Indirect DM searches with neutrinos
Neutrinos as dark matter

Talk by K. Abazajian

Dark matter

Neutrino 2020

Sergio Palomares-Ruiz
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Talk by K. Abazajian

Neutrinos with dark matter detectors

Talk by J. Monroe
Neutrinos as dark matter

Talk by
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Talk by
C. Frugiuele

Dark sector with fixed-target experiments

Neutrinos with dark matter detectors

Indirect DM searches with neutrinos
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Talk by K. Abazajian

Talk by J. Monroe

This talk

Talk by C. Frugiuele

Indirect dark matter with neutrino (detectors)

Dark sector with fixed-target experiments

Indirect DM searches with neutrinos
Indirect dark matter searches with neutrinos
Indirect dark matter searches with neutrinos

New signal

$\Phi$ vs $E$
Indirect dark matter searches with neutrinos

Features on known spectra

New signal
Indirect dark matter searches with neutrinos

New signal

Features on known spectra

Cosmo/Astro effects

Indirect DM searches with neutrinos
**(Standard) Grand Unified Neutrino Spectrum**

![Diagram showing the Grand Unified Neutrino Spectrum (GUNS) at Earth, integrated over directions and summed over flavors.](image)

Therefore, flavor conversion between source and detector does not affect this plot. Solid lines are for neutrinos, dashed or dotted lines for antineutrinos, superimposed dashed and solid lines for sources of both $\mu$ and $\tau$. The fluxes from BBN, the Earth, and reactors encompass only antineutrinos, the Sun emits only neutrinos, whereas all other components include both. The CNB is shown for a minimal mass spectrum of $m_1 = 0$, $m_2 = 8.6$, and $m_3 = 50$ meV, producing a blackbody spectrum plus two monochromatic lines of nonrelativistic neutrinos with energies corresponding to $m_2$ and $m_3$. See Appendix D for an exact description of the individual curves.

**Top panel:** Neutrino flux as a function of energy; line sources in units of $\text{cm}^{-2} \text{s}^{-1}$.

**Bottom panel:** Neutrino energy flux $E\Phi$ as a function of energy; line sources in units of $\text{eV cm}^{-2} \text{s}^{-1}$.

- **Mixing with hypothetical sterile neutrinos**
- **Large nonstandard interactions**
- **Spin-flavor oscillations by large nonstandard magnetic dipole moments**
- **Decays and annihilation into majoron-like bosons**
- **For the CNB large primordial asymmetries and other novel early-universe phenomena**
- **Or entirely new sources such as dark-matter annihilation in the Sun or Earth.**

We will usually not explore such topics and rather stay in a minimal framework which of course includes normal flavor oscillations.

In the main part of the paper we walk the reader through the GUNS plots of Fig. 1 and briefly review the different components approximately in increasing order of energy. In Sec. II we begin with the CNB, discussing primarily the impact of neutrino masses. In Fig. 1 we show a minimal example where the smallest neutrino mass vanishes, providing the traditional blackbody radiation, and two mass components which must be nonrelativistic today.

In Sec. III we turn to neutrinos from the big-bang nucleosynthesis (BBN) epoch that form a small but dominant contribution at energies just above the CNB. This very recently recognized flux derives from neutron and triton decays, $n \to p + e^- + \bar{\nu}_e$ and $^3\text{H} \to ^3\text{He} + e^- + \bar{\nu}_e$, that are left over from BBN.

In Sec. IV we discuss the following components:

- **Solar** (thermal)
- **Solar** (nuclear)
- **Reactors**
- **Geoneutrinos**
- **Atmospheric**
- **Cosmogenic**
- **DSNB**
- **BBN**

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(Standard) Grand Unified Neutrino Spectrum


FIG. 1. Grand Unified Neutrino Spectrum (GUNS) at Earth, integrated over directions and summed over flavors. Therefore, flavor conversion between source and detector does not affect this plot. Solid lines are for neutrinos, dashed or dotted lines for antineutrinos, superimposed dashed and solid lines for sources of both $\nu$ and $\bar{\nu}$. The fluxes from BBN, the Earth, and reactors encompass only antineutrinos, the Sun emits only neutrinos, whereas all other components include both. The CNB is shown for a minimal mass spectrum of $m_1 = 0$, $m_2 = 8.6$, and $m_3 = 50$ meV, producing a blackbody spectrum plus two monochromatic lines of nonrelativistic neutrinos with energies corresponding to $m_2$ and $m_3$. See Appendix D for an exact description of the individual curves.

Top panel: Neutrino flux $\nu_\phi$ as a function of energy; line sources in units of $\text{cm}^{-2} \text{s}^{-1}$.

Bottom panel: Neutrino energy flux $E \nu_\phi$ as a function of energy; line sources in units of $\text{eV cm}^{-2} \text{s}^{-1}$.

mixing with hypothetical sterile neutrinos, large nonstandard interactions, spin-flavor oscillations by large nonstandard magnetic dipole moments, decays and annihilation into majoron-like bosons, for the CNB large primordial asymmetries and other novel early-universe phenomena, or entirely new sources such as dark-matter annihilation in the Sun or Earth. We will usually not explore such topics and rather stay in a minimal framework which of course includes normal flavor oscillations.

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Detected (or soon to be detected)
Indirect DM searches with neutrinos

Sergio Palomares-Ruiz

FIG. 1. Grand Unified Neutrino Spectrum (GUNS) at Earth, integrated over directions and summed over flavors. Therefore, flavor conversion between source and detector does not affect this plot. Solid lines are for neutrinos, dashed or dotted lines for antineutrinos, superimposed dashed and solid lines for sources of both \( \nu \) and \( \bar{\nu} \). The fluxes from BBN, the Earth, and reactors encompass only antineutrinos, the Sun emits only neutrinos, whereas all other components include both. The CNB is shown for a minimal mass spectrum of \( m_1 = 0 \), \( m_2 = 8.6 \), and \( m_3 = 50 \) meV, producing a blackbody spectrum plus two monochromatic lines of nonrelativistic neutrinos with energies corresponding to \( m_2 \) and \( m_3 \). See Appendix D for an exact description of the individual curves.

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Annihilation of captured DM in the Sun/Earth

Sensitive to scattering cross section
Only for $m > \text{few GeV}$

Annihilations/decays in halos

Sensitive to annihilation cross section (link to thermal production in the early Universe?) and lifetime

DM annihilations or decays
Dark Matter capture in the Sun/Earth

- Dark Matter capture
- Particle density $\rho_\chi$
- Velocity distribution
- Sun
- Earth
- Neutrino interactions
- Scatter cross section $\sigma_{\text{scatt}}$
- Capture rate $\Gamma_{\text{capture}}$
- Annihilation rate $\Gamma_{\text{annihilation}}$
- Neutrino $\nu_\mu$
- Muon $\mu$
- Detector

References:
Dark Matter capture in the Sun/Earth

- DM particles elastically scatter with the nuclei of the Sun to a velocity smaller than the escape velocity, and they can get gravitationally bound and finally trapped inside.

Additional scatterings give rise to an isothermal distribution.

\[
\Gamma(t_\odot) = \frac{1}{2} C_\odot \tanh^2 \left( \frac{t}{t_\odot} \right) = \frac{1}{2} C_\odot
\]

- Trapped DM particles can annihilate into SM particles.

- After some time, annihilation and capture rates typically equilibrate.

- Only neutrinos can escape.

\[
C_\odot \approx 9 \times 10^{23} \text{ s}^{-1} \left( \frac{\rho_0}{0.3 \text{ GeV/cm}^3} \right) \left( \frac{270 \text{ km/s}}{v_{\text{local}}} \right)^3 \left( \frac{\sigma_{\text{SD}}}{10^{-3} \text{ pb}} \right) \left( \frac{50 \text{ GeV}}{m_\chi} \right)^2
\]

References:

Evolution equation


\[
\frac{dN}{dt} = C_\odot - A_\odot N^2 - E_\odot N
\]

Capture rate
(velocity distribution and scattering cross section)

\[
N(t_\odot) = \frac{1}{\tau A_\odot \sqrt{1 + (E_\odot \tau_\odot / 2)(t_\odot / \tau_\odot)}} \tanh\left(\sqrt{1 + (E_\odot \tau_\odot / 2)(t_\odot / \tau_\odot)}\right)
\]

Annihilation rate
(annihilation cross section)

\[
\Gamma(t_\odot) = \frac{1}{2} A_\odot N(t_\odot)^2
\]

Evaporation rate
(distribution in the Sun and scattering cross section)

\[
E_\odot \approx 0 \rightarrow \Gamma(t_\odot) = \frac{1}{2} C_\odot \tanh^2\left(\frac{t_\odot}{\tau_\odot}\right)
\]

Neutrino spectra in the Sun

Propagation through the Sun and to the Earth:
absorption and oscillations

(relevant for \( m < \text{few GeV} \))
Indirect DM searches with neutrinos

\[
\frac{dN}{dt} = C_\odot - A_\odot N^2 - E_\odot N
\]

Capture rate  
(velocity distribution and scattering cross section)

Annihilation rate  
(annihilation cross section)

Evaporation rate  
(distribution in the Sun and scattering cross section)

Neutrino spectra in the Sun

\[
N(t_\odot) = \frac{1}{\tau_\odot A_\odot} \frac{1}{\sqrt{1 + (E_\odot \tau_\odot / 2)(t_\odot / \tau_\odot)}} \tanh\left(\sqrt{1 + (E_\odot \tau_\odot / 2)(t_\odot / \tau_\odot)}\right)
\]

\[
\Gamma(t_\odot) = \frac{1}{2} A_\odot N(t_\odot)^2
\]

\[
E_\odot \propto \tau_\odot \Rightarrow \Gamma(t_\odot) = \frac{1}{2} C_\odot \tanh^2(t_\odot / \tau_\odot)
\]

\[
\tau_\odot = \frac{1}{\sqrt{C_\odot A_\odot}}
\]

Propagation through the Sun and to the Earth: absorption and oscillations

Poster #434: Q. Liu

Sergio Palomares-Ruiz
**Limits from the Sun**

**SK: (3902.7 + 4206.7) days**

**Baksan: 24.12 yrs**
M. M. Boliev et al., JCAP 09:019, 2015

**Baikal: 1038 days**

**IceCube: 532 days**

**ANTARES: 5 yrs**

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**Figure 4:**
WIMP-proton SD (left) and SI (right) scattering cross-section limits as a function of WIMP mass for the three annihilation channels considered. Comparative between 5 years of ORCA simulated data, 5 years of ANTARES data [16], Ice Cube 3 years of data [22], Super Kamiokande 16 years [23] and PICO-60 [24] 1 year.

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**References**


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**Figure 4:**
Dark Matter from the Sun - KM3NeT-ORCA

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**References**


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Sergio Palomares-Ruiz

Indirect DM searches with neutrinos
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Prospects for INO
S. Choubey, A. Ghosh and D. Tiwari, JCAP 05:006, 2018

Prospects for DUNE
C. Rott et al., JCAP 07:006, 2019

Using KamLAND
J. Kumar and P. Sandick, JCAP 06:035, 2015

Using NOvA
Poster #358: M. Strait

From the Earth: IC 8 yrs
S. In and K. Wiebe [Icecube Coll.], PoS(ICRC2017)912, 2018

Latest results and sensitivities for solar dark matter searches with IceCube


S. In and K. Wiebe [Icecube Coll.], PoS(ICRC2017)912, 2018

Using KamLAND
J. Kumar and P. Sandick, JCAP 06:035, 2015

Using NOvA
Poster #358: M. Strait

From the Earth: IC 8 yrs
S. In and K. Wiebe [Icecube Coll.], PoS(ICRC2017)912, 2018

Usually only considered annihilations into heavy quarks, gauge bosons or tau leptons...

What about annihilations into light quarks, muons or even electrons?

Electrons/positrons do not produce neutrinos...

Muons lose energy electromagnetically very rapidly and decay at rest

\[ \tau_{\text{stop}} \approx 3 \cdot 10^{-10} \left( \frac{E}{10 \text{ GeV}} \right) s \ll \tau_{\text{decay}} \approx 2 \cdot 10^{-4} \left( \frac{E}{10 \text{ GeV}} \right) s \]

Light-quark hadrons, as pions, are stopped via nuclear interactions and decay at rest

\[ \tau_{\text{int}} \approx 10^{-11} s \ll \tau_{\text{decay}} \approx 10^{-6} \left( \frac{E}{10 \text{ GeV}} \right) s \]
Usually only considered annihilations into heavy quarks, gauge bosons or tau leptons...

What about annihilations into light quarks, muons or even electrons?

What about the low-energy (tens of MeV) neutrinos from pion and muon decays at rest?


N. Bernal, J. Martín-Albo and SPR, JCAP 08:011, 2013

from kaon decays: C. Rott et al., JCAP 11:039, 2015; JCAP 01:016, 2017

Interactions and decay at rest:

\[ \tau_{\text{int}} \approx 10^{-11} \text{s} \ll \tau_{\text{decay}} \approx 10^{-6} \left( \frac{E}{10 \text{ GeV}} \right) \text{s} \]
Low-energy neutrinos

Using SK data (DSNB analysis)

spin-independent

Evaporation accounted for

Effect of reaching the geometrical limit

Unqiue limits (from DM in the Sun) on annihilations into light quarks or muons

spin-dependent

N. Bernal, J. Martin-Albo, SPR, JCAP 08:011, 2013

Indirect DM searches with neutrinos
Indirect DM searches with neutrinos

Using SK data (DSNB analysis)

spin-independent

spin-dependent

Evaporation accounted for

Effect of reaching the geometrical limit

Unique limits (from DM in the Sun) on annihilations into light quarks or muons

N. Bernal, J. Martin-Albo, SPR, JCAP 08:011, 2013
**Indirect DM searches with neutrinos**

Sergio Palomares-Ruiz

June 18, 2019

Figure 6: Excluded regions in the DM mass and spin-independent cross section parameter space from neutrino telescopes (red dotted contours), from cosmic-ray constraints (green solid contours), from high-altitude experiments as collected in Ref. 163 (orange dashed contours), from constraints from the Earth’s heat (cyan dot-dashed contours) and from surface and underground direct detection experiments as collected and computed in Ref. 164 (gray solid contours). From Ref. 164

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Larger cross sections, these limits might not apply, as the DM particles would scatter so many scatterings that would not settle to the core and annihilations might not be sufficient.

For very large cross sections or for lower DM masses, other observations can be used to set bounds.

Different constraints on the \((m_{\text{DM}}, \sigma)\) parameter space are depicted in Fig. 6.

**4.1.3. Self-interacting DM**

In addition to couplings between DM and SM particles, it is natural to expect that interactions within the DM sector would also occur. Indeed, some of the scenarios discussed in section 3 include (or can easily accommodate) self-interactions among the DM particles themselves.

Strong DM self-interactions would modify the inner structure of halos, B. J. Kavanagh, Phys. Rev. D97:123013, 2018

However... the typical momentum transfer (per collision) is \(\sim m_{\text{N}}/m_{\text{DM}}\)

Key quantity: \(q = \frac{m_{\text{DM}}}{m_{\text{N}} n \sigma R_\odot}\)

\(q > 1\): very frequent collisions, but result similar to the thin regime \(\rightarrow\) capture rate scales with inverse of DM mass squared

\(q < 1\): efficient energy transfer \(\rightarrow\) capture rate scales with inverse of DM mass
Indirect DM searches with neutrinos

What about interactions with electrons?


smaller mass of targets \rightarrow thermal motion is crucial

capture rate as a function of the DM mass

R. Garani and SPR, JCAP 05:007, 2017

constant scattering cross section

velocity-dependent scattering cross section

huge impact of thermal motion!

In leptophilic scenarios, DM-nucleon could occur at loop level. Yet, in some cases DM-electron could be more important than DM-nucleon

R. Garani and SPR, in preparation
Self-interacting Dark Matter


Suppresses small-scale structure

Alleviates cusp-core, too-big-to-fail problems

Capture in the Sun

Self interactions enhance the capture rate
DM could reach equilibrium, even if it wouldn’t without self-interactions

317 days IC79

If the two sectors have different temperatures, &5 cm T kd 29 ⇠ m 10 MeV 2 2 =⇣ kd n v i v i 100 GeV 2 represents the mediator mass scale for DM-

I. F. M. Albuquerque, C. Pérez de los Heros and D. S. Robertson, JCAP 02:047, 2014

Indirect DM searches with neutrinos
Suppresses small-scale structure

Alleviates cusp-core, too-big-to-fail problems

Capture in the Sun

Self-interactions enhance the capture rate
DM could reach equilibrium, even if it wouldnt without self-interactions

317 days IC79

Indirect DM searches with neutrinos
I. F. M. Albuquerque, C. Pérez de los Heros and D. S. Robertson, JCAP 02:047, 2014
**Secluded Dark Matter**

Metastable mediator (dark photon, dark scalar...) coupled to DM, that subsequently could decay into SM particles


**Neutrino signals:**

Once captured, DM would decay into mediators, which would (partially) escape the Sun and decay into SM before reaching the Earth

P. Meade et al., JHEP 06:029, 2010
N. F. Bell and K. Petraki, JCAP 04:003, 2011

**Higher energy neutrinos:**

mainly from pions/kaons if decays occur outside the Sun

Less absorption:

more important for higher energy neutrinos and thus, for larger DM masses


M. Ardid et al., JCAP 04:10, 2017

See also: D. S. Robertson and I. F. M. Albuquerque, JCAP 02:056, 2018
Sergio Palomares-Ruiz
More on Secluded Dark Matter

Self-interactions (dissipative DM): add a capture component and could result in a lower velocity dispersion (dark disc)

Long-range interactions: Sommerfeld enhanced annihilation cross section → particularly important for Earth signals

Di-muon signals from the Earth: collinear pair of muons

P. Meade et al., JHEP 06:029, 2010


C. Delaunay, P. J. Fox and G. Perez, JHEP 05:099, 2009
J. Chen et al., JCAP 12:021, 2015

Indirect DM searches with neutrinos

DM Annihilations/Decays in Halos: Where to Look?

- **Galactic halo**: best statistics, angular information
- **Galaxy clusters**: high DM densities
- **DM clumps**: bright enough?
- **Extragalactic background**: DM contribution from all z
- **Galactic center**: brightest DM source
- **Dwarf galaxies**: high DM densities

Figure from J. Diemand, M. Kuhlen and P. Madau, Astrophys. J. 657:262, 2007
**DARK MATTER ANNIHILATIONS/DECAYs**

**Galactic contribution** very likely to be larger

\[
\frac{d\Phi_{G,\nu_\alpha}}{dE_\nu} = \frac{1}{4\pi m_{DM}^2} \frac{dN_{\nu_\alpha}}{dE_\nu} \int_{\text{los}} \rho^2 ds
\]

**Extra-galactic**

\[
\frac{d\Phi_{EG,\nu_\alpha}}{dE_\nu} = \frac{(\Omega_{DM}\rho_c)^2}{4\pi} \frac{\langle \sigma v \rangle}{2m_{DM}^2} \int_{\text{los}} \rho^2 ds
\]

Averaged oscillations

\[
\frac{d\Phi}{dE_\nu} = \sum \frac{\rho_\beta}{\beta_\alpha}
\]

**Components**

\[
H^2 = \frac{\Omega_{DM}\rho_c}{4\pi} \int_{\text{los}} \frac{dN_{\nu_\alpha}}{dE_\nu} (1 + z)E_\nu dE_\nu
\]

**DM mass**

**DM lifetime at production**

**DM galactic density**

**DM density**

**Hubble function**

**Energy redshift**

**Halo enhancement**

\[d\Phi_{EG,\nu_\alpha} = \frac{(\Omega_{DM}\rho_c)^2}{4\pi} \frac{\langle \sigma v \rangle}{2m_{DM}^2} \int_{\text{los}} \rho^2 ds (1 + z)E_\nu dE_\nu\]
Indirect DM searches with neutrinos

**Annihilations in the Galaxy and Others**

**SK: (5325.8 + 5629.1) days**
- K. Abe et al. [Super-Kamiokande Collaboration], M. G. Aartsen et al. [IceCube Collaboration], arXiv:2005.05109

**IceCube: 1007 days**

**ANTARES: 3170 days**

**Combined IceCube/ANTARES analysis**

![Graph showing the expected signal strength for different WIMP masses and the observed limits from IceCube and ANTARES.](image-url)
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K. Abe et al. [Super-Kamiokande Collaboration], M. G. Aartsen et al. [IceCube Collaboration], A. Albert et al. [ANTARES Collaboration], arXiv:2005.05109

Combined IceCube/ANTARES analysis

339.8 day IC59: Dwarfs, M31, Virgo


M. M. de With, Ph. D. thesis, 2018
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**339.8 day IC59: Dwarfs, M31, Virgo**

M. M. de With, Ph. D. thesis, 2018


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**Sensitivities for ARCA and IceCube upgrade**


S. Baur [IceCube Collaboration], PoS(ICRC2019)506, 2020

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Indirect DM searches with neutrinos
Decays in the Galaxy and Others

For $E < 10$ TeV, there are (almost) no limits on the neutrino flux from DM decays... by the experimental collaborations

First bounds on the diffuse neutrino flux
V. Berezinsky, LNGS 91/02 preprint, 1991
J. Ellis et al., Nucl. Phys. B373:399, 1992

First bounds considering the galactic flux

Super-Kamiokande data

Prospects with 1 year IceCube+DeepCore

276 days IC22

L. Covi et al., JCAP 04:017, 2010
Heavy Dark Matter

Can the highest energy IceCube neutrinos be explained by heavy dark matter annihilations/decays?

A. Esmaili and P. D. Serpico, JCAP 11:054, 2013
Indirect DM searches with neutrinos

Heavy Dark Matter

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A. Esmaili and P. D. Serpico, JCAP 11:054, 2013

\[ \text{Rate} \sim V N_{\text{DM}} \sigma \langle v \rangle \left( \frac{m_{\text{DM}}}{\text{GeV}} \right)^2 \sim 10^{-21} \text{cm}^3/\text{s} \left( \frac{m_{\text{DM}}}{\text{GeV}} \right)^2 \]

Unitarity limit \( \rightarrow \) non-thermal or composite DM or non-standard Universe evolution

K. Griest and M. Kamionkowski,
Phys. Rev. Lett. 64:615, 1990,
## Heavy Dark Matter

Can the highest energy IceCube neutrinos be explained by heavy dark matter annihilations/decays?

<table>
<thead>
<tr>
<th>Annihilations</th>
<th>Decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \text{Rate} \sim V N_N \sigma N L_{MW} \left( \frac{\rho_{DM}}{m_{DM}} \right)^2 \langle \sigma v \rangle \sim 10/\text{year} \rightarrow \langle \sigma v \rangle \sim 10^{-21} \text{cm}^3/\text{s} \left( \frac{m_{DM}}{\text{PeV}} \right)^2 ]</td>
<td>[ \text{Rate} \sim V N_N \sigma N L_{MW} \frac{\rho_{DM}}{m_{DM}} \frac{1}{\tau_{DM}} \sim 10/\text{year} \rightarrow \left( \frac{\tau_{DM}}{10^{22}s} \right) \left( \frac{m_{DM}}{1 \text{ PeV}} \right)^{-1} ]</td>
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Unitarity limit → non-thermal or composite DM or non-standard Universe evolution

Poster #190: M. Chianese
Poster #494: A. Dekker
Heavy Dark Matter

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Poster #190: M. Chianese
Poster #494: A. Dekker

Neutrino limits are better than gamma-ray ones for relatively hard channels

A. Bhattacharya et al., JCAP 05:051, 2019
**Heavy Dark Matter**

Can the highest energy IceCube neutrinos be explained by heavy dark matter annihilations/decays?


A. Esmaili and P. D. Serpico, JCAP 11:054, 2013

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**annihilations**

\[
\text{Rate} \sim V N_N \sigma_N L_{MW} \left( \frac{m_{DM}}{\rho_{DM}} \right)^2 \left( \sigma v \right) \sim 10/\text{year} \rightarrow \langle \sigma v \rangle \sim 10^{-21} \text{cm}^3/\text{s} \left( \frac{m_{DM}}{\text{PeV}} \right)^2
\]

**decays**

\[
\text{Rate} \sim V N_N \sigma_N L_{MW} \frac{1}{\tau_{DM}} \sim 10/\text{year} \rightarrow \left( \frac{\tau_{DM}}{10^{28} \text{s}} \right) \left( \frac{m_{DM}}{1 \text{ PeV}} \right)^{-1}
\]

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**Unitarity limit** → non-thermal or composite DM or non-standard Universe evolution


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**6-yr HESE: Astro + DM**

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**annihilations**

---

**decays**

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Many analyses have followed

- Poster #190: M. Chianese
- Poster #494: A. Dekker

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Neutrino limits are better than gamma-ray ones for relatively hard channels

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7.5-yr HESE

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See also: M. G. Aartsen et al. [IceCube Collaboration], Eur. Phys. J. C78:831, 2018

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Indirect DM searches with neutrinos

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Sergio Palomares-Ruiz
**Annihilations/Decays into monochromatic neutrinos**

Given that neutrinos are the least detectable particles in the SM, considering DM annihilations/decays into a pair of neutrinos is the most conservative scenario.


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![Diagram showing the landscape of dark matter annihilation into neutrinos.](Image)

Figure 2: The landscape of dark matter annihilation into neutrinos. We show results from this work, as well as previously published limits. Data and corresponding references are detailed in Sec. 3. Solid and dashed lines represent 90% CL limits and sensitivities, respectively. Projected sensitivities assume five years of data taking for neutrino experiments and 100 hours of observation for CTA. The dotted line corresponds to the value required to explain the observed abundance via thermal freeze-out. The straight diagonal line, labeled as “Unitarity Bound,” gives the maximum allowed cross section for a non-composite DM particle. These results assume 100% of the dark matter is composed of a given particle, if instead only a fraction, $f$, is considered these results should be rescaled by $1/f^2$. The heart symbols, $\heartsuit$, indicate new results obtained in this work.

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C. A. Argüelles et al., arXiv:1912.09486

Prospects for INO


D. Tiwari, Ph. D. thesis, 2018

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Indirect DM searches with neutrinos
Annihilations/Decays into monochromatic neutrinos

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Indirect DM searches with neutrinos
Figure 5: Classification of models of new neutrino physics, according to at what stage they act — production, propagation, detection — and what observables they affect — energy spectrum, arrival directions, flavor composition, arrival times — shown as lines connected to the models. The list of models is representative.

Given the wide spread of models of new neutrino physics, it is useful to organize them. Figure 5 shows our proposed model classification scheme, applied to a representative list of new-physics models. The scheme classifies a model according to two features: during what stage in the life of the neutrino it acts — production, propagation, detection — and what neutrino observables it affects. A model may act during more than one stage, and may affect more than one observable. The representative list of models in Fig. 5 shows that many models are able to affect two or three observables, and that most of them act during propagation.

5. How well can we measure the neutrino observables?

Statistical and systematic experimental limitations complicate extracting fundamental physics from high-energy cosmic neutrinos. However, already today, these limitations are surmountable. In the next decade, larger detectors and improved detection techniques will mitigate them further. Presently, the main limitation is statistical: after 8 years, IceCube has only detected about 100 contained events, a large fraction of them from neutrinos most likely of cosmic origin. Several larger neutrino telescopes, currently under construction, will vastly improve the situation: IceCube-Gen2, KM3NeT, and Baikal-GVD. Even larger detectors, in planning, could discover neutrinos with energies 1000 times higher.

Neutrino-Dark Matter Interactions

Absorptive effects

Dips on the SN neutrino spectra
Y. Farzan and SPR, JCAP 06:014, 2014

Full absorption of SN neutrinos

Energy-dependent anisotropy of high-energy neutrinos

Distortion of high-energy neutrinos
J. Barranco et al., JCAP 10:007, 2011

Time delays of high-energy neutrinos
S. Koren, JCAP 09:013, 2019

Full absorption of high-energy neutrinos from point sources
K. J. Kelly and P. A. N. Machado, JCAP 10:048, 2018
J. B. G. Alvey and M. Fairbairn, JCAP 07:041, 2019
Redshift-Integrated Resonances (ZIRs)

Dips in cosmic neutrino spectra

\[ E_R \sim \frac{M_R^2}{2 m_T} \]

Indirect DM searches with neutrinos

SPR and T. J. Weiler, in preparation... since 2006
Neutrino-Dark Matter Interactions

Coherent effects induce an effective mass or potential

on high-energy neutrinos


on solar neutrinos (DM in the Sun)

F. Capozzi, I. M. Shoemaker and L. Vecchi, JCAP 07:021, 2017

If neutrinos couple to ultra-light dark matter, these interactions can...

alter flavor ratios of high-energy neutrinos

Y. Farzan and SPR, Phys. Rev. D99:051702(R), 2019

suppress sterile neutrino production in the early Universe

F. Bezrukov, A. Chudaykin and D. Gorbunov, JCAP 06:051, 2017

induce time variations or distortions of masses and mixings

V. Brdar et al., Phys. Rev. D97:043001, 2018
**Neutrino-Dark Matter Interactions**

**Collisional and Mixed Damping**

C. Boehm et al., MNRAS 360:282, 2005

**CMB anisotropies**

M. Escudero et al., JCAP 09:034, 2015
J. A. D. Diacoumis and Y. Y. Wong, JCAP 01:001, 2019
J. A. D. Diacoumis and Y. Y.Y. Wong, JCAP 05:025, 2019

**CMB spectral distortions**

J. A. D. Diacoumis and Y. Y. Y. Wong, JCAP 09:011, 2017

**MW satellites**

M. Escudero et al., JCAP 06:007, 2018

**Cosmo/Astro effects**

**Galaxy surveys**

M. Escudero et al., JCAP 09:034, 2015

**Diffuse neutrino flux from DM annihilations**

A. Moliné et al., JCAP 08:069, 2016

Indirect DM searches with neutrinos

Sergio Palomares-Ruiz
Combining results: interactions/annihilations

Considering all (12) possible dimension-4 operators describing neutrino-dark matter interactions

scalar DM - Majorana mediator  
Dirac DM - scalar mediator  
Dirac DM - vector mediator

Gauge-invariant scenarios: neutrino-portals


See also:
V. González Macias and J. Wudka, JHEP 07:161, 2015

A. Olivares-Del Campo et al., Phys. Rev., D97:075059, 2018
Conclusions

Different dark matter signatures for indirect searches (not all covered in this talk)...

Some unique for neutrinos

Complementary to direct searches, to indirect searches with other messengers and to astro/cosmo observables

Set the strongest limits on spin-dependent scattering cross sections for $m > 100$ GeV

Set the strongest limits on the dark matter lifetime for $m > 100$ TeV (hard channels)

Huge range of energies covered by existing and future detectors: nice complementarity between North/South detectors
Thanks for your attention!
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