WB, Vienna, 11-05

LEPTOGENESIS AND THE GRAVITINO PROBLEM

- Status of Leptogenesis
- Connection with ν-Masses
- The Gravitino Problem
- $\Omega_{DM} \simeq \Omega_{3/2}$

I. Status of Leptogenesis

– (simple) thermal leptogenesis:

Fukugita, Yanagida '86

add ν_{Ri}, $i = 1-3$, to SM, seesaw mechanism gives mass eigenstates $\nu_i \simeq \nu_{Li} + \nu_{Li}^c$, $N_i \simeq \nu_{Ri} + \nu_{Ri}^c$, with

$$\underbrace{m_N \simeq M \quad , \quad m_\nu \simeq - m_D \frac{1}{M} m_D^T}_{\Delta L = 2} \quad ,$$

Dirac neutrino mass matrix $m_D = h v$, $v = 174$ GeV, $M \gg m_D$, $m_\nu \ll m_D$; CP-violating decays of heavy Majorana neutrinos,

$$\Gamma(N_i \to l H) \neq \Gamma(N_i \to l^c H^c) \quad ,$$

generate lepton asymmetry ΔL, which is partially converted to baryon asymmetry ΔB by sphaleron processes (KRS, $\Delta B = \Delta L = 3$); in therm. equilibrium:

$$T_{EW} \sim 100 \text{ GeV} < T < T_{sph} \sim 10^{12} \text{ GeV}$$

Thermal leptogenesis is an attractive mechanism for baryogenesis:

(1) baryon asymmetry determined by neutrino properties

(2) baryon asymmetry consistent with neutrino masses

Quantitative Analysis

(→ WB, Di Bari, Plümacher, Ann. Phys. '05)

from nucleosynthesis, with $T_{BBN} \sim 1$ MeV,

$$\eta_B^{BBN} = \frac{n_B}{n_\gamma} = (2.6 - 6.2) \times 10^{-10}$$

from microwave background, with $T_{CMB} \sim 1$ eV,

$$\eta_B^{CMB} = (6.1 {}^{+0.3}_{-0.2}) \times 10^{-10}$$

impressive test of standard cosmological model → stringent bounds on ν-masses

Theory :

$$Y_B = 0.01\ \varepsilon_1\ \kappa_f \qquad (N_1 \to l\phi)$$

CP asymmetry

⋮
Davidson,
Ibarra
⋮

$$\varepsilon_1^{max} = \frac{3}{16\pi}\frac{M_1\, m_{atm}}{v^2} \qquad m_{atm} = \left(\Delta m^2_{atm}\right)^{1/2}$$

$$\simeq 10^{-6}\left(\frac{M_1}{10^{10}\,GeV}\right)\left(\frac{m_{atm}}{0.05\,eV}\right)$$

efficiency factor

$$\kappa_f = (2\pm1)\times 10^{-2}\left(\frac{0.01\,eV}{\tilde{m}_1}\right)^{1.1\pm0.1} ,$$

$$m_1 \le \tilde{m}_1 \lesssim m_3$$

light neutrino masses :

$$10^{-3}\,eV \lesssim m_i \le 0.1\,eV$$

cosmology
$\sum m_i \sim 0.10$

initial conditions ↗

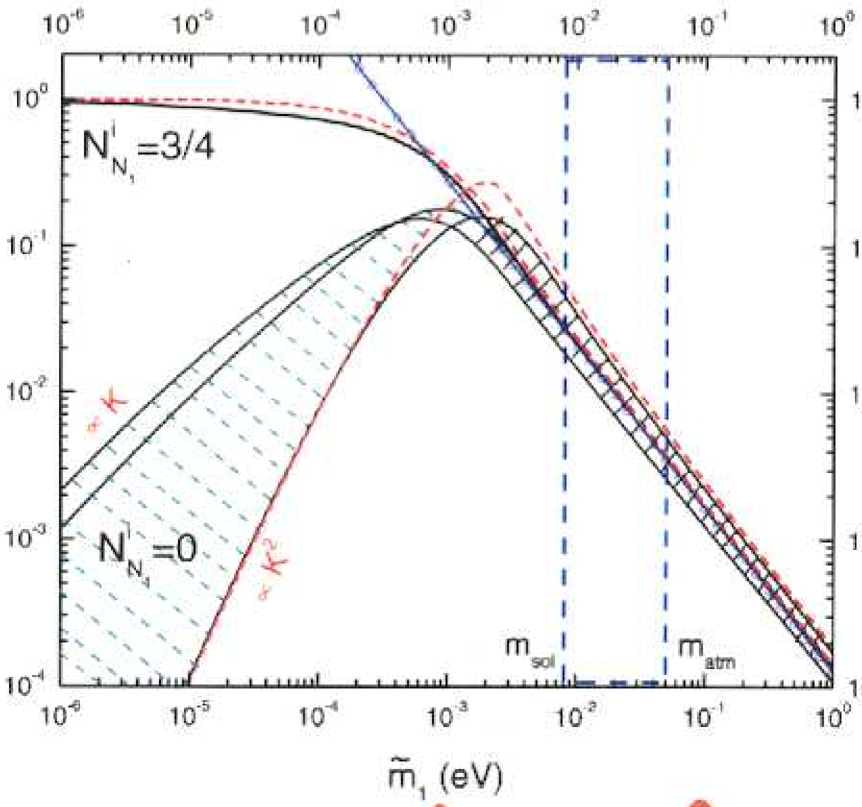
heavy neutrino masses :

$$M_1 \gtrsim 10^9\ GeV \ , \quad \boxed{T_R \gtrsim 10^9\ GeV}$$

INPUT: seesaw (ν_R) ; no triplets, mass degeneracies

Efficiency factor

$$\eta_B = d\,\varepsilon_1\,\kappa_f \simeq 10^{-2}\,\varepsilon_1\,\kappa_f$$



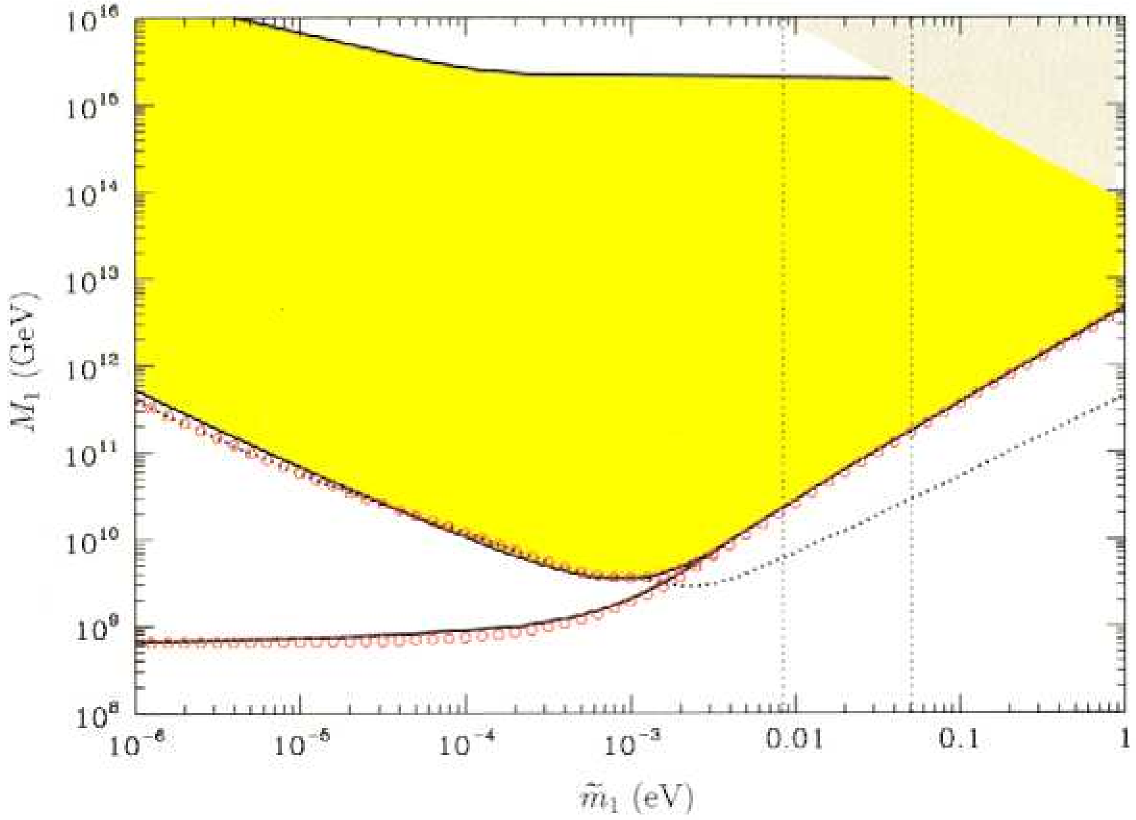
↑ ↑

neutrino mass window

$N^{i}_{N_1}=0$: $\propto K^2$, only (inverse) decays

$\propto K$, (inverse) decays + scatterings

Bounds on M_1 and T_B



—— M_1^{min}

.... T_B^{min}

II. Connection with ν-masses ; 4 examples

(i) SO(10) orbifold GUT in 6D

Asaka, WB, Covi '03

symmetry breaking :

$$G_{SM'} = SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_X \subset SO(10)$$

$$= SU(5) \times U(1)_X \cap SU(4) \times SU(2)_L \times SU(2)_R$$

quarks and leptons are mixtures of brane and bulk states; characteristic predictions for fermion mass matrices :

$m^u \sim m_N$, $m^D \sim m^e \sim m^d$

neutrino sector :

$M_1 \sim 10^{10}$ GeV , $M_2 \sim 3 \times 10^{12}$ GeV , $M_3 \sim 10^{15}$ GeV

factors O(1) unknown

$m_3 \sim 0.05$ eV , $m_2 \sim m_1 \sim 0.01$ eV , $\theta_{13} \sim 0.1$

$\tilde{m}_1 \sim 0.01$ eV , $\varepsilon_1 \sim 0.1 \frac{M_1}{M_3} \sim 10^{-6}$ LG O.K.

note : $\frac{m_1}{m_3} \sim \left(\frac{m_d}{m_b}\right)^2 \frac{m_t}{m_u} \sim 0.1$

(ii) Bi-large neutrino mixing, SO(10) SuSy GUT in 4D

Dermišek, Raby '05

SO(10) broken to G_{SM} by Higgs mechanism;
family symmetry

$$D_3 \times U(1) \times Z_2 \times Z_3$$

strongly restricts fermion mass matrices

$$m^u, \; m_N, \; m^D, \; m^e, \; m^d$$

χ^2 fit to 20 observables; 14 parameters,
6 predictions; 'additional prediction':
baryon asymmetry, sign correct !

neutrino sector:

$M_1 = 1 \times 10^{10}$ GeV, $M_2 = -9 \times 10^{11}$ GeV, $M_3 = 6 \times 10^{13}$ GeV,

$m_3 = 0.05$ eV, $m_2 = 0.01$ eV, $m_1 = 0.004$ eV,

$\Theta_{13} = 0.05$; LG: $\varepsilon_1 = -1.6 \times 10^{-7}$,

$\tilde{m}_1 \simeq 0.2$ eV $\curvearrowright$ $\eta_B = 1.5 \times 10^{-12}$ (?)

(iii) Maximal atmospheric ν-mixing and leptogenesis

Grimus, Lavoura '04

experiment : $\Theta_{23} = 45^\circ$?

what is the underlying symmetry ?

interesting possibility : μ-τ interchange symmetry ; prediction :

$$\Theta_{13} = 0$$

models with family symmetry :

(A) Z_2 , (B) D_4

compatibility with leptogenesis ?

(B) : disfavoured

(A) : predictions for M_1 , m_1

$$10^{11}\,\mathrm{GeV} \lesssim M_1 \lesssim 10^{12}\,\mathrm{GeV}$$

$$10^{-3}\,\mathrm{eV} \lesssim m_1 \lesssim 10^{-2}\,\mathrm{eV}$$

$\rightsquigarrow$ $\tilde{m}_1 \gtrsim 10^{-3}$ eV , independence of initial conditions

(iv) Nonthermal leptogenesis

Ahn, Kolb '05

recent example: 'Instant leptogenesis', in reheating after inflation; inflaton (ϕ) Higgs (H) coupling ($g = O(1)$):

$$L = -\frac{1}{2} g^2 \phi^2 H^\dagger H \quad ,$$

$m_H = g|\phi|$ oscillates, $m_H > m_N$, $m_H < m_N$, ΔL ($\to \Delta B$) from CP violating decays

$$N \to H\ell \; (\bar{H}\bar{\ell}) \quad , \quad H \to N\ell \; (N\bar{\ell})$$

constraints on neutrino masses:

$$10^{11}\,\mathrm{GeV} \; (10^{12}\,\mathrm{GeV}) < M_1 < 10^{13}\,\mathrm{GeV}$$

$$3 \times 10^{-4}\,\mathrm{eV} < \tilde{m}_1 < 1\,\mathrm{eV} \; (0.1\,\mathrm{eV})$$

reheating temperature: $T_R > 10^{10}$ GeV

(v) Resonant (TeV scale) leptogenesis (?)

degeneracy: $\frac{M_2 - M_1}{M_1} \sim 10^{-10}$

Pilaftsis, Underwood

CP asymmetry (→ hep-ph/0511248, Anisimov, Broncano, Plümacher)

III. The Gravitino Problem

gravitino couplings are universal, $\propto \frac{1}{M_P}$; the mass scale of SUSY breaking, i.e. the gravitino mass is presently unknown:

anomaly mediation		$\sim$ 10 TeV ... 100 TeV
gravity	"	$\sim$ 100 GeV ... 1 TeV
gaugino	"	$\sim$ 10 GeV ... 100 GeV
gauge	"	$\sim$ 10 eV ... 10 GeV

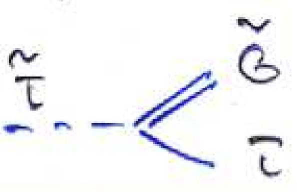
(split SUSY ...)

$$\rightarrow \quad \boxed{10\,\mathrm{eV} \lesssim m_{3/2} \lesssim 100\,\mathrm{TeV}} \quad (< M_P)$$

quasi-stable particles:

$$\tau(\tilde G \to \tilde b B) \simeq 4 \cdot 10^8 \left(\frac{100\,\mathrm{GeV}}{m_{\tilde G}}\right)^3 s$$

$$\tau(\tilde\tau \to \tilde G \tau) \simeq 8 \cdot 10^3 \left(\frac{m_{3/2}}{1\,\mathrm{GeV}}\right)^2 \left(\frac{150\,\mathrm{GeV}}{m_{\tilde\tau}}\right)^5 s$$

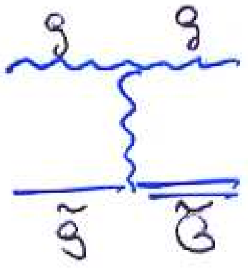


Cosmological 'problems'

severe constraints from BBN on quasi-stable heavy particles, overclosure of universe, $\Omega_{DM} > 1$ (Weinberg '82; Khlopov, Linde; Ellis, Kim, Nanopoulos '84; ...)

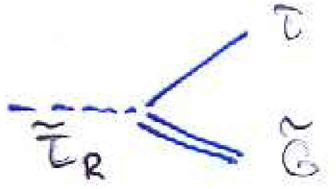
thermal production:

$$\Omega^{TH}_{3/2} h^2 \propto \frac{1}{M_P^2}\left(1+\frac{m_{\tilde g}^2}{3m_{3/2}^2}\right) T_R$$



non-thermal production ($\tilde G$ stable):

$$\Omega^{NT}_{3/2} h^2 \propto m_{3/2}\, m_{\tilde\tau_R}$$



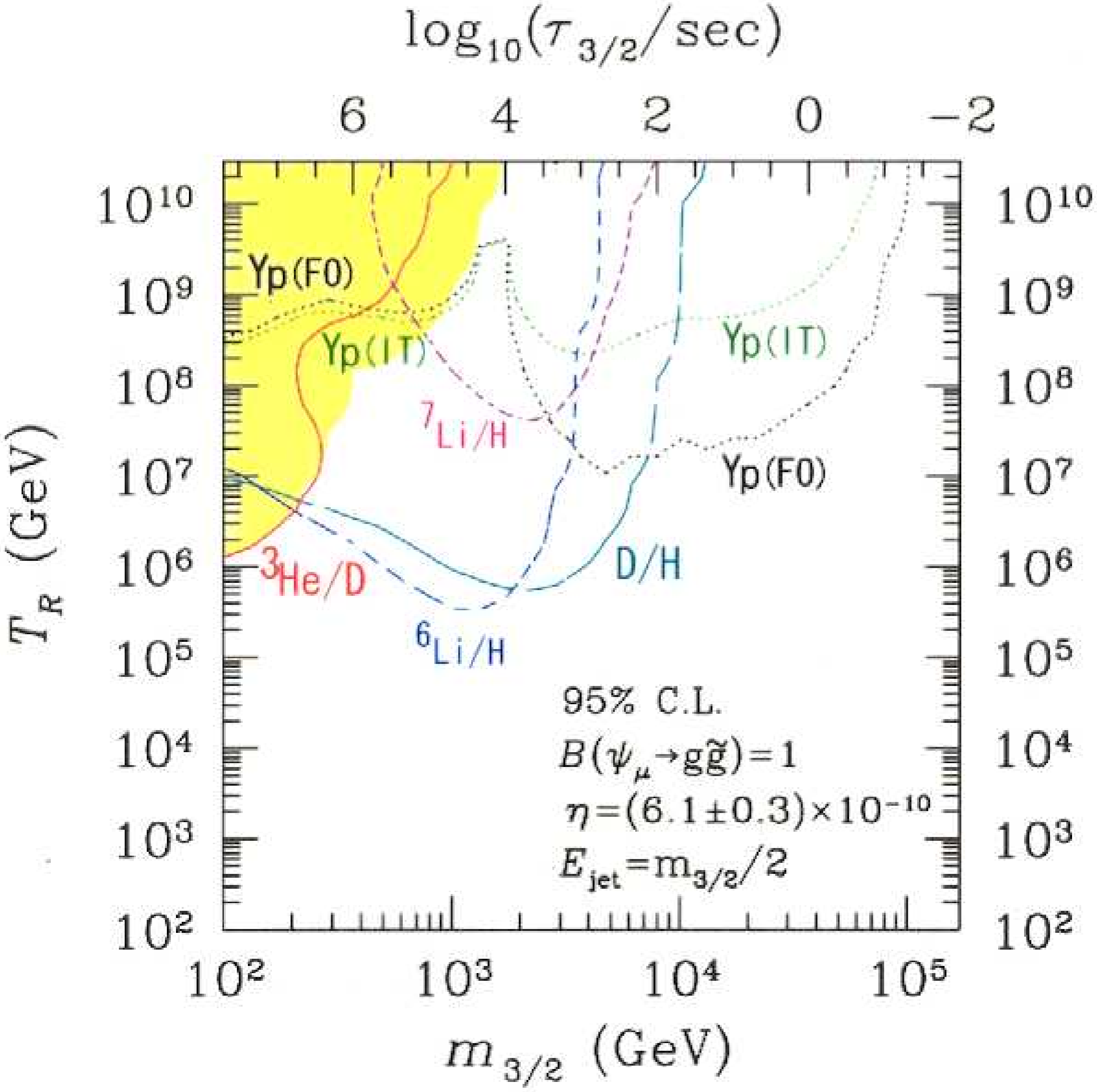
$\tilde\tau_R$ LSP

constraints:

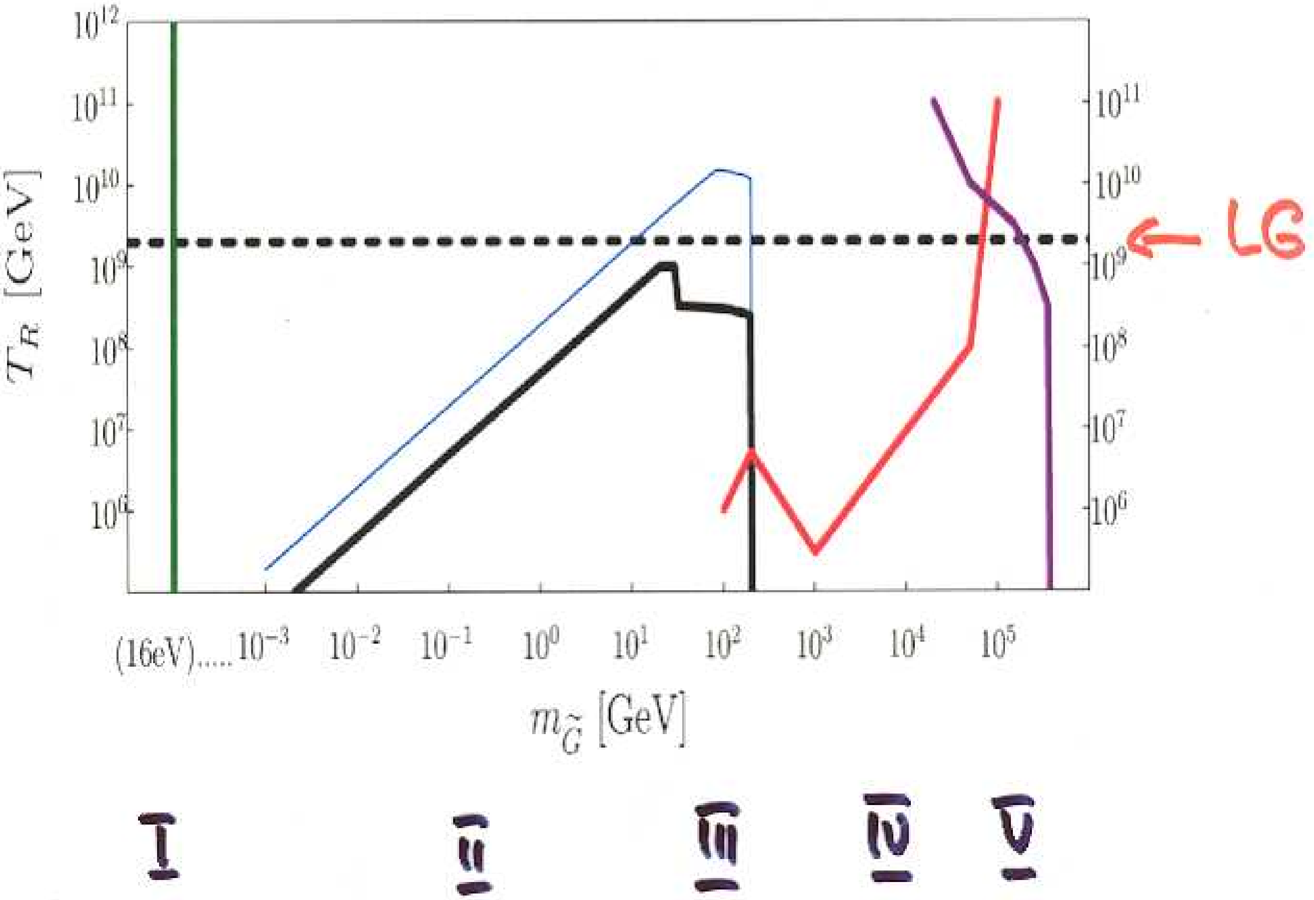
(i) BBN !

(ii) $\Omega^{TH}_{3/2} h^2 + \Omega^{NT}_{3/2} h^2 \lesssim 0.1$

Kawasaki, Kohri, Moroi hep-ph/0408426



Bound on reheating temperature



— $m_{\tilde{g}} = 500$ GeV

▬ $m_{\tilde{g}} = 1$ TeV

$\tilde{G}$ - summary : F

(i) $\tilde{G}$ unstable

$\underline{IV}$: BBN , $\underline{V}$: anomaly mediation,

$\tilde{G} \to \chi_0 \gamma, \ldots$ (Kitano, Ibe, Murayama '04)

typical $\tilde{G}$ mass , $m_{3/2} \sim 1$ TeV worst !

only $m_{3/2} \sim 100$ TeV allowed !

(ii) $\tilde{G}$ stable , $m_{3/2} \lesssim 100$ GeV

$m_{\tilde{g}} = 1$ TeV : only $m_{3/2} < 16$ eV (I)

allowed (LSS, Viel et al. '05)

$m_{\tilde{g}} = 500$ GeV : $m_{3/2}$ around 50 GeV o.k. $\underline{(iii)}$

(iii) the upper bound on T_R can be relaxed

- late entropy production

  (Fujii, Yanagida ; WB, Hamaguchi, Ibe, Yan.)

- dynamical decrease of gauge couplings

  for $T_R > T_* \simeq (m_{3/2} M_P)^{1/2} < 10^{10}$ GeV

  (WB, Hamaguchi, Ratz, '03)

$$\Omega_{3/2} h^2 \simeq (0.05 - 0.2) \times \left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^{3/2} \left(\frac{\xi}{4}\right)^{1/4}$$

IV. Gravitino Dark Matter

Supersymmetry breaking on brane (-> gaugino mediation ...) :

$$\mathcal{L}_D = \frac{1}{4g_D^2}\int d^2\theta\, W^\alpha W_\alpha + h.c.$$

$$+\, \delta^{(D-4)}(y-y_1)\,\frac{1}{4\Lambda}\int d^2\theta\, \underset{\uparrow}{S}\, W^\alpha W_\alpha + h.c.$$

$$\langle S\rangle = S_0 + \theta\theta F_S$$

$$\rightarrow \quad m_{1/2} = \frac{g_4^2 F_S}{2\Lambda}\,, \qquad m_{3/2} = \frac{1}{\sqrt{3}}\frac{F_S}{M_P} \quad (< m_{1/2})$$

(LSP)

gauge coupling at finite temperature :

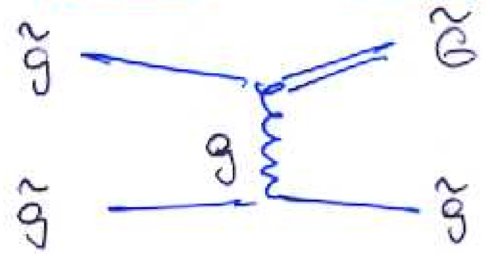
$$\frac{1}{g_4^2} + \frac{\Phi_T}{\Lambda} = \frac{1}{g^2(\Phi_T)}\,, \qquad \Phi = \mathrm{Re}\, S$$

for $T > T_* \sim \left(\frac{m_{3/2}^2 M_P}{2m_{\tilde{g}}}\right)^{1/2}$:

$$\boxed{g^2(T,\Phi_T) \simeq \frac{g_4^2(T)}{1+(T/T_*)^\alpha}}\,, \qquad \alpha = 1\ldots4$$

WB, Hamaguchi, Ratz

gravitino production from thermal bath, after inflation, number density much below equilibrium density:



+ … 10 processes

Boltzmann equations:

$$\frac{dn_{3/2}}{dt} + 3H\,n_{3/2} = C_{3/2}(T,\phi_T)\,,$$

$$C_{3/2}(T,\phi) = \ldots\, g^2(T,\phi_T)\,\frac{T^6}{M_P^2}\Big(\underset{\text{spin-}\frac{3}{2}}{1} + \underset{\text{spin-}\frac{1}{2}}{\frac{m_{\tilde g}^2}{3m_{3/2}^2}}\Big)$$

number density of gravitinos at present temperature T_0 for reheating T_R above T_*:

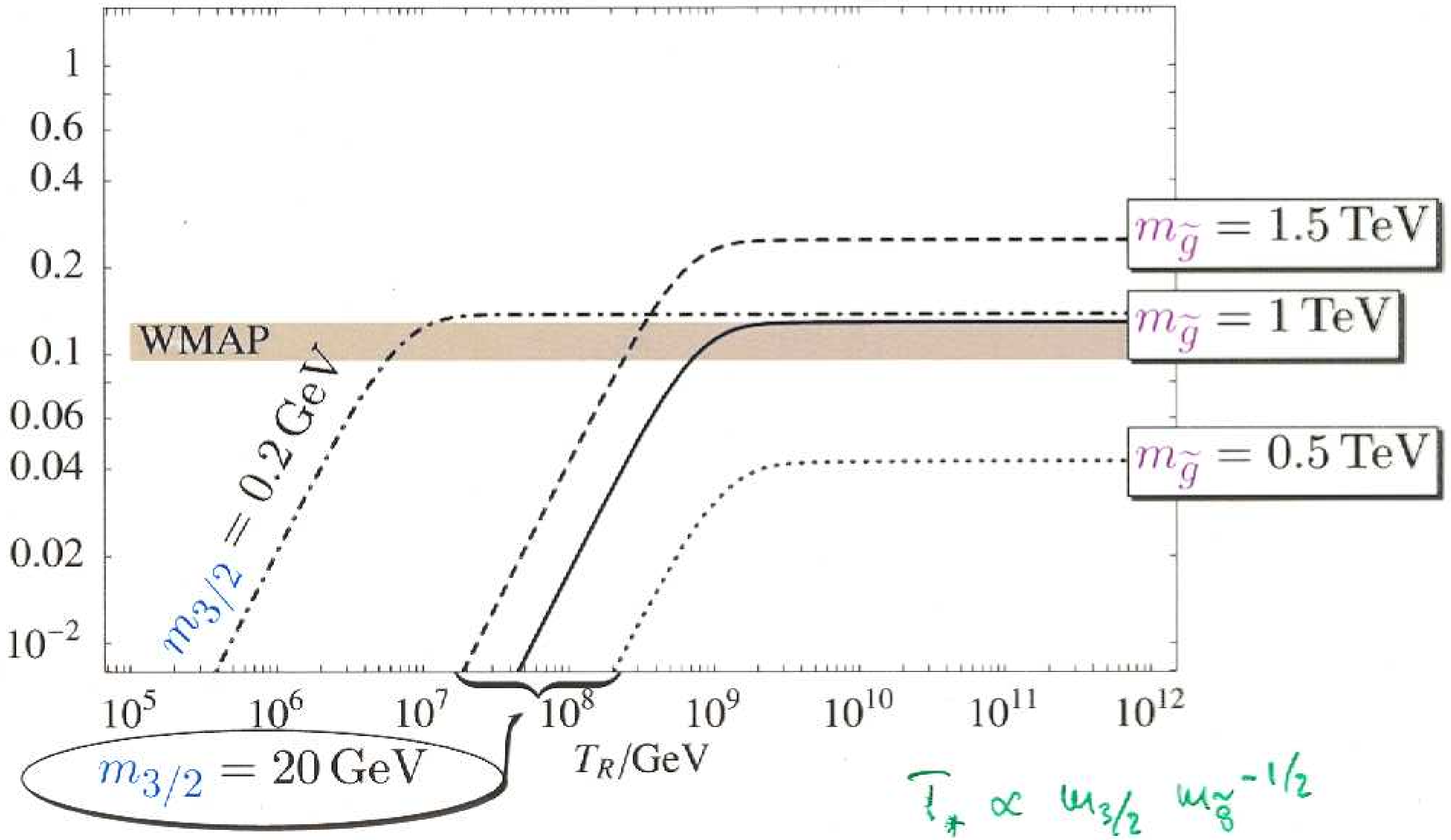
$$\left.\frac{n_{3/2}}{s}\right|_{T_0} = \frac{C_{3/2}(T_*,0)}{s(T_*)\,H(T_*)}\,\underbrace{I(\alpha)}_{0.50\ldots0.73}\,,\quad \alpha = 1\ldots4$$

temperatures above T_* don't contribute!

$$\left.\frac{\rho_{3/2}}{s}\right|_{T_0} = \ldots\ \frac{T_*\, m_{\tilde g}^2(T_*)}{M_P\, m_{3/2}} \propto \frac{m_{\tilde g}^{3/2}(\mu)}{M_P^{1/2}}$$

!

Contribution of gravitinos to Ωh^2



$T_* \propto m_{3/2}\, m_{\tilde{g}}^{-1/2}$

final result for $T_R > T_*$:

$$\Omega_{3/2} h^2 \simeq 0.1 \times \left(\frac{m_{\tilde g}(1\,\mathrm{TeV})}{1.0\,\mathrm{TeV}} \right)^{3/2} \xi^{1/4}\, \hat{I}_{(\alpha)} ,$$

$$\hat{I}_\alpha = 0.5 \ldots 2 , \quad \xi \simeq O(1)$$

WMAP : $\Omega_{CDM} h^2 = (\Omega_m - \Omega_b) h^2 = 0.113^{+0.016}_{-0.018}$

$$\boxed{m_{\tilde g} = (0.5 \ldots 2.0)\,\mathrm{TeV}\; \xi^{\frac{1}{6}}}$$

Ω_{CDM} depends only on $m_{\tilde g}$!

Simple picture of matter in the universe :

leptogenesis explains baryon density

→ $T_R > \sim 10^{10}$ GeV

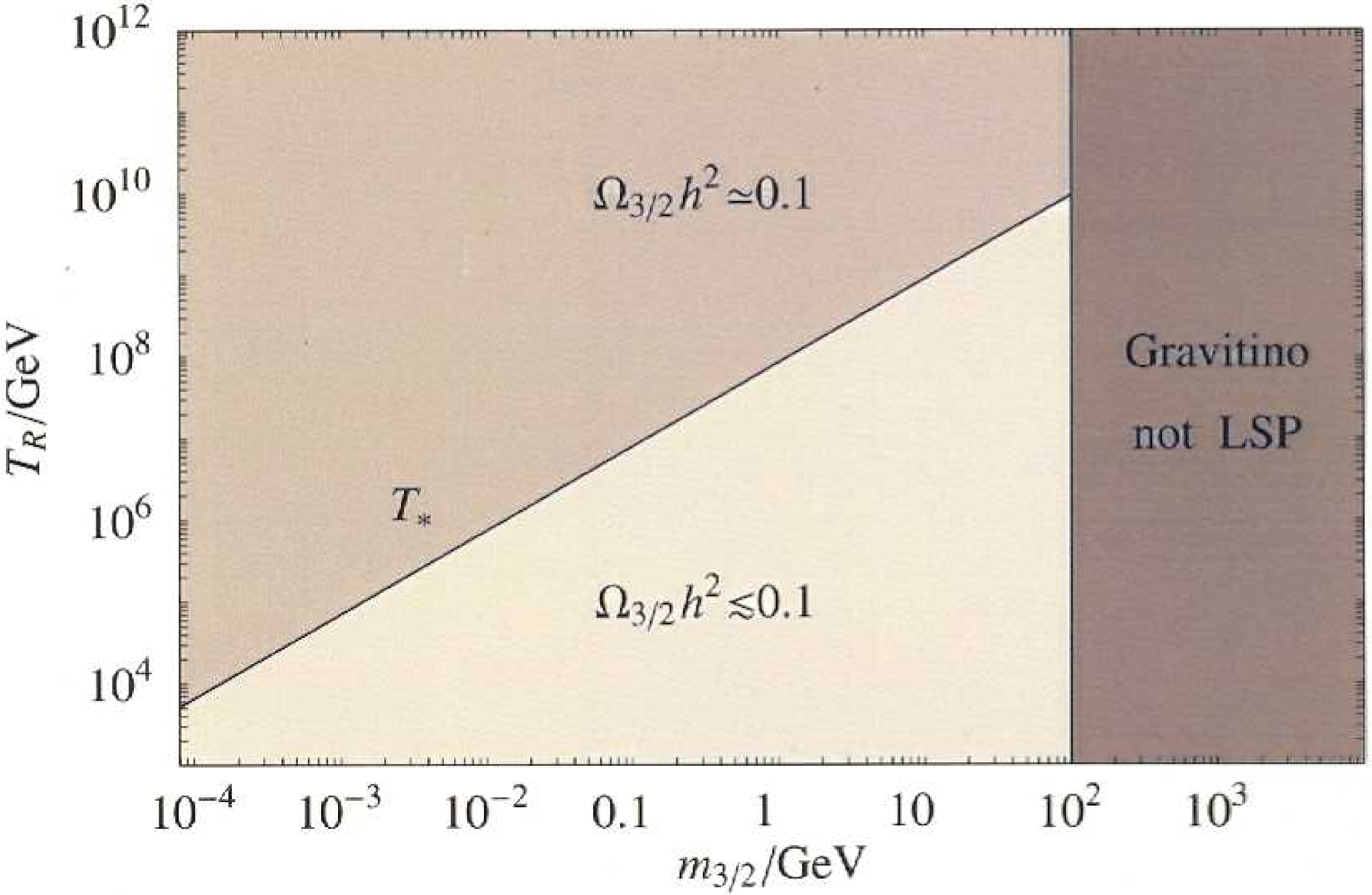
favours gravitino LSP , $m_{3/2} < 100$ GeV

→ $T_*^{max} < \sim 10^{10}$ GeV

always reached ; $\Omega_{3/2} h^2 \sim 0.1$ explained

for $m_{\tilde g} \sim 1$ TeV → LHC

Relic gravitino density



$\xi/\mu^2 = 1$, $m_{\tilde{g}} = 1$ TeV