Soft Leptogenesis in Warped Extra Dimensions

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Outline of the talk

- Elements of Baryogenesis
- Brief introduction to the Geometry of Warped Extra Dimensions (RS1).
- Brief summary of Soft Leptogenesis.
- The Model
- Numerical results
- Conclusions

Baryogenesis

- In nature we see antimatter mainly in cosmic rays, e.g. $\bar{p}$,

$$\frac{\bar{p}}{p} \sim 10^{-4}$$

- We can characterize the asymmetry between and antimatter in terms of the baryon-to-photon ratio, ($n_\gamma \equiv \frac{\zeta(3)}{\pi^2} g_* T^3$)

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

- At early times the entropy density s is a better quantity to compare

$$\frac{n_B - n_{\bar{B}}}{s} = \frac{1}{7.04} \eta$$

- Sakharov conditions for dynamic creation of baryon asymmetry

1. B violation
2. Loss of thermal equilibrium
3. C, CP violation

Warped Extra Dimensions (RS1)

• Non-factorizable geometry with one extra dimension y compactified on an orbifold S^1/Z_2 of radius R, $0 \leq y \leq \pi$.

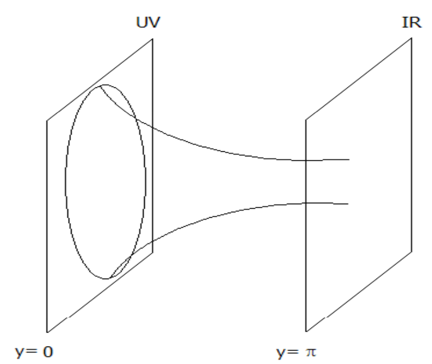
$$ds^2 = e^{-2R\sigma}\eta_{\mu\nu}dx^\mu dx^\nu + R^2 dy^2$$

where $\sigma = k|y|$. Slice of AdS_5 geometry. Mass scale at y=0, M_P and at $y=\pi$, $M_p e^{-k\pi R}$.

• Promote R to a superfield $\rightarrow$ 4D chiral radion T.

$$T = R + iB_5 + \theta\Psi_R^5 + \theta^2 F_T$$

• Geometry diagram

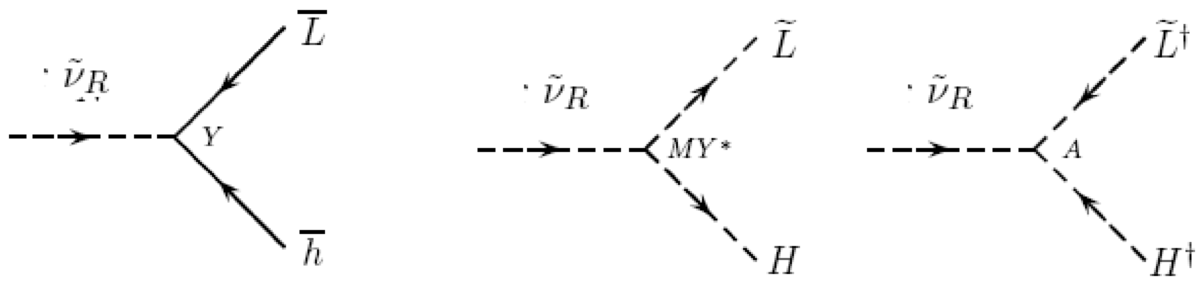


Soft Leptogenesis

- One-generation model
- Superpotential $W=(M_4NN)/2+\lambda_4 LNH$, where N, L and H stand for r.h. neutrino, lepton doublet and up-type Higgs chiral superfields.
- Width $\Gamma = M_4|\lambda_4|^2/4\pi$
- Soft SUSY breaking relevant terms $-\mathcal{L}_{soft,4D} = \ldots + A_4\lambda_4\tilde{\nu}_R\tilde{\nu}H + \frac{1}{2}B_4M_4\tilde{\nu}_R(x)\tilde{\nu}_R(x) + \ldots$
- One physical CP violating phase $\phi=\arg(A_4B_4^*)$
- Soft SUSY breaking terms induce mixing (oscillation) between r.h sneutrino and r.h. anti-sneutrino in a similar fashion to the B^0-$\underline{B}^0$ and K^0-$\underline{K}^0$ systems.
- Mass and width difference $\Delta m=|B_4|$, $\Delta\Gamma_4=2|A_4|\Gamma_4/M_4$ $\rightarrow$ significant CP violation in sneutrino decay processes.

Soft Leptogenesis

- Two-body decay diagram for r.h. sneutrino.



Tree level Feynman diagrams for r.h. sneutrino decay

- CP violation in the mixing generates lepton-number asymmetry in the final states of the r.h sneutrino decay:

$$\epsilon_L \simeq \frac{4\Gamma B_4}{4B_4^2 + \Gamma^2} \frac{ImA_4}{M_4} \Delta_{\rm BF}$$

where , $\Delta_{BF}=(c_B-c_F)/(c_B+c_F)$, where c_B and c_F represent the phase space of fermionic and bosonic channels, final states $f = h\nu$ and $f = H\tilde{\nu}$ respectively, $\Delta_{BF} \approx 0.8$ for $T = 1.2M_4$.

The Model: Right handed neutrino field interactions

- Set up: Quarks, Leptons and Higgs superfields on the UV brane (y=0), Gauge and right handed neutrino superfields in the bulk. SUSY conserving on the UV brane and bulk and SUSY breaking on the IR brane (y=π).

- 5D action for r.h. neutrino superfield N^c,

$$
\begin{aligned}
\mathcal{S}_5 = \int d^5x \Bigg(& \int d^4\theta \frac{1}{2}(T+T^\dagger)e^{-(T+T^\dagger)\sigma}(N^\dagger N + N^c N^{c\dagger}) + \\
& + \int d^2\theta e^{-3T\sigma} N^c \left[\partial_5 - (\frac{3}{2} - c_{\nu_R})T\sigma'\right] N + h.c. + \\
& + \frac{1}{2}\int d^2\theta e^{-3T\sigma} N^c(-M_1 T)N^c\delta(y) + h.c. + \\
& - \frac{1}{2}\int d^2\theta e^{-3T\sigma} N^c(-M_2 T)N^c\delta(y-\pi) + h.c. + \\
& - \int d^2\theta e^{-3T\sigma}\lambda L N^c H T\delta(y) + h.c. \Bigg)
\end{aligned}
$$

where M_1 and M_2 are 5D Majorana masses, λ is the Yukawa coupling in 5D and we parameterized the hypermultiplet mass as $c\sigma'$.

The Model: Radion F-term

- F_T responsible for SUSY breaking comes from

$$\mathcal{L}_{4D} = -\frac{6M_5^3}{k}\int d^4\theta\phi^\dagger\phi(1-e^{-(T+T^\dagger)k\pi}) + \int d^2\theta\phi^3[W_0 + e^{-3Tk\pi}W] + h.c$$

where W and W_0 are constant superpotentials at the orbifold positions y=0 and y=π, ϕ is the compensator field. Here $M_P^2 = M_5^3(1-e^{-2k\pi R})/k$.

- Zero cosmological constant in 4D theory $\rightarrow$

$$|W_0|^2 = e^{-4k\pi R}|W|^2$$

$\therefore$ Since $F_T = e^{-Rk\pi}\frac{W}{2\pi M_5^3} + \frac{W_0}{2\pi M_5^3}$ $\rightarrow$ F_T localized on IR brane with 4D form

$$F_T = e^{-k\pi R}\frac{W}{2\pi M_5^3}$$

The Model: Gaugino mass generation

- Action for vector supermultiplet

$$\mathcal{S}_5 = \int d^5x [\frac{1}{4g_5^2} \int d^2\theta T W^\alpha W_\alpha + h.c + ...]$$

- Induced gaugino mass term (universal gaugino masses)

$$\mathcal{L}_{soft} = \frac{\delta(y-\pi) e^{-k\pi R} W \lambda_1 \lambda_1}{R M_5^3} + h.c$$

- Solutions to the Eqn. of motion satisfying boundary conditions yield

$$\det \begin{pmatrix} J_0(x_n) & Y_0(x_n) \\ J_0(x_n e^{k\pi R}) - \frac{W}{4M_5^3} J_1(x_n e^{k\pi R}) & Y_0(x_n e^{k\pi R}) - \frac{W}{4M_5^3} Y_1(x_n e^{k\pi R}) \end{pmatrix}$$

where $x_n=m_n/k$. In the case $\eta \equiv W/4M_5^3 \ll 1$ and $x_n e^{kR} \ll 1$ we find

$$m_{\lambda,0} \approx -\frac{\eta}{\pi R} e^{-k\pi R}$$

The Model: zero-mode Lagrangian for r.h. sneutrinos

- Auxiliary fields for N^c and N

$$F^{\dagger}_{N^c} = -\frac{e^{-R\sigma}}{R}\left(\left[\partial_5 - \left(\frac{3}{2} - c_{\nu_R}\right) R\sigma'\right]\tilde{N} - M_1 R\tilde{\nu}_R\delta(y) + -M_2 R\tilde{\nu}_R\delta(y-\pi) - \lambda\tilde{\nu} H R\delta(y)\right) - \frac{1}{2R}\tilde{\nu}^*_R F_T(1-2R\sigma)$$

$$F^{\dagger}_{N} = \frac{e^{-R\sigma}}{R}\left[\partial_5 - \left(\frac{3}{2} + c_{\nu_R}\right) R\sigma'\right]\tilde{\nu}_R - \frac{1}{2R}\tilde{N}^* F_T(1-2R\sigma)$$

- Now replacing, integrating over superspace, the zero-mode Lagrangian for $\tilde{\nu}_R$ and $\tilde{N}$ is

$$\begin{aligned}\mathcal{L}_{5D,0} = \sqrt{-g}(&-|\partial_M\tilde{N}|^2 - |\partial_M\tilde{\nu}_R|^2 - M_1^2\tilde{\nu}_R\tilde{\nu}^*_R\delta(y)^2 + \\ &-\lambda\lambda^*\tilde{\nu}\tilde{\nu}^* H H^*\delta(y)^2 - M_1\tilde{\nu}^*_R\lambda\tilde{\nu}H\delta(y)^2 + h.c. + \\ &+\frac{e^{2R\sigma}}{2R}(2R\sigma-2)F_T F_T\sigma(\tilde{\nu}_R\tilde{\nu}^*_R + \tilde{N}\tilde{N}^*) - M_2^2\tilde{\nu}_R\tilde{\nu}^*_R\delta(y-\pi)^2 + \\ &+\frac{1}{2}M_2\sigma e^{\sigma R}F_T\tilde{\nu}_R\tilde{\nu}_R\delta(y-\pi) + h.c.)\end{aligned}$$

Nor A-term, neither B-term can be formed in the UV brane.

The Model: Effective Yukawa coupling

- $\tilde{\nu}_R$ zero-mode satisfies $[\partial_5 - (3/2 + c_{\nu_R})T\sigma']g^{(0)} = 0$ whose solution is $g^{(0)} = e^{(3/2+c_{\nu_R})T\sigma}/N_0$

with

$$\frac{1}{N_0^2} = \frac{2(1/2 + c_{\nu_R})k}{e^{2(1/2+c_{\nu_R})k\pi R} - 1}$$

- For modes stuck on UV brane $N_{0,s} = 1/\sqrt{R}$.
- Fermionic terms in Yukawa interaction $\mathcal{L}_{\text{Yukawa}} \simeq \lambda R(\nu\nu_R H + \nu_R h\tilde{\nu} + h\nu\tilde{\nu}_R) + h.c.$
- Canonically normalizing

$$\mathcal{L}_{\text{Yukawa}} \simeq \frac{\lambda\sqrt{k(1+2c_{\nu_R})}}{\sqrt{e^{2(1/2+c_{\nu_R})k\pi R} - 1}}(\nu\nu_R H + \nu_R h\tilde{\nu} + h\nu\tilde{\nu}_R) + h.c.$$

So we identify 4D yukawa coupling constant

$$\lambda_4 = \frac{\lambda\sqrt{k(1+2c_{\nu_R})}}{\sqrt{e^{2(1/2+c_{\nu_R})k\pi R} - 1}}$$

The Model: B-term

- Do the same for the fermionic part of the Majorana mass terms

$$\mathcal{L}_M \simeq \frac{1}{2} M_2 e^{2c_{\nu_R} k\pi R} \nu_R \nu_R R \delta(y-\pi) + \frac{1}{2} M_1 R \nu_R \nu_R \delta(y).$$

- Canonically normalizing

$$M_{4,IR} = 2\frac{(1/2 + c_{\nu_R}) kR e^{2c_{\nu_R} k\pi R}}{e^{2(1/2+c_{\nu_R})k\pi R} - 1} M_2,$$
$$M_{4,UV} = 2\frac{(1/2 + c_{\nu_R}) kR}{e^{2(1/2+c_{\nu_R})k\pi R} - 1} M_1.$$

- Replacing the zero mode in the Lagrangian, integrating on y and canonically normalizing we obtain

$$B_4 = k\pi F_T \frac{M_{4,IR}}{M_{4,UV}}.$$

The Model: induced A-term

- Massive gauginos → A_4 term with a CP violating phase. 1 loop triangle diagram.

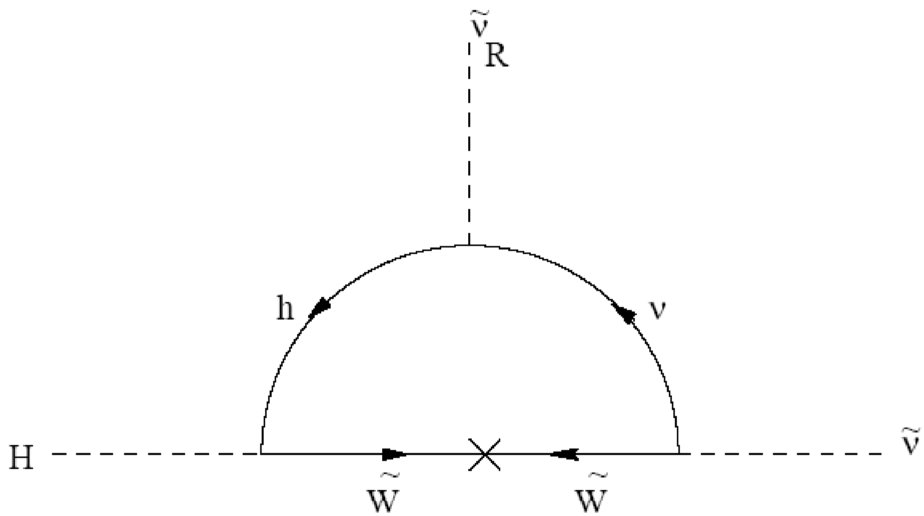


Figure 1: Feynman diagram for A_4 generation.

•Leads to

$$A_4\lambda_4 = 4\lambda_4 g_4^2 C_2(N) \int \frac{d^4p}{(2\pi)^4}\frac{1}{p^2}\frac{m_{\tilde{W}}}{p^2+m_{\tilde{W}}^2}$$

Integrating and taking most important Wino contribution we get

$$A_4 \simeq 3\alpha_2 \frac{m_{\tilde{W}} \log\left(ke^{-k\pi R}/m_{\tilde{W}}\right)}{2\pi}.$$

Numerical Results

- To calculate the gravitino mass we used $m_{3/2} \approx \frac{\eta k^2 e^{-2k\pi R}}{\sqrt{3} M_P}$.

Cosmological bounds, Lyman-α forest and WMAP $\rightarrow$ $m_{3/2} \approx 20$ eV.

Input 1	Output 1
$c_{\nu_R} = -0.12$	$\lambda_4 = 1.98 \times 10^{-5}$
$kR = 8$	$ke^{-k\pi R} = 1.216 \times 10^7\,\text{GeV}$
$M_1 = 3 \times 10^{14}\,\text{GeV}$	$M_{4,UV} = 9.23 \times 10^6\,\text{GeV}$
$M_2 = 1 \times 10^{10}\,\text{GeV}$	$M_{4,IR} = 0.73\,\text{GeV}$
$k = 1 \times 10^{18}\,\text{GeV}$	$m_{\lambda_1} = 484\,\text{GeV}$
$\lambda = 0.32/\sqrt{k}$	$A_4 = 70.11\,\text{GeV}$
$\eta = 10^{-3}$	$m_\nu = 1.29 \times 10^{-3}\,\text{eV}$
	$B_4 = 0.0019\,\text{GeV}$
	$\Gamma_4 = 0.00029\,\text{GeV}$
	$\epsilon_L = 1.12 \times 10^{-6}$
	$m_{3/2} \approx 20\,\text{eV}$
	$M_4/\lambda_4^2 = 2.44 \times 10^{16}\,\text{GeV}$
	$N_{\text{KK}} = 0.55$
	$n_B/s \simeq 7.2 \times 10^{-11}$

Table 2: Results

Input 2	Output 2
$c_{\nu_R} = -0.105$	$\lambda_4 = 1.54 \times 10^{-5}$
$kR = 8.42$	$ke^{-k\pi R} = 9.75 \times 10^6\,\text{GeV}$
$M_1 = 1.1 \times 10^{15}\,\text{GeV}$	$M_{4,UV} = 6.148 \times 10^6\,\text{GeV}$
$M_2 = 10^{10}\,\text{GeV}$	$M_{4,IR} = 0.21\,\text{GeV}$
$k = 3 \times 10^{18}\,\text{GeV}$	$m_{\lambda_1} = 479\,\text{GeV}$
$\lambda = 0.6/\sqrt{k}$	$A_4 = 66\,\text{GeV}$
$\eta = 1.3 \times 10^{-3}$	$m_\nu = 1.176 \times 10^{-3}\,\text{eV}$
	$B_4 = 0.00089\,\text{GeV}$
	$\Gamma_4 = 0.00011\,\text{GeV}$
	$\epsilon_L = 1.42 \times 10^{-6}$
	$m_{3/2} \approx 17\,\text{eV}$
	$M_4/\lambda_4^2 = 3.0825 \times 10^{16}\,\text{GeV}$
	$N_{\text{KK}} = 0.40$
	$n_B/s \simeq 9.61 \times 10^{-11}$

Table 3: Results

Conclusions

- We are able to predict a lepton asymmetry which agrees with experimental bounds in a fairly constrained simple model in warped extra dimensions. The Majorana mass $M_4 \sim T \sim O(10^7$ GeV), much smaller than in regular leptogenesis scenarios, gives us freedom not to rely on the resonance condition.

- The values of the 5D parameters are natural with the slight exception of M_2. We satisfy the out of equilibrium condition for natural values of M_1 and at the same time obtain a neutrino mass in accordance with experimental constraints which also maximizes the efficiency in the lepton asymmetry generation.

- The gravitino is the LSP and despite not being a good dark matter candidate, it satisfies the bounds from WMAP and Lyman-α forest.

Extra Slides

The Model: Interpretation of δ^2-terms

- Majorana mass term localized on UV brane

$$\frac{1}{2}M_1\nu_R(x,0)\nu_R(x,0) = M_1\sum_{n,m} f_R^{(n)}(0)f_R^{(n)}(0)\nu_R^{(n)}(x)\nu_R^{(m)}(x)$$

Interpreted in matrix form in the basis $(\nu_R^{(0)}(x), \nu_R^{(1)}(x), \nu_R^{(2)}(x), \ldots)$

$$S = \begin{pmatrix} f_R^{(1)}(0)f_R^{(1)}(0) & f_R^{(1)}(0)f_R^{(2)}(0) & f_R^{(1)}(0)f_R^{(3)}(0) & \ldots \\ f_R^{(2)}(0)f_R^{(1)}(0) & f_R^{(2)}(0)f_R^{(2)}(0) & f_R^{(2)}(0)f_R^{(3)}(0) & \ldots \\ f_R^{(3)}(0)f_R^{(1)}(0) & f_R^{(3)}(0)f_R^{(2)}(0) & f_R^{(3)}(0)f_R^{(3)}(0) & \ldots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- $g_R^{(n)}$ complete orthonormal system $\rightarrow$ $\delta(0) = \sum_k g_R^{(k)}(0)g_R^{(k)}(0)$ $\rightarrow$

$$M_1^2\sum_{n,m} g_R^{(n)}(0)g_R^{(m)}(0)\delta(0)\tilde{\nu}_R^{(n)}(x)\tilde{\nu}_R^{(m)*}(x) =$$

$$= M_1^2\sum_{n,m,k} g_R^{(n)}(0)g_R^{(k)}(0)g_R^{(k)}(0)g_R^{(m)}(0)\tilde{\nu}_R^{(n)}(x)\tilde{\nu}_R^{(m)*}(x)$$

Which can be interpreted in the basis $(\tilde{\nu}_R^{(0)}(x), \tilde{\nu}_R^{(1)}(x), \tilde{\nu}_R^{(2)}(x), \ldots)$ as $M_1^2 S' \times S'$.

The Model: CP violating phase

- Important terms for CP violation in the 4D Lagrangian

$$-\Delta\mathcal{L}_{4D} = \ldots + \lambda_4(\nu\nu_R H + \nu_R h\tilde{\nu} + h\nu\tilde{\nu}_R) + g_{4,2}\sqrt{2}(\tilde{\nu}^*\tilde{W}\nu + H^*\tilde{W}h) + \\ + \frac{1}{2}\tilde{B}_4\tilde{\nu}_R\tilde{\nu}_R + \frac{1}{2}(M_{4,IR} + M_{4,UV})\nu_R\nu_R + \frac{1}{2}m_{\tilde{W}}\tilde{W}\tilde{W} + h.c.$$

Where $\tilde{B}_4 = B_4 M_4 = k\pi F_T M_{4,IR}$ and $m_{\tilde{W}} \propto F_T$.

- Conformal sector invariant under $U(1)_R$ and $U(1)_{PQ}$ symmetries.

Field	R-Charge	PQ-Charge
H	0	-2
h	-1	-2
$\tilde{\nu}$	1	0
ν	0	0
$\tilde{\nu}_R$	1	2
ν_R	0	2
$\tilde{W}$	1	0

Table 1: R-Charges

- No possible way to eliminate CP-violating phase $\phi = \arg\left(M_4\, m_{\tilde{W}}\tilde{B}_4^*\right) \rightarrow \phi = \arg(M_4 M_{4,IR}^*)$.

Constraints

- Baryon asymmetry (WMAP and BBN):

$$6.5 \times 10^{-11} \lesssim n_B/s \lesssim 9.5 \times 10^{-11}.$$

- We can write the baryon to entropy ratio as

$$\frac{n_B}{s} = -\left(\frac{24+4n_H}{66+13n_H}\right) Y^{\rm eq}_{\tilde{\nu}_R}\,\xi \left[\frac{4\Gamma|B_4|}{4|B_4|^2+\Gamma^2}\right] \frac{|A_4|}{M_4}\sin(\phi)$$

Where $Y^{\rm eq}_{\tilde{\nu}_R} = 45\zeta(3)/(\pi^4 g_*)$ and ξ is an efficiency parameter.

- Entropy density s ~ g_* where g_* is the thermalized number of degrees of freedom.

$\therefore$KK modes, if thermalized, will contribute to $g_* \rightarrow$ dilution of asymmetry.

$\therefore \quad ke^{-k\pi R} \gtrsim M_4$. Values of kR ~ 10 stabilize R=<T(x)>.

- Left handed neutrino mass

$$m_\nu \sim \frac{v^2|\lambda_4|^2}{M_4}$$

Where v = <H(x)> = 174 GeV, tanβ » 1.

Constraints and out of equilibrium decay

- Decay rate Γ_4 slower than expansion rate $H = 1.66 g_*^{1/2} T^2/M_P$ $\rightarrow$

$$M_4/|\lambda_4|^2 \gtrsim \frac{M_P}{4\pi \times 1.66 \times (1.2)^2 \sqrt{g_*}} \mathrm{GeV}$$

when T ~ M_4 (M_P=4.2x10^{18}GeV, $g_* = N_{KK} g_{*1} + g_{*2}$).

- Now, from the expressions of M_4 and λ_4 we see $M_4/\lambda_4^2 \simeq kRM_1$

$\therefore$ M_1~O(10^{15}GeV)

- At the same time $M_4/\lambda_4^2 = \dfrac{v^2}{m_\nu}$ $\rightarrow$ $m_\nu \sim 10^{-3}$ eV

- Mass of the NLSP $\tilde{\tau}_1$ in agreement with experimental constraints $m_{\tilde{\tau}_1} \gtrsim 100$ GeV

$$\frac{dm^2_{\tilde{\tau}_1}}{dt} = \ldots + \frac{1}{8\pi^2}\left(-\frac{12}{5} g^2_{4,1} m^2_{\tilde{B}}\right) + \ldots$$

- $\therefore$ $m_{\lambda_1} \gtrsim 500$ GeV

Out of equilibrium decay

- There are 49 chiral superfields on the UV brane ⇒ 98x(1+7/8)≈184. The gauge superfields zero-modes contribute 12x2x15/8=45 d.o.f and the r.h neutrinos zero-modes 3x2x15/8≈11. ∴ g_{*2}=240.

- KK towers part of N=2 SUSY → each tower adds 60x15/8 ≈112. ∴ g_{*1}=112.
- To estimate N_{KK} we use s=(ρ+p)/T, where

$$\rho = \frac{g}{2\pi^2}\int_m^\infty \frac{(E^2-m^2)^{1/2}}{e^{(E-\mu)/T}-1}E^2dE$$
$$p = \frac{g}{6\pi^2}\int_m^\infty \frac{(E^2-m^2)^{3/2}}{e^{(E-\mu)/T}-1}dE$$

Taking T »μ, we define for each KK level $N_{\rm KK}|_n = \frac{s|_{n,non-rel}}{s|_{n,rel}}$ where $s|_{n,rel} = g(2\pi^2/45)T^3$, and $N_{\rm KK} = \sum_{n=1}^{+\infty} N_{\rm KK}|_n$

- First excited gauge KK levels $m_{n,V} \simeq (n-\frac{1}{4})\pi k e^{-k\pi R}$.

More Numerical Results

Input 3			Output 3		
c_{ν_R}	$=$	-0.105	λ_4	$=$	2.138×10^{-5}
kR	$=$	7.6	$ke^{-k\pi R}$	$=$	8.546×10^{6} GeV
M_1	$=$	3.3×10^{14} GeV	$M_{4,UV}$	$=$	1.27×10^{7} GeV
M_2	$=$	3×10^{9} GeV	$M_{4,IR}$	$=$	0.77 GeV
k	$=$	2×10^{17} GeV	m_{λ_1}	$=$	537 GeV
λ	$=$	$0.3/\sqrt{k}$	A_4	$=$	74.4 GeV
η	$=$	1.5×10^{-3}	m_ν	$=$	1.086×10^{-3} eV
			B_4	$=$	0.0015 GeV
			Γ_4	$=$	0.00046 GeV
			ϵ_L	$=$	1.71×10^{-6}
			$m_{3/2}$	$\approx$	15 eV
			M_4/λ_4^2	$=$	2.786×10^{16} GeV
			N_{KK}	$=$	1.38
			n_B/s	$\simeq$	8.35×10^{-11}

Table 4: Results