

FINGERPRINTS OF DARK MATTER IN THE GAMMA-RAY SKY

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SISSA - INTERNATIONAL SCHOOL FOR ADVANCED STUDIES, TRIESTE

ASTROPARTICLE PHYSICS 2014

A JOINT TEVPA/IDM CONFERENCE

AMSTERDAM, 23 JUNE 2014

BASED ON:

ARXIV:1307.6862, 1310.7609 JOINTLY WITH WEI-CHIH HUANG AND WEI XUE

*"It cannot be seen, cannot be felt,
Cannot be heard, cannot be smelt,
It lies behind stars and under hills,
And empty holes it fills."*

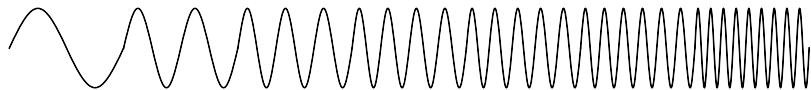
J.R.R. Tolkien, "The Hobbit"





Radio Microwave Infrared Visible Ultraviolet X-ray γ -ray

10^{-7} eV 10^{-3} eV 10^{-1} eV 1.65 - 3.27 eV 10 eV 10^4 eV $>10^6$ eV



Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	γ -ray
10^{-7} eV	10^{-3} eV	10^{-1} eV	1.65 - 3.27 eV	10 eV	10^4 eV	$>10^6$ eV

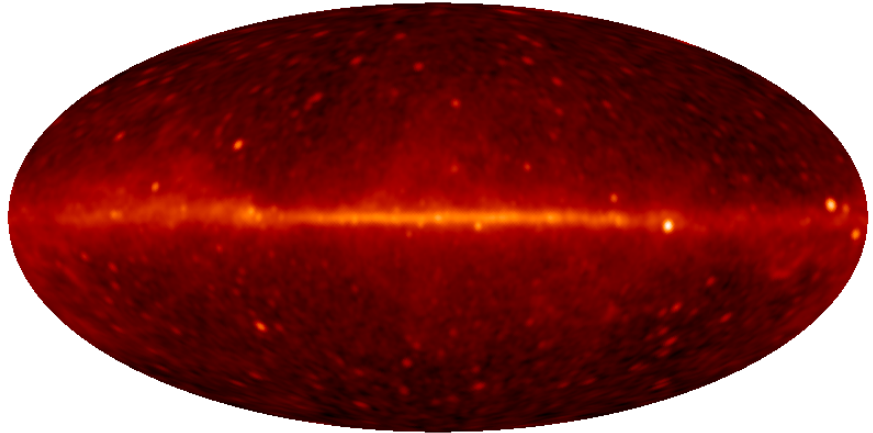
Fermi-LAT: $E_{\gamma} = 300 \text{ MeV} - 300 \text{ GeV}$

<http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi>

Data analysis

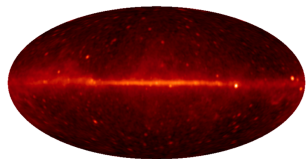
- Download data
- For each gamma-ray photon: Energy
Arrival direction (l,b)
...

Count Map
 $1.2 < E \text{ [GeV]} < 1.5$



-1.2  2.3 Log (photons)

Dissecting the gamma-ray sky



LAT Sky = ?

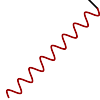
Inverse Compton

High-energy CR e^-

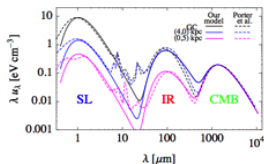


Inverse Compton

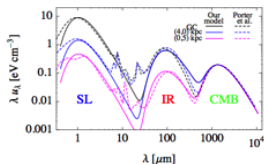
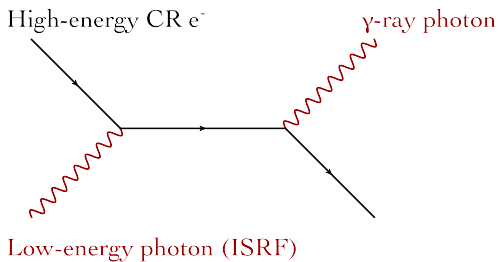
High-energy CR e^-



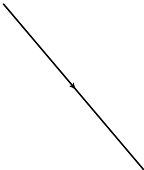
Low-energy photon (ISRF)



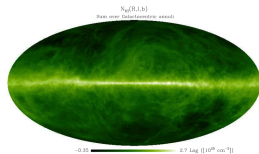
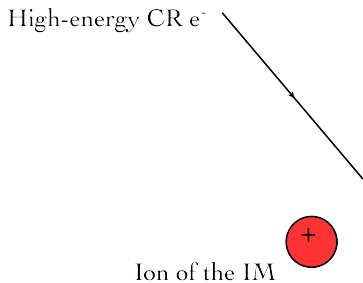
Inverse Compton



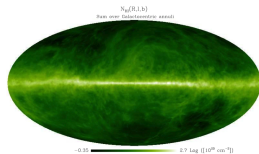
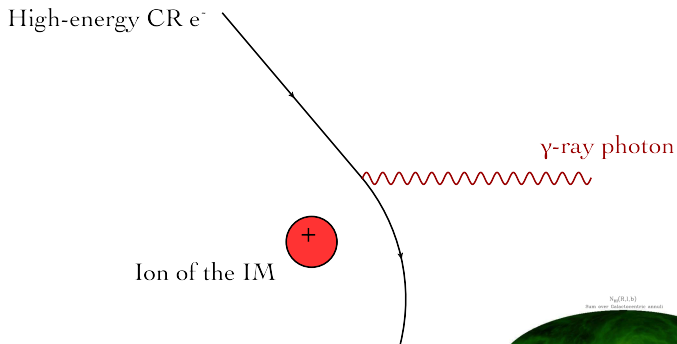
Bremsstrahlung

High-energy CR e^- 

Bremsstrahlung



Bremsstrahlung

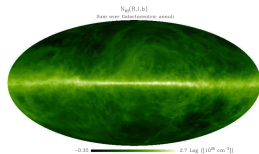


π^0 - decay

High-energy CR p



Ion of the IM

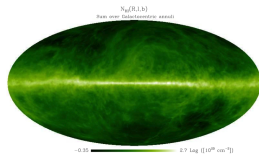


π^0 - decay

High-energy CR p

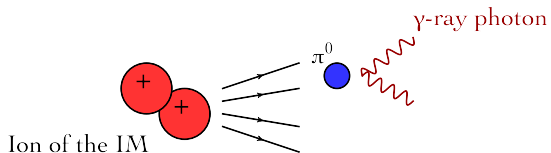


Ion of the IM

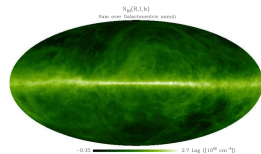


π^0 - decay

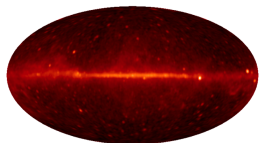
High-energy CR p



Ion of the IM



Dissecting the gamma-ray sky



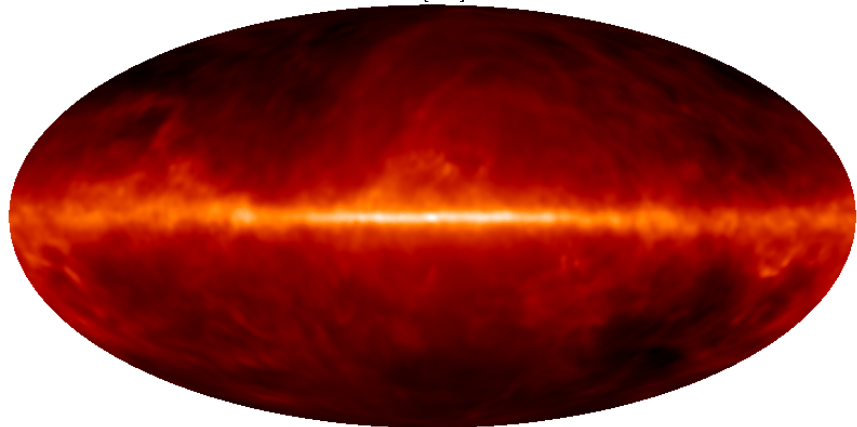
LAT Sky = Galactic Diffuse Emission + ?

IC + Bremm. + π^0 -decay

("PASS6" Galactic diffuse model)

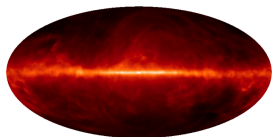
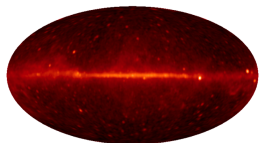
Galactic diffuse model

$1.2 < E \text{ [GeV]} < 1.5$



-6.8  -3.9 Log (photons/cm²/s/sr/GeV)

Dissecting the gamma-ray sky

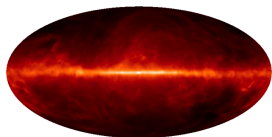
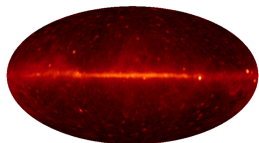


LAT Sky = Galactic Diffuse Emission + ?

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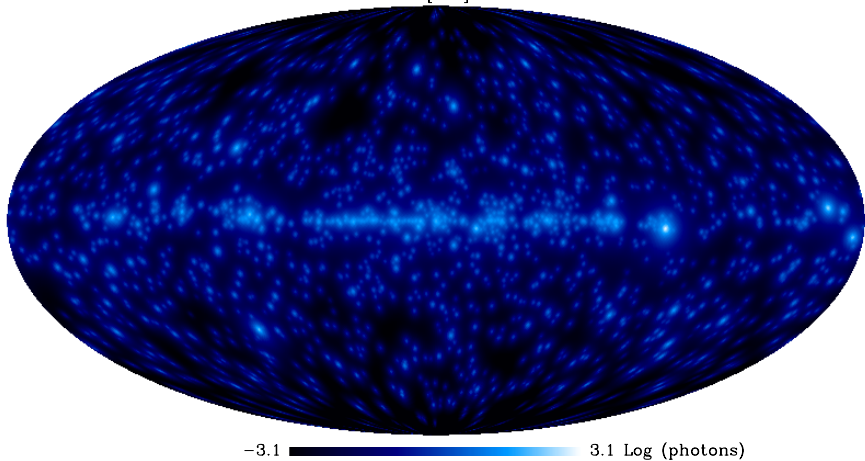
Dissecting the gamma-ray sky



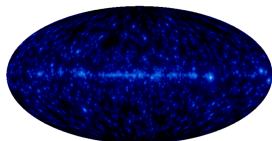
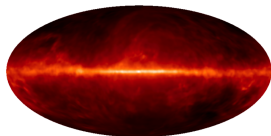
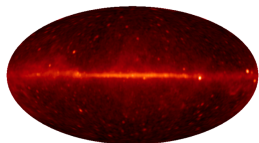
$$\text{LAT Sky} = \underbrace{\text{Galactic Diffuse Emission}}_{\substack{\text{IC + Bremm. + } \pi^0\text{-decay} \\ \text{"PASS6" Galactic diffuse model}}} + \underbrace{\text{Point Sources}}_{\text{(LAT-2 years catalogue)}}$$

Point source template

$0.38 < E \text{ [GeV]} < 0.45$



Dissecting the gamma-ray sky

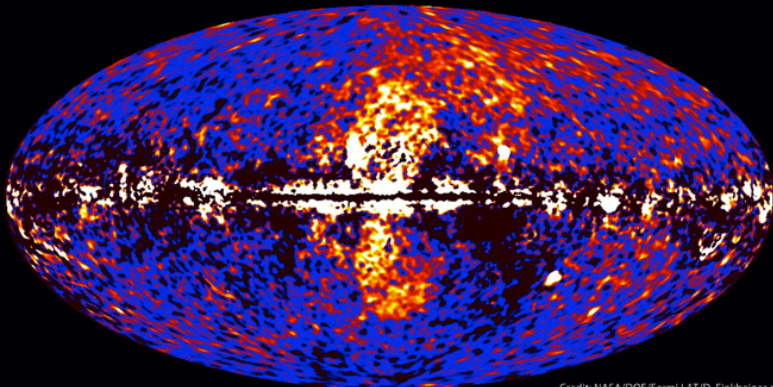


LAT Sky - Galactic Diffuse Emission - Point Sources $\stackrel{!}{=} 0$

Nota Bene: The likelihood fit implied by this equation includes an off-set constant describing the extragalactic isotropic gamma-ray background.

M. Su, T. Slatyer, D. Finkbeiner, *Astrophys.J.* 724 (2010) 1044-1082

Fermi data reveal giant gamma-ray bubbles



Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Properties of the "*Fermi bubbles*"

- Extension ($|\text{bl}| \sim 50^\circ$) (N.B.: $\sim 50,000$ light-years!!!)
- Spatial correlation with the "*WMAP haze*" ?
- Energy spectrum
- Origin: unknown

Properties of the "*Fermi bubbles*"

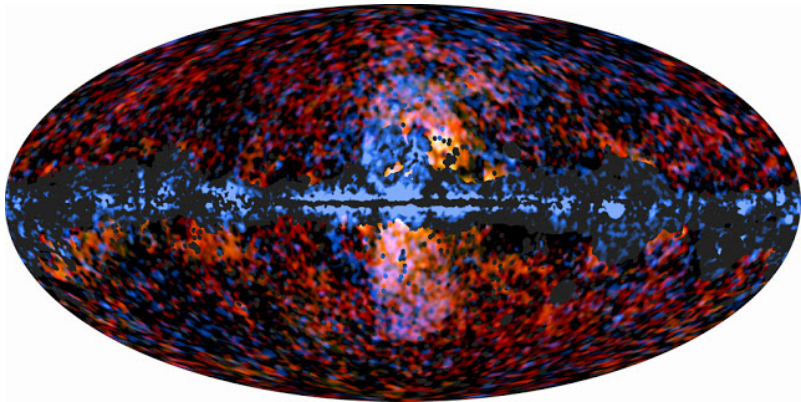
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Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	γ -ray
10^{-7} eV	10^{-3} eV	10^{-1} eV	1.65 - 3.27 eV	10 eV	10^4 eV	$>10^6$ eV

WMAP
Planck

Fermi



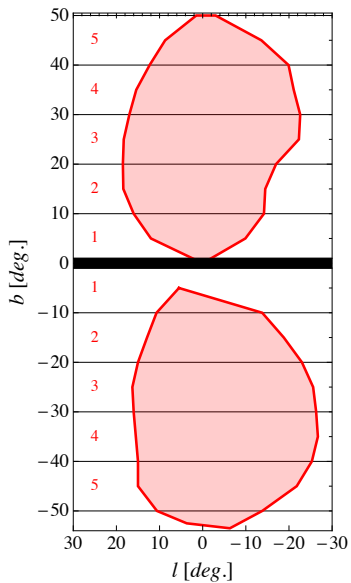
Planck coll., arXiv:1208.5483

Properties of the "*Fermi bubbles*"

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- Energy spectrum
- Origin: unknown

Properties of the "*Fermi bubbles*"

$$\frac{d\Phi}{dE_\gamma d\Omega} \quad [\text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$$

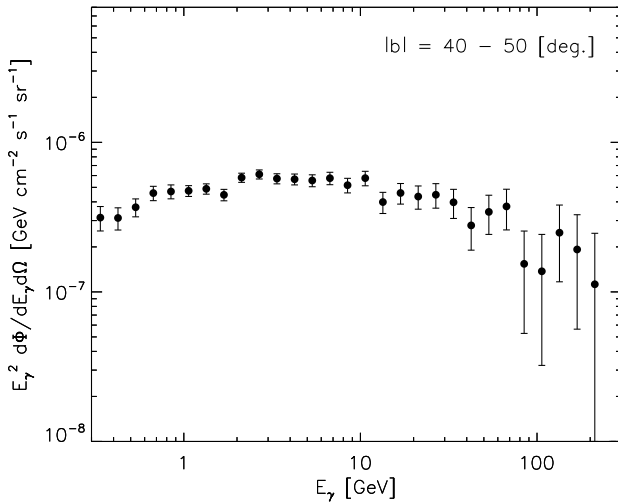


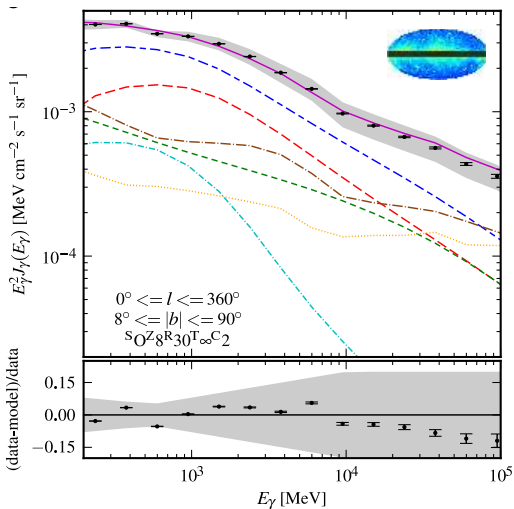
Properties of the "*Fermi bubbles*"

$$\frac{d\Phi}{dE_\gamma d\Omega} \sim E_\gamma^{-2}$$

Properties of the "*Fermi bubbles*"

$$E_\gamma^2 \frac{d\Phi}{dE_\gamma d\Omega} \sim \text{const}$$

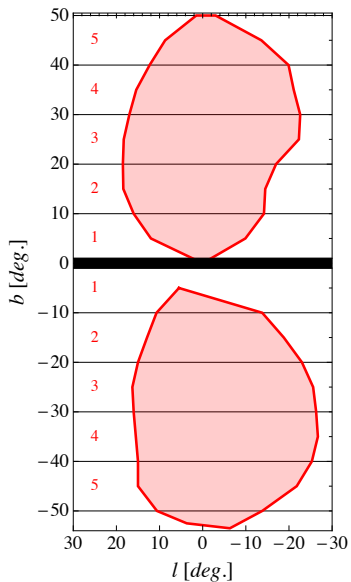


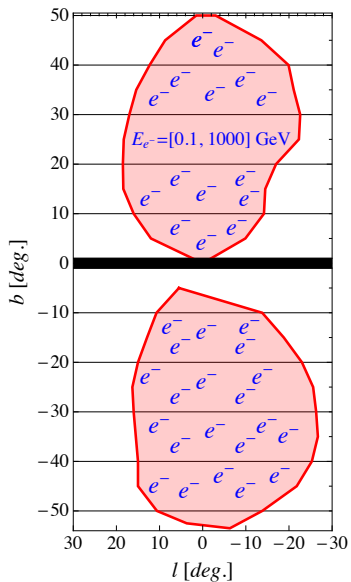


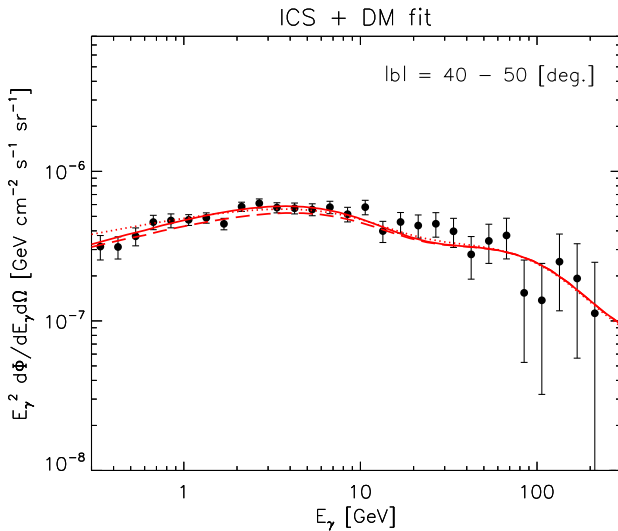
Fermi-LAT Collaboration,
Astrophys.J. 750 (2012) 3

Properties of the "*Fermi bubbles*"

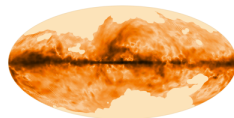
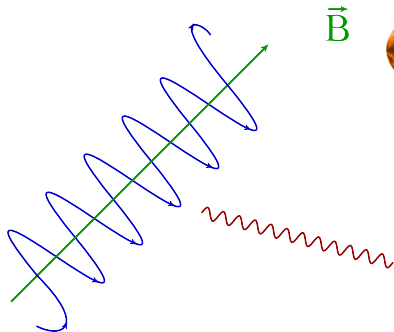
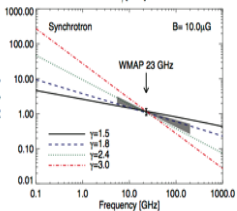
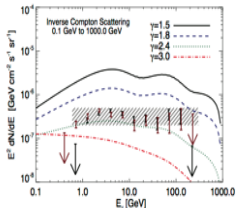
- Extension ($|\text{bl}| \sim 50^\circ$)
- Spatial correlation with the "*WMAP haze*" ?
- Energy spectrum
- Origin: unknown







A connection with the "*WMAP haze*" ?

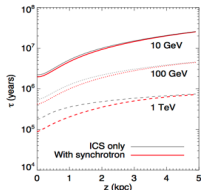


Synchrotron radiation

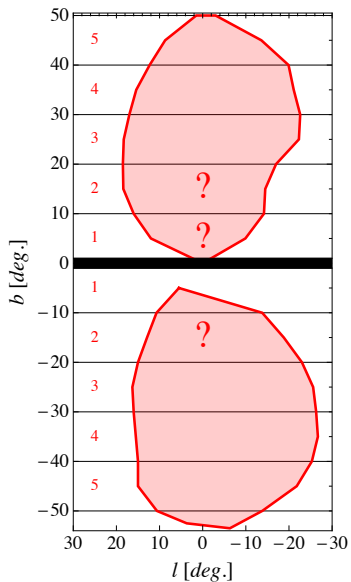
M. Su, T. Slatyer, D. Finkbeiner, *Astrophys.J.*
724 (2010) 1044-1082

The trouble with electrons

- Electrons could be produced in the inner Galaxy by mechanism such as supernova explosions...
- ...and subsequently accelerated by Bubble-pervading shocks
- However, they have problems filling the enormous volume of the Bubbles (energy losses lead to short cooling time)



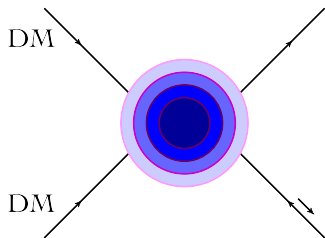
M. Su, T. Slatyer, D. Finkbeiner, *Astrophys.J.* 724
(2010) 1044-1082



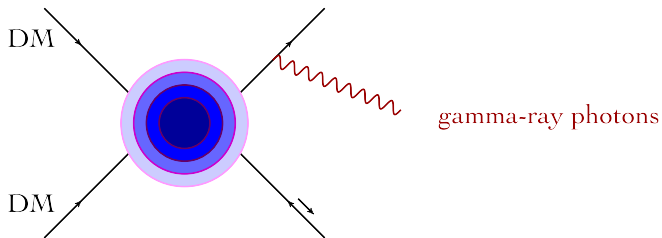
Towards lower latitudes

- How the energy spectrum of the Fermi bubbles looks at low latitudes?
- Could we find a contribution (in addition to the one given by the extra population of electrons) compatible with Dark matter annihilation?

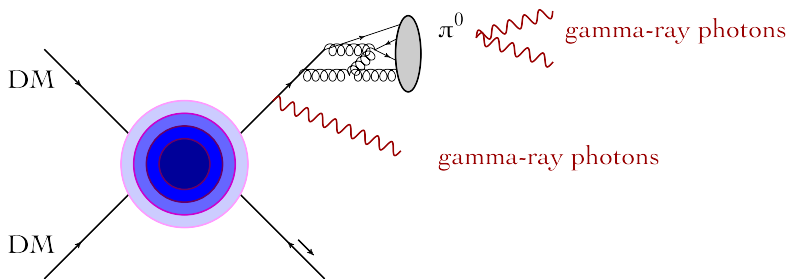
A signal of Dark Matter?



A signal of Dark Matter?



A signal of Dark Matter?

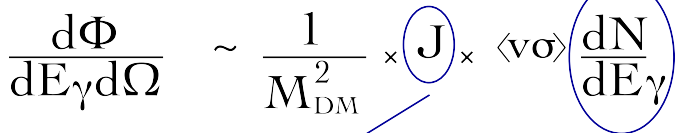


A signal of Dark Matter?

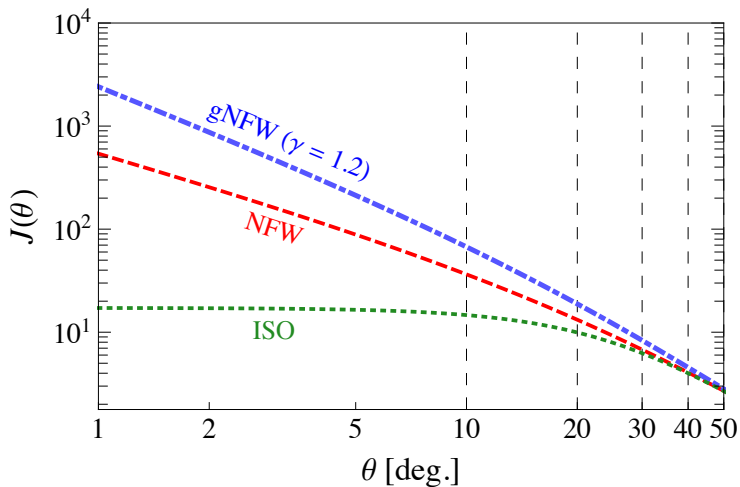
$$\frac{d\Phi}{dE_\gamma d\Omega} \sim \frac{1}{M_{\text{DM}}^2} \times \mathbf{J} \times \langle v\sigma \rangle \frac{dN}{dE_\gamma}$$

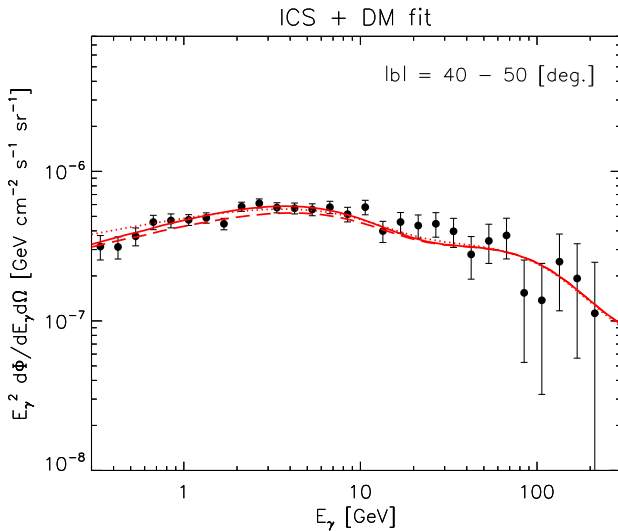
A signal of Dark Matter?

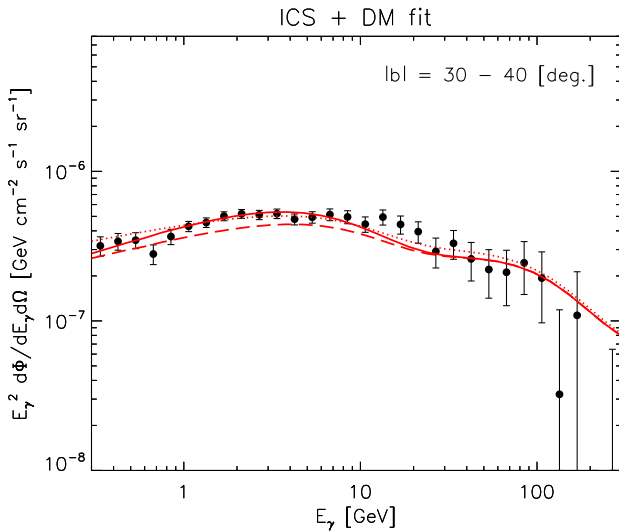
Number of photon produced in each annihilation

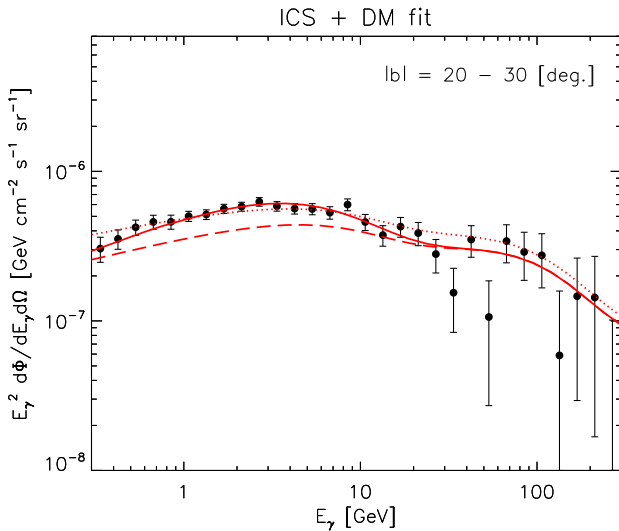
$$\frac{d\Phi}{dE_\gamma d\Omega} \sim \frac{1}{M_{\text{DM}}^2} \times \textcircled{J} \times \langle v\sigma \rangle \textcircled{\frac{dN}{dE_\gamma}}$$


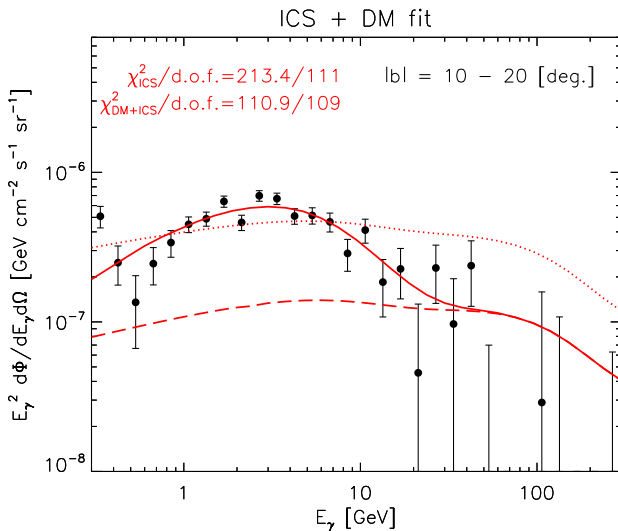
Astrophysical factor: depends on the distribution of Dark Matter in the Galaxy.



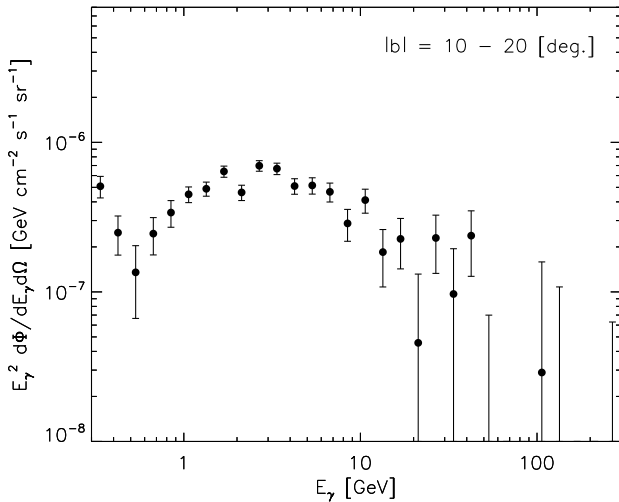


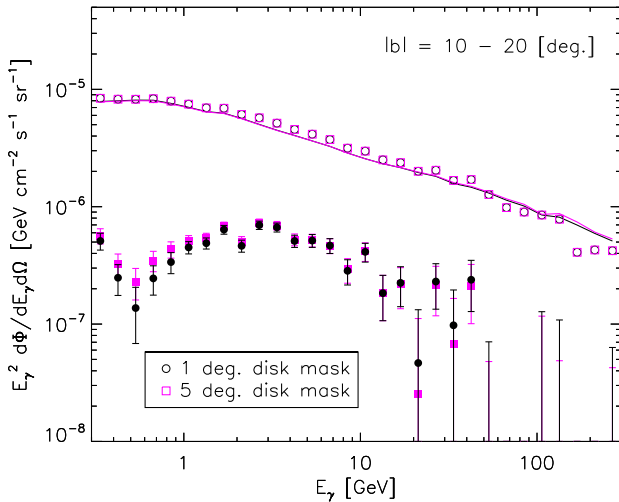


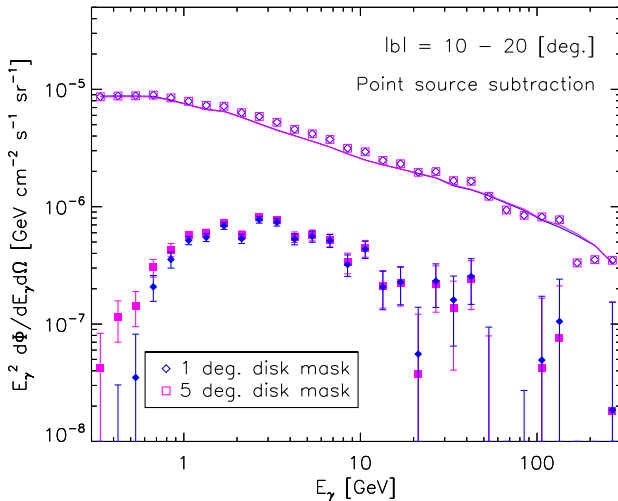


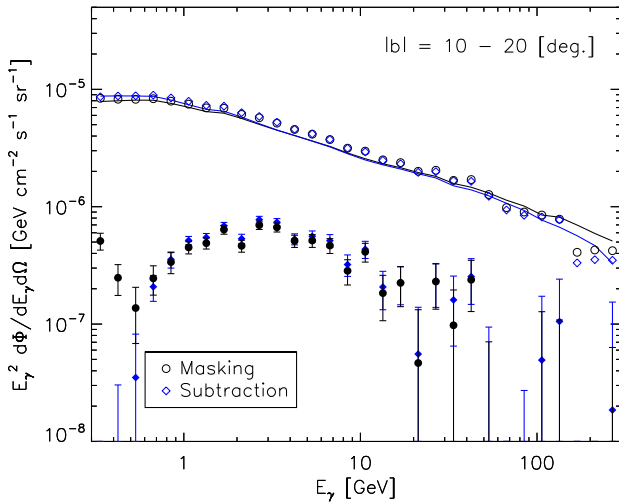


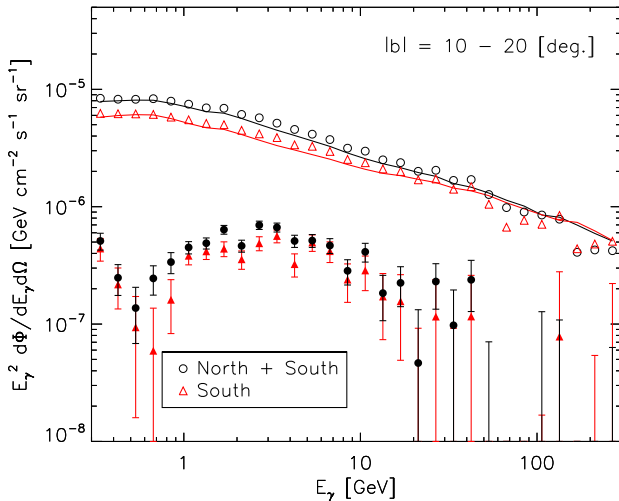
DM annihilation	$M_{\text{DM}} [GeV]$	$\langle\sigma v\rangle [cm^3s^{-1}]$	$\chi^2_{\text{min}}/\text{d.o.f.}$
$b\bar{b}$	$61.8^{+6.9}_{-4.9}$	$3.30^{+0.69}_{-0.49} \times 10^{-26}$	110.9/109
$c\bar{c}$	$29.3^{+2.4}_{-3.4}$	$1.54^{+0.26}_{-0.30} \times 10^{-26}$	112.7/109
$q\bar{q}$	$32.0^{+2.6}_{-3.8}$	$1.73^{+0.30}_{-0.30} \times 10^{-26}$	111.9/109
$\tau^+\tau^-$	$10.6^{+0.5}_{-0.6}$	$5.63^{+0.58}_{-0.64} \times 10^{-27}$	120.6/109

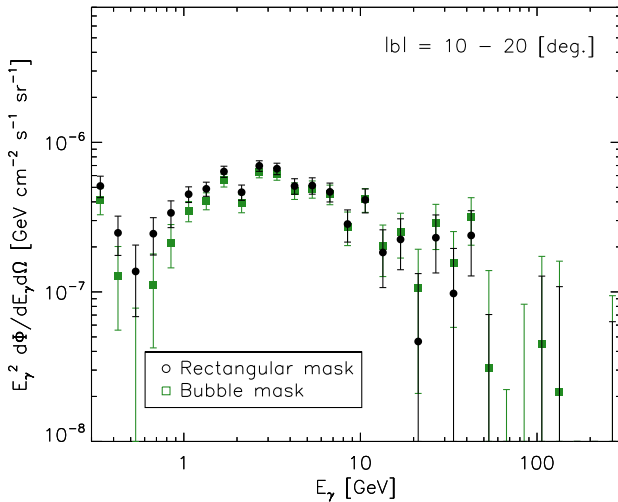


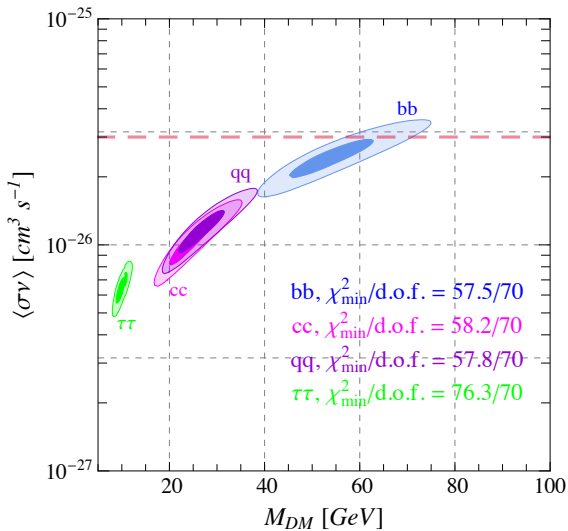












$$\frac{d\Phi}{dE_\gamma d\Omega} \sim \frac{1}{M_{\text{DM}}^2} \times \mathbf{J} \times \langle v\sigma \rangle \frac{dN}{dE_\gamma}$$

$$\frac{\Omega_{\text{DM}} h^2}{0.1199} \sim \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle v\sigma \rangle}$$

Gamma-ray flux (annihilation today)

$$\langle v\sigma \rangle \sim a + b v^2 + \dots$$

Relic density (annihilation in the early Universe)

$$\langle v\sigma \rangle \sim a + b v^2 + \dots$$

Gamma-ray flux (annihilation today)

$$\langle \mathbf{v}\sigma \rangle \sim a + \cancel{b v^2} + \dots \quad v \sim 10^{-3}$$

Relic density (annihilation in the early Universe)

$$\langle \mathbf{v}\sigma \rangle \sim a + b v^2 + \dots$$

Gamma-ray flux (annihilation today)

$$\langle v\sigma \rangle \sim a$$

Relic density (annihilation in the early Universe)

$$\langle v\sigma \rangle \sim a + b v^2 + \dots$$

$v \sim 1/3$

Gamma-ray flux (annihilation today)

$$\langle \mathbf{v} \sigma \rangle \sim a$$

Relic density (annihilation in the early Universe)

only if: $bv^2 \ll a$

$$\langle \mathbf{v} \sigma \rangle \sim a$$

$$\frac{d\Phi}{dE_\gamma d\Omega} \sim \frac{1}{M_{\text{DM}}^2} \times \mathbf{J} \times \langle v\sigma \rangle \frac{dN}{dE_\gamma}$$

$$\frac{\Omega_{\text{DM}} h^2}{0.1199} \sim \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle v\sigma \rangle}$$

$$\text{Scalar : } \mathcal{O}_S^f \equiv \frac{m_f}{\sqrt{2}} \bar{\chi} \chi \bar{f} \left[G_S^f + G_{SA}^f \gamma^5 \right] f ,$$

$$\text{Pseudoscalar : } \mathcal{O}_{PS}^f \equiv \frac{m_f}{\sqrt{2}} \bar{\chi} \gamma^5 \chi \bar{f} \left[G_{PS}^f + G_{PSA}^f \gamma^5 \right] f ,$$

$$\text{Vector : } \mathcal{O}_V^f \equiv \frac{1}{\sqrt{2}} \bar{\chi} \gamma^\mu \chi \bar{f} \gamma_\mu \left[G_V^f + G_{VA}^f \gamma^5 \right] f ,$$

$$\text{Pseudovector : } \mathcal{O}_{PV}^f \equiv \frac{1}{\sqrt{2}} \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{f} \gamma_\mu \left[G_{PV}^f + G_{PVA}^f \gamma^5 \right] f ,$$

$$\text{Tensor : } \mathcal{O}_T^f \equiv \frac{m_f}{\sqrt{2}} \bar{\chi} \sigma^{\mu\nu} \chi \bar{f} \sigma_{\mu\nu} \left[G_T^f + G_{TA}^f \gamma^5 \right] f ,$$

Fermionic Dark Matter					
Operator	Channel	Annihilation cross section		DD cross section	s/Λ^2 (%)
		m_f^2 suppression	v^2 suppression		
S	$\tau^+\tau^-$			×	
	$c\bar{c}$	✓	✓	✓	
	$b\bar{b}$			✓	
	$q\bar{q}$			✓	
PS	$\tau^+\tau^-$ (76.3)				13.7
	$c\bar{c}$ (58.2)				43.7
	$b\bar{b}$ (57.5)	✓	×	×	78.5
	$q\bar{q}$				
V	$\tau^+\tau^-$ (76.3)			✓ (1L)	0.3
	$c\bar{c}$ (58.2)	×	×	✓ (1L)	0.6
	$b\bar{b}$ (57.5)			✓ (1L)	1.9
	$q\bar{q}$ (57.8)			✓	0.7
PV	$\tau^+\tau^-$ (76.3)				2.5
	$c\bar{c}$ (58.2)				14.4
	$b\bar{b}$ (57.5)	✓	×	×	34.6
	$q\bar{q}$				
T	$\tau^+\tau^-$ (76.3)				8.3
	$c\bar{c}$ (58.2)				29.1
	$b\bar{b}$ (57.5)	✓	×	×	49.1
	$q\bar{q}$				

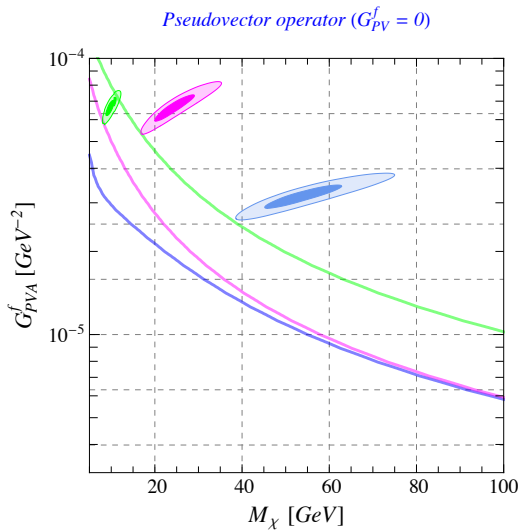
Gamma-ray flux (annihilation today)

$$\langle v\sigma \rangle \sim a$$

Relic density (annihilation in the early Universe)

$$\langle v\sigma \rangle \sim \cancel{a} + b v^2 + \dots$$

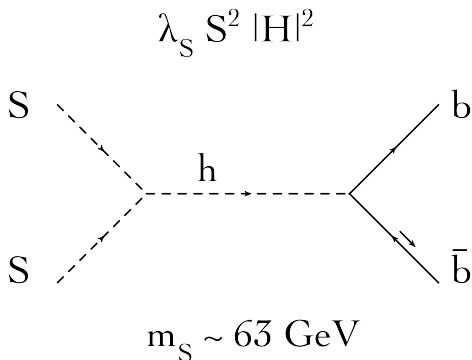
$bv^2 \gg a$

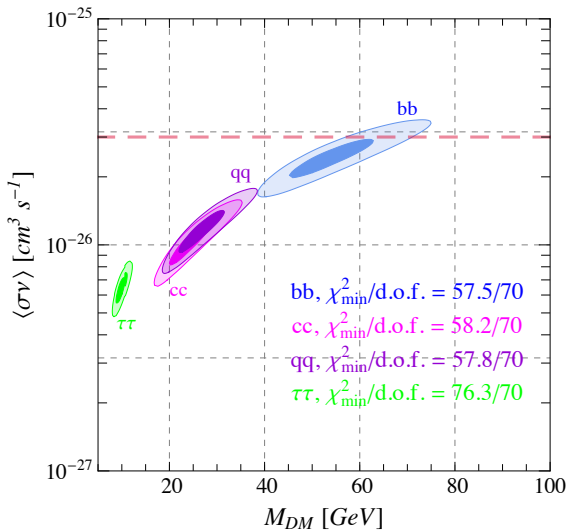


A renormalizable case: the scalar Higgs portal

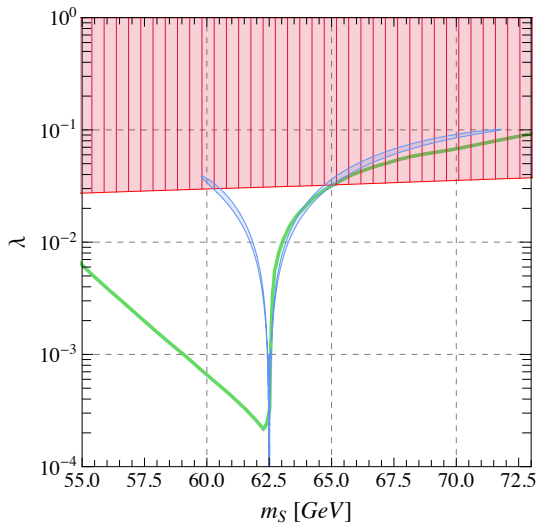
$$\lambda_S S^2 |H|^2$$

A renormalizable case: the scalar Higgs portal

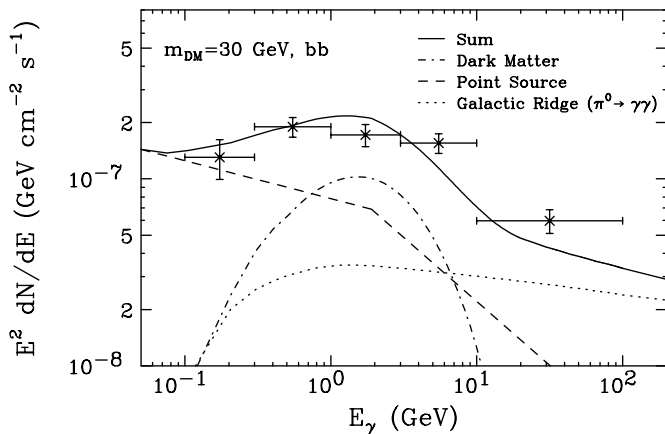




Scalar Higgs portal

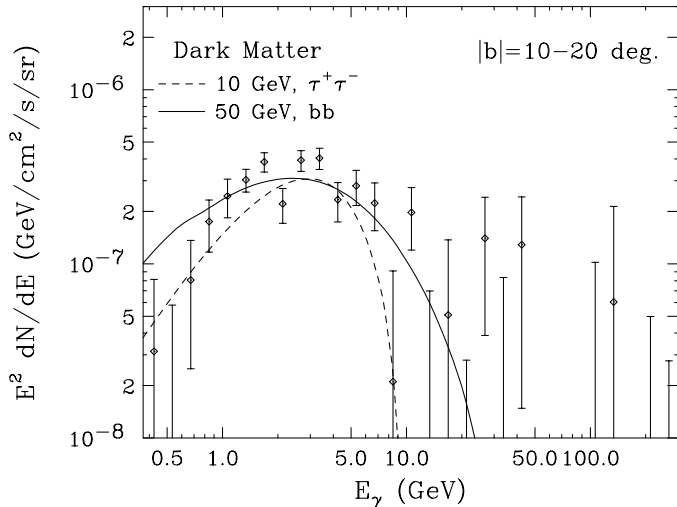


D. Hooper and T. Linden, Phys.Rev. D84 (2011) 123005

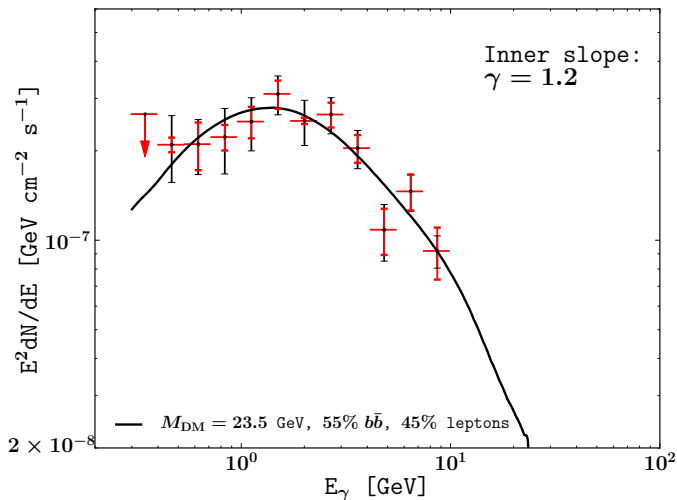


D. Hooper and T. Slatyer, Phys.Dark Univ. 2 (2013)

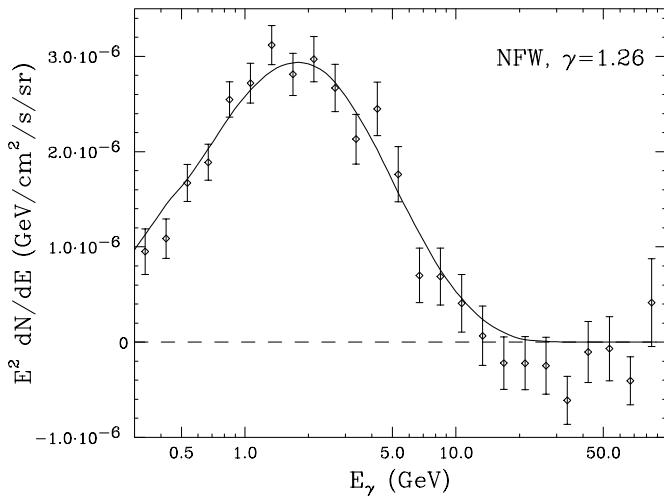
118-138



C. Gordon and O. Macias, Phys.Rev. D88 (2013) 083521



T. Daylan et al., arXiv:1402.6703



Conclusions

- Hint for a Dark Matter signal at $E_\gamma \sim 1 - 4 \text{ GeV}$?
- Galactic center + Fermi bubbles ($|b| = 1 - 30 \text{ deg.}$)
- Correlations among different wavelength?
- Understanding systematic uncertainties