Title: A Model-Independent Approach to WIMP Dark Matter

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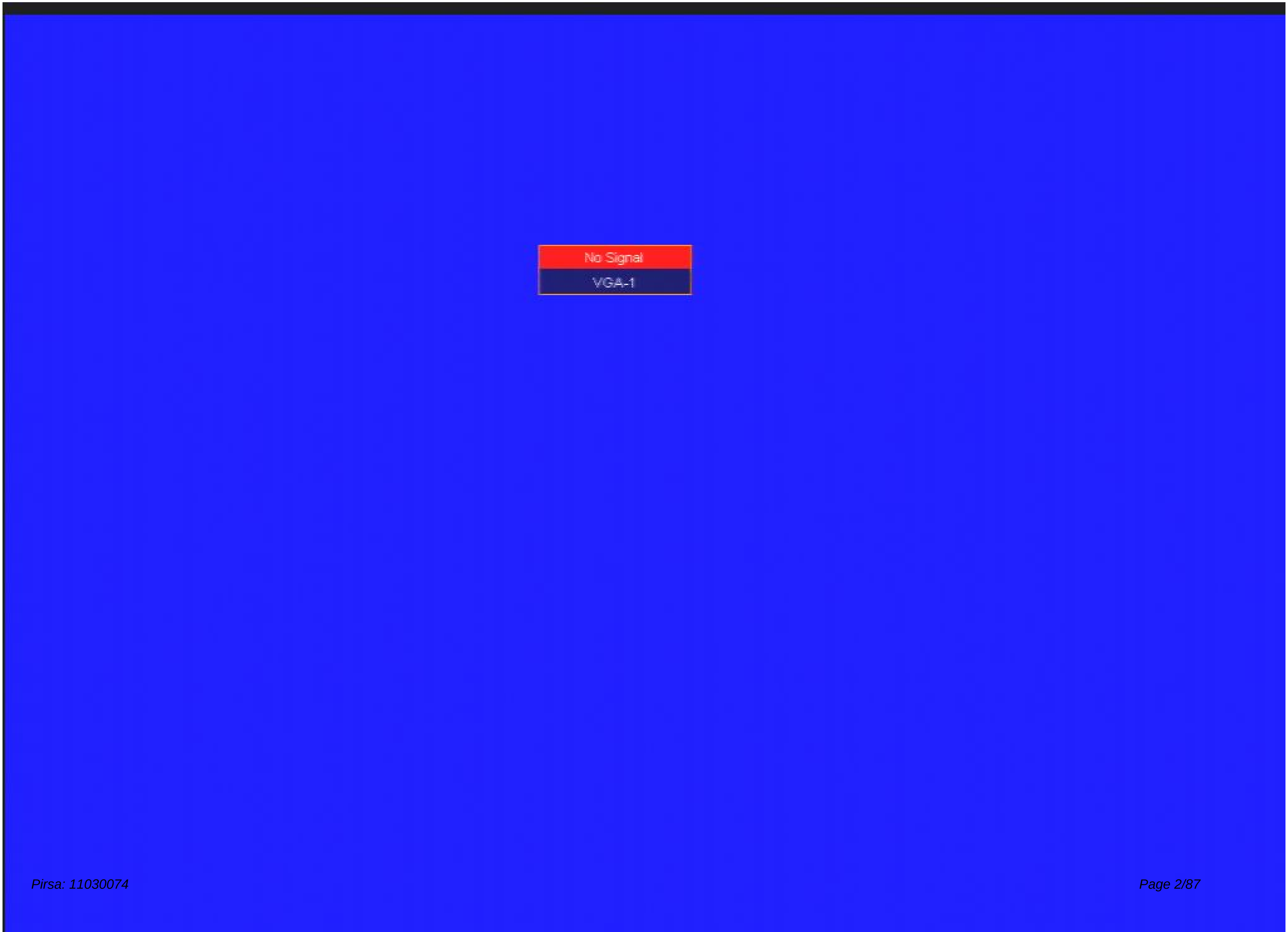
Abstract: I discuss how the results of dark matter experiments can be used to draw conclusions about the nature of WIMP dark matter that are to a large extent model-independent. Specifically, I show that combining the results of direct detection experiments with data from neutrino telescopes can help establish whether the dark matter particle is its own anti-particle. I go on to discuss how limits on the diffuse and line spectra obtained from gamma ray telescopes can be used to constrain the annihilation modes of dark matter.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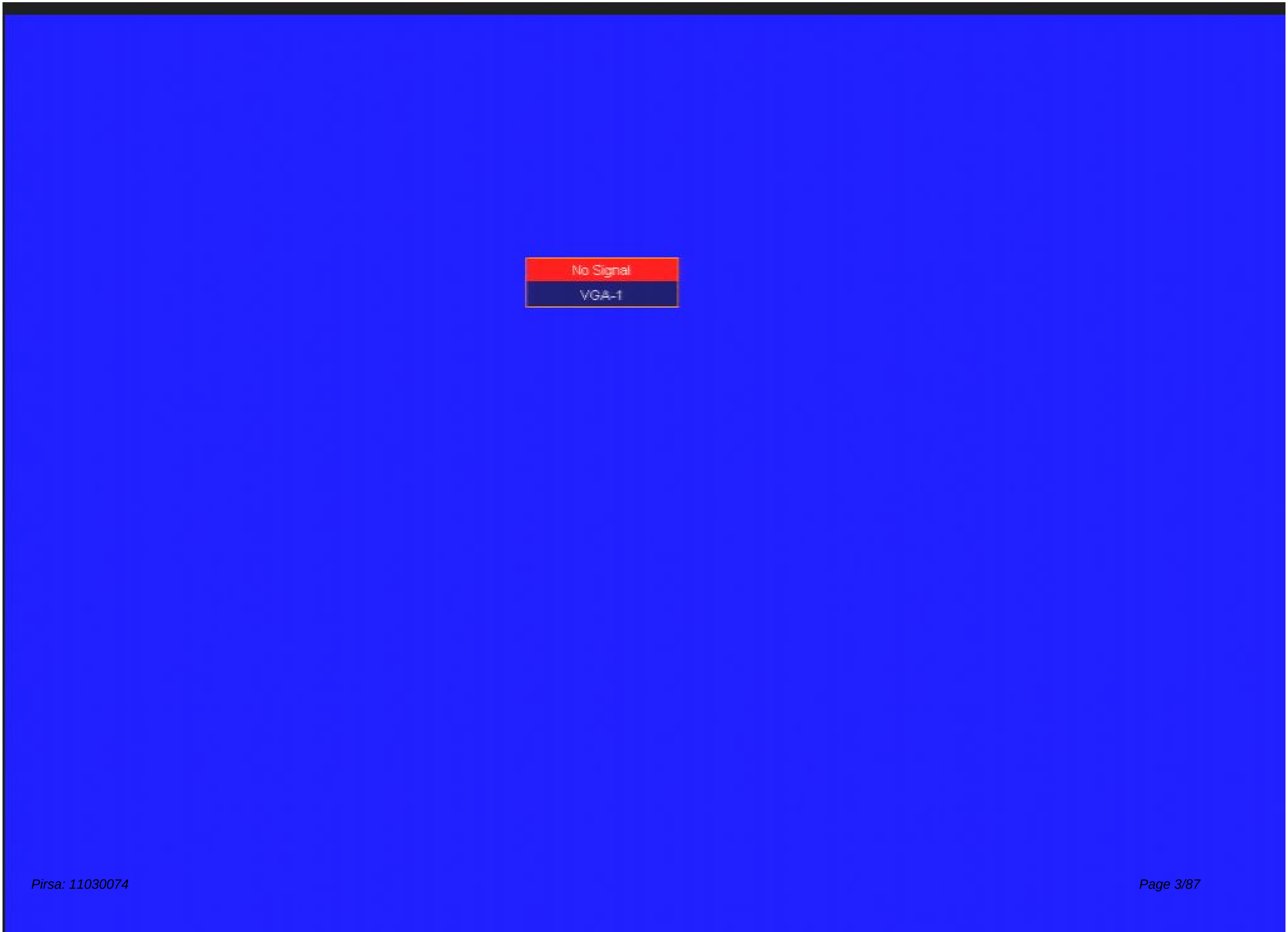
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A model-independent approach to WIMP dark matter

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K. Abazajian, P. Agrawal & C. Kilic

t is now well established from astrophysical and cosmological bservations that about 80% of the matter in the universe is made up f non-luminous, non-baryonic dark matter.

owever, the nature of the particles of which dark matter is composed emains a mystery.

Stable particles with masses of order the weak scale that have weak cale cross sections with visible matter naturally have the right relic bundance to explain observations - `the WIMP miracle'.

Since the WIMP dark matter framework is so robust, it naturally arises or can be accommodated in many different scenarios.

s a model-independent approach feasible?

To what extent is it possible to extract from experiment information about nature of WIMP dark matter independent of specific models?

Clearly, detailed predictions will not be possible.

Nevertheless, it may be possible to answer several of the most Important questions about the dark matter particle.

- What is the mass of the dark matter particle?
- What is its spin?
- Is the dark matter particle its own anti-particle? ←

Are there robust features common to large classes of models that could aid in the discovery of dark matter?

- Spectrum of photons from dark matter annihilation. ←

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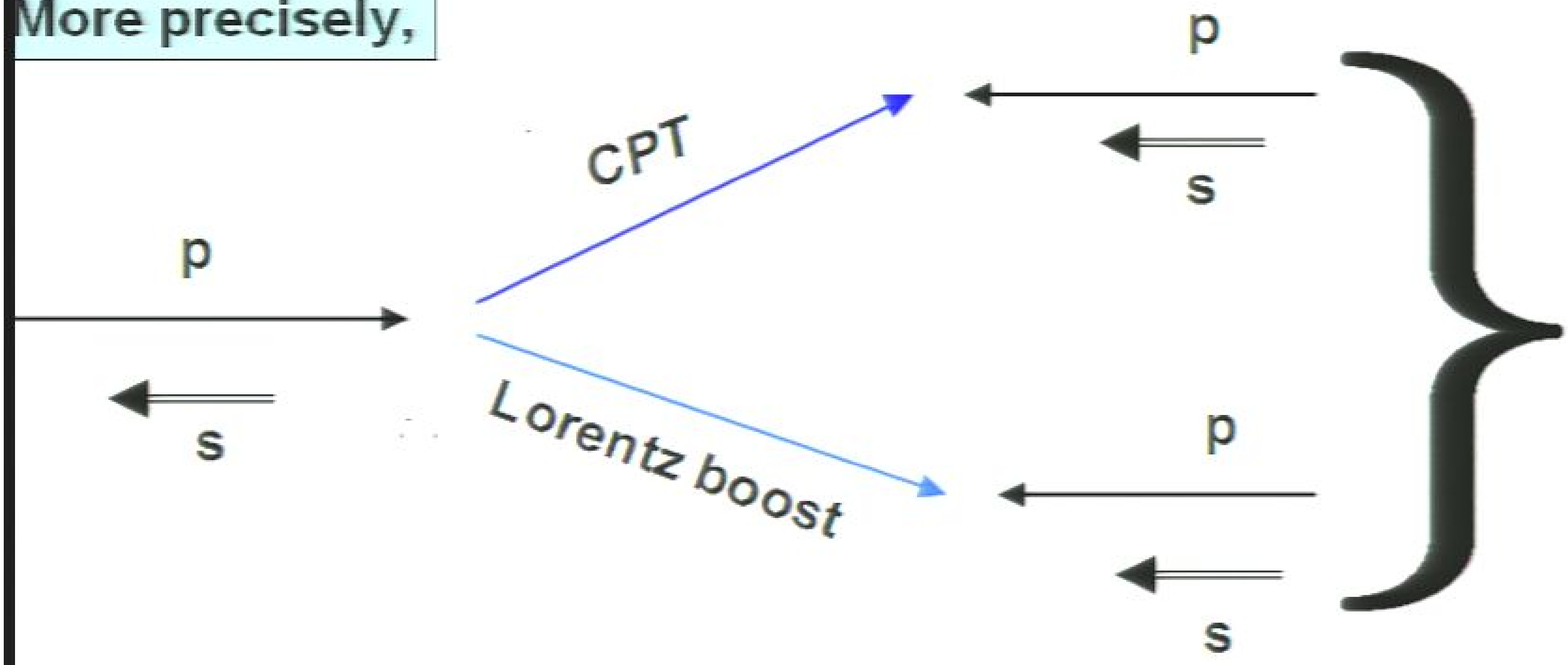
Let us formulate the problem.

According to the *CPT* theorem, for every particle there is an anti-particle with the same mass and spin, but opposite charge(s).

Since dark matter is electrically neutral, it is possible that the dark matter particle is its own anti-particle.

More precisely,



Are these the same?

To what extent can dark matter experiments address this question?

he logic is as follows.

will establish a very close association between theories where the VIMP-nucleon cross section is dominated by spin-dependent nteractions, and theories where the dark matter particle is its own nti-particle.

$$\sigma_{\mathrm{SD}} \gg \sigma_{\mathrm{SI}} \longrightarrow \chi = \chi^c$$

However $\chi = \chi^c \not\longrightarrow \sigma_{\mathrm{SD}} \gg \sigma_{\mathrm{SI}}$

The experiment that is most sensitive to spin-dependent dark matter is the IceCube neutrino telescope located at the South Pole. A signal could help establish the dark matter particle is its own anti-particle!

The problem is that IceCube is also sensitive to spin-independent interactions. Not possible to distinguish the origin of the signal.

However, I will then show that limits from direct detection expts. can be used to place a model-independent upper bound on the event

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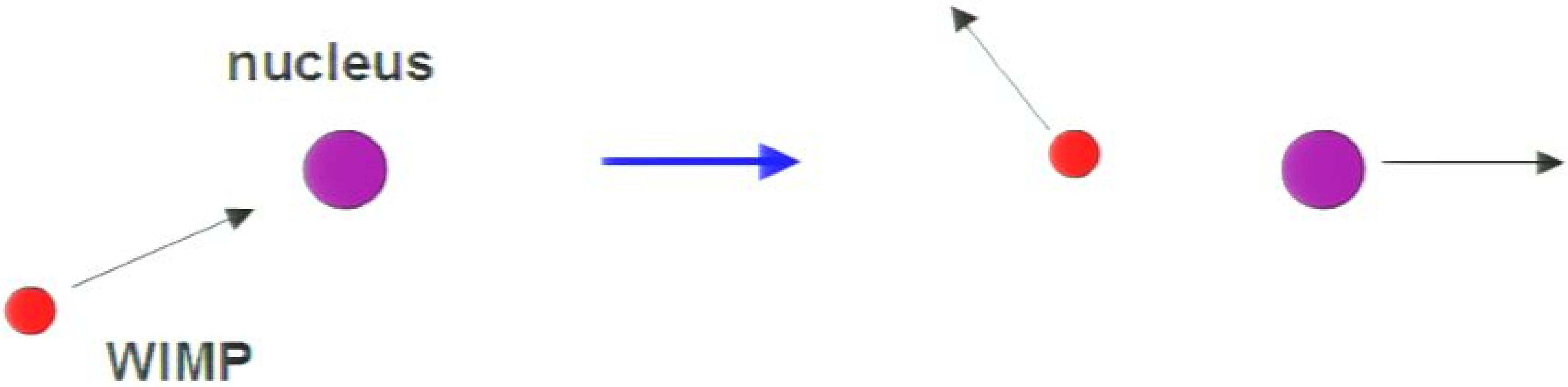
Spin-dependent dark matter candidates

irect detection experiments search for the recoil of a nucleus after he impact of a dark matter particle.



t present, they are able to place limits on the WIMP-nucleon cross ection as a function of the dark matter mass.

ince the de Broglie wavelength of the incident WIMP is larger than he typical nuclear scales, the WIMP sees nucleus as a single unit, vith a net charge, mass and spin.

In the non-relativistic limit, WIMP-nucleon interactions fall into two distinct categories.

If the WIMP interactions are sensitive to the spin of the nucleus, the corresponding cross section is `spin-dependent'. If not, the cross section is `spin-independent'.

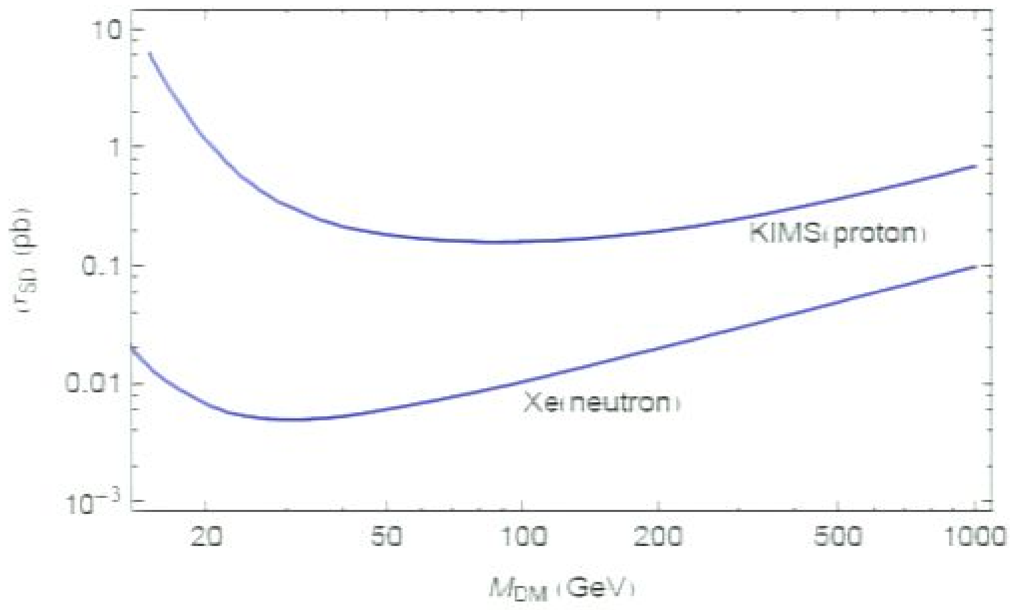
The direct detection bounds on spin-independent interactions are much tighter than the bounds on spin-dependent interactions. Why?

In the spin-independent case contributions from individual nucleons in the nucleus add coherently, leading to a large cross section.

$$\sigma_{\mathrm{SI}} \sim A^2$$

Spins of nucleons tend to cancel in pairs → no such enhancement in spin-dependent case.

SD →



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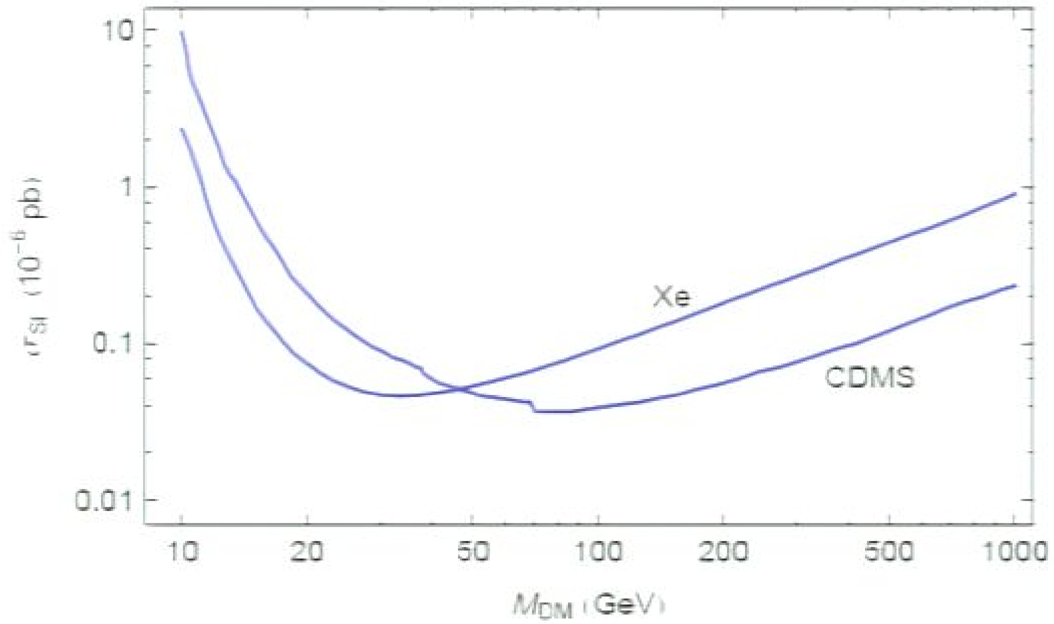

The limits on spin-independent interactions are stronger by about 10^6

Ve wish to classify theories which can naturally lead to primarily pin-dependent interactions with matter.

osmological limits constrain WIMP dark matter to be neutral under olor and electromagnetism.

imit to renormalizable theories where WIMP-nucleon scattering is lastic and arises from an effective operator generated by a tree iagram at parton level ➔ only WIMP-quark operators are relevant.

this class of theories WIMP-nucleon scattering is generated by perators of the general form

$$\frac{[\text{dark matter bilinear}]\ [\text{quark bilinear}]}{M^n}$$

ere M is the mass of the particle mediating the interaction, and n is ess than or equal to 2. In general the bilinears include derivatives

e cross section depends on the matrix element of the quark bilinear between clear states. Parity symmetry allows us to distinguish spin-dependent terms.

t *s* represent the spin of the nucleus and *v* the relative velocity of the WIMP-cleus system. While *s* is a pseudo-vector, *v* is a vector. Other parameters, ch as reduced mass and charge(s) are scalars.

calar

$$\bar{q}\; q$$

seudo-scalar

$$\bar{q}\gamma^5 q \sim \vec{s}.\vec{v}$$

ector

$$\begin{tikzcd} & \bar{q}\gamma^0 q \\ \bar{q}\gamma^\mu q \arrow[ur] \arrow[dr] & \\ & \bar{q}\gamma^i q \sim v^i \end{tikzcd}$$

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$$\begin{tikzcd} & \bar{q}\sigma^{0i} q \sim v^i \\ \bar{q}\sigma^{\mu\nu} q \arrow[ur] \arrow[dr] & \\ & \bar{q}\sigma^{ij} q \sim \epsilon^{ijk} s^k \end{tikzcd}$$

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calar WIMPs

Scalars always lead to spin-independent interactions.

ermionic WIMPs

There are two operators that can lead to scattering.

$$\bar{\chi}\gamma_\mu\gamma^5\chi\;\bar{q}\gamma^\mu\gamma^5 q \qquad \longrightarrow \qquad \text{SD}$$

$$\bar{\chi}\gamma_\mu\chi\;\bar{q}\gamma^\mu q \qquad \longrightarrow \qquad \text{SI}$$

For a Majorana fermion the second operator vanishes → scattering is spin-dependent. For Dirac case (in general) both operators contribute.

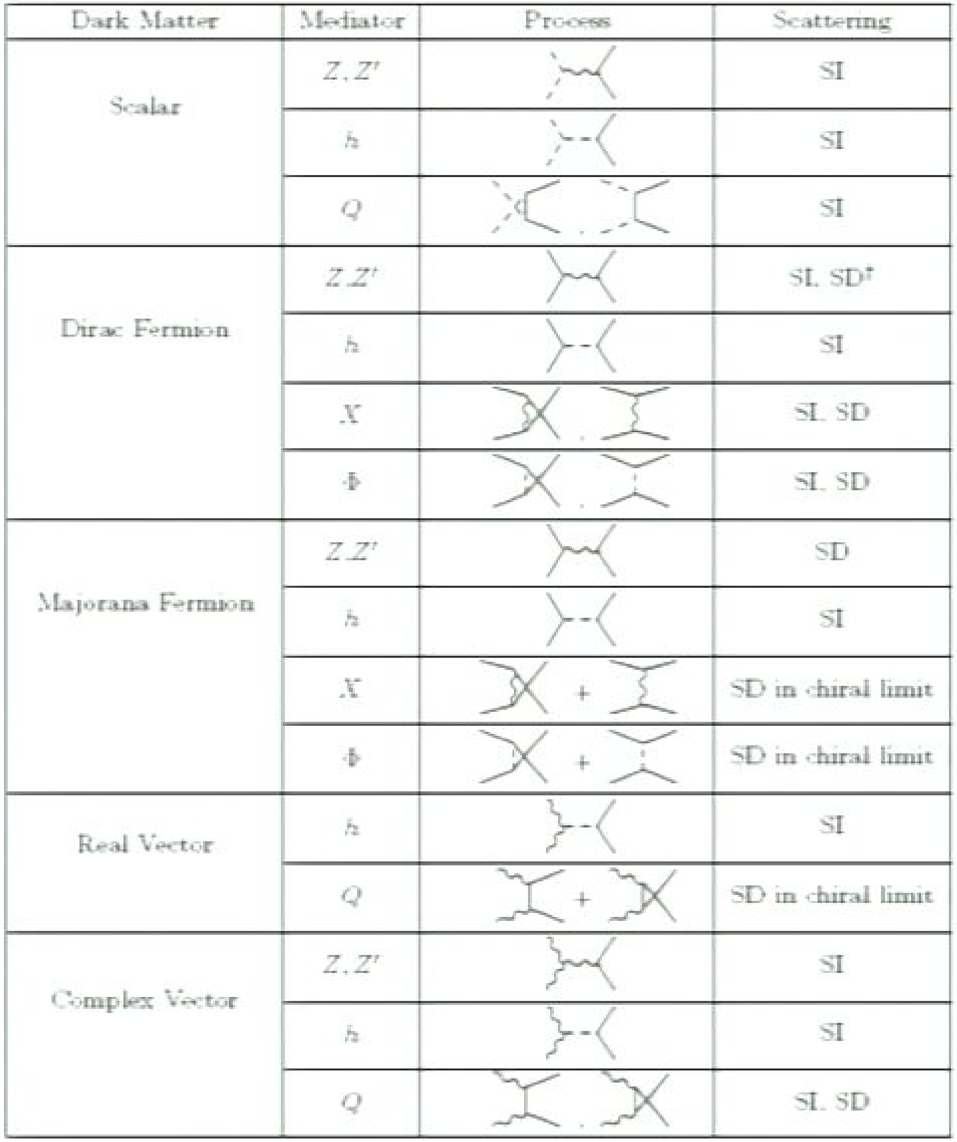
ector boson WIMPs

For real vector bosons only one operator contributes in chiral limit.

$$_{\mu\nu\lambda\sigma}\;\partial^\mu B^\nu B^\lambda\;\bar{q}\gamma^\sigma\gamma^5 q \qquad \longrightarrow \qquad \text{SD}$$

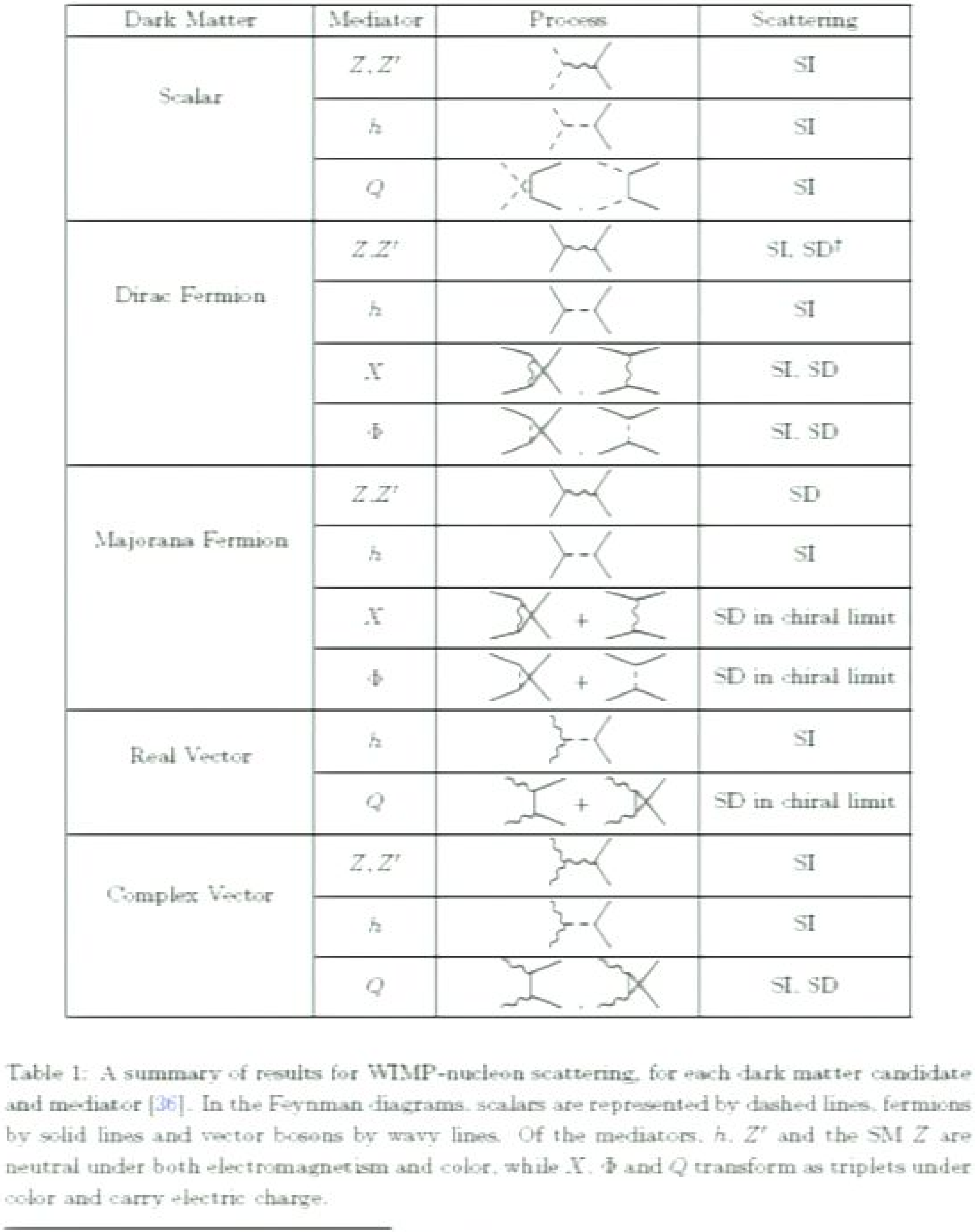
For complex vector bosons an additional operator contributes.

$$\partial_\nu B^*_\mu B^\nu \bar{q}\gamma^\mu q \qquad \longrightarrow \qquad \text{SI}$$



Dark Matter	Mediator	Process	Scattering
Scalar	Z, Z'		SI
	h		SI
	Q	,	SI
Dirac Fermion	Z, Z'		SI, SD†
	h		SI
	X	,	SI, SD
	Φ	,	SI, SD
Majorana Fermion	Z, Z'		SD
	h		SI
	X	+	SD in chiral limit
	Φ	+	SD in chiral limit
Real Vector	h		SI
	Q	+	SD in chiral limit
Complex Vector	Z, Z'		SI
	h		SI
	Q	,	SI, SD

Table 1: A summary of results for WIMP-nucleon scattering, for each dark matter candidate and mediator [36]. In the Feynman diagrams, scalars are represented by dashed lines, fermions by solid lines and vector bosons by wavy lines. Of the mediators, h, Z' and the SM Z are neutral under both electromagnetism and color, while X, Φ and Q transform as triplets under color and carry electric charge.



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the case of Dirac fermion dark matter, with scattering mediated by channel vector exchange (Z' exchange), there is one specific choice Z' charges which leads to purely spin-dependent scattering.

$Z.Z'$		SI. SD†

'an be primarily SD for specific choices of Z' charges

s there a symmetry understanding of this?

the Dirac fermion dark matter theory possesses a $\chi \leftrightarrow \chi^c$

ymmetry under which all the SM fields are invariant, the operator

$\gamma_\mu\chi\ \bar{q}\gamma^\mu q$ vanishes.

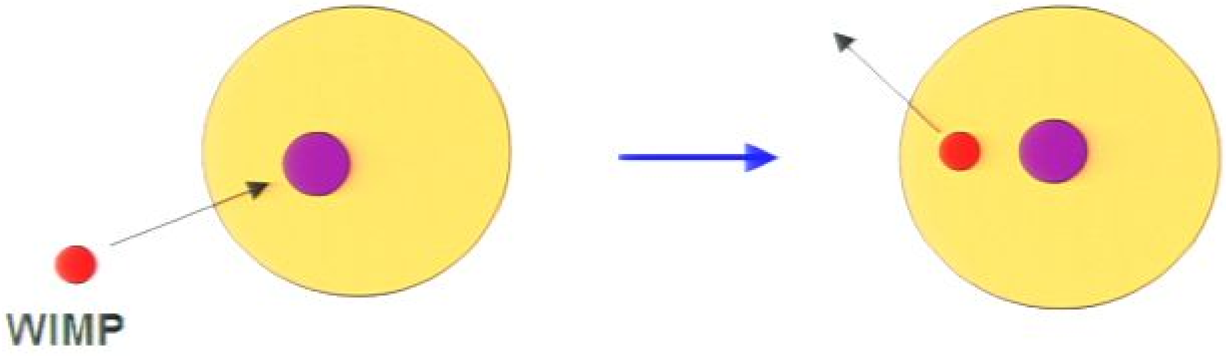
here exists a set of Z' charges for which this symmetry is realized. lowever, a Z' in the relevant mass range is disfavored.

or the other mediators, no simple realization of this symmetry exists.

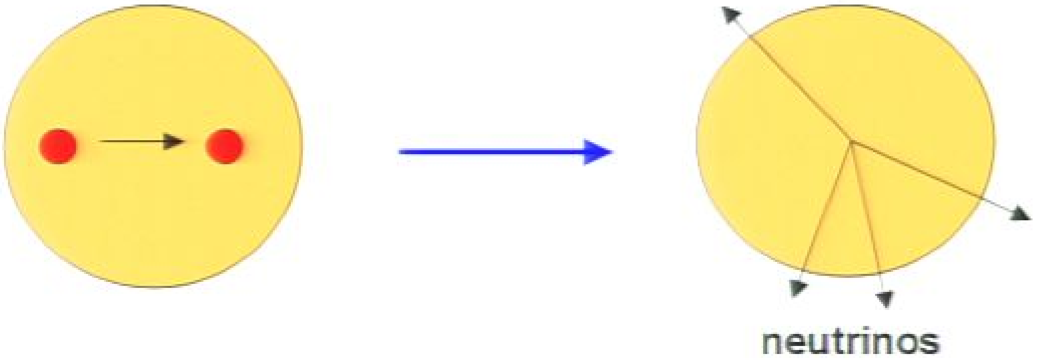
Limits on dark matter event rates in IceCube

eutrino telescopes are searching for neutrinos arising from dark
atter annihilation in the sun (and earth).

ark matter particles collide with nuclei in the sun, thereby losing
ergy. As a consequence they become gravitationally bound.



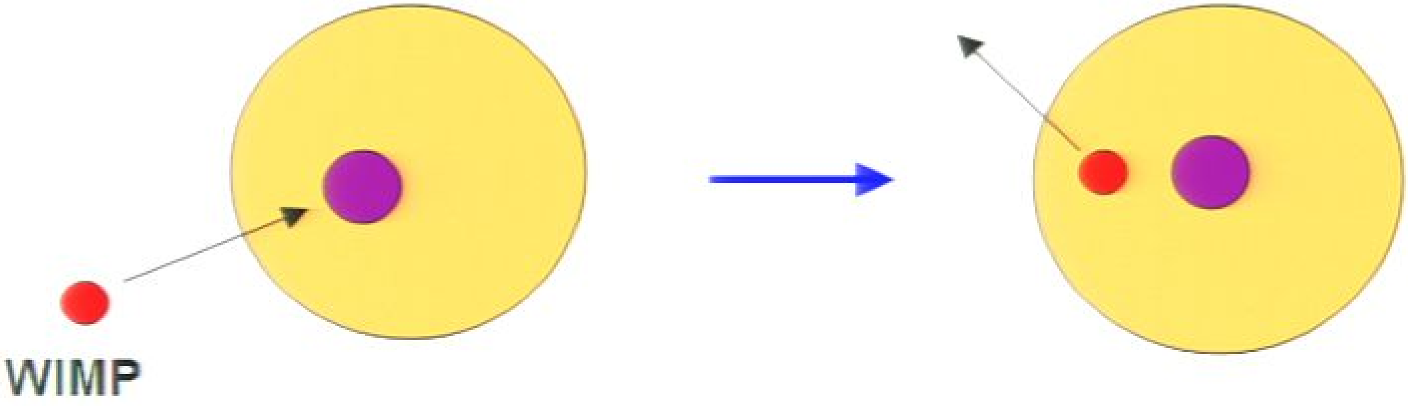
fter subsequent scatterings, accumulate in the core of the sun. Can
en pair annihilate, giving rise to neutrinos.



hese neutrinos can give rise to a signal in neutrino telescopes.

The limits from direct detection experiments can be used to place a model-independent bound on the dark matter event rate in IceCube.

How? Capture in the sun occurs through WIMP-nucleon scattering, which is bounded by direct detection experiments. The direct detection limit translates into a bound on the WIMP capture rate.



The annihilation rate can at most be equal to half the capture rate. The imit on the capture rate is then also a limit on the annihilation rate.

For a fixed dark matter mass and annihilation into the most neutrino ich final state, leads to an upper limit on the total neutrino event rate.

For spin-independent interactions, this limit is comparable to current eCube bound.

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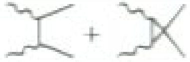
	Q		SD in chiral limit
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	Q		SI, SD

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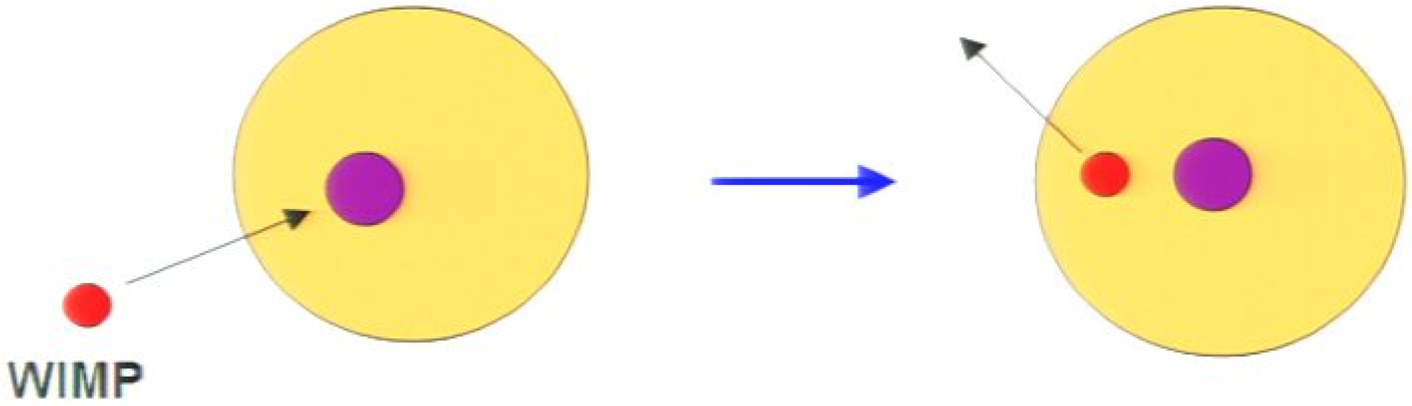

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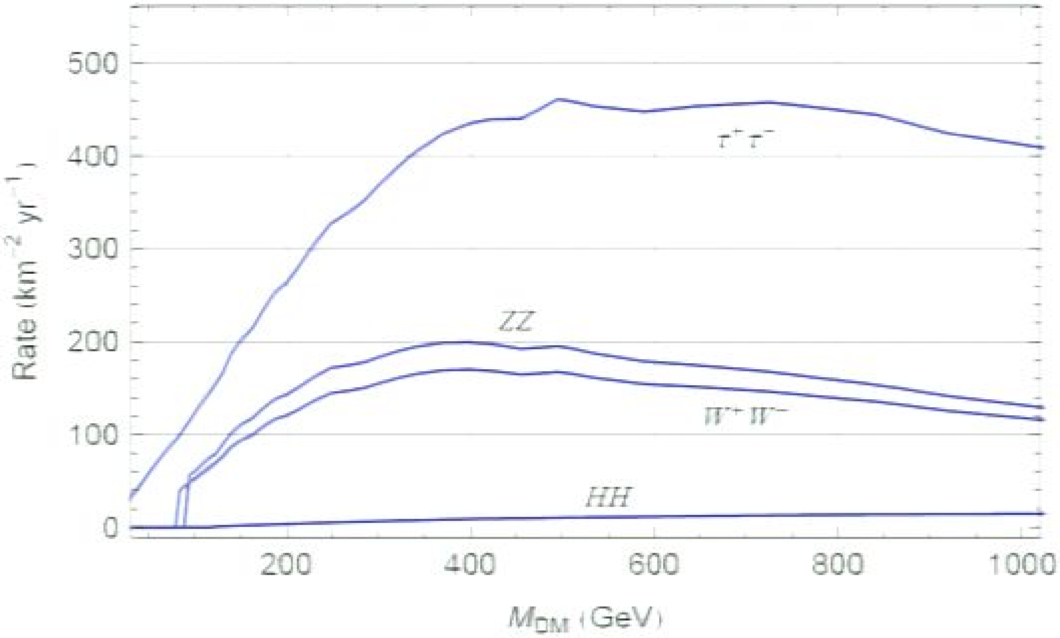
500
400
300
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100
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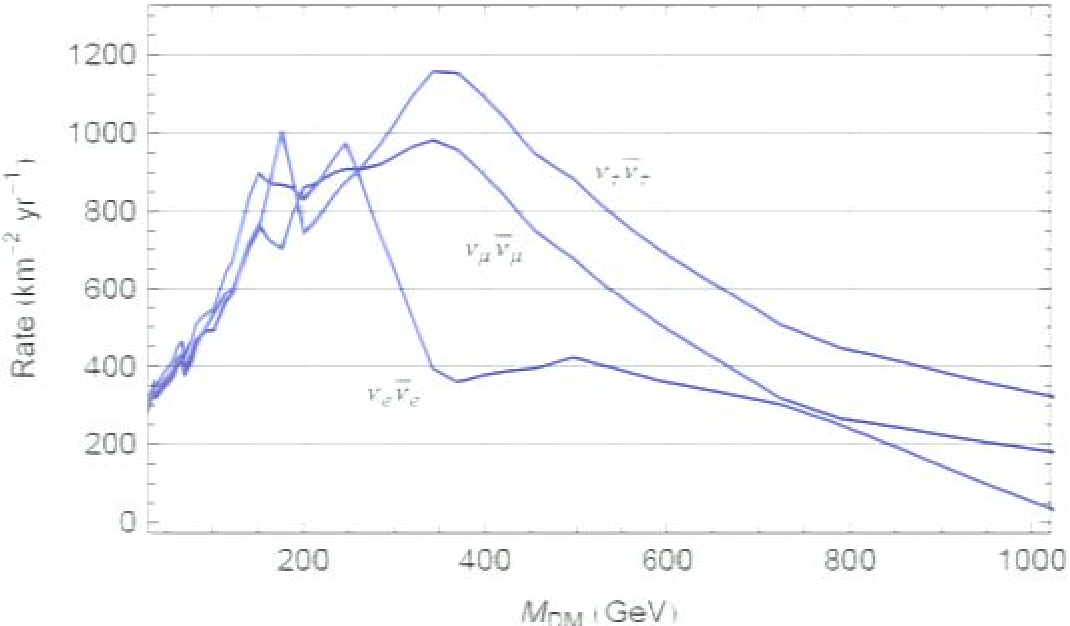
Rate (km^{-2} yr^{-1})
200
400
600
800
1000
M_{DM} (GeV)
$\tau^+\tau^-$
ZZ
W^+W^-
HH


1200
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200
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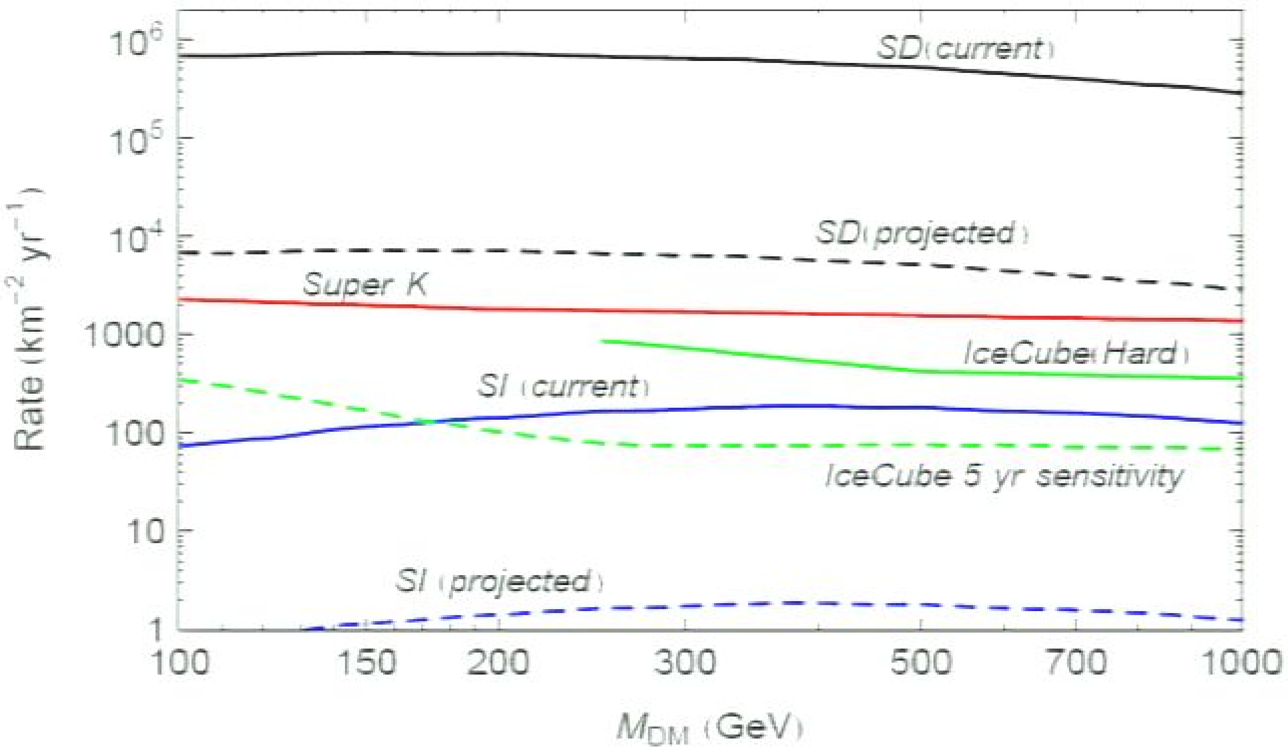


pin-independent interactions could still be responsible for generating signal at IceCube close to the current experimental bound, if nnihilation is directly to neutrino rich final states. But . . .

he limits from direct detection on spin-independent interactions are xpected to improve by two orders of magnitude in the near future.

t that point, any observed signal at IceCube must be arising from pin-dependent interactions ➔ a strong hint that the dark matter article is its own anti-particle

Assumptions that do not affect the result:

Only studied 2-body final states. Multi-body final states lead to even smaller signal → for fixed dark matter mass neutrino energy is less.

Ignored possible annihilation to new non-SM final states. Event rate is less than for annihilation directly to neutrinos.

Ignored possible Sommerfeld enhancement of the annihilation rate, since bound depends only on the capture rate.

Assumed specific value for halo density. Affects direct detection and capture rate in the same way → factors out.

Assumptions that could affect the result:

Assumed dark matter is elastic.

Assumed a specific distribution of dark matter velocities.

Did NOT assume the WIMP was a thermal relic.

Conclusions (1)

he dark matter candidates that can naturally lead to primarily spin-ependent interactions with matter are Majorana fermions and real ector bosons, so that the dark matter particle is its own anti-particle.

$$\sigma_{SD} \gg \sigma_{SI} \longrightarrow \chi = \chi^c$$

However $\chi = \chi^c \not\longrightarrow \sigma_{SD} \gg \sigma_{SI}$

IceCube is currently sensitive to both spin-independent as well as spin-dependent dark matter candidates.

If the direct detection bounds continue to improve, the case of spin-independent dark matter will soon go out of reach of IceCube.

In such a scenario, a signal at IceCube would constitute a strong hint that the dark matter particle has spin, and is its own anti-particle.

The region of parameter space where IceCube can expect a signal from spin-dependent dark matter is kinematically accessible to LHC

The photon spectrum from dark matter annihilation

he dark matter annihilation products will in general include photons. he photon spectrum typically includes both a diffuse and a onochromatic (line) component.

renormalizable theories dark matter cannot annihilate directly into hotons at tree level.

The diffuse spectrum arises in two ways.

- Decays of the primary annihilation products.
- Final state radiation off the primary annihilation products.

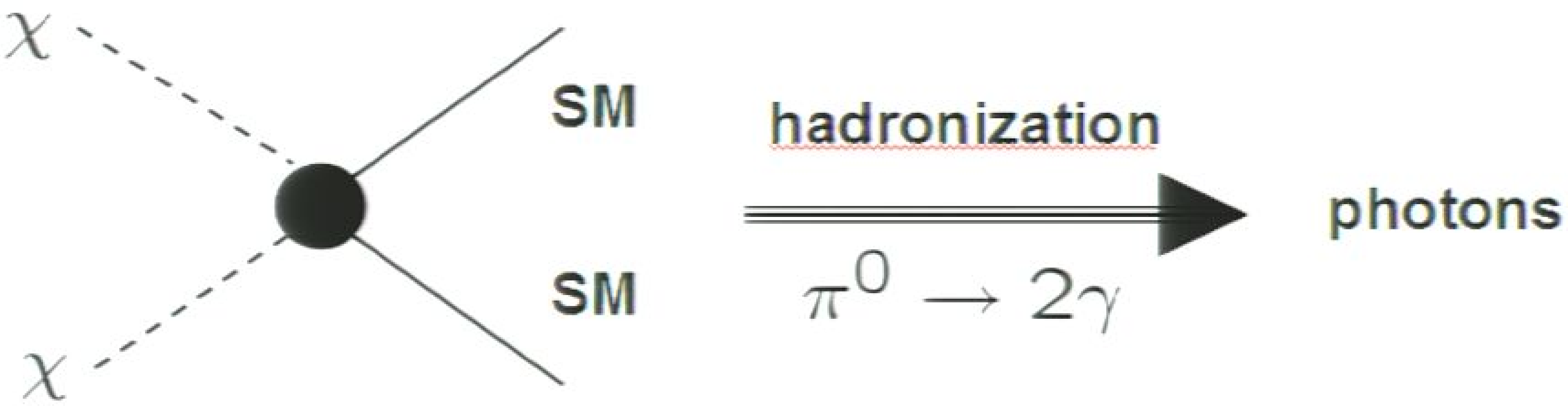
The diffuse spectrum has many model independent features which make it useful for constraining dark matter.

he line spectrum arises from annihilation of dark matter into the two hoton, photon + *Z* and photon + Higgs final states at loop level.

In general the line spectrum is much more model dependent.

Diffuse Photon Spectrum

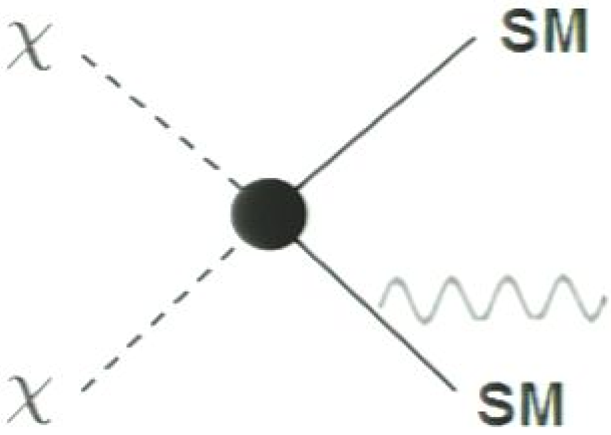
For all 2 body SM final states except electrons and muons, spectrum of diffuse photons is dominated by gamma rays arising from decays of primary (or secondary) annihilation products after hadronization.



The resulting photon spectrum is independent of the dark matter spin or form of couplings. Depends only on dark matter mass, and (to a more limited extent) on the SM final states.

Therefore this can be used to place a robust bound on annihilation nto various 2 body SM final states.

For dark matter annihilation to electrons and muons, the resulting photon spectrum is generally dominated by final state radiation.

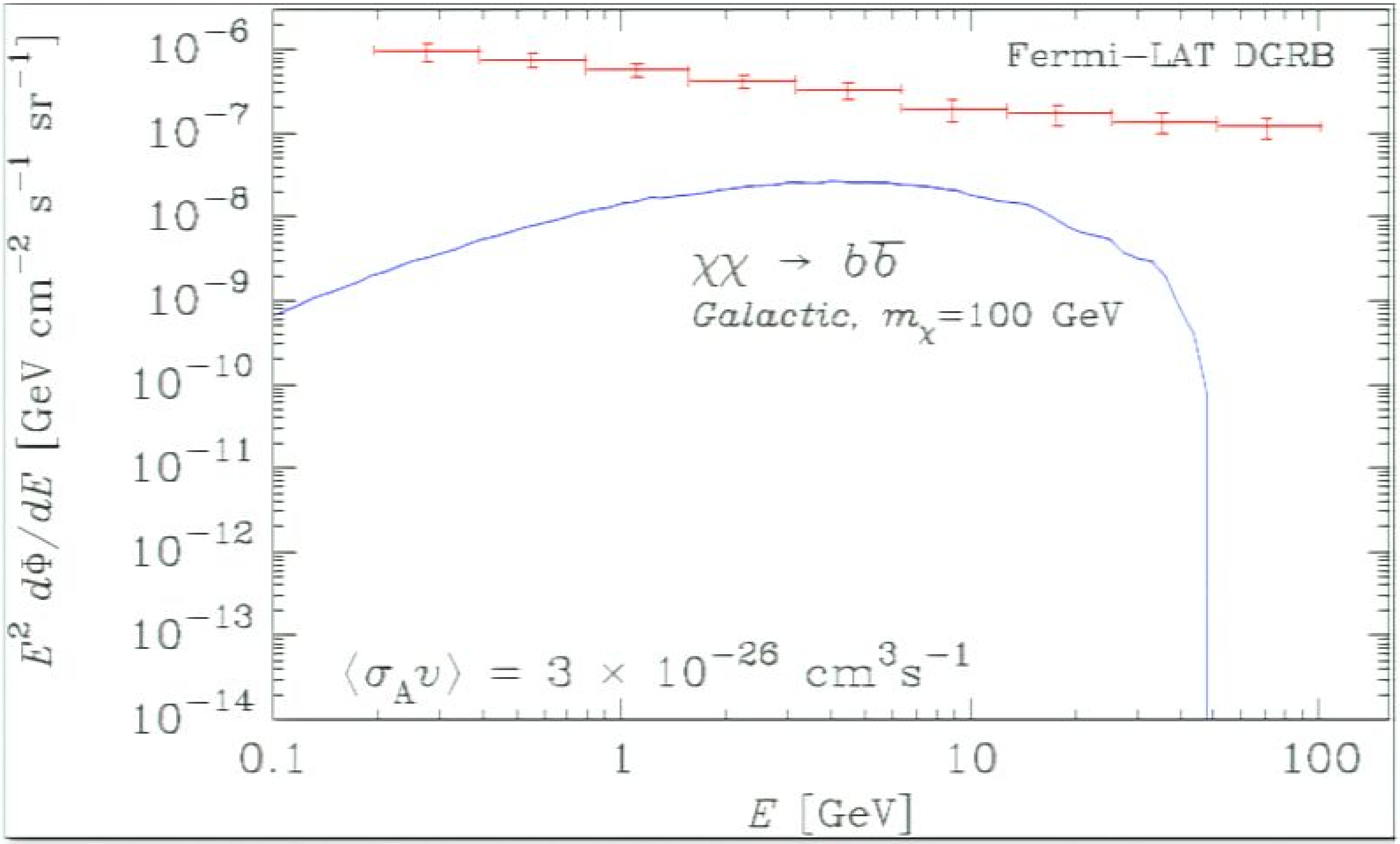


Final state radiation is generally dominated by collinear emission!

Spectrum arising from final state radiation is then independent of dark matter spin and couplings. Depends only on dark matter mass, and spin and mass of final state.

→ Leads to a robust bound on annihilation into leptonic final states.

For dark matter masses above 100 GeV, photons arising from inverse Compton scattering of the final state electrons and muons from the CMB and starlight are also important.



Fermi−LAT DGRB
$\chi\chi \rightarrow b\bar{b}$
Galactic, m_χ=100 GeV
$\langle \sigma_A v \rangle = 3 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$
$E^2\ d\Phi/dE$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
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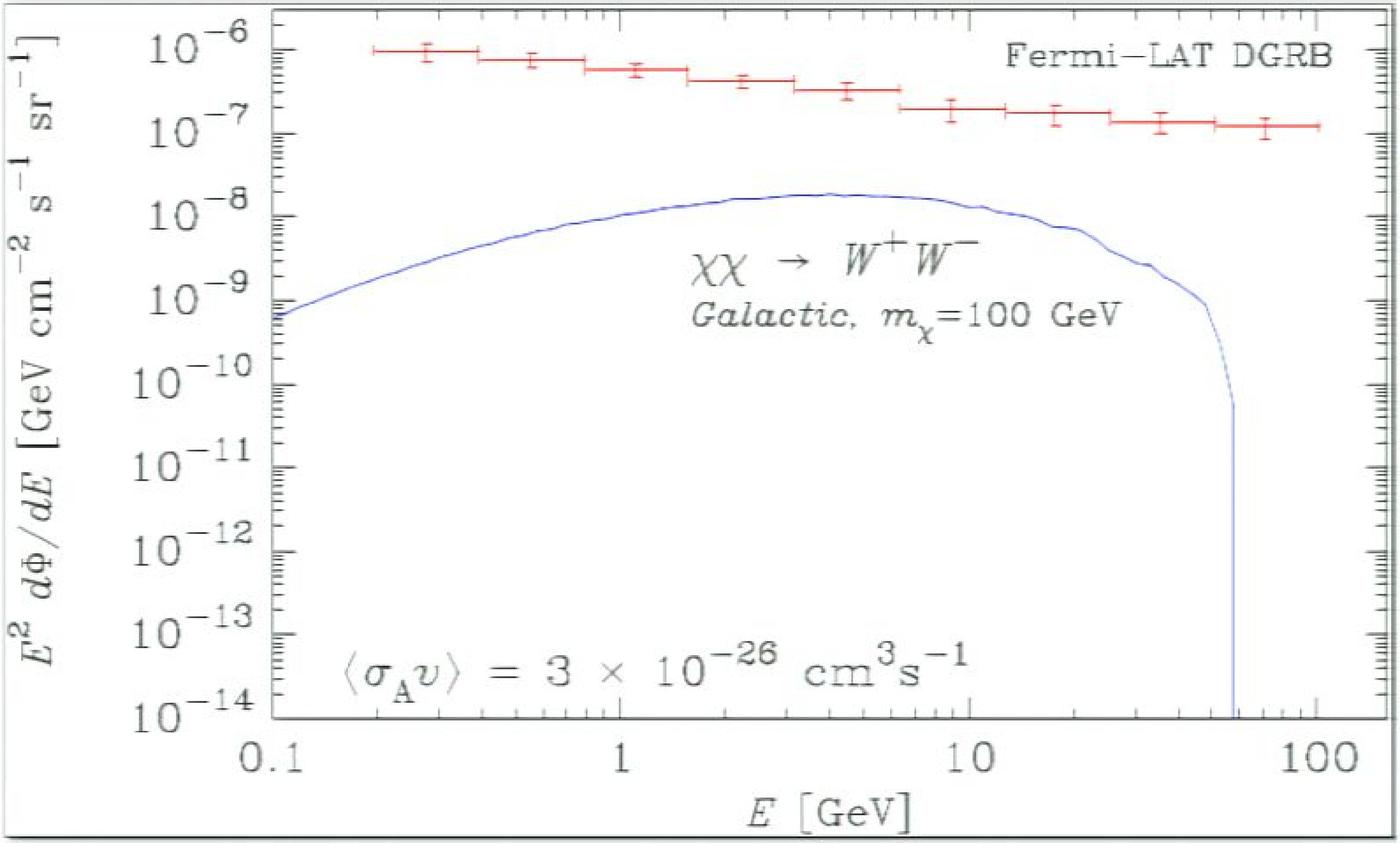
Fermi−LAT DGRB
$\chi\chi \rightarrow W^+W^-$
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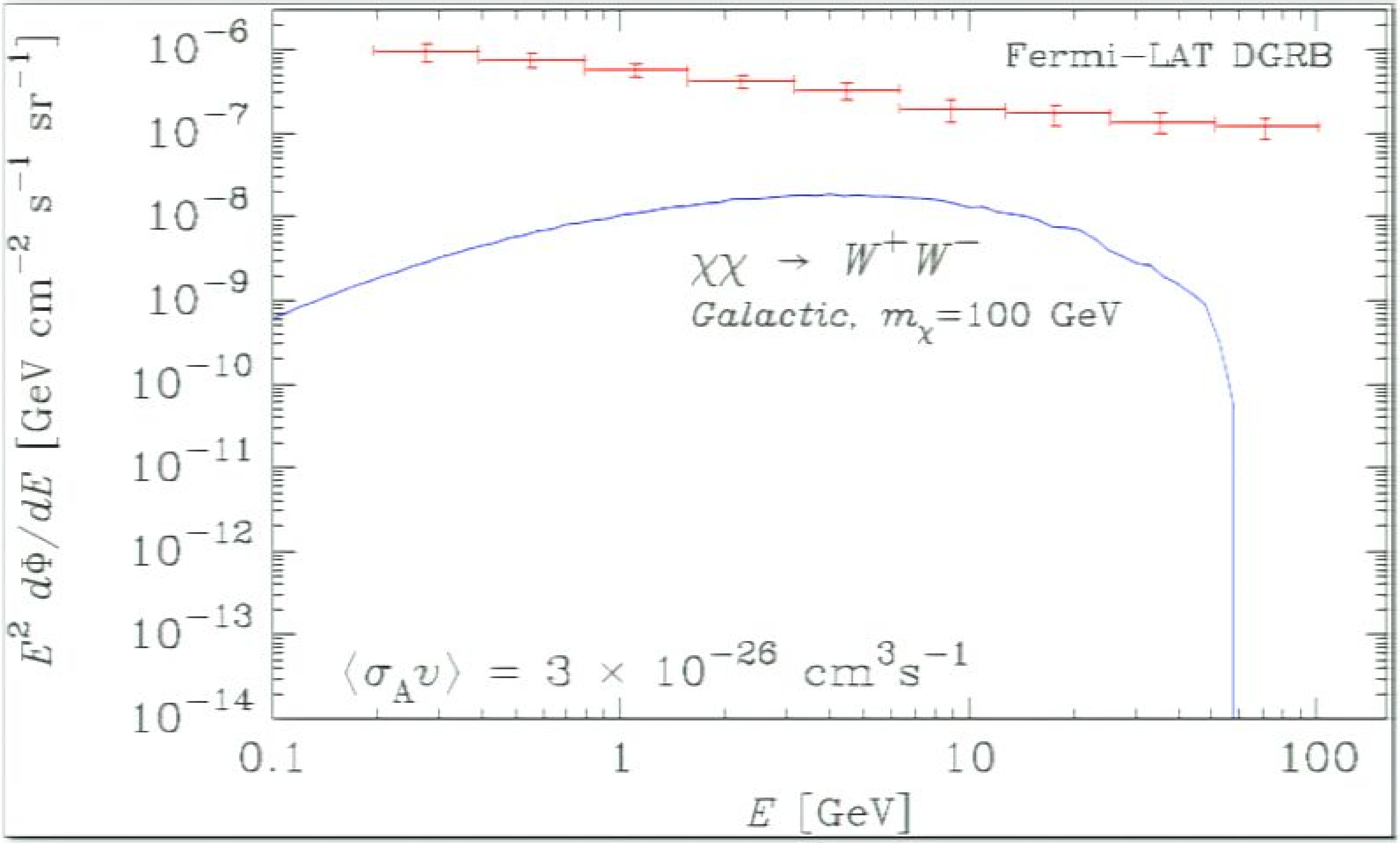
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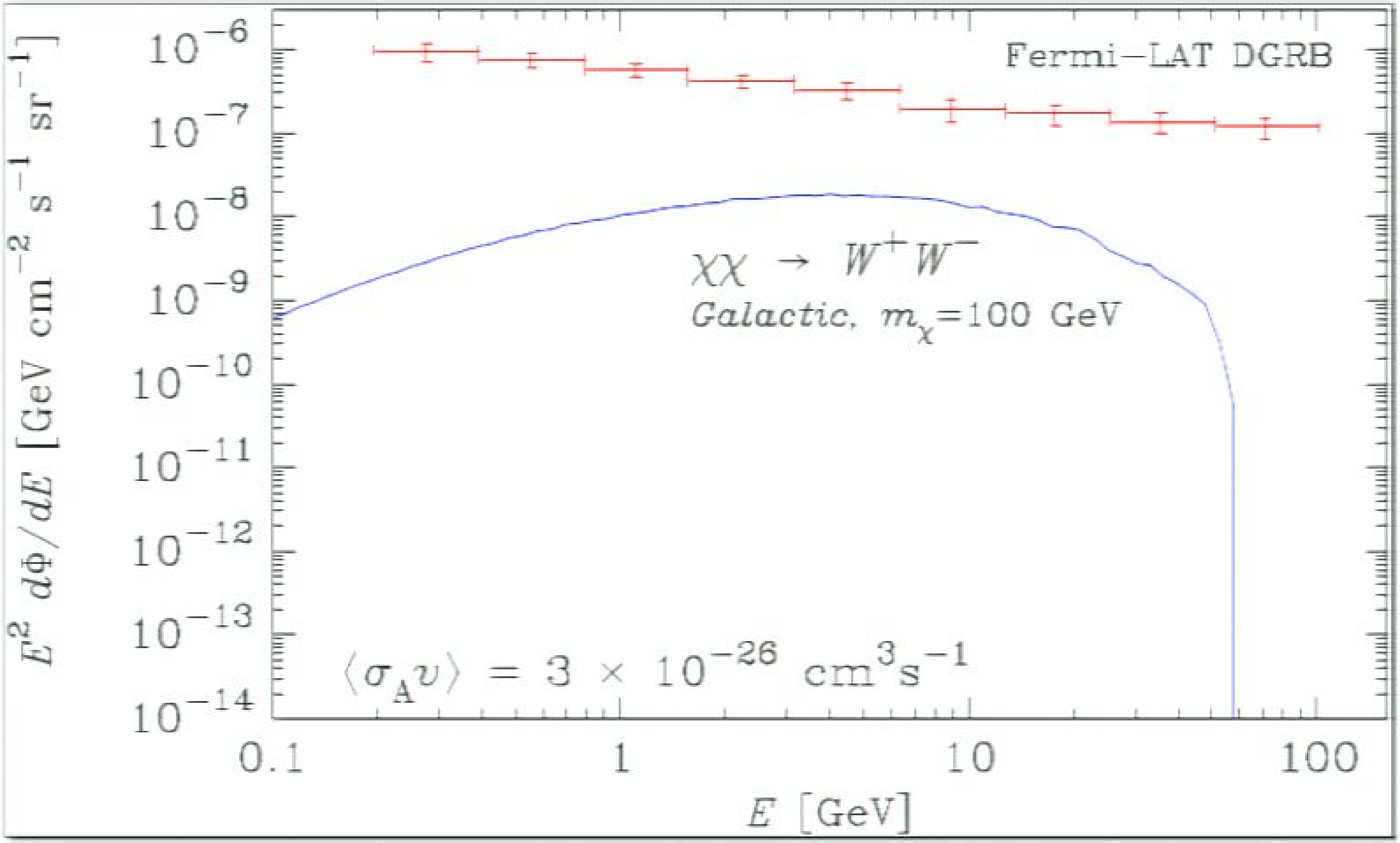
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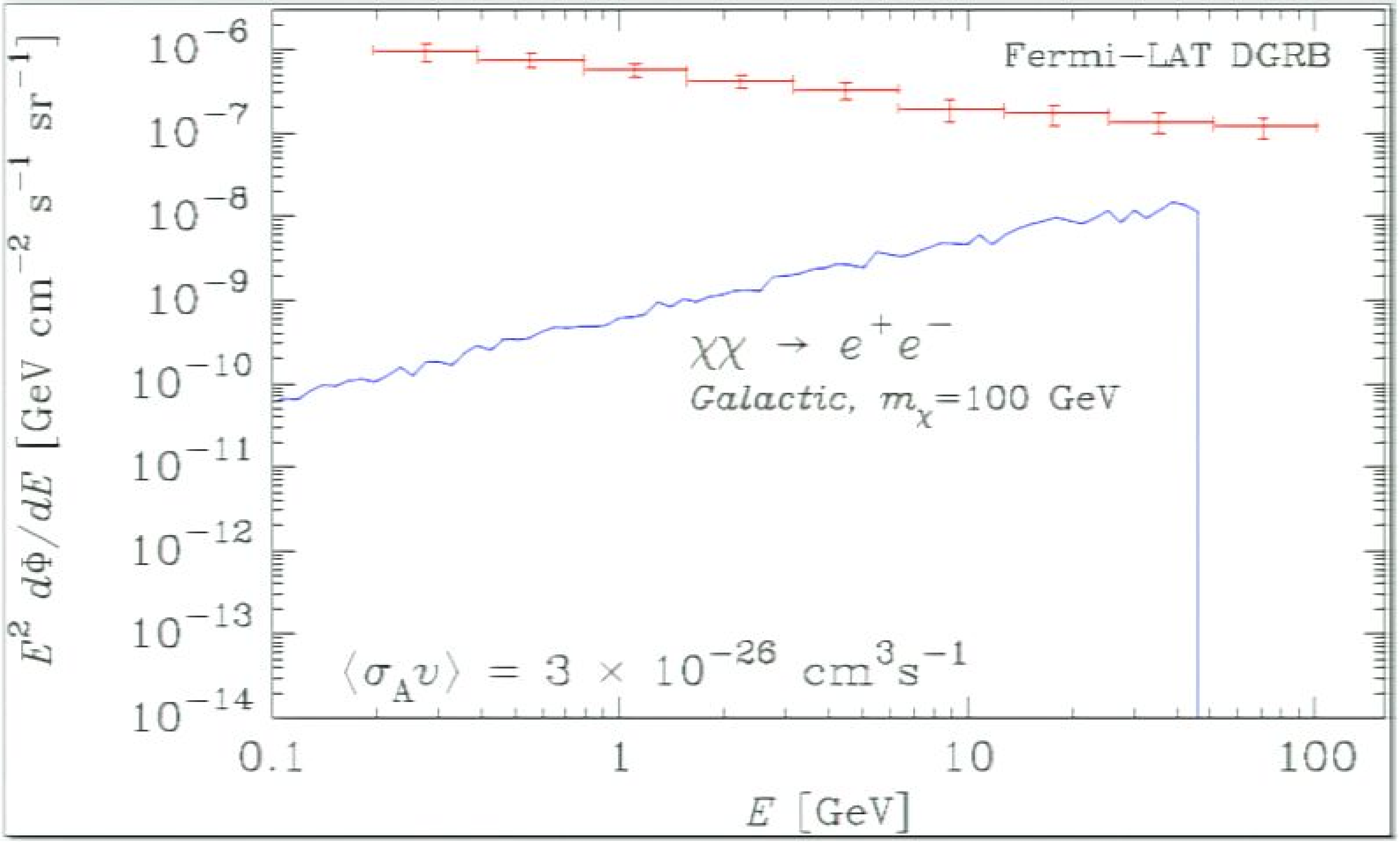
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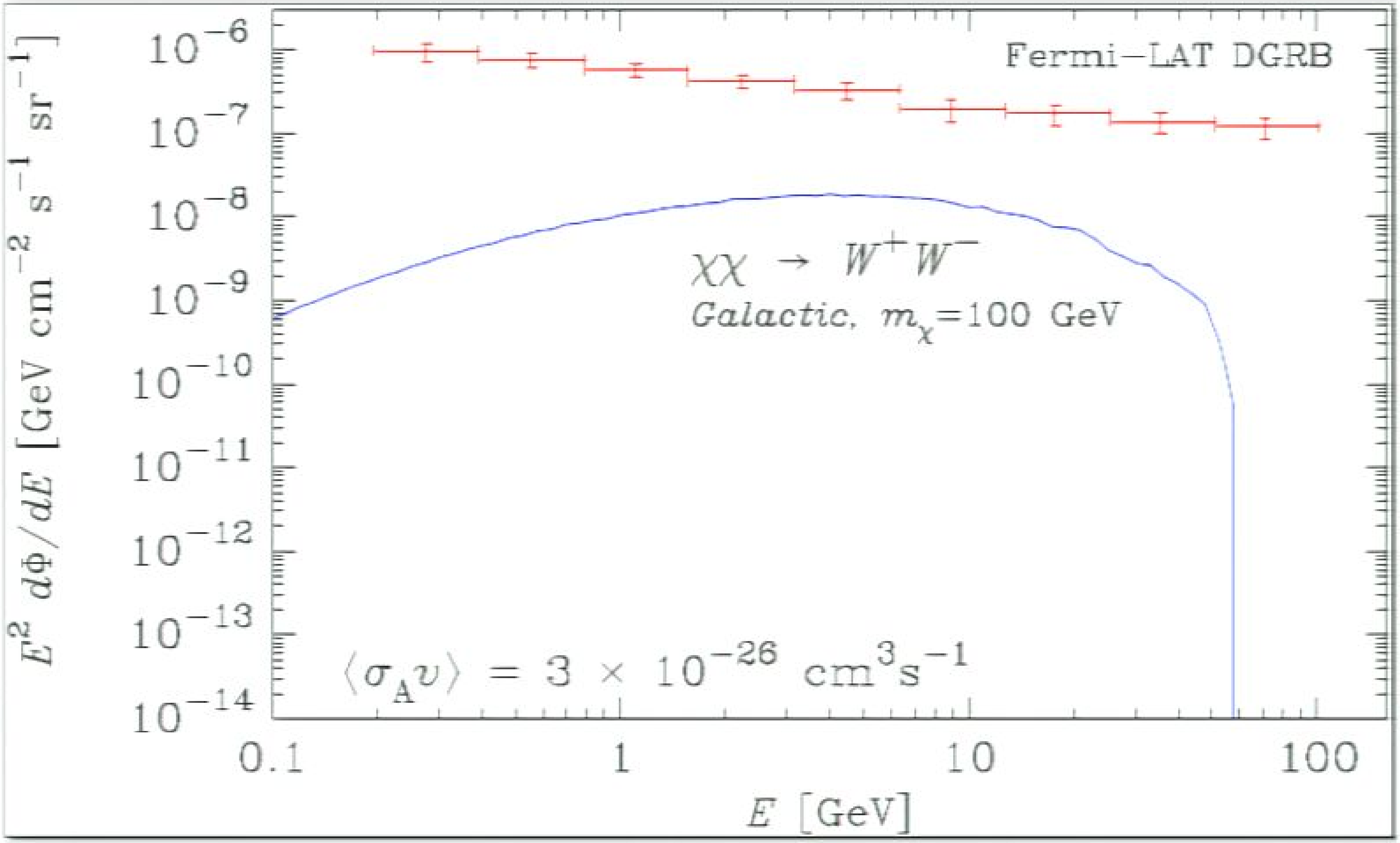
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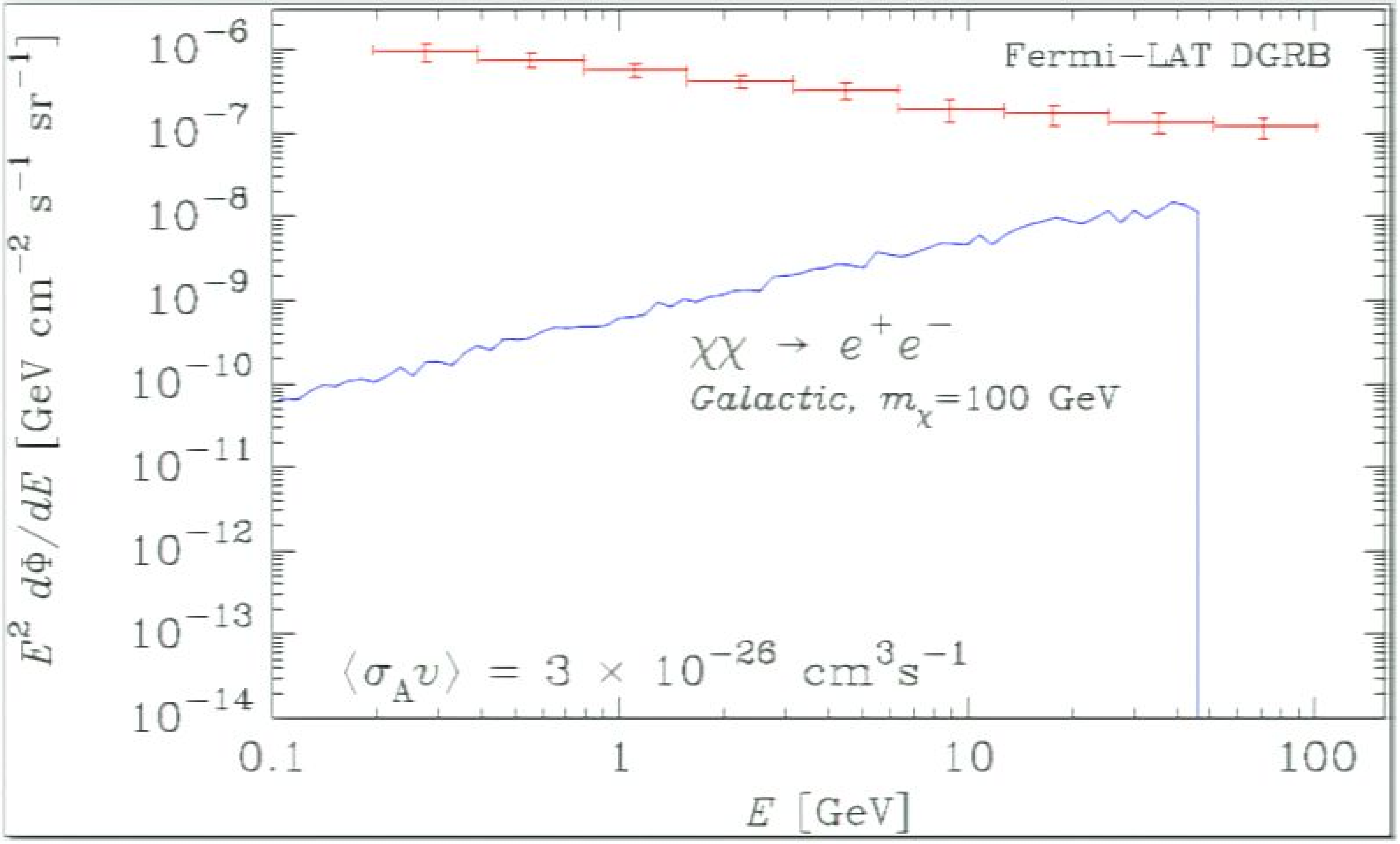
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urrently, the most sensitive gamma ray telescopes are Fermi (at nergies up to few hundred GeV) and Hess (at even higher energies).

ermi is a satellite experiment. Fermi's greatest sensitivity to dark atter is from measurements of the diffuse isotropic gamma ray flux.

ess is ground based, and measures the flux from close to galactic enter.

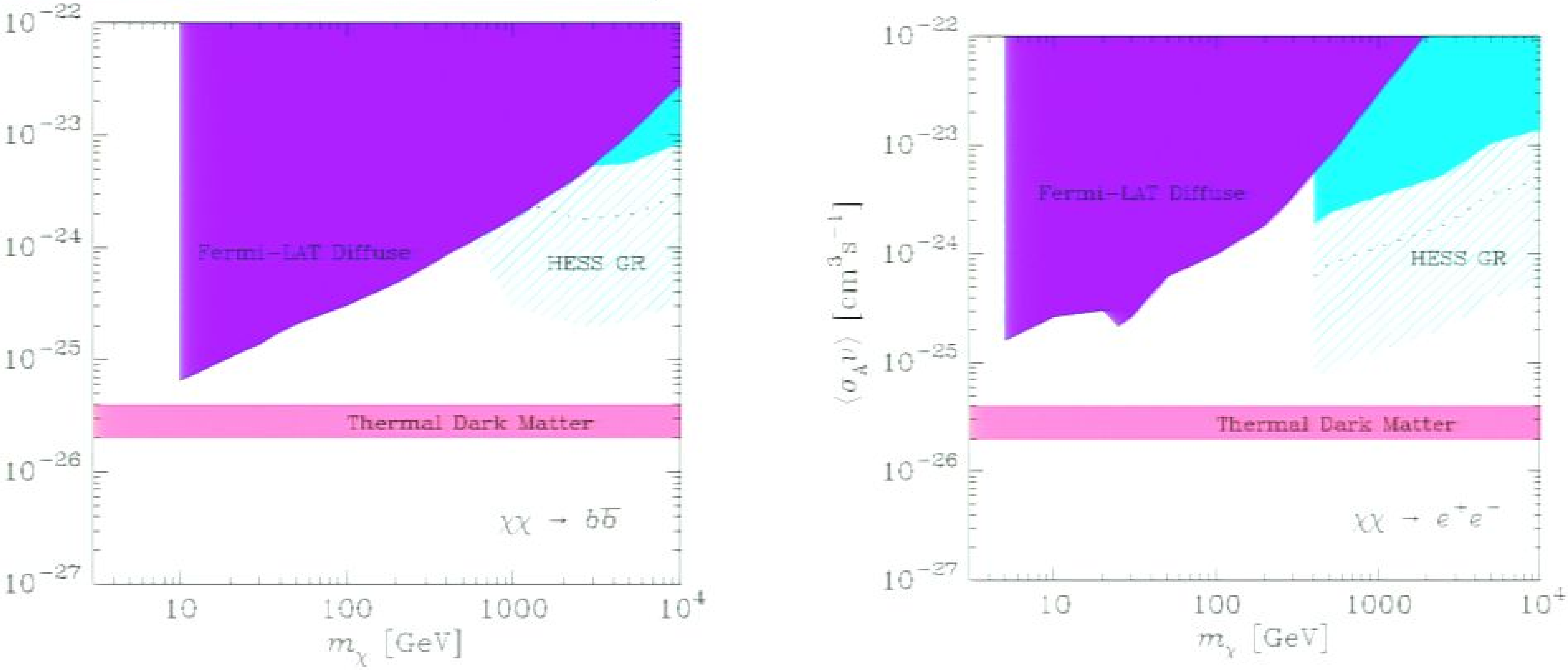
urrently no excess is seen, and so only limits can be placed.

he strength of the limit depends on the dark matter density profiles lose to the centers of galaxies.

or conservative assumptions about dark matter halos, the dark atter contribution to the isotropic gamma ray flux is dominated by ur own galaxy (not by the extra-galactic contribution)!

his allows conservative limits to be placed that are insensitive to the xact form of dark matter profile close to the galactic center.

Vhat do the limits look like?



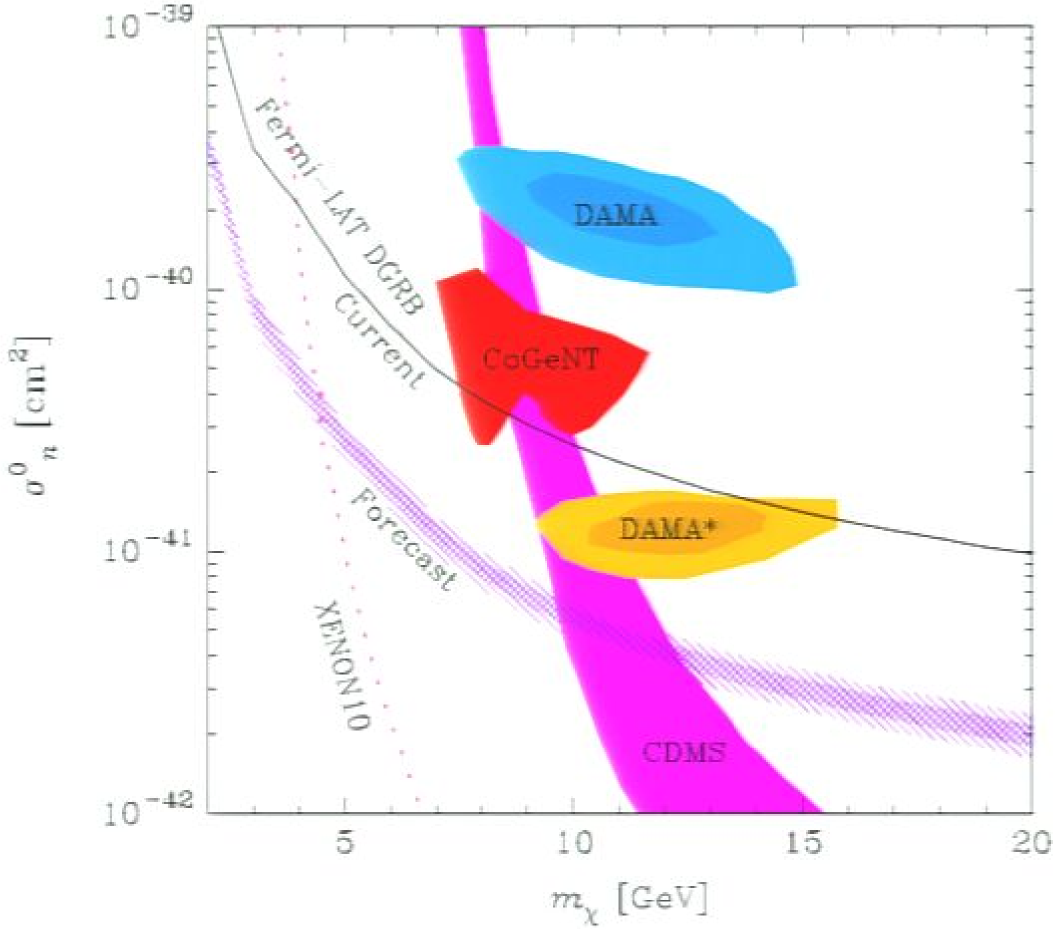
In obtaining the HESS limit a conservative Einasto profile was used.

In obtaining the FERMI limit a boost factor of 7 was assumed, to incorporate clumping. (Expected to be 20→1000).

The current limits are not quite sensitive to thermal dark matter except in the light mass range ~ few GeV. Improving these bounds

owever, gamma rays can already constrain certain models.

he model with a light scalar singlet has been invoked to explain AMA/CoGeNT/CDMS.



onstrained by gamma ray data. Can potentially be excluded.

Abazajian

Line Spectrum

Strengths of gamma ray lines tend to be highly model-dependent.

- Depend on the detailed form of the matrix element.
- Are sensitive to new physics running in the loop, not just the annihilation products. New physics often dominates.

For a given dark matter mass and spin, it is possible to use unitarity
elations to place robust lower bounds on the strengths of gamma ray
ines relative to diffuse photon spectrum if annihilation is primarily to
a single SM final state.

f annihilation is to multiple SM final states, limits are approximate.

Will focus on theories where diffuse gamma rays are produced at tree
evel from annihilation into SM states, and monochromatic gamma
ays arise at one loop. Both SM and new physics may run in the loop.

Limit to gamma-gamma annihilation.

rom unitarity,

$$S^{\dagger}S = 1$$

$$-i\left(T - T^{\dagger}\right) = T^{\dagger}\,T$$

Ve work in the angular momentum basis in the center of mass frame. hen any two body state is specified by the total energy, angular omentum quantum numbers *J, M, L* and *S*, and internal quantum umbers of the two particles.

Take matrix element between two photon final state | f $\rangle$ and initial state | i $\rangle$ consisting of two dark matter particles.

$$-i\langle f|(T - T^{\dagger})|i\rangle = \sum_{X} \langle f|T^{\dagger}|X\rangle\langle X|T|i\rangle$$

The sum is over all final states that the two dark matter particles can annihilate into. Since *J* and *M* and total energy are conserved, the sum is over *L, S,* and internal quantum numbers.

If the process respects time reversal invariance (*CP*), then

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

Now, if annihilation is primarily to a single SM final state, and furthermore this state is characterized by fixed *L* and *S*, then

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

This leads to a lower bound on the cross section to two photons.

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

DM cross section to two photons

phase space factor

DM cross section to SM

SM cross section

The dark matter cross section to SM is correlated with the diffuse spectrum → a lower bound on line strength relative to continuum rom unitarity,

$$S^\dagger S = 1$$

$$-\,i\left(T - T^\dagger\right) = T^\dagger\, T$$

Ve work in the angular momentum basis in the center of mass frame. hen any two body state is specified by the total energy, angular omentum quantum numbers *J, M, L* and *S*, and internal quantum umbers of the two particles.

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This leads to a lower bound on the cross section to two photons.

$$\underset{\substack{\uparrow\\ \text{DM cross section}\\ \text{to two photons}}}{\sigma(\chi\,\chi\to\gamma\,\gamma)} \geq \underset{\substack{\uparrow\\ \text{phase space}\\ \text{factor}}}{\rho}\, \underset{\substack{\uparrow\\ \text{DM cross section}\\ \text{to SM}}}{\sigma(\chi\chi\to X\,\bar{X})}\, \underset{\substack{\uparrow\\ \text{SM cross}\\ \text{section}}}{\sigma(X\,\bar{X}\to\gamma\,\gamma)}$$

The dark matter cross section to SM is correlated with the diffuse spectrum → a lower bound on line strength relative to continuum ow realistic is assumption that only one value of L and S contribute?

his depends on dark matter spin and annihilation mode. Whether ark matter is its own anti-particle also matters.

XAMPLE: Majorana fermion dark matter

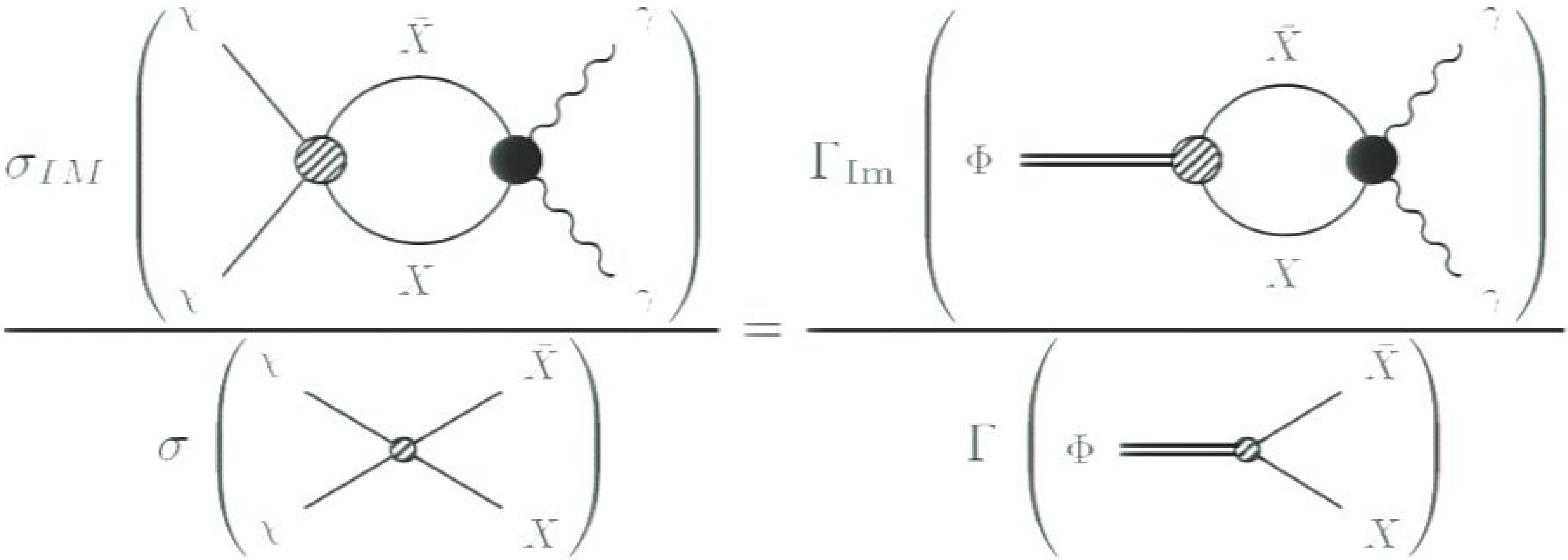
ince dark matter is non-relativistic, initial $L = 0$, so J = initial S.

f dark matter is Majorana fermion, then initial state has $S = J = 0$.

onsider annihilation to two photons through top and anti-top. The ntermediate state can have either $L = S = 1$ or $L = S = 0$. However CP onservation forbids $L = S = 1$ → intermediate state is unique.

onsider annihilation to two photons through $W^+ W^-$. Three possible ntermediate states $L = S = 2$, $L = S = 1$ and $L = S = 0$. Only $L = S = 1$ s allowed by CP → intermediate state is unique.

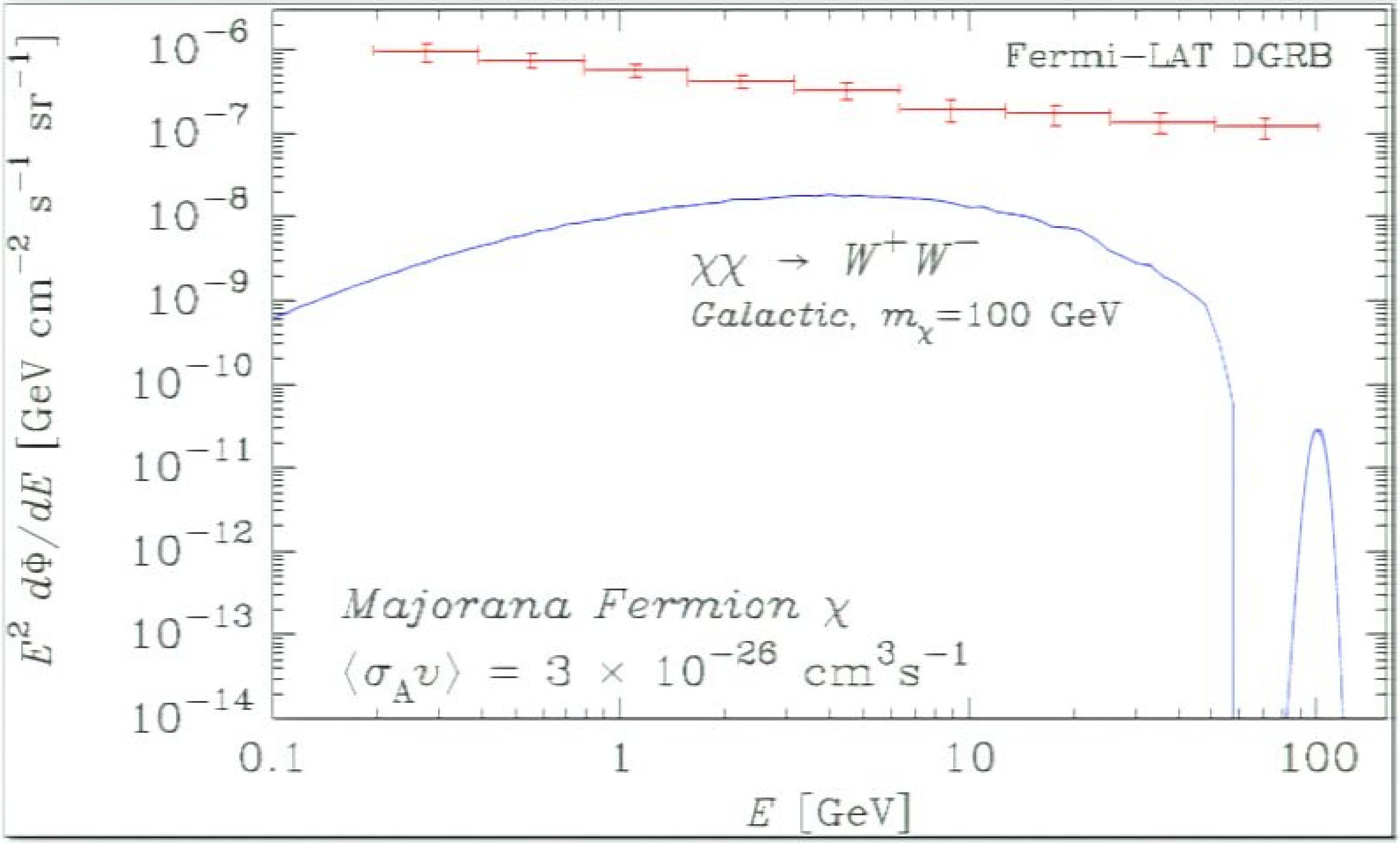
owever, in some cases multiple values of L and S are allowed, so a ound can only be obtained in specific kinematic regions ark matter annihilation can be mapped into the decay of a boson **Φ** ith spin *J* and the appropriate *CP* properties. If the intermediate tate is unique the mapping is exact.



For Majorana fermion annihilation to W$^+$ and W$^-$,

$$\frac{\Gamma_{\rm Im}(\varphi \to \gamma\gamma)}{\Gamma(\varphi \to WW)} = \frac{e^4}{32\pi^2}\eta^{3/2}\left[\tanh^{-1}\eta\right]^2$$

where *η* is the velocity of the *W* boson in the intermediate state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$\chi\chi \rightarrow W^+W^-$
Galactic, m_χ=100 GeV
Majorana Fermion χ
$\langle\sigma_A v\rangle = 3 \times 10^{-26}$ cm^{3}s^{-1}
$E^2\ d\Phi/dE$ [GeV cm^{-2} s^{-1} sr^{-1}]
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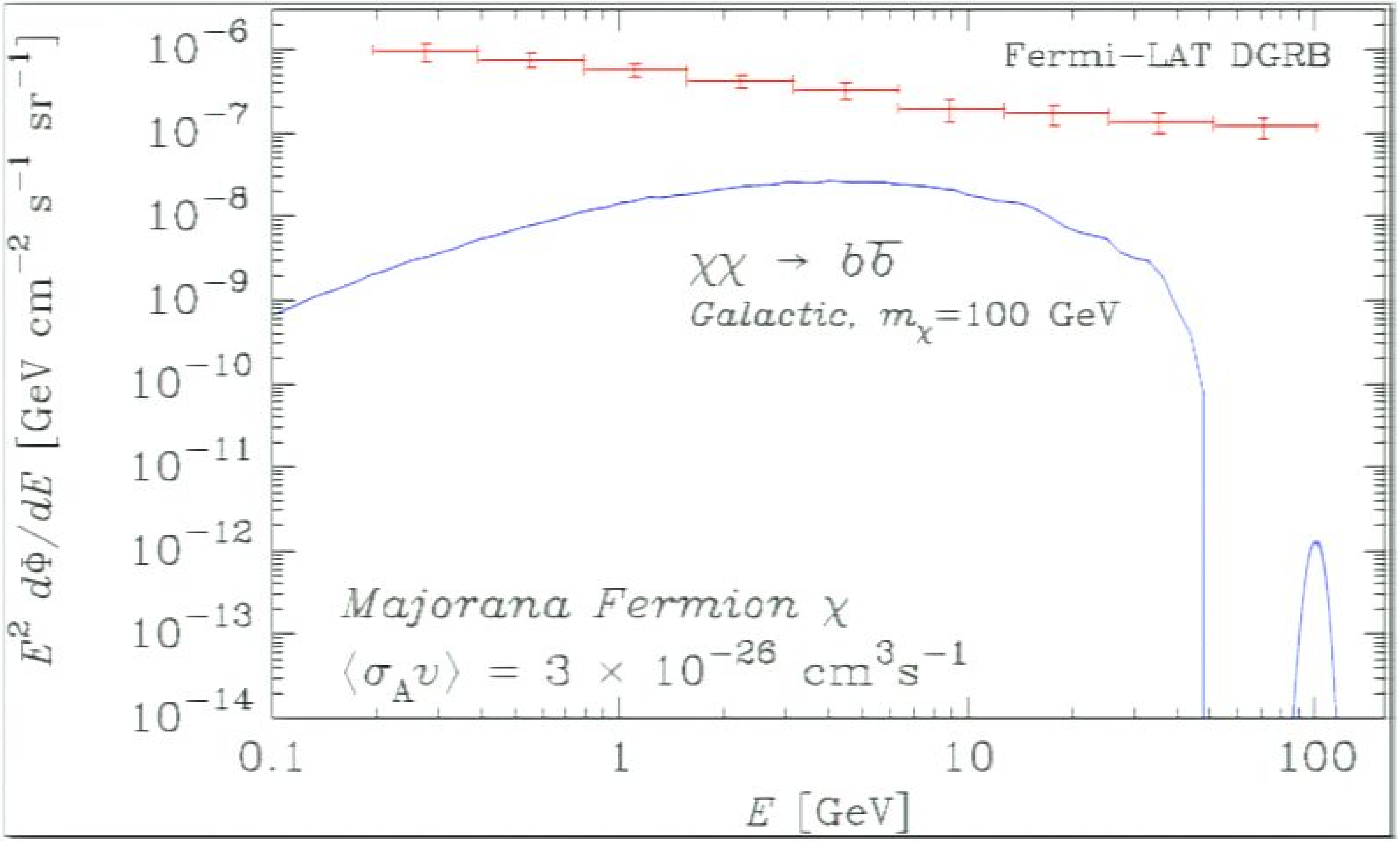
E [GeV]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E [GeV]

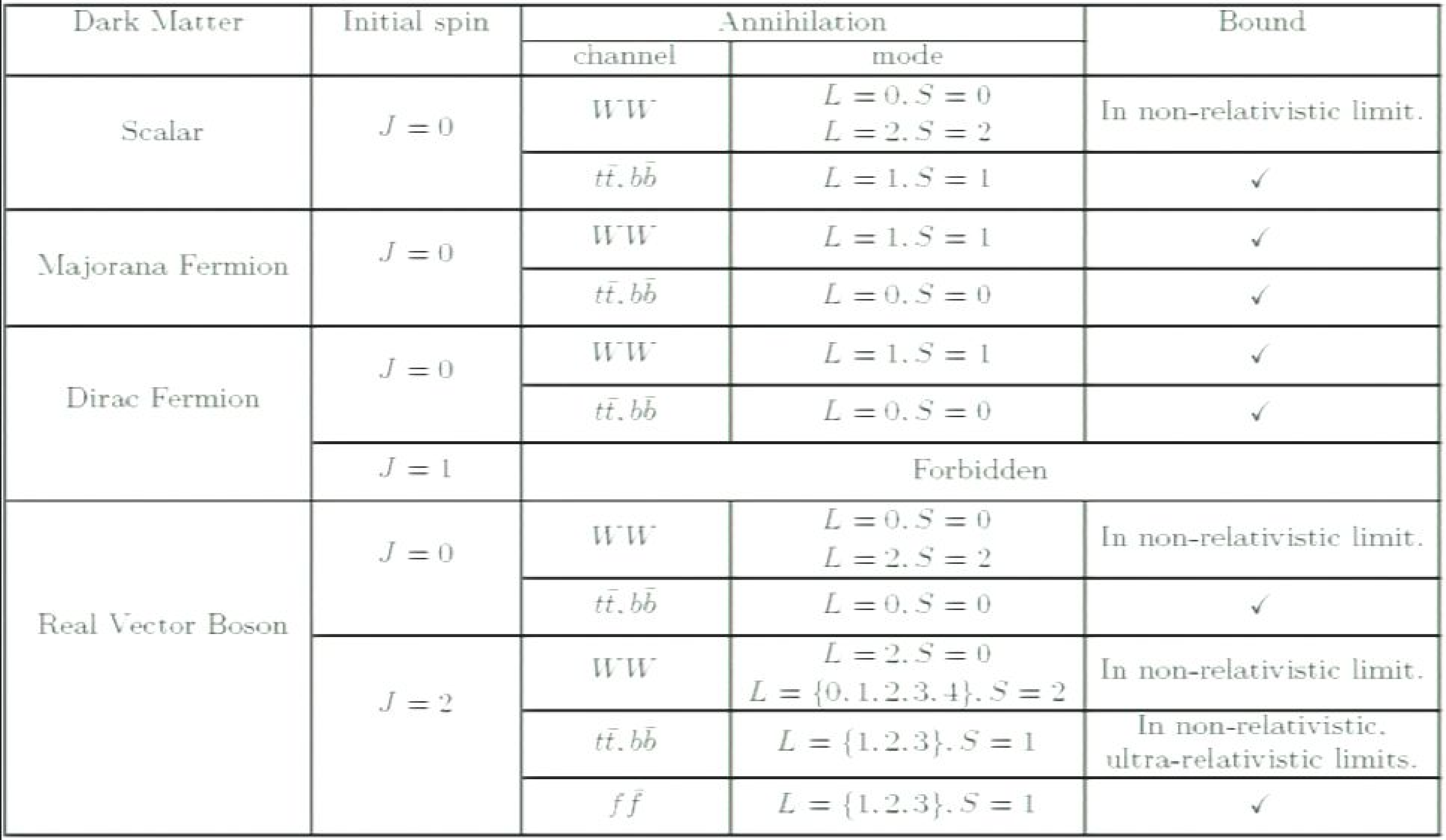
The Fermi limits on dark matter annihilation from lines are generally veaker than the corresponding diffuse limits by factors ranging from few to an order of magnitude or more.

lowever, for real vector boson dark matter annihilating to electrons r muons, lines may give the stronger bound.

Since backgrounds from lines are smaller, the strongest limits are btained from regions close to the galactic center → complementary o the diffuse limits.

Since the limits are obtained using conservative assumptions about he dark matter profile, the line strength could be many orders of nagnitude stronger. Our results show that the discovery potential is ignificant.

The bounds are largely statistics limited, and will improve over time.



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

he diffuse photon spectrum from dark matter annihilation is not ensitive to the dark matter spin, or to the form of its couplings. It only epends on the dark matter mass, and on the annihilation products.

/ith conservative assumptions about dark matter halos, the isotropic iffuse gamma ray flux is most sensitive to dark matter in our own alaxy.

his allows robust model-independent constraints to be placed on e rate of annihilation into any SM final state.

he current limits are not quite sensitive to thermal dark matter except the very light mass range (~ few GeV).

evertheless, already able to constrain certain new physics scenarios.

nitarity can be used to place model-independent lower bounds on e strengths of gamma ray lines from dark matter annihilation. Limits epend on the dark matter spin and charge conjugation properties and lso on the primary annihilation mode.

IceCube and the LHC

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Conclusions (2)

IceCube and the LHC

f the interactions of dark matter with nuclei are spin-dependent, the atural candidates are Majorana fermions and real vector bosons.

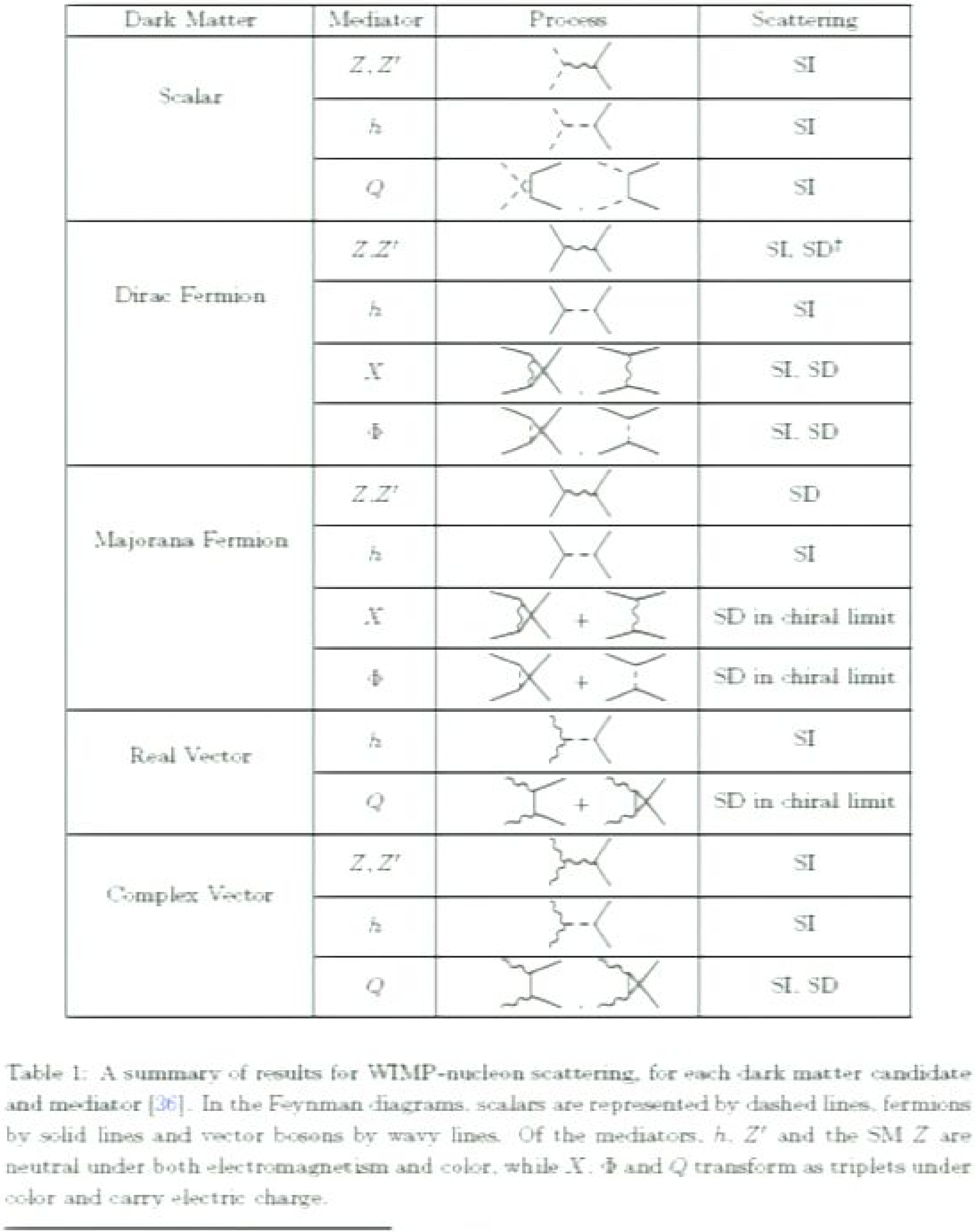
f the dark matter candidate is a Majorana fermion, spin-dependent VIMP-nucleon scattering can arise through any of:

- t-channel vector exchange
  - SM Z → WIMP carries weak charge
  - Z’ → new Z’ in the theory
- s- and u-channel vector exchange → mediator carries SM color
- s- and u-channel scalar exchange → mediator carries SM color

lf the dark matter candidate is a real vector, only one possibility:

- s- and u-channel fermion exchange → mediator carries SM color

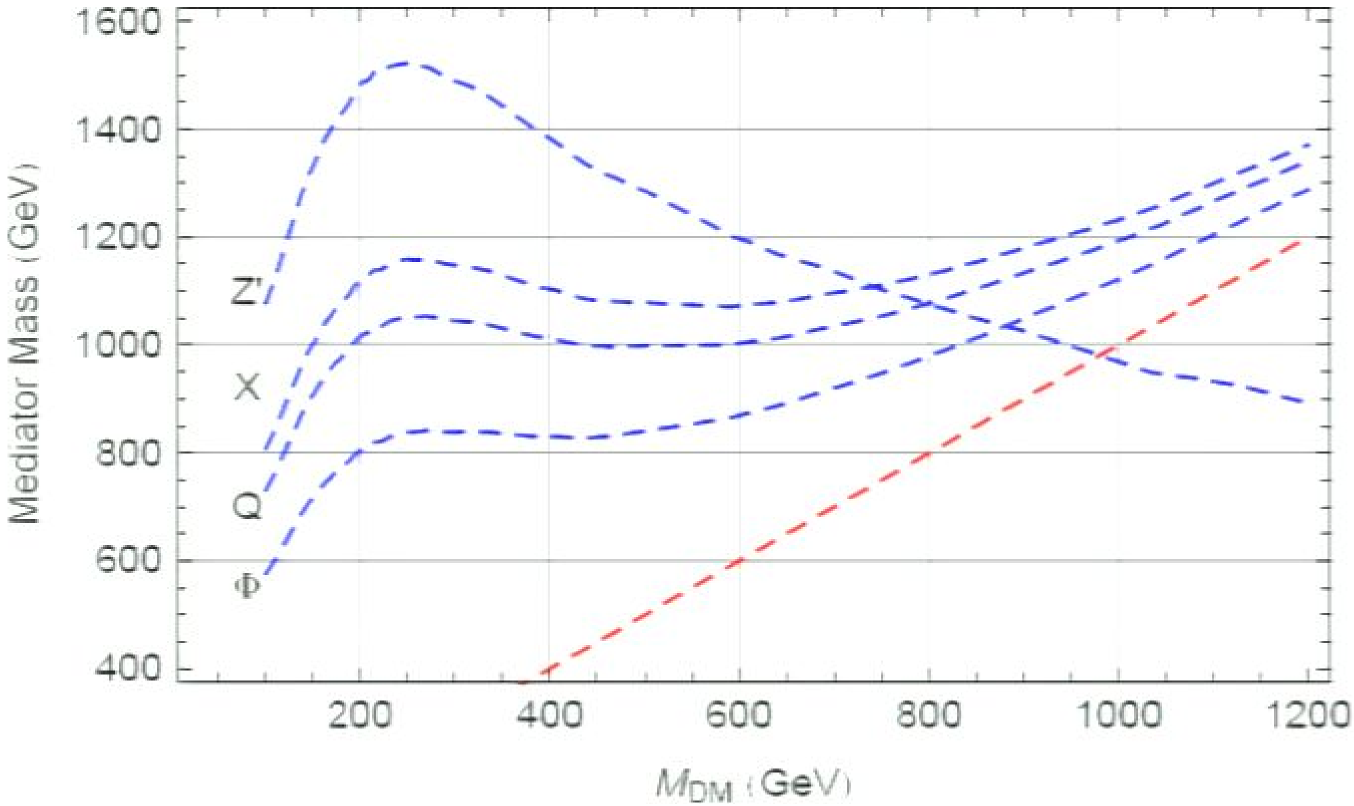
Either new Z’, or new states with SM charges → promising for LHC!



Dark Matter	Mediator	Process	Scattering
Scalar	Z, Z'		SI
	h		SI
	Q	,	SI
Dirac Fermion	Z, Z'		SI, SD†
	h		SI
	X	,	SI, SD
	Φ	,	SI, SD
Majorana Fermion	Z, Z'		SD
	h		SI
	X	+	SD in chiral limit
	Φ	+	SD in chiral limit
Real Vector	h		SI
	Q	+	SD in chiral limit
Complex Vector	Z, Z'		SI
	h		SI
	Q	,	SI, SD

Table 1: A summary of results for WIMP-nucleon scattering, for each dark matter candidate and mediator [36]. In the Feynman diagrams, scalars are represented by dashed lines, fermions by solid lines and vector bosons by wavy lines. Of the mediators, h, Z' and the SM Z are neutral under both electromagnetism and color, while X, Φ and Q transform as triplets under color and carry electric charge.

The figure shows the range of mediator masses that leads to a signal at IceCube with 5 years of data (assuming order one couplings).



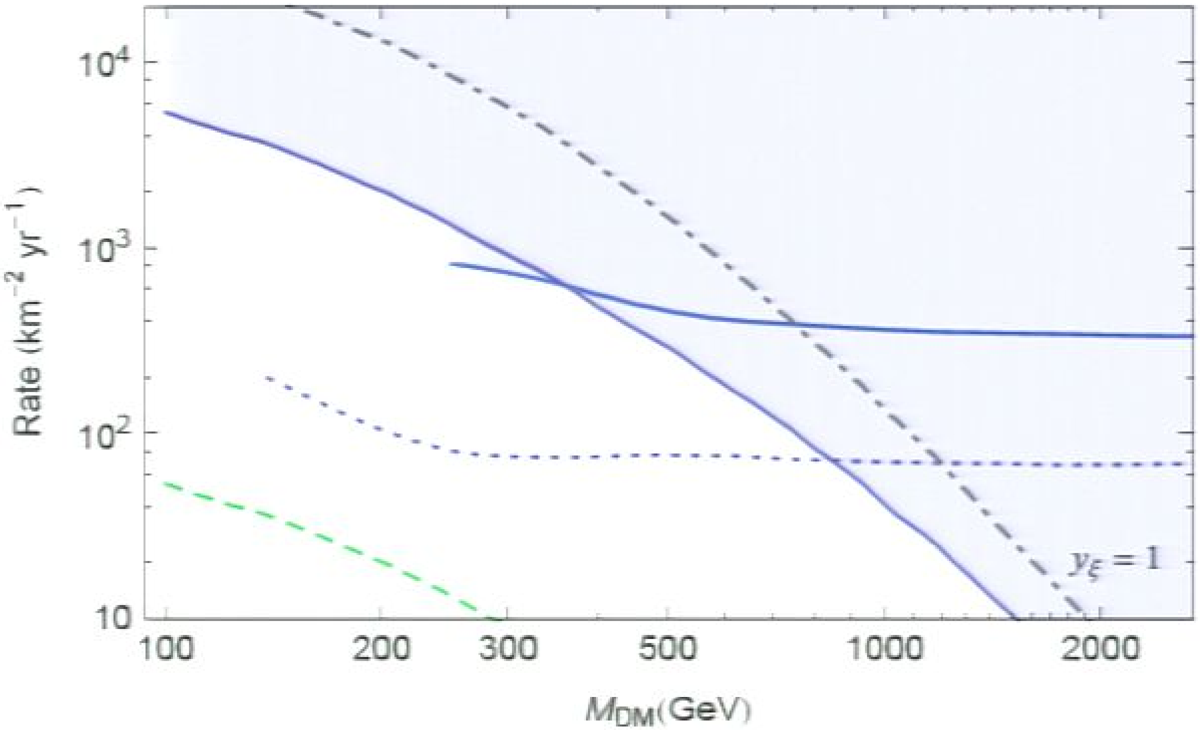
The case with a new Z' is disfavored by precision electroweak limits.

The new colored particles are kinematically accessible to the LHC.

or Majorana fermion dark matter charged under the SM Z, there is lways a small but non-negligible spin-independent contribution from M Higgs exchange.

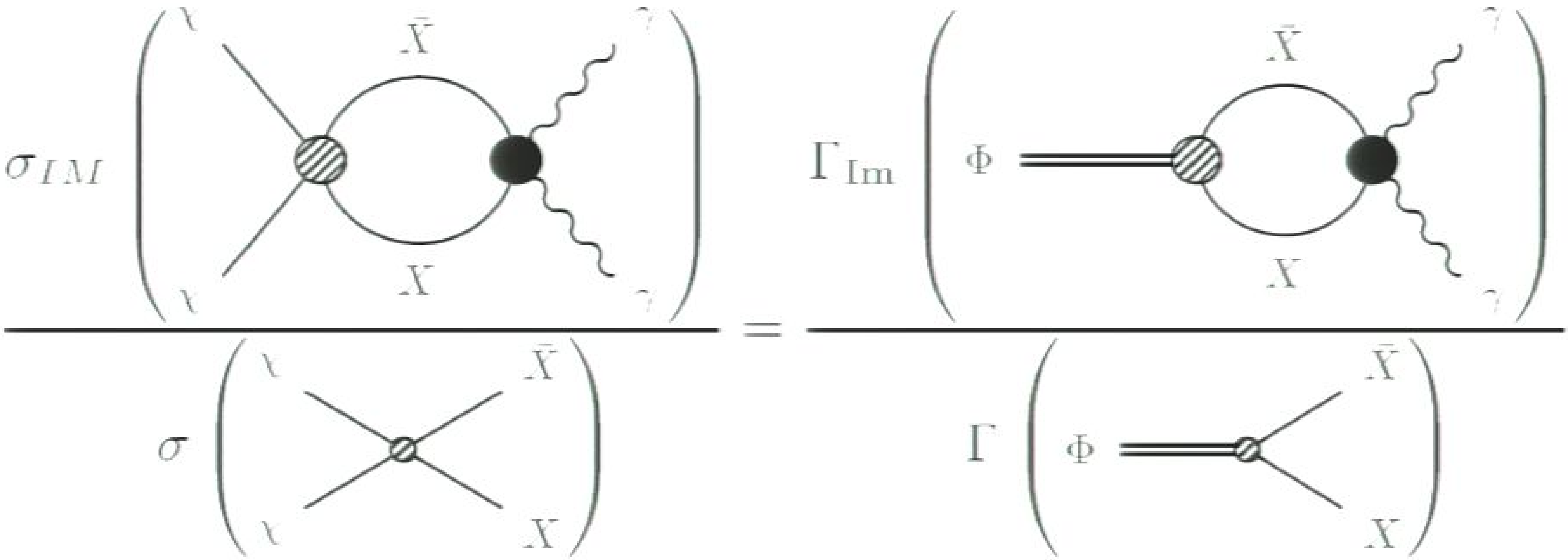
Cohen, Phalen & Pierce

irect detection experiments can expect to see a small but definite pin-independent signal, if IceCube sees a signal.



part of the parameter space is kinematically accessible to the LHC.

Dark matter annihilation can be mapped into the decay of a boson Φ with spin *J* and the appropriate *CP* properties. If the intermediate state is unique the mapping is exact.



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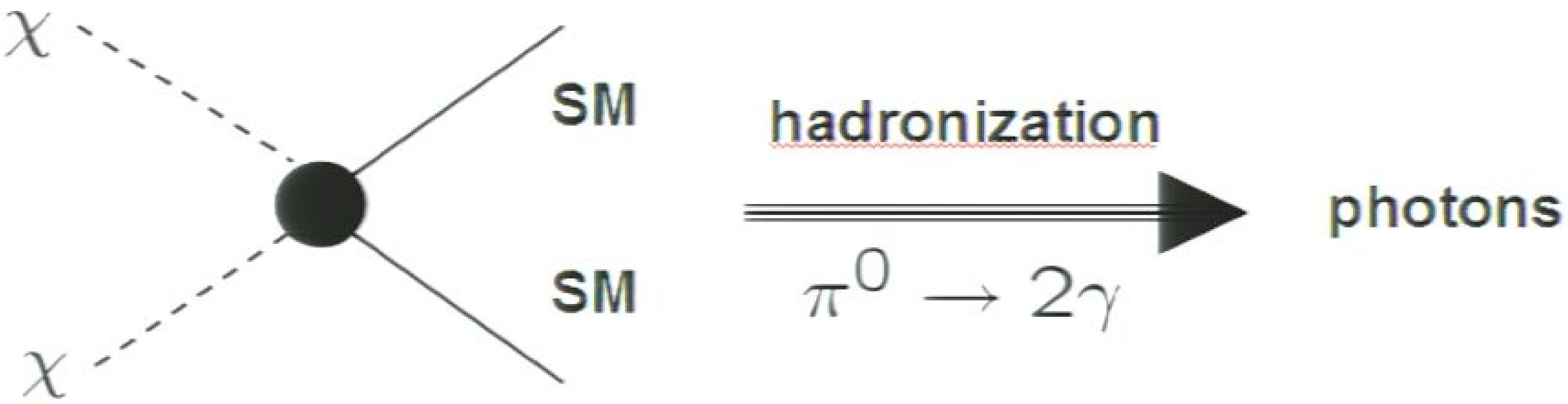
where η is the velocity of the *W* boson in the intermediate state

For all 2 body SM final states except electrons and muons, spectrum of diffuse photons is dominated by gamma rays arising from decays of primary (or secondary) annihilation products after hadronization.



The resulting photon spectrum is independent of the dark matter spin or form of couplings. Depends only on dark matter mass, and (to a more limited extent) on the SM final states.

Therefore this can be used to place a robust bound on annihilation into various 2 body SM final states.

Limits on dark matter event rates in IceCube

In the non-relativistic limit, WIMP-nucleon interactions fall into two distinct categories.

If the WIMP interactions are sensitive to the spin of the nucleus, the corresponding cross section is `spin-dependent’. If not, the cross section is `spin-independent’.

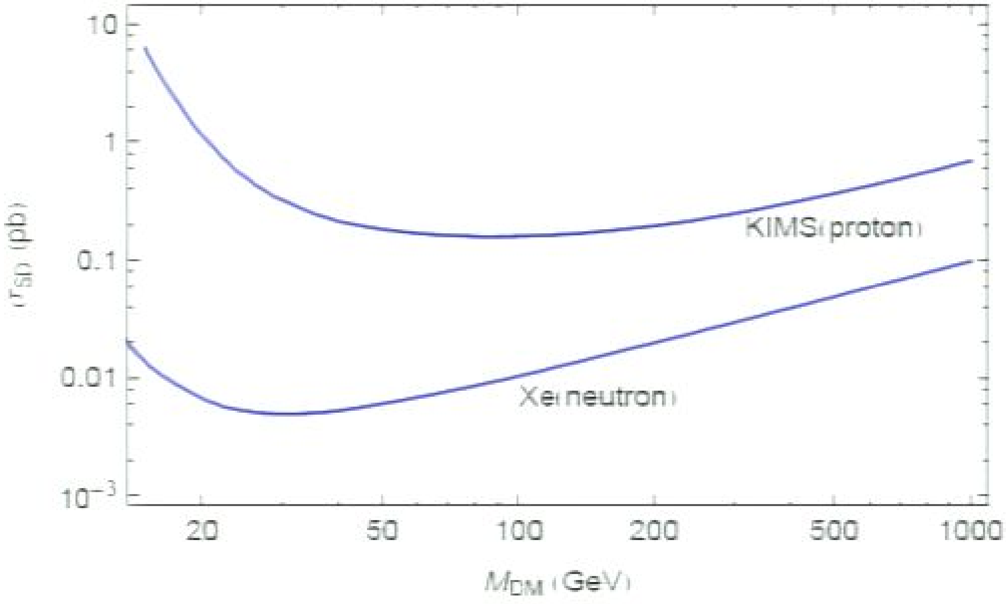
The direct detection bounds on spin-independent interactions are much tighter than the bounds on spin-dependent interactions. Why?

In the spin-independent case contributions from individual nucleons in the nucleus add coherently, leading to a large cross section.

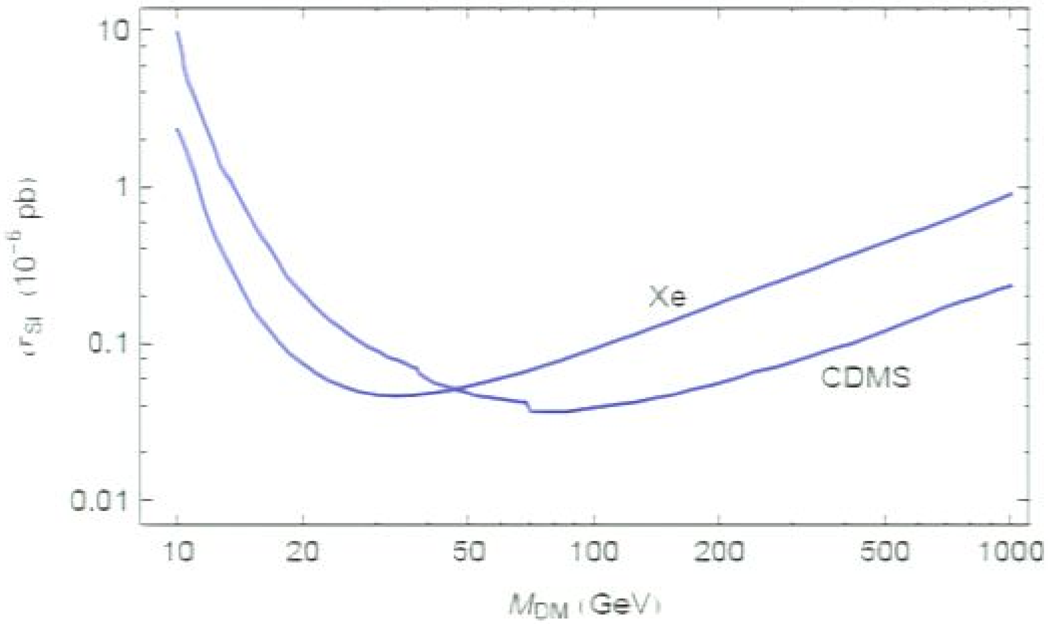
$$\sigma_{\mathrm{SI}} \sim A^2$$

Spins of nucleons tend to cancel in pairs ➔ no such enhancement in spin-dependent case.

SD →



SI →



The limits on spin-independent interactions are stronger by about 10^6

Spin-dependent dark matter candidates

he logic is as follows.

will establish a very close association between theories where the VIMP-nucleon cross section is dominated by spin-dependent nteractions, and theories where the dark matter particle is its own nti-particle.

$$\sigma_{SD} \gg \sigma_{SI} \longrightarrow \chi = \chi^c$$

However $$\chi = \chi^c \not\longrightarrow \sigma_{SD} \gg \sigma_{SI}$$

The experiment that is most sensitive to spin-dependent dark matter is the IceCube neutrino telescope located at the South Pole. A signal could help establish the dark matter particle is its own anti-particle!

The problem is that IceCube is also sensitive to spin-independent interactions. Not possible to distinguish the origin of the signal.

However, I will then show that limits from direct detection expts. can be used to place a model-independent upper bound on the event

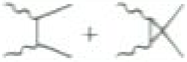
Dark Matter	Mediator	Process	Scattering
Scalar	Z, Z'		SI
	h		SI
	Q		SI
Dirac Fermion	Z, Z'		SI, SD†
	h		SI
	X		SI, SD
	Φ		SI, SD
Majorana Fermion	Z, Z'		SD
	h		SI
	X		SD in chiral limit
	Φ		SD in chiral limit
Real Vector	h		SI
	Q		SD in chiral limit
Complex Vector	Z, Z'		SI
	h		SI
	Q		SI, SD

Table 1: A summary of results for WIMP-nucleon scattering, for each dark matter candidate and mediator [36]. In the Feynman diagrams, scalars are represented by dashed lines, fermions by solid lines and vector bosons by wavy lines. Of the mediators, h, Z' and the SM Z are neutral under both electromagnetism and color, while X, Φ and Q transform as triplets under color and carry electric charge.

calar WIMPs

Scalars always lead to spin-independent interactions.

ermionic WIMPs

There are two operators that can lead to scattering.

$$\bar{\chi}\gamma_\mu\gamma^5\chi\ \bar{q}\gamma^\mu\gamma^5 q \quad \longrightarrow \quad \textbf{SD}$$

$$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu q \quad \longrightarrow \quad \textbf{SI}$$

For a Majorana fermion the second operator vanishes → scattering is spin-dependent. For Dirac case (in general) both operators contribute.

ector boson WIMPs

For real vector bosons only one operator contributes in chiral limit.

$$_{\mu\nu\lambda\sigma}\ \partial^\mu B^\nu B^\lambda\ \bar{q}\gamma^\sigma\gamma^5 q \quad \longrightarrow \quad \textbf{SD}$$

For complex vector bosons an additional operator contributes.

$$\partial\, B^{*}\, B^{\nu}\bar{q}\gamma^{\mu} q$$

he velocity dependent terms can be neglected, since v ~ 10^{-3}

f the remaining terms, $\bar{q}q$ and $\bar{q}\sigma^{\mu\nu}q$

re only generated by effects that break chiral symmetry, and can aturally be small. Assume this, and check for consistency later.

hen, for spin-dependent interactions to dominate terms involving

$\gamma^{\mu}\gamma^{5}q$ must be present in the theory, while terms involving the

perator $\bar{q}\gamma^{\mu}q$ must be absent.

Vhat are the theories where this can happen naturally?

he theories where spin-dependent interactions dominate are closely ssociated with either Majorana fermion or real vector boson dark natter. ➔ The dark matter has spin and is its own anti-particle.