Significant effects of second KK particles on LKP dark matter physics

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Refs:

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

1. Motivation

Recent observation of
cosmic microwave background anisotropies
by WMAP:

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

→ **Non-baryonic cold dark matter**

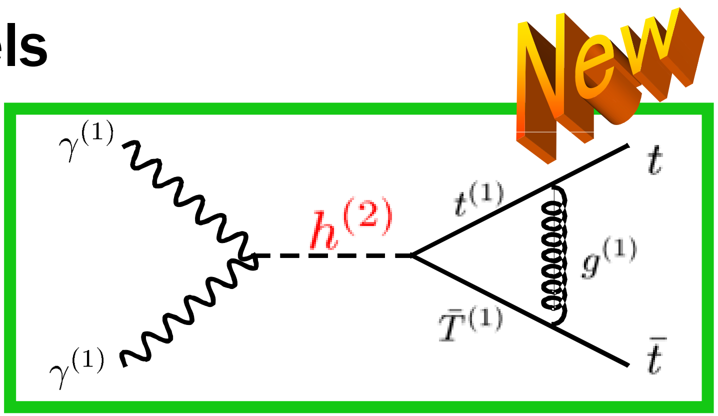
What is the constituent of dark matter?

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

Outline

- In universal extra dimension (UED) models, Kaluza-Klein (KK) dark matter physics is drastically affected by second KK particles
- Reevaluation of relic density of KK dark matter including coannihilation and resonance effects
  ⇒ Dark matter particle mass consistent with WMAP increases

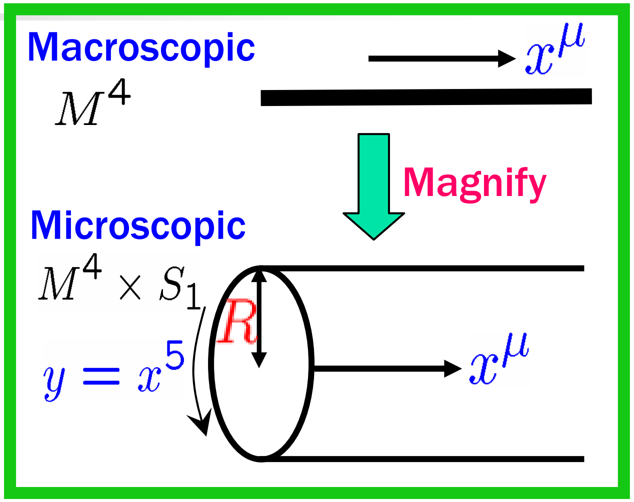
1. Motivation
2. Universal extra dimension (UED) models
3. Relic abundance of KK dark matter
4. Resonant KK dark matter annihilation
5. Summary



2. Universal extra dimension (UED) models

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

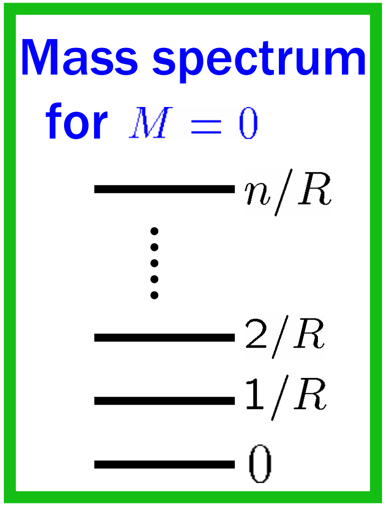
Idea: All SM particles propagate flat compact spatial extra dimensions



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

➡ Momentum along the extra dimension → Mass in four-dimensional viewpoint

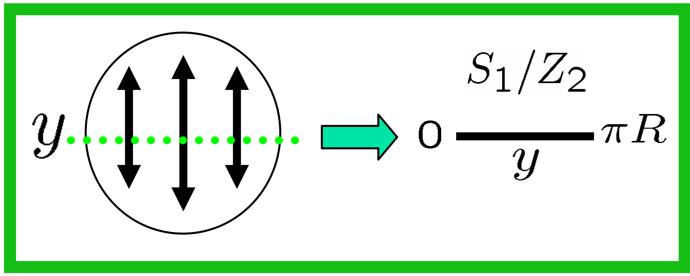
In case of S^1 compactification with radius R,
$p_5 = n/R \quad (n = 0, 1, 2, \cdots)$ is quantized



- 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 minimal UED (MUED) model:

  R : Size of extra dimension Λ : Cutoff scale

- Constraints from electroweak measurements are weak:

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

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

  [Flacke, Hooper, March-Russel, hep-ph/0509352 (2005)]

Mass spectra of KK states

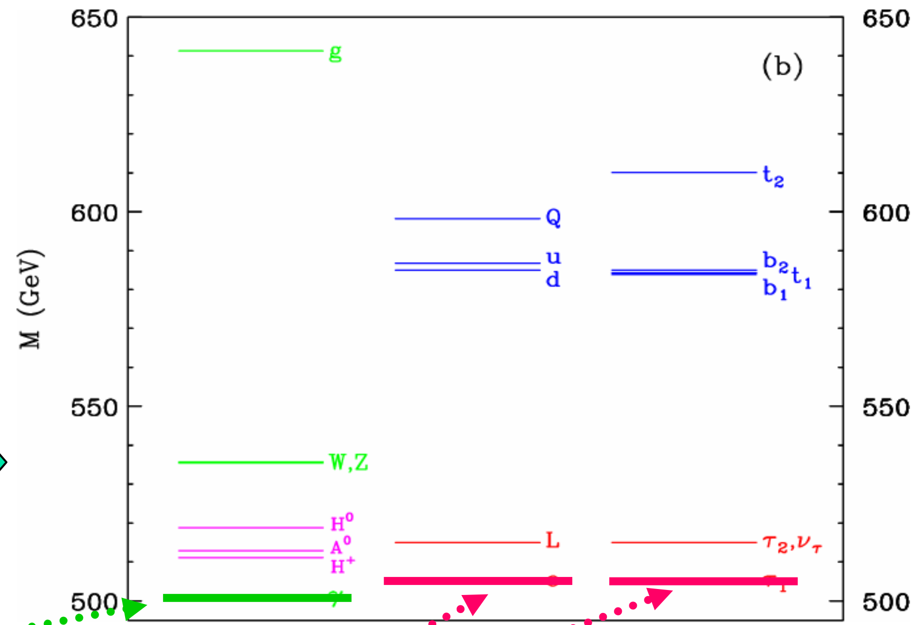
- KK modes are degenerate in mass at each KK level:

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

- 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



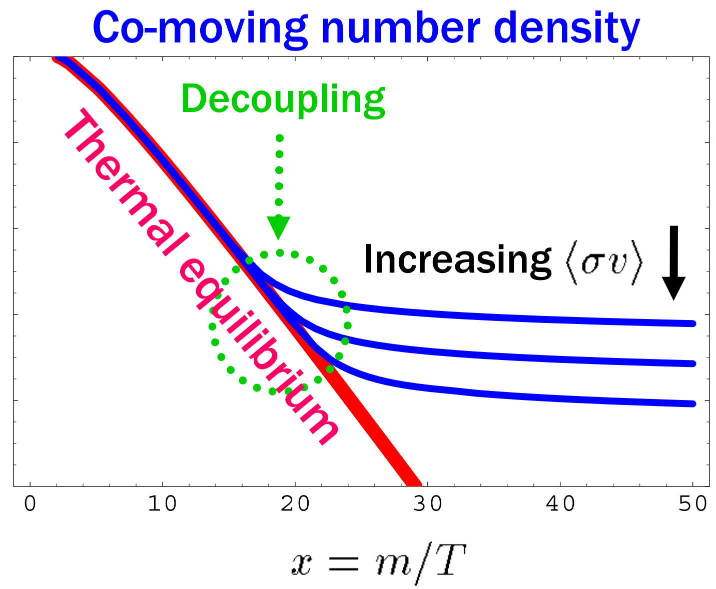
$R^{-1} = 500\ {\rm GeV},\ \Lambda R = 50,\ m_h = 120\ {\rm GeV}$

Λ : Cutoff scale

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

- Lightest KK Particle (LKP): $\gamma^{(1)}$
  Next to LKP: $SU(2)_L$ singlet leptons: $E_i^{(1)},\ i = e, \mu, \tau$

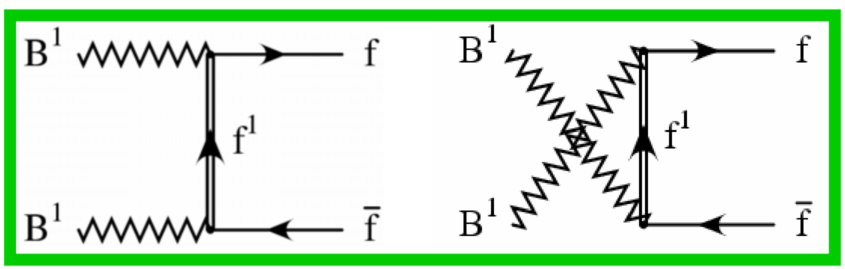
3. Relic abundance of KK dark matter

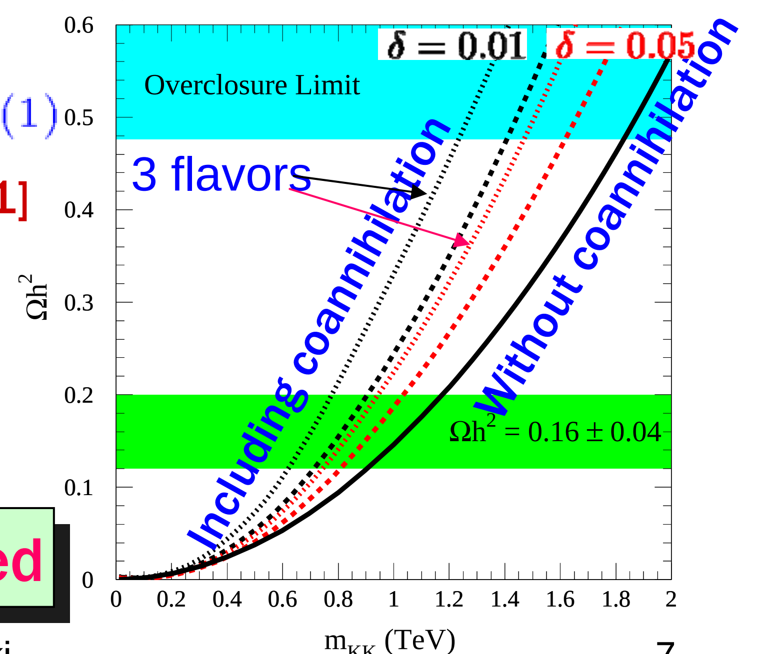


- Generic picture
  - Dark matter was at thermal equilibrium in the early universe
  - After the annihilation rate dropped below the expansion rate, the number density per comoving volume is almost fixed

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

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



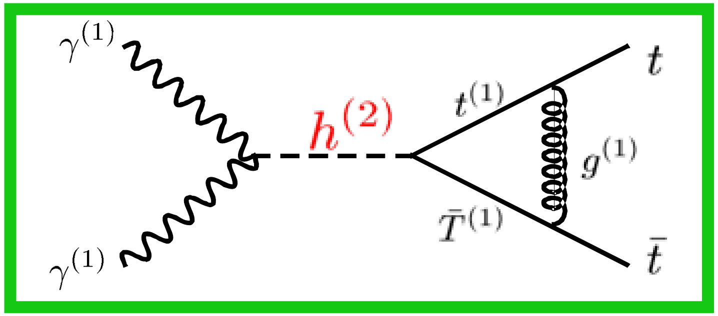


Only tree level diagrams are considered

4. Resonant KK dark matter annihilation

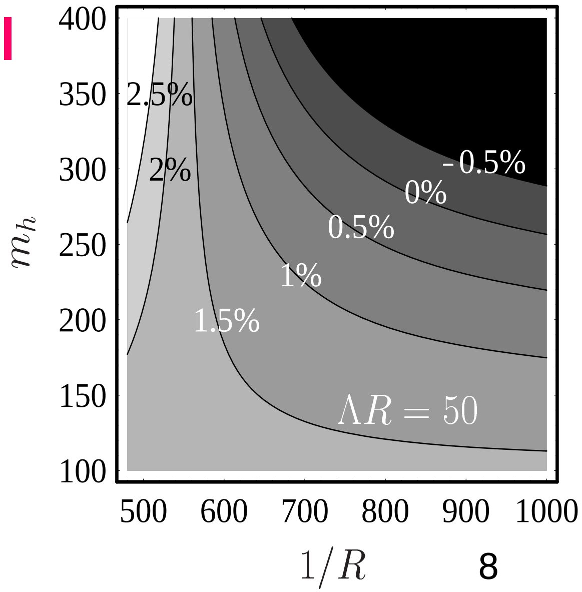
- Dark matter is non-relativistic in the early universe
  ⇒ (Incident energy of two LKPs) $\simeq$ (Masses of 2nd KK modes)

- **The annihilation cross section for the LKP is enhanced due to the resonance by s-channel 2nd KK Higgs boson at loop level**

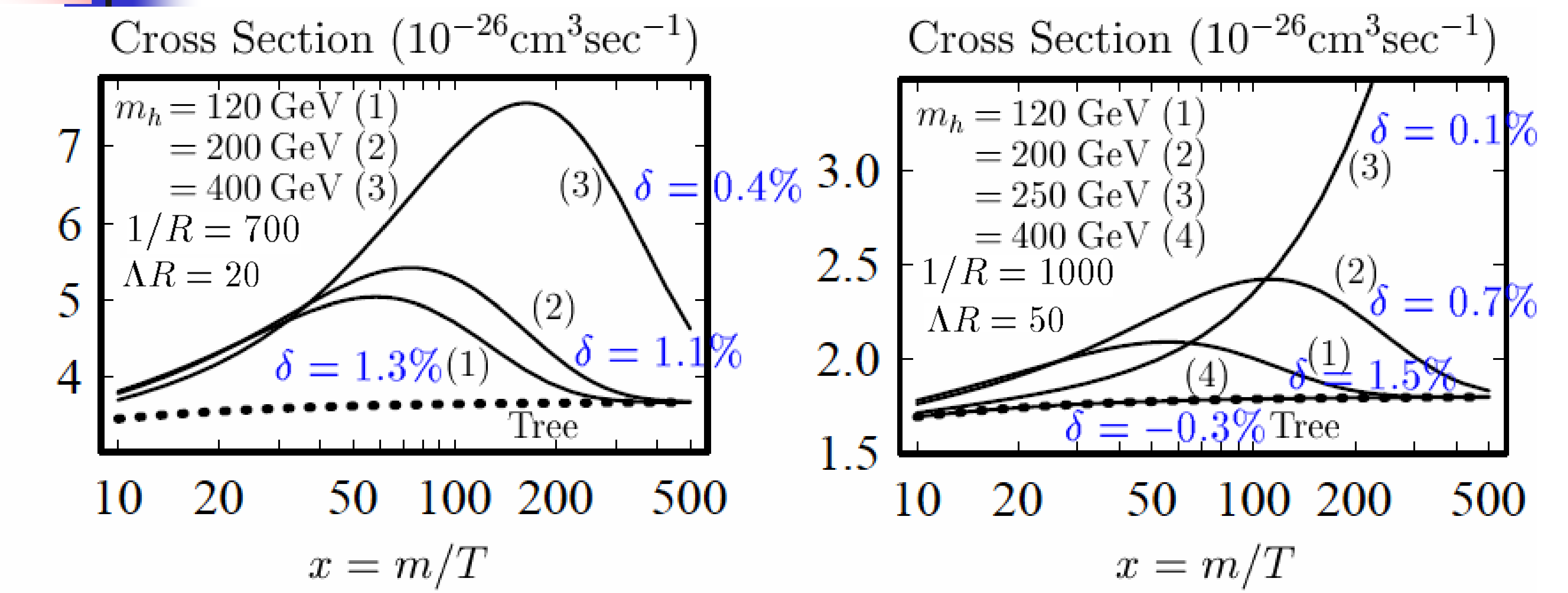


- Mass splitting in MUED:

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



Thermal average of annihilation cross section for LKP



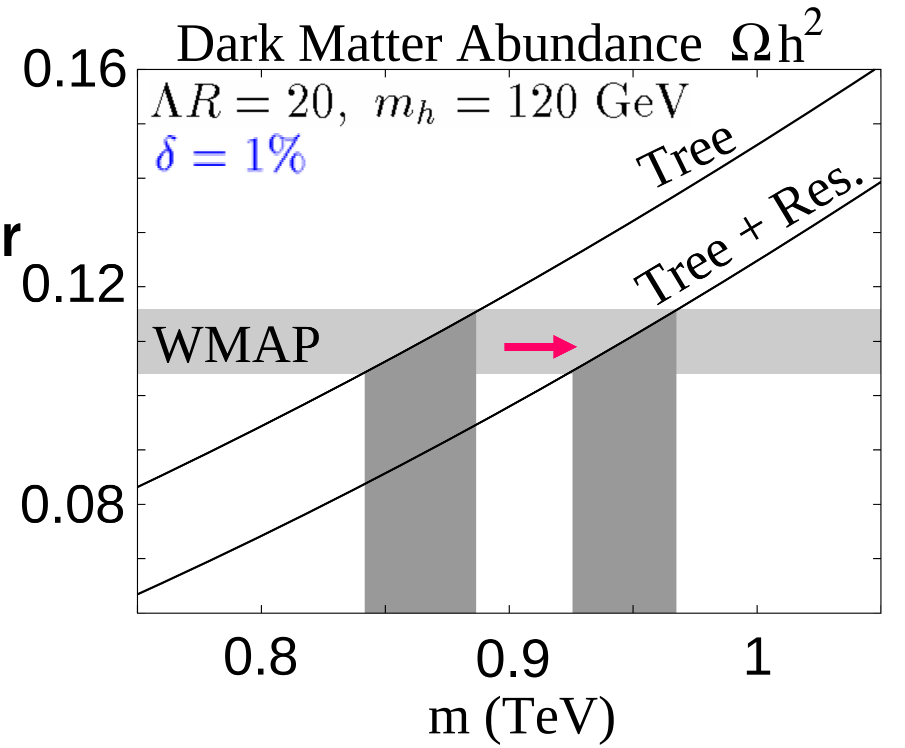
Smaller δ

→ The averaged cross section becomes maximum at later time and has larger maximum value

Relic abundance of LKP (without coannihilation)

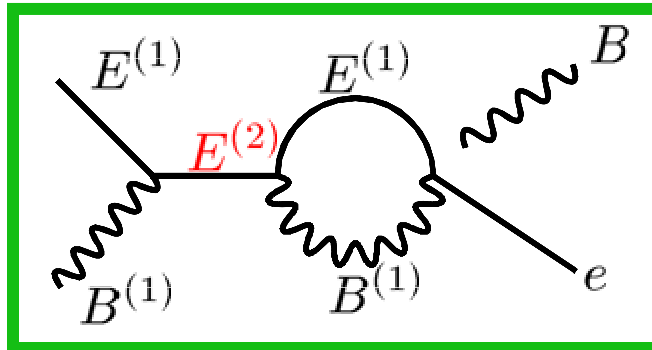
- The resonant annihilation by $h^{(2)}$ effectively reduces the number density of dark matter

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

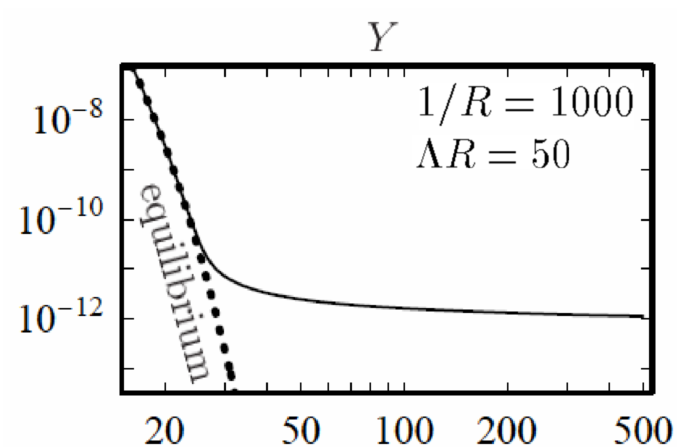


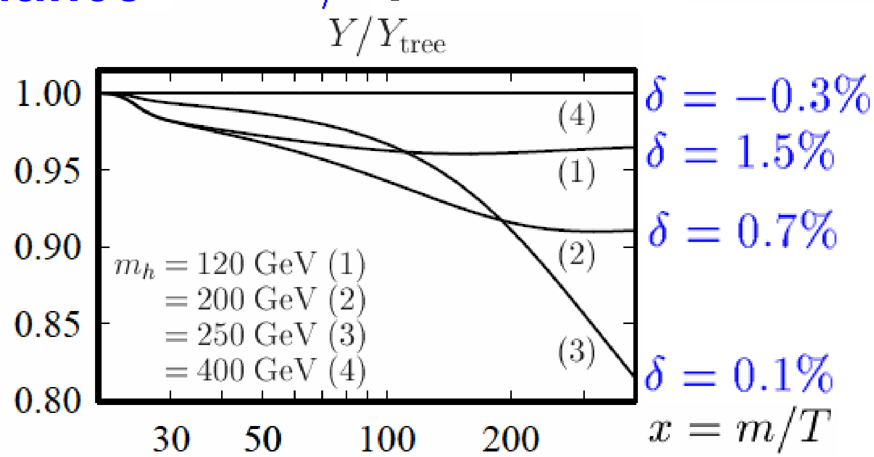
2nd KK modes play an important role in calculation of the relic density of the LKP dark matter

Coannihilation with NLKP $E^{(1)}$



- We can systematically survey effects of 2nd KK resonances:
  - $h^{(2)}$-resonance in $\gamma^{(1)}\gamma^{(1)} \to \mathrm{SM\ particles}$: sizable
  - $E^{(2)}$-resonance in $B^{(1)}E^{(1)} \to \mathrm{SM\ particles}$: relatively small
  - No second 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 number density gradually decreases even after decoupling

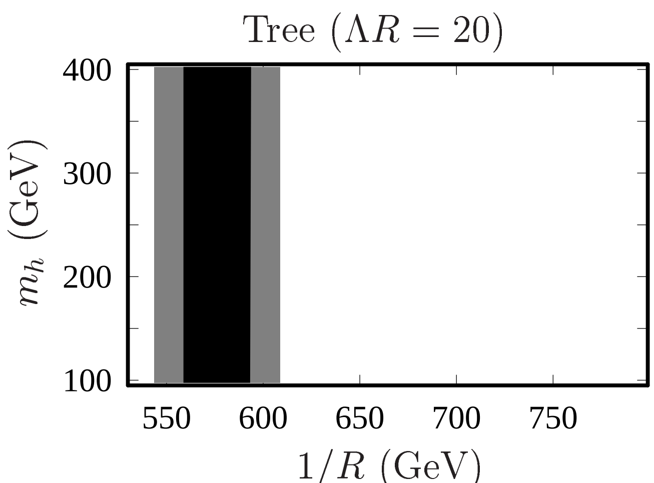
Allowed mass region

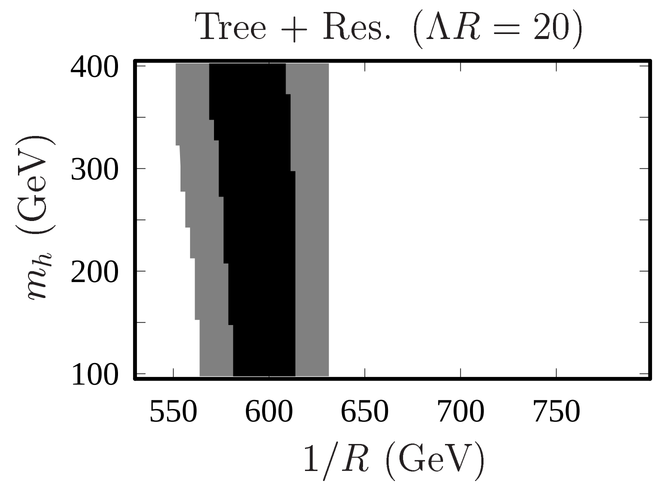
$0.104 \leq \Omega h^2 \leq 0.116$ (black)

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

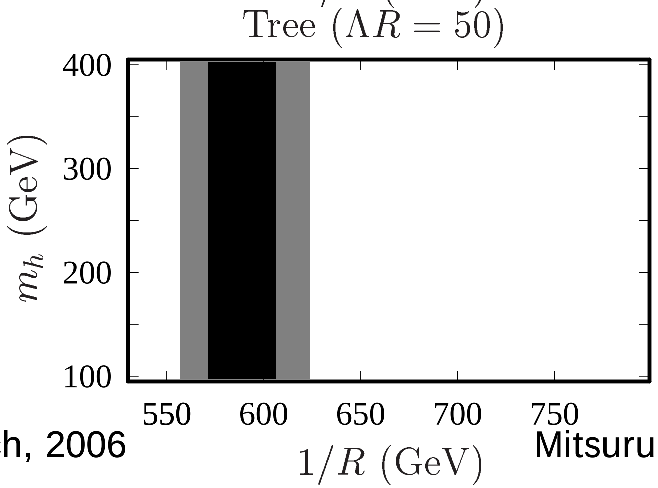
Tree level results | **Including resonance**

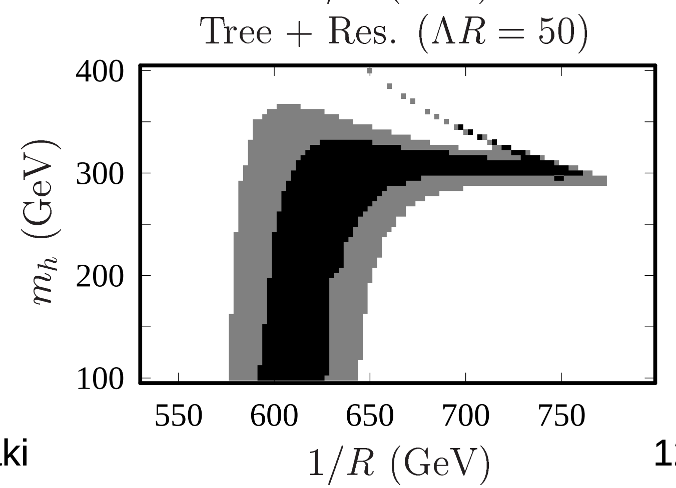
$\Lambda R = 20$

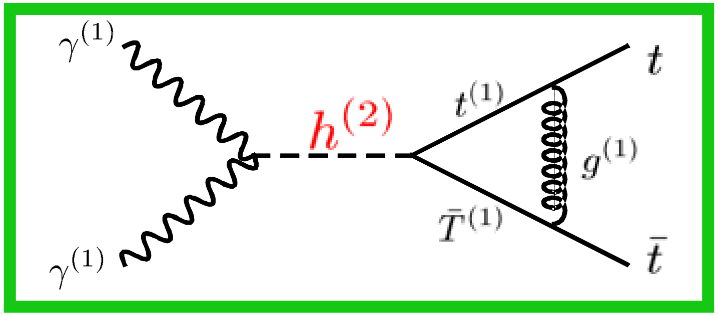




$\Lambda R = 50$







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)

  ⇨ Resonant annihilation

- We evaluated the relic abundance of the LKP dark matter including the resonance and coannihilation effects (with the NLKPs)
- The LKP mass consistent with WMAP is sizably raised due to the s-channel second KK resonance