Probing Dark Matter with Neutrinos

In collaboration with
Arif Erkoca, Graciela Gelmini
and Mary Hall Reno

Ina Sarcevic
University of Arizona

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In a galaxy cluster, but failed to fit the data. The Newtonian dark matter result outweighed the visible ICM gas mass profiles by an order of magnitude.

In the solar system, the Doppler data from the Pioneer 10 and 11 space crafts suggested deviation from the Newtonian \( \frac{1}{r^2} \) gravitational force law beyond Saturn's orbit. Brownstein and Moffat (2006c) applied MOND to the available anomalous acceleration data (Nieto and Anderson, 2005) for the Pioneer 10/11 space craft. The solutions showed remarkably low variance corresponding to a reduced \( \chi^2 \) per degree of freedom of 0.42 signalling a good fit. The magnitude of the satellite acceleration exceeded the MOND critical acceleration, negating the MOND solution (Sanders, 2006). The dark matter paradigm is severely limited within the solar system by stability issues of the sun, and precision gravitational experiments including satellite, lunar laser ranging, and measurements of the Gaussian gravitational constant and Kepler's law of planetary motion. Without an actual theory of dark matter, no attempt to fit the Pioneer anomaly with dark matter has been suggested. Remarkably, MOG provides a closely fit solution to the Pioneer 10/11 anomaly and is consistent with the accurate equivalence principle, all current satellite, laser ranging observations for the inner planets, and the precession of perihelion for all of the planets.

A fit to the acoustic wave peak observed in the cosmic microwave background (CMB) data using MOG has been achieved without dark matter. Moreover, a possible explanation for the accelerated expansion of the Universe has been obtained in MOG (Moffat, 2007).

Presently, on both an empirical and theoretical level, MOG is the most successful alternative to dark matter. The successful application of MOG across scales ranging from clusters of galaxies (Megaparsecs) to HSB, LSB and dwarf galaxies (kiloparsecs), to the solar system (AU's) provides answers to questions from missing mass. The apparent necessity of the dark matter paradigm may be an artifact of applying the Newtonian \( \frac{1}{r^2} \) gravitational force law to scales where it is not valid, where a theory such as MOG takes over. The "excess gravity" that MOG accounts for may have nothing to do with the hypothesized missing mass of dark matter. But how can we distinguish the two?

In most observable systems, gravity creates a central potential, where the baryon density is naturally the highest. So in most situations, the matter which is creating the gravity potential occupies the same volume as the visible matter. Clowe et al. (2006c) describe this age degeneracy between gravitational forces from dark matter, or from the observed baryonic mass of the hot ICM and visible galaxies where the excess gravity is due to MOG. This degeneracy may be split by examining a system that is out of steady state, where there is spatial separation between the hot ICM and visible galaxies. This is precisely the case in galaxy cluster mergers: the galaxies will experience different gravitational potential created by the hot ICM than if they were concentrated at the center of the ICM.

Moffat (2006a) considered the possibility that MOG may provide an explanation of the recently reported "extra gravity" without non-baryonic dark matter which has so far been interpreted as direct evidence of dark matter. The research presented here addresses the full-sky data produced for the Bullet Cluster 1E0657-558, recently released to the public (Clowe et al., 2006b).

FIG. 1: False colour image of Bullet Cluster 1E0657-558. The surface density \( \Sigma \)-map reconstructed from X-ray imaging observations is shown in red and the convergence \( \kappa \)-map as reconstructed from strong and weak gravitational lensing observations is shown in blue. Image provided courtesy of Chandra X-ray Observatory.
Many observations indicate presence of dark matter: Galaxy rotation curves, galaxy clusters, BBN, CMB radiation, gravitational lensing, etc.
Dark Matter - What do we know?

- Dark matter is about 23% of the total density of the Universe, while baryonic matter is only 4%

- Large-scale structure formation in the Universe imply that dark matter is “cold” (i.e. non-relativistic at freeze-out time)
What is dark matter? The unknowns:

- Modification of the standard, Newtonian $1/r^2$ law, so that the observed effect is due to only baryonic matter is ruled out by Bullet Cluster observations.

- Particle physics candidate for dark matter: weakly interacting particle which is non-relativistic at the time of freeze-out.

- No viable candidate for dark matter in the Standard Model.
DARK MATTER DETECTION

scattering
(Direct detection)

production
(Particle colliders)

annihilation
(Indirect detection)
Dark Matter Detection

Direct Detection Experiments:
Look for energy deposition via nuclear recoils from dark matter scattering by using different target nuclei and detection strategies

DAMA, NAIAD, KIMS, CDMS, EDELWEISS, EURECA, ZEPLIN, XENON, WARP, LUX

Indirect Detection Experiments:
Look for annihilation products of dark matter (Gamma-rays, positrons, electrons, neutrinos)

HESS, MAGIC, VERITAS, CANGAROO-III, EGRET, Fermi/LAT, INTEGRAL, PAMELA, ATIC, AMS, HEAT, ICECUBE, KM3NET
Indirect DM searches:
Detection of the products of DM annihilation (or decay) in the Galactic Center, Sun, Earth, DM halo, etc. producing electrons, positrons, gamma-rays (PAMELA, ATIC, FERMI/LAT, HESS, Veritas ...) and neutrinos (IceCube, KM3Net...)

PAMELA Positron Fraction

The graph shows the positron fraction $e^+/e^+ + e^-$ as a function of energy. The data points represent measurements from various experiments and theories, with error bars indicating the uncertainties. The graph includes a comparison with theoretical predictions and previous experimental results.
FERMI Cosmic Ray Electron Spectrum

\[ E^3 J(E) \text{ (GeV}^2 \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1}) \]

\[ \Delta E/E = \pm 5\%-10\% \]

- AMS (2002)
- ATIC-1,2 (2008)
- PPB-BETS (2008)
- HESS (2008)
- FERMI (2009)
- Kobayashi (1999)
- HEAT (2001)
- BETS (2001)

**conventional diffusive model**

\[ 10 \quad 100 \quad 1000 \]

\[ E \text{ (GeV)} \]
If the observed anomalies are due to dark matter annihilation the annihilation cross sections must be $10^{0-1000}$ times more than the thermal relic value of

$$< \sigma v > = 3 \times 10^{-26} \text{cm}^3/\text{s}$$

The required enhancement in the signal is quantified by the factor called the “Boost Factor”:

$$B = B_v \times B_\rho$$

- **Low-velocity enhancement** (particle physics)
- **Sub-halo structures in the Galaxy** (astrophysics)
Dark Matter Signals in Neutrino Telescopes

Neutrinos are highly stable, neutral particles. Detection of neutrinos depend on their interactions, i.e. cross section.

Annihilation of dark matter particles could produce neutrinos, directly or via decay of Standard Model particles.

Neutrinos interacting with the matter, i.e. nucleons, produce muons which leave charged tracks in the neutrino detector.
- Neutrino flux from DM annihilation in the core of the Sun/Earth, produced directly or from particles that decay into neutrinos (taus, W's, b's)
  
  Erkoca, Reno and Sarcevic, PRD 80, 043514 (2009)

- Model-independent results for neutrino signal from DM annihilation in the Galactic Center
  
  Erkoca, Gelimini, Reno and Sarcevic, PRD 81, 096007 (2010)

- Signals for dark matter when DM is gravitino, Kaluza-Klein particle or leptophilic DM.
  
  Erkoca, Reno and Sarcevic, PRD 82, 113006 (2010)
Neutrinos from DM annihilations in the core of the Sun/Earth

Neutrino flux depends on annihilation rate, distance to source (Earth’s core or Sun-Earth distance) and energy distribution of neutrinos, i.e.

\[
\left(\frac{d\phi_\nu}{dE_\nu}\right)_i = \frac{\Gamma_A}{4\pi R^2} \sum_{F \neq F'} B_F \left(\frac{dN}{dE_\nu}\right)_{F,i}
\]

In equilibrium, annihilation rate and capture rate related: \(\Gamma_A = C/2\)
Dark Matter Capture Rate:

\[
C \sim \frac{\rho_{DM}}{m_X v_{DM}} \left( \frac{M}{m_p} \right) \sigma_{\chi N} < v_{esc}^2 >
\]

\[\rho_{DM} = 0.3 \text{ GeV cm}^{-3}\]
\[v_{DM} \sim 270 \text{ km s}^{-1}\]
\[v_{esc} = 1156 \text{ km/s}\]
\[v_{esc} = 13.2 \text{ km/s}\]

for the Sun

for the Earth

M is the mass of the Sun/Earth

Capture rate in the Sun is about \(10^9\) times larger than capture rate in the Earth

For the Sun, annihilation rate = \(C/2\)
Neutrinos from DM annihilation interact with matter \( \Rightarrow \) attenuation of the neutrino Flux in the Sun is important effect

Neutrinos also interact as they propagate through the Earth producing muons below the detector (upward muons) or in the detector (contained muons)
**Contained and Upward Muon Flux**

- The contained muon flux, for a detector with size $l$

$$
\frac{d\phi_\mu}{dE_\mu} = \int_R^{R+l} dr \int_{E_\mu}^{m_\chi} dE_\nu \frac{dP_{CC}}{drdE_\mu dE_\nu} \frac{d\phi_\nu}{dE_\nu}(E_\nu, R)
$$

- The upward muon flux is given by

$$
\frac{d\phi_\mu}{dE_\mu} = \int_{R_{min}}^R dr \int_{E_{\nu min}}^{m_\chi} dE_\nu \frac{dP_{CC}}{drdE_\mu dE_\nu} \frac{d\phi_\nu}{dE_\nu} \times \frac{dE_\mu^i}{dE_\mu} P_{surv}(E_\mu^i, E_\mu) \frac{dE_\mu}{dE_\mu}
$$
where the neutrino flux is

\[
\frac{d\phi_{\nu}}{dE_{\nu}}(E_{\nu}, R) = \frac{\Gamma_A}{4\pi R^2} \sum_F B_F \left( \frac{dN_{\nu}}{dE_{\nu}} \right)_{F, \mu}
\]

Muon survival probability is

\[
P_{\text{surv}}(E_{\mu}^{i}, E_{\mu}^{f}) = \left( \frac{E_{\mu}^{f}}{E_{\mu}^{i}} \right)^{\Gamma} \left( \frac{\alpha + \beta E_{\mu}^{i}}{\alpha + \beta E_{\mu}^{f}} \right)^{\Gamma}
\]

where \( \Gamma = m_{\mu}/(c\rho\alpha\tau) \)

\( R_{E} = 6400 \text{ km} \) or \( R_{SE} = 150 \text{ Mkm} \) (Sun-Earth distance)
Neutrinos from DM annihilations

Neutrinos produced directly or through decays of leptons, quarks and gauge bosons:

\[ \chi \chi \rightarrow \nu_i \bar{\nu}_i \]

\[ \rightarrow \tau^- \tau^+ \rightarrow (\nu_\tau \ell^- \bar{\nu}_l) (\bar{\nu}_\tau \ell^+ \nu_l) \]

\[ \rightarrow W^+ W^- \rightarrow (l^+ \nu_l) (l^- \bar{\nu}_l) \]

\[ \rightarrow b\bar{b} \rightarrow (c l^- \bar{\nu}_l) (\bar{c} l^+ \nu_l) \]

\[ \rightarrow t\bar{t} \rightarrow bW^+ \bar{b}W^- \rightarrow (c l^- \bar{\nu}_l)(l^+ \nu_l)(\bar{c} l^+ \nu_l)(l^- \bar{\nu}_l) \]
Neutrino Energy Distribution

- $\chi \chi \rightarrow \nu \bar{\nu}$ channel:

$$\frac{dN_\nu}{dE_\nu} = \delta(E_\nu - m_\chi)$$

- $\chi \chi \rightarrow \tau^+ \tau^-, b \bar{b}, c \bar{c}$ channels:

$$\frac{dN_\nu}{dE_\nu} = \frac{2B_f}{E_{in}}(1 - 3x^2 + 2x^3), \quad \text{where} \quad x = \frac{E_\nu}{E_{in}} \leq 1$$

$$(E_{in}, B_f) = \begin{cases} (m_\chi, 0.18) & \tau \text{ decay} \\ (0.73m_\chi, 0.103) & b \text{ decay} \\ (0.58m_\chi, 0.13) & c \text{ decay.} \end{cases}$$
Upward and Contained Muon Flux from DM Annihilation in the Core of the Earth

FIG. 1: Muon flux obtained from dark matter annihilation

TABLE I: Parameters for the atmospheric neutrino flux, in

\[
\frac{d\phi}{dE_{\mu}} \text{ (GeV}^{-1} \text{ km}^{-2} \text{ yr}^{-1})
\]

\[
m_{\chi} = 500 \text{ GeV}
\]

\[
\chi\chi \rightarrow \nu \bar{\nu} \text{ (upward)}
\]

\[
\chi\chi \rightarrow \nu \bar{\nu} \text{ (contained)}
\]

\[
\chi\chi \rightarrow \tau^+ \tau^- \text{ (upward)}
\]

\[
\chi\chi \rightarrow \tau^+ \tau^- \text{ (contained)}
\]

\[
\text{ATM (contained)}
\]

\[
\text{ATM (upward)}
\]
Attenuation of the neutrino Flux in the Sun

\[
\frac{d\phi_\mu}{dE_\mu} = \frac{\Gamma_A}{4\pi R_{SE}^2} \int_0^{R_{SE}(m_\chi,E_\mu)} dz e^{\beta_\rho z} \int_{E^i_\mu}^{m_\chi} dE_\nu \left( \frac{dN_\nu}{dE_\nu} \right) \\
\times \left( \frac{E_\mu \alpha + \beta E^i_\mu}{E^i_\mu \alpha + \beta E_\mu} \right)^{1/2} \times \left( \frac{d\sigma^p_\nu}{dE^i_\mu} \rho_p + (p \rightarrow n) \right) \\
\times \prod_{\delta r^i} \exp(-\rho(r^i)\sigma_{CC}\delta r^i/m_H) \\
+ (\nu \rightarrow \bar{\nu}).
\]

The muon flux decreases by a factor of \(3, 10, 100\) for \(m=250\text{ GeV}, 500\text{ GeV}, 1\text{ TeV}\).
Upward and contained muon flux from DM annihilation in the core of the Sun

In Fig. 3, we show the upward muon and the contained flux for muon energies, which manifests itself when \( t_{\mu} \) is large. Recall that the charged current neutrino nucleon cross section does not vanish at the kinematic limit when \( m_\chi \) is large, followed by \( \tau^+\tau^- \).

For direct annihilation of DM in the Earth and the Sun, it is possible to produce neutrinos into neutrinos in the core of the Sun, for upward events (dot-dash and dot-dot-dash curves), and for contained events (dashed and dot-dot-dash curves), and for contained event flux (dot-dot-dot-dash curve).

The interaction length becomes even smaller and the neutrino flux is reduced significantly. We refer the reader to Ref. [22], where there is an assumption of dark matter distribution in the core of the Sun, and contribution from dark matter annihilation around the center of the core.
Neutrino Flux from DM Annihilation in the Galactic Center


• Model independent DM signals: neutrino-induced upward and contained muons and cascades (showers)

• For dark matter density, we use different DM density profiles (Navarro-Frenk-White, isothermal, etc)

• Predictions for IceCube and Km3Net
Neutrino Flux from Dark Matter

Neutrino flux from DM annihilation/decay:

\[
\left( \frac{d\phi_\nu}{dE_\nu} \right) = R \times \sum_F B_F \left( \frac{dN_\nu}{dE_\nu} \right)_F
\]

here \( R \) for DM annihilation is:

\[
R = B \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \int d\Omega \int_{l.o.s} \rho(l)^2 dl
\]

and for DM decay:

\[
R = \frac{1}{4\pi m_\chi \tau} \int d\Omega \int_{l.o.s} \rho(l) dl
\]
Define $< J_n >_\Omega$ as:

$$< J_n >_\Omega = \int \frac{d\Omega}{\Delta \Omega} \int_{l.o.s.} \frac{dl(\theta)}{R_o} \left( \frac{\rho(l)}{\rho_o} \right)^n$$

$l(\theta)$ distance from us in the direction of the cone-half angle $\theta$ from the GC

$\rho(l)$ is density distribution of dark matter halos

$R_o$ is distance of the solar system from the GC

$\rho_o$ is local dark matter density near the solar system

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

$R_o = 8.5 \text{kpc}$ \hspace{1cm} $\rho_o^2 = 0.3 \text{GeV cm}^{-3}$
In the Milkyway, the rotation curves of the stars suggest that the dark matter density in the vicinity of our Solar System is:

$$\rho(r = 8.5\text{kpc}) = 0.3\text{ GeV/cm}^3$$
Neutrinos can be produced directly or through decays of leptons, quarks and gauge bosons:

\[ \chi \chi \rightarrow \nu_i \bar{\nu}_i \]

\[ \rightarrow \tau^- \tau^+ \rightarrow (\nu_\tau l^- \bar{\nu}_l) (\bar{\nu}_\tau l^+ \nu_l) \]

\[ \rightarrow W^+ W^- \rightarrow (l^+ \nu_l) (l^- \bar{\nu}_l) \]

\[ \rightarrow b \bar{b} \rightarrow (c l^- \bar{\nu}_l) (\bar{c} l^+ \nu_l) \]

\[ \rightarrow t \bar{t} \rightarrow b W^+ b W^- \rightarrow (c l^- \bar{\nu}_l) (l^+ \nu_l) (\bar{c} l^+ \nu_l) (l^- \bar{\nu}_l) \]
• **Detection:** neutrinos interacting below detector or in the detector producing muons

• **Signals:** upward and contained muons and cascade/showers

• **Upward muons** lose energy before reaching the detector
Energy loss of the muons over a distance $dz$:

$$\frac{dE}{dz} = -(\alpha + \beta E) \rho$$

- $\alpha$: ionization energy loss $\alpha = 10^{-3}\text{GeVcm}^2/\text{g}$.
- $\beta$: bremsstrahlung, pair production and photonuclear interactions $\beta = 10^{-6}\text{cm}^2/\text{g}$.

Relation between the initial and the final muon energy:

$$E^i_\mu(z) = e^{\beta \rho z} E^f_\mu + (e^{\beta \rho z} - 1) \frac{\alpha}{\beta}$$

Muon range:

$$R_\mu \equiv z = \frac{1}{\beta \rho} \log \left( \frac{\alpha + \beta E^i_\mu}{\alpha + \beta E^f_\mu} \right)$$
Contained and Upward Muon Flux

Contained muon flux is given by

$$\frac{d\phi_\mu}{dE_\mu} = \int_{E_\mu}^{E_{max}} dE_\nu \left( \frac{dN}{dE_\nu} \right) N_A \rho \frac{d\sigma_\nu(E_\nu)}{dE_\mu}$$

Upward muon flux is given by

$$\frac{d\phi_\mu}{dE_\mu} = \int_0^{R_\mu(E^i_\mu, E_\mu)} e^{\beta \rho z} dz \int_{E^i_\mu}^{E_{max}} dE_\nu \left( \frac{dN}{dE_\nu} \right) N_A \rho \times P_{\text{surv}}(E^i_\mu, E_\mu) \frac{d\sigma_\nu(E_\nu)}{dE_\mu}$$
Hadronic Shower Flux

\[
\frac{d\phi_{sh}}{dE_{sh}} = \int_{E_{sh}}^{E_{max}} dE_\nu \left( \frac{d\phi_\nu}{dE_\nu} \right) N_A \rho \frac{d\sigma_\nu(E_\nu, E_\nu - E_{sh})}{dE_{sh}}
\]
Muon Flux

\[ \chi \chi \rightarrow \nu \nu \]

NFW profile, \( B = 200, \theta = 5^\circ \)

solid lines: contained
dashed lines: upward

\( m_\chi = 200 \text{ GeV} \)
\( m_\chi = 500 \text{ GeV} \)
\( m_\chi = 800 \text{ GeV} \)

\[ \frac{d\phi}{dE_\mu} \text{ (GeV}^{-1} \text{ yr}^{-1} \text{ km}^{-2}) \]

\[ E_\mu \text{ (GeV)} \]
Hadronic Shower Spectra without track-like events

NFW profile, $B=200$, $\theta = 5^0$, $m_\chi = 500$ GeV

$\frac{d\phi}{dE_h}$ (GeV$^{-1}$ km$^{-2}$ yr$^{-1}$)

$E_h$ (GeV)

$Z$, $W$, tau, top, $b$, ATM NC, ATM em
Probing the Nature of Dark Matter with Neutrinos


- DM candidates: gravitino, Kaluza-Klein particle, a particle in leptophilic models.
- Dark matter signals: upward and contained muon flux and cascades (showers) from neutrino interactions
- We include neutrino oscillations
- Experimental signatures that would distinguish between different DM candidates
Model parameters used to explain Fermi/LAT and PAMELA

<table>
<thead>
<tr>
<th>Particle/mode</th>
<th>mass</th>
<th>$B_\tau$ or $B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Psi_{3/2} \rightarrow l^+ l^- \nu$</td>
<td>400 GeV</td>
<td>$B_\tau=2.3$</td>
</tr>
<tr>
<td>$\Psi_{3/2} \rightarrow (W l, Z \nu, \gamma \nu)$</td>
<td>400 GeV</td>
<td>$B_\tau=2.3$</td>
</tr>
<tr>
<td>$\chi \rightarrow \mu^+ \mu^-$</td>
<td>2 TeV</td>
<td>$B_\tau=2.9$</td>
</tr>
<tr>
<td>$B^{(1)}B^{(1)} \rightarrow (q\bar{q}, l^+ l^-, W^+ W^-, ZZ, \nu\bar{\nu})$</td>
<td>800 GeV</td>
<td>$B = 200$</td>
</tr>
<tr>
<td>$\chi \chi \rightarrow \mu^+ \mu^-$</td>
<td>1 TeV</td>
<td>$B = 400$</td>
</tr>
</tbody>
</table>

$$\tau = \frac{B_\tau}{10^{26} s}$$
\[ x = \frac{E_\nu}{E_{\nu,\text{max}}} \]
are given by \[16\]

\[\begin{align*}
\text{positron excess in the PAMELA data and positron plus} \\
\text{it can have a su} \\
\text{cay rate of the gravitino in this scenario is so small that} \\
\text{the superpartner of the graviton. With the existence of} \\
\text{lightest supersymmetric particle (LSP). The gravitino is} \\
\text{than the value required for a thermal relic abundance} \\
\text{cific to the model is required. Characteristically for an-} \\
\text{convention, we write} \\
\text{to the FERMI data, the direct production of electrons} \\
\text{the overproduction of antiprotons. Moreover, according} \\
\text{PAMELA positron excess, the DM annihilation or decay} \\
\text{explain the lepton excesses, some models have constraints} \\
\text{of the boost factor [35], however, we treat the boost fac-} \\
\text{cross section times velocity}
\end{align*}\]

\[\langle \tau \mu \rangle \] which determine the overall normaliza-

\[\text{persymmetry is the gravitino (} \chi \text{)} [14]. The LKP is also assumed to be neutral and non-

\[\text{count for the HESS results [6], the lightest Kaluza-Klein} \\
\text{is less favored by the data [16].}
\]

\[\text{In order to account for the observed anomalous} \\
\text{In leptophilic DM models [7, 16] explaining the} \\
\text{masses [15].}
\]

\[\text{29} \times \text{10}^{-5} \text{GeV}\]

\[\text{E}_{\nu} \text{d} \phi_{\nu} / \text{d}E_{\nu} \text{(GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1})}
\]

\[\langle \nu \rangle = \text{max}
\]

\[\text{2.3} \times \text{max}
\]

\[\text{2.3} \times \text{max}
\]

\[\text{2.9} \times \text{max}
\]

\[\text{85} \times \text{max}
\]

\[\text{66} \times \text{max}
\]

\[\text{34} \times \text{max}
\]

\[\text{0} \times \text{max}
\]

\[\text{10}^{1} \text{ to } \text{10}^{6} \text{ GeV}
\]

\[\text{AMANDA-II}
\]

\[\text{ATM } \theta = 60^\circ
\]

\[\text{ATM angle-averaged}
\]
In Fig. 5 we show the contained muon flux from the annihilation, for the leptophilic model. In Fig. 4 we show the contained muon flux from the annihilation, for the leptophilic model. One cannot enhance the signal rate by increasing the boost factor or the lifetime \( \tau \). Even though the shapes of the decays (lower thin lines) have lower fluxes than the Kaluza-Klein annihilations (upper thick lines), the shapes of the decays (lower thin lines) have lower fluxes than the Kaluza-Klein annihilations (upper thick lines).

The decays (lower thin lines) have lower fluxes than the Kaluza-Klein annihilations (upper thick lines). For leptophilic models, one cannot enhance the signal rate by increasing the boost factor or the lifetime \( \tau \). Even though the shapes of the decays (lower thin lines) have lower fluxes than the Kaluza-Klein annihilations (upper thick lines), the shapes of the decays (lower thin lines) have lower fluxes than the Kaluza-Klein annihilations (upper thick lines).

\( \psi_{3/2} \rightarrow l^+l^- \), \( m_{\psi_{3/2}} = 400 \text{ GeV} \), \( \tau = 2.3 \times 10^{26} \text{ sec} \)

\( \psi_{3/2} \rightarrow (Wl,Z\nu,\gamma\nu), m_{\psi_{3/2}} = 400 \text{ GeV} \), \( \tau = 2.3 \times 10^{26} \text{ sec} \)

\( \chi \rightarrow \mu^+\mu^- \), \( m_\chi = 2 \text{ TeV} \), \( \tau = 2.9 \times 10^{26} \text{ sec} \)

\( \chi \chi \rightarrow \mu^+\mu^- \), \( m_\chi = 1 \text{ TeV} \), \( B = 400 \)

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\( \chi \chi \rightarrow \mu^+\mu^- \), \( m_\chi = 1 \text{ TeV} \), \( B = 400 \)

\( \chi \chi \rightarrow \mu^+\mu^- \), \( m_\chi = 1 \text{ TeV} \), \( B = 400 \)
Upward Muon Flux

The figure shows the upward muon flux for different annihilation and decay scenarios of dark matter (DM) candidates. The flux is plotted as a function of the muon energy ($E_\mu$) on a log-log scale.

- **$\psi_{3/2} \rightarrow l^+ l^- \nu$, $m_{\psi_{3/2}} = 400$ GeV, $\tau = 2.3 \times 10^{26}$ sec**
- **$\psi_{3/2} \rightarrow (Wl, Z\nu, \gamma\nu)$, $m_{\psi_{3/2}} = 400$ GeV, $\tau = 2.3 \times 10^{26}$ sec**
- **$\chi \rightarrow \mu^+ \mu^-$, $m_\chi = 2$ TeV, $\tau = 2.9 \times 10^{26}$ sec**
- **$B^{(1)}B^{(1)} \rightarrow (qq, l^+ l^-, WW, ZZ, \nu \bar{\nu})$, $m_{B^{(1)}} = 800$ GeV, $B = 200$**
- **$\chi \chi \rightarrow \mu^+ \mu^-$, $m_\chi = 1$ TeV, $B = 400$**

The black line represents the atmospheric muon flux (ATM). Each curve corresponds to a different DM model, with the parameters listed next to the curves.

The calculations take into account the detector threshold, typically 10-100 GeV for deep ice, and the contained muon flux would have a little harder spectrum. This is a direct consequence of the muon range dependence on the DM mass.
Upward Muon Rates with $E_{\mu}^{th} = 50\text{GeV}$

![Graph showing upward muon rates as a function of DM mass for different decay modes.](image)

- $\psi_{3/2} \rightarrow l^+l^-\nu$
- $\psi_{3/2} \rightarrow (Wl, Z\nu, \gamma\nu)$
- $\chi \rightarrow \mu^+\mu^-$
- $B^{(1)}B^{(1)} \rightarrow (q\bar{q}, l^+l^-, W^+W^-, ZZ, \nu\bar{\nu})$
- $\chi\chi \rightarrow \mu^+\mu^-$
- ATM

For DM masses in the range $10^{-2} - 10^2$, the integration region is sensitive to $E_{\mu}^{th} = 50\text{GeV}$, the event rates decrease with increasing $m_\chi$, the event rates for decaying DM particles are responsible for the observed upward muon event rates, because of the energy dependent detection significance for each DM mass, $\sigma_{\text{eff}}(m_\chi)$.

In contrast to the contained muon rates, for DM masses in the range $10^3$, the contained muon event rates have weak dependence on $m_\chi$, the event rates for decaying DM particles are responsible for the observed contained muon event rates, because of the energy dependent detection significance for each DM mass, $\sigma_{\text{eff}}(m_\chi)$.

Therefore, in order to have the same detection significance for a five year observation period, the contained muon event rates require a larger effective volume which increases with $m_\chi$. The upward muon event rates have weak dependence on $m_\chi$, the event rates for decaying DM particles are responsible for the observed contained muon event rates, because of the energy dependent detection significance for each DM mass, $\sigma_{\text{eff}}(m_\chi)$.

In Fig. 9, we present results for DM annihilation cross section $\sigma_{\text{eff}}$. The contained muon event rates have weak dependence on $E_{\mu}^{th}$, while for annihilating DM models, the contained muon event rates increase with $E_{\mu}^{th}$.

In Fig. 10 we show the decay time as a function of the DM mass for the contained muon events. The parameter space for the decaying DM models increases with $m_\chi$. Therefore, in order to have the same detection significance independent of the DM mass, $\sigma_{\text{eff}}(m_\chi)$, the event rates have weak dependence on $m_\chi$, the event rates for decaying DM particles are responsible for the observed contained muon event rates, because of the energy dependent detection significance for each DM mass, $\sigma_{\text{eff}}(m_\chi)$.

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DM Detection with Neutrino Telescopes

IceCUBE: 1 km$^3$ neutrino detector at South Pole
- detects Cherenkov radiation from the charged particles produced in neutrino interactions
- contained and upward muon events and showers
- contained muons from GC
- showers from GC with IceCUBE+DeepCore

KM3Net: a future deep-sea neutrino telescope
- contained and upward muon events and showers
- upward muons from GC
IceCube DM search from the Galactic Halo
(arXiv:1101.3349)
IceCube DM search from the Galactic Halo (arXiv:1101.3349; PRD 84 (2011))
Summary

- Neutrinos could be used to detect dark matter and to probe its physical origin.
- Contained and upward muon flux is sensitive to the DM annihilation mode and to the mass of dark matter particle.
- Combined measurements of cascade events and muons with IceCube+DeepCore and KM3Net look promising.
- Neutrinos can probe DM candidates, such as gravitino, Kaluza-Klein DM, and a particle in leptophilic models.