Fermi bubbles under Dark Matter scrutiny

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arXiv:1307.6862 1310.7609 with Alfredo Urbano and Wei Xue

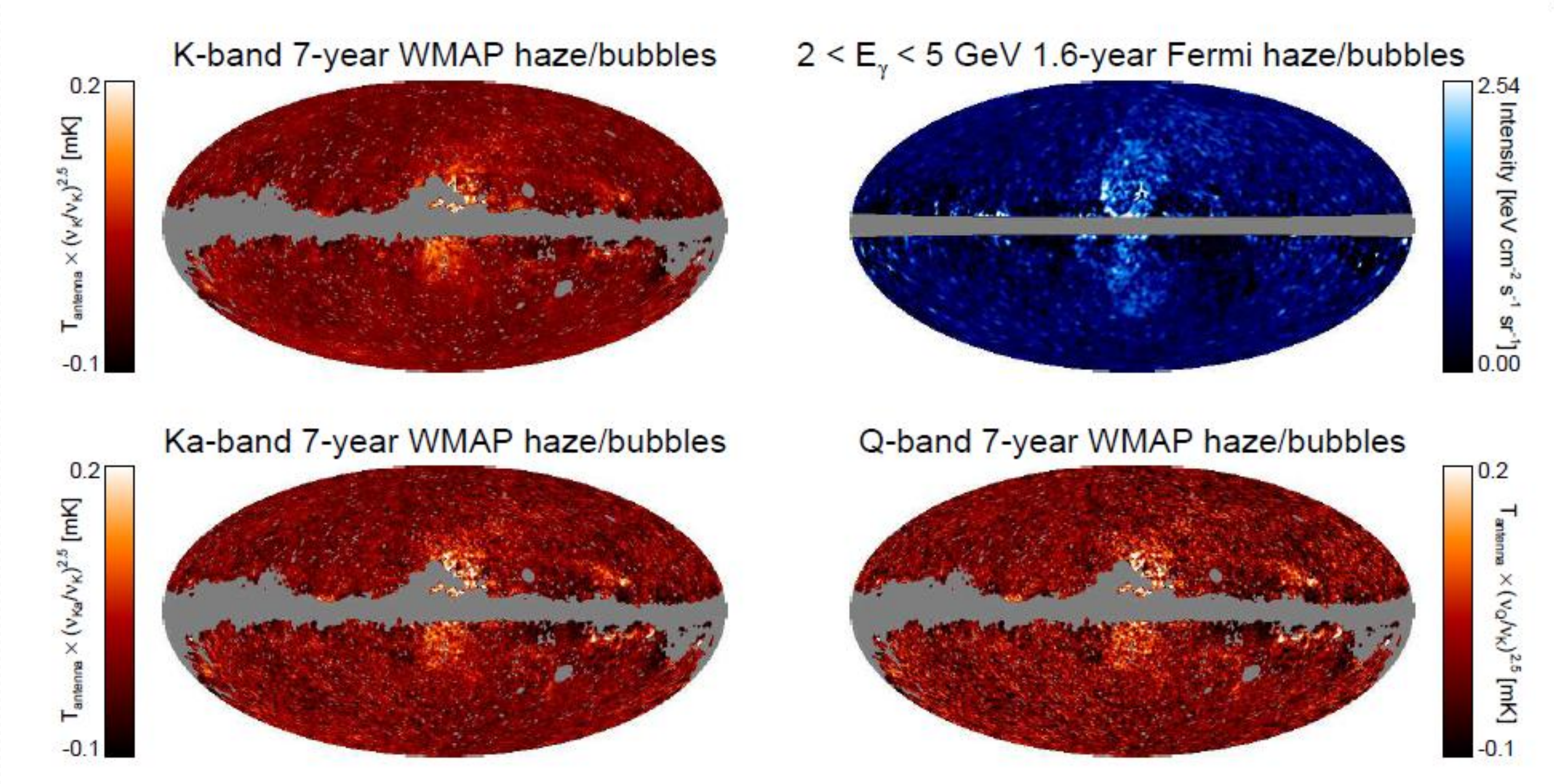
Outline

- Introduction
- Inverse Compton Scattering (ICS) and Dark Matter (DM) annihilation
- Fermionic DM in the context of Effective Field Theory (EFT) approach
- Scalar dark matter
- Realizations
- conclusions

Fermi Bubbles

- The Fermi bubbles (M. Su et al , arXiv:1005.5480.) refer to a pair of large gamma-ray lumps extending 50^o both north and south of the Galactic Center.
- There exists a fairly flat energy spectrum and almost constant as a function of the latitude b for the regions of $|b| > 30^o$.
- For lower latitudes, the energy spectrum of the Fermi Bubbles peaks between 1 to 4 GeV. (D. Hooper et al, arXiv:1302.6589)

WMAP haze and Fermi bubbles



D. P. Finkbeiner arXiv:astro-ph/0311547
Gregory Dobler arXiv:1109.4418v2

WMAP haze and Fermi bubbles

- Due to the spatial correlation, a population of GeV-TeV electrons with an approximately power-law spectrum can explain the WMAP haze via the microwave synchrotron radiation in the presence of microgauss-scale magnetic fields (arXiv:1302.6589).

- The same electron population scattering off Cosmic Microwave Background (CMB), infrared, and starlight photons can also account for Fermi bubbles for high latitudes with flat energy spectrum.

- For low latitudes, there still exists the residue excess after subtracting the ICS component in the Fermi bubbles.

ICS photons

- Assume a population of GeV – TeV electrons with a power-law energy spectrum
- The electrons scatter off InterStellar Radiation Field (ISRF), including CMB, infrared, and starlight photons

$$\frac{d\Phi}{dE_\gamma d\Omega} = \frac{1}{E_\gamma} \int_{\mathrm{l.o.s.}} ds \; \frac{j[E_\gamma, r(s)]}{4\pi}$$

$$j[E_\gamma, r(s)] = \int_{m_e}^{E_{\mathrm{cut}}} dE_e \; \mathcal{P}(E_\gamma, E_e, r) \; n_e(r, E_e)$$

$$\mathcal{P}(E_\gamma, E_e, r) = \frac{3\sigma_T}{4\gamma^2} E_\gamma \int_{1/4\gamma^2}^{1} dq \left[1 - \frac{1}{4q\gamma^2(1-\tilde{E}_\gamma)}\right] \frac{n_\gamma(E'_\gamma, r)}{q} \left(2q\log q + q + 1 - 2q^2 + \frac{1-q}{2}\frac{\tilde{E}_\gamma{}^2}{1-\tilde{E}_\gamma}\right)$$

arXiv:0904.3830

DM annihilation FSR

$$\frac{d\Phi_\gamma}{d\Omega dE_\gamma} = \frac{r_\odot}{4\pi} \begin{cases} \frac{1}{2c}\left(\frac{\rho_\odot}{M_\chi}\right)^2 \bar{J} \sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE_\gamma} & \text{(annihilation)} \\ \frac{\rho_\odot}{M_\chi} \bar{J} \sum_f \Gamma_f \frac{dN_\gamma^f}{dE_\gamma} & \text{(decay)} \end{cases}$$

$$\rho_{\text{gNFW}}(r) = \rho_s \left(\frac{r}{R_s}\right)^{-\gamma} \left(1 + \frac{r}{R_s}\right)^{\gamma-3} \quad J(\theta) = \int_{\text{l.o.s.}} \frac{ds}{r_\odot} \left[\frac{\rho_{\text{NFW}}(r(s,\theta))}{\rho_\odot}\right]^a$$

$\gamma = 1.2$

$R_s = 20$ kpc

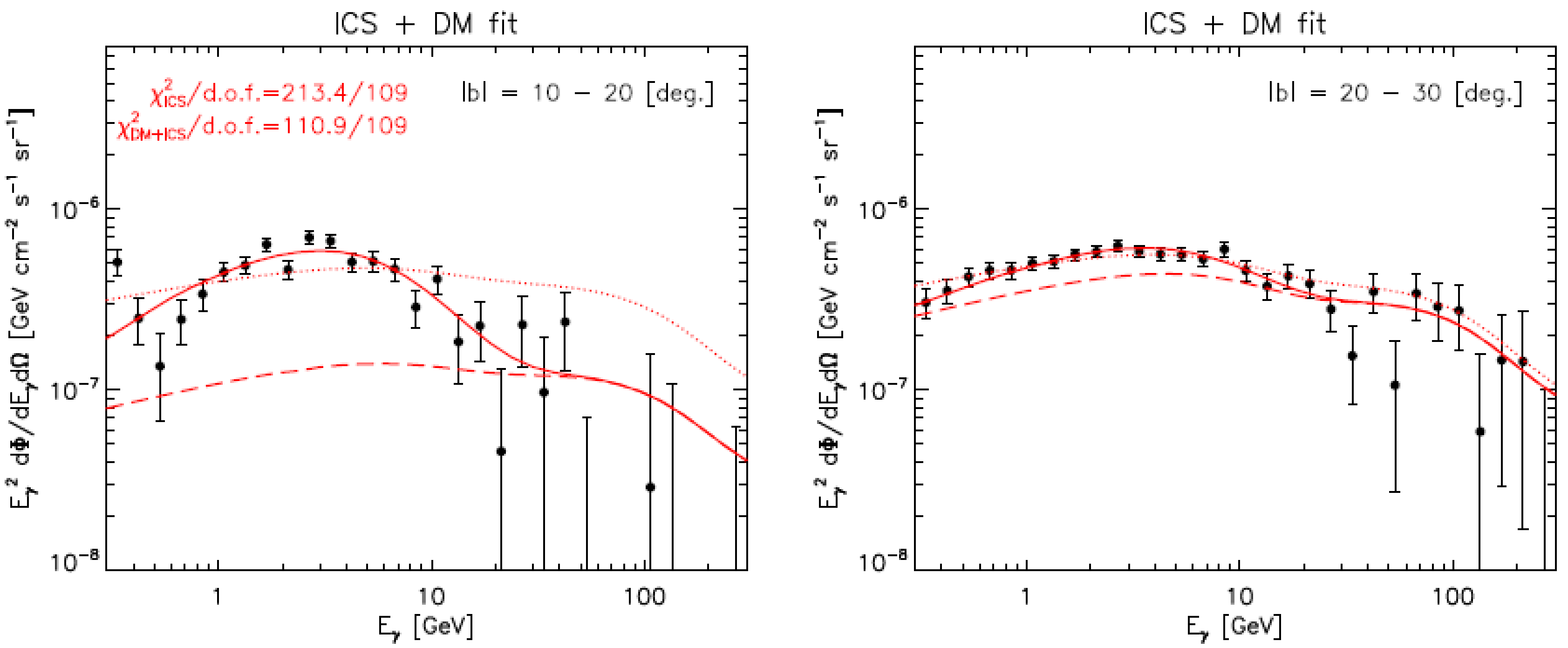
$r_\odot = 8.33$ kpc

$\rho_\odot = 0.4\ \text{GeV/cm}^3$

$a = 1(2)$ decay(annihilation)

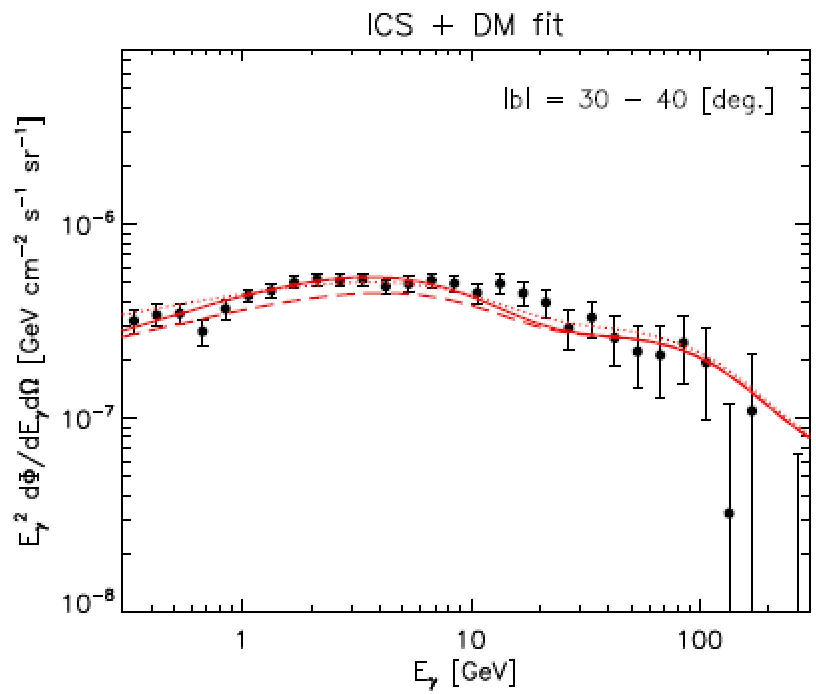
$c = 1(2)$ Majorana DM(Dirac DM)

ICS +DM(b) FSR

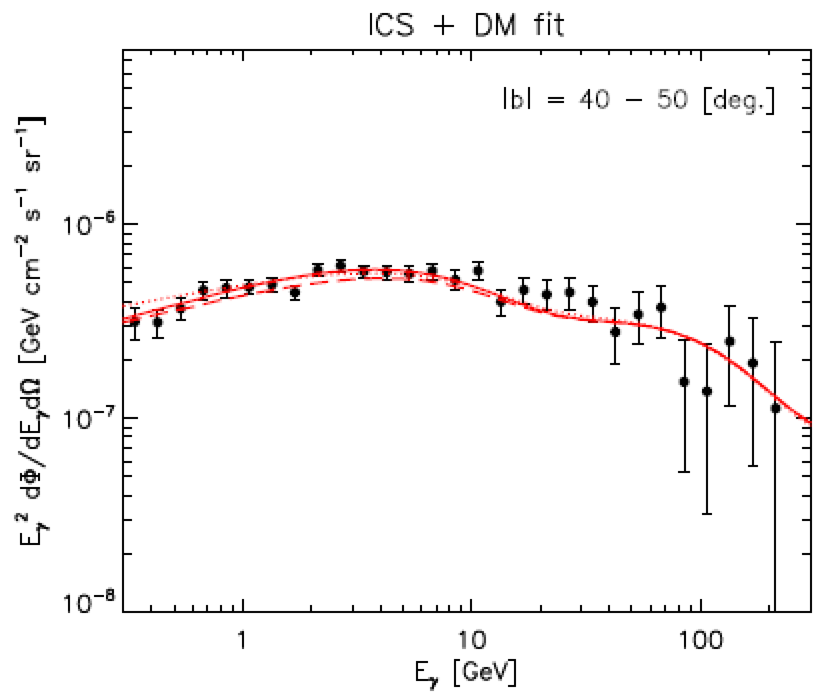


ICS + DM fit
χ^2_{ICS}/d.o.f.=213.4/109
χ^2_{DM+ICS}/d.o.f.=110.9/109
|b| = 10 − 20 [deg.]
$E_\gamma^2\ d\Phi/dE_\gamma d\Omega$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_γ [GeV]
ICS + DM fit
|b| = 20 − 30 [deg.]
$E_\gamma^2\ d\Phi/dE_\gamma d\Omega$ [GeV cm^{-2} s^{-1} sr^{-1}]
E_γ [GeV]

ICS +DM(b) FSR



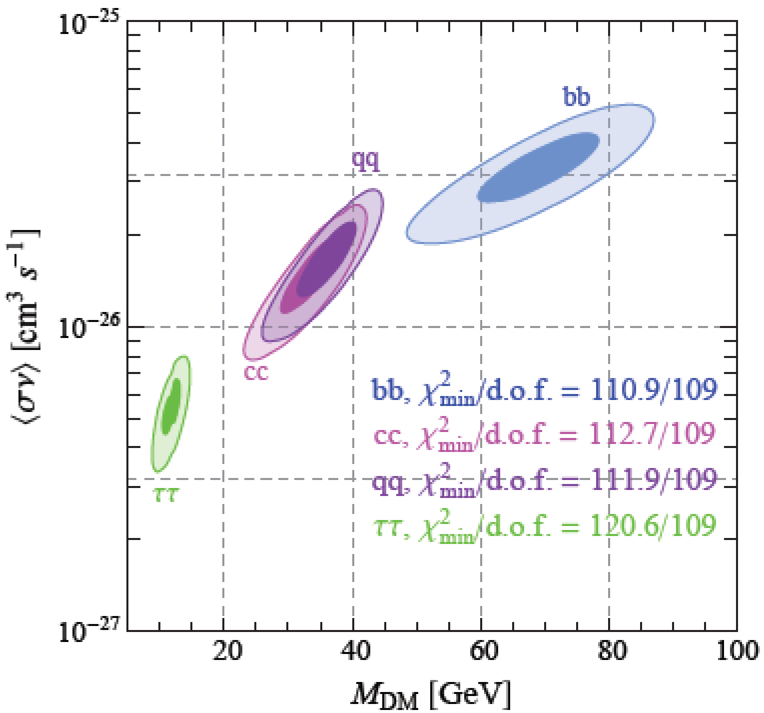
ICS + DM fit
|b| = 30 − 40 [deg.]
$E_\gamma^2\, d\Phi/dE_\gamma d\Omega$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
1
10
100
E_γ [GeV]

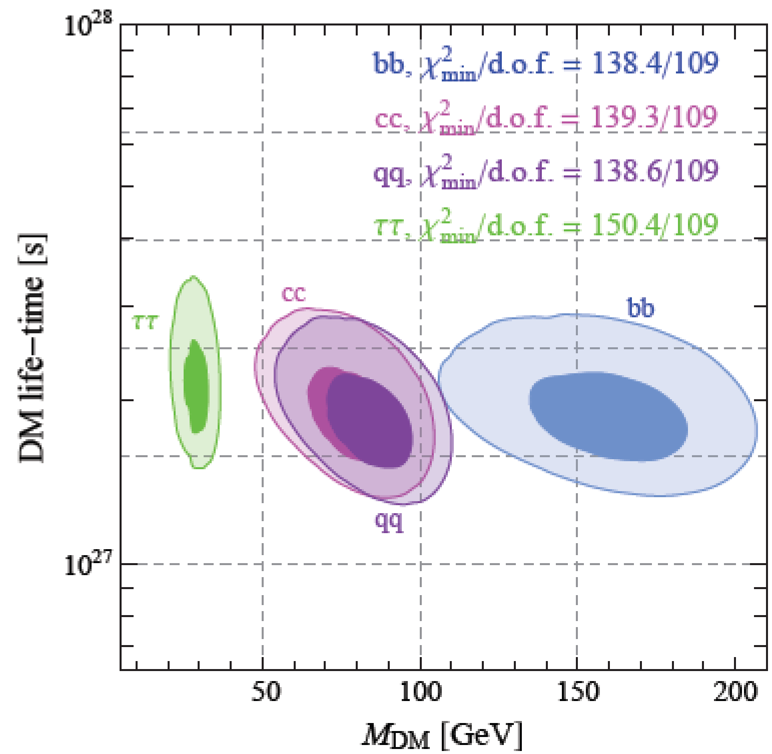


ICS + DM fit
|b| = 40 − 50 [deg.]
$E_\gamma^2\, d\Phi/dE_\gamma d\Omega$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
1
10
100
E_γ [GeV]

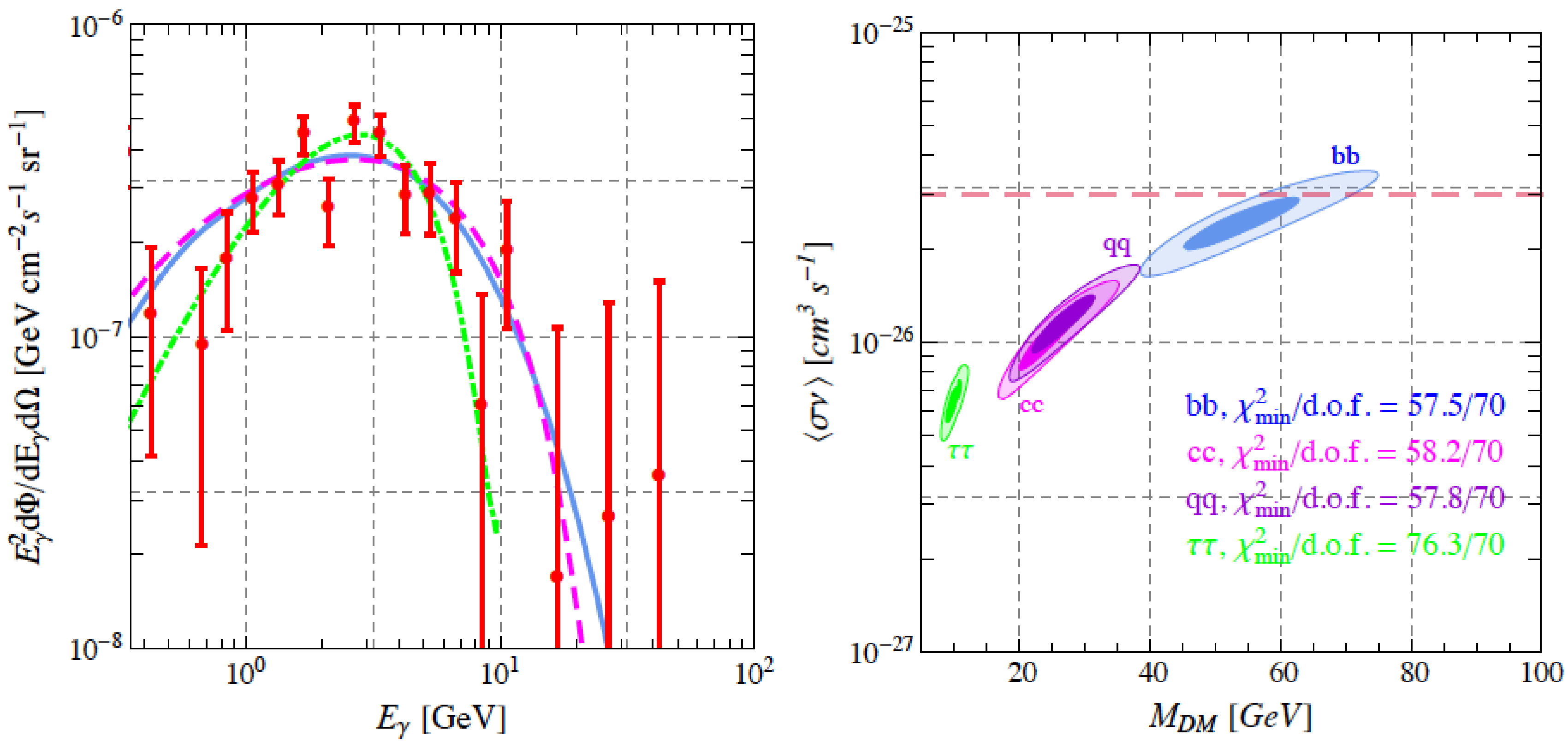
ICS +DM FSR

- Annihilating DM is preferred due to concentration of the gamma ray excess toward the Galactic center

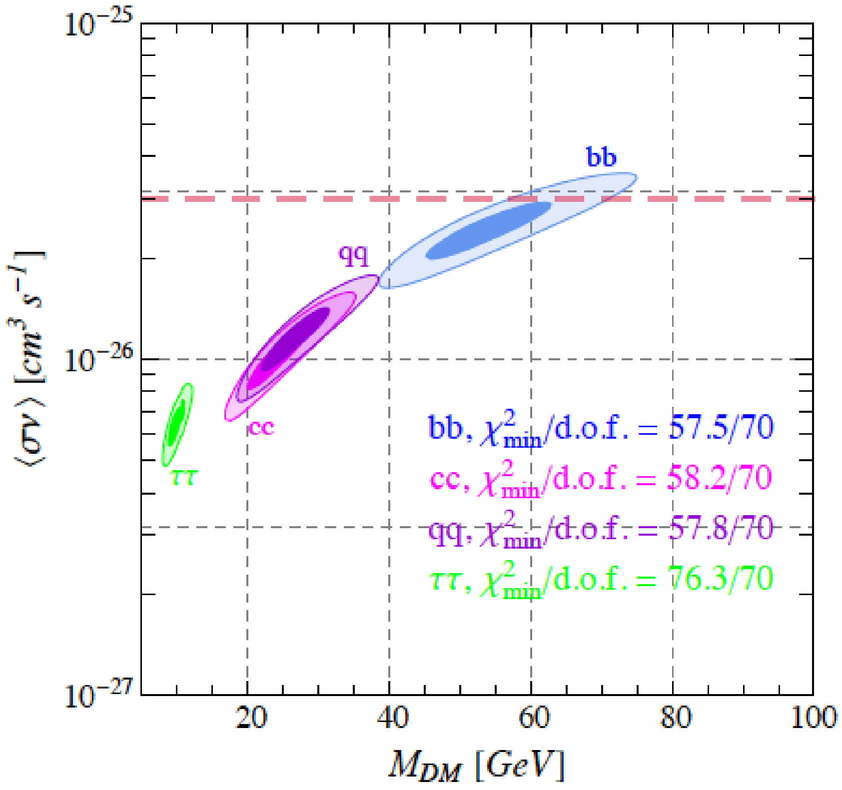




DM signal after ICS removal



DM signal after ICS removal



- ➢If the annihilation cross section is dominated by the s-wave component, only b channel can simultaneously explain the bubbles and yield the correct relic density

- ➢We shall see one counterexample.

DM explanation in EFT

- We look for operators that *simultaneously* account for the bubbles and generate the correct relic density.
- Any operators suffering from velocity suppression can not explain the bubbles due to the current low DM velocity.
- Any operators with the suppression of the final state mass will disfavor the light final states, such as u- and d-quark.
- We include direct search bounds, especially XENON 100 SI bounds.
- The validity of the EFT approach is also taken into account.

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

Effective operators (Fermionic DM)

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

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

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

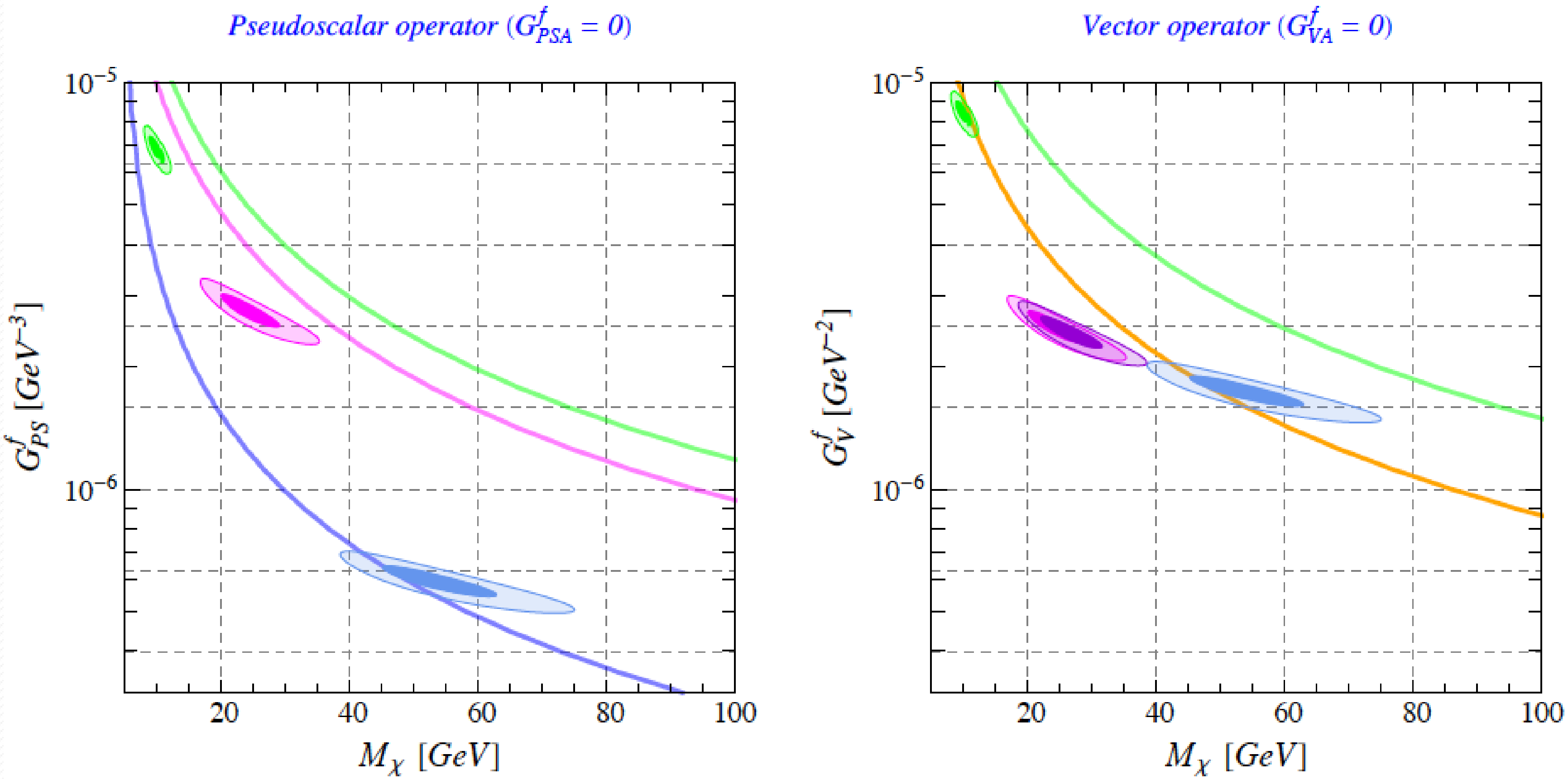
$$\text{Pseudovector}: \quad \mathcal{O}^f_{\rm PV} \equiv \frac{1}{\sqrt{2}} \bar{\chi}\gamma^\mu\gamma^5\chi \, \bar{f}\gamma_\mu\left[G^f_{\rm PV} + G^f_{\rm PVA}\gamma^5\right] f \, ,$$

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

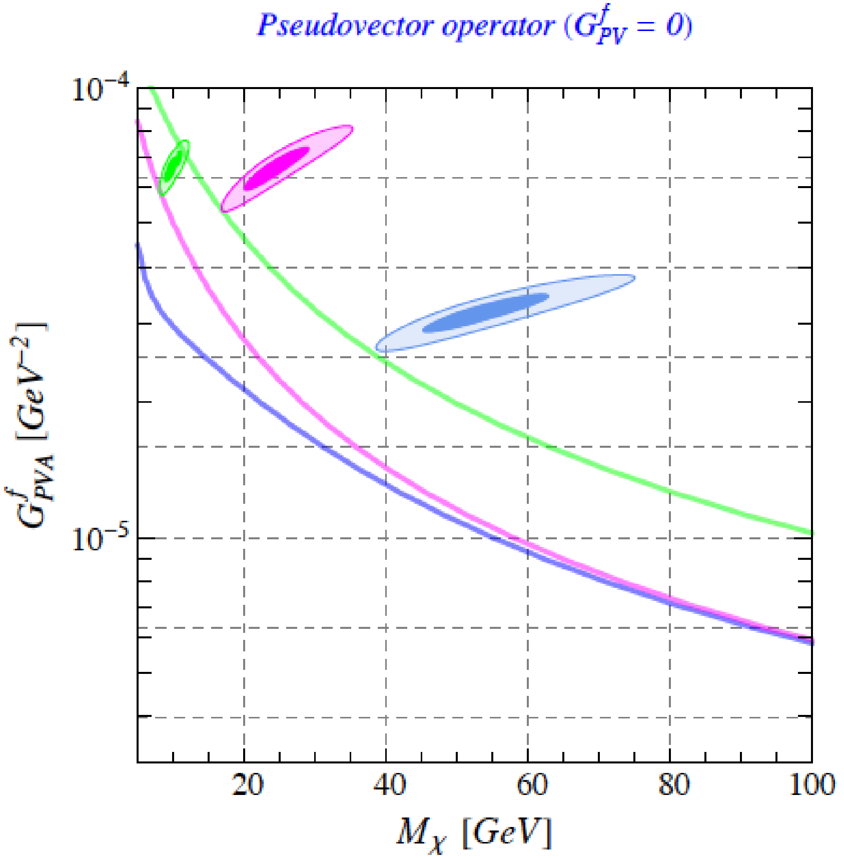
Effective operators (Fermionic DM)

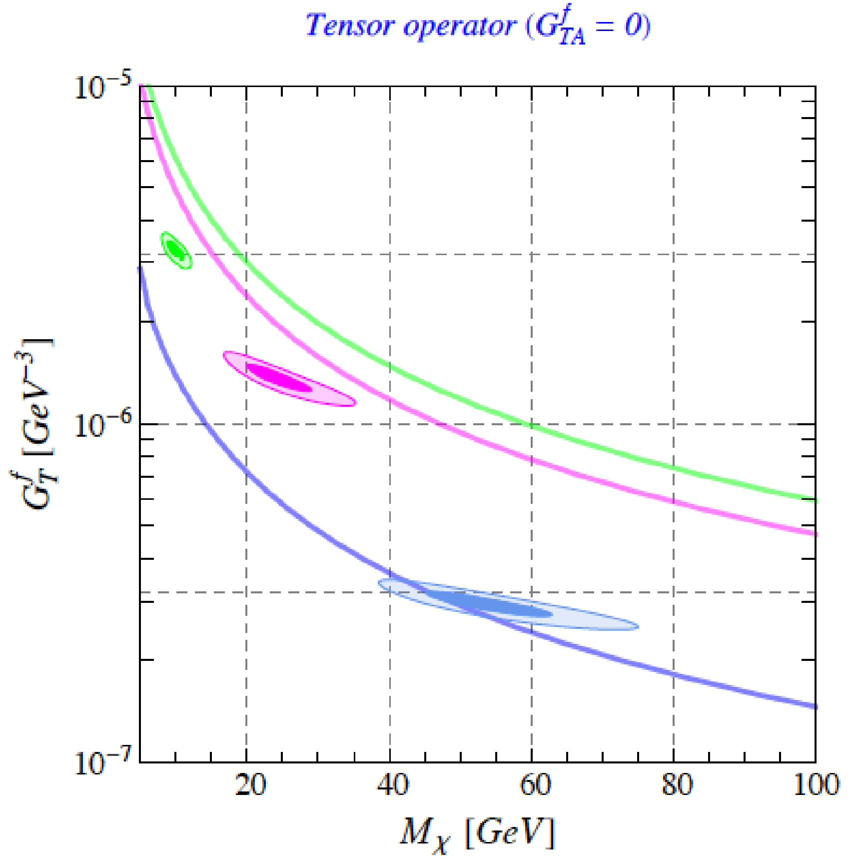
Fermionic Dark Matter					
Operator	Channel	Annihilation cross section		DD cross section	s/Λ^2 (%)
		m_f^2 suppression	v^2 suppression		
S	$\tau^+\tau^-$			×	
	$c\bar{c}$	√	√	√	
	$b\bar{b}$			√	
	$q\bar{q}$			√	
PS	$\tau^+\tau^-$ (76.3)				13.7
	$c\bar{c}$ (58.2)	√	×	×	43.7
	$b\bar{b}$ (57.5)				78.5
	$q\bar{q}$				
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
	$q\bar{q}$				

Effective operators (Fermionic DM)



Effective operators (Fermionic DM)





Effective operators (Scalar DM)

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

$$\text{Vectorscalar}: \quad \mathcal{O}^s_{\rm VS} \equiv \frac{m_f}{\sqrt{2}} \partial_\mu\bar{\phi}\partial^\mu\phi \; \bar{f}\left[F^s_{\rm VS} + F^s_{\rm VSA}\gamma^5\right] f \;,$$

$$\text{Vector}: \quad \mathcal{O}^s_{\rm V} \equiv \frac{i}{\sqrt{2}} \bar{\phi}\overleftrightarrow{\partial}_\mu\phi \; \bar{f}\gamma^\mu\left[F^s_{\rm V} + F^s_{\rm A}\gamma^5\right] f \;,$$

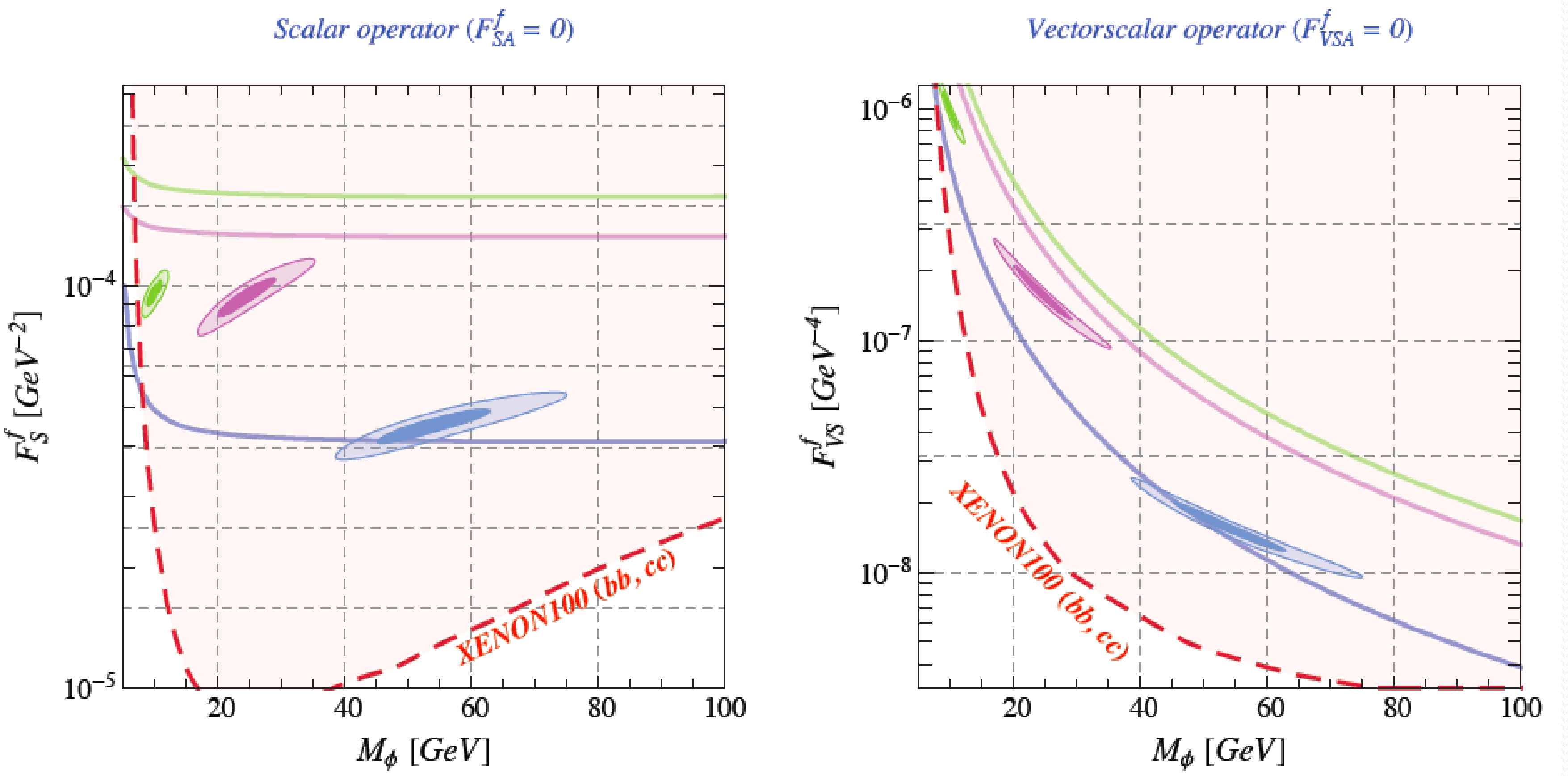
$$\text{Tensor}: \quad \mathcal{O}^s_{\rm T} \equiv \frac{m_f}{\sqrt{2}} \partial^{[\mu}\bar{\phi}\partial^{\nu]}\phi \; \bar{f}\sigma_{\mu\nu}\left[F^s_{\rm T} + F^s_{\rm TA}\gamma^5\right] f \;,$$

Effective operators (Scalar DM)

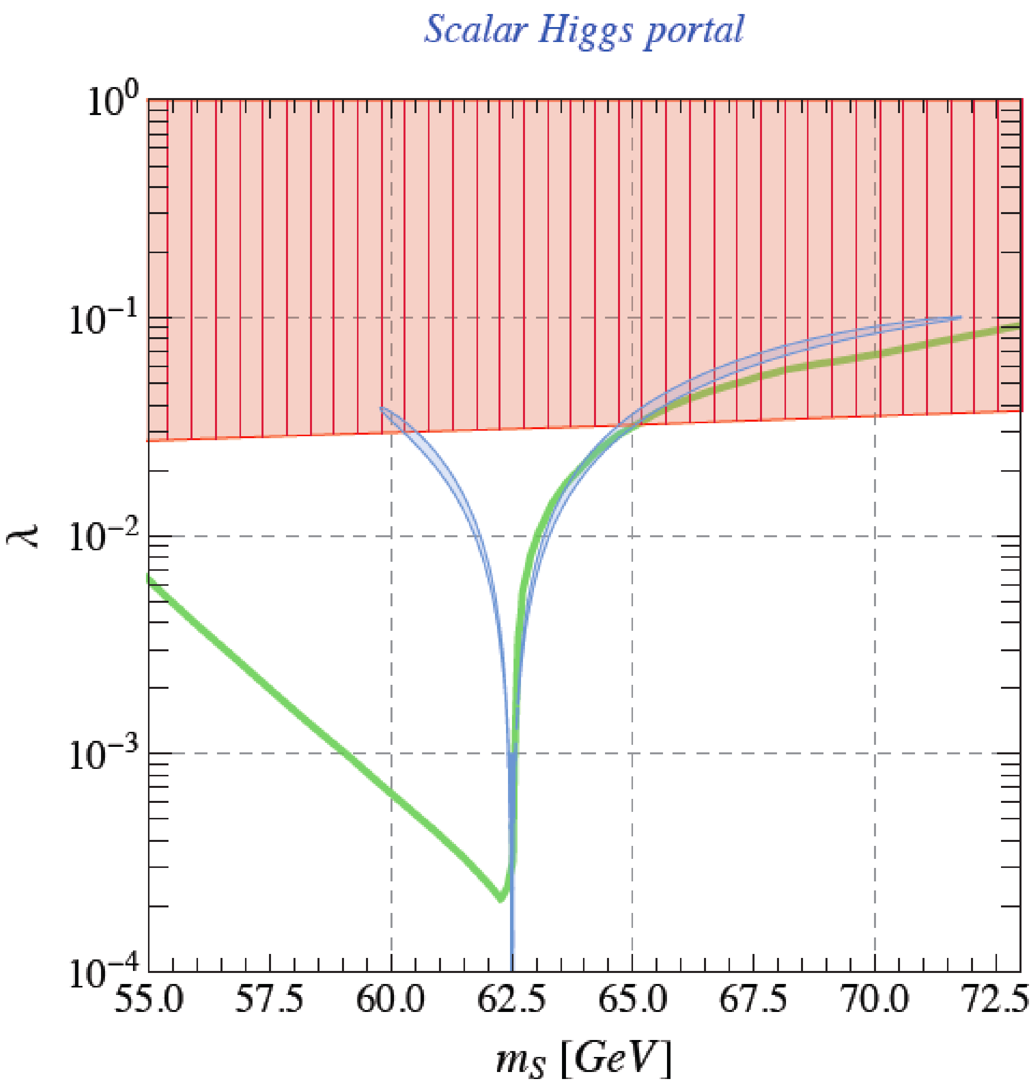
Complex Scalar Dark Matter

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	$\tau^+\tau^-$	✓	✓	×	
	$c\bar{c}$				
	$b\bar{b}$				
	$q\bar{q}$				

Effective operators (Scalar DM)



Scalar Higgs Portal



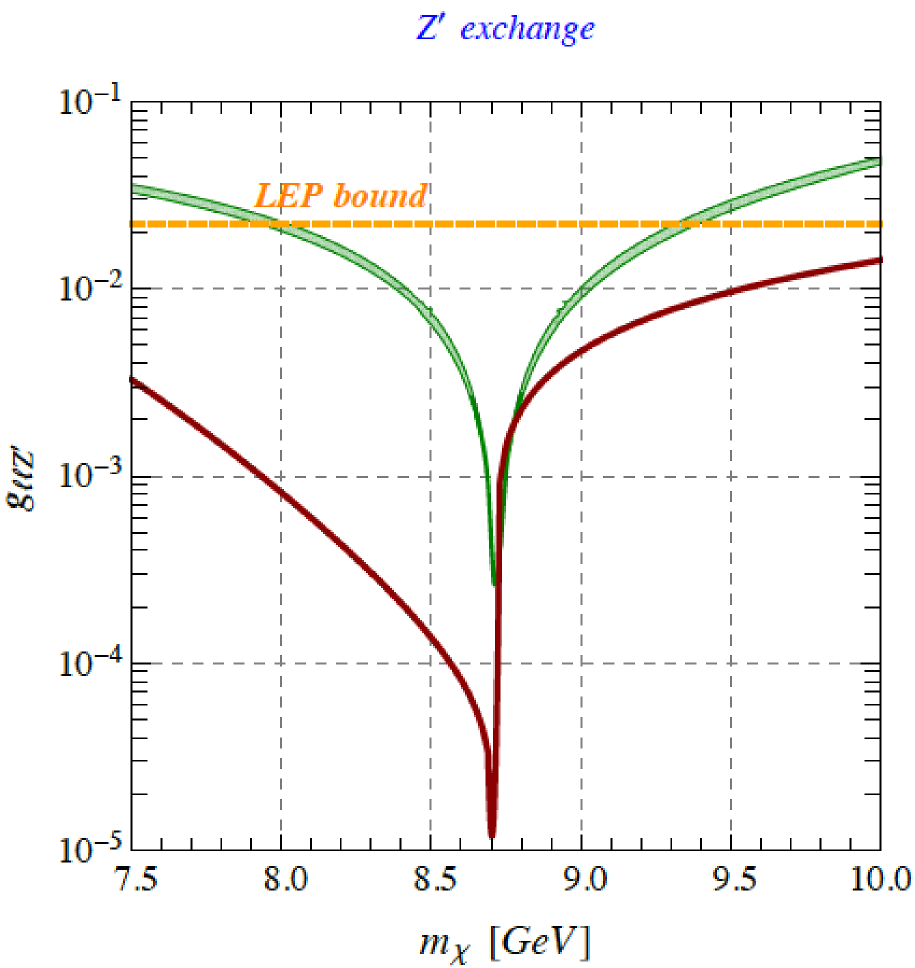
$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{1}{2}\mu_S^2 S^2 - \frac{1}{2}\lambda S^2 |H|^2 \ ,$$

$$\sigma_S v = \frac{2}{\sqrt{s}} \left[\frac{\lambda^2 v^2}{(s - m_h^2)^2 + \Gamma_{h,S}^2 m_h^2} \right] \Gamma_h(\sqrt{s}) \ ,$$

$$\mathrm{BR}_{\mathrm{inv}}(m_S, \lambda) \equiv \frac{\Gamma_{\mathrm{inv}}(h \to SS)}{\Gamma_{\mathrm{inv}}(h \to SS) + \Gamma_{\mathrm{vis}}} \ ,$$

V. Silveira and A. Zee 1985
J. McDonald 1995
C. Burgess, M. Pospelov, and T. ter Veldhuis, 2001
B. Patt and F. Wilczek, 2006

Z’ exchange with Fermionic DM



In order to avoid direct search bounds, we simply assume:

- ➢the pseudovector-type coupling between DM and Z’
- ➢leptophilic Z’

In addition, couplings of the Z’ and SM leptons are proportional to those of Z to SM leptons.

$$\mathcal{L} \supset g_{\chi\chi Z'}\bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu + g_{\ell\ell Z'}\bar{\ell}\gamma^\mu(g_{\ell_R}P_R + g_{\ell_L}P_L)\ell Z'_\mu,$$

$$g_{\chi\chi Z'} = 1 \text{ and } m'_Z = 17.5 \text{ GeV}$$

Conclusions

- The residue after subtracting the diffuse background features a peak around 4 GeV in low latitudes, that can be explained by DM annihilation, and a flat spectrum in high latitudes, that can be accounted for by the additional GeV-TeV electron population.
- In the context of the EFT, the peak feature can be realized with fermionic DM annihilating into b-quark via the vector operator and into τ via the pseudovector operator.
- In addition, we provide two models , i.e., the Higgs portal with scalar DM and the Z' exchange with fermionic DM.
- These two models exhibit the resonance enhancement and fall outside the territory of EFT.