Gravitino LSP in the Constrained MSSM

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Contents of present Unverse

WMAP data with other CMB experiments (ACBAR and CBI), 2dFGRAS measurements, and Lyα forest data determines the best-fit cosmological parameters[Spergel et.al, (2003)]:

$$\Omega_{tot} = \Omega_\Lambda + \Omega_m + \cdots = 1.02 \pm 0.02 \text{ (Flat Universe)}$$

$$\Omega_{tot} = \begin{cases} \text{energy} & \Omega_\Lambda = 0.73 \pm 0.04 \text{ (accelerating)} \\ \text{matter} & \Omega_m = 0.27 \pm 0.04 \\ & \qquad \begin{cases} \Omega_b h^2 = 0.0224 \pm 0.0009 \text{ (BBN, CMB)} \\ \Omega_{DM} h^2 = 0.113^{+0.008}_{-0.009} \\ \Omega_\nu h^2 < 0.0076 \qquad (h = 0.71^{+0.04}_{-0.03}) \end{cases} \\ \text{radiation} & \Omega_\gamma = (2.471 \pm 0.004) \times 10^{-5} \ (T_0 = 2.275 \pm 0.002\text{K } 95\% \text{ CL}) \end{cases}$$

Dark Matter?

What is Dark Matter?

neutrino, neutralino, generic WIMP, axion, axino, Gravitino, WIMPzilla,...

LSP (Lightest Supersymmetric Particle) is a possible candidate for the cold dark matter if R-parity is conserved. The lightest Neutralino is the most promising candidate with an abundance calculated from the freeze-out of annihilation processes in a thermal initial state.

Gravitino LSP : spin 3/2, the superpartner of Graviton, always exists in local SUSY, with mass $m_{\tilde{G}} = \frac{F}{\sqrt{3}M_p}$ F: SUSY breaking scale, M_p: reduced Planck mass

Gravitino Dark Matter

- Gravitino problem
- Is Gravitino stable? LSP or not?
- Relic density of Gravitino for Dark Matter, $\Omega_{\tilde{G}} = \Omega_{DM}$?
- NLSP decay to Gravitino at late times
  - non-thermal production (NTP) of Gravitino
  - Big Bang Nucleosynthesis (BBN) constraints
  - CMB constraints
- Thermal production (TP) from scattering during reheating
- Unbounded From Below (UFB) constraints

Gravitino Problem

If $T_R > T_f$, Gravitino freezes out from thermal equilibrium with the relic density $\Omega_{\tilde{G}} h^2 = 1.17 \left(\frac{100}{g_*}\right) \left(\frac{m_{\tilde{G}}}{1\ \mathrm{keV}}\right)$

$\Omega_{\tilde{G}} \equiv \frac{\rho_{\tilde{G}}}{\rho c}$

- Stable : $m_{\tilde{G}} \lesssim 1$ keV from $\Omega_{tot} < 1$ or Gravitino dilution
- Unstable : $m_{\tilde{G}} \gtrsim 10$ TeV from BBN constraint

If $T_R < T_f$, the freeze-out Gravitino is diluted away by Inflation and reproduced by thermal scattering in the reheating period with abundance

$$Y_{\tilde{G}} \equiv \frac{n_{\tilde{G}}}{n_\gamma} = 7.7 \times 10^{-12} \left(1 + \frac{m_{\tilde{g}}^2}{12 m_{\tilde{G}}^2}\right) \left(\frac{T_R}{10^{10}\mathrm{GeV}}\right)$$

T_R : Reheating temperature

[Bolz,Brandenburg,Buchmüller, (2001)]

- unstable : $T_R \lesssim 10^8$ GeV from BBN [Ellis,Kim,Nanopoulos('84), Cyburt et al.('02), Kawasaki et al.('04)]
- stable : $T_R \lesssim 10^{10}$ GeV from $\Omega_{tot} < 1$ $\Omega h^2 = 3.63 \times 10^9 \frac{m}{100 \text{ GeV}} Y$

Gravitino LSP in the CMSSM

Constrained MSSM

At M_{GUT}

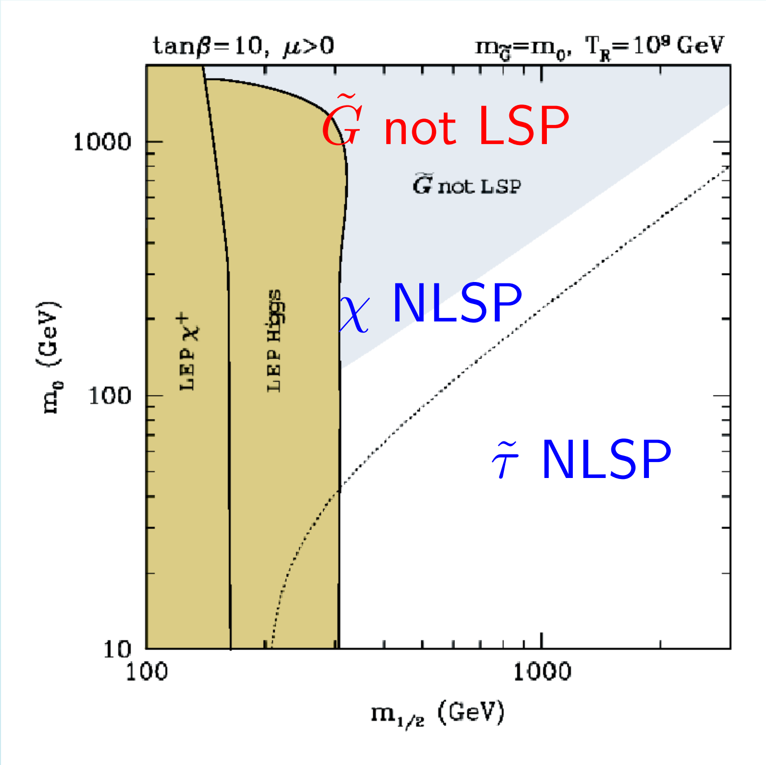
- gauginos $M_1 = M_2 = M_3 = m_{1/2}$
- scalars $m_{\tilde{q}}^2 = m_{\tilde{l}}^2 = m_{H_b}^2 = m_{H_t}^2 = m_0^2$
- trilinear soft terms $A_b = A_t = A_0$
- radiative EWSB
- five independent parameters: $\tan\beta, m_{1/2}, m_0, A_0, sgn(\mu)$

Free parameter: $m_{\tilde{G}} \sim M_{SUSY}$

Experimental constrains

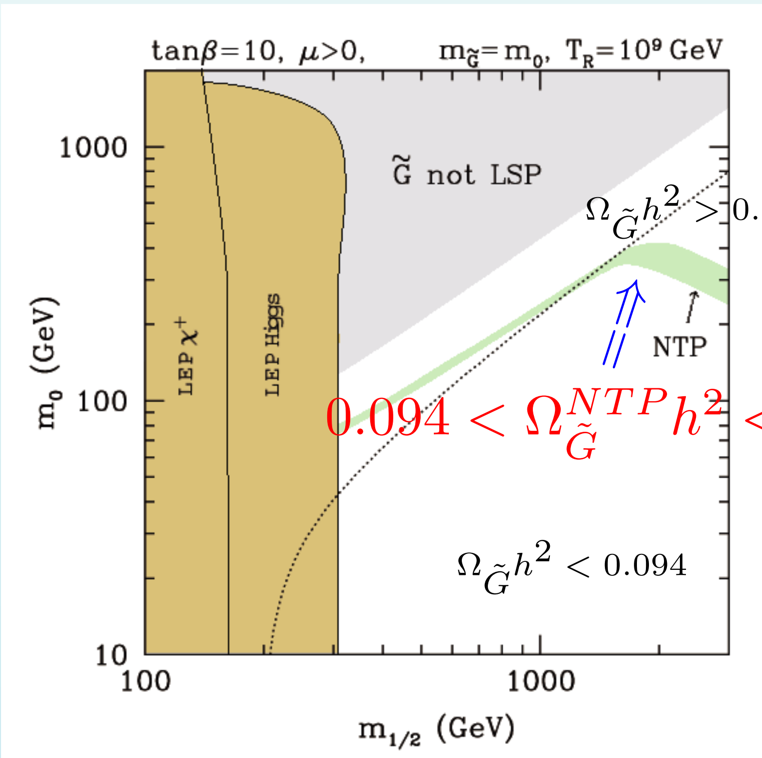
- $m_{\chi^\pm} > 104$ GeV(LEP)
- light higgs: $m_h > 114.4$ GeV(LEP)
- BR(B$\rightarrow X_s\gamma$)= $(3.34 \pm 0.68) \times 10^{-4}$

e.g., $\tan\beta = 10, \ \mu > 0, \ m_{\tilde{G}} = m_0$



Gravitino Relic abundance

$m_{\tilde{G}} = m_0$



$0.094 < \Omega_{\tilde{G}}^{NTP} h^2 < 0.129$

Non-thermal production: NLSP decay

χ NLSP

$\chi \longrightarrow \tilde{G}\gamma$

$\chi \longrightarrow \tilde{G}Z, \tilde{G}Higgs, \tilde{G}(\gamma^*/Z^*)q\bar{q}$

$\tilde{\tau}$ NLSP

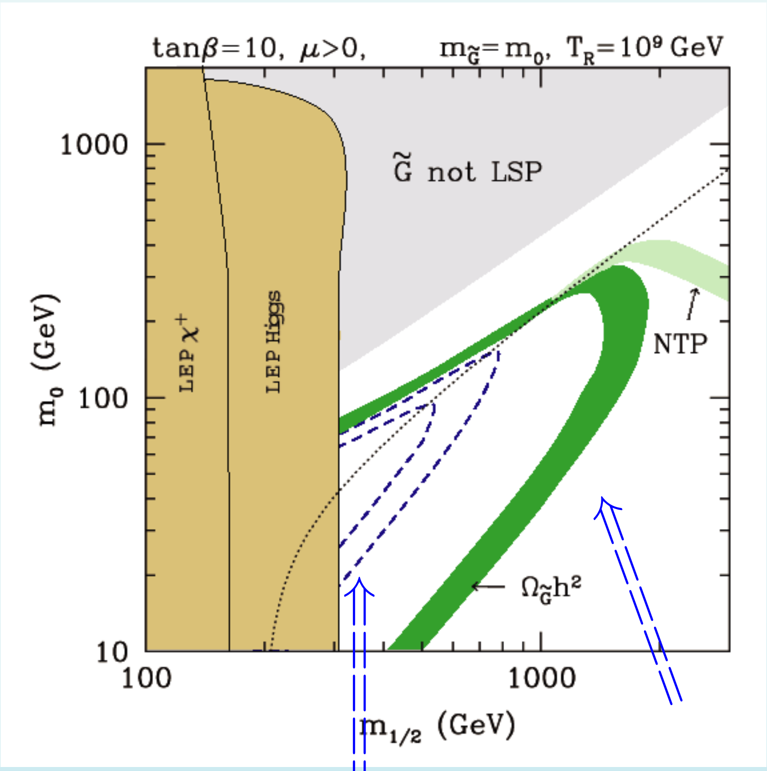
$\tilde{\tau} \longrightarrow \tilde{G}\tau$

$\tilde{\tau} \longrightarrow \tilde{G}\tau Z, \tilde{G}\nu_\tau W s, \tilde{G}\tau(\gamma^*/Z^*)q\bar{q}$

$$\Omega_{\tilde{G}}^{NTP} h^2 = \frac{m_{\tilde{G}}}{m_{NLSP}} \Omega_{NLSP} h^2$$

Gravitino Relic abundance

$m_{\tilde{G}} = m_0$



$T_R = 10^9$ GeV

$T_R = 5 \times 10^9$ GeV

Thermal production:
scattering during reheating

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

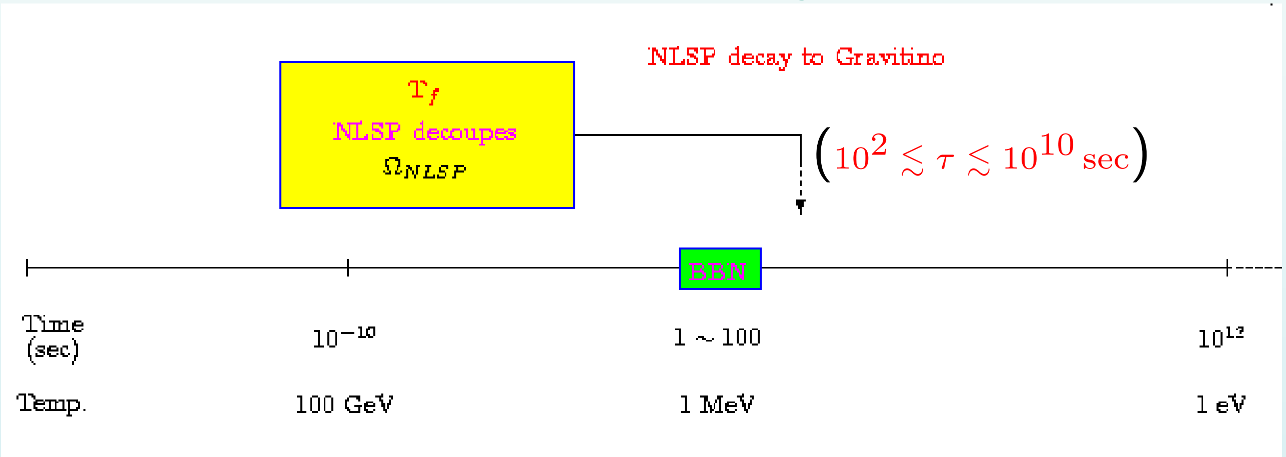
[Bolz,Brandenburg,Buchmüller., (2001)]

$\Downarrow$

$$\Omega_{\tilde{G}} h^2 = \Omega_{\tilde{G}}^{TP} h^2 + \Omega_{\tilde{G}}^{NTP} h^2$$

$$0.094 < \Omega_{\tilde{G}} h^2 < 0.129$$

NLSP decay



- NLSP decay produces photons and hadrons with high energy

χ NLSP

$\chi \rightarrow \tilde{G}\gamma \Rightarrow$ EM showers

$\chi \rightarrow \tilde{G}Z, \tilde{G}Higgs, \tilde{G}\gamma^*/Z^*$

$\Rightarrow$ had showers

$\tilde{\tau}$ NLSP

$\tilde{\tau} \rightarrow \tilde{G}\tau \Rightarrow$ EM showers

$\tilde{\tau} \rightarrow \tilde{G}\tau Z, \tilde{G}\nu_\tau W, \tilde{G}\tau\gamma^*/Z^*$

$\Rightarrow$ had showers

- Late time decay due to gravitational interaction: $10^2 \sim 10^{10}\,\mathrm{sec}$

- The high energy injection(EM,had) at late times during or after BBN changes the light element abundances $\Rightarrow$ Strong constraints on NLSP

BBN constraints

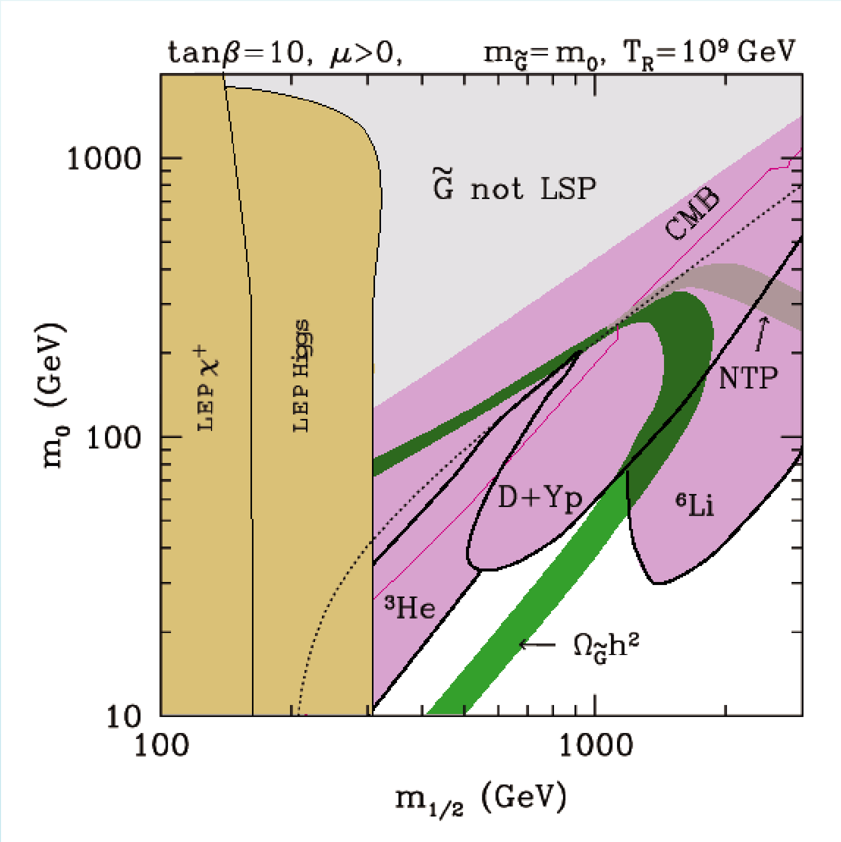
BBN constraints
conservative observational limit

$$2.2 \times 10^{-5} < \mathrm{D/H} < 5.3 \times 10^{-5}$$
$$0.232 < \mathrm{Y_p} < 0.258$$
$$1.11 \times 10^{-10} < {}^7\mathrm{Li/H} < 4.5 \times 10^{-10}$$
$${}^3\mathrm{He/D} < 1.72$$
$${}^6\mathrm{Li}/{}^7\mathrm{Li} < 0.1875$$

CMB constraints
dimensionless chemical potential μ

$$|\mu| < 9 \times 10^{-5}$$

$m_{\tilde{G}} = m_0,\ T_R = 10^9$ GeV

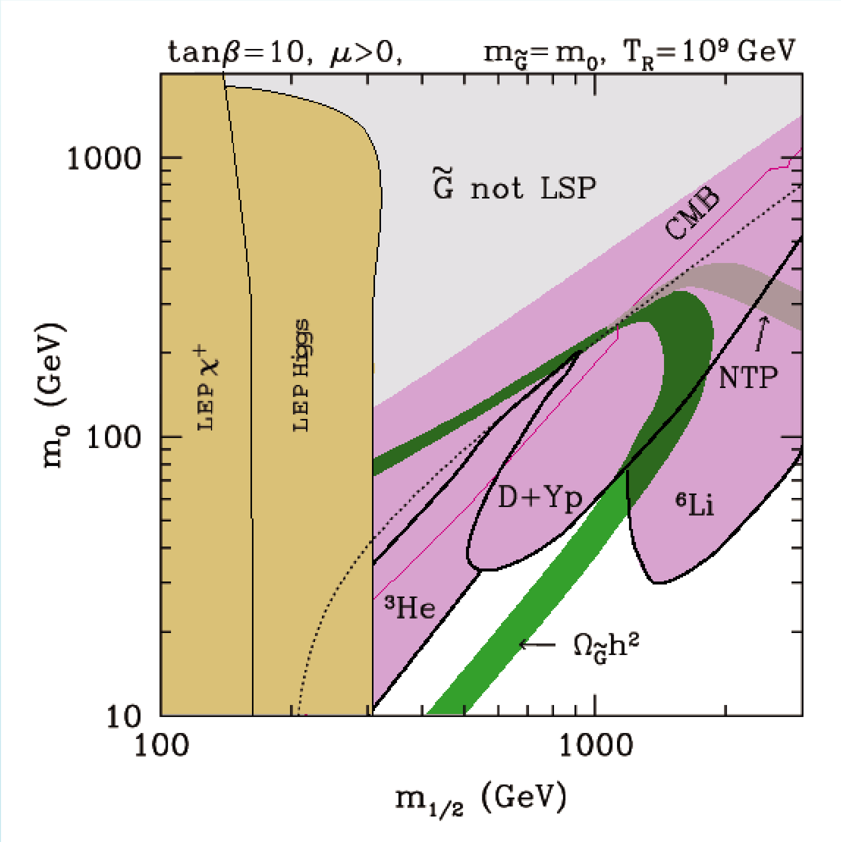


D/H+Y_p+^{7}Li/H+^{3}He/D+^{6}Li/^{7}Li

BBN constraints

- χ NLSP is inconsistent with BBN : still possibility for sub-GeV Gravitino ($\tau_\chi < 1\,\mathrm{sec}$)
- $\tilde{\tau}$ NLSP region is allowed
- CMB constraint is weaker than BBN: potentially important for more precise CMB measurements
- NTP only region is disallowed by BBN: we need another mechanism for Gravitino production
- How high T_R is possible?

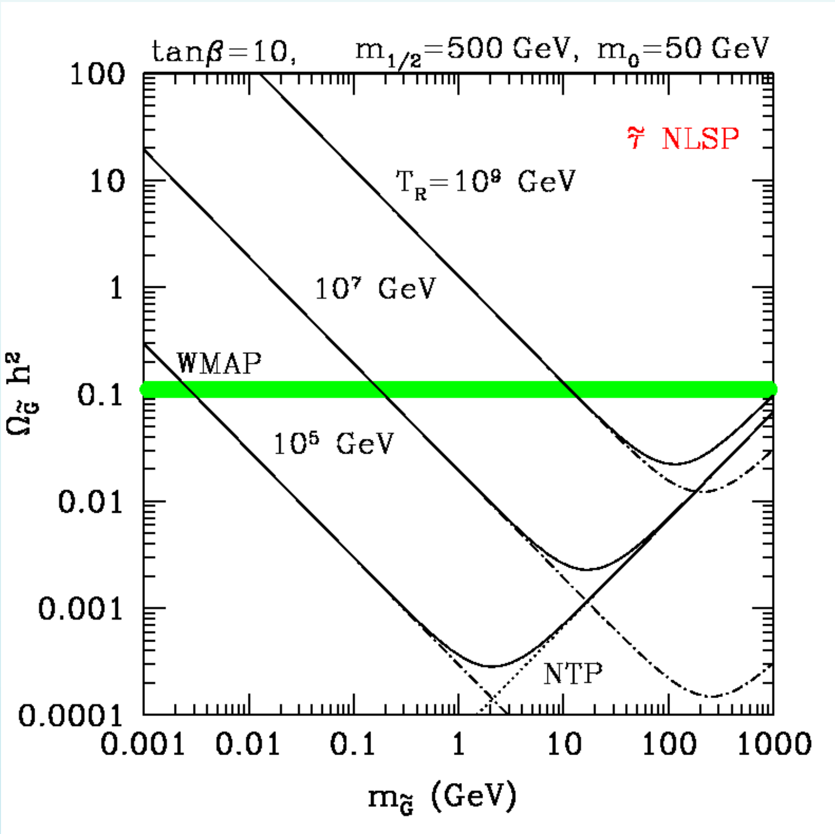
$m_{\tilde{G}} = m_0,\ T_R = 10^9\ \mathrm{GeV}$

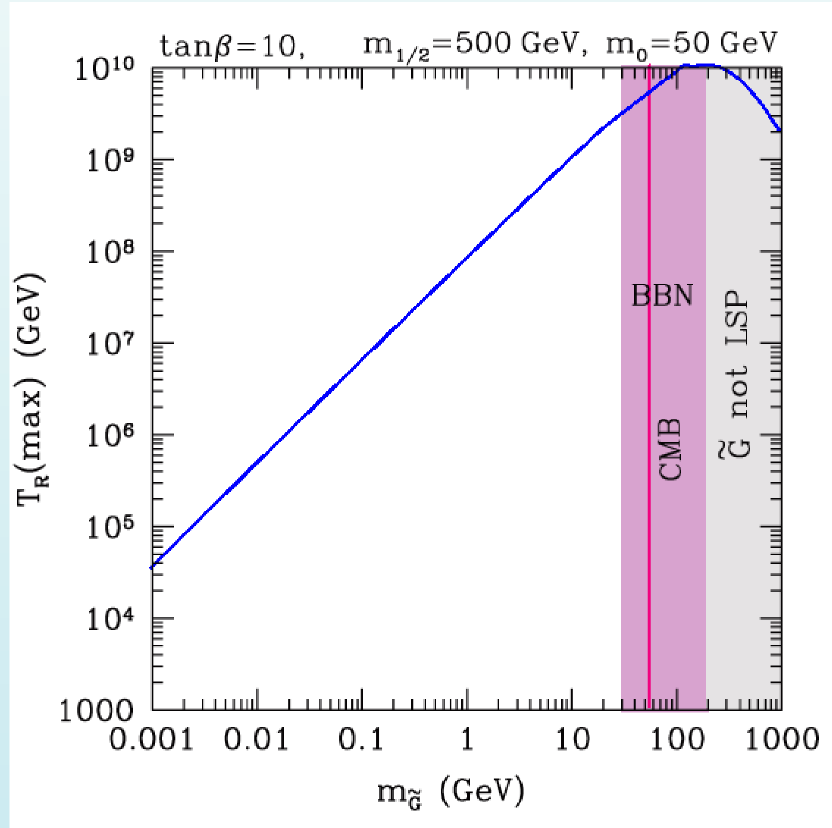


D/H+Y$_p$+^{7}Li/H+^{3}He/D+^{6}Li/^{7}Li

Thermal production

$\tan\beta = 10,\ m_{1/2} = 500\text{GeV},\ \text{m}_0 = 50\text{GeV}(\tilde{\tau}\text{NLSP})$





$\Omega_{\tilde{G}} h^2 = \Omega_{\tilde{G}}^{TP} h^2 + \Omega_{\tilde{G}}^{NTP} h^2$

$T_R \lesssim 3 \times 10^9$ GeV for $m_{\tilde{G}} \sim 30$ GeV

UFB constraints

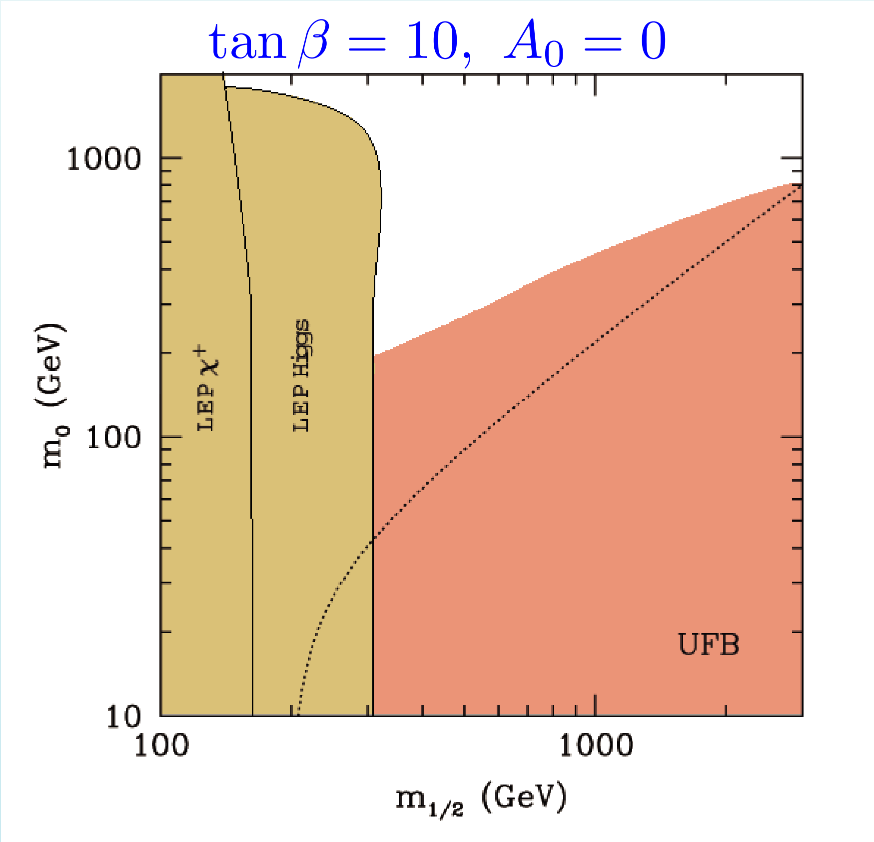
Two types of constraints:

- charge and/or color breaking (CCB) minima

- unbounded from below (UFB) directions (UFB-1,2,3)

  $\Rightarrow$ Among them, UFB-3= $\{H_u,\ \nu_{L_i},\ e_{L_j},\ e_{R_j}\}$, $i \neq j$ direction leads to electric charge breaking also (the strongest constraints) [Casas, Lleyda, Muñoz('96)]

Condition
$V_{\text{UFB-3}}(Q = \hat{Q}) > V_{\text{real min}}$



UFB constraints

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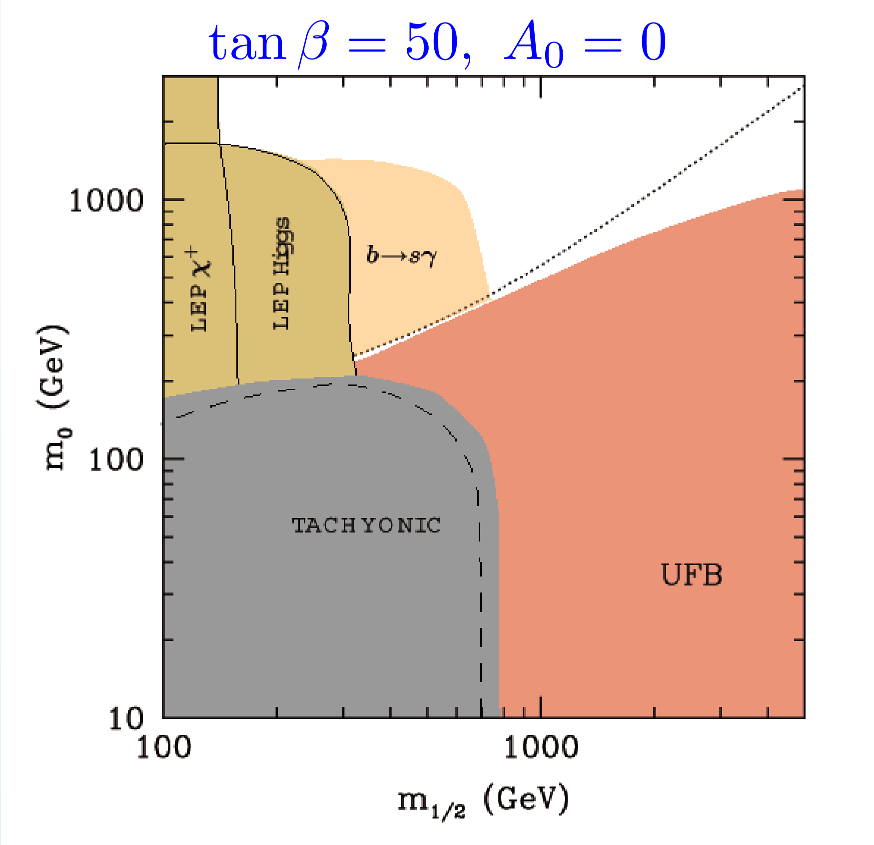

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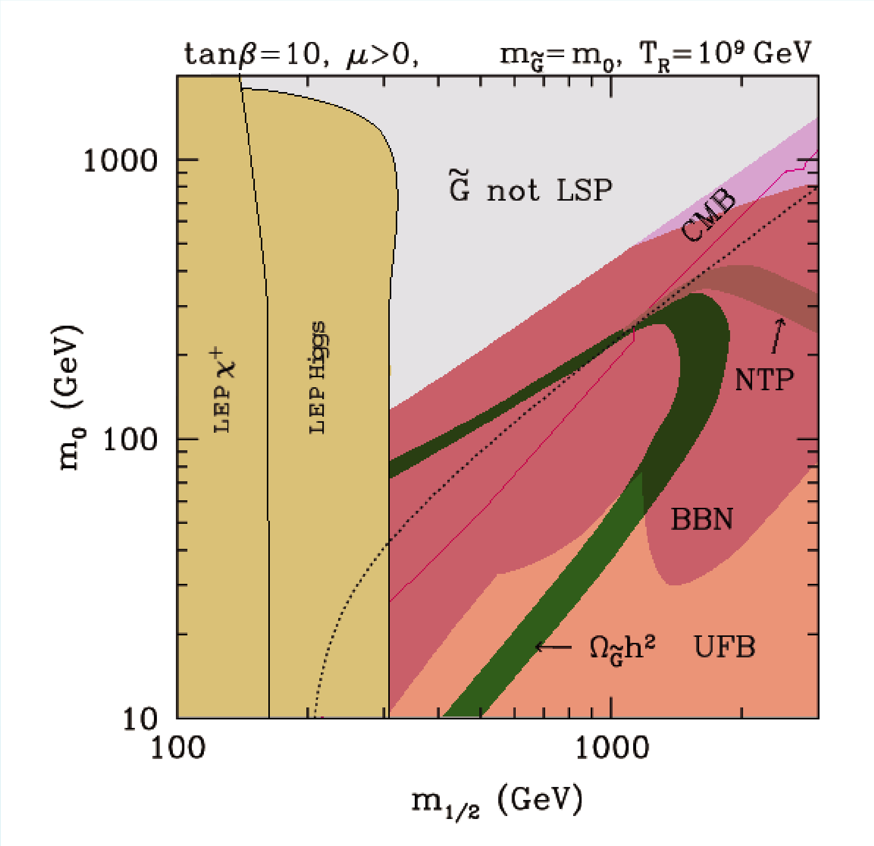
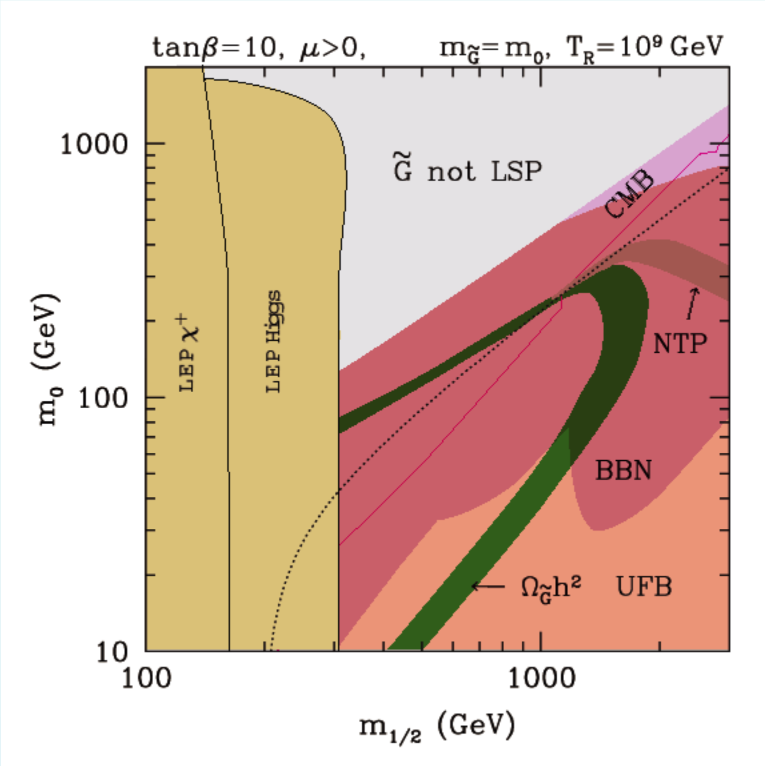


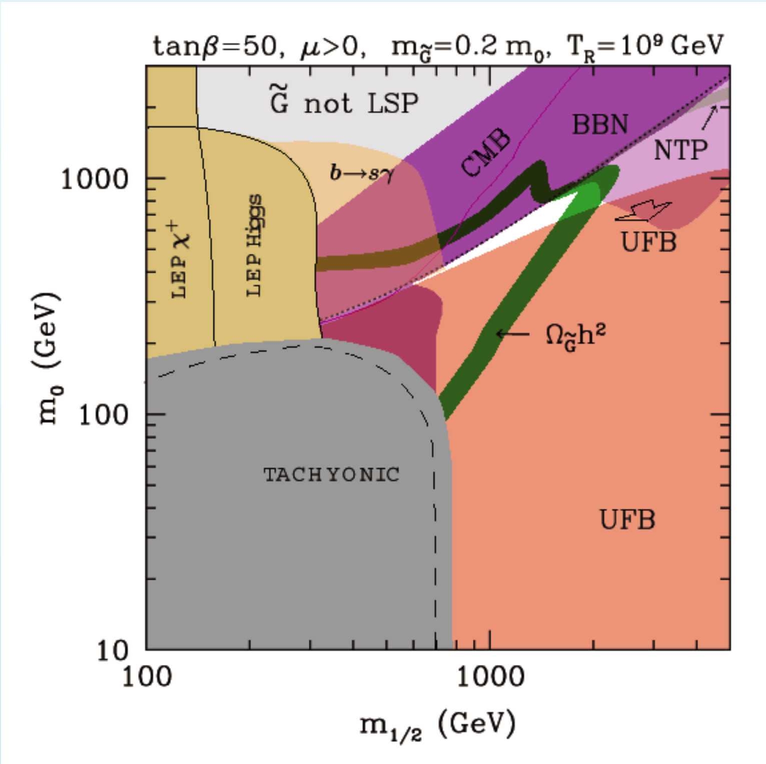
Combining UFB and BBN

For $T_R = 10^9$ GeV,

- $m_{\tilde{G}} = m_0, \ \tan\beta = 10$
- $m_{\tilde{G}} = 0.2 m_0, \ \tan\beta = 50$

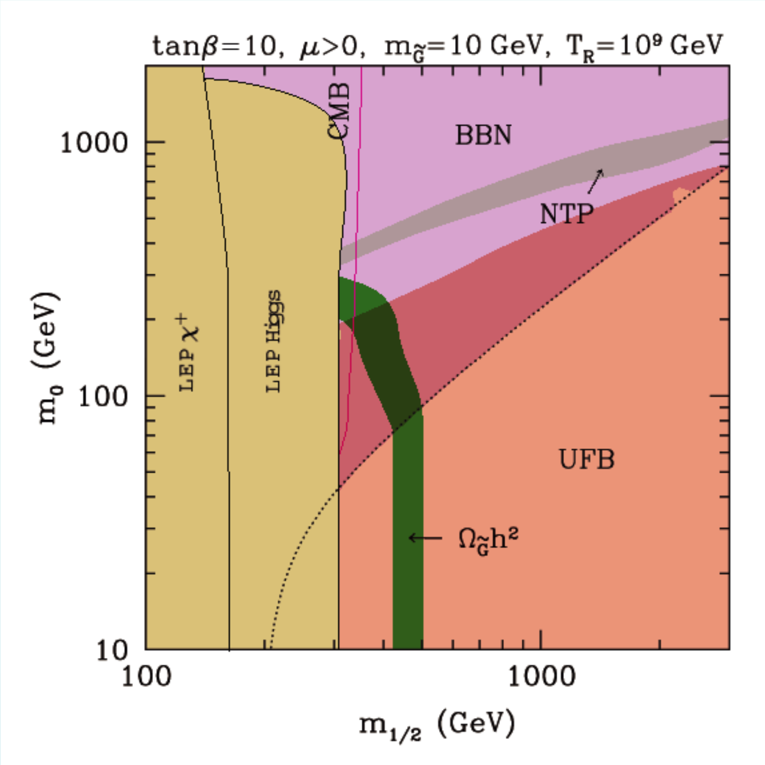


all excluded

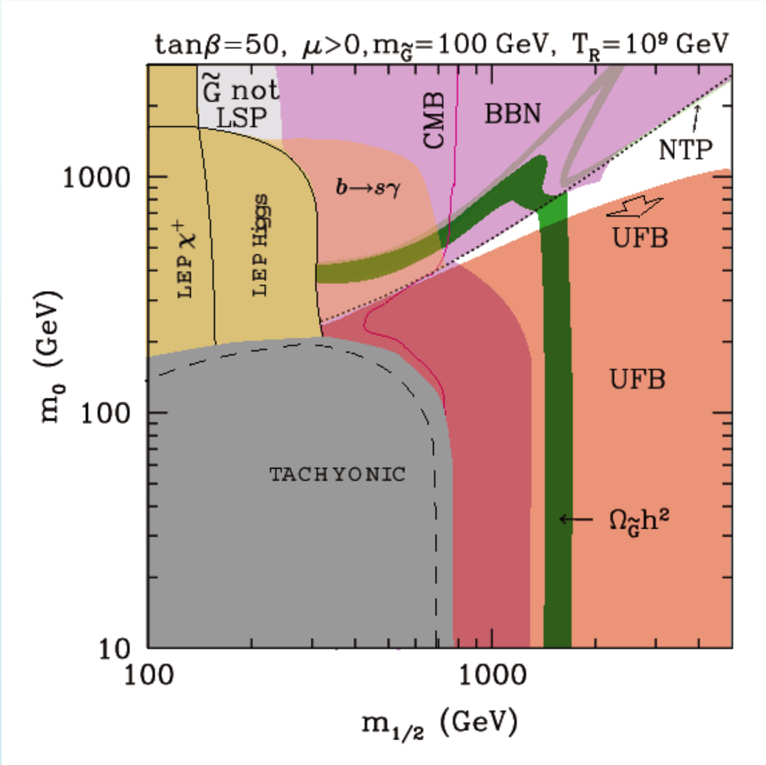


small regions left allowed

- $m_{\tilde{G}} = 10$ GeV, $\tan\beta = 10$



- $m_{\tilde{G}} = 100$ GeV, $\tan\beta = 50$



Discussion

- Neutralino NLSP and O(100)GeV Gravitino LSP is disfavored by BBN: neutralino + sub-GeV Gravitino?

- Stau NLSP and Gravitino LSP is a possible combination in CMSSM for O(100) GeV Gravitino with additional Gravitino production:
  E.g.,for thermal production, up to $T_R \simeq 3 \times 10^9$ GeV is available

- UFB constraints may be consistent if the lifetime of realistic vacuum is longer than the age of the Universe due to non-trivial cosmology

- Warm property of NTP Gravitino may solve the small scale problem of CDM or [Borgani et al. (1996)]

- Charged stau NLSP decay may suppress the matter power spectrum on small scales due to the coupling of charged stau to the photon-baryon system [Sigurdson, Kamionkowski (2004)] and/or induces the scale dependent spectral index [Profumo et al. (2005)].