The $B\!-\!L$ Phase Transition

as the Origin of the Hot Early Universe

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In collaboration with Wilfried Buchmüller, Valerie Domcke and Gilles Vertongen.

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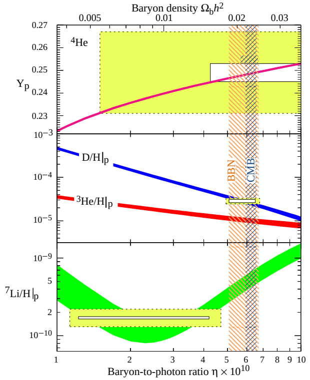
Outline

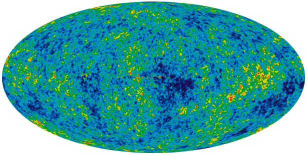
Outline

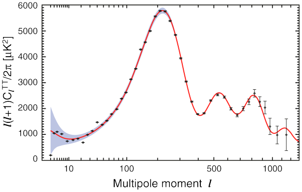
The Advent of the Era of Precision Cosmology

BBN

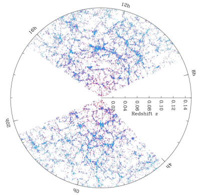


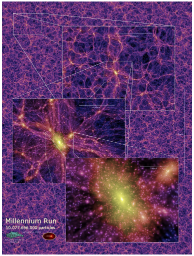
CMB



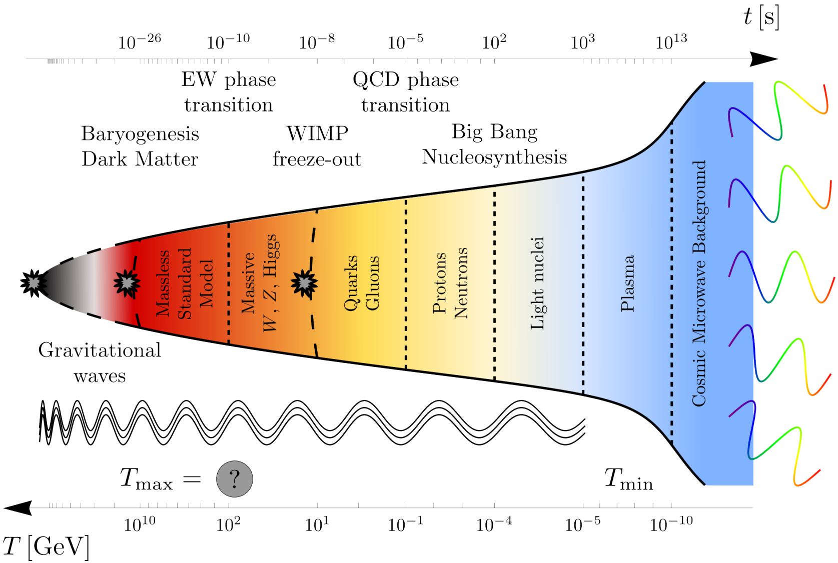


LSS





The Hot Thermal Phase of the Early Universe



Call for New Physics Beyond the Standard Model

The Cosmic Pie [WMAP7 + BAO + H_0 fitted to ΛCDM]

72.8 % Dark Energy

What is it?

Properties?

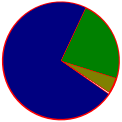
Origin?

22.7 % Dark Matter

What is it?

Properties?

Origin?



$\ll 1$ % Radiation

What is it?

Properties?

Origin?

4.5 % Baryonic Matter

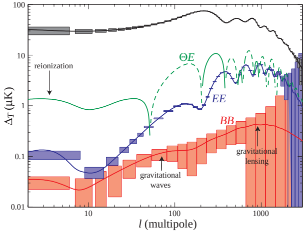
What is it?

Properties?

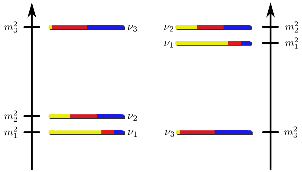
Origin?

New physical phenomena in the very early universe!

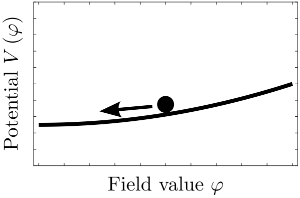
Primordial Metric Fluctuations



Neutrino Flavour Oscillations



The Origin of the Hot Early Universe?



Paradigm of standard Big Bang cosmology:

- Thermal phase preceded by cosmic inflation.
- Slowly rolling homogeneous inflaton field φ drives stage of accelerated expansion.

Open questions of contemporary particle cosmology:

- How does the transition between inflation and the thermal phase take place?

Goal: Description of the reheating process, evolution of the radiation temperature.

- What determines the initial conditions of the hot early universe?

Goal: Mechanism for the generation of entropy, baryon asymmetry and dark matter.

Outline

Phase Transition at the End of Hybrid Inflation

[Linde '91, Linde '94]
[Copeland et al. '94, Dvali et al. '94]

Our idea: The hot early universe is ignited in consequence of the phase transition at the end of hybrid inflation.

- Supersymmetric F-term hybrid inflation:

$$W \supset \frac{\sqrt{\lambda}}{2}\Phi\left(v_{B-L}^2 - S^2\right)$$

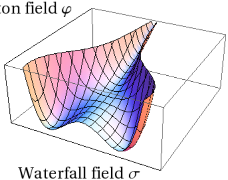
- False vacuum energy density drives inflation:

$$\rho_0 = \frac{1}{4}\lambda\, v_{B-L}^4$$

- At $\varphi = \varphi_c = v_{B-L}$, the waterfall field σ becomes tachyonically unstable and inflation ends:

$$m_\sigma^2\left(\varphi\right) = \frac{\lambda}{2}\left(\varphi^2 - v_{B-L}^2\right)$$

Scalar potential:



False vacuum:

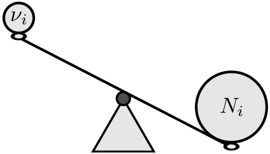
$$\langle\Phi\rangle \neq 0,\ \langle S\rangle = 0$$

True vacuum:

$$\langle\Phi\rangle = 0,\ \langle S\rangle = v_{B-L}$$

Connection between Cosmology and Particle Physics

Observation: The waterfall transition at the end of hybrid inflation corresponds to the *cosmological realization* of the spontaneous breaking of a global / local $U(1)$ symmetry.



We identify this symmetry with the local $U(1)_{B-L}$:

- Easily embedded into a bigger GUT picture.
- Need three generations of right-handed neutrinos to ensure anomaly freedom:

$$W \supset \frac{1}{2} h_i^n n_i^c n_i^c S \,, \quad M_i = h_i^n v_{B-L}$$

- After SSB three heavy Majorana neutrinos N_i plus superpartners $\tilde{N}_i$.
- Sets the stage for the seesaw mechansim and baryognesis via leptogenesis.

Summary: We claim that *the $B-L$ phase transition* serves as the origin of the hot big bang!

The Abelian Higgs Model of the $B\!-\!L$ Phase Transition

We need: Masses and decay rates of all particles involved in the PT and reheating.

We derive the Lagrangians for the:

① Supersymmetric Abelian gauge theory:

- For N chiral multiplets, arbitrary W.
- In arbitrary gauge.

② Supersymmetric Abelian Higgs Model:

- For our chiral multiplets and our W.
- In unitary gauge.

Implement SSB by shifting the Higgs field:

$$\frac{\sigma}{\sqrt{2}} \rightarrow v(t) + \frac{\sigma}{\sqrt{2}}\,, \qquad \lim_{t\rightarrow\infty} v(t) = v_{B-L}$$

$$\begin{aligned}
\mathscr{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - i\bar{\xi}\bar{\sigma}^{\mu}\partial_{\mu}\xi - \partial_{\mu}\phi^{*}\partial^{\mu}\phi - i\bar{\tilde{\phi}}\bar{\sigma}^{\mu}\partial_{\mu}\tilde{\phi} \\
& - \cosh\left(\sqrt{2}C/\tilde{v}\right)\left(\partial_{\mu}s^{*}\partial^{\mu}s + i\bar{\tilde{s}}\bar{\sigma}^{\mu}\partial_{\mu}\tilde{s}\right) \\
& + \sinh\left(\sqrt{2}C/\tilde{v}\right)\left[\frac{p_S}{2}\left(is^{*}\partial^{\mu}s - is\partial^{\mu}s^{*} + \bar{\tilde{s}}\bar{\sigma}^{\mu}\tilde{s}\right)A_{\mu}\right] \\
& - \cosh\left(\sqrt{2}C/\tilde{v}\right)\frac{p_S^2}{4}|s|^2 A_{\mu}A^{\mu} \\
& + \left\{\sinh\left(\sqrt{2}C/\tilde{v}\right)\frac{ip_S}{\sqrt{2}}s^{*}\tilde{s}\xi + \frac{1}{2}\sqrt{\lambda}\phi\tilde{s}\tilde{s} + \sqrt{\lambda}s\tilde{\phi}\tilde{s} + \text{h.c.}\right\} \\
& - \frac{\lambda}{4}\left|v_{B-L}^2 - s^2\right|^2 - \cosh\left(\sqrt{2}C/\tilde{v}\right)\lambda|s|^2|\phi|^2 \\
& - \frac{p_S^2}{8}\sinh^2\left(\sqrt{2}C/\tilde{v}\right)|s|^4 + \left\{\frac{\sqrt{\lambda}s^2}{2\tilde{v}^2}\phi\chi^2 + \text{h.c.}\right\} \\
& + \sinh\left(\sqrt{2}C/\tilde{v}\right)\left[\frac{|s|^2}{2\sqrt{2}}\Box\frac{C}{\tilde{v}} + \frac{p_S|s|^2}{2\tilde{v}^2}\bar{\chi}\bar{\sigma}^{\mu}\chi A_{\mu}\right. \\
& - \left\{\frac{s^{*}}{\tilde{v}}\bar{\chi}\bar{\sigma}^{\mu}\partial_{\mu}\tilde{s} + \text{h.c.}\right\} \\
& \left. + \frac{i}{\sqrt{2}}\left(\frac{i}{2}s^{*}\partial_{\mu}s + \frac{i}{2}s\partial_{\mu}s^{*} - \bar{\tilde{s}}\bar{\sigma}_{\mu}\tilde{s} - \frac{|s|^2}{\tilde{v}^2}\bar{\chi}\bar{\sigma}_{\mu}\chi\right)\partial^{\mu}\frac{C}{\tilde{v}}\right] \\
& - \cosh\left(\sqrt{2}C/\tilde{v}\right)\left[\frac{is^{*}}{\tilde{v}}\bar{\chi}\bar{\sigma}^{\mu}\partial_{\mu}\frac{s\chi}{\tilde{v}} + \frac{p_S|s|^2}{\sqrt{2}\tilde{v}}\left(\chi\xi + \bar{\chi}\bar{\xi}\right)\right. \\
& \left. + \left\{\frac{s^{*}}{\sqrt{2}\tilde{v}}\bar{\chi}\bar{\sigma}^{\mu}\tilde{s}\partial_{\mu}\frac{C}{\tilde{v}} + \frac{ip_S s^{*}}{2\tilde{v}}\bar{\chi}\bar{\sigma}^{\mu}\tilde{s}A_{\mu} + \text{h.c.}\right\}\right]
\end{aligned}$$

Tachyonic Preheating [Felder et al. '01]

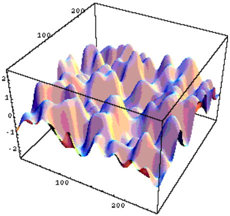
Energy transfer from the false vacuum to a gas of nonrelativistic Higgs bosons:

- Tachyonic instability for $\varphi < \varphi_c$ causes exponential growth of the long-wavelength Higgs modes.

We generalize Linde's conditions for a very rapid and abrupt waterfall transition to the supersymmetric case:

- Always fulfilled in the viable parameter region.
- Quench approximation applicable: $m_\sigma^2 \rightarrow -\frac{\lambda}{2} v_{B-L}$.

Growth of the Higgs quantum fluctuations:



[Garcia-Bellido et al. '01]

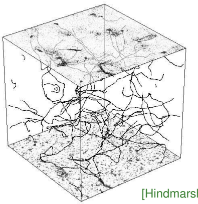
Nonadiabatic production of particles coupled to the Higgs field: [Garcia-Bellido & Ruiz Morales '02]

- Excitation of low-momentum modes due to sudden change in the masses.
- We calculate all relevant number and energy densities.
- All generated abundances subdominant to the one of the Higgs bosons.

Production of Cosmic Strings

[Jeannerot & Postma '05] [Battye et al. '06, Battye et al. '10]

Network of infinite strings and string loops:



[Hindmarsh '11]

Topological defects in the form of cosmic strings:

- Vacuum manifold of the Abelian Higgs model (brim of the Mexican hat) is isomorphic to S^1.
- Thus one-dimensional solitonic solutions of the classical equations of motion, i.e. cosmic strings.
- Possible source of isocurvature perturbations, gravitational lensing and gravitational waves.

Hybrid inflation & cosmic strings require:

[Yanagida et al. '10]

$$3 \times 10^{15}\,\mathrm{GeV} \lesssim v_{B-L} \lesssim 7 \times 10^{15}\,\mathrm{GeV}$$

$$10^{-4} \lesssim \sqrt{\lambda} \lesssim 10^{-1}$$

We fix v_{B-L} at $5 \times 10^{15}\,\mathrm{GeV}$ and determine:

- The number and energy densities of cosmic strings as functions of λ.
- The cosmic evolution during reheating in the case of extremal string production.

We find: Effects of cosmic strings always irrelevant. Hence we are allowed to neglect them.

Outline

Masses in Mixings in the Lepton Sector

Superpotential for all chiral quark and lepton superfields in $SU(5)$ notation:

$$W \supset \frac{1}{2} h_i^n n_i^c n_i^c S + h_{ij}^\nu \mathbf{5}_i^* n_j^c H_u + h_{ij}^u \mathbf{10}_i \mathbf{10}_j H_u + h_{ij}^d \mathbf{5}_i^* \mathbf{10}_j H_d$$

- $\mathbf{5}^* = (d^c, \ell)$ and $\mathbf{10} = (q, u^c, e^c)$ contain the MSSM quark and lepton fields.
- $\langle S \rangle = v_{B-L}$ and $\langle H_{u,d} \rangle = v_{u,d}$ break $B-L$ and the EW symmetry, respectively.

Neutrino and charged lepton masses:

$$M = v_{B-L} h^n\,, \quad m_D = v_u h^\nu\,, \quad m_e = v_d h^d$$

Seesaw formula for the light-neutrino mass matrix:

$$m_\nu = -m_D M^{-1} m_D^T$$

Mass diagonalization:

$$m_e^{\mathrm{diag}} = L^T m_e R$$
$$m_\nu^{\mathrm{diag}} = \Omega^T m_\nu \Omega$$

Lepton mixing matrix:

$$U_{\mathrm{PMNS}} = L^\dagger \Omega$$

Low-energy observables: Masses ($m_{1,2,3}$), angles (θ_{12}, θ_{13}, θ_{23}), phases (δ, α_{21}, α_{31}).

Parameterizing our Model in Terms of Flavour Charges

Froggatt-Nielsen flavour structure: [Froggatt & Nielsen '79]

- Based on a $U(1)_{\mathrm{FN}}$ flavour symmetry:
  [Buchmüller & Yanagida '99]

$\mathbf{10}_3$	$\mathbf{10}_2$	$\mathbf{10}_1$	$\mathbf{5}^*_3$	$\mathbf{5}^*_2$	$\mathbf{5}^*_1$
0	1	2	a	a	$a+1$
n^c_3	n^c_2	n^c_1	$S, H_{u,d}$	Φ	Σ
b	c	d	0	e	-1

- Yukawa interactions from nonrenormalizable terms in the effective field theory below Λ:

$$W \supset C_{ijk} \left(\frac{\Sigma}{\Lambda}\right)^{Q_i+Q_j+Q_k} \psi_i \psi_j \psi_k$$

$$h_{ij} \sim \eta^{Q_i+Q_j}, \quad \sqrt{\lambda} \sim \eta^{e}, \quad \eta = \frac{\langle\Sigma\rangle}{\Lambda} \sim \frac{1}{\sqrt{300}}$$

$$M \sim v_{B-L} \begin{pmatrix} \eta^{2d} & 0 & 0 \\ 0 & \eta^{2c} & 0 \\ 0 & 0 & \eta^{2b} \end{pmatrix}$$

$$m_D \sim v_u \eta^a \begin{pmatrix} \eta^{d+1} & \eta^{c+1} & \eta^{b+1} \\ \eta^{d} & \eta^{c} & \eta^{b} \\ \eta^{d} & \eta^{c} & \eta^{b} \end{pmatrix}$$

$$m_\nu \sim \frac{v_u^2}{v_{B-L}} \eta^{2a} \begin{pmatrix} \eta^2 & \eta & \eta \\ \eta & 1 & 1 \\ \eta & 1 & 1 \end{pmatrix}$$

$$m_e \sim v_d \eta^a \begin{pmatrix} \eta^3 & \eta^2 & \eta \\ \eta^2 & \eta & 1 \\ \eta^2 & \eta & 1 \end{pmatrix}$$

We restrict ourselves to: $e = 2b = 2c = 2(d-1)$ s.t. $m_\sigma = M_3 = M_2 = M_1/\eta^2$.

Physical parameters: $v_{B-L} \sim \eta^{2a} M_0\,, \quad M_1 \sim \eta^{2d} v_{B-L}\,, \quad M_0 \sim 10^{15}\,\mathrm{GeV}.$

Monte-Carlo Sampling of $\mathcal{O}(1)$ Factors

The low-energy neutrino observables depend on 39 real $\mathcal{O}(1)$ factors C:

$$h_i^n = C_i^n \eta^{2Q_i}, \quad h_{ij}^\nu = C_{ij}^\nu \eta^{Q_i+Q_j}, \quad h_{ij}^d = C_{ij}^d \eta^{Q_i+Q_j}$$

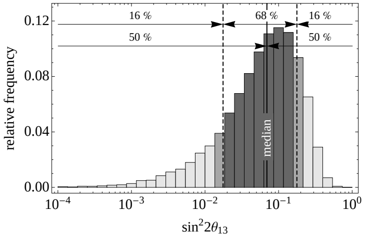
In a numerical study we generate random numbers to model these parameters:

$$-1/2 \leq \log_{10}|C_{ij}| \leq 1/2, \quad 0 \leq \arg C_{ij} < 2\pi$$

We compile roughly 20 000 sets of $\mathcal{O}(1)$ factors (hits) which yield lepton mass matrices that are consistent with the known neutrino data (@ $3\,\sigma$): [PDG '11]

$$2.07 \times 10^{-3}\,\mathrm{eV}^2 \leq |\Delta m^2_{\mathrm{atm}}| \leq 2.75 \times 10^{-3}\,\mathrm{eV}^2,$$
$$7.05 \times 10^{-5}\,\mathrm{eV}^2 \leq \Delta m^2_{\mathrm{sol}} \leq 8.34 \times 10^{-5}\,\mathrm{eV}^2,$$
$$0.75 \leq \sin^2(2\theta_{12}) \leq 0.93,$$
$$0.88 \leq \sin^2(2\theta_{23}) \leq 1.$$

Predictions for Neutrino Observables

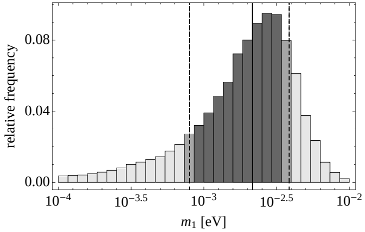


Sharp and robust predictions:

- Dispersion around median often $\lesssim \mathcal{O}(1)$.
- Robust against slight variation of exp. error margins & details of the MC study.
- Shapes of the distributions due to flavour structure *and* experimental input.

Numerical results:

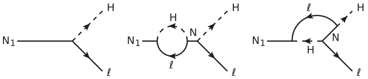
- Spectrum always has a *normal hierarchy*.
- $\sin^2 2\theta_{13} = 0.07^{+0.11}_{-0.05}$, compare with $\simeq 0.09$ [Daya Bay '12] and $\simeq 0.11$ [Reno '12].
- Low mass scale, $m_1 = 2.2^{+1.7}_{-1.4} \times 10^{-3}\,\mathrm{eV}$.
- Peak in Majorana phase, $\alpha_{21}/\pi = 1.0^{+0.2}_{-0.2}$.



Outline

Reheating through Heavy (S)neutrino Decays

Reheating driven by the decays of the N_1 & $\tilde{N}_1$ produced in Higgs decays!



Cosmological gravitino problems:

- Light stable $\widetilde{G}$: overclosure!
- Heavy unstable $\widetilde{G}$: spoils BBN!

Gravitino dark matter: $\Omega^0_{\widetilde{G}} h^2 = \Omega^0_{\mathrm{DM}} h^2$

- $\widetilde{G}$ is LSP with $m_{\widetilde{G}} \sim 100\,\mathrm{GeV}$.
- $\Omega^0_{\widetilde{G}} h^2 = \Omega^0_{\widetilde{G}} h^2 \left(\widetilde{m}_1, M_1, m_{\widetilde{G}}, m_{\tilde{g}}\right)$.

Definition of the reheating temperature:

$$H\left(T_{\mathrm{RH}}\right) = \Gamma^S_{N_1} \;\Rightarrow\; T_{\mathrm{RH}} \sim 0.2\sqrt{\Gamma^S_{N_1} M_P}$$

Zero-temperature neutrino decay rate:

$$\Gamma^0_{N_1} = \frac{\widetilde{m}_1}{4\pi}\left(\frac{M_1}{v_u}\right)^2, \quad \widetilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1}$$

T_{RH} controlled by neutrino parameters:

$$T_{\mathrm{RH}} = T_{\mathrm{RH}}\left(\widetilde{m}_1, M_1\right)$$

Typical values (FN and th. leptogenesis):

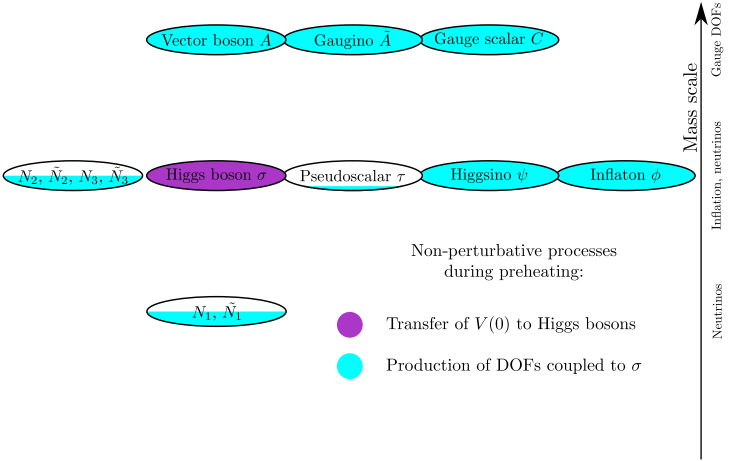
$$\widetilde{m}_1 \sim 0.01\,\mathrm{eV}, \; M_1 \sim T_{\mathrm{RH}} \sim 10^{10}\,\mathrm{GeV}$$

Thermal gravitino production:

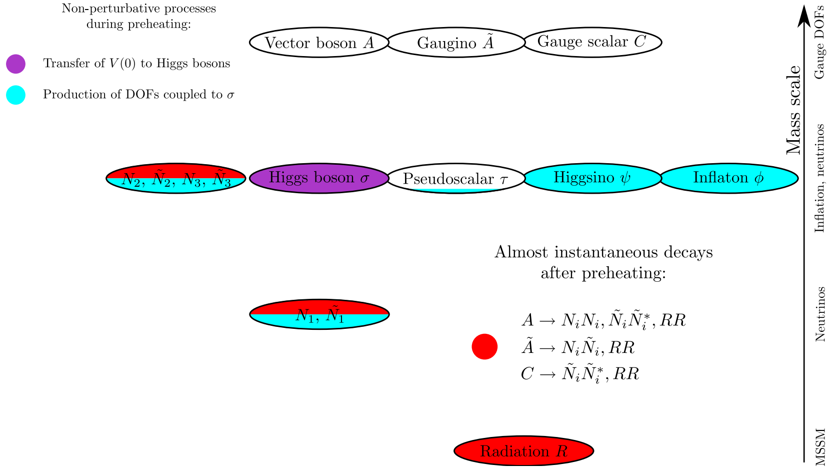
[Bolz et al. '01, Steffen & Pradler '07]

$$\Omega^0_{\widetilde{G}} h^2 = 0.26\left(\frac{T_{\mathrm{RH}}}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{G}}}\right)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2$$

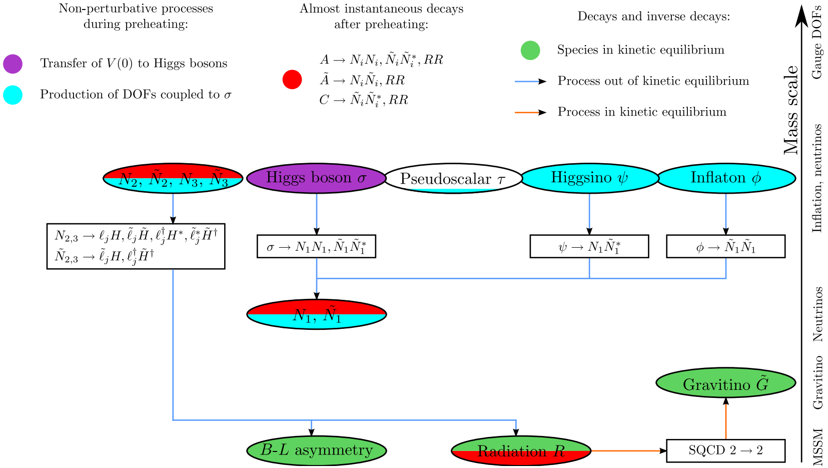
Particle Production during Tachyonic Preheating



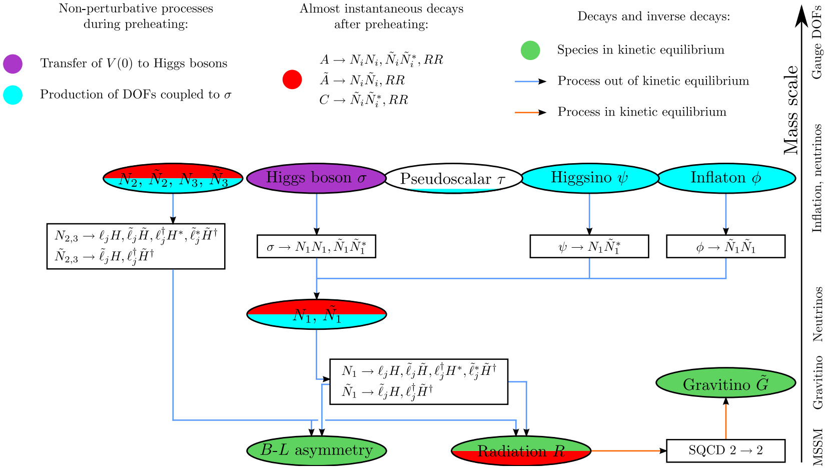
Decay of the Gauge Degrees of Freedom



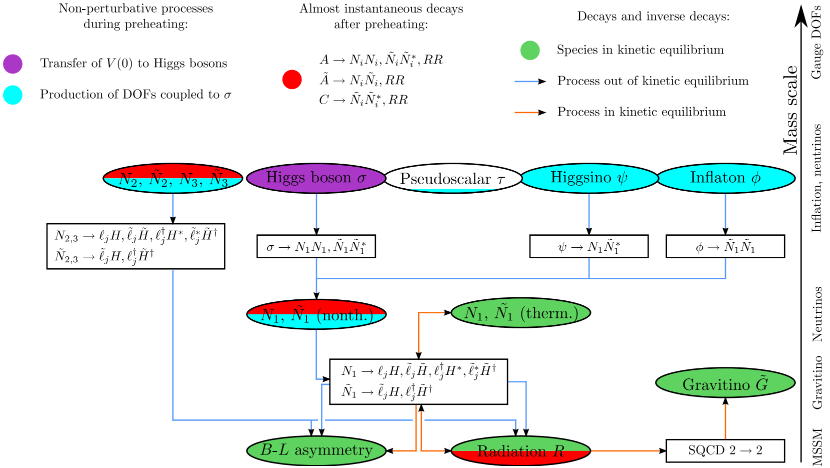
Decay of N_2, $\tilde{N}_2$, N_3, $\tilde{N}_3$, σ, ψ and ϕ



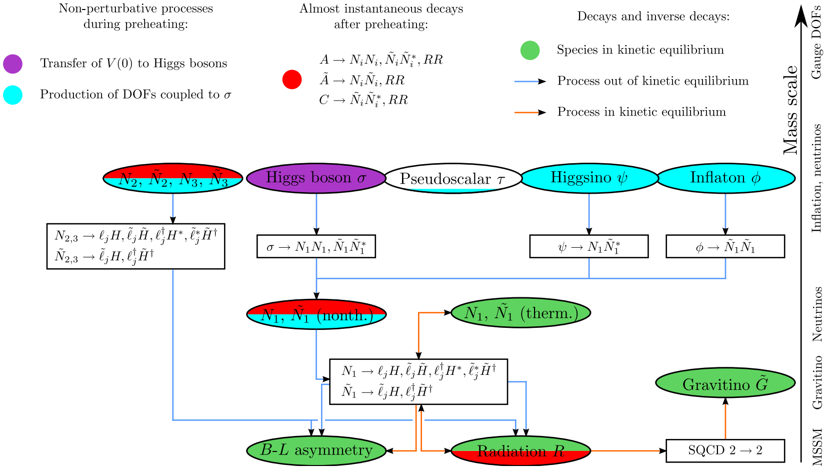
Decay of the Nonthermal Neutrinos



Production and Decay of Thermal Neutrinos



Production and Decay of Thermal Neutrinos



Math. description: Boltzmann equations—coupled system of non-linear first-order PDEs.

Solve for phase space distr. funcs. and number densities in expanding FLRW background.

Boltzmann Equations

$$\hat{\mathcal{L}} f_X(t,p) = E_X \left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_X(t,p) = \mathcal{C}_X$$

$$\hat{\mathcal{L}} f_X(t,p) = -m_X \Gamma_X^0 f_X(t,p)$$

$$\hat{\mathcal{L}} f_X(t,p) = \frac{2\pi^2 E_X}{g_X} \sum_{ij} (1+\delta_{Xj})\gamma(i \to Xj)\frac{\delta(p-p_*)}{p^2} - m_X \Gamma_X^0 f_X(t,p)$$

$$aH\frac{d}{da}N_X^{\text{th}} = -\Gamma_X^{\text{th}}\left(N_X^{\text{th}} - N_X^{\text{eq}}\right), \quad \hat{\Gamma}_W = \sum_i N_{N_i}^{\text{eq}} / \left(2N_\ell^{\text{eq}}\right)\Gamma_{N_i}^{\text{th}}$$

$$aH\frac{d}{da}N_L = \hat{\Gamma}_L^{\text{nt}} N_L^{\text{nt}} + \hat{\Gamma}_L^{\text{th}} N_L^{\text{th}} - \hat{\Gamma}_W N_L, \quad aH\frac{d}{da}N_R = \hat{\Gamma}_R^{\text{nt}} N_R^{\text{nt}} + \hat{\Gamma}_R^{\text{th}} N_R^{\text{th}}$$

$$\hat{\Gamma}_L^{\text{nt}} N_L^{\text{nt}} = \sum_{R_i} \varepsilon_i \left(\Gamma_{R_i}^{\text{PH}} N_{R_i}^{\text{PH}} + \Gamma_{R_i}^{G} N_{R_i}^{G}\right) + \varepsilon_1 \left(\Gamma_{N_1}^{S} N_{N_1}^{S} + \Gamma_{\tilde{N}_1}^{S} N_{\tilde{N}_1}^{S}\right)$$

$$\hat{\Gamma}_L^{\text{th}} N_L^{\text{th}} = \sum_i \varepsilon_i \Gamma_{N_i}^{\text{th}} \left(N_{N_i}^{\text{th}} + N_{\tilde{N}_i}^{\text{th}} - 2N_{N_i}^{\text{eq}}\right)$$

$$\hat{\Gamma}_R^{\text{nt}} N_R^{\text{nt}} = \sum_{R_i} \left(r_{R_i}^{\text{PH}} \Gamma_{R_i}^{\text{PH}} N_{R_i}^{\text{PH}} + r_{R_i}^{G} \Gamma_{R_i}^{G} N_{R_i}^{G}\right) + \left(r_{N_1}^{S} \Gamma_{N_1}^{S} N_{N_1}^{S} + r_{\tilde{N}_1}^{S} \Gamma_{\tilde{N}_1}^{S} N_{\tilde{N}_1}^{S}\right)$$

$$\hat{\Gamma}_R^{\text{th}} N_R^{\text{th}} = \sum_i r_{R_i}^{\text{th}} \Gamma_{N_i}^{\text{th}} \left(N_{N_i}^{\text{th}} + N_{\tilde{N}_i}^{\text{th}} - 2N_{N_i}^{\text{eq}}\right)$$

$$aH\frac{d}{da}N_{\tilde{G}} = a^3 \left(1 + \frac{m_{\tilde{g}}^2(T)}{3m_{\tilde{G}}^2}\right) \frac{54\zeta(3) g_s^2(T)}{\pi^2 M_P^2} T^6 \left[\ln\left(\frac{T^2}{m_g^2(T)}\right) + 0.8846\right]$$

$$\Gamma_{R_i}^{\text{x}} = \left\langle \frac{M_i}{E_{R_i}} \right\rangle_{\text{x}} \Gamma_{R_i}^0, \quad r_{R_i}^{\text{x}} = \frac{3\rho_{R_i}^{\text{x}}/n_{R_i}^{\text{x}}}{4\rho_R/n_R}$$

Novel technical procedure:

- Decompose distr. funcs. into independently evolving parts:

$$f_{N_1} = f_{N_1}^{\text{PH}} + f_{N_1}^{G} + f_{N_1}^{S} + f_{N_1}^{\text{th}}$$

- Solve eqs. for nonthermal contributions analytically.
- Remaining eqs. numerically.

We solve the Boltzmann eqs. for:

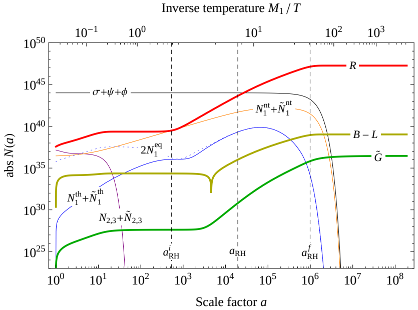
① A representative parameter point:

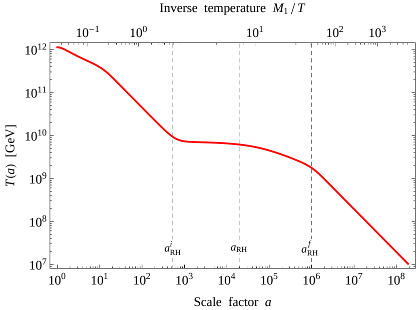
- Time-resolved descript. of RH.

② All points in the parameter space:

- Functional dependences and parameter relations.

Comoving Number Densities and Radiation Temperature





Initial conditions of the hot early universe:

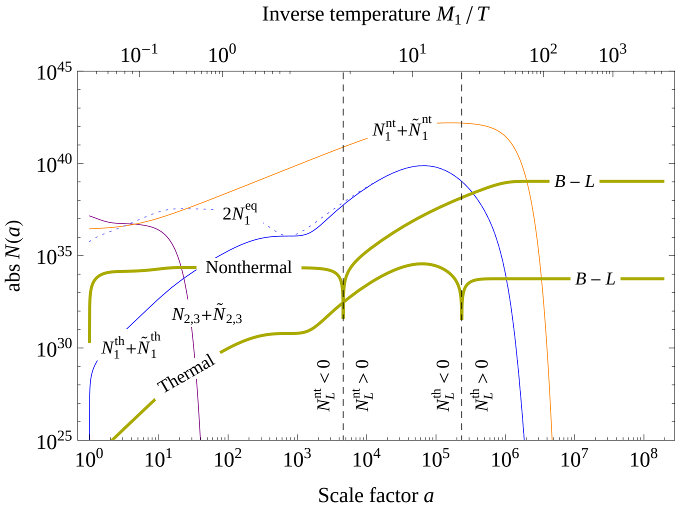
- $T_{\mathrm{RH}} = 6 \times 10^9\,\mathrm{GeV}$.
- $\eta_B^0 = 4 \times 10^{-9} > \eta_B^{\mathrm{obs}} = 6 \times 10^{-10}$.
- $\Omega_{\widetilde{G}}^0 h^2 = 0.11 = \Omega_{\mathrm{DM}}^0 h^2$.

Plateau in the temperature evolution:

- Entropy prod. balances expansion.
- Constant temperature until η_B^0 and $\Omega_{\widetilde{G}}^0 h^2$ cooked to the right point.

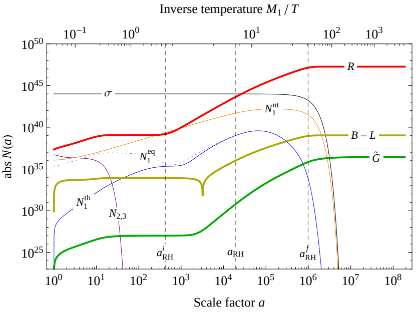
$$v_{B-L} = 5 \times 10^{15}\,\mathrm{GeV}\,,\ \widetilde{m}_1 = 0.04\,\mathrm{eV}\,,\ M_1 = 5 \times 10^{10}\,\mathrm{GeV}\,,\ m_{\widetilde{G}} = 100\,\mathrm{GeV}\,,\ m_{\tilde{g}} = 1\,\mathrm{TeV}$$

(Non)thermal Contributions to the $B-L$ Asymmetry

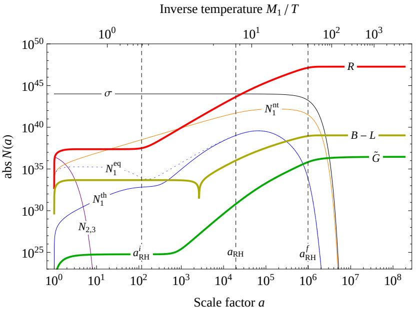


$$v_{B-L} = 5 \times 10^{15}\,\mathrm{GeV}\,,\ \widetilde{m}_1 = 0.04\,\mathrm{eV}\,,\ M_1 = 5 \times 10^{10}\,\mathrm{GeV}\,,\ m_{\widetilde{G}} = 100\,\mathrm{GeV}\,,\ m_{\tilde{g}} = 1\,\mathrm{TeV}$$

Robustness against Theory Uncertainties



All heavy sparticles neglected.

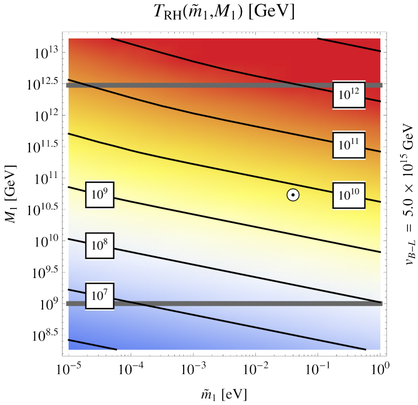


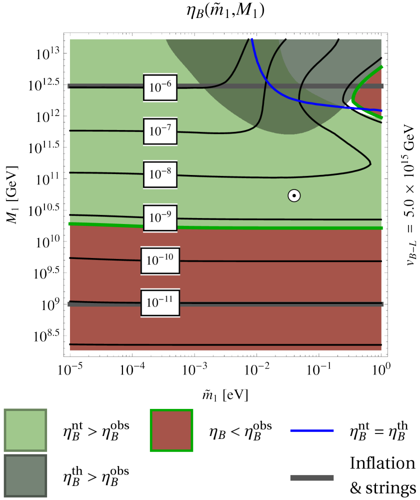
All heavy sparticles and gauge DOFs neglected.

- Same numerical results for the key quantities $T_{\rm RH}$, η_B^0 and $\Omega_{\widetilde{G}}^0 h^2$.
- Different evolution at early times, but irrelevant since evolution at late times dominated by the decays of the nonthermal neutrinos.

$$v_{B-L} = 5 \times 10^{15}\,\mathrm{GeV}\,,\ \widetilde{m}_1 = 0.04\,\mathrm{eV}\,,\ M_1 = 5 \times 10^{10}\,\mathrm{GeV}\,,\ m_{\widetilde{G}} = 100\,\mathrm{GeV}\,,\ m_{\tilde{g}} = 1\,\mathrm{TeV}$$

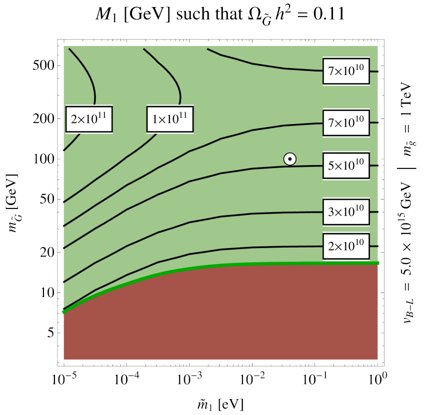
Reheating Temperature and Baryon Asymmetry

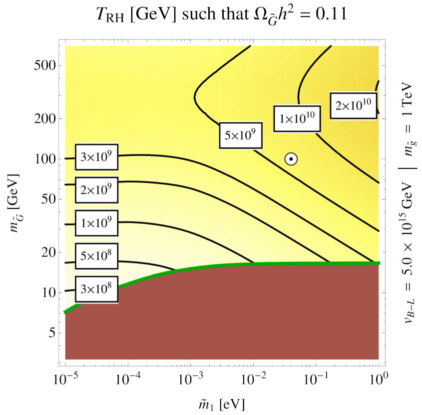




Hybrid inflation, cosmic strings and leptogenesis constrain $\widetilde{m}_1$ and M_1.

Relations between SUGRA and Neutrino Parameters





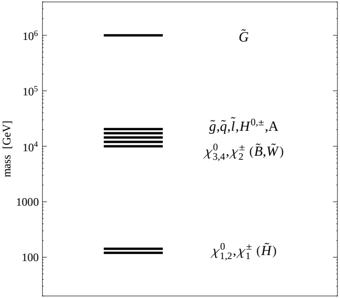
- Solve $\Omega^0_{\widetilde{G}} h^2(\widetilde{m}_1, M_1, m_{\widetilde{G}}) = \Omega^0_{\mathrm{DM}} h^2$ for M_1.
- Require $\eta^0_B(\widetilde{m}_1, M_1(\widetilde{m}_1, m_{\widetilde{G}})) > \eta^{\mathrm{obs}}_B$.

Lower bound: $m_{\widetilde{G}}(\widetilde{m}_1) \gtrsim 10\,\mathrm{GeV}$.

$M_1 \sim 10^{11}\,\mathrm{GeV}$, $T_{\mathrm{RH}} \sim 10^{9..10}\,\mathrm{GeV}$.

Outline

Thermal and Nonthermal Neutralino Production



[Yamaguchi et al. '11]

125 GeV Higgs realized in anomaly mediation:

[Ibe & Yanagida '12] [Nilles et al. '12]

- Gravitino heaviest superparticle.
- LSP pure wino or higgsino, almost mass-degenerate with corresponding chargino.

No cosmol. gravitino problems if $m_{\widetilde{G}} \gtrsim 10\,\mathrm{TeV}$:

[Weinberg '82]

- Gravitino decays into LSP before BBN.

Our idea: Produce WIMP DM in gravitino decays!

Neutralinos from thermal freeze-out:

[Arkani-Hamed et al. '06]

$$\Omega^{\rm th}_{\widetilde{w},\widetilde{h}} h^2 = c_{\widetilde{w},\widetilde{h}} \left(\frac{m_{\widetilde{w},\widetilde{h}}}{1\,\mathrm{TeV}}\right)^2$$

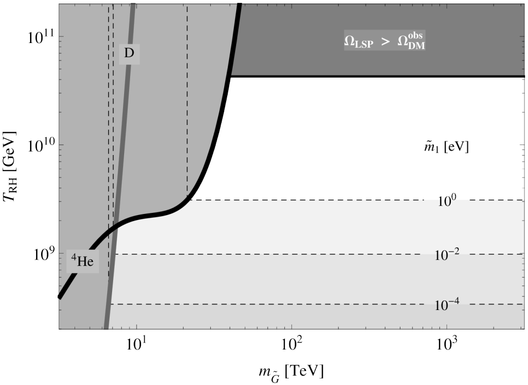
$$c_{\widetilde{w}} = 0.014\,, \quad c_{\widetilde{h}} = 0.10$$

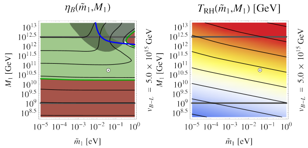
Neutralinos from gravitino decays:

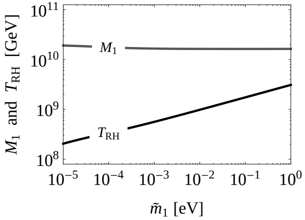
$$\Omega^{\widetilde{G}}_{\widetilde{w},\widetilde{h}} h^2 = \frac{m_{\widetilde{w},\widetilde{h}}}{m_{\widetilde{G}}} \Omega_{\widetilde{G}} h^2$$

$\Omega_{\widetilde{G}} h^2 \propto m_{\widetilde{G}} T_{\rm RH}$ from Boltzmann eqs.

Bounds on the Reheating Temperature







- Upper bounds from BBN. [Kawasaki et al. '08]
- Lower bounds from leptogenesis.

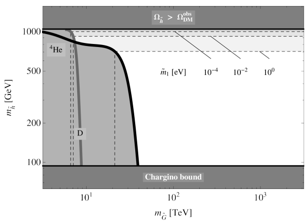
$\Omega^{\tilde{G}}_{\tilde{w},\tilde{h}} h^2 + \Omega^{th}_{\tilde{w},\tilde{h}} h^2 = \Omega^0_{DM} h^2$ yields

$T_{RH} \leftrightarrow m_{\tilde{w},\tilde{h}}$.

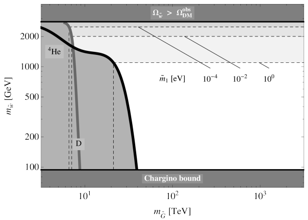
Bounds on the Neutralino and the Gravitino Mass

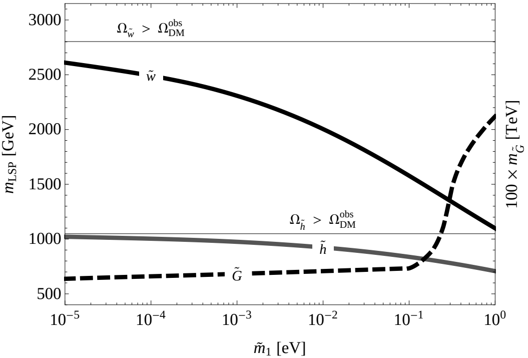
Map viable region in the $(m_{\widetilde{G}}, T_{\mathrm{RH}})$-plane into region in the $(m_{\widetilde{G}}, m_{\widetilde{w},\widetilde{h}})$-plane.

Higgsino LSP



Wino LSP





- Upper bounds on $m_{\widetilde{w},\widetilde{h}}$ from leptogenesis.
- Absolute lower bounds on $m_{\widetilde{G}}$ from BBN.
- All bounds functions of neutrino mass $\widetilde{m}_1$.

Outline

Topics not Covered in this Talk

Further results:

- Lower value of v_{B-L} (assuming a more complicated inflationary sector).
- Generalization of the gravitino LSP scenario to other gluino masses.
- Various technical issues: analytical reconstructions, etc.

Topics which have remained unaddressed so far:

- Alternatives to supersymmetric F-term inflation (D-term inflation)?
- Inflaton dynamics during SSB beyond the quench approximation (add. W_0)?
- Production of gravitational waves during the $B-L$ phase transition?
- Connection between our scenario & a solution to the NLSP decay problem?
- Implications of warm WIMP dark matter for structure formation?

The $B\!-\!L$ PT as the Origin of the Hot Early Universe

Question ①: Transition between inflation and thermal phase? Answer:

- Hybrid inflation ends in a waterfall transition during which $B\!-\!L$ gets broken.
- Abundance of heavy (s)neutrinos from Higgs decays, preheating, etc.
- Heavy (s)neutrinos decay into MSSM DOFs which immediately thermalize.

Question ②: Initial conditions of the hot early universe? Answer:

- Entropy generated in the decays of heavy nonthermal (s)neutrinos.
- Baryogenesis via a mixture of nonthermal and thermal leptogenesis.
- Thermally produced gravitinos constitute or decay into dark matter.

- T_{RH}, η_B^0 and $\Omega_{\widetilde{G}}h^2$ controlled by Lagrangian parameters (v_{B-L}, M_1, $\widetilde{m}_1$, $m_{\widetilde{G}}$ and $m_{\tilde{g}}$).
- No longer unknown cosmological parameters, but related to masses and couplings, which can be measured in HEP experiments and astrophyical observations.

Intriguing & testable mechanism to generate the initial conditions of the hot early universe!

Technical Achievements and Quantitative Findings

We have carried out a detailed study of the:

- Supersymmetric Abelian Higgs model of the $B\!-\!L$ phase transition.
- Boltzmann equations governing the reheating process.
- Froggatt-Nielsen flavour model in combination with exp. neutrino data.

We have obtained the following phenomenological results:

- Time-resolved picture of the reheating process (temperature plateau).
- Relations b/t SUGRA and neutrino parameters from requiring consistency between hybrid inflation, cosmic strings, leptogenesis and gravitino DM.
- Relations between the masses of the LSP, gravitino and light neutrinos from requiring consistency between leptogenesis, WIMP dark matter and BBN.
- Sharp predictions for undetermined observables of the neutrino sector.

The experimental confirmation of these relations would provide important indirect evidence for the $B\!-\!L$ phase transition as the origin of the hot early universe.

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The experimental confirmation of these relations would provide important indirect evidence for the $B{-}L$ phase transition as the origin of the hot early universe.

Thank you for your attention!

Supplementary Material

Important Formulae: Hybrid Inflation

Coleman-Weinberg 1-loop potential: [Coleman & Weinberg '73]

$$V_{\rm CW} = \frac{1}{64\pi^2}\,\mathrm{Str}\left[M^4 \ln\left(\frac{M^2}{\Lambda^2}\right)\right] = \frac{\lambda\rho_0}{16\pi^2}\left[\ln\left(\frac{\lambda\varphi^2}{2\Lambda^2}\right) + \frac{1}{2}\sum_{s=\pm1}\left(1+sx^2\right)^2 \ln\left(1+\frac{s}{x^2}\right)\right]$$

Slow-roll parameters:

$$\varepsilon_V = \frac{1}{2\kappa}\left(\frac{V'}{V}\right)^2 \approx \frac{\lambda}{16\pi^2}\left|\eta_V\right|\,, \quad \eta_V = \frac{1}{\kappa}\frac{V''}{V} \approx -\frac{1}{2N_e}\,, \quad \kappa = \frac{8\pi}{M_P^2}\,, \quad N_e \approx \frac{32\pi^3}{\lambda M_P^2}\varphi^2$$

Inflationary observables:

$$P_s(k) = \frac{\kappa^2 V}{24\pi^2\varepsilon_V}\,, \quad P_t(k) = \frac{2\kappa^2 V}{3\pi^2}\,, \quad n_s = 1 + 2\eta_V - 6\varepsilon_V\,, \quad r = 16\varepsilon_V\,, \quad n_t = -2\varepsilon_V$$

Predictions:

$$v_{B-L} \simeq 8\times 10^{15}\,\mathrm{GeV}\left(\frac{A_s}{2.441\times 10^{-9}}\right)^{1/4}\left(\frac{50}{N_e^*}\right)^{1/4}\,, \quad n_s \simeq 1 - \frac{1}{N_e^*} \simeq 0.98$$

Important Formulae: Time-Dependent Mass Eigenvalues

Time-dependent Higgs vacuum expectation value in the quench approximation:

[Garcia-Bellido & Ruiz Morales '02]

$$v(t) = \langle s_+^* s_+ \rangle = \int \frac{d^3k}{(2\pi)^3} \left|s_+(k,t)\right|^2 = \frac{v_{B-L}}{2}\left[1 + \tanh\frac{m_S(t-t_{\rm PH})}{2}\right], \quad m_S = \sqrt{\lambda}\, v_{B-L}$$

Time-dependent mass eigenvalues:

$$m_\sigma^2(t) = \frac{\lambda}{2}\left(3v^2(t) - v_{B-L}^2 + \varphi^2(t)\right), \quad m_\tau^2(t) = \frac{\lambda}{2}\left(v^2(t) + v_{B-L}^2 + \varphi^2(t)\right)$$

$$m_\psi^2(t) = m_\phi^2(t) = \lambda\, v^2(t)$$

$$m_A^2(t) = m_{\tilde{A}}^2(t) = 8g^2 v^2(t), \quad m_C^2(t) = 8g^2 v^2(t) + 2\frac{\dot{v}^2(t)}{v^2(t)} - \frac{\ddot{v}(t)}{v(t)}$$

$$M_i(t) = h_i^n v(t)$$

Important Formulae: Cosmic Strings

[Vilenkin '85] [Hindmarsh & Kibble '95] [Hindmarsh '11]

String tension, string energy per unit length:

$$\mu = 2\pi v_{B-L}^2 B(\beta)\,, \quad B(\beta) \simeq \begin{cases} 1.04\,\beta^{0.195}\,, & 10^{-2} \lesssim \beta \ll 1\,, \\ 2.4/\ln(2/\beta)\,, & \beta \lesssim 10^{-2}\,, \end{cases}\,, \quad \beta = \frac{\lambda}{8g^2}$$

String separation scale:

$$\xi \approx \left(-\lambda\, v_{B-L}\dot{\varphi}_c\right)^{-1/3}\,, \quad -\dot{\varphi}_c = \left[\frac{1}{3H}\left(V' + \ddot{\varphi}\right)\right]_{\varphi=\varphi_c}$$

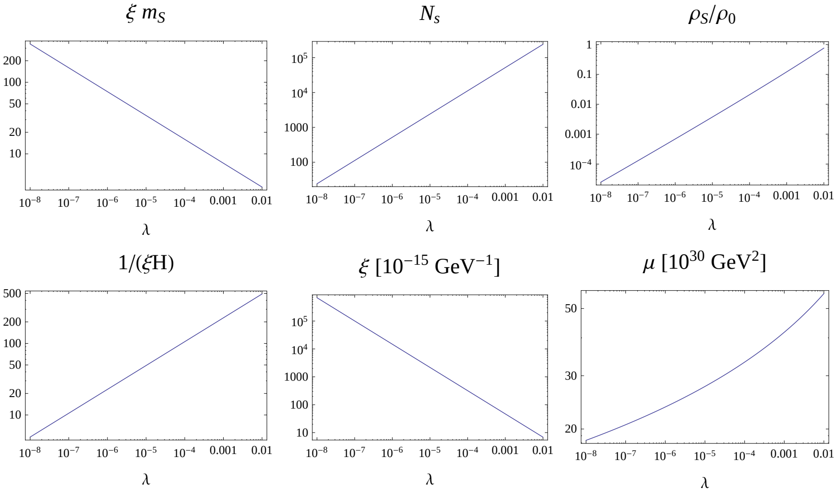
String energy density:

$$\rho_{\text{string}} = \frac{\mu}{\xi^2}$$

Bound on the string tension: [Battye & Moss '10] [Dunkley et al. '11] [Urrestilla et al. '11] [Dvorkin et al. '11]

$$G\mu \lesssim 5\times 10^{-7} \quad \Rightarrow \quad v_{B-L} \lesssim 1.8\times 10^{-4}\left(\ln\frac{16g^2}{\lambda}\right)^{1/2} M_P \lesssim 10^{16}\,\text{GeV} \quad \text{for } \lambda > 10^{-20}$$

Properties of Cosmic Strings



No SUGRA corrections included, otherwise no inflation for $\lambda < \lambda_{\mathrm{min}}$.

Conditions for a Rapid and Abrupt Waterfall Condition

Require Δt_σ and Δt_ϕ to be much shorter than H^{-1} at the end of inflation:

$$\Delta t_\sigma, \Delta t_\phi \ll H_I^{-1}\,, \quad H_I^2 = \frac{8\pi}{3M_P^2}\rho_0$$

- Δt_σ: time it takes until negative mass squared of the waterfall field sizable.
- Δt_ϕ: time scale on which the inflaton field value changes after $\varphi = \varphi_c$.

Nonsupersymmetric hybrid inflation: [Linde '94]

$$V(\varphi,\sigma) = \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4}\left(v_{B-L} - \sigma^2\right)^2 + \frac{1}{2}g^2\varphi^2\sigma^2\,, \quad m_\sigma^2 = \lambda v_{B-L}^2$$

$$m_\sigma^3 \ll \lambda m M_P^2$$

$$m_\sigma^3 \ll \sqrt{\lambda}\, g m M_P^2$$

Supersymmetric F-term hybrid inflation (based on Coleman-Weinberg potential):

$$\frac{256\pi^4}{3\ln 3}\left(\frac{v_{B-L}}{M_P}\right)^4 \ll \lambda$$

$$v_{B-L} \ll \sqrt{\frac{3}{2\pi}\frac{M_P}{C_\phi}}\,, \quad C_\phi \sim 10$$

Important Formulae: Tachyonic Preheating

Linearized mode equations of the $B\!-\!L$ Higgs boson (neglecting the cosmic expansion):

$$\ddot{s}_+(k,t) + \left(k^2 + m_{s_+}^2\right) s_+(k,t) = 0\,, \quad m_{s_+}^2 = \frac{\lambda}{2}\left(\varphi^2 - \varphi_c^2\right)\,, \quad \varphi \le \varphi_c$$

Solution for fixed inflaton field value φ:

$$s_+(k,t) = A(k)\exp\left(\omega_k t\right) + B(k)\exp\left(-\omega_k t\right)\,, \quad \omega_k = \sqrt{-m_{s_+}^2 - k^2}$$

Higgs dispersion and occupation numbers:

$$v^2(t) = \left\langle s_+^* s_+ \right\rangle = \int \frac{d^3k}{(2\pi)^3} \left|s_+(k,t)\right|^2\,, \quad n_k(t) = \left|s_+^*(k,t)\dot{s}_+(k,t)\right| - \frac{1}{2}$$

Number and energy densities generated during preheating: [Garcia-Bellido & Ruiz Morales '02]

$$n_B\left(t_{\mathrm{PH}}\right) \simeq 1\times 10^{-3} g_i m_S^3 f(\alpha,1.3)/\alpha\,, \quad n_F\left(t_{\mathrm{PH}}\right) \simeq 3.6\times 10^{-4} g_i m_S^3 f(\alpha,0.8)/\alpha\,,$$

$$\rho_B\left(t_{\mathrm{PH}}\right)/\rho_0 \simeq 2\times 10^{-3}\, g_i\,\lambda\, f(\alpha,1.3)\,, \quad \rho_F\left(t_{\mathrm{PH}}\right)/\rho_0 \simeq 1.5\times 10^{-3}\, g_i\,\lambda\, f(\alpha,0.8)\,,$$

$$f(\alpha,\gamma) = \sqrt{\alpha^2+\gamma^2} - \gamma\,, \quad \alpha = m_i/m_S\,, \quad m_S = \sqrt{\lambda}\, v_{B-L}$$

Important Formulae: Neutrino Observables

Pontecorvo-Maki-Nakagawa-Sakata matrix: [PDG '11]

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13}e^{i\frac{\alpha_{21}}{2}} & s_{13}e^{i(\frac{\alpha_{31}}{2}-\delta)} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & (c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta})e^{i\frac{\alpha_{21}}{2}} & s_{23}c_{13}e^{i\frac{\alpha_{31}}{2}} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & (-c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta})e^{i\frac{\alpha_{21}}{2}} & c_{23}c_{13}e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

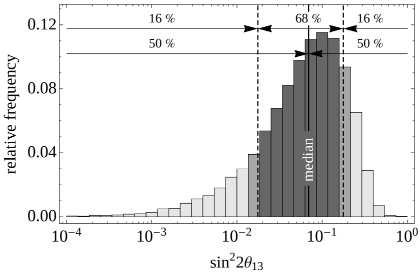
Neutrino masses:

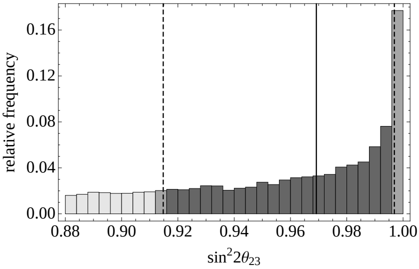
$$0.05\,\text{eV} \lesssim m_{\text{tot}} = \sum_i m_i \lesssim 0.28\,\text{eV}\,, \qquad \text{PLANCK: } m_{\text{tot}} \to 0.1\,\text{eV}$$ [PLANCK '06]

$$m_\beta^2 = \sum_i |U_{ei}|^2\, m_i^2 < 4\,\text{eV}^2\,, \qquad \text{KATRIN: } m_\beta^2 \to 0.04\,\text{eV}^2$$ [Beck '10]

$$m_{0\nu\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| \overset{?}{\simeq} 0.11..0.56\,\text{eV}\,, \qquad \text{GERDA: } m_{0\nu\beta\beta} \to 0.09..0.20\,\text{eV}$$ [Meierhofer '11]

Distributions of Possible $\sin^2 2\theta_{13}$ and $\sin^2 2\theta_{23}$ Values

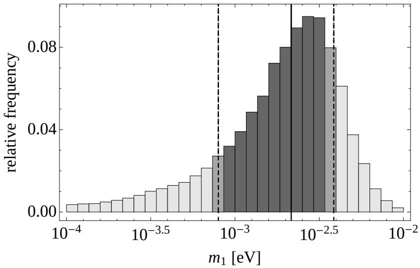


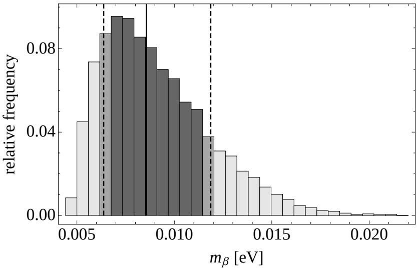


$$\sin^2 2\theta_{13} = 0.07^{+0.11}_{-0.05}$$

$$\sin^2 2\theta_{23} = 0.97^{+0.03}_{-0.05}$$

Distributions of Possible m_1 and m_β Values

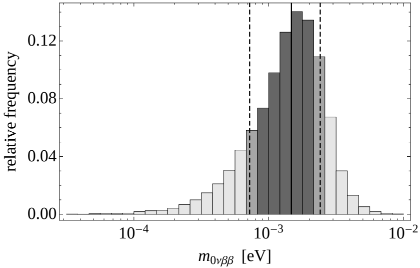


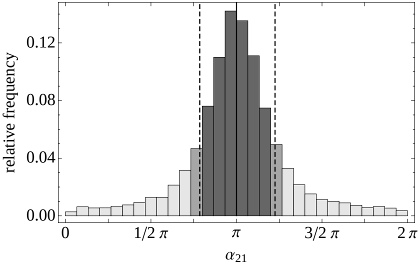


$$m_1 = 2.2^{+1.7}_{-1.4} \times 10^{-3}\,\mathrm{eV}$$

$$m_\beta = 8.6^{+3.3}_{-2.2} \times 10^{-3}\,\mathrm{eV}$$

Distributions of Possible $m_{0\nu\beta\beta}$ and α_{21} Values

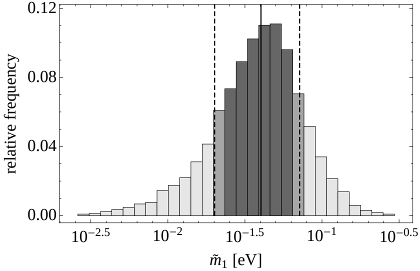


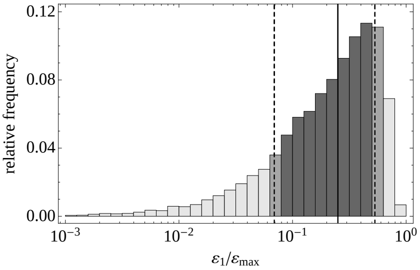


$$m_{0\nu\beta\beta} = 1.5^{+0.9}_{-0.8} \times 10^{-3}\,\mathrm{eV}$$

$$\alpha_{21}/\pi = 1.0^{+0.2}_{-0.2}$$

Distributions of Possible $\widetilde{m}_1$ and ε_1 Values

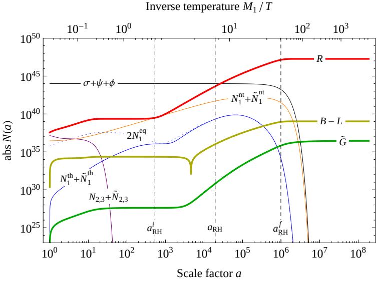


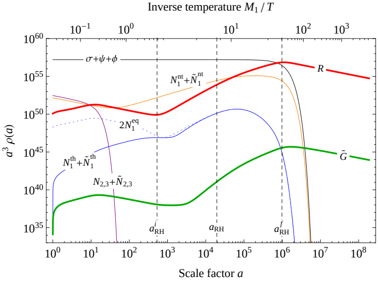


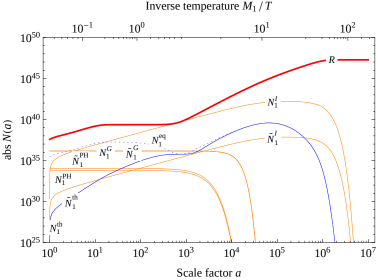
$$\widetilde{m}_1 = 4.0^{+3.1}_{-2.0} \times 10^{-2}\,\mathrm{eV}$$

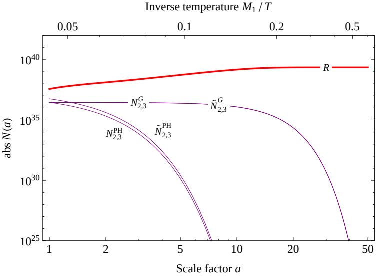
$$\varepsilon_1/\varepsilon_1^{\max} = 0.25^{+0.28}_{-0.18}$$

Comoving Number and Energy Densities









$$v_{B-L} = 5\times 10^{15}\,\mathrm{GeV}\,,\;\; \widetilde{m}_1 = 0.04\,\mathrm{eV}\,,\;\; M_1 = 5\times 10^{10}\,\mathrm{GeV}\,,\;\; m_{\widetilde{G}} = 100\,\mathrm{GeV}\,,\;\; m_{\tilde{g}} = 1\,\mathrm{TeV}$$

Important Formulae: Leptogenesis and EW Sphalerons

CP violation parameters: [Covi et al. '96] [Buchmüller & Plumacher '98]

$$\varepsilon_i = -\sum_{j\neq i} \frac{\mathrm{Im}\{[(h^\nu)^\dagger h^\nu]^2_{ij}\}}{8\pi[(h^\nu)^\dagger h^\nu]_{ii}} F\left(\frac{M_j^2}{M_i^2}\right), \quad F(x) = \sqrt{x}\left[\ln\left(\frac{1+x}{x}\right) + \frac{2}{x-1}\right]$$

Davidson-Ibarra bound on ε_1: [Hamaguchi et al. '02] [Davidson & Ibarra '02]

$$\varepsilon_1^{\mathrm{max}} \approx \frac{3}{8\pi}\frac{|\Delta m^2_{\mathrm{atm}}|^{1/2} M_1}{v^2_{\mathrm{EW}} \sin^2\beta} \simeq 2.1 \times 10^{-6}\left(\frac{1}{\sin^2\beta}\right)\left(\frac{M_1}{10^{10}\,\mathrm{GeV}}\right)$$

Anomalous baryon and lepton number currents: ['t Hooft '76, 't Hooft '76]

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{N_f}{32\pi^2}\varepsilon^{\mu\nu\sigma\tau}\left(-g_W^2 \mathrm{Tr} W_{\mu\nu}W_{\sigma\tau} + g_Y^2 B_{\mu\nu}B_{\sigma\tau} + g^2 A_{\mu\nu}A_{\sigma\tau}\right)$$

Sphaleron conversion factor in the MSSM (SM): [Khlebnikov & Shaposhnikov '88]

$$\eta_B^0 = C_{\mathrm{sph}} \frac{g_{*,s}^2}{g_{*,s}} \frac{n_{B-L}}{n_\gamma}\bigg|_{t_f}, \quad C_{\mathrm{sph}} = \frac{8N_f + 4N_H}{22N_f + 13N_H} = \frac{8}{23}\left(\frac{28}{79}\right)$$

Prospects for Direction Detection and Collider Experiments

Spin-independent elastic scattering cross section at tree level (h_0 exchange): [Hisano et al. '05]

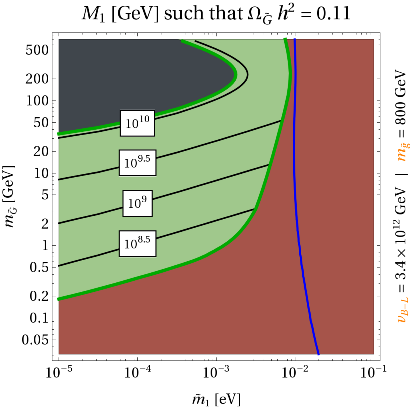
$$\sigma_{\rm SI}^{\widetilde{w}} \sim 2 \times 10^{-43}\,\mathrm{cm}^2 \left(\frac{125\,\mathrm{GeV}}{m_{h^0}}\right)^4 \left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{h}}}\right)^2 \left(\sin 2\beta + \frac{m_{\widetilde{w}}}{m_{\widetilde{h}}}\right)^2$$

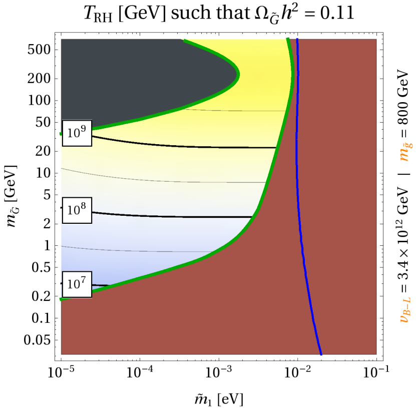
$$\sigma_{\rm SI}^{\widetilde{h}} \sim 7 \times 10^{-44}\,\mathrm{cm}^2 \left(\frac{125\,\mathrm{GeV}}{m_{h^0}}\right)^4 \left(\frac{100\,\mathrm{GeV}}{m_{\widetilde{w}}}\right)^2$$

Collider signatures: [Baer et al. '11] [Bobrovskyi et al. '12] [Moroi & Nakayama '12]

- No events with LSPs in the final state and missing E_T, since coloured particles heavy.
- Macroscopic charged tracks due to charginos produced along with LSPs.
- Monojets due to initial-state gluon radiation in Drell-Yan pair production processes.

Relations between SUGRA and Neutrino Parameters

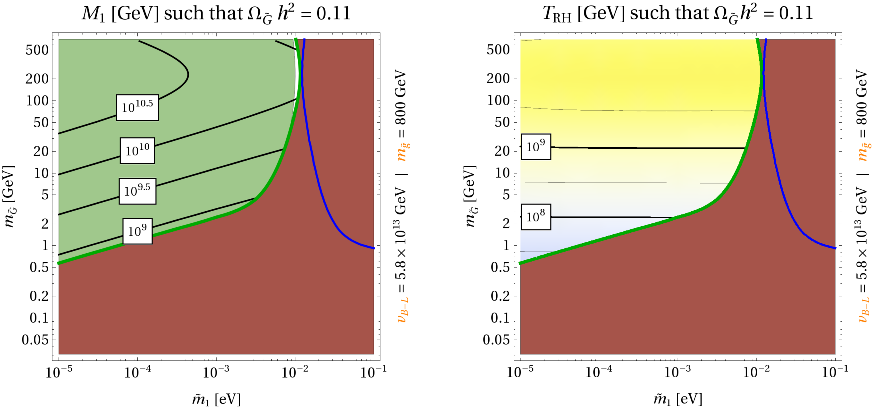




- Solve $\Omega^0_{\widetilde{G}} h^2(\widetilde{m}_1, M_1, m_{\widetilde{G}}) = \Omega^0_{\rm DM} h^2$ for M_1.
- Require $\eta^0_B(\widetilde{m}_1, M_1(\widetilde{m}_1, m_{\widetilde{G}})) > \eta^{\rm obs}_B$.

$v_{B-L} = 3.4 \times 10^{12}\,\mathrm{GeV}$

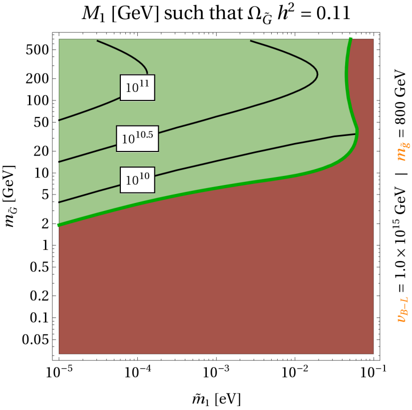
Relations between SUGRA and Neutrino Parameters

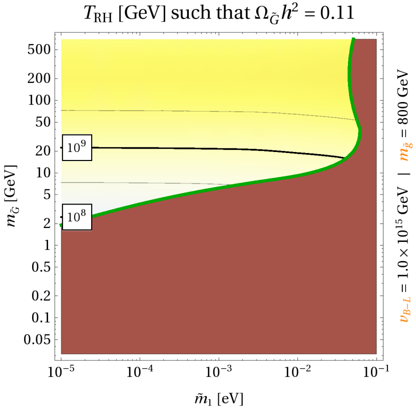


- Solve $\Omega^0_{\tilde{G}} h^2(\widetilde{m}_1, M_1, m_{\widetilde{G}}) = \Omega^0_{\mathrm{DM}} h^2$ for M_1.
- Require $\eta^0_B(\widetilde{m}_1, M_1(\widetilde{m}_1, m_{\widetilde{G}})) > \eta^{\mathrm{obs}}_B$.

$v_{B-L} = 5.8 \times 10^{13}\,\mathrm{GeV}$

Relations between SUGRA and Neutrino Parameters

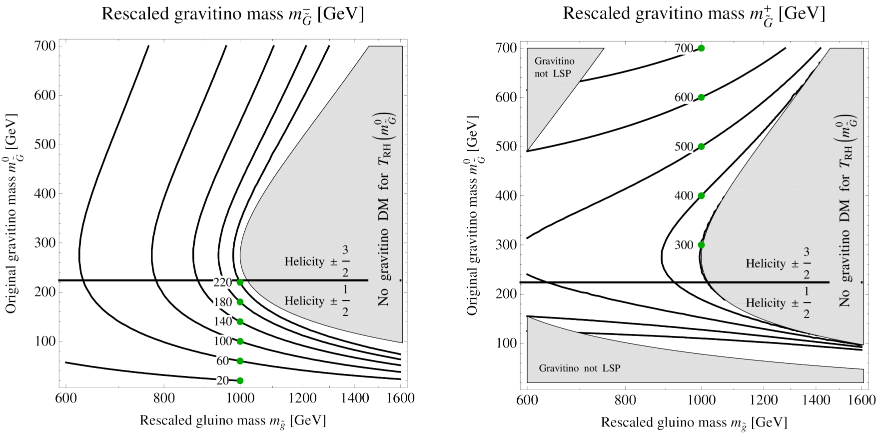




- Solve $\Omega^0_{\widetilde{G}} h^2(\widetilde{m}_1, M_1, m_{\widetilde{G}}) = \Omega^0_{\mathrm{DM}} h^2$ for M_1.
- Require $\eta^0_B(\widetilde{m}_1, M_1(\widetilde{m}_1, m_{\widetilde{G}})) > \eta^{\mathrm{obs}}_B$.

$v_{B-L} = 1.0 \times 10^{15}\,\mathrm{GeV}$

Rescaling the Gravitino Mass for $m_{\tilde{g}} \neq 1\,\mathrm{TeV}$



Solve $\Omega_{\tilde{G}}h^2\left(T_{\mathrm{RH}}, m^0_{\tilde{G}}, 1\,\mathrm{TeV}\right) = \Omega_{\tilde{G}}h^2\left(T_{\mathrm{RH}}, m_{\tilde{G}}, m_{\tilde{g}}\right)$.

- Quadratic eq. for $m_{\tilde{G}}\left(m_{\tilde{g}}, m^0_{\tilde{G}}\right)$ w/ two solutions $m^\pm_{\tilde{G}}$.
- For $m^0_{\tilde{G}} \ll m_{\tilde{g}}$: $\quad m_{\tilde{G}} = m^0_{\tilde{G}}\left(m_{\tilde{g}}/1\,\mathrm{TeV}\right)^2$.

T_{RH} and η_B unaffected as long as v_{B-L}, $\widetilde{m}_1$ and M_1 are kept constant.