Constraints on the size of the extra dimension from KK gravitino decay

hep-ph/0702183

David Gherson
Institut de Physique Nucléaire de Lyon
Lyon University

About Gravitino

- Local Susy : Supergravity.
- Gravitino (spin $3/2$) susy partner of graviton.
- Gravitino can be a problem for cosmology:
  - Can disturb BBN because of its decay during or after.
    BBN starts nearly at $t = 0.76$ sec (so for $T = 1$ MeV). Gravitino lifetime runs from one second to 10^8 secondes for masses between 20 TeV to 200 GeV. This implies a bound on gravitino abundance: so on reheating temperature because gravitino abundance nearly proportionnal to reheating temperature. Between 10^5 GeV and 10^8 GeV : See Kohri and al. (2006).
  - Baryogenesis through leptogenesis because this theory needs large reheating temperature $> 10^9$ GeV.

Framework

- 5D supergravity compactified on S^1/Z_2 orbifold.
- Only gravitational fields can propagate in the bulk. Graviton and Gravitino have Kaluza-Klein excitations.
- Two branes (orbifold fixed points): hidden sector on one brane, MSSM on the other.
- Radion stabilized : Standard Friedman equation.
- R-parity is conserved. The LSP is stable. LSP chosen: the lightest Neutralino : candidate for Dark Matter.
- In the present work : gravitinos are produced during the reheating period after inflation by scattering processes.

- First KK mode (the 0 mode) of gravitino: heavy enough to decay before BBN starts. Its mass calculated to 26.4 TeV. Possible in Anomaly mediation or in a mix between Anomaly mediation and Scherk-Scharwz mechanism.
- KK gravitinos decay into SM particles and Susy partners (see the interaction Lagrangian). Consequence: Non thermal production of LSPs.
- Dark matter density constrained to be (see Seljak and al. (2006))

$$0.106 \ < \Omega \, h^2 \ < \ 0.123, \text{with a central value around } 0.114 \tag{1}$$

- Dark matter density made of thermal production and non thermal production from KK gravitino decay :

$$0.106 \leq \Omega_{th} \, h^2 + \Delta\Omega \, h^2 \leq 0.123 \tag{2}$$

- Only the gravitino modes decaying after thermal freeze-out of neutralino contribute to the non-thermal production of neutralinos.

Interaction KK gravitino-MSSM

We find the interactions of each KK mode with matter and gauge fields after integrating on the fifth dimension the interaction part of the 5D action. (for details: see hep-ph/0702183)

$$\mathcal{L}^{4d}_{interKK} = \sum_{n=0}^{\infty}(-\frac{1}{\sqrt{2}M} e g_{ij^*} \tilde{\mathcal{D}}_\nu \phi^{*j} \chi^i \sigma^\mu \bar{\sigma}^\nu \psi_{n,\mu} - \frac{1}{\sqrt{2}M} e g_{ij^*} \tilde{\mathcal{D}}_\nu \phi^i \overline{\chi}^j \bar{\sigma}^\mu \sigma^\nu \overline{\psi}_{n,\mu}$$
$$- \frac{i}{2M} e \left(\psi_{n,\mu} \sigma^{\nu\lambda} \sigma^\mu \overline{\lambda}_{(a)} + \overline{\psi}_{n,\mu} \bar{\sigma}^{\nu\lambda} \bar{\sigma}^\mu \lambda_{(a)} \right) F^{(a)}_{\nu\lambda}) \quad (3)$$

Each KK mode has the same interaction with matter and gauge fields.

Masses and lifetime

Lifetime :

$$\tau_k = 1.4\ 10^7 \times \left(\frac{M_k}{100\mathrm{GeV}}\right)^{-3}\ \mathrm{Sec} \tag{4}$$

Masses : see Bagger and al. (2002) and Curtis and al. (2004)

$$M_k = M_0 + \frac{k}{R} \tag{5}$$

Production processes

$$A : g^a + g^b \longrightarrow \tilde{g}^c + G$$

$$B : g^a + \tilde{g}^b \longrightarrow g^c + G$$

$$C : g^a + \tilde{q}_i \longrightarrow q_j + G$$

$$D : g^a + q_i \longrightarrow \tilde{q}_j + G$$

$$E : q_i + \tilde{q}_j \longrightarrow g^a + G$$

$$F : \tilde{g}^a + \tilde{g}^b \longrightarrow \tilde{g}^c + G$$

$$G : \tilde{g}^a + q_i \longrightarrow q_j + G$$

$$H : \tilde{g}^a + \tilde{q}_i \longrightarrow \tilde{g}^c + G$$

$$I : q_i + q_j \longrightarrow \tilde{g}^a + G$$

$$J : \tilde{q}_i + \tilde{q}_j \longrightarrow \tilde{g}^a + G$$

Abundance for the 0 mode

$$\begin{aligned} Y_{3/2} &\simeq 1.9 \times 10^{-12} \\ &\times \left(\frac{T_{\rm R}}{10^{10}\ {\rm GeV}}\right)\left[1 + 0.045 \ln\left(\frac{T_{\rm R}}{10^{10}\ {\rm GeV}}\right)\right]\left[1 - 0.028 \ln\left(\frac{T_{\rm R}}{10^{10}\ {\rm GeV}}\right)\right], \end{aligned} \tag{6}$$

see Kohri and al.(2006)

Where $Y_{3/2} = \frac{n_{3/2}}{s}$ and $n_{3/2}$ is the number density, s is the entropy density.
$Y = \frac{n}{s}$ is the density per comoving volume.
$Y_{3/2}$ is found by solving the Boltzmann equation: $\frac{dn_{3/2}}{dt} + 3Hn_{3/2} = C_{3/2}$

Abundance for modes $k > 0$

We have to take into account in our calculation the different masses of gravitino modes. We find as a good approximation this rule for the abundance of the different modes:

$$
\begin{aligned}
Y^k_{3/2} = Y^0_{3/2} \ , &\quad \text{for } M^k \leq T_{\rm R} \quad \text{and} \\
Y^k_{3/2} = 0 \ , &\quad \text{for } M^k > T_{\rm R}
\end{aligned}
\tag{7}
$$

Numerical cases

$$\Omega_{th}\ h^2 = 3.614222\ 10^6\ \frac{m_{lsp}}{1\ GeV}\ x_f^2\ e^{-x_f} \tag{8}$$

We choose :

Cases	x_f	T_f(GeV)	$\Omega_{th}\ h^2$	$(\Delta\Omega_{th}\ h^2)_{min}$	$(\Delta\Omega_{th}\ h^2)_{max}$	M_n(GeV)
Case 1	28.7787	4.1697	0.114	-	0.009	9.844×10^6
Case 2	29.6006	4.0540	0.053	0.053	0.070	9.661×10^6
Case 3	30.4224	3.9445	0.025	0.081	0.098	9.486×10^6

Table 1: *The three numerical cases for* $m_{lsp} = 120$ *GeV*

Equations of constraints

Abundance of gravitinos is related to T_R and number of KK modes is related to the size of the extra dimension. To respect the requirement on the dark matter density we find:

For $M^n \leq T_R$:

$$R^{-1} = \frac{M^n - M^0}{E\left[\Delta\Omega\, h^2 \frac{\rho_c}{m_{lsp}\ s_0\ h^2}\ \frac{1}{1.9\times10^{-12}\times\frac{T_{\rm R}}{10^{10}}\left[1+0.045\ln\left(\frac{T_{\rm R}}{10^{10}}\right)\right]\left[1-0.028\ln\left(\frac{T_{\rm R}}{10^{10}}\right)\right]}\right] - 1} \quad (9)$$

For $M^n > T_R$, M^n is replaced by T_R in the above equation.

Maximum reheating temperature

If there is only one gravitino mode, there is a maximum reheating temperature:

case 1	case 2	case 3
$1.455\ 10^{9}$ GeV	$1.088\ 10^{10}$ GeV	$1.521\ 10^{10}$ GeV

Table 2: *Maximum reheating temperature*

KK gravitons

Masses:

$$m_k = \frac{k}{R} \tag{10}$$

Abundance:

$$Y_m = \frac{1485}{256\pi^5 M \; g^{\star 1/2} g^\star_S} \; m \int\limits_{m/T_R}^{\infty} x^3 K_1(x) dx \tag{11}$$

Where $g^\star$ and $g^\star_S$ are taken constant equal to 10 since most of the lifetime of the gravitons that we consider is after $T = 1$ MeV.

Lifetime:

$$\tau = 3.310 \times \frac{\pi \; M^2}{m^3} \; \mathrm{GeV}^{-1} \tag{12}$$

For details see hep-ph/0702183.

We checked that for $R^{-1} \geq 1$ TeV, BBN was not disturbed by decay of KK gravitons using the curves given by Jedamzik (2006).

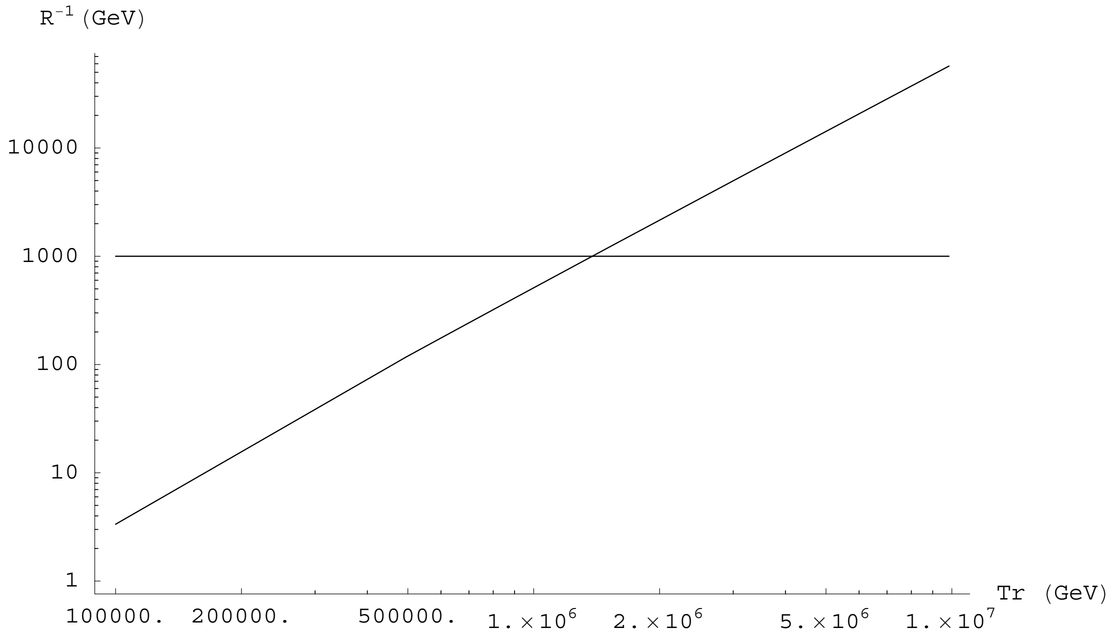

Figure 1: Case 1. T_R less than $9.84\ 10^6$ GeV. The excluded zone is below the diagonal curve and below the straight line $R^{-1} = 1$ TeV if the KK gravitons constraint is taken into account.

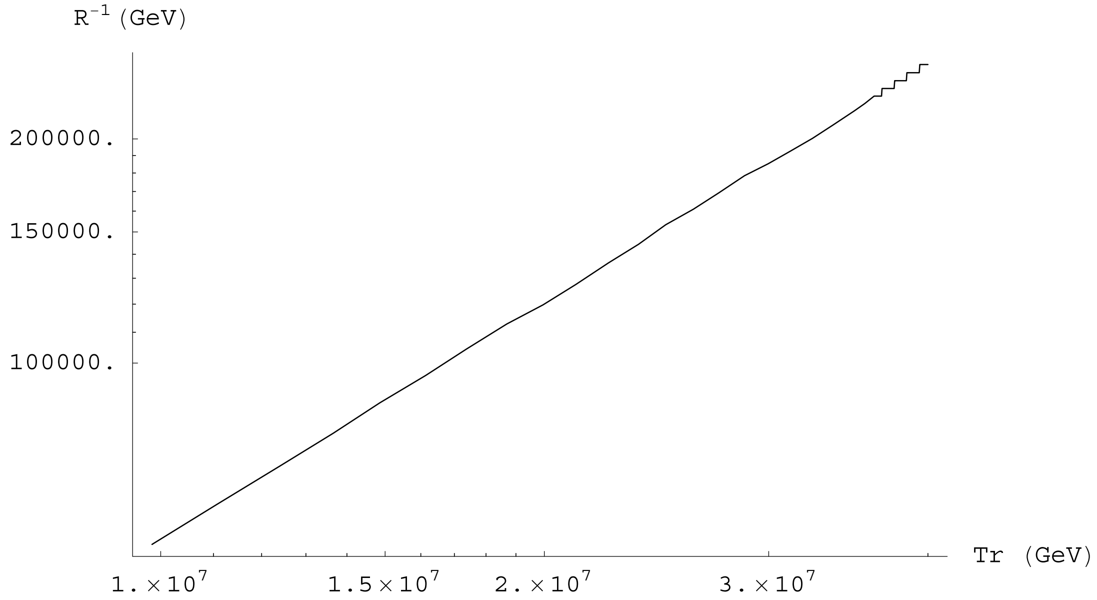

Figure 2: Case 1. $9.84\ 10^6\ GeV \leq T_R \leq 4\ 10^7\ GeV$. The excluded zone is below the curve.

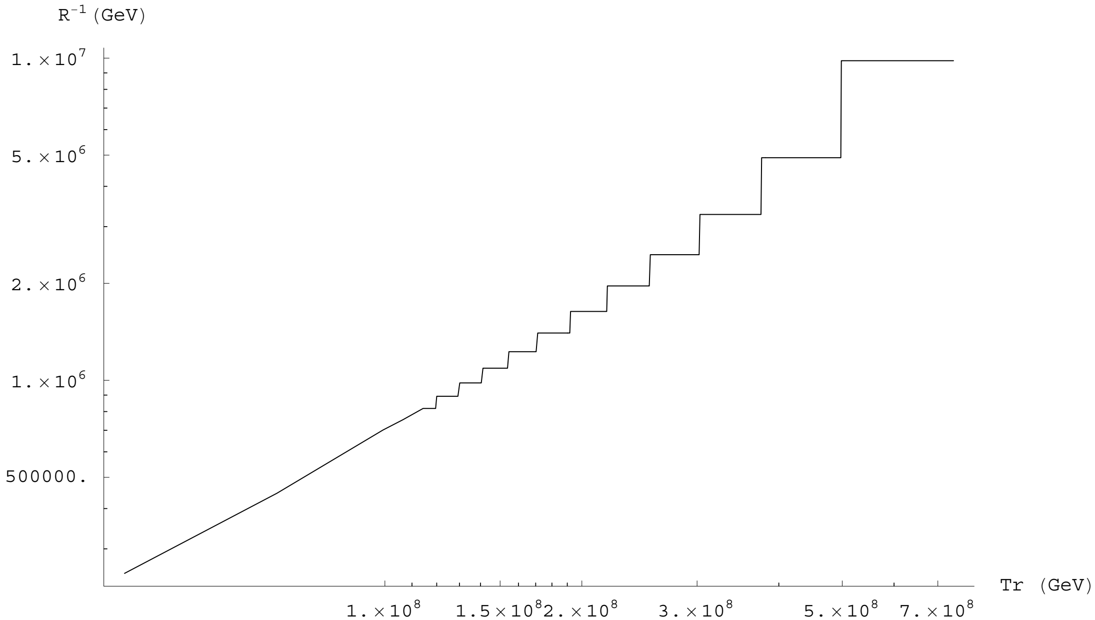

Figure 3: Case 1. $4\ 10^7\ GeV \leq T_R \leq 7.396\ 10^8\ GeV$. The excluded zone is below the curve.

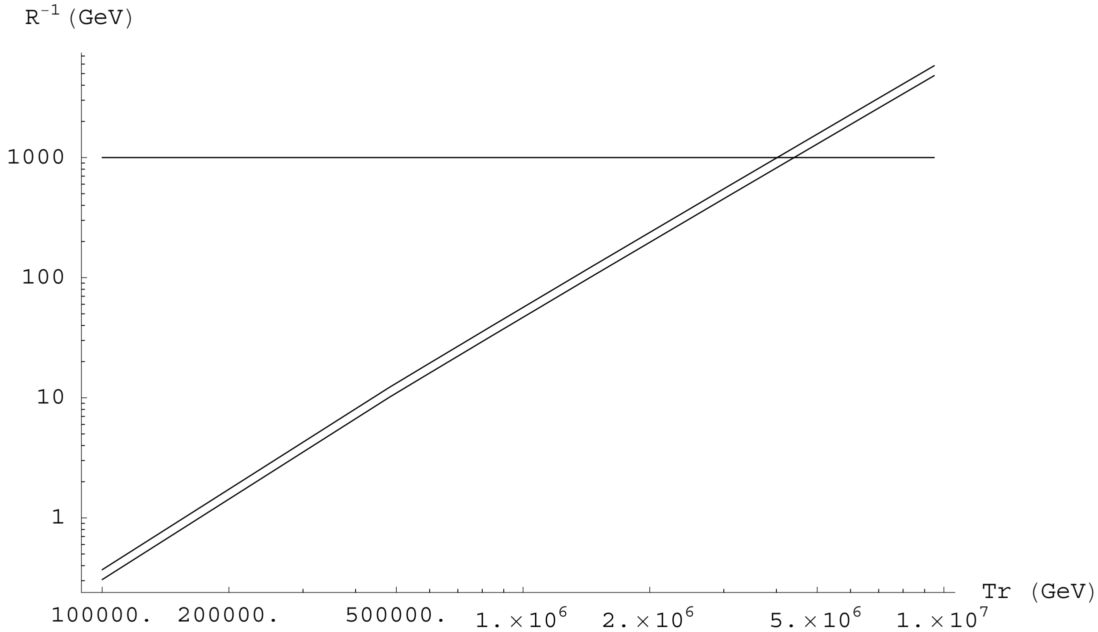

Figure 4: T_R less than $9.48\ 10^6$ GeV. Only the band between the two diagonal curves is allowed. The zone below the straight line $R^{-1} = 1$ TeV is excluded if KK gravitons constraint is taken into account. In that case a minimum value for T_R appears equal to $4.02\ 10^6$ GeV.

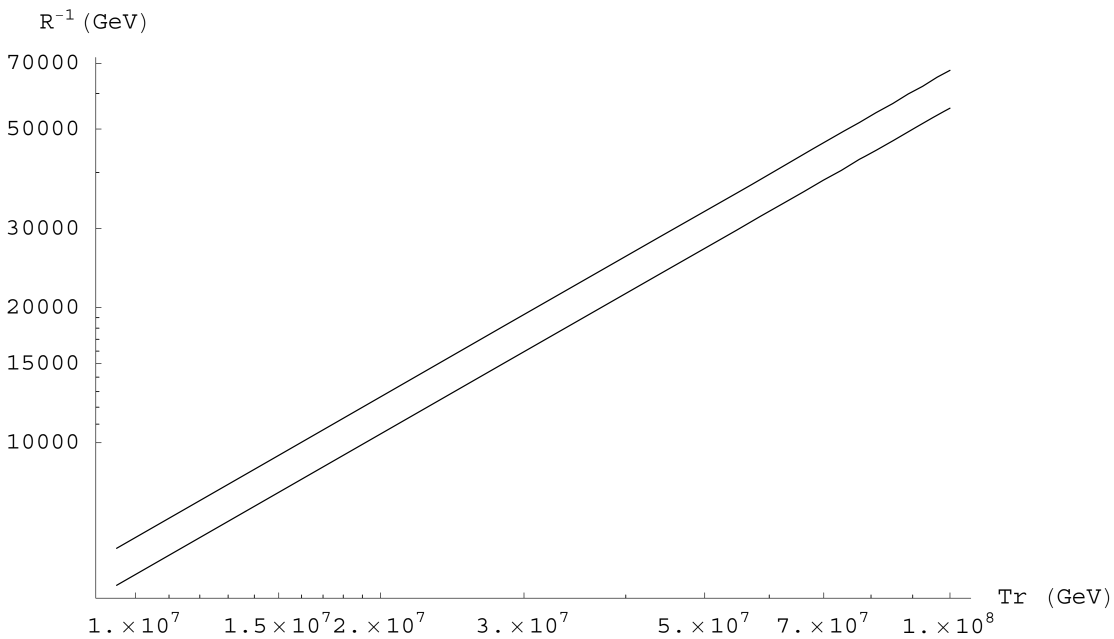

Figure 5: Case 3. $9.48\ 10^6\ GeV \leq T_R \leq 10^8\ GeV$. Only the band between the two curves is allowed.

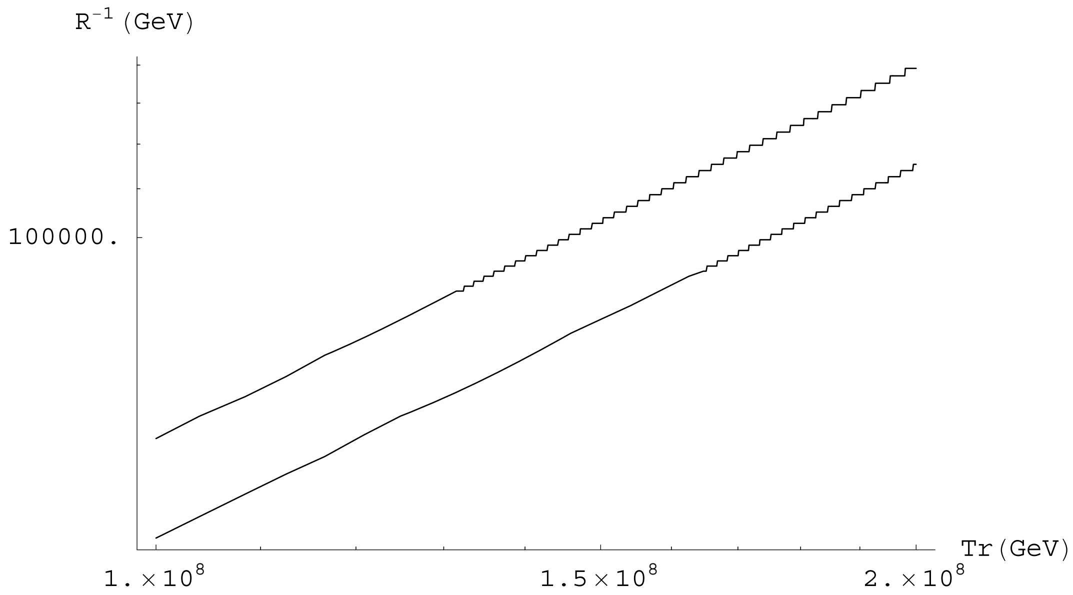

Figure 6: $10^8\ GeV \leq T_R \leq 2\ 10^8\ GeV$. Only the band between the two curves is allowed.

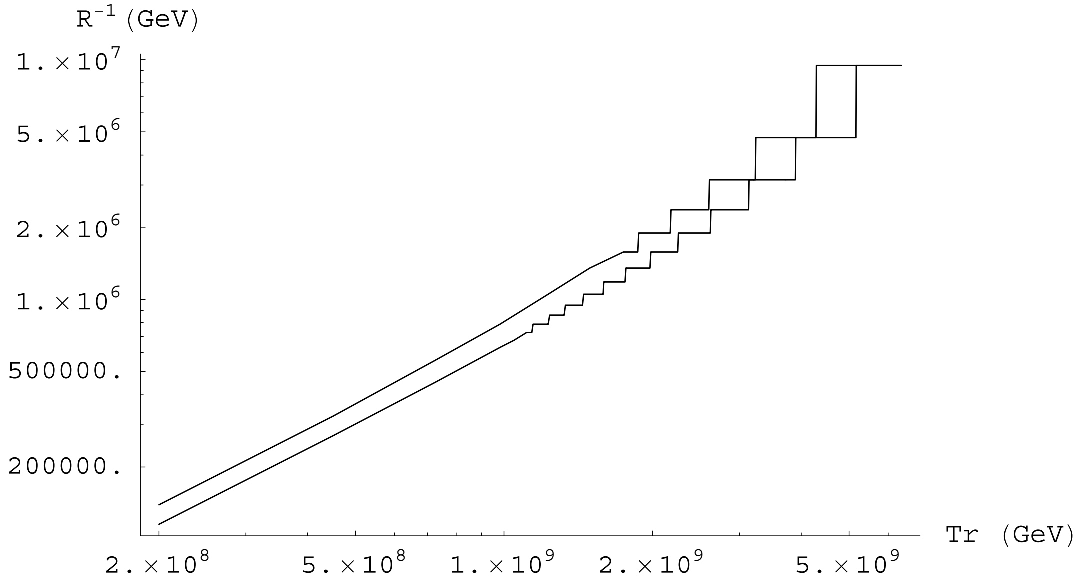

Figure 7: Case 3. $2\ 10^8\ GeV \leq T_R \leq 6.385\ 10^9\ GeV$. Only the band between the two curves is allowed.

Conclusion

- Cosmological models with high reheating temperature i.e. 10^5 GeV to 10^{10} GeV in the framework of a 5D supergravity compactified on S^1/Z_2 where matter and gauge fields live on tensionless branes at the orbifold fixed points.
- Framework can be linked to Horava-Witten M-theory where a 5 dimensional stage of the universe appears in which bulk fields are gravitational and where supersymmetry is natural but also to theories of baryogenesis through leptogenesis which imply large reheating temperature.
- Assumption that dark matter is made by the lightest supersymmetric particle which is supposed to be the lightest neutralino.
- Neutralinos density is a sum of a thermal production and a non thermal production from gravitino decay.
- Gravitinos in the model do not disturb BBN because they are heavy enough to decay before BBN starts. Heavy gravitinos are natural in a certain class of Susy breaking models (anomaly mediation and mix between anomaly and Scherk Schwarz mechanism).

We find:

- Curves of constraints between the size R of the extra-dimension and the reheating temperature of the Universe after inflation.
- Results independent from the susy mass spectrum since the gravitino is heavy enough to make negligible the influence of other susy particles.
- Size of the radius R is not only bounded by a maximum value but also by a minimum value in a range of possible values for the thermal production of neutralinos and in a range of values for the reheating temperature.
- KK gravitons may disturb BBN. For R^{-1} above 1 TeV it is not the case. It implies a bound on the reheating temperature which can not be lower than a minimum value in the cases where the radius R is bounded by a minimum value.

A few perspectives:

- To look at RS model : so to include a cosmological constant. Problem (?): Non standard cosmology at high energy.
- To include new elements in the calculation of the thermal production of gravitinos (see Rychkov and Strumia (2007))
- To treat more accurately the problem of KK gravitons with BBN. (Work with Jedamzik)
- Cold + Warm dark matter ? (with Jedamzik and al.)