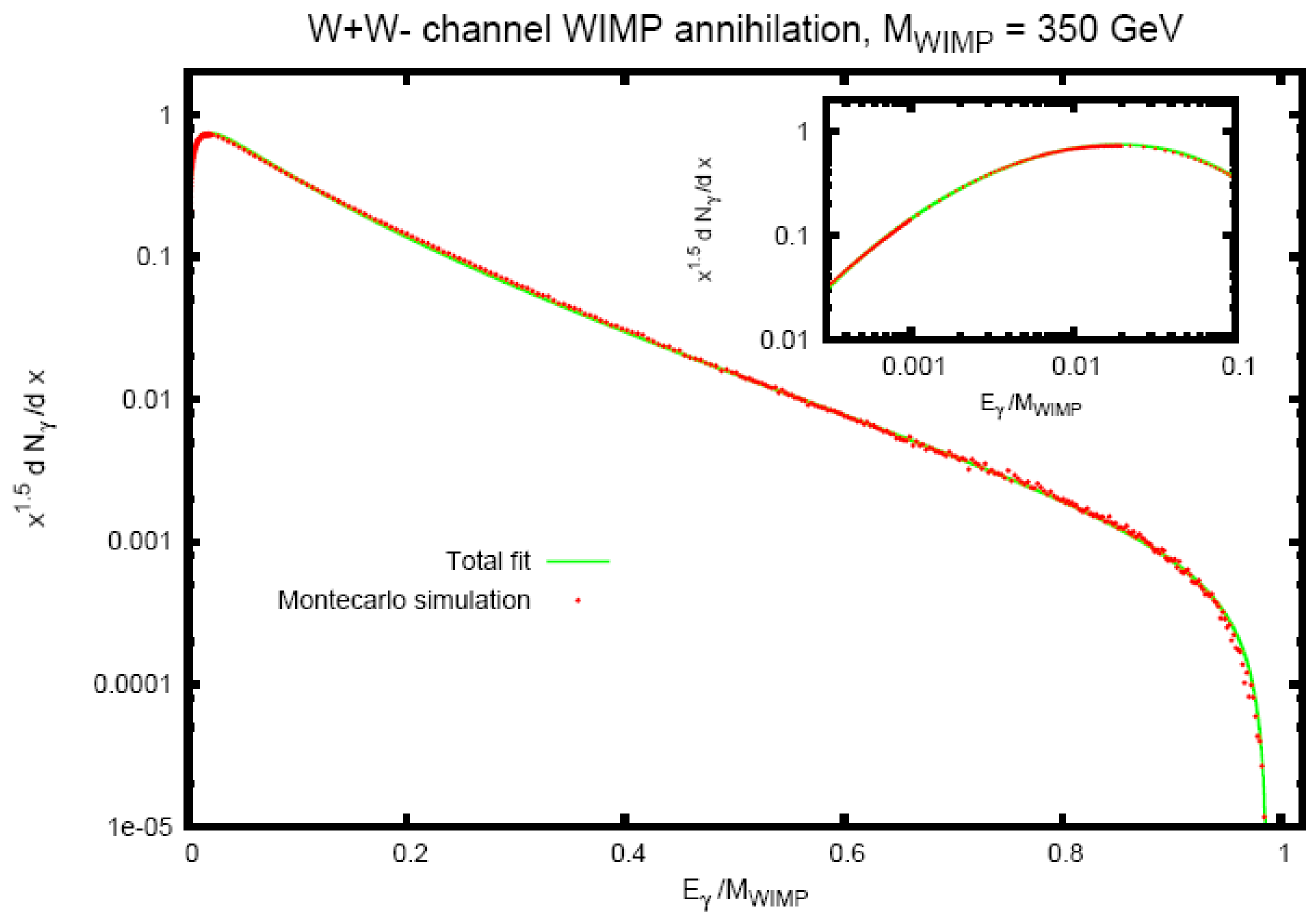

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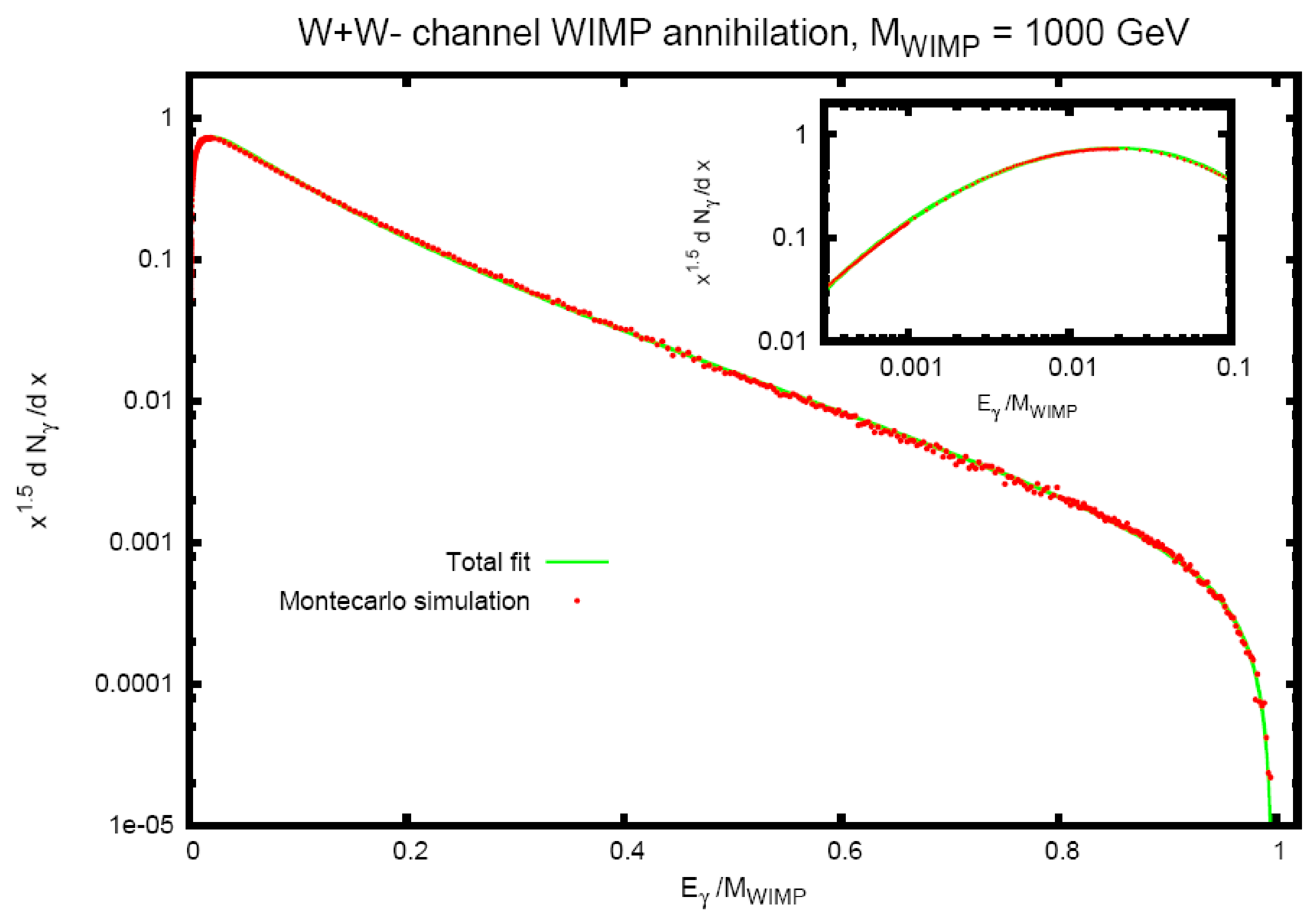


Gamma Ray Fitting Functions

✓ MATHEMATICA **[AdICD et *al.*, 2010]**

MultiDark
Multimessenger Approach for Dark Matter Detection

http://teorica.fis.ucm.es/PaginaWeb/downloads.html

✓ ROOT-based **[D. Nieto et *al.*, 2011]**

DAMASCO (DArk Matter Analytical Spectral COde)

http://cta.gae.ucm.es/gae/damasco

MAGIC
Major Atmospheric Gamma Imaging Cerenkov Telescopes

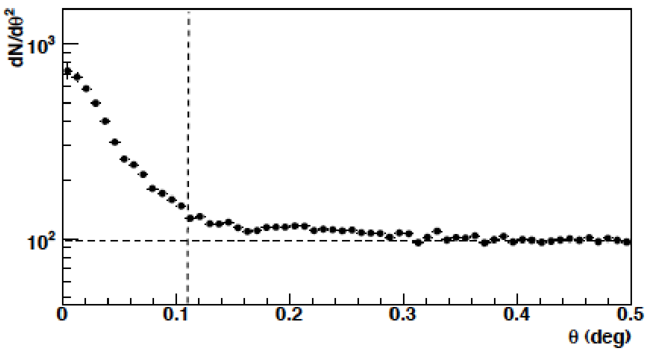
JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

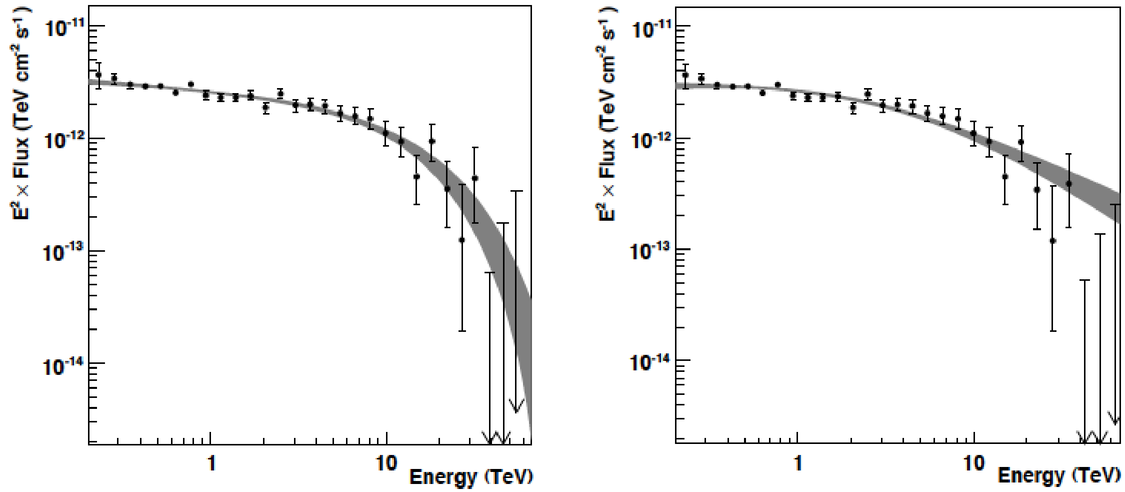
Application to HESS data

By HESS: 270 GeV-70 TeV

$\Theta < 0.1^{o}$



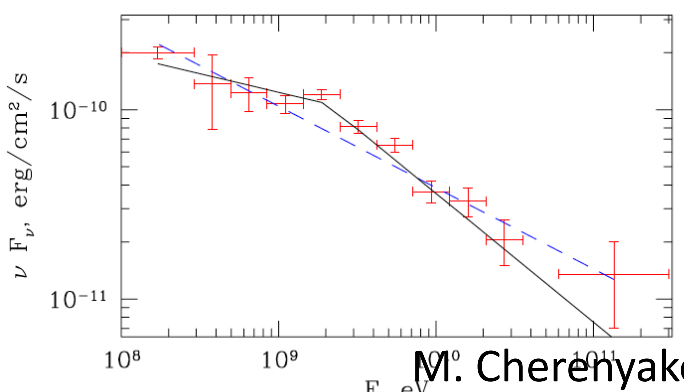
F. Aharonian et al. A&A 503, 817-825 (2009)



F. Prada et al. Phys. Rev. Lett. 95, 241301 (2004)

By Fermi-LAT:

100 MeV-300 GeV

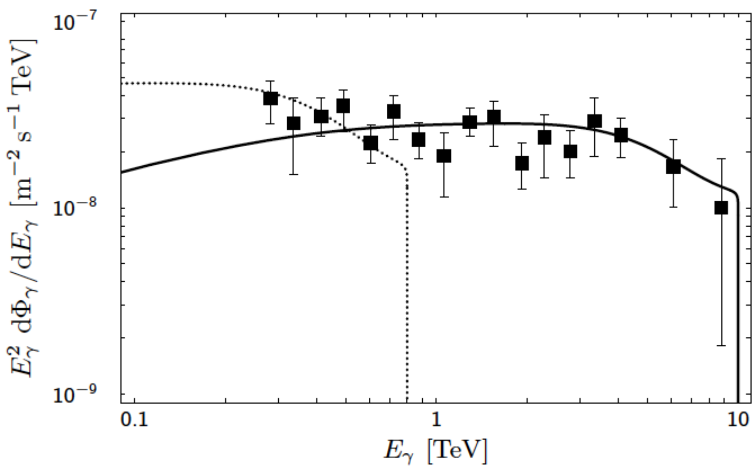


$$E > E_{br}$$
$$\chi^2/d.o.f. = 0.81$$
$$\Gamma = 2.68 \pm 0.05$$

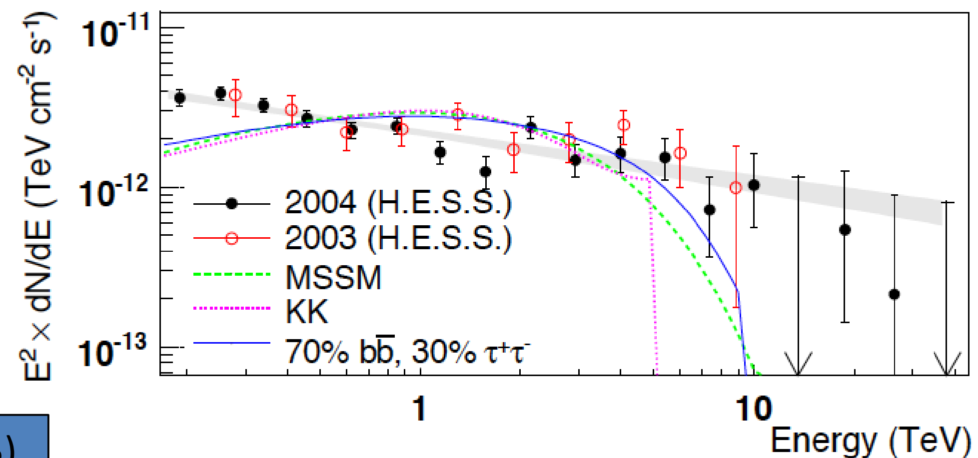
M. Cherenyakova et al. ApJ 726, 60 (2011)

Gamma Rays from the Galactic Center

Previous fits of DM signals are not able to be consistent with HESS observations without taking into account a background contribution.



L. Bergstöm et al. arXiv:astro-ph/0410359v2(2005)



F. Aharonian et al. arXiv: astrp-ph/0610509v2 (2006)

Galactic Center

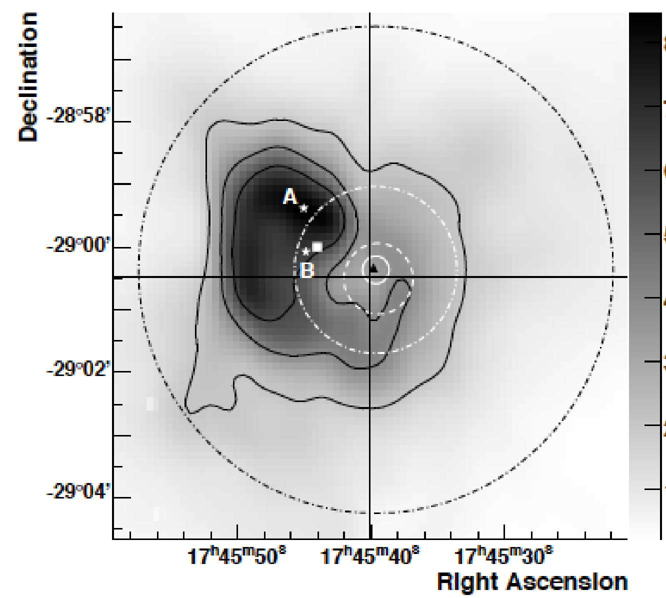
- Possible DM distribution close to the Earth but embedded in a very complex region due to the presence of multiplies sources.

- Multiplies sources observed (Radio flux, Sgr A* black hole, SNR Sgr A East, pulsar candidate, gamma emission).

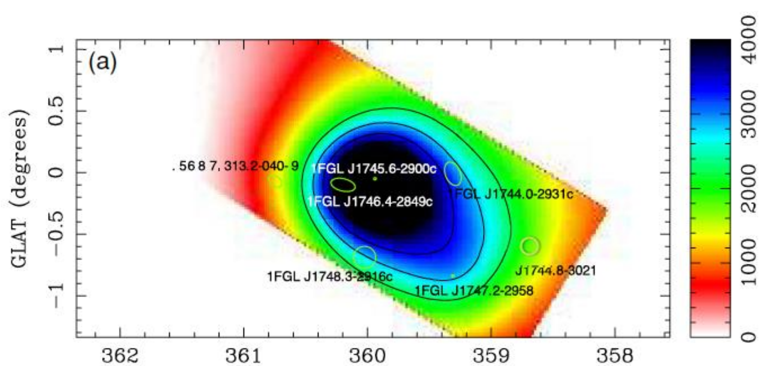
- Variability in Radio and X,

  but not in gamma flux

HESS J1745-290



1FGL J1745.6-2900c



Gamma Rays from the Galactic Center

Background component:

$$\frac{d\Phi_{Bg}}{dE} = B^2 \cdot \left(\frac{E}{\mathrm{GeV}}\right)^{-\Gamma}$$

$$\frac{d\Phi_{Tot}}{dE} = \frac{d\Phi_{Bg}}{dE} + \frac{d\Phi_{DM}}{dE}$$

4 free parameters:

$$B, \Gamma, A, M$$

DM contribution:

$$\frac{\mathrm{d}\,\Phi_{\mathrm{DM}}}{\mathrm{d}\,E} = \sum_i \frac{\langle\sigma_i v\rangle}{2}\frac{\mathrm{d}\,N_i}{\mathrm{d}\,E} \times \underbrace{\frac{\Delta\Omega\,\langle J_{(2)}\rangle_{\Delta\Omega}}{4\pi M^2}}_{A}$$

Gamma Rays from the Galactic Center

Channel	M (TeV)	$A\,(10^{-7}\,\mathrm{cm}^{-1}\mathrm{s}^{-1/2})$	$B\,(10^{-4}\,\mathrm{GeV}^{-1/2}\mathrm{cm}^{-1}\mathrm{s}^{-1/2})$	Γ	$\chi^2/\,\mathrm{dof}$	$\Delta\chi^2$	b
e^+e^-	7.51 ± 0.11	8.12 ± 0.73	2.78 ± 0.79	2.55 ± 0.06	2.09	32.6	111 ± 20
$\mu^+\mu^-$	7.89 ± 0.21	21.2 ± 1.92	2.81 ± 0.53	2.55 ± 0.06	2.04	31.4	837 ± 158
$\tau^+\tau^-$	12.4 ± 1.3	7.78 ± 0.69	3.17 ± 0.62	2.59 ± 0.06	1.59	20.6	278 ± 76
$u\bar{u}$	27.9 ± 1.8	6.51 ± 0.46	9.52 ± 9.47	3.08 ± 0.35	0.78	1.2	987 ± 189
$d\bar{d}$	42.0 ± 4.4	4.88 ± 0.48	8.26 ± 7.86	3.03 ± 0.34	0.73	0.0	1257 ± 361
$s\bar{s}$	53.9 ± 6.2	4.85 ± 0.57	6.59 ± 5.43	2.92 ± 0.29	0.90	4.1	2045 ± 672
$c\bar{c}$	31.4 ± 6.0	6.90 ± 1.06	53.0 ± 157	3.70 ± 1.07	1.78	25.0	1404 ± 689
$b\bar{b}$	82.0 ± 12.8	3.69 ± 0.61	6.27 ± 6.07	2.88 ± 0.35	1.32	14.2	2739 ± 1246
$t\bar{t}$	87.7 ± 8.2	3.68 ± 0.34	6.07 ± 3.34	2.86 ± 0.19	0.88	3.6	3116 ± 820
W^+W^-	48.8 ± 4.3	4.98 ± 0.40	5.18 ± 2.23	2.80 ± 0.15	0.84	2.6	1767 ± 419
ZZ	54.5 ± 4.9	4.73 ± 0.40	5.38 ± 2.45	2.81 ± 0.16	0.85	2.9	1988 ± 491

$$A^2 = \frac{\langle \sigma v \rangle\, \Delta\Omega\, \langle J_{(2)} \rangle_{\Delta\Omega}}{8\pi M^2}$$

$$\langle \sigma v \rangle = 3 \cdot 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$$

$$\Delta\Omega \simeq 10^{-5}$$

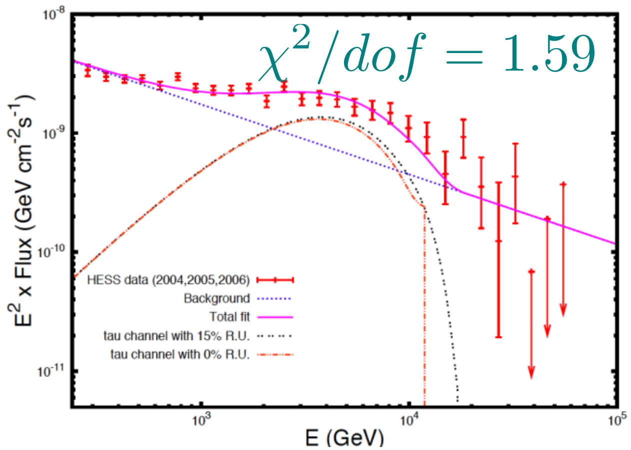
$$b \equiv \langle J_{(2)} \rangle / \langle J_{(2)}^{\mathrm{NFW}} \rangle$$

$$\langle J_{(2)}^{\mathrm{NFW}} \rangle \simeq 280 \cdot 10^{23}\ \mathrm{GeV}^2\mathrm{cm}^{-5}$$

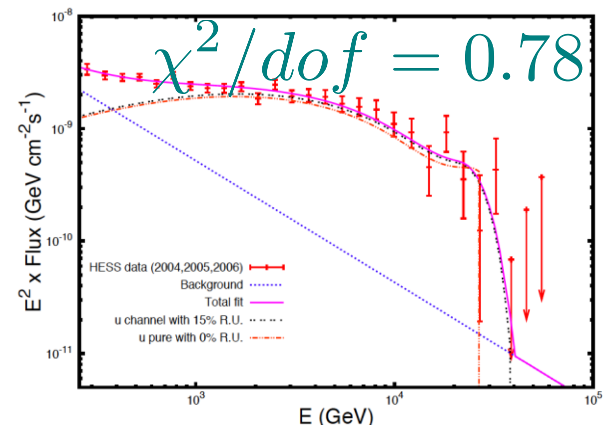
J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1204.0655v1], [Phy. Rev. D 85, 043505] ; [arXiv:1302.6871v2][astro-ph.CO], JCAP04 (2013) 051

Gamma Rays from the Galactic Center

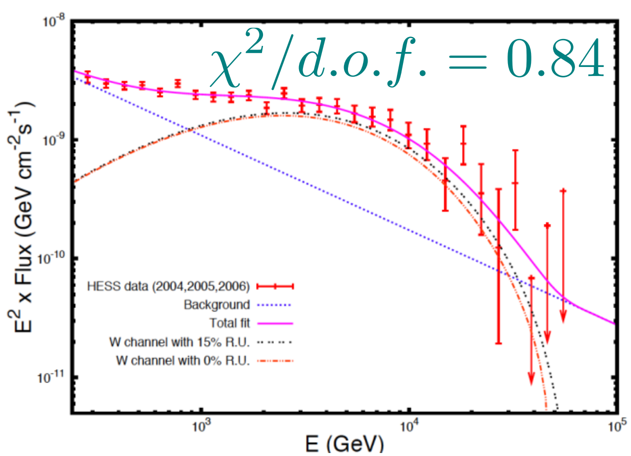
Lepton channel best fit: $\tau^+\tau^-$



Quark channel best fit: u-ubar



Boson channel best fit: W^+W^-

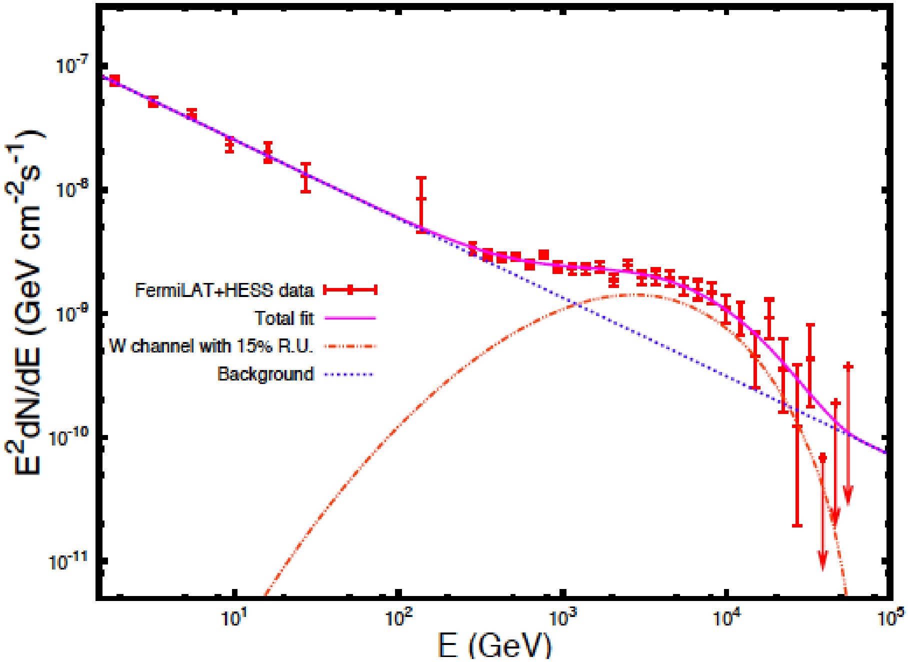


M_{DM}>10 TeV

Boost factor $=\langle J\rangle/\langle J\rangle_{NFW} \approx 10^3$

J. A. R Cembranos, V. G., A. L. Maroto arXiv [1204.0655v1], PRD 86, 103506 (2012); [arXiv:1302.6871v2][astro-ph.CO], JCAP04 (2013) 051

Gamma Rays from the Galactic Center



M_{DM}>10 TeV

Boost factor =<J>/$<J>_{NFW}$≈ 10^3

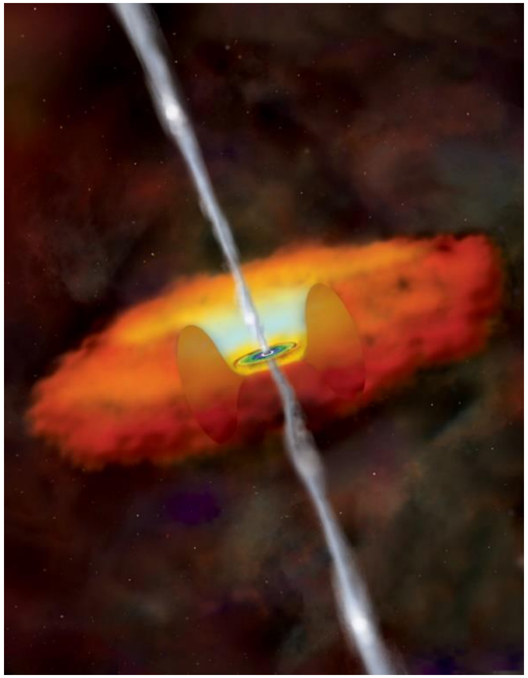
Bg. compatible with Fermi-LAT

(Fermi-LAT Data)	W^+W^-
M	51.7 ± 5.2
A	4.44 ± 0.34
B	3.29 ± 1.03
Γ	2.63 ± 0.02
$\chi^2/\,\mathrm{dof}$	0.75

J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1204.0655v1], PRD 86, 103506 (2012); [arXiv:1302.6871v2][astro-ph.CO], JCAP04 (2013) 051

Neutrinos

Cosmic Neutrino Sources



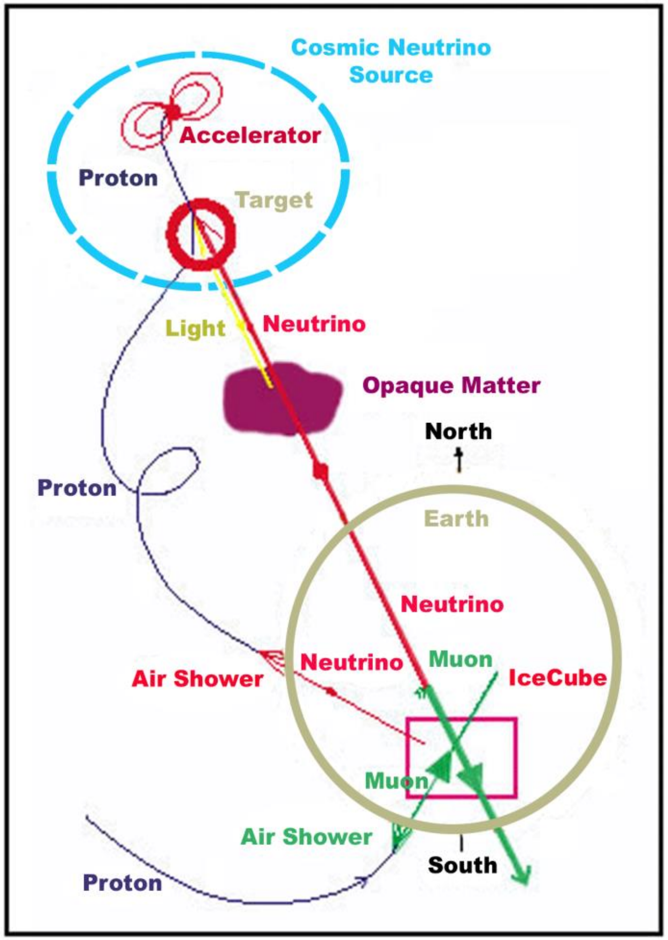
$$p + (p \text{ or } \gamma) \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$
$$\rightarrow \pi^{\pm} \rightarrow \nu_e \nu_\mu \rightarrow \nu_e \nu_\mu \nu_\tau$$

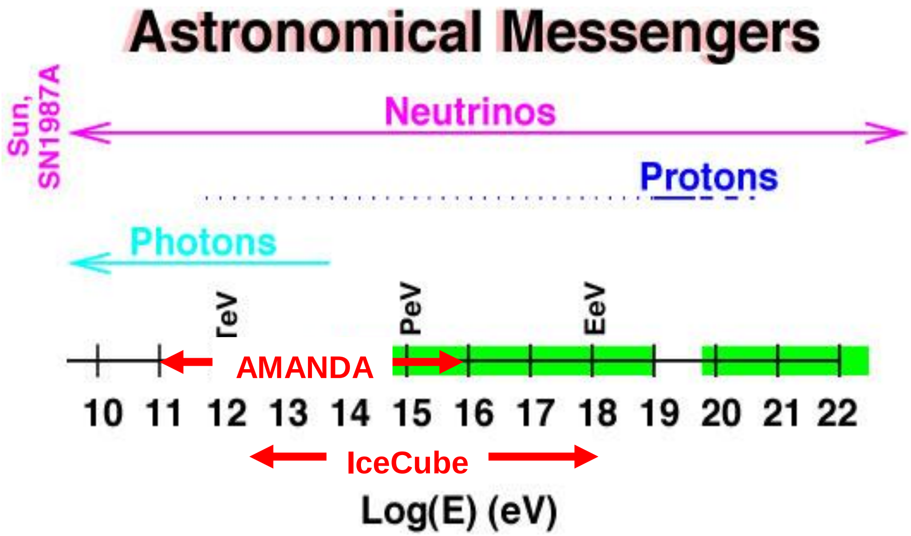
(1:2:0) (1:1:1)

- Protons interact in target and produce pions
- Neutral pions $\rightarrow$ photons
- Charged pions $\rightarrow$ neutrinos
- Oscillations result in 1:1:1 flavor ratio at detector

Sources:
- Active Galactic Nuclei
- Supernova Remnants
- Gamma Ray Bursts

Astronomical Messengers





Protons
- bent below 10 EeV
- above 50EeV GZK cut-off

Photons
- scattered/absorbed above 50 TeV

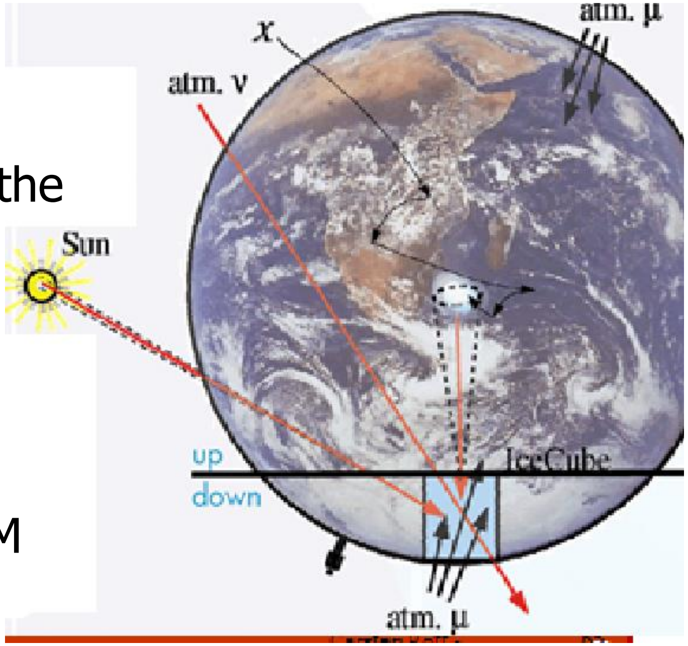
Neutrinos
- Unobscured view
- Point back to their sources
- Cover entire energy spectrum

Neutrinos

$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3} \sum_{a=1}^{2} \sum_{i}^{\text{channels}} P_{fp} \cdot \frac{\zeta_i^{(a,\nu_p)}}{a} \frac{dN_i^{(\nu_p)}}{dE} \cdot \frac{\Delta\Omega \langle J_{(a)} \rangle_{\Delta\Omega}}{4\pi M^a}$$

Massive bodies could gravitationally trap Dark Matter

- The Sun could capture WIMPs directly
- WIMPs orbiting the sun could be captured by the Earth



WIMPs could accumulate in the center of these massive bodies and annihilate to produce neutrinos as part of the annihilation products

Neutrino Telescopes can search indirectly for DM by detecting these neutrinos

Neutrinos from the Galactic Center

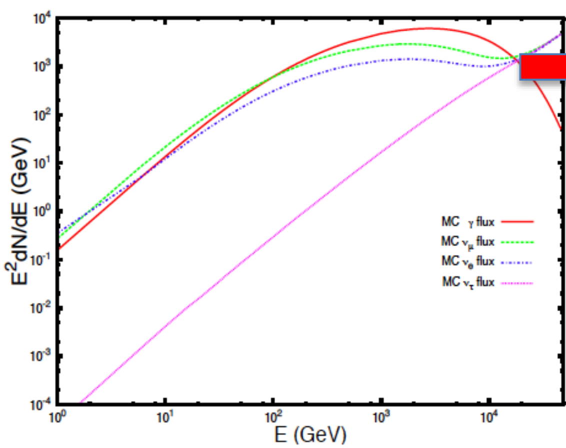
$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3}\sum_{a=1}^{2}\sum_{i}^{\text{channels}} P_{fp}\cdot\frac{\zeta_i^{(a,\nu_p)}}{a}\frac{dN_i^{(\nu_p)}}{dE}\cdot\frac{\Delta\Omega\,\langle J_{(a)}\rangle_{\Delta\Omega}}{4\pi M^a}$$

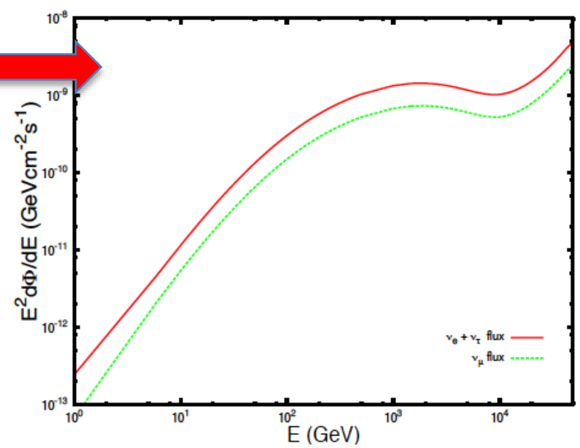
1. W^+W^- boson channel parameters from gamma-rays fit:

$M_{DM} \approx 50$ TeV

Neutrinos flux at the Earth needs to account for:

2. neutrino oscillation



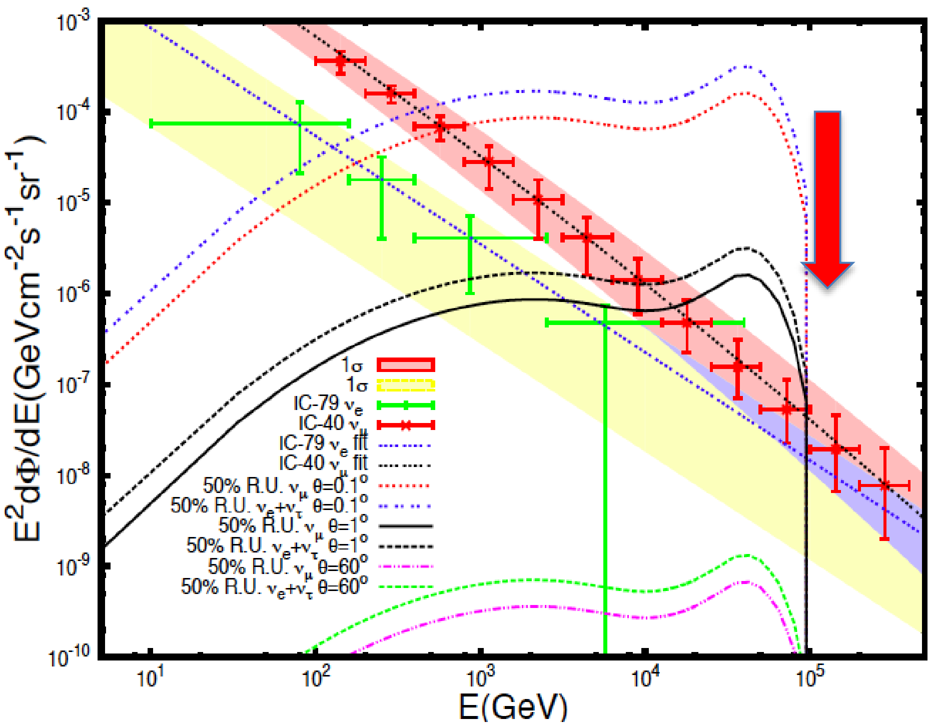


3. detector different (in)sensitivity to neutrinos flavors and antineutrinos

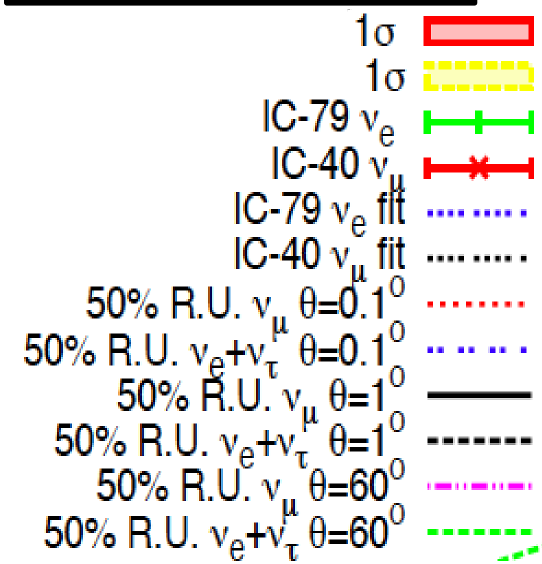
J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1403.6018], PRD; [arXiv:1404.2067]TAUP 2013 Proceedings

Neutrinos from the Galactic Center

$$\frac{d\Phi_{\nu_f}}{dE} = \sum_{p=1}^{3}\sum_{a=1}^{2}\sum_{i}^{\text{channels}} P_{fp}\cdot\frac{\zeta_i^{(a,\nu_p)}}{a}\frac{dN_i^{(\nu_p)}}{dE}\frac{\Delta\Omega\langle J_{(a)}\rangle_{\Delta\Omega}}{4\pi M^a}$$



$$\Delta\Omega = 2\pi(1-\cos\theta)$$

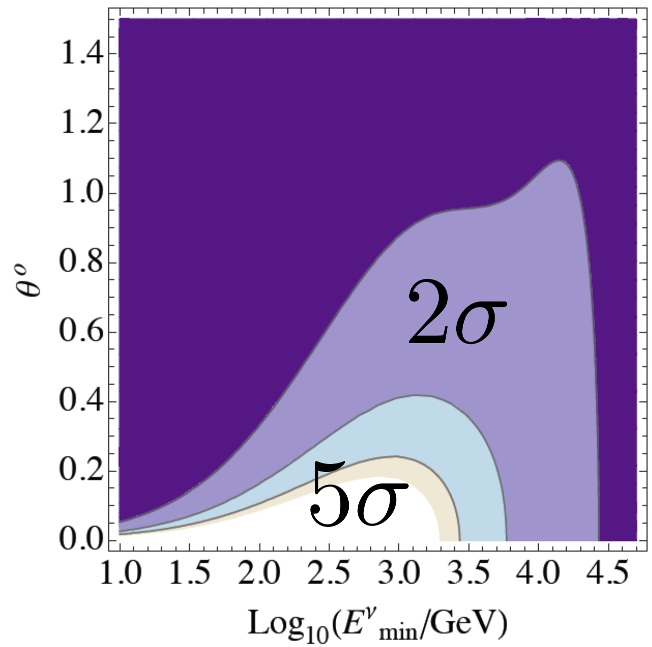


Neutrinos from the Galactic Center

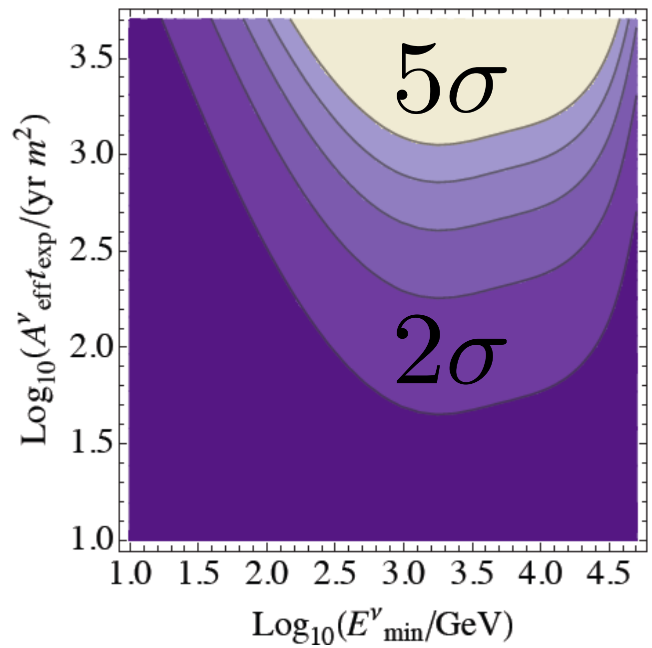
W^+W^- **channel**, with $\theta = 0.6^o$, $E_{min} \approx 1$ TeV and 5 years we need:

$A_{eff} \approx 40\ m^2$ to get ≈2σ signal; $A_{eff} \approx 200\ m^2$ to get a ≈5σ signal;

$$Af = A_{\rm eff} \times t_{\rm exp} = 100\,{\rm m}^2\,{\rm yr}$$



$$\theta = 0.6^\circ$$



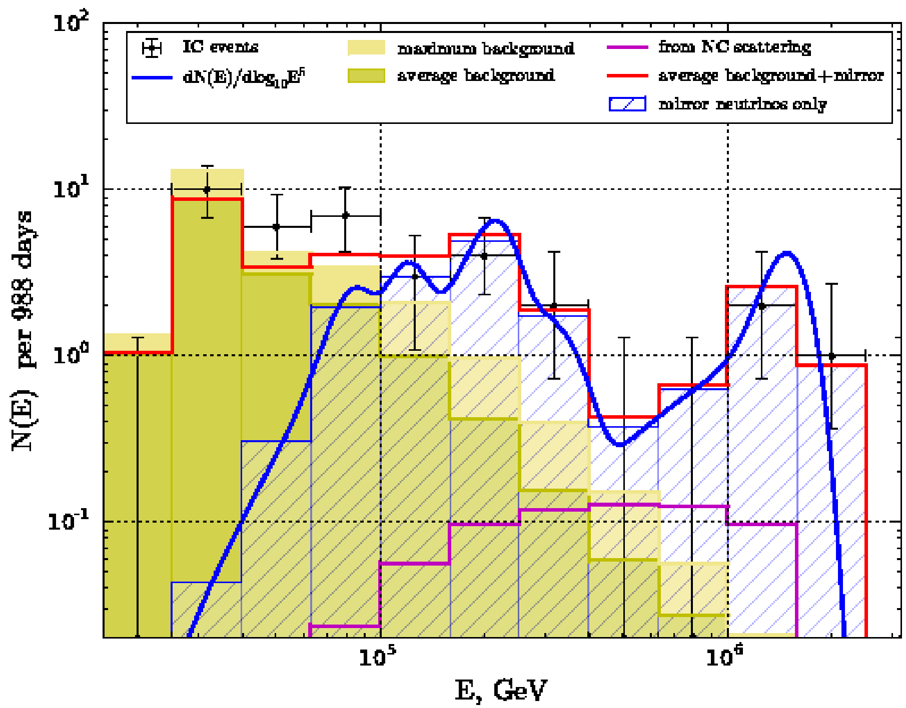
J. A. R C., V. Gammaldi, A. L. Maroto arXiv [1403.6018], PRD; [arXiv:1404.2067]TAUP 2013 Proceedings

PeV neutrinos

Non-atmospheric origin.

Neutrinos

If related to Dark Matter, it demands very heavy Dark Matter



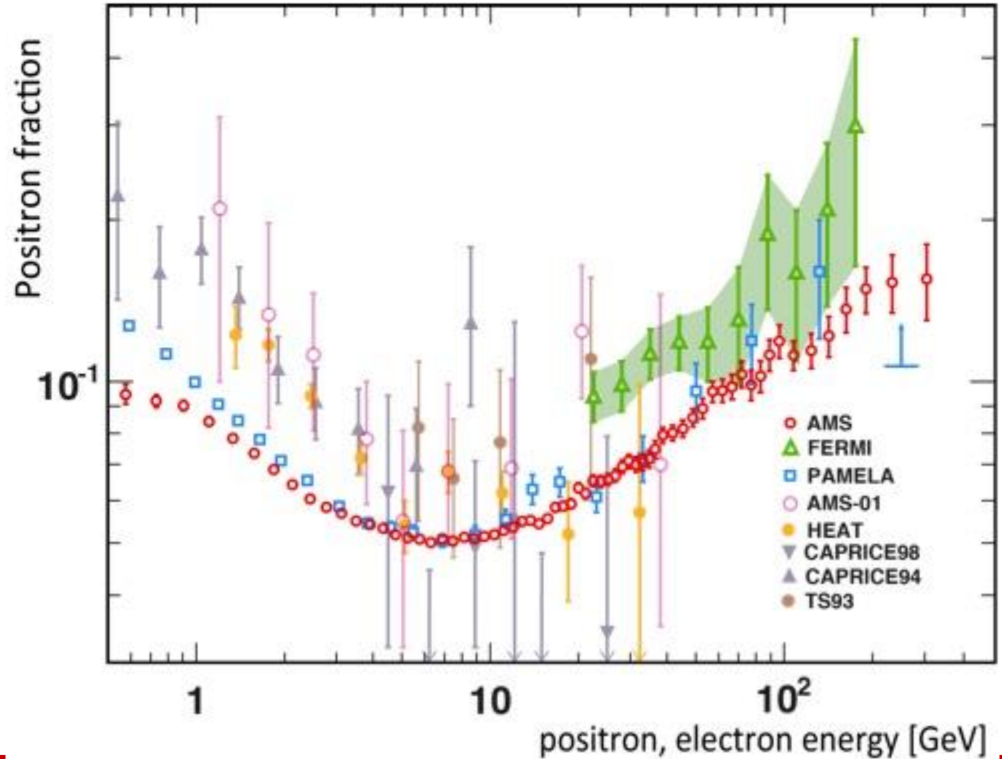
Antimatter: Positrons

Positron fraction increases at high energy

1.- Dark Matter

2.- Pulsars

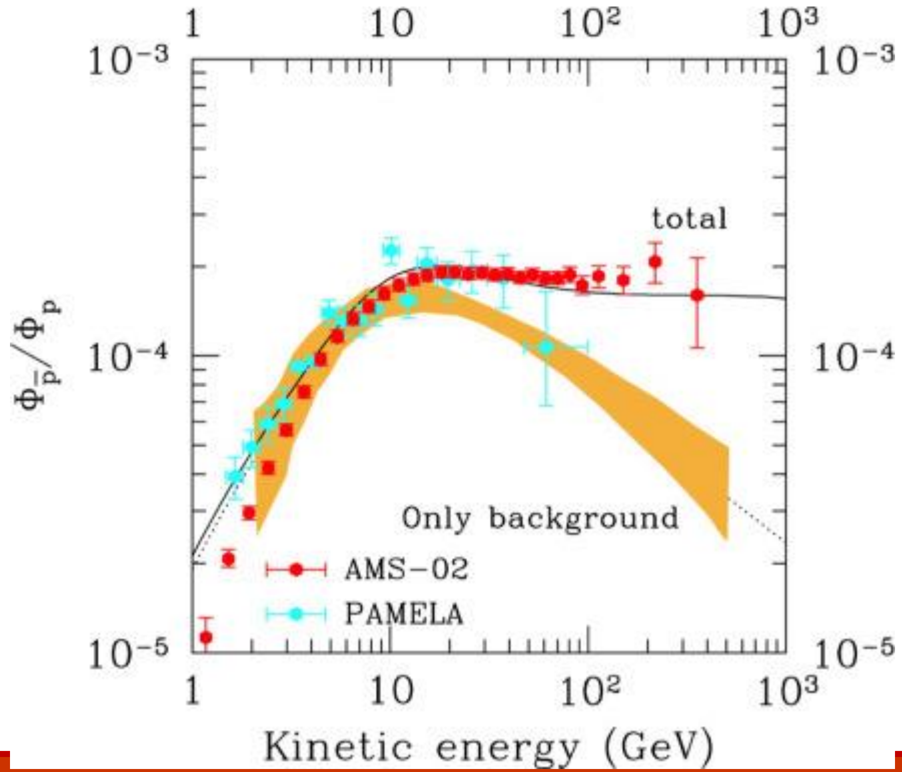
Positrons



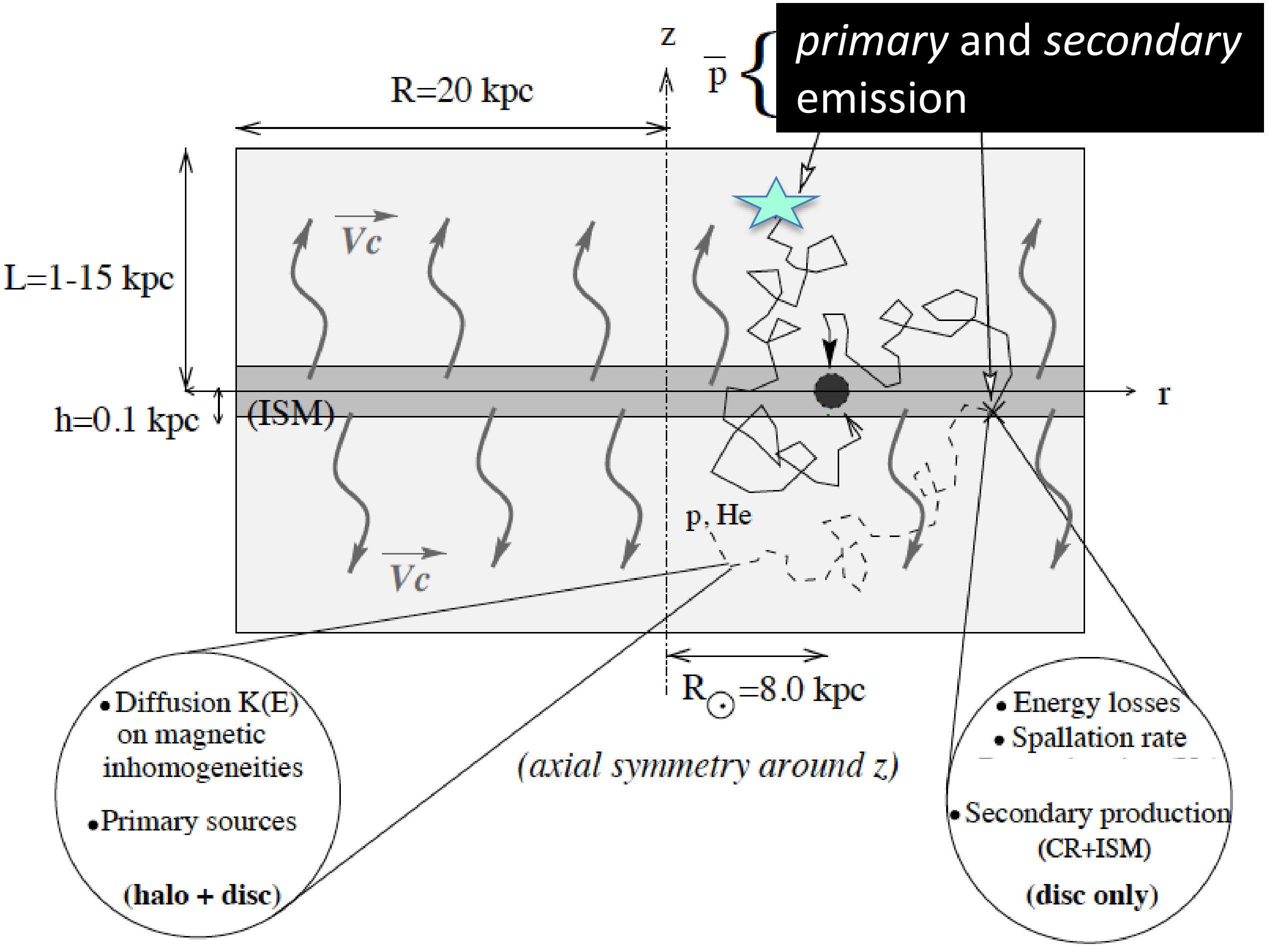
Antimatter: Antiprotons

Antiproton flux observations constraint the dark matter explanation

Antiprotons



Antiprotons from the Galactic Center



- V_c convective velocity
- $K(E_{\bar{p}})$ pure diffusion term
- p-$\bar{p}$ annihilations (secondary) and ISM interactions (tertiary)
- $Q(E_{\bar{p}}, x, t)$ is the primary source

A&A 388, 676-687 (2002) Barrau et al. , arXiv:0112486v2

Antiprotons from the Galactic Center

$$\frac{\partial}{\partial t}\frac{dN_{\bar{p}}}{dE_{\bar{p}}} - K(E_{\bar{p}})\cdot\nabla^2\frac{dN_{\bar{p}}}{dE_{\bar{p}}} + \frac{\partial}{\partial z}\left(sign(z)\frac{dN_{\bar{p}}}{dE_{\bar{p}}}V_c\right) = \hat{Q} - 2h\delta(z)\Gamma_{inel}\frac{dN_{\bar{p}}}{dE_{\bar{p}}}$$

≈ 0

The anti-proton differential flux at the Top of the Atmosphere (TOA) is the solution of the diffusion equation for steady state condition:

$$\frac{\mathrm{d}\Phi_{\bar{p}}}{\mathrm{d}E_{\bar{p}}} = \sum_{a=1}^{2}\sum_{i}^{\text{channels}}\frac{\zeta^{(a)}}{a}\frac{\mathrm{d}N_i^{(a,\bar{p})}}{\mathrm{d}E_{\bar{p}}}\cdot\frac{v_{\bar{p}}}{4\pi}\left(\frac{\rho_\odot}{M}\right)^a R_{(a)}(E_{\bar{p}})$$

- $R(E_{\bar{p}})$ encodes all the astrophysics of spatial production and propagation ($\Pi(L)$ depends on the DM distribution):

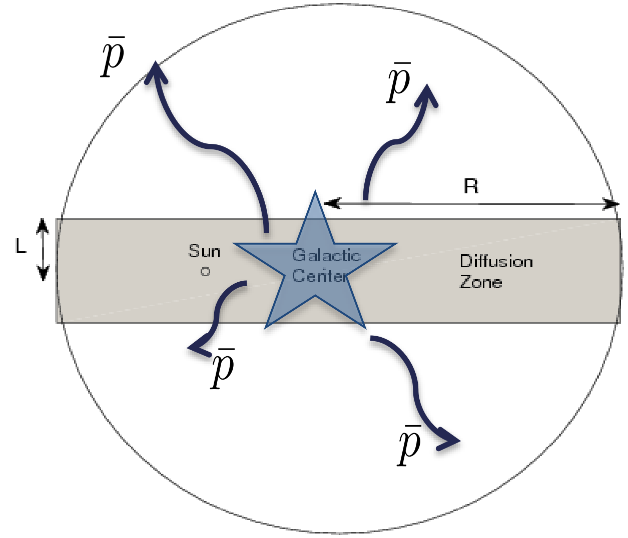
$$R(E_{\bar{p}}) = \sum_{m=1}^{\infty} J_0\left(\zeta_m\frac{r_\odot}{R}\right)\exp\left[-\frac{V_c L}{2K\left(E_{\bar{p}}\right)}\right]\frac{\Pi_m\left(L\right)}{A_m \sinh\left(S_m L/2\right)}$$

Antiprotons from the Galactic Center

The antiprotons spatial production and propagation is described by :

$$R^{\delta}(E_{\bar{p}}) = \frac{2}{R^2}\sum_{m=1}^{\infty}\frac{J_0\left(\zeta_1\frac{r_\odot}{R}\right)}{A_m J_1^2(\zeta_m)} \times Const$$

$$A_m(E_{\bar{p}}) = 2h\Gamma_{inel} + V_c + K(E_{\bar{p}})\, S_m \coth\left[S_m L/2\right]$$



$$K(E_{\bar{p}}) = K_0\beta(p/GeV)^{\delta}$$

Model	δ	K_0 [kpc^2/Myr]	V_c [km/s]	L [kpc]
MIN	0.85	0.0016	13.5	1
MED	0.70	0.0112	12	4
MAX	0.46	0.0765	5	15

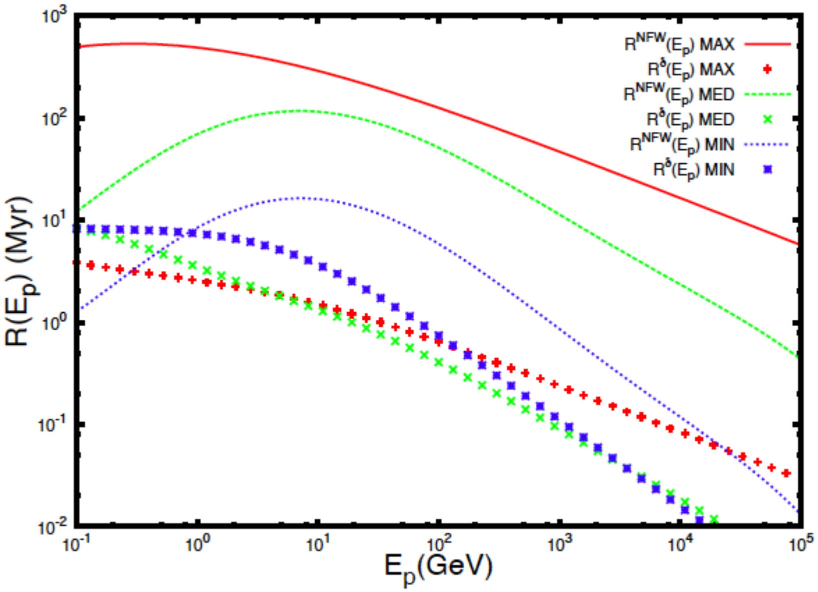
Where the new constant volume needs to be determined.

Antiprotons from the Galactic Center

To determine the new constant, we refer to the astrophysical factor for "not charged" particles:

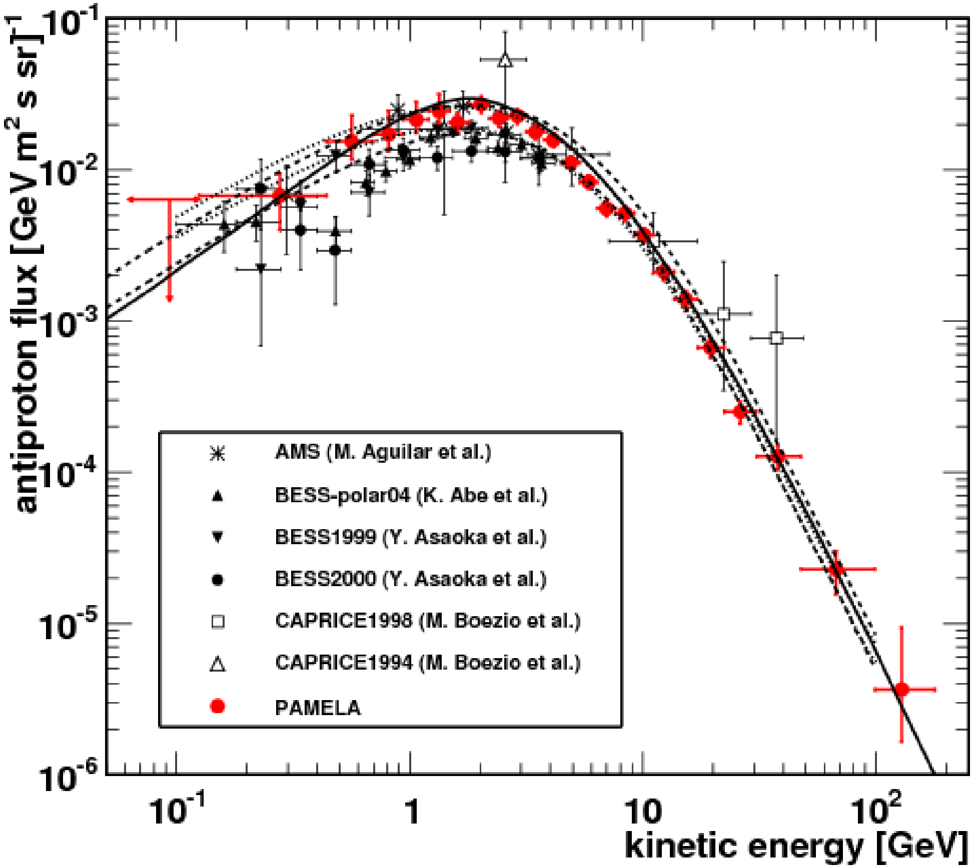
$$\langle J_a \rangle = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \mathrm{d}\Omega \int_0^{l_{max}(\Psi)} \rho^a[r(l)]dl(\Psi)$$

$$\left(\frac{\rho(r,0)}{\rho\odot}\right)^2 \simeq C_2 \times \delta^{(3)}(\vec{r})$$



$$C_2 = Const \times 2\pi = \langle J \rangle_{\Delta\Omega}^{NFW} \Delta\Omega_{HESS} \left(\frac{D_\odot}{\rho_\odot}\right)^2 \approx \quad 2.13 \times 10^{60} m^3 \mathrm{sr}$$

Pamela Antiproton Data



Phys. Rev. Lett. 105, 121101 – Adriani et al. arXiv:1007.0821v1

- Compatible with antiproton *secondary* emission

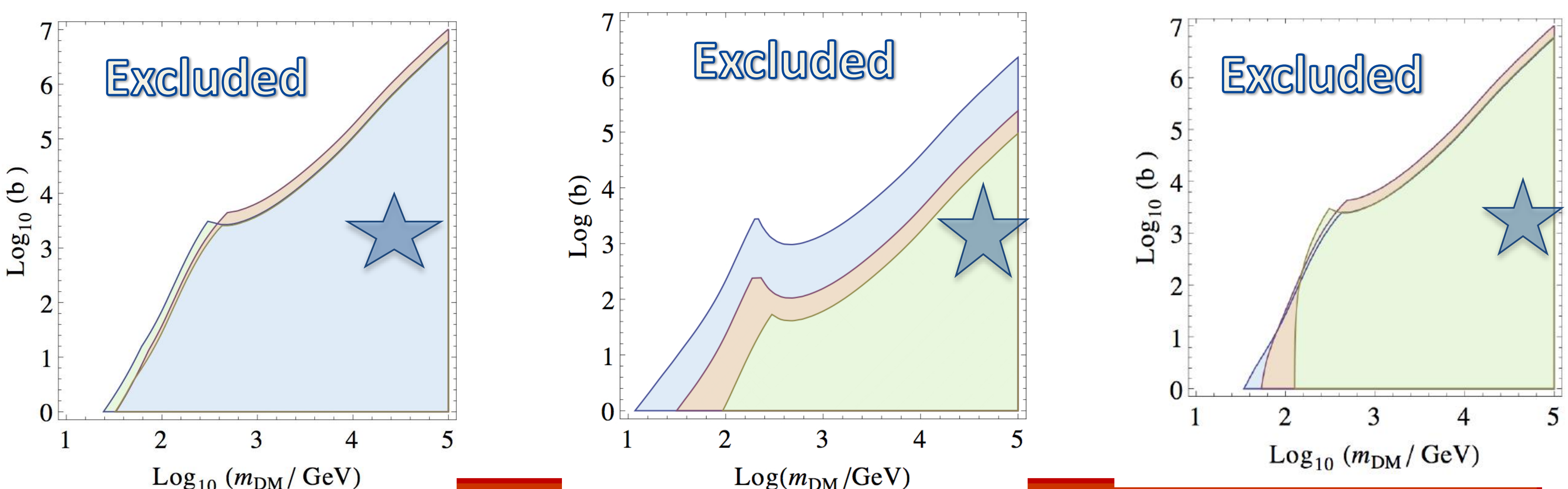
- Any new primary source needs to be compatible with such antiproton flux.

Antiprotons from the Galactic Center

$$\frac{d\Phi_{\bar{p}}}{dE_{\bar{p}}} = \frac{v_{\bar{p}}}{4\pi}\frac{1}{2}\left(\frac{\rho_\odot}{m_{DM}}\right)^2 \sum_j \langle\sigma v\rangle_j \frac{dN^j_{\bar{p}}}{dE_{\bar{p}}}\left(b^j_{NFW} \times R^{NFW}(E_{\bar{p}}) + b^j_\delta \times C_1 \times R^\delta(E_{\bar{p}})\right).$$

MIN MED MAX

$b^W_{NFW}=0$ $b^W_\delta=0$ $b^W_{NFW}=1$



Antiprotons from the Galactic Center

- Gamma-ray HESS data from the J1745-290 point-like source in the GC is well fitted by heavy 50 TeV DM annihilating into W^+W^-

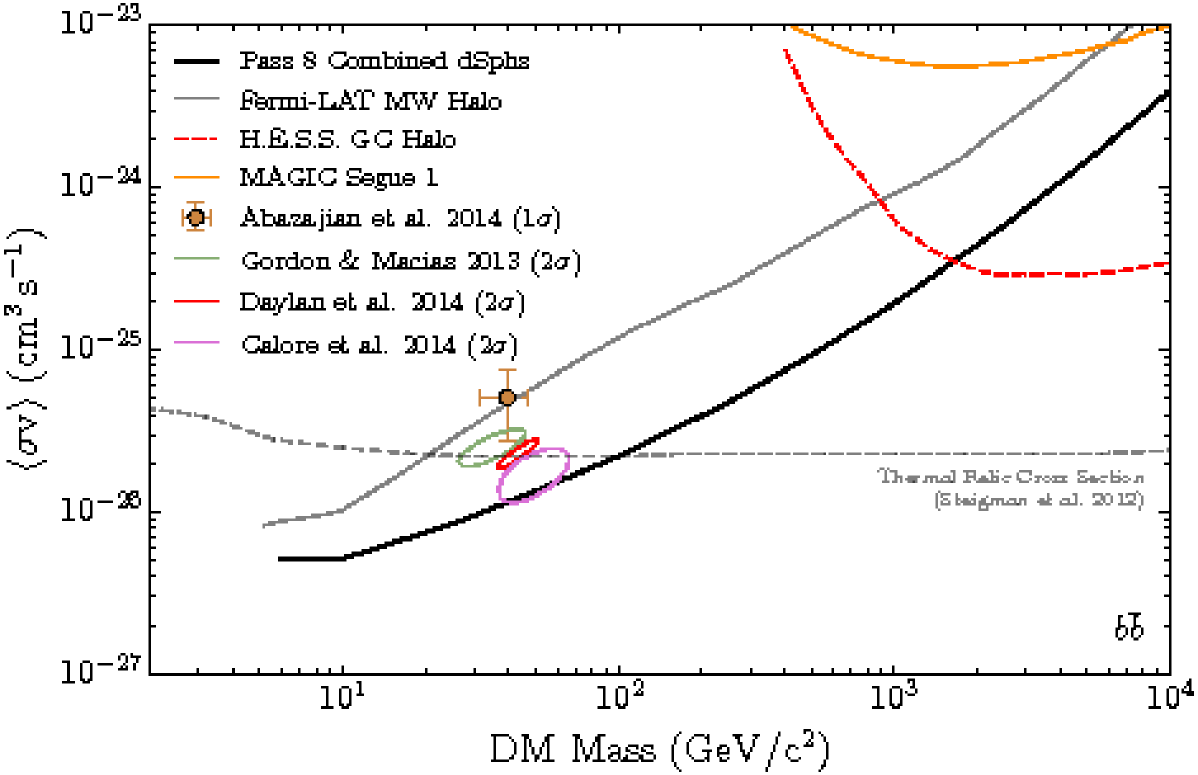
- Fermi-LAT gamma-rays data from the same region are compatible with a power-law background component.

- Actual generation of neutrino experiment is not able to exclude such DM hypothesis mainly due to detector angular resolution.

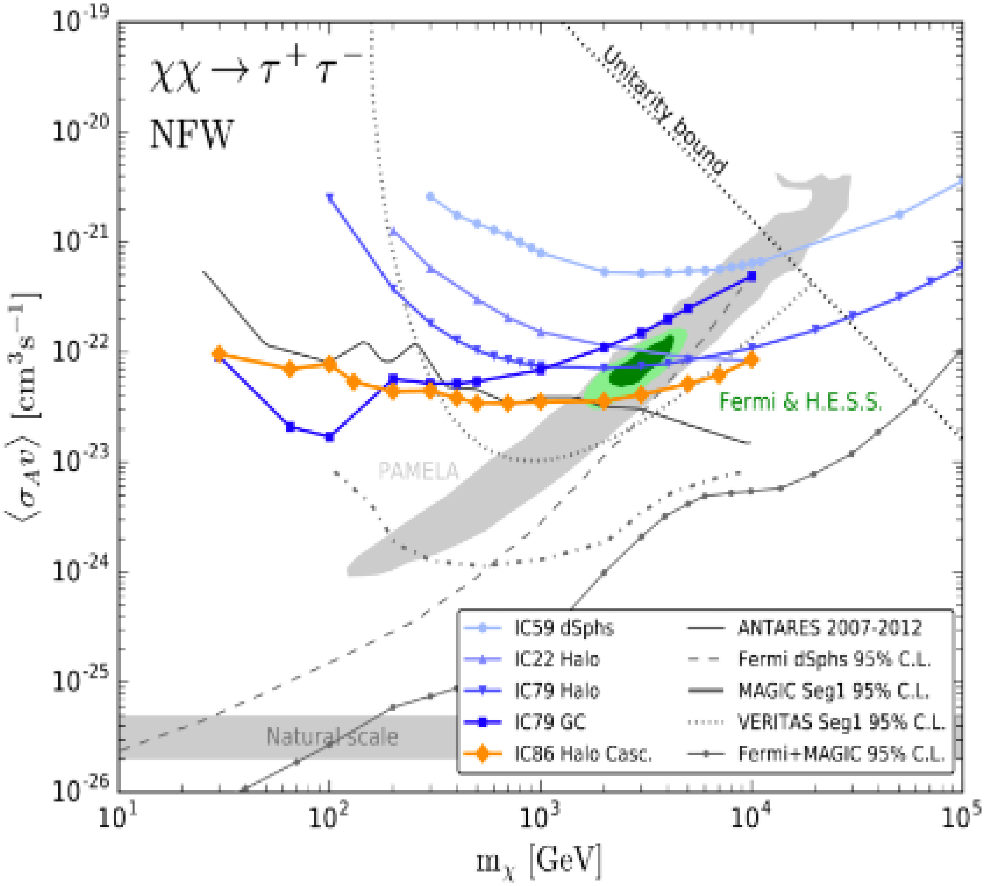
- PAMELA antiprotons data are compatible with a NFW heavy DM.

Resume of indirect constraints

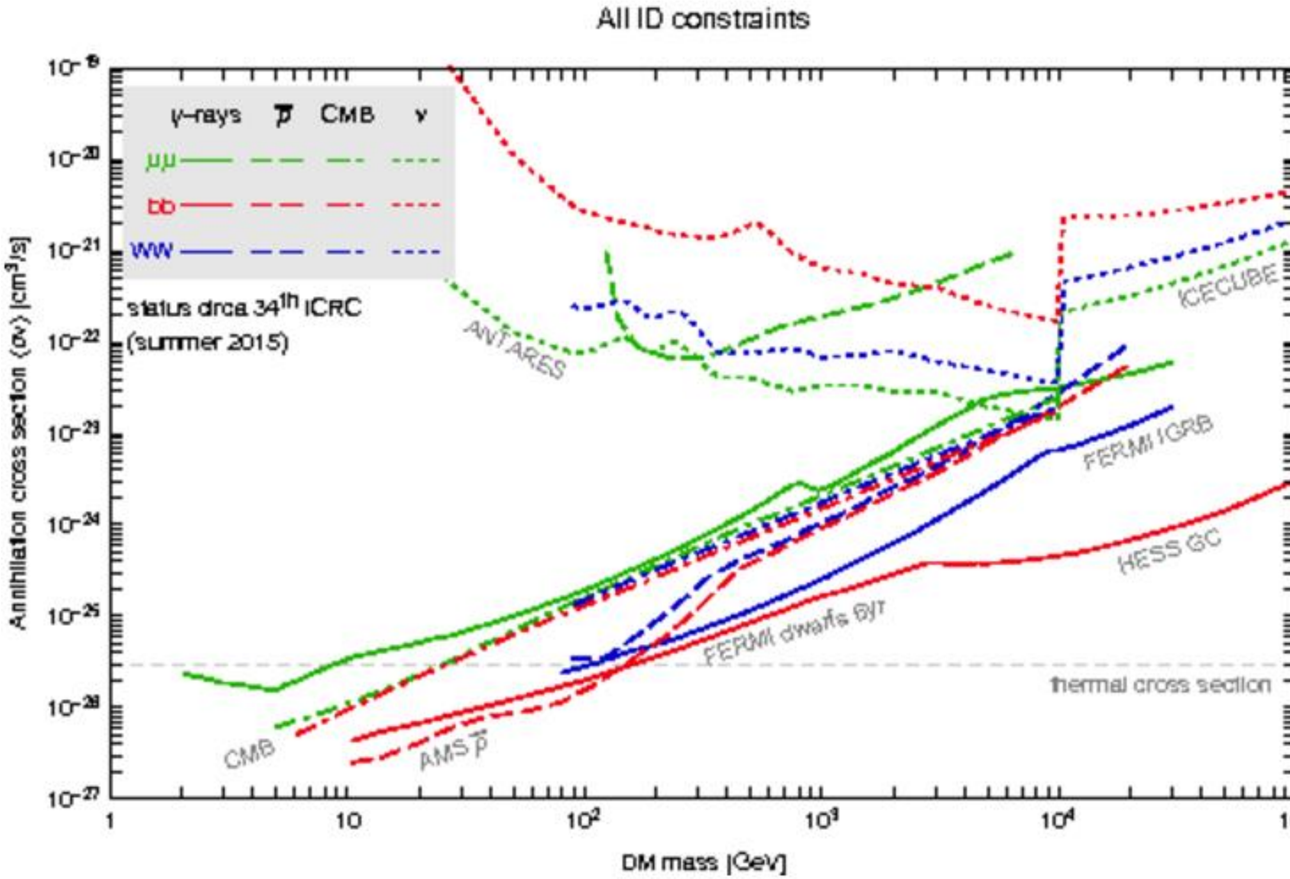
Gamma rays



Resume of indirect constraints



Resume of indirect constraints



Uncertainties in indirect searches

- Indirect Dark Matter searches suffer from important uncertainties:
  - DM distribution:
    - Baryonic effects
    - Central density of DM halos
    - Substructures
  - DM particle models:
    - Model dependent analyses
    - Not very constrained space of parameters.

- Monte Carlo event generators
  - Focus in collider physics

Outline: Monte Carlo Event Generators

- Introduction
- Comparison of Monte Carlo event generators
- Software:
  - PYTHIA 6.418 (Fortran)
  - HERWIG 6.5.10 (Fortran)
  - PYTHIA 8.165 (C++)
  - HERWIG 2.6.1 (C++)
- Conclusions

JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

Motivation

- Gamma-ray spectra do not depend on DM model or DM model except for small particular tuned regions of the parameter space:

- Fitting functions for particle-antiparticle channels.

JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

- Numerical functions for particle-antiparticle channels.

Cirelli et al., JACP 1103 (2011) arXiv :1012.4515

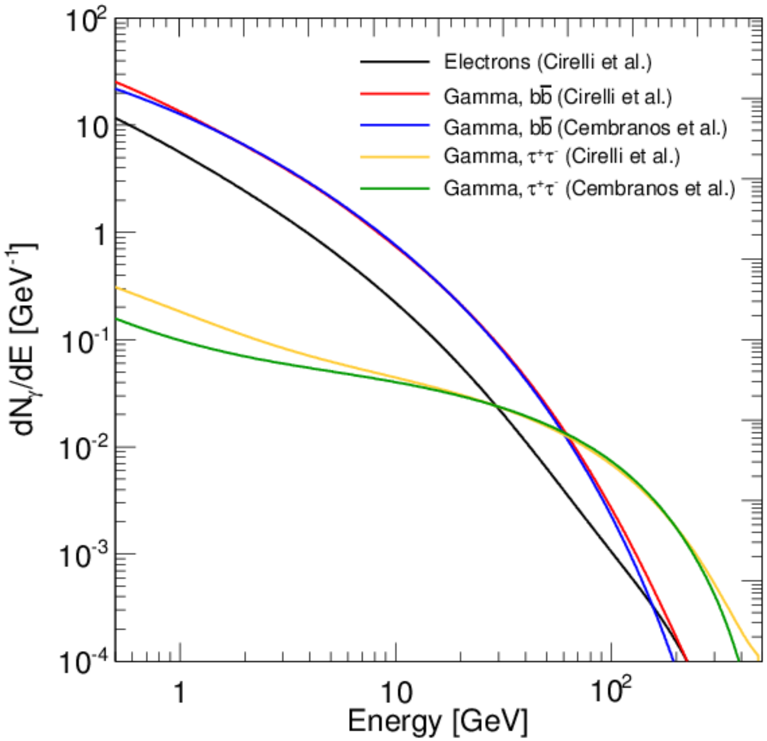
(PYTHIA 8.165 , C++)

Motivation

- Comparison

Miguel Angel Sanchez Conde and Mattia Fornasa, private communication (2012).

$$M_{DM} = 500 \text{ GeV}$$



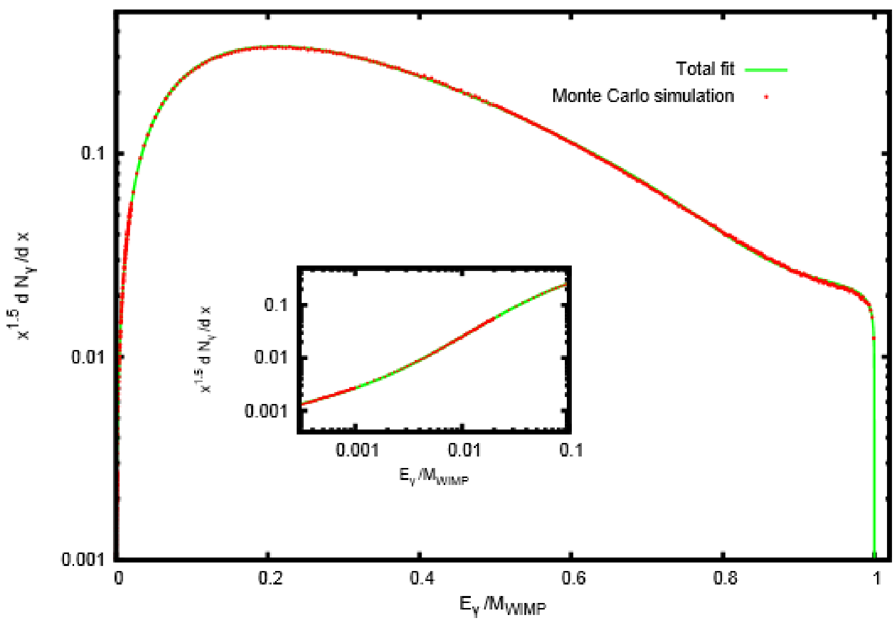
JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

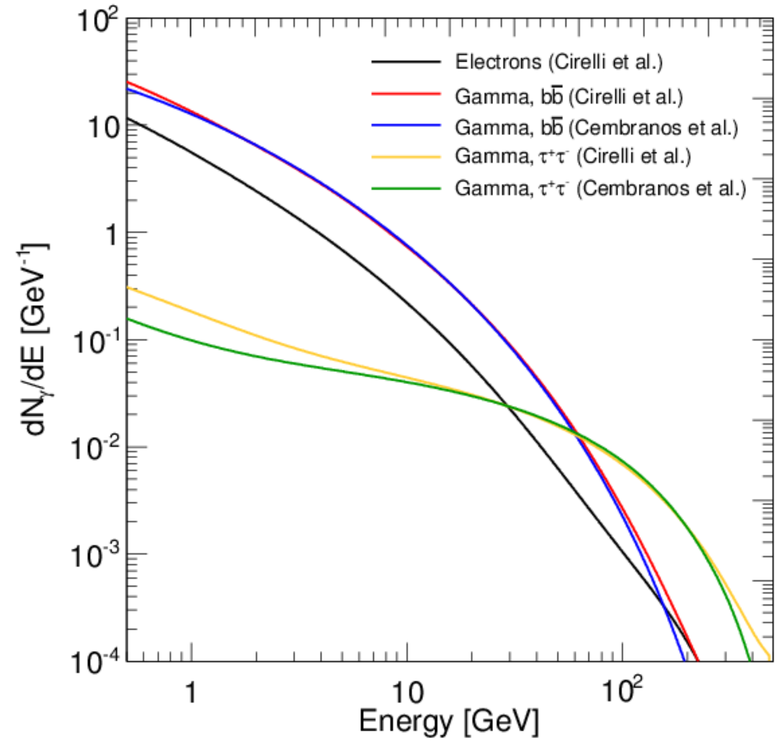
Cirelli et al., JACP 1103 (2011) arXiv :1012.4515

(PYTHIA 8.165 , C++)

Motivation



(c) Photon spectrum for $M = 1000\,\mathrm{GeV}$ for $\tau^+\tau^-$ channel.



JARC, Cruz-Dombriz, Dobado, Lineros and Maroto, Phys. Rev. D 83, 083507 (2011) arXiv: 1009.4939

(PYTHIA 6.418, Fortran)

Cirelli et al., JACP 1103 (2011) arXiv :1012.4515

(PYTHIA 8.165 , C++)

Comparison analysis

- Comparison of Monte Carlo event generators:
  - PYTHIA 6.418 (Fortran)
  - HERWIG 6.5.10 (Fortran)
  - PYTHIA 8.165 (C++)
  - HERWIG 2.6.1 (C++)

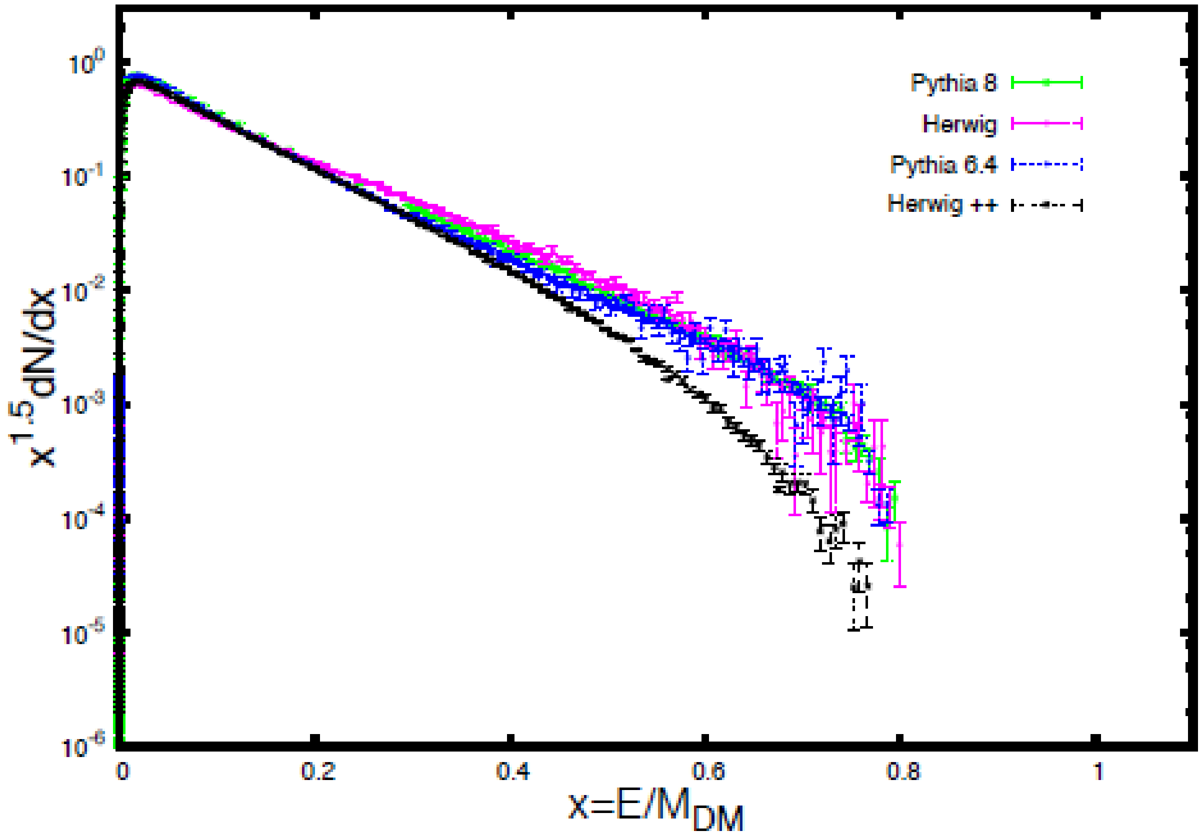
- DM Annihilating/decaying Channels:
  - W^+W^-
  - $\tau^+\tau^-$
  - $b\,\bar{b}$
  - $t\,\bar{t}$

- DM masses: $50\ \mathrm{GeV} < M_{DM} < 10\ \mathrm{TeV}$

JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

W^+W^- channel

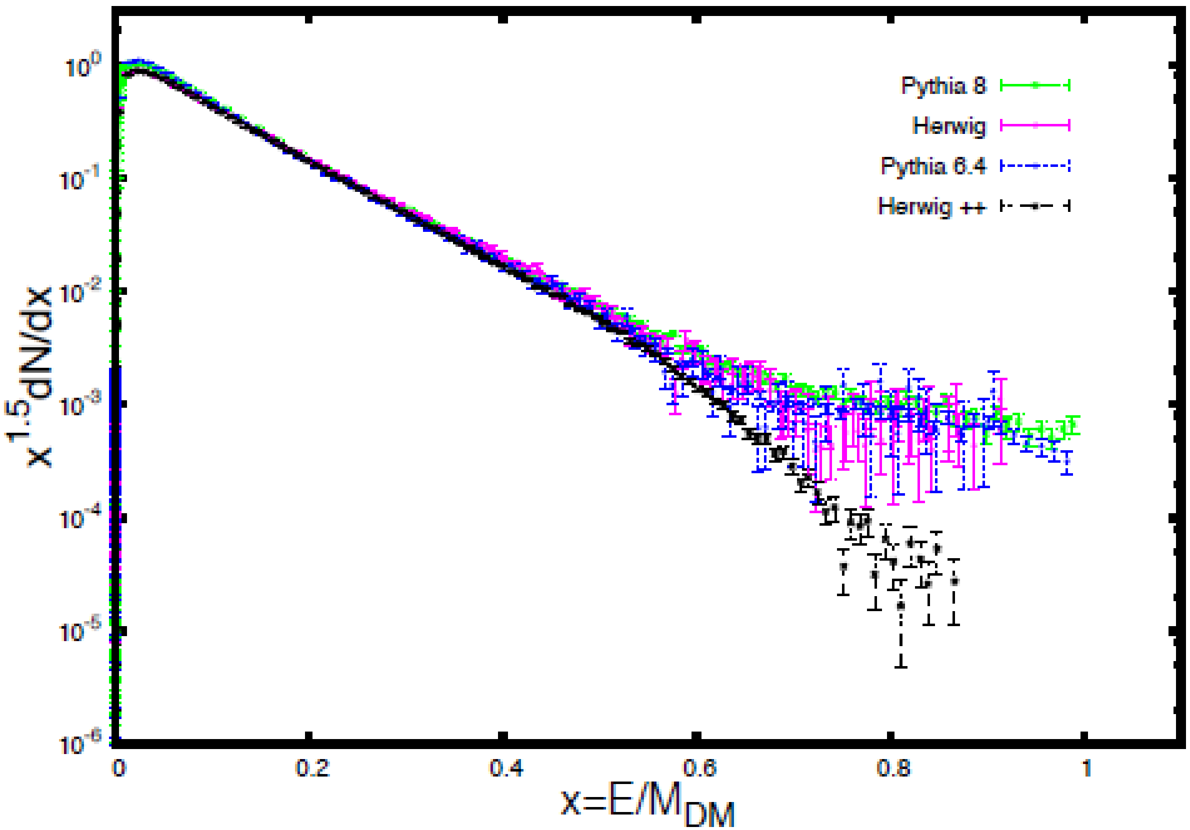
$M_{DM} = 100$ GeV



JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

$b\,\bar{b}$ channel

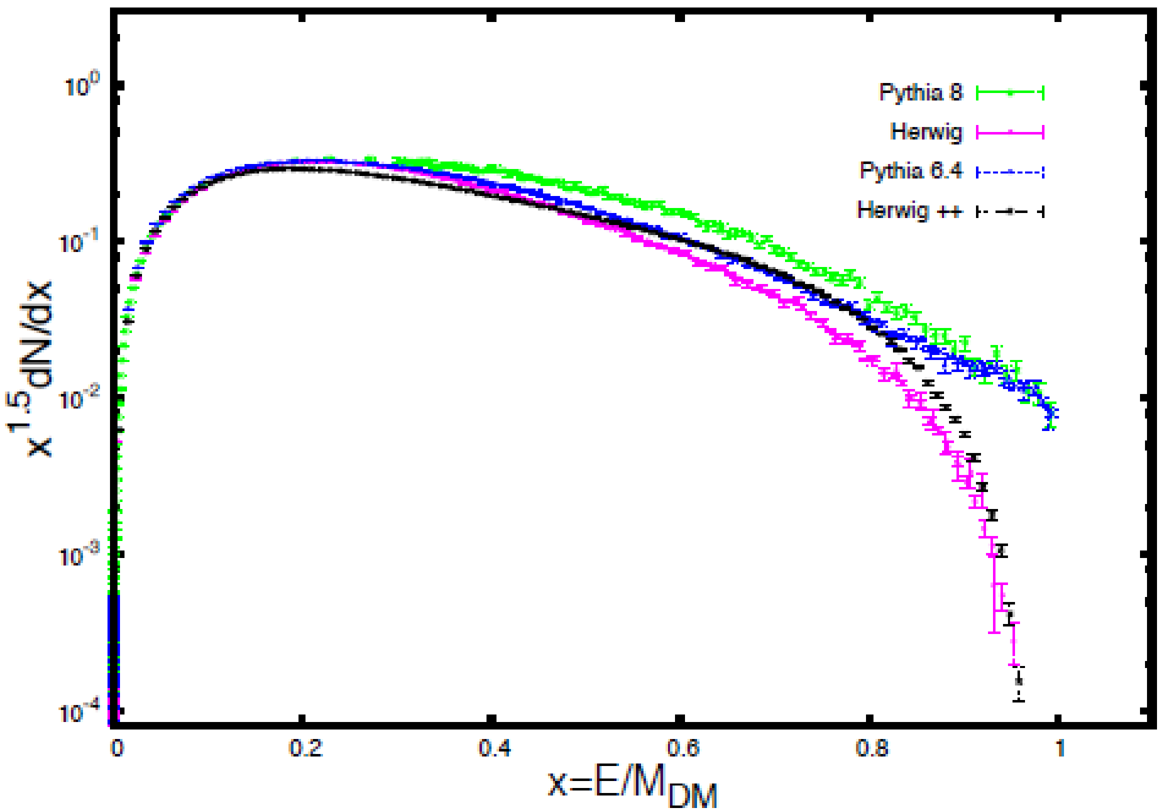
$M_{DM} = 100\ \text{GeV}$



JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

$\tau^+\tau^-$ channel

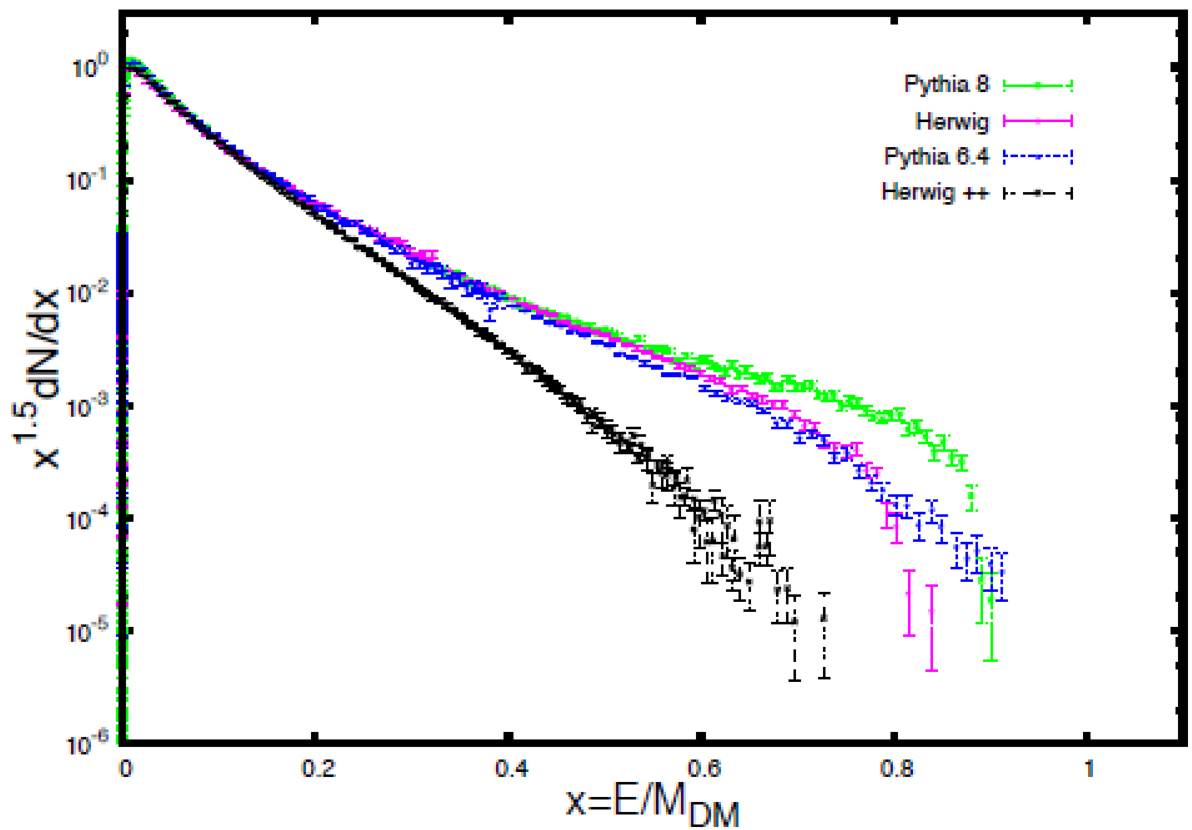
$M_{DM} = 100$ GeV



JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

$t\,\bar{t}$ channel

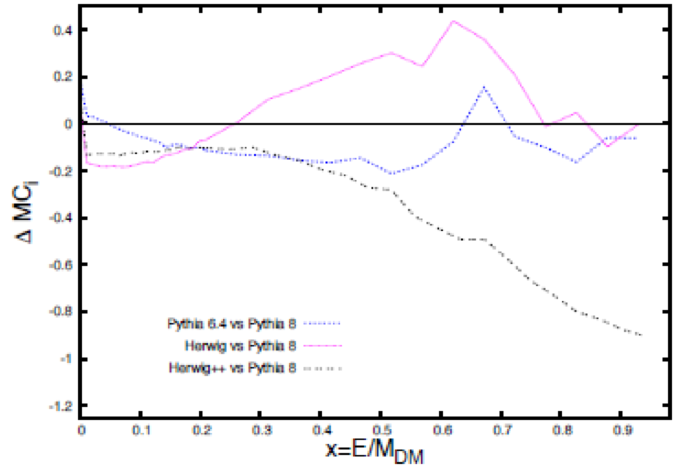
$M_{DM} = 500$ GeV



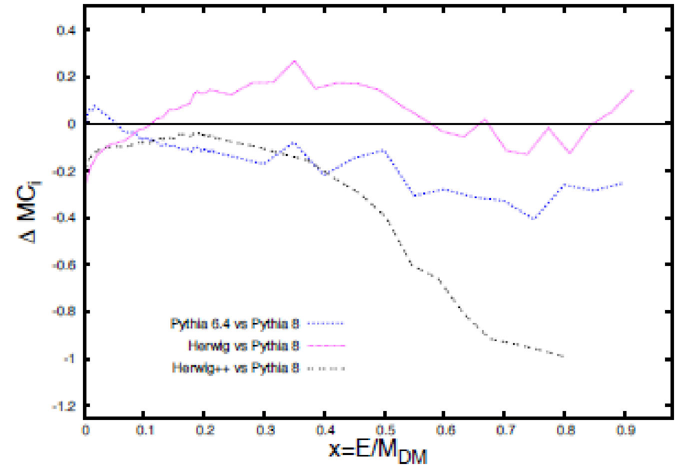
JARC, Cruz-Dombriz, Gammaldi, Lineros and Maroto, JHEP 1309, 077 (2013) [arXiv:1305.2124 [hep-ph]].

Deviations

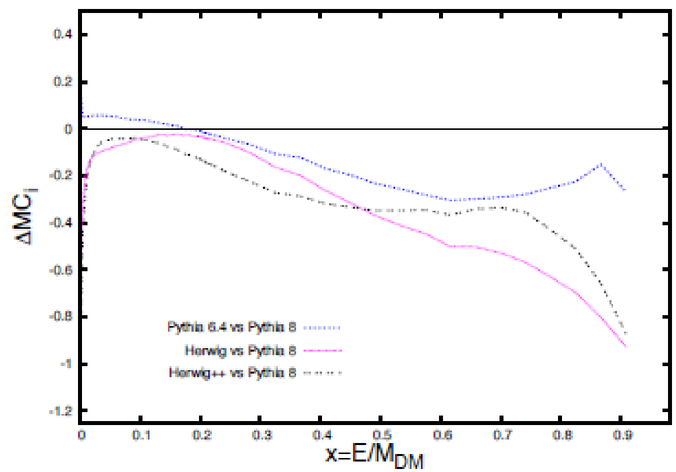
$$\Delta MC_i = \frac{MC_i - \text{PYTHIA 8}}{\text{PYTHIA 8}},$$



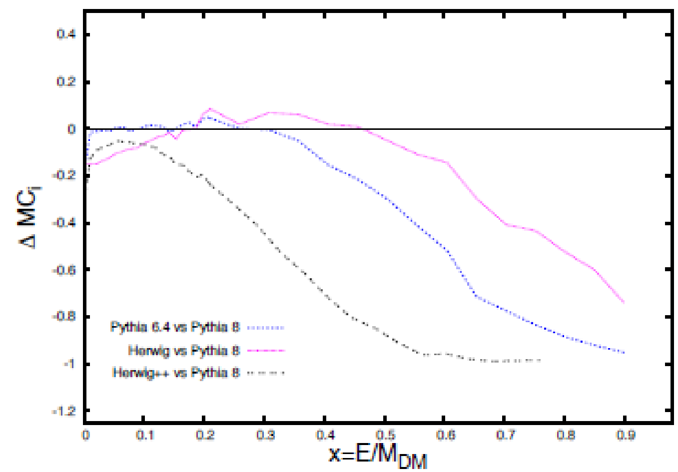
(a) W^+W^- channel



(b) $b\bar{b}$ channel



(c) $\tau^+\tau^-$ channel



(d) $t\bar{t}$ channel

$M_{DM} = 1$ TeV

Photon multiplicities

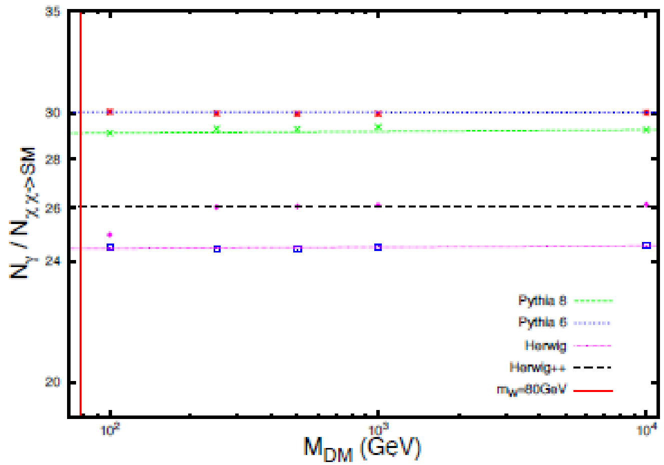
The total amount of photons is well fitted by a power law of the DM mass, *M*:

$$\frac{N_\gamma}{N_{\chi\chi\to SM}} \simeq a \cdot \left(\frac{M}{1\,\mathrm{GeV}}\right)^b ,$$

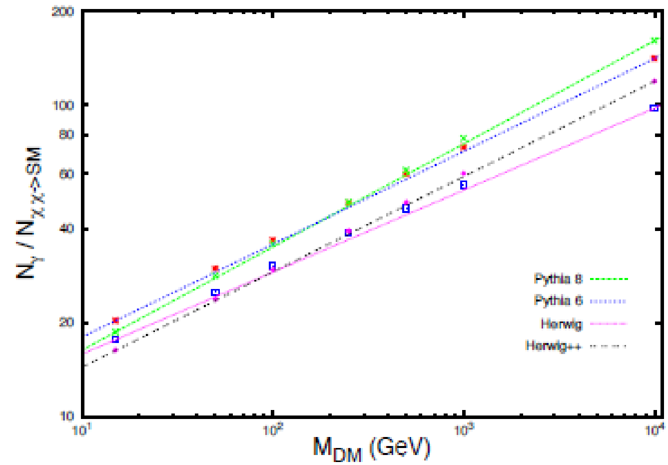
Software/PYTHIA 8	W^+W^-	$b\bar{b}$	$\tau^+\tau^-$	$t\bar{t}$
PYTHIA 6.4	$A = 1.04$ $B = 0$	$A = 1.18$ $B = -0.033$	$A = 0.96$ $B = 0.020$	$A = 1.49$ $B = -0.077$
HERWIG	$A = 0.84$ $B = 0$	$A = 1.13$ $B = -0.068$	$A = 1.00$ $B = -0.029$	$A = 1.02$ $B = -0.038$
HERWIG++	$A = 0.90$ $B = 0$	$A = 0.93$ $B = -0.025$	$A = 0.96$ $B = -0.039$	$A = 0.93$ $B = -0.031$

PYTHIA 8	$a = 28.9$ $b = 0.001$	$a = 7.62$ $b = 0.331$	$a = 2.29$ $b = 0.042$	$a = 14.1$ $b = 0.276$

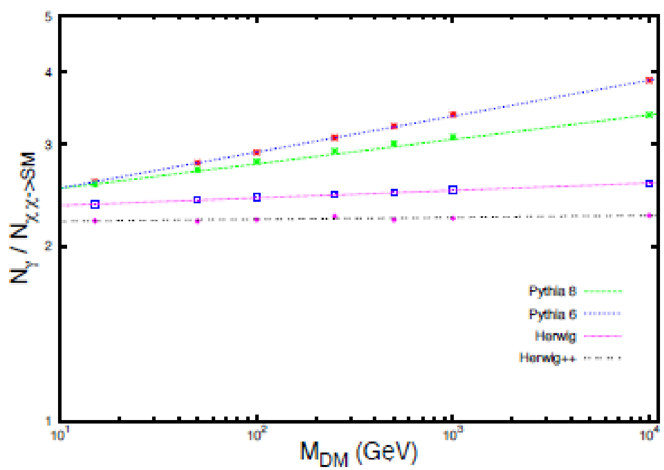
Photon multiplicities



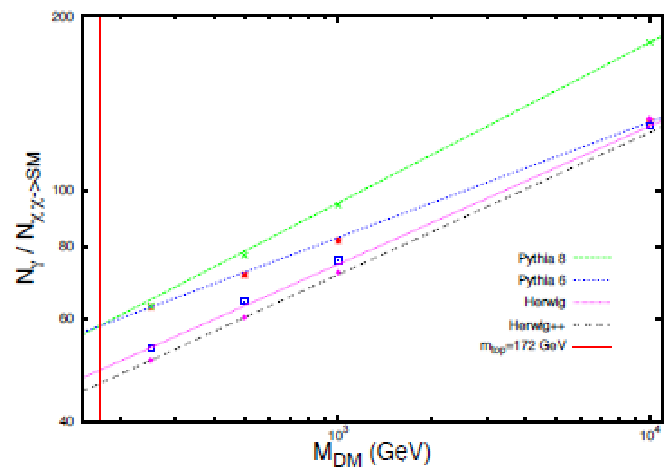
(a) W^+W^- channel.



(b) $b\bar{b}$ channel



(c) $\tau^+\tau^-$ channel



(d) $t\bar{t}$ channel