Addressing theoretical uncertainties in direct dark matter searches

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In collaboration with Andreas Rappelt, arXiv:1703.09168
There is evidence for dark matter in a wide range of distance scales.
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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 WIMP dark matter 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.

Sun

$\approx 200 \text{ km/s}$

WIMPs

$\approx 200 \text{ km/s}$
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.

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.
Direct dark matter searches

no evidence for DM-induced nuclear recoils
Annual modulation
Annual modulation

- June 2nd
- December 2nd
Annual modulation

Modulation signal

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

Modulation observed over 14 annual cycles, with a combined significance of 9.3σ.

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

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

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

IceCube collaboration
ArXiv:1612.05949
Theoretical interpretation of the experimental results
Theoretical interpretation of the experimental results

• Rate of DM-induced scatterings

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

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

\[
C = \int_0^{R_{\odot}} 4\pi r^2 dr \frac{\rho_{\text{loc}}}{m_{\text{DM}}} \int_{v \leq (v_{\text{max}}^{\text{Sun}})} d^3v \frac{f(\vec{v})}{v} (v^2 + [v_{\text{esc}}(r)]^2) \times \\
\int_{m_{\text{DM}} v^2 / 2}^{2\mu_A^2 (v^2 + [v_{\text{esc}}(r)]^2) / m_A} \frac{dE_R}{dE_R}
\]
Theoretical interpretation of the experimental results

- Rate of DM-induced scatterings

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

Uncertainties from particle/nuclear physics and from astrophysics

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

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

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

\[
\int \frac{m_{\text{DM}} v^2}{2}
\]
Theoretical interpretation of the experimental results

Uncertainties from particle/nuclear physics.

- Dark matter mass?

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

- Differential cross section?

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

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

(In some DM frameworks, other operators may also arise)
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.

  \[ \rho(r) \sim \frac{1}{r^2} \quad \longrightarrow \quad f(v) \sim \exp(-v^2/v_0^2) \]
Theoretical interpretation of the experimental results

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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
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.
- Dark matter-only simulations. Show deviations from Maxwell-Boltzmann
- Hydrodynamical simulations (DM+baryons). Inconclusive at the moment.

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Bozorgnia et al'16
**Theoretical interpretation of the experimental results**

Common approach: assume SI or SD interaction only, assume $r_{\text{loc}} = 0.3$ GeV/cm$^3$ and assume a Maxwell-Boltzmann velocity distribution.
Theoretical interpretation of the experimental results

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SI

1 is ruled out (by PandaX, among others)
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

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2. explains the DAMA results, but is ruled out by other direct detection experiments and by neutrino telescopes

![Graph showing cross-section vs. WIMP mass with various experimental data points and curves, indicating the theoretical interpretations and exclusions.](image-url)
Theoretical interpretation of the experimental results

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3. is allowed by current experiments, and will be tested by LZ.
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What is the impact of the astrophysical uncertainties?
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What is the impact of the astrophysical uncertainties?

Do these conclusions hold for arbitrary velocity distributions?
Addressing astrophysical uncertainties in dark matter detection
Halo-independent approach for DM frameworks

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

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

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\]

Fix \(\sigma, m_{\text{DM}}\)
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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

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

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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

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

Optimization problem with constraints
Halo-independent approach for DM frameworks

Technically complicated...

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

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

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

\[ dE_R \frac{d\sigma}{dE_R} \]
Halo-independent approach for DM frameworks

Technically complicated...

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

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

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

Take-home result:

The velocity distribution that minimizes the rate is composed by a number of dark matter “streams”, at most as many as constraints.
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.
Spin-independent interaction

The optimal velocity distribution corresponds to a superposition of two dark matter streams.

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
Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

Spin-independent interaction

![](graph.png)

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

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

Halo-independent upper limit on the scattering cross section from combining PandaX and IceCube/SK.

- is ruled out by PandaX assuming the SHM, but allowed for some velocity distributions
- 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 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 of two streams). Add physically plausible assumptions (e.g. MB distribution + “distortions”).

Spin-independent interaction
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:

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

![SI interaction only](image)
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 $m_{DM}$ are excluded in a halo independent manner if:

$$\min_{f(\nu)} \left\{ C^{(NT)}(\sigma, m_{DM}) \right\}_{\text{constraints}} \geq C^{(NT)}_{\text{max}}$$

---

Graphs showing the excluded regions for DAMA-1 (SHM), PandaX (SHM), DAMA-Na (SHM), and IceCube/Super-Kamiokande (SHM) in the $(m_{DM}, \sigma)$ plane.
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

At least 3000 events expected at Panda-X

AI, Rappelt '17
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
Conclusions

- The interpretation of any experiment probing the dark matter distribution inside the Solar System is subject to our ignorance of the local dark matter density and velocity distribution.

- We have developed a method to calculate the minimum/maximum number of signal events in an experiment probing the dark matter distribution inside the Solar System, in view of a number of constraints from direct detection experiments and/or neutrino telescopes.

- Some applications are:
  i) to derive a halo-independent upper limit on the cross section from a set of null results.
  ii) to confront in a halo-independent way a detection claim to a set of null results.
  iii) to assess, in a halo-independent manner, the prospects for detection in a future experiment given a set of current null results.

- The method could be extended to include other dark matter interactions, or to account for more realistic velocity configurations.