LEPTOGENESIS & GRAVITINO DARK MATTER

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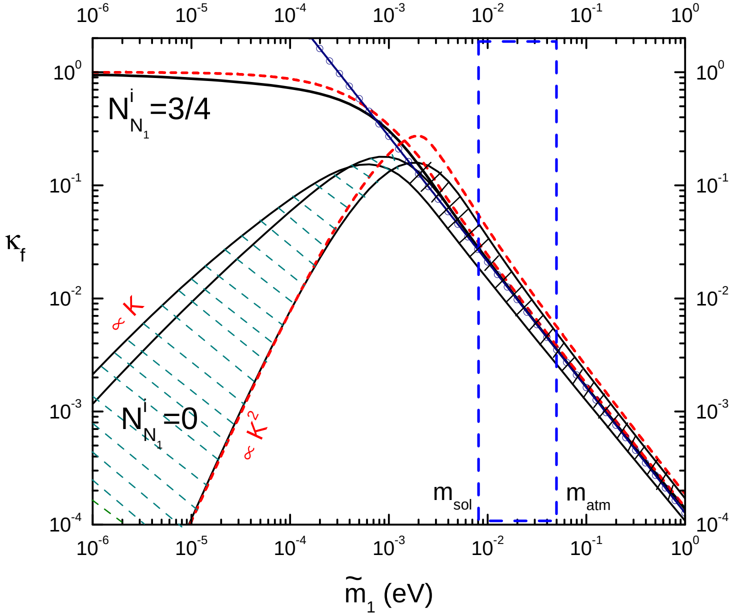
OUTLINE

1. Status of leptogenesis
2. Constraints from nucleosynthesis
3. Gravitino dark matter
4. Gravitino signatures at future colliders

(1) Status of leptogenesis

Leptogenesis is attractive theory for origin of matter. Non-equilibrium process yields quantitative relation between neutrino masses and baryon asymmetry; in the simple case of 'N_1-dominance' crucial quantities (cf. WB, Di Bari, Plümacher,'05): CP asymmetry ε_1 and efficiency factor κ_f,

$$\eta_B \simeq 0.01\, \varepsilon_1\, \kappa_f\,.$$



Implications: light neutrino mass window, $10^{-3}\ \mathrm{eV} < m_{\nu_i} < 0.1\ \mathrm{eV}$, can be tested in laboratory experiments and cosmology; lower bound on the heavy neutrino mass and maximal temperature of the early universe, $T_B \sim M_1 > 10^9\ \mathrm{GeV}$ → in supersymmetric theories strong constraints on superparticle mass spectrum.

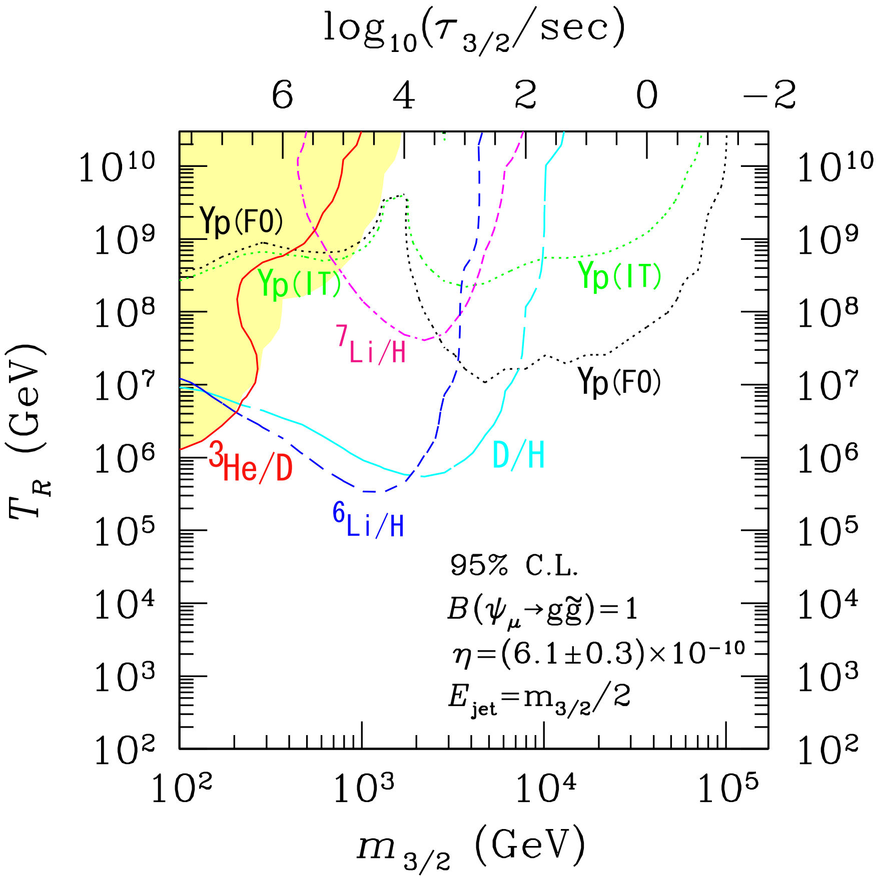
Current research on Leptogenesis

There are two main directions:

- How can one avoid the implications of standard 'thermal leptogenesis' (light neutrino mass window and lower bound on baryogenesis temperature)?
  There are various possibilities: addition of new SU(2) triplet fields (→ modifies seesaw mechanism); degeneracy of heavy Majorana neutrinos, 'resonant leptogenesis'; non-thermal leptogenesis,... (cf. T. Hambye, hep-ph/0412053)

- Further development of standard 'thermal leptogenesis': Connection between CP violation in leptogenesis, neutrino oscillations and $0\nu\beta\beta$ decay; quantum theory beyond Boltzmann equations; dependence of the baryon asymmetry on lepton flavour (cf. Abada et al., hep-ph/0601083; Nardi, Nir, Roulet, Racker, hep-ph/0601084; Blanchet, Di Bari, hep-ph/0603107; Abada et al., hep-ph/0605281); affects upper bound on light neutrino mass scale, 'mild' decrease of lower bound on temperature T_B; constraints on superparticle mass spectra in supersymmetric theories,...

(2) Constraints from nucleosynthesis (BBN)



Gravitino problem: production dominated by QCD processes; gravitino number density grows with reheating temperature after inflation,

$$\frac{n_{3/2}}{n_\gamma} \propto \frac{\alpha_3}{M_{\rm p}^2} T_R.$$

Most stringent upper bound on T_R (Kawasaki, Kohri, Moroi '05):

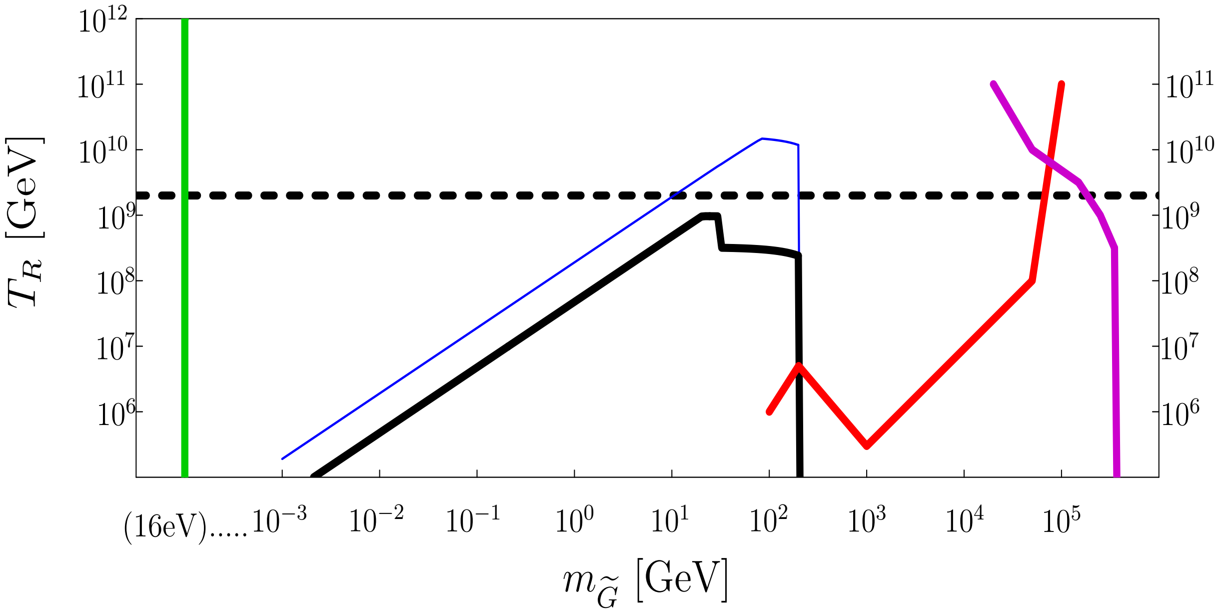
$$T_R < \mathcal{O}(1) \times 10^5 \ \mathrm{GeV},$$

incompatible with thermal leptogenesis !!

Possible way out: gravitino is LSP and stable, can then be dominant component of dark matter; enhanced gravitino production:

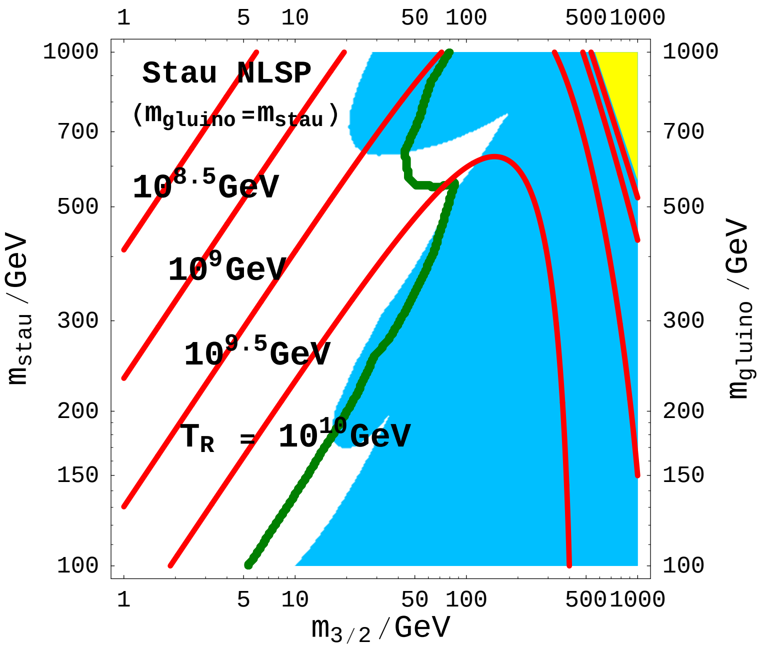
$$\frac{n_{3/2}}{n_\gamma} \propto \frac{\alpha_3}{M_{\rm p}^2} \left(\frac{m_{\tilde g}}{m_{3/2}} \right)^2 T_R .$$

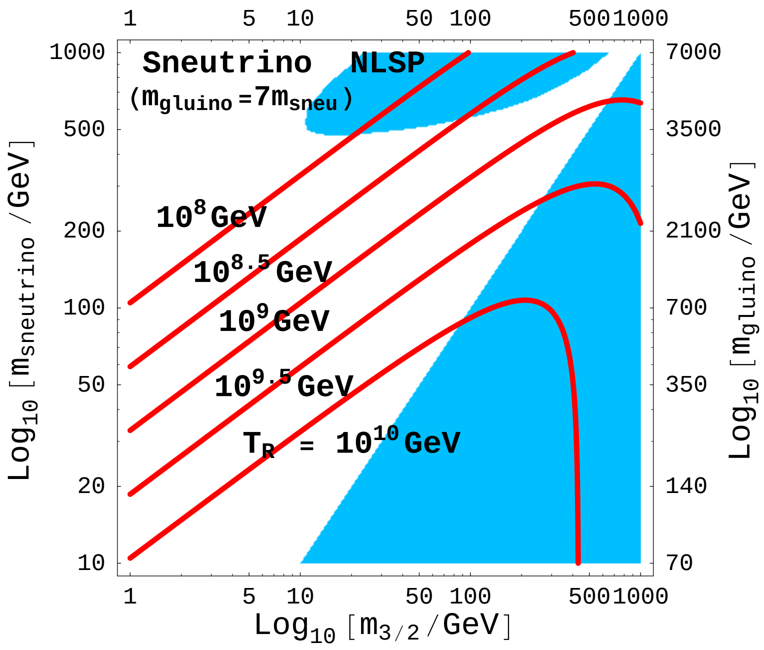
Consistency with BBN and $\Omega_{\rm CDM}$ yields upper bound on gravitino mass, lower bound on NLSP ($\tilde\tau$, $\tilde\nu$,...) mass, upper bound on T_R (Figure: $m_{\tilde g} = 1~{\rm TeV}$ ($m_{\tilde g} = 500~{\rm GeV}$), cf. Moroi et al., Viel et al., Ibe et al.); also possible: unstable gravitino with $m_{3/2} \sim 10^5~{\rm GeV}$.



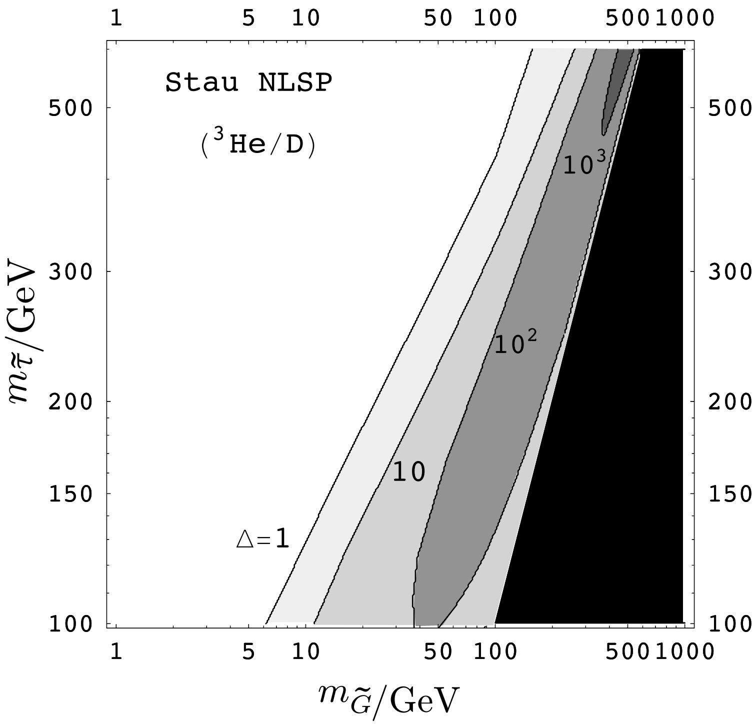
Most promising (leptogenesis & SUSY): $m_{3/2} = \mathcal{O}(10\ \mathrm{GeV})$.

Details depend on nature of NLSP: scalar tau, scalar neutrino, gluino,... $\tilde{\tau}$-NLSP requires non-universal gaugino masses; for $\tilde{\nu}$-NLSP universal gauginos with $m_{\tilde{g}} = 1\ \mathrm{TeV}$ are OK (based on Feng, Su, Takayama '04; ⟶ recent detailed study: F. Steffen '06).





Late time entropy production



'Relic' thermal density of $\widetilde{\tau}$'s,

$$Y_{\widetilde{\tau}}^{\text{thermal}} = \frac{n_{\widetilde{\tau}}}{s}$$

can be diluted by entropy production after $\widetilde{\tau}$ decoupling,

$$Y_{\widetilde{\tau}} = \frac{1}{\Delta} Y_{\widetilde{\tau}}^{\text{thermal}}.$$

This considerably enlarges the parameter region with relatively large gravitino mass, $m_{\widetilde{G}} \geq \mathcal{O}(0.1)\, m_{\widetilde{\tau}}$, which is wanted for SUGRA tests at colliders.

(3) Gravitino dark matter

Can one understand the amount of dark matter,

$$\Omega_{DM}h^2 = 0.1126^{+0.0161}_{-0.0181}\ ,$$

where $\Omega_{DM} = \rho_{DM}/\rho_c$, if gravitinos are the dominant component, i.e., $\Omega_{DM} \simeq \Omega_{3/2}$?

Production mechanisms: (i) 'super-WIMPs' (Feng, Rajaraman, Takayama '03), i.e., gravitinos from WIMP decays,

$$\Omega_{3/2} = \frac{m_{3/2}}{m_{\mathrm{NLSP}}}\Omega_{\mathrm{NLSP}}\ ,$$

independent of initial temperature T_R (!!), requires heavy NLSP, e.g. $m_{\widetilde{\tau}} > 500\ \mathrm{GeV}$, disfavoured by BBN constraints; (ii) thermal production dominated by $2 \rightarrow 2$ QCD processes.

The solution of the Boltzmann equations,

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

with the collision term

$$C_{3/2}(T) = \frac{3\zeta(3)\alpha_3(T)}{\pi^2}\frac{T^6}{M_P^2}\left(1 + \frac{m_{\tilde{g}}^2}{3m_{3/2}^2}\right) F(T) \ ,$$

and the thermal factor $F(T) = \mathcal{O}(10)$, yields the gravitino relic density

$$\Omega_{3/2}h^2 \simeq 0.2 \left(\frac{T_R}{10^{10}\mathrm{GeV}}\right)\left(\frac{100\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}(\mu)}{1\mathrm{TeV}}\right) \ .$$

NOTE: wanted amount of dark matter for typical SUSY breaking parameters (!)

Question: Is the gravitino relic density necessarily dependent on T_R, i.e., on initial conditions? Are the 'typical' superparticle masses consistent with the BBN constraints?

Gauge couplings at high temperature

In effective theories obtained after compactification, gauge couplings are dynamical fields (cf., e.g., gaugino mediation),

$$\mathcal{L}_{eff} = \left(1 + g_0^2 \frac{\phi}{M}\right) \left(-\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - i\lambda^a \sigma^\mu (D_\mu \bar{\lambda})^a\right) + \ldots \ .$$

The effective gauge coupling depends on the 'moduli' field ϕ:

$$\frac{1}{g_0^2} + \frac{\phi}{M} = \frac{1}{g^2(\phi)} \ .$$

At high temperatures, the scalar field is driven to larger values,

$$\left\langle -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - i\lambda^a (\sigma^\mu D_\mu \bar{\lambda})^a \right\rangle_T = a_2 g_0^2 T^4 > 0 \ ,$$

which yields a negative term in the effective potential. Hence, gauge couplings decrease at high temperature !

Supersymmetry breaking parameters, i.e., gravitino, gluino and ‘moduli’ masses,

$$m_{3/2} = \eta \frac{F_\phi}{M_\mathrm{P}} , \quad m_{\tilde{g}} = \frac{g_0^2}{2} \frac{F_\phi}{M} , \quad m_\phi^2 = \xi m_{3/2}^2 .$$

Gauge couplings decrease above the ‘critical temperature’ T_*,

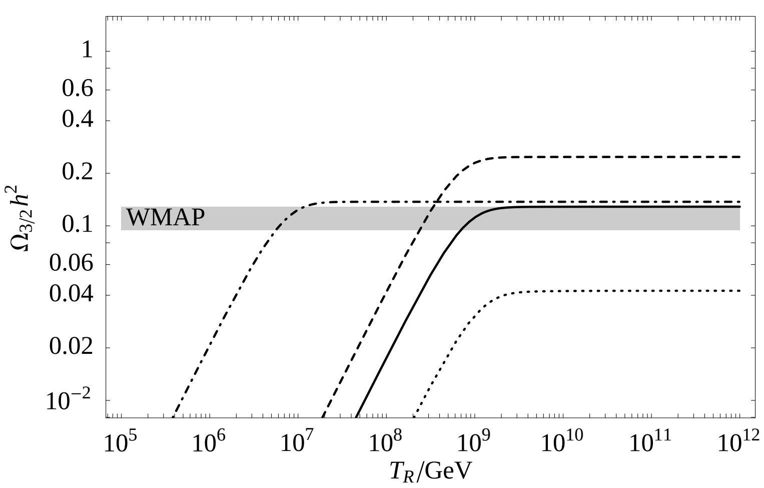
$$T_* = \left(\frac{\xi}{a_2 g_0^2 \eta^2} \right)^{1/4} \left(\frac{m_{3/2}^2 M_\mathrm{P}}{2 m_{\tilde{g}}} \right)^{1/2} .$$

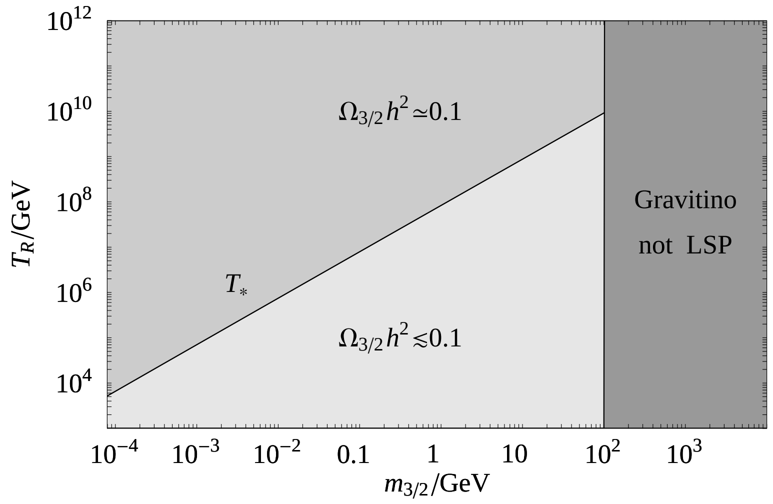
As a consequence, the gravitino production saturates and becomes independent of T for $T > T_*$,

$$\Omega_{3/2} h^2 = 0.1 \times \left(\frac{m_{\tilde{g}}(1\ \mathrm{TeV})}{1.0\ \mathrm{TeV}} \right)^{3/2} \left(\frac{\xi}{\eta^2} \right)^{1/4} I_{(\alpha)} F(T_*) ,$$

with $I_{(\alpha)} F(T_*) = 0.5 \ldots 2$. The observed amount of dark matter is obtained for $m_{\tilde{g}} \sim 1\ \mathrm{TeV}$, if $\xi/\eta^2 = \mathcal{O}(1)$.

Gravitino production: saturation; left Figure, parameters: $m_{3/2} = (0.2, 20)$ GeV, $m_{\tilde{g}} = (0.5, 1, 1.5)$ TeV





Simple picture of matter in the universe:

- baryon asymmetry via leptogenesis: $T_R > 10^{10}$ GeV
- gravitino LSP favoured , with $m_{3/2} < 100$ GeV
- consequence: $T_* < 10^{10}$ GeV, always reached; therefore $\Omega_{3/2} \sim 0.1$ explained for $m_{\tilde{g}} \sim 1$ TeV $\longrightarrow$ WAIT FOR LHC ! (BUT: moduli problem)

(4) Gravitino signatures at future colliders

How can one detect gravitino dark matter? Cosmological observations? For a $\tilde{\tau}$-NLSP, gravitinos with mass $m_{3/2} = \mathcal{O}(10\ \mathrm{GeV})$ can be discovered at LHC/ILC.

The gravitino mass can be kinematically determined from 2-body decay (with accuracy of $m_{\tilde{\tau}}$, E_τ): $m_{3/2}^2 = m_{\tilde{\tau}}^2 + m_\tau^2 - 2m_{\tilde{\tau}} E_\tau$. Then the $\tilde{\tau}$-lifetime yields Planck mass:

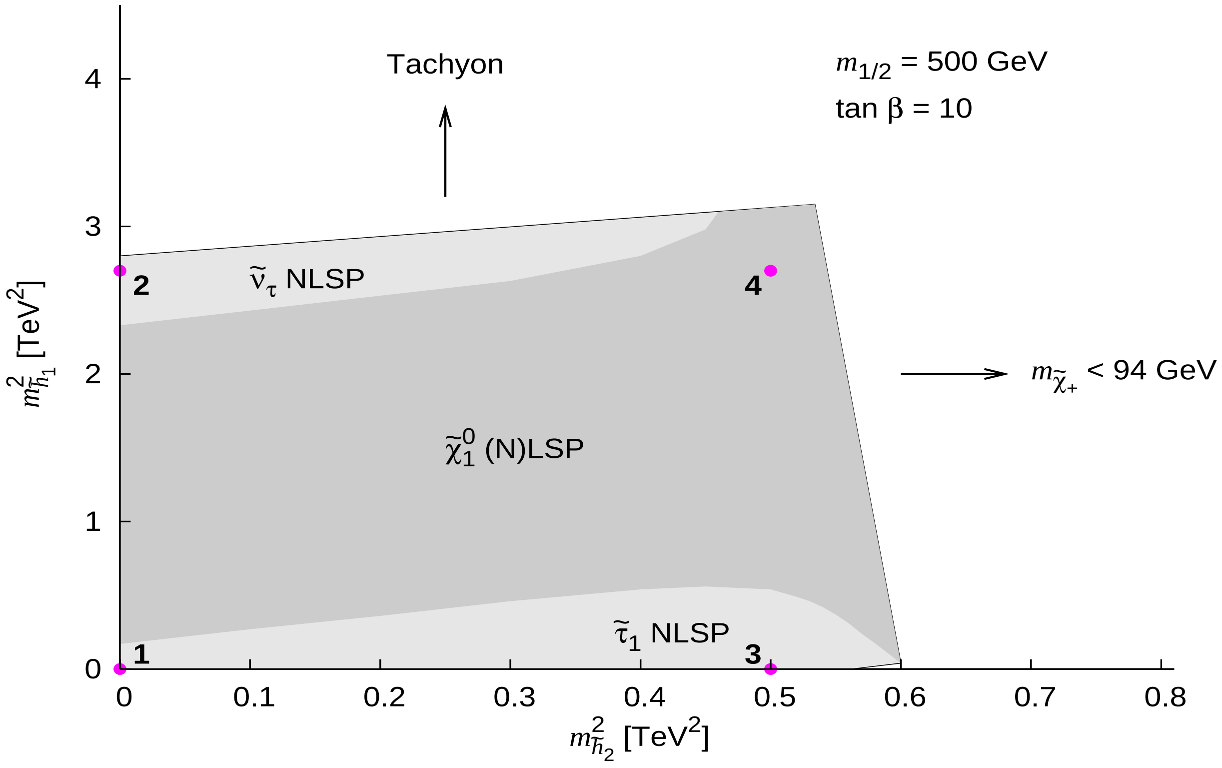
$$M_{\mathrm{P}}^2(\mathrm{supergravity}) = \frac{\left(m_{\tilde{\tau}}^2 - m_{3/2}^2\right)^4}{48\pi\, m_{3/2}^2\, m_{\tilde{\tau}}^3\, \Gamma_{\tilde{\tau}}}$$

with mass dependence from derivative coupling. Comparison with the ‘macroscopic’ Planck mass ($G_{\mathrm{N}} = 6.707(10) \times 10^{-39}\ \mathrm{GeV}^{-2}$):

$$M_{\mathrm{P}}^2(\mathrm{gravity}) = (8\pi\ G_{\mathrm{N}})^{-1} = (2.436(2) \cdot 10^{18}\ \mathrm{GeV})^2\ .$$

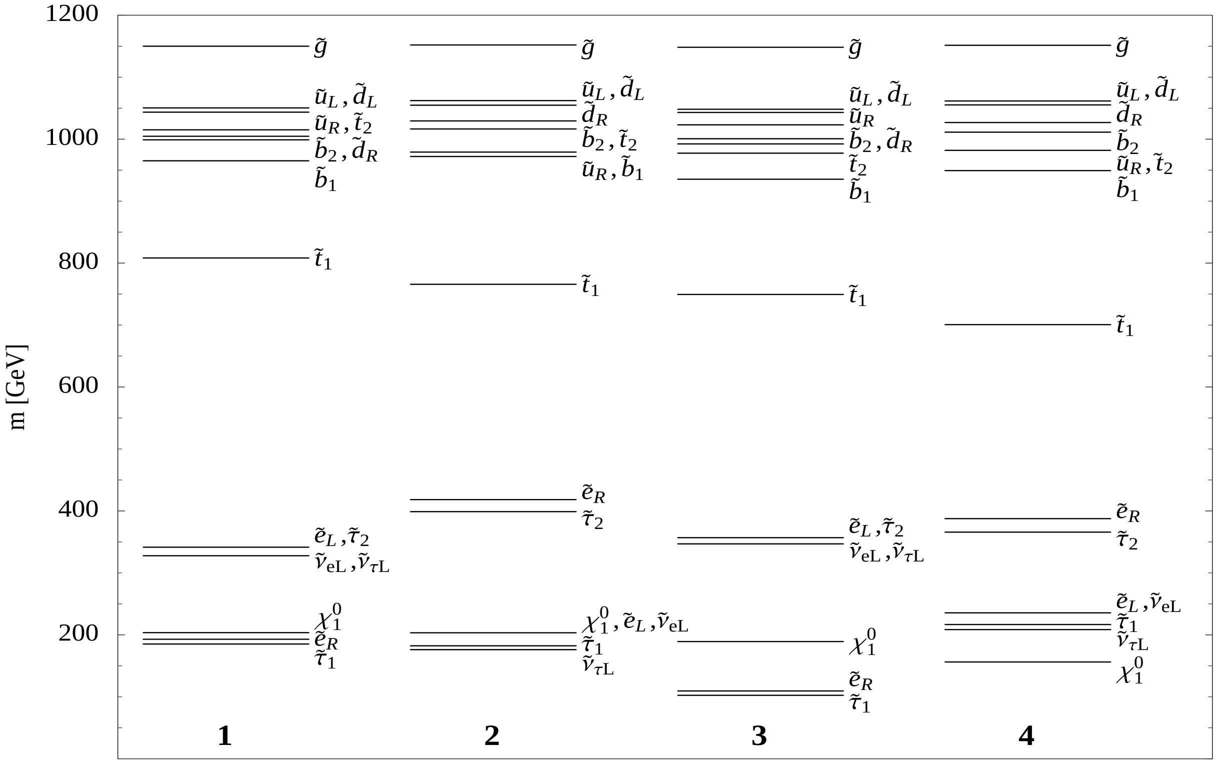
⟶ direct test of SUPERGRAVITY !!

Example: superparticle mass spectrum from gaugino mediation



characteristic feature: Higgs mass parameters non-universal (bulk fields); universal boundary conditions for squarks and sleptons (mostly brane fields)

different cases: $\tilde{\tau}$-NLSP (1), (3); $\tilde{\nu}$-NLSP (2), neutralino NLSP (4); $m_{3/2} > 10\ \mathrm{GeV}$

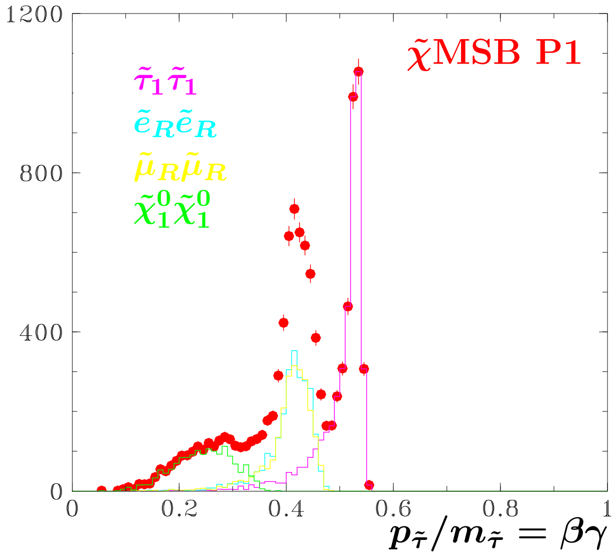


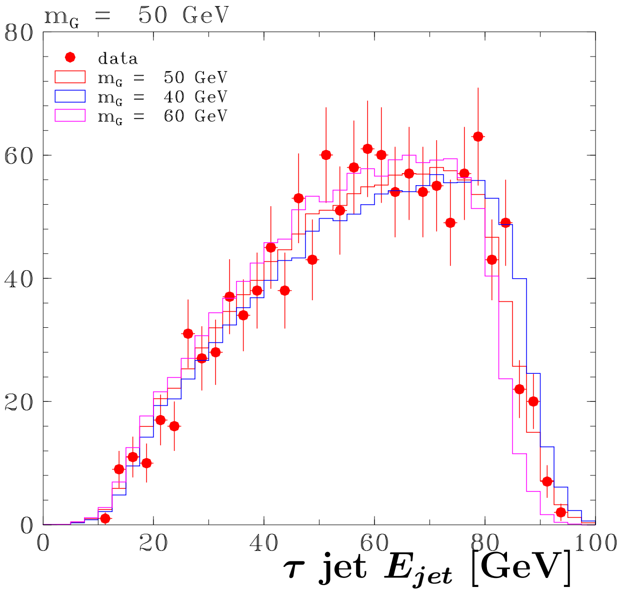
parameters of P1: $m_{\tilde{\tau}} = 185.2\ \mathrm{GeV}$, $m_{3/2} = 50\ \mathrm{GeV}$, $t_{\tilde{\tau}} = 9.1 \times 10^6\ \mathrm{s}$; slow, quasi-stable stau's can be stopped in detector $\longrightarrow$ wait for their decays !

Monte Carlo study for the ILC

H.-U. Martyn, hep-ph/0605257

Case study: $\mathcal{L} \sim 200\ \mathrm{fb}^{-1}$, $\sqrt{s} = 420$ GeV, $\sigma_{SUSY} = 27$ fb; yields ~ 4000 slow ($\beta < 0.3$) stau's in hadron calorimeter (HCAL)





Results:

[table: gaugino mediation, P1]

$m_{\tilde{\tau}}$ [GeV]	$t_{\tilde{\tau}}$ [s]	$m_{3/2}(\Gamma_{\tilde{\tau}})[GeV]$	$m_{3/2}(E_\tau)$ [GeV]
185.2 ± 0.1	$(9.1 \pm 0.2) \times 10^6$	50 ± 0.6	50 ± 3

→ 'microscopic' determination of Planck mass with 10% accuracy !!

What can be done at the LHC ?

- Stop stau's inside the detector; accuracy of $m_{3/2}(E_\tau)$ and therefore M_P ?
- Stop stau's in new detector outside ATLAS/CMS
  (Hamaguchi, Kuno, Nakaya, Nojiri '04; Feng, Smith '04; Hamaguchi, Nojiri, de Roeck, in preparation;...)

How can one realistically measure the gravitino spin?

→ discovery of supergravity at LHC/ILC !!

SUMMARY

- Gravitino is viable dark matter candidate, favoured by the simplest version of thermal leptogenesis

- Gravitino dark matter can be consistent with BBN constraints, for reasonable values of gravitino and NLSP masses

- In the case of $\tilde{\tau}$-NLSP, for favourable masses, gravitino mass (and spin) can be determined at LHC/ILC