Identifying Dark Matter Annihilation to Neutrinos

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R. Allahverdi., K. R. (work in progress)
R. Allahverdi., S. Bornhauser, B. Dutta, K. R. PRD 80, 055026 (2009)

Outline

- Dark Matter Indirect Detection
- Neutrino Telescopes as Dark Matter (DM) Detectors
- Discriminating Final States of DM Models
- An explicit model: Sneutrino Dark Matter

Introduction

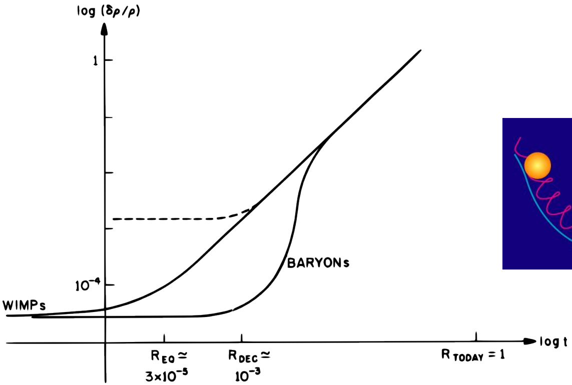
Evidence for Dark Matter

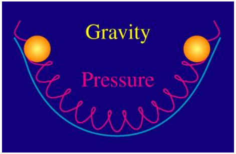
- Gravitational: Rotation curves, Cosmic Microwave Background, Large Scale Structure, Weak Lensing
- Cosmological: Big Bang Nucleosynthesis
- Particle: LSP missing energy?

Weakly Interacting Massive Particles (WIMPs)

The relic abundance of WIMPs is governed by thermal freeze-out scenarios.

Large Scale Structure





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

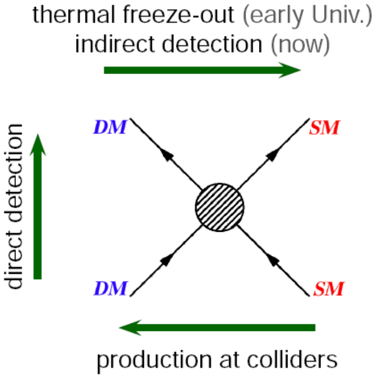
Direct Detection: CDMS, DAMA, XENON...

- Measures WIMP-nucleon scattering cross-section
- Cannot test relic density

Indirect Detection: PAMELA, Fermi, IceCube... (See Strigari's talk)

- Measures WIMP annihilation cross-section or decay rate
- Astrophysical backgrounds

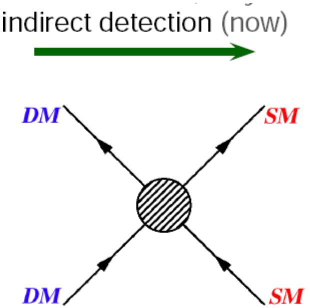
How does dark matter interact with standard matter?

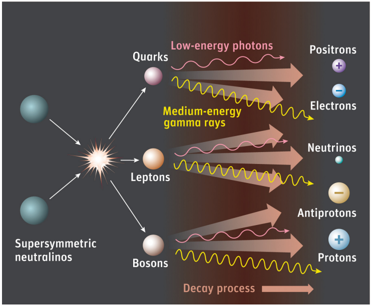


Goals

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

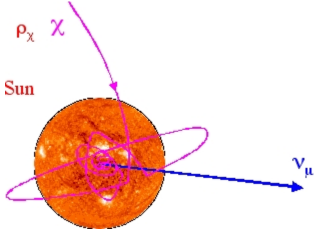
Difficult to distinguish from background, weak monochromatic smoking gun possible

Neutrinos

- Directly from source, yet weak interactions create a detection challenge
- Atmospheric background well understood

Gravitational WIMP capture by the Sun and Earth

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

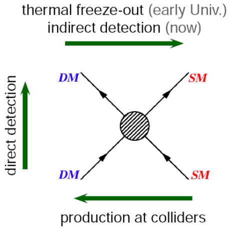
Only the neutrino signal directly escapes.

WIMP Capture and Annihilation Rates

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

$$N(t) = \sqrt{\frac{C}{A}} \tanh \sqrt{CA}t \,.$$

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

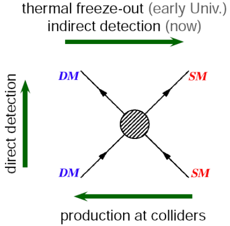


Competition between WIMP Capture and Annihilation

- 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

WIMP Capture and Annihilation Rates

$$\Gamma_A = \frac{C}{2}\tanh^2\left(\frac{t}{\tau}\right) \approx \frac{C}{2}\,.$$



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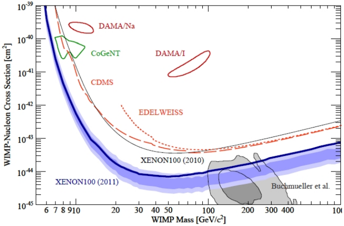
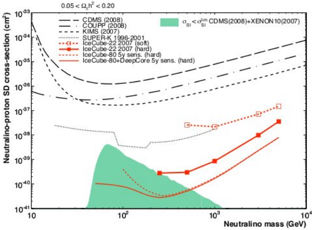
Neutrino Signal From the Sun Similar to Direct Detection

The capture rate depends on the elastic scattering cross-section, whereas most indirect detection methods measure the annihilation cross-section.

Direct Detection Bounds on Cross Section



$\sigma_{SI} \propto A^4$



$\sigma_{SD} \propto J(J+1)$

Direct Detection Bounds

$\sigma_{SI} < 10^{-8}$ pb @ 55GeV, Xenon100

$\sigma_{SD} < 10^{-4}$pb @ 100GeV, IceCube − 80

Xenon100 2011; Halzen & Hooper 2009

Bounds on Equilibrium

Equilibrium is easily achieved inside the sun for the freeze-out rate

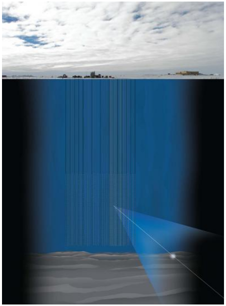
$$\langle \sigma v \rangle = 3 \times 10^{-26} \ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

The scattering cross-section then must be either

$$\sigma_{SI} > 10^{-8} \ \mathrm{pb} \ \textit{or} \ \sigma_{SD} > 3 \times 10^{-6} \ \mathrm{pb}.$$

Equilibrium in the earth requires σ_{SI} to be several orders of magnitude larger.

IceCube Detector



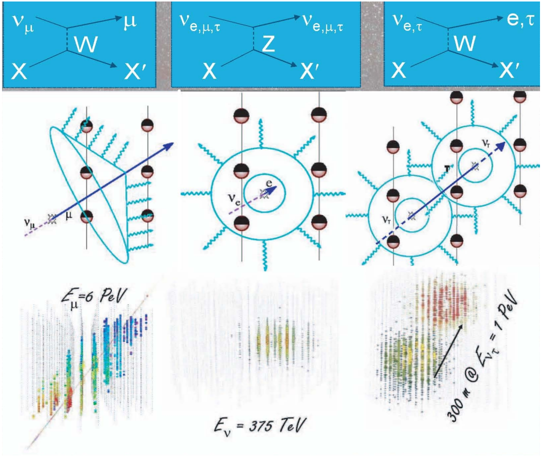
IceCube Collaboration

IceCube looks for neutrinos by measuring Cerenkov light from muon tracks with energies $100\ \mathrm{GeV} < E_\nu < 10^9\ \mathrm{GeV}$

Extent of Muon Tracks

Muons move $\sim 5\mathrm{m/GeV}$ through IceCube

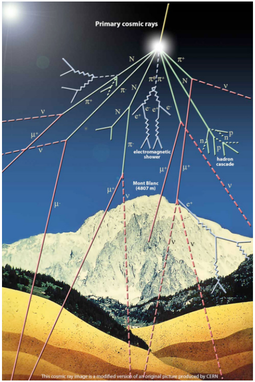
Signals in the Ice



IceCube PDD, 2000

The Background Challenge

- Charged Cosmic Rays
  - 1 in 10^6 muon tracks are from neutrinos
  - 2000 $\mathrm{tracks/s}$
  - Use the earth as a shield: Up-going tracks only 10 $\mathrm{tracks/hr}$
  - Deep Core veto volume (See Koskinen's talk)
- Atmospheric Neutrinos
  - Largest IceCube background challenge



Graphic from CERN

Angular Resolution

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

Discriminating Models with Different States

Spectra of μ's at IceCube depend on ν 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

ν spectra differ at the point of production. Futher, 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 τ Final States

Muon spectra may be used to distinguish different final states.

Cirelli, Fornengo, Montaruli, Sokalski, Strumia, Vissani NPB 727, 99 (2005)

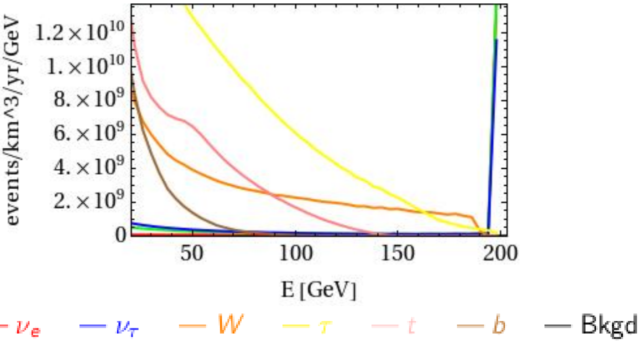
- We focus on discriminating the neutrino final state from the W boson and tau final states
- τ: common final state for coannihilation mSUGRA
- top, W: common in focus point scenarios
- We consider contained muons (vertex inside detector)

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

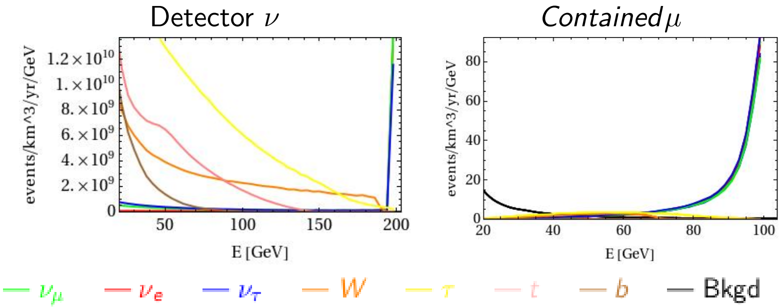
R. Abbasi, et al Phys. Rev. Lett. 102, 21302 (2009)

Neutrino Spectra



Spectra of ν_μ are monochromatic from neutrino final state
They are smeared from two- and three-body final state decays

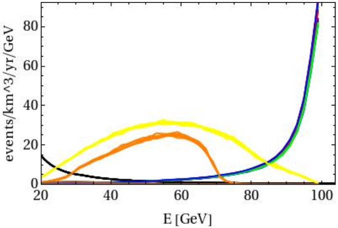
1° cut necessary on muons, $\sigma_{SD} = 3x10^{-5}\mathrm{pb}$



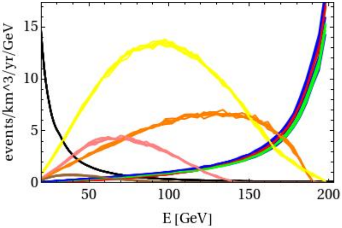
$$\theta_{\nu\mu} \approx 5.7^\circ \sqrt{\frac{100}{E_\mu} - \frac{100}{E_\nu}}$$

$\sigma_{SD} = 3x10^{-4}$; $BR_W/\tau = 90\%$, $BR_\nu = 10\%$

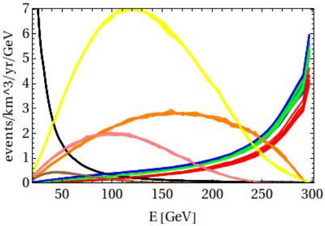
100 GeV



200 GeV

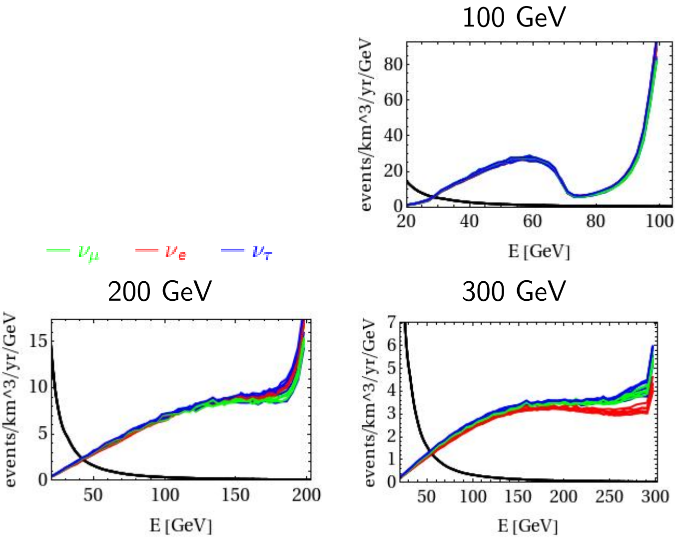


300 GeV

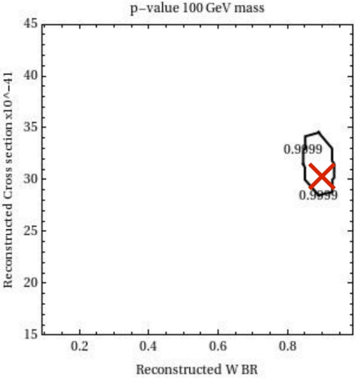


— ν_μ — ν_e — ν_τ — W — τ — t — b — Bkgd

Experimentally, we see the sum of channels

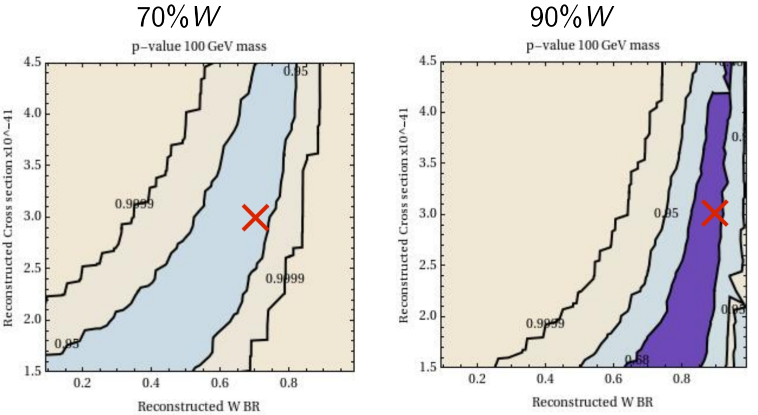


Chi-Squared with Poisson Error, 90% W, $\sigma_{SD} = 3 \times 10^{-4}\mathrm{pb}$



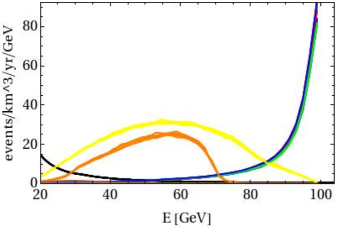
Some choices of BR_W can be determined very precisely
1° cut separates W and ν peaks

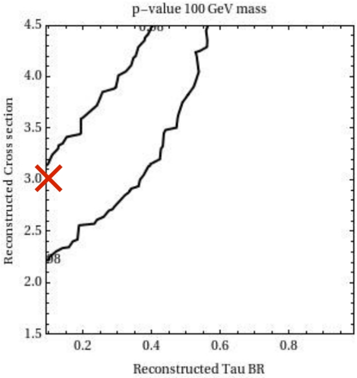
Chi-Squared with Poisson Error, W, $\sigma_{SD} = 3 \times 10^{-5}\mathrm{pb}$



For some of the parameter space, the neutrino tail contributes, so that larger σ_{SD} and larger W are indistinguishable.

Chi-Squared with Poisson Error, $10\%\tau, \sigma_{SD} = 3 \times 10^{-5}\mathrm{pb}$

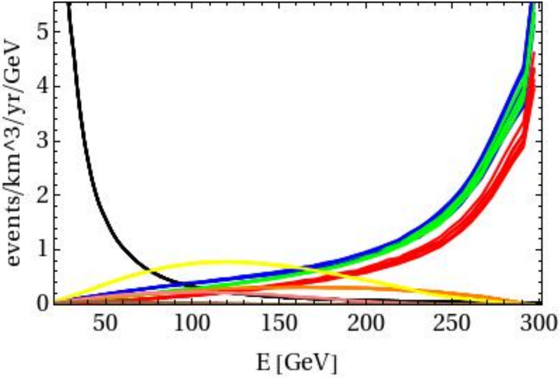




The tau peak can also be distinguished easily

Neutrino Flavor Determination

If we can know ν BR and cross section up to some uncertainty in oscillation scheme, can we learn anything about neutrino flavors?



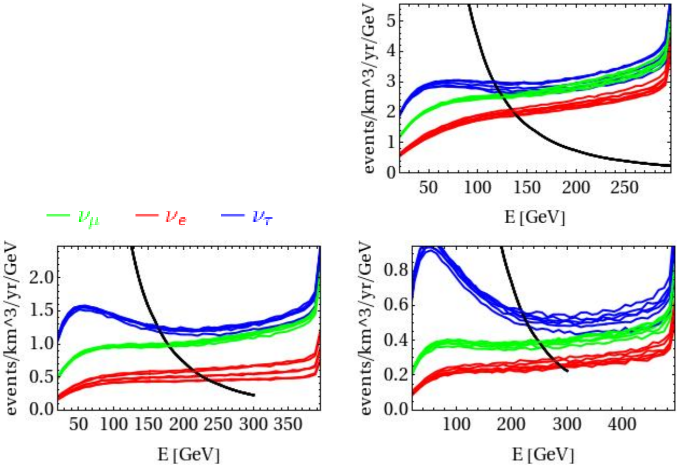
Tau regeneration

1. CC interaction: $\nu_\tau \; p \to \tau n$
2. *Tau*-lifetime is very short: $\tau \to W \; \nu_{tau}$
3. Oscillations in the sun can mix ν_τ and ν_μ

1. Atmospheric oscillation length depends on energy: $L_{osc} \propto \frac{E}{\delta m^2}$
2. As DM mass increases, ν_τ no longer efficiently oscillate to ν_μ
3. ν_μ are similar to ν_τ below ~ 300 GeV, but are similar to ν_e above ~ 300 GeV

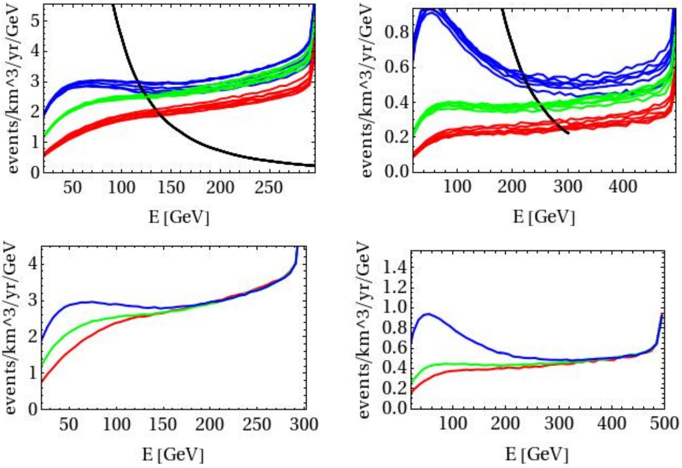
Since the angle between the signal μ and incident ν at IC depends on energy, regenerated ν_τ can only be seen at larger angles, with bkgd contribution being a limiting factor

5° cut on muons, $\sigma_{SD} = 10^{-5}$



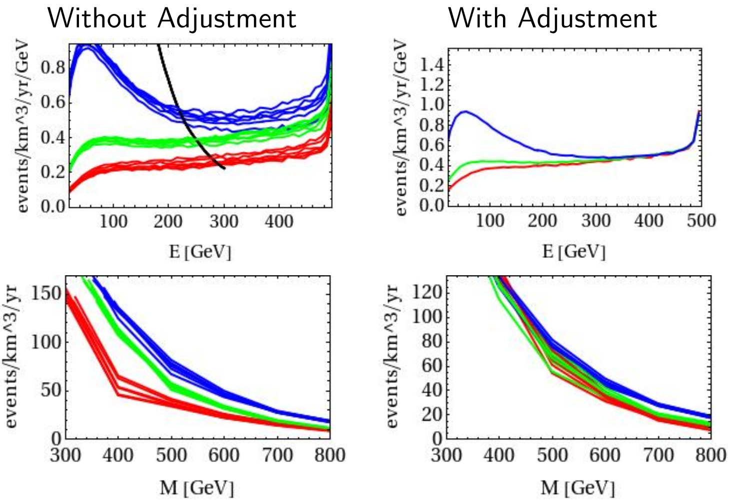
Regeneration increases ν_τ at low E_ν. Most effective at high m_{DM}

5° cut on muons, $\sigma_{SD} = 10^{-5}$



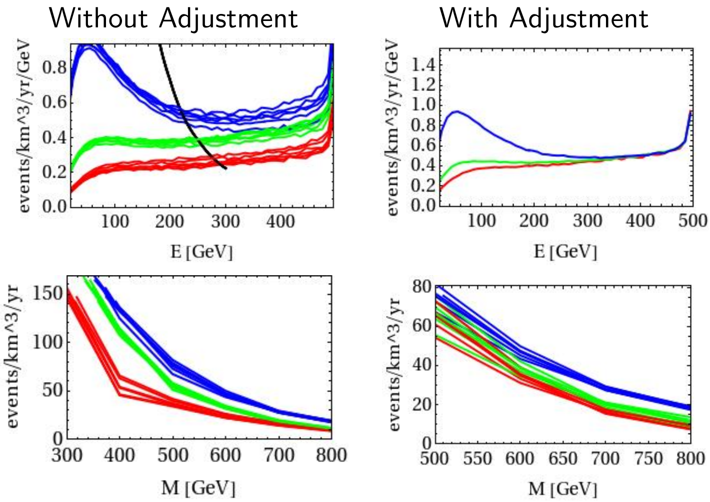
Adjusting ν peaks to match replicates our uncertainty in σ_{SD}

Integrated Regeneration



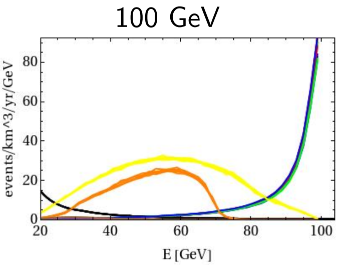
Integration from 100 GeV to DM mass

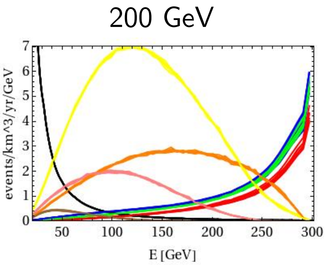
Integrated Regeneration



Integration from 100 GeV to DM mass

Theoretical Energy Reconstruction Resolution

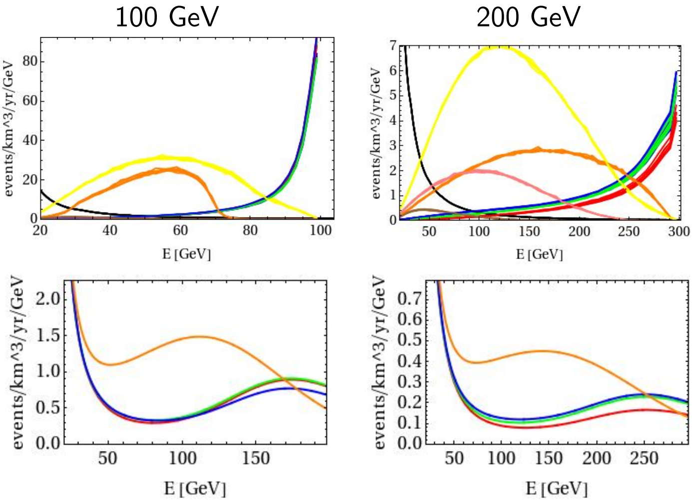




$1\mathrm{TeV}$ event energy is proportional to light produced:
$\sigma(log_{10}E) = 0.3$ Zornoza, Chirkin (ICRC 2007)

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

Theoretical Energy Reconstruction Resolution



An Explicit Model: Sneutrino Dark Matter

In the MSSM,

$$\text{DM DM} \to \nu\overline{\nu}$$

This process is p-wave suppressed and subdominant.

However, if DM carries lepton number, then

$$\text{DM DM} \to \nu\nu$$

is allowed, and happens in the s-wave.

For example, see:
Lindner, Merle, Niro PRD82, 123529 (2010) Farzan PRD 80, 073009 (2009)
Allahverdi, Bornhauser, Dutta, K.R. PRD80, 055026 (2009)

Sneutrino Dark Matter

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

Mohapatra, Marshak PRL 44, 1316 (1980)

- Right-handed $\widetilde{N}$ 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. $\widetilde{N}\ \widetilde{N} \to N\ N$
2. $N \to \nu h^0$
3. We have monochromatic ν's: $E_\nu \approx \frac{m_{\widetilde{N}}}{2}$ if $m_{\widetilde{N}} - m_N \ll m_{\widetilde{N}}$

Model Detection Prospects

1. $\widetilde{N}^* \, \widetilde{N} \to \phi \, \Phi$
2. $\phi \to \tau^+ \, \tau^-$
3. R. Allahverdi., B. Dutta, K. R., Y. Santoso Phys. Lett. B677, (2009)

- σ_{SI} is large enough to have a detectable IceCube signal.
- Determining BR_ν would yield insight on neutrino Yukawa couplings and, therefore, model predictions for masses/mixings and leptogenesis.
- If $\widetilde{N}$ mass is determined in a collider and IceCube can find σ_{SI}, we learn about the Z' mass.

Conclusion

- Neutrinos are excellent probes of dark matter annihilation
- Detection of ν'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 τ 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.