Is the dark matter particle its own anti-particle?

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Introduction

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

However, the nature of the particles of which dark matter is composed remains a mystery.

Stable particles with masses of order the weak scale that have weak scale cross sections with visible matter naturally have the right relic abundance 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.

As a consequence, the phenomenology of WIMP dark matter has primarily focused on studying the implications of specific models. The models which have been studied tend to fall into one of three categories.

- Theories primarily formulated to address the hierarchy problem of the Standard Model (such as supersymmetry) that have a WIMP dark matter candidate.

- Theories of WIMP dark matter motivated primarily by simplicity (such as the scalar singlet model). Often very predictive.

These approaches have drawbacks. In particular, even relatively mild modifications of these theories tend to affect their consequences for experiment. Detailed predictions not robust.

- Theories proposed to explain an observed signal (DAMA, PAMELA).

At present no conclusive evidence for a dark matter signal.

Is a model-independent approach feasible?

To what extent is it possible to extract from experiment information about the nature of the dark matter particle independent of any specific model?

Clearly, detailed predictions will not be possible.

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

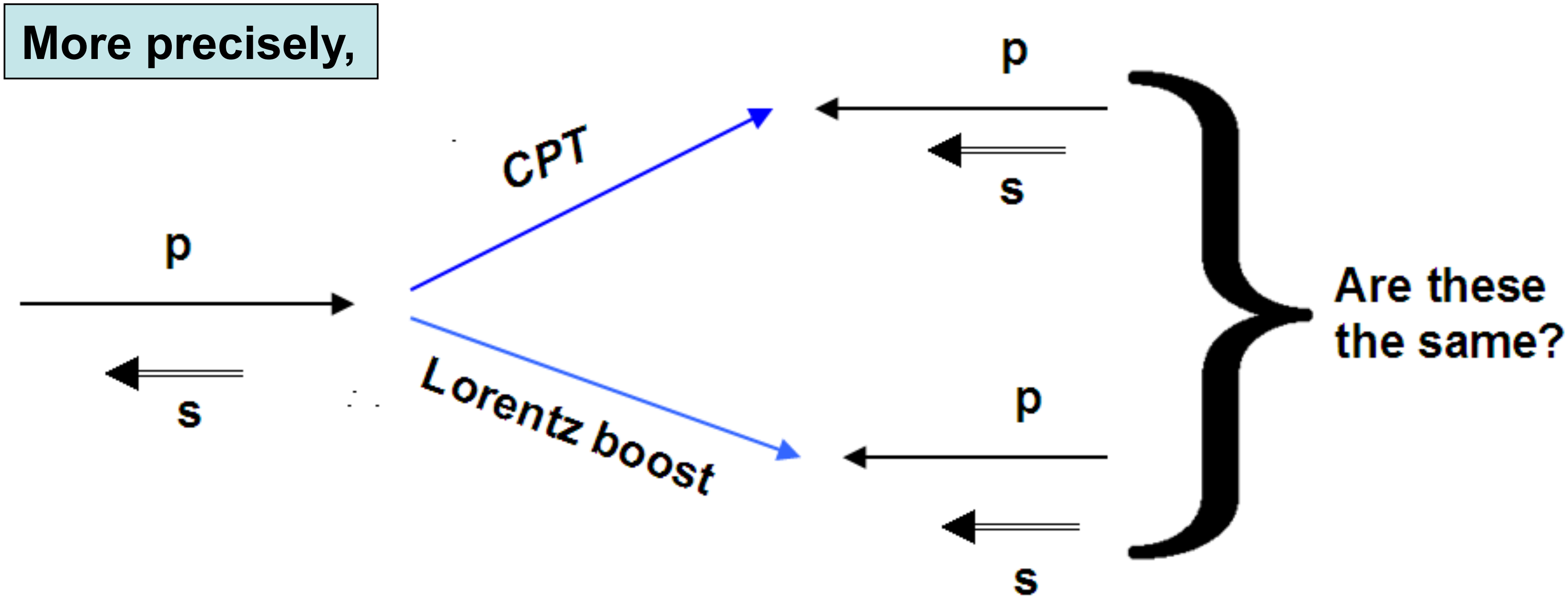
- What is the mass of the dark matter particle?
- What is its spin?
- Is the dark matter particle its own anti-particle?
- What are its SM quantum numbers?

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,



Can dark matter experiments address this question?

The logic of this talk is as follows.

I will establish a very close correlation between theories where the WIMP-nucleon cross section is dominated by spin-dependent interactions, and theories where the dark matter particle is its own anti-particle.

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

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

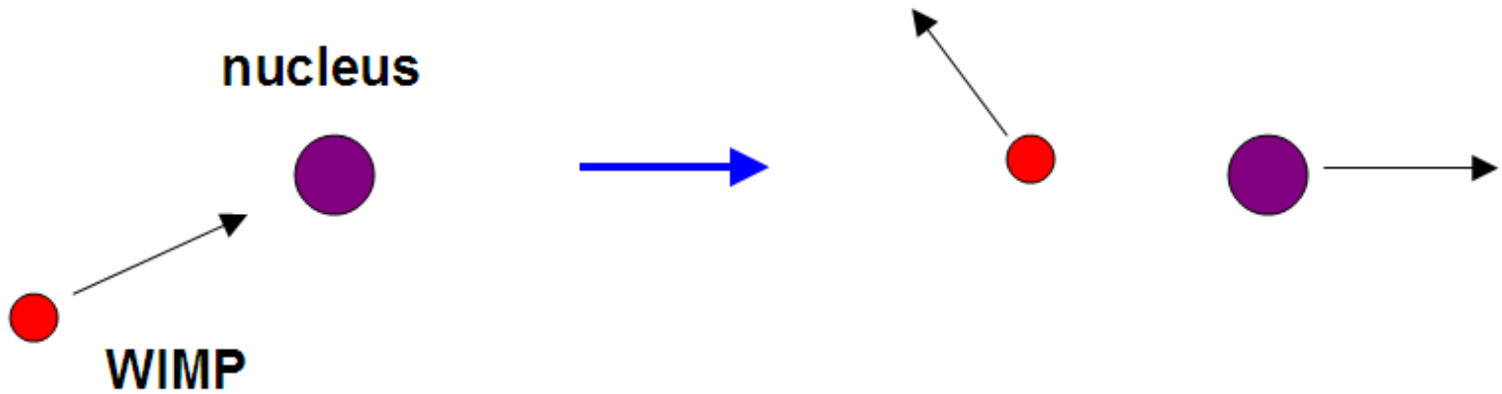
The experiment that is most sensitive to spin-dependent dark matter is the IceCube neutrino telescope located at the South Pole. A signal could help establish the dark matter particle is its own anti-particle!

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 rate from spin-independent interactions, closing the loophole.

Spin-dependent dark matter candidates

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



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

Since the de Broglie wavelength of the incident WIMP is larger than the typical nuclear scales, the WIMP sees nucleus as a single unit, with 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'.

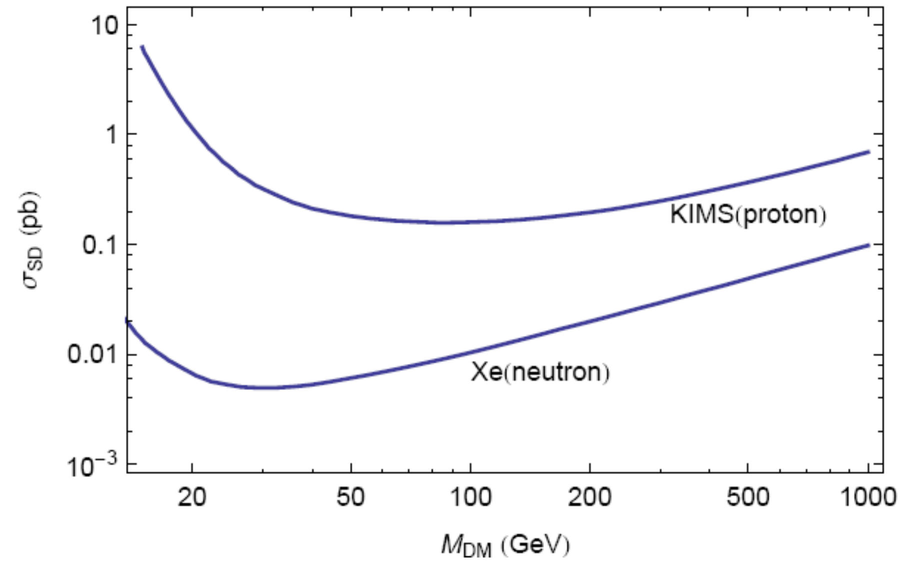
The direct detection bounds on spin-independent interactions are much tighter than the bounds on spin-dependent interactions. Why?

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

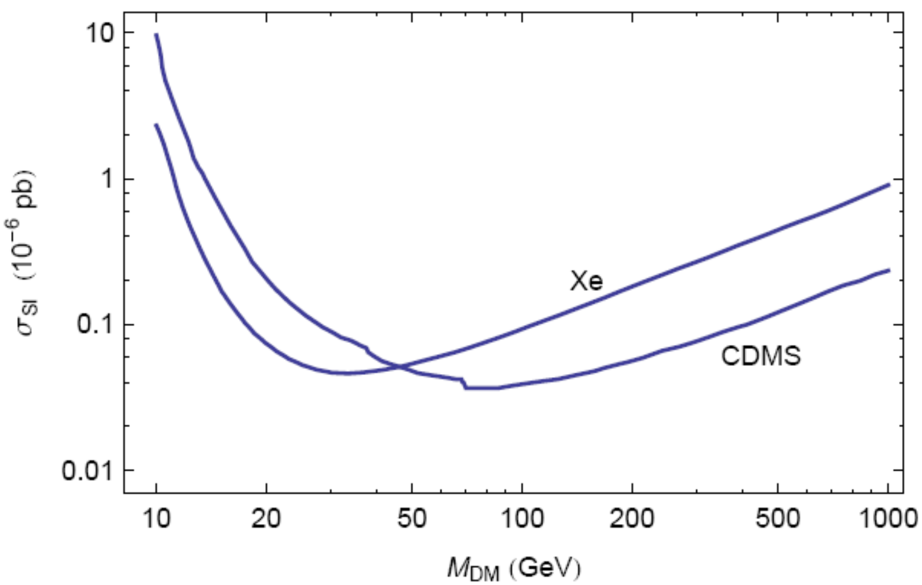
$$\sigma_{\mathrm{SI}} \sim A^2$$

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

SD



SI



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

We wish to classify theories which can naturally lead to primarily spin-dependent interactions with matter.

Cosmological limits constrain WIMP dark matter to be neutral under color and electromagnetism.

We will limit to theories where WIMP-nucleon scattering is elastic and arises from an effective operator generated by a tree diagram at parton level ➔ only WIMP-quark operators need be considered.

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

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

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

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

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

scalar $\bar{q}\ q$

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

vector $\bar{q}\gamma^\mu q \to \bar{q}\gamma^0 q$, $\quad \bar{q}\gamma^\mu q \to \bar{q}\gamma^i q \sim v^i$

pseudo-vector $\bar{q}\gamma^\mu\gamma^5 q \to \bar{q}\gamma^0\gamma^5 q \sim \vec{s}.\vec{v}$, $\quad \bar{q}\gamma^\mu\gamma^5 q \to \bar{q}\gamma^i\gamma^5 q \sim s^i$

tensor $\bar{q}\sigma^{\mu\nu} q \to \bar{q}\sigma^{0i} q \sim v^i$, $\quad \bar{q}\sigma^{\mu\nu} q \to \bar{q}\sigma^{ij} q \sim \epsilon^{ijk} s^k$

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

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

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

Then, for spin-dependent interactions to dominate terms involving

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

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

What are the theories where this can happen naturally?

The theories where spin-dependent interactions can naturally dominate involve either Majorana fermions or real vector bosons.
➔ The dark matter particle has spin and is its own anti-particle.

Scalar WIMPs

Scalars always lead to spin-independent interactions.

Fermionic WIMPs

There are two operators that can lead to scattering.

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

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

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

Vector boson WIMPs

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

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

For complex vector bosons an additional operator contributes.

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

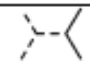
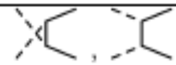
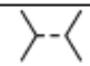
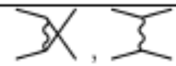
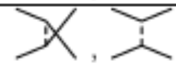
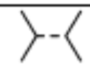
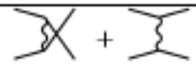
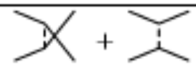
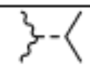
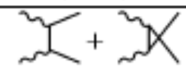
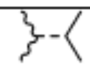
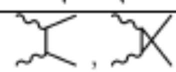
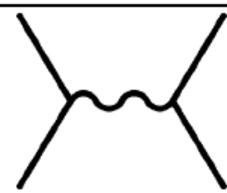
Dark Matter	Mediator	Process	Scattering
Scalar	Z, Z'		SI
	h		SI
	Q		SI
Dirac Fermion	Z,Z'		SI, SD†
	h		SI
	X		SI, SD
	Φ		SI, SD
Majorana Fermion	Z,Z'		SD
	h		SI
	X		SD in chiral limit
	Φ		SD in chiral limit
Real Vector	h		SI
	Q		SD in chiral limit
Complex Vector	Z, Z'		SI
	h		SI
	Q		SI, SD

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.

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

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

Z, Z'		SI, SD†

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

Is there a symmetry understanding of this?

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

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

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

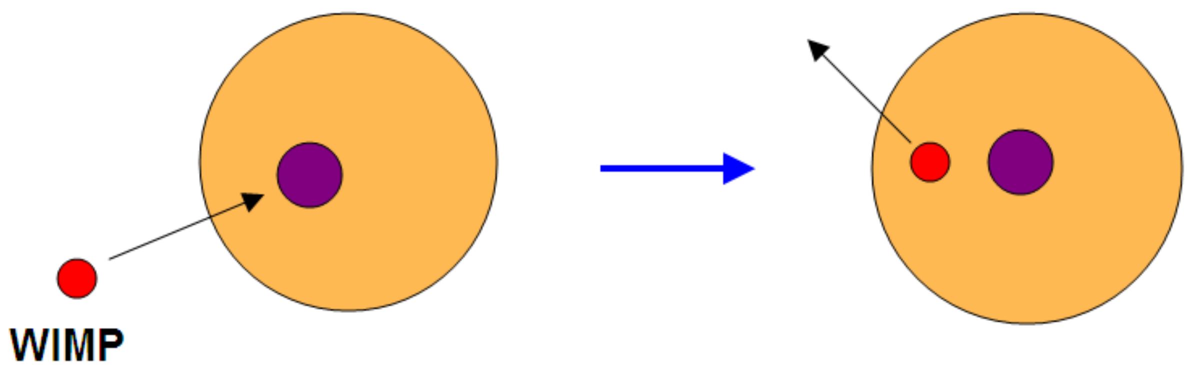
There exists a set of Z' charges for which this symmetry is realized.

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

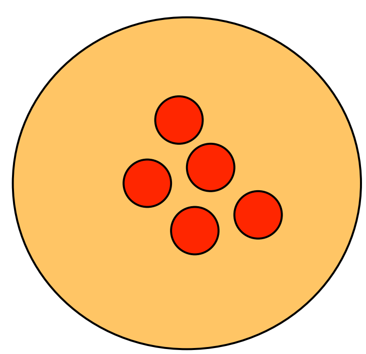
Limits on dark matter event rates in IceCube

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

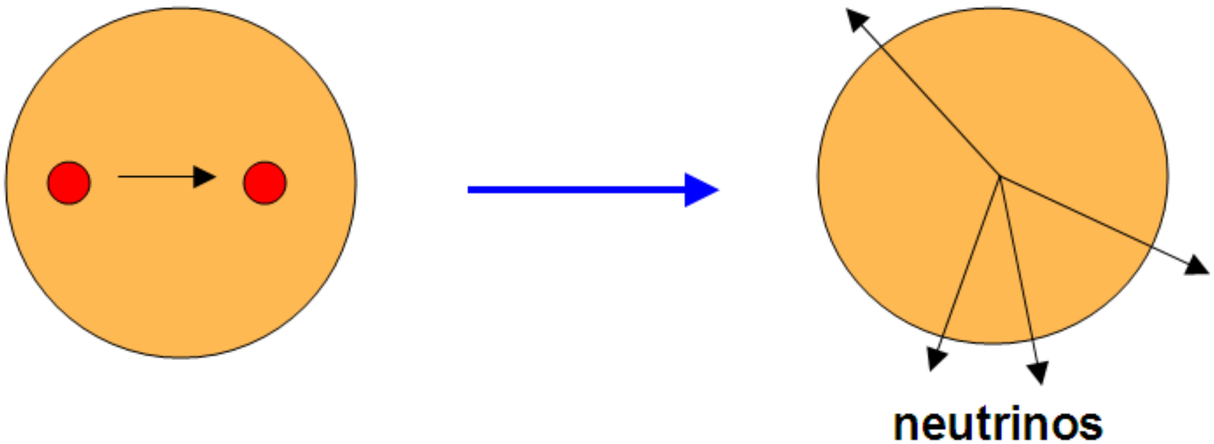
Dark matter particles collide with nuclei in the sun, thereby losing energy. As a consequence they become gravitationally bound.



After subsequent scatterings they eventually accumulate in the core of the sun.



Dark matter particles in the core of the sun can pair annihilate, giving rise to neutrinos (directly, or from decay of the annihilation products).



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

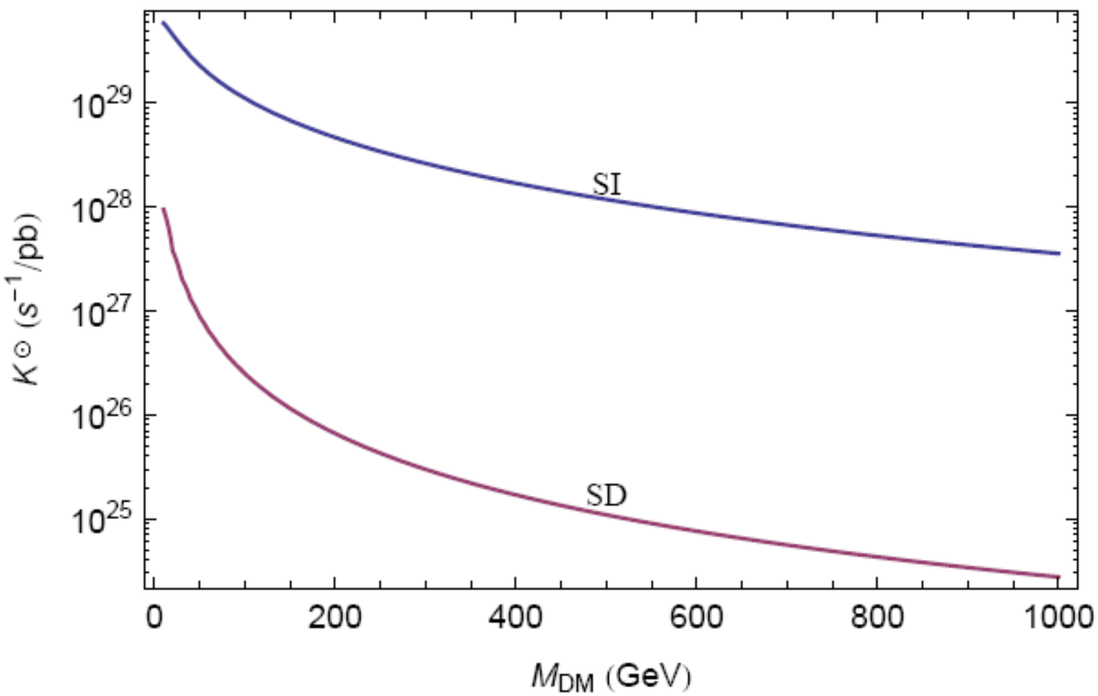
What does the strength of the signal depend on?

- The rate of annihilation of the dark matter particles. At equilibrium, (generally achieved) this is equal to (half) the capture rate.
- The number of neutrinos produced per annihilation (depends on how `neutrino rich' the dark matter annihilation products are).
- The energies of the neutrinos produced (depends on the WIMP mass and also on the annihilation products).

Capture in the sun can occur either through spin-dependent or through spin-independent interactions. As a consequence, neutrino telescopes are sensitive to both types of interactions.

Hydrogen has a net spin, and contributes to spin-dependent capture.

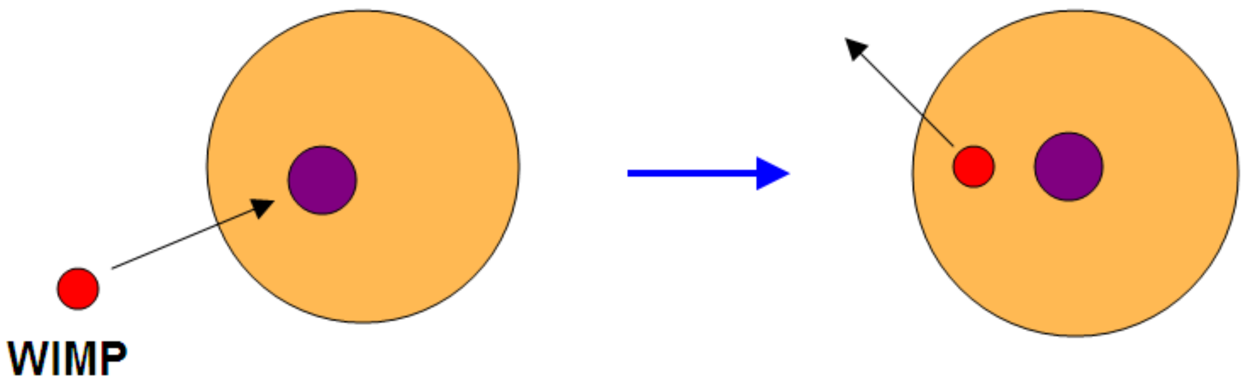
Oxygen and neon contribute the most to spin-independent capture.



Spin-independent capture is more efficient (~ two orders of magnitude), but spin-dependent capture cannot in general be neglected.

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

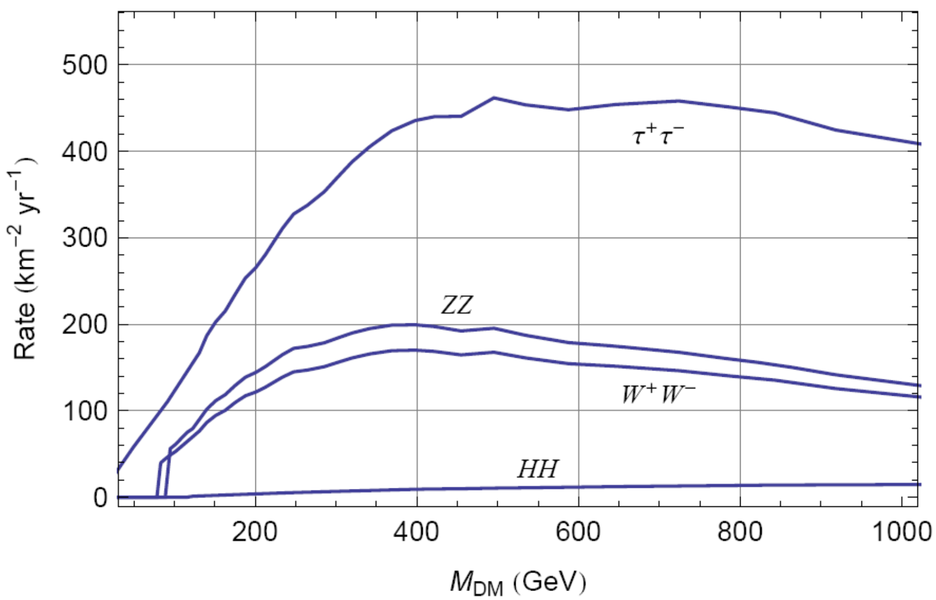
How? Capture in the sun occurs through WIMP-nucleon scattering, which is bounded by direct detection experiments. The direct detection limit translates into a bound on the WIMP capture rate.



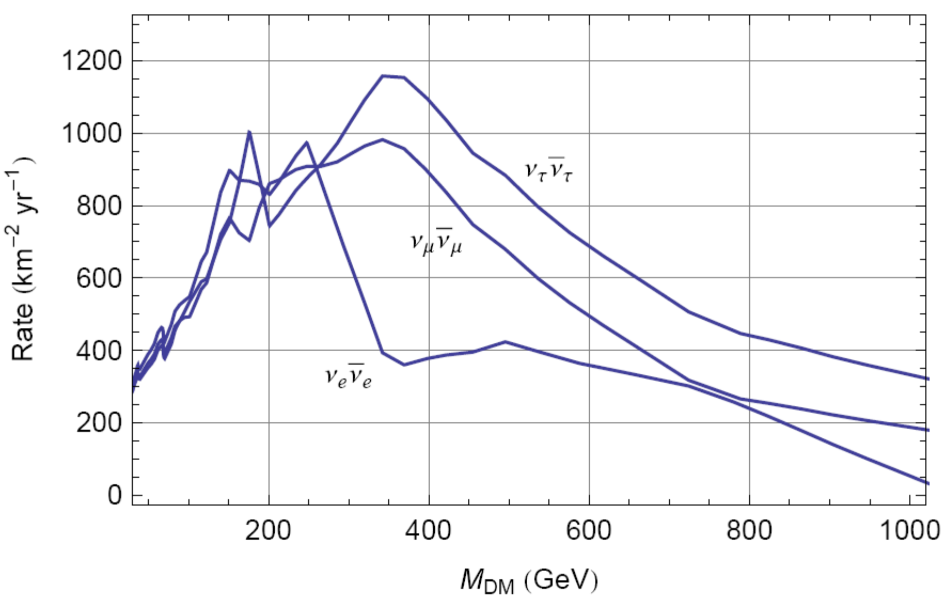
The annihilation rate can at most be equal to half the capture rate. The limit on the capture rate is then also a limit on the annihilation rate.

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

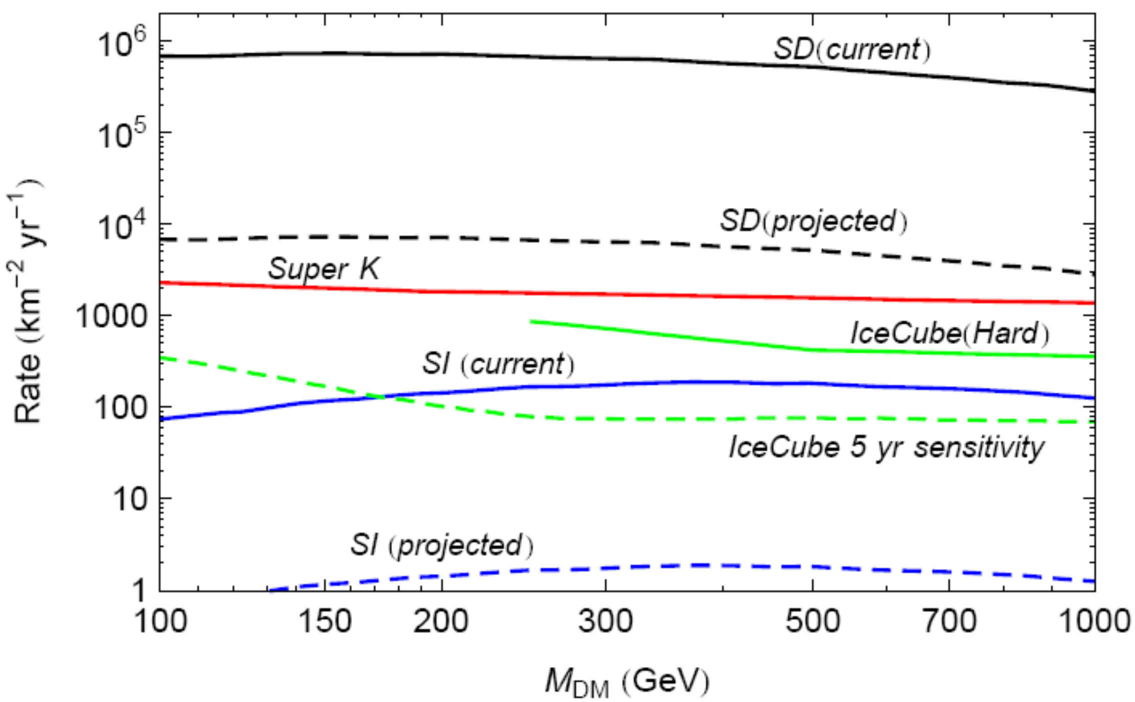
For spin-independent interactions, this limit is comparable to current IceCube bound.



Rate (km^{-2} yr^{-1})
M_{DM} (GeV)
$\tau^+\tau^-$
ZZ
W^+W^-
HH



Rate (km^{-2} yr^{-1})
M_{DM} (GeV)
$\nu_\tau\overline{\nu}_\tau$
$\nu_\mu\overline{\nu}_\mu$
$\nu_e\overline{\nu}_e$



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

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

At that point, any observed signal at IceCube must be arising from spin-dependent interactions ➔ a strong hint that the dark matter particle 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.

IceCube and the LHC

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

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

- t-channel vector exchange
  - $\xrightarrow{\text{SM Z}}$ WIMP carries weak charge
  - $\xrightarrow{\text{Z'}}$ new Z' in the theory

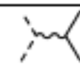
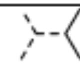
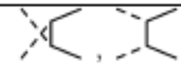
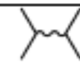
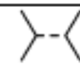
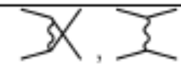
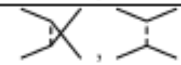
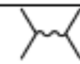
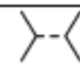
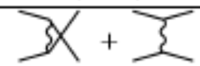
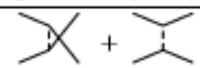
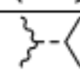
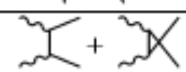
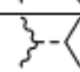
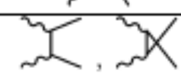
- s- and u-channel vector exchange → mediator carries SM color

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

If 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

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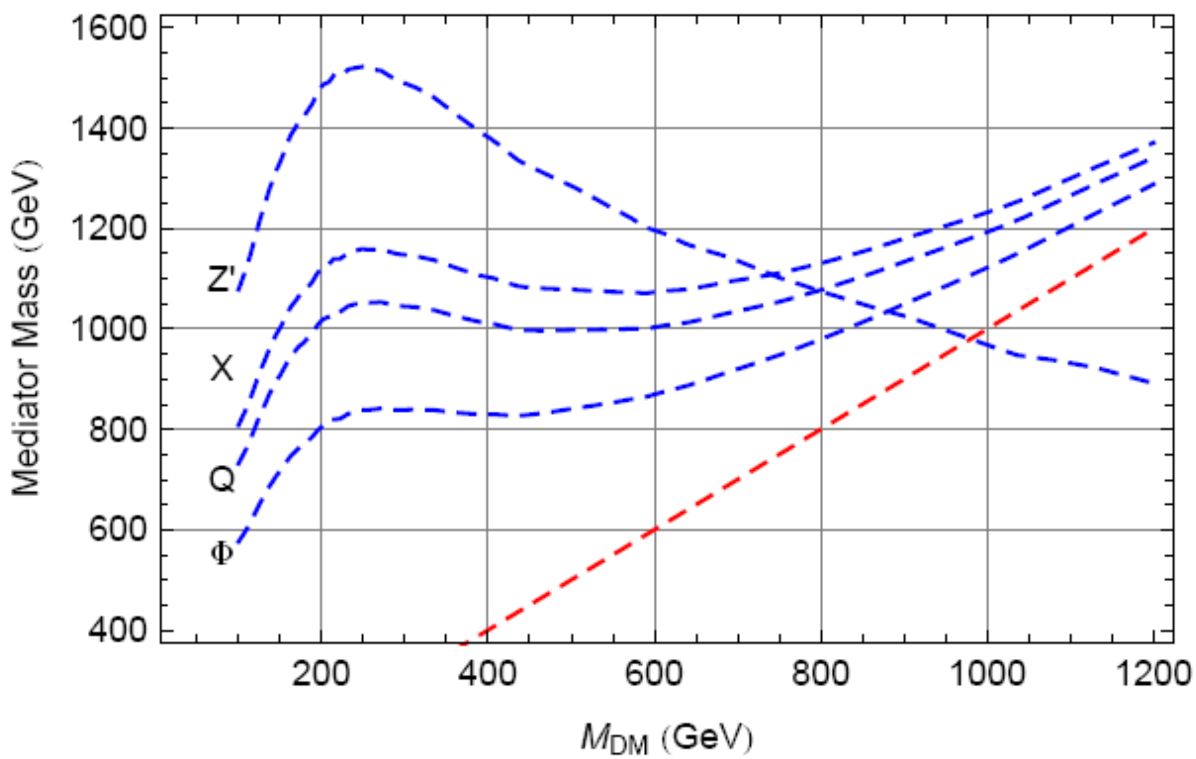
†Can be primarily SD for specific choices of Z' charges

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

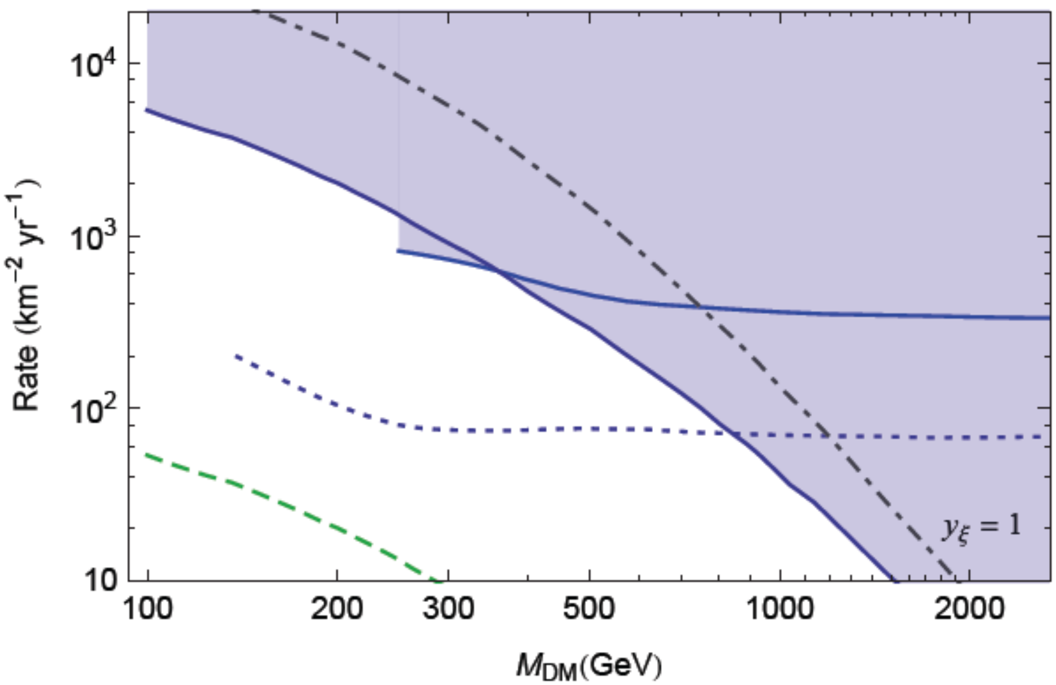


The case with a new Z' is disfavored by precision electroweak limits.

The new colored particles are kinematically accessible to the LHC.

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

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



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

Conclusions

The dark matter candidates that naturally tend to have primarily spin-dependent interactions with matter are Majorana fermions and real vector 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.