Kaluza-Klein Dark Matter: a review

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Based on work with

- Tim Tait: hep-ph/0206071 (NPB)

- Bertone & Sigl: hep-ph/0211342 (PRD)

- Kaustubh Agashe: hep-ph/0403143 (PRL)
  hep-ph/0411254 (JCAP)

- Dan Hooper: to appear
**ADD models**

- only gravity in bulk
  - radion dark matter $m \sim \text{meV}$; (fine-tuned)
  - branon dark matter (fine-tuned)

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**R \sim \text{meV}^{-1}** (flat)

**TeV^{-1} X-dims**

- gauge bosons in bulk
  - radion dark matter $m \sim \text{meV}$; (fine-tuned)

- all SM fields in bulk
  - KK dark matter WIMP!

**R \sim \text{TeV}^{-1}** (flat)

- radion unstable
  - KK dark matter WIMP!

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**Warped geometries (Randall-Sundrum)**

- (AdS) if GUT in bulk
  - radion unstable
  - KK dark matter WIMP!

**R \sim M_{Pl}^{-1}** but **M \sim \text{TeV}_{KK}**
So far, two working models:

- **Universal Extra Dimensions (UED)**

  WIMP = Lightest KK particle (LKP)
  stability symmetry = KK parity

- **Warped GUTs**

  WIMP = Lightest $Z_3$ charged particle (LZP)
  stability symmetry = $Z_3$ symmetry

  + a potential link between the LZP and baryogenesis...
<table>
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<th>Reference</th>
<th>Topic</th>
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<tbody>
<tr>
<td>Kolb &amp; Slansky '84</td>
<td>Thought about it, but in 1984 $R^{-1} \sim \text{TeV}$ was inconceivable...</td>
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<td>Dienes, Dudas &amp; Gherghetta '99</td>
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<td>Mohapatra &amp; Perez-Lorenzana '02</td>
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<td>Servant &amp; Tait '02</td>
<td>Detailed relic density calculation</td>
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<td>Cheng, Feng &amp; Matchev '02</td>
<td>Direct and indirect detection</td>
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<td>Servant &amp; Tait '02</td>
<td>Direct detection</td>
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<td>Majumdar '02</td>
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<td>Hooper &amp; Kribs '02</td>
<td>Prospects for neutrino telescopes</td>
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<td>Bertone, Servant &amp; Sigl '02</td>
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<td>Hooper &amp; Kribs '04</td>
<td>Positron excess</td>
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<td>Bergstrom, Bringmann, Eriksson &amp; Gustafsson '04</td>
<td>Indirect detection</td>
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<tr>
<td>Baltz &amp; Hooper '04</td>
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<td>Bergstrom, Bringmann, Eriksson &amp; Gustafsson II '04</td>
<td></td>
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<tr>
<td>Kakizaki, Matsumoto, Sato &amp; Senami '05</td>
<td>A 2nd look at the relic density calculation</td>
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<td>+ superWimp KK graviton papers</td>
<td></td>
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<tr>
<td>Agashe &amp; Servant '04</td>
<td>Model building, relic density,</td>
</tr>
<tr>
<td>Agashe &amp; Servant II '04</td>
<td>direct detection, collider signatures...</td>
</tr>
<tr>
<td>Hooper &amp; Servant, upcoming</td>
<td>Indirect detection</td>
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</table>

KK dark matter in UED

Warped KK dark matter
LKP dark matter in Universal Extra Dimensions

UED: ALL SM particles propagate into flat dimensions

Conservation of momentum along extra dimension translates in 4D into conservation of KK number by the orbifold we impose to recover a chiral theory.

Other consequence of KK parity: Production of 1rst KK modes only by pairs:

Weak bound on 1/R:

\[ R^{-1} \geq 300 \text{ GeV for } \delta = 1 \]

\[ R^{-1} \geq 2500 \text{ GeV for } \delta = 2 \]
1-loop spectrum of 1rst KK modes

Cheng, Matchev & Schmaltz'02

assuming: $1/R = 500$ GeV, $\Lambda R = 20$, $m_h = 120$ GeV
and vanishing boundary terms at the cutoff $\Lambda$

$LKP$: most likely a $\gamma^1$ (actually a $B^1$)

Another intriguing possibility: $LKP=KK$ graviton (see S. Su's talk)
Relic density predictions

Reminder:
\[
\Omega h^2 \approx \frac{10^9}{m_*} \frac{\alpha_F}{\sqrt{g_*_F}} \frac{\text{GeV}^{-1}}{\langle \sigma v \rangle}
\]

\[\Omega h^2 = 0.11 \quad \Rightarrow \quad \langle \sigma v \rangle \approx 1 \text{ pb}
\]

\[\text{for } \alpha_F = 25-35\]

Annihilation cross sections
**Coannihilation effects**

- Servant-Tait

**Effect of 2nd KK modes**

"natural KK resonance"

Kakizaki & al, hep-ph/0502059

- Servant-Tait

**Possible effect of additional dimension**
Direct detection

Experimental limits:

LKP signal:

Cheng, Feng, Matchev '02

Servant, Tait '02
Particle physics model building in warped space

2005 FAVOURITE SET-UP:

- hierarchy pb
- fermion masses
- High scale unification
- FRW cosmology

Now embed this into a GUT + solve proton stability

- Dark matter
In GUTs \( \phi \) where \( M_{X,Y} \sim \text{few TeV} \) very fast proton decay

Solution: Break GUT by boundary conditions which split GUT multiplets

\[ \text{zero modes= SM fermions} \]
Mass spectrum of KK fermions

Depends on:

- type of boundary conditions on TeV and Planck branes
- c-parameter (=5D bulk mass) (=localization of zero-mode wave function)

For certain type of boundary conditions on fermions, there can be a hierarchy between the mass of KK fermion and the mass of KK gauge bosons

- Not a single KK scale
and smallest c: c of the top quark

LZP belongs to the multiplet containing SM top quark

There exists a very light KK fermion as a consequence of the heaviness of the top quark
zero modes = SM fermions
Relic density predictions

\[ h^2 = 0.110 \pm 0.01 \]

\[ M_{KK} = 3 \text{ TeV} \]

\[ M_{KK} = 6 \text{ TeV} \]

Agashe-Servant '04
Direct detection

Wimp-nucleon elastic scattering cross section (spin-independent)

masses of KK gauge bosons

CDMS limit (only applies for some range of wimp masses)

Agashe-Servant '04
Collider Signature: example

\[ 4 \ W + 2 \ b + E_T \]

\[ 6 \ W + 4 \ b + E_T \]
Indirect detection in neutrino telescopes

Large elastic scattering cross section: large capture rate in the Sun
Efficient production of neutrinos in annihilations

Hooper & Servant, in prep.
Cosmic positrons from LZP annihilations

Fit of the HEAT data from LZP annihilations

Hooper & Servant, in prep.
Our dark matter candidate carries baryon number! \((B=1/3)\)

\[
B_{\text{UNIVERSE}} = 0 = B + (-B)
\]

Assume an asymmetry between \(t\) and \(\bar{t}\) is created via the out-of-equilibrium and CP-violating decay:

Baryon number conservation leads to:

\[
3 (n_{LZP} - n_{\bar{LZP}}) = n_b - n_{\bar{b}}
\]

Assuming efficient annihilation between \(LZP\) and \(\bar{LZP}\), and \(b\) and \(\bar{b}\):

\[
\rho_{\text{DM}} = m_{LZP} \frac{n_{LZP}}{n_{LZP}} \approx 6 \rho_b \quad \Rightarrow \quad m_{LZP} \approx 18 \text{ GeV}
\]
<table>
<thead>
<tr>
<th>Nature</th>
<th>LKP</th>
<th>LZP</th>
<th>LSP</th>
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<tr>
<td>Gauge boson</td>
<td></td>
<td>Dirac fermion</td>
<td>Majorana fermion</td>
</tr>
<tr>
<td>KK parity</td>
<td>$(-1)^n$</td>
<td>$Z_3$</td>
<td>$(-1)^{3(B-L)+2S}$</td>
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<tr>
<td>Symmetry</td>
<td></td>
<td>$B - (n_c - \bar{n}_c)/3$</td>
<td></td>
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<tr>
<td>Mass range</td>
<td>~600-1000 GeV</td>
<td>20 GeV-few TeV</td>
<td>~50 GeV-1 TeV</td>
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<tr>
<td>Annihilation</td>
<td>s-wave</td>
<td>s-wave</td>
<td>Helicity suppressed</td>
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<td>Cross section</td>
<td></td>
<td></td>
<td>(p-wave)</td>
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<td>LHC fav. det.</td>
<td>☑️</td>
<td>Direct detection!</td>
<td>☑️</td>
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<tr>
<td>Indirect det.</td>
<td>☑️</td>
<td>LHC!</td>
<td>Full parameter space is testable</td>
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</table>
To conclude

Abundance of experimental activity related to dark matter detection:
- Colliders
- Direct detection: CDMS, Edelweiss, Dama, Cresst, Zeplin, Xenon, Naiad ...
- Indirect detection:
  - Gamma-ray telescopes: Hess, Veritas, Glast, Magic
  - Neutrino telescopes: Amanda, IceCube, Antares
  - Cosmic positron experiments: HEAT, Pamela, AMS-2

It is timely to study the distinctive signatures expected in different dark matter scenarios.

LKPs, LZPs: viable alternatives to LSPs