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WB, CERN, 6-98

LEPTOGENESIS AND DARK MATTER *

- Leptogenesis

  CP violation, neutrino properties, washout processes

- Dark Matter

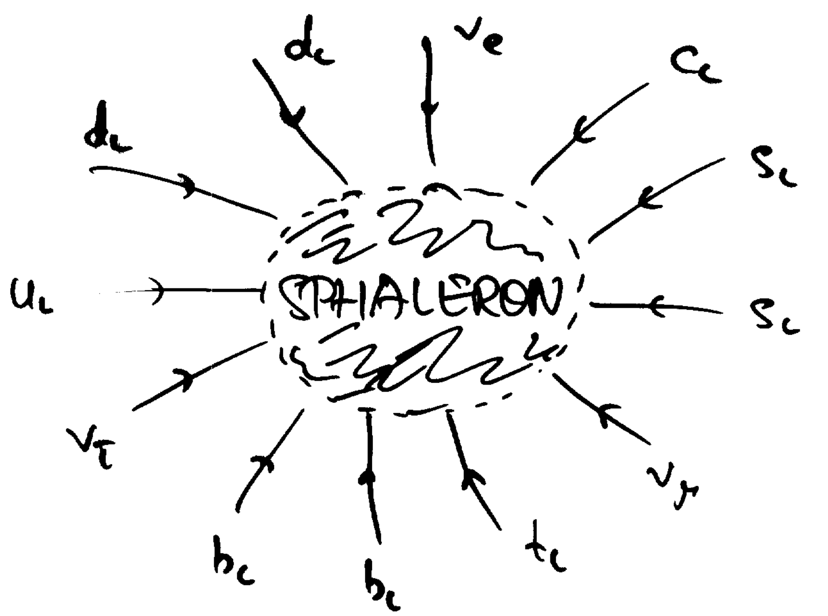
  Implication for SUSY mass spectrum, gravitino as dark matter candidate

* work with M. Plümacher + M. Bolz

(1) Leptogenesis

In the high-temperature, symmetric phase of the standard model baryon-number (B) and lepton-number (L) violating processes are in <u>thermal equilibrium</u>, for temperatures

$$T_c^{ew} \sim 100 \text{ GeV} < T < T_{SPH} \sim 10^{12} \text{ GeV} :$$



⋮
Kuzmin, Rubakov, Shaposhnikov '85
⋮

→ relation between asymmetries

$$\boxed{\langle B\rangle_T = c\,\langle B-L\rangle_T = \frac{c}{c-1}\,\langle L\rangle_T} \quad , \; c = O(1)$$

implications: baryon asymmetry is related to neutrino properties for $T_B > T_c^{ew}$, important constraints on neutrino masses

— Decays of heavy Majorana neutrinos

Fukugita, Yanagida '86

simplest realization of lepton-number violation:
SM with ν_R's ; most general couplings :

$$\mathcal{L}_Y = -\bar{l}_L \tilde{\varphi}\, e_R - \bar{l}_L \varphi\, g_\nu \nu_R - \frac{1}{2} \bar{\nu}_R^c M \nu_R + h.c.$$

3x3 complex matrices (g_ν, M)

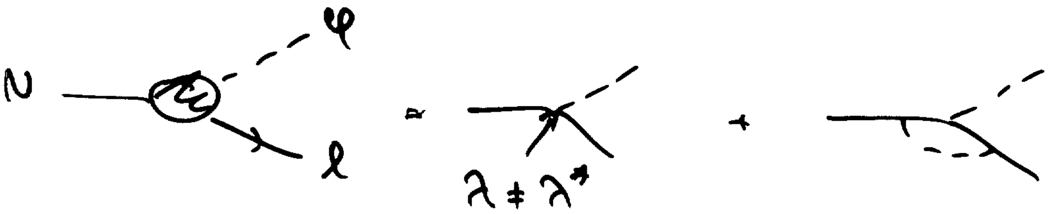
$$l_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L ; \quad \varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} , \ldots$$

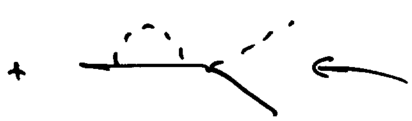
6 Majorana mass eigenstates via 'see-saw' :

$$N \simeq \nu_R + \nu_R^c \quad , \quad \nu \simeq K^\dagger \nu_L + \nu_L^c K \quad , \quad K^\dagger K = 1$$

$$m_N \simeq M \qquad m_\nu \simeq -K^\dagger m_D \frac{1}{M} m_D^T K^* \quad , \quad m_D = g_\nu v$$

CP-asymmetry in decay





Covi, Roulet, Vissani
Flanz, Paschos, Sarkar

$$\varepsilon = \frac{\Gamma(N \to l\varphi) - \Gamma(N \to \bar{l}\bar{\varphi})}{\quad " \quad + \quad " \quad}$$, yields lepton asymmetry

Example, based on quark-lepton unification, motivated by SO(10) - GUT:

$$m_D = \underset{\uparrow}{V} \begin{pmatrix} m_1 & & 0 \\ & m_2 & \\ 0 & & m_3 \end{pmatrix} \underset{\uparrow}{U}^\dagger , \quad M = \begin{pmatrix} M_1 & & 0 \\ & M_2 & \\ 0 & & M_3 \end{pmatrix}$$

leptonic CKM — baryogenesis

$$\frac{m_1}{m_2} \sim \frac{m_2}{m_3} \sim \frac{M_1}{M_2} \sim \frac{M_2}{M_3} \sim \lambda^2 , \quad \lambda \simeq 0.1$$

$$\left(\text{cf. quarks} : \frac{m_u}{m_c} \sim \frac{m_c}{m_t} \sim \lambda^2 \right)$$

$$U \sim U_{CKM}^{\text{Wolfenstein}} \left(\lambda \simeq 0.1 \right) , \quad m_3 \underset{\uparrow}{=} m_{top} \simeq 174 \text{ GeV}$$

SO(10)

$\rightarrow$ neutrino masses:

$$m_{\nu_e} \simeq 8 \cdot 10^{-6} \text{ eV} , \quad m_{\nu_\mu} \simeq 3 \cdot 10^{-3} \text{ eV (INPUT)} , \quad m_{\nu_\tau} \simeq 0{,}15 \text{ eV}$$

$$\underset{\uparrow}{M_1 \simeq 2 \cdot 10^{10}} \text{ GeV} , \quad M_3 \simeq \underset{\uparrow}{2 \cdot 10^{14}} \text{ GeV}$$

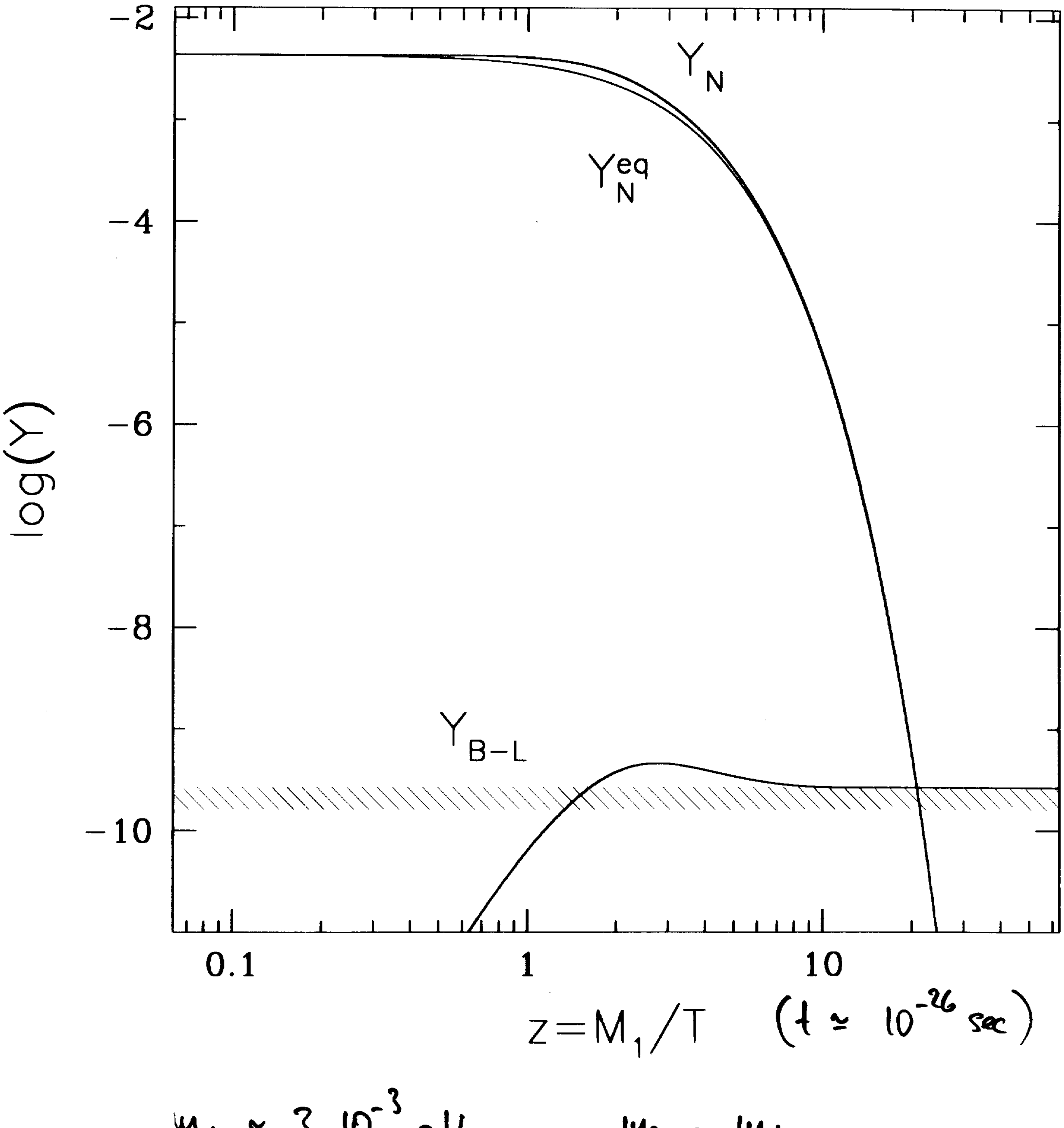
temperature of baryogenesis — $\Lambda_{B-L} \sim \Lambda_{GUT}$

Baryon asymmetry:

$$Y_{B-L} = \frac{\langle n_{B-L} \rangle}{s} = \kappa \frac{\varepsilon}{g_*} , \quad \varepsilon \simeq \underset{\uparrow}{\frac{1}{32\pi} \lambda^4 \frac{m_3^2}{v^2}}$$

washout, 10^{-2} — $\sim 10^2$ — 10^{-6}

$\hookrightarrow$ Boltzmann equations



$m_{\nu_\mu} \simeq 3 \cdot 10^{-3}$ eV , $m_3 = m_{top}$,

$M_1 \simeq 2 \cdot 10^{10}$ GeV

- Remark on atmospheric neutrino anomaly (SuperK)

possible interpretation : $\nu_\mu - \nu_\tau$ oscillation, compatible with MSW via $\nu_e - \nu_\mu$ oscillation and $m_{\nu_e} < m_{\nu_\mu} < m_{\nu_\tau}$;

observation : $m_{\nu_\tau} \sim 0.07$ eV , $\sin^2 2\Theta \sim 1$

large mixing angle in V requires explanation : compatible with hierarchical neutrinos due to structure of Majorana mass matrix $\longrightarrow$ Bando, Kugo, Yoshioka hep-ph/9710417

- Supersymmetric extension

motivation : unification of gauge couplings

MSSM with ν_R's :

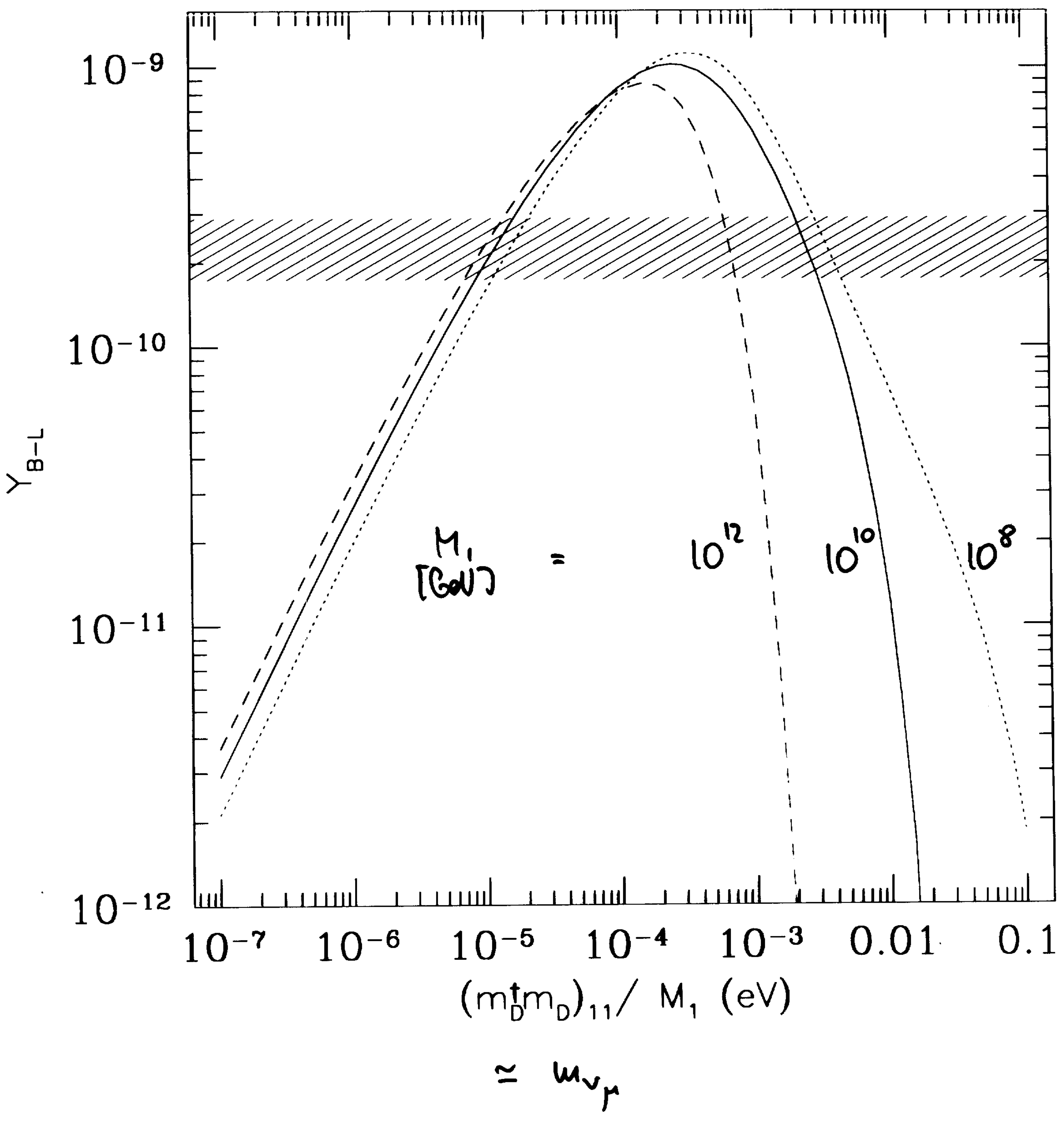
$$W = L g_e E_c H_1 + L g_\nu N_c H_2 + \frac{1}{2} N_c M N_c + \dots ,$$

(chiral superfields) Campbell, Davidson, Olive; Covi, Roulet, Vissani

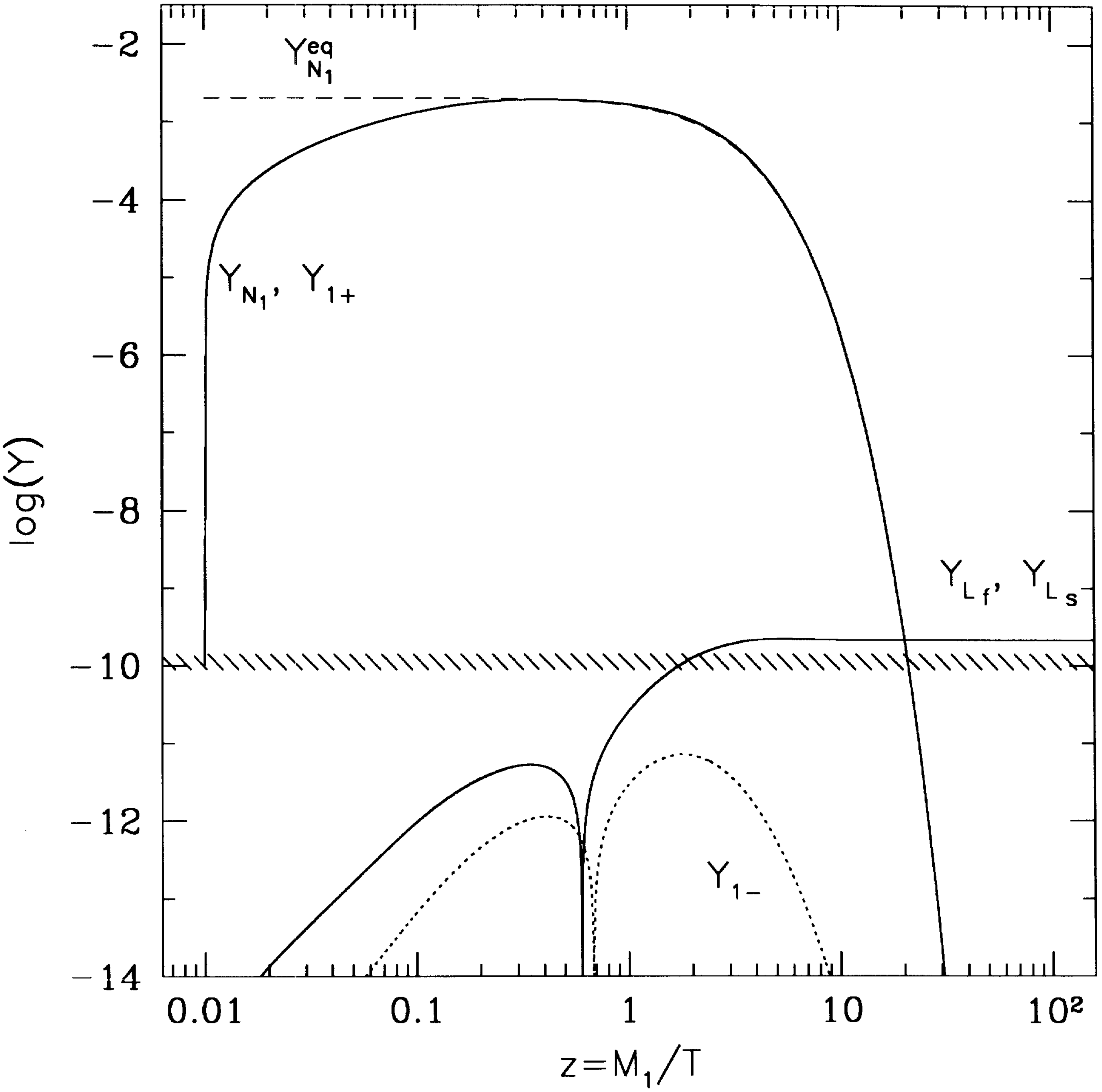
larger CP asymmetry ; many more washout processes , generation of initial equilibrium distribution (Plümacher '97) ; crucial parameter :

$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1} \simeq m_{\nu_\mu} , \quad 10^{-5}\,\mathrm{eV} < \tilde{m}_1 < 5 \cdot 10^{-3}\,\mathrm{eV}$$

Plümacher


10^{-9}
10^{-10}
10^{-11}
10^{-12}
Y_{B-L}
M_1 [GeV] =
10^{12}
10^{10}
10^{8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
$(m_D^\dagger m_D)_{11}/\ M_1$ (eV)
$\simeq m_{\nu_\mu}$

Plümacher

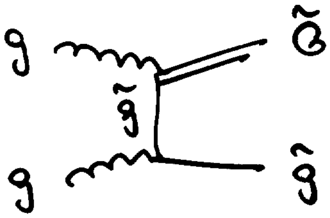


$$Y_{1\pm} = Y_{\tilde{N}_{c1}} \pm Y_{\tilde{N}_{c1}^*}$$

(2) SUSY mass spectrum and dark matter *

characteristic feature of leptogenesis : asymmetry is generated at large temperature ; in the considered model $T_B \sim 10^{10}$ GeV . Is this consistent with the 'gravitino constraint' ? general expectation : $T_B < 10^8 - 10^9$ GeV GeV . Previous work : Khlopov, Linde ; Ellis, Kim, Nanopoulos , '84 Moroi et al. , '93 - '97

'gravitino problem' :



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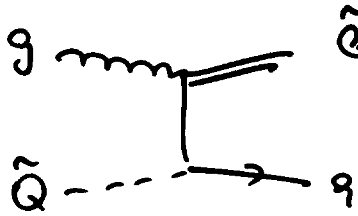


, ...

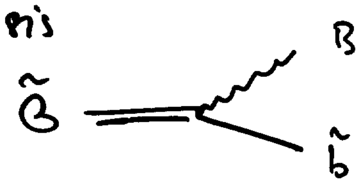
$$\sigma \propto \frac{g_3^2}{M^2} \quad , \quad \Gamma(T) \propto \frac{g_3^2}{M^2} T^3$$

problems :

(i) stable gravitinos may overclose the universe

(ii) unstable gravitinos may generate too much entropy after nucleosynthesis

e.g.



* DESY-98-066

Requirement: upper bound on energy release, depending on lifetime! Sufficient conditions (Ellis et al., '92):

(I) $m_X Y_X(T) < 4 \cdot 10^{-10}$ GeV , $\tau < 2 \cdot 10^{6}$ sec or

(II) $m_X Y_X(T) < 4 \cdot 10^{-12}$ GeV , τ arbitrary ,

$$Y_X(T) = n_X(T) / n_{rad}(T) \quad , \quad n_{rad}(T) = \frac{\zeta(3)}{\pi^2} T^3$$

gravitino density from Boltzmann equations:

$$\frac{dn_{\tilde{G}}}{dt} + 3H n_{\tilde{G}} = \underbrace{C(T)}_{\text{all relevant processes}} n_{rad}^2 \quad ,$$

$$C(T) \propto \frac{g_3^2(T)}{M^2} \left(\frac{m_{\tilde{g}}(T)}{m_{\tilde{G}}} \right)^2 \quad , \quad \text{for } m_{\tilde{G}} < m_{\tilde{g}}$$

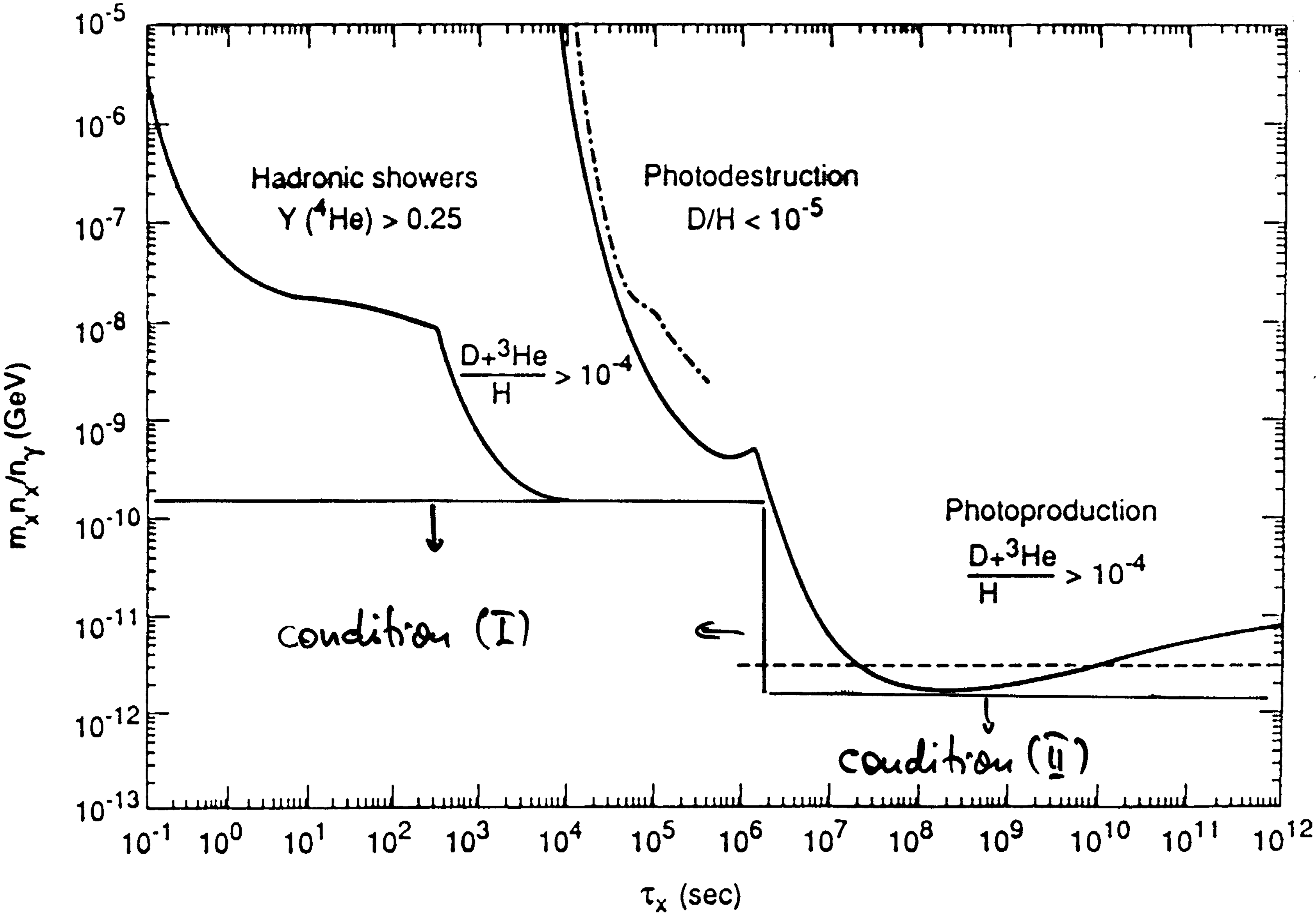
$$Y_{\tilde{G}}(T) \simeq 1.4 \cdot 10^{-10} \left(\frac{T_B}{10^{10} \text{GeV}} \right) \left(\frac{100 \text{ GeV}}{m_{\tilde{G}}} \right)^2 \left(\frac{m_{\tilde{g}}(\mu)}{1 \text{ TeV}} \right)^2 \quad ,$$

$$\Omega_{\tilde{G}} h^2 = m_{\tilde{G}} Y_{\tilde{G}}(T) \, n_{rad}(T) \, \rho_c^{-1}$$

$$\simeq 0.26 \left(\frac{T_B}{10^{10} \text{GeV}} \right) \left(\frac{100 \text{ GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\tilde{g}}(\mu)}{1 \text{ TeV}} \right)^2 \quad ,$$

$$\rho_c = 3 H_0^2 M^2 \quad .$$

Ellis, Gelmini, Lopez, Nanopoulos, Sarkar, NP '92



- unstable gravitino

  $m_{\tilde{G}} Y_{\tilde{G}}$ typically 3 order of magnitude too large! ↯

- stable gravitino (= LSP)

  (i) $m_{\tilde{G}} < 1$ keV

  consistent, origin of dark matter?

  Borgiani, Masiero, Yamaguchi '96

  (ii) $m_{\tilde{G}} \sim 10 \ldots 100$ GeV

  late decays of neutralino (NSP), BBN constraint:

  $\tau_\chi < 7 \cdot 10^6$ sec $\curvearrowright$ $m_\chi > m_\chi^{min}(m_{\tilde{G}})$

  $m_\chi Y_\chi < 4 \cdot 10^{-10}$ GeV $(\Omega_\chi h^2 < 0.008)$

  neutralino density (→ Edsjö, Gondolo):

  $$10^{-4} < \Omega_\chi h^2 < 10^4 \quad , \qquad F's$$

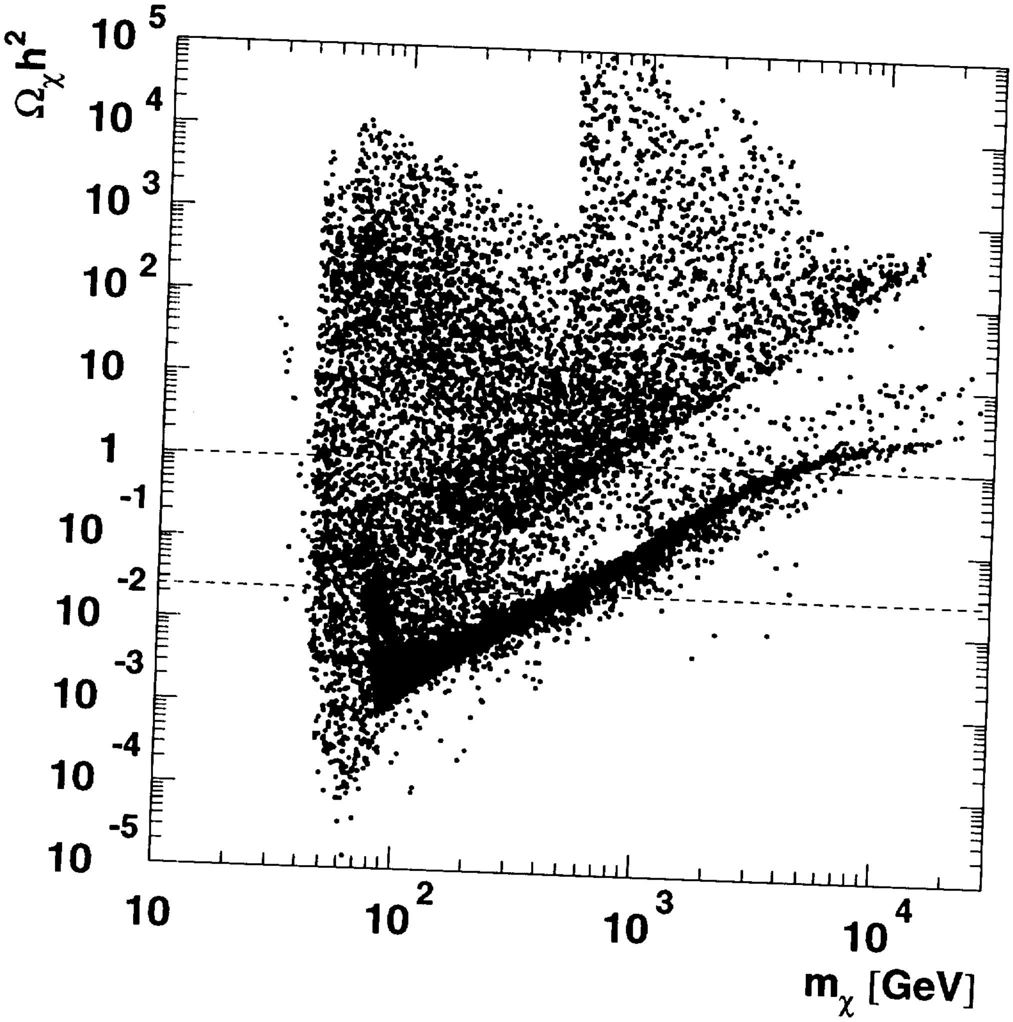
  for MSSM parameter range, small for 'higgsinos' with $m_\chi > m_W$ ('higgsino hole'); massive gravitino natural dark matter candidate! F's

  (may be visible via late R_p decays, Berezinsky '91)

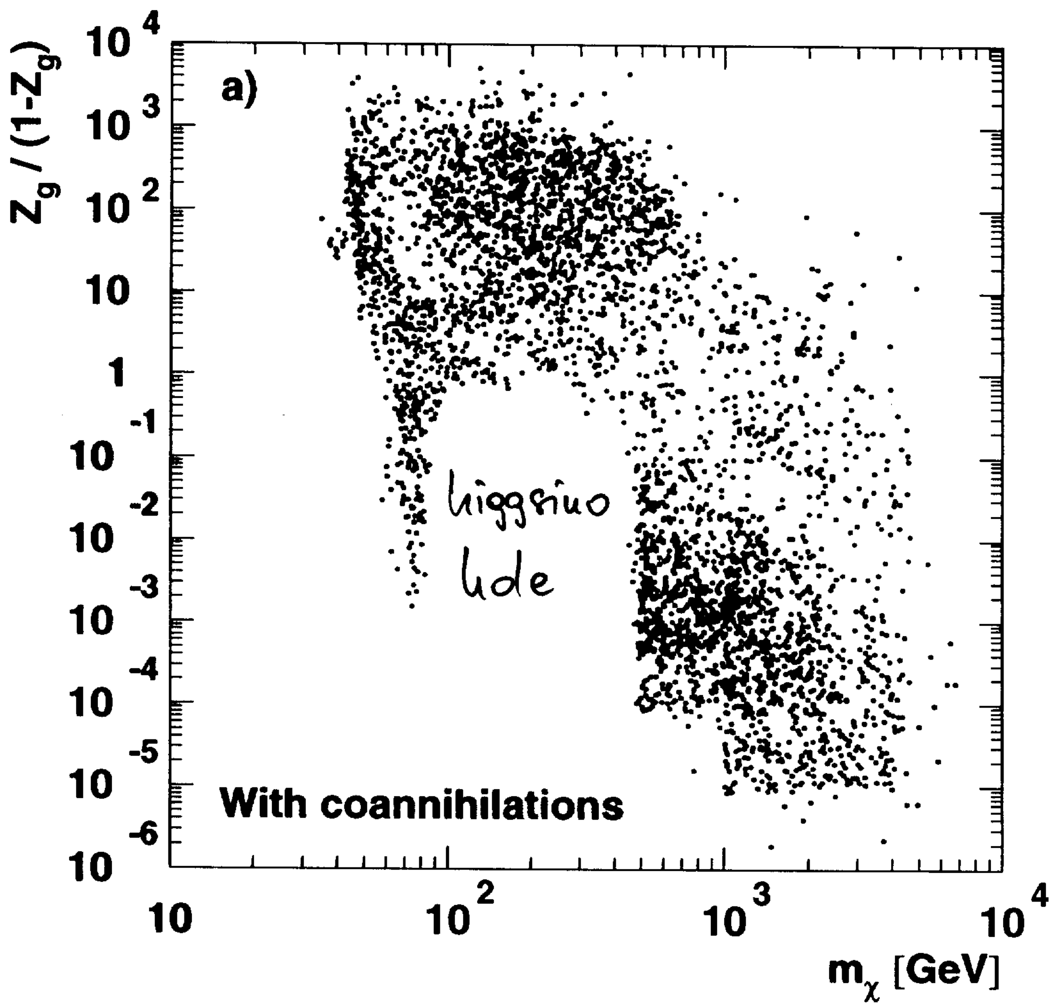
Implications: Dark matter is problem of gravity + SUSY breaking

no WIMPs

Edsjö, Gondolo, PRD '97

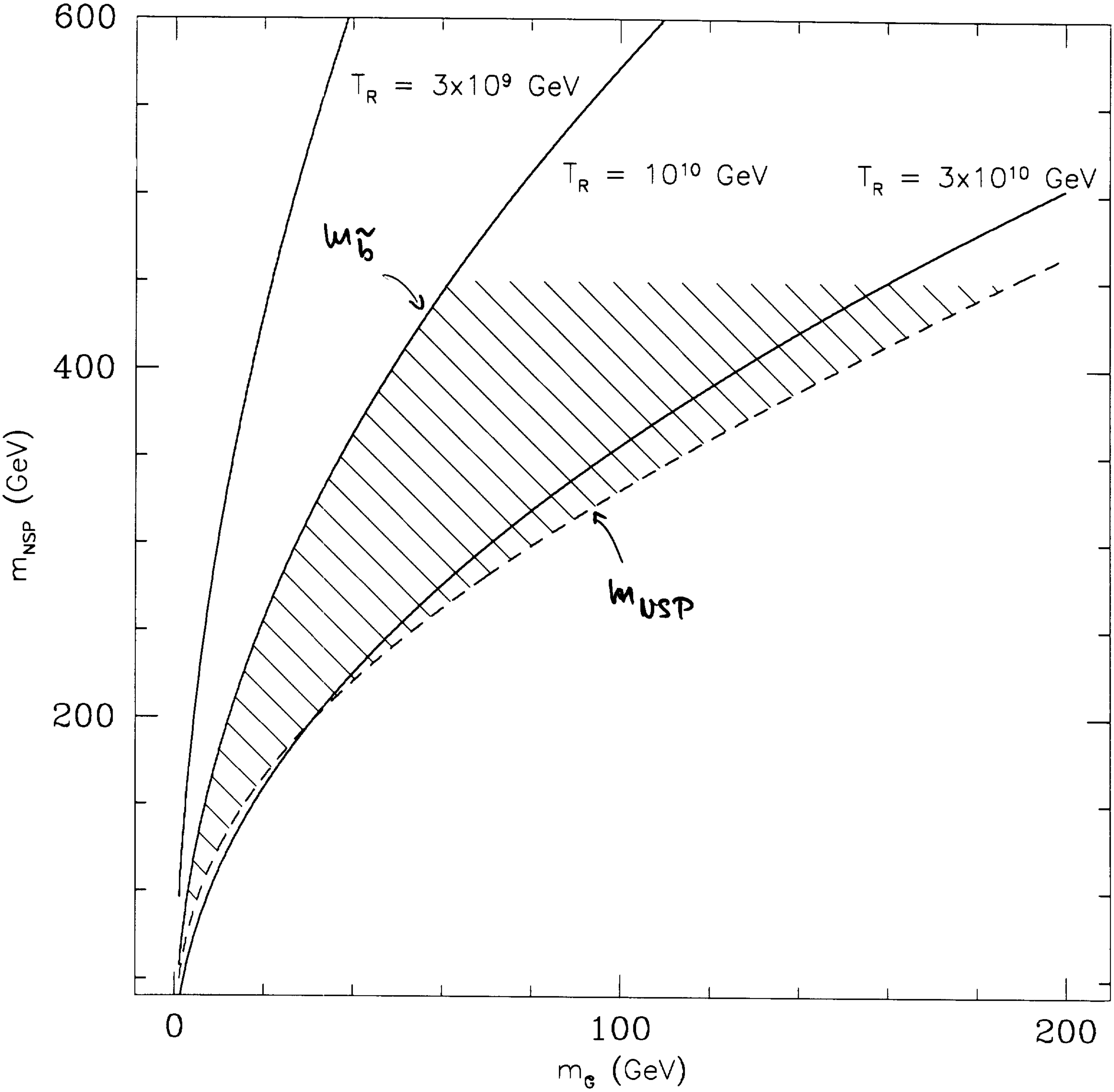


Edsjö, Gondolo, PRD '97



$0.025 < \Omega_\chi h^2 < 1$

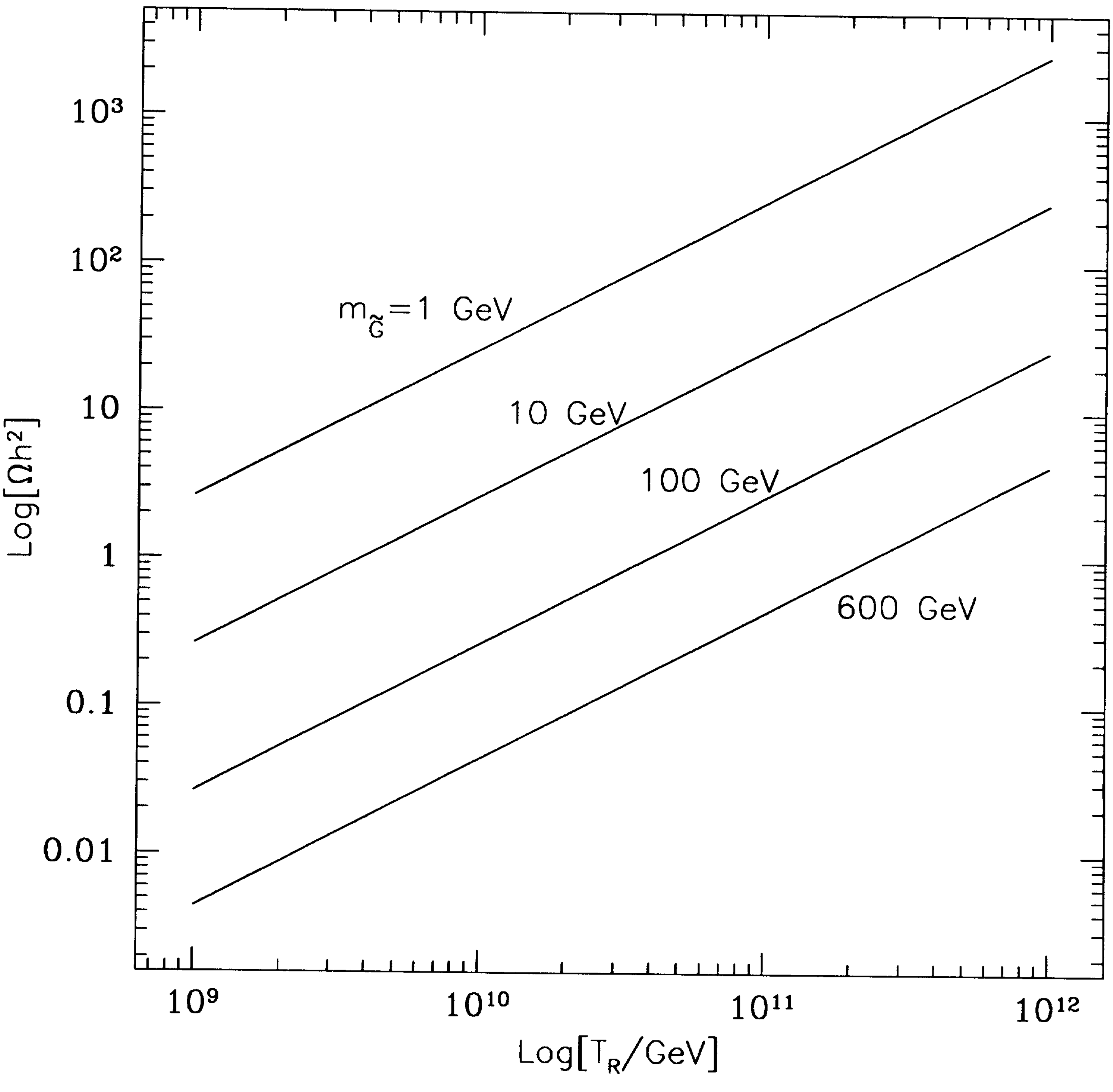
PRELIMINARY Bolz, WB, Plümacher



$$m_{\tilde{G}} < m_\chi < m_{\tilde{b}} \quad , \quad \chi = NSP$$

$$m_{\tilde{b}}(\mu) = \frac{5}{3} \frac{g_1^2(\mu)}{g_3^2(T_R)} m_{\tilde{g}}(T_R)$$

PRELIMINARY Bolz, WB, Plümacher



$m_{\tilde{g}} = 1$ TeV