Neutrinos From Kaluza–Klein Dark Matter Annihilations in the Sun

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Outline

- Introduction
- Extra-dimensional models
- Capture rates and IceCube
- Results
- Summary & Conclusions
Paper & Collaboration

Based on:

\textbf{JCAP 01, 018 (2010)}
\texttt{arXiv:0910.1588 [hep-ph]}

In collaboration with:
Mattias Blennow and Henrik Melbéus
Paper & Collaboration

Based on:

**JCAP 01, 018 (2010)**

In collaboration with:
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Dark matter in the Universe

Cosmological and astronomical observations ⇒
- 4 % ordinary baryonic matter
- 23 % dark matter
- 73 % dark energy

WMAP Collaboration (2008)

One of the most plausible dark matter candidates: Weakly Interacting Massive Particles (WIMPs)

In particular, neutralinos ($\chi$) are promising WIMP candidates.
Extra-dimensional models

In this talk, we will study Kaluza–Klein particles, which are another type of WIMPs.

- Extra-dimensional field theory is non-renormalizable
  \[ \Rightarrow \text{View as an effective theory.} \]

- A need for a UV completion of the theory.

- Kaluza–Klein particles arise in models with extra dimensions.

- If so-called KK parity is conserved, the LKP is stable.

- If neutral, the LKP can be a good DM candidate.

$LKP = \text{lightest Kaluza–Klein particle (cf., LSP)}$

$KKDM = \text{Kaluza–Klein dark matter}$

Related talks by Neubert and Volkas.
WIMP capture and annihilation in the Sun

- WIMPs in the Milky Way halo can scatter in the Sun and be gravitationally bound to the Sun.
- Eventually, they will scatter again and sink to the core.
- In the core, WIMPs (here: KKDM) will accumulate and can annihilate and produce neutrinos.

\[ \chi \chi \rightarrow u\bar{u}, d\bar{d}, \ell^- \ell^+, hh, W^- W^+, Z^0 Z^0, \nu\bar{\nu} \]

(no $g\bar{g}$ on tree level for KKDM annihilations)
Propagation from the Sun to the Earth

- Only $\nu$'s escape the Sun (from WIMP annihilations)
- Neutrino oscillations from production to detection are used.
- Muons are induced by $\nu$'s in Earth matter.

$\therefore$ Flux of muons are detected at Earth!

Note: We use the DarkSUSY and WimpSim packages to compute muon fluxes at an Earth-based detector.
Extra-dimensional models II

Extra-dimensional models: WIMPs = KKDM
UED models: all SM particles allowed to propagate in one or more extra dimensions (hep-ph/0012100)
MUED model: LKP = first mode of $U(1)$ gauge boson
Five- and six-dimensional UED models:
  ● more general mass spectrum
  ● based on the SM gauge group

Our approximations:
  ● all SM particles are massless
  ● ignore EWSB effects
  ● neglect Yukawa couplings ($<$ gauge couplings)
  ● ignore self-couplings of the Higgs boson (none of the studied processes involve this interaction)
  ● low-energy theory: only zero modes
  ● odd field has no zero mode $\rightarrow$ not present in low-energy theory
The five-dimensional model

In five dimensions:

- Spinors are four-component objects.
- No chirality operator \( \Rightarrow \) Dirac repr. irreducible
  \( \Rightarrow \) The simplest choice of geometry, the circle \( S^1 \), for the fifth dimension does not work.
- However, the orbifold \( S^1 / \mathbb{Z}_2 \) does the job!

Gauge fields in extra dimensions: extra component \( A_5 \)
In four dimensions: massless scalars
Therefore, take \( A_5 \) to be odd in \( y \) \( \rightarrow \) no zero mode
The five-dimensional model II

KK expansions of fields:

\[ A^{(\text{even})}(x^\mu, y) = \frac{1}{\sqrt{\pi R}} \left[ A^{(0)}(x^\mu) + \sqrt{2} \sum_{n=1}^{\infty} \cos \left( \frac{n\pi y}{R} \right) A^{(n)}(x^\mu) \right], \]

\[ A^{(\text{odd})}(x^\mu, y) = \sqrt{\frac{2}{\pi R}} \sum_{n=1}^{\infty} \sin \left( \frac{n\pi y}{R} \right) A^{(n)}(x^\mu) \]

Index \( n = 1 \) gives first KK modes.

In addition to SM parameters, the compactification radius \( R \) and the cut-off scale \( \Lambda \) are the only free parameters.

Here: Ignore effects of KK modes > first level (\( n = 1 \))
The five-dimensional model III

The gauge part of the five-dimensional Lagrangian is:

\[
\mathcal{L}_{\text{gauge}} = -\frac{g}{2} f^{abc} F^{(0),a}_{\mu\nu} A^{(1),b\mu} A^{(1),c\nu} - \frac{g}{2} f^{abc} (\partial_\mu A^{(1),a}_\nu - \partial_\nu A^{(1),a}_\mu) \\
\times (A^{(0),b\mu} A^{(1),c\nu} + A^{(0),c\nu} A^{(1),b\mu}) - \frac{g^2}{4} \left[ f^{abc} (A^{(0),b}_\mu A^{(1),c}_\nu + A^{(0),c}_\nu A^{(1),b}_\mu) \right]^2
\]

Possible DM candidates: neutrinos, the two neutral components of the Higgs doublet, and the $B$ and $W^3$ bosons
However, neutrinos are ruled out as DM and scalar DM is not interesting (since it has no spin-dependent interactions).
Thus, the interesting DM candidates are: $B^{(1)}$ & $W^{3(1)}$
Comments on BLTs

BLT = boundary localized term
Orbifold fixed points → BLTs → momentum
non-conservation in extra dimensions → conservation of KK-parity
BLTs:

- included in the Lagrangian
- affect the spectrum (at tree level) → different LKPs
- affect the coupling constants (at tree level) [not taken into account]
- not determined by the SM parameters
- decrease predictivity of the models
- vanish at the cut-off scale $\Lambda$
The six-dimensional model

In six dimensions:

- Spinors are eight component objects.
- As in four dimensions, there is a chirality operator.
- Here, the orbifold is the chiral square $T^2/\mathbb{Z}_4$. 
The six-dimensional model II

KK expansion of the fields:

\[ A(x^\mu, x^4, x^5) = \frac{1}{L} \left[ \delta_{n,0} A^{(0,0)}(x^\mu) \right. \]

\[ + \sum_{j \geq 1} \sum_{k \geq 0} f^{(j,k)}_n(x^4, x^5) A^{(j,k)}(x^\mu) \left. \right] \]

where

\[ f^{(j,k)}_n(x^4, x^5) = \frac{1}{1 + \delta_{j,0}} \left[ e^{-in\pi/2} \cos \left( \frac{j x^4 + k x^5}{R} + \frac{n\pi}{2} \right) \right. \]

\[ \pm \cos \left( \frac{k x^4 - j x^5}{R} + \frac{n\pi}{2} \right) \]

Indices \((j, k) = (1, 0)\) give the first KK modes.
The six-dimensional model III

The gauge part of the five-dimensional Lagrangian is:

$$\mathcal{L}_{\text{gauge}} = -gf^{abc} \delta_{0,0,0}^{j_1,j_2,j_3} A_{\mu}^{(j_1),a} A_{\nu}^{(j_2),b} \partial \nu A^{(j_3),c,\nu}$$

$$+ \left( \frac{g}{2} f^{abc} A_{H}^{(1),a} (\partial \mu A_{H}^{(1),b}) A_{\mu}^{(0),c} + \text{h.c.} \right)$$

$$- \frac{g^2}{4} f^{abc} f^{ade} \delta_{0,0,0}^{j_1,j_2,j_3,j_4} A_{\mu}^{(j_1),b} A_{\nu}^{(j_2),c} A^{(j_3),d,\mu} A^{(j_4),e,\nu}$$

$$- \frac{g^2}{2} f^{abc} f^{ade} A_{H}^{(1),c} A_{H}^{(1),e} A_{\mu}^{(0),b} A^{(0),d,\mu}$$

Possible DM candidates are: the possible DM candidates in five dimensions, and in addition, the first-level adjoint scalars $B_{H}^{(1)}$ and $W_{H}^{3(1)}$

However, adjoint scalar DM is not interesting. Thus, the interesting DM candidates are the same as in five dimensions.
The ratio of the capture rates

\[ C_{\text{approx}} \simeq 3.35 \times 10^{18} \, \text{s}^{-1} \left( \frac{\rho}{0.3 \, \text{GeV/cm}^3} \right) \left( \frac{270 \, \text{km/s}}{\bar{v}} \right)^3 \times \left( \frac{\sigma_{\text{WIMP,p}}^{SD}}{10^{-6} \, \text{pb}} \right) \left( \frac{1 \, \text{TeV}}{m_{\text{WIMP}}} \right)^2 \]

About 25 % difference between approx and DarkSUSY
Branching ratios for pair annihilations of KKDM

<table>
<thead>
<tr>
<th>Final state</th>
<th>$B^{(1)}$</th>
<th>$W^3(1)$</th>
<th>$B^{(1)}$</th>
<th>$W^3(1)$</th>
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<tbody>
<tr>
<td>$r_q$</td>
<td>1.0</td>
<td>1.3</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>$\bar{u}u$</td>
<td>0.125</td>
<td>0.084</td>
<td>0.017</td>
<td>0.010</td>
</tr>
<tr>
<td>$\bar{d}d$</td>
<td>0.008</td>
<td>0.006</td>
<td>0.017</td>
<td>0.010</td>
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<tr>
<td>$\nu\nu$</td>
<td>0.011</td>
<td>0.013</td>
<td>0.005</td>
<td>0.005</td>
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<tr>
<td>$l^+l^-$</td>
<td>0.183</td>
<td>0.223</td>
<td>0.005</td>
<td>0.005</td>
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<tr>
<td>$hh$</td>
<td>0.004</td>
<td>0.005</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.004</td>
<td>0.005</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>0.010</td>
<td>0.012</td>
<td>0.866</td>
<td>0.908</td>
</tr>
</tbody>
</table>

Blennow, Melbéus, and Ohlsson (2010)

$$r_q = \frac{m_q^{(1)} - m_{LKP}}{m_{LKP}}$$
The muon-antimuon flux at IceCube from the Sun

\[ \text{Muon flux from the Sun (km}^2\text{y}^{-1}) \]

\[ \text{allowed } m_{\gamma'}, \Delta_{q'} \]

\[ \Delta_{q'}=0.01 \]

\[ \Delta_{q'}=0.1 \]

\[ \text{IceCube-22 LKP } \gamma' (2007) \]

0910.4480 [astro-ph.CO]
The muon-antimuon flux at Earth

\((\text{LKP} = B^{(1)})\) from the Sun

![Graph showing the muon-antimuon flux at Earth as a function of LKP mass.]

Blennow, Melbéus, and Ohlsson (2010)

Muon energy threshold \(E^\text{th}_\mu = 1\) GeV

Thicker curve segment = correct relic abundance
The muon-antimuon flux at Earth

\( (LKP = W^{3(1)}) \) from the Sun

Muon energy threshold \( E^{\text{th}}_\mu = 1 \text{ GeV} \)

Thicker curve segment = correct relic abundance
Comments on earlier results

Neutrinos from KKDM annihilations in the Sun have previously been studied by:

- D. Hooper and G.D. Kribs, hep-ph/0208261

Our study arXiv:0910.1588:

- is a more careful treatment
- includes a six-dimensional model
- gives different branching ratios for $W^3(1)$
- results in a difference of 20 %–30 %

The IceCube collaboration (arXiv:0910.4480) have computed fluxes for the five-dimensional MUED model, which are similar to our results.
Summary & Conclusions

- We have investigated KKDM in two extra-dimensional models – one five-dimensional model and one six-dimensional model.
- In both models, $B^{(1)}$ and $W^{3(1)}$ as LKP’s are the interesting DM candidates.
- We have calculated the flux of neutrino-induced muons and antimuons in an Earth-based neutrino telescope (e.g. IceCube).
- The fluxes for the five- and six-dimensional models are equal. Therefore, it is not possible to distinguish them.
- The flux of neutrinos is somewhat larger for $B^{(1)}$ than for $W^{3(1)}$.
- If $B^{(1)}$ is the LKP, IceCube can put constraints on the parameter space. However, not if $W^{3(1)}$ is the LKP.