

# The neutrino masses and the change of allowed parameter region in universal extra dimension models

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**Abstract.** Relic abundance of dark matter is investigated in the framework of universal extra dimension models with right-handed neutrinos. These models are free from the serious Kaluza-Klein (KK) graviton problem that the original universal extra dimension model possesses. The first KK particle of the right-handed neutrino is a candidate for dark matter in this framework. When ordinary neutrino masses are large enough such as the degenerate mass spectrum case, the dark matter relic abundance can change significantly. The scale of the extra dimension consistent with cosmological observations can be 500 GeV in the minimal setup of universal extra dimension models with right-handed neutrinos.

## 1. Introduction and UED models

As is well known, there is dark matter in this universe, and many models beyond the Standard Model (SM) have been proposed to explain the dark matter. Among those, Universal Extra Dimension (UED) models are one of interesting candidates for new physics. However, because only a short term passes since UED model was proposed, many subject remains which should be investigated. We have solved problems inherent in these models, and calculated the allowed parameter for UED models by estimating the dark matter relic abundance. This proceeding is based on our works [1] and [2].

First, we briefly review UED model. This model is the simplest extension of the SM in the five-dimensional space-time, where the extra dimension is compactified on an  $S^1/Z_2$  orbifold with the radius  $R$ . By expanding SM fields on fifth-dimensional space time, we can show that there are infinite tower of excited states. These excited states are called Kaluza-Klein (KK) particles. The SM particles and their KK particles have identical gauge charges. All interactions relevant to KK particles are determined by the SM Lagrangian.

Though the original UED model is phenomenologically good model, the model has two shortcomings. The first one is called the KK graviton problem. In the parameter region where (extra dimension scale  $1/R$ )  $< 800$  GeV, the KK graviton is the lightest KK particle (LKP), and the next LKP (NLKP) is the KK photon. Hence, the KK photon decays into a KK graviton and a photon at very late time due to gravitational interactions. This fact leads to the serious

problem; KK photons produced in the early universe decay into photons in the late universe, and these photons distort the CMB spectrum or the diffuse photon spectrum.

The second problem is the absence of neutrino masses. Since UED model has been constructed as minimal extension of the SM, neutrinos are treated as massless particles. However we know that it is not true. Therefore we must introduce neutrino masses into UED models.

## 2. Solving the problems

In order to solve these problems, we introduce the right-handed neutrinos into UED models, and assume that they form Dirac mass with ordinary neutrinos. The neutrino masses are expressed as

$$\mathcal{L}_{\nu\text{-mass}} = y_\nu \bar{N} L \Phi + \text{h.c.} , \quad (1)$$

where  $N$  is the right-handed neutrino,  $L$  is the left-handed (doublet) lepton. Thus the second problem, the absence of the neutrino masses, are clearly solved. Once we introduce right-handed neutrinos in the MUED model, their KK particles automatically appear in the spectrum. The mass of the first KK particle of the right-handed neutrino,  $N^{(1)}$ , is estimated as

$$m_{N^{(1)}} \simeq \frac{1}{R} + O\left(\frac{m_\nu^2}{1/R}\right) . \quad (2)$$

By comparing the mass of  $N^{(1)}$  with the mass of other KK particles, we can see that  $N^{(1)}$  is the NLKP, and the KK photon is the next to next lightest KK particle.

The existence of the  $N^{(1)}$  NLKP changes the late time decay of the KK photon. In the models with the KK right-handed neutrino, the KK photon dominantly decays into  $N^{(1)}$  and SM left-handed neutrino at tree level. Calculating the decay rate of KK photon decay modes, we can show that the decay of the KK photon is governed by the process,  $\gamma^{(1)} \rightarrow N^{(1)} \bar{\nu}$ . On the other hand, the dominant decay mode associated with a photon,  $\gamma^{(1)} \rightarrow G^{(1)} \gamma$ , comes from the Planck suppressed process, and its branching ratio is

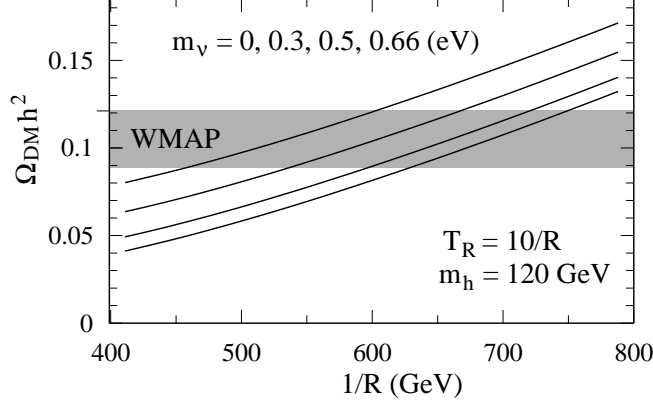
$$\text{Br}_{X\gamma} = \frac{\Gamma(\gamma^{(1)} \rightarrow G^{(1)} \gamma)}{\Gamma(\gamma^{(1)} \rightarrow N^{(1)} \bar{\nu})} = 5 \times 10^{-7} \left(\frac{1/R}{500\text{GeV}}\right)^3 \left(\frac{0.1\text{eV}}{m_\nu}\right)^2 \left(\frac{\delta m}{1\text{GeV}}\right) . \quad (3)$$

As a result, by introducing the right-handed neutrino into UED models, neutrino masses are introduced, and problematic high energy photon emission is highly suppressed. Therefore, two problems in UED models have been solved simultaneously.

## 3. $N^{(1)}$ dark matter and parameter determination

$N^{(1)}$  cannot decay because it is forbidden by the kinematics. Since  $N^{(1)}$  is neutral, massive, and stable,  $N^{(1)}$  can be dark matter candidate. Hence, if we introduce the right-handed neutrinos into UED models, dark matter changes from the LKP KK graviton to the NLKP KK right-handed neutrino. The KK graviton dark matter is produced from only decoupled KK photon decay, while  $N^{(1)}$  dark matter is produced from decoupled KK photon decay and from the high temperature thermal bath. As a result, in our model, there are additional contribution to the dark matter relic abundance. As total dark matter number density becomes large, the dark matter mass,  $\sim 1/R$ , becomes small. Therefore, in order to determine the compactification scale  $1/R$ , we must reevaluate the number density of  $N^{(1)}$  dark matter.

Because the number density of the decoupled KK photon has been calculated in previous works [3], we can see the  $N^{(1)}$  number density produced from the decoupled KK photon decay. So, we need to calculate the  $N^{(1)}$  number density produced from the thermal bath. To do



**Figure 1.** The dependence of the abundance on  $m_\nu$  with fixed reheating temperature  $T_R = 10/R$  and  $m_h = 120$  GeV. The solid lines are the relic abundance for  $m_\nu = 0, 0.3, 0.5, 0.66$  eV from bottom to top. The gray band represents the allowed region from the WMAP observation at the  $2\sigma$  level

this, we must take account of the thermal effects. If the thermal bath temperature is high enough, the mass of a particle receives a correction which is proportional to square of thermal bath temperature. For example, the thermal mass of the KK Higgs boson  $\Phi^{(n)}$  is given by the following formula,

$$m_{\Phi^{(n)}}^2(T) = m_{\Phi^{(n)}}^2(T=0) + \left[ a(T) \cdot 3\lambda_h + x(T) \cdot 3y_t^2 \right] \frac{T^2}{12}. \quad (4)$$

Coefficients  $a(T)$  and  $x(T)$  are determined by evaluating how many KK modes contribute to the correction at the temperature  $T$ . Taking account of such a thermal masses, we calculated the  $N^{(1)}$  number density.

Finally, we show the numerical result. In Fig.1, the neutrino mass dependence of the abundance. The horizontal axis is the compactification scale of the extra dimension, and the vertical axis is the relic abundance of the dark matter. The solid lines correspond to the result with  $m_\nu = 0, 0.3, 0.5, 0.66$  eV from bottom to top. As shown in this figure, as neutrino mass becomes large, compactification scale can be less than 500 GeV. If compactification scale is less than 500 GeV, in ILC experiment,  $n=2$  KK particles can be produced. Such a particles are very important for discriminating UED from SUSY at collider experiment.

#### 4. Summary

We have solved two problems in UED models (absence of the neutrino mass, energetic photon emission) by introducing the right-handed neutrinos. We have shown that by introducing right-handed neutrino, the dark matter is the KK right-handed neutrino, and we have calculated the relic abundance of the KK right-handed neutrino dark matter. In the UED model with right-handed neutrinos, the compactification scale  $1/R$  can be less than 500 GeV. This fact has important consequence on the collider physics, in particular on future linear colliders, because first KK particles can be produced in a pair even if the center of mass energy is around 1 TeV.

#### References

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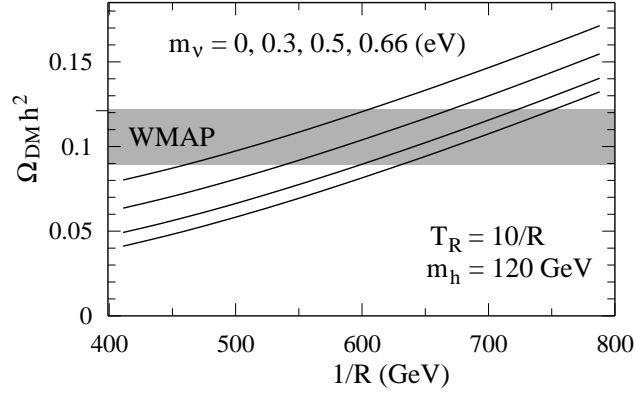
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