Non Thermal Production of Neutralino LSP

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based on
G. Arcadi and P. Ullio (to appear)

Non thermal production of LSP

In general, UV completions of MSSM, especially the ones coming from string theory, allow the presence of heavy scalars (moduli fields) in general associated to flat directions which acquire mass from SUSY breaking. Since the have only gravitational interactions are not in equilibrium with the primordial thermal bath. In general it can be shown that moduli tend to dominate the energy density of the Early Universe until their decay. This must happen before BBN, otherwise its succesfull predictions would be destroyed. This implies that the mass of the moduli must be at least O(10-100) TeV.

Implications:
The heavy modulus decay producing superpartners which decay down to LSP.
This scenario favours a Wino LSP

(L. Randall and T. Moroi hep-ph 9906527)

→ Possible solution to the e+/e- Pamela puzzle (contrived because of antiproton data).

→ Usually the NLSP is the lightest chargino. Their typical mass splitting is O(100) MeV
(J.L. Feng , T. Moroi, ,L. Randall, M. Strassler and S. Fu hep-ph 9904250)

→ Characteristic signal at LHC

Plan of the talk

General framework

Theoretical computations

Numerical evaluation of the relic density

A specific framework: G2-MSSM

Bounds on the parameters of the model

Conclusions

General framework

Let's consider a scalar field of mass M. Its evolution can be described by:

$$\ddot{\phi} + (3H + \Gamma_\phi)\,\dot{\phi} + V'(\phi) = 0$$

Because of inflation the potential gain a mass term proportional to H:

↓

The minimum of the potential is displaced by O(Mplanck) respect the T=0 value.

H>M → The field is freezed at the minimum (time dipendent because its value depend on H) of the potential.

H=M → Damped Coherent Oscillations → Production of particles

Oscillations behave as matter

↓

They dominate the energy density of the Universe (provided that enough energy is stored in the field)

The epoch dominated by the decaying oscillation is referred as reheating.

Peculiar features:

$$T \propto f(a) \quad f(a) \simeq a^{-3/8}$$

The decay of the oscillations produces entropy. → Dilution of the number density of the species present in the thermal bath.

Products of the decay → LSP

Products of the decay → Gravitino → Bound from BBN → Gravitino must decay before BBN

The typical decay rate for moduli and gravitino is:

$$\Gamma \propto \frac{m^3}{M_{Planck}^2}$$

In general the bound is avoided requiring m>10 TeV

It is customary to define the reheating temperature as the temperature at which the usual epoch of radiation domination starts after the decay of the modulus .

$$H = \sqrt{\frac{1}{3M_{Planck}^2}\frac{\pi^2}{90}g_{EFF}(T_R)T_R^4} = \Gamma_\phi$$

$$\Gamma_\phi = D_\phi \frac{m_\phi^3}{M_{Planck}^2} \longrightarrow T_R \sim \sqrt{\Gamma_\Phi M_{Planck}} \propto m_\phi^{3/2}$$

Forgetting for simplicity the gravitino, in general, one has to solve a system of coupled Boltzmann equations.

$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi\rho_\phi$$

$$\frac{dn_X}{dt} = -3Hn_X - \langle\sigma v\rangle\left(n_X^2 - n_{X,eq}^2\right) + \frac{b}{m_\phi}\Gamma_\phi\rho_\phi$$

$$\frac{d\rho}{dt} = -3H(\rho + p) + \rho_\phi\Gamma_\phi \longrightarrow d\left((\rho_\phi + \rho)a^3\right) + p\,da^3 = T\,ds$$

$$\frac{ds}{dt} = -3Hs + \frac{\Gamma_\phi\rho_\phi}{T} \longrightarrow$$

Entropy production.

Theoretical predictions

By general inspection of the equations one can distinguish two regimes. If the number density of the LSP produced is above the following critical value:

$$n_\chi^C = \frac{3H}{\langle \sigma v \rangle}(T = T_R)$$

then the annihilation processes become effective and drive the number density towards this critical value. This implies:

$$Y_{LSP} = \frac{n_\chi^C}{s} \qquad s = \frac{2\pi^2}{45} h_{eff}(T_R) T_R^3$$

$$\longrightarrow \qquad \Omega_{LSP} h^2 = \left(\frac{T_{t.f.o.}}{T_R} \right) \Omega_{LSP}^{SC} h^2$$

Otherwise all the LSP's produced survive:

$$n_\chi^{(0)} \sim \overline{N_{LSP}} n_\phi (T_R)$$

G2-MSSM

Heavy moduli m=O(100)m3/2
Light moduli m=O(1) m3/2

String M theory

Sugra type spectrum

$$\mu = z_{eff}\, m_{3/2}$$
$$A \simeq 1.48\, m_{3/2}$$
$$m_0 = m_{3/2}$$
$$tan\beta \simeq 1.5 - 2$$

Non Universal gaugino masses

$$M_a = (f_a \alpha_{GUT} - \varepsilon\eta) m_{3/2}$$
$$\eta = 1 - \alpha_{GUT}\,\delta$$

Wino LSP with mass O(100-500) GeV. The NLSP is the lightest chargino. The second lightest neutralino is a pure Bino. Also the gluino has typically a mass lower than 1 TeV. The other superpartners have masses of the order of the gravitino's one[1].

(1) Our numerical results are based on the assumptions done in Acharya et al. 0801.0478

Framework of the numerical computation

G2-MSSM

(Acharya et al. arXiV:0804.0863)

N+1 moduli →
- 1 heavy modulus of mass 600 m3/2
- 1 meson field of mass 1.96 m3/2
- N-1 light modulus of mass 1.96 m3/2

$$\Gamma_\Phi = D_\Phi \frac{m_\Phi^3}{M_{Planck}^2}$$

$$D_{X_N} = 2 \qquad D_{Meson} = 710 \qquad 0.1 \leq D_{X_i} \leq 14 \qquad D_{3/2} = \frac{1}{2\pi}$$

The constants in the decay rates are such that the lifetime of the three kinds of moduli differ by orders of magnitudes. We expect in principle three reheating phases. For a gravitino of mass 50 TeV we have:

- First Phase (Heavy Modulus) Reheating temperature O(40) GeV.
- Second Phase (Meson) Reheating temperature O(100) MeV.
- Third Phase (Light Moduli) Reheating temperature O(10) MeV.

Sources of Dark Matter → Gravitino (Neglegible)

Sources of Dark Matter → Light moduli (B. R. O(25) %)

The contribution coming from the gravitino decay is negligible since the number density of the gravitino is diluted by the entropy production of the last reheating phases. This is true if the light moduli have, as above, no phase space to decay into gravitinos. This is a simplicity assumption made to deal more easiliy with the gravitino problem and in general can be relaxed.

The relevant contribution is the one coming from the light moduli. For typical values of the parameters of the model the “reannihilation” regime is realized. Then we have:

$$\langle \sigma v \rangle = \frac{g_2^4}{2\pi} \frac{1}{m_{LSP}^2} \frac{(1 - x_W)^{3/2}}{(2 - x_W)^2}$$

$$\Omega_{LSP}^{X_i} \propto \frac{m_{LSP}^3}{D_{X_i}^{1/2} m_{3/2}^{3/2}}$$

Numerical Computation

We have to solve six coupled Boltzmann equations.
Variables:

$$\Phi_X = \frac{\rho_X a^4}{\Lambda} \qquad X_{LSP,3/2} = n_{LSP,3/2} a^3 \qquad A = a/a_I$$

(Giudice, Kolb , Riotto hep-ph/0005123)

Initial conditions:
The initial conditions are fixed at the time at which the heaviest moduli starts its oscillations. Before this time the Universe is assumed to be radiation dominated. The initial energy of the moduli is:

$$\frac{1}{2} m_{X_N}^2 M_{Planck}^2$$

First step:

Three equations for the heavy modulus, the gravitino and the temperature of the thermal bath:

$$\frac{d\Phi_{X_N}}{dA} = -\frac{\Gamma_{X_N}\Phi_{X_N}A^{1/2}a_I^{3/2}}{DEN}$$

$$\frac{dX_{3/2}}{dA} = \frac{2B_{3/2}\Gamma_{X_N}\Phi_{X_N}\Lambda A^{1/2}a_I^{-3/2}}{DEN} - \frac{\Gamma_{3/2}X_{3/2}A^{1/2}a_I^{-3/2}}{DEN}$$

$$\frac{dT}{dA} = \left(3 + \frac{T}{h_{EFF}}\frac{dh}{dT}\right)^{-1}\left(-3\frac{T}{A} + \frac{\left(\Gamma_{X_N}\Phi_{X_N}\Lambda + \Gamma_{3/2}E_{3/2}X_{3/2}\right)A^{-5/2}a_I^{3/2}}{s\ DEN}\right)$$

$$DEN = \sqrt{\frac{1}{3M_{Planck}^2}\left(E_{3/2}X_{3/2} + \Phi_{X_N}\Lambda + \frac{\pi^2}{30}g_{EFF}T^4\frac{A^3}{a_I^3}\right)} \qquad E_{3/2} = \sqrt{m_{3/2}^2 + 9T^2}$$

Second Step:

At the time at which the other moduli start to oscillate the other variables are added:

$$\frac{d\Phi_{\phi,X_i}}{dA} = -\frac{\Gamma_{\phi,X_i}\Phi_{\phi,X_i}A^{1/2}a_I^{3/2}}{DEN}$$

$$\frac{dX_{LSP}}{dA} = -\frac{\langle\sigma v\rangle a_I^{3/2}A^{-5/2}\left(X_{LSP}^2 - X_{LSP,eq}^2\right)}{DEN} + \frac{N_{X_i}N_{LSP}\Gamma_{X_i}\Lambda\Phi_{X_i}A^{1/2}a_I^{-3/2}}{DEN} + \frac{\Gamma_{3/2}X_{3/2}A^{1/2}a_I^{3/2}}{DEN}$$

Summary of the numerical analisis

- Check of the agreement among the general predictions for non thermal production of DM and the numerical results.

  Considering the gravitino and the LSP mass and the other parameters relevant for the relic density as free parameters:

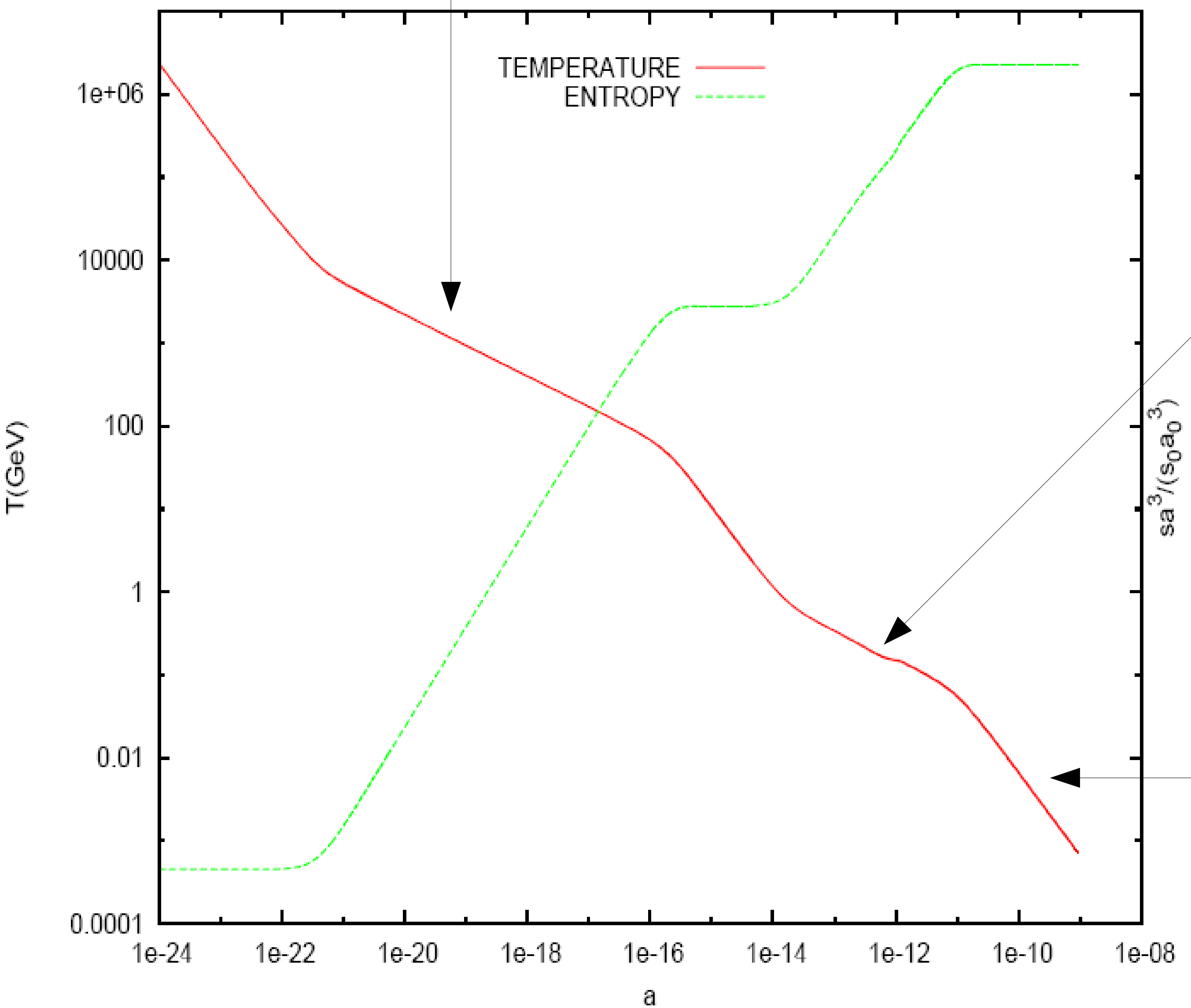
  1) We have chosen a set parameters such that the computed relic density is in agreement with the experimental value and verified that the entropy, the temperature and the DM abundance evolve as theoretically predicted. In particular for the last we cheched if the reannihilation regime was realized.

  2) We have further investigated the reannihilation regime varying the relevant parameters (the modulus decay rate and the branching ratio for the decay channel into dark matter) in order to see the transition to the regime in which the annihilations are no more effective.

- We took for granted the assumption done in the paper cited before and we performed a scan of the parameters relevant for the relic density in order to determine the parameter space allowed by the bounds on the DM relic density.

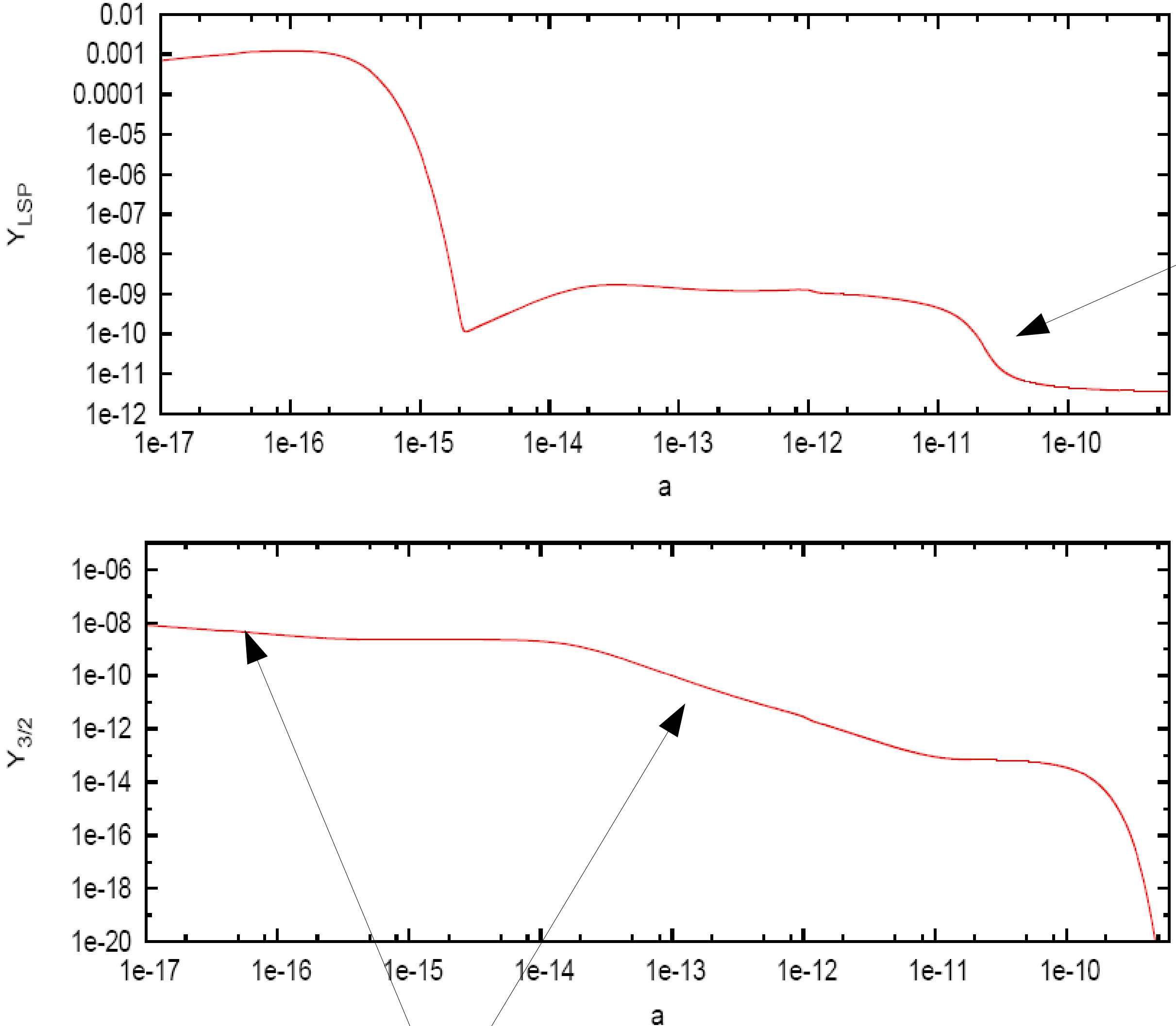
- We relaxed the assumption of no decay of the light moduli into gravitinos and studied how the relic density changes in this case.

Reheating of heavy modulus



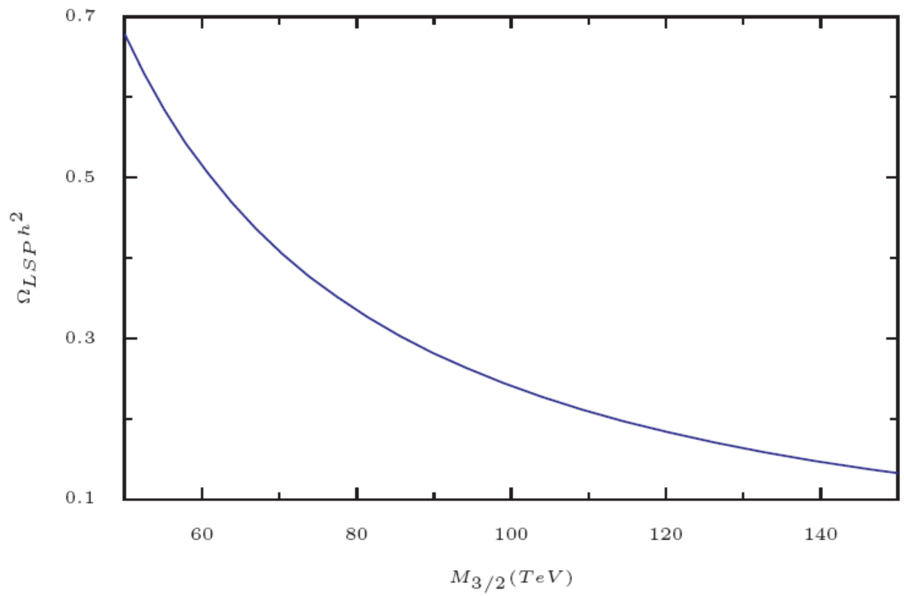
Reheating of the meson and the light moduli

Standard cosmology

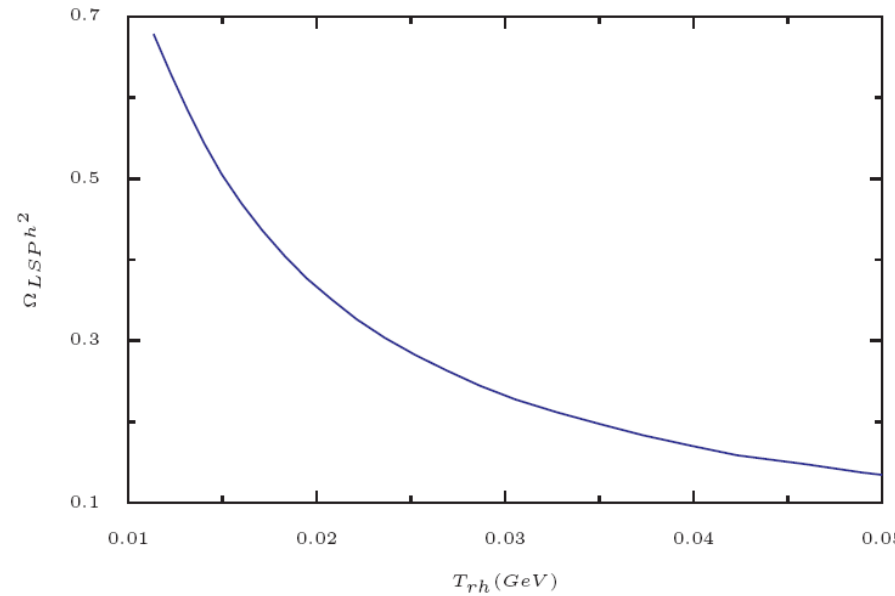


Non thermal freeze-out

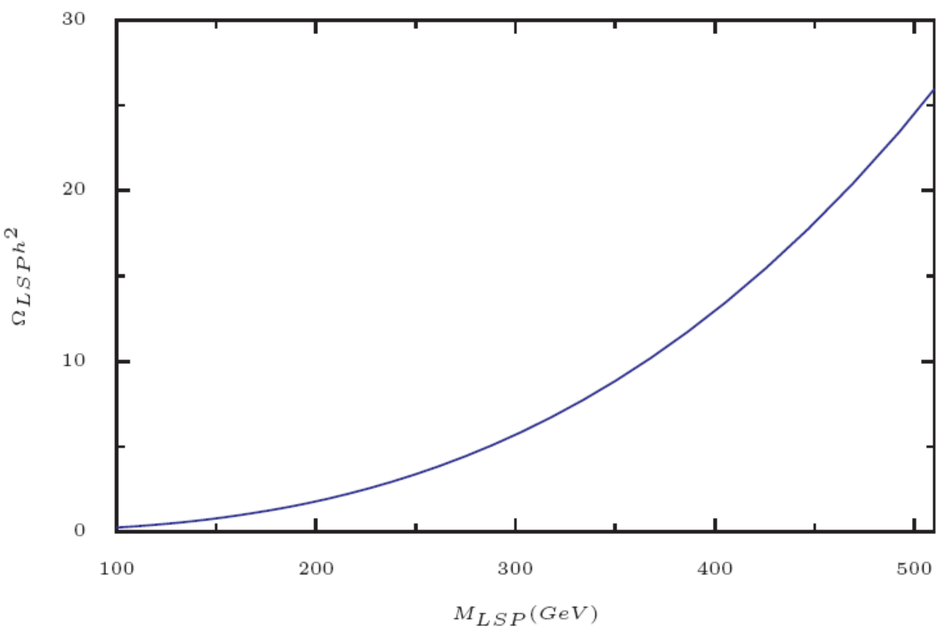
The reheating phases suppress the gravitino abundance then it's decay does not affect the relic density



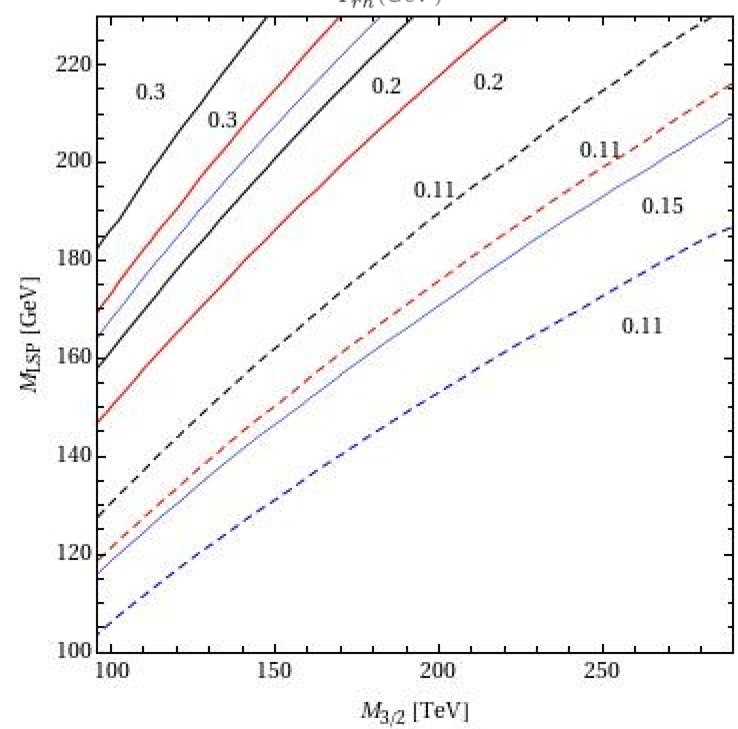
0.7
0.5
0.3
0.1
60
80
100
120
140
$\Omega_{LSP}h^2$
$M_{3/2}(TeV)$



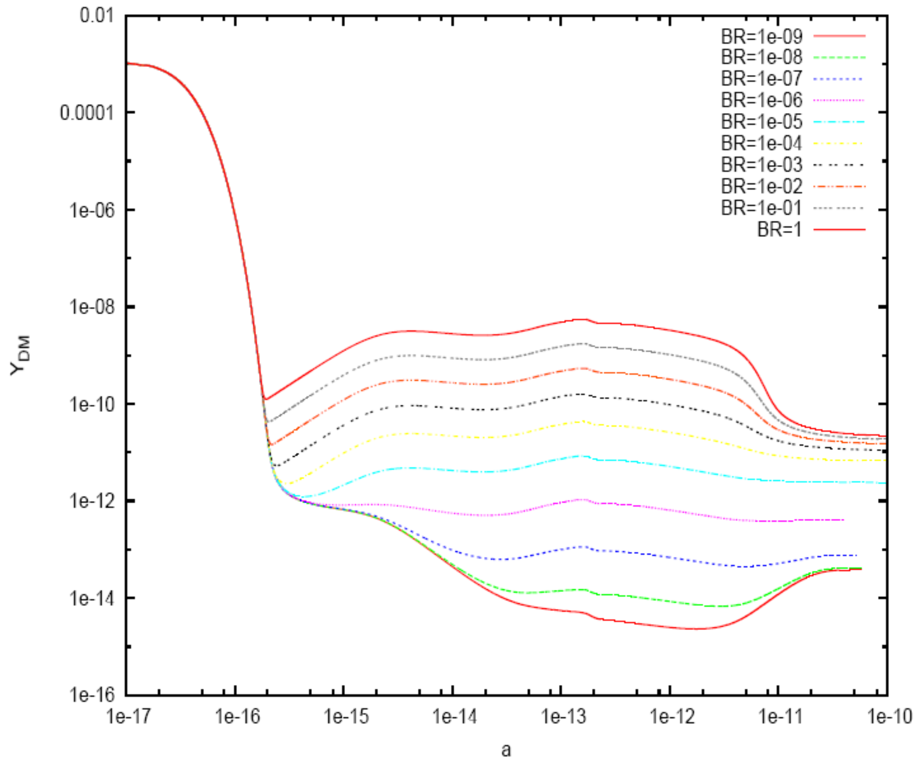
0.7
0.5
0.3
0.1
0.01
0.02
0.03
0.04
0.05
$\Omega_{LSP}h^2$
$T_{rh}(GeV)$



30
20
10
0
100
200
300
400
500
$\Omega_{LSP}h^2$
$M_{LSP}(GeV)$

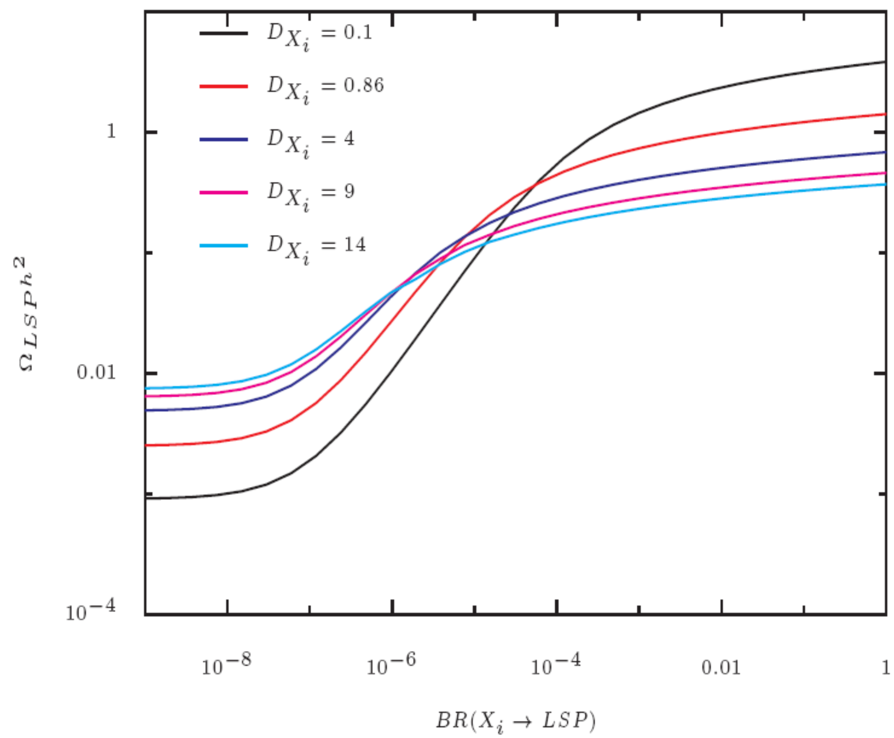


220
200
180
160
140
120
100
100
150
200
250
0.3
0.3
0.2
0.2
0.11
0.11
0.15
0.11
M_{LSP} [GeV]
$M_{3/2}$ [TeV]



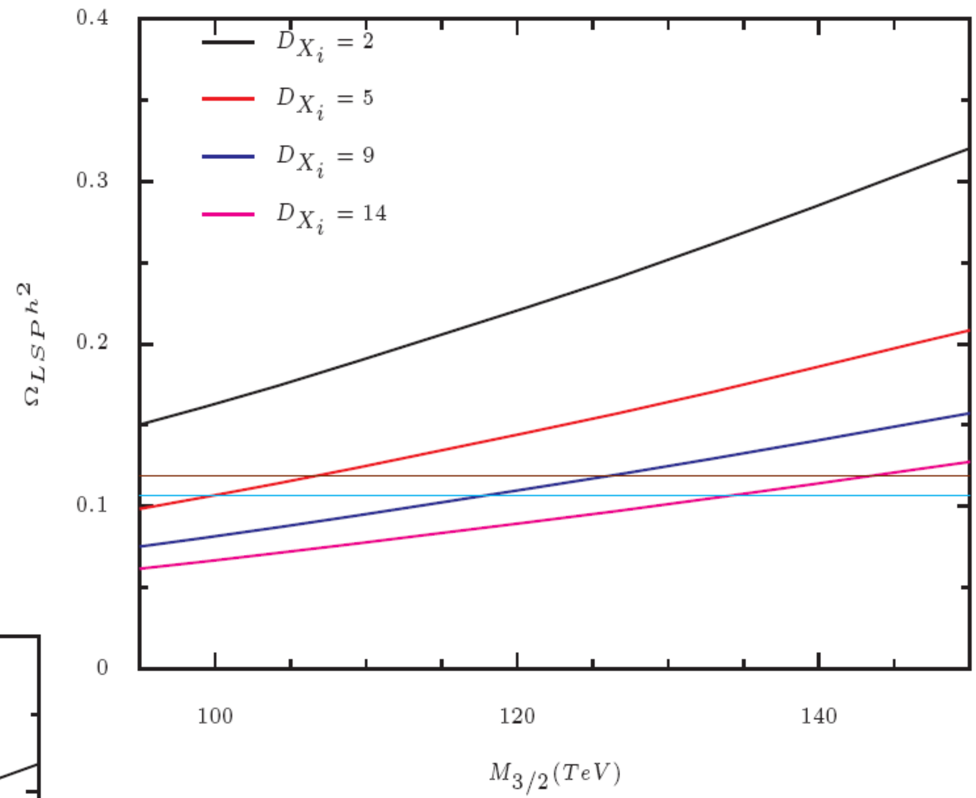
The two regimes: production with or without reannihilations are controlled by the decay rate of the modulus and the branching ratio of the decay channel into DM. By varying the suitable parameters is possible to go from one regime to the other.

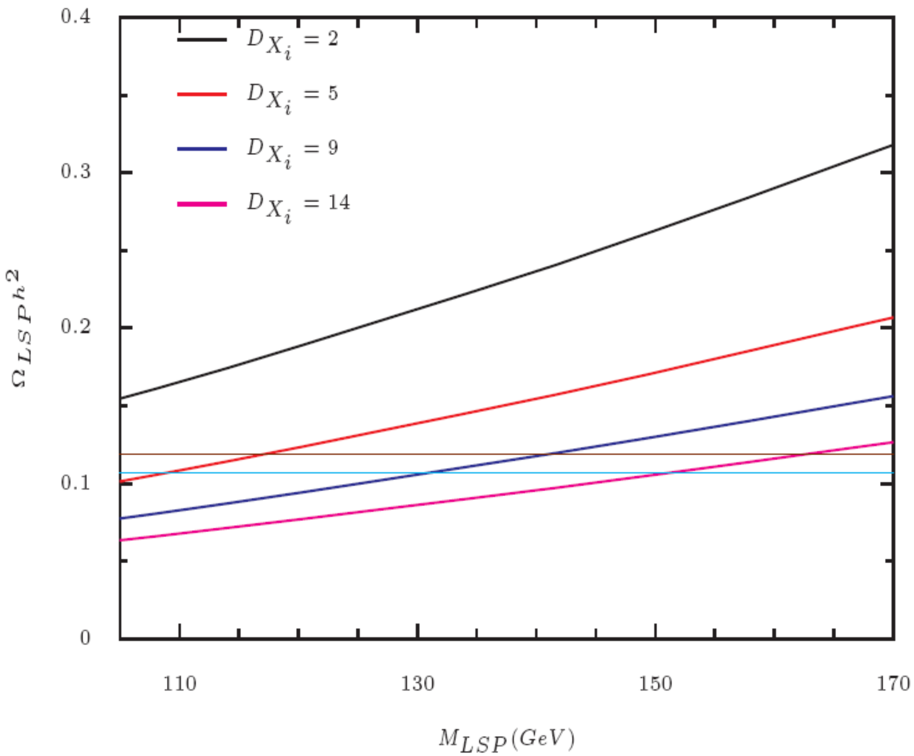
The relic density has an asymptotic value which corresponds to the contribution of the gravitino decay which is not sensitive to the parameters above.

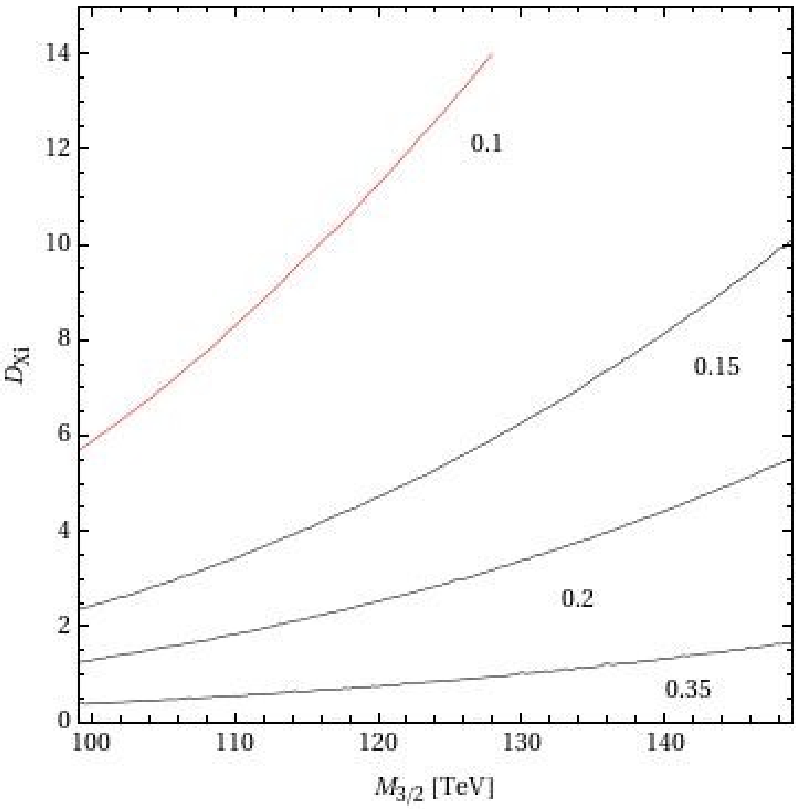


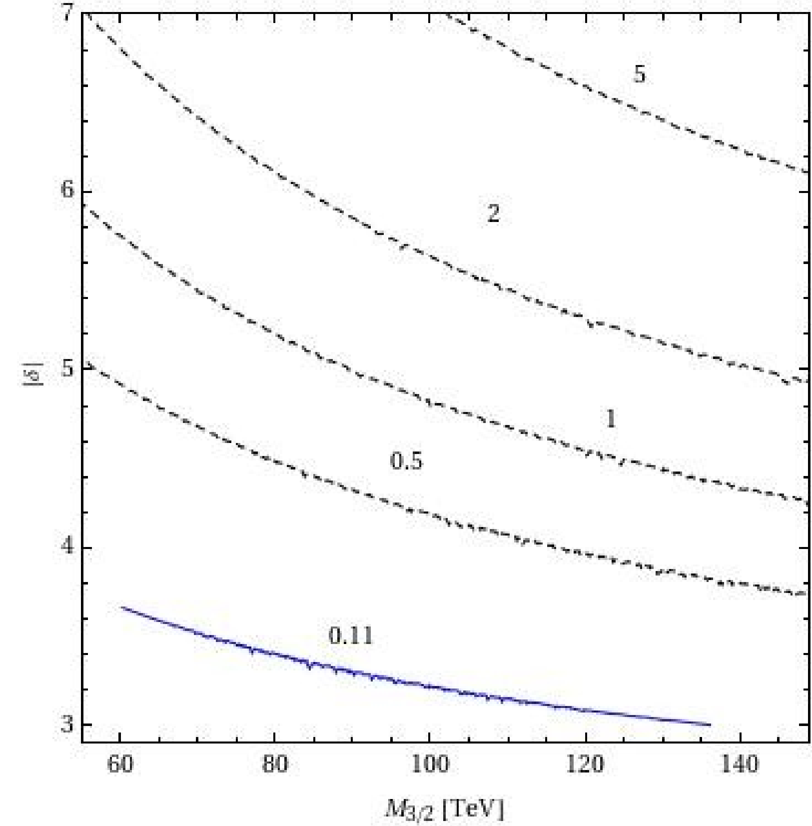
Because of the relation among the LSP mass and the gravitino mass the relic density is, differently respect to the general case, an increasing function of both the two masses.

$$\Omega_{LSP}h^2 \propto F(\delta)^3 \frac{m_{3/2}^3}{D_{X_i}^{1/2}}$$





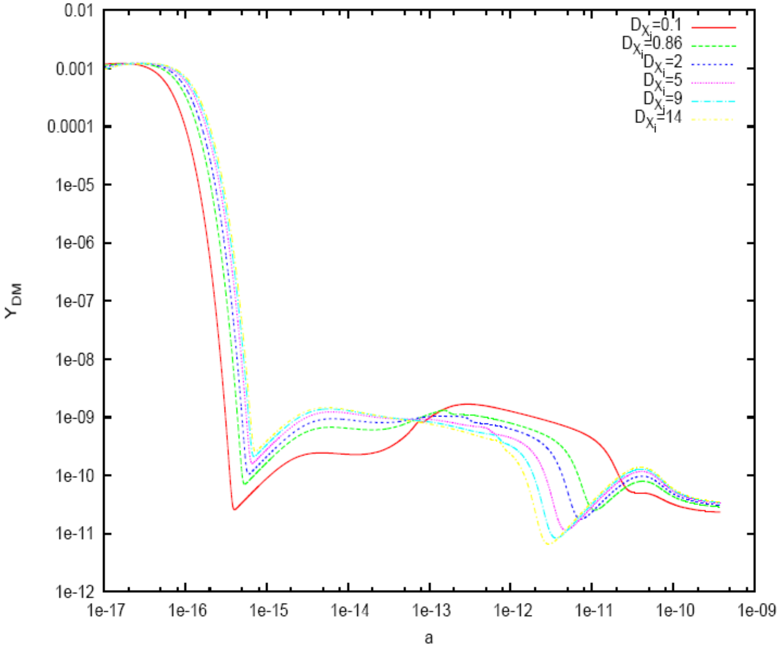




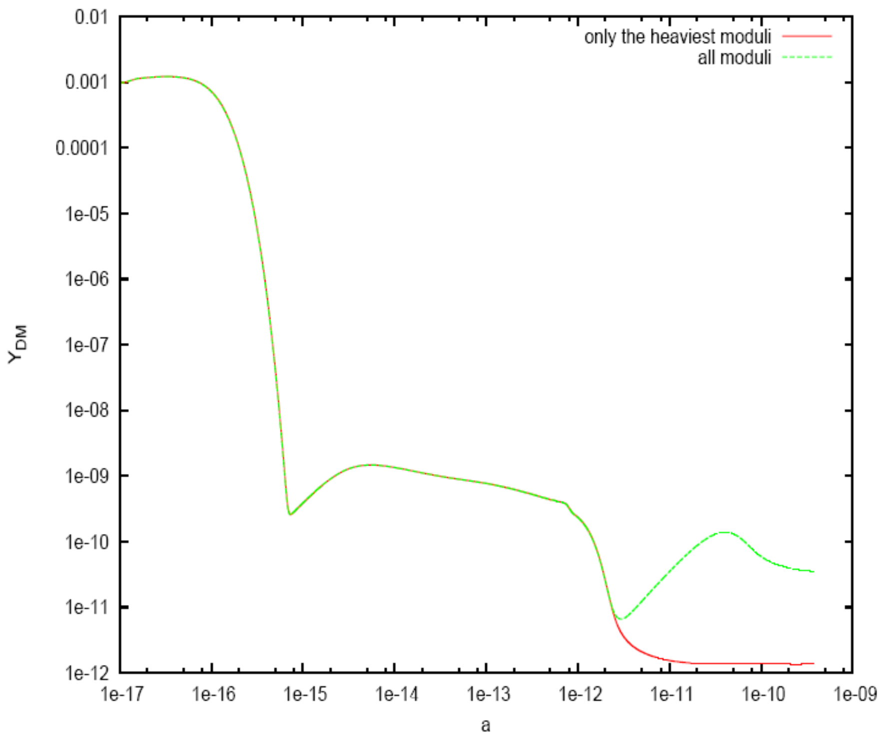
The relic density has a very strong dependence on the ratio among the LSP mass and the gravitino mass which is fixed by the parameter delta.

The model is extremely constrained. It's essential a precise knowledge of the high energy theory.

In general one can relax the hypothesis that the mass of the light moduli is lower than two times the gravitino mass and then allow them to decay into gravitinos. In this case the contribution to the LSP relic density from gravitino is no more suppressed and can become dominant.



These plots have been realized by putting the masses of the light moduli and the meson to 2.82m3/2



Conclusions and Issues

- The non thermal production is a viable scheme to provide the correct relic density for dark matter candidates with large pair annihilation cross sections
- Usually it implies a characteristic mass pattern which can be tested at LHC.
- A numerical code has been developed to compute the LSP relic density by following the entire evolution of the relevant components ,and it has be used to study a testable model.

Future prospectives and issues:

- Develop a model indipendent approach in order to derive bounds on the physical observables such has the LSP mass.
- The system of equation implies the assumptions that the products of the decay of the modulus are able to thermalize with the existing heat bath. This is not granted for low reheating temperatures (O(1-10) MeV). We need to develop a method to compute the kinetic decoupling temperature of the DM.