Cosmological Constraint on the Minimal Universal Extra Dimension Model

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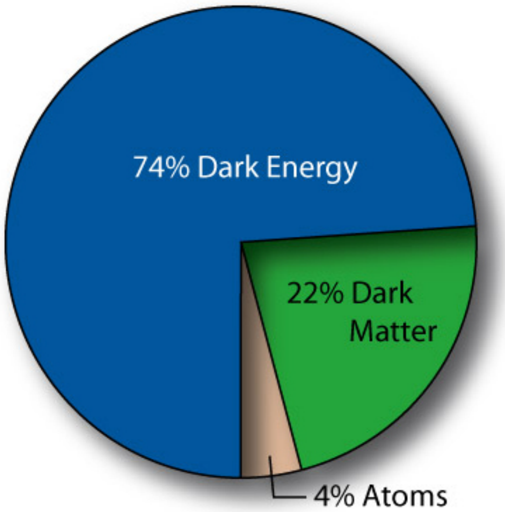
Refs:

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

1. Motivation

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



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

→ **Non-baryonic dark matter**

- **Weakly interacting massive particles (WIMPs) are good candidates**

  The predicted thermal relic abundance naturally explains the observed dark matter abundance

  - Neutralino (LSP) in supersymmetric (SUSY) models
  - 1st KK mode of the B boson (LKP) in universal extra dimension (UED) models ← **Today's topic**
  - etc.

Outline

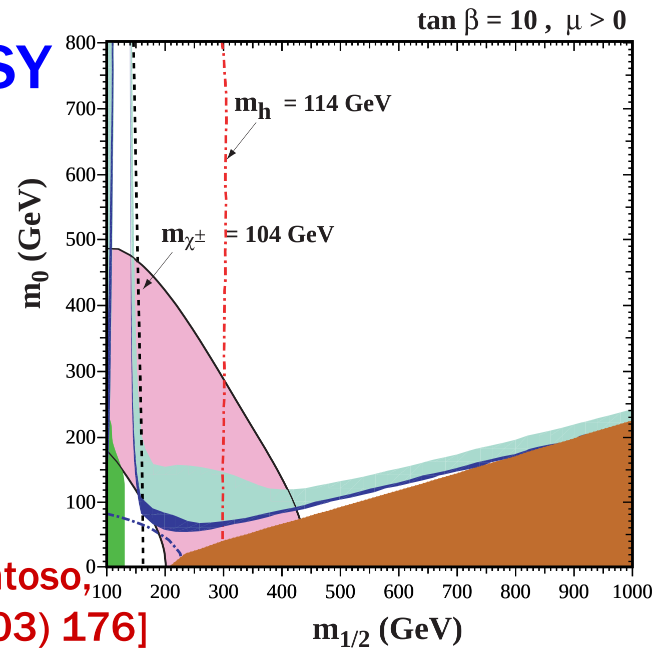
This work

- Reevaluation of the relic density of LKPs in the minimal UED model including both coannihilation and resonance effects

→ Cosmological constraint on the minimal UED model

c.f.: SUSY

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

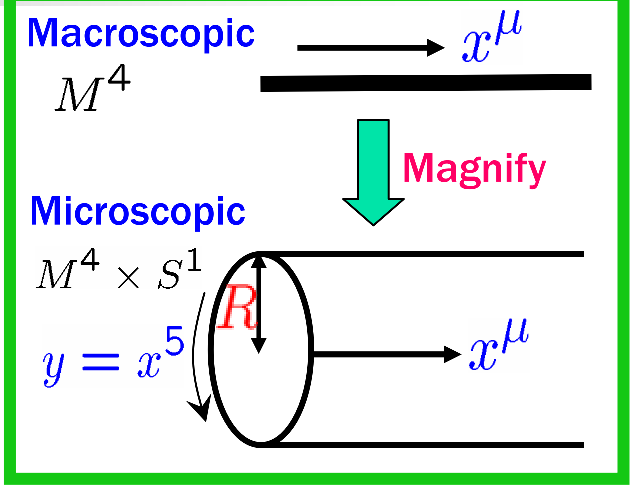


[From Ellis, Olive, Santoso, Spanos, PLB565 (2003) 176]

2. Universal extra dimension (UED) models

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

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

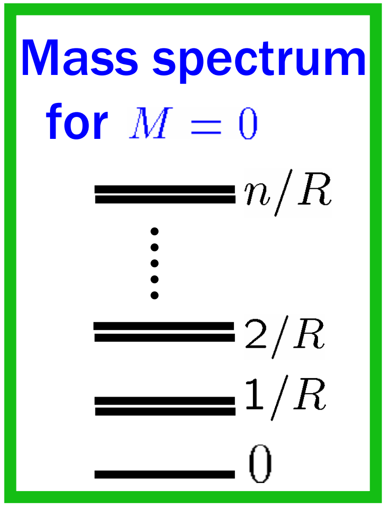


- **Dispersion relation:** $E^2 = \vec{p}^2 + (p_5^2 + M^2)$

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

- S^1 compactification with radius R:

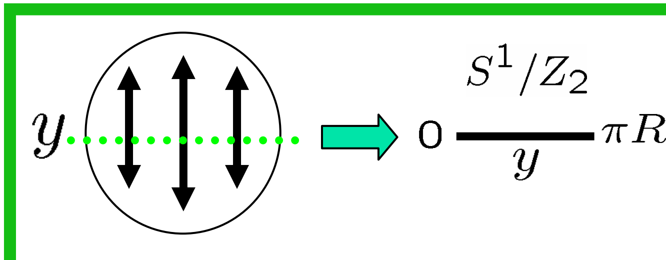
  $p_5 = n/R \quad (n = 0, \pm 1, \pm 2, \cdots)$ quantized ⇨ KK tower



- Momentum conservation in the extra dimension

  ⇨ Conservation of KK number n at each vertex

Minimal UED (MUED) model



- S^1/Z_2 orbifold ⇨ Chiral zero-mode fermions
- Conservation of KK parity [+ (–) for even (odd) n]

⇨ The lightest KK particle (LKP) is stable c.f. R-parity and LSP

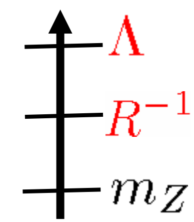
The LKP is a good candidate for dark matter

- Only two new parameters 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

More fundamental theory



- Constraints coming from electroweak measurements are weak
  - Precision tests

$R^{-1} > 600\ \mathrm{GeV}\ (90\%\ \mathrm{C.L.})$ for $m_h = 115\ \mathrm{GeV}$

[Flacke, Hooper, March-Russell, PRD73 (2006); Erratum: PRD74 (2006); Gogoladze, Macesanu, PRD74 (2006)]

  - $\mathrm{Br}(\bar{B} \to X_s \gamma)$

$R^{-1} > 600\ \mathrm{GeV}\ (95\%\ \mathrm{C.L.})$

[Haisch, Weiler, hep-ph/0703064 (2007)]

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.~~

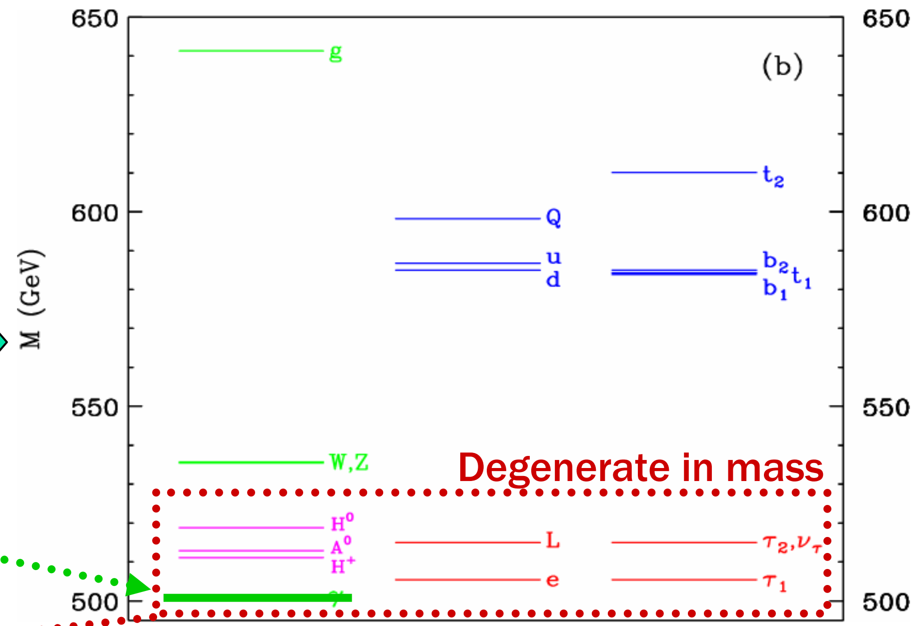
  ↳ Radiative corrections relax the degeneracy ⇒

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

- $m_{\rm LKP} \simeq m^{(1)}$

  ⇒ Coannihilation plays an important role

- 1-loop corrected mass spectrum for the 1st KK level



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

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

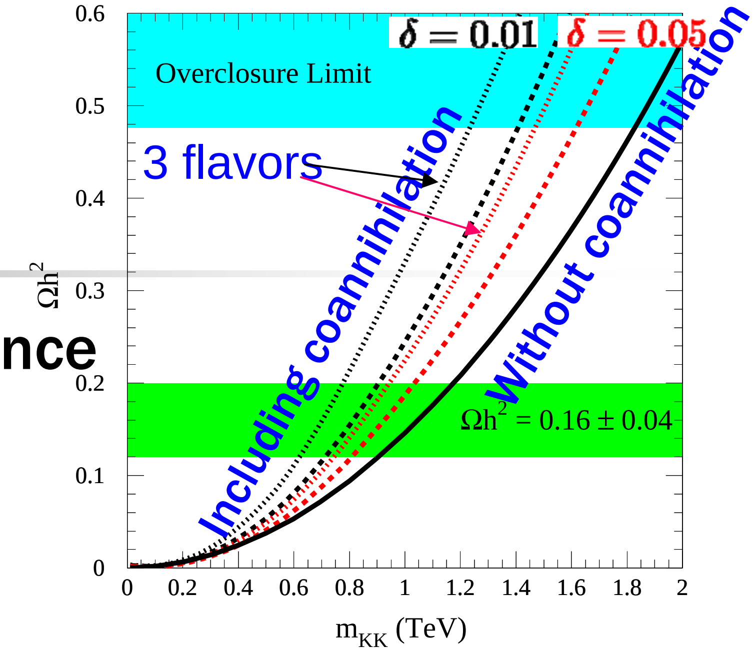
3. Relic abundance of KK dark matter

- Earliest work on the LKP ($\gamma^{(1)}$) abundance

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

Shortcomings:

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

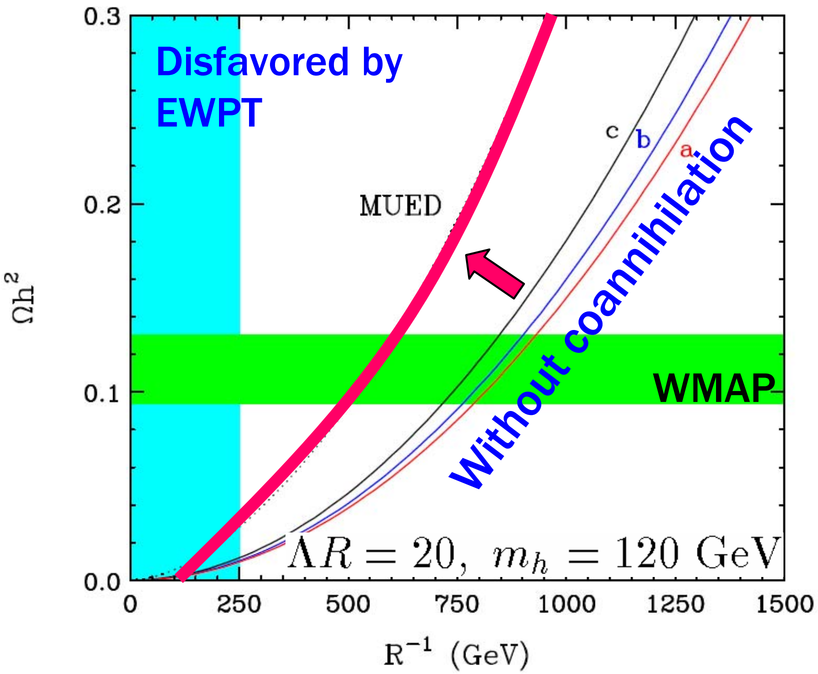


- Inclusion of coannihilation modes with all 1st KK particles

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

Shortcomings:

- The Higgs mass is fixed to $m_h = 120$ GeV
- No resonance process included



4. KK Higgs coannihilation

- **1st KK Higgs boson masses:**

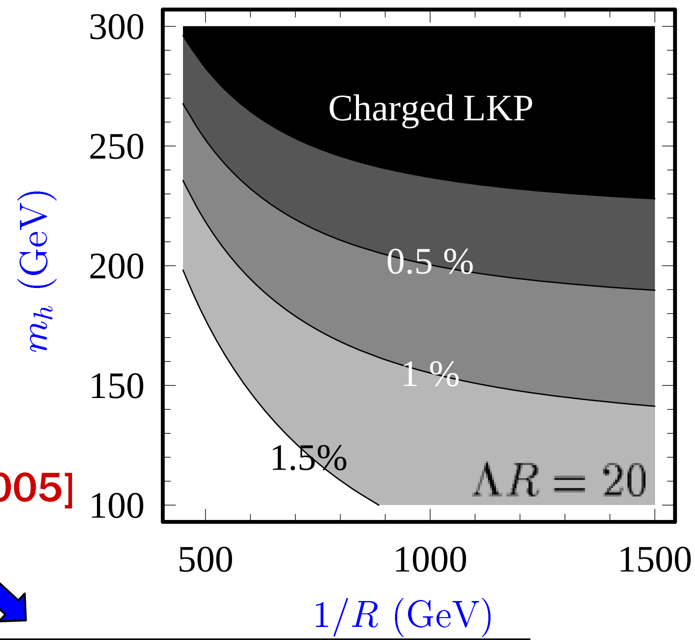
$$m^2_{H^{(1)}} = 1/R^2 + m_h^2 + \delta m^2_{H^{(1)}}$$
$$m^2_{A^{(1)}} = 1/R^2 + m_Z^2 + \delta m^2_{H^{(1)}}$$
$$m^2_{H^{\pm(1)}} = 1/R^2 + m_W^2 + \delta m^2_{H^{(1)}}$$

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

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

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

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

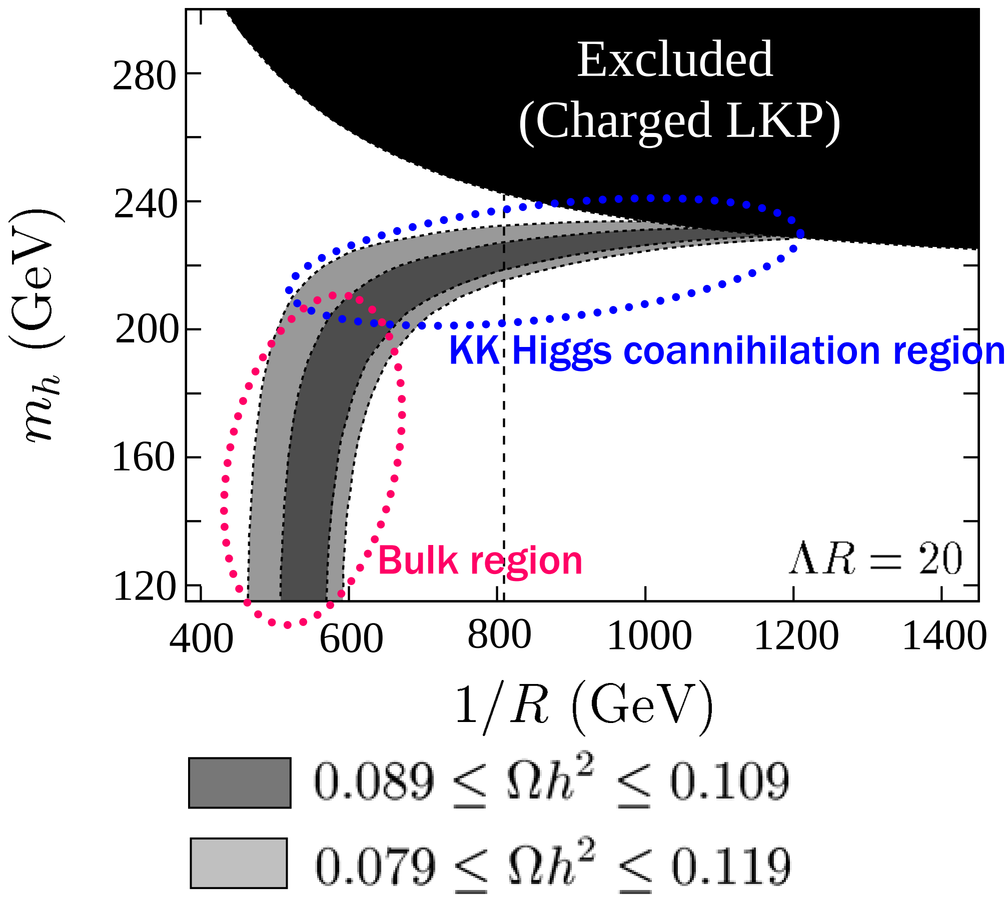


- m_h ↗ ⇒ $\lambda_H = m_h^2/v^2$ ↗ ; δm_H^2 ↘

(Co)annihilation cross sections for 1st KK Higgs bosons are enhanced for large m_h [Matsumoto, Senami, PLB633 (2006)]

- **Too large m_h ⇒ The 1st KK charged Higgs boson is the LKP**

Allowed region (without resonance effects)



- All coannihilation modes with 1st KK particles included
- Bulk region (small m_h)

  Our result is consistent with earlier 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

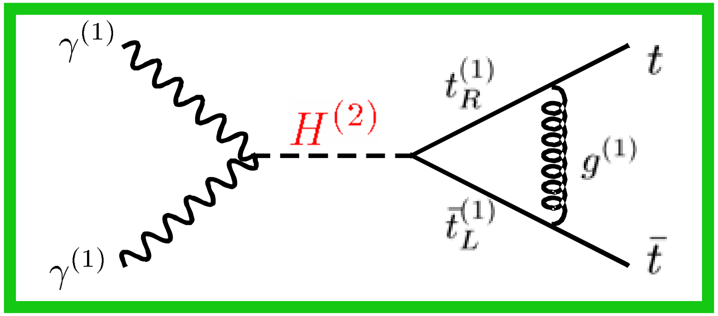
5. Resonance processes

- KK particles were non-relativistic when they decoupled:

$$\sqrt{s} \simeq m^{(1)} + m^{(1)} \simeq m^{(2)}$$

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

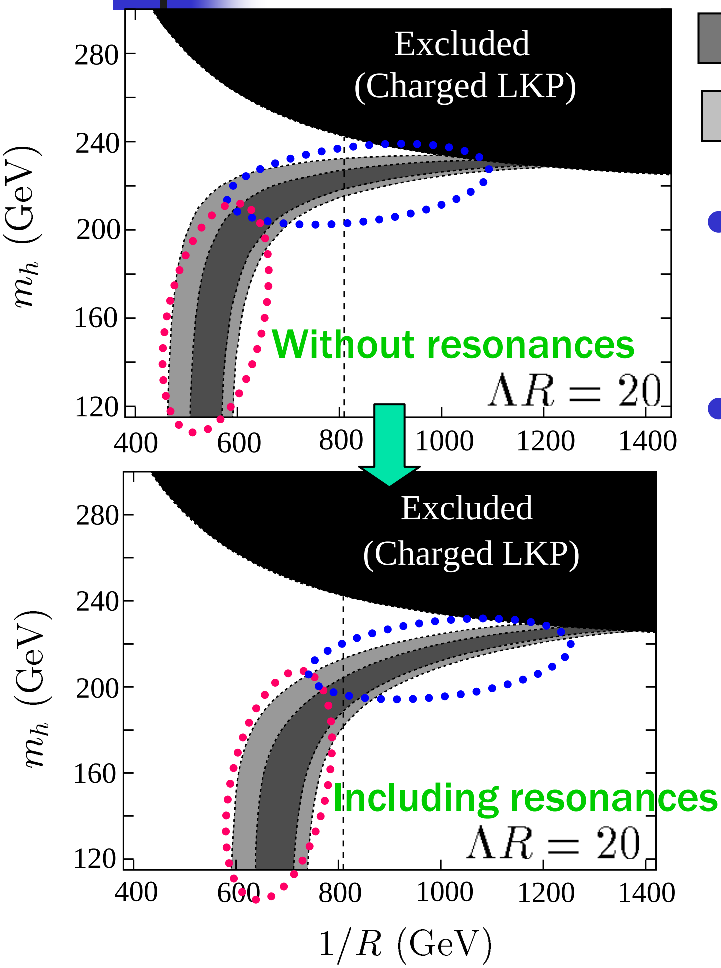
e.g.



- Important processes:

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

Allowed region (including coannihilation and resonance)

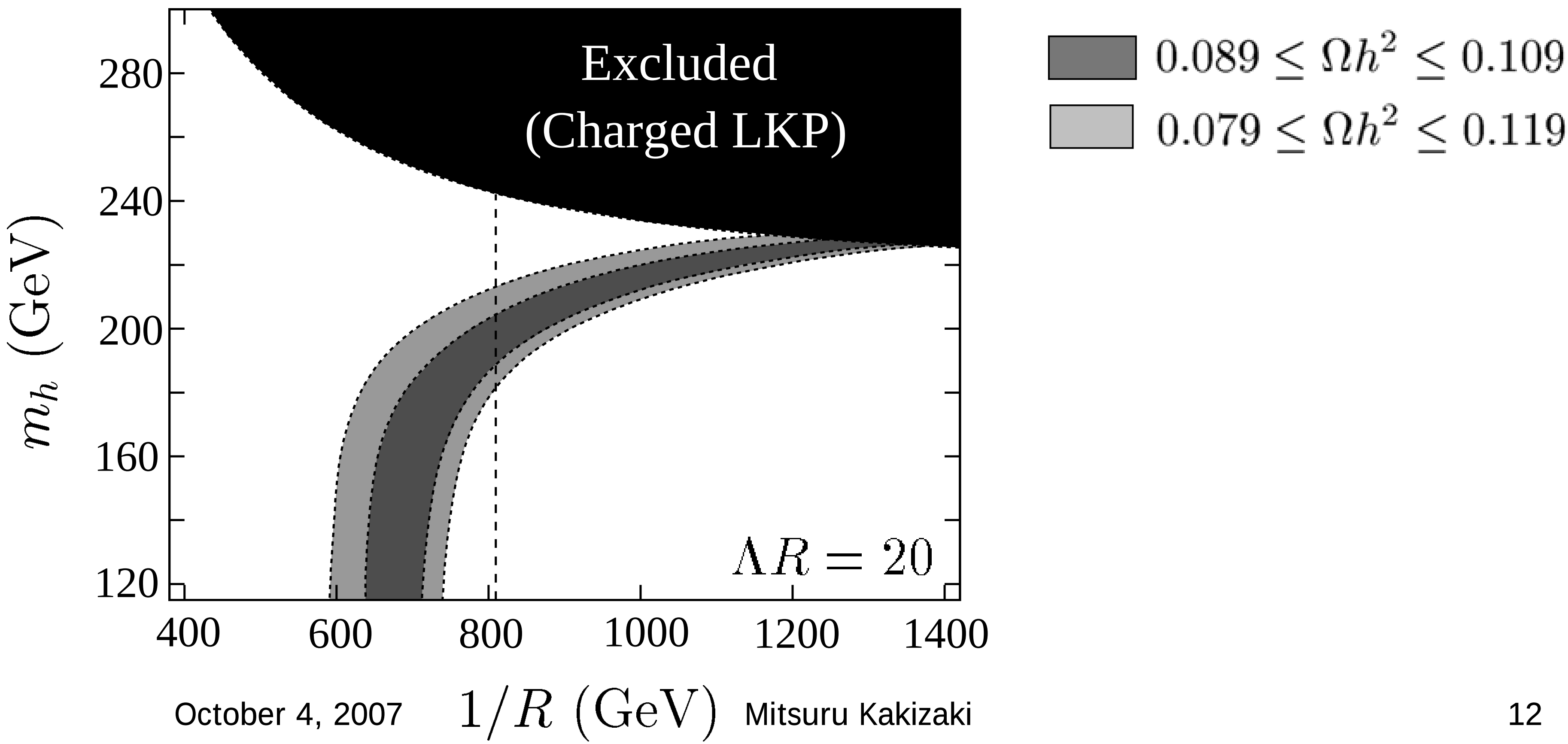


- $0.089 \le \Omega h^2 \le 0.109$;
- $0.079 \le \Omega h^2 \le 0.119$

- Cosmologically allowed region is shifted upward by $150 - 300\mathrm{GeV}$
- Resonance effects are important for all Higgs masses:
  - In the Bulk region:
    $W^{(2)}, Z^{(2)}$-resonances are effective
  - In the KK Higgs coannihilation region:
    $H^{(2)}$ -resonance contributes as large as $W^{(2)}, Z^{(2)}$ -resonances

6. Summary

- We reevaluated the relic density of LKPs in the minimal UED model including **both coannihilation and resonance effects**



Backup slides

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 the 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

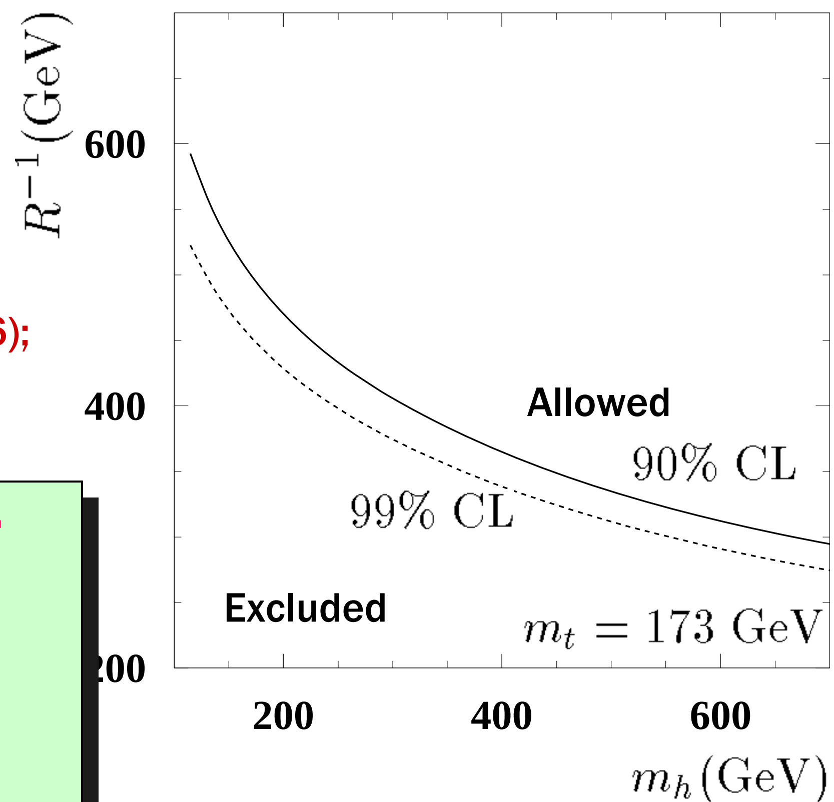
  $\sigma_{\rm eff}$ ↗ ; Ωh^2 ↘

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

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

- Constraints coming from electroweak measurements are weak

[Appelquist, Cheng, Dobrescu PRD64 (2001);
Appelquist, Yee, PRD67 (2003);
Flacke, Hooper, March-Russell, PRD73 (2006);
Erratum: PRD74 (2006);
Gogoladze, Macesanu, PRD74 (2006)]



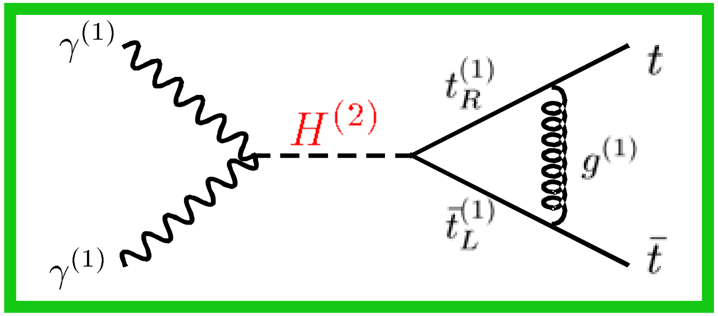
- Requiring that LKPs account for the CDM abundance in Universe, the parameter space gets more constrained

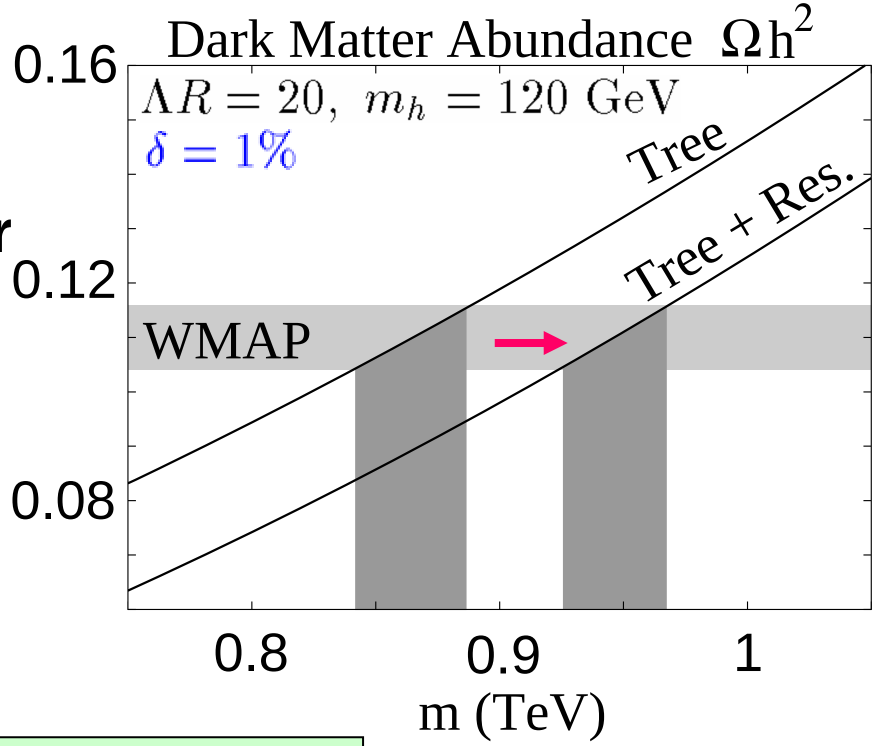
(Under the assumption of thermal production)

[From Gogoladze, Macesanu, PRD74 (2006)]

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

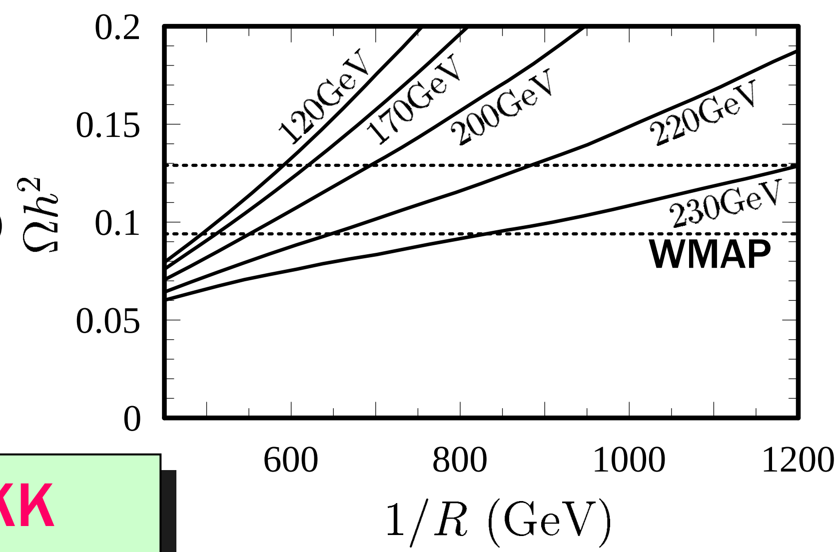
[Matsumoto, Senami, PLB633 (2006)]

- 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**

- LKP relic abundance
  (ignoring resonance effects)



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

KK Higgs coannihilation region

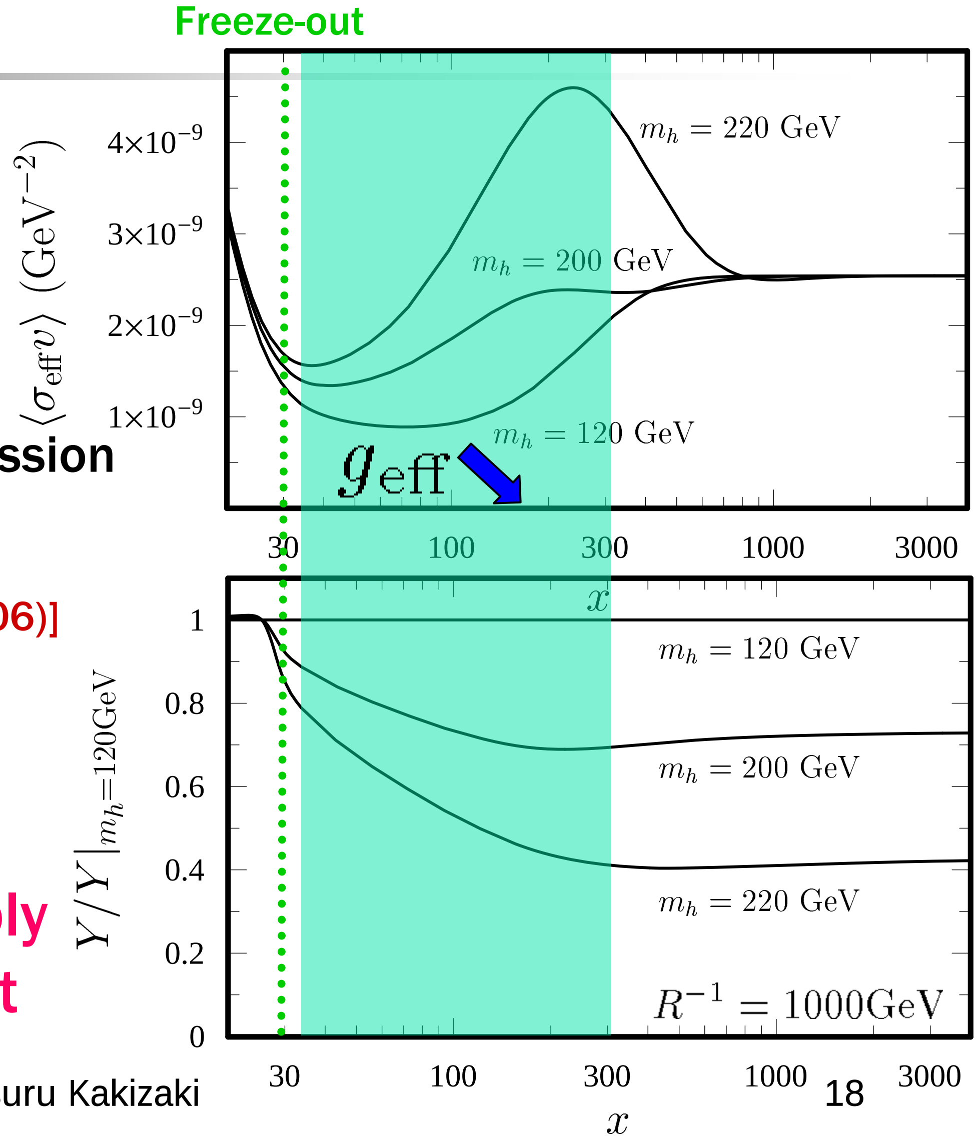
- For larger m_h
  (larger Higgs self-coupling)
  - Degeneracy between the LKP and $A^{(1)}$, $H^{\pm(1)}$
  - Free from a Boltzmann suppression

→ Larger $\sigma_{\rm eff}$

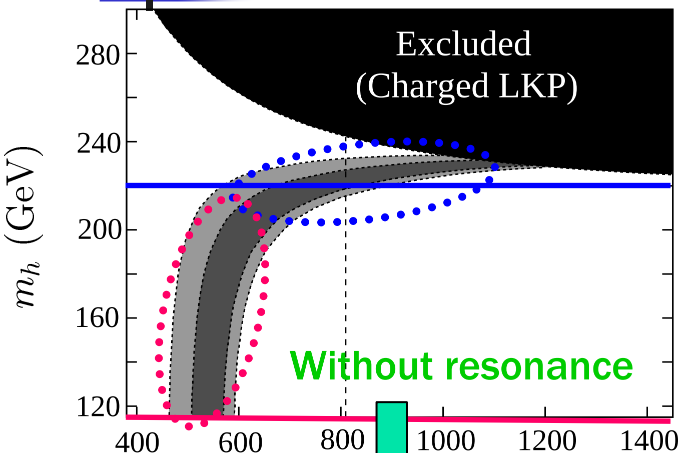
[Matsumoto, Senami, PLB633 (2006)]

- The effective cross section can increase after freeze-out

→ The LKP abundance can sizably decrease even after freeze-out

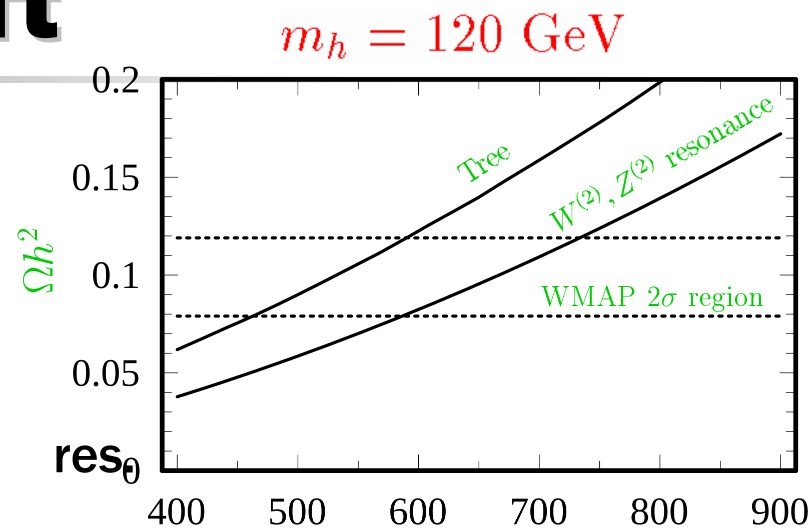


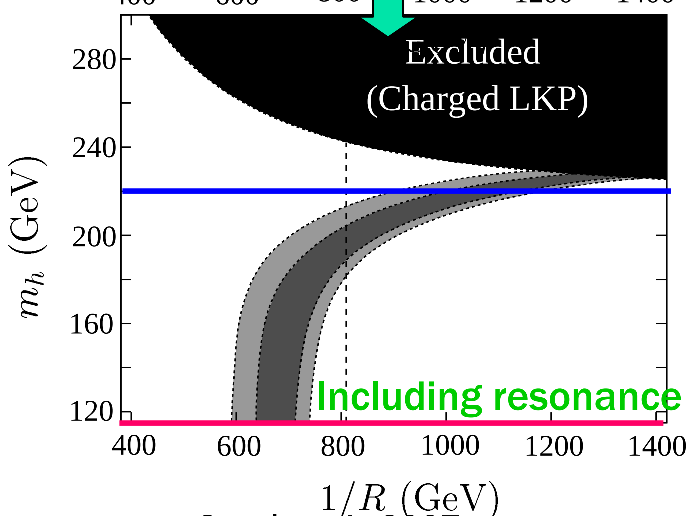
Origin of the shift



- **Bulk region**

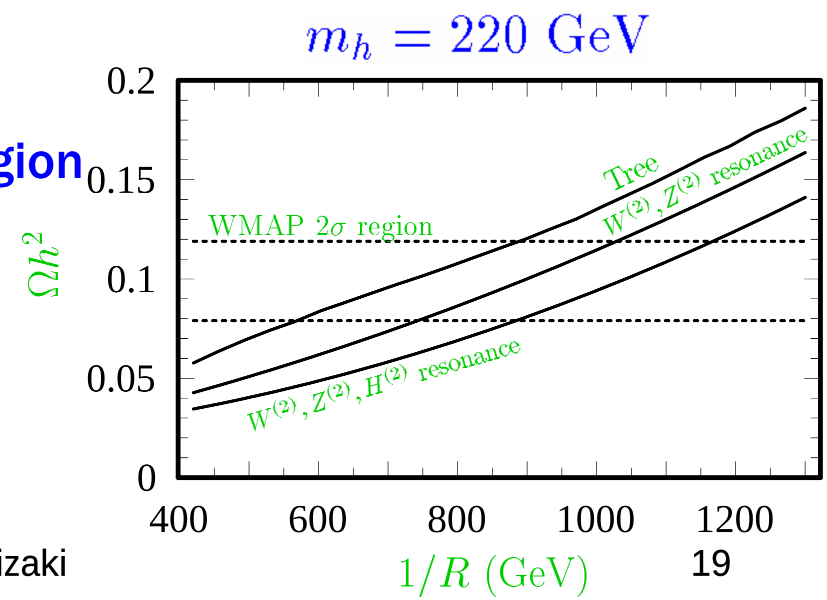
  $W^{(2)}, Z^{(2)}$-res. are effective





- **KK Higgs co-annihilation region**

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



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

$$\begin{matrix} \sigma(\gamma^{(1)}\gamma^{(1)} \to \mathrm{SM\ particles}) \\ \sigma(\ E^{(1)}\bar{E}^{(1)} \to \mathrm{SM\ particles}) \end{matrix} > \sigma(\gamma^{(1)}E^{(1)} \to \mathrm{SM\ particles})$$

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

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

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

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

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

- In generic:

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

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

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

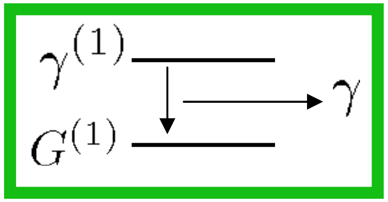
e.g.: coannihilation with KK Higgs bosons: $H^{(1)}, A^{(1)}, H^{\pm(1)}$

Remark: KK graviton problem

- For $R^{-1} < 800$ GeV, $m_{G^{(1)}} < m_{\gamma^{(1)}}$

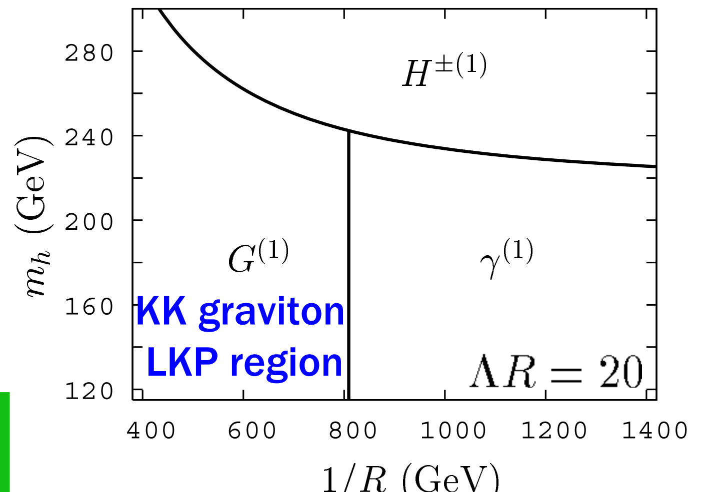
  $\gamma^{(1)}$ decays at late times

  ⇒ Emitted photons would distort the CMB spectrum



[Feng, Rajaraman, Takayama PRL91 (2003)]

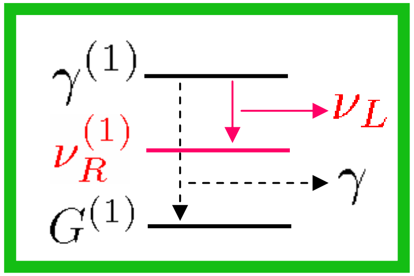
- LKP in the MUED



[From Matsumoto, Sato, Senami, Yamanaka, PLB647, 466 (2007)]

- Attempts:
  - Introduction of right-handed neutrinos of Dirac type

    ⇒ $\nu_R^{(1)}$ is a DM candidate



  - WMAP data ⇒ R^{-1} can be as low as 500 GeV

[Matsumoto, Sato, Senami, Yamanaka, PRD76 (2007)]

- Radion stabilization?