Dark Matter Parameters from Neutrino Telescopes

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CCAPP Seminar

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R. Allahverdi., K. R. (work in progress)
Outline

- Dark Matter Indirect Detection
- Neutrino Telescopes as Dark Matter (DM) Detectors
- Discriminating Final States of DM Models: Sneutrino Dark Matter
- Discriminating Neutrino Flavor
Evidence for Dark Matter

- Gravitational: Rotation curves, Cosmic Microwave Background, Large Scale Structure, Weak Lensing
- Cosmological: Big Bang Nucleosynthesis
- Particle: LSP missing energy?

Weakly Interacting Massive Particles (WIMPs)

The relic abundance of WIMPs is governed by thermal freeze-out scenarios.
DM decouples from the universe before baryons and enables baryons to form structure more quickly.
Three Complementary Probes of Dark Matter (DM)

**Particle Accelerators: LHC, ILC**
- Measure missing energy from decay chains
- Cannot prove cosmological stability

**Direct Detection: CDMS, DAMA, XENON...**
- Measures WIMP-nucleon scattering cross-section
- Cannot test relic density

**Indirect Detection: PAMELA, Fermi, IceCube...**
- Measures WIMP annihilation cross-section or decay rate
- Astrophysical backgrounds
How does dark matter interact with standard matter?

Goals

Find models consistent with current direct and indirect data
Provide predictive signals to discriminate among WIMPs
Indirect Detection Challenges

Astrophysical Background
Look at sources and energy ranges where background is known.

Tracing Particles Back to Their Source
Consider particles that are least affected on course to detectors.
Indirect Detection

Charged Cosmic Rays
Influenced by the galactic magnetic field
- Synchrotron emission
- Inverse Compton Scattering with starlight and CMB

Gamma Rays
Difficult to distinguish from background, weak monochromatic smoking gun possible

Neutrinos
- Directly from source, yet weak interactions create a detection challenge
- Atmospheric background well understood
**Indirect Neutrino Signal**

**DM Final States; Example Neutrino Final States**

## Intersecting Science

\[
N_\gamma = \int_{\text{line of sight}} \rho_{\text{DM}}^2 \, dl(\psi) \cdot \frac{\langle \sigma_v \rangle}{M_X^2} \cdot \left[ \int_{E_{th}}^{M_X} \left( \frac{dN_\gamma}{dE} \right)_{\text{SUSY}} A_{\text{eff}}(E) dE' \right] \cdot \frac{\Delta \Omega}{4\pi} \cdot \tau_{\text{exp}}
\]

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*slide from Kahlen*

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Indirect Neutrino Signal
DM Final States; Example Neutrino Final States

Fermi Satellite

Fig. 5.1: The freeze out of a massive particle species. The dashed line is the actual abundance, and the solid line is the equilibrium abundance.

Limits on annihilation rate

Fermi-LAT places limits on annihilation rate today. CMB abundance $\Omega \sim 1$ predicts annihilation rate at freeze-out.
Indirect Detection

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**Neutrinos**
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WIMP velocity drops as it scatters off of quarks. Eventually the WIMP is gravitationally bound. WIMPs fall to center and become isothermally distributed.

Graphic from Joakim Edsjo

Only the neutrino signal directly escapes.
WIMP Capture and Annihilation Rates

\[ \frac{dN}{dt} = C - AN^2 , \]

\[ N(t) = \sqrt{\frac{C}{A}} \tanh \sqrt{CA}t . \]

\[ \Gamma_A = \frac{A}{2} N^2(t) = \frac{C}{2} \tanh^2 \left( \frac{t}{\tau} \right) . \]

**Competition between WIMP Capture and Annihilation**

- Opposite signs
- If \( t > 1/\sqrt{CA} \), these processes come to an equilibrium
- \( \tau_\odot \sim 10^7 \) years
- \( \tau_\oplus \sim 10^{10} \) years
\[ \Gamma_A = \frac{C}{2} \tanh^2 \left( \frac{t}{\tau} \right) \approx \frac{C}{2}. \]

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**Neutrino Signal From the Sun Similar to Direct Detection**

The capture rate depends on the elastic scattering cross-section, whereas most indirect detection methods measure the annihilation cross-section.
Effect of $\sigma_{SI} \propto A^4$

$$C_{SI} \propto \frac{\rho_X}{v_d} \sum_i F_i(m_\chi) \sigma_{SI}^i f_i \phi_i S \left( \frac{m_\chi}{m_{Ni}} \right)$$

Xenon100 2011; Kumar & Marfatia 2011
Direct Detection Bounds on Cross Section

Effect of Solar Composition and $\sigma_{SI} \propto A^4$

$$C_{SI} \propto \frac{\rho_X}{v_d} \sum_i F_i(m_\chi)\sigma_{SI}^i f_i \phi_i S \left( \frac{m_\chi}{m_{Ni}} \right)$$

$$C_{SD} \propto \frac{\rho_X}{v_d} \sigma_{SD}^H S \left( \frac{m_\chi}{m_H} \right)$$

Xenon100 2011; Jungman, Kamionkowski, Griest 1995
Indirect Neutrino Signal
DM Final States; Example
Neutrino Final States

Direct Detection Bounds on Cross Section

\[ \sigma_{SI} \propto A^4 \]

\[ \sigma_{SD} \propto J(J + 1) \]

Direct Detection Bounds

\[ \sigma_{SI} < 10^{-8} \text{ pb} @ 55\text{GeV}, \text{Xenon100} \]
\[ \sigma_{SD} < 10^{-4} \text{ pb} @ 100\text{GeV}, \text{IceCube} - 80 \]

Xenon100 2011; Halzen & Hooper 2009
Equilibrium is easily achieved inside the sun for the freeze-out rate

\[ \langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \]

The scattering cross-section then must be either

\[ \sigma_{SI} > 10^{-8} \text{ pb \ or \ } \sigma_{SD} > 3 \times 10^{-6} \text{ pb.} \]

Equilibrium in the earth requires \( \sigma_{SI} \) to be several orders of magnitude larger.
IceCube looks for neutrinos by measuring Cerenkov light from muon tracks with energies $100 \text{ GeV} < E_\nu < 10^9 \text{ GeV}$

\[
\frac{dN_\nu}{dE} = \frac{\Gamma_A}{4\pi D^2} \sum_f B_f^f \frac{dN^f_\nu}{dE_\nu}
\]

Extent of Muon Tracks

Muons move $\sim 5\text{ m/GeV}$ through IceCube
Signals in the Ice

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IceCube PDD, 2000
The Background Challenge

- Charged Cosmic Rays
  - 1 in $10^6$ muon tracks are from neutrinos
  - 2000 tracks/s
  - Use the earth as a shield: Up-going tracks only 10 tracks/hr
  - Deep Core veto volume

- Atmospheric Neutrinos
  - Largest IceCube background challenge

Angular Resolution

For the sun (extent $< 1^\circ$), look at angles between $90^\circ$ and $113^\circ$
Muon track angles can be determined within $1^\circ$
The Background Challenge

- **Charged Cosmic Rays**
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Muon track angles can be determined within 1$^\circ$
Discriminating Models with Different States

Spectra of $\mu$’s at IceCube depend on $\nu$ spectra from DM annihilation
There are 3 cases:

1. **Primary neutrinos (very hard spectrum)**
   P-wave suppressed, subdominant in MSSM

2. **Secondary neutrinos from 2-body decay (hard spectrum)**
   Gauge boson final states, dominant in focus point scenarios

3. **Secondary neutrinos from 3-body decay (soft spectrum)**
   Quark/lepton final states, dominant in co-annihilation point scenarios
Discriminating Models with Different States

\( \nu \) spectra differ at the point of production. Further, these spectra are changed in propagation due to

1. Energy loss and absorption in the sun
2. Oscillations in the sun, and from the sun to the earth
3. Interactions in the detector

1 and 3 become more important for high energy neutrinos \((\sigma_{\nu N} \propto E)\)

2 becomes less important for high energy neutrinos \((L \propto E)\)

This leads to a different total count and spectrum of muons in the detector for each final state.
Neutrino Final State vs. W or $\tau$ Final States

Muon spectra may be used to distinguish different final states.
Cirelli, Fornengo, Montaruli, Sokalski, Strumia, Vissani NPB 727, 99 (2005)

- We focus on discriminating the neutrino final state from the W boson and tau final states
- $\tau$: common final state for coannihilation mSUGRA
- top, W: common in focus point scenarios
- We consider contained muons (vertex inside detector)

IceCube Limits

For W’s at 250 GeV, $\sigma_{SD} < 2 \times 10^{-4}$ pb
This limit is stronger by a factor of 10 for neutrinos
Spectra of $\nu_\mu$ are monochromatic from neutrino final state. They are smeared from two- and three-body final state decays.
1° cut necessary on muons, $\sigma_{SD} = 3 \times 10^{-5}$ pb

Detector $\nu$

\[ \theta_{\nu\mu} \approx 5.7^\circ \sqrt{\frac{100}{E_\mu} - \frac{100}{E_\nu}} \]
$\sigma_{SD} = 3 \times 10^{-4}$; $BR_W/\tau = 90\%$, $BR_\nu = 10\%$
Experimentally, we see the sum of channels

100 GeV

200 GeV

300 GeV
An Explicit Model: Sneutrino Dark Matter

In the MSSM,

\[ \text{DM DM} \rightarrow \nu\bar{\nu} \]

This process is p-wave suppressed and subdominant.

However, if DM carries lepton number, then

\[ \text{DM DM} \rightarrow \nu\nu \]

is allowed, and happens in the s-wave.

For example, see:
Allahverdi, Bornhauser, Dutta, K.R. PRD80, 055026 (2009)
The $U(1)_{B-L}$ Model

A minimal and well-motivated extension of the MSSM includes a gauged $U(1)_{B-L}$

Mohapatra, Marshak PRL 44, 1316 (1980)

<table>
<thead>
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<th>3 right-handed $N + \tilde{N}$</th>
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### The $U(1)_{B-L}$ Model

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### Dark matter candidates in $U(1)_{B-L}$

- **New neutralino:** $\chi'^1_0$, fermion
- **Right-handed sneutrino:** $\tilde{N}$, scalar
Sneutrino Dark Matter

- Right-handed $\tilde{N}$ is a viable DM candidate
- $\sigma_{SD} = 0$
- $\sigma_{SI} < 8 \times 10^{-9}$ pb from LEP/Tevatron bound on $Z'$ mass

Allahverdi, Bornhauser, Dutta, K.R. PRD80, 055026 (2009)

1. 10% s-wave $\tilde{N} \tilde{N} \rightarrow N N$
2. $N \rightarrow \nu h^0$
3. $E_\nu \approx \frac{m_{\tilde{N}}}{2}$ if $m_{\tilde{N}} - m_N \ll m_{\tilde{N}}$


1. 90% s-wave $\tilde{N} \tilde{N}^* \rightarrow \phi \phi$
2. $\phi \rightarrow f \bar{f}$ at one-loop level via $Z'$
Chi-Squared with Poisson Error, 90%, 99% \( \tau, \sigma_{SD} = 3 \times 10^{-5} \text{ pb} \)

The tau peak can be distinguished easily from the neutrino peak. 1° cut separates \( \tau \) and \( \nu \) peaks.
Chi-Squared with Poisson Error, 90%; 99% $W$, $\sigma_{SD} = 3 \times 10^{-4}$ pb

Some choices of $BR_W$ can be determined very precisely
Theoretical Energy Reconstruction Resolution

100 GeV

300 GeV

$1 \text{ TeV}$ event energy is proportional to light produced:

$$\sigma(\log_{10}E) = 0.3$$  Zornoza, Chirkin (ICRC 2007)

$200 \text{ GeV}$ event energy is proportional to track length  Wiebusch thesis (1995)

$$- \frac{dE}{dx} = a + bE$$

$a$: loss due to ionization

$b$: loss due to pair production, Brehmsstrahlung and Nuclear interactions of muons
Theoretical Energy Reconstruction Resolution

100 GeV

300 GeV

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Dark Matter Parameters from Neutrino Telescopes
Track length reconstruction possible \( \leq 200 \text{ GeV} \)

Threshold-width Gaussian

Smeared Spectrum

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Dark Matter Parameters from Neutrino Telescopes
Model Detection Prospects

- $\sigma_{SI}$ is large enough to have a detectable IceCube signal.
- Determining $BR_\nu$ would yield insight on neutrino Yukawa couplings and, therefore, model predictions for masses/mixings and leptogenesis.
- If $\tilde{N}$ mass is determined in a collider and IceCube can find $\sigma_{SI}$, we learn about the $Z'$ mass.
If we can know $\nu$ BR and cross section up to some uncertainty in oscillation scheme, can we learn anything about neutrino flavors?
Tau regeneration

1. CC interaction: $\nu_\tau \, p \rightarrow \tau \, n$
2. $\tau$-lifetime is very short: $\tau \rightarrow W \, \nu_{\text{tau}}$
3. Oscillations in the sun can mix $\nu_\tau$ and $\nu_\mu$

1. Atmospheric oscillation length depends on energy: $L_{\text{osc}} \propto \frac{E}{\Delta m^2}$
2. As DM mass increases, $\nu_\tau$ no longer efficiently oscillate to $\nu_\mu$
3. $\nu_\mu$ are similar to $\nu_\tau$ below $\sim 300$ GeV, but are similar to $\nu_e$ above $\sim 300$ GeV

Since the angle between the signal $\mu$ and incident $\nu$ at IC depends on energy, regenerated $\nu_\tau$ can only be seen at larger angles, with bkgd contribution being a limiting factor.
$5^\circ$ cut on muons, $\sigma_{SD} = 10^{-5}$

Regeneration increases $\nu_\tau$ at low $E_\nu$. Most effective at high $m_{DM}$.
An Electron Neutrino Signal

Hierarchies and $\theta_{13}$ choices all have electron neutrino mixing less efficiently as the energy increases.

$$(\Delta m_{12}^2)L/E >> 2\pi$$
Integrated Regeneration from 100 GeV to DM mass

A Tau Neutrino Signal

Since \((\Delta m^2_{12}) < (\Delta m^2_{23})\) Muon neutrino stops mixing with tau neutrino at higher energies.
Neutrinos are excellent probes of dark matter annihilation

Detection of $\nu$'s from DM annihilation in the sun provides information about DM parameters

Shape of muon spectrum can discriminate different final states

Neutrino final states can be reliably distinguished from $W$ and $\tau$ final states. Branching ratios for these modes can be determined by making proper angular cuts

Distinguishing neutrino final states with different flavors is more challenging since it relies on the shape of spectrum at lower energies.