Cosmological Constraint on the Minimal Universal Extra Dimension Model

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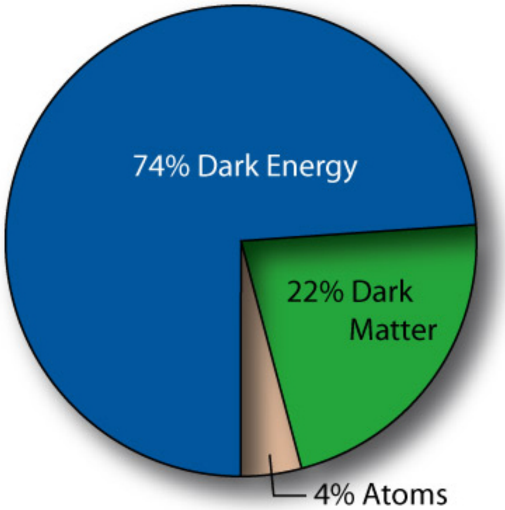
Refs:

- PRD 71 (2005) 123522 [hep-ph/0502059]
- NPB 735 (2006) 84 [hep-ph/0508283]
- PRD 74 (2006) 023504 [hep-ph/0605280]

1. Motivation



[http://map.gsfc.nasa.gov]

Observations of

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

→ **Non-baryonic cold dark matter**

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 ← Today's topic
  - etc.

Calculation of the LKP abundance

- The 1st KK particle of the B boson is assumed to be the LKP
- The LKP relic abundance Ωh^2 is dependent on effective annihilation cross section $\sigma_{\rm eff}$

- **Naïve calculation without coannihilation nor resonance**

  WMAP data ⇒ $m_{\rm LKP} \simeq 800~{\rm GeV}$ [Servant, Tait, NPB650 (2003) 391]

- **Coannihilation**

  Coannihilation with KK right-handed leptons

  [Servant, Tait, NPB650 (2003) 391]

  Coannihilation with all 1st KK particles

  $\sigma_{\rm eff}$ ↘ ; Ωh^2 ↗ [Burnell, Kribs, PRD73(2006); Kong, Matchev, JHEP0601(2006)]

  Coannihilation with KK Higgs bosons for large m_h

  $\sigma_{\rm eff}$ ↗ ; Ωh^2 ↘ [Matsumoto, Senami, PLB633 (2006)]

- **Resonance**

  $\sigma_{\rm eff}$ ↗ ; Ωh^2 ↘

  [MK, Matsumoto, Sato, Senami, PRD71 (2005) 123522; NPB735 (2006) 84; PRD74 (2006) 023504]

Outline

Our work

- Reevaluation of the relic density of LKPs including coannihilation and resonance effects

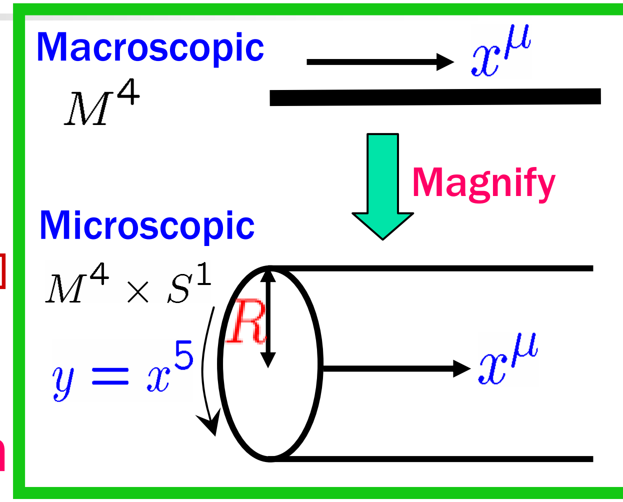
⇨ Constraint on the parameter space of the minimal UED model

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

[Appelquist, Cheng, Dobrescu, PRD64 (2001) 035002]

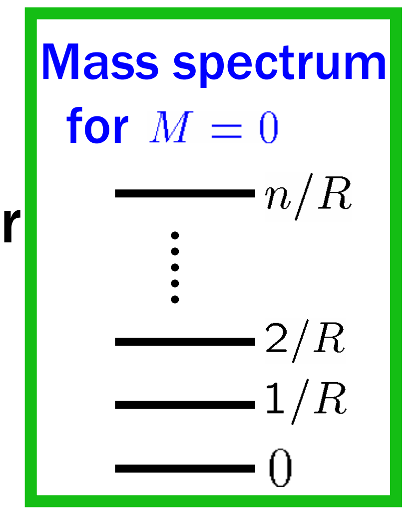


- **Dispersion relation:** $E^2 = \vec{p}^2 + (p_5^2 + M^2)$

  ⇨ Momentum along the extra dimension = Mass in four-dimensional viewpoint

- In case of S^1 compactification with radius R,

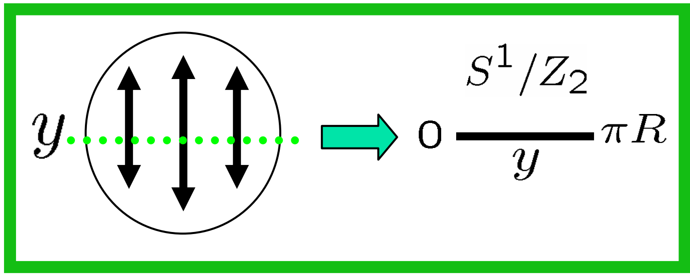
  $p_5 = n/R \quad (n = 0, 1, 2, \cdots)$ is quantized ⇨ KK tower



- Momentum conservation in the extra dimension

  ⇨ Conservation of KK number n at each vertex

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

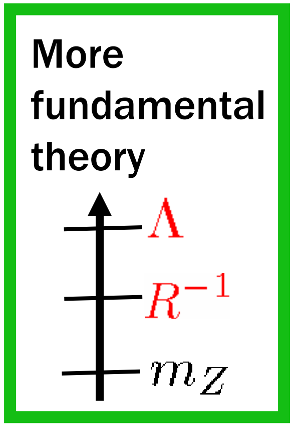
The LKP is a good candidate for dark matter

- Only two new parameters appear in the MUED model:

R : Size of extra dimension

Λ : Scale at which boundary terms vanish

The Higgs mass m_h remains a free parameter



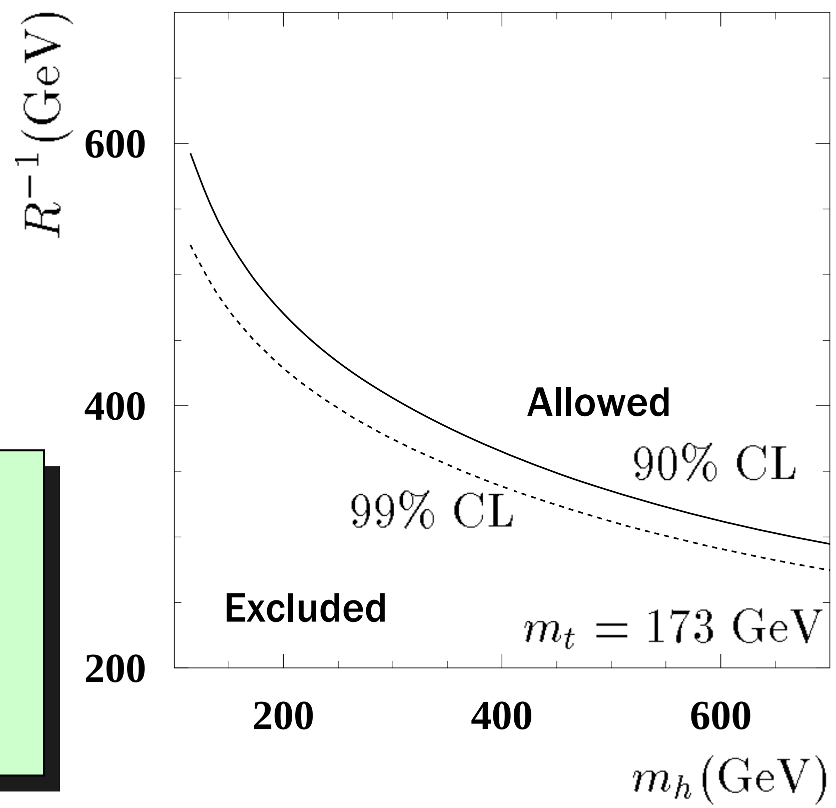
Constraint on R^{-1} in the MUED model

- 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)



[From Gogoladze, Macesanu, hep-ph/0605207]

Mass spectra of KK states

- KK particles are degenerate in mass at tree level: $m^{(n)} = \sqrt{(n/R)^2 + m_{\rm SM}^2} \simeq n/R$

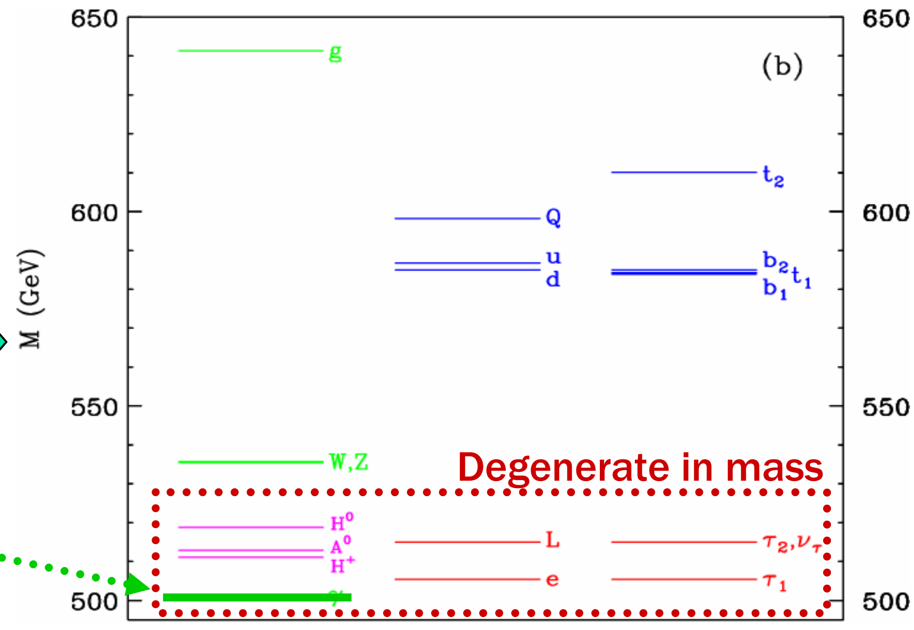
- Compactification → 5D Lor. inv.
  Orbifolding → Trans. Inv. in 5th dim.

  ↳ Radiative corrections relax the degeneracy →

Lightest KK Particle (LKP):

$\gamma^{(1)}$ (mixture of $B^{(1)} - W^{3(1)}$)

1-loop corrected mass spectrum at the first KK level



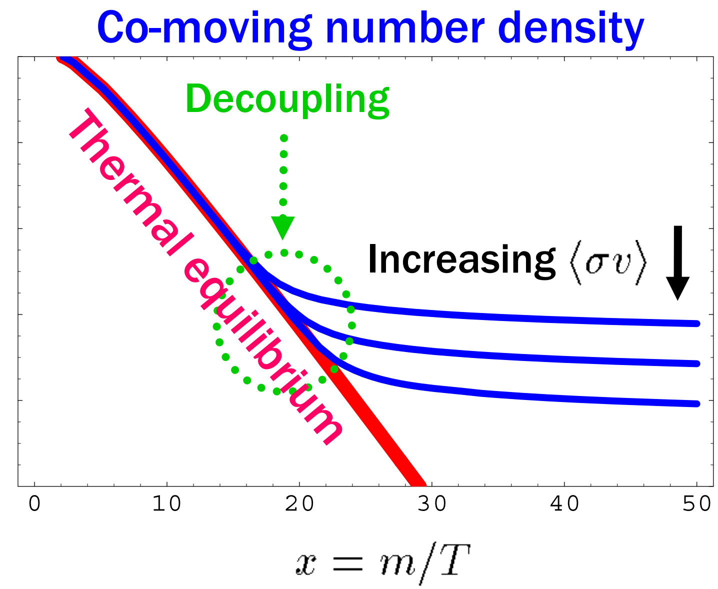
$R^{-1} = 500\ {\rm GeV},\ \Lambda R = 20,\ m_h = 120\ {\rm GeV}$

[From Cheng, Matchev, Schmaltz, PRD66 (2002) 036005]

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

  → Coannihilation plays an important role in calculating the relic density

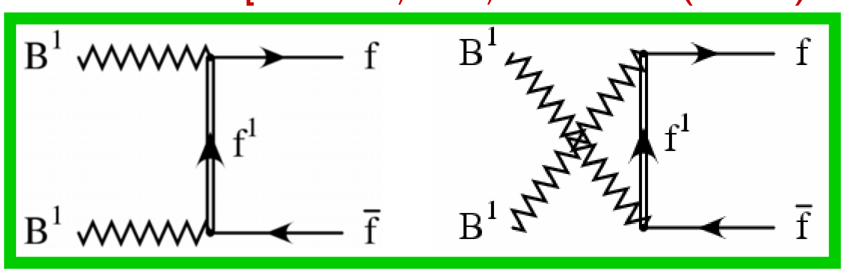
3. Relic abundance of KK dark matter



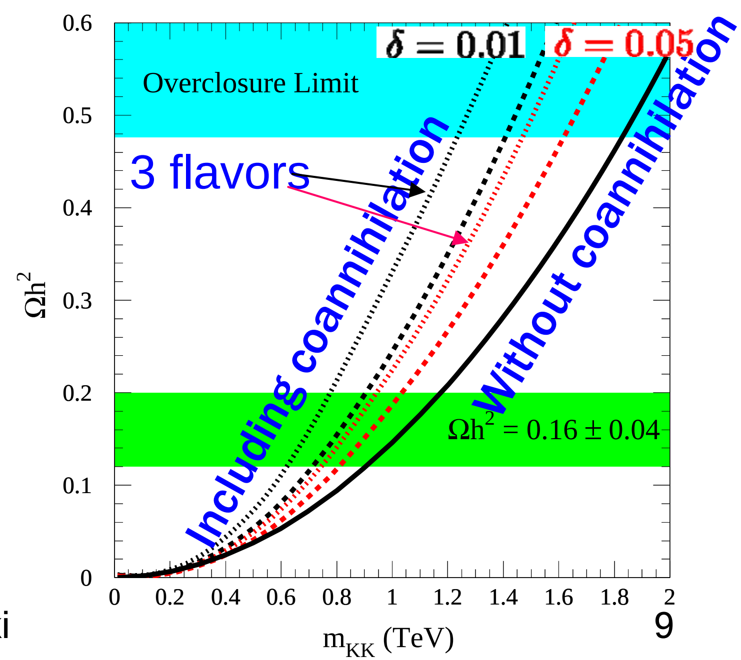
- Generic picture
  - Dark matter particles were in thermal equilibrium in the early universe
  - After the annihilation rate dropped below the expansion rate, the number density per comoving volume is almost fixed

- Relic abundance of the LKP $\gamma^{(1)}$

[Servant, Tait, NPB 650 (2003) 391]



  - Coannihilation only with the NLKP $l_R^{(1)}$
  - No resonance process



4. Coannihilaition processes

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

  ⇒ Coannihilation plays an important role in calculating the relic density

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

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

$$\Delta_i = \frac{m_i - m_{\gamma^{(1)}}}{m_{\gamma^{(1)}}}$$

- In generic

$\sigma_{\rm co} < \sigma(\gamma^{(1)}\gamma^{(1)} \to {\rm SM})$ ⇒ Ωh^2 ↗

e.g.: KK leptons: $l_R^{(1)}, l_L^{(1)}, \nu^{(1)}$

$\sigma_{\rm co} > \sigma(\gamma^{(1)}\gamma^{(1)} \to {\rm SM})$ ⇒ Ωh^2 ↘

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

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

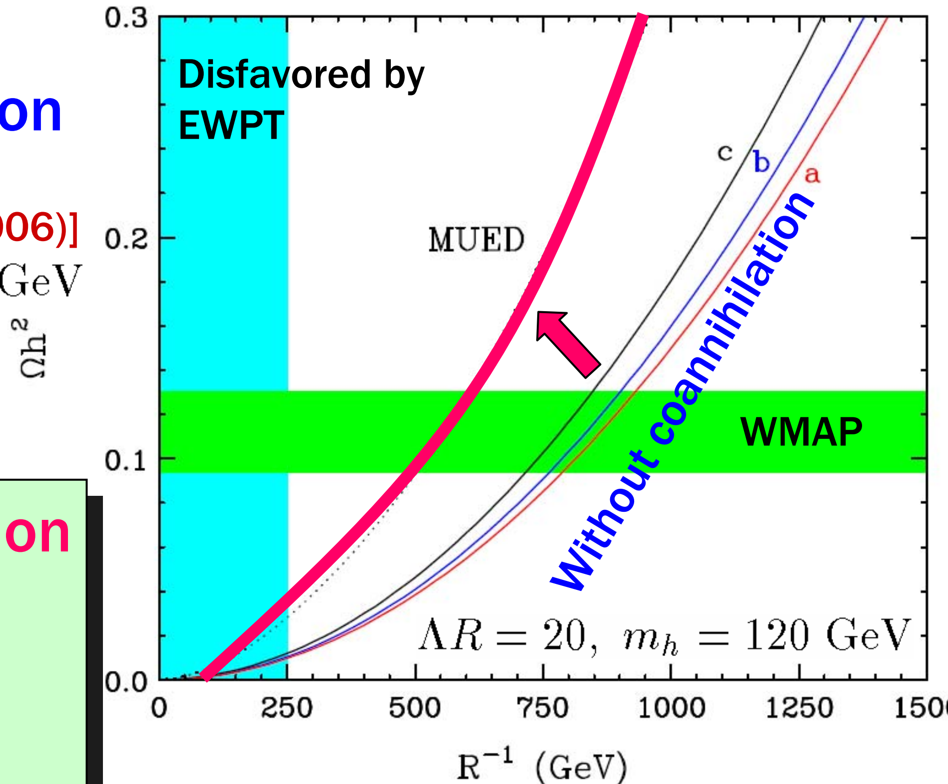
The Higgs mass is fixed to $m_h = 120$ GeV

No resonance process is considered

We emphasize:

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

Relic abundance of the LKP



[From Kong, Matchev, JHEP0601(2006)]

Masses of the KK Higgs bosons

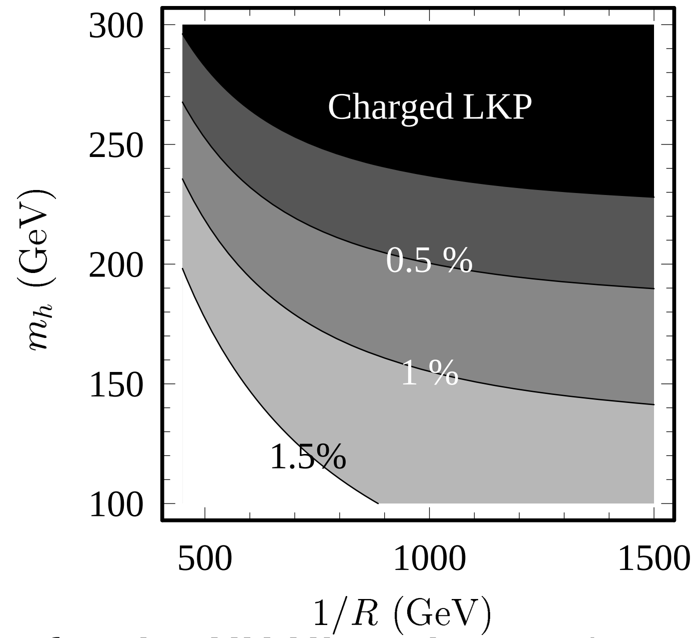
- 1st KK Higgs boson masses:

$$m^2_{H^{(1)}} = 1/R^2 + m_h^2 + \delta m^2_{H^{(1)}}$$
$$m^2_{H^{\pm(1)}} = 1/R^2 + m_W^2 + \delta m^2_{H^{(1)}}$$
$$m^2_{A^{(1)}} = 1/R^2 + m_Z^2 + \delta m^2_{H^{(1)}}$$
$$\delta m^2_{H^{(1)}} = \left(\frac{3}{2}g_2^2 + \frac{3}{4}g'^2 - \lambda_H\right)\frac{1}{16\pi^2 R^2}\ln(\Lambda^2 R^2)$$

⇒ $m^2_{H^{\pm(1)}} < m^2_{A^{(1)}} < m^2_{H^{(1)}}$

Contour plot of mass splitting

$(m_H^{\pm(1)} - m_\gamma^{(1)})/m_\gamma^{(1)}$



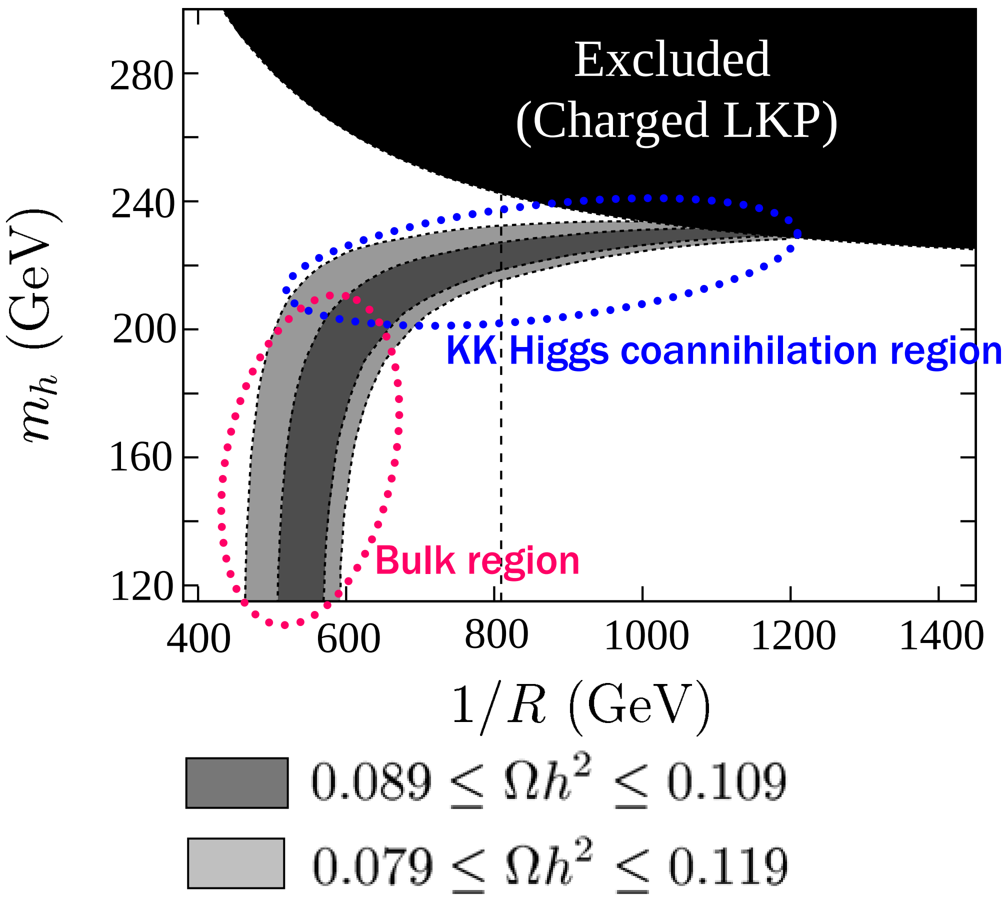
- Larger m_h

⇒ Larger $\lambda_H = m_h^2/v^2$; smaller δm_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

New Allowed region without resonance processes



- 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)

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

⇨ The relic abundance decreases through the Higgs coannihilation

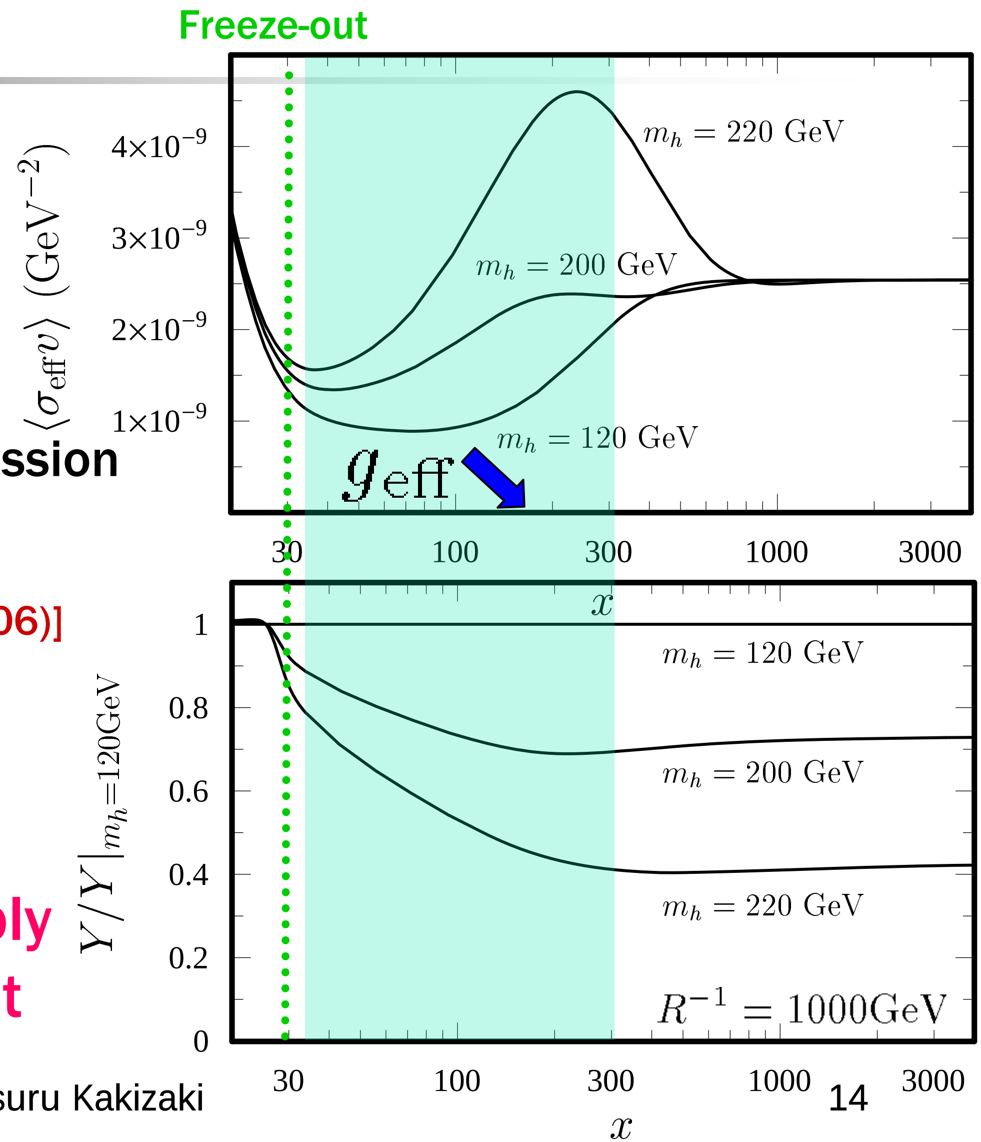
⇨ Larger R^{-1} is allowed

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 $\sigma_{\rm eff}$

[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

⇨ (Incident energy of two 1st KK particles)

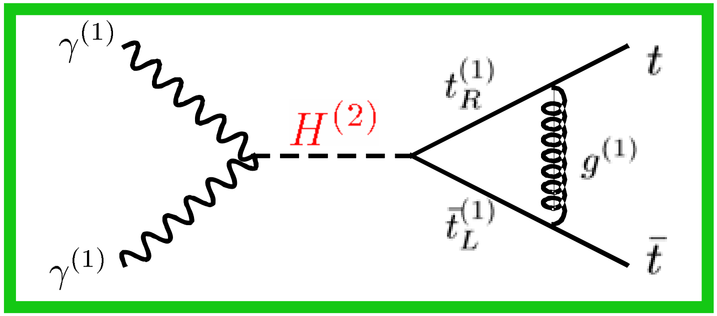
$\simeq$ (Masses of 2nd KK particles) $\sqrt{s} \simeq m^{(1)} + m^{(1)} \simeq m^{(2)}$

⇨ Annihilation cross sections are enhanced through s-channel 2nd KK particle exchange at loop level

- Important processes:

$$\begin{aligned} \gamma^{(1)}\gamma^{(1)} &\rightarrow H^{(2)} \rightarrow \text{SM particles} \\ e^{(1)}\bar{e}^{(1)}, \nu(1)\bar{\nu}^{(1)} &\rightarrow Z^{(2)} \rightarrow \text{SM particles} \\ e^{(1)}\bar{\nu}^{(1)} &\rightarrow W^{-(2)} \rightarrow \text{SM particles} \\ A^{(1)}A^{(1)}, H^{+(1)}H^{-(1)} &\rightarrow H^{(2)} \rightarrow \text{SM particles} \end{aligned}$$

c.f.



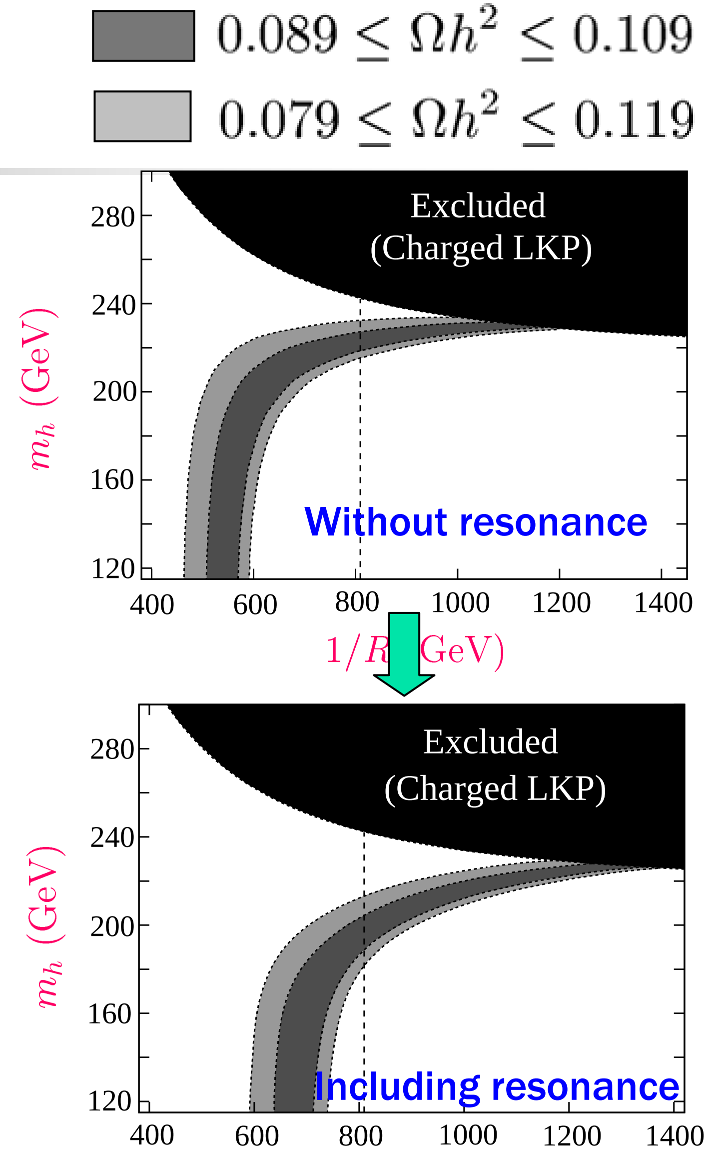
Inclusion of resonance processes

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

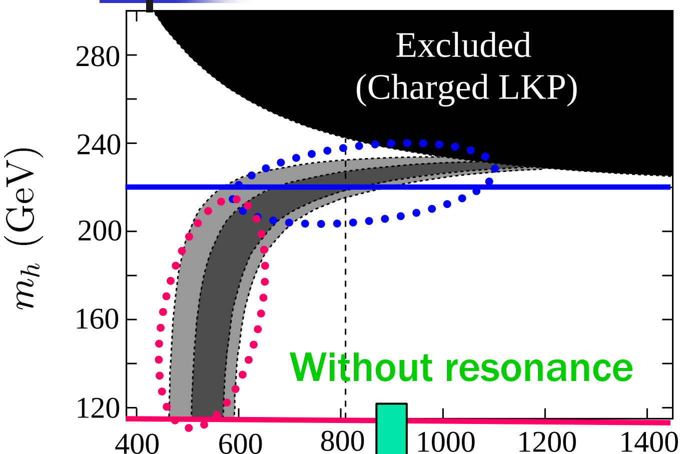
- For $R^{-1} < 800\ \mathrm{GeV}$ the LKP may be the KK graviton

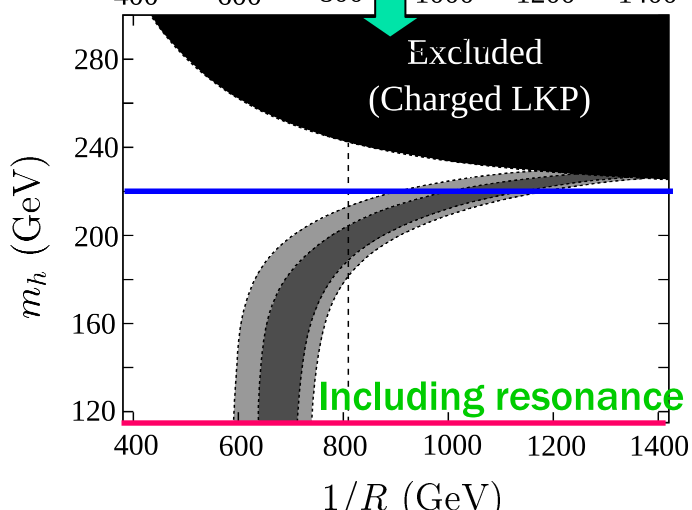
  ➡ 'KK graviton problem' like the gravitino problem

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



Origin of the shift



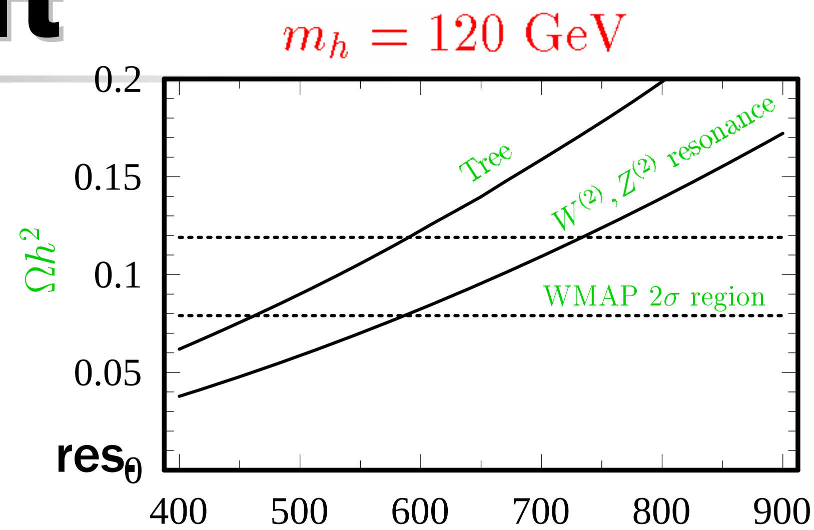


- **Bulk region**

  $W^{(2)}, Z^{(2)}$-res. are effective

- **KK Higgs co-annihilation region**

  $H^{(2)}$-res. contributes as large as $W^{(2)}, Z^{(2)}$-res.



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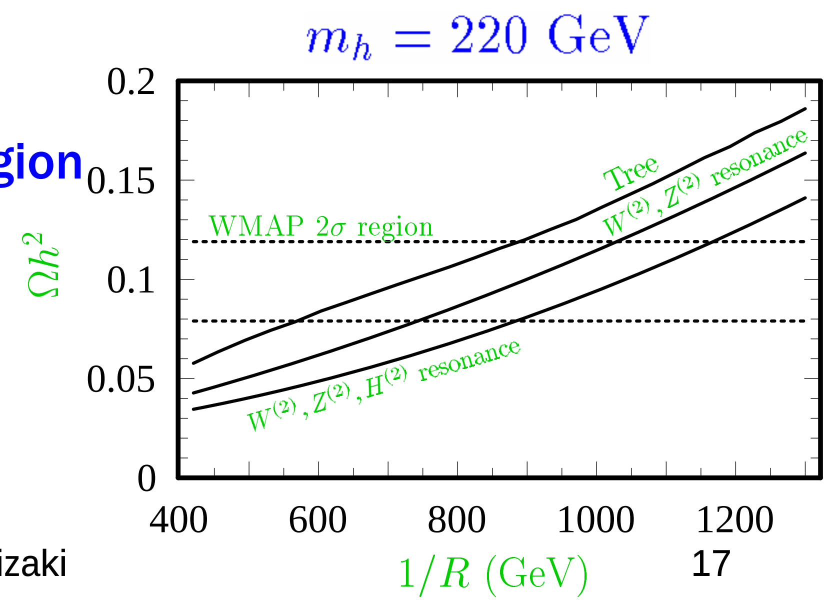


6. Summary

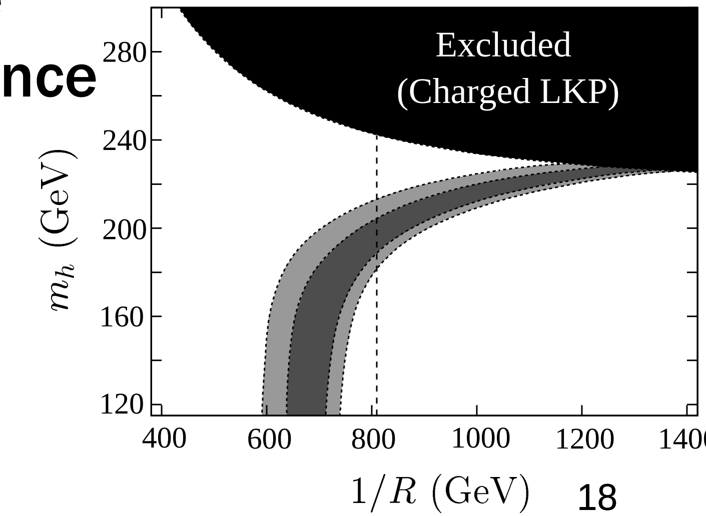
- UED models provide a viable dark matter candidate:

  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 coannhilation modes

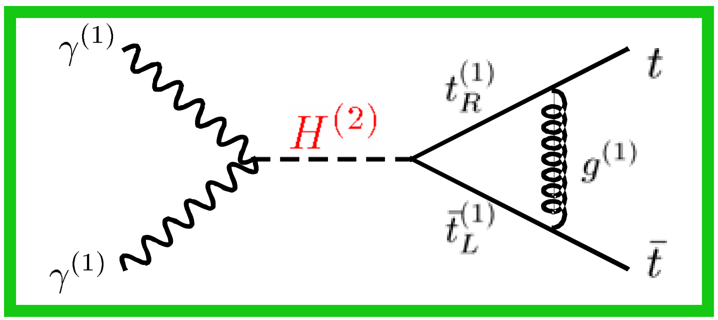
- Cosmologically allowed region in the MUED model

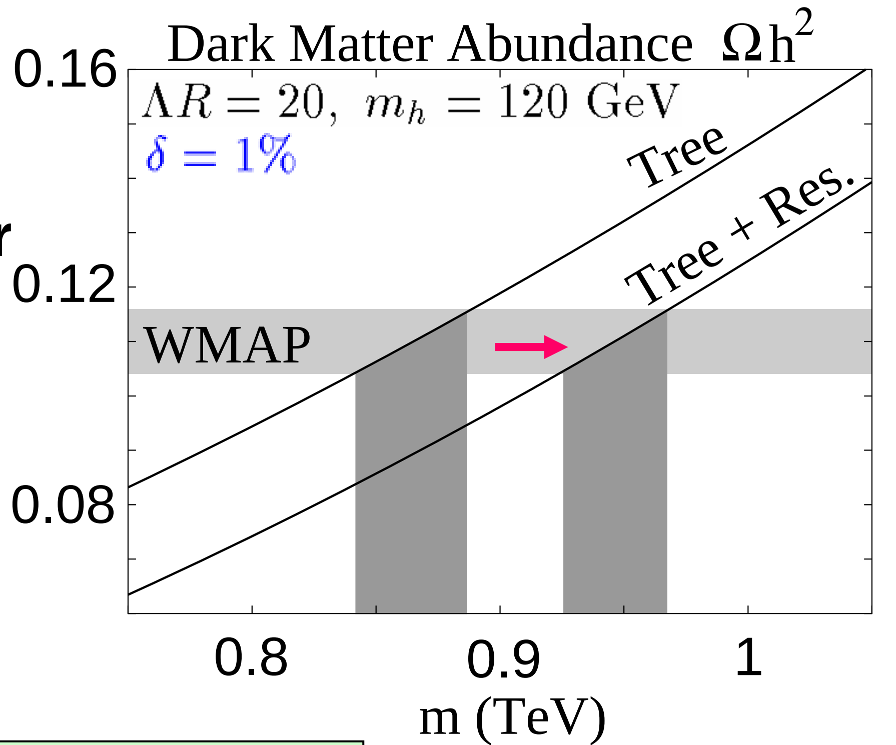


Backup slides

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

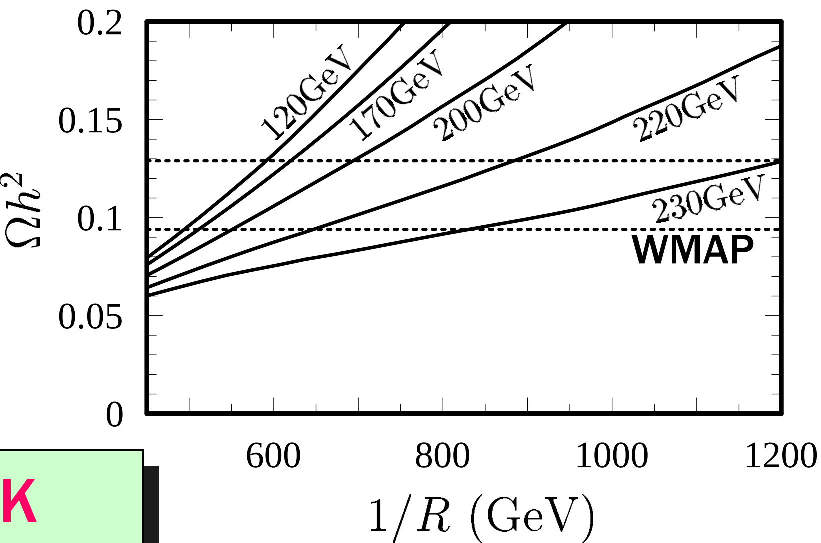
[Matsumoto, Senami, PLB633 (2006)]

- Larger Higgs mass
  (larger Higgs self–coupling)

  - Mass degeneracy between 1st KK Higgs bosons and the LKP in MUED
  - Larger annihilation cross sections for the 1st KK Higgs bosons

→ Coannihilation effect with 1st KK Higgs bosons efficiently decrease the LKP abundance

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



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

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 1st KK singlet leptons

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

→ Coannihilation effect is important

- Annihilation cross sections

$$\sigma(\gamma^{(1)}\gamma^{(1)} \to \text{SM particles}) \quad \sigma(E^{(1)}\bar{E}^{(1)} \to \text{SM particles}) > \sigma(\gamma^{(1)}E^{(1)} \to \text{SM particles})$$

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

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