Detecting and discriminating WIMP Dark Matter

A model-independent approach

Prateek Agrawal

Maryland Center for Fundamental Physics
University of Maryland

University of California, Davis

arXiv:1002.3820

K. Abazajian, Z. Chacko, C. Kilic

arXiv:1003.1912, 1003.5905

Z. Chacko, C. Kilic, R. K. Mishra

Experimental evidence for dark matter

The astrophysical evidence for dark matter is very strong.

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

The WIMP miracle

A Weakly Interacting Massive Particle is a theoretically well-motivated dark matter candidate.

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

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

- It is an attractive proposition that with the already observed scales in the universe, we can explain dark matter.

Two recipes for dark matter models

Add Salt to taste

Use models of new physics at the weak scale which are motivated by some problem in the Standard Model(SM).

- Supersymmetry solves the Planck-weak hierarchy problem.
- A simple discrete symmetry makes the lightest particle in this extension stable.
- The WIMP miracle ensures that it naturally yields present day relic abundance.

We get a dark matter particle "for free".

Two recipes for dark matter models

Microwave-ready dark matter

Minimally extend the Standard Model, introducing fewest additional degrees of freedom.

- As before, a symmetry ensures the stability of the dark matter particle.
- An extension as simple as a singlet scalar particle works.

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Most of the machinery in the first case is incidental from the dark matter physics perspective.

Model-independent analysis

Two fold question

- To what extent is it possible to extract from experiment information about nature of WIMP dark matter independent of specific models?
    - What is the mass of the dark matter particle?
    - What is the spin of the dark matter particle?
    - Is the dark matter particle its own antiparticle?
    - What are the interactions of dark matter with SM?
- Are there robust features common to large classes of models that could aid in the discovery of dark matter?
    - Direct detection signals
    - Photons from dark matter annihilation
    - Missing energy signals in colliders

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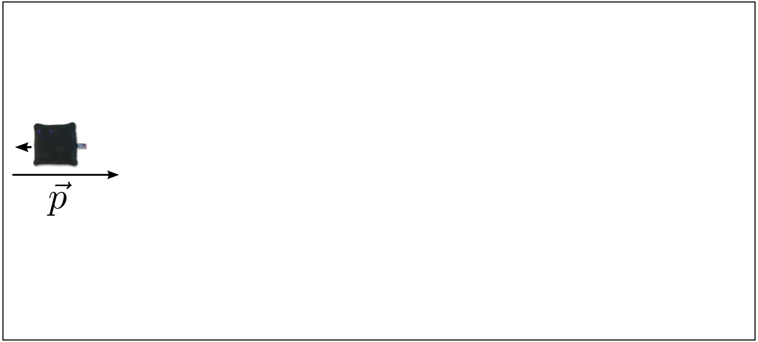
The question

CPT Theorem

For every particle there is an anti-particle with the same mass and spin but with an opposite charge(s).



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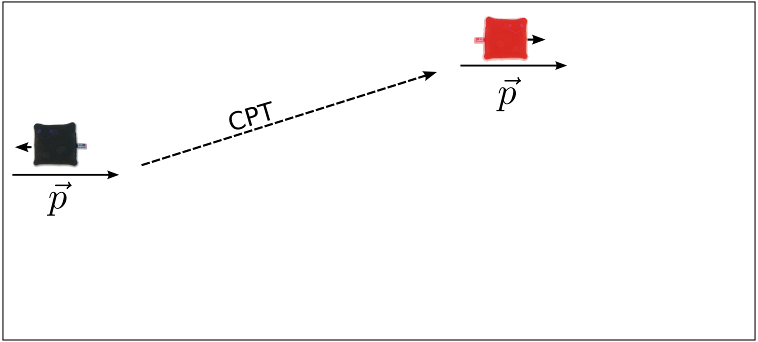

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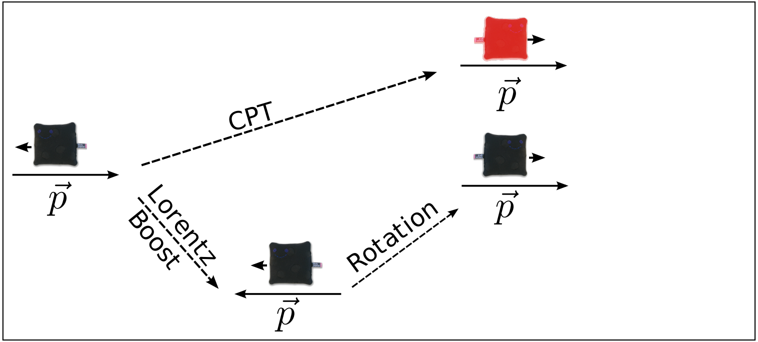

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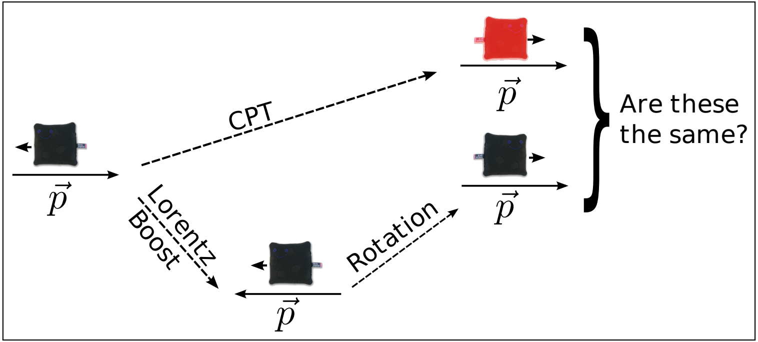

The answer

Non-relativistic WIMP interactions with protons (or neutrons)

- Spin-independent (SI)
- Spin-dependent (SD)

Theories where the WIMP-nucleon cross-section is **dominated by SD interactions** are associated with theories where the dark matter particle is **its own anti-particle**.

$$\sigma_{SD} \gg \sigma_{SI} \Rightarrow \chi = \chi^c \quad (\text{but} \quad \chi = \chi^c \nRightarrow \sigma_{SD} \gg \sigma_{SI})$$

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Which dark matter models give rise to a dominantly spin-dependent WIMP-nucleon cross-section?

Classification of dark matter interactions

Setup

- Cosmological limits constrain WIMP dark matter to be neutral under color and electromagnetism.
- Limit to theories where WIMP-nucleon scattering is elastic and arises at tree-level.
  - Only WIMP-quark coupling contributes to the WIMP-nucleon scattering.

$$\mathcal{O}_{\chi\chi qq} \sim \text{[DM bilinear] [quark bilinear]}$$

- Cross-section depends on the matrix element of quark bilinears between nuclear states.

Symmetry - Quark bilinears

Parity allows us to distinguish between SI and SD terms.
WIMP-nucleon scattering is non-relativistic.

The quark bilinears depend on:

- Relative velocity $\vec{v}$
- Nuclear spin $\vec{s}$
- Charge(s) Q
- QCD scale $\sim m_p$
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Operator			NR limit
Scalar	$\bar{q}q$		$\frac{m_p}{m_\chi}$
Pseudo-scalar	$\bar{q}\gamma^5 q$		$\vec{s}\cdot\vec{v}\,\frac{m_p}{m_\chi}$
Vector	$\bar{q}\gamma^\mu q$	$\bar{q}\gamma^0 q$ $\bar{q}\gamma^i q$	Q Qv^i
Pseudo-vector	$\bar{q}\gamma^\mu\gamma^5 q$	$\bar{q}\gamma^0\gamma^5 q$ $\bar{q}\gamma^i\gamma^5 q$	$\vec{s}\cdot\vec{v}$ s^i
Tensor	$\bar{q}\sigma^{\mu\nu} q$	$\bar{q}\sigma^{0i} q$ $\bar{q}\sigma^{ij} q$	$v^i\,\frac{m_p}{m_\chi}$ $\epsilon^{ijk}s^k\,\frac{m_p}{m_\chi}$

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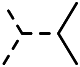
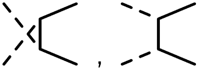
Scalar Dark Matter

Mediator	Process	Scattering
Z, Z'		SI
h		SI
Q		SI

Fermionic Dark Matter

The effective 4-fermion operators for the scattering process:

$$\bar{\chi}\gamma^{\mu}\chi\,\bar{q}\gamma_{\mu}q \qquad \bar{\chi}\gamma^{\mu}\gamma^{5}\chi\,\bar{q}\gamma_{\mu}q$$
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- For a Majorana fermion, $\bar{\chi}\gamma^{\mu}\chi$ vanishes identically.

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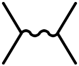
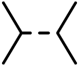
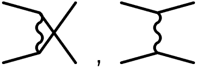
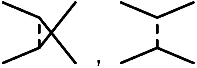
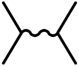
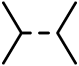
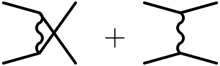
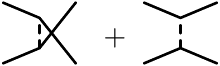
A consequence of the self-conjugacy of the Majorana field!

Dirac Fermion

Mediator	Process	Scattering
Z, Z'		SI, SD†
h		SI
X		SI, SD
Φ		SI, SD

† Can be primarily SD for specific choices of Z' charges

Majorana Fermion

Mediator	Process	Scattering
Z, Z'		SD
h		SI
X		SD (in chiral limit)
Φ		SD (in chiral limit)

Vector Boson

We can repeat the above operator analysis for vector boson dark matter.

$$
\begin{aligned}
\epsilon_{\mu\nu\lambda\sigma} B^\nu \partial^\lambda B^\sigma \; \bar{q}\gamma^\mu\gamma^5 q & \\
B^\nu \partial_\mu B_\nu \; \bar{q}\gamma^\mu\gamma^5 q & \qquad B^\nu \partial_\mu B_\nu \; \bar{q}\gamma^\mu q \\
B^\nu \partial_\nu B_\mu \; \bar{q}\gamma^\mu\gamma^5 q & \qquad B^\nu \partial_\nu B_\mu \; \bar{q}\gamma^\mu q \\
\epsilon^{\mu\nu\lambda\sigma} B^\dagger{}_\nu \partial_\lambda B_\sigma \; \bar{q}\gamma_\mu\gamma^5 q & \qquad B^\nu \partial_\mu B^\dagger{}_\nu \; \bar{q}\gamma^\mu q
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$$

The operators which lead to spin-independent scattering only survive if the vector boson is complex.

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$$B^\nu \partial_\nu B_\mu \; \bar{q}\gamma^\mu\gamma^5 q \qquad B^\nu \partial_\nu B_\mu \; \bar{q}\gamma^\mu q$$

$$\epsilon^{\mu\nu\lambda\sigma} B^\dagger{}_\nu \partial_\lambda B_\sigma \; \bar{q}\gamma_\mu\gamma^5 q \qquad B^\nu \partial_\mu B^\dagger{}_\nu \; \bar{q}\gamma^\mu q$$

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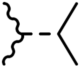
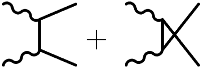
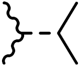
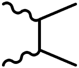
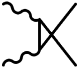
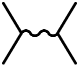
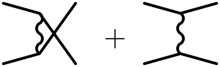
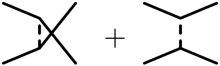
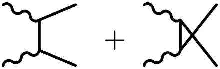
Real Vector Boson

Mediator	Process	Scattering
h		SI
Q		SD (in chiral limit)

Complex Vector Boson

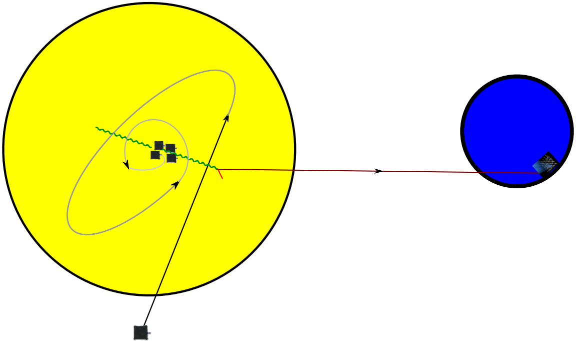
Mediator	Process	Scattering
Z, Z'		SI
h		SI
Q	 , 	SI, SD

Models with exclusively spin-dependent couplings

Dark Matter	Mediator	Process	Scattering
Majorana Fermion	Z, Z'		SD
	X		SD (in chiral limit)
	Φ		SD (in chiral limit)
Real Vector	Q		SD (in chiral limit)

IceCube

Spin-dependent dark matter detector



Capture → Annihilation → Decay → Detection

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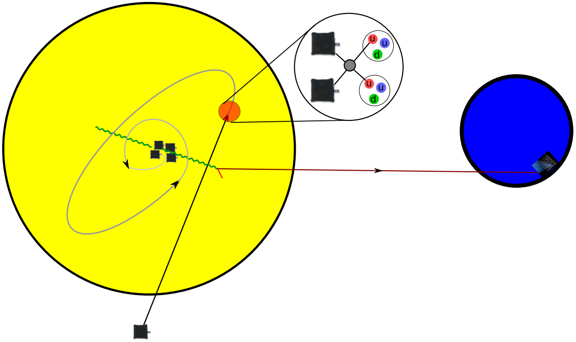

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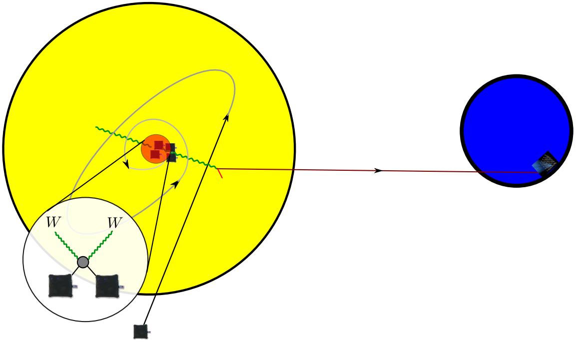

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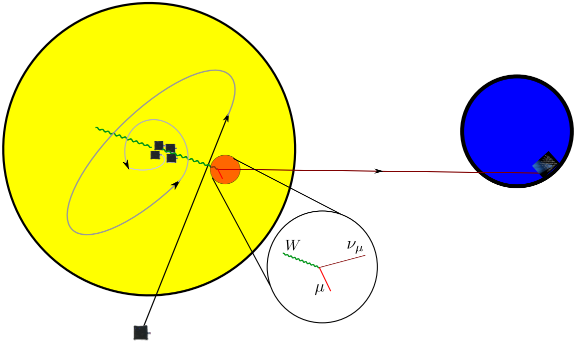

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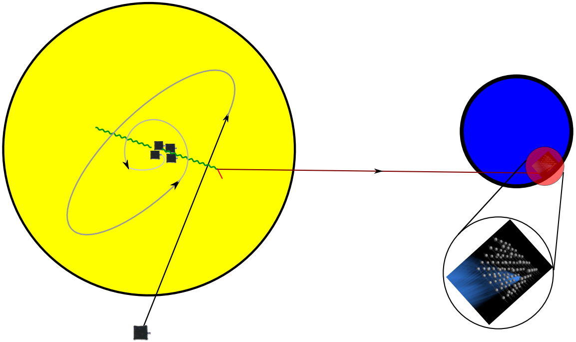

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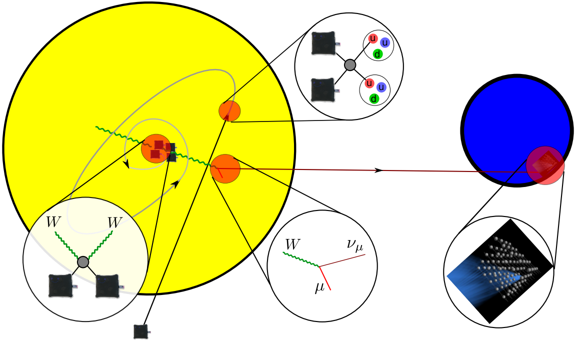


The neutrino signal is bounded by the WIMP-nucleon cross-section.

Direct Detection bounds

The bound on spin-independent interaction is much stronger than the corresponding bound on spin-dependent interaction.

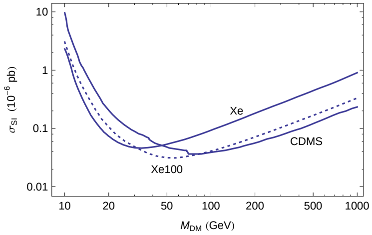


Figure: WIMP-nucleon cross-section bounds

We use the bounds from direct detection to calculate the maximum signal in IceCube.

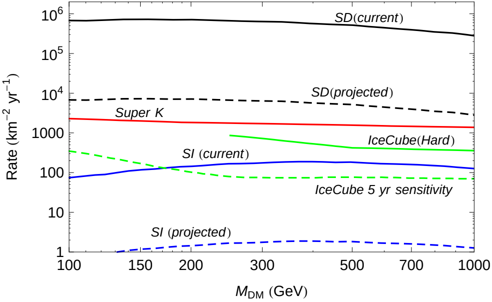


Figure: Rate in IceCube assuming W^+W^- final state

Summary

- Dark matter candidates with primarily spin-dependent interactions with matter are Majorana fermions and real vector bosons
  - dark matter particle is its own anti-particle

$$\sigma_{SD} \gg \sigma_{SI} \Rightarrow \chi = \chi^c \quad (\text{but} \quad \chi = \chi^c \not\Rightarrow \sigma_{SD} \gg \sigma_{SI})$$

- If direct detection bounds continue to improve, spin-independent dark matter will fall below IceCube reach.
  - Signal at IceCube will imply that the dark matter particle has spin, and is its own conjugate.
  - Region of parameter space where IceCube can expect a signal is kinematically accessible to the LHC.

Intermission

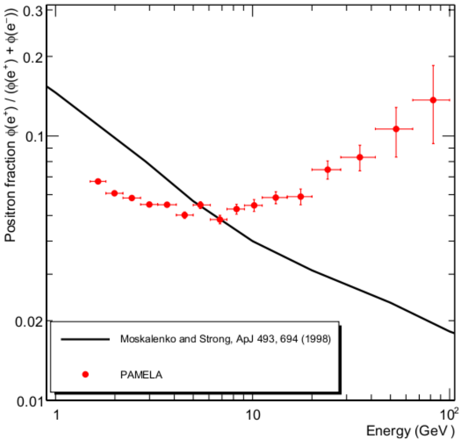
Astrophysical signatures

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

- Complementary to direct detection
  - coupling to other standard model states
  - different set of astrophysical parameters
- Thermal relic abundance $\Rightarrow \langle \sigma_A v \rangle \sim 3 \times 10^{-26}$cm^3/s
  - Overall scale of signal known!
- Sensitive to background: hard to pin-down

Example: Positron excess in PAMELA

Detection of dark matter?



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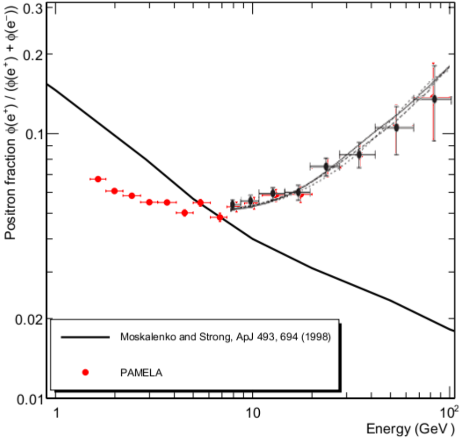

- Annihilation through a light boson

Example: Positron excess in PAMELA

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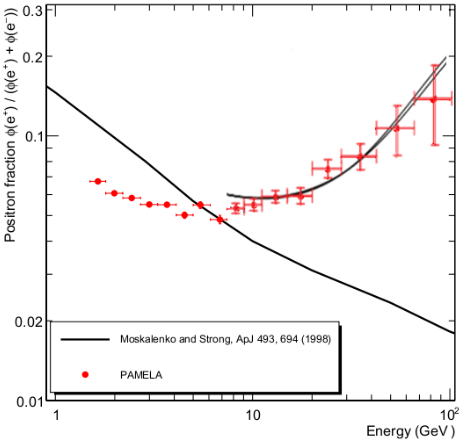
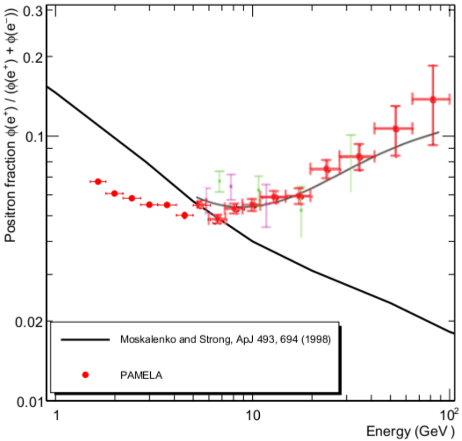


- Kaluza-Klein dark matter

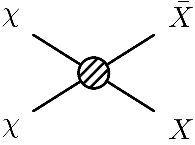
Example: Positron excess in PAMELA

Detection of dark matter?



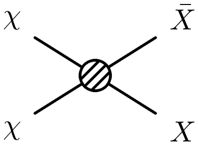
- Geminga pulsar

Continuum photon spectrum

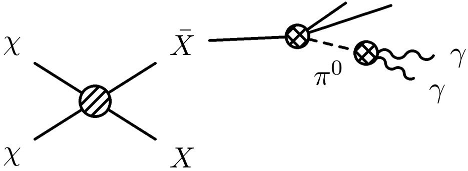


- Tree level annihilation to two-body SM final states arising from a renormalizable theory
- Cannot annihilate to photons directly

Hadronization

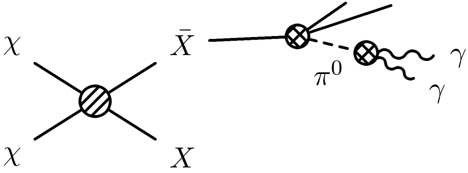


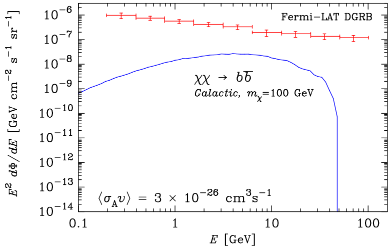
Hadronization



- Dominant mode for all two-body SM final states except $X = e, \mu$
- Independent of
  - dark matter spin
  - form of couplings
- Depends on
  - dark matter mass
  - SM final state
    (to a small extent)

Hadronization





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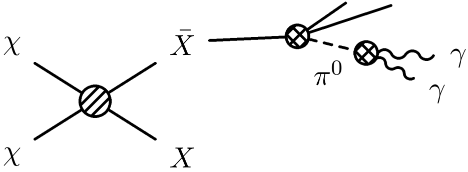

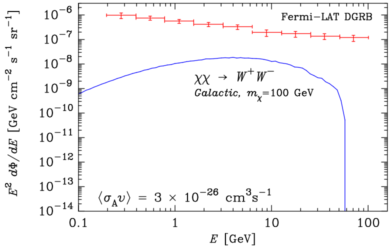

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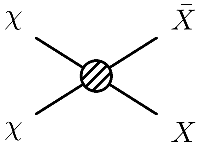
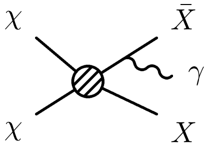
Bremsstrahlung



Bremsstrahlung



- Dominant contribution for $X = e, \mu$
- Dominated by the collinear limit
- Independent of
  - dark matter spin
  - form of couplings
- Depends on
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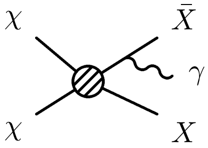
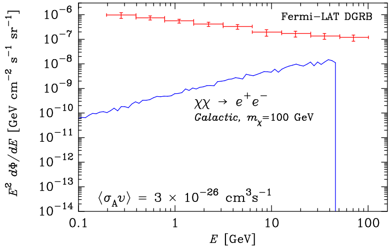
  - SM final state mass and spin

Bremsstrahlung





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- Independent of
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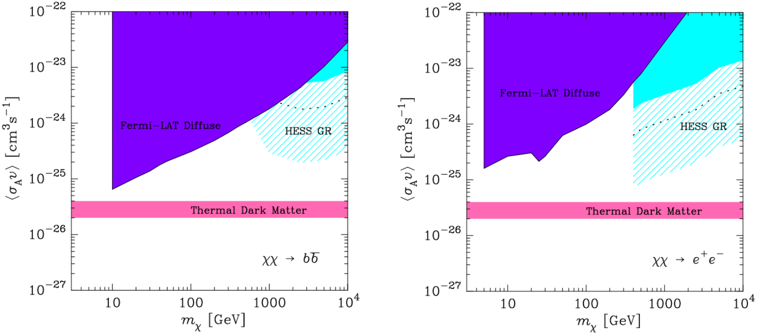
- Depends on
  - dark matter mass
  - SM final state mass and spin

Limits

- Strongest constraints
  - FERMI - diffuse isotropic emission
  - HESS - Galactic ridge
- No excess is seen, so we can only derive limits
- Limit depends in general on dark matter profiles at the center of galaxies
- With conservative dark matter profiles
  - Extra-galactic contribution is sub-dominant
  - Galactic contribution is insensitive to the choice of profile
  - Conservative limits on the WIMP annihilation cross-section

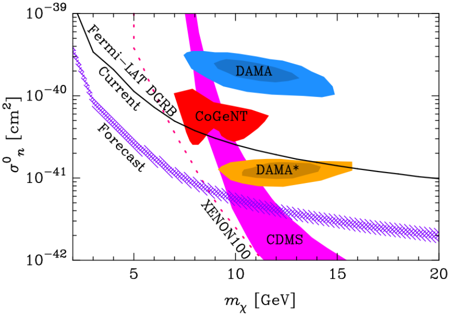
Limits



- The HESS constraint is sensitive to choice of profiles.
- FERMI limit assumes a clumping boost factor of 7.

  (expected to be $\sim 20 \to 1000$)
- Almost at thermal cross-section for $m_{DM} \sim$ few GeV.

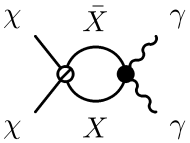
Forecast

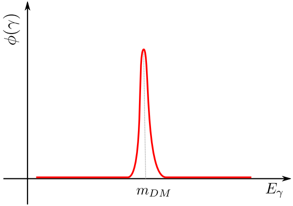


Abazajian et al
[arXiv:1011.5090]

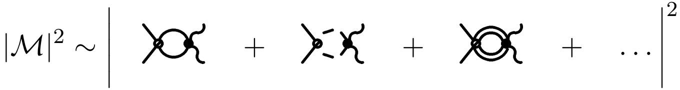
- Light scalar singlet dark matter arises in the explanation for DAMA/CoGeNT/CDMS
- With resolution of blazar sources, Fermi-LAT data can probe most of the parameter space.

Photon lines





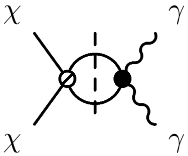
- No known astrophysical background
- Model dependent



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

Photon lines

- Focus on theories where
  - Continuum γ-rays produced at tree-level from annihilation to SM states
  - Photon lines arise at one loop
  - Both SM and new physics may run in the loop
  - Limit to $\gamma\gamma$ mode



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

- Tree-level annihilation dominantly to one SM state
- Limits approximate if many states contribute

Unitarity

- From unitarity ($S^\dagger S = 1$)

$$-i(T - T^\dagger) = T^\dagger T$$

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

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

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

- Consider the matrix element between
  - $|f\rangle$ two photon final state
  - $|i\rangle$ initial state with two dark matter particles

$$-i\langle f|(T - T^\dagger)|i\rangle = \sum_X \langle f|T^\dagger|X\rangle\langle X|T|i\rangle$$

Unitarity

- Assuming time-reversal (CP) invariance, and in the $|J, M; L, S\rangle$ basis,

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

Unitarity

- Assuming time-reversal (CP) invariance, and in the $|J, M; L, S\rangle$ basis,

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

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

- If there is a unique intermediate state X with unique L, S values,

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

$$\sigma(\chi\chi \to \gamma\gamma) \geq \rho\, \sigma(\chi\chi \to X\bar{X})\, \sigma(X\bar{X} \to \gamma\gamma)$$

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$\uparrow$

DM cross section to two photons

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$\uparrow$ DM cross section to two photons

$\uparrow$ phase space factor

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$\uparrow$ DM cross section to two photons

$\uparrow$ phase space factor

$\uparrow$ DM cross section to SM

Unitarity

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$$\sigma(\chi\chi \to \gamma\gamma) \geq \rho\, \sigma(\chi\chi \to X\bar{X})\, \sigma(X\bar{X} \to \gamma\gamma)$$

$\sigma(\chi\chi \to \gamma\gamma)$ ↑ DM cross section to two photons

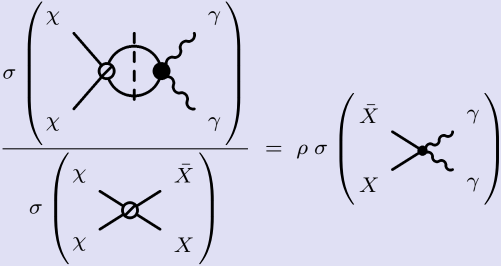
ρ ↑ phase space factor

$\sigma(\chi\chi \to X\bar{X})$ ↑ DM cross section to SM

$\sigma(X\bar{X} \to \gamma\gamma)$ ↑ SM cross section

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

Since the dark matter particles are non-relativistic, the initial $L = 0$. Then, in the initial state $J = S$. The anti-symmetry of the wavefunction constrains the initial state to be in the $S = 0$ state.

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

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

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		$t\bar{t}, b\bar{b}$	$L=0, S=0 \quad -$ $L=1, S=1 \quad +$	✓

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

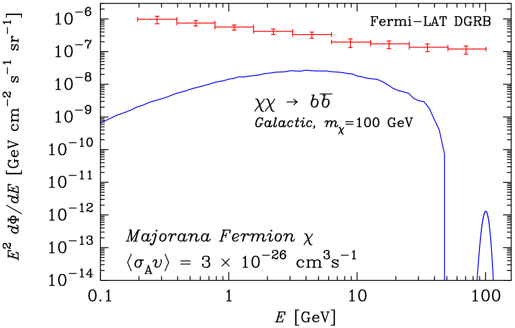
Example 2: Dirac Fermion

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

Example 2: Dirac Fermion

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

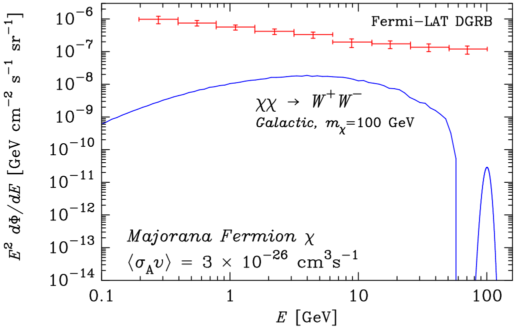
Phenomenology of Majorana Fermion



$$\frac{\sigma(\chi\chi \to \gamma\gamma)}{\sigma(\chi\chi \to b\bar{b})} \geq \frac{3e^4 m_b^2}{128\pi^2 m_\chi^2} \frac{1}{\beta} \left[\tanh^{-1}\beta\right]^2$$

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

Phenomenology of Majorana Fermion



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

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

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.
		$t\bar{t}, b\bar{b}$	$L=1, S=1$	✓
Majorana Fermion	$J=0$	WW	$L=1, S=1$	✓
		$t\bar{t}, b\bar{b}$	$L=0, S=0$	✓
Dirac Fermion	$J=0$	WW	$L=1, S=1$	✓
		$t\bar{t}, b\bar{b}$	$L=0, S=0$	✓
	$J=1$	Forbidden		
Real Vector Boson	$J=0$	WW	$L=0, S=0$ $L=2, S=2$	In non-relativistic, ultra-relativistic limits.
		$t\bar{t}, b\bar{b}$	$L=0, S=0$	✓
	$J=2$	WW	$L=2, S=0$ $L=\{0,1,2,3,4\}, S=2$	In non-relativistic limit.
		$t\bar{t}, b\bar{b}$	$L=\{1,2,3\}, S=1$	In non-relativistic, ultra-relativistic limits.
		$f\bar{f}$	$L=\{1,2,3\}, S=1$	✓

Summary

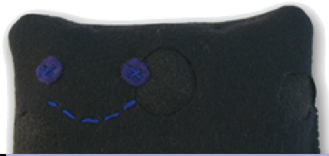
- Limits from line are weaker than the diffuse isotropic spectrum by a factor of few to an order of magnitude.
- For real vector boson dark matter annihilating to electrons and muons, lines give stronger bound.
- Bounds are largely statistics limited will improve with more data
- For favorable halo profiles, the line strength could be orders of magnitude stronger.

Photon searches from dark matter annihilation are complementary to direct detection experiments. In particular, a line signal is a smoking gun signal.

Conclusion

- We highlight a model-independent approach to the question of dark matter.
- We show that if neutrino telescopes see a signal in the near future, while current direct detection experiments do not, the favored scenario is that the dark matter is its own anti-particle.
- The continuum photon spectrum is a generic signal in a large class of dark matter models
  - Only depends on dark matter mass and annihilation products
- Unitarity can be used to get model-independent lower bounds on the strengths of photon lines from dark matter annihilations
  - Depend on the spin and charge conjugation properties of dark matter and primary annihilation mode

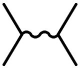
$\mathscr{F}\ \mathscr{I}\ \mathscr{N}$



Backup slides

What about the Dirac fermion?

- In the case of Dirac fermion dark matter, a t-channel exchange vector exchange (Z' exchange), there is a choice of charges which leads to purely spin-dependent scattering

Mediator	Process	Scattering
Z,Z'		SI, SD†

†Can be primarily SD for specific choices of Z' charges

- If there is a $\chi \to \chi^c$ symmetry under which SM fields are invariant, then $\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$ vanishes.
- For other mediators, no simple realization of this symmetry exists.

Evaluating assumptions

- Assumptions that do not affect the result
  - Only studied two-body final states. Multi-body final states lead to softer neutrino spectrum and hence a weaker signal.
  - Ignored possible annihilation to new non-SM final state
  - Ignored Sommerfeld enhancement of the annihilation rate. The bound only depends on the capture rate.
  - Assumed specific value for halo density. The halo density affects direct detection and neutrino telescopes in the same way.
- Assumptions that could affect the result
  - Assumed dark matter is elastic.
  - Assumed a specific dark matter velocity distribution.

Did not assume thermal relic abundance!