Cosmological Constraint on the Minimal Universal Extra Dimension Model

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Refs:
1. Motivation

What is the constituent of dark matter?

- Weakly interacting massive particles are good candidates:
  - Lightest supersymmetric particle (LSP) in supersymmetric (SUSY) models
  - Lightest Kaluza-Klein particle (LKP) in universal extra dimension (UED) models
  - etc.

Today's topic

Observations of

- cosmic microwave background
- structure of the universe
- etc.

Non-baryonic cold dark matter

[http://map.gsfc.nasa.gov]
Calculation of the LKP abundance

- The 1\textsuperscript{st} KK particle of the B boson is assumed to be the LKP
- The LKP relic abundance $\Omega h^2$ is dependent on effective annihilation cross section $\sigma_{\text{eff}}$
- Naïve calculation without coannihilation nor resonance
  
  WMAP data $m_{\text{LKP}} \simeq 800 \text{ GeV}$

- Coannihilation
  
  Coannihilation with KK right-handed leptons
  
  Coannihilation with all 1\textsuperscript{st} KK particles
  
  Coannihilation with KK Higgs bosons for large $m_h$

- Resonance
  
  $\sigma_{\text{eff}}$ ; $\Omega h^2$

References:

[Servant, Tait, NPB650 (2003) 391]

[Burnell, Kribs, PRD73(2006); Kong, Matchev, JHEP0601(2006)]

Outline

- Reevaluation of the relic density of LKPs including coannihilation and resonance effects
- Constraint on the parameter space of the minimal UED model

1. Motivation
2. Universal extra dimension (UED) models
3. Relic abundance of KK dark matter
4. Coannihilation processes
5. Resonance processes
6. Summary
2. Universal extra dimension (UED) models

Idea: All SM particles propagate in flat compact spatial extra dimensions

- Dispersion relation: \( E^2 = \vec{p}^2 + (p_5^2 + M^2) \)
  - Momentum along the extra dimension = Mass in four-dimensional viewpoint

- In case of \( S^1 \) compactification with radius \( R \),
  \( p_5 = n/R \) (\( n = 0, 1, 2, \cdots \)) is quantized \( \rightarrow \) KK tower

- Momentum conservation in the extra dimension
  - Conservation of KK number \( n \) at each vertex

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Minimal UED (MUED) model

- In order to obtain chiral zero-mode fermions, the extra dimension is compactified on an $S^1/Z_2$ orbifold
- Conservation of KK parity [ + (−) for even (odd) $n$ ]
  The lightest KK particle (LKP) is stable
  c.f. R-parity and LSP

The LKP is a good candidate for dark matter

- Only two new parameters appear in the MUED model:
  $R$ : Size of extra dimension
  $\Lambda$ : Scale at which boundary terms vanish
  The Higgs mass $m_h$ remains a free parameter

More fundamental theory

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Constraints coming from electroweak measurements are weak

[Appelquist, Cheng, Dobrescu PRD64 (2001); Appelquist, Yee, PRD67 (2003); Gogoladze, Macesanu, hep-ph/0605207]

Requiring that LKPs account for the CDM abundance in Universe, the parameter space gets more constrained

(Under the assumption of thermal production)
Mass spectra of KK states

- KK particles are degenerate in mass at tree level:
  \[ m^{(n)} = \sqrt{(n/R)^2 + m_{\text{SM}}^2} \approx n/R \]

- Compactification → 5D Lor. inv.
  Orbifolding → Trans. Inv. in 5th dim.

  Radiative corrections relax the degeneracy

  Lightest KK Particle (LKP):
  \[ \gamma^{(1)} \text{ (mixture of } B^{(1)} - W^{3(1)} \text{) } \]

- KK particles of leptons and Higgs bosons are highly degenerate with the LKP

  Coannihilation plays an important role in calculating the relic density

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[From Cheng, Matchev, Schmaltz, PRD66 (2002) 036005]
3. Relic abundance of KK dark matter

- Generic picture
  - Dark matter particles were in thermal equilibrium in the early universe
  - After the annihilation rate dropped below the expansion rate, the number density per comoving volume is almost fixed

- Relic abundance of the LKP \( \gamma^{(1)} \)
  - [Servant, Tait, NPB 650 (2003) 391]

  \[
  \begin{align*}
  B^1 & \rightarrow f \bar{f} \\
  B^1 & \rightarrow f^1 \bar{f}^1 \\
  B^1 & \rightarrow f \bar{f} \\
  B^1 & \rightarrow f^1 \bar{f}^1
  \end{align*}
  \]

- Coannihilation only with the NLKP \( \ell^{(1)}_R \)
- No resonance process

\[
\Omega h^2 = 0.16 \pm 0.04
\]
4. Coannihilation processes

- KK particles of leptons and Higgs bosons are highly degenerate with the LKP. Coannihilation plays an important role in calculating the relic density.

\[
\sigma_{\text{eff}} = \sum_{ij} \sigma_{ij} \frac{g_i g_j}{g_{\text{eff}}} \frac{(1 + \Delta_i)^{3/2}}{g_{\text{eff}}} \frac{(1 + \Delta_j)^{3/2}}{g_{\text{eff}}} \exp[-x(\Delta_i + \Delta_j)]
\]

\[
g_{\text{eff}} = \sum_i g_i (1 + \Delta_i)^{3/2} \exp(-x\Delta_i)
\]

- In generic:

\[
\sigma_{\text{co}} < \sigma(\gamma^{(1)} \gamma^{(1)} \rightarrow \text{SM}) \quad \Omega h^2 \quad \text{e.g.: KK leptons: } l_R^{(1)}, l_L^{(1)}, \nu^{(1)}
\]

\[
\sigma_{\text{co}} > \sigma(\gamma^{(1)} \gamma^{(1)} \rightarrow \text{SM}) \quad \Omega h^2 \quad \text{e.g.: KK Higgs bosons: } H^{(1)}, A^{(1)}, H^{\pm(1)}
\]
Previous calculation

- Inclusion of coannihilation modes with all 1st KK particles reduces the effective cross section

\[ m_h = 120 \text{ GeV} \]

No resonance process is considered

We emphasize:

- The relic abundance depends on the SM Higgs mass
- Resonance effects also shift the allowed mass scale

[From Kong, Matchev, JHEP0601(2006)]
Masses of the KK Higgs bosons

- 1st KK Higgs boson masses:
  \[ m_{H(1)}^2 = \frac{1}{R^2} + m_h^2 + \delta m_{H(1)}^2 \]
  \[ m_{H\pm(1)}^2 = \frac{1}{R^2} + m_W^2 + \delta m_{H(1)}^2 \]
  \[ m_{A(1)}^2 = \frac{1}{R^2} + m_Z^2 + \delta m_{H(1)}^2 \]
  \[ \delta m_{H(1)}^2 = \left( \frac{3}{2} g_2^2 + \frac{3}{4} g^2 - \lambda_H \right) \frac{1}{16\pi^2 R^2} \ln(\Lambda^2 R^2) \]
  \[ m_{H\pm(1)}^2 < m_{A(1)}^2 < m_{H(1)}^2 \]

- Larger \( m_h \)
  - Larger \( \lambda_H = \frac{m_h^2}{v^2} \); smaller \( \delta m_H^2 \)
  - (Enhancement of the annihilation cross sections for the KK Higgs bosons)

- Too large \( m_h \)
  - The 1st KK charged Higgs boson is the LKP
We investigate dependence of the LKP relic abundance on the Higgs mass, including all coannihilation modes with 1st KK particles.

- **Bulk region (small $m_h$)**
  
  The result is consistent with previous works.

- **KK Higgs coannihilation region (large $m_h$)**

  $$\sigma(H^{\pm(1)}H^{\mp(1)} \to \text{SM}) \gg \sigma(\gamma^{(1)}\gamma^{(1)} \to \text{SM})$$

  - The relic abundance decreases through the Higgs coannihilation.
  - Larger $R^{-1}$ is allowed.
KK Higgs coannihilation region

- For larger $m_h$ (larger Higgs self-coupling)
  - Degeneracy between the LKP and $A^{(1)}$, $H^{\pm(1)}$
  - Free from a Boltzmann suppression
  - Larger $\sigma_{\text{eff}}$

[Matsumoto, Senami, PLB633 (2006)]

- The effective cross section can increase after freeze-out

The LKP abundance can sizably decrease even after freeze-out
5. Resonance processes

- KK particles are non-relativistic when they decouple

\[ \text{(Incident energy of two 1}^{\text{st}} \text{KK particles)} \]
\[ \simeq \text{(Masses of 2}^{\text{nd}} \text{KK particles)} \]
\[ \sqrt{s} \simeq m^{(1)} + m^{(1)} \simeq m^{(2)} \]

- Annihilation cross sections are enhanced through s-channel 2\textsuperscript{nd} KK particle exchange at loop level

- Important processes:
  \[ \gamma^{(1)} \gamma^{(1)} \rightarrow H^{(2)} \rightarrow \text{SM particles} \]
  \[ e^{(1)} e^{(1)}, \nu^{(1)} \bar{\nu}^{(1)} \rightarrow Z^{(2)} \rightarrow \text{SM particles} \]
  \[ e^{(1)} \bar{\nu}^{(1)} \rightarrow W^{- (2)} \rightarrow \text{SM particles} \]
  \[ A^{(1)} A^{(1)}, H^{(1)} H^{(1)} \rightarrow H^{(2)} \rightarrow \text{SM particles} \]
Inclusion of resonance processes

- Cosmologically allowed region is shifted upward by $150 - 300 \text{GeV}$

- For $R^{-1} < 800 \text{ GeV}$
  
  the LKP may be the KK graviton

  `KK graviton problem`
  like the gravitino problem

- Some mechanism to make the KK graviton heavy is proposed [Dienes PLB633 (2006)]
**Origin of the shift**

- **Bulk region**
  \( W^{(2)}, Z^{(2)} \)-res. are effective

- **KK Higgs co-annihilation region**
  \( H^{(2)} \)-res. contributes as large as \( W^{(2)}, Z^{(2)} \)-res.

\( m_h = 120 \text{ GeV} \)

\( m_h = 220 \text{ GeV} \)
6. Summary

- UED models provide a viable dark matter candidate:
  The lightest Kaluza-Klein particle (LKP)

- The LKP relic abundance is reduced by the coannihilation with the KK Higgs bosons and second KK resonance

- We calculated the LKP relic abundance in the MUED model including the resonance processes in all coannihilation modes

- Cosmologically allowed region in the MUED model
Backup slides
Relic abundance of the LKP (without coannihilation)

- The $H^{(2)}$-resonance in annihilation effectively reduces the number density of dark matter

- The resonance effect shifts upwards the LKP mass consistent with the WMAP data
KK Higgs coannihilation region

- Larger Higgs mass
  (larger Higgs self-coupling)
- Mass degeneracy between 1\textsuperscript{st} KK Higgs bosons and the LKP in MUED
- Larger annihilation cross sections for the 1\textsuperscript{st} KK Higgs bosons

Coannihilation effect with 1\textsuperscript{st} KK Higgs bosons efficiently decrease the LKP abundance

\( R^{-1} \) of 1 TeV is compatible with the observation of the abundance

Dependence of the LKP relic abundance on the Higgs mass (ignoring resonance effects)

[Matsumoto, Senami, PLB633 (2006)]
Positron experiments

- The HEAT experiment indicated an excess in the positron flux:
  - Unnatural dark matter substructure is required to match the HEAT data in SUSY models [Hooper, Taylor, Silk, PRD69 (2004)]
  - KK dark matter may explain the excess [Hooper, Kribs, PRD70 (2004)]

- Future experiments (PAMELA, AMS-02, ...) will confirm or exclude the positron excess
Including coannihilation with $1^{\text{st}}$ KK singlet leptons

- The LKP $\gamma^{(1)}$ is nearly degenerate with the $2^{\text{nd}}$ KK singlet leptons $E_i^{(1)}$

  Coannihilation effect is important

- Annihilation cross sections

  \[
  \sigma(\gamma^{(1)}\gamma^{(1)} \rightarrow \text{SM particles}) > \sigma(\gamma^{(1)}E^{(1)} \rightarrow \text{SM particles})
  \]

  The allowed LKP mass region is lowered due to the coannihilation effect

  c.f. SUSY models: coannihilation effect raises the allowed LSP mass