Dark Matter annihilation to neutrinos: New limits and future prospects

Ibrahim Safa in collaboration with:
Carlos Argüelles, Ali Kheirandish, Andrés Olivares Del-Campo, and Aaron Vincent

Thermal Relic Abundance
Outline

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- Expected neutrino flux at Earth
  - Galactic Contribution
  - Extragalactic Contribution
- Relevant experiments
- Results/Future Prospects
- Summary
Motivation

๏ Dark matter gravitational effects unambiguously observed.

๏ Merging halos + CMB measurements hint at a particle nature of DM.

๏ Gauge invariant models where neutrinos are the dominant SM product have been proposed (1903.00006).

๏ Neutrinos are our only evidence of new physics Beyond the SM and could be the link to the dark sector.
Indirect Detection

Indirect signatures in the neutrino sector include:

- Features in geo, solar, atmospheric, and astrophysical neutrino spectra due to annihilation/decay.
- Anisotropies in the angular distributions of high-energy neutrinos due to DM-nu scattering.
- Features in the diffuse supernova neutrino background.
Galactic contribution

Flux of neutrinos from Dark matter annihilation in our very own galaxy is

\[
\frac{d\Phi_\nu}{dE} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{1}{3} \frac{dN_\nu}{dE} J(\Omega),
\]

\[\langle \sigma v \rangle \text{ & } m_\chi\]

Are the thermally averaged annihilation cross section, and the dark matter mass, respectively.

\[
\frac{dN_\nu}{dE} = \delta(m_\chi - E_\nu)
\]

is the neutrino production spectrum. In this work, we study direct annihilation to neutrinos.

\[J \equiv \int d\Omega \int_{l.o.s.} \rho_\chi^2(x) dx,\]

is a three-dimensional integral over the target solid angle in the sky d\Omega and the line of sight and is referred to as the ‘J-factor’.
Dark Matter Profile

- We use a generalized NFW profile:

\[ \rho = \frac{2^{3-\gamma} \rho_s}{\left(\frac{r}{r_s}\right)^\gamma \left(1 + \frac{r}{r_s}\right)^{3-\gamma}} \]

- 1901.02460 fits for the above free parameters using the “Rotation Curve” method.

- Limits here use the best-fit parameters and uncertainties are accounted for.
Extragalactic contribution

An isotropic neutrino signal is also expected due to annihilation of dark matter in every other galactic halo, and is given by

\[
\frac{d\Phi_\nu}{dE} = \frac{c}{4\pi} \frac{\Omega_{DM}^2 \rho_{\text{crit}}^2 \langle \sigma v \rangle}{2 m_{\chi}^2} \int_{0}^{z_{\text{up}}} \frac{(1 + G(z))(1 + z)^3}{H(z)} \frac{dN_\nu(E')}{dE},
\]

where

\[
G(z) = \frac{1}{\Omega_{DM,0}^2 \rho_c^2} \frac{1}{(1 + z)^6} \int dM \frac{dn(M, z)}{dM} \int dr \ 4\pi r^2 \rho_{\text{halo}}(r).
\]

Time-dependent Hubble parameter

\[
H(z) = H_0 \left[ (1 + z)^3 \Omega_{DM} + \Omega_\Lambda \right]^{1/2}
\]

Production spectrum

\[
\frac{2}{3E} \delta \left[ z - \left( \frac{m_\chi}{E} - 1 \right) \right]
\]
Halo Uncertainties

- We adopt four halo mass function (hmf) parameterizations.
- The band shows the uncertainty from the choice of minimum halo mass from $10^{-9}$ to $10^{-3} \, M_{\text{sun}}$
- Limits shown in this work use Watson et. al (calibrated using N-body simulations) and the most conservative choice of minimum mass ($M_{\text{min}} = 10^{-3} \, M_{\text{sun}}$).
Super-Kamiokande

- 50K ton water Cherenkov detector located in the Kamioka mine, Japan.

- Dark Matter annihilation signatures can be found by looking for:
  - Excess in the direction of the galactic center above $\nu_e$ and $\nu_\mu$ atmospheric neutrinos in the 1 GeV-10 TeV range.
  - Excess in the diffuse atmospheric flux from the extragalactic contribution.
  - Excess above the Diffuse Supernova Neutrino Background in the $15 - 10^3$ MeV range.
IceCube

- 1 Gton of antarctic ice instrumented with ~5800 PMTs.
- IceCube has measured a diffuse astrophysical neutrino flux in the TeV-10PeV range.
- Atmospheric neutrinos measured by DeepCore and IceCube in the GeV - 100 TeV range.
- Competitive limits on the cosmogenic neutrino flux.
- Dark matter - neutrino connections manifest as features in the above measured spectra.
Expected neutrino flux
And many, many more

- **Borexino**: Organic liquid scintillator experiment in Gran Sasso, Italy. Measures solar neutrinos (MeV).

- **ANTARES**: Water Cherenkov detector in the Mediterranean Sea. Has measured atmospheric neutrinos (GeV-TeV).

- **CTA**: Air Cherenkov telescope array. Designed for high energy gamma-rays. Will have sensitivity to muon and tau-neutrinos interacting in the atmosphere (TeV).


- **ANITA**: Radio balloon flying above Antarctica. Has set limits on the cosmogenic neutrino flux (EeV).

- **GRAND**: Proposed radio array that will (hopefully) detect mountain-skimming tau-neutrinos (EeV).
Results: s-wave

\[ \langle \sigma v \rangle \propto k \]
Results: s-wave

\[ \langle \sigma v \rangle \propto k \]
Results: s-wave (High-Mass region)

\[ \langle \sigma v \rangle \propto k \]
Results: p-wave

\(\langle \sigma v \rangle \propto v^2\)

\[m \geq 10^3 \text{ [GeV]}\]

\[\langle \sigma v \rangle \text{ [cm}^3 \text{/s]}\]

\[m_X \text{ [GeV]}\]
Summary

- Both the nature of Dark Matter and its connection to the Standard Model are still open questions.
- Neutrinos are the first chink in the SM armor. New physics in the neutrino sector is inevitable.
- Indirect detection of Dark Matter in the neutrino channel is a necessary complement to searches via charged particles.
- We have updated existing limits and derived new ones in the MeV to EeV range, this work will appear soon.
- Next-generation experiments will dip their toes in the thermal relic abundance region.
- Lots of work to do!
Backups
ANTARES

- ANTARES: Roughly 10% of IceCube volume in the Mediterranean Sea.

- Photon scattering length in the Mediterranean is much longer than in ice. ANTARES has, on average, better angular resolution.

- Galactic center is below the horizon more than 50% of the time. Earth can be used as a veto to cosmic-ray muons.
Dark Matter Profile Uncertainties

![Graph showing the thermal relic abundance and dark matter profile uncertainties.](image-url)

- **Borexino**
- **SuperK Low Energy**
- 2σ (Fabio)
- 2σ (Fabio + GRAVITY)

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<th>$m_\chi$ (GeV)</th>
<th>(σv) (cm$^3$/s)</th>
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Velocity-dependent J-factors

\[ \langle v^n \rangle = \int d^3v v^n f(v, r), \]  
\( f \) is the normalized dark matter phase space distribution

\[ \langle v^2 \rangle = 3v_0^2(r), \]  
For p-wave

\[ \langle v^4 \rangle = 15v_0^4(r). \]  
For d-wave

\( v_0 \) can be found by solving the spherical Jeans equation, assuming isotropy:

\[ \frac{d(\rho(r)v_0^2(r))}{dr} = -\rho(r)\frac{d\phi(r)}{dr} \]  
\( \phi \) here is the gravitational potential and includes the halo, bulge and disk contributions

\[ J_{vn} = \int d\Omega \int_{1.o.s.} \langle (v/c)^n \rangle(r)\rho_\chi^2(r)dx. \]  
Modified J-Factor
Uncertainties from choice of minimum halo mass

Watson et. al (2012)

\[ \langle \sigma v \rangle \text{ [cm}^3 \text{/s]} \]

\[ m_\chi \text{ [GeV]} \]

\[ M_{\text{min}} = 10^{-3} \]
\[ M_{\text{min}} = 10^{-6} \]
\[ M_{\text{min}} = 10^{-9} \]

Tinker et. al (2008)

\[ \langle \sigma v \rangle \text{ [cm}^3 \text{/s]} \]

\[ m_\chi \text{ [GeV]} \]

\[ M_{\text{min}} = 10^{-3} \]
\[ M_{\text{min}} = 10^{-6} \]
\[ M_{\text{min}} = 10^{-9} \]