Supersymmetric Higgs-Sneutrino Inflation and Reheating

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Hot Topics in Modern Cosmology

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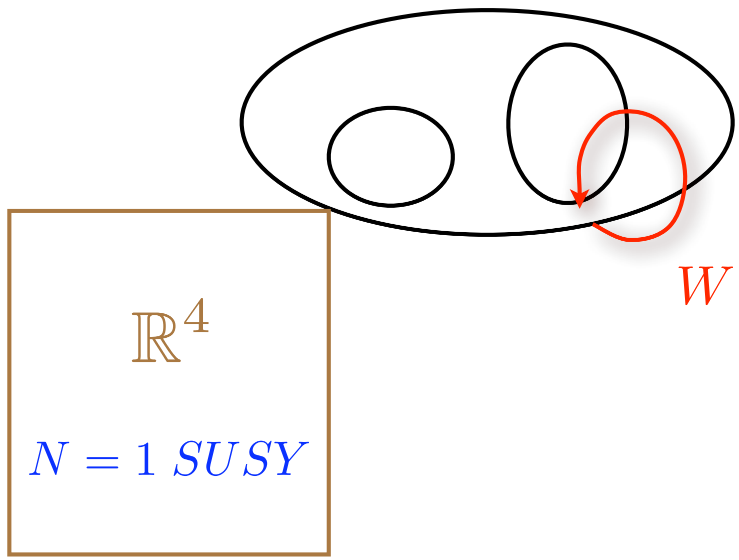
Brief Review of a Realistic String Vacuum:

SU(4) Heterotic Compactification:

$X,\ D = 6$ "Schoen" CY



$V\ , G = SU(4)$
"slope" stable

$W\ , F = \mathbb{Z}_3 \times \mathbb{Z}_3$

$\mathbb{R}^4$ Theory Gauge Group:

$$G = SU(4) \Rightarrow \quad E_8 \longrightarrow \ Spin(10)$$

Choose the $\mathbb{Z}_3 \times \mathbb{Z}_3$ Wilson lines to be

$$\chi_{T_{3R}} = e^{iY_{T_{3R}}\frac{2\pi}{3}} \ , \quad \chi_{B-L} = e^{iY_{B-L}\frac{2\pi}{3}}$$

where

$$Y_{B-L} = \quad 2(H_1 + H_2 + H_3) = 3(B-L)$$
$$Y_{T_{3R}} = \quad H_4 + H_5 = 2(Y - \frac{1}{2}(B-L)) = 2T_{3R}$$

arise "naturally" and is called the "canonical basis". $\Rightarrow$

$$Spin(10) \to SU(3)_C \times SU(2)_L \times U(1)_{T_{3R}} \times U(1)_{B-L}$$

$\mathbb{R}^4$ Theory Spectrum:

$n_r = (h^1(X, U_R(V)) \otimes \mathbf{R})^{\mathbb{Z}_3 \times \mathbb{Z}_3} \Longrightarrow$ 3 families of quarks/leptons

$$Q = (U, D)^T = (\mathbf{3}, \mathbf{2}, 0, \frac{1}{3}), \quad u = (\bar{\mathbf{3}}, \mathbf{1}, -\frac{1}{2}, -\frac{1}{3}), \quad d = (\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{2}, -\frac{1}{3})$$
$$L = (N, E)^T = (\mathbf{1}, \mathbf{2}, 0, -1), \quad \nu = (\mathbf{1}, \mathbf{1}, -\frac{1}{2}, 1), \quad e = (\mathbf{1}, \mathbf{1}, \frac{1}{2}, 1)$$

and 1 pair of Higgs-Higgs conjugate fields

$$H = (\mathbf{1}, \mathbf{2}, \frac{1}{2}, 0), \quad \bar{H} = (\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 0)$$

under $SU(3)_C \times SU(2)_L \times U(1)_{T_{3R}} \times U(1)_{B-L}$.

Wilson Line Breaking:

$\pi_1(X/(\mathbb{Z}_3 \times \mathbb{Z}_3)) = \mathbb{Z}_3 \times \mathbb{Z}_3 \Rightarrow$ 2 independent classes of non-contractible curves. $\Rightarrow$ each Wilson line has a mass scale $M_{\chi_{T_{3R}}}$, $M_{\chi_{B-L}}$. At a generic region of moduli space

$$M_{\chi_{T_{3R}}} \simeq M_{\chi_{B-L}} (\simeq \ M_U)$$

which we henceforth assume. We find that

$$M_U = 3.15 \times 10^{16} \text{ GeV}$$

At this scale, we statistically scatter the 24 soft supersymmetry parameters in the range $(\frac{M}{f}, Mf)$ where, to make all sparticle masses CERN accessible, we choose $M = 2.7\ TeV$, $f = 3.3$. The results are subjected to all present phenomenological constraints-- namely

A) B-L symmetry is radiatively broken at $M_{B-L} > 2.5 \text{ TeV}$

B) EW symmetry is radiatively broken at $M_Z = 91.2 \text{ GeV}$

C) The Higgs mass is given by $M_{H^0} = 125.36 \pm 0.82$ GeV

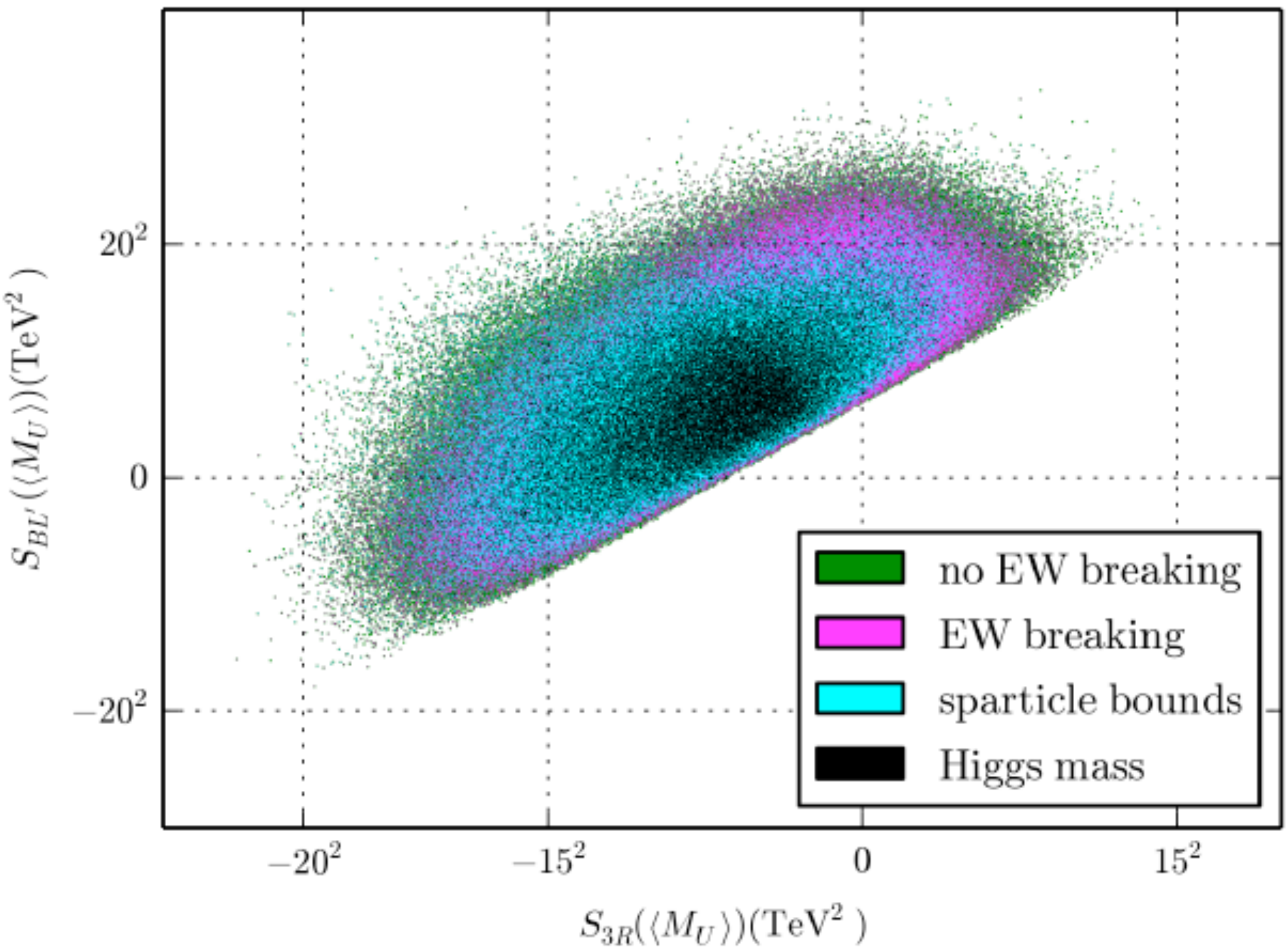
In addition, we will enforce that all sparticle masses exceed their present experimental bounds. These are given by

Particle(s)	Lower Bound
Left-handed sneutrinos	45.6 GeV
Charginos, sleptons	100 GeV
Squarks, except for stop or sbottom LSP's	1000 GeV
Stop LSP (admixture)	450 GeV
Stop LSP (right-handed)	400 GeV
Sbottom LSP	500 GeV
Gluino	1300 GeV
Z_R	2500 GeV

We find that most of the RGE scaling behaviour is dominated by the two parameters

$$S_{BL'} = \text{Tr}\,(2m_{\tilde{Q}}^2 - m_{\tilde{u}^c}^2 - m_{\tilde{d}^c}^2 - 2m_{\tilde{L}}^2 + m_{\tilde{\nu}^c}^2 + m_{\tilde{e}^c}^2)\,,$$
$$S_{3R} = m_{H_u}^2 - m_{H_d}^2 + \text{Tr}\left(-\frac{3}{2}m_{\tilde{u}^c}^2 + \frac{3}{2}m_{\tilde{d}^c}^2 - \frac{1}{2}m_{\tilde{\nu}^c}^2 + \frac{1}{2}m_{\tilde{e}^c}^2\right)$$

$\Rightarrow$ we can plot our results in a two-dimensional space. We find that out of 10 million random initial points in SUSY breaking parameter space, all points that break B-L symmetry with $M_{B-L} > 2.5\ TeV$ are



Of these, there are 44,884 "valid" black points that satisfy all phenomenological requirements.

Sneutrino-Higgs Inflation:

Once again consider the B-L MSSM, but now as a possible framework for inflationary cosmology satisfying all Planck2015 bounds. To do this, we must couple the theory to N=1 supergravity.

Recall that the B-L MSSM arises as the observable sector of a class of vacua of heterotic M-theory. The generic coupling of such a theory to N=1 supergravity was carried out in

A. Lukas, B. A. Ovrut and D. Waldram, "On the four-dimensional effective action of strongly coupled heterotic string theory," Nucl. Phys. B **532**, 43 (1998)

The results are easily applied to the B-L MSSM. To begin, we first assume that--with the exception of the two complex "universal" geometrical moduli--all other geometric and vector bundle moduli are stabilized and sufficiently heavy to be ignored at low energy.

The real parts of the two universal moduli are the "breathing modes" of the CY and S_1/Z_2 orbifold, a(x) and c(x) respectively, defined in the in the 11 -dimensional metric by

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu + e^{2a(x)}\Omega_{AB}dx^A dx^B + e^{2c(x)}(dx^{11})^2$$

In the $M_P \to \infty$ limit, these moduli also decouple from ordinary matter and can be ignored. However, for finite M_P this is no longer the case, and must be included when coupling the B-L MSSM to supergravity. Specifically, the Kahler potential is altered to

no-scale supergravity→ $$K = -\ln(S+\bar{S}) - 3\ln(T+\bar{T} - \sum_i \frac{|C_i|^2}{M_P^2})$$

where the sum is over all complex scalar matter fields C_i and

$$S = e^{6a} + i\sqrt{2}\sigma\ , \ \ T = e^{2\hat{c}} + i\sqrt{2}\chi + \frac{1}{2}\sum_i \frac{|C_i|^2}{M_P^2}$$

where $\hat{c} = c + 2a.$

Similarly, to lowest order, the gauge kinetic function is given by

$$f = S$$

Both the Kahler potential and gauge kinetic function are identical to those found in the weakly coupled heterotic string and are consistent with the requisite "new minimal" supergravity multiplet.

Putting K and f, as well as the superpotential W, into the above formalism gives the Lagrangian for the B-L MSSM coupled to N=1 supergravity. Henceforth, we set $M_P = 1$ and assume that both S and T are stabilized at fixed VEV's. By scaling

$$C_i' = \left(\frac{3}{T+\bar{T}}\right)^{1/2} C_i \,, \qquad g_a' = \left(\frac{2}{S+\bar{S}}\right)^{1/2} g_a \,, \quad \text{for } a = 3, 2, 3R, BL'$$

both S and T can be eliminated from the Lagrangian. $\Rightarrow$

$$K = -3\ln\left(1 - \sum_i \frac{|C_i|^2}{3}\right) \,, \qquad f = 1$$

Recalling that the matter kinetic energy terms are

$$-K_{i\bar{j}}\partial_\mu C^i \partial^\mu C^{\bar{j}}$$

$\Rightarrow$ for small values of the fields there is no mixing and the KE is canonically normalized. However, this is no longer true for fields approaching the Planck scale.

Now consider the remaining parts of the Lagrangian. The purely gravitational action is simply

$$-\frac{1}{2}\int_{M_4}\sqrt{-g}R$$

That is

- *The pure gravitational action is canonical. We do not require any "non-canonical" coupling of matter to the curvature tensor R.*

The matter potential energy breaks into supersymmetric F-terms and D-terms given by

$$V_F = e^K \left(K^{i\bar{j}} D_i W \overline{D_{\bar{j}} W} - 3|W|^2 \right) , \qquad V_D = \frac{1}{2} \sum_a D_a^2$$

where W is the B-L MSSM superpotential and $D_a, a = 3, 2, 3R, BL'$ are the functions

$$D_a^r = -g_a \frac{\partial K}{\partial C_i} [T^r_{(a)}]_i{}^j C_j = \frac{g_a}{(1 - \frac{1}{3} \sum_i |C_i|^2)} \mathcal{D}^r_{(a)} , \qquad \mathcal{D}^r_{(a)} = -\overline{C}^i [T^r_{(a)}]_i{}^j C_j$$

In addition, there is a soft SUSY breaking potential

$$V_{soft} = (m^2_{Q_{\rm f}} |Q_{\rm f}|^2 + m^2_{u_{R,{\rm f}}} |u_{R,{\rm f}}|^2 + m^2_{d_{R,{\rm f}}} |d_{R,{\rm f}}|^2 + m^2_{L_{\rm f}} |L_{\rm f}|^2 + m^2_{\nu_{R,{\rm f}}} |\nu_{R,{\rm f}}|^2$$
$$+ m^2_{e_{R,{\rm f}}} |e_{R,{\rm f}}|^2) + m^2_{H_u} |H_u|^2 + m^2_{\bar{H}_d} |H_d|^2 + (b H_u H_d + h.c.) + \ldots$$

Given these potentials, we want to search for a "stable" valley down which a scalar field can "slow roll" and, hence, produce inflation.

To enhance the stability of the valley, we demand that it be D-flat; that is

$$V_D = 0$$

We will restrict ourselves to fields not charged under $SU(3)_C$ or $U(1)_{EM}$. $\Longrightarrow$ We are led naturally to the field configuration

$$H_u^0 = \nu_{R,3} = \nu_{L,3}$$

with all other fields set to zero. It is helpful to define three new fields $\phi_i,\ i = 1, 2, 3$ using

$$H_u^0 = \frac{1}{\sqrt{3}} (\phi_1 - \phi_2 - \phi_3)\,,$$
$$\nu_{L,3} = \frac{1}{\sqrt{3}}\phi_1 + \left(\frac{1}{2} + \frac{1}{2\sqrt{3}}\right)\phi_2 + \left(\frac{1}{2\sqrt{3}} - \frac{1}{2}\right)\phi_3$$
$$\nu_{R,3} = \frac{1}{\sqrt{3}}\phi_1 + \left(\frac{1}{2\sqrt{3}} - \frac{1}{2}\right)\phi_2 + \left(\frac{1}{2} + \frac{1}{2\sqrt{3}}\right)\phi_3$$

The ϕ_1 field corresponds to the D-flat direction while ϕ_2, ϕ_3 are orthogonal directions with positive potential. Note that

$$\phi_1 = \frac{1}{\sqrt{3}} \left(H_u^0 + \nu_{L,3} + \nu_{R,3}\right)$$

with the associated soft mass squared given by

$$m^2 = \frac{1}{3}(m^2_{H_u^0} + m^2_{\nu_{L,3}} + m^2_{\nu_{R,3}})$$

Setting all fields to zero except $\phi_1 \Longrightarrow V_D = 0$ and the Lagrangian becomes

$$\mathcal{L} = -\frac{1}{\left(1 - \frac{1}{3}|\phi_1|^2\right)^2} \partial_\mu \overline{\phi}_1 \partial^\mu \phi_1 - V_F(\phi_1) - V_{soft}(\phi_1)$$

where

$$V_F(\phi_1) = \frac{3|\phi_1|^2 \left(\mu^2 + Y_{\nu 3}^2 |\phi_1|^2\right)}{\left(3 - |\phi_1|^2\right)^2} , \qquad V_{soft}(\phi_1) = m^2 |\phi_1|^2$$

$Y_{\nu 3} \sim \mathcal{O}(10^{-12})$ is the third family sneutrino Yukawa coupling and μ is the supersymmetric Higgs parameter. Note that $\mathcal{L}$ is globally U(1) invariant. Henceforth, restrict to the real field $\phi_1 = \phi_1^*$. $\Longrightarrow$

- *The inflaton is a linear combination of the real parts of H_u^0, $\nu_{L,3}$ and $\nu_{R,3}$ and, hence, is composed of fields already appearing in the $B-L$ MSSM.*

To canonically normalize the kinetic energy term, define a new real scalar field ψ by

$$\phi_1 = \sqrt{3} \tanh\left(\frac{\psi}{\sqrt{6}}\right)$$

The Lagrangian now becomes

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\psi\partial^\mu\psi - V_F(\psi) - V_{soft}(\psi)$$

where $V_F(\psi)$ is determined from the above and

$$V_{soft}(\psi) = 3m^2 \tanh^2\left(\frac{\psi}{\sqrt{6}}\right)$$

Primordial Parameters:

For an arbitrary potential V define

$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 , \qquad \eta = \frac{V''}{V}$$

In an interval of slow-roll inflation, these parameters must satisfy

$$\epsilon, |\eta| \ll 1$$

We define the smallest value of the field where inflation ends to be ψ_{end}. The value of the field which precedes ψ_{end} by exactly 60 e-foldings is denoted ψ_*.

The "spectral index" and the "scalar to tensor" ratio are defined by

$$n_s \simeq 1 + 2\eta_* - 6\epsilon_* \ , \qquad r \simeq 16\epsilon_*$$

respectively. The label "$*$" denotes quantities evaluated at ψ_*.

In addition, the Planck2015 normalization of the CMB fluctuations requires that

$$V_*^{1/4} = 1.88(\frac{r}{0.10})^{1/4} \times 10^{16}\ \mathrm{GeV}$$

where we have restored dimensionful units for clarity.

Let us now evaluate these quantities for the B-L MSSM potential $V = V_F + V_{soft}$. Begin by considering V_{soft} alone. We find that

$$\psi_{end} = 1.21 \ , \qquad \psi_* = 6.23$$

and

$$n_s \simeq 0.967 \ , \qquad r \simeq 0.00326$$

which are consistent with the Planck2015 data.

Inserting this value for r above gives

$$V_*^{1/4} = 7.97 \times 10^{15}\ \text{GeV} \quad \Longrightarrow \quad m = 1.55 \times 10^{13}\ \text{GeV}$$

$\Rightarrow$

- *In order to be consistent with the Planck2015 cosmological data, supersymmetry must be broken at a high scale of* $\mathcal{O}(10^{13}\ \text{GeV})$.

Note that for $M_{\chi_{T_{3R}}} \simeq M_{\chi_{B-L}} (\simeq M_U)$ the analysis presented earlier is valid for arbirarily high values of soft SUSY breaking. Also note that although ψ must be trans-Planckian at the start of inflation

- *The physical fields* H_u^0, $\nu_{3,R}$ *and* $\nu_{3,L}$ *are all sub-Planckian during the entire inflationary epoch.*

The form of our potential V_{soft} has arisen in other contexts. However

- *Our* V_{soft} *potential arises entirely from the associated soft supersymmetry breaking quadratic term, rescaled to canonically normalize the kinetic energy.*

Now consider the F-term potential V_F. The Yukawa coupling $Y_{\nu 3} \sim \mathcal{O}(10^{-12})$ is small and, hence, that term in V_F can be ignored. However, to keep from ruining the slow-roll behavior of V_{soft}, we must choose the μ parameter to be at least three order of magnitude smaller than m. For specificity, take

$$\mu = 1.20 \times 10^{10} \text{ GeV}$$

Combining both potentials, we find

$$\psi_{end} \simeq 1.21 \,, \quad \psi_* \simeq 6.25$$

and

$$n_s \simeq 0.969 \,, \qquad r \simeq 0.00334$$

again both consistent with the Planck2015 data. Also

$$V_*^{1/4} = 8.07 \times 10^{15} \text{ GeV} \;\Rightarrow\; m = 1.58 \times 10^{13} \text{ GeV}$$

The potentials V_{soft} and V_F are individually plotted in Figure 1.

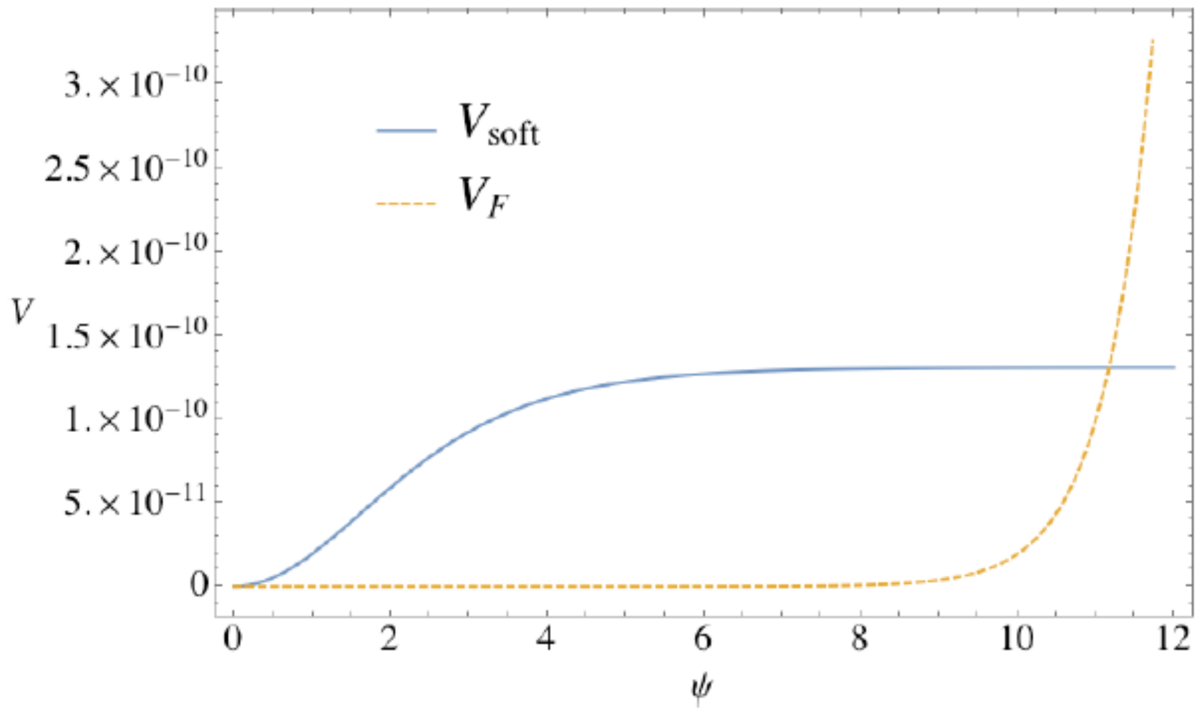


FIG. 1. The blue line is a plot of V_{soft} for the soft mass value $m = 1.58 \times 10^{13}$ GeV. The orange line is a graph of V_F for the parameters $Y_{\nu 3} \sim 10^{-12}$ and $\mu = 1.20 \times 10^{10}$ GeV

Note that the F-term potential acts as a natural "cut-off" of the inflation potential V_{soft} for values of $\psi \gtrsim 8.$ This gives a supersymmetric realization of the "Inflation without Selfreproduction" mechanism introduced by Mukhanov.

The complete potential is plotted in Figure 2.

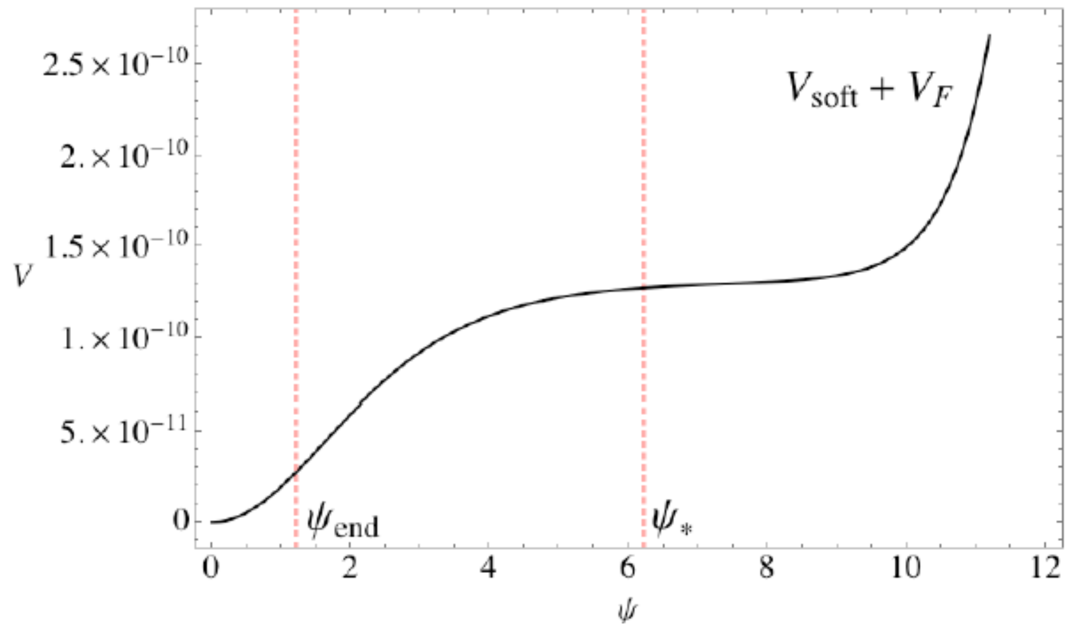


FIG. 2. The black line is a graph of the potential $V_{soft}+V_F$ for the parameters $m = 1.58\times10^{13}$ GeV, $Y_{\nu 3}\sim10^{-12}$ and $\mu = 1.20\times10^{10}$ GeV. For these values of the parameters, the vertical red dashed lines mark $\psi_{end}\simeq 1.21$ and $\psi_*\simeq 6.25$ respectively.

We have now demonstrated that the B-L MSSM coupled to N=1 supergravity can naturally produce a period of slow-roll inflation. However, to do so we had to raise the soft SUSY breaking scale to

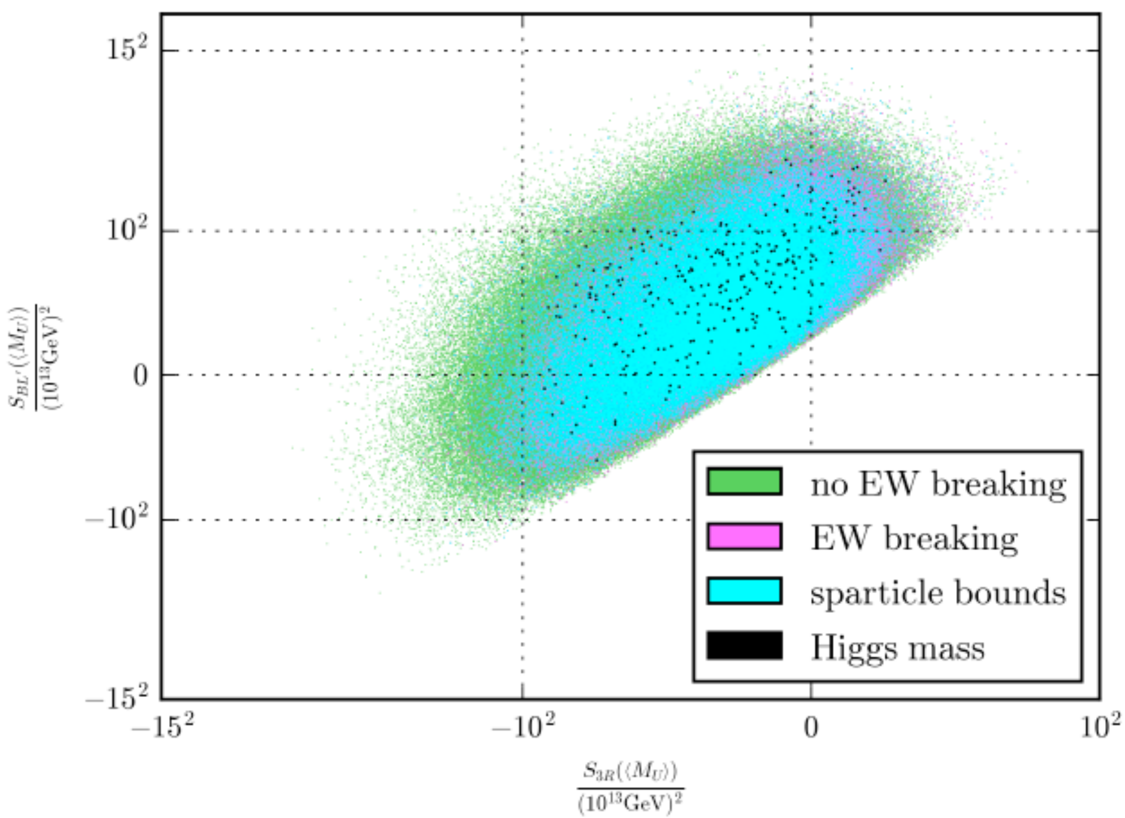
$$m = 1.58\times10^{13}\ \text{GeV} \;\; >> \mathcal{O}(1-10\ \text{TeV})$$

Is this still consistent with all low energy phenomenology?

Redoing our earlier analysis, but now taking

$$\left(\frac{M}{f}, Mf\right) \quad \text{where} \quad M = m = 1.58 \times 10^{13}\ \text{GeV},\ \ f = 3.3$$

we find



Each black "valid" point is consistent with all low energy phenomenology as well as being a theory of inflation satisfying all Planck2015 constraints.

Perturbative Reheating:

It was shown in several papers by J. Ellis and K. Olive that within the context of Higgs and Sneutrino inflation in no-scale N=1 supergravity perturbative reheating can predominate over "preheating" for a significant range of input parameters. Here, we assume that is the case and focus exclusively on perturbative reheating.

Classical Behavior of ψ and H :

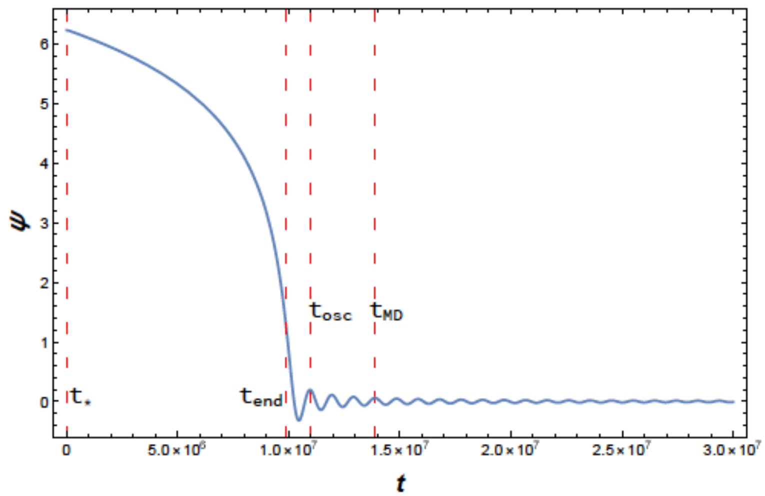
The relevant equations of motion in the inflationary and post-inflationary regimes are

$$3H^2 = \frac{1}{2}\dot{\psi}^2 + V(\psi)$$
$$\dot{H} = -\frac{1}{2}\dot{\psi}^2 \, ,$$
$$\ddot{\psi} + 3H\dot{\psi} + V_{,\psi} = 0 \, ,$$

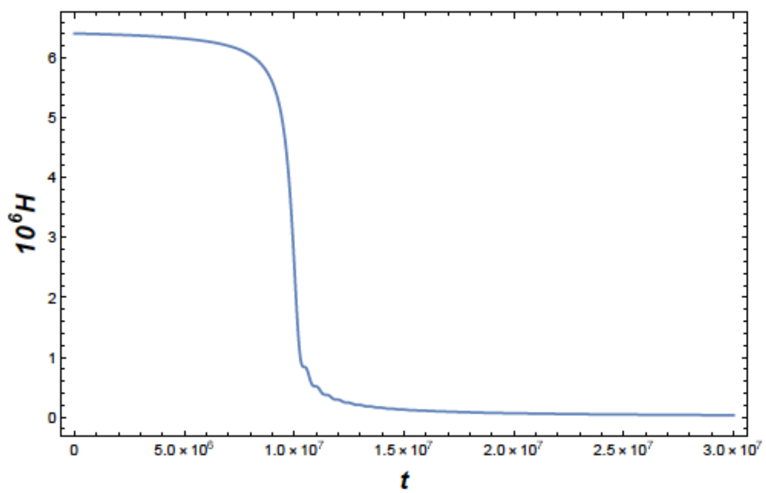
where $M_P = 1$ and, since $V_F \ll V_{soft}$ we can take $V = V_{soft} \quad \Rightarrow$

$$V(\psi) = 3m^2 \tanh^2\left(\frac{\psi}{\sqrt{6}}\right) = \frac{1}{2}m^2\psi^2\left[1 - \left(\frac{\psi}{3}\right)^2 + \left(\frac{17\psi^4}{1620}\right) + \ldots\right]$$

Solving these equations numerically, we find



(a)



(b)

The numerical solutions for $\psi(t)$ and $H(t)$, where we have set $M_P = 1$. Note that $t_* = 0$ and $t_{end} \simeq 9.89 \times 10^6$ mark the beginning and end of the inflationary period. The times $t > t_{end}$ correspond to the post inflationary epoch. As defined in the text, $t_{osc} \simeq 1.096 \times 10^7$ marks the time at which the potential energy is well approximated by $V = \frac{1}{2}m\psi^2$ and $t_{MD} \simeq 1.387 \times 10^7$ is the time at which our analytic solutions for ψ and H become valid.

Behavior of ψ and H during Particle Decay:

The relevant equations of motion in the post-inflationary regime are modified to

$$3H^2 = \frac{1}{2}\dot{\psi}^2 + V(\psi) + \sum_i \rho_i \,,$$
$$\dot{H} = -\frac{1}{2}\dot{\psi}^2 - \frac{1}{2}\sum_i (\rho_i + p_i) \,,$$
$$\ddot{\psi} + \left(3H + \sum_i \Gamma_{d,i}\right)\dot{\psi} + V'(\psi) = 0 \,,$$
$$\dot{\rho}_i + 3\,(1 + \omega_i(t))\,H\rho_i - \Gamma_{d,i}\dot{\psi}^2 = 0 \,,$$

where $\Gamma_{d,i}$ is the decay rate of ψ into the i-th matter species, and ρ_i and p_i are the energy density and pressure respectively of the i-th species in the decay products. The quantities ρ_i and p_i are related by the relation $p_i = \omega_i(t)\rho_i$, where $\omega_i = 0$ and $1/3$ respectively for matter and radiation. The initial conditions for ψ and H are set by their classical values at the end of the inflationary epoch.

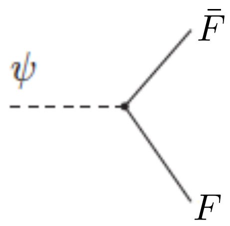
Expansion of ψ :

We expand ψ around its root mean square value. That is

$$\psi = \sqrt{\langle \psi^2 \rangle} + \delta\psi \; (\equiv \psi)$$

Decay Species:

a) up-quarks- Let F denote an up-quark. Then



$$\Rightarrow \quad \Gamma_d(\psi \to F\bar{F}) = \frac{y_{\psi F}^2 m_\psi}{8\pi}\left[1-4\left(\frac{m_F}{m_\psi}\right)^2\right]^{\frac{3}{2}},$$

where

$$m_F = y_{\psi F}\sqrt{\langle\psi^2\rangle} \quad , \quad m_\psi = m = 6.49\times 10^{-6}.$$

Note that

$$\langle\psi^2\rangle \longrightarrow 0 \;\Rightarrow \qquad \Gamma_d \longrightarrow \frac{y_{\psi F}^2 m_\psi}{8\pi} \equiv \Gamma_d^{\max}$$ =constant

b) charginos

c) neutralinos

$\longleftarrow$ scale of R-parity breaking << reheating temperature

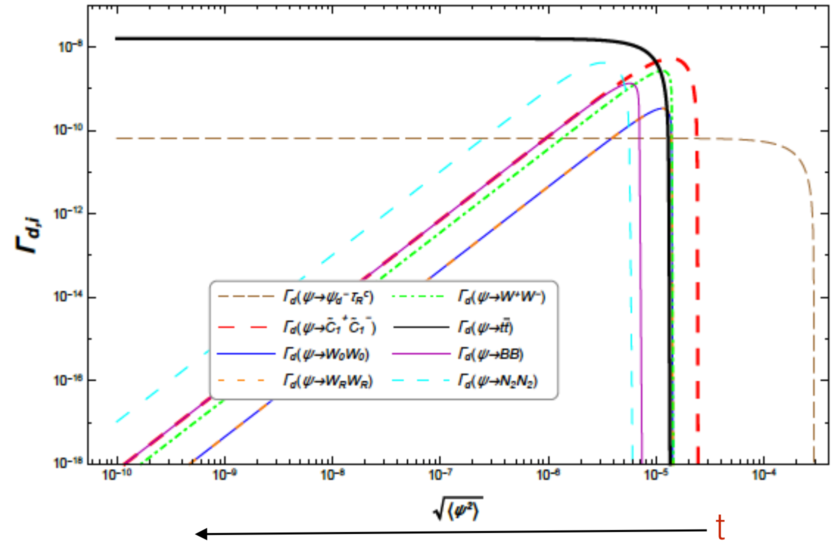
d) gauge bosons- For example, consider W_R . Then

$$\Gamma_d(\psi \to W_{R\mu}W_R^\mu) = \frac{g_2^4\langle\psi^2\rangle}{1152\pi m_\psi}\left[1-4\frac{m_{W_R}^2}{m_\psi^2}\right]^{1/2}$$

Note that

$$\Gamma_d \longrightarrow 0$$

Plotted as a function of $\sqrt{\langle\psi^2\rangle}$, we find

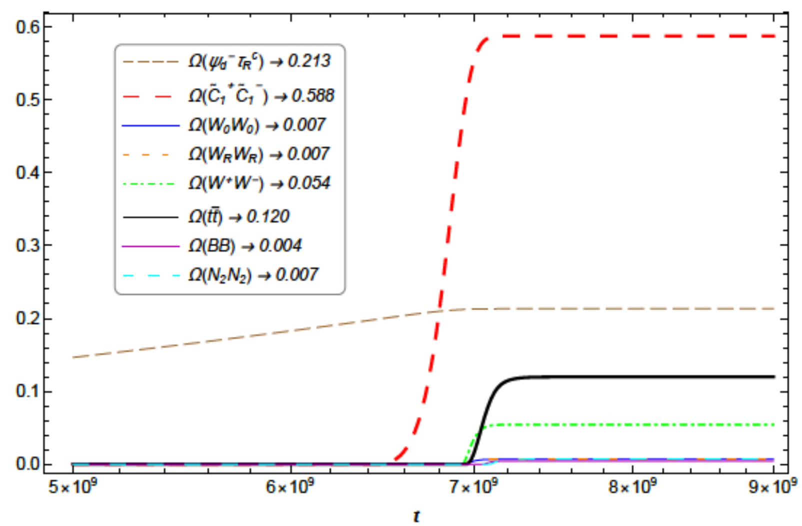


The fractional energy density for the i-th decay species is given by

$$\Omega_i(t) = \frac{\rho_i(t)}{\rho_{total}} ,$$

where $\rho_{total} = 3H^2$. Plotted as a function of t

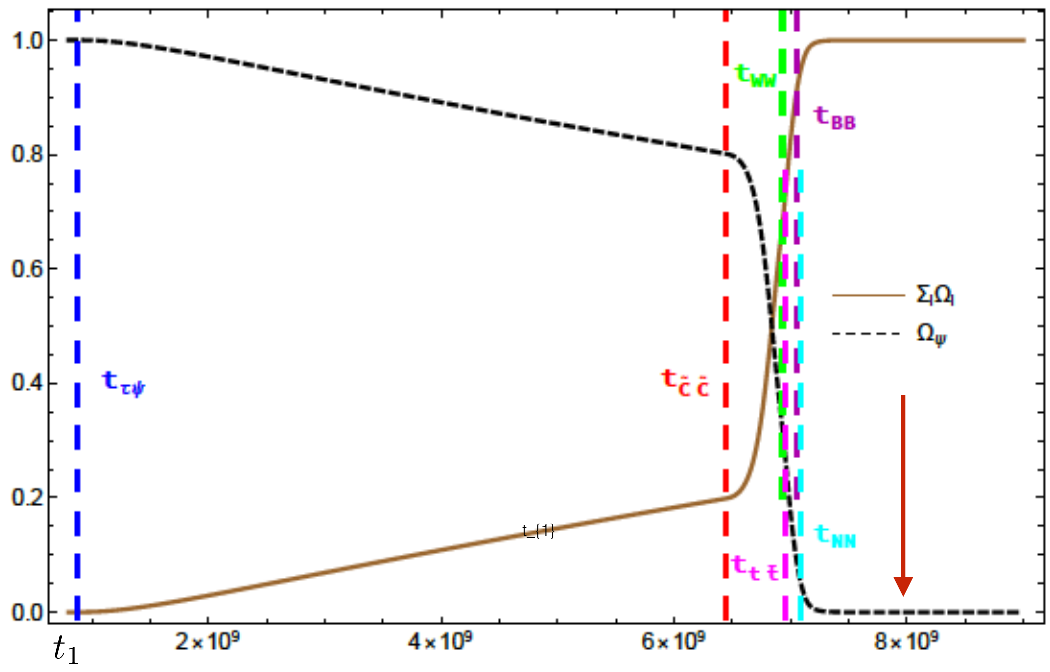
recall $3H^2 = \frac{1}{2}\dot{\psi}^2 + V(\psi) + \sum_i \rho_i$



Defining

$$\Omega_\psi = \rho_\psi/\rho_{total} \text{ with } \rho_\psi = \frac{1}{2}\dot{\psi}^2 + V(\psi)$$

we find



We plot the evolutions of Ω_ψ and $\sum_i \Omega_i$ from t_I to sometime after the end of reheating. The time at which each specie is turned on is marked with a vertical line, where $t_{\tau\psi *} = 8.78 \times 10^8, t_{\bar{C}\bar{C}*} = 6.45 \times 10^9, t_{WW*} = 6.93 \times 10^9, t_{t\bar{t}*} = 6.95 \times 10^9, t_{BB*} = 7.06 \times 10^9$ and $t_{NN*} = 7.08 \times 10^9$.

Complete reheating has occurred at the time when

$$\sum_i \Omega_i \to 1 \;\Rightarrow\; \Omega_\psi \to 0$$

It follows that

$$t_R \simeq 8 \times 10^9$$

Attaining Thermal Equilibrium:

In order to define a reheating temperature for the plasma of decay products, one must show they have obtained thermal equilibrium by the end of reheating.This will be the case if the interaction rate

$$\Gamma^{i}_{int} > H \, , \forall \, i$$

This $\Rightarrow$ the mean interaction length $1/\Gamma^{i}_{int}$ is within the causal horizon $1/H$.

As an example, let us determine the rate for the process

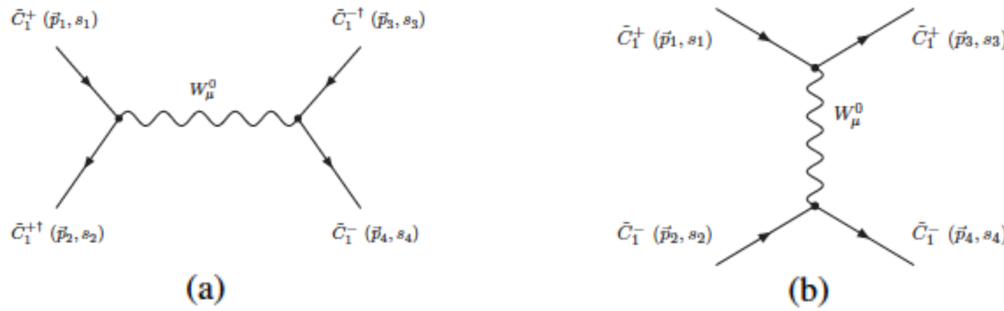
$$\tilde{C}^{+}_{1}\tilde{C}^{-}_{1} \rightarrow \tilde{C}^{+}_{1}\tilde{C}^{-}_{1}$$

where $\tilde{C}^{\pm}_{1}$ are the charginos. They can self-interact via the neutral gauge bosons

$$W^{0}_{\mu} \;\; , \;\; W_{R\mu} \;\; , \;\; B_{\mu}$$

However, at this scale their gauge coupling parameters and mass are very similar. Hence, for simplicity, we consider the interactions via W^{0}_{μ} only.

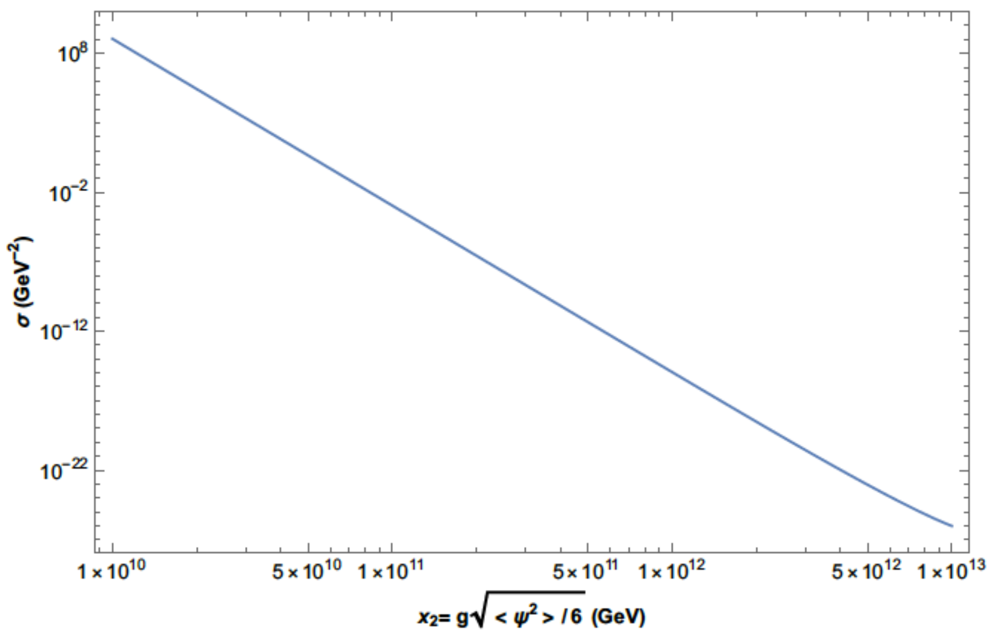
The associated Feynman diagrams are



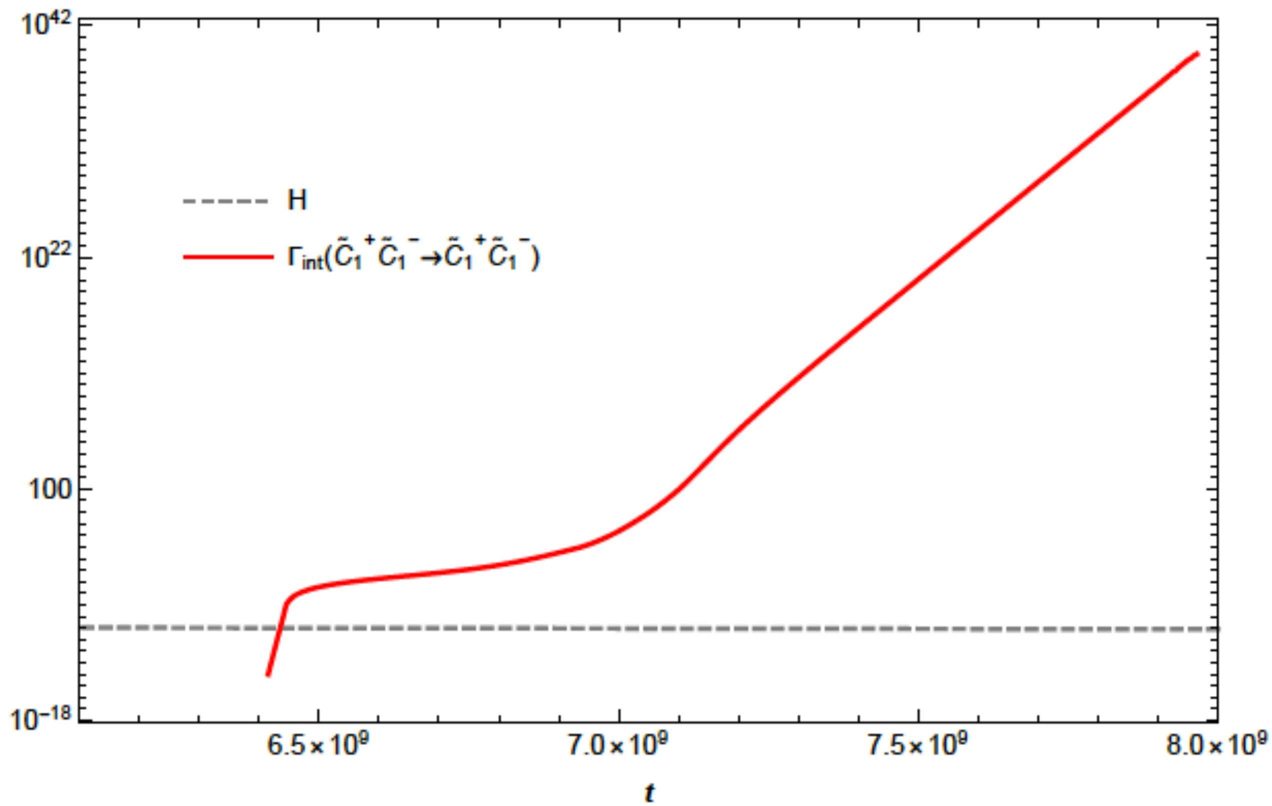
We find that

$$\Gamma_{int}(\tilde{C}_1^+\tilde{C}_1^- \to \tilde{C}_1^+\tilde{C}_1^-) \;=\; n\sigma v$$

where $n = \dfrac{\rho}{\langle E \rangle}$, $v \sim c = 1$ and



The result for the decay rate of charginos is



The rate Γ_{int} for the process $\tilde{C}_1^+\tilde{C}_1^- \to \tilde{C}_1^+\tilde{C}_1^-$ plotted against time (shown in units where $M_P = 1$). The rate almost immediately becomes larger than the Hubble parameter H, which is approximately 7.8×10^{-11} at the very end of the plot. The time at the end of reheating, $t_R \simeq 8\times10^9$.

We find a similar result for all decay species.

$\Rightarrow$ We have shown that the plasma is in thermal equilibrium at $t_R \simeq 8 \times 10^9$ and using a standard formula that the reheat temperature is

$$T_R \simeq 1.13 \times 10^{13} \ \mathbf{GeV}$$