Dark matter abundance in universal extra dimension models

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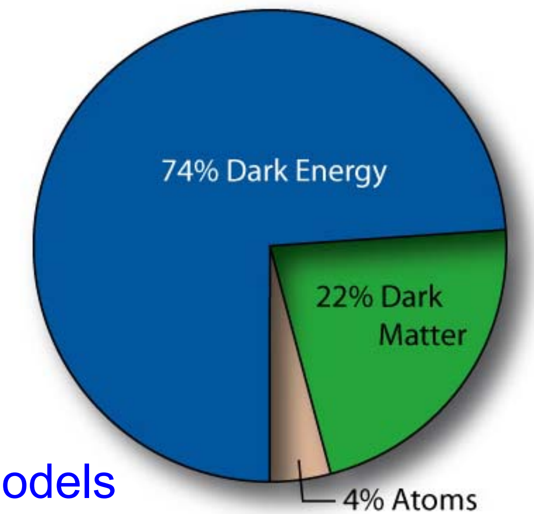
Kaluza-Klein dark matter

- Non-baryonic cold dark matter is established.
- Weakly Interacting Massive Particle (WIMP) is excellent candidate
  - Relic abundance
  - Large scale structure
- WIMP candidate
  - Lightest supersymmetric particle
  - Lightest Kaluza-Klein particle (LKP) in universal extra dimension (UED) models
  - …



Universal Extra Dimension model

Appelquist, Cheng, Dobrescu (2000)

Universal means
all SM particles propagate in spatial extra dimensions

- KK tower appear
  (All particle has KK particles)
- KK number n conservation

KK number conservation

Orbifold Compactification

For deriving chiral fermion zero modes,
an extra dimension is compactified on an orbifold

KK parity conservation

nevertheless

stable LKP is a good candidate for dark matter

c.f. R-parity and LSP

The Minimal UED model

- The Minimal Universal Extra Dimension model (MUED)
  - Five space-time dimension
  - The extra dimension is compactified on S^1/Z_2
- MUED model brings only two new parameters.

R^{-1} (extra dimension size)

Λ (cut off scale)

in addition to
the standard model parameter, m_h

Which particle is the LKP?

- KK particle has degenerate mass in tree level

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

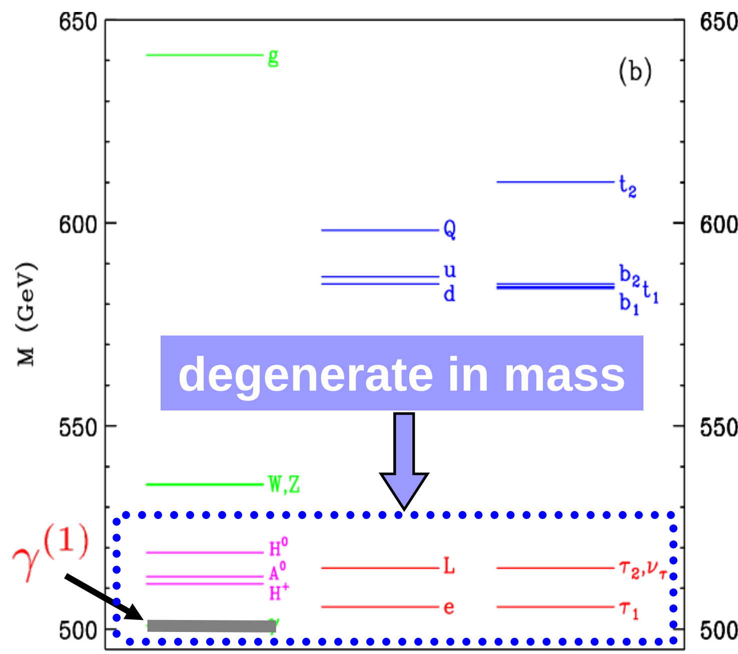
(SM massless particles are exactly degenerate)

- Radiative corrections remove the degeneracy

LKP : $\gamma^{(1)}$

- some KK particle are well degenerate with LKP

1-loop corrected mass spectrum



$1/R$=500 GeV, ΛR=20, m_h=120 GeV

Cheng, Matchev, Schmaltz (2002)

$$l_R^{(1)}, l_L^{(1)}, \nu^{(1)}, H^{(1)}, A^{(1)}, H^{\pm(1)}$$

1〜5%

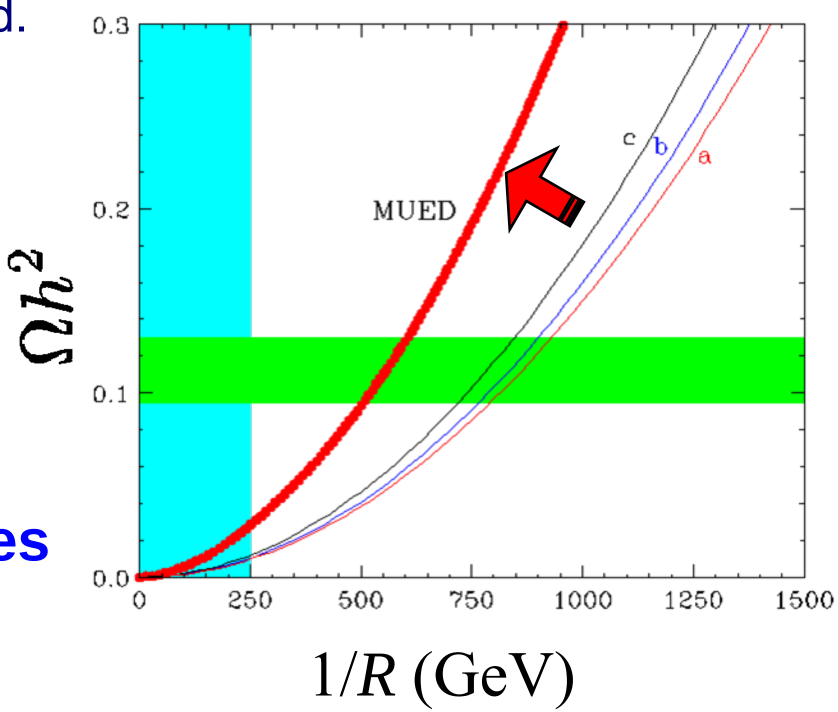
Coannihilation

- Some KK particles are degenerate with LKP in mass

δ=O(1)% : MUED model

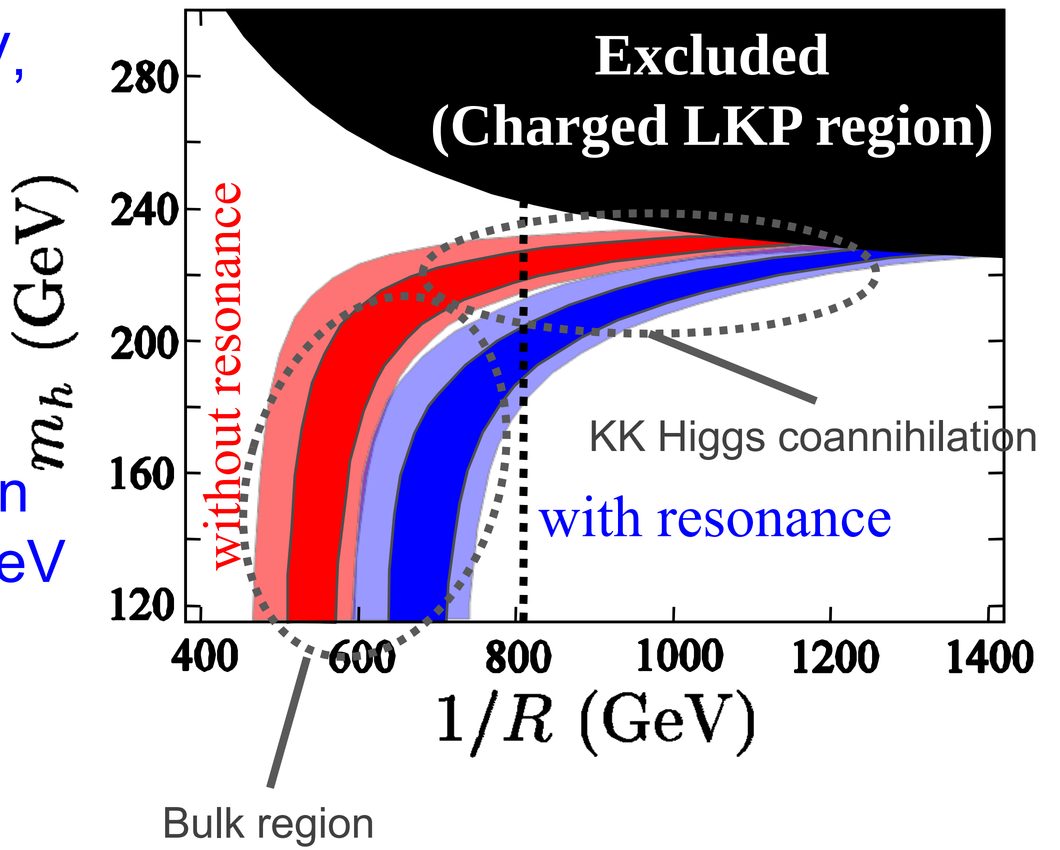
- Coannihilation changes relic abundance of DM.
  - Effective annihilation cross section is decreased.
  - m_h=120 GeV is assumed.
  - resonance processes are not included.
- **But, Relic abundance is dependent on**
  - **second KK particle resonance processes**
  - **SM Higgs mass**

Kong, Matchev (2005)



Result with resonance process

- For m_h > 200GeV, KK Higgs coannihilation is important
- Resonance effects shift the allowed region about 150-300 GeV
- m_h=120GeV without resonance = Kong, Matchev result



KK Higgs particle

- KK Higgs mass $m_{H^{\pm(1)}} < m_{A^{(1)}} < m_{H^{(1)}}$

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

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

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

KK particles for Goldstone boson

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

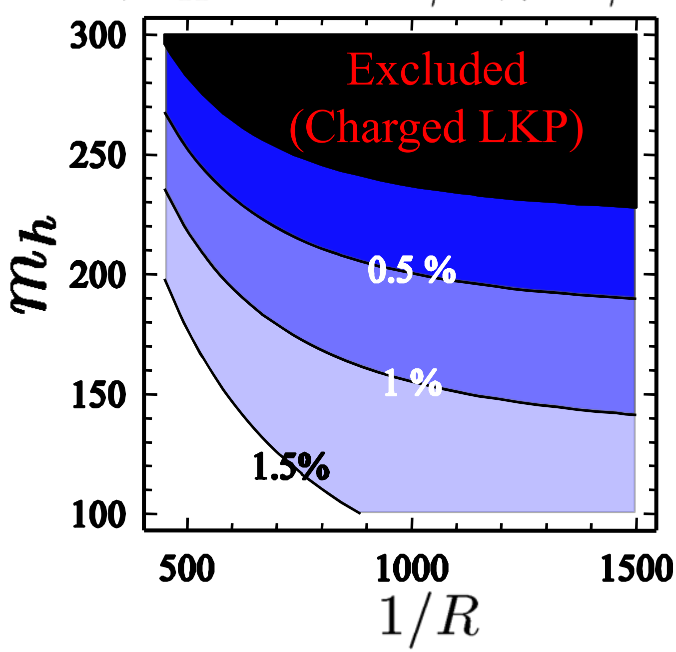
- larger m_h

⇨ larger λ_h, smaller δm^2_H

$$\lambda_h \equiv m_h^2/v^2$$

(enhance annihilation of KK Higgs
$H^{\pm(1)}$ NLKP

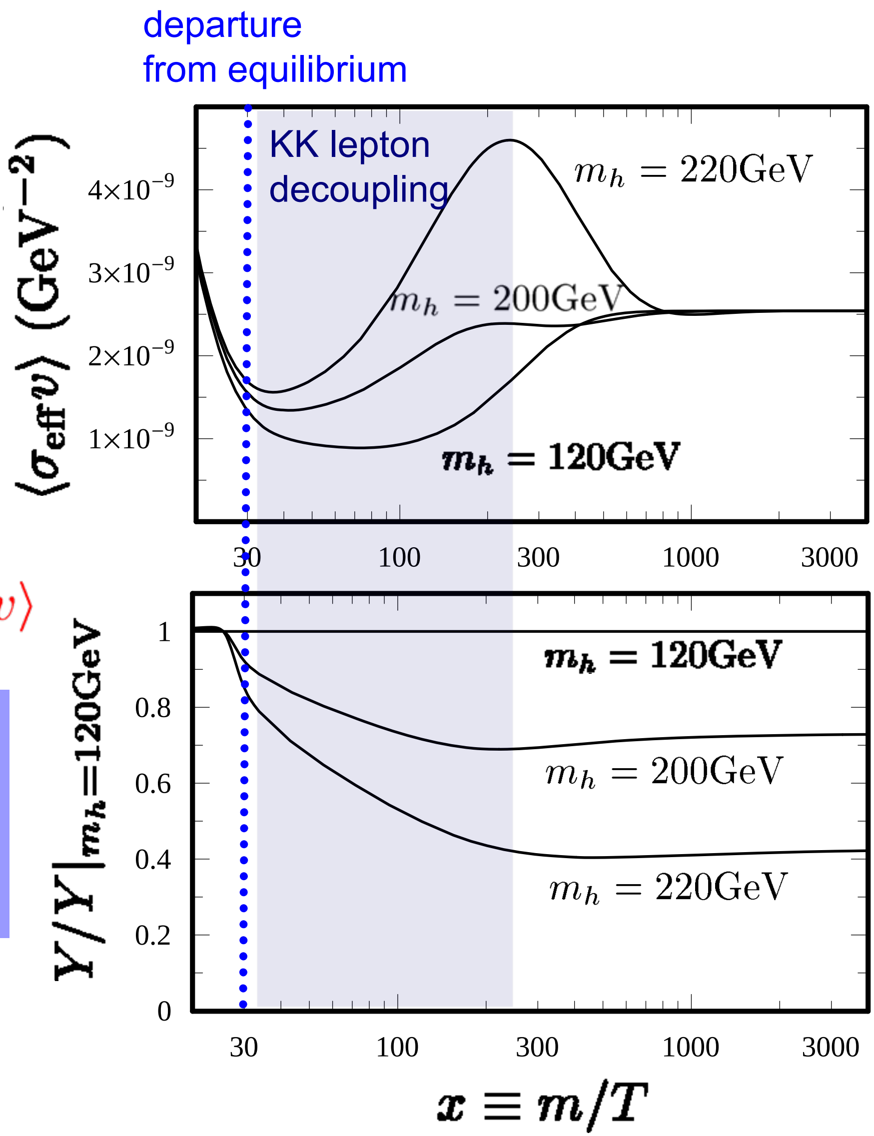
$(m_{H^{\pm(1)}} - m_{\gamma^{(1)}})/m_{\gamma^{(1)}}$



KK Higgs coannihilation region

- For large m_h
  - large cross section of KK Higgs annihilation
  - $H^{\pm(1)}$ and $A^{(1)}$ degenerated with LKP
  - free from a Boltzmann suppression after KK leptons decoupling
  - large contribution to $\langle\sigma_{\rm eff} v\rangle$

Late time enhancement of the cross section reduces the abundance after the departure from equilibrium



Resonance processes

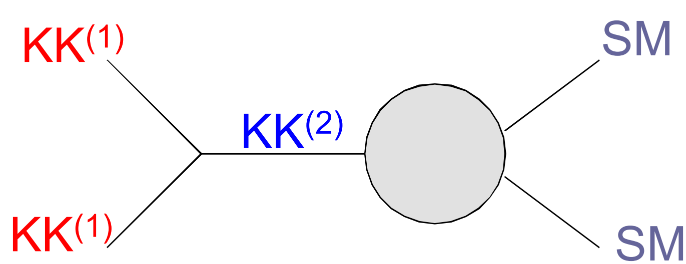
- Important processes

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

  - DM is non-relativistic
  - The energy of two first KK particles is almost degenerate with the mass of second KK modes

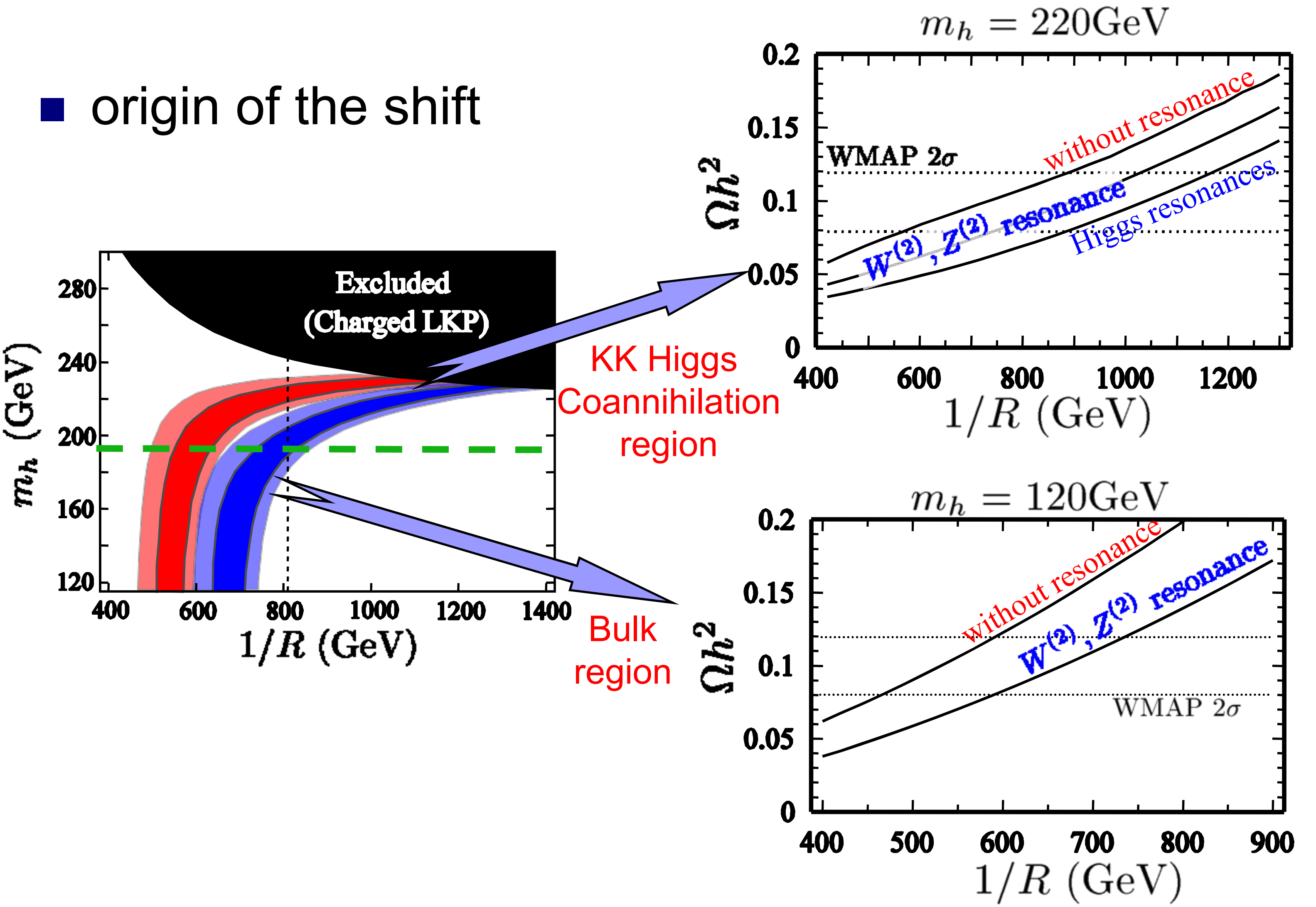
$$m_{KK^{(1)}} + m_{KK^{(1)}} \sim m_{KK^{(2)}}$$

- Resonance process mediated by second KK particles are important.



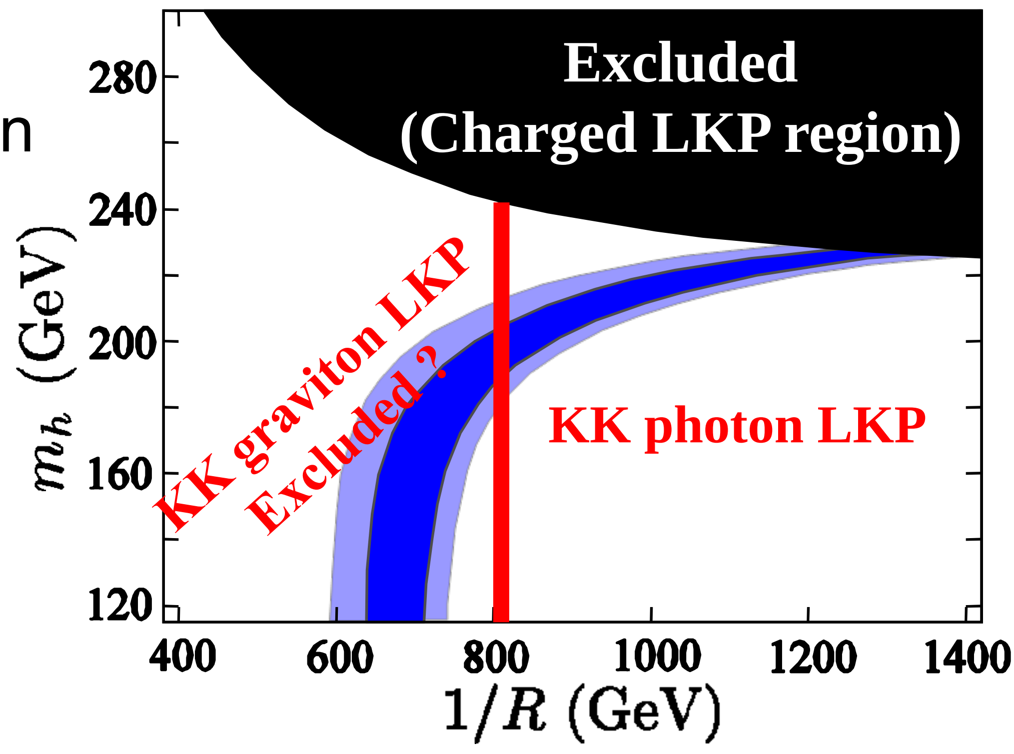
Resonance effects

- origin of the shift



KK Graviton

- $1/R < 800$ GeV : LKP is KK graviton
  - KK graviton may be LKP i.e. DM is SuperWIMP
  - diffuse photon spectrum is inconsistent with NLKP decay to KK graviton Feng, Rajaraman, Takayama, PRL91, PRD68
- $1 > R$ 800 GeV : LKP is KK photon
  - MUED is consistent with DM relic abundance only if $m_h > 180$GeV.



KK Graviton LKP

- NLKP(KK photon) has very long life time.

  (Decay occurs after the recombination (last scattering))
  - Planck suppressed interaction
  - very small mass difference, typically < 1GeV.

$$\Gamma \sim \frac{10\cos^2\theta_w \delta m^3}{9\pi M_{\rm Pl}^2} \sim 10^{-13}{\rm s}^{-1} \times \left(\frac{\delta m}{1{\rm GeV}}\right)^3$$

  - Photons emitted by NLKP decay is inconsistent with observations of diffuse gamma ray (background photon with energy O(MeV))

KK Graviton LKP is not allowed
= KK graviton problem

Right-handed neutrino

- KK graviton problem is avoided by including right-handed neutrino
- KK right-handed neutrino
  - provides Dirac neutrino mass
  - their Yukawa interaction is very small $O(10^{-13})$
    - out of equilibrium in the evolution of our universe
    - radiative correction is very small

NNLKP :KK photon
NLKP :KK right-handed neutrino
LKP :KK graviton

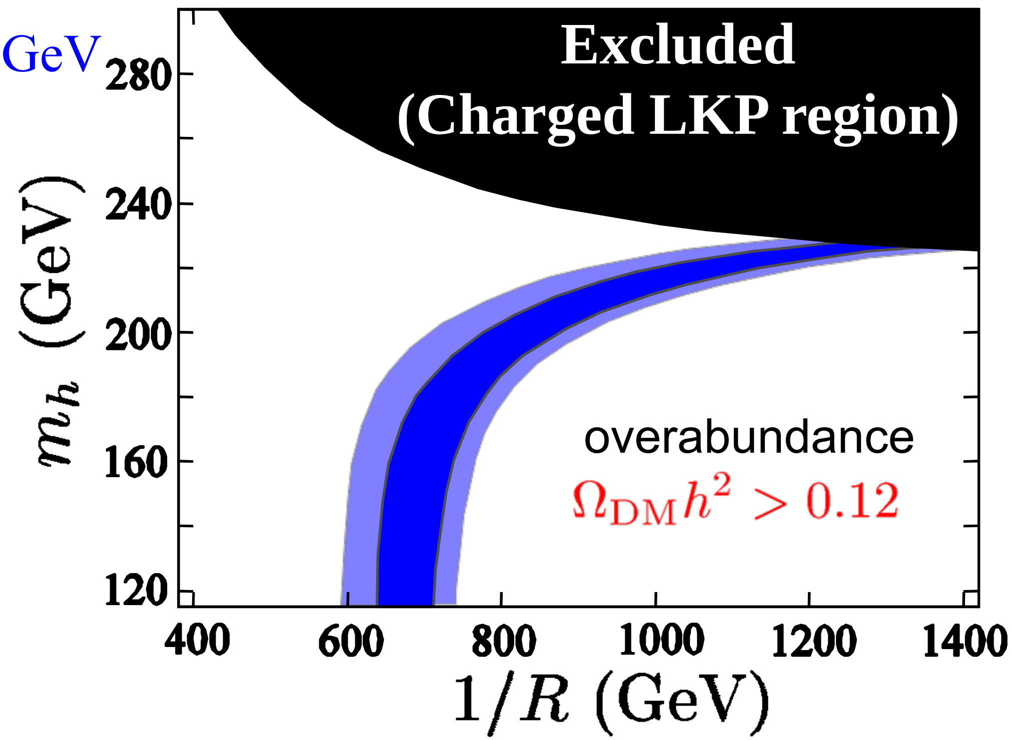
KK photon decays dominantly into
KK right-handed neutrino and ordinary neutrino

⇓

No photons emitted and KK graviton problem is avoided

Summary

- Relic abundance of the LKP is reduced by
  - KK Higgs coannihilation
  - second KK resonance processes
- Allowed region
  - 600GeV<1/R<1300GeV
  - m_h < 230 GeV



Charged Higgs LKP

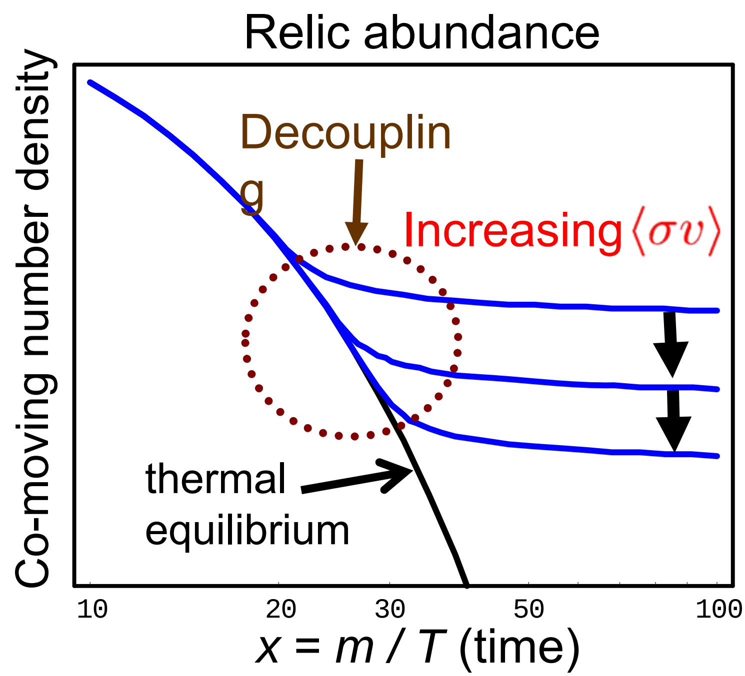
- Too large m_h
  - Charged KK Higgs is the LKP
- Charged LKP
  - Charged LKP can not be a candidate for dark matter.
  - Charged LKP ($1/R <$ 1 TeV)
    - Excluded by the anomalous heavy water molecule search in sea water if $T_R >$ 1 MeV.
    - Inconsistent with the successful big bang nucleosynthesis.

Two allowed region

- Small m_h (Bulk region)
  - Consistent with previous results
- Large m_h (KK Higgs coannihilation region)
  - Relic abundance is decreased drastically, allowed value of $1/R$ is increased.
  - This is due to the KK Higgs coannihilation.
  - $\sigma(H^{\pm(1)}H^{\mp(1)} \to \mathrm{SM}) \gg \sigma(\gamma^{(1)}\gamma^{(1)} \to \mathrm{SM})$

Dark matter relic abundance

- General picture
  - At $T \sim m$ (x~1), dark matter particle is in thermal equilibrium.
  - After annihilation rate dropped below the Hubble parameter, dark matter can not annihilate and the density per comoving volume is fixed.



- Large cross section

  ⇨ small relic abundance of dark matter

KK Higgs coannihilation region

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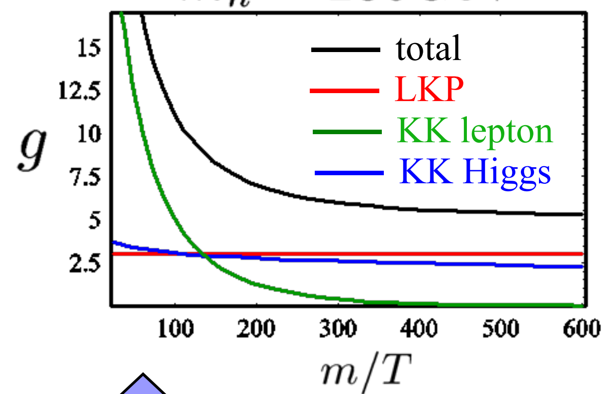
  - large contribution to $\langle \sigma_{\rm eff} v \rangle$

$$\sigma_{\rm tot} \propto \sum \sigma_{ij} g_i g_j$$

g : degree of freedom of KK particles

$m_h = 230\text{GeV}$



Difference : KK Higgs

$m_h = 120\text{GeV}$