Lower limits on gamma lines from WIMP annihilations

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Phenomenology 2011 Symposium

May 9, 2011

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to appear

Weakly Interacting Massive Particles

There are many gravitational observations which point towards existence of dark matter.

- Galactic rotation curves
- Cosmic Microwave Background
- Gravitational lensing observations

The WIMP miracle

- The relic abundance of a particle with a weak-scale mass and weak-scale interactions is consistent with observations.

$$\langle \sigma_A v \rangle \sim \frac{g^4}{4\pi (1\ \mathrm{TeV})^2} \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

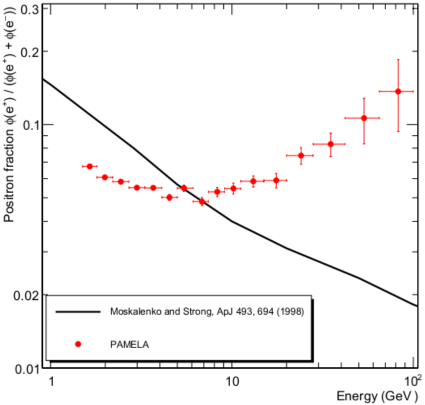
Indirect detection of WIMPs

Dark matter particles in galactic haloes can find each other and annihilate into SM states.

- Tests robust prediction of the WIMP hypothesis, $\langle \sigma_A v \rangle \sim 3 \times 10^{-26}$ cm^3/s
- Complementary to direct detection
  - coupling to other standard model states
  - different set of astrophysical parameters
- Background estimation is hard.

Example: Positron excess in PAMELA

Detection of dark matter?



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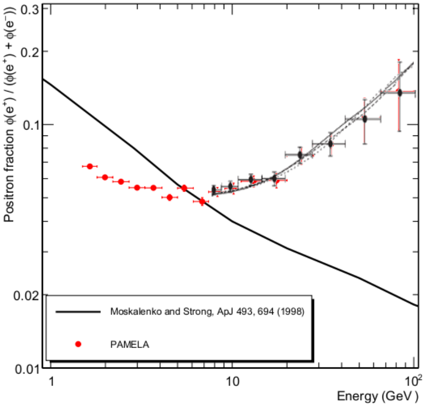

- Annihilation through a light boson

Example: Positron excess in PAMELA

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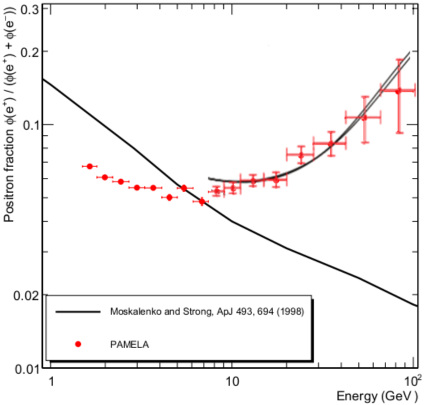

- Kaluza-Klein dark matter

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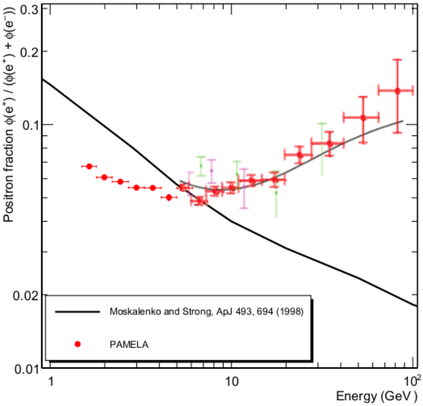
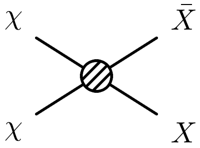


- Geminga pulsar

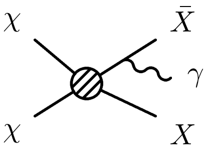
Continuum photon spectrum

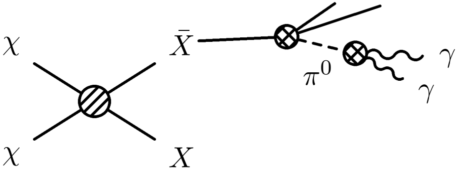


- Tree level annihilation to two-body SM final states arising from a renormalizable theory
- Cannot annihilate to photons directly

Continuum photon spectrum

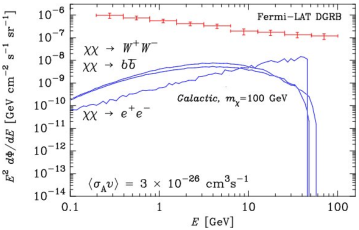
Bremsstrahlung/Hadronization



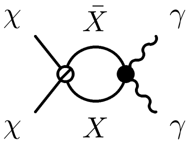


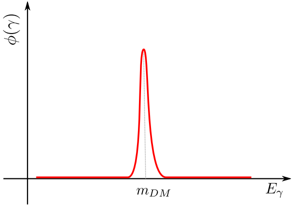
- Independent of the form of the coupling
- Depends on
  - dark matter mass
  - SM final state

Model independent!

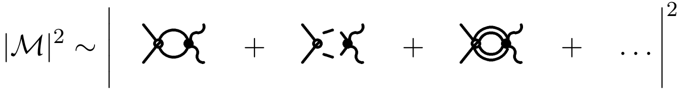


Photon lines



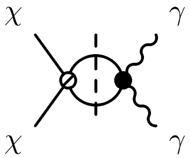


- No known astrophysical background
- Model dependent



  - Depends on detailed form of the couplings
  - New physics often dominates

Photon lines



Use unitarity relations to put lower bounds on the line strength relative to continuum strength

- Continuum γ-rays produced at tree-level from annihilation to SM states
- Photon lines arise at one loop
- Limit to $\gamma\gamma$ mode
- Assume single SM channel dominates the imaginary part

Unitarity

- We use the $|J, M; L, S\rangle$ basis

$$\left.\begin{array}{ll} J & : \text{total angular momentum} \\ M & : z\text{-component of } J \end{array}\right\} \text{conserved}$$

$$\left.\begin{array}{ll} L & : \text{orbital angular momentum} \\ S & : \text{total spin} \end{array}\right\} \text{not conserved}$$

- From unitarity, assuming time-reversal (CP) invariance,

$$2\,\mathrm{Im}\langle f|T|i\rangle = \sum_X \langle f|T^\dagger|X\rangle\langle X|T|i\rangle$$

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- From unitarity, assuming time-reversal (CP) invariance,

$$4|\mathrm{Im}\langle f|T|i\rangle|^2 = \left|\sum_X \langle f|T^\dagger|X\rangle\langle X|T|i\rangle\right|^2$$

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- From unitarity, assuming time-reversal (CP) invariance,

$$\sigma_{IM}(\chi\chi \to \gamma\gamma) = \rho\, \sigma(\chi\chi \to X\bar{X})\, \sigma(X\bar{X} \to \gamma\gamma)$$

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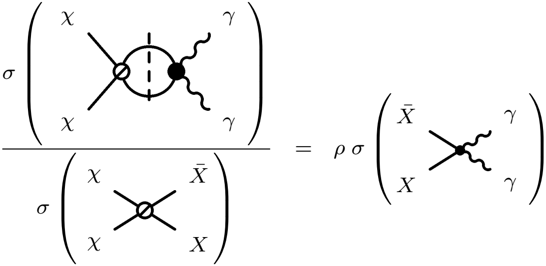
We have assumed a unique state X with unique L, S values.

Model-independent limits

$$\frac{\phi_{\text{line}}}{\phi_{\text{continuum}}} \propto \frac{\sigma(\chi\chi \to \gamma\gamma)}{\sigma(\chi\chi \to X\bar{X})} \geq$$



When can we find unique intermediate states?

Example 1: Majorana Fermion

- Dark matter particles are non-relativistic $\Rightarrow$ Initial $L = 0$
- Wavefunction is anti-symmetric $\Rightarrow$ Initial $S = 0$

Dark Matter	Initial spin	Annihilation channel	Annihilation mode	Bound
Majorana Fermion	$J = 0 \quad -$	WW	$L=0, S=0 \quad +$ $L=1, S=1 \quad -$ $L=2, S=2 \quad +$	
		$f\bar{f}$	$L=0, S=0 \quad -$ $L=1, S=1 \quad +$	

Majorana fermion dark matter will always give a photon line with at least a certain strength.

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Majorana Fermion	$J = 0 \quad -$	WW	$L = 0, S = 0 \quad +$ $L = 1, S = 1 \quad -$ $L = 2, S = 2 \quad +$	✓
		$f\bar{f}$	$L = 0, S = 0 \quad -$ $L = 1, S = 1 \quad +$	✓

Majorana fermion dark matter will always give a photon line with at least a certain strength.

Example 2: Dirac Fermion

Dark Matter	Initial spin	Annihilation channel	Annihilation mode	Bound
Dirac Fermion	$J = 0 \quad -$	WW	$L=0, S=0 \quad +$ $L=1, S=1 \quad -$ $L=2, S=2 \quad +$	
		$f\bar{f}$	$L=0, S=0 \quad -$ $L=1, S=1 \quad +$	
	$J = 1 \quad +$			

Example 2: Dirac Fermion

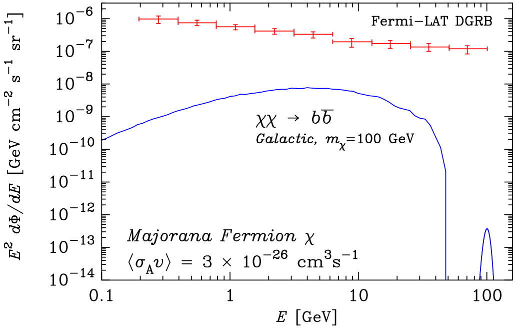
Dark Matter	Initial spin	Annihilation channel	Annihilation mode	Bound
Dirac Fermion	$J=0 \quad -$	WW	$L=0, S=0 \quad +$ $L=1, S=1 \quad -$ $L=2, S=2 \quad +$	✓
		$f\bar{f}$	$L=0, S=0 \quad -$ $L=1, S=1 \quad +$	✓
	$J=1 \quad +$	Forbidden by Landau-Yang theorem		

Other cases

Dark Matter	Initial spin	Annihilation channel	Annihilation mode	Bound
Scalar	$J=0$	WW	$L=0, S=0$ $L=2, S=2$	In non-relativistic, ultra-relativistic limits.
Scalar	$J=0$	$f\bar{f}$	$L=1, S=1$	✓
Majorana Fermion	$J=0$	WW	$L=1, S=1$	✓
Majorana Fermion	$J=0$	$f\bar{f}$	$L=0, S=0$	✓
Dirac Fermion	$J=0$	WW	$L=1, S=1$	✓
Dirac Fermion	$J=0$	$f\bar{f}$	$L=0, S=0$	✓
Dirac Fermion	$J=1$	Forbidden		
Real Vector Boson	$J=0$	WW	$L=0, S=0$ $L=2, S=2$	In non-relativistic, ultra-relativistic limits.
Real Vector Boson	$J=0$	$f\bar{f}$	$L=0, S=0$	✓
Real Vector Boson	$J=2$	WW	$L=2, S=0$ $L=\{0,1,2,3,4\}, S=2$	In non-relativistic limit.
Real Vector Boson	$J=2$	$f\bar{f}$	$L=\{1,2,3\}, S=1$	In non-relativistic, ultra-relativistic limits.

Phenomenology of Majorana Fermion

$b\bar{b}$ spectrum

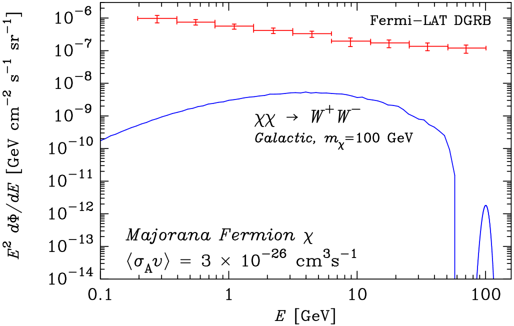


$$\frac{\sigma(\chi\chi \to \gamma\gamma)}{\sigma(\chi\chi \to b\bar{b})} \geq \frac{3e^4 m_b^2}{32\pi^2 m_\chi^2} \frac{1}{\beta} \left[\tanh^{-1}\beta\right]^2$$

$$\beta = \sqrt{1 - \frac{m_b^2}{m_\chi^2}}$$

Phenomenology of Majorana Fermion

WW spectrum

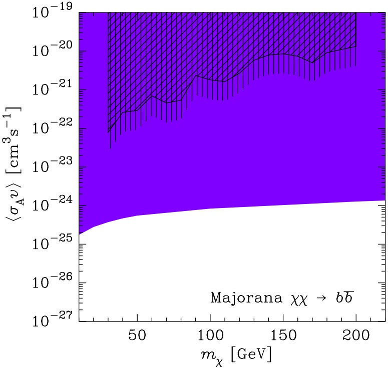


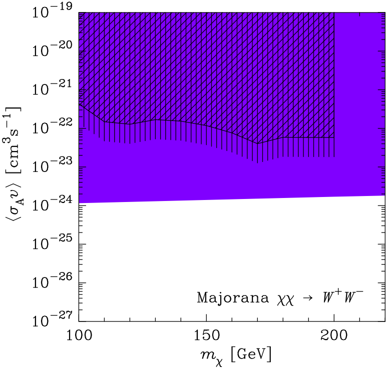
$$\frac{\sigma(\chi\chi \to \gamma\gamma)}{\sigma(\chi\chi \to WW)} \geq \frac{e^4}{8\pi^2}\beta^{3/2}\left[\tanh^{-1}\beta\right]^2$$

$$\beta = \sqrt{1 - \frac{m_W^2}{m_\chi^2}}$$

Phenomenology of Majorana Fermion

Limits





Comments

Bounds obtained from lower limit of lines are currently weaker than the diffuse isotropic spectrum

- Bounds are largely statistics limited and will improve with more data.
- Future experiments with better resolution will be more sensitive to lines.
- If these bounds are comparable, the overall bound from lines in a given model are expected to dominate.