Cosmological Constraint on the Minimal Universal Extra Dimension Model

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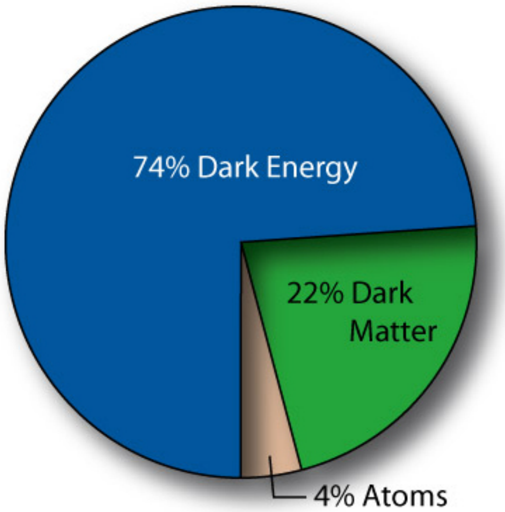
Refs:

- 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.

→ **Non-baryonic dark matter**



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

- 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.

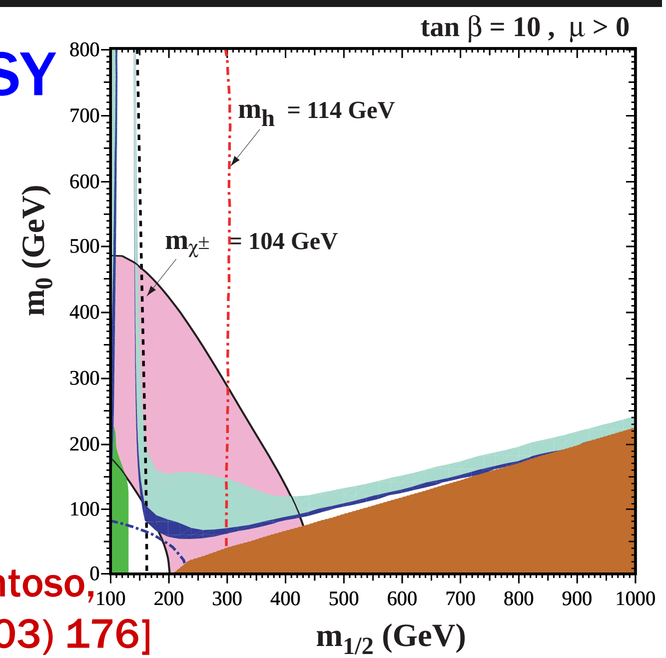
Outline

This work

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

→ Cosmological constraint on the minimal UED model

c.f.: SUSY



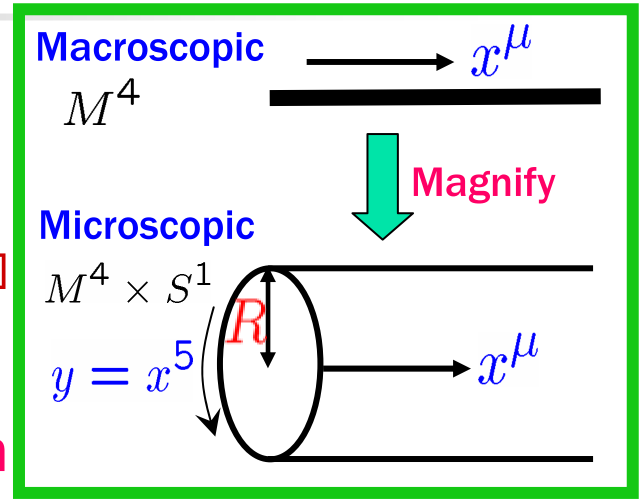
[From Ellis, Olive, Santoso, Spanos, PLB565 (2003) 176]

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]

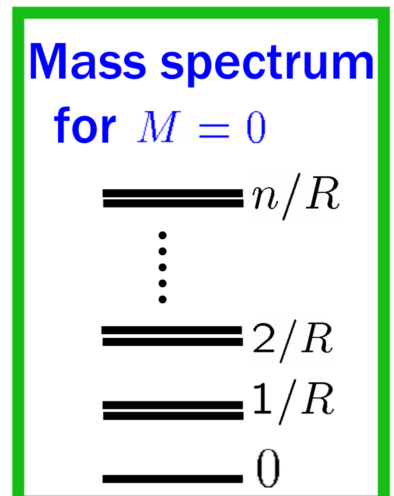


- **Dispersion relation:** $E^2 = \vec{p}^2 + (p_5^2 + M^2)$

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

- S^1 compactification with radius R:

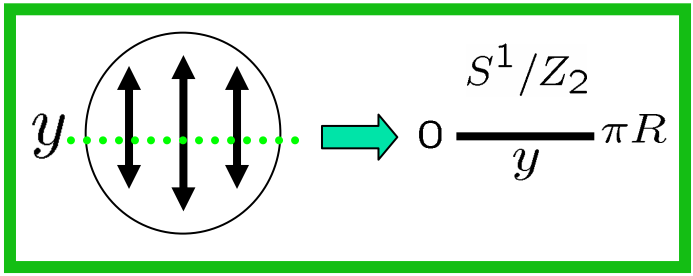
  $p_5 = n/R \quad (n = 0, \pm 1, \pm 2, \cdots)$ quantized ⇒ KK tower



- Momentum conservation in the extra dimension

  ⇒ Conservation of KK number n at each vertex

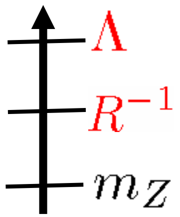
Minimal UED (MUED) model



- 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

More fundamental theory



- **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

- **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.~~

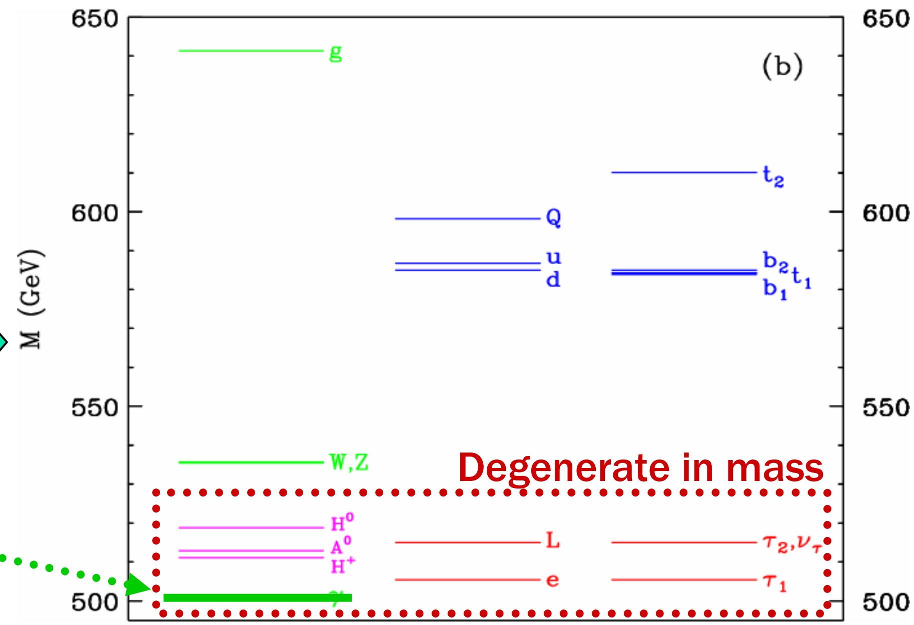
  Radiative corrections relax the degeneracy

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

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

  → Coannihilation plays an important role in calculating the relic density

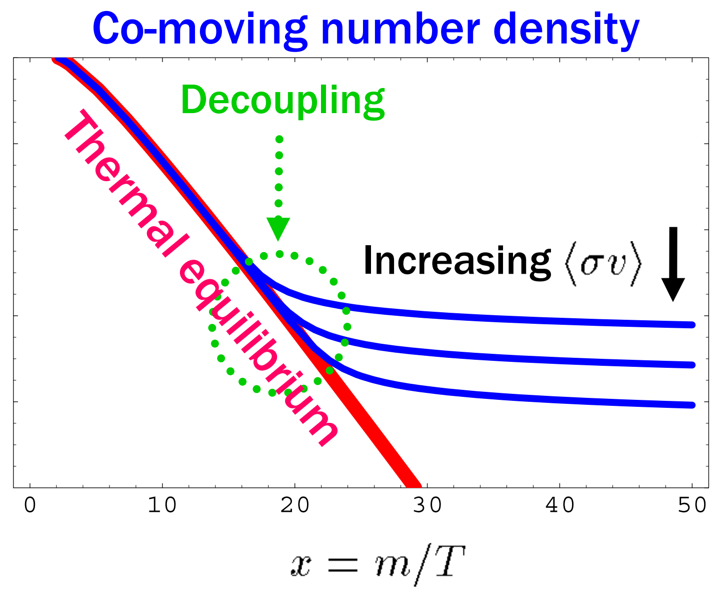
1-loop corrected mass spectrum at the first KK level



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

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

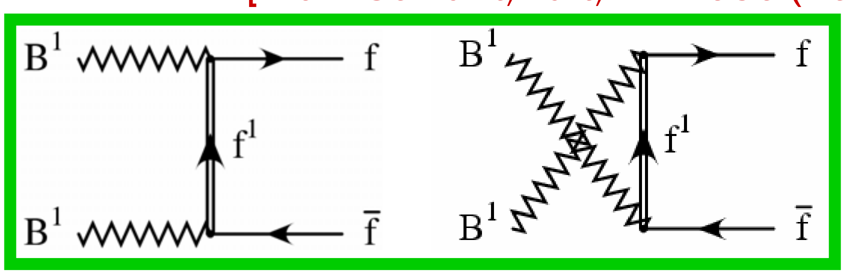
3. Relic abundance of KK dark matter

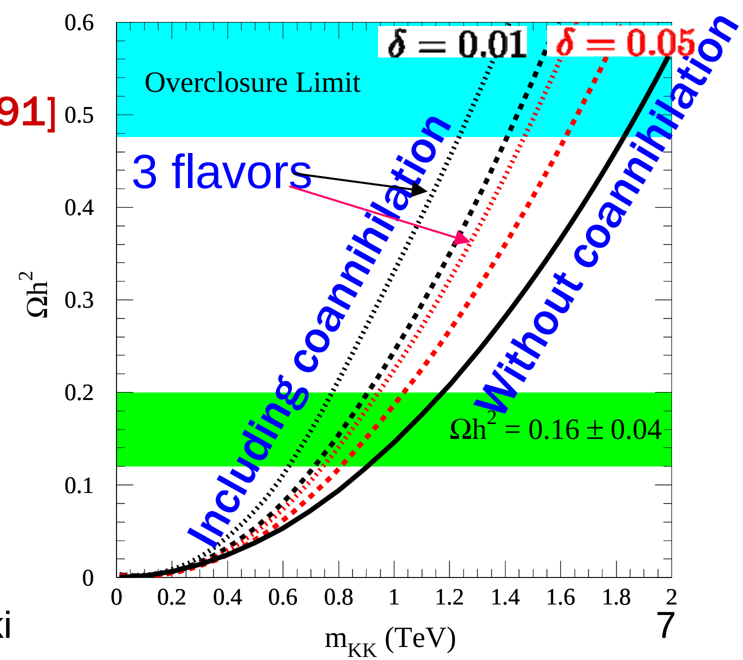


- Standard thermal scenario
  - Dark matter particles were in thermal equilibrium in the early universe
  - After the annihilation rate dropped below the expansion rate, the number density per comoving volume is almost fixed

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

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





Shortcomings:

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

4. Coannihilaition processes

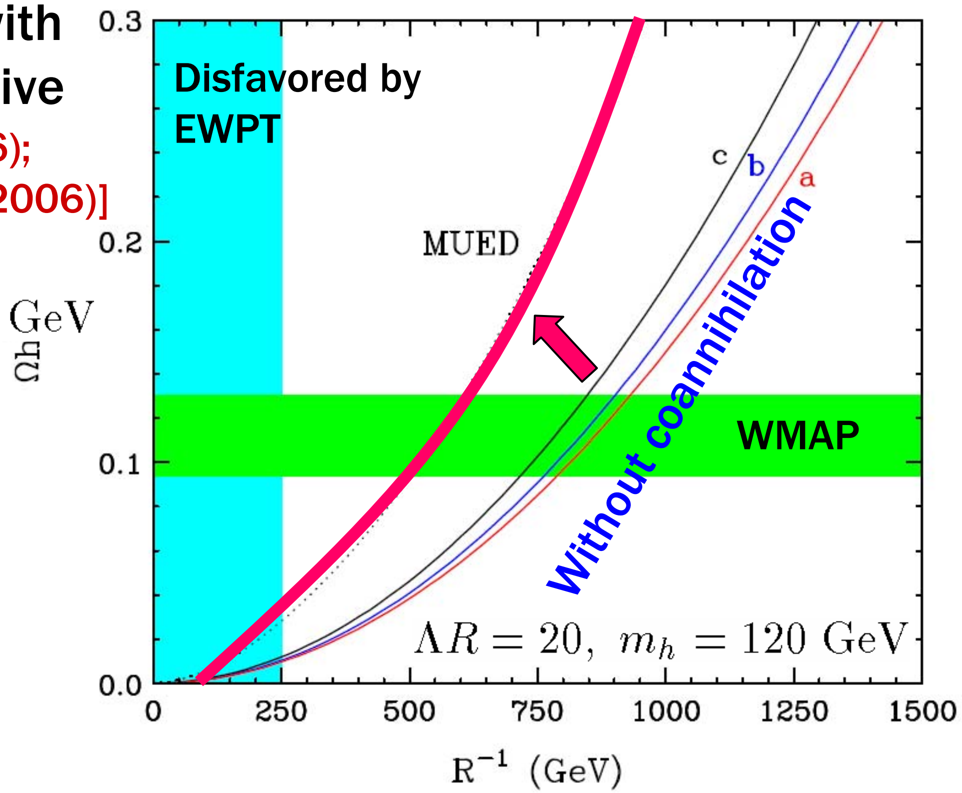
- Previous calculation:
  - Inclusion of coannihilation modes with all 1st KK particles reduces the effective cross section [Burnell, Kribs, PRD73(2006); Kong, Matchev, JHEP0601(2006)]

Shortcomings:

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

- Our emphasis:
  - 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

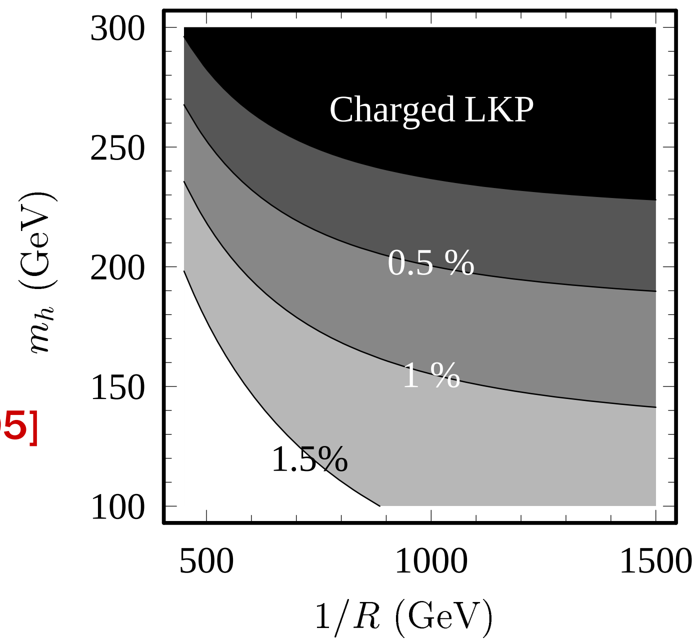
- 1^{st} KK Higgs boson masses:

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

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

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

- Contour plot of the mass splitting of $(m_H^{\pm(1)} - m_\gamma^{(1)})/m_\gamma^{(1)}$



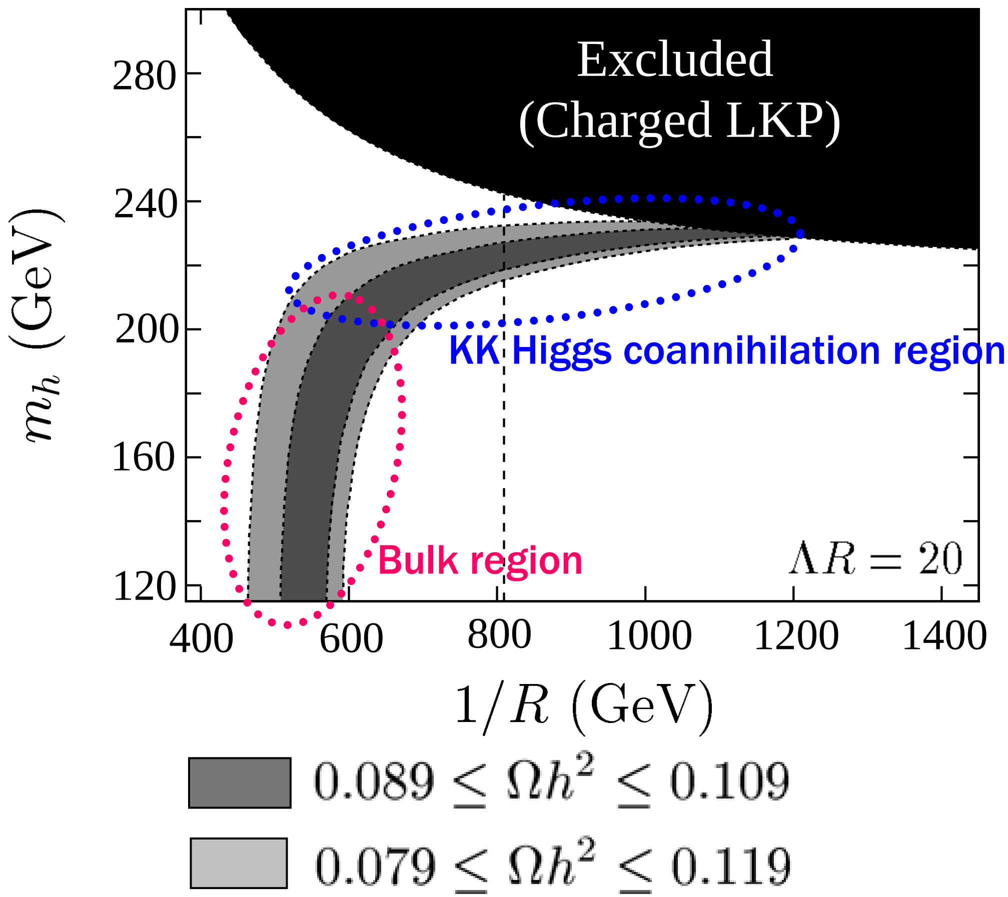
- Larger m_h

⇒ 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 1^{st} KK charged Higgs boson is the LKP

Allowed region without resonance processes



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

  Our 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

5. Resonance processes

- KK particles were non-relativistic when they decoupled

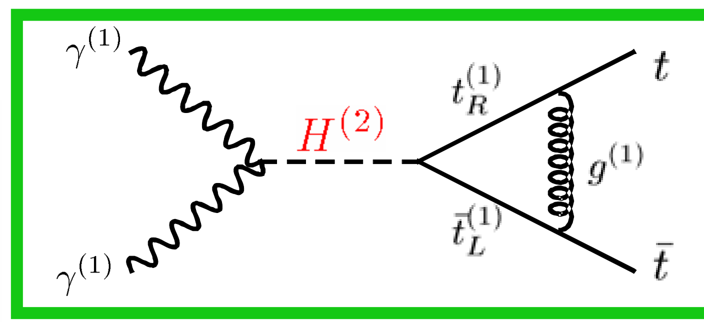
➡ (Incident energy of two 1st KK particles)

$\simeq$ (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**

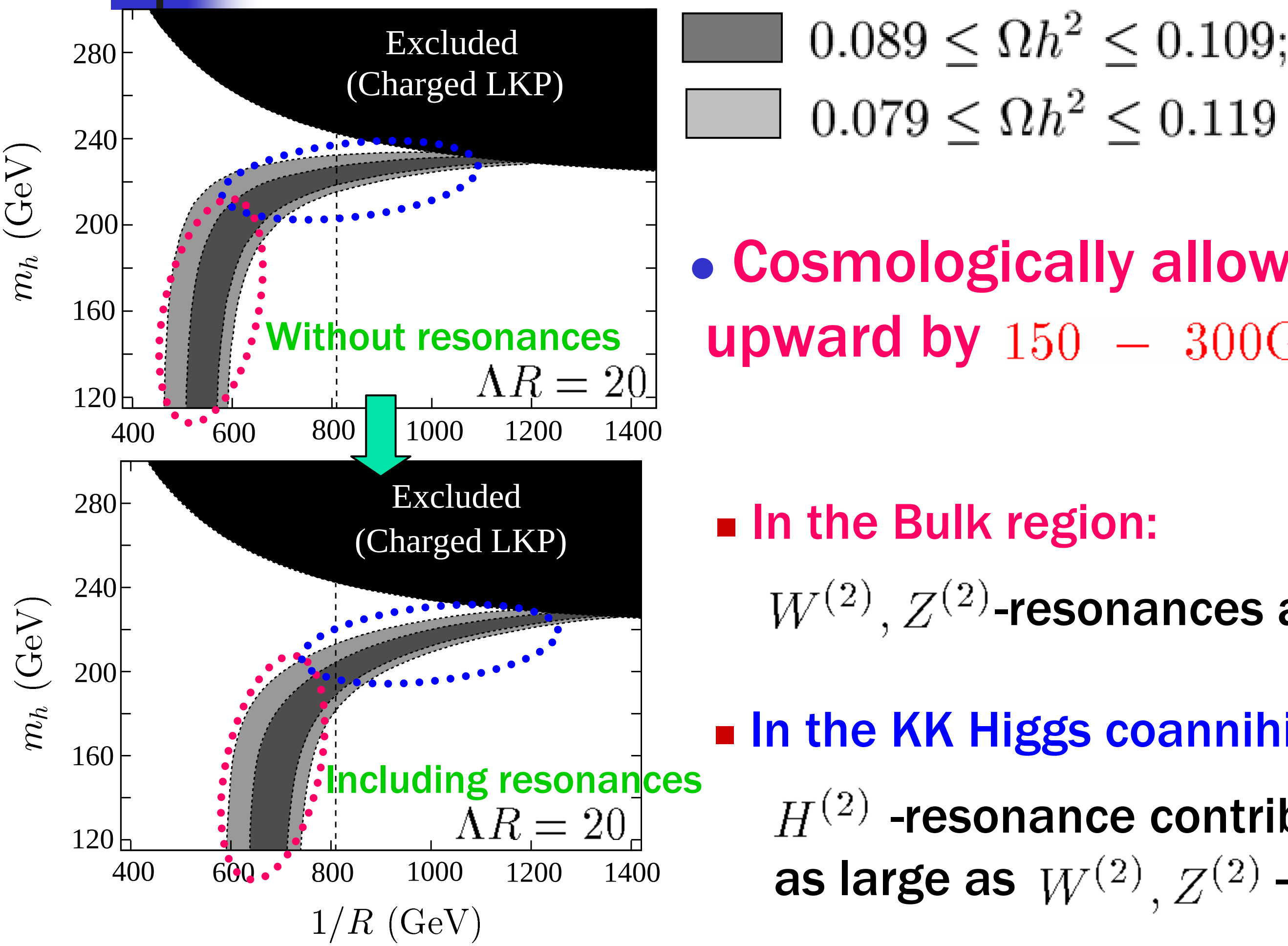
e.g.



- Important processes:

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

Allowed region including coannihilation and resonance



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

  - In the Bulk region:

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

  - In the KK Higgs coannihilation region:

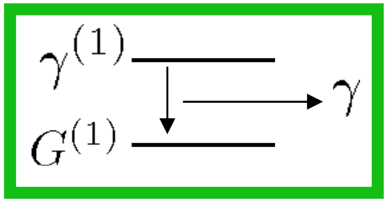
    $H^{(2)}$ -resonance contributes as large as $W^{(2)}, Z^{(2)}$ -resonances

Remark: KK graviton problem

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

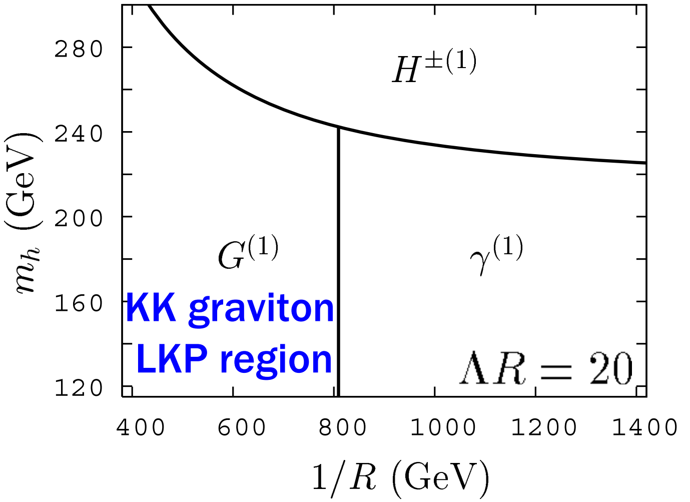
  $\gamma^{(1)}$ decays at late times

  ⇨ Emitted photons would distort the CMB spectrum



[Feng, Rajaraman, Takayama PRL91 (2003)]

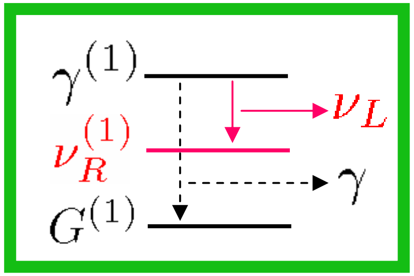
- LKP in the MUED



[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 $500\ \mathrm{GeV}$

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

- Radion stabilization?

6. Summary

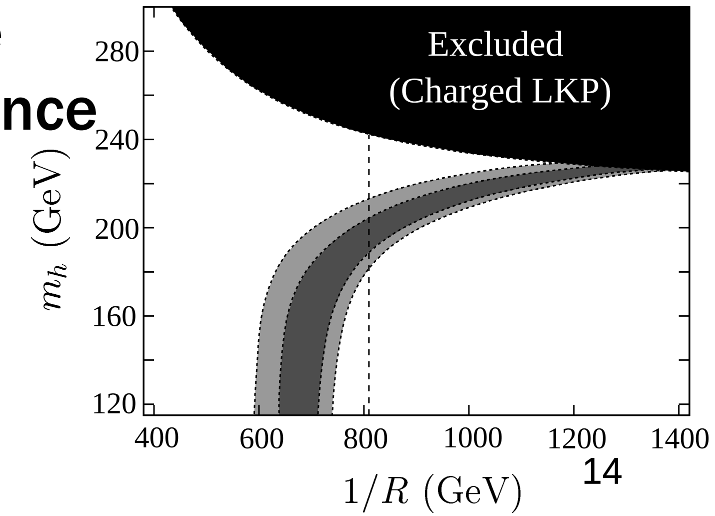
- UED models contain a candidate particle for CDM:

  The 1st KK mode of the B boson (LKP)

- In UED models
  - $m_{\mathrm{LKP}} \simeq m^{(1)}$ ⟹ Coannihilation
  - $\sqrt{s} \simeq m^{(1)} + m^{(1)} \simeq m^{(2)}$ ⟹ 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

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]

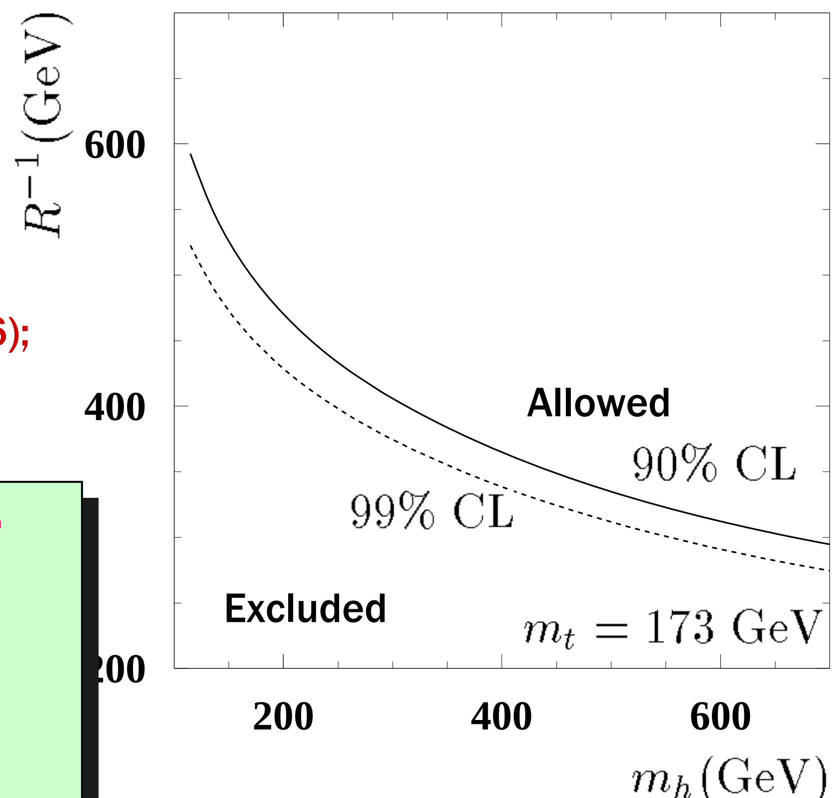
Constraint on R^{-1} in the MUED model

- 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

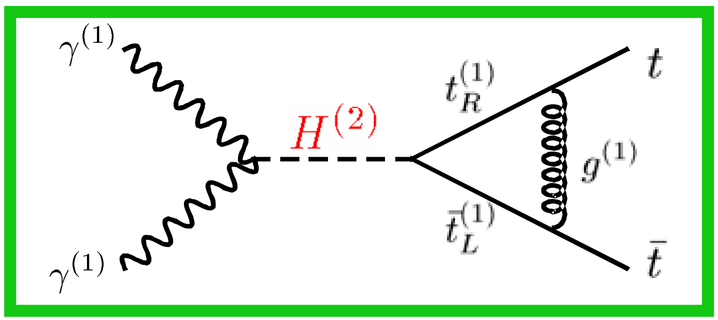
(Under the assumption of thermal production)

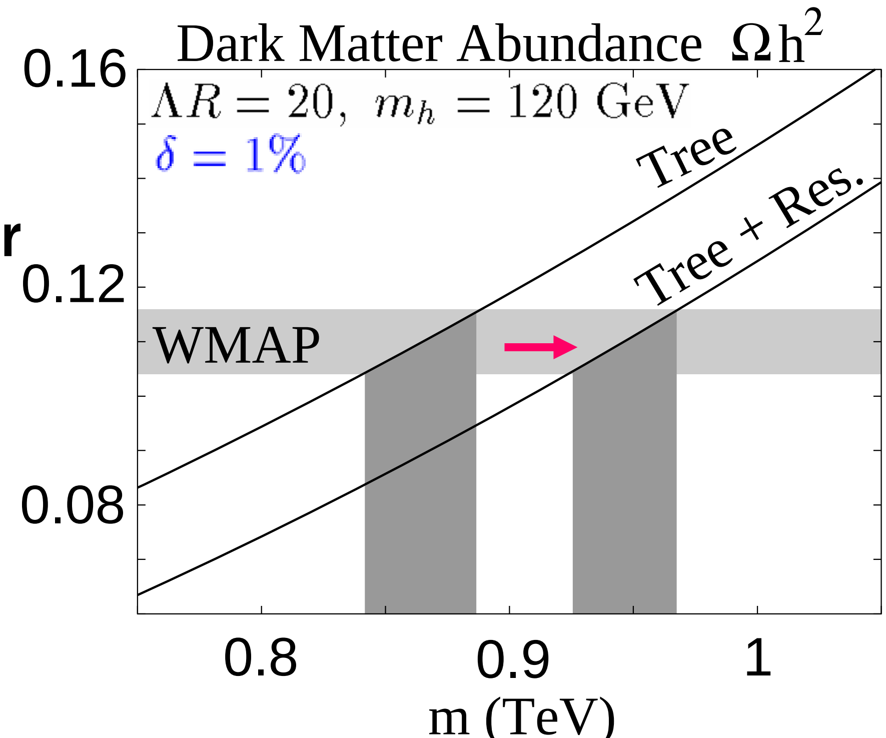


[From Gogoladze, Macesanu, PRD74 (2006)]

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

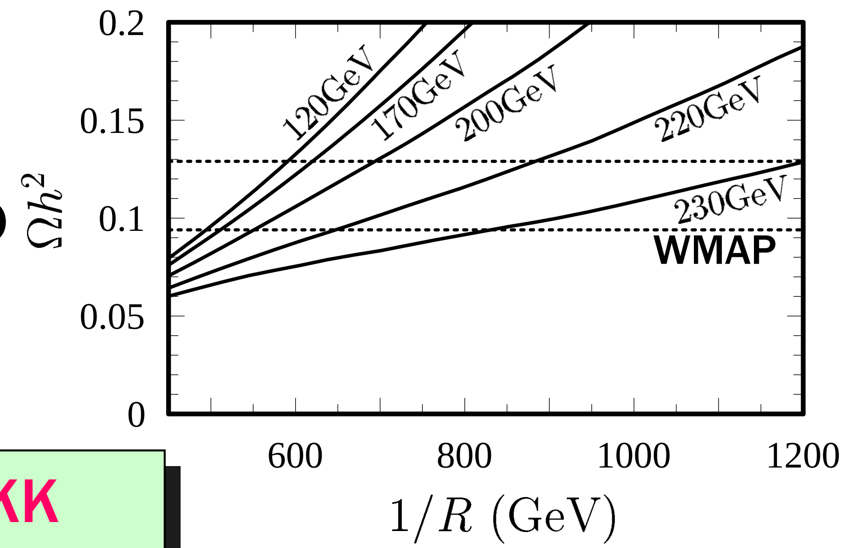
[Matsumoto, Senami, PLB633 (2006)]

- 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

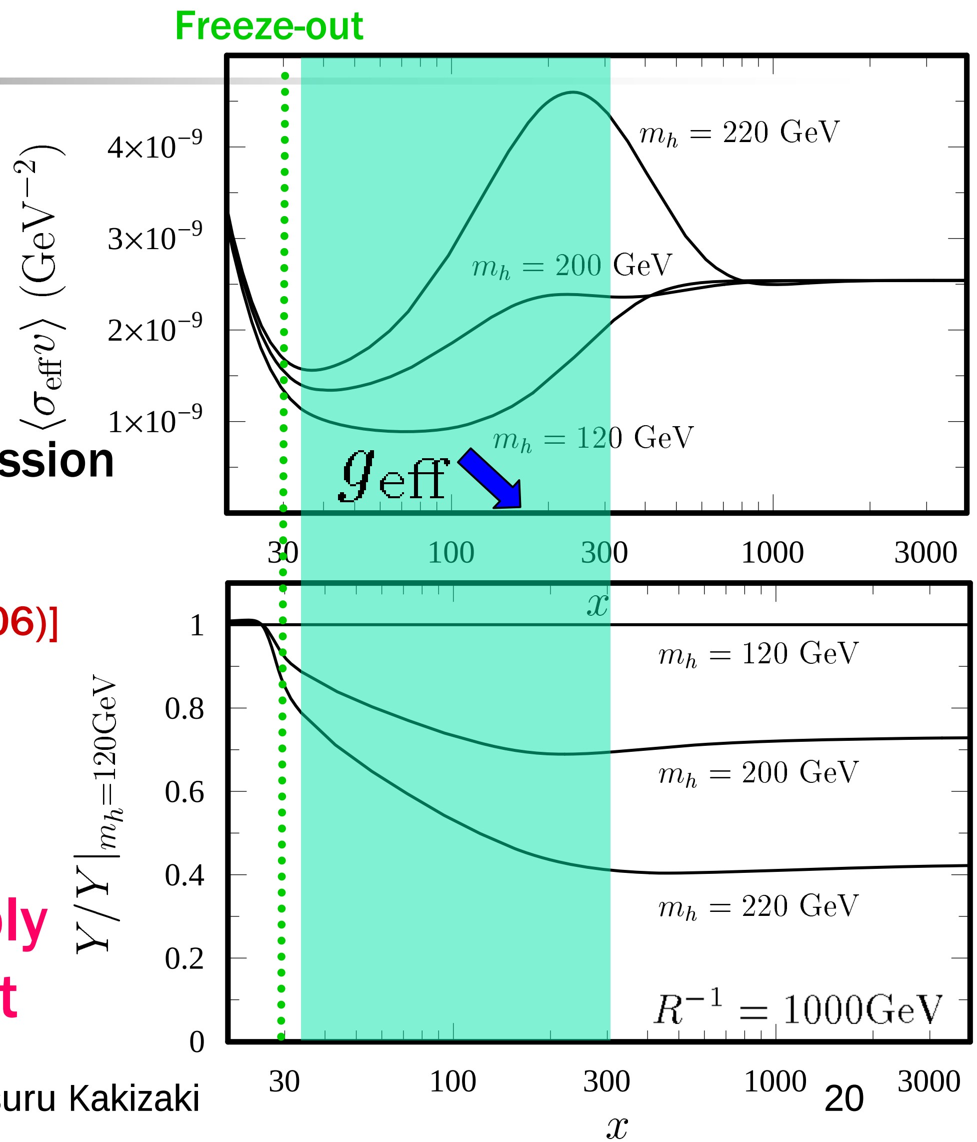
- For larger m_h
  (larger Higgs self-coupling)
  - ➡ Degeneracy between the LKP and $A^{(1)}$, $H^{\pm(1)}$
  - Free from a Boltzmann suppression

➡ **Larger σ_{eff}**

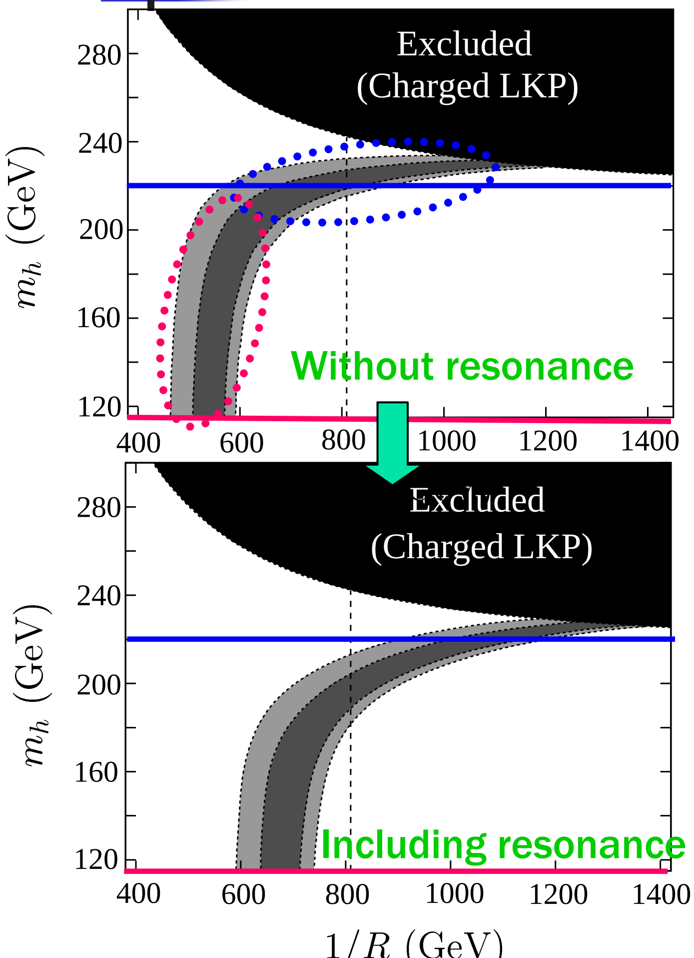
[Matsumoto, Senami, PLB633 (2006)]

- The effective cross section can increase after freeze-out

➡ **The LKP abundance can sizably decrease even after freeze-out**



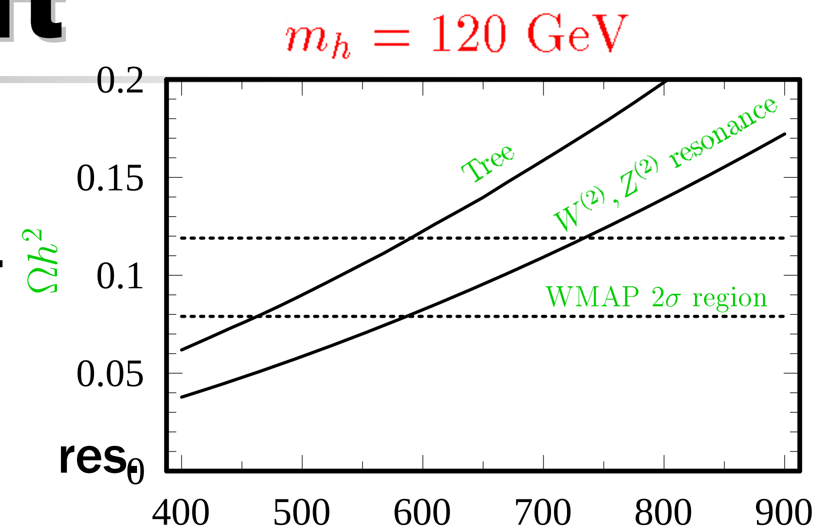
Origin of the shift



- **Bulk region**

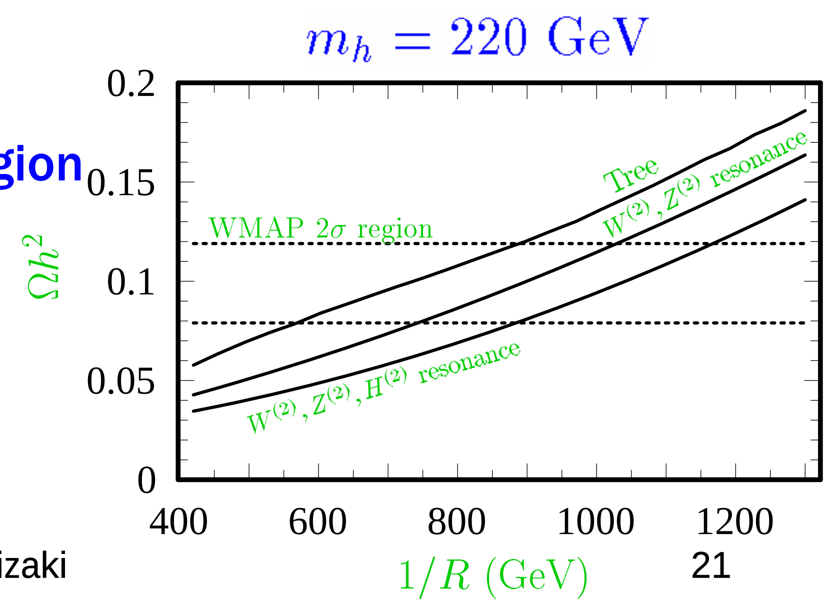
  $W^{(2)}, Z^{(2)}$-res. are effective

  res.



- **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

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

⇨ 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

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

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

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

- In generic:

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

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

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

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