Reheating, Matter, Dark Matter – All You Need is Neutrino Decays.

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Based on arXiv:1008.2355, 1104.2750 and 1110.xxxx [hep-ph].
In collaboration with W. Buchmüller, V. Domcke and G. Vertongen.

DESY Theory Workshop

Cosmology meets Particle Physics | September 28, 2011

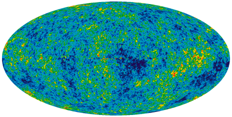
Outline

1. Idea
   - Reheating through heavy neutrino decays
   - Leptogenesis and gravitino dark matter
2. Scenario
   - $B-L$ breaking during false vacuum decay
   - Network of particle interactions
3. Analysis
   - Exemplary parameter point
   - Study of the parameter space
   - Summary and conclusion

Origin of the hot phase of the early universe?

Epoch dominated by energy in radiation:

- Evidence: CMB $(T \simeq 0.25\,\mathrm{eV})$ and BBN $(T \simeq 1\,\mathrm{MeV})$.
- Paradigm: Preceded by inflation (vacuum domination).
- Transition? Reheating mechanism and T_{RH} unknown.



Definition T_{RH}: $H(T =: T_{\mathrm{RH}}) = \Gamma_X \Rightarrow T_{\mathrm{RH}} \simeq 0.2\sqrt{\Gamma_X M_P}$.

Γ_X free parameter!

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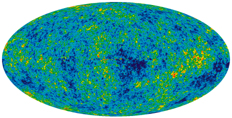

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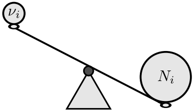
$$m_\nu = -m_D \frac{1}{M} m_D^T$$



Type I seesaw:

Add heavy Majorana neutrinos N_i to the SM.

Our idea: Entropy from heavy neutrino decays

- Assume dominant $N_1 + \tilde{N}_1$ abundance after inflation.
- At tree-level $\Gamma_{N_1} = \frac{\widetilde{m}_1}{4\pi}(M_1/v_{\mathrm{EW}})^2$, $\widetilde{m}_1 := (m_D^\dagger m_D)_{11}/M_1$.
- $T_{\mathrm{RH}} = T_{\mathrm{RH}}(\widetilde{m}_1, M_1) \sim 10^{9\div10}\,\mathrm{GeV}$ for typical $\widetilde{m}_1$ & M_1.
- Baryon asymmetry & dark matter are natural by-products.

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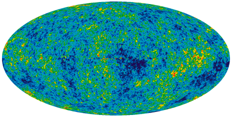

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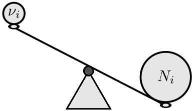

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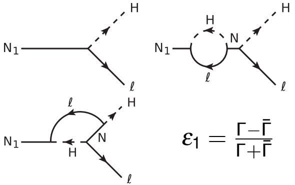
Consistent cosmology and non-trivial parameter relations!

Baryon asymmetry and dark matter

[Fukugita & Yanagida '86] [Buchmüller et al. '05] [Bolz et al. '01] [Steffen & Pradler '07]

Baryogenesis through leptogenesis:

- $\eta_B := n_B/n_\gamma \simeq 6 \times 10^{-10} \gg \eta_B^{\mathrm{sym}} \simeq 10^{-18}$.
- SM sphalerons convert L into B asymmetry (c_{sph}).
- Seesaw & neutrino data: $M_1 \sim T_L \sim 10^{9\div10}\,\mathrm{GeV}$.
- Hierarchical masses M_i lead to $\eta_B = \eta_B(\widetilde{m}_1, M_1)$.



$$\varepsilon_1 = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$$

CP-violating out-of-equilibrium neutrino decays

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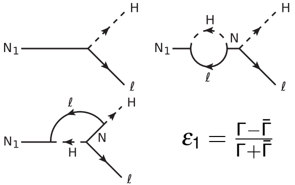

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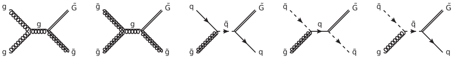
CP-violating out-of-equilibrium neutrino decays

Thermal prod. of gravitinos in SQCD:

- Do not spoil BBN or overclose the universe.
- DM for free if gravitino is heavy stable LSP.
- $\Omega_{\widetilde{G}} h^2 (T_{\rm RH}, m_{\widetilde{G}}, m_{\tilde{g}}) \simeq 0.11 \simeq \Omega_{\rm DM} h^2$.



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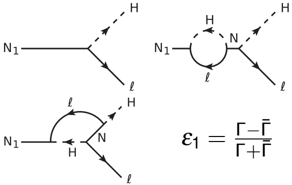

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CP-violating out-of-equilibrium neutrino decays

Connect the two sectors!

$$\Omega_{\widetilde{G}} h^2(\widetilde{m}_1, M_1, m_{\widetilde{G}}, m_{\tilde{g}}) = \Omega_{\mathrm{DM}} h^2$$

- Keep $m_{\tilde{g}}$ fixed & solve for M_1.
- $M_1, T_{\mathrm{RH}}, \eta_B = f(\widetilde{m}_1, m_{\widetilde{G}})$.
- Impose $\eta_B(\widetilde{m}_1, m_{\widetilde{G}}) \geq \eta_B^{\mathrm{obs}}$.
- Mutual bounds $\widetilde{m}_1 \leftrightarrow m_{\widetilde{G}}$.

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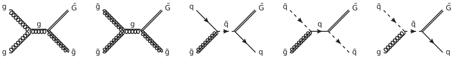

Generating a dominant nonthermal $N_1 + \tilde{N}_1$ abundance

SSB of $U(1)_{B-L}$ at v_{B-L} by gauge singlet σ:

- Seesaw: $\frac{1}{2} M_i \left(\overline{n^C_{Ri}} n_{Ri} + \mathrm{h.c.}\right)$ violates lepton number L.
- Interpretation: $\frac{1}{2} h_i^{(n)} \left(\overline{n^C_{Ri}} n_{Ri} \frac{\sigma}{\sqrt{2}} + \mathrm{h.c.}\right)$, $\sigma \to \sqrt{2} v_{B-L} + \sigma$.

- σ be the field coupling to the inflaton ϕ in hybrid inflation.
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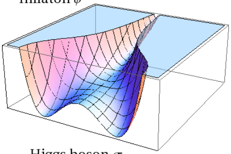
Hybrid inflation $=$
Chaotic inflation $+$ SSB



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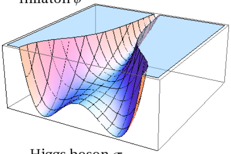

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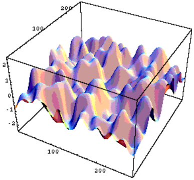

Tachyonic preheating: [Felder et al. '01] [García-Bellido & Ruiz Morales '02]

- Instability for $\phi < \phi_{\mathrm{crit}}$ causes explosive spinodal growth of long-wavelength Higgs modes: Waterfall transition!
- False vacuum energy density $\to$ Nonrelativistic σ bosons, DOFs coupled to σ: Gauge, inflation & neutrino multiplets.

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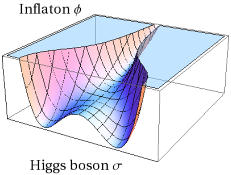
Hybrid inflation = Chaotic inflation + SSB



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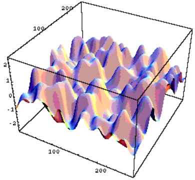

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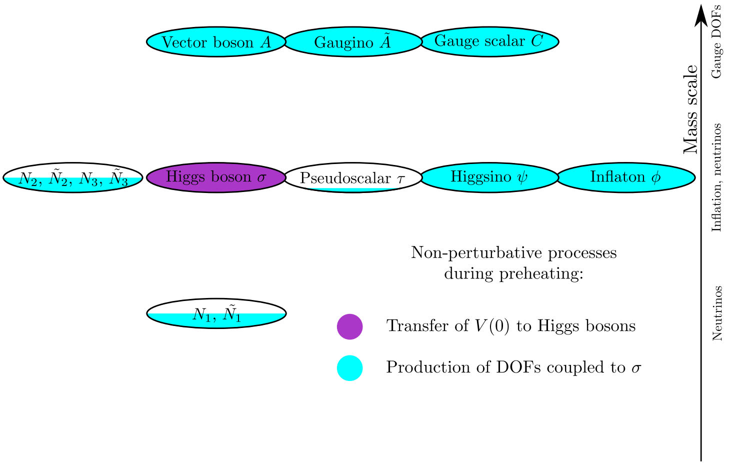
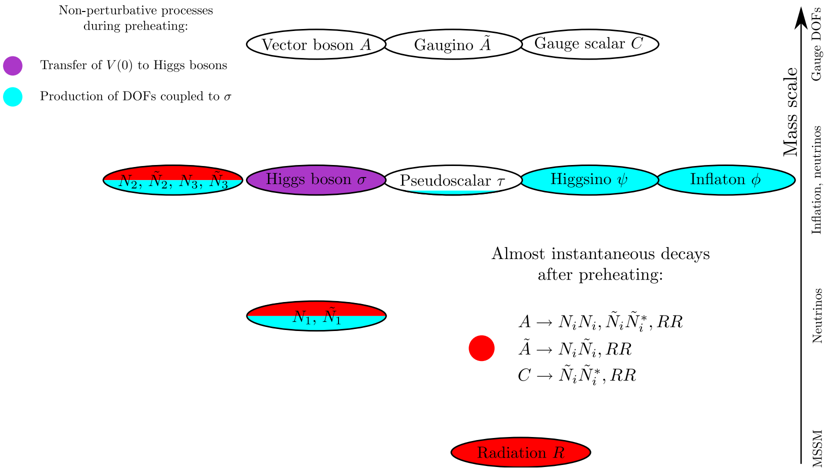
Assume $2M_1 \ll m_\sigma \lesssim 2M_{2,3}$ *s.t.* σ decays exclusively into N_1 and $\tilde{N}_1$ after SSB.

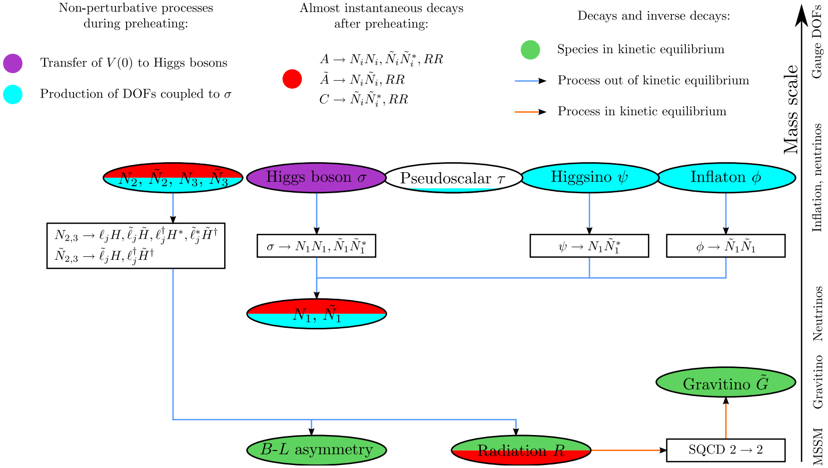
Particle production during tachyonic preheating



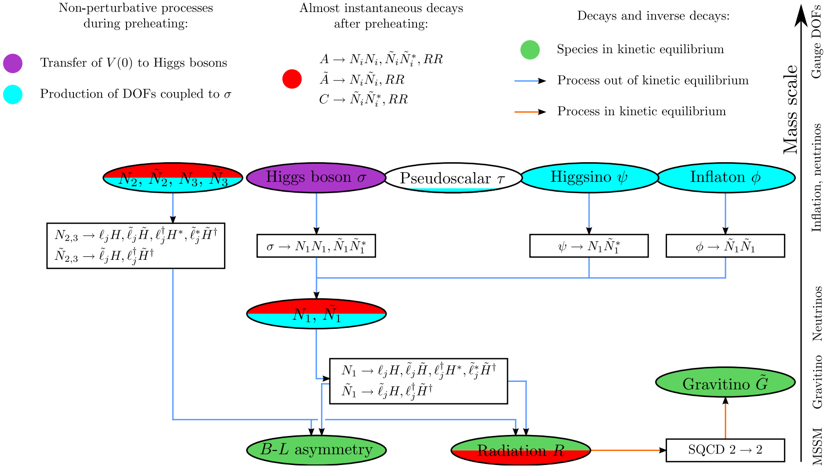
Decay of the gauge degrees of freedom



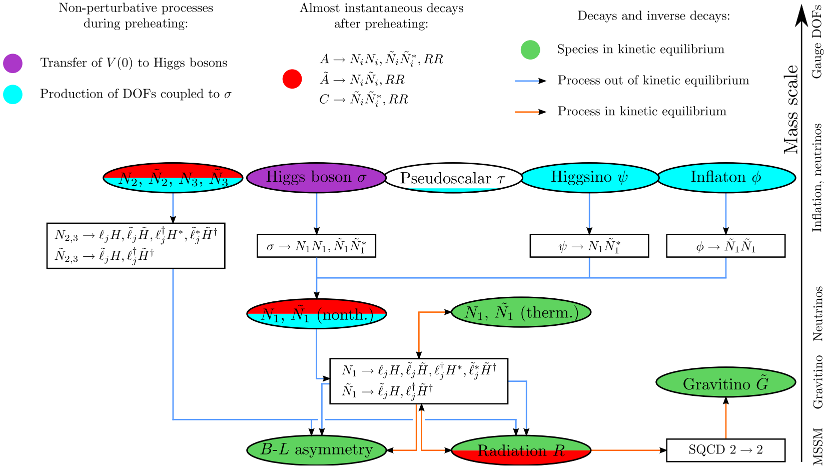
Decay of N_2, $\tilde{N}_2$, N_3, $\tilde{N}_3$, σ, τ, ψ and ϕ



Decay of nonthermal neutrinos



Production and decay of thermal neutrinos



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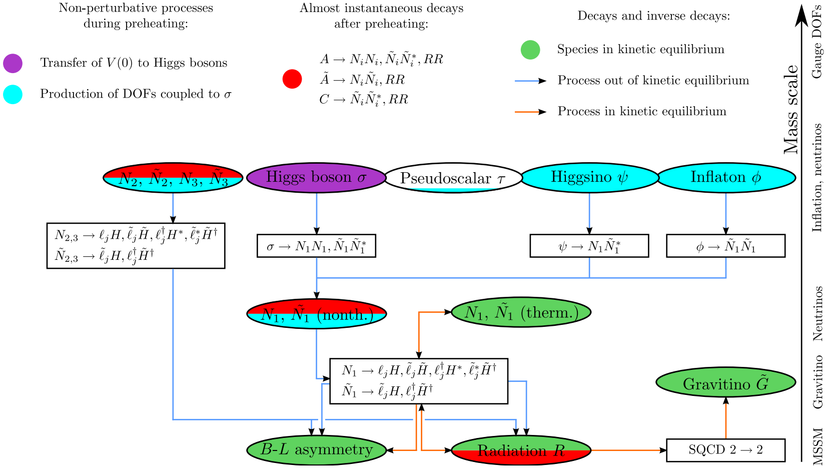
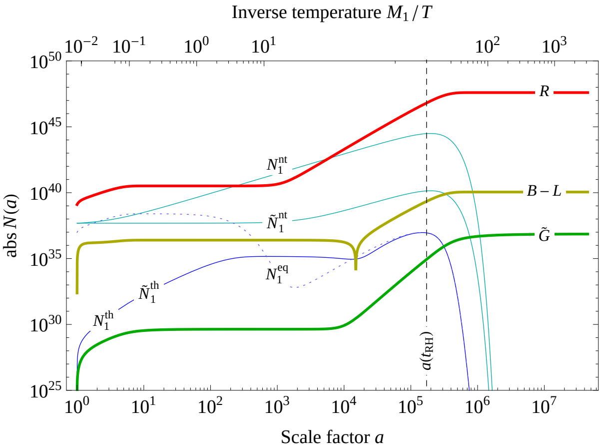


Math: Boltzmann equations, coupled system of non-linear first-order PDEs.

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

Comoving number densities



$$N(a) = a^3 n(a)$$

$$v_{B-L} = 5 \times 10^{15}\,\mathrm{GeV}$$
$$M_1 = 2 \times 10^{11}\,\mathrm{GeV}$$
$$\widetilde{m}_1 = 3 \times 10^{-4}\,\mathrm{eV}$$
$$m_{\tilde{G}} = 160\,\mathrm{GeV}$$
$$m_{\tilde{g}} = 1000\,\mathrm{GeV}$$
$$\varepsilon_1^{\max} = +2 \times 10^{-5}$$
$$\varepsilon_{2,3}^{\max} = -5 \times 10^{-3}$$

Large enough baryon asymmetry:

$$\eta_B^{\max} = 9 \times 10^{-9} > \eta_B^{\mathrm{obs}} \simeq 6 \times 10^{-10}$$

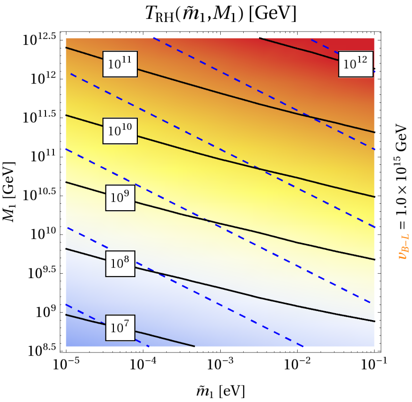
Right DM abundance:

$$\Omega_{\tilde{G}} h^2 = 0.11 = \Omega_{\mathrm{DM}}^{\mathrm{obs}} h^2$$

Reheating temperature and baryon asymmetry

$M_1\left(v_{B-L}, \widetilde{m}_1, m_{\widetilde{G}}, m_{\tilde{g}}\right)$ s. t. $\Omega_{\widetilde{G}} h^2 = 0.11$

$\eta_B\left(v_{B-L}, \widetilde{m}_1, M_1\right) = \eta_B^S + \eta_B^T > \eta_B^{\text{obs}}$



- Results of nonsupersymmtric study (arXiv:1104.2750 [hep-ph]).
- Inclusion of full particle spectrum is work in progress.
- Publication soon, qualitative findings remain unchanged.

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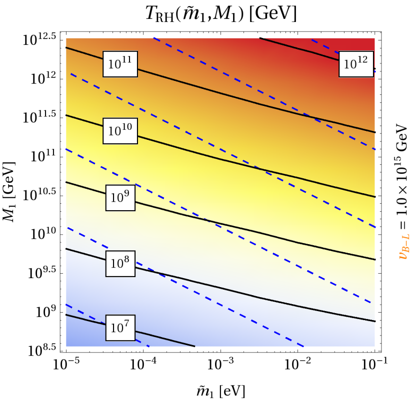

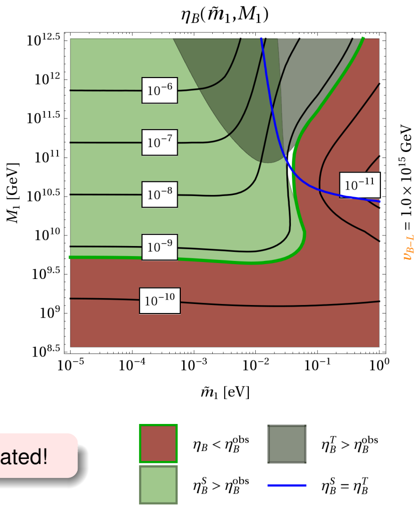

Appreciate: Thermal bounds significantly alleviated!

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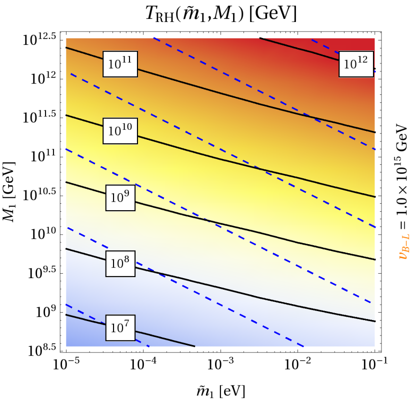

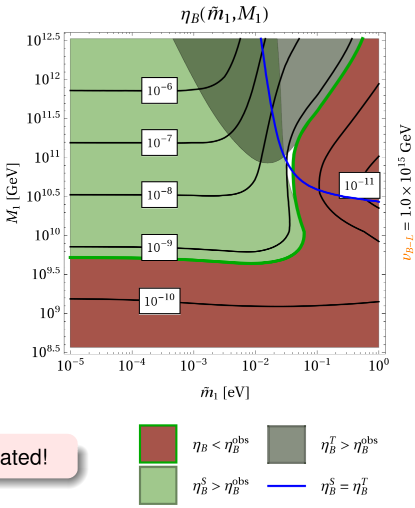

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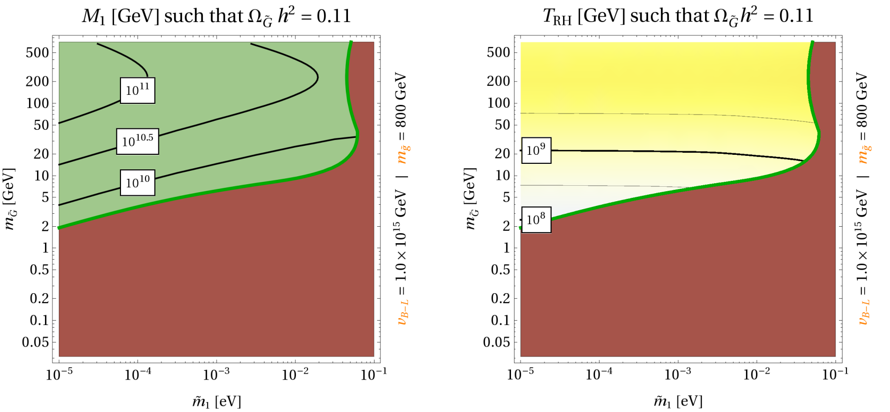
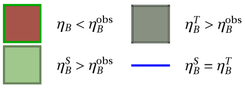
Connection between SUGRA and neutrino parameters





Scenario works in large region of parameter space!

- $T_{\rm RH}$ bound lowered: $\gtrsim 10^9\,\mathrm{GeV} \rightarrow \gtrsim 10^8\,\mathrm{GeV}$.
- $\tilde{m}_1$ and $m_{\tilde{G}}$ mutually constrain each other.

A common origin of entropy, matter and dark matter

Idea: Neutrino decays produce all entropy of the hot early universe.

- Reheating temperature T_{RH} determined by neutrino lifetime $\Gamma_{N_1}(\widetilde{m}_1, M_1)$.
- BAU through leptogenesis and gravitino DM follow naturally $+$ interrelated.

Scenario: Dominant nonth. N_1 abundance after false vacuum decay.

- Hybrid inflation ends in SSB of local $U(1)_{B-L}$ and tachyonic preheating.
- Vacuum energy density $\longrightarrow$ Higgs bosons of $B-L$ breaking $\longrightarrow$ N_1 neutrinos.

Analysis: Quantitative results after solving the Boltzmann equations.

- T_{RH}, η_B and $\Omega_{\widetilde{G}}h^2$ from Lagrangian parameters v_{B-L}, $\widetilde{m}_1$, M_1, $m_{\widetilde{G}}$ and $m_{\tilde{g}}$.
- $\widetilde{m}_1$ constrains $m_{\widetilde{G}}$ and vice versa. Falsification: Measure $m_i \gtrsim 0.1\,\mathrm{eV}$.
- Connection b/t collider searches, laboratory exps. and cosmological obs.

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Thank you for your attention!

Yukawa couplings

Superpotential for matter fields in $SU(5)$ notation:

- $W_M = h_{ij}^{(u)} \mathbf{10}_i \mathbf{10}_j H_u + h_{ij}^{(d)} \mathbf{5}_i^* \mathbf{10}_j H_d + h_{ij}^{(\nu)} \mathbf{5}_i^* \mathbf{1}_j H_u + h_i^{(n)} \mathbf{1}_i \mathbf{1}_i S.$
- Fermion irreps: $\mathbf{10}_i = (q_i, u_i^c, e_i^c)$; $\mathbf{5}_i^* = (d_i^c, \ell_i)$; $\mathbf{1}_i = (n_i)$; $N_i := n_i + n_i^c$.

Froggatt-Nielson $U(1)_{\mathrm{FN}}$ flavor symmetry: [Buchmüller & Yanagida '99]

- Yukawa terms are generated from non-renorm. $U(1)_{\mathrm{FN}}$-inv. higher-dim. operators: $h_{ij} \sim \eta^{Q_i+Q_j}$; $\eta := v_{\mathrm{FN}}/\Lambda \simeq 1/\sqrt{300}$; $\Lambda > \Lambda_{\mathrm{GUT}}$.
- FN parameter η and charges Q_i determined from quark and lepton mass hierarchies.

ψ_i	$\mathbf{10}_3$	$\mathbf{10}_2$	$\mathbf{10}_1$	$\mathbf{5}_3^*$	$\mathbf{5}_2^*$	$\mathbf{5}_1^*$	$\mathbf{1}_3$	$\mathbf{1}_2$	$\mathbf{1}_1$
Q_i	0	1	2	a	a	$a+1$	b	c	d

Specific example: $a = 0.5$, $d = 1.5$.

- Require $M_1 \ll M_{2,3} = m_S \quad \Rightarrow \quad b = c = d - 1 = 0.5$.
- $v_{B-L} \sim 6 \times 10^{13}\,\mathrm{GeV}$; $M_1 \sim 10^{10}\,\mathrm{Gev}$; $M_{2,3} = m_S \sim v_{B-L}$.

Boltzmann equations

$$(S) \qquad \hat{\mathcal{L}} f_S(t,p) = -\frac{m_S}{E_S}\Gamma_S^0 f_S(t,p)$$

$$(N_1^S) \qquad \hat{\mathcal{L}} f_{N_1}^S(t,p) = -\frac{M_1}{E_{N_1}}\Gamma_{N_1}^0 f_{N_1}^S(t,p) + 2 \times \frac{\pi^2 \Gamma_S^0 N_S}{a^3 E_{N_1}^2} \frac{\delta\left(E_{N_1} - m_S/2\right)}{\sqrt{1-(2M_1/m_S)^2}}$$

$$(N_1^T) \qquad aH\frac{d}{da}N_{N_1}^T = -\Gamma_{N_1}^T\left(N_{N_1}^T - N_{N_1}^{\mathrm{eq}}\right)$$

$$(B-L) \qquad aH\frac{d}{da}N_{B-L} = \varepsilon_1 \Gamma_{N_1}^S N_{N_1}^S + \varepsilon_1 \Gamma_{N_1}^T\left(N_{N_1}^T - N_{N_1}^{\mathrm{eq}}\right) - \frac{N_{N_1}^{\mathrm{eq}}}{2N_\ell^{\mathrm{eq}}}\Gamma_{N_1}^T N_{B-L}$$

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

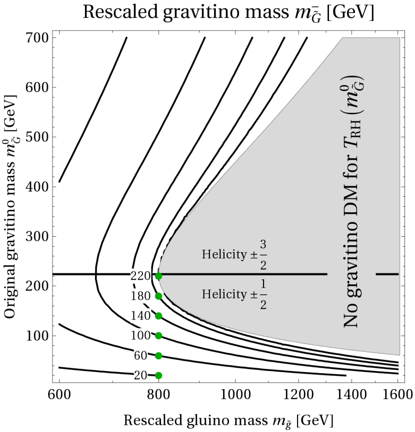
$$(R) \qquad aH\frac{d}{da}N_R = r_R^S\Gamma_{N_1}^S N_{N_1}^S + r_R^T\Gamma_{N_1}^T\left(N_{N_1}^T - N_{N_1}^{\mathrm{eq}}\right)$$

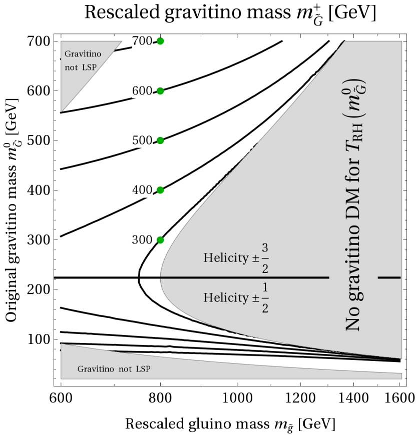
with $\hat{\mathcal{L}} = \frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}$, $\Gamma_{N_1}^{S/T} = \left\langle \frac{M_1}{E_{N_1}} \right\rangle_{S/T}\Gamma_{N_1}^0$, $\kappa_{\widetilde{G}} \sim \mathcal{O}(1)$ and $r_R^{S/T} = \frac{3\rho_{N_1}^{S/T} n_R}{4n_{N_1}^{S/T}\rho_R}$.

Coupled system of non-linear first-order partial differential eqns.

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

Rescaling the gravitino mass for $m_{\tilde{g}} \neq 800\,\mathrm{GeV}$



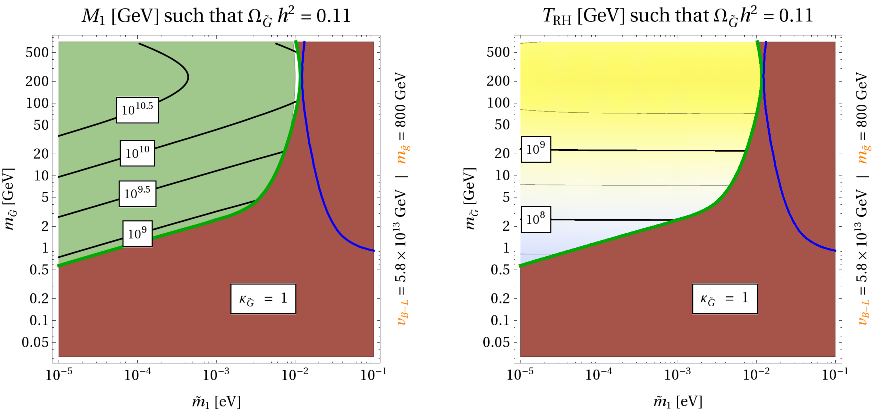


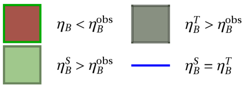
Solve $\Omega_{\tilde{G}}h^2\left(T_{\mathrm{RH}}, m^0_{\tilde{G}}, 800\,\mathrm{GeV}\right) = \Omega_{\tilde{G}}h^2\left(T_{\mathrm{RH}}, m_{\tilde{G}}, m_{\tilde{g}}\right)$.

- Quadratic eq. for $m_{\tilde{G}}\left(m_{\tilde{g}}, m^0_{\tilde{G}}\right)$ w/ two solutions $m^{\pm}_{\tilde{G}}$.
- For $m^0_{\tilde{G}} \ll m_{\tilde{g}}$: $\quad m_{\tilde{G}} = m^0_{\tilde{G}}\left(m_{\tilde{g}}/800\,\mathrm{GeV}\right)^2$.

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

Connection between SUGRA and neutrino parameters



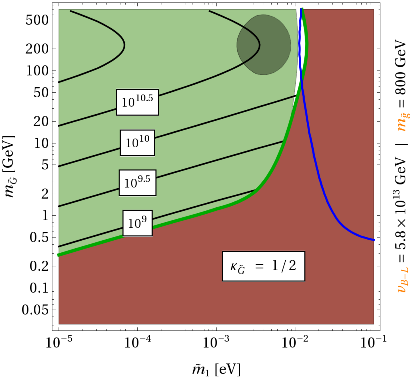


Scenario works in large region of parameter space!

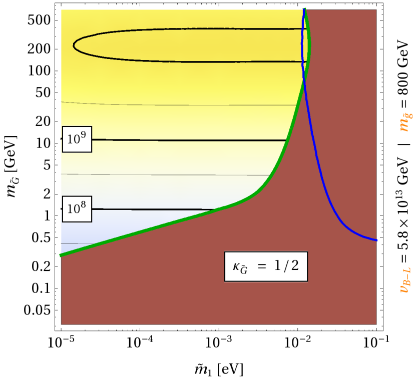
- $T_{\rm RH}$ bound lowered: $\gtrsim 10^9\,\mathrm{GeV} \rightarrow \gtrsim 10^7\,\mathrm{GeV}$.
- $\widetilde{m}_1$ and $m_{\tilde{G}}$ mutually constrain each other.

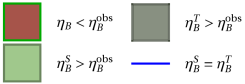
Connection between SUGRA and neutrino parameters

M_1 [GeV] such that $\Omega_{\tilde{G}} h^2 = 0.11$



$T_{\rm RH}$ [GeV] such that $\Omega_{\tilde{G}} h^2 = 0.11$





Scenario works in large region of parameter space!

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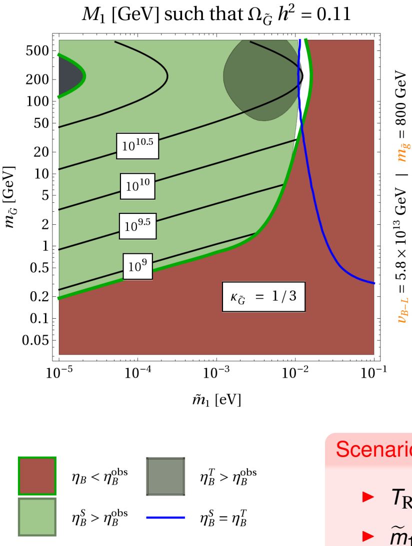

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