FERMI BUBBLES UNDER DARK MATTER SCRUTINY

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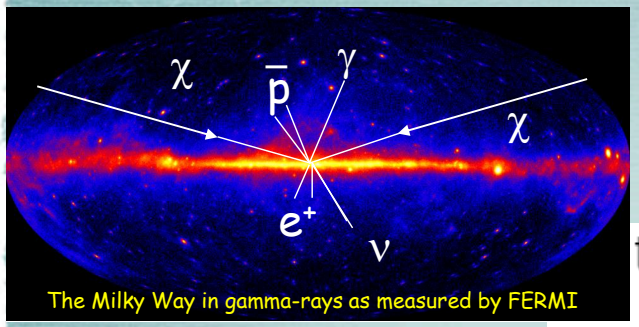
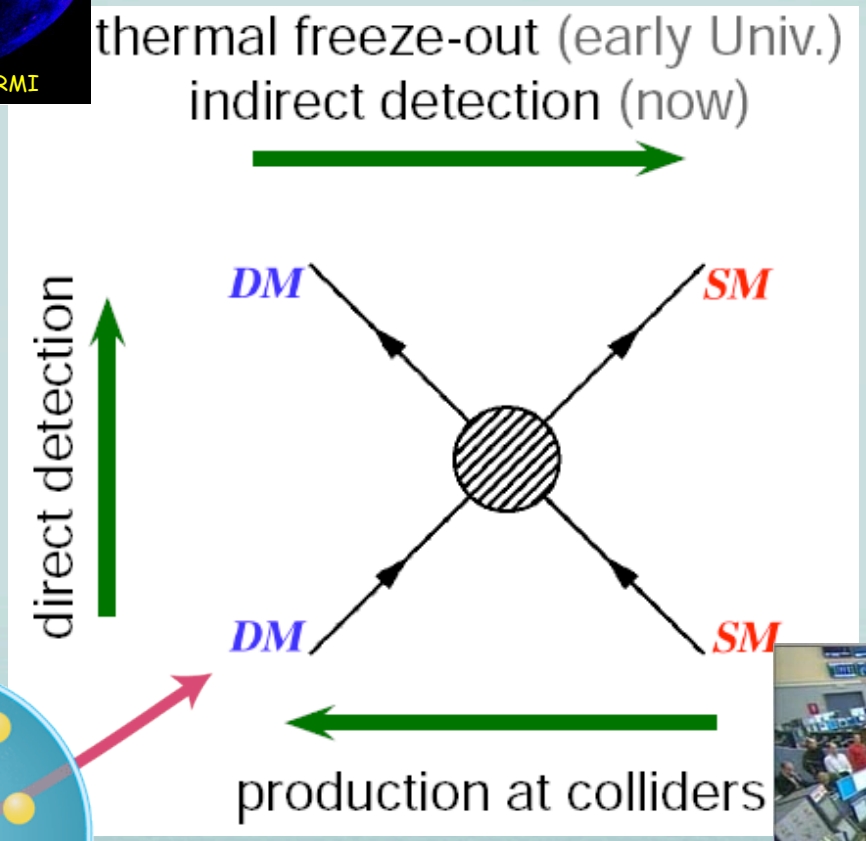
OUTLINE

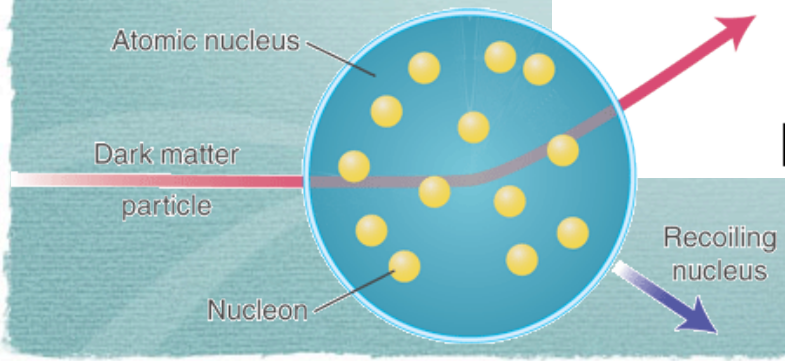
1. Indirect detection from Fermi Bubbles
   arXiv:1307.6862 w/ Alfredo Urbano, Wei-chih Huang
   Background
   Dark Matter Fit
   Dark Matter Constraints

2. Particle Physics Analysis
   arXiv: 1310.???? w/ Alfredo Urbano, Wei-chih Huang
   Effective Field Theory
   Concrete Models (Higgs Portal Dark Matter)

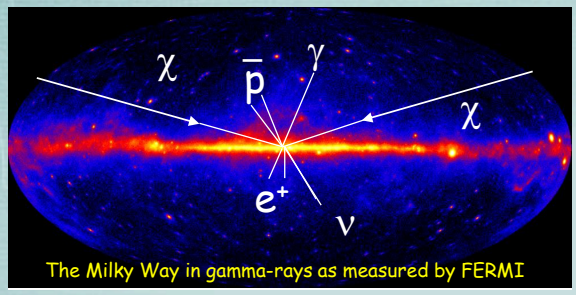
DARK MATTER DETECTION

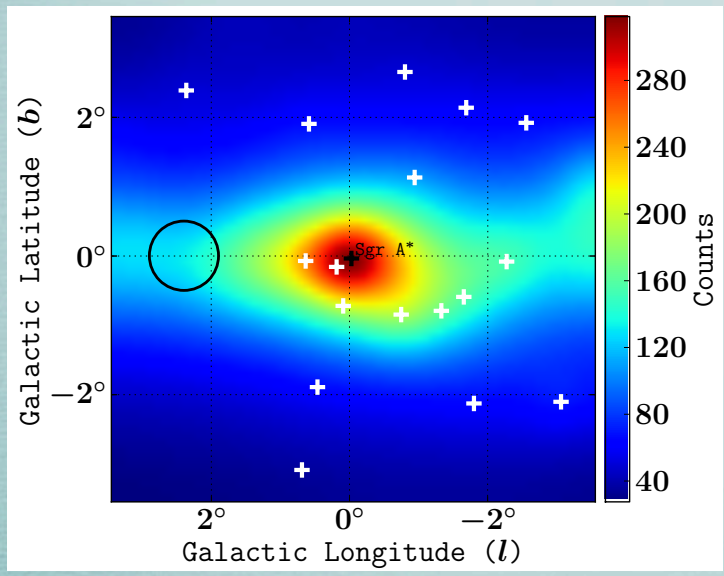




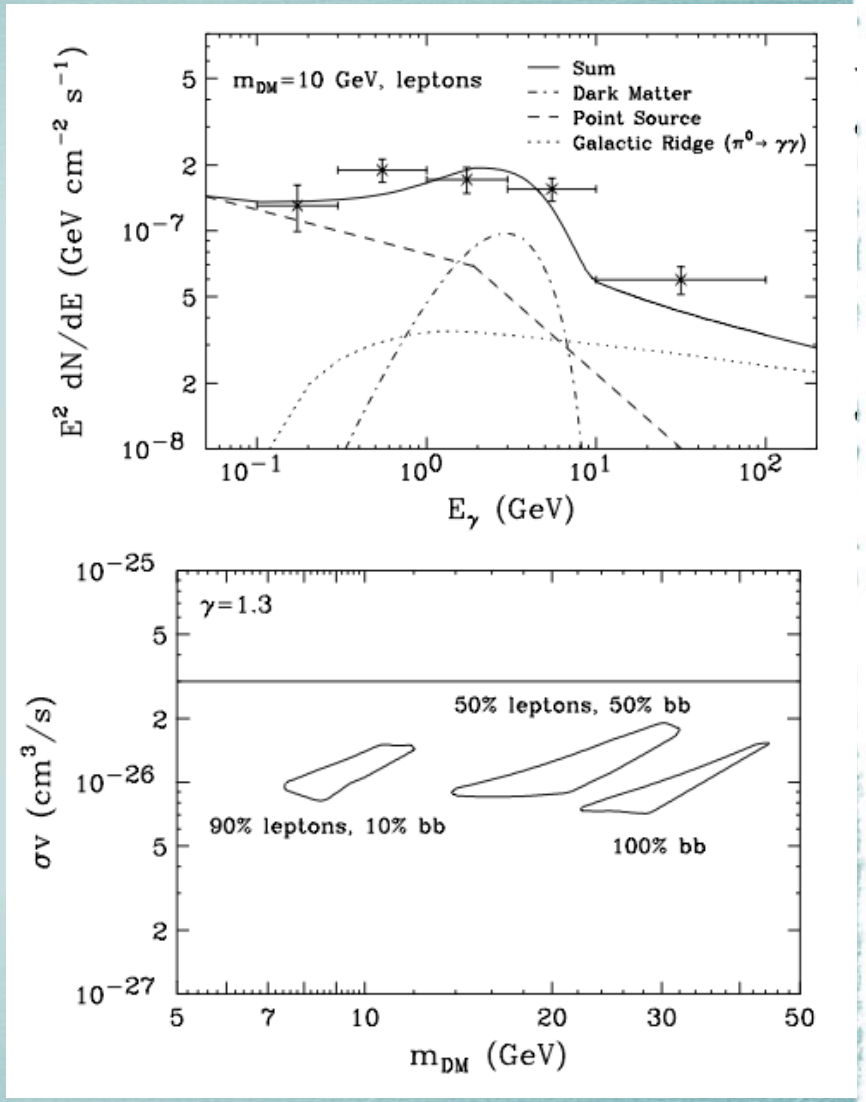


Indirect detection Galactic Centre





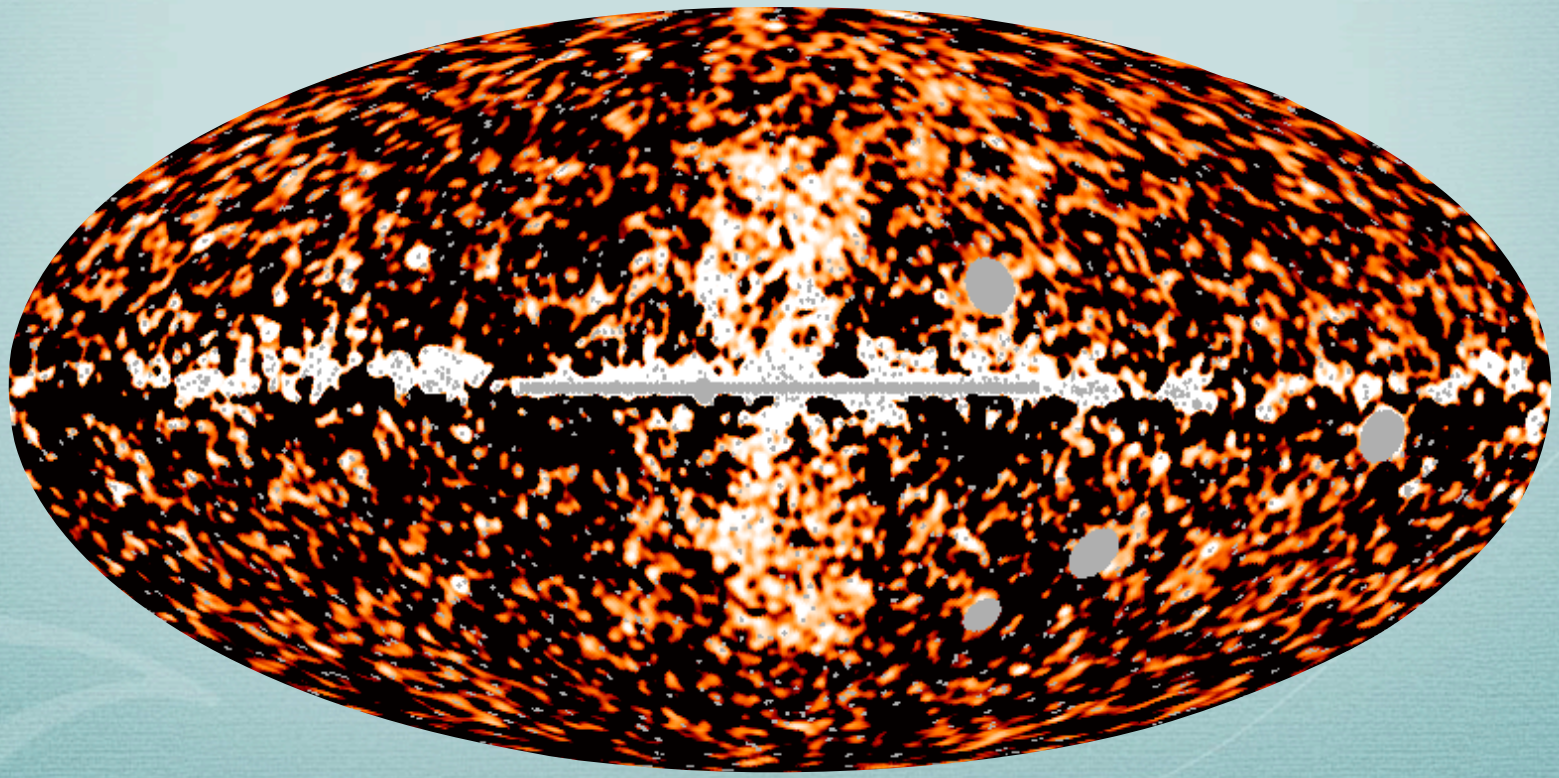
Gordon and Macias (2013)



Hooper and Linden (2011)

Fermi Bubbles

1. less uncertainties compared with Galactic Centre
2. latitude-dependent spectrum (Hooper and Slatyer)
3. Hooper and Cholis, etc. Pulsar can not account for the GeV excess



Background

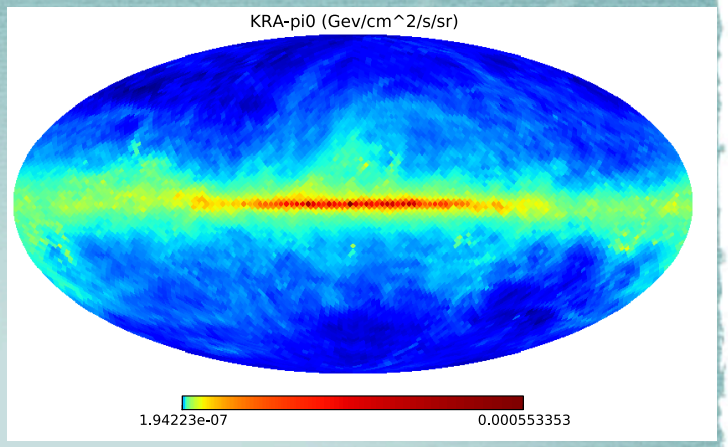
1. Decay of π^0 (cosmic-ray protons striking on Interstellar medium)

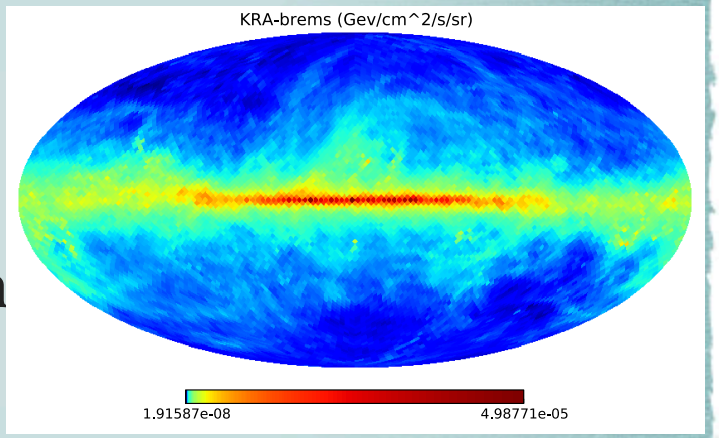
2. Bremsstrahlung (fast moving electron scattering on the gas)

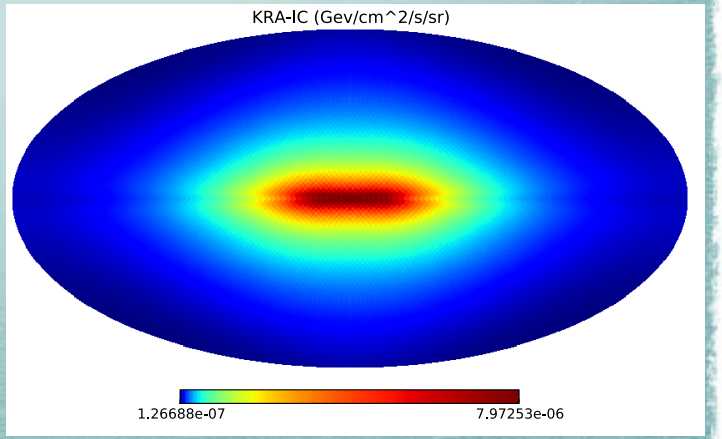
3. ICS from CR electrons scattering with ISRF

4. Extended Source &Point Source

6. Fermi Bubbles







Residual Maps

1. Event data, Exposure data and Diffuse map

2. Mask Rectangular region covering Fermi Bubbles

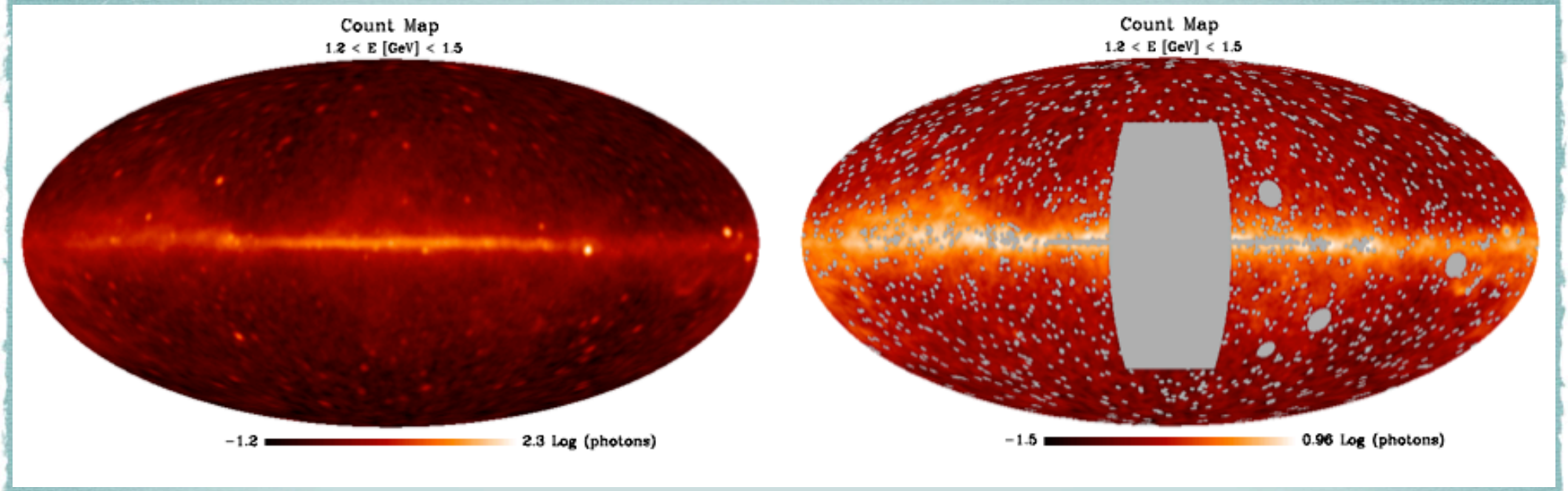
3. Mask the point sources and extended sources
   radius r_{95}(E) 95% flux containment (Assume a Gaussian distribution)

4. Mask the inner disk $|b| < 1^o$, $|l| < 60^o$

5. Smooth the maps to the same kernel in order to compare different maps properly
   f_{kernel} = Sqrt(f_{target}^2 - f_{raw}^2)

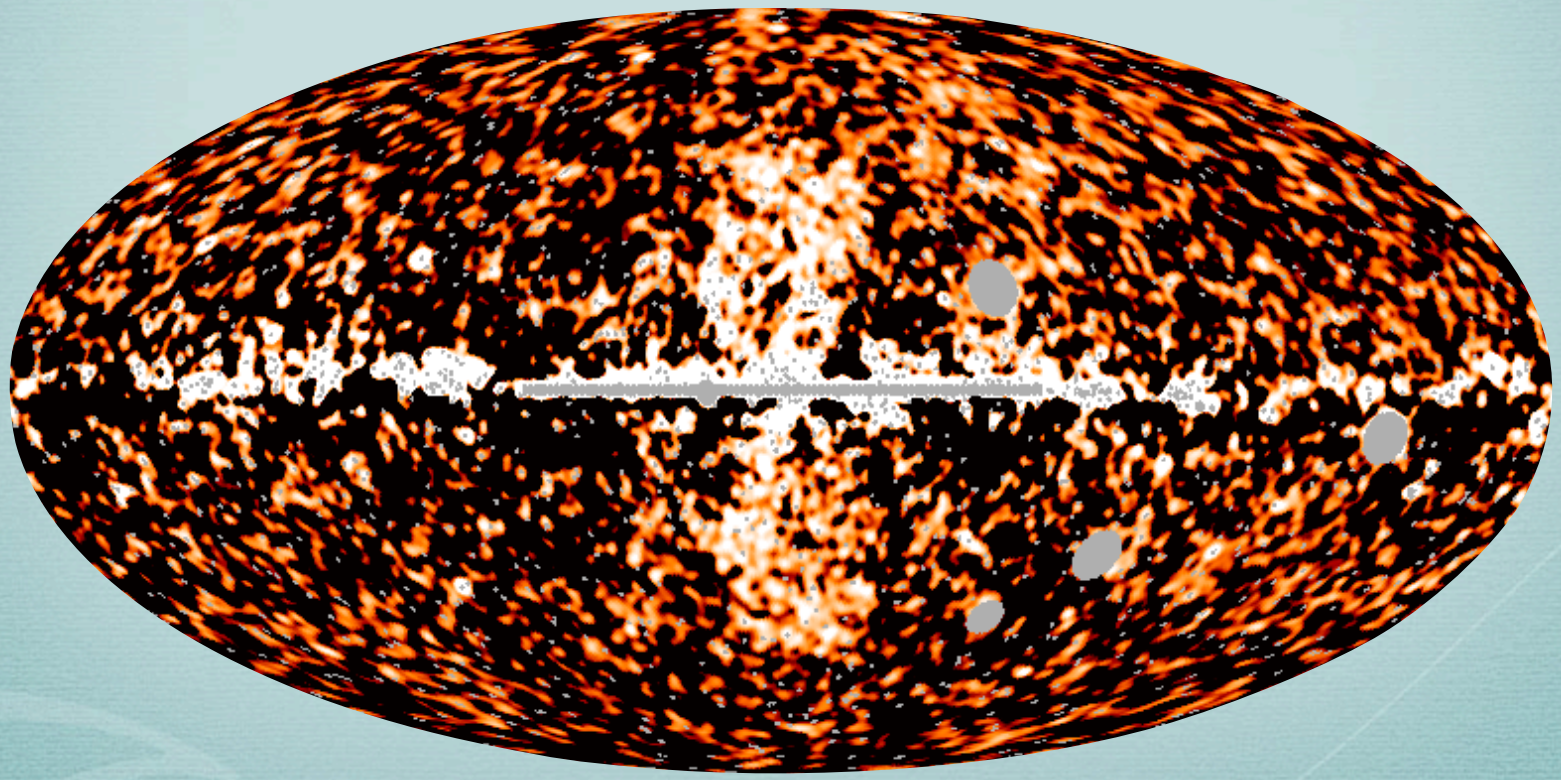
6. $$\mathrm{Res} = \sum_i \mathrm{Count\ Map}|_i - \sum_i [(a_0 \cdot \mathrm{Diffuse\ Model}|_i + b_0) \cdot \mathrm{Exposure\ Map}|_i \cdot \mathrm{px} \cdot \Delta E_\gamma]$$

Count Maps

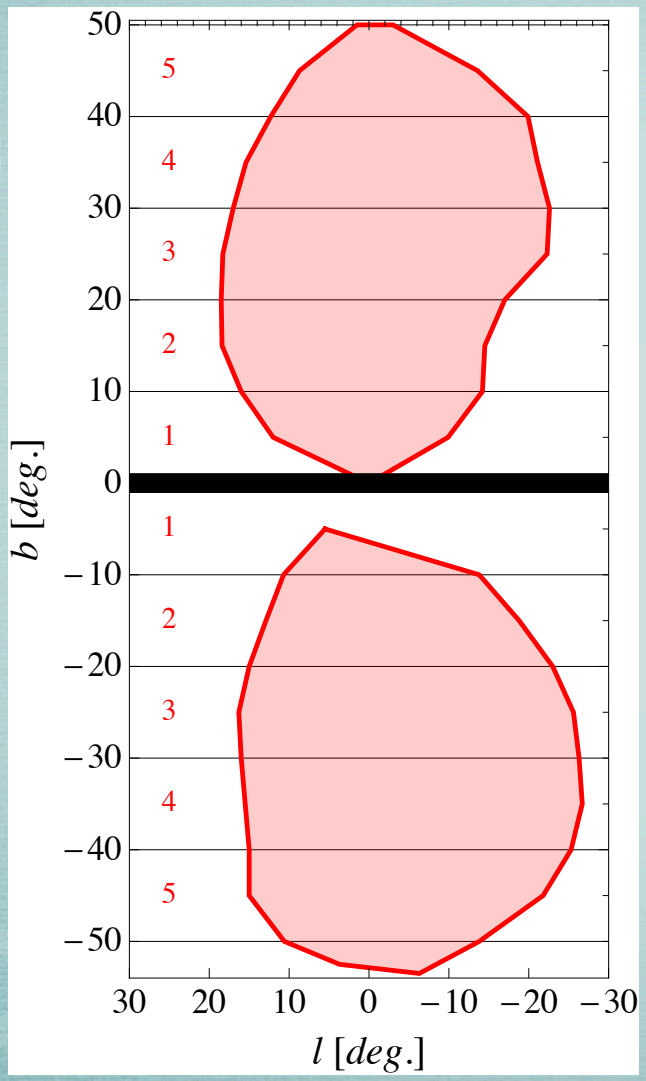


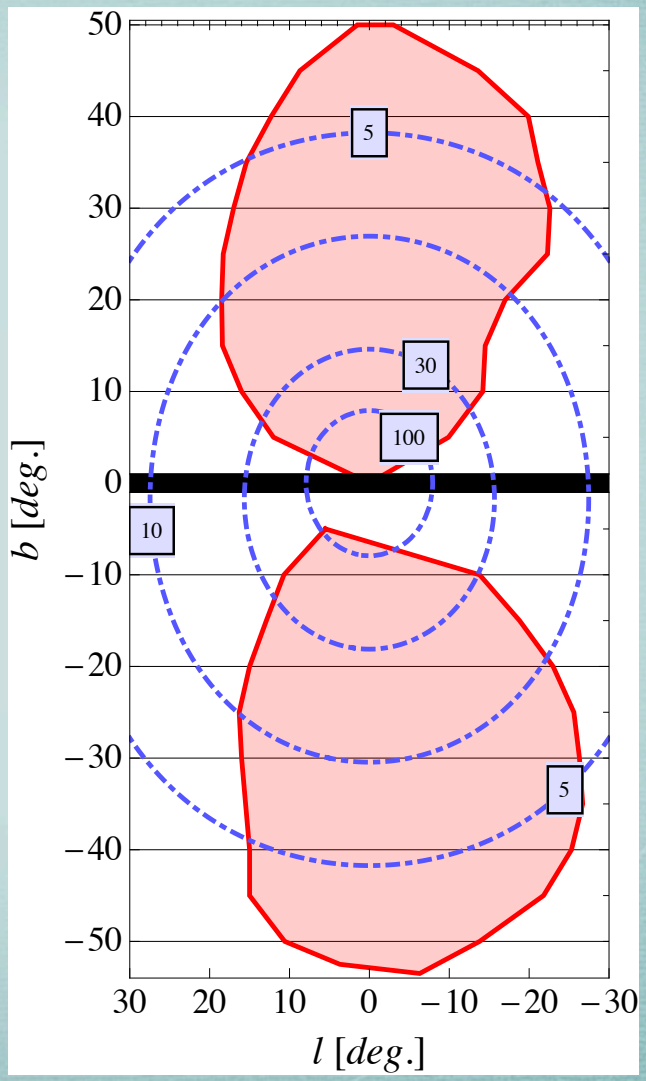
1. Pass7 (V6)
2. ULTRACLEAN, but SOURCE and CLEAN are tested
3. different zenith angle cut are tested
3. Fermi tools: gtselect, gtmktime

Fermi Bubbles



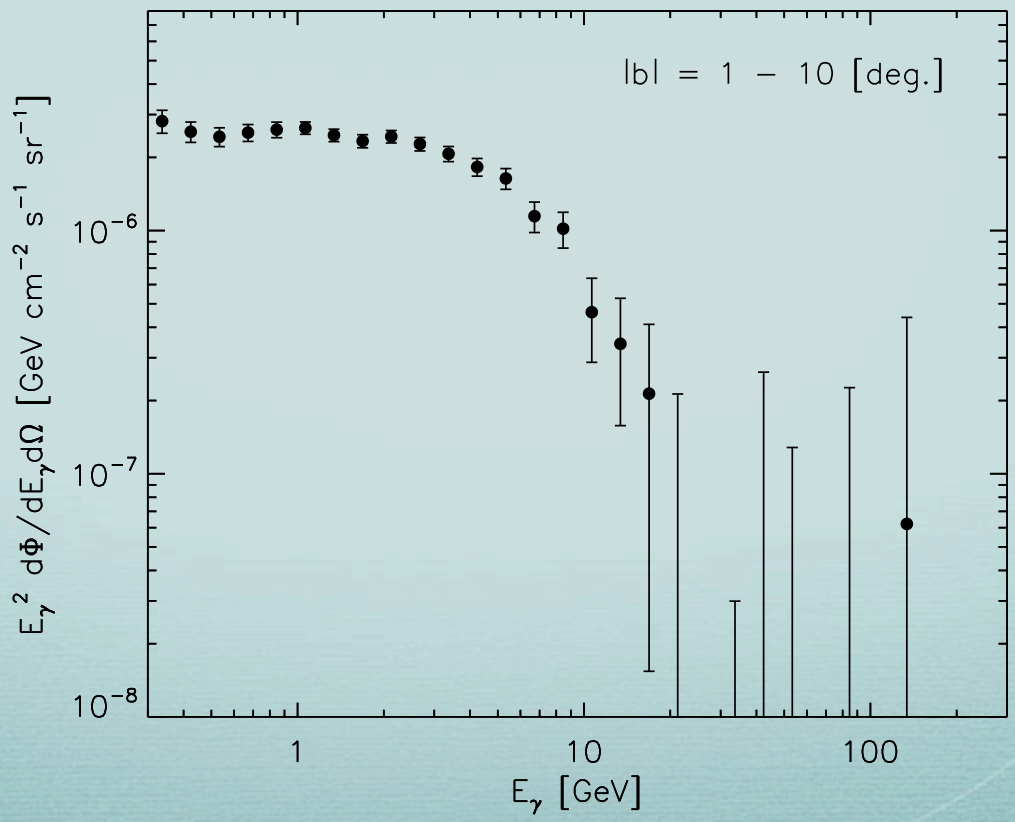
Fermi Bubbles Template





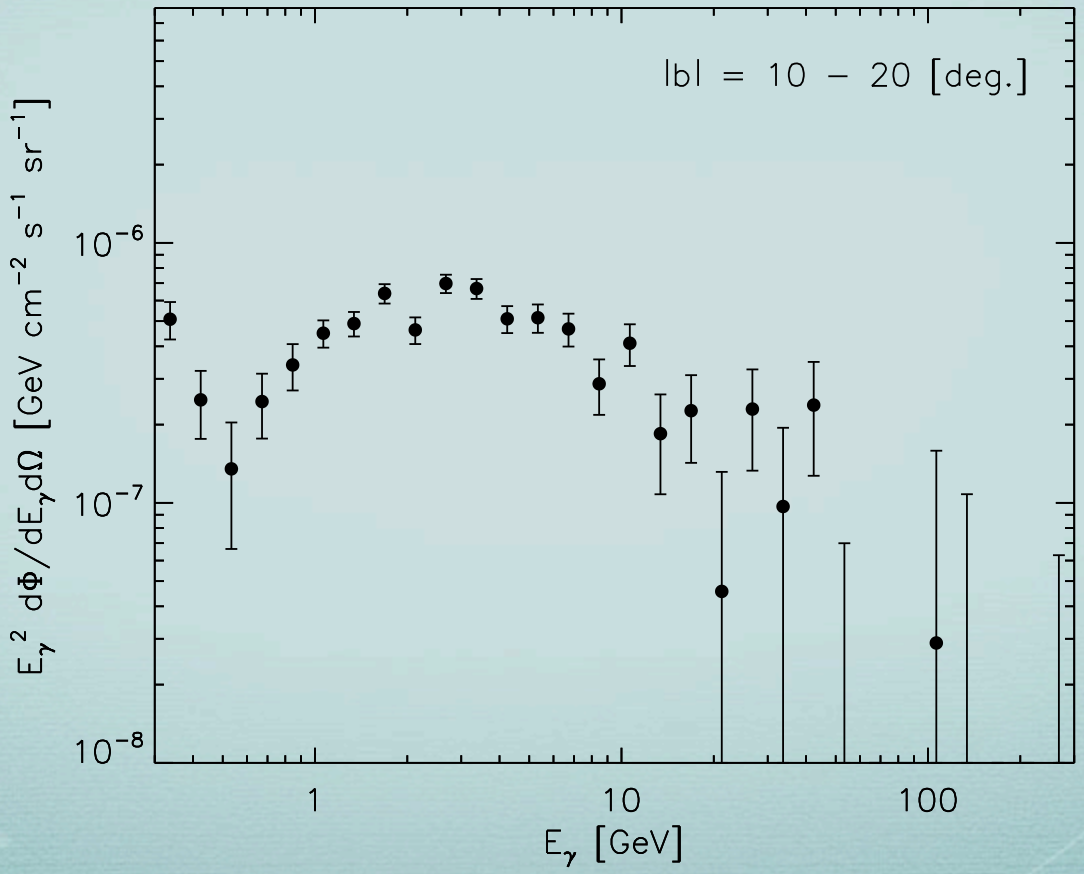
Latitude-dependence

$|b| = 1^o - 10^o$. The spectrum is flat up to energies $E_\gamma \sim 5$ GeV, thereafter it starts to decrease; at energies larger than 10 GeV the signal is swamped by large statistical uncertainties.



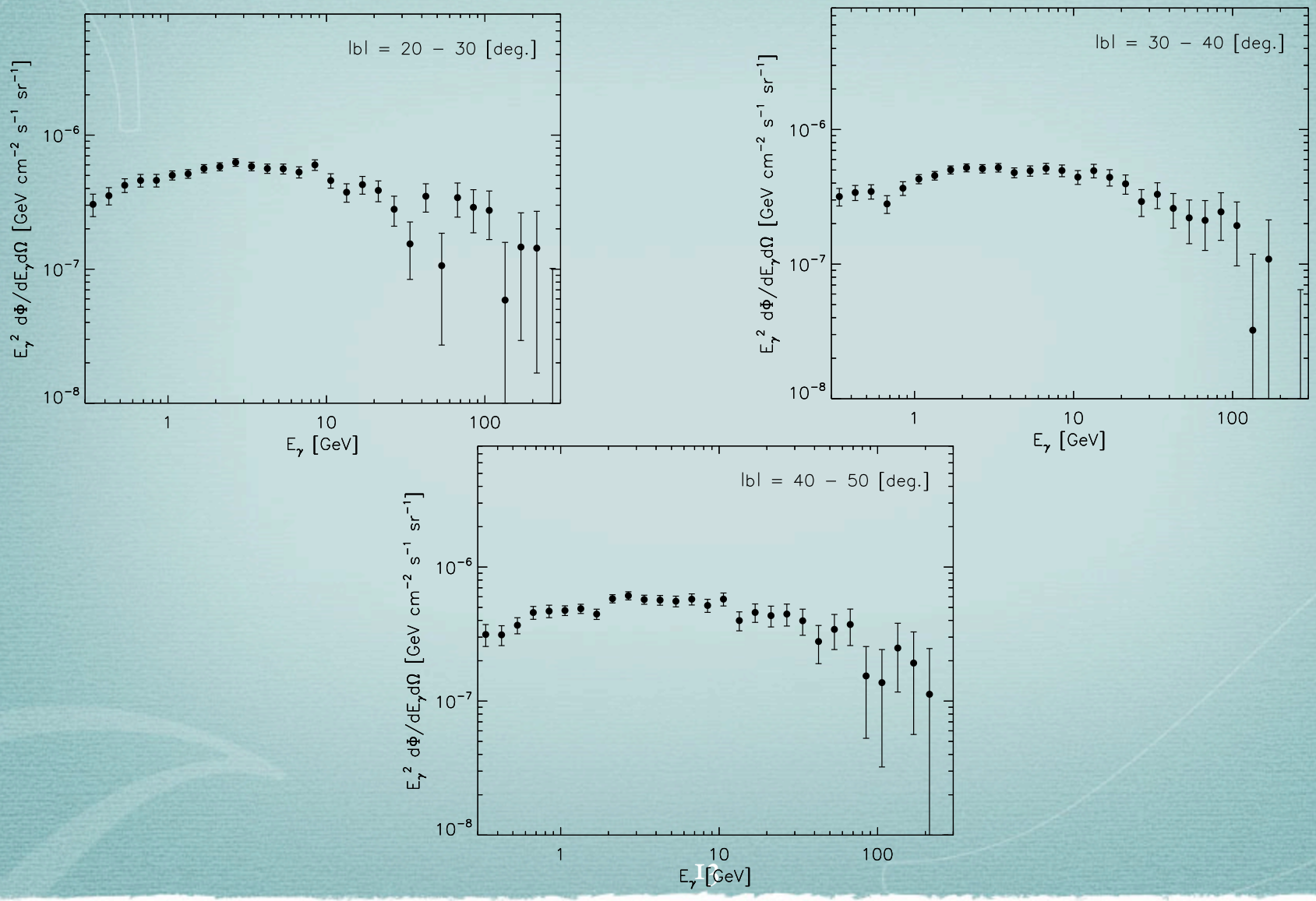
Latitude-dependence

$|b| = 10^o - 20^o$. The spectrum is clear shows a bump peaked around $E_\gamma \sim 1$ - 4 GeV.

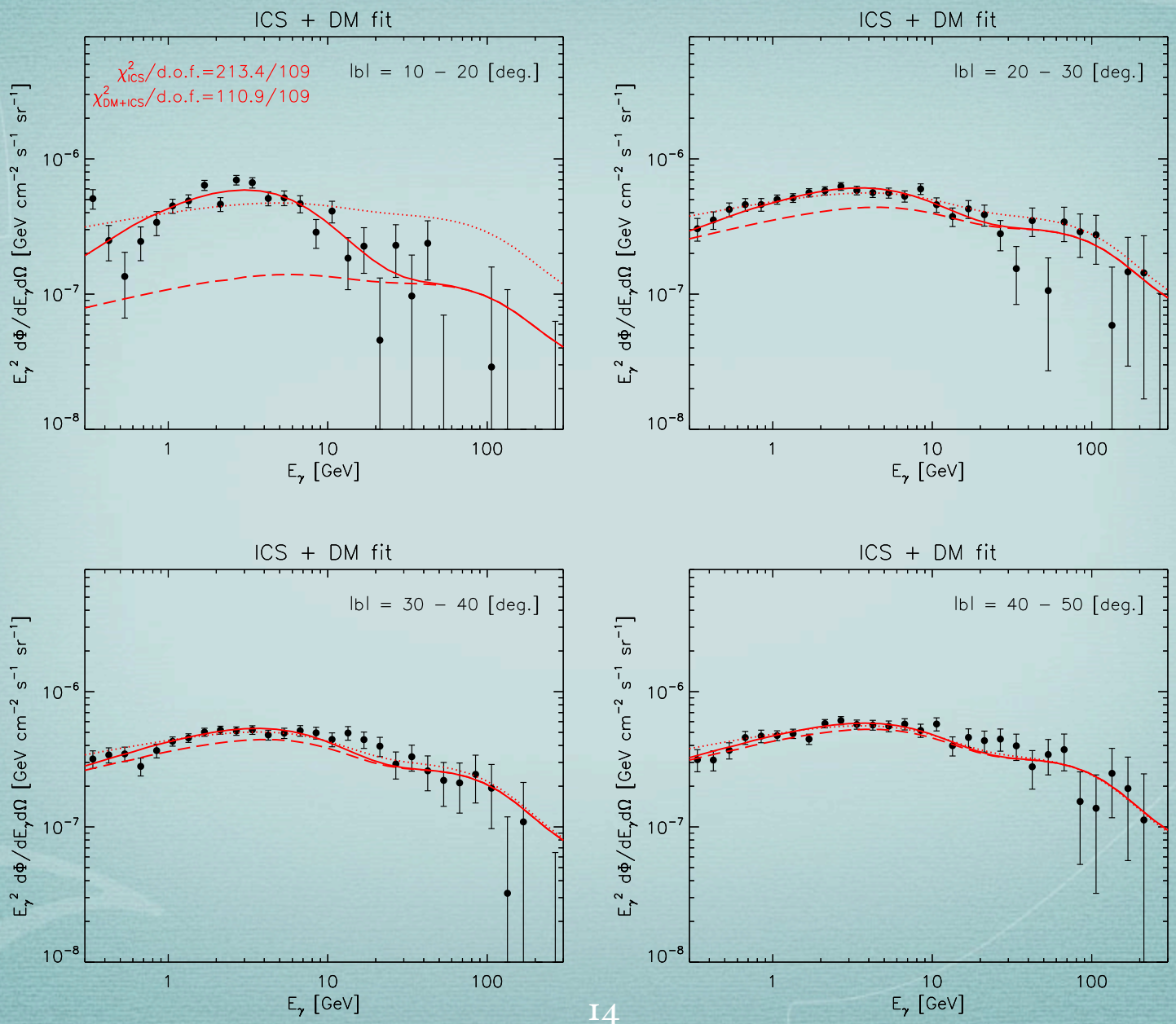


Latitude-dependence

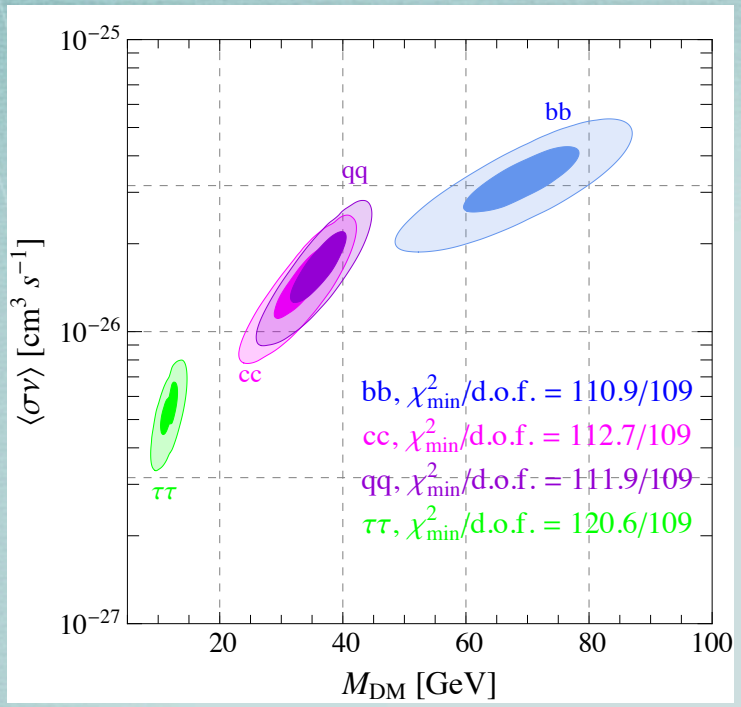
|b| = 20° – 50°. The spectrum presents a flattish behaviour.

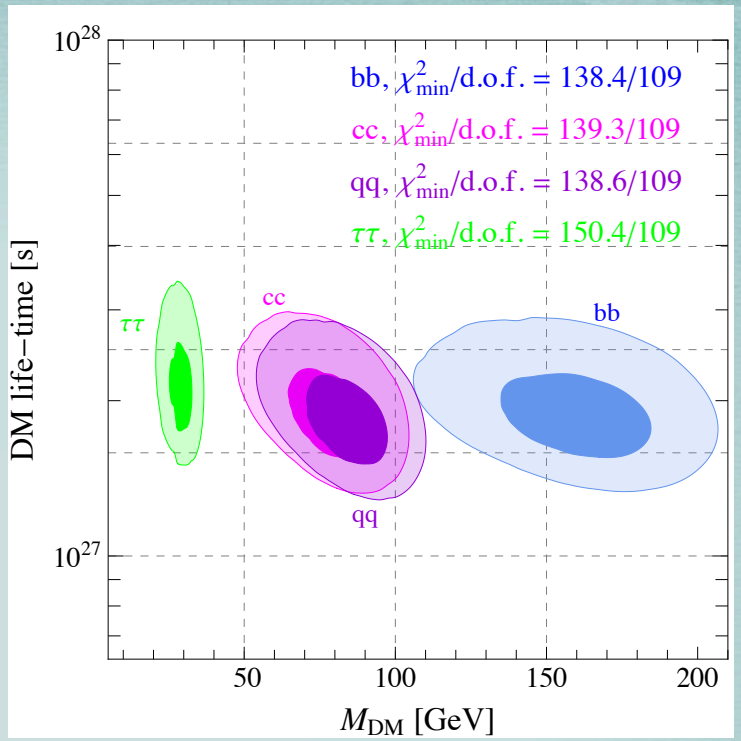


Inverse Compton Scattering



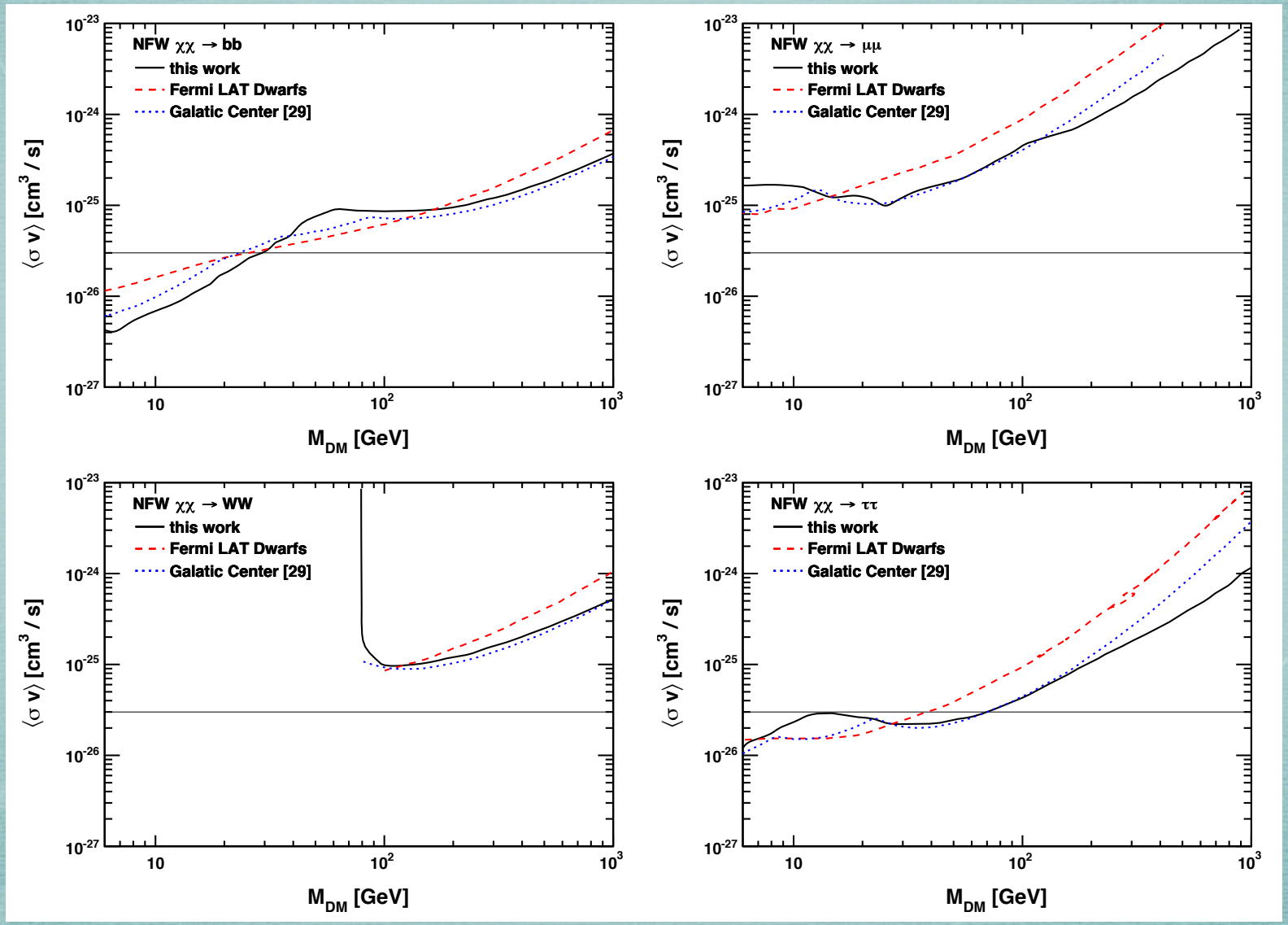
Chi-square fit





DM annihilation	$M_{\rm DM}$ $[GeV]$	$\langle\sigma v\rangle$ $[cm^3 s^{-1}]$	$\chi^2_{\rm min}$/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

Final State Radiation



Summary

1. The spectrum is latitude dependent

2. 1 GeV excess on Fermi bubbles photon spectrum

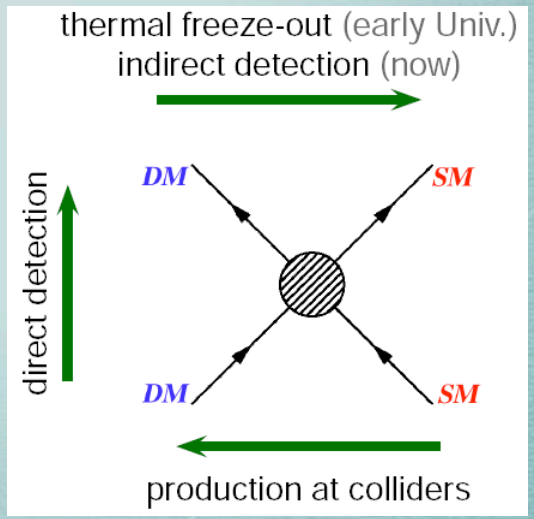
3. Derive conservative but stringent bound on DM annihliation

Dark Matter Detection

1. The thermal relic observed by CMB requires that DM annihilation cross section 3.0×10^{-26} $cm^3 s^{-1}$

2. Direct Detection constrains the DM-nucleon cross section $10^{-44} cm^2$ at 50 GeV

3. Dark Matter indirect detection:
   Fermi LAT gamma ray all sky



Effective Field Requirement

1. Fit Fermi Bubbles latitude-dependent Spectrum

2. Thermal Relic

3. Viable from the Direct Detection limits (XENON)

4. Validity of EFT , cutoff cannot be too small

$$\frac{1}{s-\Lambda^2} = -\frac{1}{\Lambda^2} - \frac{s}{\Lambda^4} + \mathcal{O}(s^2)$$

Effective Field Approach

1. Hidden Sector × Standard Model Sector

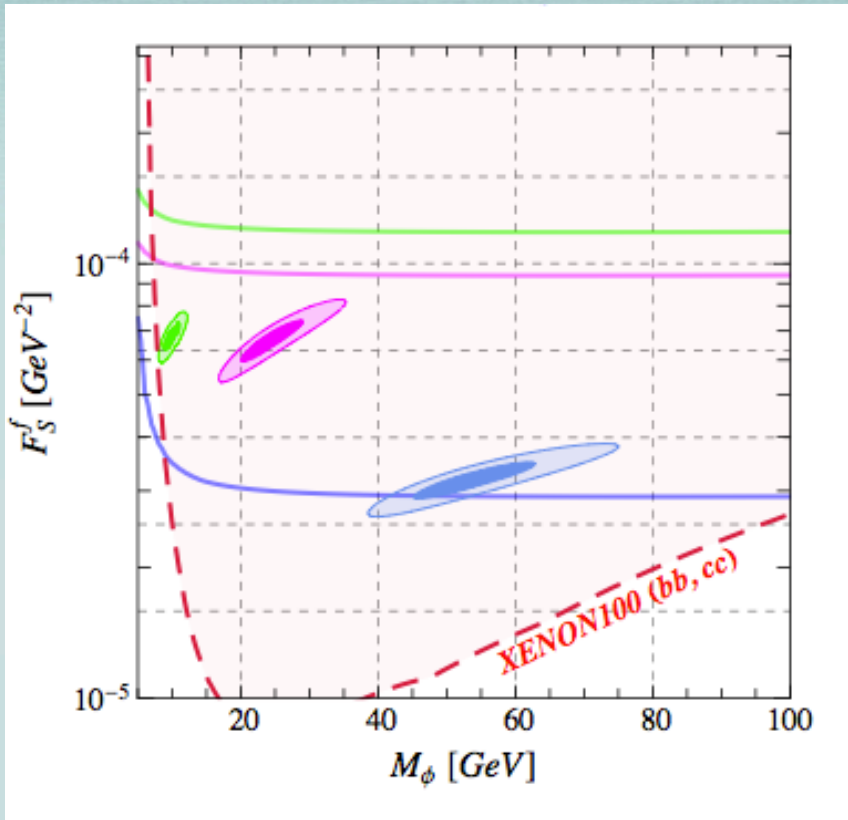
2. Neglect heavy final state (W, Z bosons and Higgs boson)

3. CP Violation : F_{SA} F_{VSA} F_A F_{TA}

$$
\begin{aligned}
\text{Scalar :} \quad \mathcal{O}^s_{\rm S} &\equiv \frac{m_f}{\sqrt{2}}\, \bar{\phi}\phi\ \bar{f}\left[F^s_{\rm S} + F^s_{\rm SA}\gamma^5\right] f\ , \\
\text{Vectorscalar :} \quad \mathcal{O}^s_{\rm VS} &\equiv \frac{m_f}{\sqrt{2}}\, \partial_\mu\bar{\phi}\partial^\mu\phi\ \bar{f}\left[F^s_{\rm VS} + F^s_{\rm VSA}\gamma^5\right] f\ , \\
\text{Vector :} \quad \mathcal{O}^s_{\rm V} &\equiv \frac{1}{\sqrt{2}}\, \bar{\phi}\overleftrightarrow{\partial}_\mu\phi\ \bar{f}\gamma^\mu\left[F^s_{\rm V} + F^s_{\rm A}\gamma^5\right] f\ , \\
\text{Tensor :} \quad \mathcal{O}^s_{\rm T} &\equiv \frac{m_f}{\sqrt{2}}\, \partial^\mu\bar{\phi}\partial^\nu\phi\ \bar{f}\sigma_{\mu\nu}\left[F^s_{\rm T} + F^s_{\rm TA}\gamma^5\right] f\ ,
\end{aligned}
$$

Complex Scalar Dark Matter					
Operator	Channel	Annihilation cross section		DD cross section	s/Λ^2 (%)
		m_f^2 suppression	v^2 suppression		
S	$\tau^+\tau^-$ (76.3)			×	2.5
	$c\bar{c}$ (58.2)	√	×	√	15.7
	$b\bar{b}$ (57.5)			√	34.8
	$q\bar{q}$			√	
VS	$\tau^+\tau^-$ (76.3)			×	31.8
	$c\bar{c}$ (58.2)	√	×	√	76
	$b\bar{b}$ (57.5)			√	118
	$q\bar{q}$			√	
V	$\tau^+\tau^-$			√ (1L)	
	$c\bar{c}$	×	√	√ (1L)	
	$b\bar{b}$			√ (1L)	
	$q\bar{q}$			√	
T	$\tau^+\tau^-$				
	$c\bar{c}$	√	√	×	
	$b\bar{b}$				
	$q\bar{q}$				

$$\text{Scalar}: \quad \mathcal{O}_{\rm S}^{s} \equiv \frac{m_f}{\sqrt{2}}\,\bar{\phi}\phi\,\bar{f}\left[F_{\rm S}^{s} + F_{\rm SA}^{s}\gamma^5\right] f$$



1. ττ, cc does not have the right thermal relic
2. bb is ruled out by direct detection. Also, it does not give reliable EFT description.

Singlet Scalar Dark Matter

$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{1}{2}\mu_S^2 S^2 - \frac{1}{2}\lambda S^2 |H|^2$$

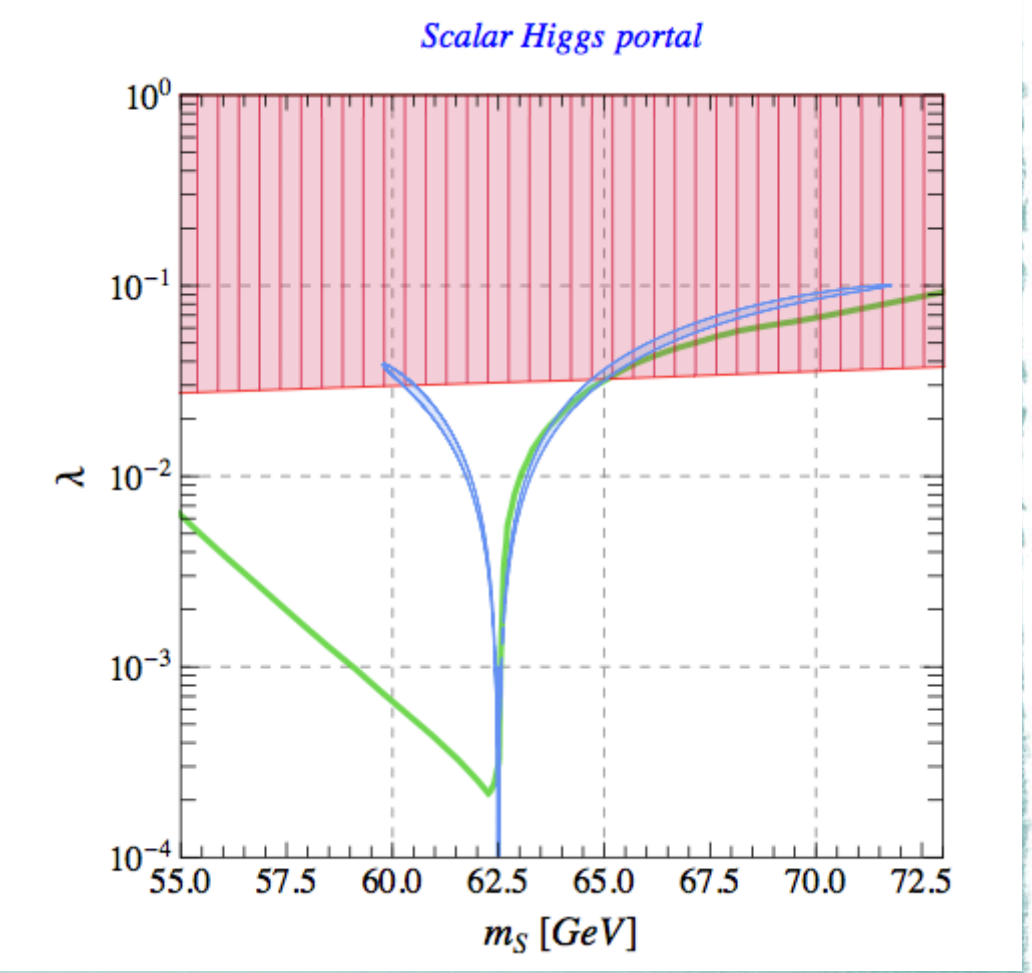
1. Red Direct Detection

2. Green Thermal Relic

3. Blue Fermi Bubble

4. < 60 GeV. invisible Higgs decay

5. 62.5 GeV < m_S < 65 GeV



Fermions (EFT)

$$
\begin{aligned}
\text{Scalar}: \quad \mathcal{O}_{\rm S}^f &\equiv \frac{m_f}{\sqrt{2}}\,\bar{\chi}\chi\;\bar{f}\left[G_{\rm S}^f + G_{\rm SA}^f\gamma^5\right] f\ , \\
\text{Pseudoscalar}: \quad \mathcal{O}_{\rm PS}^f &\equiv \frac{m_f}{\sqrt{2}}\,\bar{\chi}\gamma^5\chi\;\bar{f}\left[G_{\rm P}^f + G_{\rm PA}^f\gamma^5\right] f\ , \\
\text{Vector}: \quad \mathcal{O}_{\rm V}^f &\equiv \frac{1}{\sqrt{2}}\,\bar{\chi}\gamma^\mu\chi\;\bar{f}\gamma_\mu\left[G_{\rm V}^f + G_{\rm A}^f\gamma^5\right] f\ , \\
\text{Pseudovector}: \quad \mathcal{O}_{\rm PV}^f &\equiv \frac{1}{\sqrt{2}}\,\bar{\chi}\gamma^\mu\gamma^5\chi\;\bar{f}\gamma_\mu\left[G_{\rm PV}^f + G_{\rm PA}^f\gamma^5\right] f\ , \\
\text{Tensor}: \quad \mathcal{O}_{\rm T}^f &\equiv \frac{m_f}{\sqrt{2}}\,\bar{\chi}\sigma^{\mu\nu}\chi\;\bar{f}\sigma_{\mu\nu}\left[G_{\rm T}^f + G_{\rm TA}^f\gamma^5\right] f\ ,
\end{aligned}
$$

Scalar Operator

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

1. Annihilation cross section is mass suppressed

2. Annihilation cross section is p-wave (velocity suppressed)
   $< \sigma v> = a + b v^2$

3. Due to p-wave, there is no indirect detection signal ($v \sim 10^{-3}$)

PseudoScalar Operator

$$\text{Pseudoscalar}: \quad \mathcal{O}^f_{\rm PS} \equiv \frac{m_f}{\sqrt{2}}\,\bar{\chi}\gamma^5\chi\;\bar{f}\left[G^f_{\rm P} + G^f_{\rm PA}\gamma^5\right] f$$

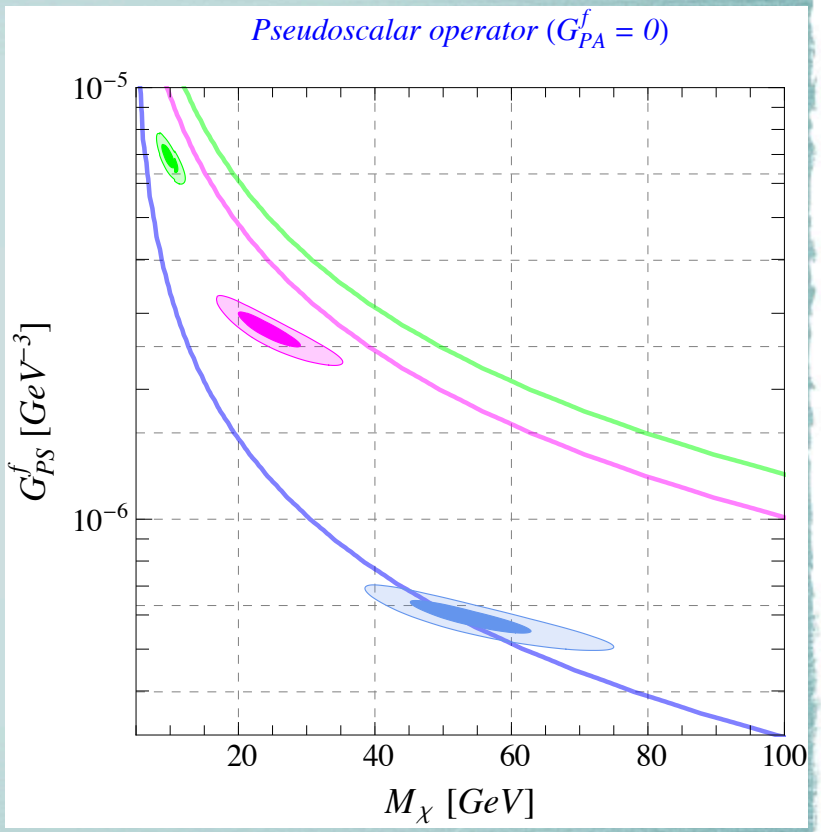
1. Annihilation cross section is mass suppressed, but not velocity suppressed

2. DM-nucleus scattering is proportional to $\mathbf{S}\cdot\mathbf{q}$,momentum suppression

3. b b final state, $\Lambda \sim (G_{PS})^{-1/3} \sim 120$ GeV, $S/\Lambda^2 \sim 78.5\ \%$

$$\frac{1}{s-\Lambda^2} = -\frac{1}{\Lambda^2} - \frac{s}{\Lambda^4} + \mathcal{O}(s^2)$$

4. Majorana Dark Matter cannot solve the EFT tension



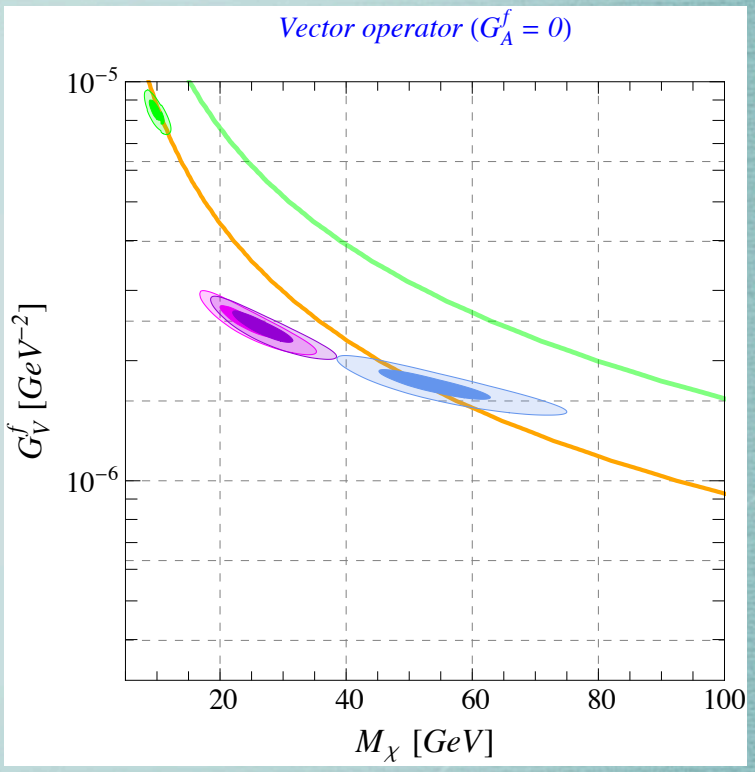
Vector Operator

$$\text{Vector}: \quad \mathcal{O}_{\rm V}^f \equiv \frac{1}{\sqrt{2}}\,\bar{\chi}\gamma^\mu\chi\;\bar{f}\gamma_\mu\left[G_{\rm V}^f + G_{\rm A}^f\gamma^5\right] f$$

1. s-wave

2.DM-nucleus scattering 1

3. b b final state, $\Lambda \sim (G_{PS})^{-1/3} \sim 760$ GeV, $S / \Lambda^2 \sim 1.9\ \%$

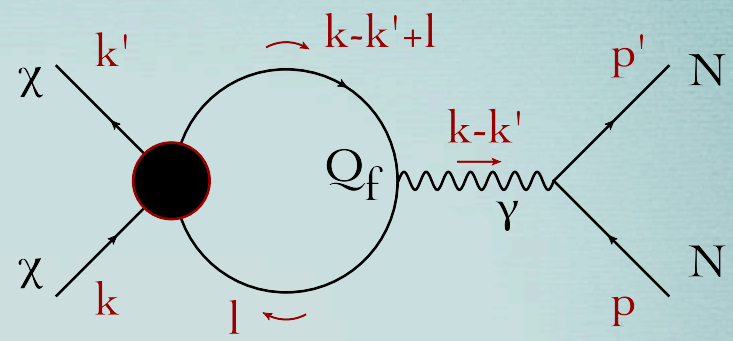


Vector Operator (DD)

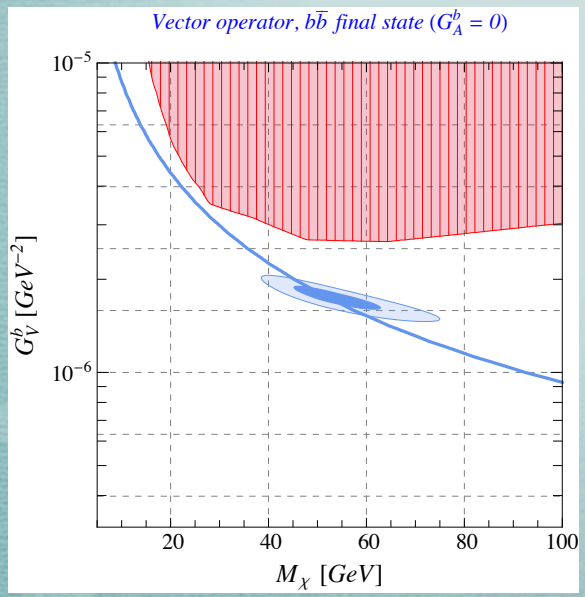
$$\text{Vector}: \quad \mathcal{O}_{\rm V}^f \equiv \frac{1}{\sqrt{2}}\,\bar{\chi}\gamma^\mu\chi\;\bar{f}\gamma_\mu\left[G_{\rm V}^f + G_{\rm A}^f\gamma^5\right]f$$

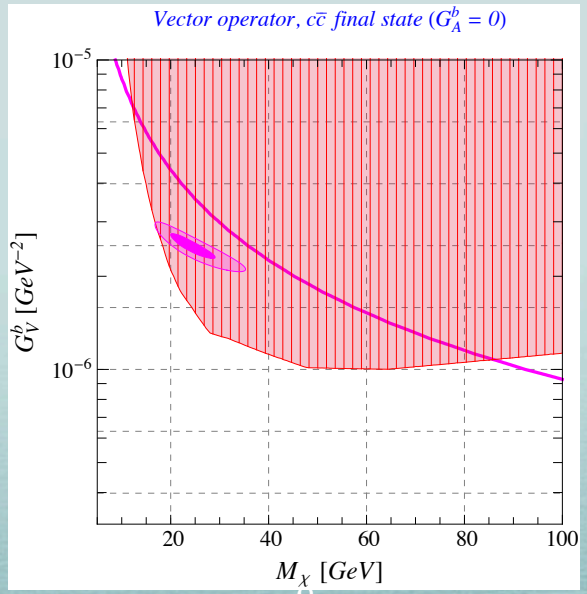
1. sea quark is ruled out

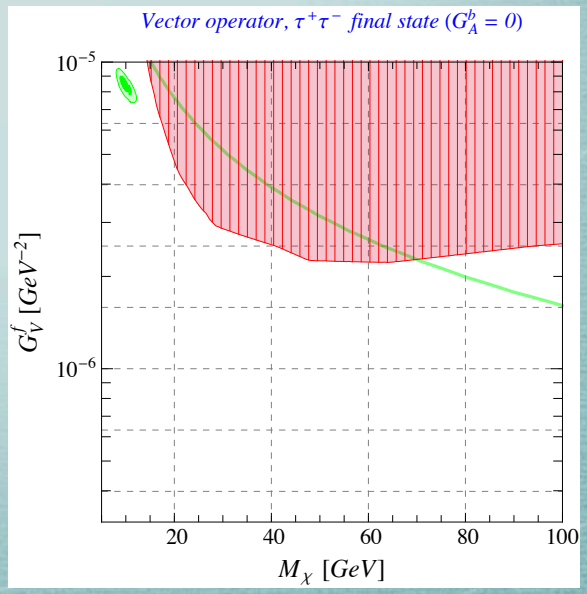
2. valence quark is from one-loop



3. G_A is safe, due to Spin-dependent scattering







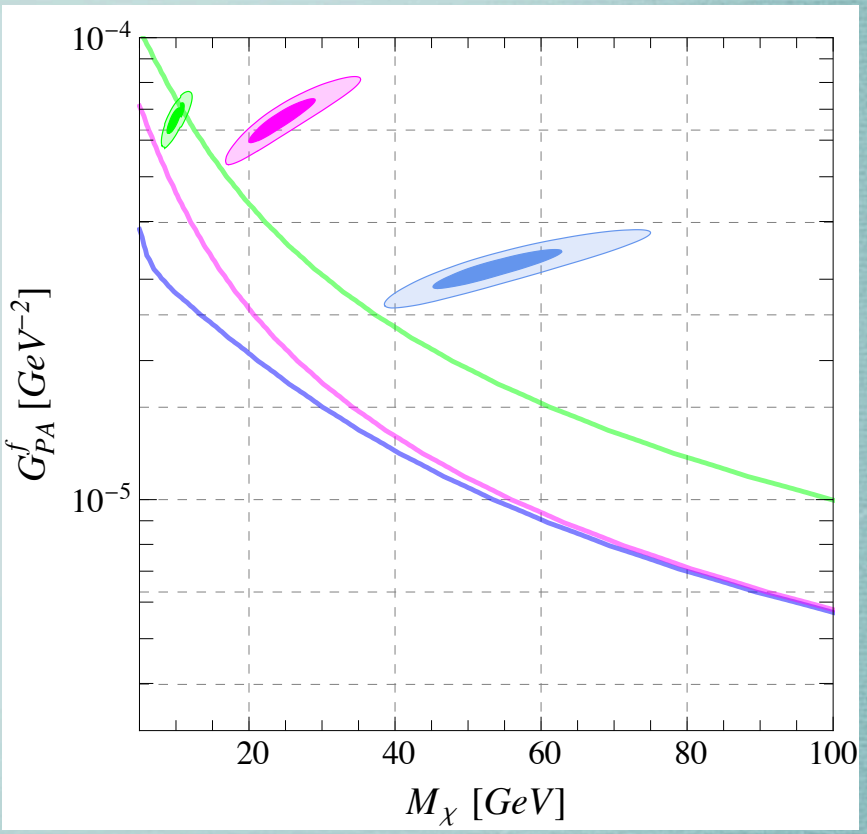
PesudoVector Operator

$$\text{Pseudovector}: \quad \mathcal{O}^f_{\rm PV} \equiv \frac{1}{\sqrt{2}}\,\bar{\chi}\gamma^\mu\gamma^5\chi\;\bar{f}\gamma_\mu\left[G^f_{\rm PV}+G^f_{\rm PA}\gamma^5\right]f$$

1. s-wave

2.DM-nucleus scattering is velocity suppression

3. b b EFT, $S/\Lambda^2 \sim 34.6\,\%$
   τ τ EFT, $S/\Lambda^2 \sim 2.5\,\%$



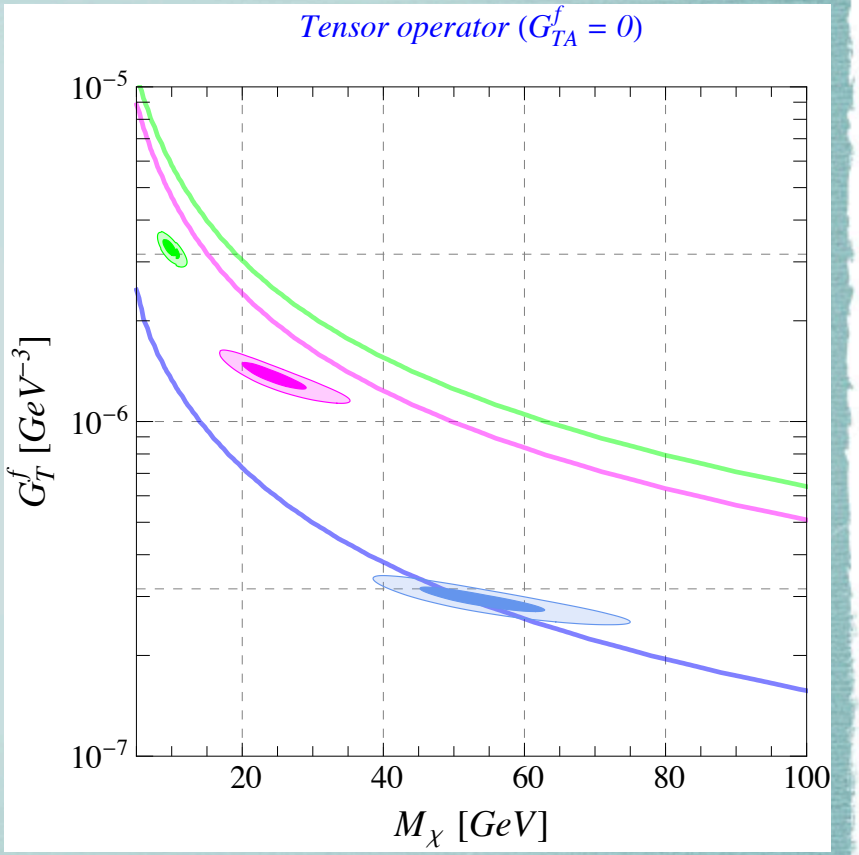
Tensor Operator

$$\text{Tensor}: \quad \mathcal{O}_{\mathrm{T}}^{f} \equiv \frac{m_f}{\sqrt{2}} \bar{\chi}\sigma^{\mu\nu}\chi \; \bar{f}\sigma_{\mu\nu}\left[G_{\mathrm{T}}^{f} + G_{\mathrm{TA}}^{f}\gamma^5\right] f$$

1. mass suppression, s-wave, bb

2.DM-nucleus scattering is velocity suppression

3. b b EFT, S / Λ^2 ~ 49.1 %



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
	$q\bar{q}$				

Conclusion

1. Fermi Bubbles residual spectrum, 10°<|b| < 20°, bump feature

2.Fermi Bubbles spectrum can be fitted by Dark Matter + ICS bb final state:

$$M_{\rm DM} = 61.8^{+6.9}_{-4.9}\ {\rm GeV} \quad \langle \sigma v \rangle = 3.30^{+0.69}_{-0.49} \times 10^{-26}\ {\rm cm}^3{\rm s}^{-1}$$

3. Study EFT theory to explain Fermi bubbles,
   Scalar DM does not work
   Fermion DM Vector bb, PseudoVector τ τ

4. Concrete Model: Singlet Dark Matter is viable