Multimediator Models for the Galactic Center Gamma Ray Excess

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in collaboration with James Cline, Grace Dupuis and Wei Xue

arXiv:1405.7691 (JHEP), arXiv:1503.08213 (PRD)

Outline

(1) Hints of gamma ray excess in Fermi data

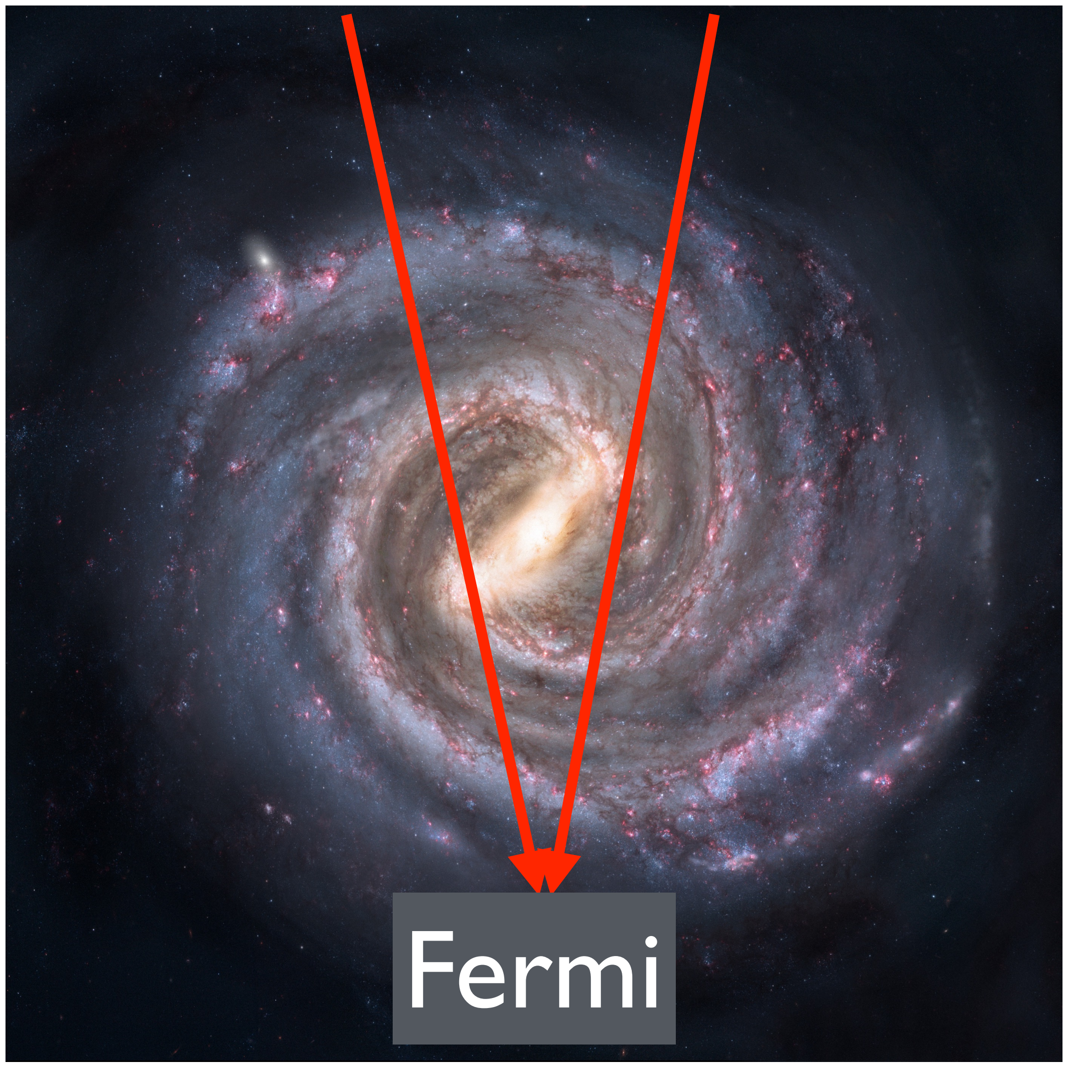
(2) DM models with on-shell mediators

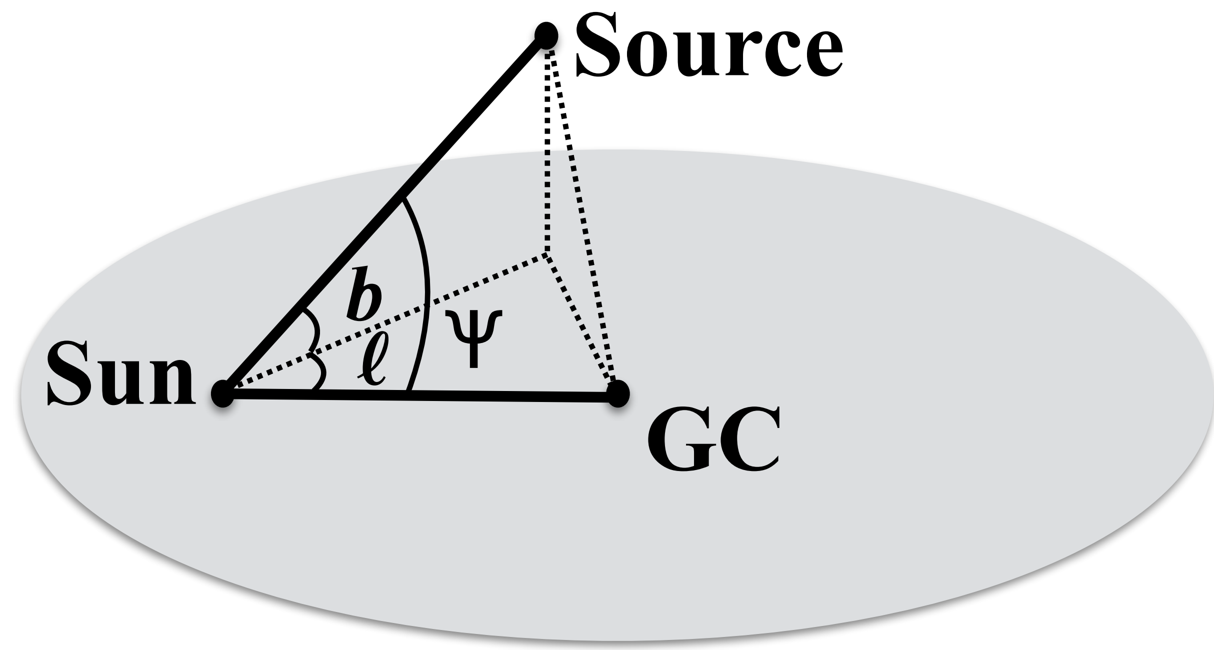
(3) Multiple on-shell mediator models

(4) Experimental Constraints

(5) Summary

Gamma rays from the Galactic Center





Fermi can look for gamma ray excess near the center of the galaxy.

Many analyses focus on the region within 10-20 degrees near GC.

BGs along the line-of-sight poses a challenge for signal analyses.

Gamma ray excess in Galactic Center

Several groups have identified possible excess signals of gamma rays in the galactic center.

Daylan et al. (arXiv:1402.6703) finds excess of gamma rays with energy in the GeV range and at least 10 degree from the GC. The gamma ray excess agrees with what is expected from dark matter annihilations in the halo.

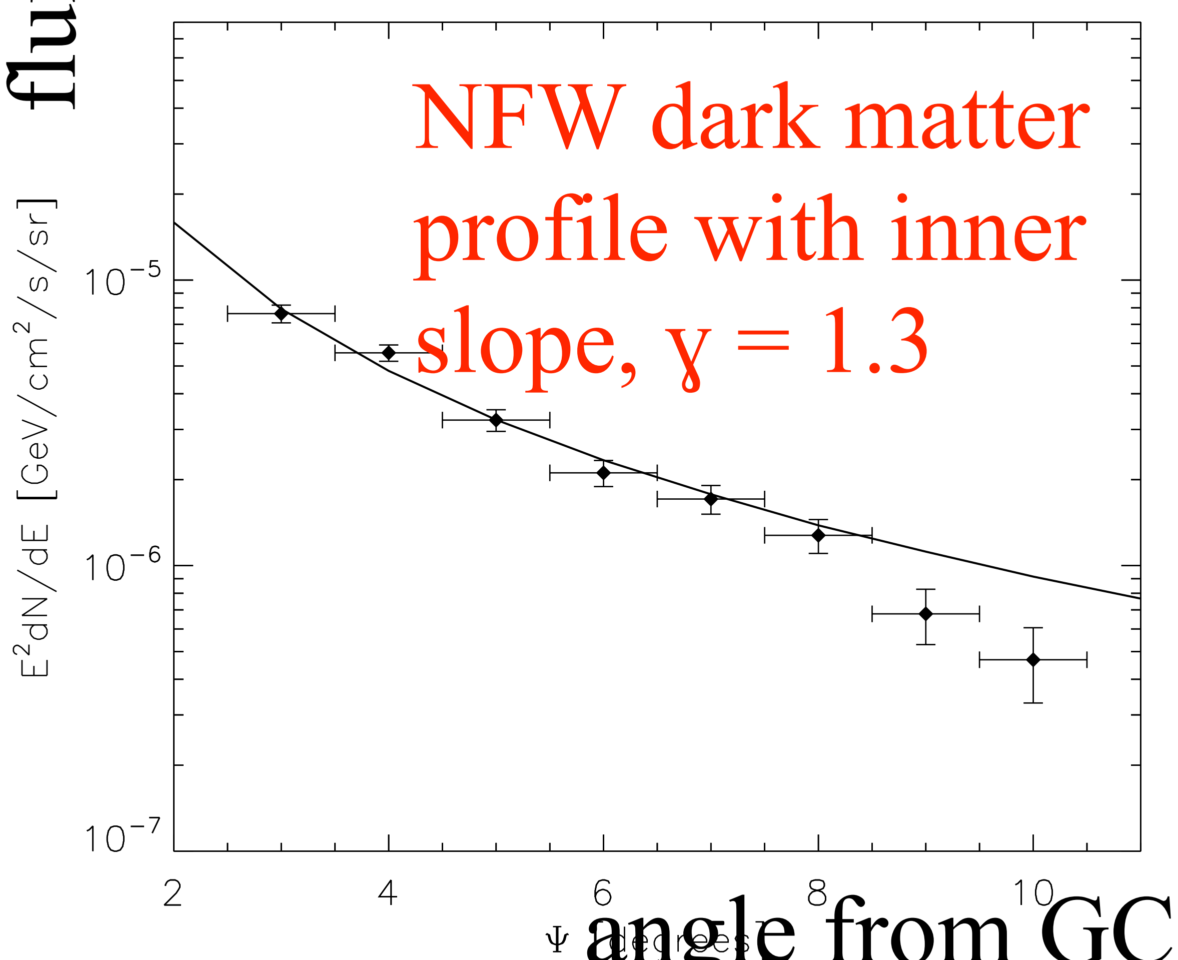
Calore, Cholis and Weniger (CCW) (arXiv:1409.0042) studied the background model systematics for the GeV excess, and found the excess extending to larger latitudes.

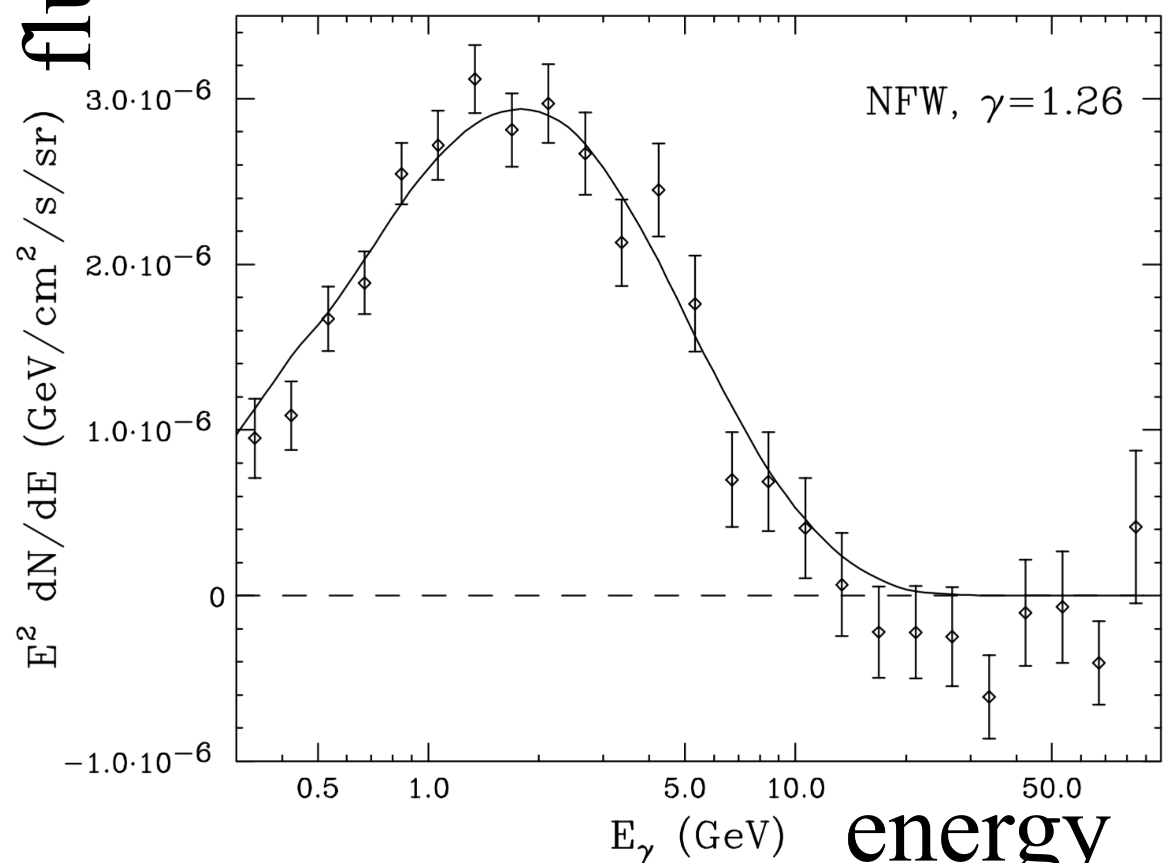
Fermi talk presented by Murgia (Fermi) in 5th Fermi Symposium shows a similar gamma ray excess as previous analyses.

see also Abazajian et al. (arXiv:1402.4090), Zhou et al. (arXiv:1406.6948) etc for similar analyses.

Compare excess with DM predictions

Daylan et al. 2014





gNFW profile

$$\rho(r) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$

$$m_{\mathrm{DM}} = 35.25 \text{ GeV}$$

$$\chi\chi \to b\bar{b}$$

$$\sigma v = 1.7 \cdot 10^{-26} \text{ cm}^3/\text{s}$$

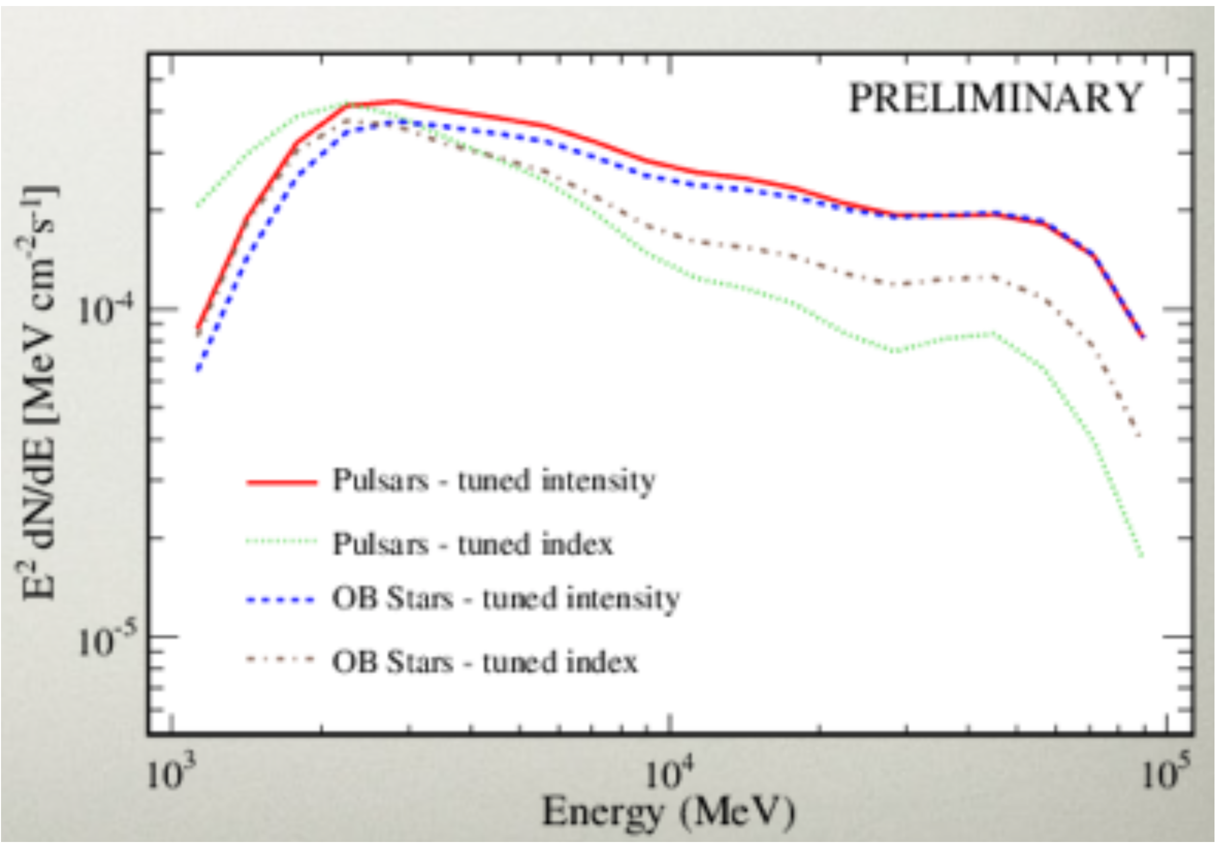
$$\rho_{\mathrm{local}} = 0.3 \text{ GeV/cm}^3$$

Fluxes based on Fermi talk by Murgia

ROI: $15^\circ \times 15^\circ$ around GC

Cline, Dupuis, ZL, Xue 1503.08213

20 energy bins



E_γ [GeV]	$d\Phi/dE_\gamma d\Omega$	$\sigma_{\rm stat}$	$\sigma_{\rm syst}$
1.122	1.587e-06	1.036e-07	8.225e-07
1.413	1.624e-06	7.138e-08	5.810e-07
1.778	1.483e-06	5.330e-08	3.240e-07
2.239	1.122e-06	4.272e-08	1.226e-07
2.818	7.298e-07	3.655e-08	5.857e-08
3.548	4.265e-07	3.106e-08	4.964e-08
4.467	2.475e-07	2.074e-08	3.511e-08
5.623	1.405e-07	1.270e-08	2.735e-08
7.079	7.662e-08	8.267e-09	1.874e-08
8.913	4.039e-08	5.435e-09	1.226e-08
11.220	2.272e-08	3.688e-09	7.959e-09
14.125	1.345e-08	2.433e-09	4.936e-09
17.783	7.828e-09	1.566e-09	3.016e-09
22.387	4.341e-09	1.023e-09	1.820e-09
28.184	2.503e-09	6.953e-10	1.115e-09
35.481	1.600e-09	4.805e-10	6.589e-10
44.668	1.029e-09	3.146e-10	4.090e-10
56.234	5.832e-10	2.113e-10	2.782e-10
70.795	2.753e-10	1.355e-10	1.556e-10
89.125	9.287e-11	7.851e-11	6.110e-11

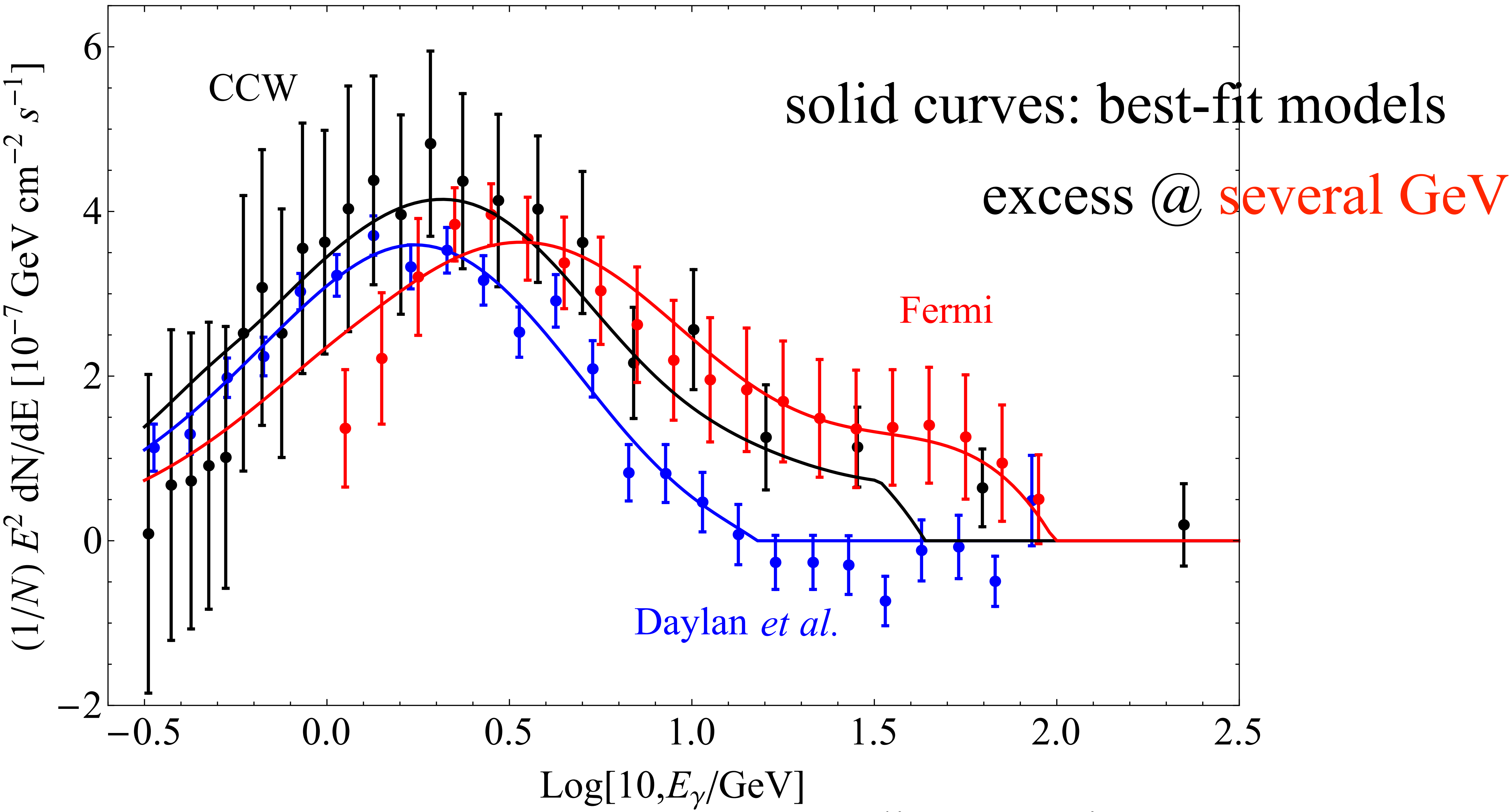
statistical errors: $\sqrt{N}$

systematic errors: diff' between the spectra with the 4 BG templates

average of the total flux in ROI as the flux intensity (2nd column)

1/GeV/cm^2/s/sr

3 Groups: Daylan et al., CCW & Fermi



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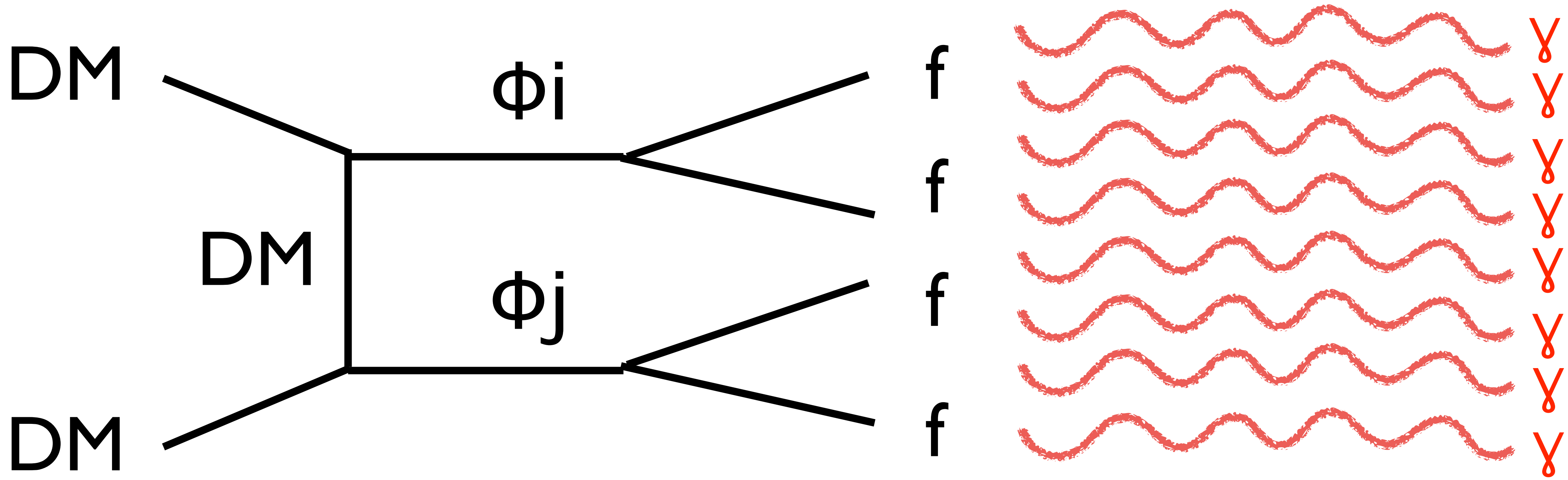
The Fermi flux presented is the total flux from the $15^\circ \times 15^\circ$ square around the GC; the other two fluxes are normalised accordingly with same DM profile.

On-shell mediator DM models

DM is heavier than the mediator(s) (see also: Abdullah et al. Martin et al. etc)



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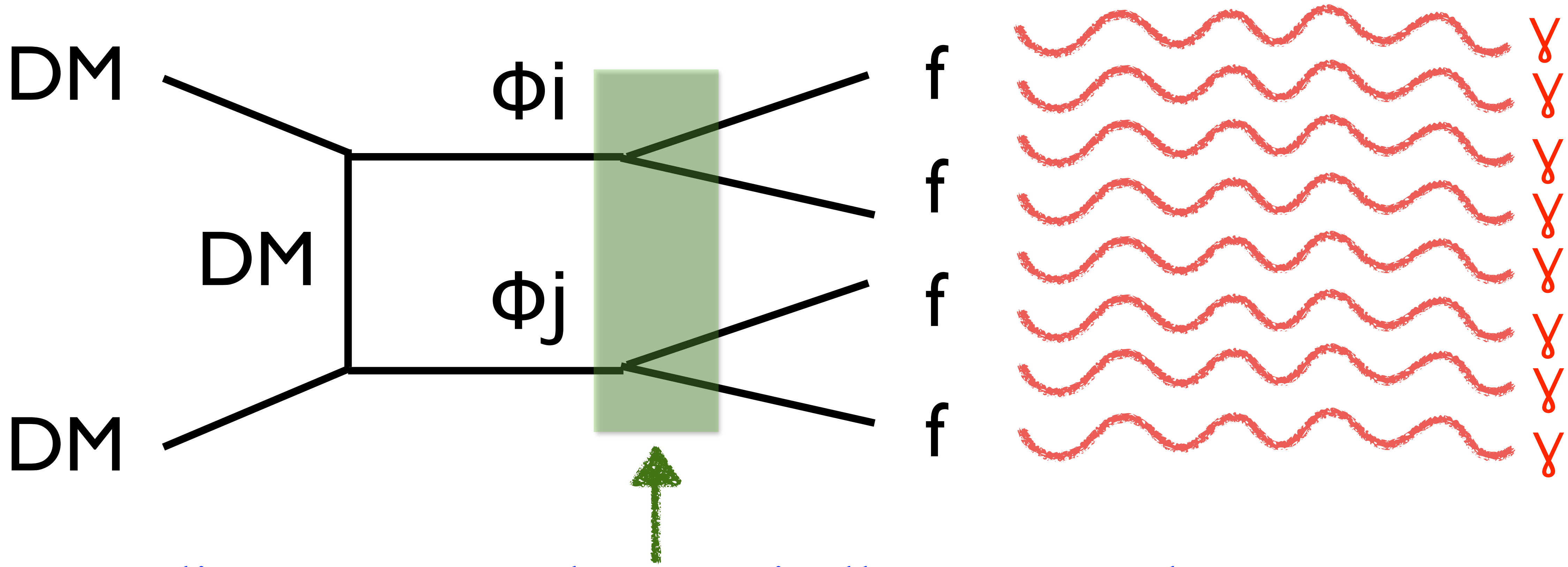

couplings to SM can be generically suppressed

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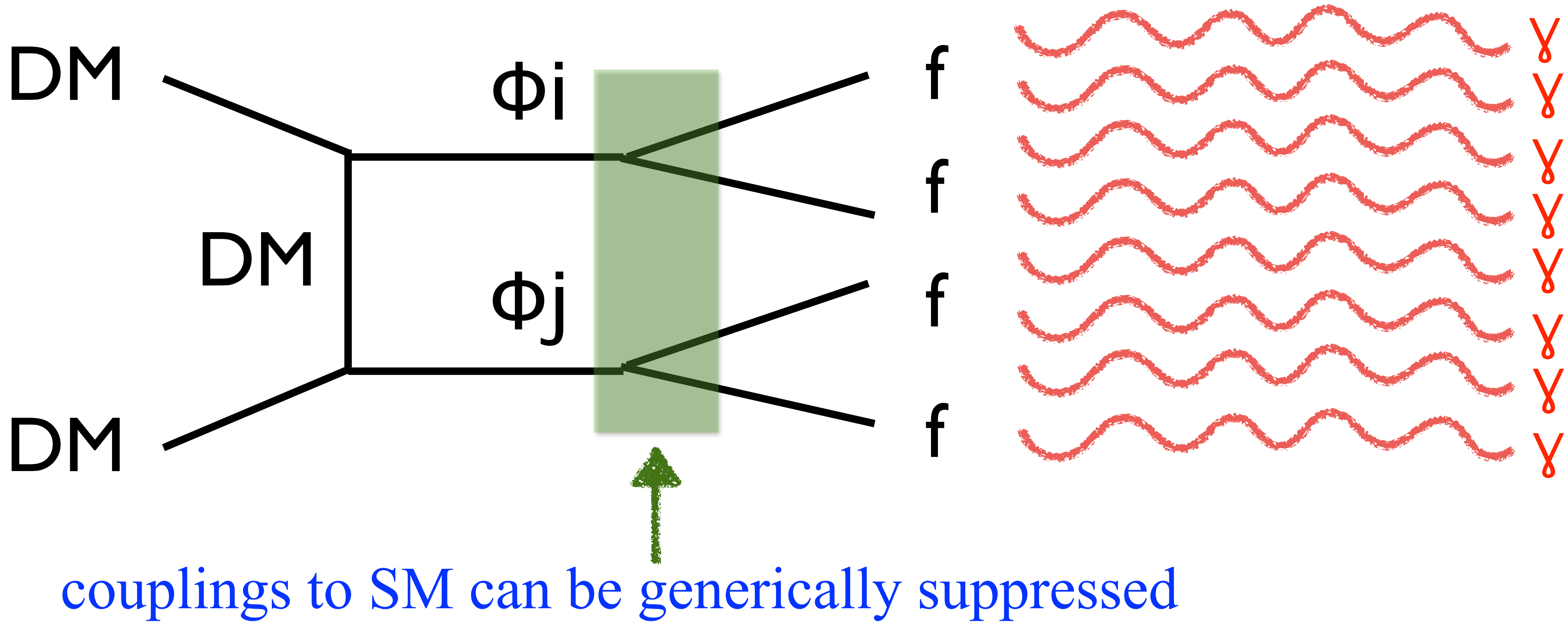
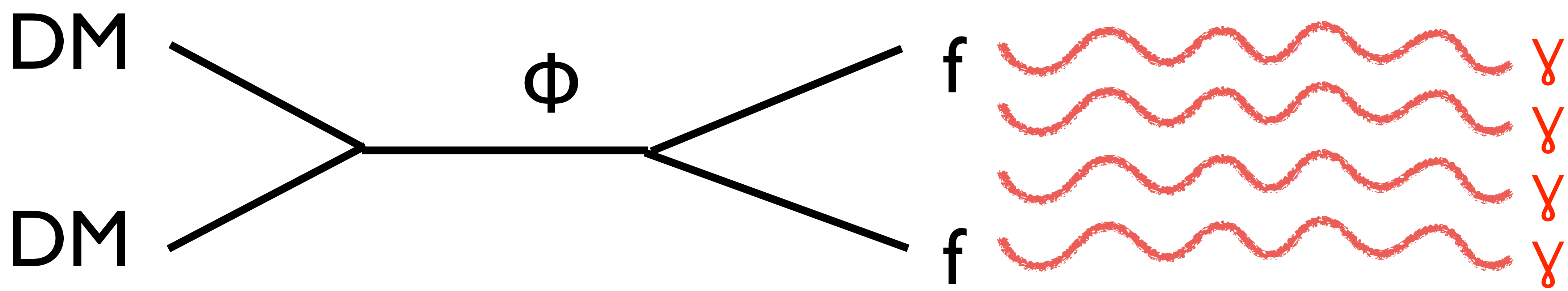


Generic s-channel Z' models face collider and direct detection constraints.



Flux from DM annihilations

Photon flux from DM annihilation into mediators that subsequently decay

$$E_\gamma^2 \frac{dN^{\rm th}}{dE_\gamma}(E_\gamma) = \frac{1}{2} \cdot \frac{\bar{J}\langle\sigma v\rangle}{4\pi m_\chi^2} \sum_f {\rm BR}_{\phi\to f\bar{f}}\, E_\gamma^2 \frac{dN^f}{dE_\gamma}$$

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The averaged J-factor over the ROI (for average flux intensity)

$$\bar{J} = \frac{\int_{\rm ROI} d\Omega\, J(l,b)}{\int_{\rm ROI} d\Omega} = \frac{\int_{\rm ROI} \cos(b) db\, d\ell \int_0^\infty dx\, \rho^2\left(\sqrt{x^2 + R_\odot^2 - 2xR_\odot \cos(\ell)\cos(b)}\right)}{\int_{\rm ROI} \cos(b) db\, d\ell}$$

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Boost the photon spectrum from the DM rest frame to the halo frame.

$$\frac{dN^f}{dE_\gamma} = \frac{2}{(x_+ - x_-)} \int_{E_\gamma x_-}^{E_\gamma x_+} \frac{dE'_\gamma}{E'_\gamma} \frac{dN_0^f}{dE'_\gamma} \qquad x_\pm = m_\chi/m_\phi \pm \sqrt{(m_\chi/m_\phi)^2 - 1}.$$

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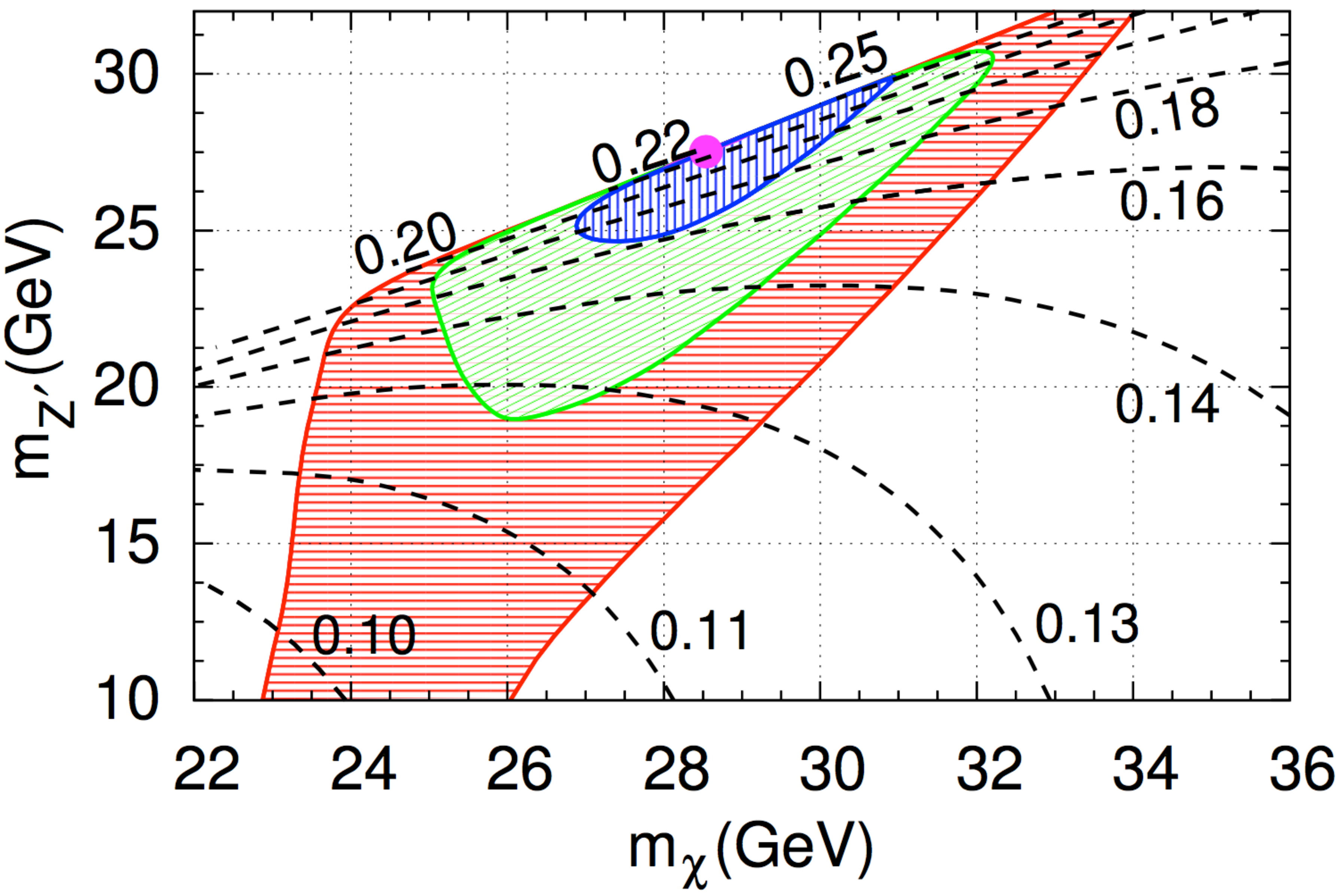
$\frac{dN_0^f}{dE_\gamma}$ is obtained via PPPC4DMID, except for μ which is given analytically

KM on-shell Z' mediator model

Cline, Dupuis, ZL, Xue, 1405.7691

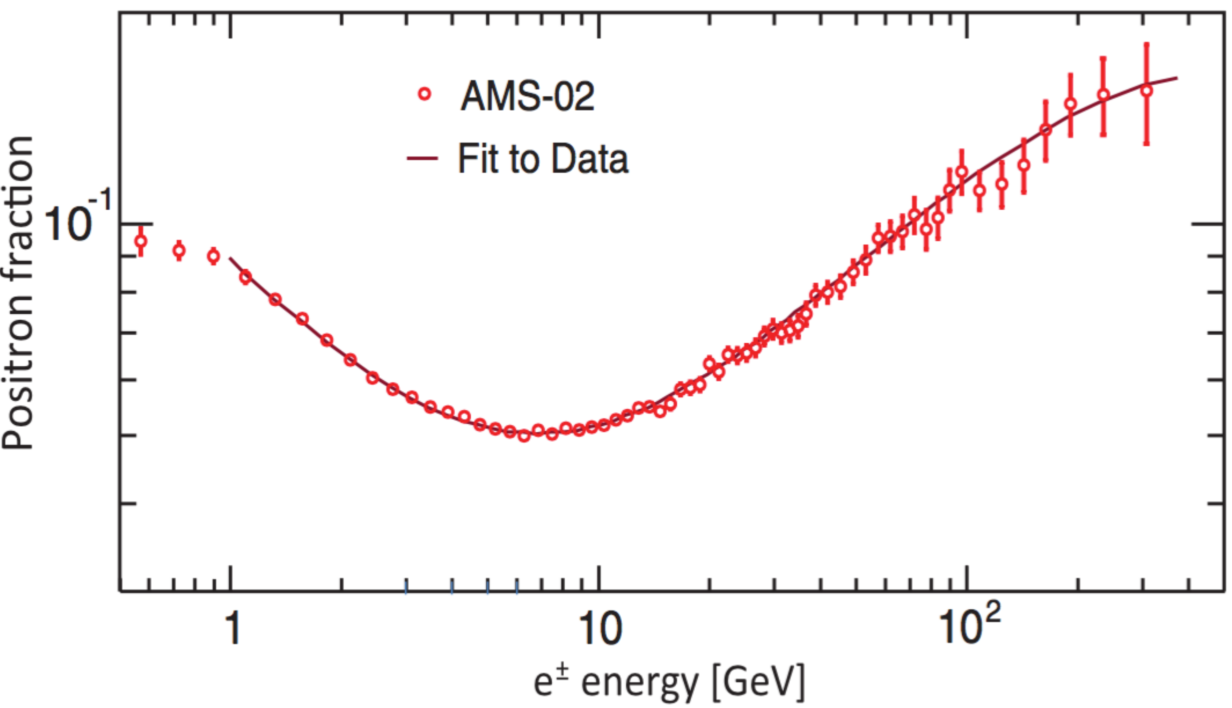


The on-shell Z' (kinetically mixed with SM) mediator model can fit the Daylan et al. spectrum quite well.

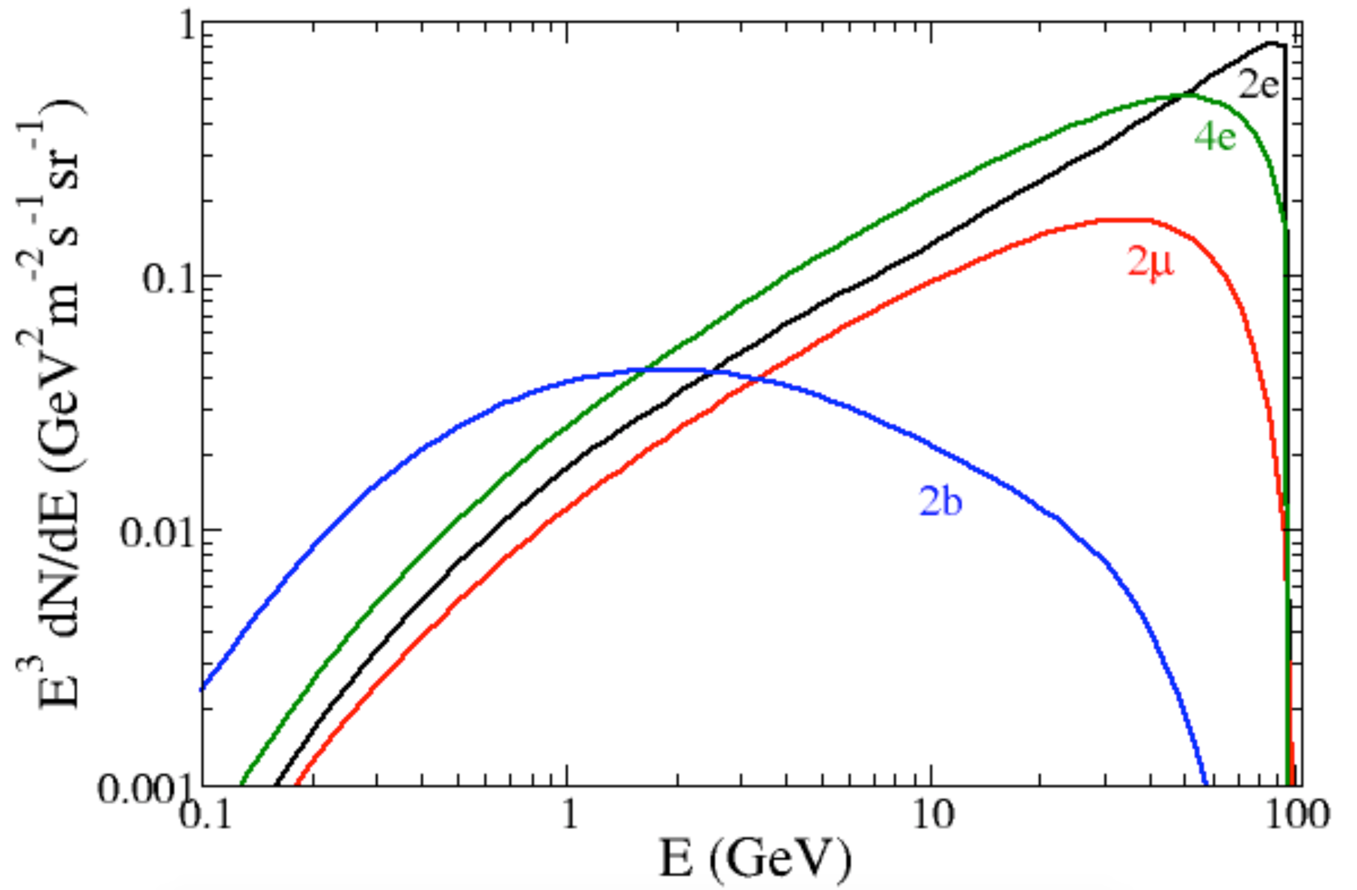
However, the kinetically mixed Z' has a significant branching ratio into electrons, which is not favored by the constraints from the AMS electron data.

AMS electron/positron constraints

AMS-02 2013



Cline, Dupuis, ZL, Xue 1503.08213



The precisely measured electron/positron spectrum in AMS can constrain DM annihilation channels.

2e final states is strongly constrained! (delta function injection)

$\chi\chi \to \phi\phi \to eeee$ produces a box-shape spectrum, which is localised in energy even after propogation. Thus it is also strongly constrained by the AMS data.

generic Z' models w/ unsuppressed electron BR is not favored

General single-mediator DM models

Cline, Dupuis, ZL, Xue 1503.08213

$$\chi + \chi \to \phi + \phi \to f + \bar{f} + f' + \bar{f}' \to \gamma\text{'s}$$

General single-mediator DM models

Cline, Dupuis, ZL, Xue 1503.08213

$$\chi + \chi \to \phi + \phi \to f + \bar{f} + f' + \bar{f}' \to \gamma\text{'s}$$

We perform a model-blind search in the parameter space: m_χ, m_ϕ, f_i with $i = (\mu, \tau, q, b)$, $\langle \sigma v \rangle$.

f_e must be negligible, so we take $f_e \simeq 0$.

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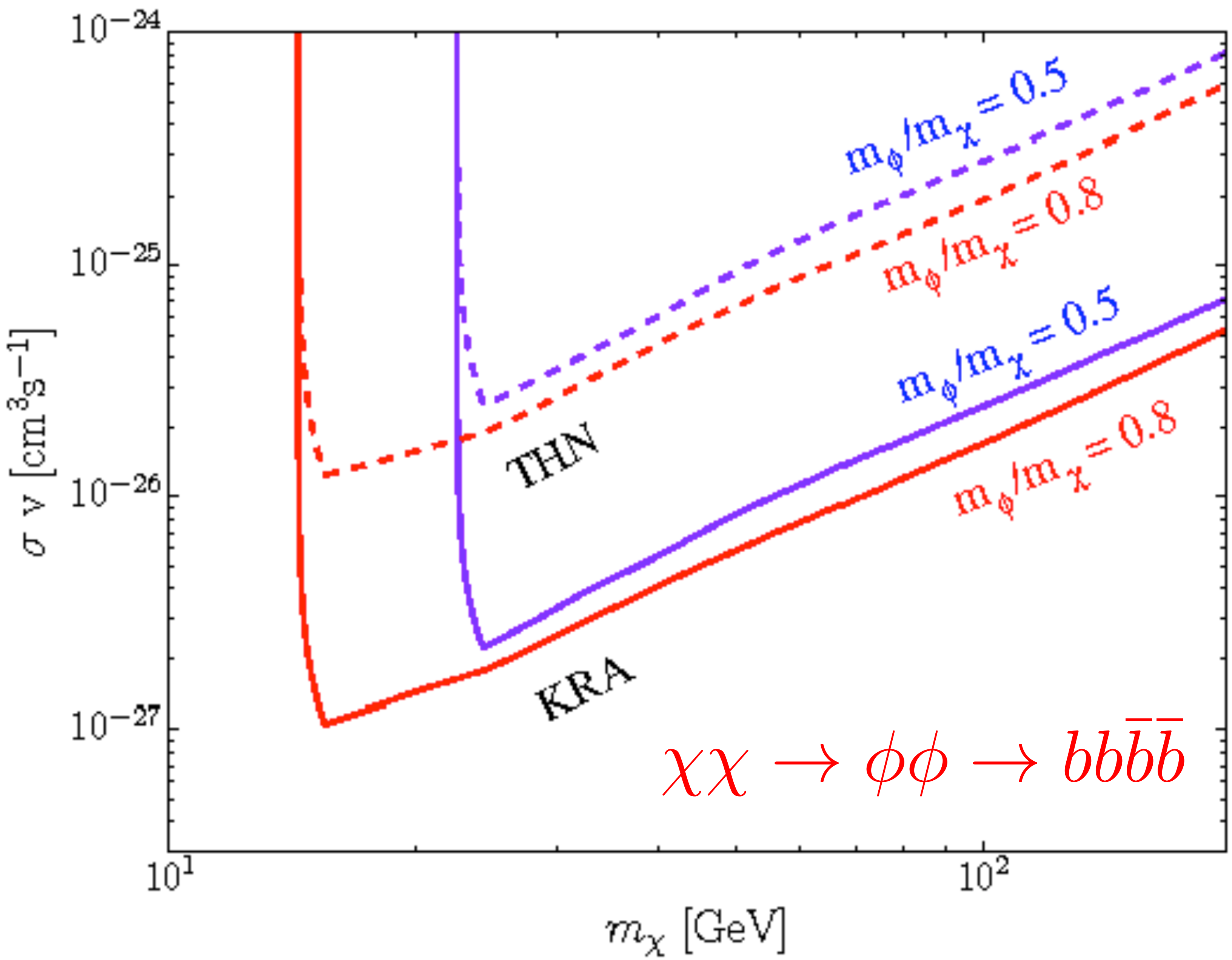
CCW and Fermi further disfavor any significant τ, q final states.

Data set	m_χ	m_ϕ	f_μ	f_τ	f_q	f_b	$\langle \sigma v \rangle$	χ^2_{min}	DOF
CCW	46	12.3	0.82	0	0.02	0.16	1.1	18.8	24
Fermi	130	114.5	0.80	0	0	0.20	2.8	6.4	20
Daylan+	14.6	4.0	0.49	0.01	0.06	0.44	0.7	22.9	25

sufficient to consider only μ and b

PAMELA antiproton constraints

Cline, Dupuis, ZL, Xue 1503.08213



THN, z=0.5 kpc

KRA, z=4 kpc

two benchmark propagation models: THN and KRA

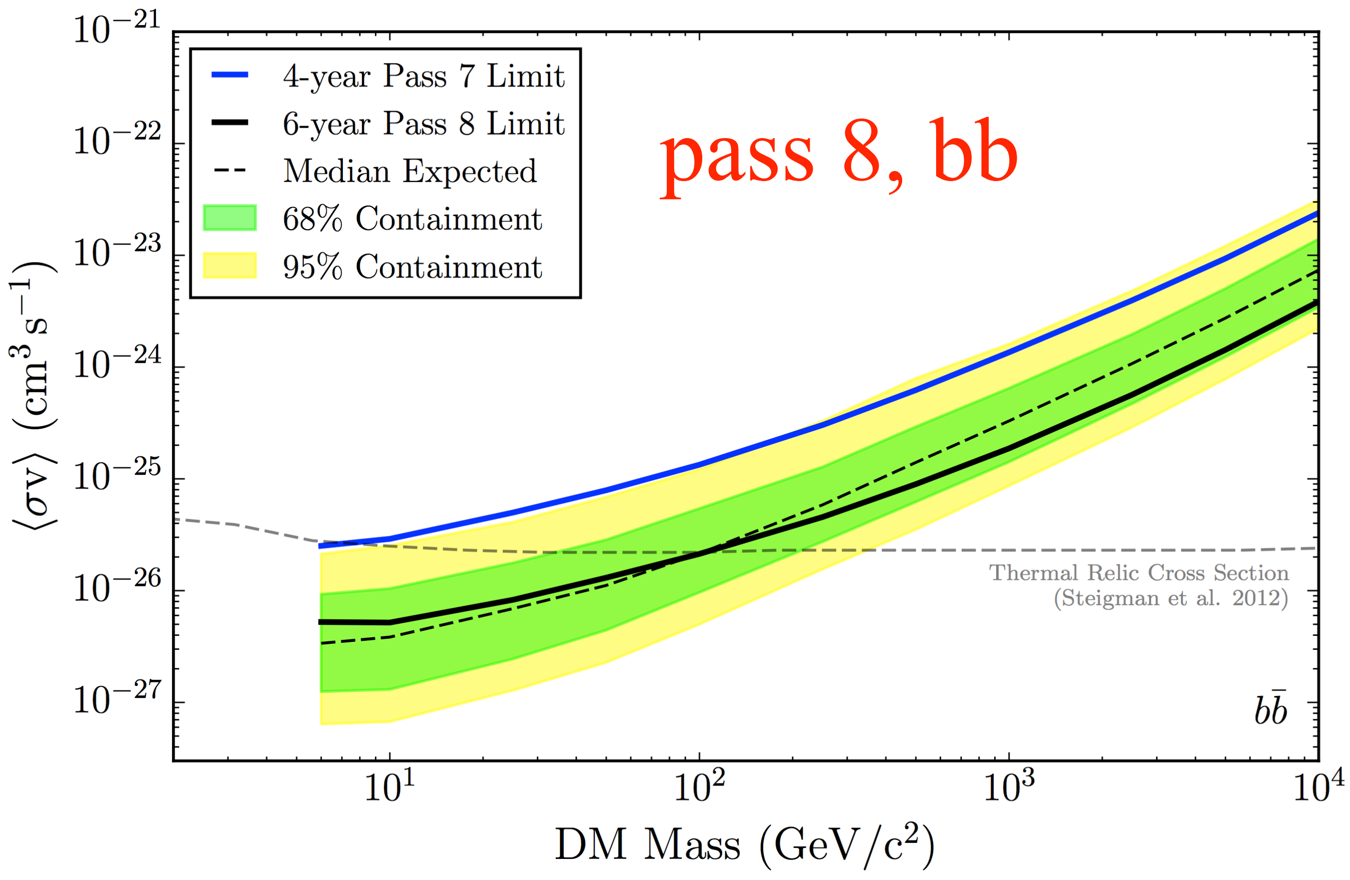
Limits from Dwarf Spheroidal Galaxies

Fermi-LAT Collaboration, 1310.0828 (pass7), 1503.02641 (pass8)

A combination of 15 dwarf galaxies based on 6 years of Fermi-LAT data.

TABLE I. Properties of Milky Way dSphs.

Name	ℓ^{a} (deg)	b^{a} (deg)	Distance (kpc)	$\log_{10}(J_{obs})^{b}$ ($\log_{10}[\mathrm{GeV}^2\,\mathrm{cm}^{-5}]$)	Ref.
Bootes I	358.1	69.6	66	18.8 ± 0.22	[39]
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25	[40]
Carina	260.1	−22.2	105	18.1 ± 0.23	[41]
Coma Berenices	241.9	83.6	44	19.0 ± 0.25	[40]
Draco	86.4	34.7	76	18.8 ± 0.16	[42]
Fornax	237.1	−65.7	147	18.2 ± 0.21	[41]
Hercules	28.7	36.9	132	18.1 ± 0.25	[40]
Leo II	220.2	67.2	233	17.6 ± 0.18	[43]
Leo IV	265.4	56.5	154	17.9 ± 0.28	[40]
Sculptor	287.5	−83.2	86	18.6 ± 0.18	[41]
Segue 1	220.5	50.4	23	19.5 ± 0.29	[44]
Sextans	243.5	42.3	86	18.4 ± 0.27	[41]
Ursa Major II	152.5	37.4	32	19.3 ± 0.28	[40]
Ursa Minor	105.0	44.8	76	18.8 ± 0.19	[42]
Willman 1	158.6	56.8	38	19.1 ± 0.31	[45]



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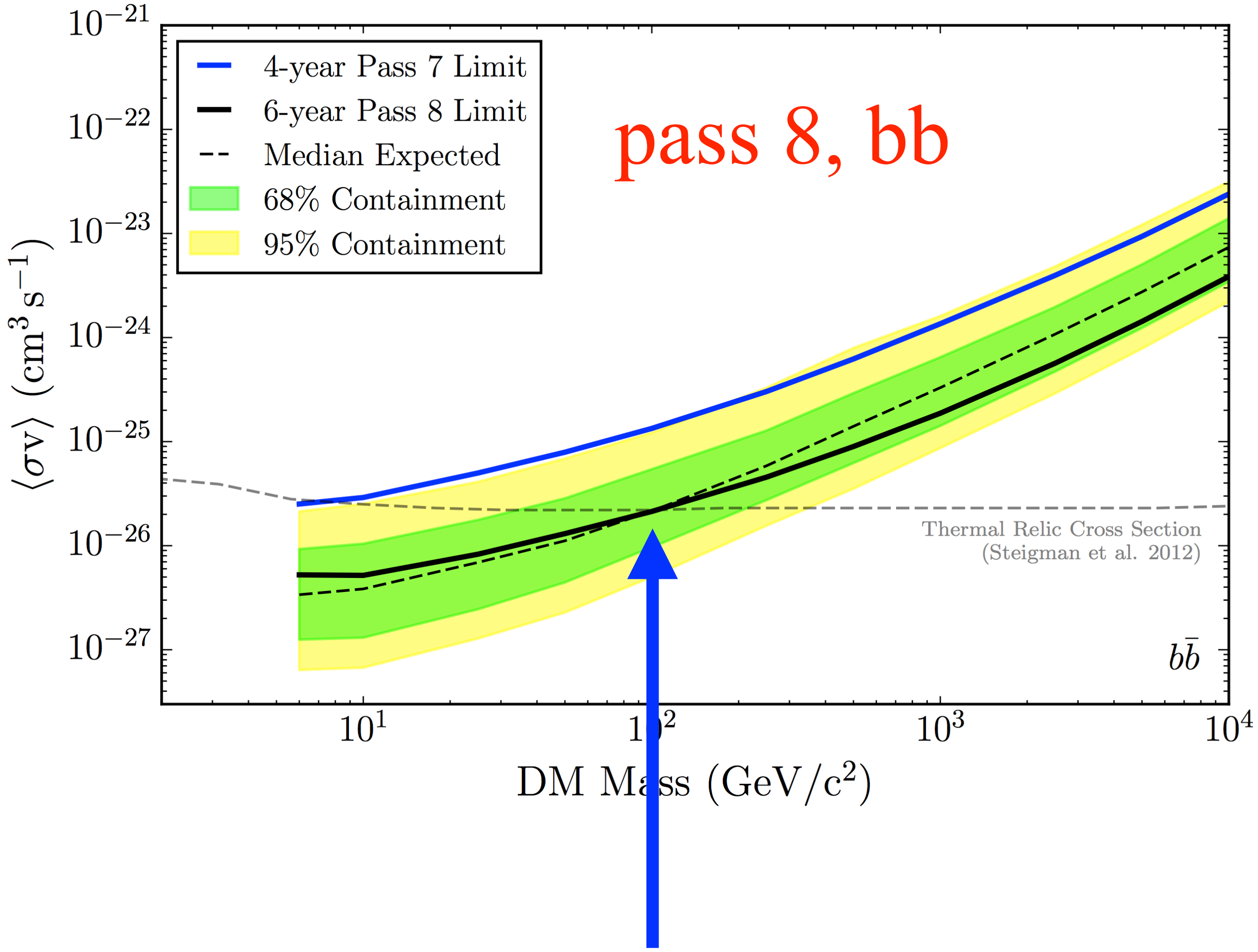
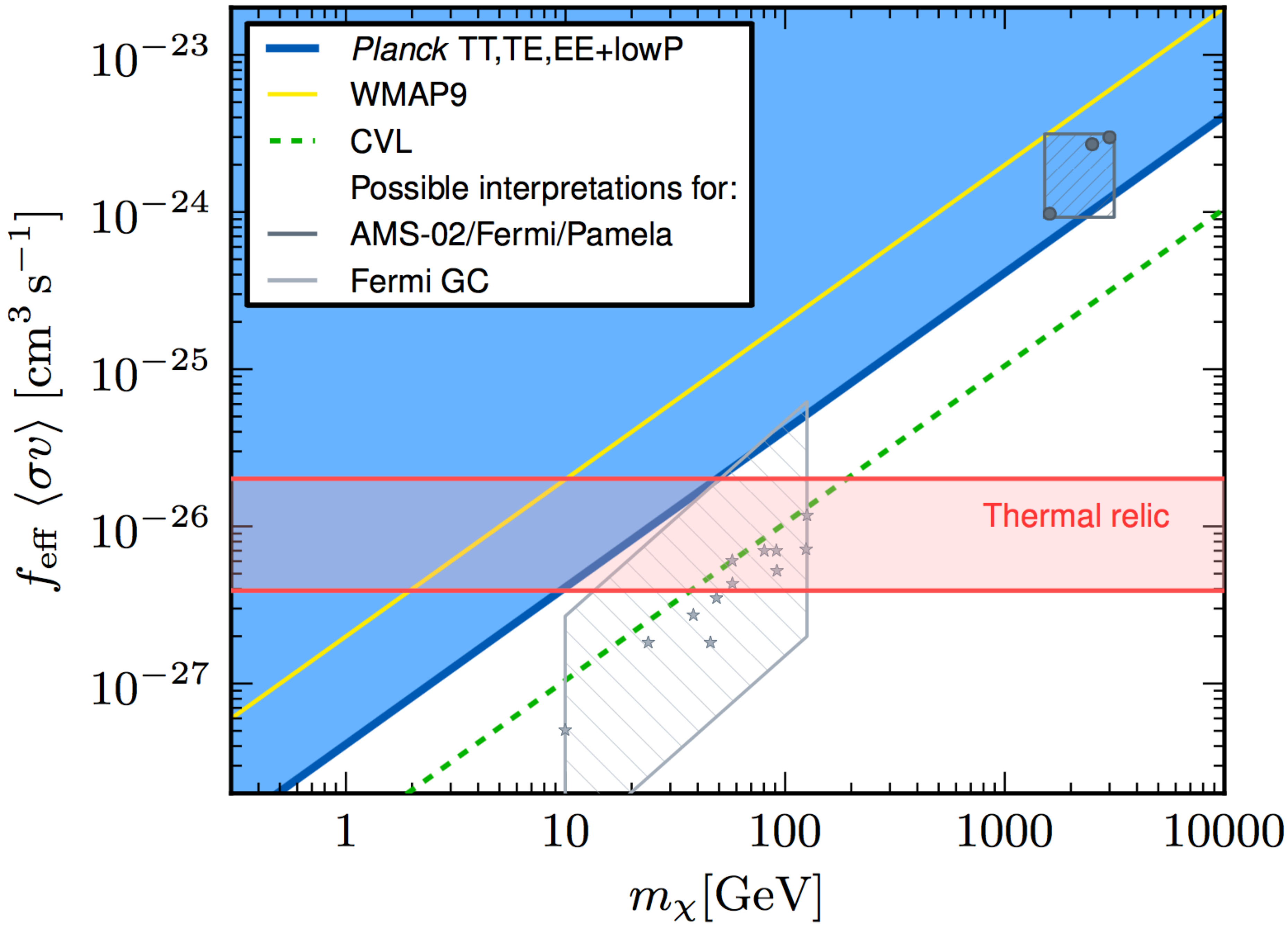


probe thermal DM cross section at 100 GeV DM mass

CMB limits from Planck

DM annihilation can impact temperature and polarisation in CMB



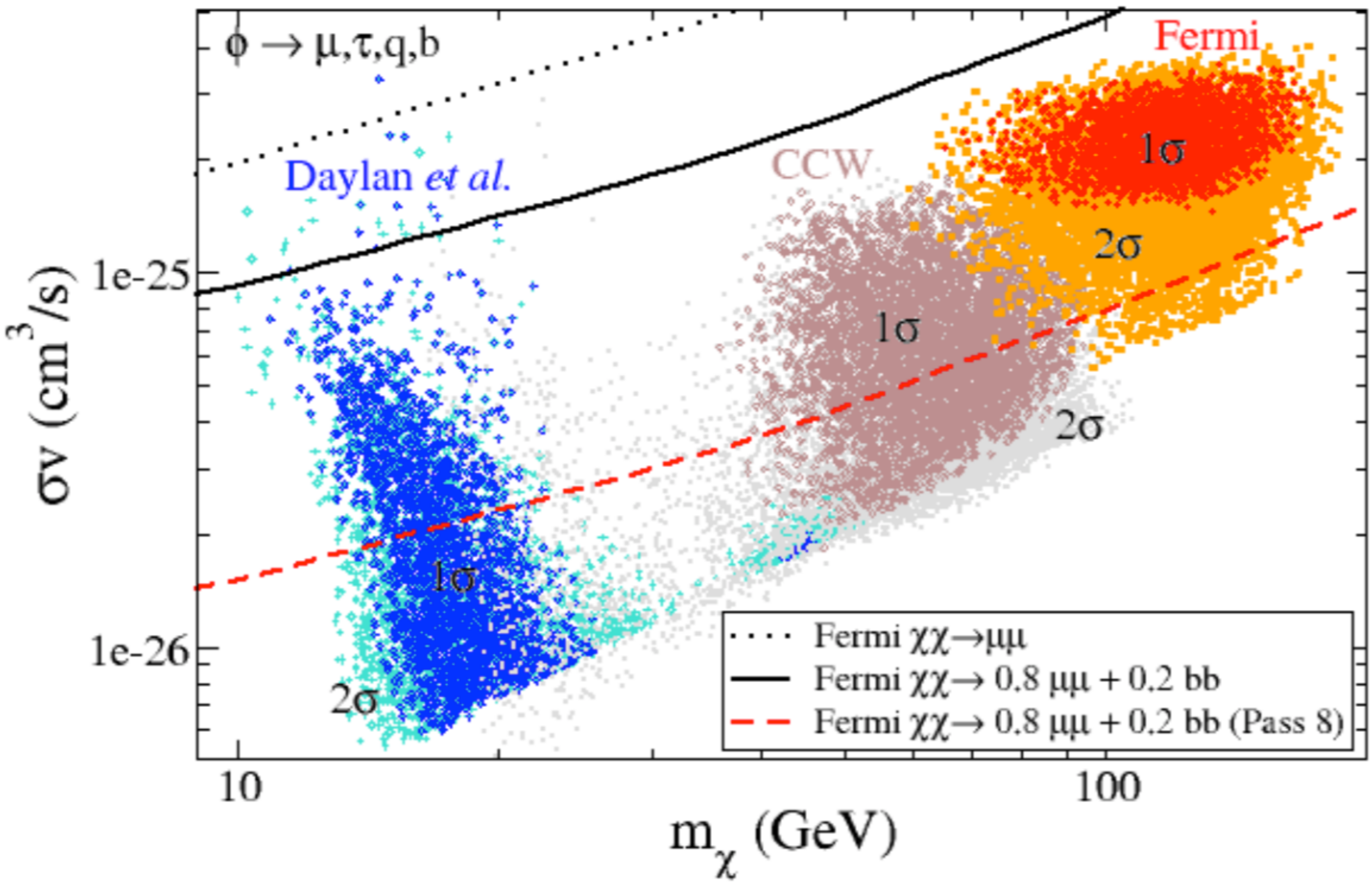
For efficiency,
see eg.
Slatyer et al,
Scott et al.

$$f_{\rm eff}\langle\sigma v\rangle < 4\times 10^{-26}\left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)\mathrm{cm^3/s}$$

Planck Collaboration, 1502.01589

Single mediator DM models (MCMC)

Markov Chain Monte Carlo scans Cline, Dupuis, ZL, Xue 1503.08213



Some tension exists between dwarf limits and preferred region in Fermi and CCW data, which is somewhat relieved by reducing the bottom final state.

Two-mediator models

Cline, Dupuis, ZL, Xue 1503.08213

Motivated by the fact that a mixture of μ and b final states gives the best fits to Fermi and CCW data, we try to build a theory model that works like this.

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Two scalar singlet mediators mix with the Higgs boson.

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Two scalar singlet mediators mix with the Higgs boson.

Need 2 mediators with mass: $2m_\mu < m_{\phi_1} < 2m_\tau$ and $2m_b < m_{\phi_2} < m_\chi$

$$\mathcal{L}_{\text{int}} = \sum_{i=1}^{2} \bar{\chi}\phi_i(g_i + i g_{i,5}\gamma_5)\chi$$

Two-mediator models

Cline, Dupuis, ZL, Xue 1503.08213

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$$\mathcal{L}_{\rm int} = \sum_{i=1}^{2} \bar{\chi}\phi_i(g_i + i g_{i,5}\gamma_5)\chi$$

The relic density of χ is determined by $\chi\bar{\chi} \to \phi_i\phi_j$

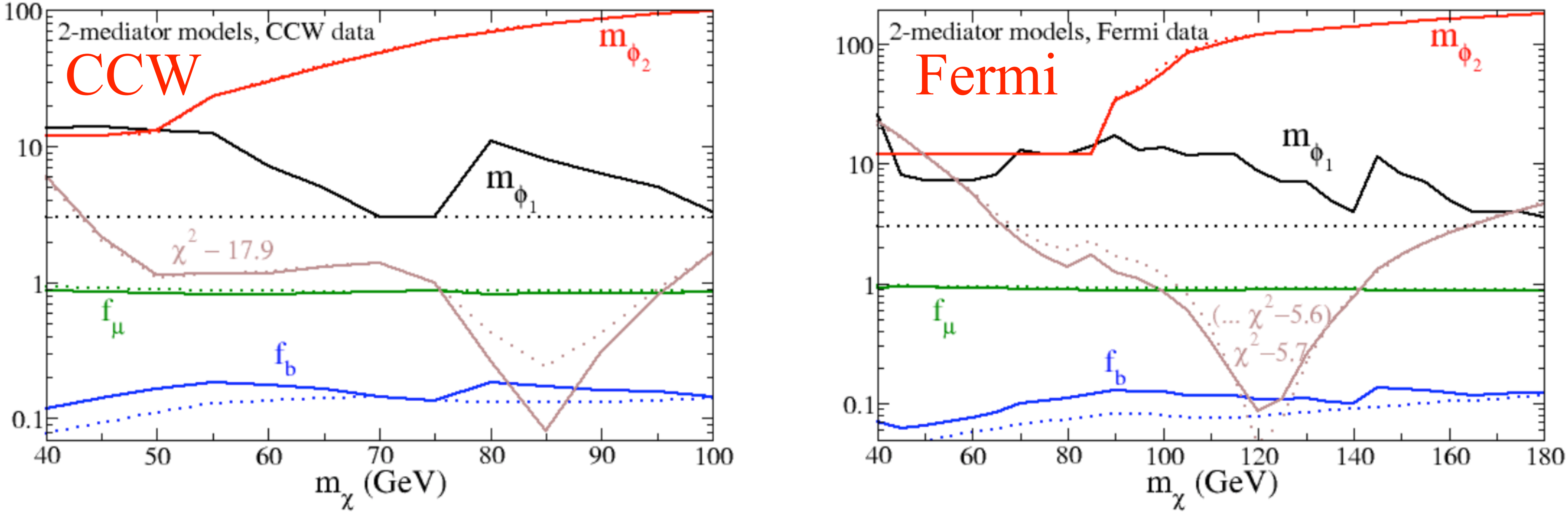
$$\sigma v_{\rm rel} \cong \sum_{i=1,2} \frac{g_i^2 g_{i,5}^2 m_\chi \sqrt{m_\chi^2 - m_i^2}}{8\pi \left(m_\chi^2 - m_i^2/2\right)^2} + \frac{F^2}{16\pi(m_\chi^2 - m_2^2/4)}$$

$$F = (g_1 g_{2,5} + g_2 g_{1,5}) + (g_1 g_{2,5} - g_2 g_{1,5})\frac{m_2^2}{4m_\chi^2}$$

Fits in 2-mediator DM models

5 parameter space: $\{m_\chi, m_{\phi_1}, m_{\phi_2}, f_b/f_\mu, \langle\sigma v\rangle\}$

Solid lines: free varying m_{ϕ_1}; Dotted lines: $m_{\phi_1} = 3$ GeV.



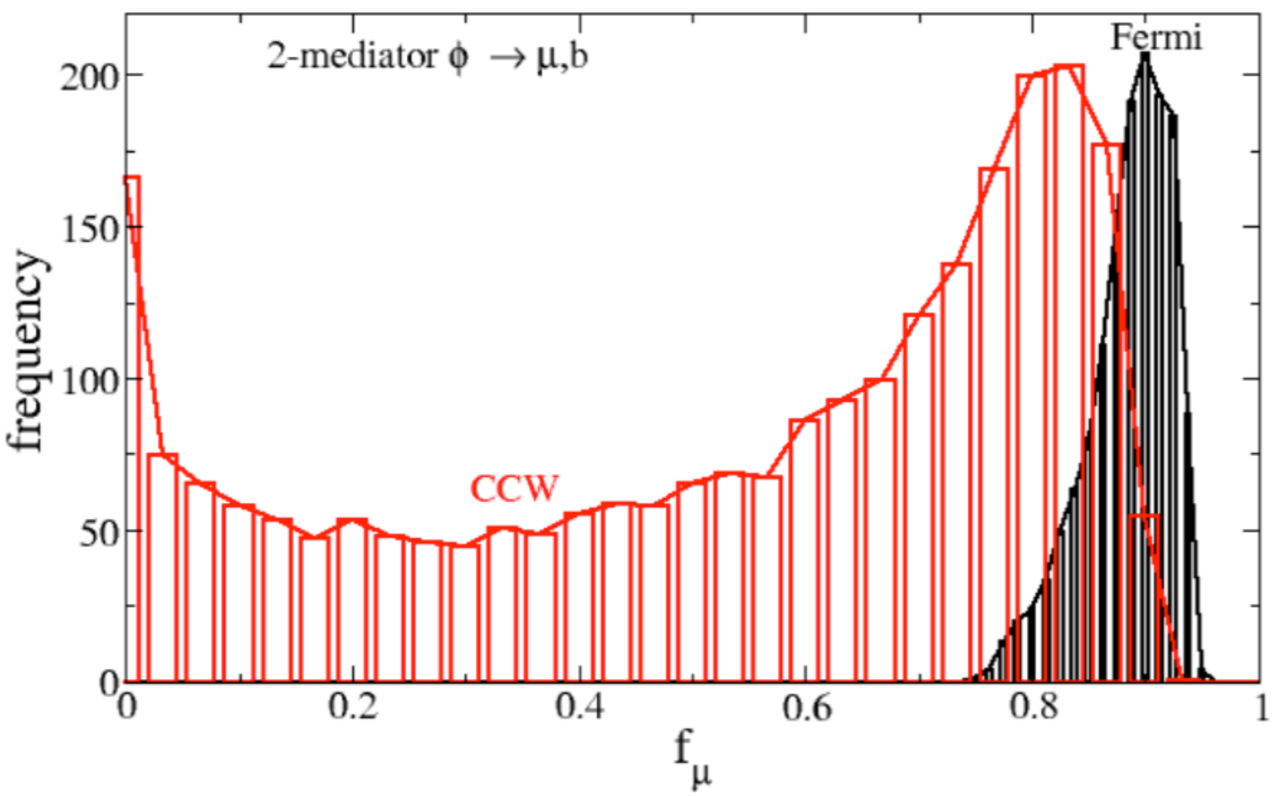
Interestingly, the fits to Fermi and CCW data, in which m_{ϕ_1} is free to vary, are consistent with values that are not far from the theoretical threshold $2m_\tau$.

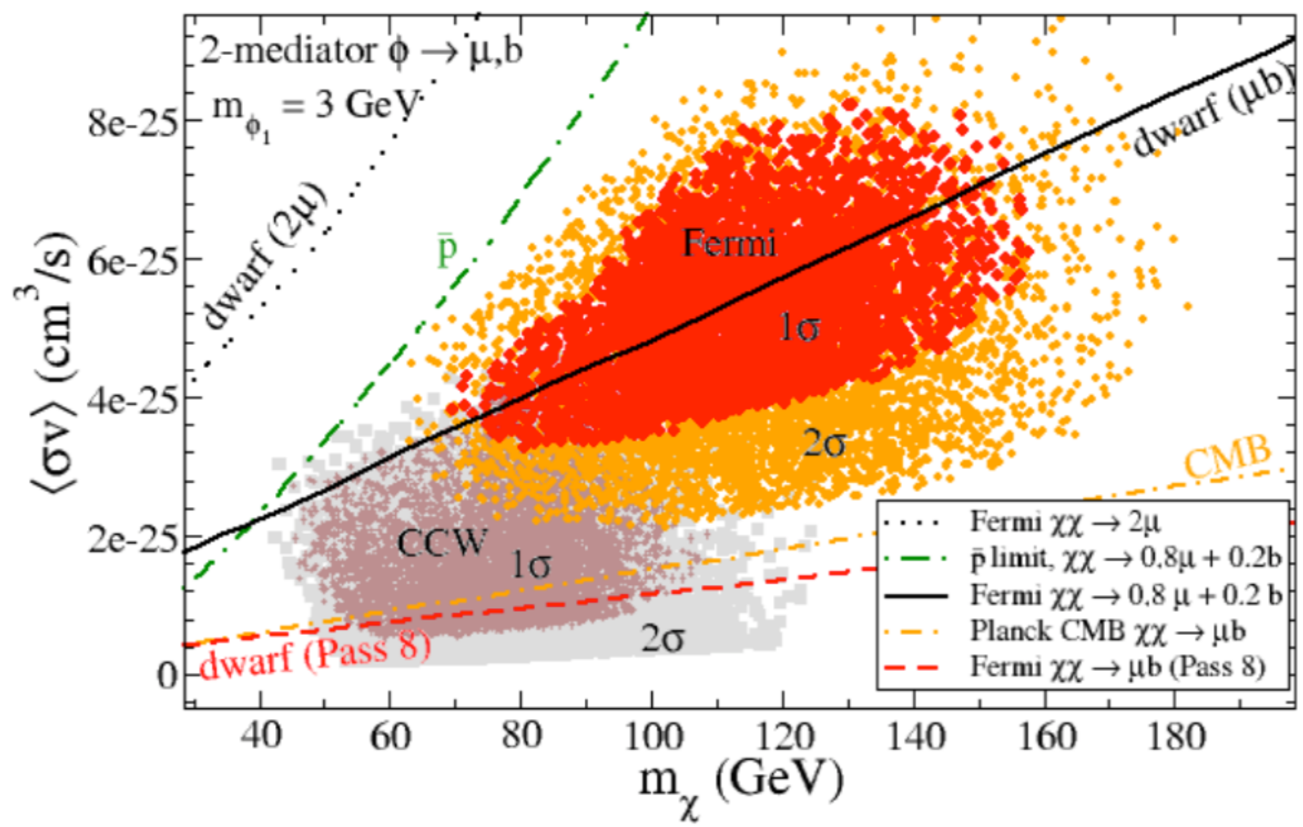
χ^2 is sufficiently flat as a function of m_{ϕ_1} that the models remain good fits even when m_{ϕ_1} is restricted to stay below $2m_\tau$.

Two-mediator DM models (MCMC)

f_{μ}=0.9 for Fermi

Cline, Dupuis, ZL, Xue 1503.08213





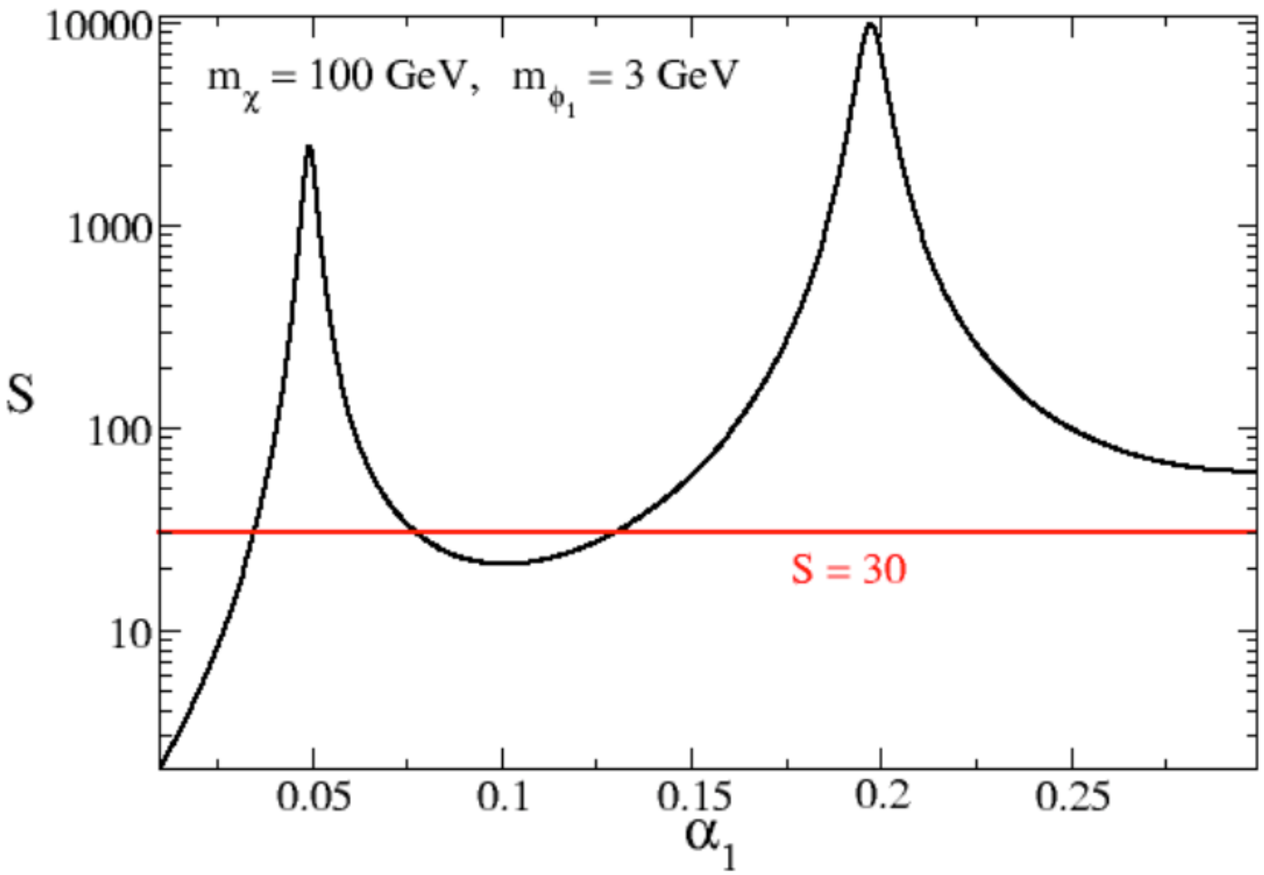
The best-fit values of the annihilation cross section are shifted upwards by a factor of a few, relative to the single-mediator model.

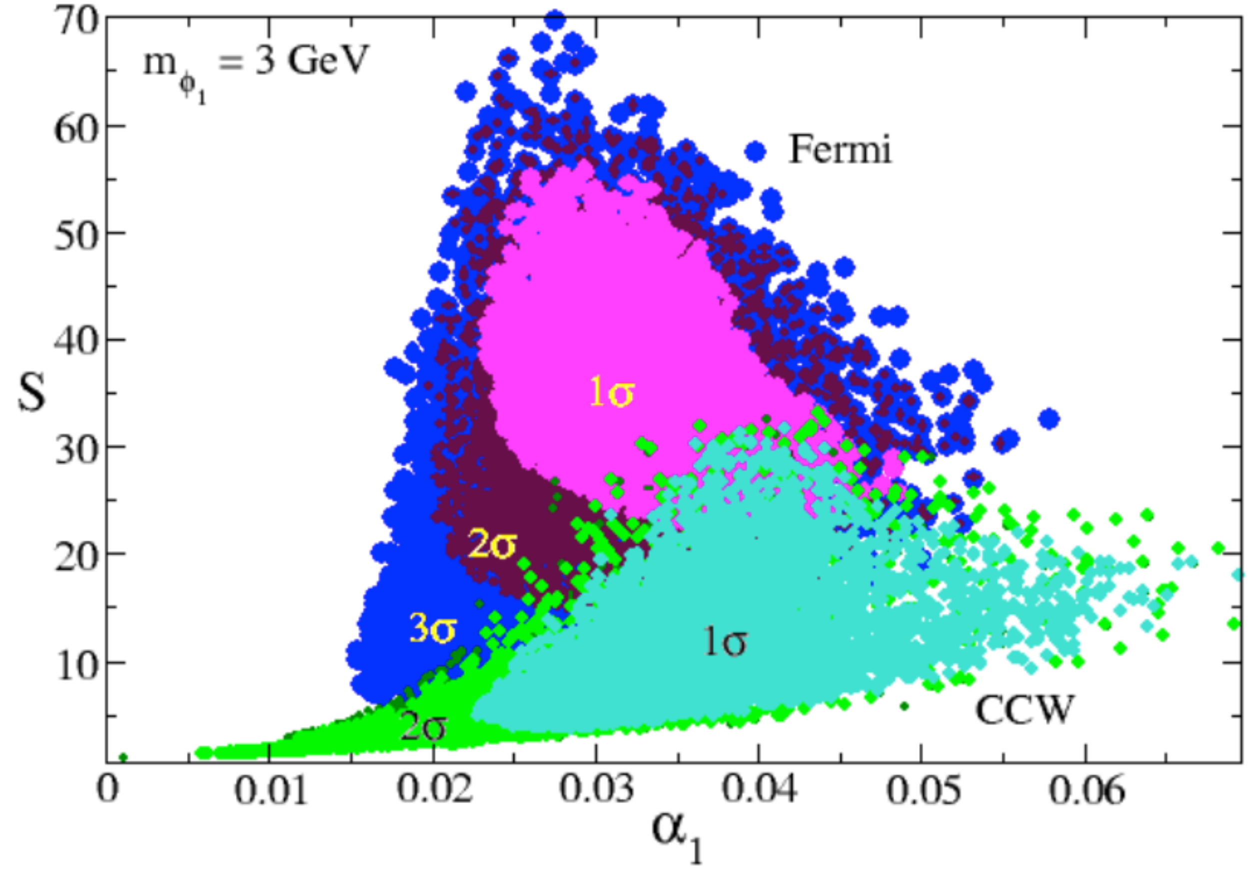
Tension between GCE and the dwarf limits (also Planck).

Preferred annihilation cross section is larger than the thermal cross section.

Sommerfeld enhancement

The presence of the lighter mediator (~ 3 GeV) can resolve the difference due to the low velocity of the DM in the galaxy relative to the early universe.

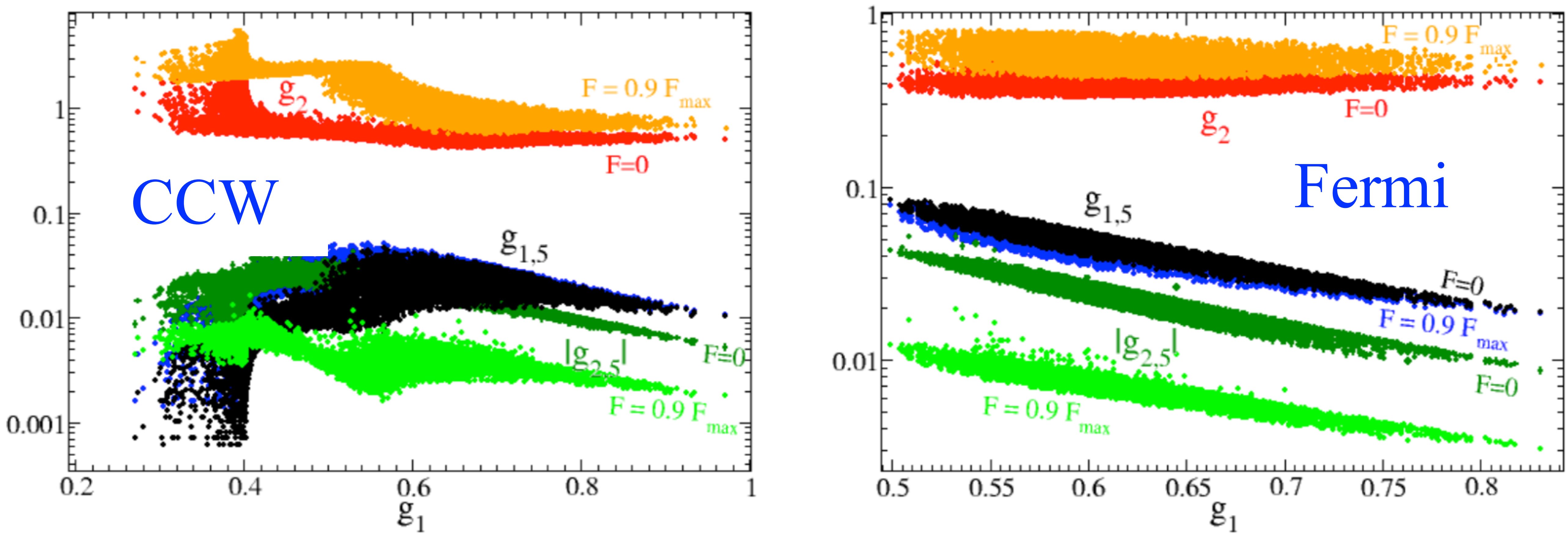




For each MCMC model point, we determine the required enhancement factor S, and the minimum coupling constant.

We can get the right amount of relic density by invoking reasonably small values of the couplings, in the range of 0.01-0.06.

Scalar couplings to DM



Taking into account both the relic density and the GCE data, the preferred values of the scalar coupling are in the range (0.5-0.8), and the pseudo-scalar ones are in the range of (0.02-0.1).

$$\mathcal{L}_{\rm int} = \sum_{i=1}^{2} \bar{\chi}\phi_i(g_i + i g_{i,5}\gamma_5)\chi$$

Summary

Gamma rays from the GC hints a possible signature of DM annihilations in the halo, with the morphology consistent with the expected DM distribution.

Models in which DM annihilates into on-shell mediators can generate the gamma ray excess, and also avoid collider and direct detection constraints easily.

On-shell mediators with decays to a mixture of muon and bottom final states yield the best fit to the data. A theoretical model with 2 mediators coupled to Higgs can generate such a feature easily.

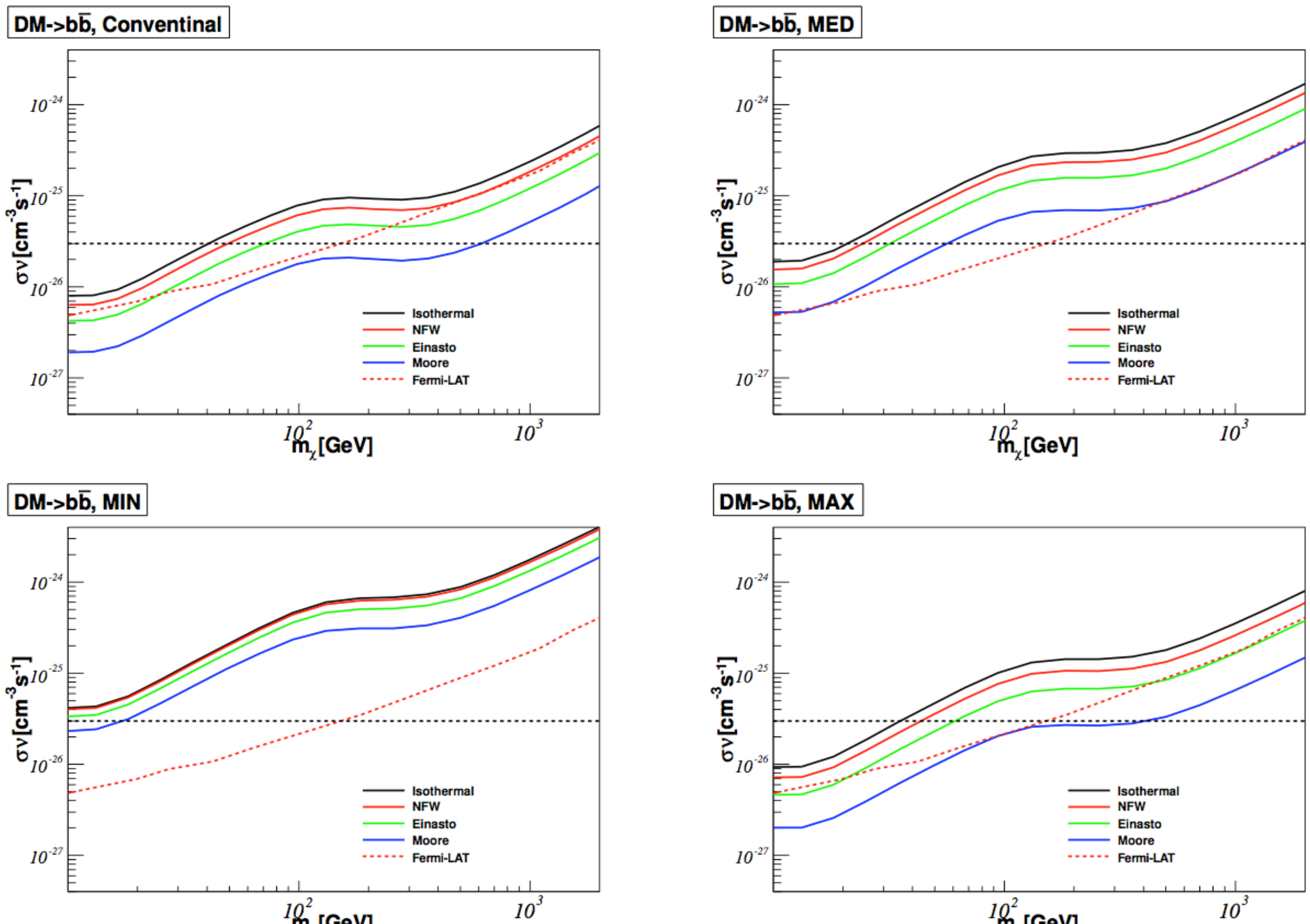
The relevant parameter space in the multi-mediator models is being probed by the CMB data from Planck, electron/positron and antiproton data from AMS, and dwarf galaxy data from Fermi.

Thank you!

Additional Slides

AMS-02 2015 antiproton Constraints

Jin, Wu, Zhou 1504.04604



Antiproton limit is weaker than Fermi 6-yr dwarf limits for 100 GeV DM.

Sommerfeld enhancement

Suppose that ϕ_1 couples to χ with strength g_1 and define $\alpha_1 = g_1^2/4\pi$. (Both scalar g_1 and pseudoscalar $g_{1,5}$ couplings are needed to get s-wave annihilation, but that $g_{1,5} \ll g_1$.) The Sommerfeld enhancement S is controlled by the two small parameters (Arkani-Hamed+ 2008)

$$\epsilon_\phi = \frac{m_{\phi_1}}{\alpha_1 m_\chi}, \quad \epsilon_v = \frac{v}{\alpha_1}$$

A good approximation to S is given by the expression (Cassel 2009, Slatyer 2009)

$$S = \left(\frac{\pi}{\epsilon_v}\right) \frac{\sinh X}{\cosh X - \cos\sqrt{(2\pi/\bar{\epsilon}_\phi) - X^2}}$$

where $\bar{\epsilon}_\phi = (\pi/12)\epsilon_\phi$ and $X = \epsilon_v/\bar{\epsilon}_\phi$. The cosine becomes cosh if the square root becomes imaginary.