Gravitino LSP in the Constrained MSSM

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In collaboration with

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Dark Matter?

Recent cosmological data coming from CMB anisotropies, Large Scale Structures and Super novae data shows the current density of the universe: $\Omega_0 \simeq 1$

$$\Omega_\Lambda = 0.73 \pm 0.04$$
$$\Omega_m = 0.27 \pm 0.04$$
$$\Omega_b = 0.044 \pm 0.004$$

$$\Rightarrow \quad \boxed{0.094 < \Omega_{DM} h^2 < 0.129}$$

$h = H_0/100\text{km sec}^{-1}\text{ Mpc}^{-1} \simeq 0.71$

$\Omega \equiv \rho/\rho_c$, $\rho_c = 3H^2/8\pi G$

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What is Dark Matter?

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.

Another general possibility is Gravitino LSP :

spin 3/2, the superpartner of Graviton
always exists in local SUSY
with mass $m_{\tilde{G}} = \frac{F}{\sqrt{3}M_p} \sim 1\ \mathrm{keV} - 1\ \mathrm{TeV}$

F: SUSY breaking scale, M_p: reduced Planck mass

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If Gravitino is the lightest supersymmetric particle,
and produced with right abundance for dark matter
then it may solve the dark matter problem.
However Gravitino has another problem called Gravitino Problem.

Gravitino Problem

If the Universe cools down from M_p, Gravitino freezes out from thermal equilibrium with the relic density

$$\Omega_{\tilde{G}} h^2 = 1.17 \left(\frac{100}{g_*}\right) \left(\frac{m_{\tilde{G}}}{1 \text{ keV}}\right)$$

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$$\Omega_{tot} < 1 \Rightarrow m_{\tilde{G}} \lesssim 1 \text{ keV}$$

[Pagels,Primack, '82]

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- Unstable

Decay at $\tau_{\tilde{G}} \sim \frac{M_p^2}{m_{\tilde{G}}{}^3} \sim 10^8 \sec \left(\frac{100 \ \mathrm{GeV}}{m_{\tilde{G}}}\right)^3$

BBN constraints $\Rightarrow m_{\tilde{G}} \gtrsim 10$ TeV

[Weinberg, '82]

Gravitino production from reheating

The primordial Gravitino is diluted away by Inflation. However Gravitino is 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)]

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stable: $T_R \lesssim 10^{10}$ GeV from $\Omega_{tot} < 1$

$\Omega h^2 = 3.63 \times 10^9 \frac{m}{100 \text{ GeV}} Y$

unstable: $T_R \lesssim 10^8$ GeV from BBN

[Cyburt et al.('02), Kawasaki et al.('04)]

Gravitino LSP as Dark Matter

If the Gravitino is LSP,

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$$\tau(NLSP \to \tilde{G} + \cdots) \sim 10^8 \ \text{sec} \left(\frac{100 \ \text{GeV}}{m_{NLSP}}\right)^5 \left(\frac{m_{\tilde{G}}}{100 \ \text{GeV}}\right)^2$$

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BBN + CMB $\Rightarrow$ Constraints on NLSP parameters

BBN constraint on EM showers

$$\boxed{NLSP \to \tilde{G} + \gamma}$$

The emitted high energy photon from decaying particle may interact with the background plasmas, and change the light element abundances.

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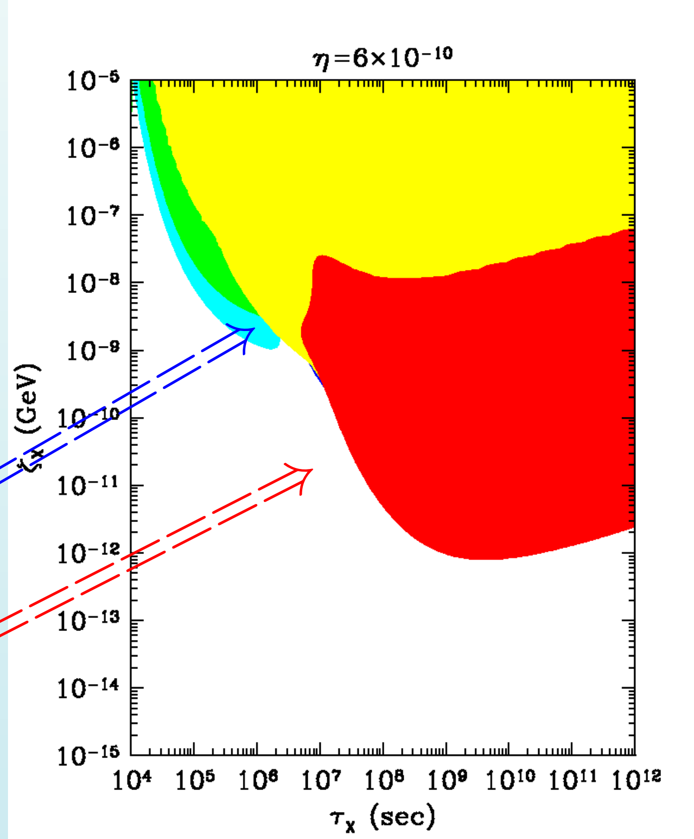
- D overdestruction($10^4\,\mathrm{sec} \lesssim \tau \lesssim 10^6\,\mathrm{sec}$)
  $\gamma + \mathrm{D} \rightarrow \mathrm{n} + \mathrm{p}$
- Li6 overproduction
  $\gamma +^4 He \rightarrow^3 He + n\ (T + p)$
  $^4\mathrm{He} +^3 \mathrm{He(T)} \rightarrow \mathrm{n(p)} +^6 \mathrm{Li}$

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



$(\zeta_X = m_X n_X / n_\gamma)$

Cyburt, Ellis, Fields & Olive (2002)

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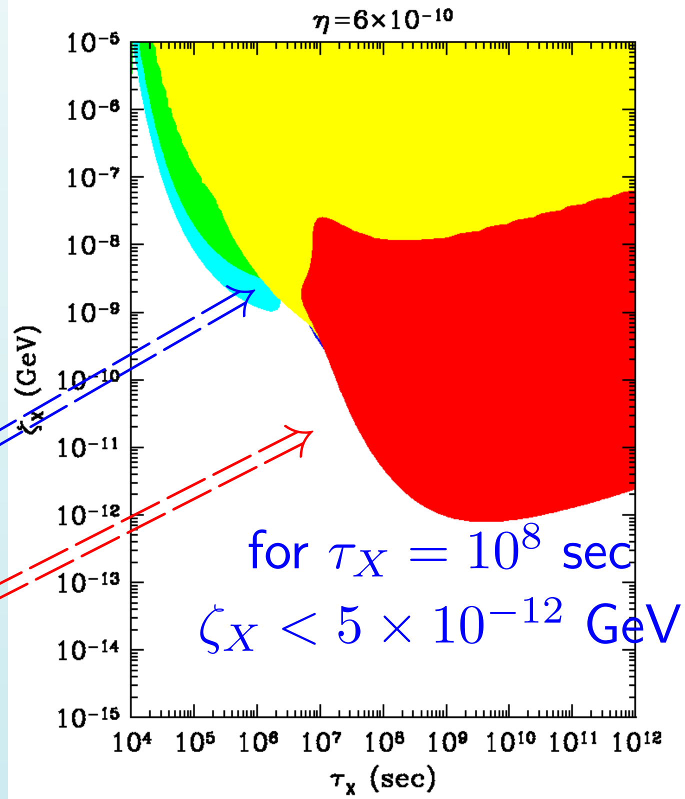

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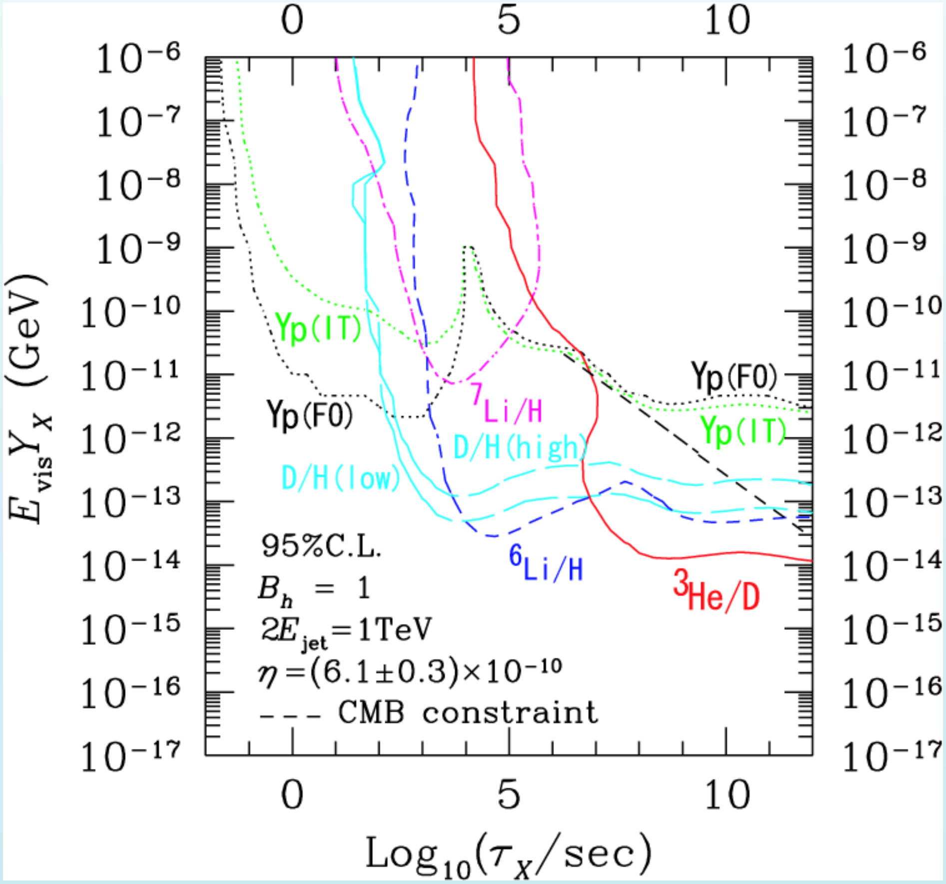

Kawasaki, Kohri & Moroi (2004)

Hadronic shower + photonic shower

- ^{4}He overproduction$(\tau \lesssim 10^2\,\mathrm{sec})$
  $n + p \to D \to^4 \mathrm{He}$
- D overproduction$(\tau \gtrsim 10^2\,\mathrm{sec})$
  $n + p \to D, n +^4 He \to D$
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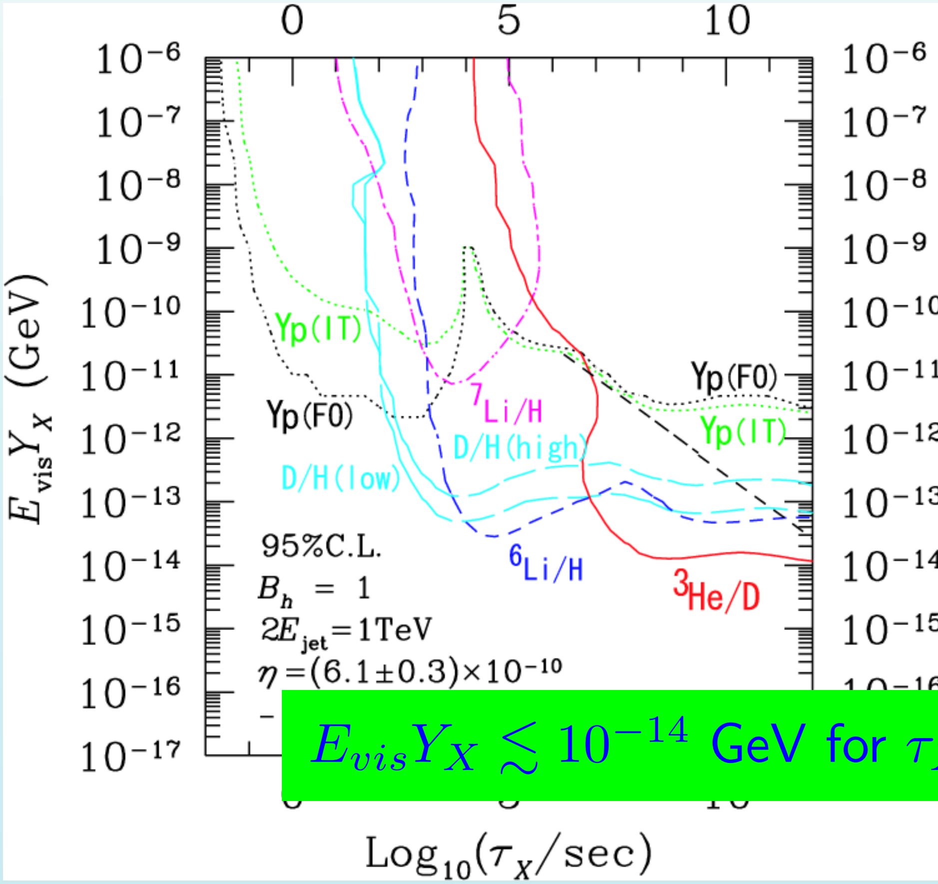

$E_{vis} Y_X \lesssim 10^{-14}$ GeV for $\tau_X = 10^8$ sec

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Large constraitns for late decay!

CMB constraints

EM energy injection from NLSP decay may distort the Planckian distribution of Cosmic Microwave Background [Hu, Silk (1993)]

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- $10^6\,\text{sec} < \tau_X < 4 \times 10^{11}\Omega_b h^2\,\text{sec}$
  kinetic eq., not chemical eq. $\Rightarrow$ B-E distribution with chemical potential μ, with $f_\gamma(E) = \frac{1}{exp(E/kT+\mu)-1}$

$$|\mu| < 9 \times 10^{-5}\ (95\ \%CL)$$

[Fixen et.al., (1996)]

$$\zeta_X < 1.12 \times 10^{-11} \left(\frac{10^8\ \text{sec}}{\tau_X}\right)^{1/2} \text{GeV}$$

for $\tau_X \gtrsim 10^7\ \text{sec}$

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- $\tau_X > 4\times 10^{11}\Omega_b h^2\,\mathrm{sec}$
  distortion of CMB from energy injection $\longrightarrow$ constraints on compton parameter y, where $4y = \frac{\delta\epsilon}{\epsilon}$

  $$|y| < 1.2\times 10^{-5}\ (95\ \%CL)$$

  [Hagiwara et.al., (2002)]

  $$\zeta_X < 3.11\times 10^{-13}\left(\frac{10^{10}\ \mathrm{sec}}{\tau_X}\right)^{1/2}\mathrm{GeV}$$

  for $\tau_X \gtrsim 10^{10}\ \mathrm{sec}$

In our analysis

To study the possibility of Gravitino LSP as dark matter,

- Calculate the low energy parameters in the CMSSM :
  - Gravitino mass : free parameter

- Calculate the relic density of Gravitino LSP
  : Thermal + Non-thermal

- BBN & CMB constraints for each point in the $m_0 - m_{1/2}$ space
  - calculate decay amplitudes and branching ratios : varying B_h's
  - obtain the light element abundances : with EM + had contribution

- Apply observation : D/H+Y_p+^{7}Li/H+^{3}He/D+^{6}Li/^{7}Li
  Jedamzik's inputs somewhat more conservative than KKM

Gravitino LSP in the CMSSM

Constrained MSSM

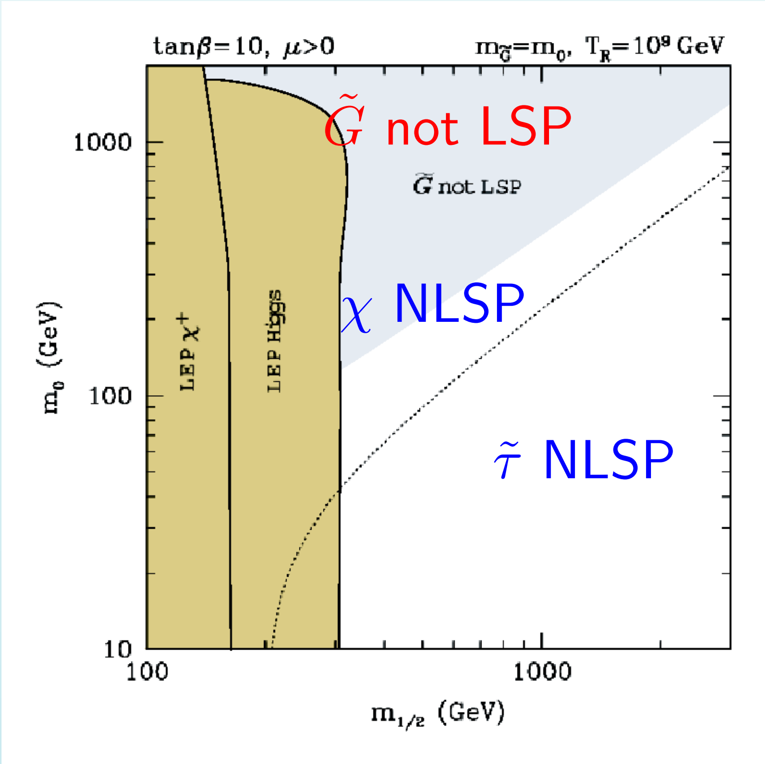
At M_{GUT}

- gauginos $M_1 = M_2 = M_3 = m_{1/2}$
- scalars
  $m^2_{\tilde{q}} = m^2_{\tilde{l}} = m^2_{H_b} = m^2_{H_t} = m^2_0$
- trilinear soft terms $A_b = A_t = A_0$
- radiative EWSB
- five independent parameters:
  $\tan\beta, m_{1/2}.m_0, A_0, sgn(\mu)$

Experimental constrains

- $m_{\chi^\pm} > 104$ GeV(LEP)
- light higgs: $m_h > 114.4$ GeV(LEP)
- BR(B$\rightarrow X_s\gamma$)$= (3.34 \pm 0.68) \times 10^{-4}$
- DM relic density
  $0.094 < \Omega_{DM} < 0.129(2\sigma)$
- BBN & CMB constraints
- UFB constraints

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



NLSP decay

χ NLSP

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

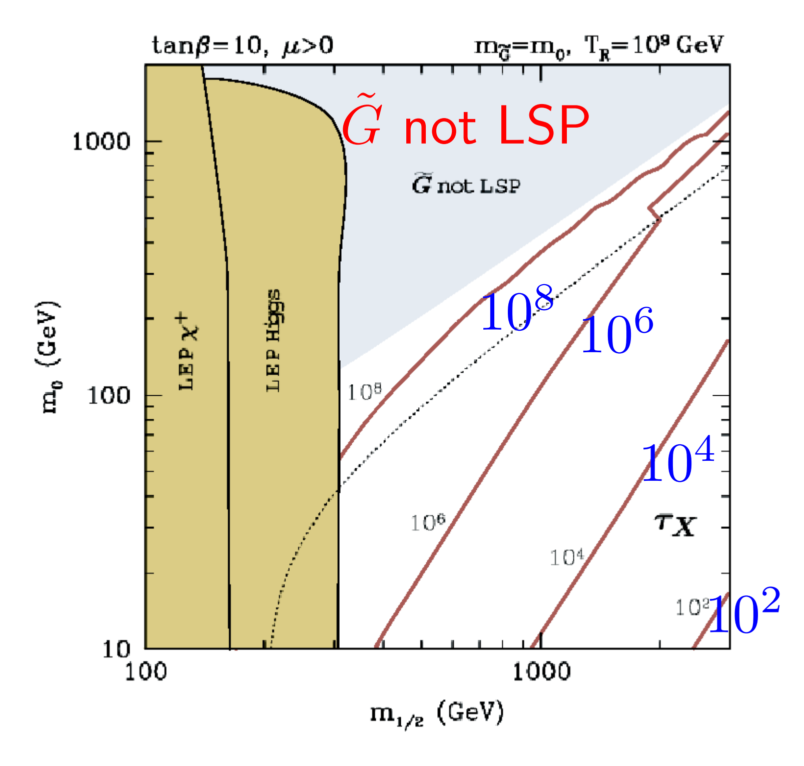
$\chi \to \tilde{G}Z, \tilde{G}Higgs, \tilde{G}\gamma^*$

$\Rightarrow$ had showers

$$\tau \simeq 2.3 \times 10^7 \left(\frac{100\ \text{GeV}}{m_\chi - m_{\tilde{G}}}\right)^3 \text{sec}$$

(when $\chi \simeq \tilde{B}$)

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



$\tilde{\tau}$ NLSP

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

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

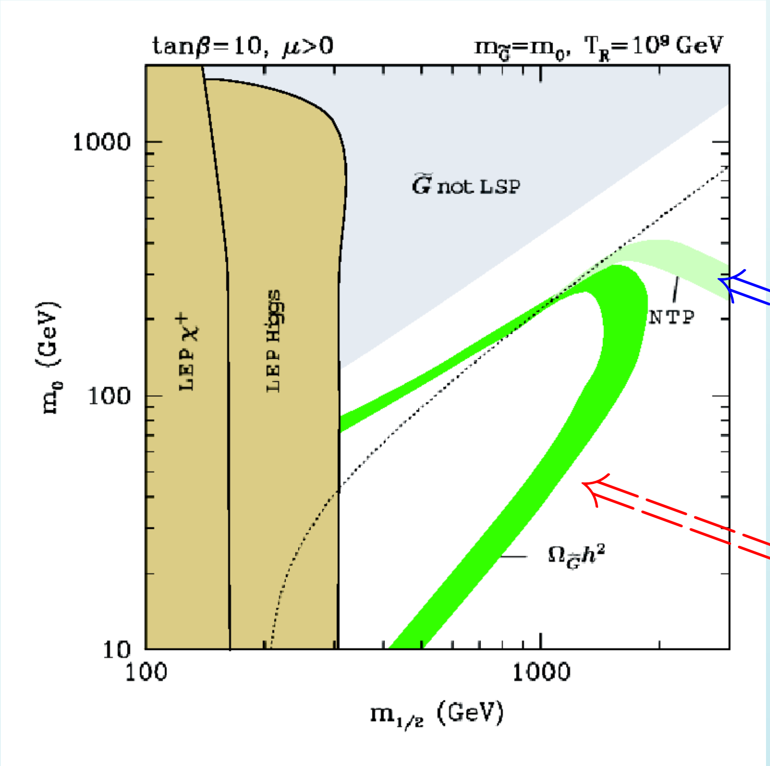
$\Rightarrow$ had showers

$$\tau \simeq 3.6 \times 10^8 \left(\frac{100\ \text{GeV}}{m_{\tilde{\tau}} - m_{\tilde{G}}}\right)^4 \left(\frac{m_{\tilde{G}}}{1\ \text{TeV}}\right) \text{sec}$$

Feng et al.('04)

Gravitino Relic abundance

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



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

Thermal production: scattering during reheating

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

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

Non-thermal production: NLSP decay

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

[using DarkSusy]

$\Downarrow$

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

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apply D/H+Y_p+^{7}Li/H+^{3}He/D+^{6}Li/^{7}Li using conservative observational data [K.Jedamzik]

$$2.2 \times 10^{-5} < \mathrm{D/H} < 5.3 \times 10^{-5}$$

$$0.232 < \mathrm{Y_p} < 0.258$$

$$1.11 \times 10^{-10} < {}^7\mathrm{Li/H} < 4.5 \times 10^{-10}$$

$$^3\mathrm{He/D} < 1.72$$

$$^6\mathrm{Li}/^7\mathrm{Li} < 0.1875$$

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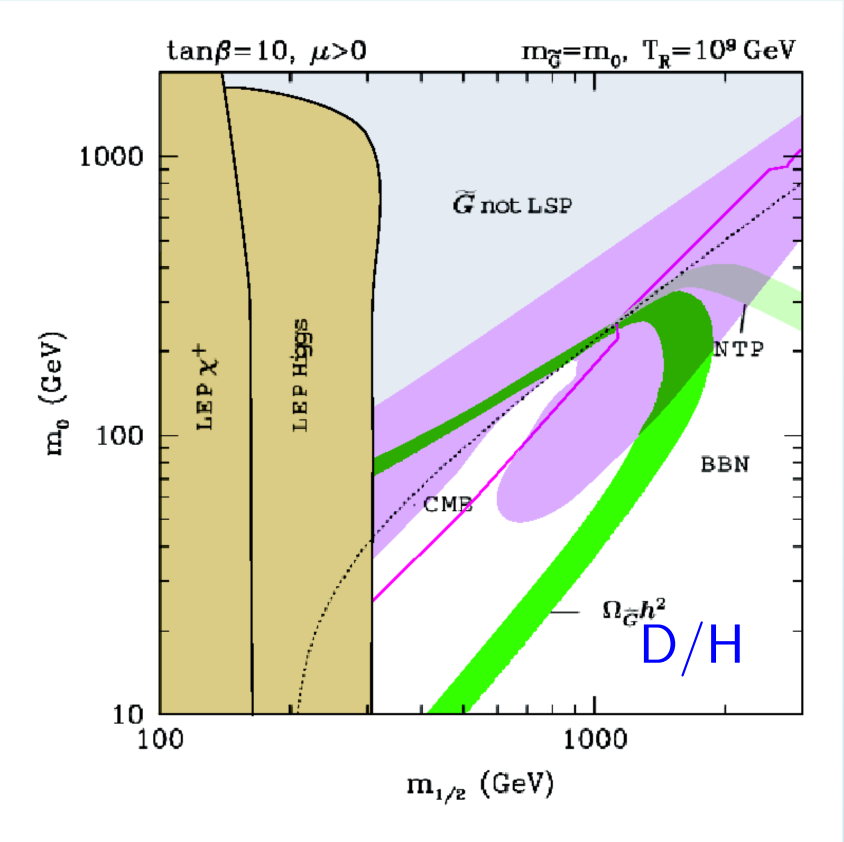

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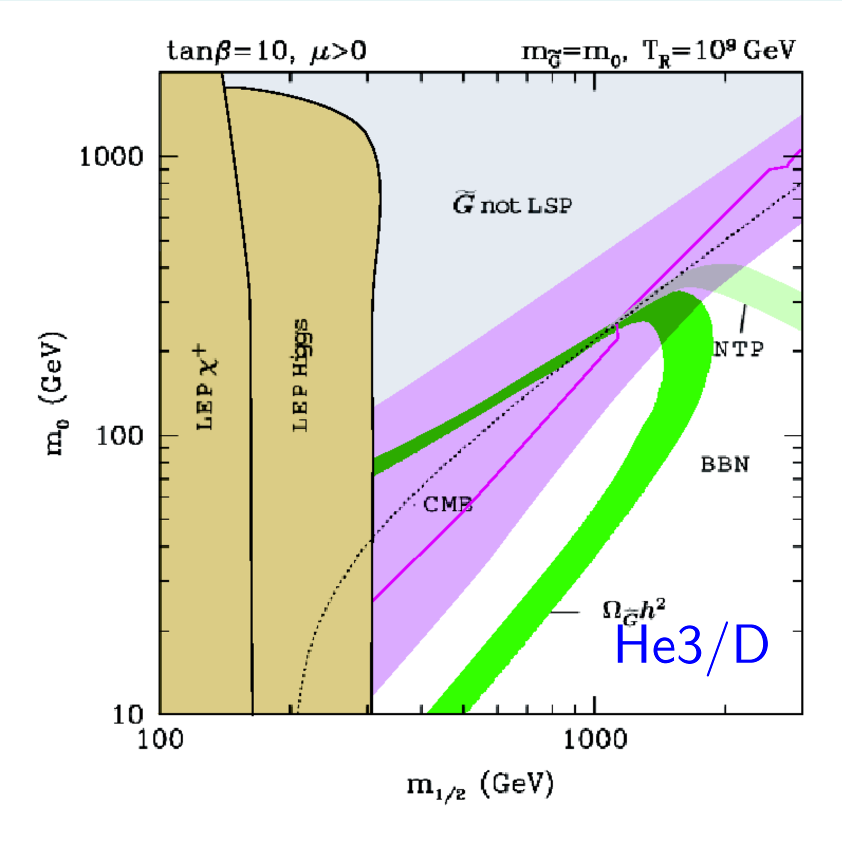

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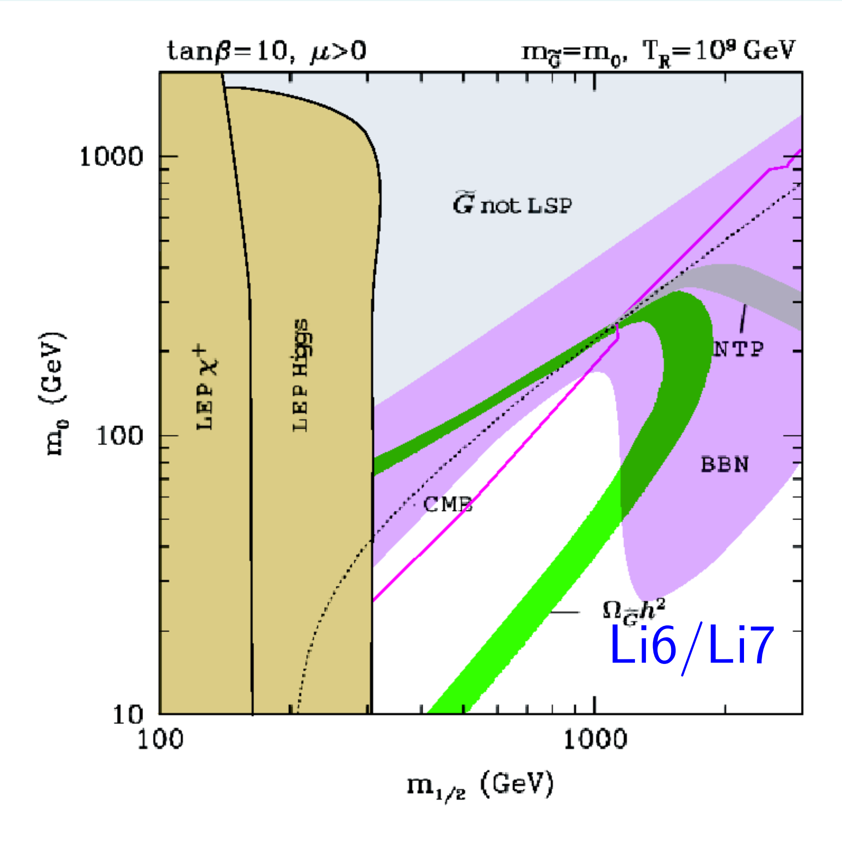

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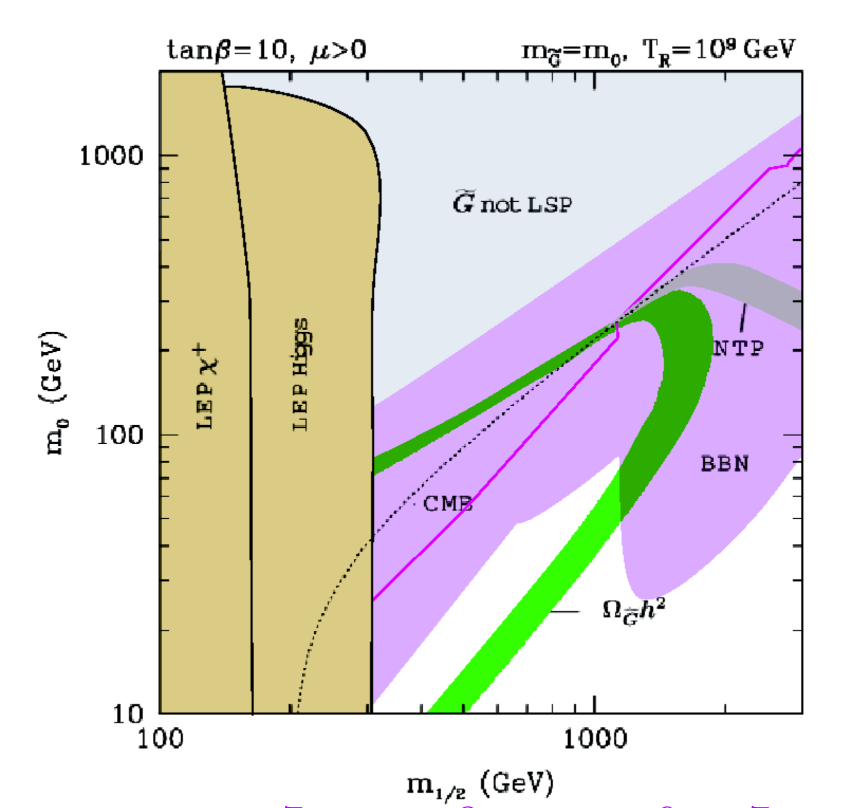

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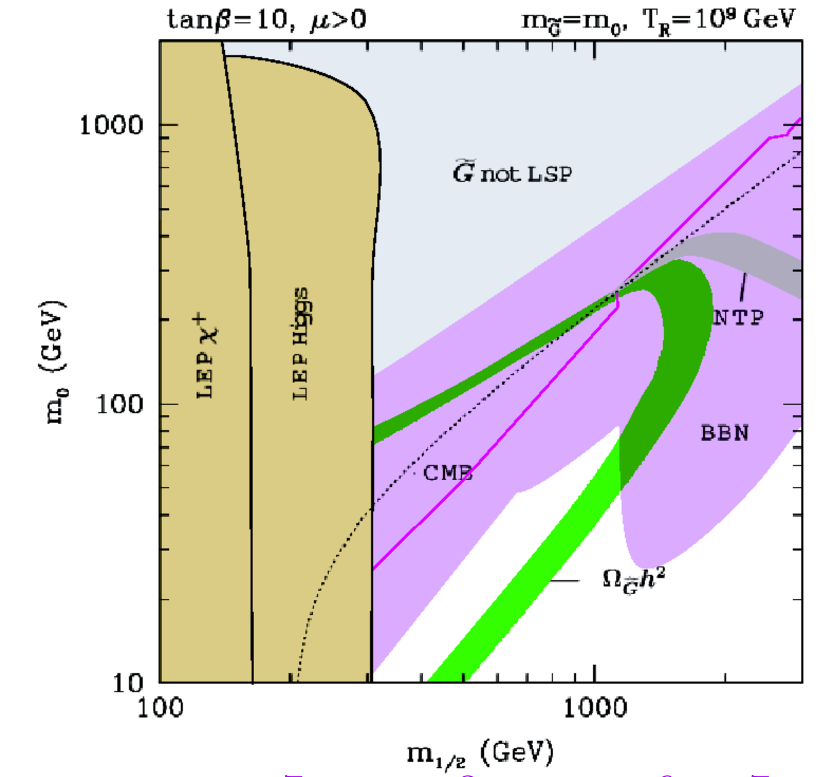


D/H+Y_p+^{7}Li/H+^{3}He/D+^{6}Li/^{7}Li

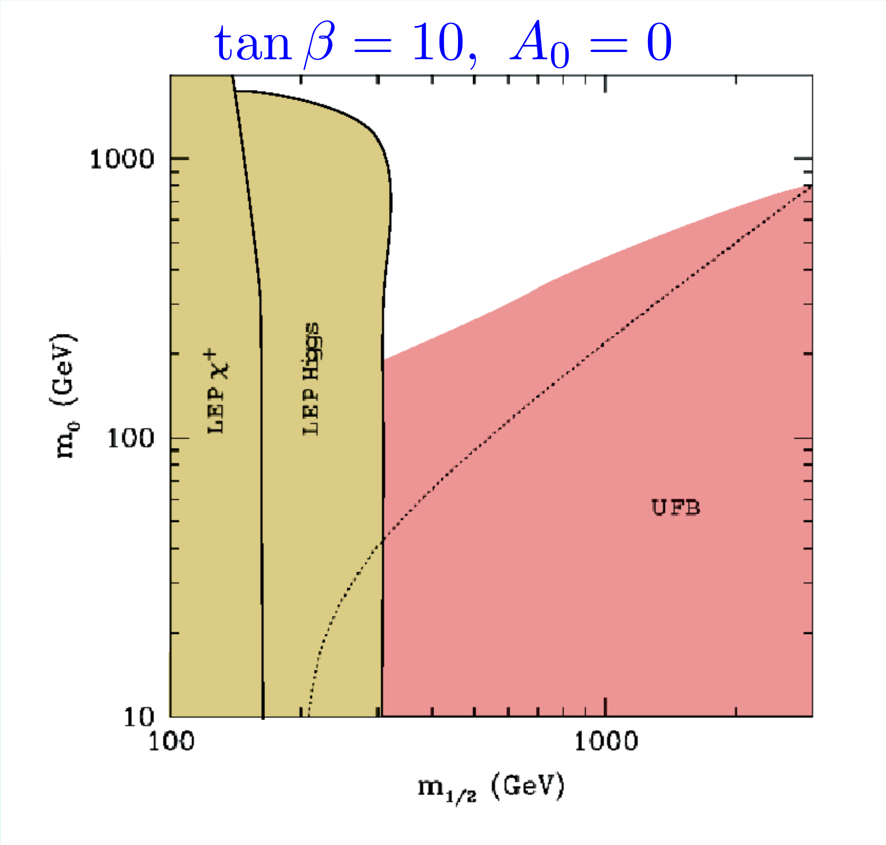
only $\tilde{\tau}$ region remains allowed

low T_R basically excluded(NTP part only), must include TP contribution($\Omega_{\tilde{G}}h^2$)

UFB constraints

Two types of constraints:

- charge and/or color breaking (CCB) minima
- unbounded from below (UFB) directions,
  UFB-3= $\{H_u,\ \nu_{L_i},\ e_{L_j},\ e_{R_j}\ \},\ i \neq j$ direction also leads to electric charge breaking(typically strongest constraints) [Casas, Lleyda, Muñoz('96)]



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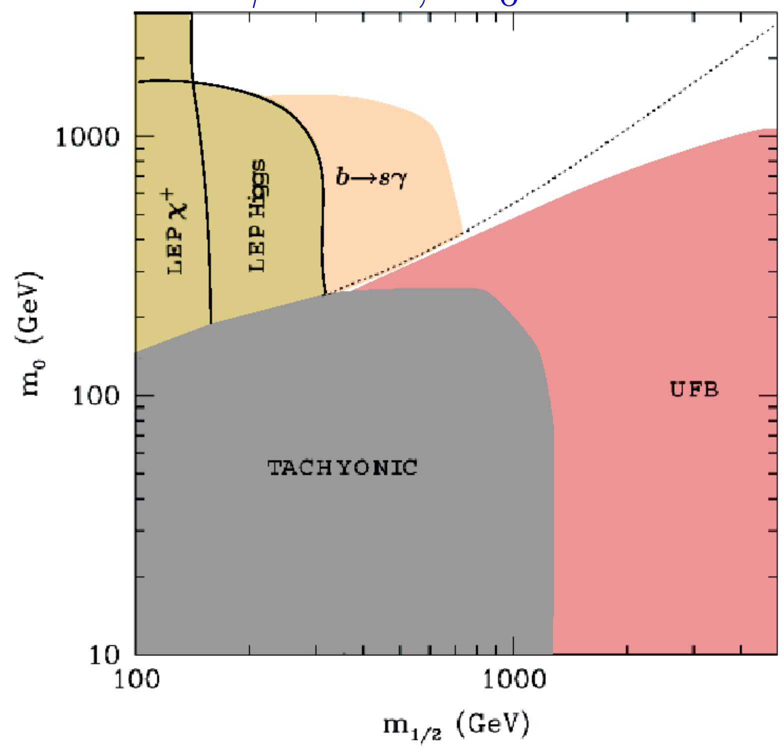
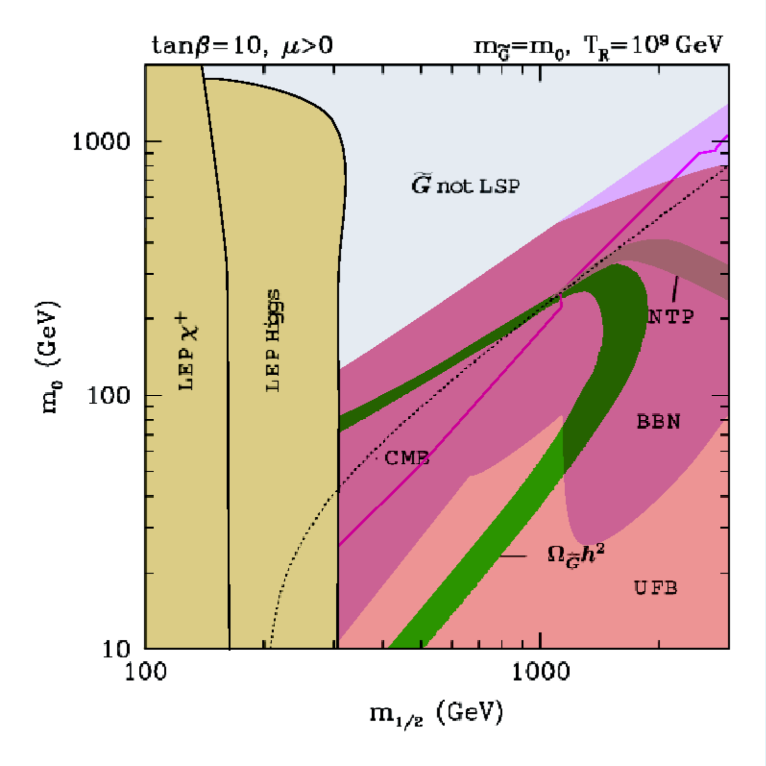
$\tan\beta = 50,\ \ A_0 = 0$



Combining UFB and BBN

For $T_R = 10^9$ GeV,

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



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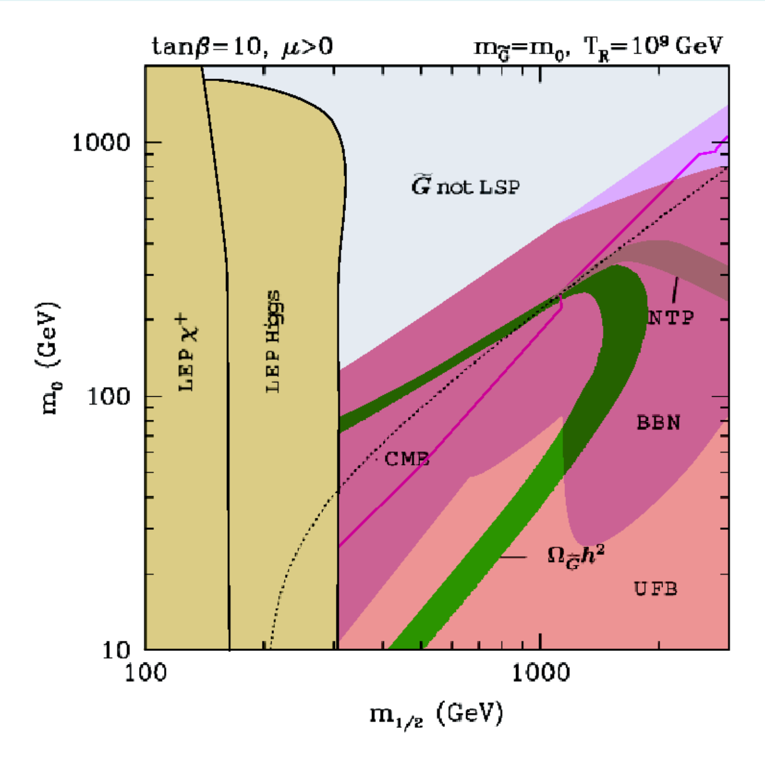
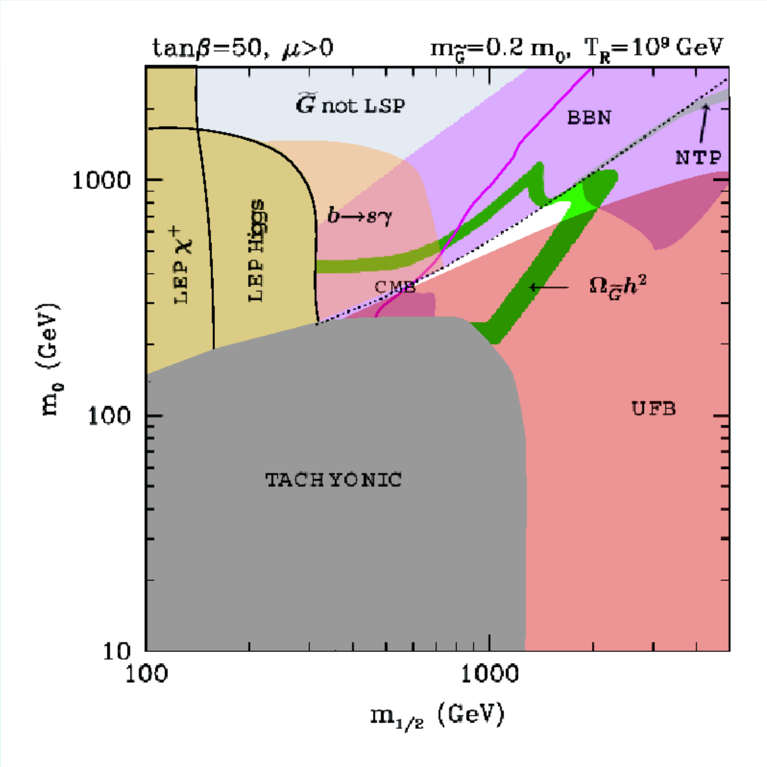


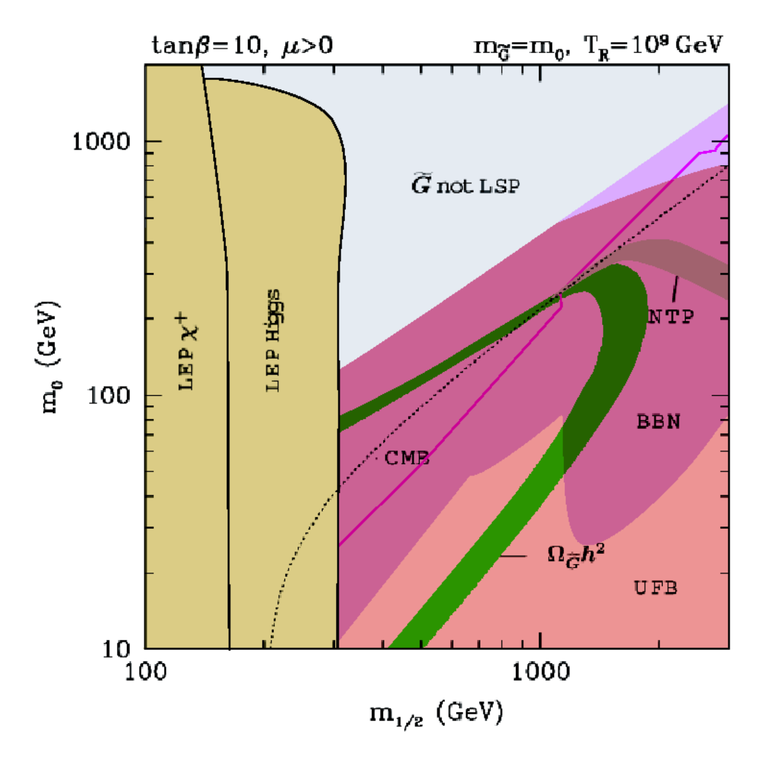
- $m_{\tilde{G}} = 0.2 m_0, \ \tan\beta = 50$



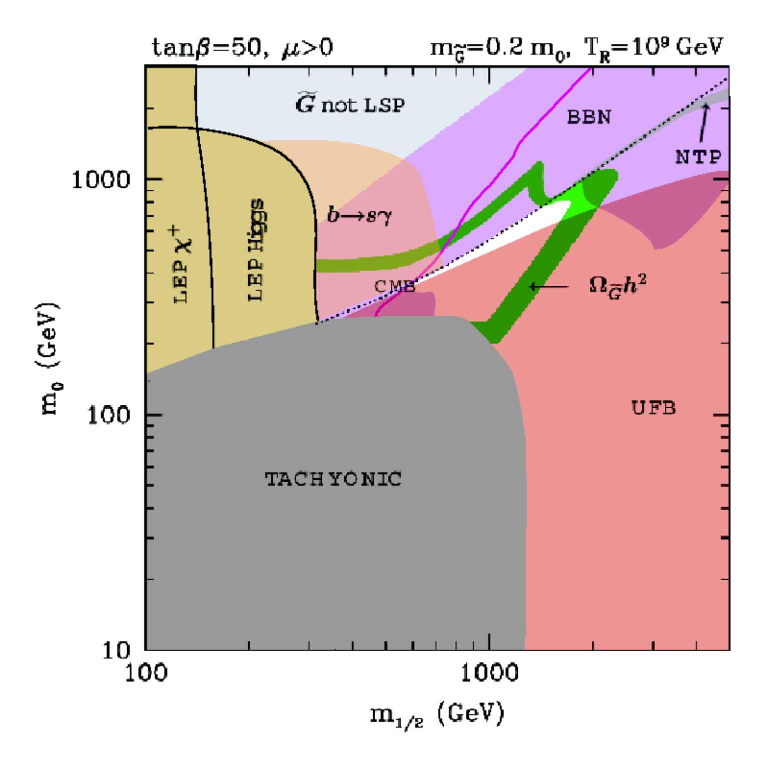
Combining UFB and BBN

For $T_R = 10^9$ GeV,

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

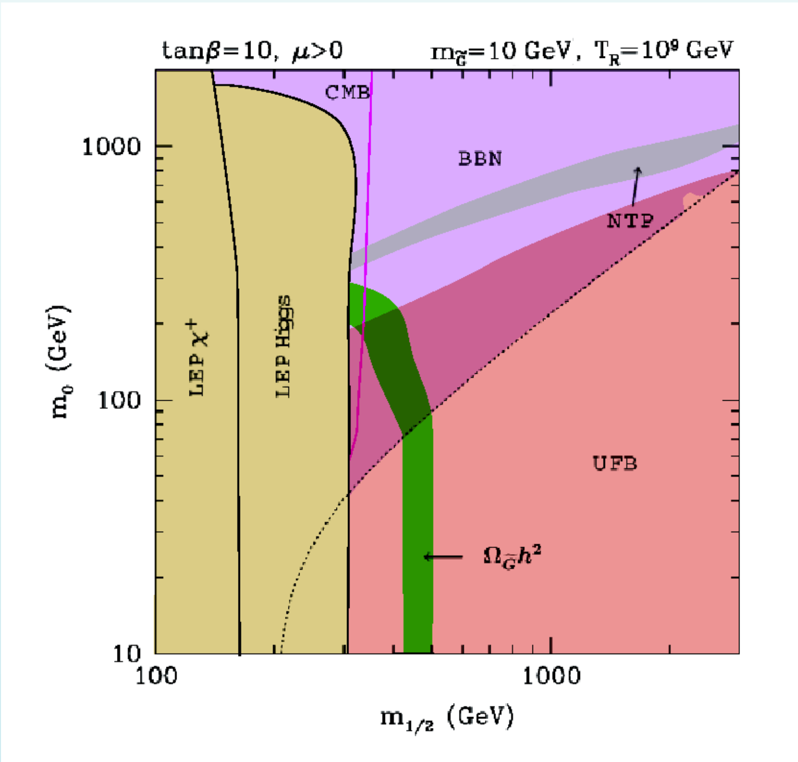


all excluded

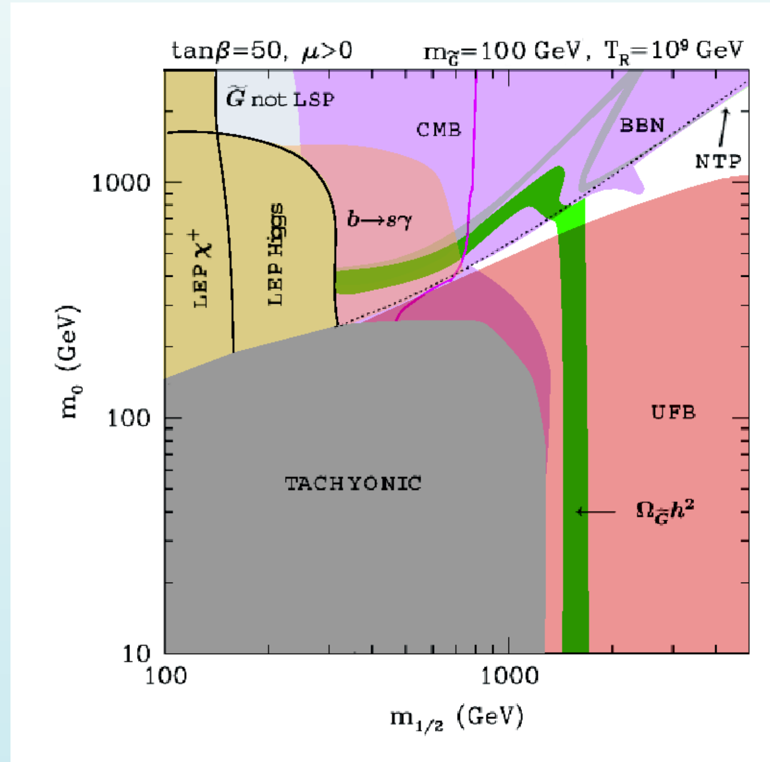


small regions left allowed

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



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



Conclusion

- Gravitino is a general possibility for Cold Dark Matter
- Both the thermal and non-thermal contribution to relic density of Gravitino : thermal production is necessary
- BBN and CMB constraints are strong: Neutralino NLSP excluded
- UFB constraints disfavour stau NLSP region:
  or we live in a metastable vacuum