Significant effects of second KK particles on LKP dark matter physics

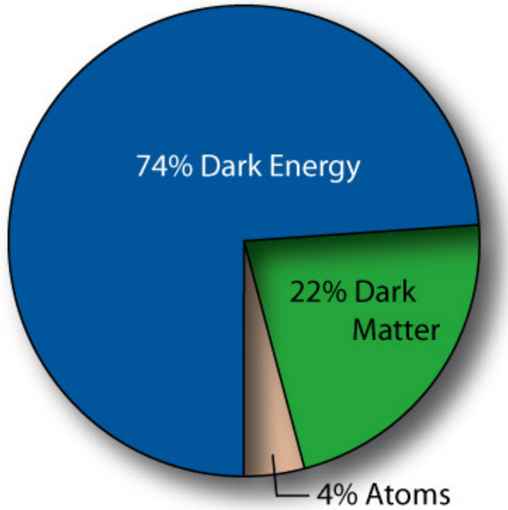
Mitsuru Kakizaki (Bonn Univ. & ICRR, Univ. of Tokyo)

12 May, 2006 @ Bielefeld Univ.

Collaborated with
- Shigeki Matsumoto (KEK)
- Yoshio Sato (Saitama U.)
- Masato Senami (ICRR)

Refs:
- PRD 71 (2005) 123522 [hep-ph/0502059]
- NPB 735 (2006) 84 [hep-ph/0508283]

1. Motivation



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

Observations of

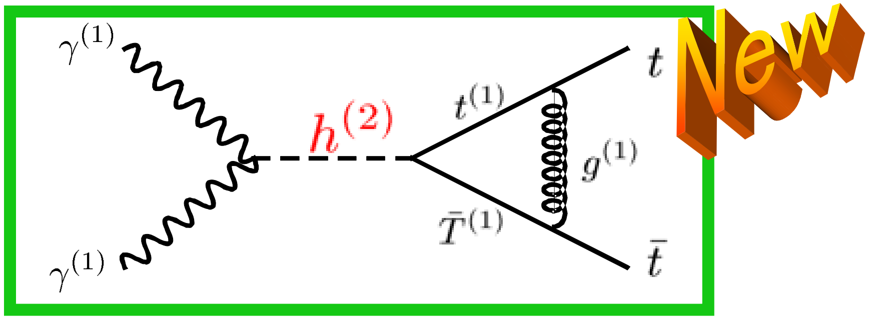
- cosmic microwave background
- structure of the universe
- etc.

⇒ **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.

Outline



- In universal extra dimension (UED) models, Kaluza-Klein (KK) dark matter physics is drastically affected by 2nd KK particles
- Reevaluation of relic density of KK dark matter including coannihilation and resonance effects

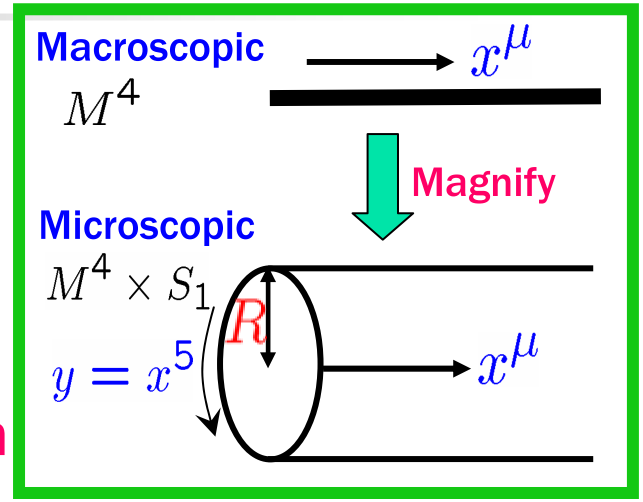
  ⇨ Dark matter particle mass consistent with WMAP increases

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

2. Universal extra dimension (UED) models

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

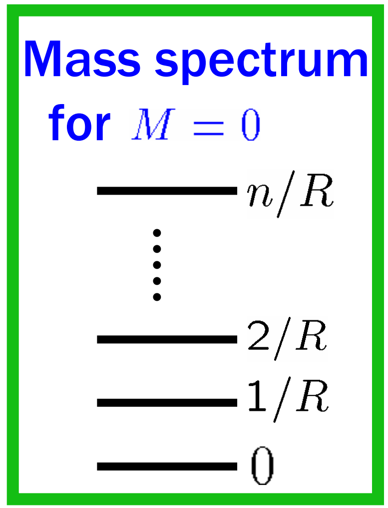
Idea: All SM particles propagate in flat compact spatial extra dimensions



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

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

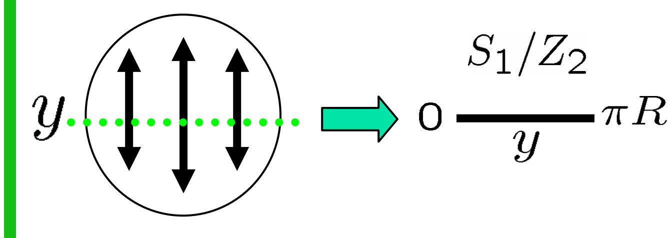
In case of S^1 compactification with radius R,
$p_5 = n/R \quad (n = 0, 1, 2, \cdots)$ is quantized



- Momentum conservation in the extra dimension

⇨ Conservation of KK number n in each vertex

Minimal UED model



- In order to obtain chiral fermions at zeroth KK level, the extra dimension is compactified on an S^1/Z_2 orbifold
- **Conservation of KK parity** [+ (–) for even (odd) n]

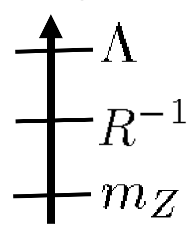
⇒ **The lightest KK particle (LKP) is stable** c.f. R-parity and LSP

The LKP is a good candidate for dark matter

- **Only two new parameters in the MUED model:**

R : Size of extra dimension Λ : Scale at which boundary terms vanish

More fundamental theory



- **Constraints from electroweak measurements are weak:**

$R^{-1} > 250 \text{ GeV}$ [Appelquist, Cheng, Dobrescu (2001); Appelquist, Yee, PRD67 (2003)]

$R^{-1} > 700 \text{ GeV}$: Inclusion of 2-loop SM contributions and LEP2 data

[Flacke, Hooper, March-Russel, PRD73 (2006)]

Mass spectra of KK states

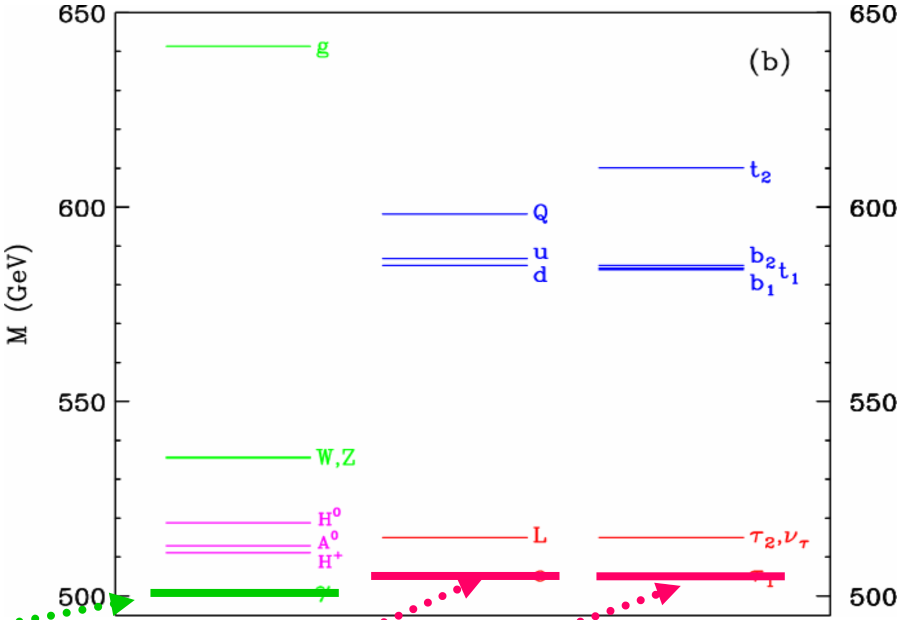
- KK modes are degenerate in mass at each KK level:

$$m_n = \sqrt{(n/R)^2 + m_{\rm SM}^2} \simeq n/R$$

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

  Radiative corrections relax the degeneracy →

1-loop corrected mass spectrum at the first KK level

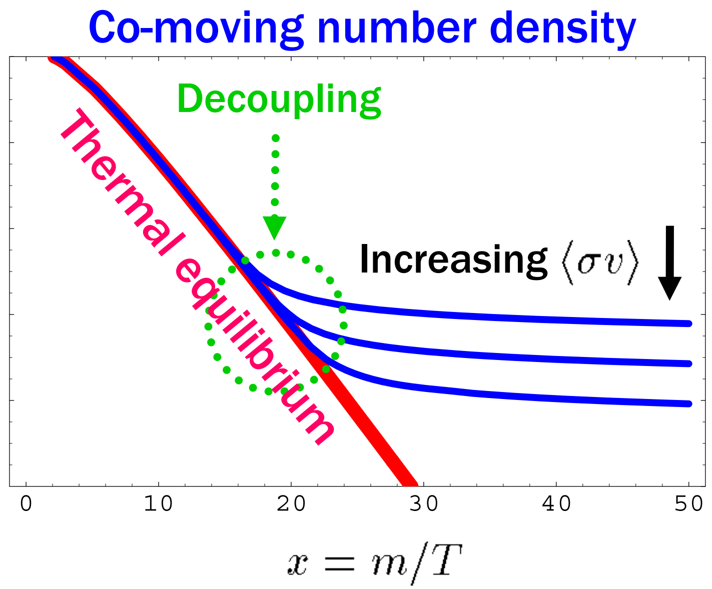


$R^{-1} = 500$ GeV, $\Lambda R = 20$, $m_h = 120$ GeV

- Lightest KK Particle (LKP): $\gamma^{(1)}$
  Next to LKP: 1st KK singlet leptons: $E_i^{(1)},\ i = e, \mu, \tau$
  1st KK Higgs bosons (for larger m_h)

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

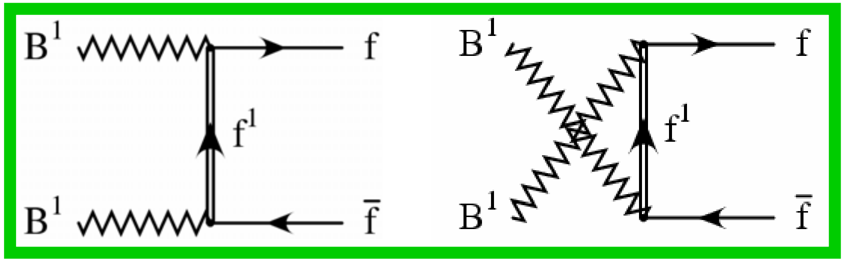
3. Relic abundance of KK dark matter

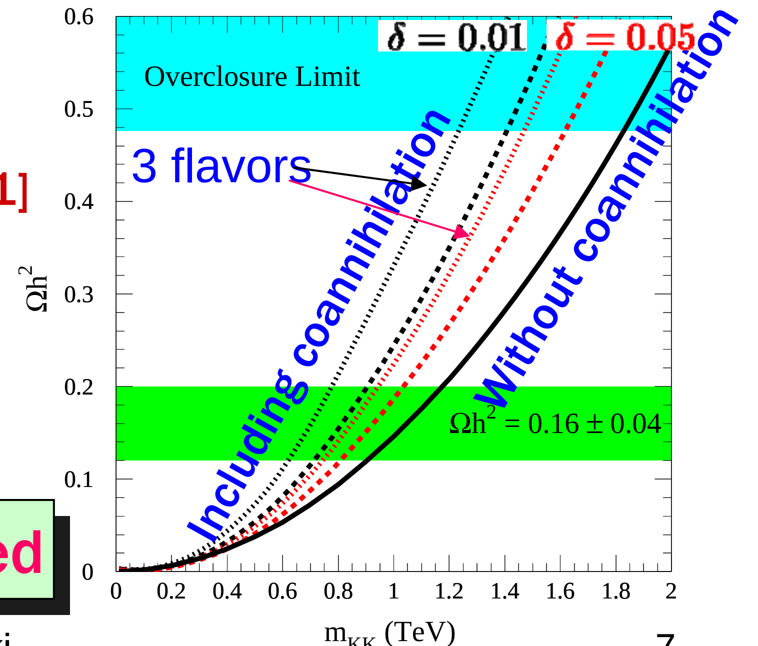


- Generic picture
  - Dark matter particles were in thermal equilibrium in the early universe
  - After the annihilation rate dropped below the expansion rate, the number density per comoving volume is almost fixed

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

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



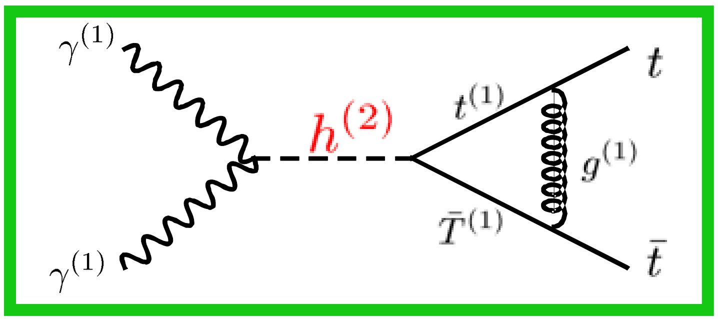


Only tree level diagrams are considered

4. Resonance in KK dark matter annihilation

- Dark matter particles were non-relativistic when they decoupled
  ⇒ (Incident energy of two LKPs) $\simeq$ (Masses of 2nd KK modes)

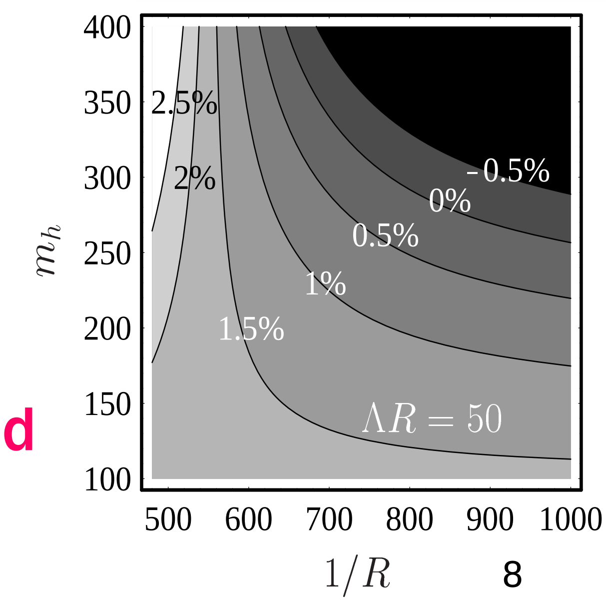
- LKPs annihilate through s-channel 2nd KK Higgs boson exchange at loop level



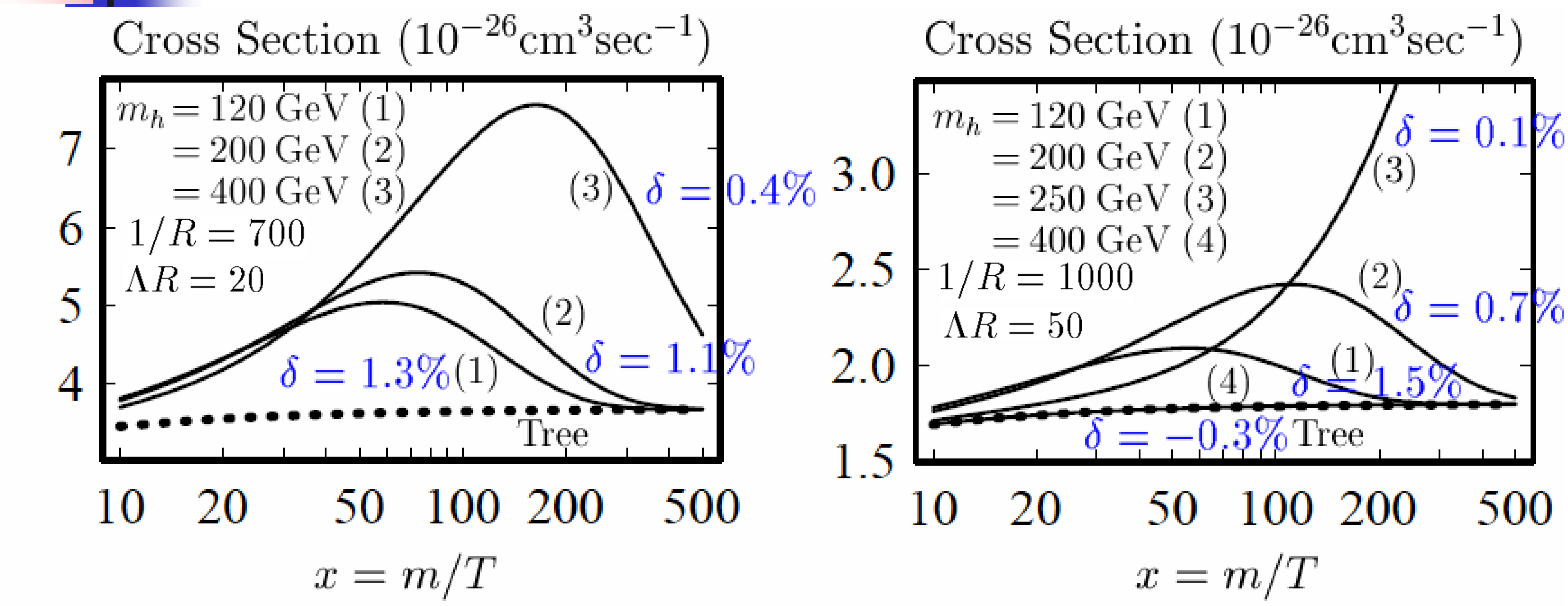
⇒ **The annihilation cross section is enhanced**

- Mass splitting in MUED:

$$\delta \equiv (m_h^{(2)} - 2m)/2m$$



Thermal average of annihilation cross section for LKP



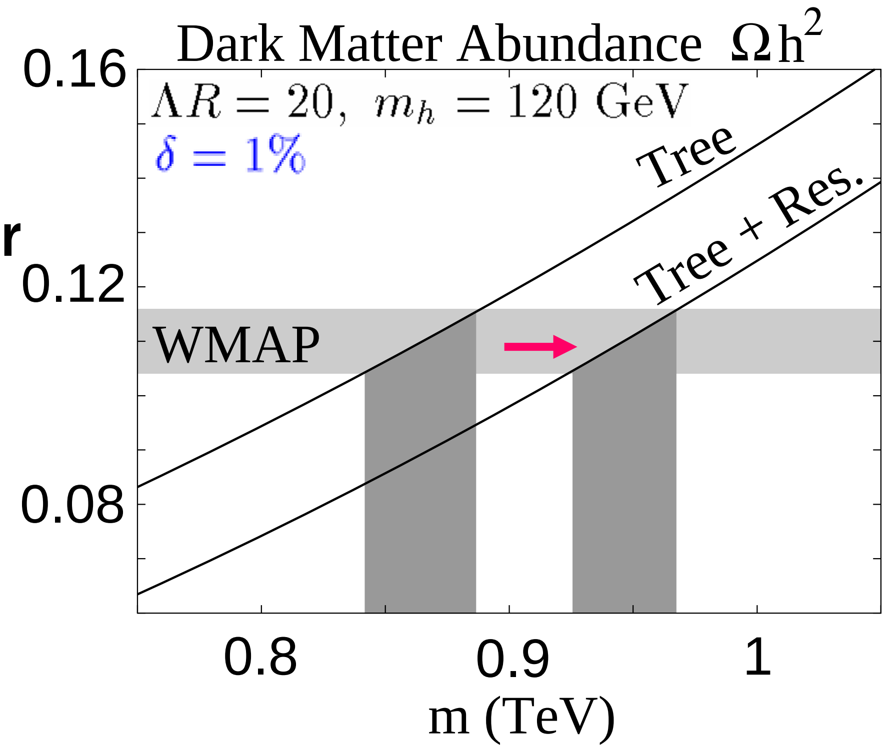
Smaller δ

➡ The averaged cross section becomes maximum at later time

The maximum value is larger

Relic abundance of the LKP (without coannihilation)

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

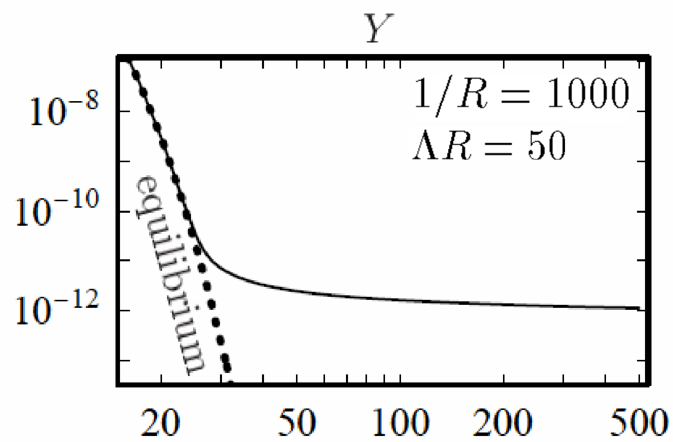


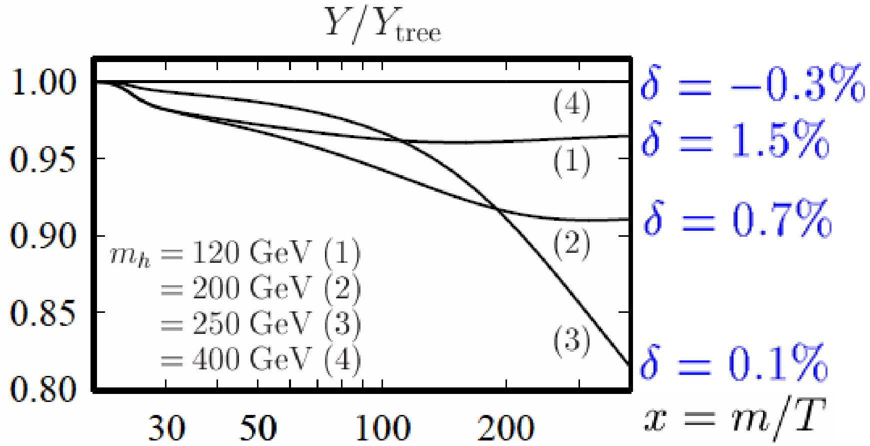
- The resonance effect raises the LKP mass consistent with the WMAP data

2nd KK modes play an important role in calculations of the relic density of the LKP.

Coannihilation with 1st KK singlet leptons $E^{(1)}$

- We can systematically survey 2nd KK–resonance effects
  - $h^{(2)}$–resonance effect in $\gamma^{(1)}\gamma^{(1)} \to \mathrm{SM\ particles}$: sizable
  - $E^{(2)}$–resonance effect in $\gamma^{(1)}E^{(1)} \to \mathrm{SM\ particles}$: relatively small
  - No 2nd KK–resonance in $E^{(1)}\bar{E}^{(1)} \to \mathrm{SM\ particles}$
- Evolution of dark matter abundance $Y = n/s$ [Three flavors: $E_i^{(1)},\ i = e, \mu, \tau$]





The abundance falls below the tree level result after decoupling

Allowed mass region

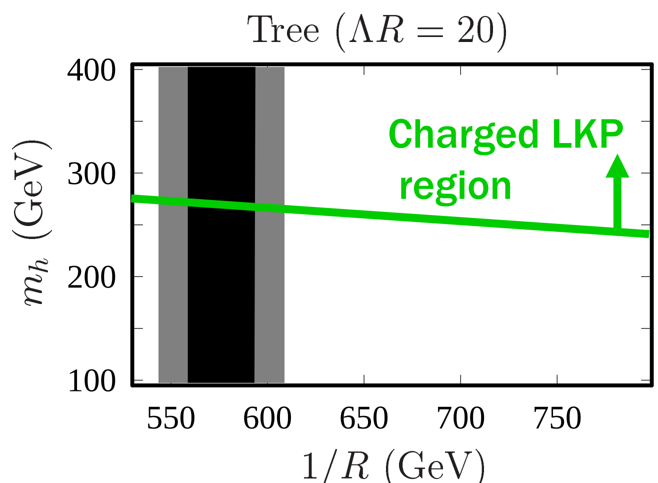
$0.104 \leq \Omega h^2 \leq 0.116$ (black)

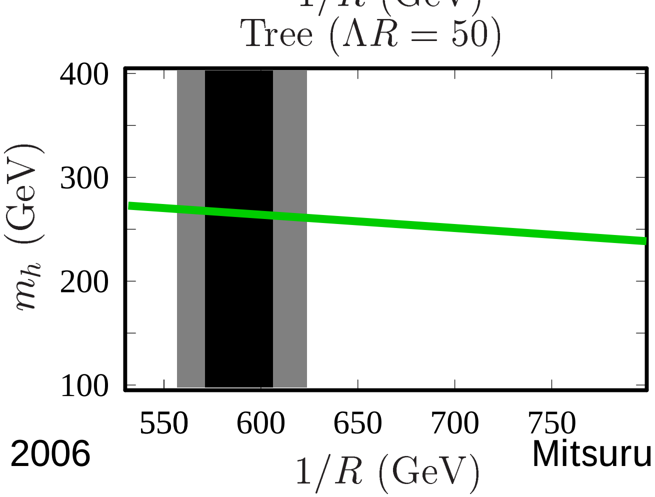
$0.098 \leq \Omega h^2 \leq 0.122$ (gray)

$\Lambda R = 20$

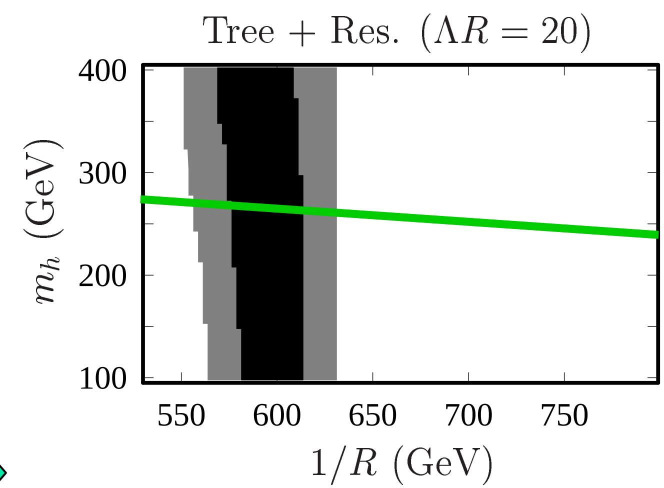
$\Lambda R = 50$

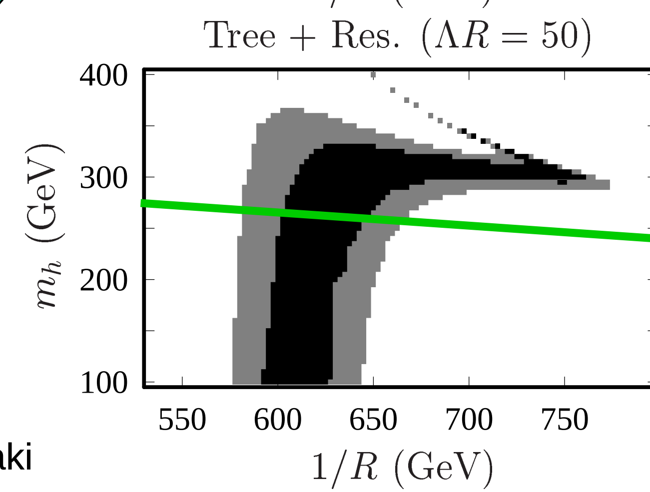
Tree level results





Including resonance





5. Including various coannihilation processes

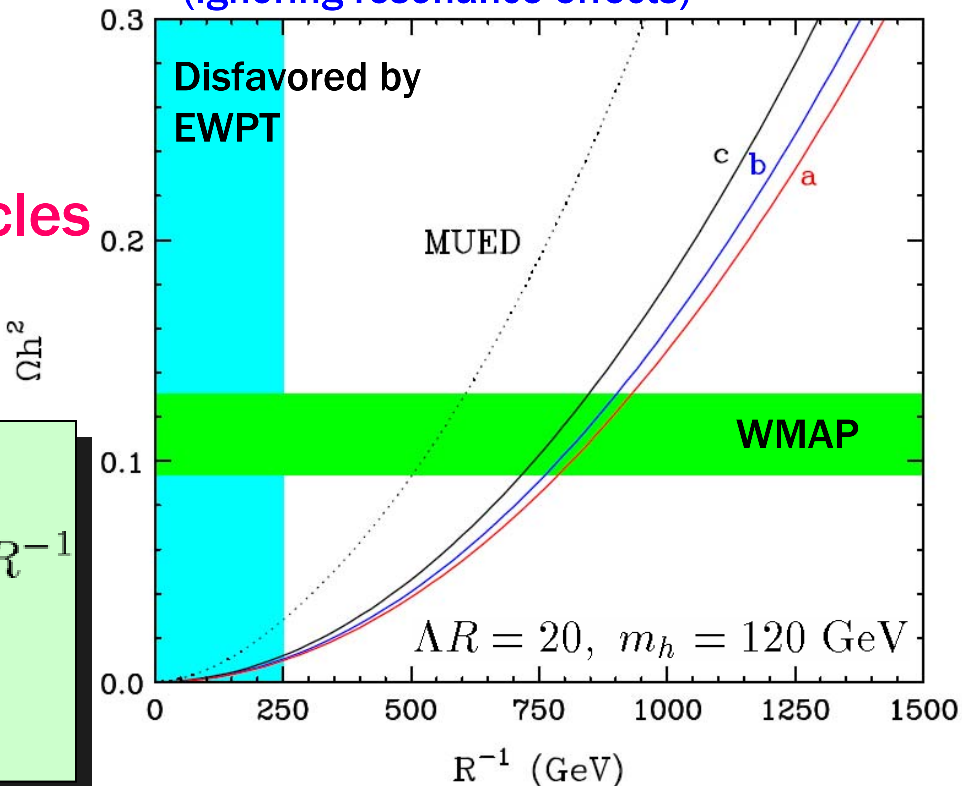
[Burnell, Kribs, PRD73(2006); Kong, Matchev, JHEP0601(2006)]

- 1^{st} KK mass spectrum is rather degenerate

➡ Inclusion of coannihilation modes with all 1^{st} KK particles changes the abundance

- In MUED, inclusion of full coannihilation processes lowers R^{-1}
- Resonance effects may shift the allowed mass scale

Relic abundance including coannihilation processes with all level one KK particles (ignoring resonance effects)



[From Kong, Matchev, JHEP0601(2006)]]

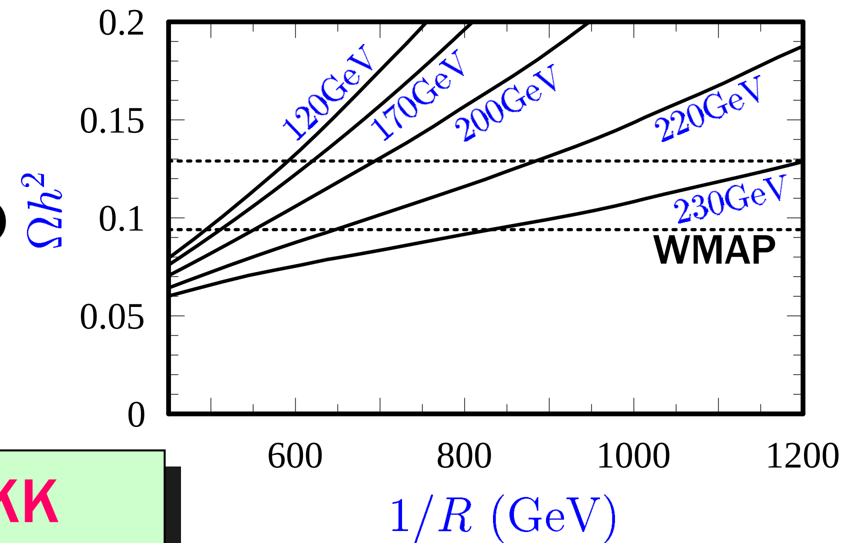
Efficient coannihilation processes through strong Higgs coupling

[Matsumoto, Senami, PLB633(2006)]

- Larger Higgs mass (larger Higgs self–coupling)

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

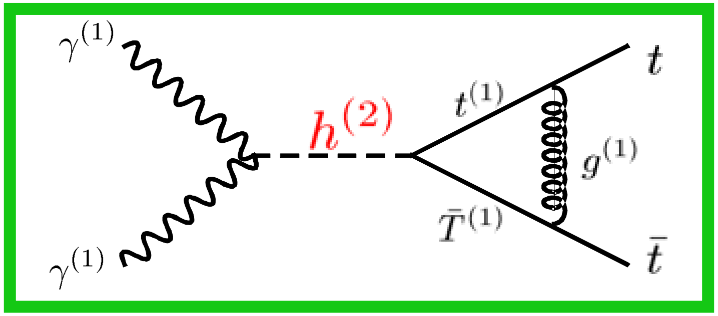
Dependence of the LKP relic abundance on the Higgs mass (ignoring resonance effects)



[From Matsumoto, Senami, PLB633(2006)]

→ **Coannihilation effect with 1^{st} KK Higgs bosons efficiently decrease the LKP abundance**

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



6. Summary

- UED models provide a viable dark matter candidate:

  The lightest Kaluza-Klein particle (LKP)

- (Masses of 2nd KK particles) $\simeq 2\times$ (Masses of 1st KK particles)

  ⇒ Annihilation takes place near poles

- We evaluate the relic abundance of the LKP including resonance and coannihilation with the 1st KK singlet leptons, and find the allowed compactification scale shifts upward due to the resonance effect

- Various coannihilation processes also affect the relic abundance