Soft Leptogensis and Gravitino DM in Gauge Mediation

Norimi Yokozaki (The Univ. of Tokyo)
with Koichi Hamaguchi (The Univ. of Tokyo, IPMU)

Talk Plan

1. Introduction
2. Soft Leptogenesis
3. Soft Leptogenesis in Gauge Mediation
4. Our Scenario
5. Summary

Gauge Mediation

- SUSY breaking effects are transmitted by gauge interaction
- No CPV and No FV beyond CKM exist
- (Well)defined and predictive

Gravitino DM

- The scales of sparticles are determined by 1-loop order

$$m_{soft} \sim \frac{g^2}{16\pi^2}\frac{F_X}{M_{\rm mess}} \sim 1\mathrm{TeV} \;\Rightarrow\; \frac{F_X}{M_{\rm mess}} \sim 100\,\mathrm{TeV}$$

$$m_{3/2} \sim \frac{F_{\rm total}}{M_P} \sim \frac{F_X}{M_{\rm mess}}\frac{M_{\rm mess}}{M_P} \ll 1\mathrm{TeV}$$

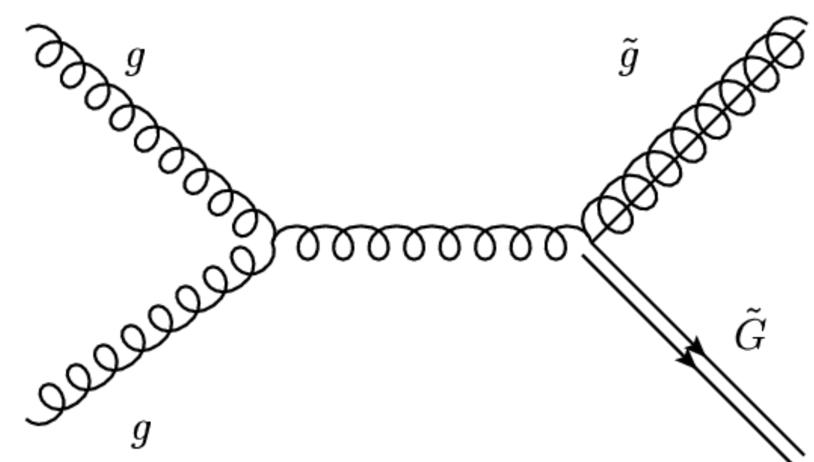
Gravitino is the LSP ⇒ DM candidate

The Abundance of Gravitino DM

Dominant production of gravitino

- Thermal scattering
- Inflaton decay
- Moduli decay

e.g. of a scattering



$$\Omega_{3/2}h^2 \lesssim 0.121$$

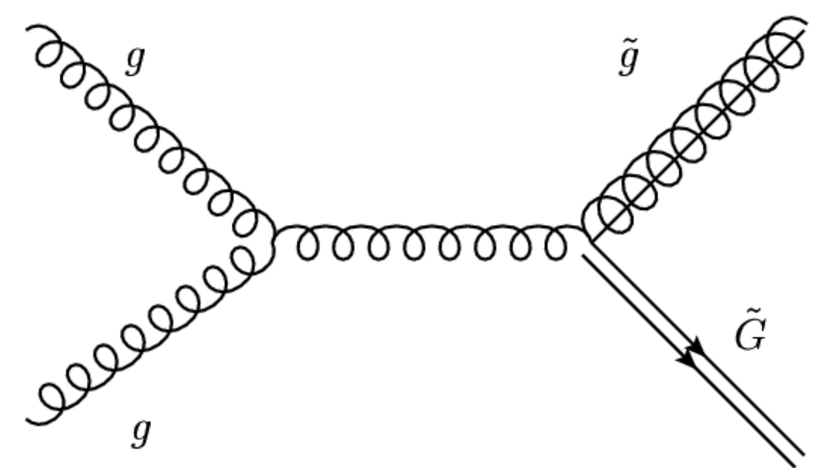
(WMAP)

The Abundance of Gravitino DM

Dominant production of gravitino

- Thermal scattering
- Inflaton decay
- Moduli decay

e.g. of a scattering



$$\Omega_{3/2}h^2 \lesssim 0.121$$

(WMAP)

For $T_R > T_D$ (decoupling temperature),

i.e. gravitino is thermalized

$$\Omega_{3/2}h^2 \sim 0.5 \left(\frac{m_{3/2}}{\mathrm{keV}}\right)$$

⇏ $\Omega_{3/2}h^2 \lesssim 0.121$ (WMAP)

(CDM)

Warm DM constraint ⇒ $m_{3/2} \lesssim 16\,\mathrm{eV}$

(Viel, Lesgourgues, Haehnelt, Matarrese, Riotto,2005)

We can not explain the abundance of DM

For $T_R < T_D$, gravitino is not thermalized

$$\Omega_{3/2}h^2 \approx 0.4 \times \left(\frac{m_{3/2}}{0.1\mathrm{GeV}}\right)^{-1} \left(\frac{m_{\tilde{g}}}{1\mathrm{TeV}}\right)^2 \left(\frac{T_R}{10^7\mathrm{GeV}}\right)$$

(T. Moroi, H. Murayama, M. Yamagachi,1993;
M. Bolz, A. Brandenburg, and W. Buchmuller, 2001;
J. Pradler and F. D. Steffen, 2006)

$$\Omega_{3/2}h^2 \lesssim 0.121$$

$$T_R \lesssim \mathcal{O}(10^7\mathrm{GeV}) \times \left(\frac{m_{3/2}}{0.1\mathrm{GeV}}\right) \left(\frac{m_{\tilde{g}}}{1\mathrm{TeV}}\right)^{-2}$$

The abundance gives an upper bound for T_R

Gravitino DM vs BAU

Another important observable

Baryon Number $n_B/s \sim 10^{-10}$

The simplest mechanism to generate baryon number is Thermal Leptogenesis

$\Omega_{3/2}h^2 \lesssim 0.121(2\sigma)$ ⇒ The upper bound for T_R

conflict

$n_B/s \sim 10^{-10}$ ⇒ The lower bound for T_R

Thermal Leptogensis (in SUSY)

$$W = Y_{\nu,ij} L_i H_2 N_j + M_{N,i} N_i^2/2$$

RH neutrino and sneutrino are created in thermal bath

- out of equilibrium
- CPV

$$n_L \equiv n_l - n_{\bar{l}}$$

- sphaleron

Baryon number

Thermal Leptogensis (in SUSY)

$$W = Y_{\nu,ij} L_i H_2 N_j + M_{N,i} N_i^2/2$$

RH neutrino and sneutrino are created

lepton number +1		lepton number -1
$N_1 \to L + H_2$ $\tilde{L} + \overline{\tilde{H}_2}$ $\tilde{N}_1 \to \tilde{L} + H_2$ $\tilde{N}_1^* \to L + \overline{\tilde{H}_2}$	$\neq$	$N_1 \to \overline{L} + H_2^*$ $\tilde{L}^* + \tilde{H}_2$ $\tilde{N}_1^* \to \tilde{L}^* + H_2^*$ $\tilde{N}_1 \to \bar{L} + \tilde{H}_2$

Thermal Leptogensis (in SUSY)

$$W = Y_{\nu,ij} L_i H_2 N_j + M_{N,i} N_i^2/2$$

RH neutrino and sneutrino are created in thermal bath

↓

- out of equilibrium
- CPV

$$n_L \equiv n_l - n_{\bar{l}}$$

↓

- sphaleron

Baryon number

Baryon number

equilibrium density $\simeq 4 \times 10^{-3}$

sphaleron $\simeq 0.35$

washout
production of N1 $\simeq \mathcal{O}(0.1)$

$$\frac{n_B}{s} = \frac{n_{N_1}^{eq}}{s} \times \epsilon_L \times \left(-\frac{24 + 4N_H}{66 + 13N_H} \right) \times \kappa$$

$$\sim 10^{-4} \times \epsilon_L \sim 10^{-10}$$

Lepton number density par decay

$$\epsilon_L = \frac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \bar{L}H^*)}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \bar{L}H^*)}$$

(The asymmetry from RH sneutrinos is included in the equilibrium density)

$$|\epsilon_L| \lesssim \frac{3}{8\pi} \frac{M_{N_1}}{\langle H_u^0 \rangle^2} m_{\nu,3}$$ for $M_{N_1} \ll M_{N_2} \ll M_{N_3}$

$m_{\nu,1}, m_{\nu,2} \ll m_{\nu,3}$

(S. Davidson and A. Ibarra, 2002)

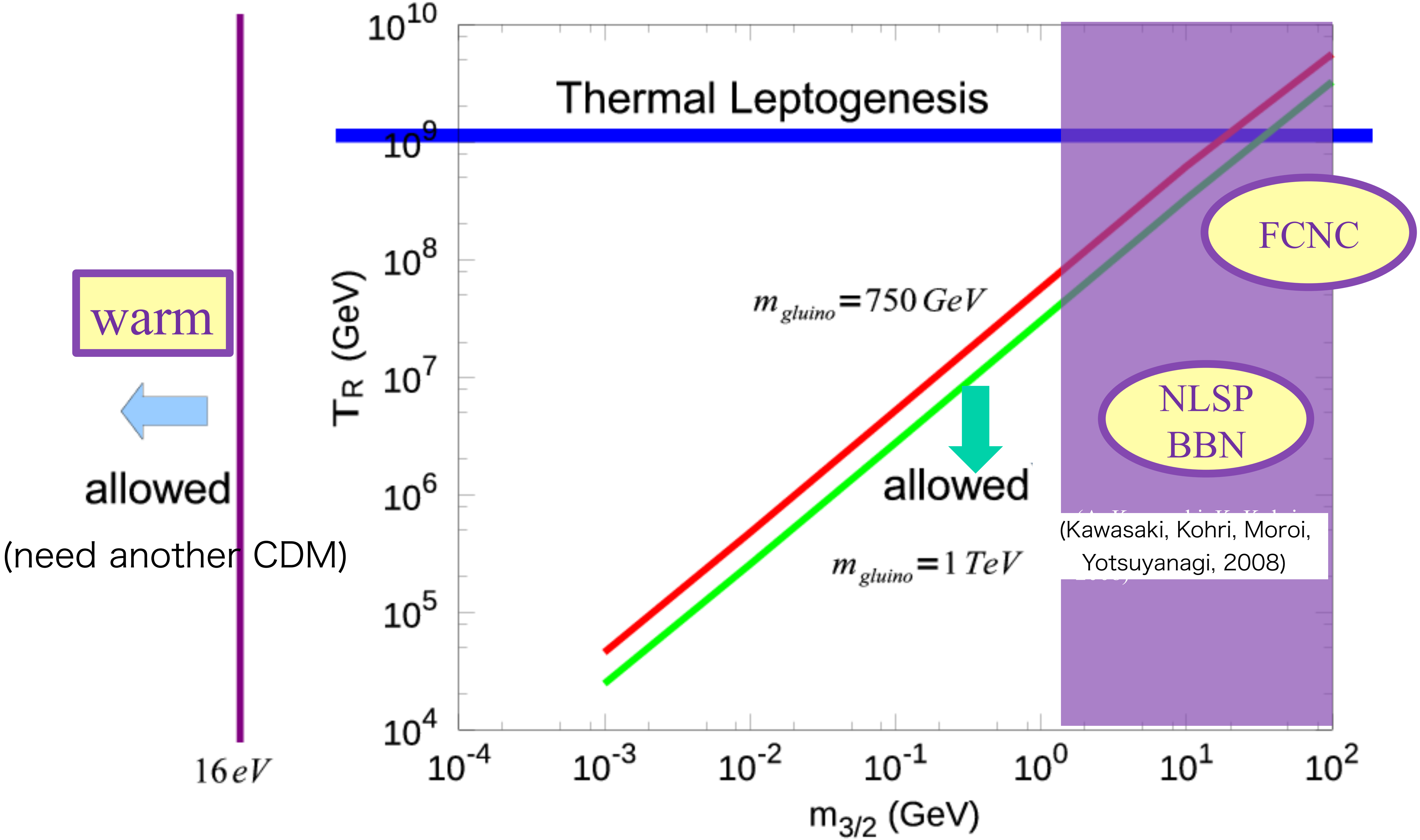
$$\left(\frac{n_B}{s}\right)_{\text{obs}} = 8.7 \times 10^{-11} \Rightarrow \epsilon_L \sim 10^{-6}$$

lower bound

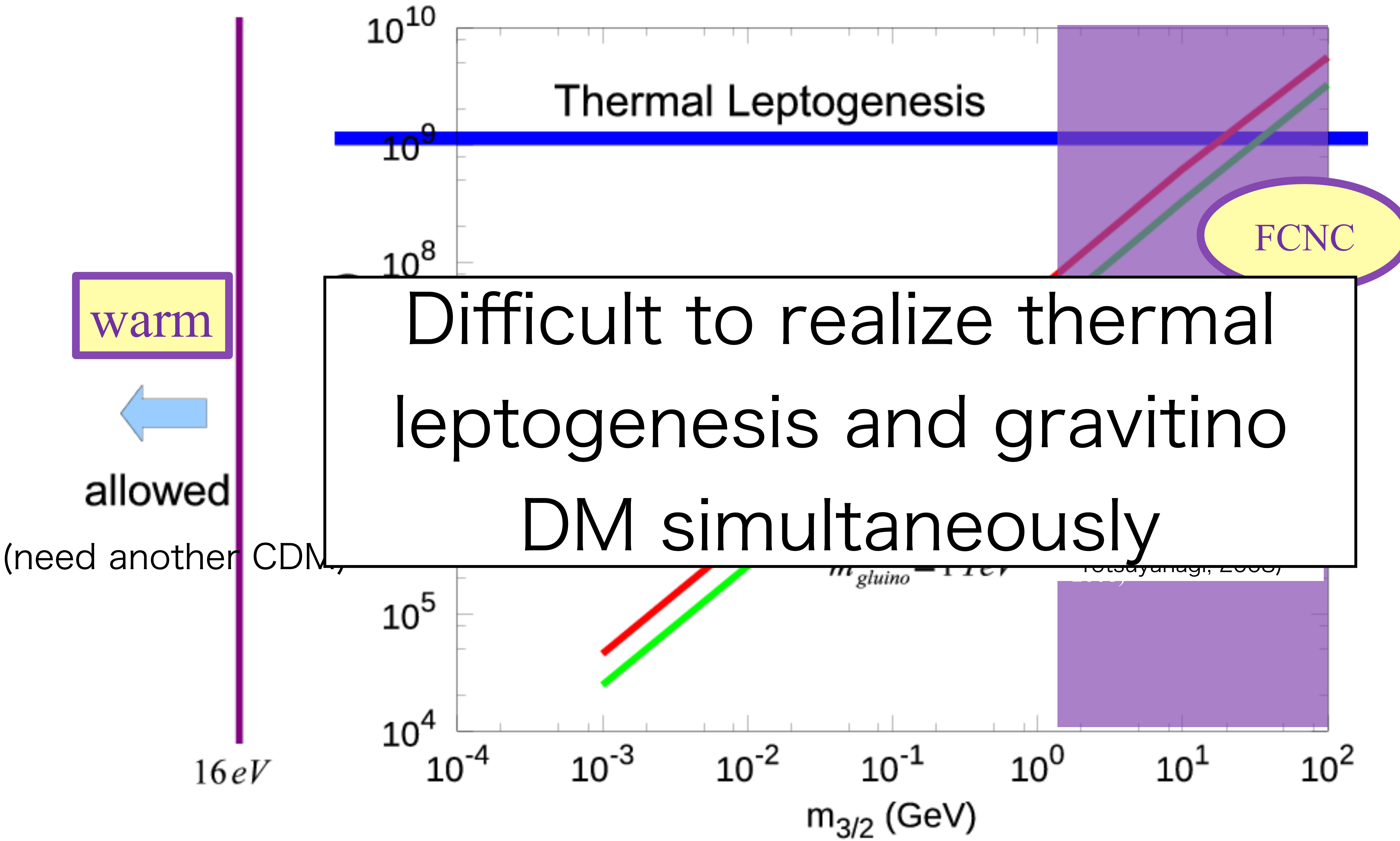
$$\epsilon_L \sim 10^{-6} \Rightarrow T_R \gtrsim M_{N_1} \gtrsim 10^9\,\text{GeV}$$

for $m_{\nu,3} \sim 0.05\,\text{eV}$

The lower bound conflict with gravitino DM



Thermal Leptogenesis
FCNC
NLSP
BBN
$m_{gluino} = 750\,GeV$
$m_{gluino} = 1\,TeV$
allowed
(Kawasaki, Kohri, Moroi,
Yotsuyanagi, 2008)
warm
allowed
(need another CDM)
$16\,eV$
T_R (GeV)
$m_{3/2}$ (GeV)
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}



Difficult to realize thermal leptogenesis and gravitino DM simultaneously

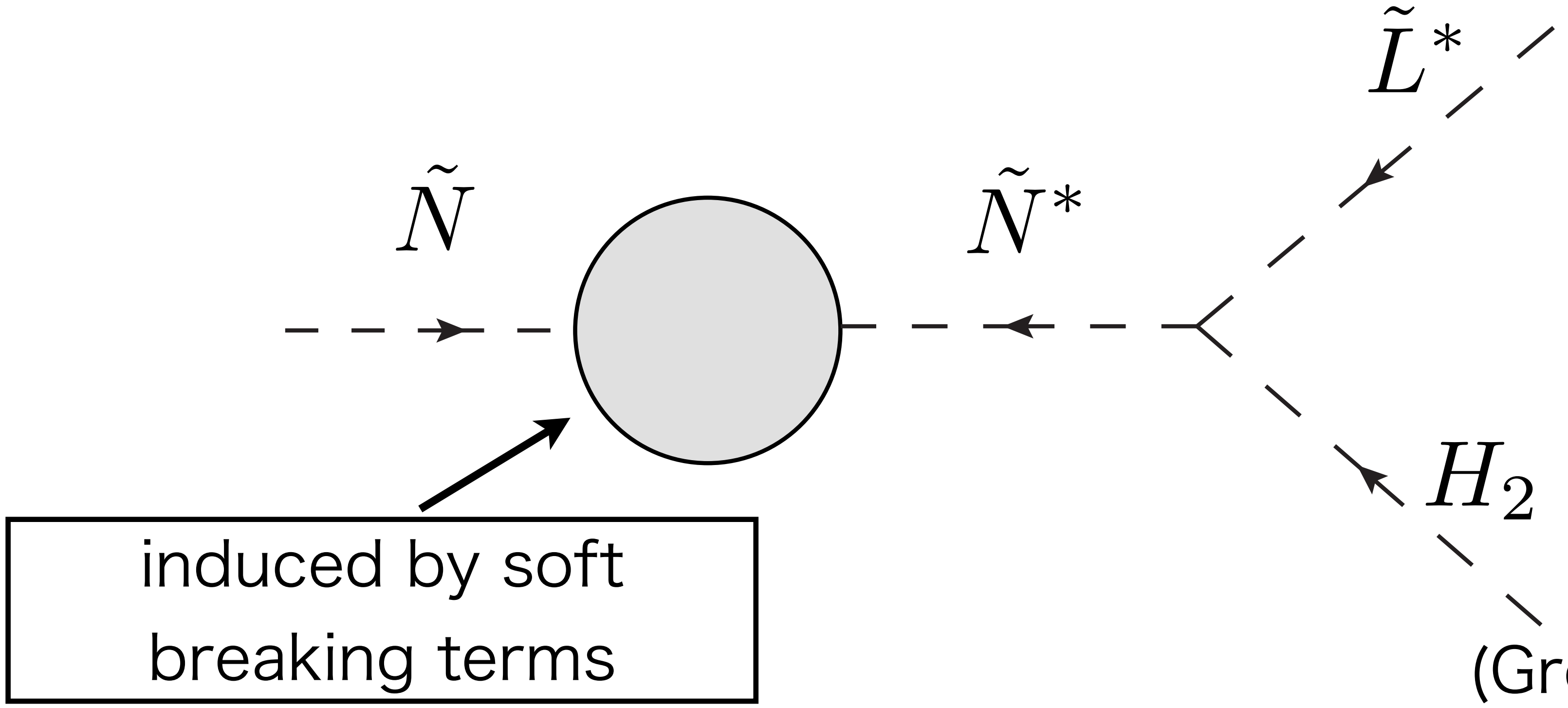
- We want to reduce T_R (required size of M_{N1})
- In some cases, SUSY breaking effects are important
- There is a chance to reduce the size of M_{N1}

Soft Leptogenesis

- Lepton numbers are generated dominantly by effects of soft SUSY breaking terms
- CP-asymmetry from RH sneutrino decays
- Two-ways to accommodate CP asymmetry in RH sneutrino decays

(Grossman, Kashti, Nir, Roulet, 2003)
(D'Ambrosio, Giudice, Raidal, 2003)
(Grossman, Kashti, Nir and Roulet, 2004)

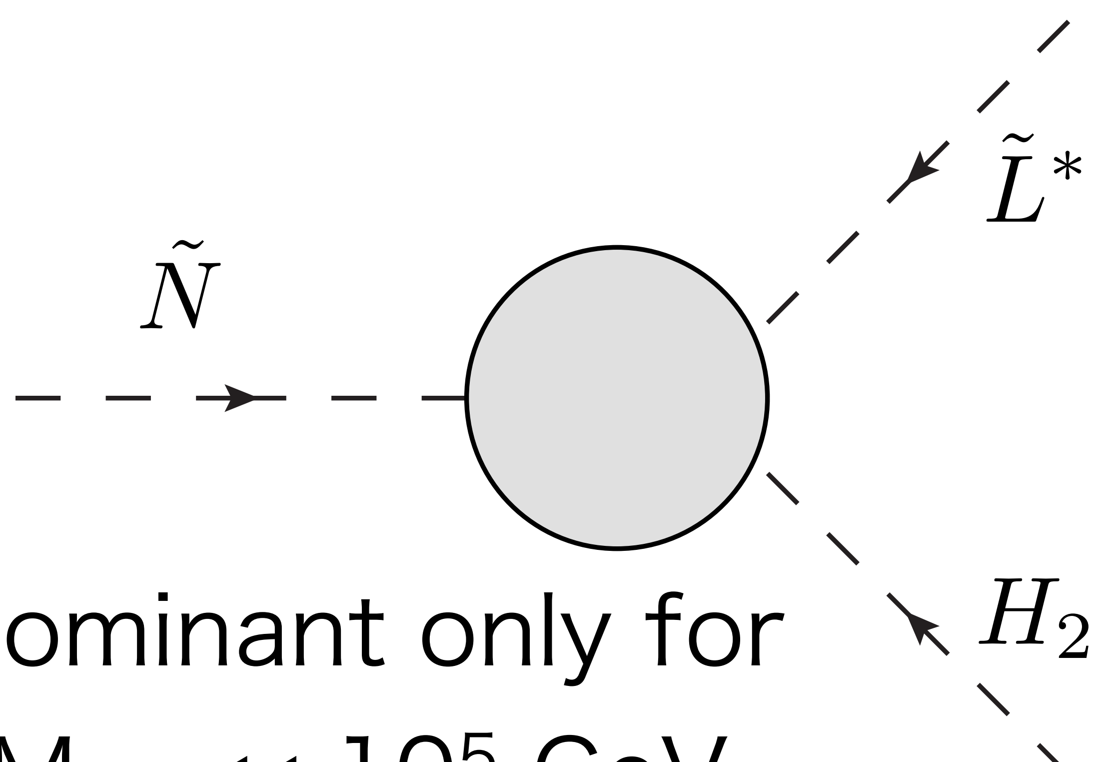
1, Corrections to propagator



+ fermin final states

(Grossman, Kashti, Nir, Roulet, 2003)
(D'Ambrosio, Giudice, Raidal, 2003)

2, Corrections to vertices

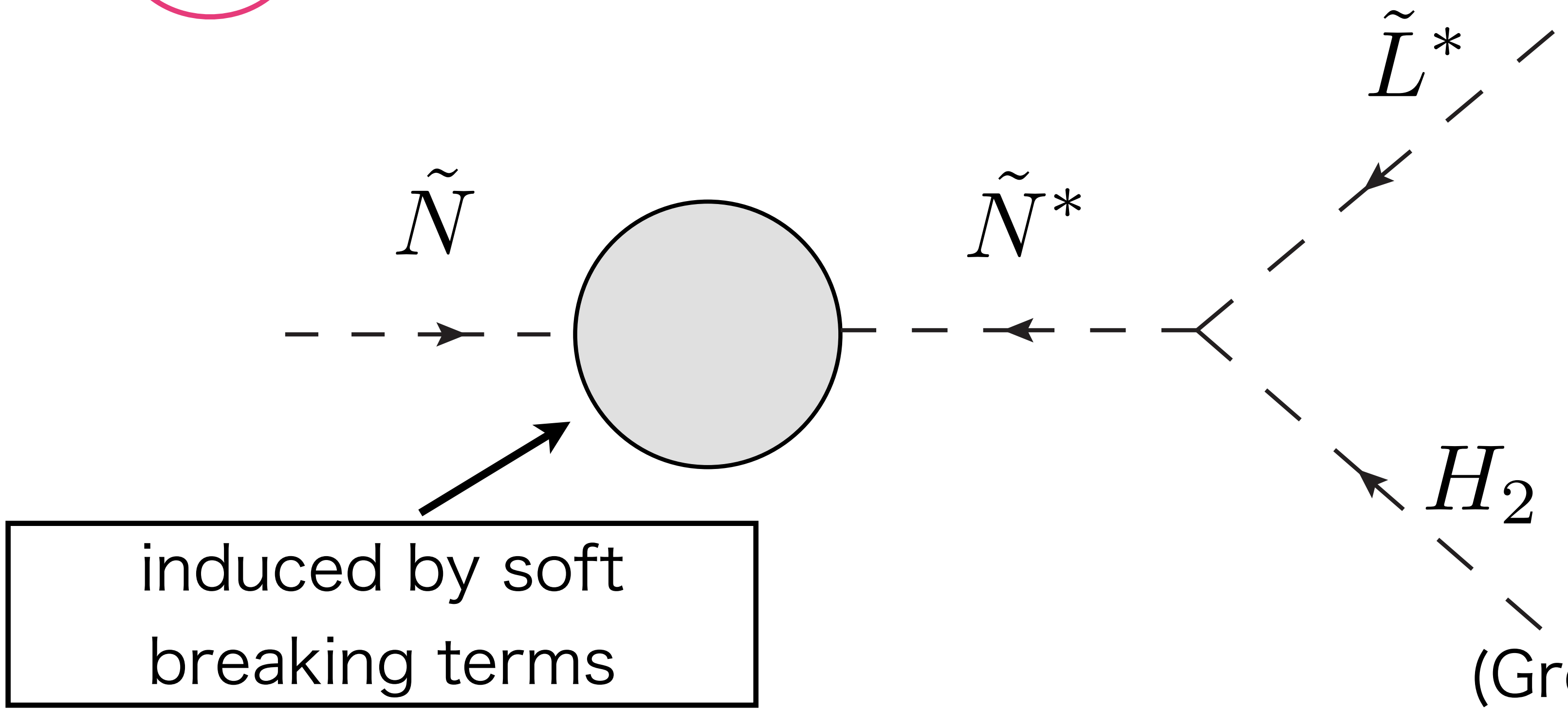


+ fermin final states

Dominant only for
$M_{N1} \ll 10^5$ GeV

(Grossman, Kashti, Nir and Roulet, 2004)

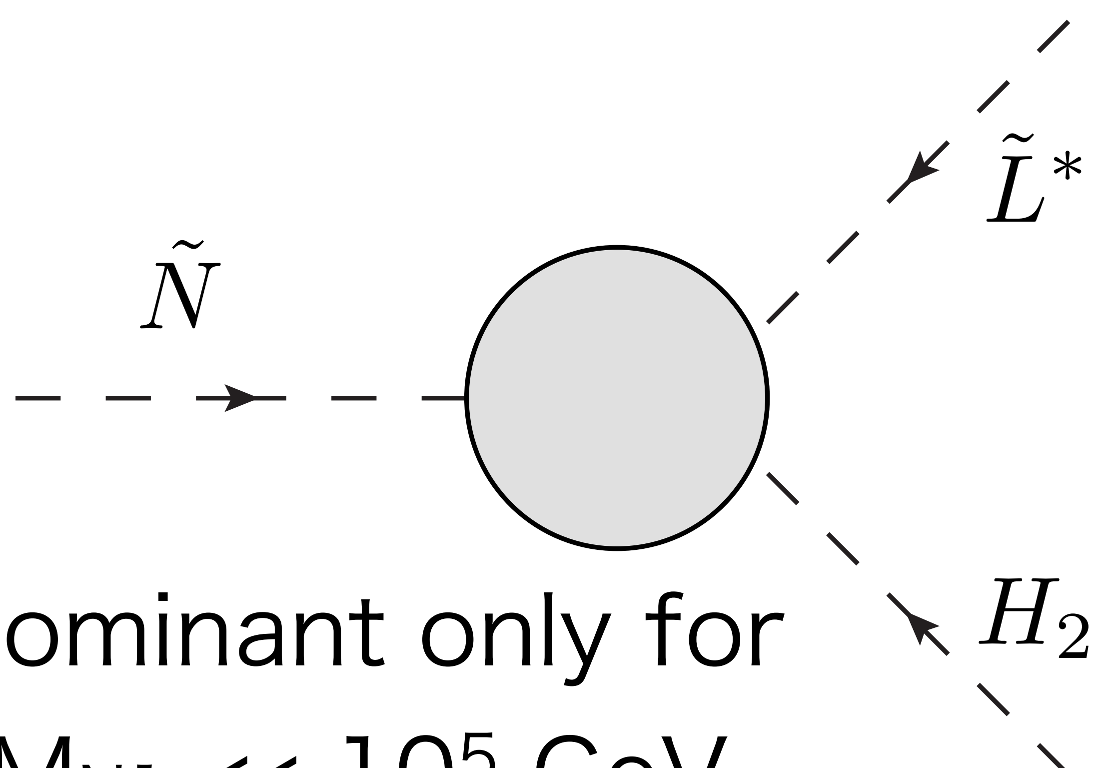
1, Corrections to propagator



+ fermin final states

(Grossman, Kashti, Nir, Roulet, 2003)
(D'Ambrosio, Giudice, Raidal, 2003)

2, Corrections to vertices



+ fermin final states

Dominant only for $M_{N1} \ll 10^5$ GeV

(Grossman, Kashti, Nir and Roulet, 2004)

RH sneutrino mixing

- The effects of the mixing propagator can be understood by the same way of a meson(e.g. K meson) mixing

Relevant Terms

$$W = Y_\nu L H_2 N + M_N N^2/2$$

$$-\mathcal{L}_{\rm soft} = A_\nu Y_\nu \tilde{L} H_2 \tilde{N} + B_\nu M_N \tilde{N}^2/2 + h.c.$$

Neutrino A-term and B-term are important

RH sneutrino mixing

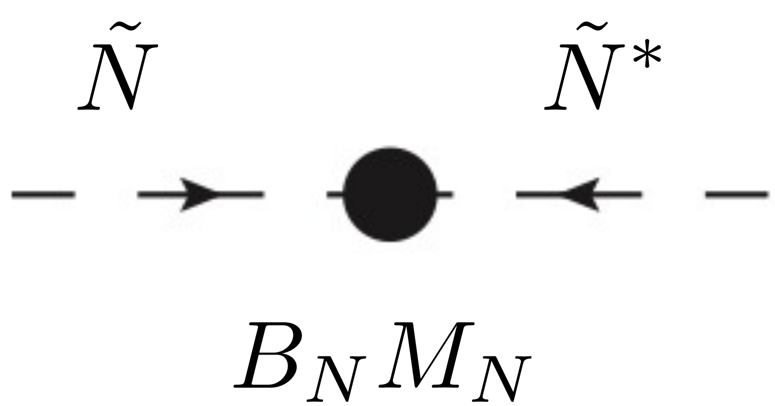
Assuming N and N tilde are produced equally

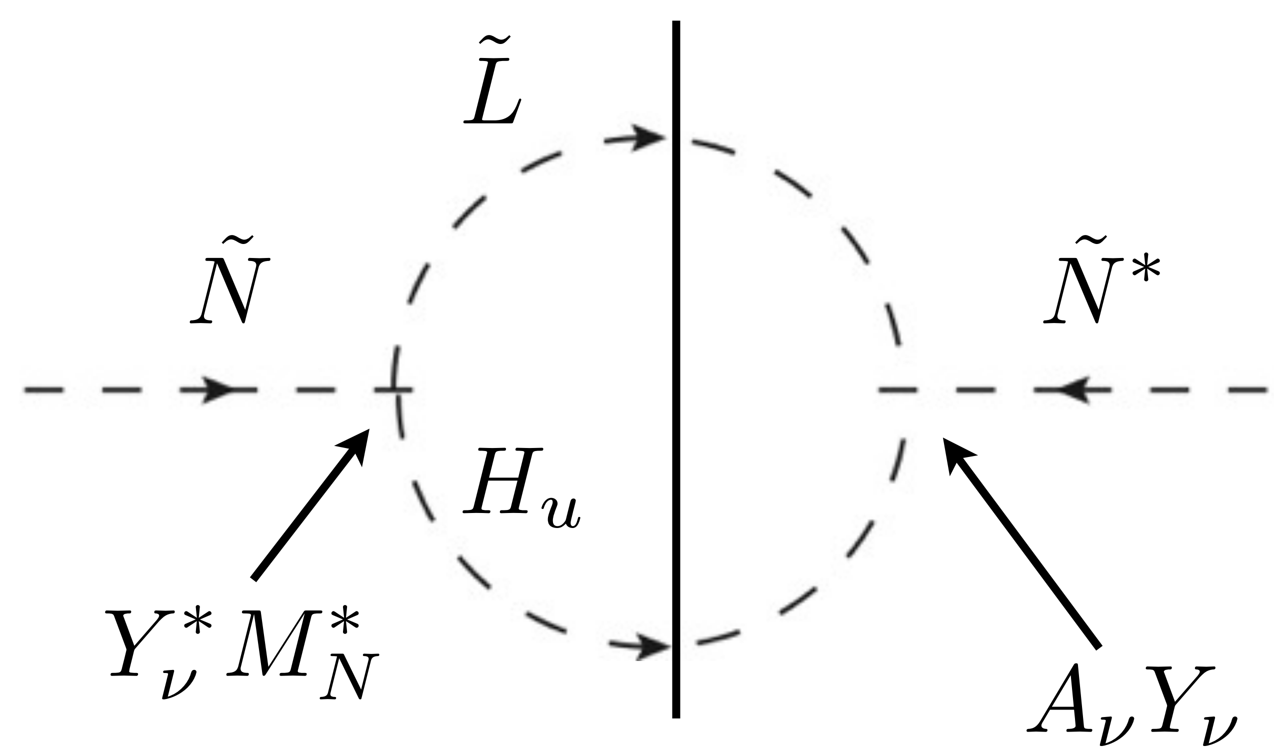
$$\tilde{N}^* \quad \tilde{N}$$

RH sneutrino mixing

Transition between N and N tilde occurs due to soft SUSY breaking terms

$$\tilde{N} \longleftarrow \tilde{N}^* \quad \tilde{N} \longrightarrow \tilde{N}^*$$





RH sneutrino mixing

Transition between N and N tilde occurs due to soft SUSY breaking terms

$$\tilde{N} \longleftarrow \tilde{N}^* \quad \tilde{N} \longrightarrow \tilde{N}^*$$

relevant terms

$$B_\nu M_N \tilde{N}^2/2 + h.c.$$

$$Y_\nu M_N \tilde{L} H_u \tilde{N}^* + h.c.$$

$$A_\nu Y_\nu \tilde{L} H_u \tilde{N} + h.c.$$

we can not erase the all phases

RH sneutrino mixing

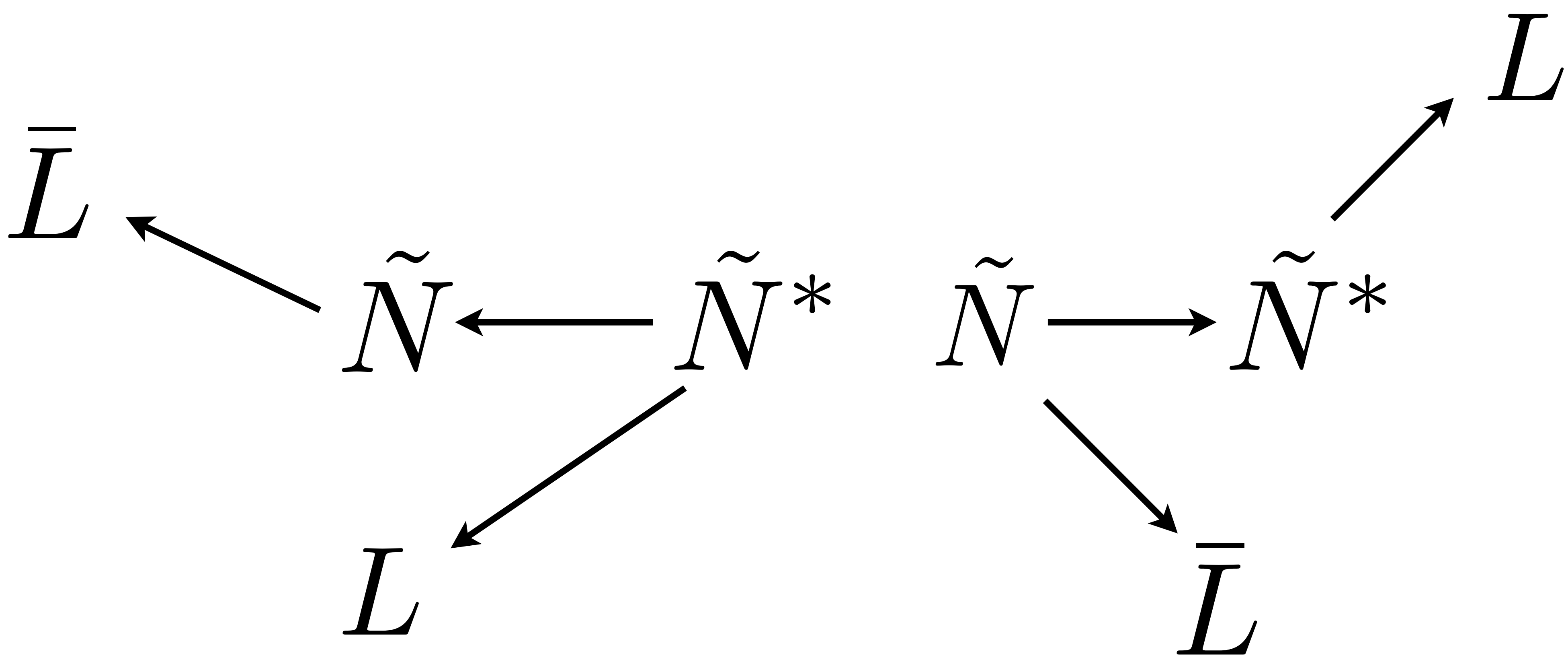
Transition between N and N tilde occurs due to soft SUSY breaking terms

$$\tilde{N} \longleftarrow \tilde{N}^* \qquad \tilde{N} \longrightarrow \tilde{N}^*$$

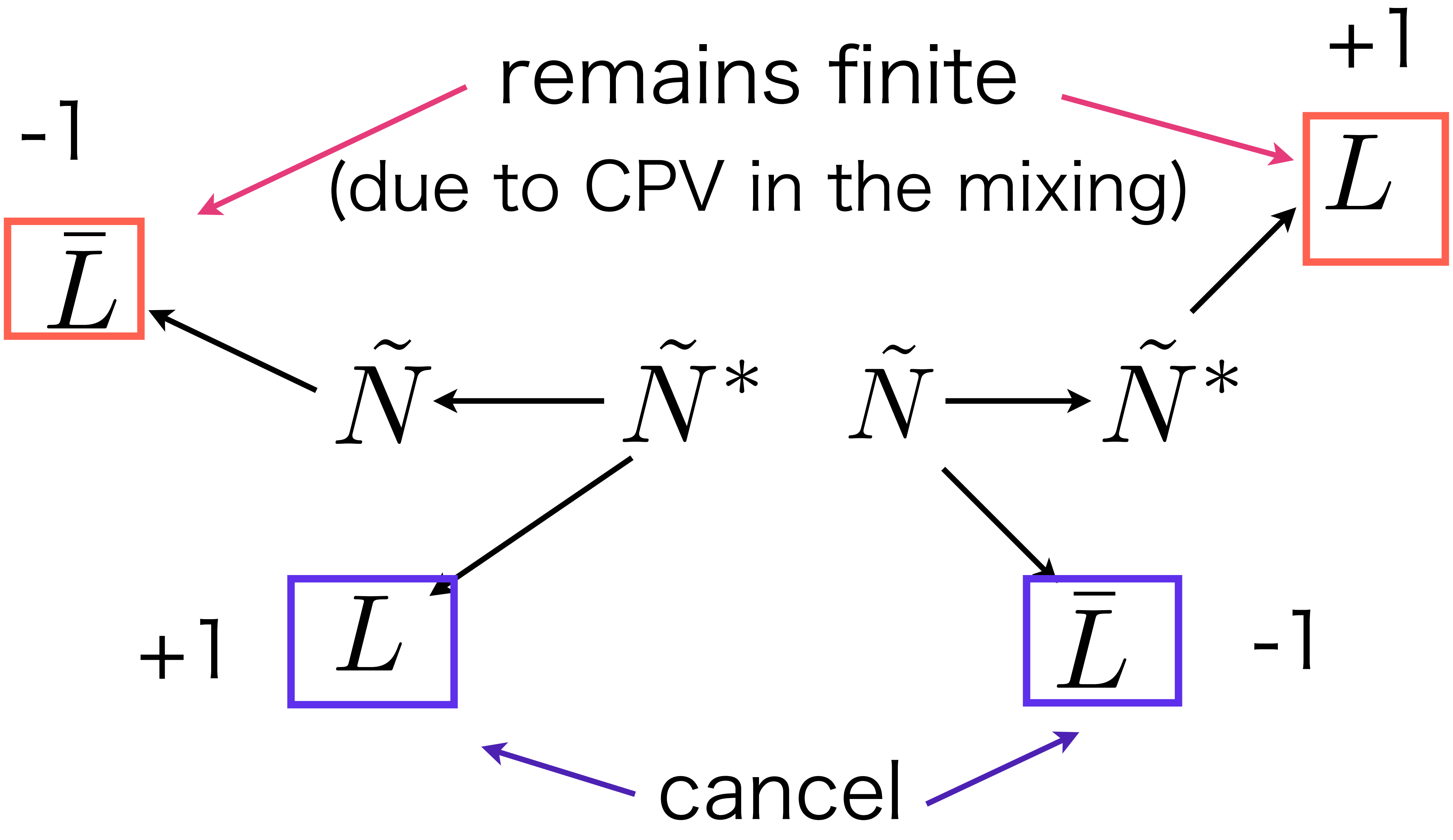
asymmetry is induced by CPV in the soft SUSY breaking terms

RH sneutrino mixing

They decays to lepton and anti-lepton



RH sneutrino mixing



(neglecting asymmetries in decays)

Lepton asymmetry

$|\tilde{N}>$ at t=0

Total decay width $\sim \frac{m_\nu M_N^2}{\langle H_u^0 \rangle^2}$

$$\left|\left\langle \tilde{N}^* | \tilde{N}(t) \right\rangle\right|^2 \simeq \left(1 + 2\frac{\Gamma}{M_N}\mathrm{Im}\frac{A_\nu}{B_\nu}\right) g(t)$$

$$g(t) \simeq e^{-\Gamma t} \sin^2(\Delta M t/2)$$

$$\Delta M = |B_\nu M_N|$$

$|\tilde{N}^*>$ at t=0

$$\left|\left\langle \tilde{N} | \tilde{N}^*(t) \right\rangle\right|^2 \simeq \left(1 - 2\frac{\Gamma}{M_N}\mathrm{Im}\frac{A_\nu}{B_\nu}\right) g(t)$$

The probabilities are different with $\arg(A_\nu) \neq \arg(B_\nu)$

(assuming $\Gamma^{-1} \gg (\Delta M)^{-1}$)

Lepton asymmetry

$$\epsilon = \frac{\sum_f \int_0^\infty dt \left[\Gamma(\tilde{N}(t) \to f) + \Gamma(\tilde{N}(t)^\dagger \to f) - \Gamma(\tilde{N}(t) \to \bar{f}) - \Gamma(\tilde{N}(t)^\dagger \to \bar{f})\right]}{\sum_f \int_0^\infty dt \left[\Gamma(\tilde{N}(t) \to f) + \Gamma(\tilde{N}(t)^\dagger \to f) + \Gamma(\tilde{N}(t) \to \bar{f}) + \Gamma(\tilde{N}(t)^\dagger \to \bar{f})\right]}$$

f lepton number +1 $\qquad$ $\bar{f}$ lepton number -1

Lepton asymmetry is induced by

$$\left|\left\langle \tilde{N}^* | \tilde{N}(t) \right\rangle\right|^2 - \left|\left\langle \tilde{N} | \tilde{N}^*(t) \right\rangle\right|^2 \simeq \left(4 \frac{\Gamma}{M_N} \mathrm{Im} \frac{A_\nu}{B_\nu}\right) g(t)$$

Lepton asymmetry

phase space difference of final states

$$\epsilon = \frac{4\Gamma|B_\nu|^2}{4\Gamma^2 + |B_\nu|^2}\mathrm{Im}\left(\frac{A_\nu}{B_\nu}\right)\frac{1}{M_N}\Delta_{BF}$$

- distribution function
- thermal mass

$$\Gamma \simeq \frac{\widetilde{m_1}}{4\pi v^2}M_N^2$$

We are interested in the region where M_N is small, i.e. Γ is small.

for $\Gamma \lesssim B_\nu$

$$\epsilon \propto \mathrm{Im}\frac{A_\nu}{B_\nu}$$

⇒ small B_ν and large A_ν is preferred

Baryon number

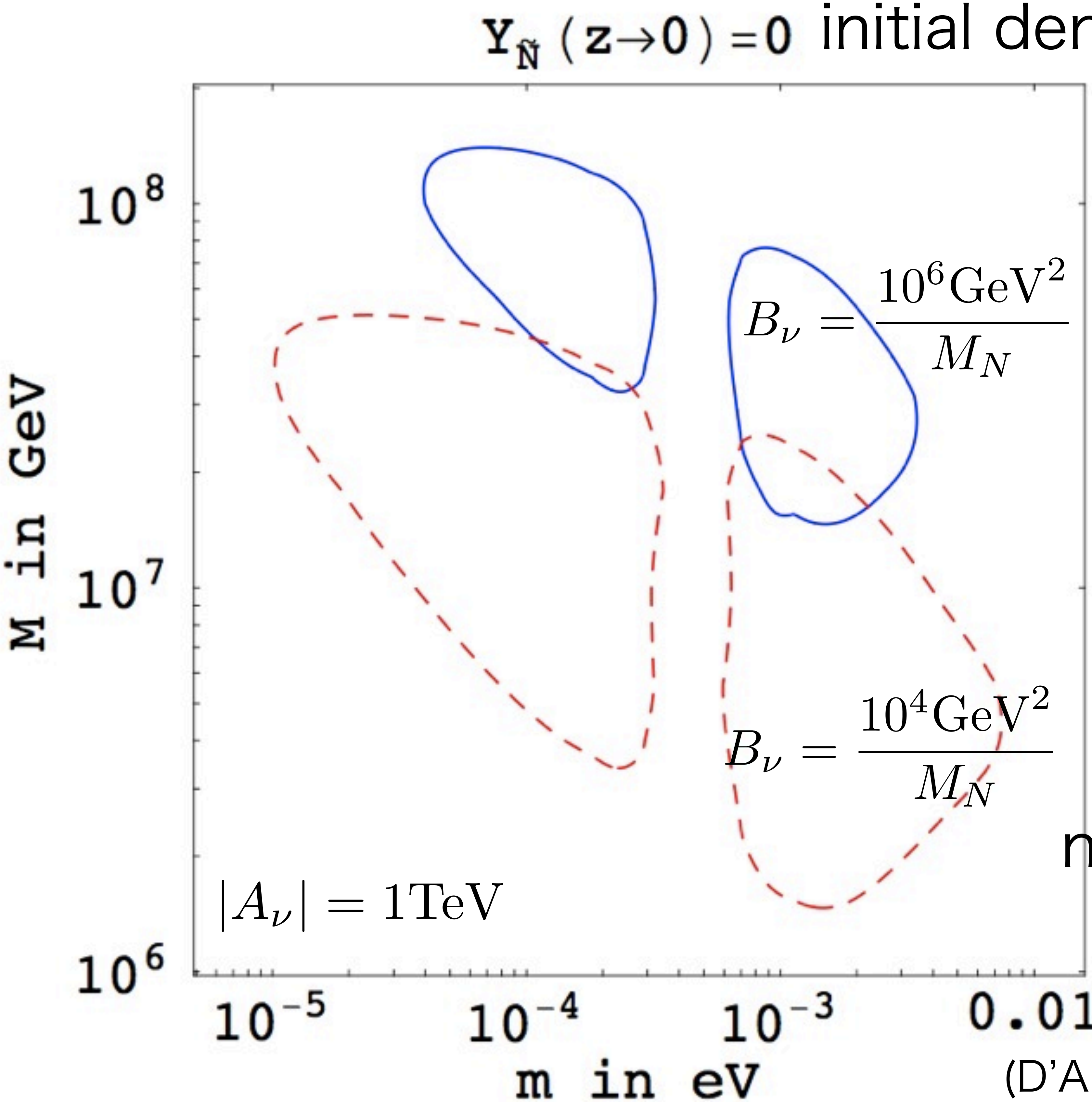
$$\epsilon = \frac{4\Gamma|B_\nu|^2}{4\Gamma^2 + |B_\nu|^2}\mathrm{Im}\left(\frac{A_\nu}{B_\nu}\right)\frac{1}{M_N}\Delta_{BF}$$

$$\frac{n_B}{s} = \frac{n_{\tilde{\mathrm{N}}_1}}{s} \times \frac{\epsilon}{\Delta_{\mathrm{BF}}} \times \left(-\frac{24+4N_H}{66+13N_H}\right)\eta$$

$$\simeq -8.6\times 10^{-4}\frac{\epsilon}{\Delta_{\mathrm{BF}}}\eta$$

- wash out effects
- production of RH sneutrino
- phase space difference of lepton and slepton

Consequences



relevant to washout and ε

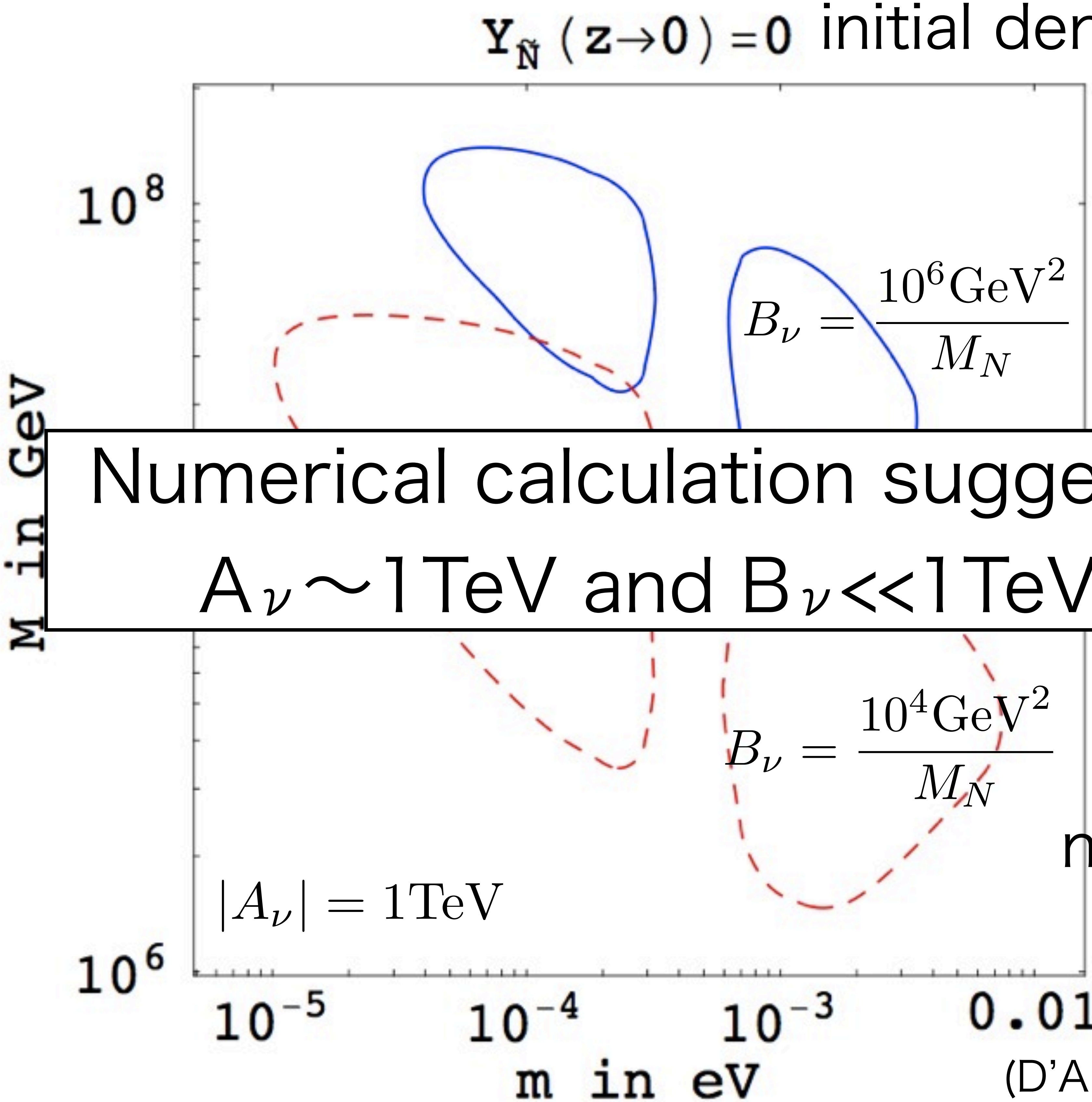
$$m = \frac{|Y_{\nu,i}|^2 v_2^2}{M_N}$$

n_B becomes maximum for $m \sim 10^{-3}\,\mathrm{eV}$

(D'Ambrosio, Giudice, Raidal, 2003)

Consequences

initial density



Numerical calculation suggests
A_ν～1TeV and B_ν<<1TeV

relevant to washout and ε

$$m = \frac{|Y_{\nu,i}|^2 v_2^2}{M_N}$$

n_B becomes maximum for $m \sim 10^{-3}\,\mathrm{eV}$

(D'Ambrosio, Giudice, Raidal, 2003)

Soft Leptogenesis in Gauge Mediation

- Small B_N is naturally explained
- AMSB and Gravity Mediation generate $B_N \sim m_{3/2} << m_{soft}$

$$\mathcal{L} = \int d^2\theta (1 + c\frac{F}{M_P}\theta^2 + m_{3/2}\theta^2)\frac{M_N}{2}N^2 + h.c.$$

$$\sim m_{3/2} M_N \tilde{N}^2/2 + h.c.$$

$\arg(A_\nu) \neq \arg(B_\nu)$ in general

(Y. Grossman, R. Kitano and H. Murayama; 2005)

- A_ν of O(1) TeV is difficult
- A-term is zero at the messenger scale and only generated by RGE running effects

$$\frac{dA_\nu}{dt} \ni -\frac{1}{8\pi^2}\left(\frac{3}{5}g_1^2 M_1 + 3g_2^2 M_2\right)$$

⇓

$$A_\nu(M_N) \simeq -\frac{1}{8\pi^2}\frac{M_2}{g_2^2}\int_{\ln M_{\rm mess}}^{\ln M_N} dt \left(\frac{3}{5}g_1^4 + 3g_2^4\right)$$

(assuming GUT relation)

$A_\nu(M_N) \sim 50\mathrm{GeV}$ is generated radiatively

- A-term is not large enough
- We can not enlarge wino mass since gluino mass also increases

$$A_\nu(M_N) \simeq -\frac{1}{8\pi^2}\frac{M_2}{g_2^2}\int_{\ln M_{\rm mess}}^{\ln M_N} dt \left(\frac{3}{5}g_1^4 + 3g_2^4\right)$$

heavier gluino ➡ tighter constraint

$$T_R \lesssim \mathcal{O}(10^7 \mathrm{GeV}) \times \left(\frac{m_{3/2}}{0.1\mathrm{GeV}}\right)\left(\frac{m_{\tilde{g}}}{1\mathrm{TeV}}\right)^{-2}$$

Difficult to realize gravitino DM

Our Scenario with A-term

A_ν-term generation

- We include interaction terms

$$W = M_S S^2 + \lambda S H_u l + \lambda' S H_d \bar{l}$$

Messenger Parity (and R-parity) controls interactions

A_ν-term generation

- We include interaction terms

$$W = M_S S^2 + \lambda S H_u l + \lambda' S H_d \bar{l}$$

The terms which generates B_ν

Messenger Parity

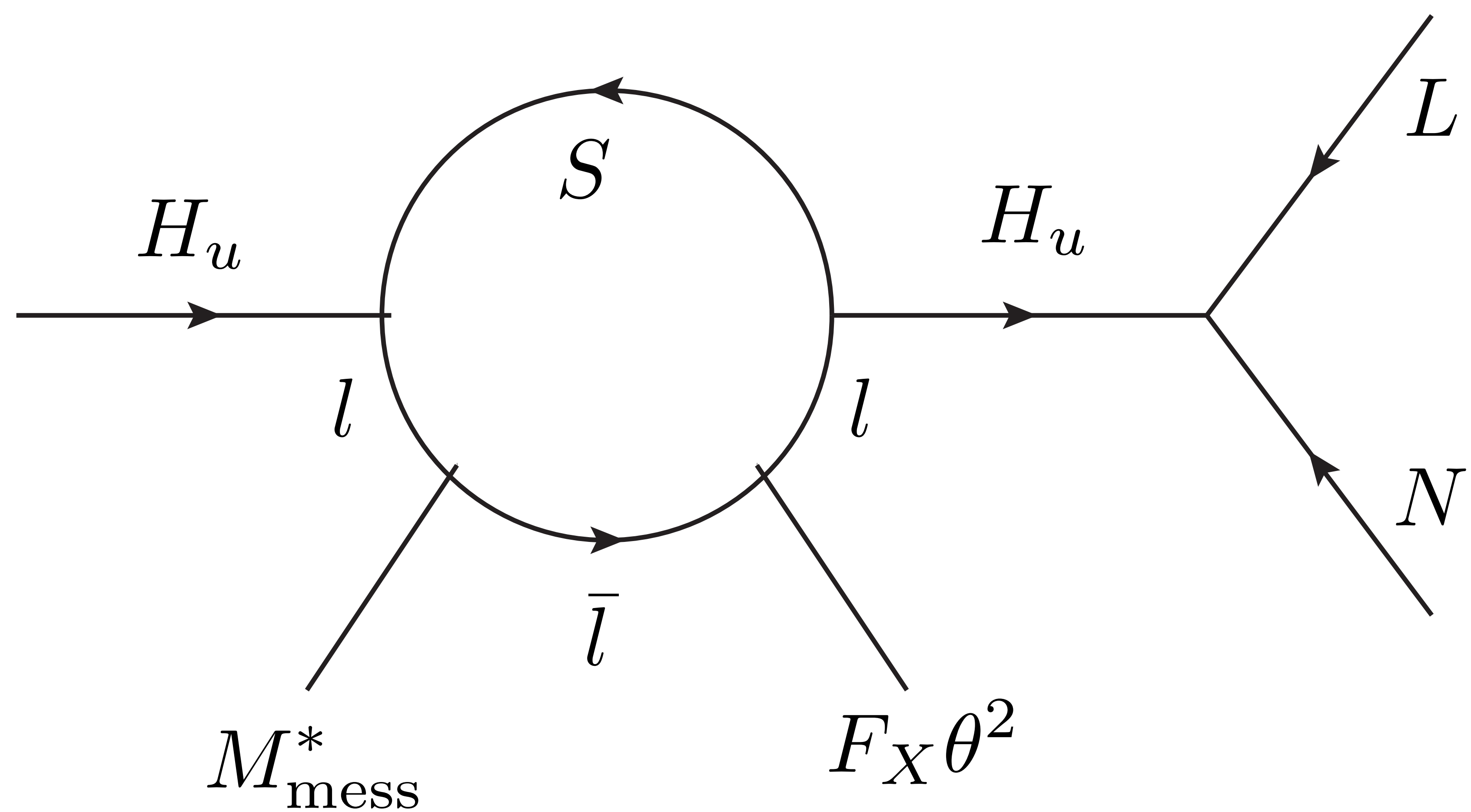
$$S, \Psi, \bar{\Psi} \quad -1$$
$$N, H_u, H_d \quad +1$$

forbid ⇒

$$N\Psi\bar{\Psi}$$
$$N H_u l$$
$$N H_d \bar{l}$$

A_ν-term generation

- A-term is generated at 1-loop level



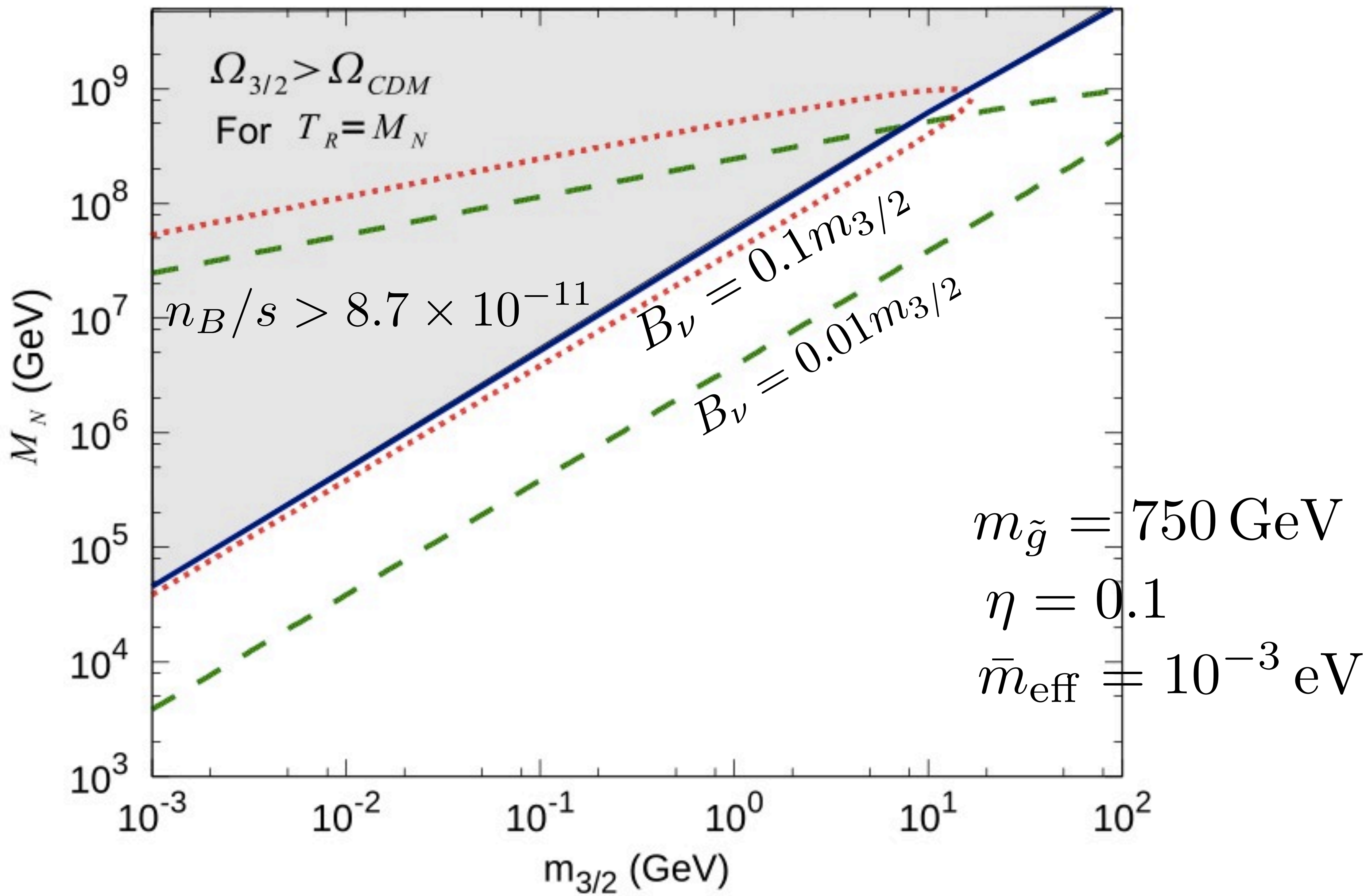
$$|A_\nu| \simeq \frac{|\lambda|^2}{16\pi^2}\left|\frac{F_X}{M_{\rm mess}}\right| \gtrsim 1\mathrm{TeV}$$ with O(1) λ

Soft Letogenesis in Gauge Mediation (modified)

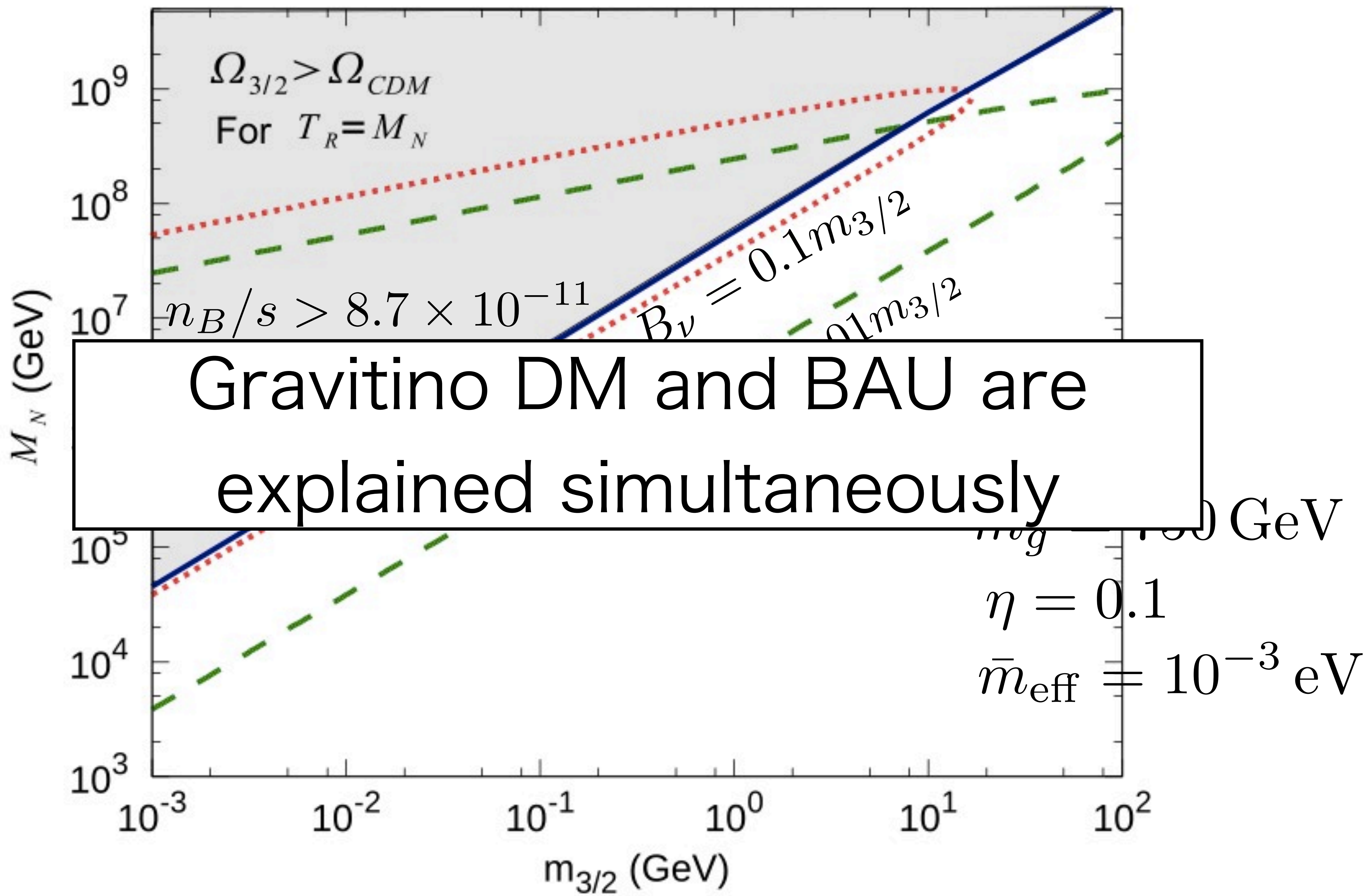
- B_ν << 1 TeV ---> OK
- A_ν of the order of 1 TeV ---> OK

- The requirements are satisfied!

Baryon Number



Baryon Number



Gravitino DM and BAU are explained simultaneously

Scalar masses and CP phase

CP phases

- We can remove all dangerous phases by the rotations of H_u, H_d, S and messengers

$$X\Psi\overline{\Psi} \quad M_S S^2 \quad \lambda S H_u l \quad \lambda' S H_d \bar{l} \quad \mu H_d H_u$$

$F_X \theta^2 \Psi\overline{\Psi}$ ← Remove the phase by $U(1)_R$

EDM constraints are OK

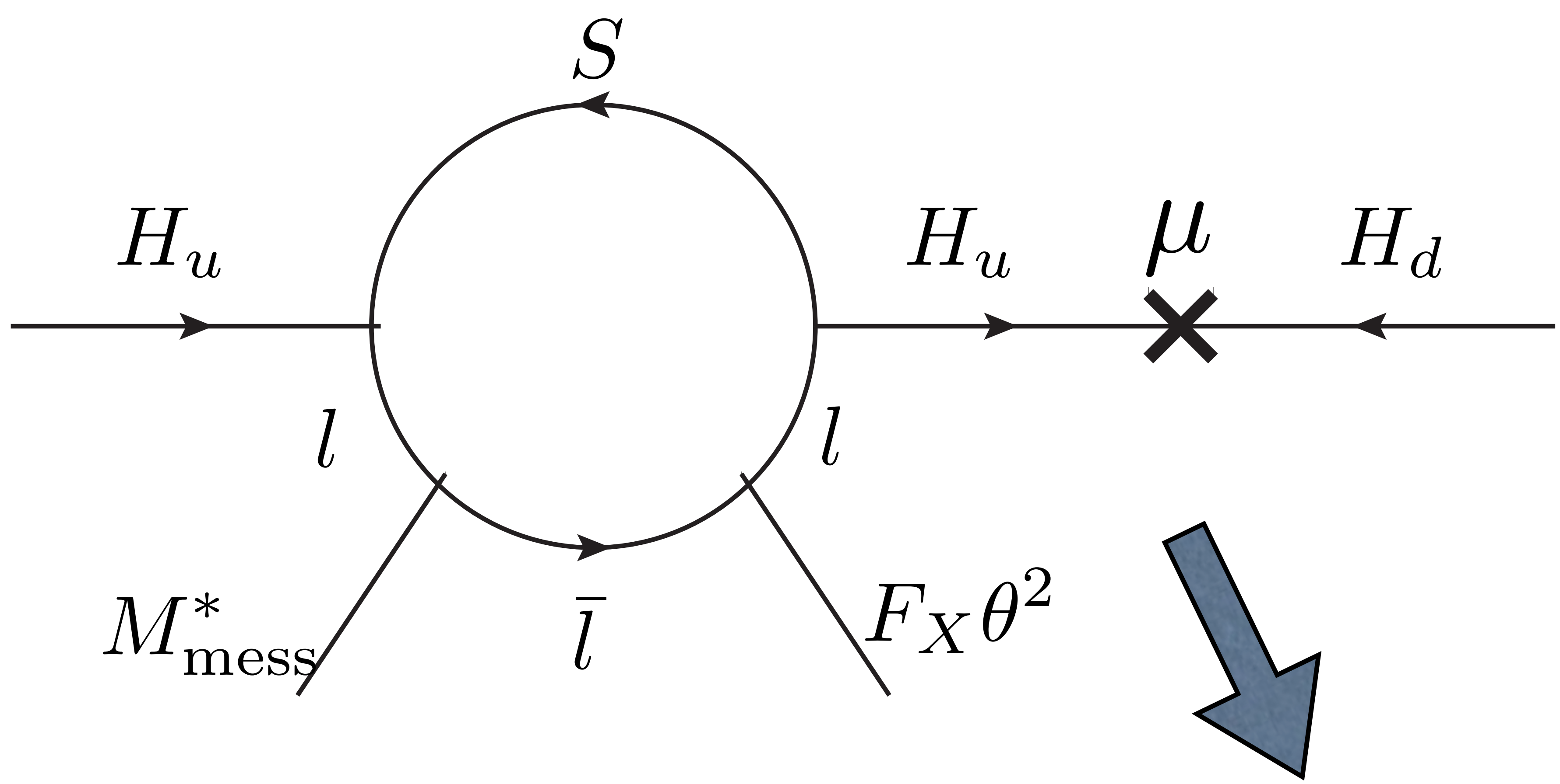
Soft Terms

- Soft-terms are modified through wave-function renormalization of H_u and H_d
- (Additional) μ-term and Higgs B-term at 1-loop level
- Scalar masses are completely different from those in minimal gauge mediation
- λ' is small when EWSB is taken into account

μ-term and B-term

Higgs B-term through wave-function renormalization of Hu

(if tree level μ-term exists)



$$\mathcal{L}_{\rm soft} = B\mu H_d H_u + h.c.$$

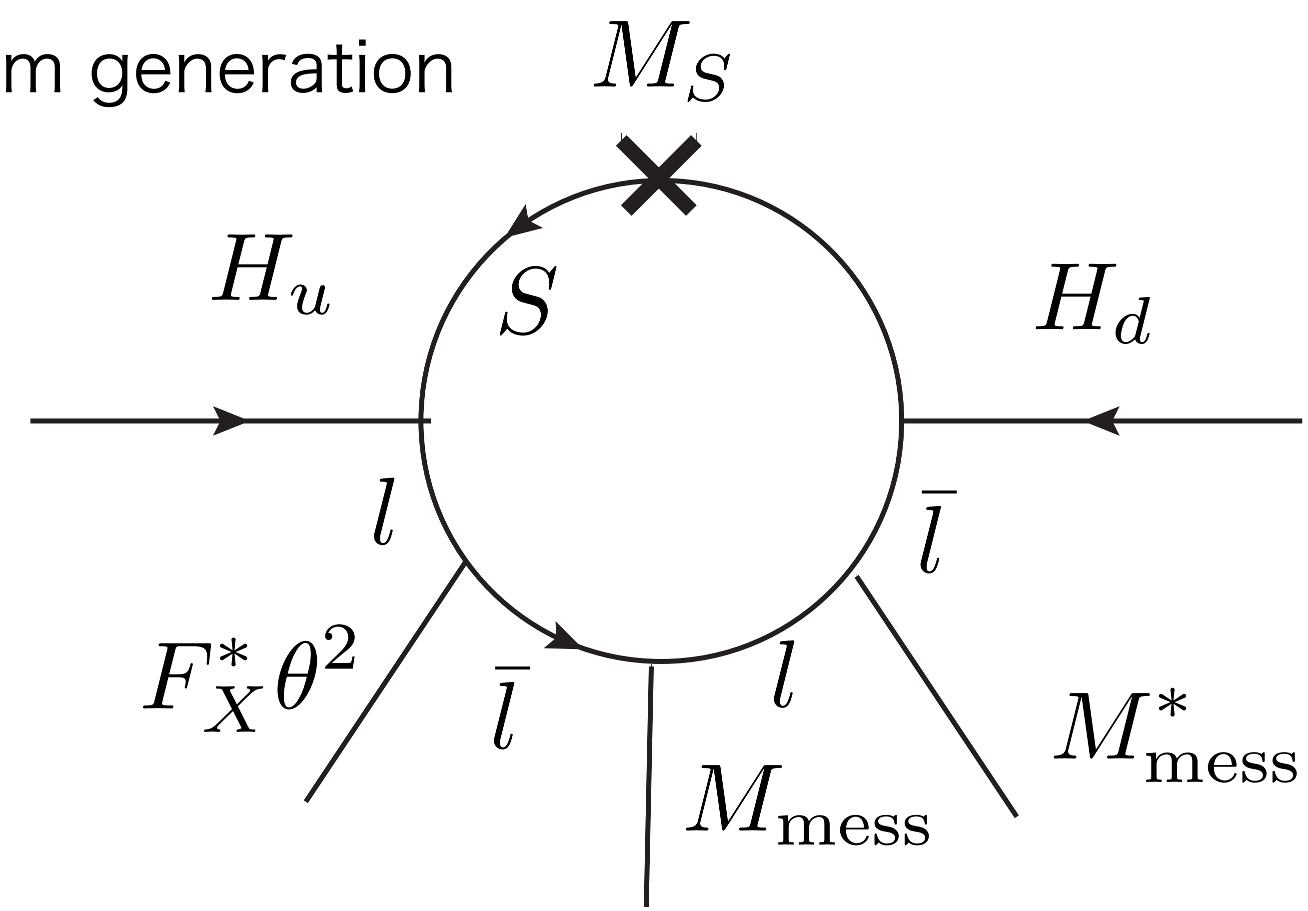
$$B = -\frac{\lambda^2}{16\pi^2}\frac{F_X}{M_{\rm mess}}$$

- Higgs μ-term and B-term is generated by λ and λ' at 1-loop level

$$\delta\mu \sim \frac{\lambda\lambda'}{16\pi^2}\frac{F}{M}\frac{M_S}{M}\ln\frac{M_S^2}{M^2} \qquad \delta B\mu \sim \frac{\lambda\lambda'}{16\pi^2}\left(\frac{F}{M}\right)^2\frac{M_S}{M}\ln\frac{M_S^2}{M^2}$$

for $M_S/M \ll 1$

μ-term generation



Scalar masses

Up-type Higgs mass and stop mass are modified

$$Z_{H_u}(\mu, M + F\theta^2, M^* + F^*\bar{\theta}^2)$$

$$Z_Q(\mu, M + F\theta^2, M^* + F^*\bar{\theta}^2)$$

$$Z_{\bar{U}}(\mu, M + F\theta^2, M^* + F^*\bar{\theta}^2)$$

$$\Delta Z_{H_u} = \frac{\lambda^2}{16\pi^2} \ln \frac{\hat{M}^\dagger \hat{M}}{\Lambda^2}$$

$$Y_t(\mu, \hat{M})$$

$$\int d^4\theta Z_\phi \phi^\dagger \phi \quad \Rightarrow \quad \frac{\partial^2 Z_\phi}{\partial M \partial M^*} |F|^2 \tilde{\phi}^\dagger \tilde{\phi}$$

$$\phi = Q, \bar{U}, H_u$$

Up-type Higgs mass

$$\delta m_{H_u}^2 \simeq \frac{\lambda^2}{(16\pi^2)^2}(4\lambda^2 - \frac{3}{5}g_1^2 - 3g_2^2)\left(\frac{F}{M}\right)^2 \text{ +1-loop}$$

$$\text{(1-loop)} \approx \frac{\lambda^2}{(16\pi^2)}\left(\frac{F}{M}\right)^2\left(2 + \ln\frac{M_S^2}{M^2}\right)\frac{M_S^2}{M^2}$$

for $(M_S/M) \ll 1$

1-loop part is negative for $\frac{M_S^2}{M^2} \lesssim 0.1$

assist EWSB

Stop masses

$$\delta m^2_{\tilde{Q}_3} = -\frac{Y_t^2\lambda^2}{(16\pi^2)^2}\left(\frac{F}{M}\right)^2$$

$$\delta m^2_{\tilde{t}_R} = -2\frac{Y_t^2\lambda^2}{(16\pi^2)^2}\left(\frac{F}{M}\right)^2$$

$$A_t Y_t = -\frac{\lambda^2}{16\pi^2} Y_t \frac{F}{M}$$

Negative contributions

Large mixing

↓

Stop tends to be light

Sparticle Spectrum

$\lambda = 1.4, \quad (M_S/M_{\rm mess})^2 = 0.03$

```
Block MINPAR  # SUSY breaking input parameters
     3    2.50000000000000e+01   # tanb
     4    1.00000000000000e+00   # sign(mu)
     1    1.00000000000000e+05   # lambda
     2    1.00000000000000e+10   # M_mess
     5    1.00000000000000e+00   # N5
     6    1.00000000000000e+00   # cgrav
```

```
22    -1.75155060048020e+06   # mH2^2(Q)
```

at $M_{\rm mess}$

```
     25        1.18991199529499e+02   # h0
1000006        3.88501217662820e+02   # ~t_1
2000006        8.56992361387124e+02   # ~t_2
```

Summary

- By simple modification of gauge mediation, we explain correct abundance of gravitino DM and BAU
- The mass spectrum for scalar particles are significantly modified
- light stop and (bit)heavy Higgs