Dark matter detection: challenges and future prospects

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Distance scales:
- pc (Parsec)
- kpc (Kiloparsec)
- Mpc (Megaparsec)
- Gpc (Gigaparsec)

Diagram showing:
- Solar system
- Galaxies
- Clusters of galaxies
- Observable Universe

Graph showing the Solar System Rotation Curve:
\[ v = \sqrt{GM/r} \]
There is evidence for dark matter in a wide range of distance scales. Assumption, but well motivated.
Three different methods have been proposed to probe the DM population inside the Solar System.
Direct dark matter searches

The Sun (and the Earth) is moving through a “gas” of dark matter particles. Or, from our point of view, there is a flux of dark matter particles going through the Earth.

$\text{Sun} \quad v \approx 200 \text{ km/s}$

$\text{WIMPs} \quad v \approx 200 \text{ km/s}$
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$v \approx 200 \text{ km/s}$

Once in a while a dark matter particle will interact with a nucleus. The nucleus then recoils, producing vibrations, ionizations or scintillation light in the detector.

$\text{Nuclear recoil}$
Direct dark matter searches

Backgrounds are very large: similar experimental signals can be induced by interactions of electrons, photons, neutrons...

Current strategy:

1) Take experiments deep underground

2) Shield the detector against natural radioactivity in the laboratory.

3) Devise techniques to further reduce residual backgrounds
Dark matter searches

Direct dark matter searches

Results from a Search for Dark Matter in the Complete LUX Exposure

First Dark Matter Search Results from the PICO-60 C3F8 Bubble Chamber

New Results from the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment

Silicon Detector Dark Matter Results from the Final Exposure of CDMS II
Direct dark matter searches

Most experiments report no evidence for DM-induced nuclear recoils.
We report results of a search for weakly interacting massive particles (WIMPS) with the silicon detectors of the CDMS II experiment. This blind analysis of 140.2 kg day of data taken between July 2007 and September 2008 revealed three WIMP-candidate events with a surface-event background estimate of $0.41 \pm 0.20 \text{(stat)} \pm 0.28 \text{(syst)}$. Other known backgrounds from neutrons and $^{206}\text{Pb}$ are limited to $<0.13$ and $<0.08$ events at the 90% confidence level, respectively. The exposure of this analysis is equivalent to 23.4 kg day for a recoil energy range of 7–100 keV for a WIMP of mass 10 GeV/c$^2$. The probability that the known backgrounds would produce three or more events in the signal region is 5.4%. A profile likelihood ratio test of the three events that includes the measured recoil energies gives a 0.19% probability for the known-background-only hypothesis when tested against the alternative WIMP + background hypothesis. The highest likelihood occurs for a WIMP mass of 8.6 GeV/c$^2$ and WIMP-nucleon cross section of $1.9 \times 10^{-41}$ cm$^2$. 
Annual modulation
Annual modulation

- WIMP Wind
- $v_0 \sim 220$ km/s
- Cygnus
- $60^\circ$
- Galactic plane

Graph:
- Rate
- June 2nd
- December 2nd

Diagram:
- June
- December
- Sun
Annual modulation

Modulation signal

\[ S_{[E_-,E_+]} = \frac{1}{2} \frac{1}{E_+ - E_-} \left( R_{[E_-,E_+]} \big|_{\text{June 1st}} - R_{[E_-,E_+]} \big|_{\text{Dec 1st}} \right) \]
Annual modulation: the DAMA/LIBRA experiment

Modulation observed over 14 annual cycles, with a combined significance of $9.3\sigma$.

$$S^{(\text{DAMA})}_{[2.0,2.5]} = (1.75 \pm 0.37) \times 10^{-2} \text{ day}^{-1} \text{ kg}^{-1} \text{ keV}^{-1}$$

$$S^{(\text{DAMA})}_{[2.5,3.0]} = (2.51 \pm 0.40) \times 10^{-2} \text{ day}^{-1} \text{ kg}^{-1} \text{ keV}^{-1}$$

$$S^{(\text{DAMA})}_{[3.0,3.5]} = (2.16 \pm 0.40) \times 10^{-2} \text{ day}^{-1} \text{ kg}^{-1} \text{ keV}^{-1}$$
Neutrinos from annihilations in the Sun
Neutrinos from annihilations in the Sun

Neutrino flux related to the scattering cross-section
Neutrinos from annihilations in the Sun
Neutrinos from annihilations in the Sun
Neutrinos from annihilations in the Sun

Observations consistent with the background-only hypothesis
Theoretical interpretation of the experimental results
Theoretical interpretation of the experimental results

- Differential rate of DM-induced scatterings

\[
\frac{dR}{dE_R} = \frac{\rho_{\text{loc}}}{m_A m_{\text{DM}}} \int_{v \geq v_{\text{min}}(E_R)} d^3v \, v f(\vec{v} + \vec{v}_{\text{obs}}(t)) \frac{d\sigma}{dE_R}
\]

- The neutrino flux from annihilations inside the Sun is, under plausible assumptions, determined by the capture rate inside the Sun:

\[
C = \int_0^{R_{\odot}} 4\pi r^2 \, dr \frac{\rho_{\text{loc}}}{m_{\text{DM}}} \int_{v \leq v_{\text{max}}^{(\text{Sun})}(r)} d^3v \, \frac{f(\vec{v})}{v} \left( v^2 + [v_{\text{esc}}(r)]^2 \right) \times
\]

\[
\int_{m_{\text{DM}}v^2/2}^{2\mu_A^2(\nu^2 + [v_{\text{esc}}(r)]^2)/m_A} dE_R \frac{d\sigma}{dE_R}
\]
Theoretical interpretation of the experimental results

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Uncertainties from particle/nuclear physics and from astrophysics

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\int \frac{2\mu_A^2 (v^2 + [v_{\text{esc}}(r)]^2)}{m_A} \frac{d\sigma}{dE_R} \frac{dE_R}{dE_R} m_{\text{DM}} v^2 / 2
\]
Theoretical interpretation of the experimental results

Uncertainties from particle/nuclear physics.

- Dark matter mass?

For thermally produced dark matter, \( m_{DM} = \text{few MeV} - 100 \text{ TeV} \)

- Differential cross section?

\[
\frac{d\sigma}{dE_R} = \frac{m_A}{2\mu_A^2\nu^2}(\sigma_{SI} F_{SI}^2(E_R) + \sigma_{SD} F_{SD}^2(E_R))
\]

Spin-independent and spin-dependent cross sections at zero momentum transfer

Nuclear form factors
Theoretical interpretation of the experimental results

Uncertainties from astrophysics

- Local dark matter density?

- “local measurements”:
  From vertical kinematics of stars near (~1 kpc) the Sun

- “global measurements”:
  From extrapolations of $\rho(r)$ determined from rotation curves at large $r$, to the position of the Solar System.

Read '14
Theoretical interpretation of the experimental results

Uncertainties from astrophysics

- Local dark matter velocity distribution?

  **Completely unknown.** Rely on theoretical considerations

  - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.

  $\rho(r) \sim \frac{1}{r^2} \rightarrow f(v) \sim \exp\left(-\frac{v^2}{v_0^2}\right)$
Theoretical interpretation of the experimental results

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  - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
Theoretical interpretation of the experimental results

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- Local dark matter velocity distribution?
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    - If the density distribution follows a singular isothermal sphere profile, the velocity distribution has a Maxwell-Boltzmann form.
    - Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
    - Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.

![Graphs showing velocity distribution](image-url)

Bozorgnia et al'16
Theoretical interpretation of the experimental results

Common approach: assume SI or SD interaction only, assume $\rho_{\text{loc}} = 0.3 \text{ GeV/cm}^3$ and assume a Maxwell-Boltzmann velocity distribution.

### SI

- DAMA/LIBRA
- Super-K
- IceCube
- CDMS
- Xenon100
- LUX
- PandaX
- Xenon1

### SD

- DAMA/LIBRA
- PICASSO
- COUPP
- Super-K
- PICO-2L
- IceCube
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2. explains the DAMA results, but is ruled out by other direct detection experiments and by neutrino telescopes
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Are all particle physics models covered?
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What is the impact of the astrophysical uncertainties on these conclusions?

Do these conclusions hold for arbitrary velocity distributions?
Addressing theoretical uncertainties in dark matter detection
Addressing uncertainties in dark matter detection
Addressing uncertainties in dark matter detection
The effective theory of dark matter-nucleon interactions

In the non-relativistic limit, the scattering amplitude is restricted by:

- momentum conservation
- Galilean invariance

Most general form of the invariant amplitude:

\[ \mathcal{M} = \mathcal{M}(\vec{q}, \vec{u}, \vec{S}_X, \vec{S}_N) \]
The effective theory of dark matter-nucleon interactions

In the non-relativistic limit, the scattering amplitude is restricted by:

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Most general form of the invariant amplitude:

\[ \mathcal{M} = \mathcal{M}(\vec{q}, \vec{v}^\perp, \vec{S}_\chi, \vec{S}_N) \]

- Momentum transfer
- “Transverse velocity”
- Dark matter spin
- Nuclear spin

\[ \vec{v}^\perp \equiv \vec{v} + \frac{\vec{q}}{2\mu_N} \]
\[ \vec{v}^\perp \cdot \vec{q} = 0 \]
The effective theory of dark matter-nucleon interactions

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- Galilean invariance

Most general form of the invariant amplitude:

\[ \mathcal{M} = \mathcal{M}(\vec{q}, \vec{v}^\perp, \vec{S}_X, \vec{S}_N) \]

The Hamiltonian of the system must be a combination of operators that depend only on \(i\vec{q}, \vec{v}^\perp, \vec{S}_X, \vec{S}_N, 1\)
The effective theory of dark matter–nucleon interactions

14 possible operators, up to first order in the velocity and momentum transfer:

\[
\mathcal{O}_1 = 1_{\chi N}
\]
\[
\mathcal{O}_3 = i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v} \right)
\]
\[
\mathcal{O}_4 = \vec{S}_x \cdot \vec{S}_N
\]
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\mathcal{O}_5 = i \vec{S}_x \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v} \right)
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\mathcal{O}_6 = \left( \vec{S}_x \cdot \frac{\vec{q}}{m_N} \right) \left( \vec{S}_N \cdot \frac{\vec{q}}{m_N} \right)
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\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}
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\mathcal{O}_{15} = - \left( \vec{S}_x \cdot \frac{\vec{q}}{m_N} \right) \left[ \left( \vec{S}_N \times \vec{v} \right) \cdot \frac{\vec{q}}{m_N} \right]
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\[ \mathcal{O}_3 = i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{u}^\perp \right) \]
\[ \mathcal{O}_4 = \vec{S}_x \cdot \vec{S}_N \]
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Hamiltonian: \[ \mathcal{H}_N(r) = \sum_k c_k \mathcal{O}_k(r) \]
The effective theory of dark matter-nucleon interactions

14 possible operators, up to first order in the velocity and momentum transfer:

\[
\begin{align*}
\mathcal{O}_1 &= \mathbb{1}_{\chi N} \\
\mathcal{O}_3 &= i \vec{\mathcal{S}}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \\
\mathcal{O}_4 &= \vec{\mathcal{S}}_\chi \cdot \vec{\mathcal{S}}_N \\
\mathcal{O}_5 &= i \vec{\mathcal{S}}_\chi \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \\
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\end{align*}
\]

Hamiltonian: $\mathcal{H}_N(r) = \sum_{\tau=0,1} \sum_k c_k^\tau \mathcal{O}_k(r) t^\tau$

\[
\begin{align*}
\mathbf{t}^0 &= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\
\mathbf{t}^3 &= \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \\
c_k^0 &= \frac{c_k^0 + c_k^1}{2} \\
c_k^1 &= \frac{c_k^0 - c_k^1}{2}
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\[ c_k^0 = (c_k^0 + c_k^1)/2 \]

\[ c_k^1 = (c_k^0 - c_k^1)/2 \]

\[ \mathcal{O}_1 = 1 \times N \quad \text{SI interaction} \]

\[ \mathcal{O}_3 = i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \]

\[ \mathcal{O}_4 = \vec{S}_x \cdot \vec{S}_N \quad \text{SD interaction} \]

\[ \mathcal{O}_5 = i \vec{S}_x \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \]

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So what?
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\]

In some models, the leading operator is \( q \)-dependent or \( v \)-dependent

- e.g. Dirac fermion DM with pseudo-scalar mediator \( \leftrightarrow \mathcal{O}_6 \)
- Anapole interaction \( \leftrightarrow \mathcal{O}_8, \mathcal{O}_9 \)

So what?

Fitzpatrick et al'12
Anand et. al'13
Gluscevic et. al'15
The effective theory of dark matter-nucleon interactions

14 possible operators, up to first order in the velocity and momentum transfer:

\[ \mathcal{O}_1 = 1_{\chi N} \]
\[ \mathcal{O}_3 = i \vec{S}_N \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \]
\[ \mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N \]
\[ \mathcal{O}_5 = i \vec{S}_\chi \cdot \left( \frac{\vec{q}}{m_N} \times \vec{v}^\perp \right) \]
\[ \mathcal{O}_6 = \left( \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left( \vec{S}_N \cdot \frac{\vec{q}}{m_N} \right) \]
\[ \mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp \]
\[ \mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp \]
\[ \mathcal{O}_9 = i \vec{S}_\chi \cdot \left( \vec{S}_N \times \frac{\vec{q}}{m_N} \right) \]
\[ \mathcal{O}_{10} = i \vec{S}_N \cdot \frac{\vec{q}}{m_N} \]
\[ \mathcal{O}_{11} = i \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \]
\[ \mathcal{O}_{12} = \vec{S}_\chi \cdot \left( \vec{S}_N \times \vec{v}^\perp \right) \]
\[ \mathcal{O}_{13} = i \left( \vec{S}_\chi \cdot \vec{v}^\perp \right) \left( \vec{S}_N \cdot \frac{\vec{q}}{m_N} \right) \]
\[ \mathcal{O}_{14} = i \left( \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left( \vec{S}_N \cdot \vec{v}^\perp \right) \]
\[ \mathcal{O}_{15} = - \left( \vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left[ \left( \vec{S}_N \times \vec{v}^\perp \right) \cdot \frac{\vec{q}}{m_N} \right] \]

So what?

In some models, the leading operator is \( q \)-dependent or \( v \)-dependent

The effective theory description includes all possible dark matter models (with a heavy mediator)
The effective theory of dark matter–nucleon interactions

Some applications:

1) Model independent analysis of null search experiments (in the same spirit as for the “traditional” SI and SD interactions)

Liu et al. '17
Fitzpatrick et al'12
Catena, Gondolo'15

\[ \mathcal{O}_1 \equiv 1_{\chi N} \]

\[ \mathcal{O}_4 \equiv S_{\chi} \cdot S_N \]

\[ M \]

\[ \Sigma'' + \Sigma' \]
The effective theory of dark matter–nucleon interactions

Some applications:

1) Model independent analysis of null search experiments (in the same spirit as for the “traditional” SI and SD interactions)

\[ \mathcal{O}_6 = (S_\chi \cdot \frac{q}{m_N})(S_N \cdot \frac{q}{m_N}) \]

\[ \mathcal{O}_8 = S_\chi \cdot \nu^\perp \]

Liu et al. '17

Fitzpatrick et al. '12
Catena, Gondolo '15
The effective theory of dark matter-nucleon interactions

Some applications:

1) Model independent analysis of null search experiments (in the same spirit as for the “traditional” SI and SD interactions

2) Model independent analysis of the DAMA signal, in view of the null results from other direct detection experiments.

\[
\text{event rate } \propto c^T X c
\]
The effective theory of dark matter–nucleon interactions

Some applications:

1) Model independent analysis of null search experiments (in the same spirit as for the “traditional” SI and SD interactions)

2) Model independent analysis of the DAMA signal, in view of the null results from other direct detection experiments.
Addressing uncertainties in dark matter detection

Particle physics

Astrophysics

MB velocity distribution

SI, SD interaction

Particle physics
Halo independent approach for DM frameworks

\( (\sigma, m_{DM}) \) is ruled out regardless of the velocity distribution if

\[
\min_{f(\vec{v})} \left\{ R(\sigma, m_{DM}) \right\} > R_{\text{max}}
\]
Halo independent approach for DM frameworks

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Note: one single direct detection experiment is not sufficient to probe a dark matter model in a halo-independent manner.
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Note: one single direct detection experiment is not sufficient to probe a dark matter model in a halo-independent manner.

Some velocity distributions will escape detection in the experiment.
Halo independent approach for DM frameworks

- \((\sigma, m_{DM})\) is ruled out regardless of the velocity distribution if

\[
\min_{f(\vec{v})} \left\{ R(\sigma, m_{DM}) \right\} > R_{\text{max}}
\]

Note: one single direct detection experiment is not sufficient to probe a dark matter model in a halo-independent manner

Neutrino telescopes probe low dark matter velocities. In combination with direct detection experiments, one can probe the whole velocity space.
Halo independent approach for DM frameworks

- $(\sigma, m_{DM})$ is ruled out regardless of the velocity distribution if

$$\min_{f(\sigma)} \left\{ R(\sigma, m_{DM}) \right\} > R_{\text{max}}$$

Optimization problem with constraints

$$\min_{f(\vec{v})} \left\{ R(\sigma, m_{DM}) \right\} \bigg|_{C(\sigma,m) \leq C_{\text{max}}} > R_{\text{max}}$$
Halo independent approach for DM frameworks

Technically complicated...

\[ R(\sigma, m_{\text{DM}}) = \int_{E_{\text{th}}}^{\infty} dE_R \frac{\rho_{\text{loc}}}{m_A m_{\text{DM}}} \int_{v \geq v_{\text{min}}(E_R)} d^3v \sqrt{v + \vec{v}_{\text{obs}}(t)} \frac{d\sigma}{dE_R} \]

\[ C(\sigma, m_{\text{DM}}) = \int_0^{R_{\odot}} 4\pi r^2 dr \frac{\rho_{\text{loc}}}{m_{\text{DM}}} \int_{v \leq v_{\text{max}}(r)} d^3v \frac{f(\bar{v})}{v} \left( v^2 + [v_{\text{esc}}(r)]^2 \right) \times \]

\[ \int \frac{2\mu_A^2 (v^2 + [v_{\text{esc}}(r)]^2)}{m_A} dE_R \frac{d\sigma}{dE_R} \int m_{\text{DM}}v^2/2 \]
Halo independent approach for DM frameworks

Technically complicated...

\[ R(\sigma, m_{DM}) = \int_{E_{th}}^{\infty} dE_R \frac{\rho_{loc}}{m_A m_{DM}} \int_{v \geq v_{\text{min}}(E_R)} d^3 \vec{v} \sqrt{f(\vec{v} + \vec{v}_{\text{obs}}(t))} \frac{d\sigma}{dE_R} \]

\[ C(\sigma, m_{DM}) = \int_0^{R_\odot} 4\pi r^2 dr \frac{\rho_{loc}}{m_{DM}} \int_{v \leq v_{\text{max}}^{(\text{Sun})}(r)} dv \sqrt{\frac{f(\vec{v})}{v^2 + [v_{\text{esc}}(r)]^2}} \times \]

\[ \int \frac{2\mu_A^2 (v^2 + [v_{\text{esc}}(r)]^2) / m_A}{m_{DM} v^2 / 2} dE_R \frac{d\sigma}{dE_R} \]

The objective function and the constraints are both linear in the velocity distribution \( \leftrightarrow \) Optimize using linear programming techniques.
The objective function and the constraints are both linear in the velocity distribution → Optimize using linear programming techniques.

The optimal solution consists of a superposition of dark matter streams with fixed velocity and fixed direction. (One can show that the number of streams is less or equal to the number of constraints.)
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Spin-independent interaction

\[ \sigma_{SI} \rho_{0.3 \text{ GeV/cm}^3} \] vs. \( m_{DM} \) [GeV]
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Spin-independent interaction

\[ \sigma_{\text{SI}} \cdot \rho_{0.3 \text{ GeV/cm}^3} \]

Halo independent upper limit (neutrino telescopes only)

IceCube/Super-Kamiokande (SHM)

Halo independent upper limit

PandaX (SHM)

AI, Rappelt '17
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Spin-independent interaction

![Graph showing halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.]

\[ \sigma_{SI} \cdot \rho_0.3 \text{ GeV/cm}^3 \]

- Halo independent upper limit (neutrino telescopes only)
- IceCube/Super-Kamiokande (SHM)
- Halo independent upper limit
- PandaX (SHM)

1 is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Spin-independent interaction

1 is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions.

2 is ruled out from combining PandaX and neutrino telescopes, for *any* velocity distribution.
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Spin-independent interaction

1 is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions.

2 is ruled out from combining PandaX and neutrino telescopes, for any velocity distribution.

3 is ruled out by neutrino telescopes only, for any velocity distribution.
**Halo independent prospects for future experiments**

The parameters $\sigma$ and $m_{\text{DM}}$ are **fully testable** in a halo independent manner if:

$$\min_{f(\bar{v})} \left\{ R^{(LZ)}(\sigma, m_{\text{DM}}) \right\}_{\text{constraints}} > 1$$

The parameters $\sigma$ and $m_{\text{DM}}$ are **untestable** in a halo independent manner if:

$$\max_{f(\bar{v})} \left\{ R^{(LZ)}(\sigma, m_{\text{DM}}) \right\}_{\text{constraints}} < 1$$

LZ reach to the SI cross-section from null results at neutrino telescopes.
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

It is unlikely that the halo independent upper limit saturates (it is unlikely that the velocity distribution consists just on two streams). Add physically plausible assumptions (e.g. MB distribution + “distortions”).

\[ f(v) \]
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

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It is unlikely that the halo independent upper limit saturates (it is unlikely that the velocity distribution consists just on two streams). Add physically plausible assumptions (e.g. MB distribution + “distortions”).
DAMA confronted to null results in a halo independent way

**Strategy:** minimize the rate at a given experiment, with the constraints that the modulation signal at DAMA in the bins [2.0,2.5], [2.5,3.0] and [3.0,3.5] keV are as reported by the experiment.

The parameters $\sigma$ and $m_{\text{DM}}$ are excluded in a halo independent manner if:

$$\min_{f(\vec{v})} \left\{ R^{(\text{PandaX})}(\sigma, m_{\text{DM}}) \right\} \bigg|_{\text{constraints}} \geq R^{(\text{PandaX})}_{\text{max}}$$
**DAMA confronted to null results in a halo independent way**

**Strategy**: minimize the rate at a given experiment, with the constraints that the modulation signal at DAMA in the bins [2.0, 2.5], [2.5, 3.0] and [3.0, 3.5] keV are as reported by the experiment.

The parameters $\sigma$ and $m_{\text{DM}}$ are excluded in a halo independent manner if:\n
\[
\min_{f(\nu)} \left\{ C^{(\text{NT})}(\sigma, m_{\text{DM}}) \right\} \bigg|_{\text{constraints}} \geq C^{(\text{NT})}_{\text{max}}
\]

---

**SI interaction only**

![Graph showing excluded regions for DAMA and PandaX](image1.png)

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![Graph showing excluded regions for DAMA and IceCube/Super-Kamiokande](image2.png)
DAMA confronted to null results in a halo independent way

Strategy 2: minimize the rate at a given direct detection experiment, with the constraints that the modulation signal at DAMA in the bins $[2.0,2.5]$, $[2.5,3.0]$ and $[3.0,3.5]$ keV are as reported by the experiment, and the capture rate at IceCube is below the current upper limit.

The parameters $\sigma$ and $m_{\text{DM}}$ are excluded in a halo independent manner if:

$$\min_{f(\vec{v})} \left\{ R^{(\text{PandaX})}(\sigma, m_{\text{DM}}) \right\}_{\text{constraints}} \geq R^{(\text{PandaX})}_{\text{max}}$$

SI interaction only

AI, Rappelt '17
DAMA confronted to null results in a halo independent way

Strategy 2: minimize the rate at a given direct detection experiment, with the constraints that the modulation signal at DAMA in the bins [2.0,2.5], [2.5,3.0] and [3.0,3.5] keV are as reported by the experiment, and the capture rate at IceCube is below the current upper limit.

The parameters $\sigma$ and $m_{\text{DM}}$ are excluded in a halo independent manner if:

$$\min_{f(\vec{v})} \left\{ R^{(\text{PandaX})}(\sigma, m_{\text{DM}}) \right\}_{\text{constraints}} \geq R^{(\text{PandaX})}_{\text{max}}$$

SD interaction only

AI, Rappelt '17
DAMA confronted to null results in a halo independent way

Strategy 2: minimize the rate at a given direct detection experiment, with the constraints that the modulation signal at DAMA in the bins [2.0,2.5], [2.5,3.0] and [3.0,3.5] keV are as reported by the experiment, and the capture rate at IceCube is below the current upper limit.

The parameters $\sigma$ and $m_{DM}$ are excluded in a halo independent manner if:

$$\min_{f(\vec{v})} \left\{ R^{(\text{PandaX})}(\sigma, m_{DM}) \right\}_{\text{constraints}} \geq R^{(\text{PandaX})}_{\text{max}}$$

Allowed in our analysis, but possibly ruled out:
- Unlikely that the velocity distribution consists of 5 streams.
- A small smearing of the streams spoils the solution
- Only the modulation signals were used, but not the time dependence of the signal

![Graph showing residuals over time](image)
Addressing uncertainties in dark matter detection
CDMS-Si confronted to null results in a halo independent way

The silicon detectors of the CDMS II experiments observed three DM candidate events, with relatively little exposure (23.4 kg day).
The silicon detectors of the CDMS II experiments observed three DM candidate events, with relatively little exposure (23.4 kg day). Is the DM interpretation ruled out, for all models and all velocity distributions?
Future prospects
Summary and outlook

- The interpretation of any experiment probing the dark matter distribution inside the Solar System is challenged by our ignorance of the concrete form of the DM-nucleus interaction and of the local dark matter density and velocity distribution.

- In recent years some methods have been developed to address both, thus allowing to make statements about the outcome of experiments with fewer assumptions.

- These techniques are important to “make the best” out of the experiments, and are specially relevant to scrutinize a possible dark matter signal.