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:

JCAP **01**, 018 (2010)
arXiv:0910.1588 [hep-ph]

In collaboration with:

Mattias Blennow and Henrik Melbéus

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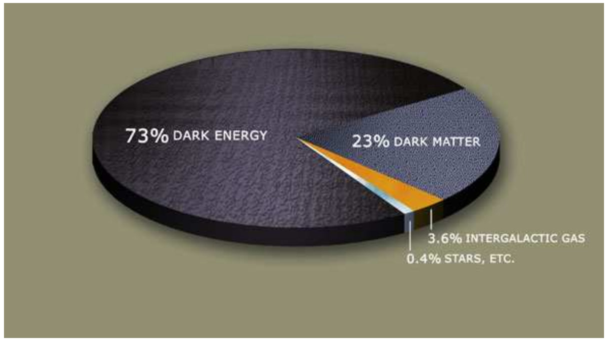
Dark matter in the Universe

Cosmological and astronomical observations $\Rightarrow$

- 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 (χ) are promising WIMP candidates.

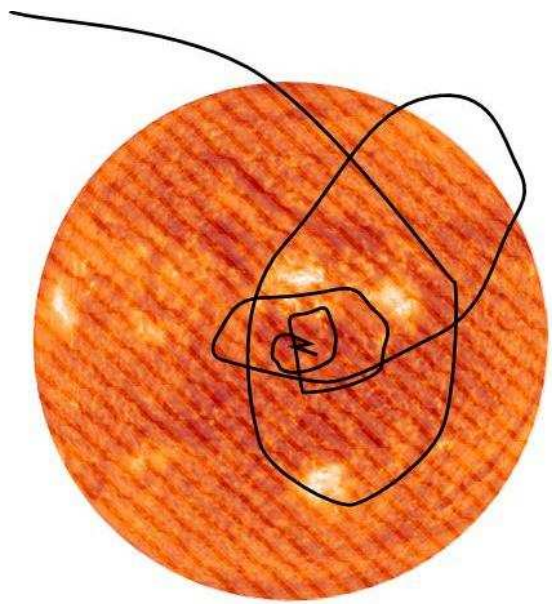
Extra-dimensional models

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

- Extra-dimensional field theory is non-renormalizable
  $\Rightarrow$ 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 = lightest Kaluza–Klein particle (*cf.*, LSP)
KKDM = Kaluza–Klein dark matter
Related talks by Neubert and Volkas.

WIMP capture and annihilation in the Sun

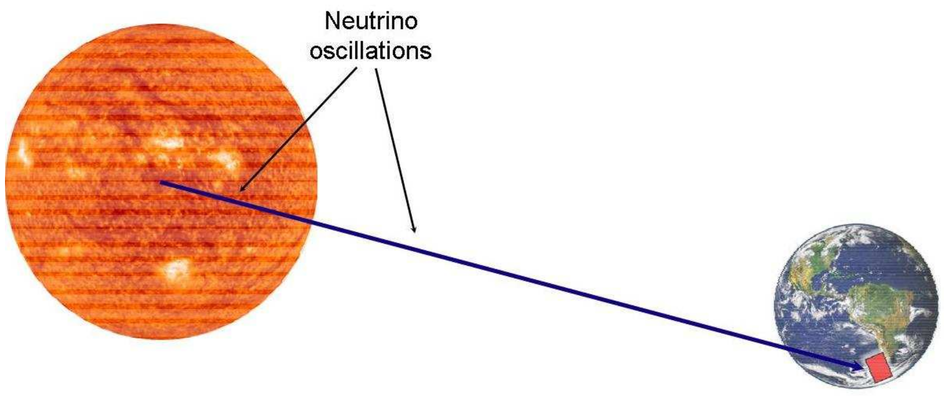


- WIMPs in the Milky Way halo can scatter in the Sun and be gravitationally bound to the Sun.
- Eventually, they will scatter again and sink to the core.
- In the core, WIMPs (here: KKDM) will accumulate and can annihilate and produce neutrinos.

$$\chi\chi \to u\bar{u}, d\bar{d}, \ell^- \ell^+, hh, W^- W^+, Z^0 Z^0, \nu\bar{\nu}$$

(no $g\bar{g}$ on tree level for KKDM annihilations)

Propagation from the Sun to the Earth



- Only ν's escape the Sun (from WIMP annihilations)
- Neutrino oscillations from production to detection are used.
- Muons are induced by ν'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

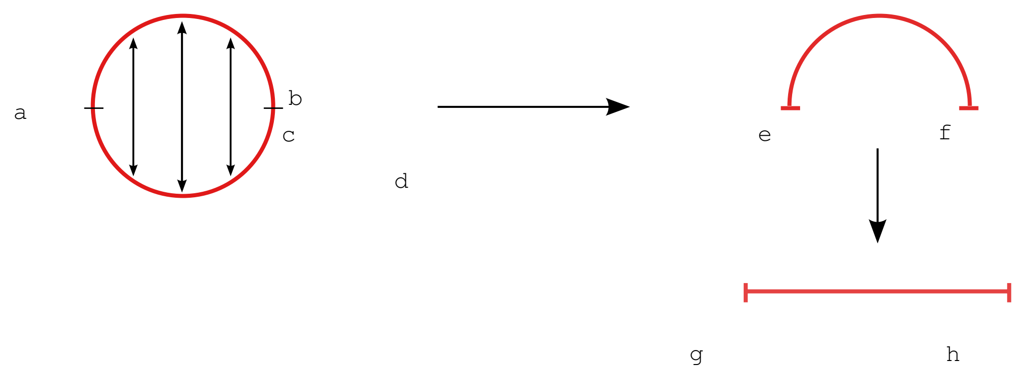
Our approximations:

- 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 Λ 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:

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

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

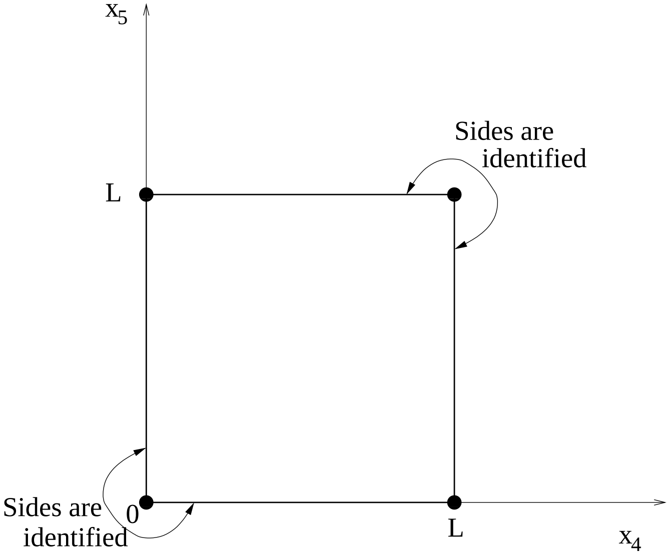
BLT = boundary localized term
Orbifold fixed points $\longrightarrow$ BLTs $\longrightarrow$ momentum non-conservation in extra dimensions $\longrightarrow$ conservation of KK-parity
BLTs:

- included in the Lagrangian
- affect the spectrum (at tree level) $\longrightarrow$ 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 Λ

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:

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

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

where

$$f_n^{(j,k)}(x^4, x^5) = \frac{1}{1+\delta_{j,0}}\left[e^{-\mathrm{i}n\pi/2}\cos\left(\frac{jx^4 + kx^5}{R} + \frac{n\pi}{2}\right)\right.$$

$$\left. \pm \cos\left(\frac{kx^4 - jx^5}{R} + \frac{n\pi}{2}\right)\right]$$

Indices $(j,k) = (1,0)$ give the first KK modes.

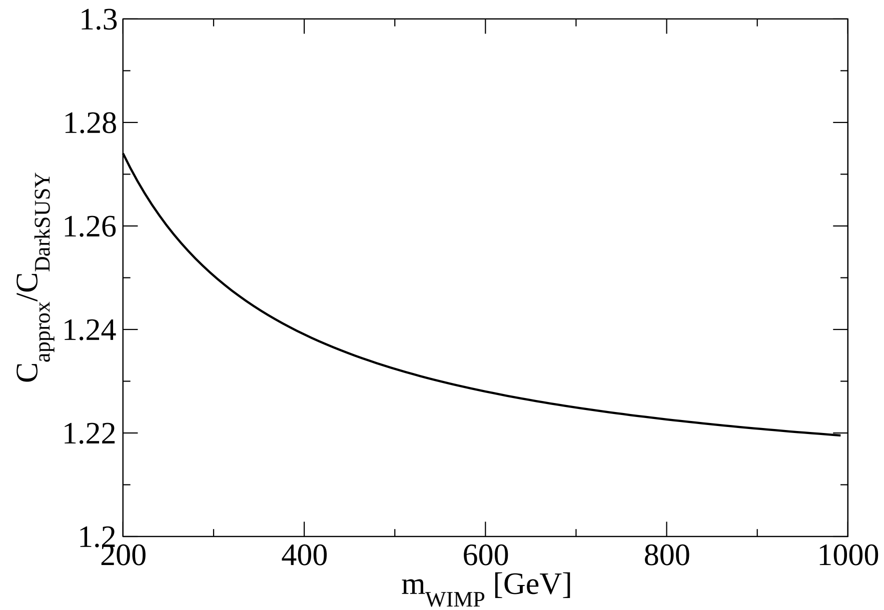
The six-dimensional model III

The gauge part of the five-dimensional Lagrangian is:

$$\mathcal{L}_{\text{gauge}} = -g f^{abc} \delta_{0,0,0}^{j_1,j_2,j_3} A_\mu^{(j_1),a} A_\nu^{(j_2),b} \partial^\mu A^{(j_3),c\nu}$$
$$+ \left(\frac{g}{2} f^{abc} A_H^{(1),a} (\partial^\mu A_H^{(1),b}) A_\mu^{(0),c} + \text{h.c.} \right)$$
$$- \frac{g^2}{4} f^{abc} f^{ade} \delta_{0,0,0,0}^{j_1,j_2,j_3,j_4} A_\mu^{(j_1),b} A_\nu^{(j_2),c} A^{(j_3),d\mu} A^{(j_4),e\nu}$$
$$- \frac{g^2}{2} f^{abc} f^{ade} A_H^{(1),c} A_H^{(1),e} A_\mu^{(0),b} A^{(0),d\mu}$$

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



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

About 25 % difference between approx and `DarkSUSY`

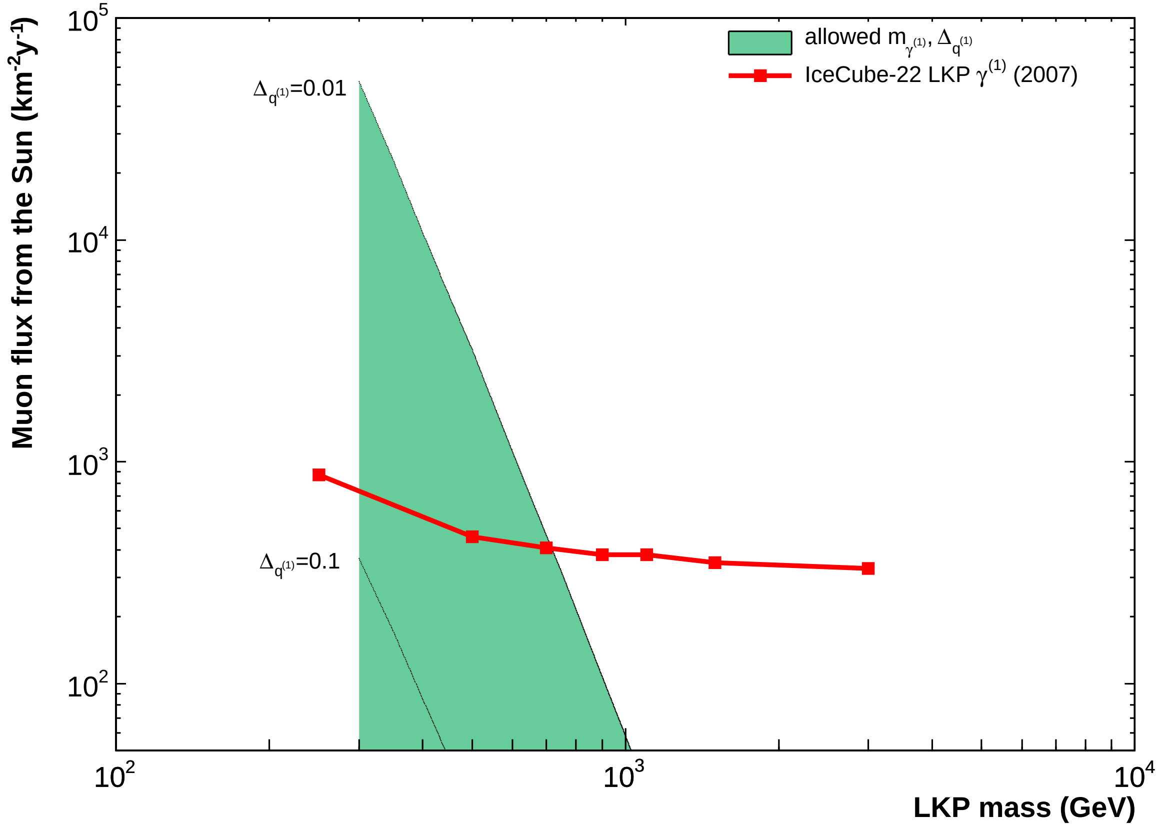
Branching ratios for pair annihilations of KKDM

Final state	$B^{(1)}$		$W^{3(1)}$		$B^{(1)}$	$W^{3(1)}$
r_q	1.0	1.3	1.0	1.3	0908.0899	
$\bar{u}u$	0.125	0.084	0.017	0.010	0.04	0.043
$\bar{d}d$	0.008	0.006	0.017	0.010	0.04	0.043
$\bar{\nu}\nu$	0.011	0.013	0.005	0.005	0.013	0.013
l^+l^-	0.183	0.223	0.005	0.005	0.20	0.01
hh	0.004	0.005	0.002	0.002	$\times$	$\times$
ZZ	0.004	0.005	0.002	0.002	$\times$	$\times$
W^+W^-	0.010	0.012	0.866	0.908	0	0.65

Blennow, Melbéus, and Ohlsson (2010)

$$r_q = \frac{m_{q^{(1)}} - m_{\mathrm{LKP}}}{m_{\mathrm{LKP}}}$$

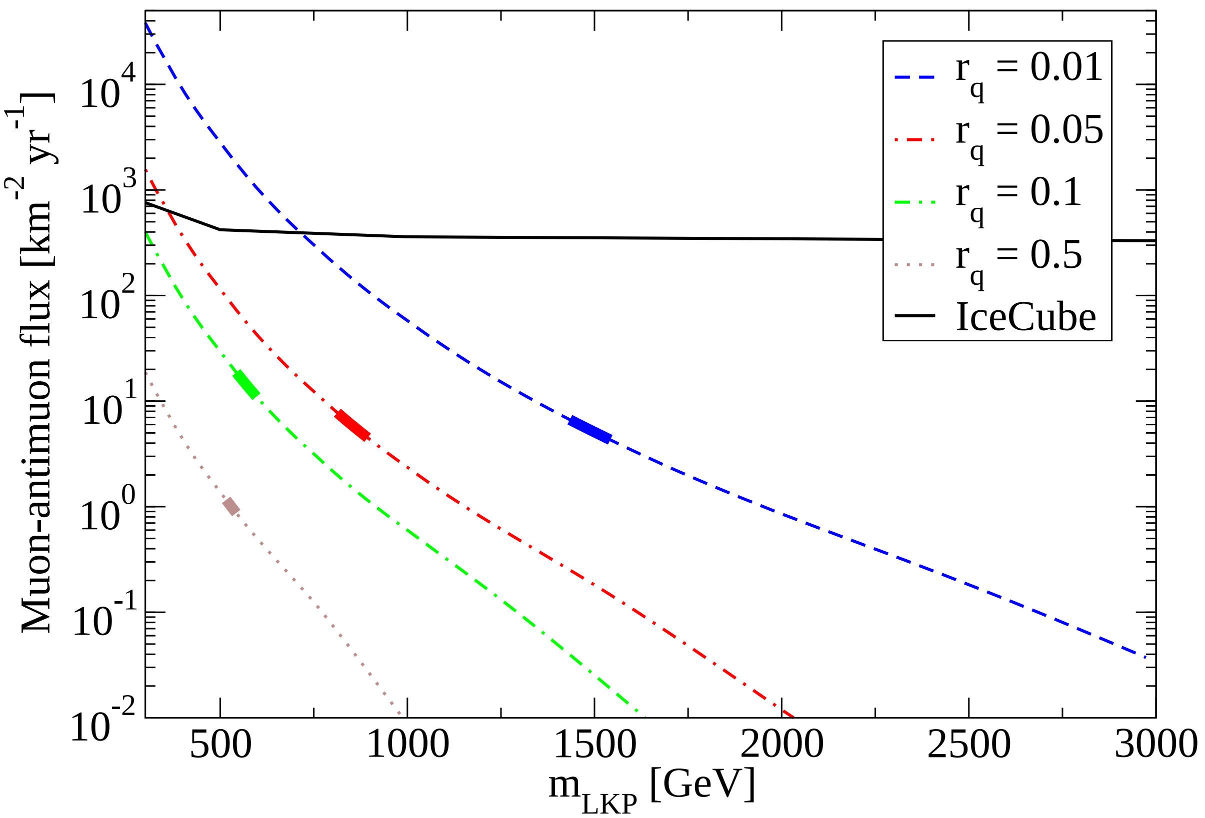
The muon-antimuon flux at IceCube from the Sun



0910.4480 [astro-ph.CO]

The muon-antimuon flux at Earth

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



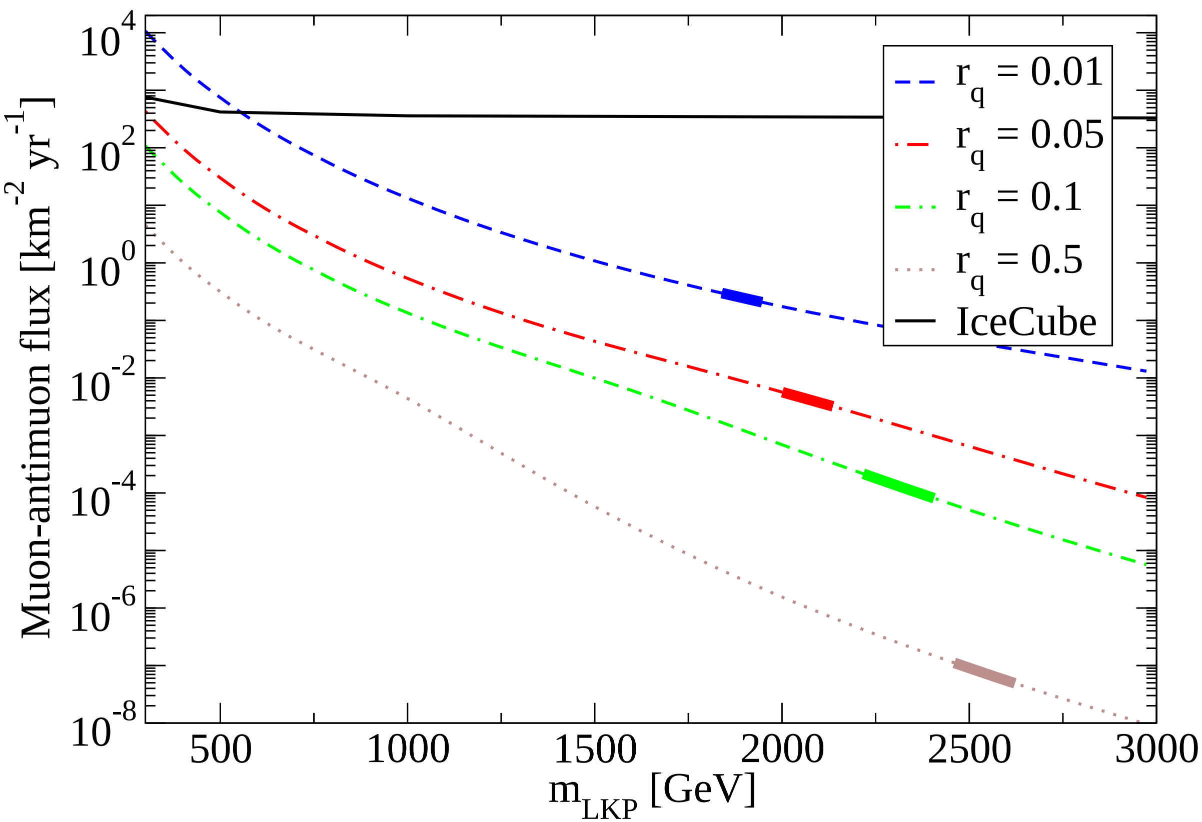
Blennow, Melbéus, and Ohlsson (2010)

Muon energy threshold $E_\mu^{\mathrm{th}} = 1$ GeV

Thicker curve segment = correct relic abundance

The muon-antimuon flux at Earth

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



Blennow, Melbéus, and Ohlsson (2010)

Muon energy threshold $E_\mu^{\rm th} = 1$ 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`
- T. Flake, A. Menon, D. Hooper, and K. Freese, `arXiv:0908.0899`

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.