Superparticle Mass Window from Thermal Leptogenesis and Decaying Gravitino Dark Matter

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1/Oct/2008 DESY Theory Workshop
"Dark Matter at the Crossroads"

W. Buchmüller, M. Endo and T.S. arXiv:0809.4667

Needs of New Physics

We have several suggestions of the new physics by experiments/observations.

- Finite neutrino masses
- Baryon asymmetry of the Universe
- Dark matter
- Muon $g - 2$
- $\cdots$

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Needs of New Physics

We have several suggestions of the new physics by experiments/observations.

- Finite neutrino masses
  - By construction, neutrinos are massless in the SM.
  - $\Delta m^2_{\rm atm} \sim 2.5 \times 10^{-3}{\rm eV}^2$, $\sin^2 2\theta_{\rm atm} \simeq 1$
  - $\Delta m^2_{\odot} \sim 8.5 \times 10^{-5}{\rm eV}^2$, $\tan^2\theta_{\rm atm} \simeq 0.4$
- Baryon asymmetry of the Universe
- Dark matter
- Muon $g-2$
- $\cdots$

Needs of New Physics

We have several suggestions of the new physics by experiments/observations.

- Finite neutrino masses
- Baryon asymmetry of the Universe
  - $\eta_B = (6.15 \pm 0.25) \times 10^{-10}$
- Dark matter
- Muon $g-2$
- $\cdots$

Needs of New Physics

We have several suggestions of the new physics by experiments/observations.

- Finite neutrino masses
- Baryon asymmetry of the Universe
- Dark matter
  - WMAP5yr $\rightarrow \Omega_{\rm DM} h^2 \simeq 0.1223$
- Muon $g-2$
- $\cdots$

Needs of New Physics

We have several suggestions of the new physics by experiments/observations.

- Finite neutrino masses
- Baryon asymmetry of the Universe
- Dark matter
- Muon $g-2$
  - $\delta a_\mu \equiv a_\mu(\text{exp}) - a_\mu(\text{SM}) = 302(88) \times 10^{-11}$ $\rightarrow 3.4\sigma$!!
- $\cdots$

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SUSY seesaw model may answer these problems

Seesaw

Seesaw model is a simple model to explain the smallness of neutrino masses.

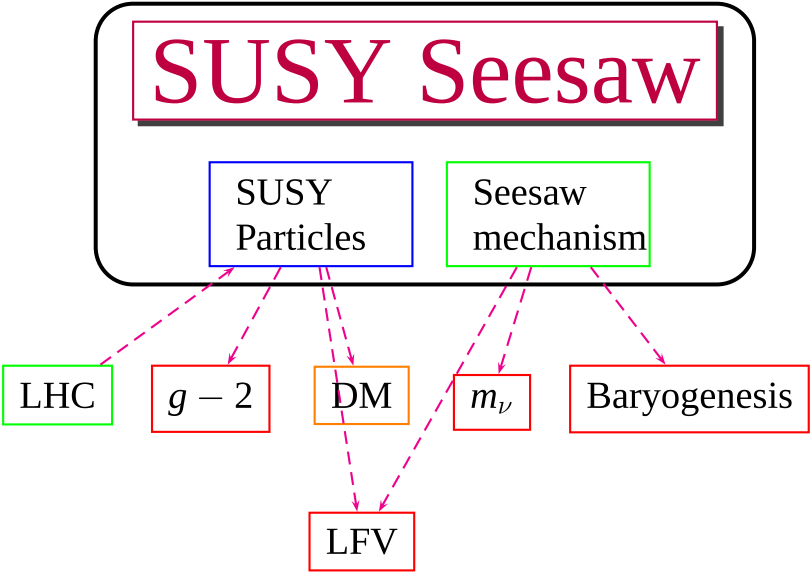
- Introducing righthanded neutrinos, N, to the SM
- N is SM singlet $\Rightarrow$ Majorana mass terms
- Majorana mass is heavy $\rightarrow$ light neutrinos

$$-\mathcal{L} = Y_E \bar{e}_R l_L \cdot \bar{\phi} + Y_N \bar{N} l_L \cdot \phi + \frac{1}{2} M_R \bar{N} N^c$$

$\Downarrow$: RN are integrated out

$$-\mathcal{L} = Y_E \bar{e}_R l_L \cdot \bar{\phi} - \frac{1}{2} \kappa (l_L \cdot \phi)^2 \ , \quad \kappa = Y_N^T M_R^{-1} Y_N$$

SUSY Seesaw model



Leptogenesis

M. Fukugita and T. Yanagida, PLB174, 45;

W. Buchmüller, P. Di Bari, and M. Plümacher, Annals. Phys.315,305; G. F. Giudice *et al.*, NPB685,89; $\cdots$

Basic idea is

- Out of equilibrium decay of heavy neutrinos produce $B-L$ asymmetry
- Sphaleron interaction which breaks both B- and L-numbers but conserves $B-L$ is in equilibrium for $100\text{GeV} \leq T \leq 10^{12}\text{GeV}$.
- $B-L$ produced by N decay is converted to B-asymmetry through Sphaleron

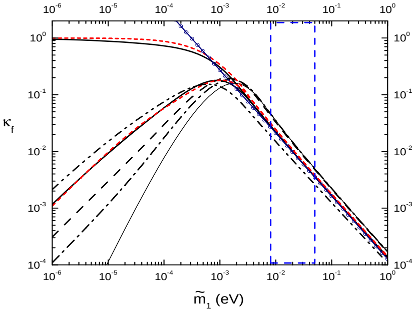
Leptogenesis

A prediction on the BAU is

$$\eta_B = -1.0 \times 10^{-3} \epsilon_1 \kappa(\tilde{m})$$

Sphaleron effect etc   CPV in N_1 decay   Efficiency

WMAP5yr: $\eta_B = (6.21 \pm 0.16) \times 10^{-10}$



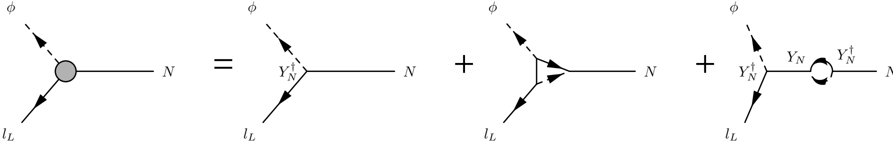
Zero-initial condition:

$$\kappa \leq 0.2 \Rightarrow \epsilon_1 \geq 10^{-6}$$

[W. Buchmuller P. Di Bari, M. Plumacher]

CP violation in neutrino decay

Lepton asymmetry can be produced by the N decay:



$$\epsilon_1 = \frac{\Gamma(N_1 \to l_L \phi) - \Gamma(N_1 \to \bar{l}_L \bar{\phi})}{\Gamma(N_1 \to l_L \phi) + \Gamma(N_1 \to \bar{l}_L \bar{\phi})}$$

$$= \frac{1}{8\pi (Y_N Y_N^\dagger)_{11}} \sum_{i \neq 1} \mathrm{Im}\left[(Y_N Y_N^\dagger)^2_{i1} \right] f\left(\frac{M_i^2}{M_1^2} \right)$$

$$\simeq -\frac{3}{8\pi (Y_N Y_N^\dagger)_{11}} \sum_{i \neq 1} \mathrm{Im}\left[(Y_N Y_N^\dagger)^2_{i1} \right] \frac{M_1}{M_i}$$

$M_1 \ll M_2, M_3$

Lower bound on T_R

S. Davidson and A. Ibarra, PLB535,25

$$|\epsilon_1| \le \frac{3M_1}{8\pi\langle H_u\rangle^2}\frac{\Delta m^2_{\rm atm}}{m_1+m_3} \Rightarrow M_1 \ge 1.4\times 10^9\,\mathrm{GeV}$$

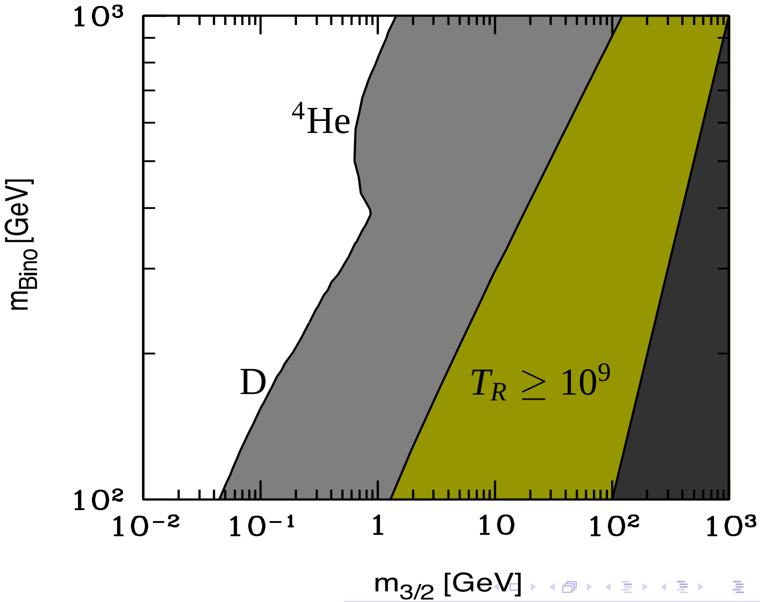
$$\Rightarrow \boxed{T_R \gtrsim 1\times 10^9\,\mathrm{GeV}}$$

(For the Standard Thermal Leptogenesis)

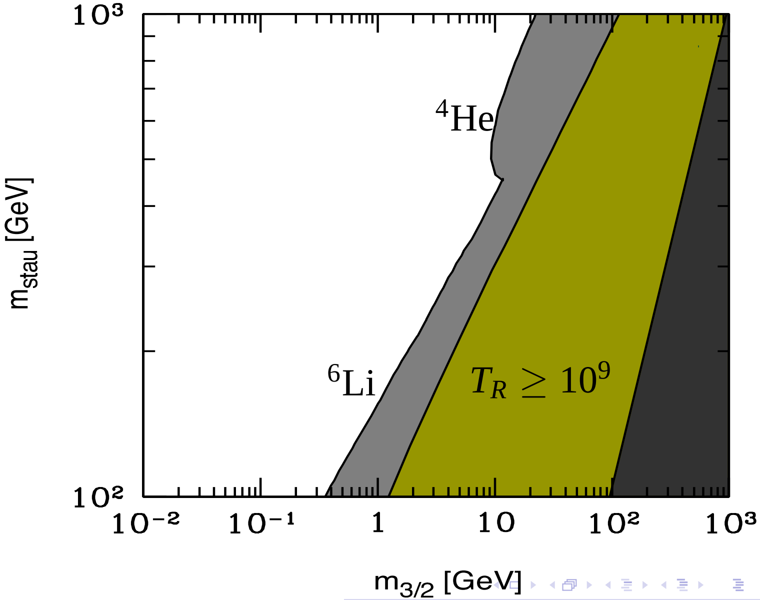
Nightmare from the gravitino

- The thermal gravitino production:
  $\Omega_{\rm DM}h^2 \geq \Omega_{3/2}h^2 \propto m_{3/2}\left(1+\frac{M_3(T_R)^2}{3m_{3/2}^2}\right) T_R$
- Bound on T_R is
  $T_R \leq 2\times 10^9{\rm GeV}\left(\frac{m_{3/2}}{100{\rm GeV}}\right)\left(\frac{m_{\rm gluino}}{1{\rm TeV}}\right)^{-2}$
- However the NLSP decay affects the BBN !
  - $\tilde{\chi}^0$ NLSP : Hadronic shower is released.
  - $\tilde{\tau}$ NLSP : the catalyzed effect $(\tilde{\tau}^4{\rm He})+D \to {}^6{\rm Li}+\tilde{\tau}$
- Even if the gravitino is not LSP, the over-closure bound is severe.
  $T_R \geq 10^9{\rm GeV} \Rightarrow m_{3/2} > \mathcal{O}(10^4){\rm GeV}$

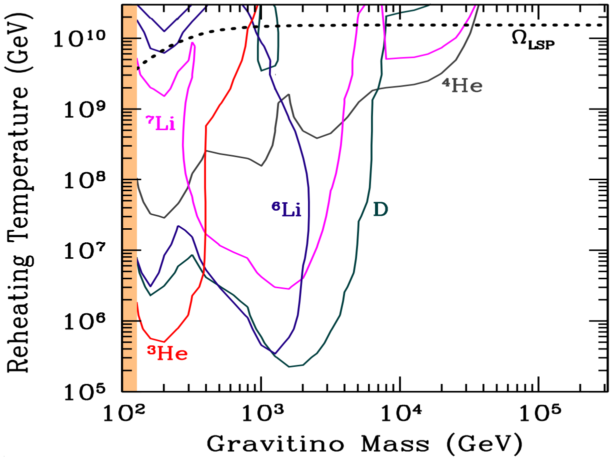
BBN constraints (LSP gravitino)



BBN constraints (LSP gravitino)



BBN constraints (nonLSP gravitino)



T. Kanzaki, M. Kawasaki, K. Kohri and T. Moroi,
PRD75,025011

Purpose of this work

Thermal leptogenesis conflicts with the gravitino problem.

- The standard thermal leptogenesis $\rightarrow T_R \geq 10^9\text{GeV}$
- The thermal gravitino production $\rightarrow T_R \ll 10^9\text{GeV}$

$$\Downarrow$$

Can we rescue the thermal leptogenesis scenario in the SUSY model?

A light from R-parity Violation

We introduce R-parity violation

- We consider gravitino LSP case
- NLSP can decay to SM particles before BBN
  $\longrightarrow$ BBN constraints are relaxed !
  $\longrightarrow$ T_R can be higher than 10^9GeV
- The gravitino is no longer stable, but the life time is long enough to be DM

A sample model

$$\mathcal{L}_{\mathrm{RPV}} = (\bar{M}^2_{HL})_i H_d^* \tilde{L}_i + (\bar{B}_L)_i H_u \tilde{L}_i + \text{h.c.}$$

- The bi-linear terms in superpotential can be rotated away w/o loss of generality
- Lefthanded sneutrinos have VEV
  $$\langle \tilde{\nu} \rangle \simeq \frac{\bar{M}^2_{HL} \cos\beta + \bar{B}_L \sin\beta}{M^2_{\tilde{\nu}}} \frac{v}{\sqrt{2}}$$
  $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
  $\rightarrow$ It is useful to define $\eta_i \equiv \frac{\sqrt{2}\langle \tilde{\nu} \rangle}{v}$
- η characterizes the phenomena induced by $\mathcal{L}_{\mathrm{RPV}}$

Constraints on η

- Neutrino masses from PRV
  $(\Delta m_\nu) \simeq \frac{m_Z^2 \eta^2}{m_{\tilde{Z}}} \to \boxed{\eta \ll 10^{-7}}$
- The RPV operator violates lepton number
  $\to$ They may washout the baryon asymmetry
  $\Gamma \simeq 10^{-2} m_W^2 |\eta|^2 / T_{\rm sph} < H \Rightarrow \boxed{\eta \lesssim 10^{-(7-8)}}$
- RPV is introduced for avoiding BBN constraints
  - $\tilde{B}$ NLSP case
    $\tilde{B} \to Z\nu, Wl, h\nu$
    $\Rightarrow \tau_{\tilde{B}} \sim 0.01\text{sec} \times (\eta/10^{-11})^{-2}$ for $m_{\rm soft} \sim 100\text{GeV}$
  - $\tilde{\tau}$ NLSP case
    $\tilde{\tau}_R \to \tau\nu \Rightarrow \tau_{\tilde{\tau}} \sim 0.1\text{sec} \times (\eta/10^{-11})^{-2}$

Then $\tau_{\rm NLSP} \lesssim 0.1\text{sec} \Rightarrow \boxed{\eta \gtrsim 10^{-(11-12)}}$

Constraints on η

- The stability of the gravitino (gravitino DM)
  Doubly suppressed by gravitational and RPV
  The lifetime should be long enough
  $\Rightarrow \boxed{\eta \ll 10^{-(5-6)}}$ for $m_{3/2} = \mathcal{O}(100)\text{GeV}$
- High energetic photon/positron are emitted
  They might be observed in cosmic rays
  ?? excess in EGRET, HEAT result ??

A. Ibarra and D. Tran, PRL100,061301;JCAP0807,002, K. Ishiwata et al., arXiv:0805.1133

- EGRET (photon)
  $m_{3/2} \gtrsim 100\text{GeV}$ & $\tau_{3/2} = \mathcal{O}(10^{26})\text{sec}$
- HEAT (positron):
  $m_{3/2} \gtrsim 100\text{GeV}$ & $\tau_{3/2} = \mathcal{O}(10^{26-27})\text{sec}$

Summary of the constraints on η

Estimation of the B.G. has large uncertainty
$\rightarrow$ EGRET, HEAT data is used as a constraint,
$\rightarrow$ $\boxed{\eta \lesssim 10^{-(9-10)}}$

Then,

$$\boxed{10^{-(11-12)} \leq \eta \leq 10^{-(9-10)}}$$

BBN   EGRET,HEAT

There is a parameter region consistent with
cosmological/phenomenological constraints

Setup for the Analysis

We study two typical SUSY SM with a universal boundary condition and GUT gaugino masses.

(a) $m_0 = m_{1/2}$, $a_0 = 0$ at $\mu_G = 2 \times 10^{16}$GeV, $\tan\beta$ NLSP (lightest MSSM particle) is Bino

(b) $m_0 = 0$, $m_{1/2}$, $a_0 = 0$ at $\mu_G = 2 \times 10^{16}$GeV, $\tan\beta$ NLSP (lightest MSSM particle) is stau

Observables

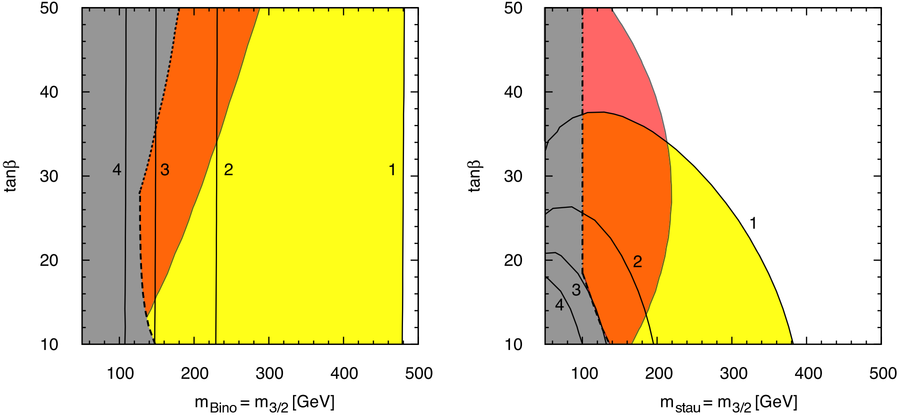
The T_R consistent with $\Omega_{3/2}h^2 \leq \Omega_{\rm DM}h^2$ is

$$T_R \lesssim 2 \times 10^9 \mathrm{GeV} \left(\frac{m_{3/2}}{m_{\rm NLSP}}\right) \left(\frac{m_{3/2}}{100\mathrm{GeV}}\right) \left(\frac{m_{\rm gluino}}{1\mathrm{TeV}}\right)^{-2}$$

We consider the following low energy observables:

- Higgs mass bound : $m_h > 114.4\mathrm{GeV}$
- $b \to s\gamma$: $2 \times 10^{-4} \leq \mathrm{Br}(B_d \to X_s\gamma) \leq 4 \times 10^{-4}$
- Charged particle : $m_{\rm charged} > 100\mathrm{GeV}$
- muon $g-2$:
  $a_\mu(\mathrm{exp.}) - a_\mu(\mathrm{SM}) = 302(88) \times 10^{-11}$

$T_R[10^9 GeV]$ on $m_{3/2}$ and $\tan\beta$

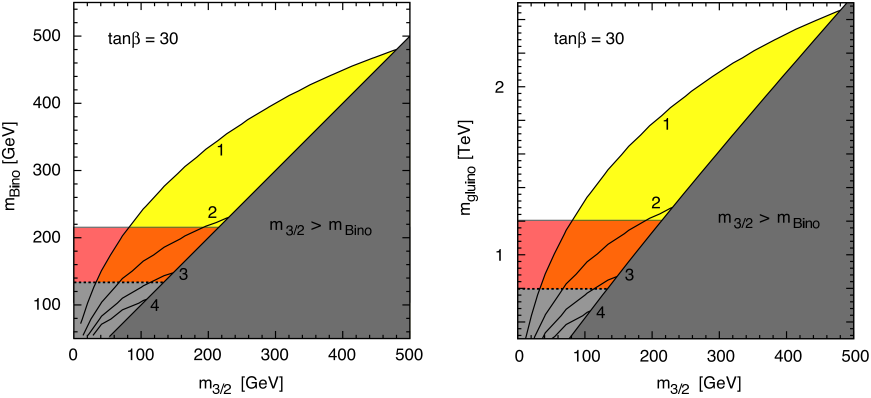


(model a) (model b)

The maximal T_R case is given by $m_{3/2} = m_{\rm NLSP}$.

$T_R[10^9 GeV]$ on $m_{3/2}$ and m_{SUSY}

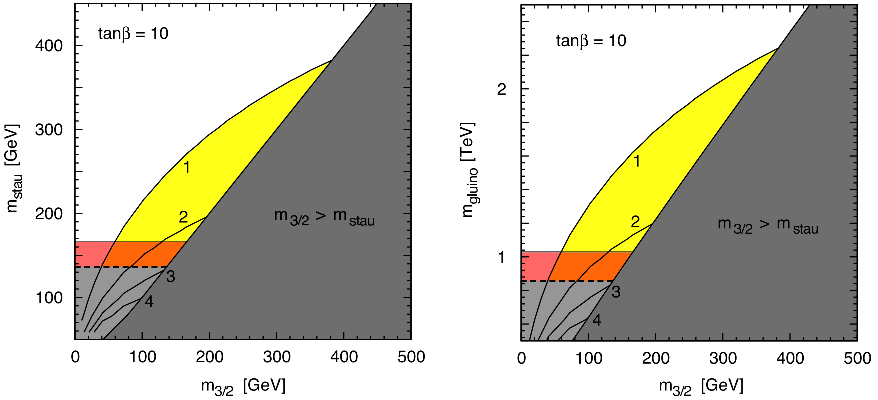
Model a: bino NLSP case



Interesting region is within the LHC reach !

$T_R[10^9 GeV]$ on $m_{3/2}$ and m_{SUSY}

Model b: stau NLSP case



Interesting region is within the LHC reach !

Conclusion

- Leptogenesis in SUSY conflicts with the gravitino problem.
- The problem can be solved by introducing R-parity violation.
- The consistent region is within LHC test.
- The gravitino is unstable and may begin to decay now.
- This scenario may explain the excesses-like data in EGRET and HEAT
- The HEAT excess can be confirmed by PAMERA
- The EGRET excess can be confirmed by the Fermi Gamma-ray Space Telescope