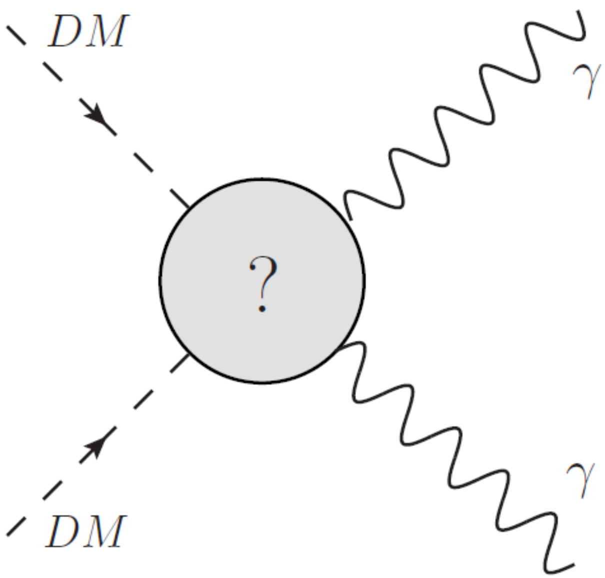
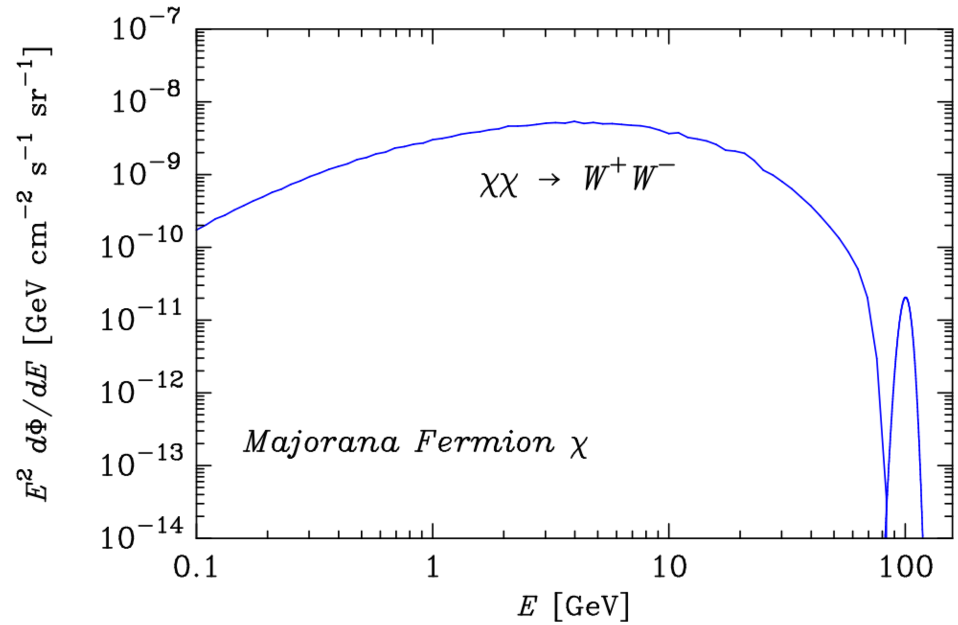
Limits on γ-ray Lines from Unitarity





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in collaboration with

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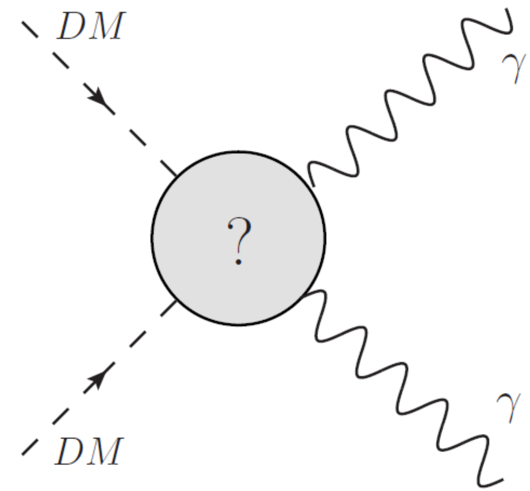
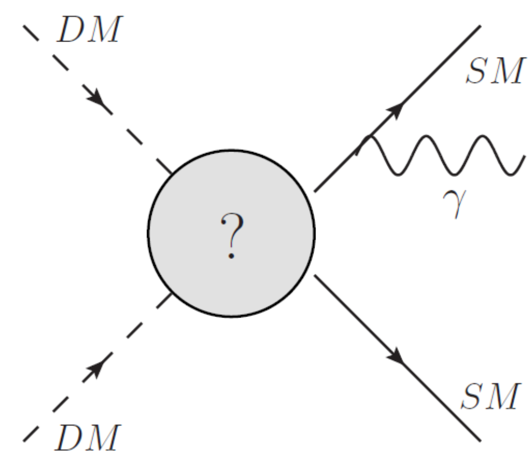
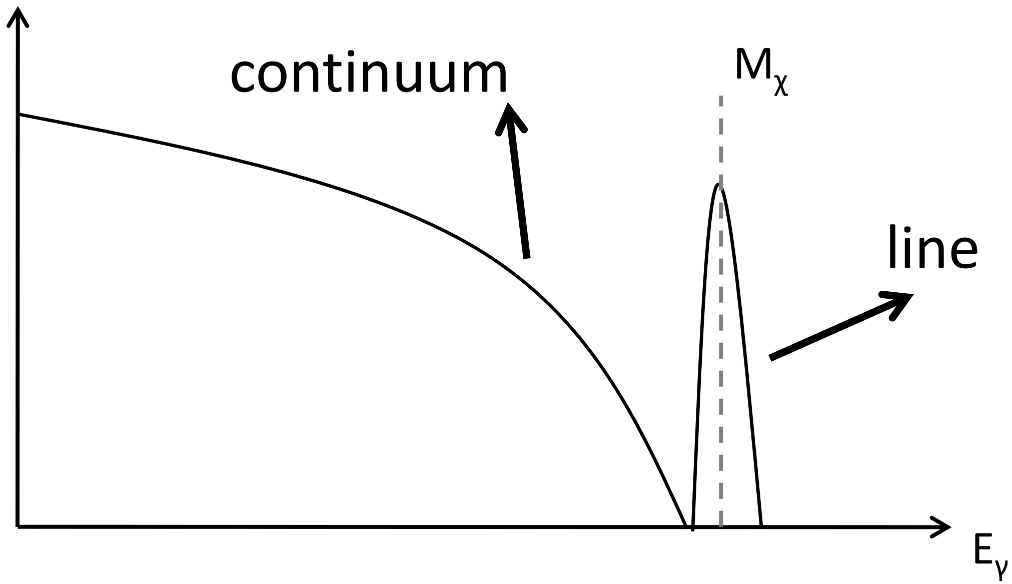
Beacon in the Dark

- Indirect detection at astrophysical distances: gammas are best.
- Direct annihilation gives monoenergetic photons. Rare.
- Bremsstrahlung and hadronic decays give continuum.
- Potential check on anomalies in other indirect detection channels.





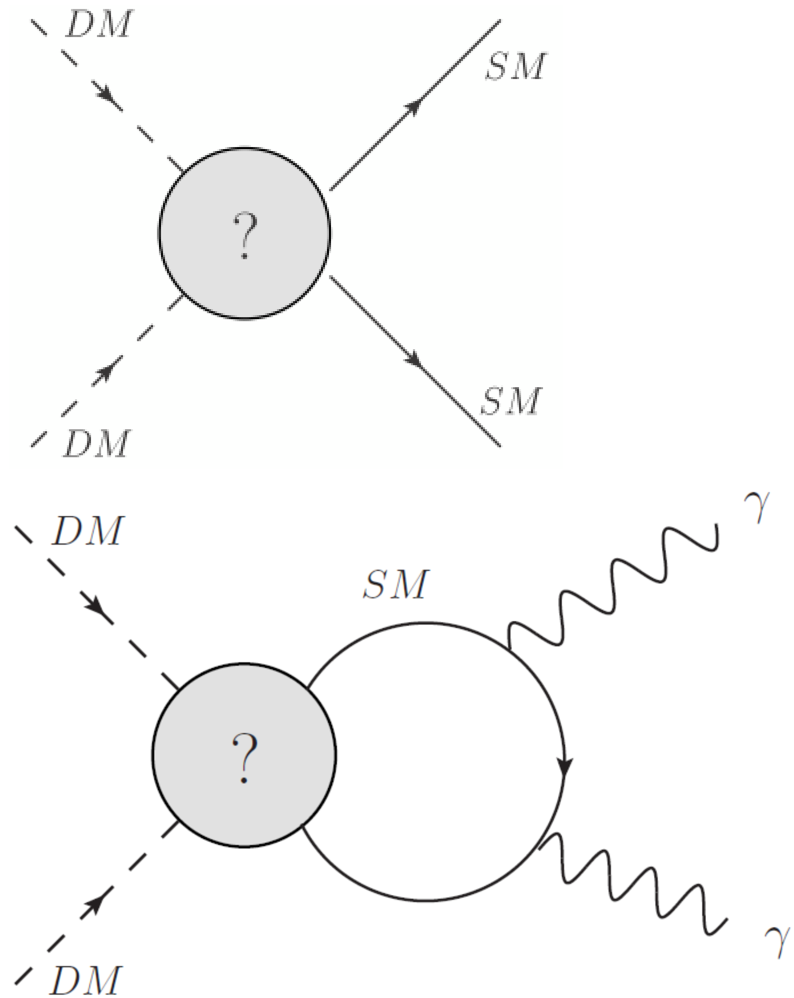
Line and Continuum



Minimum strength for line
with respect to continuum?

Line Bound From Unitarity

- Strength of line is related to the primary annihilation mode.
- No model independent bound for the full amplitude.
- Imaginary part of loop is much more robust.
- Ratio to continuum also model-independent.



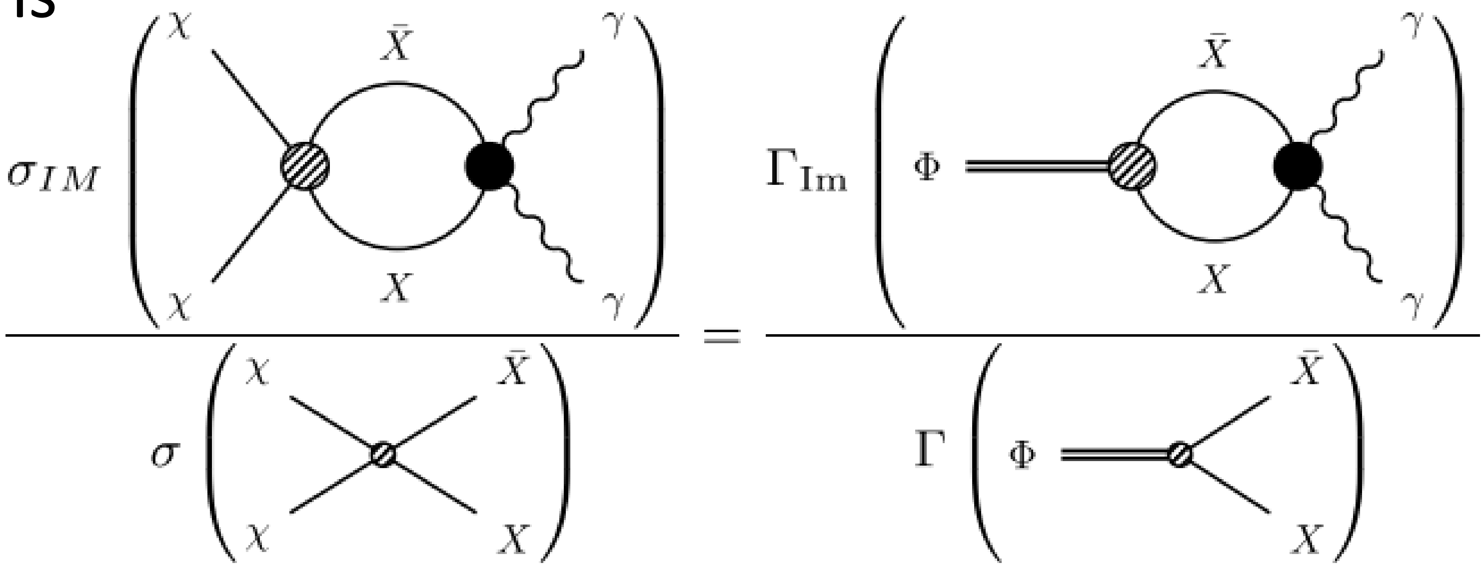
Unitarity

- S matrix is unitary $$S^\dagger S = 1$$
- S=1+iT $$-i(T - T^\dagger) = T^\dagger T$$
- put in intermediate states $$-i\langle f|(T - T^\dagger)|i\rangle = \Sigma_m \langle f|T^\dagger|m\rangle\langle m|T|i\rangle$$

  γ DM SM
- CP $$-2i\mathrm{Im}\langle f|T|i\rangle = \Sigma_m \langle f|T^\dagger|m\rangle\langle m|T|i\rangle$$
- single channel $$4|\mathrm{Im}\langle f|T|i\rangle|^2 = |\langle f|T^\dagger|m\rangle|^2|\langle m|T|i\rangle|^2$$

Methods

- Use |J,M;L,S> basis.
- Map annihilation into decay process.
- Calculate imaginary part of loop amplitude.
- Bound is

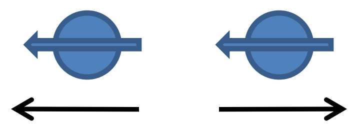


- Can also translate to line / continuum.

Case of Spin-0 Dark Matter

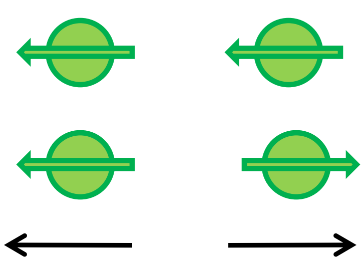
J=0, CP even

spin 1/2



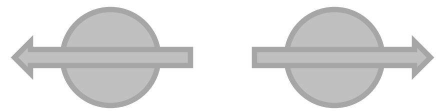
chirally suppressed,
heavy preferred
CP forces S=1, L=1

spin 1



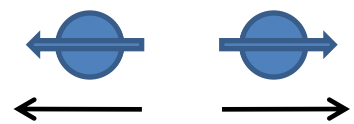
CP allows S=2, L=2
as well as S=0, L=0
latter preferred in
non-relativistic limit

Case of Spin-1/2 (Majorana) DM



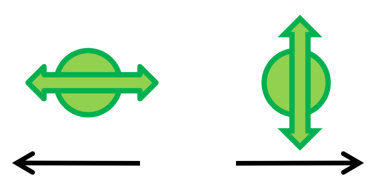
antisymmetry forces
S=0, J=0, CP odd

spin 1/2



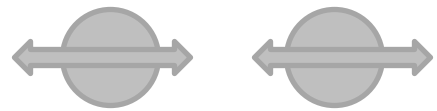
heavy preferred
CP forces S=0, L=0

spin 1



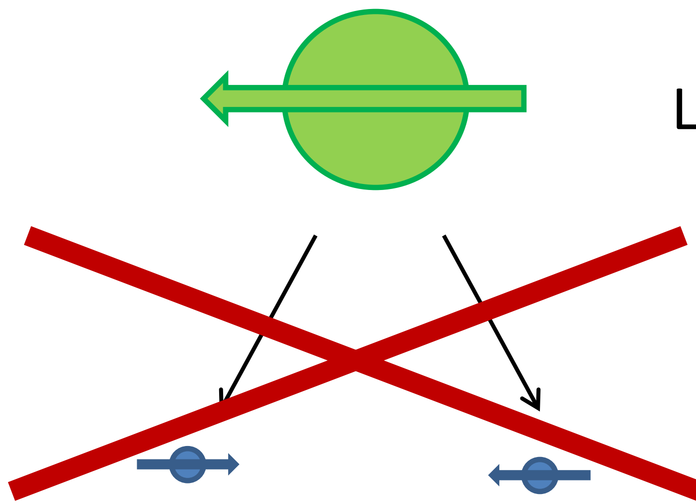
CP allows S=1, L=1 only

Case of Spin-1/2 (Dirac) DM



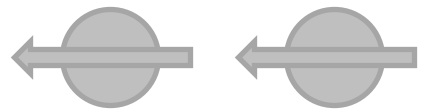
J can be 0,1

take conservative case?



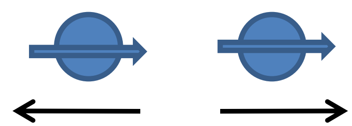
Landau-Yang theorem

Case of Spin-1 (real) DM



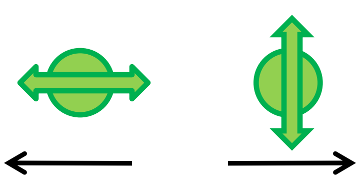
symmetry forces J=0,2
J=0 already covered

spin 1/2



light is now OK.
CP forces S=1
L can be {1,2,3}

spin 1



S=0, L=2 or
S=2, L={0,1,2,3,4}

bound only in kinematic limits

Summary of Results

Dark Matter	Initial spin	Annihilation		Bound
		Channel	Mode	
Scalar	$J=0$	WW	$L=0, S=0$ $L=2, S=2$	In NR / UR limits.
		$f\bar{f}$	$L=1, S=1$	✓
Majorana Fermion	$J=0$	WW	$L=1, S=1$	✓
		$f\bar{f}$	$L=0, S=0$	✓
Dirac Fermion	$J=0$	WW	$L=1, S=1$	✓
		$f\bar{f}$	$L=0, S=0$	✓
	$J=1$	Forbidden		
Real Vector Boson	$J=0$	WW	$L=0, S=0$ $L=2, S=2$	In NR / UR limits.
		$f\bar{f}$	$L=0, S=0$	✓
	$J=2$	WW	$L=2, S=0$ $L=\{0,1,2,3,4\}, S=2$	In NR limit.
		$f\bar{f}$	$L=\{1,2,3\}, S=1$	In NR / UR limits.

Results – Scalar DM

Can be represented as decay of heavy scalar.

To fermions :

$$\mathcal{L}_{int} = \lambda \bar{f} f \phi$$

$$\frac{\Gamma_{\mathrm{Im}}(\phi \to \gamma\gamma)}{\Gamma(\phi \to f\bar{f})} = \frac{N_c Q^4 e^4 m_f^2}{32\pi^2 m_\chi^2} \beta \left[\tanh^{-1}\beta\right]^2$$

To W's :

$$\mathcal{L}_{int} = \frac{1}{\Lambda} \phi \, \mathrm{Tr}\left[F_{\mu\nu} F^{\mu\nu}\right]$$

$$\frac{\Gamma_{\mathrm{Im}}(\phi \to \gamma\gamma)}{\Gamma(\phi \to WW)} = \frac{3e^4}{64\pi^2} \beta \qquad \text{(NR)}$$

Results – Scalar DM

To W's, ultra-relativistic regime

Ultra-relativistic: Use equivalence theorem to separate transverse and longitudinal modes.

- Longitudinal state is unique.

$$\mathcal{L}_{int} = \alpha\phi\, H^\dagger H \qquad \frac{\Gamma_{\rm Im}(\phi\to\gamma\gamma)}{\Gamma(\phi\to WW)} \sim \frac{e^4}{16\pi^2}\frac{m_W^4}{m_\chi^4}\left[\log\left(\frac{4m_\chi^2}{m_W^2}\right)\right]^2$$

- Transverse state as well, once CP is taken into account.

$$\mathcal{L}_{int} = \frac{1}{\Lambda}\phi\,{\rm Tr}\left[F_{\mu\nu}F^{\mu\nu}\right] \qquad \frac{\Gamma_{\rm Im}(\phi\to\gamma\gamma)}{\Gamma(\phi\to WW)} = \frac{e^4}{32\pi^2}\left[\log\left(\frac{4m_\chi^2}{m_W^2}\right)\right]^2$$

- Combine: $$\frac{\Gamma_{\rm Im}(\phi\to\gamma\gamma)}{\Gamma(\phi\to WW)} = {\rm F_T}\frac{e^4}{32\pi^2}\left[\log\left(\frac{4m_\chi^2}{m_W^2}\right)\right]^2$$

Results – Majorana Fermion DM

Can be represented as decay of heavy pseudoscalar.

To fermions : $$\mathcal{L}_{int} = i\lambda \bar{f}\,\gamma^5 f\,\varphi$$

$$\frac{\Gamma_{\rm Im}(\varphi \to \gamma\gamma)}{\Gamma(\varphi \to f\bar{f})} = \frac{N_c Q^4 e^4 m_f^2}{32\pi^2 m_\chi^2}\frac{1}{\beta}\left[\tanh^{-1}\beta\right]^2$$

To W's : $$\mathcal{L}_{int} = \frac{1}{\Lambda}\varphi \mathrm{Tr}(F_{\mu\nu}\tilde{F}^{\mu\nu})$$

$$\frac{\Gamma_{\rm Im}(\varphi \to \gamma\gamma)}{\Gamma(\varphi \to WW)} = \frac{e^4}{8\pi^2}\beta\left[\tanh^{-1}\beta\right]^2$$

both cases consistent with known SUSY results.

Results – Real Vector DM

J=0 case already covered, consider J=2
(more conservative bound applies)
Can be represented as decay of heavy spin-2 particle

To fermions : Non-relativistic limit. Single species assumed.

$$\mathcal{L}_{int} = -\frac{\kappa}{2} h^{\mu\nu} \bar{f}\, i\gamma_\mu \partial_\nu f$$

$$\left.\frac{\Gamma_{\rm Im}(h \to \gamma\gamma)}{\Gamma(h \to f\bar{f})}\right|_{J=2} = \frac{N_c Q^4 e^4 \beta^3}{120\pi^2}$$

p-wave,
weak limit

Results – Real Vector DM

J=0 case already covered, consider J=2
(more conservative bound applies)
Can be represented as decay of heavy spin-2 particle

To fermions : Ultra-relativistic limit.
If there are multiple final states and no phases,
then bound still applies.

$$\mathcal{L}_{int} = -\frac{\kappa}{2} h^{\mu\nu} \bar{f}\ i\bar{\sigma}_\mu \partial_\nu f$$

$$\left.\frac{\Gamma_{\mathrm{Im}}(h \to \gamma\gamma)}{\Gamma(h \to f\bar{f})}\right|_{J=2} = \frac{N_f N_c Q^4 e^4}{144\pi^2}$$

J=0 suppressed.
bound applies.

Results – Real Vector DM

J=0 case already covered, consider J=2
(more conservative bound applies)
Can be represented as decay of heavy spin-2 particle

To W's : Non-relativistic limit.

$$\mathcal{L}_{int} = \frac{\kappa}{2} h^{\mu\nu} \left(\left[(\partial_\mu W^{+\rho} - \partial^\rho W^+_\mu)(\partial_\nu W^-_\rho - \partial_\rho W^-_\nu) \right.\right.$$
$$\left.\left. - m_W^2 W^+_\mu W^-_\nu \right] + \mu \leftrightarrow \nu \right)$$

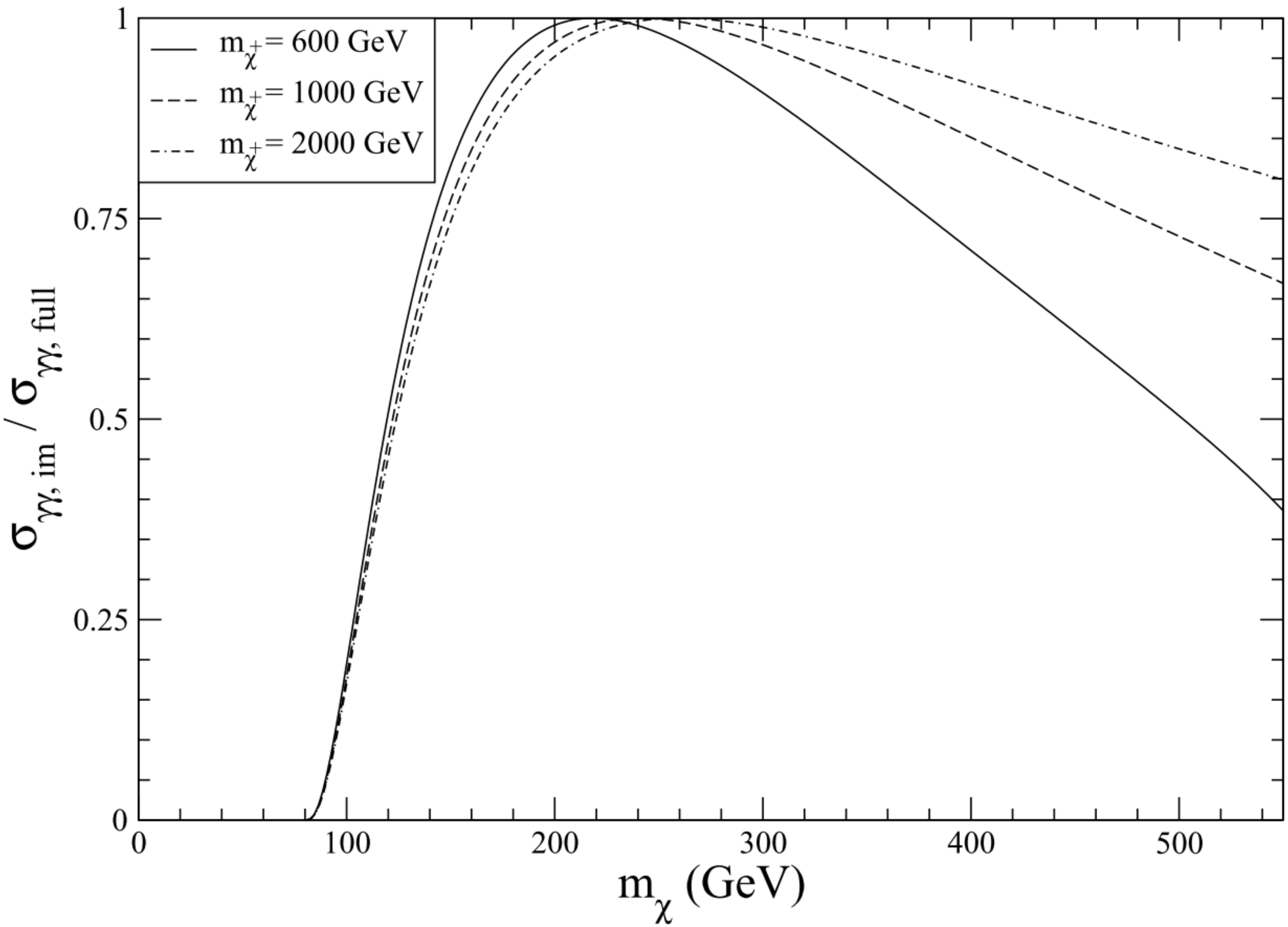
$$\left. \frac{\Gamma_{\mathrm{Im}}(h \to \gamma\gamma)}{\Gamma(h \to WW)} \right|_{J=2} = \frac{e^4}{20\pi^2} \beta$$

J=0 bound applies
(More conservative)

Comparison With Known Cases

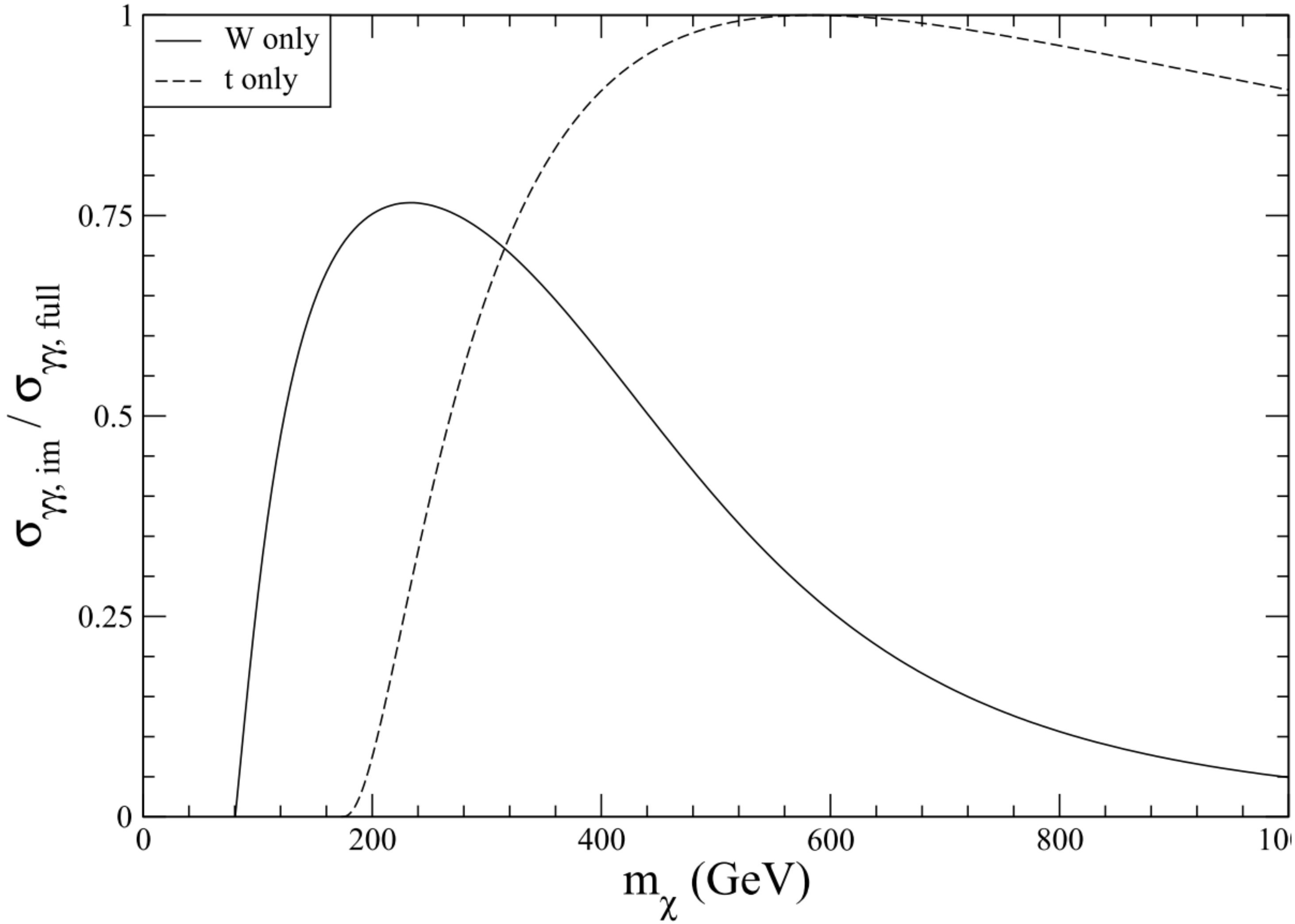
SUSY

χχ→WW



Comparison With Known Cases

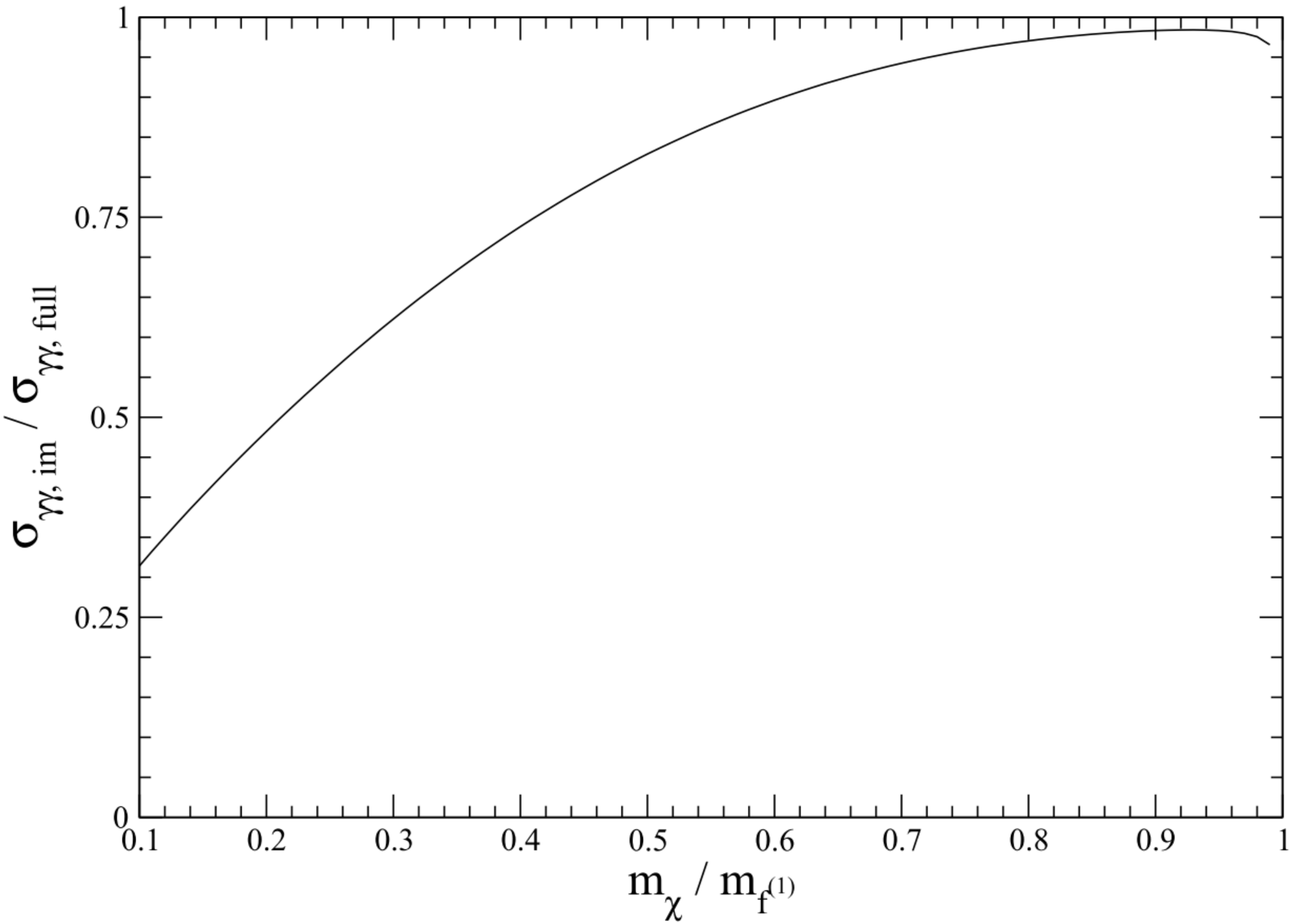
Little Higgs
$\chi\chi \rightarrow (h)$
$\rightarrow tt, WW$



Comparison With Known Cases

UED

$\chi\chi \rightarrow ff$



Comparison with Continuum Bound

For Lines: $$\frac{d\Phi}{dE} = \frac{\langle \sigma_{\rm A} v \rangle}{8\pi m_\chi^2} \frac{\mathcal{J}}{\rm J_0} \frac{dN}{dE}$$ where $$\frac{dN}{dE} = 2\delta(E_\gamma - m_\chi)$$

Search region includes caps $|b| \; > \; 10^\circ$

and Galactic center $|b| < 10^\circ$ $\quad |\ell| < 10^\circ$

Choose Einasto DM profile with parameters to minimize signal

specifically $$\rho_{\rm Einasto}(r) = \rho_s \exp\left[-\frac{2}{\alpha}\left(\left[\frac{r}{r_s}\right]^\alpha - 1\right)\right]$$

$$\begin{aligned} \alpha &= 0.22 \\ r_s &= 21 \text{ kpc} \\ r_\odot &= 8.28 \text{ kpc} \\ \rho_\odot &= 0.385 \text{ GeV cm}^{-3} \end{aligned}$$

Comparison with Continuum Bound

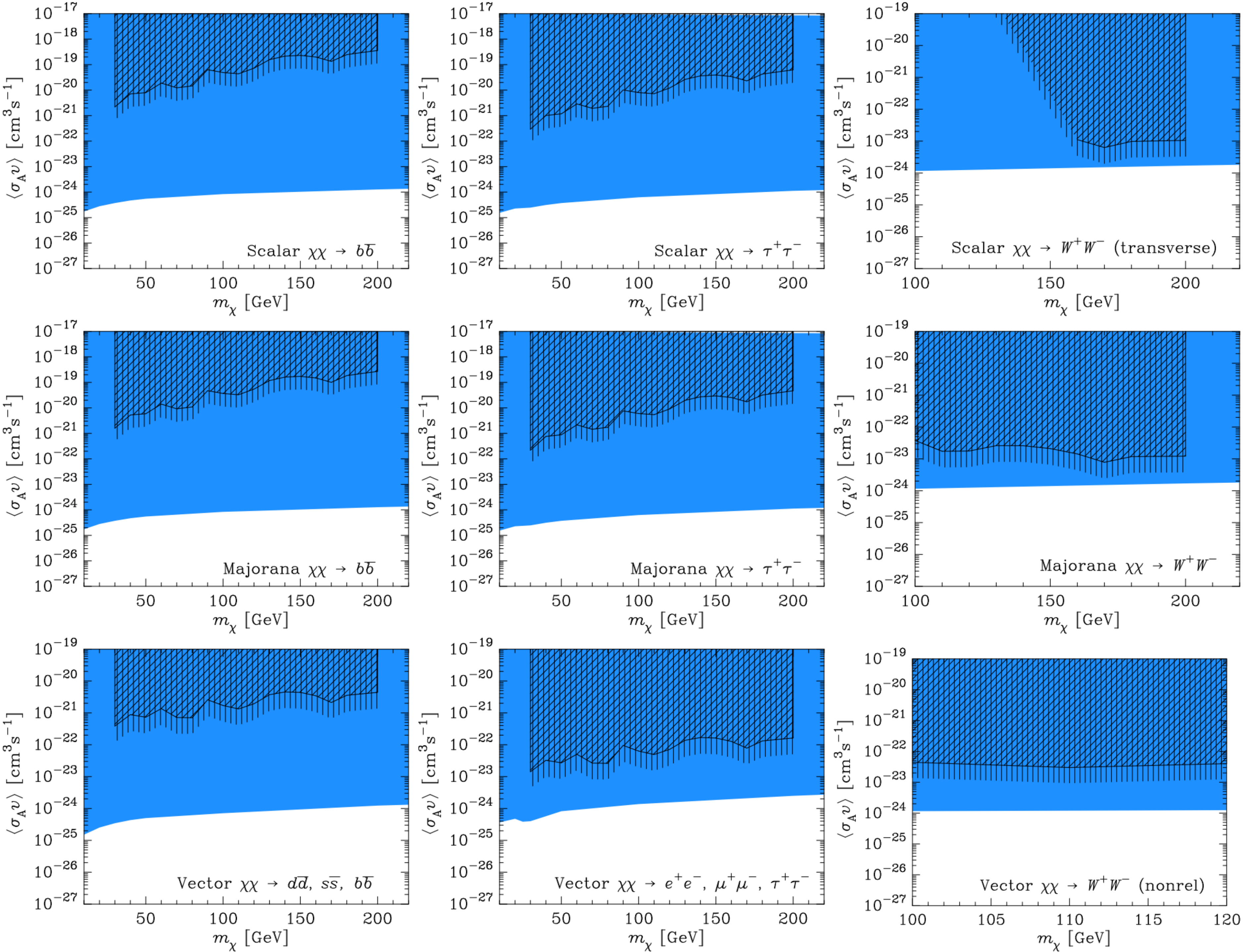
For Continuum:

Isotropic Diffuse Gamma Rays

(Galactic + Extragalactic)

Conservative, dwarf galaxy limits could be an order of magnitude stronger.

Conservative boost factor (2.3)



Scalar $\chi\chi \to b\bar{b}$
Scalar $\chi\chi \to \tau^+\tau^-$
Scalar $\chi\chi \to W^+W^-$ (transverse)
Majorana $\chi\chi \to b\bar{b}$
Majorana $\chi\chi \to \tau^+\tau^-$
Majorana $\chi\chi \to W^+W^-$
Vector $\chi\chi \to d\bar{d}$, $s\bar{s}$, $b\bar{b}$
Vector $\chi\chi \to e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$
Vector $\chi\chi \to W^+W^-$ (nonrel)
$\langle\sigma_A v\rangle$ [cm^{3}s^{-1}]
m_χ [GeV]

Conclusions

- Robust bounds obtained for gamma ray lines from DM annihilation through unitarity considerations.
- Minimal line bounds apply to some cases without restriction and to most other cases in certain kinematic regimes.
- In selected cases, the minimal bounds are found to be an O(1) fraction of the full cross section.
- Experimental limits are less stringent than continuum limits, but useful to identify when full calculation is important.

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