Gravitino LSP as Dark Matter in the Constrained MSSM

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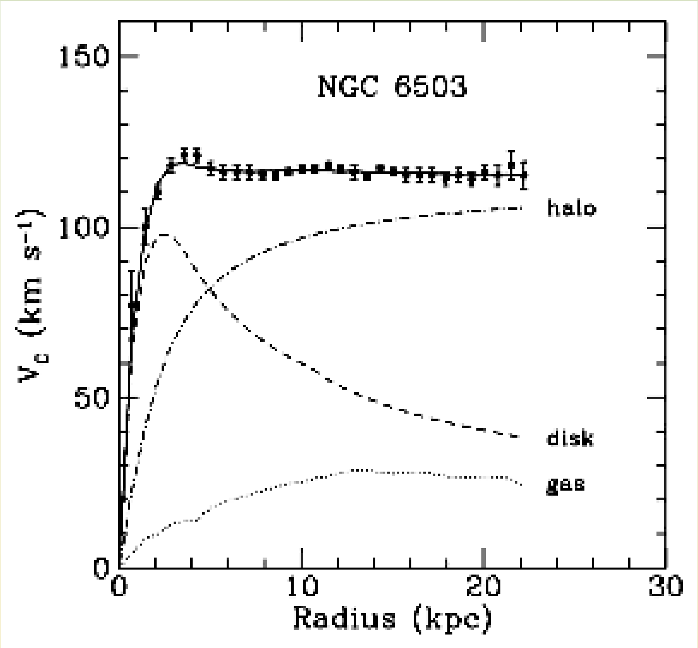
Contents

- Dark matter
- Supersymmetry and Gravitino Problem
- Gravitino as Dark Matter
- Cosmic Lithium Problems with Gravitino
- Implications on vacuum structure of Universe
- Summary

Evidence for Dark Matter

- Rotation curves of galaxies in 21cm line from hyperfine splitting
- Flat behavior beyond the visible disks
- $M(r) \propto r,\ \rho \propto 1/r^2$

- Mass of a cluster of galaxies
- Distribution of hot gas from X-ray emission
- Shape of the potential well using weak gravitational lensing



Cosmic Microwave Background

WMAP satellitet 3-year results (2006)

- $\Omega_m h^2 = 0.126 \pm 0.009$
- $\Omega_b h^2 = 0.0223 \pm 0.0008$
- $h = 0.734^{+0.028}_{-0.038}$

$$\Omega_{DM} = 0.192 \pm 0.017$$

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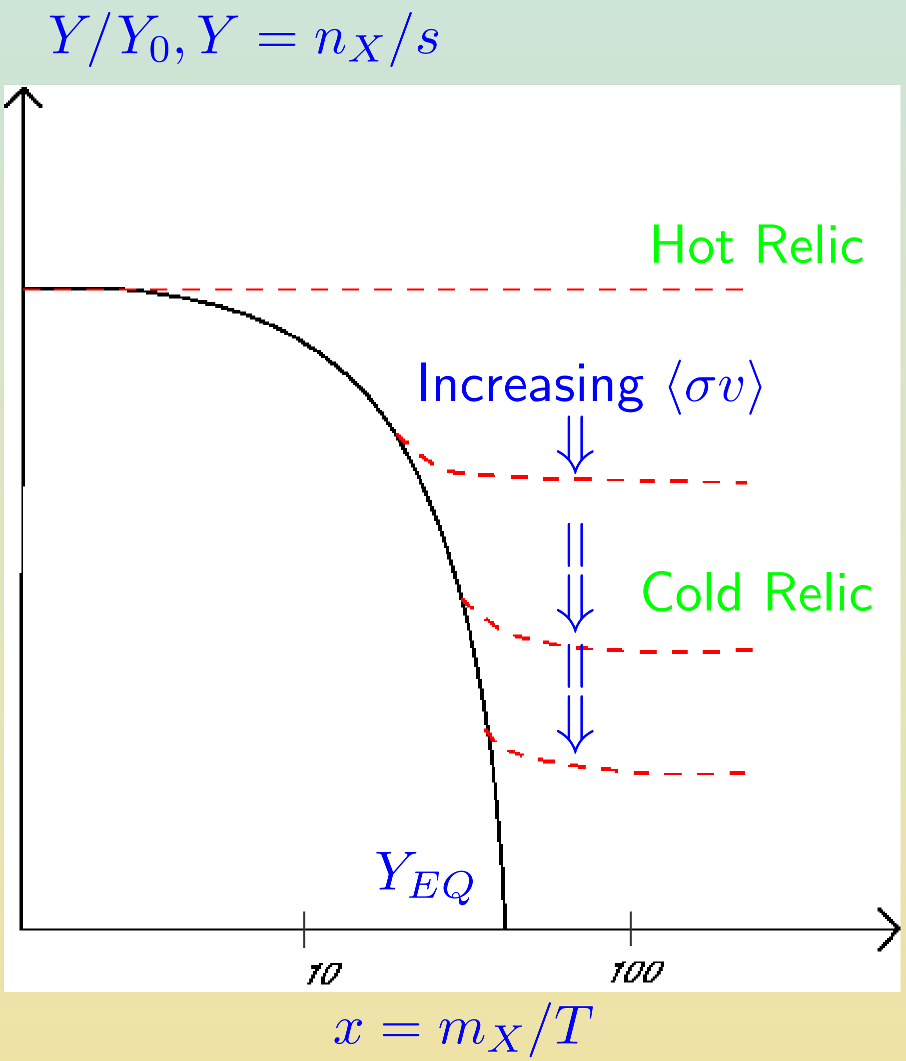
"What is Dark Matter"

Particle Dark Matter



- Standard Model neutrinos $\Omega_\nu h^2 = \sum \frac{m_i}{93 \text{ eV}} < 0.022$ (WMAP)
- WIMP(Weak Interacting Massive Particle) is strongly favored
- Freeze-out of a massive particles $\Omega_X = m_X n_X \sim \frac{10^9 GeV^{-1} x_f}{g_*^{1/2} M_P \langle \sigma_A v \rangle}$
- Beyond Standard Model

Supersymmetry

- Standard Model particles are doubled by superpartners
- LSP(Lightest Supersymmetric Particle) is stable with R-parity and a good candidate for Dark Matter
- Which is LSP?

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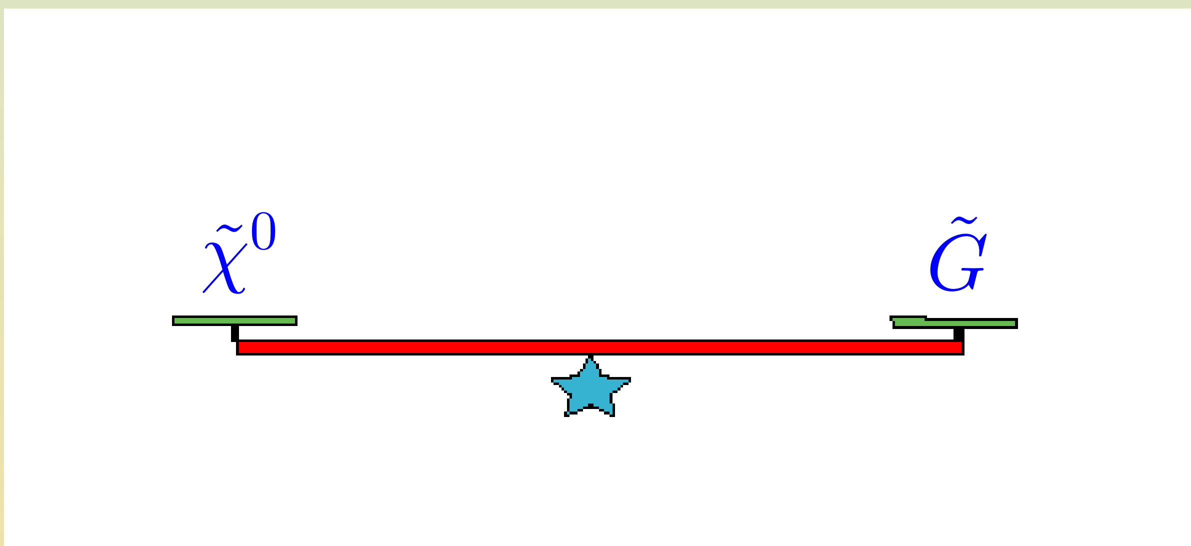


Gravitino Problem

$T_R > T_f$

- Primordial Gravitino
- Freeze-out from thermal eq.

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

- unstable : $m_{\tilde{G}} \gtrsim 10$ TeV
- stable : $m_{\tilde{G}} \lesssim 1$ keV
  or Gravitino dilution

$T_R < T_f$

- Diluted out by inflation
- Reproduced by thermal scatterings

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

- unstable : $T_R \lesssim 10^8$ GeV from BBN
- stable : $T_R \lesssim 10^{10}$ GeV from $\Omega_{tot} < 1$

Gravitino LSP in the CMSSM

Constrained MSSM

At M_{GUT}

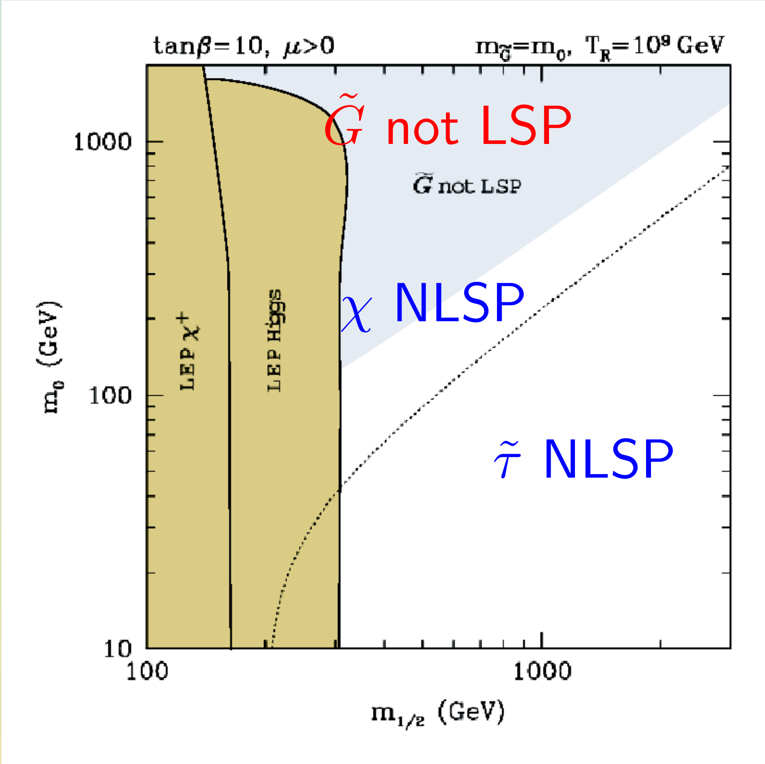
- gauginos $M_1 = M_2 = M_3 = m_{1/2}$
- scalars
  $m_{\tilde{q}}^2 = m_{\tilde{l}}^2 = m_{H_b}^2 = m_{H_t}^2 = m_0^2$
- trilinear soft terms $A_b = A_t = A_0$
- radiative EWSB
- five independent parameters:
  $\tan\beta, m_{1/2}, m_0, A_0, sgn(\mu)$

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

Experimental constraints

- $m_{\chi^\pm} > 104$ 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

- Thermal production: from thermal scattering,

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

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

- Non-thermal production: from the decay of NLSP ($\tau \sim 1 - 10^8 sec$)

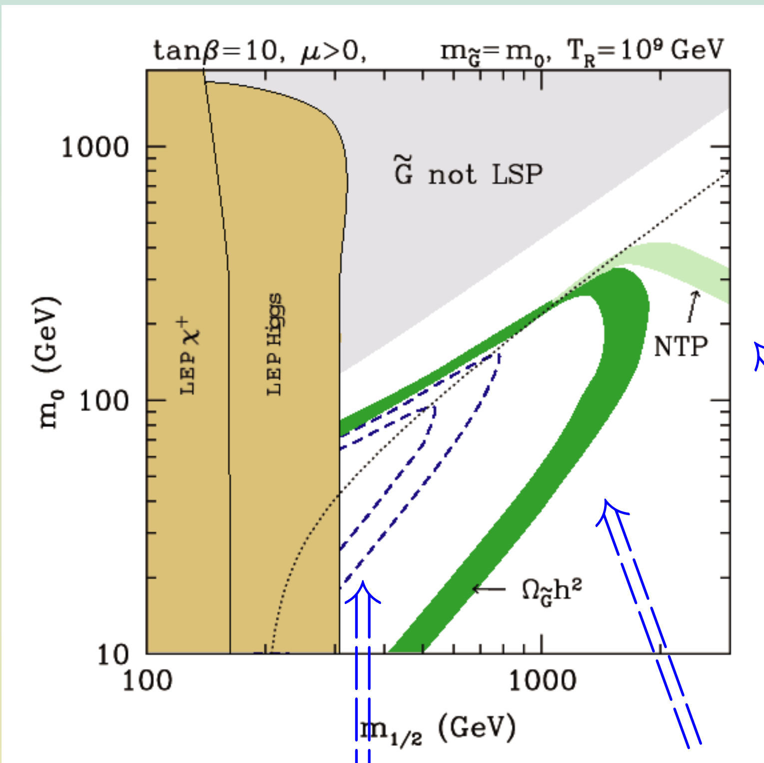
$$\boxed{\Omega_{\tilde{G}}^{NTP} h^2 = \frac{m_{\tilde{G}}}{m_{NLSP}} \Omega_{NLSP} h^2}$$

- Total Gravitino relic abundance

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

Gravitino Relic abundance

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



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

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

(WMAP)

small T_R

$T_R = 10^9$ GeV

$T_R = 5 \times 10^9$ GeV

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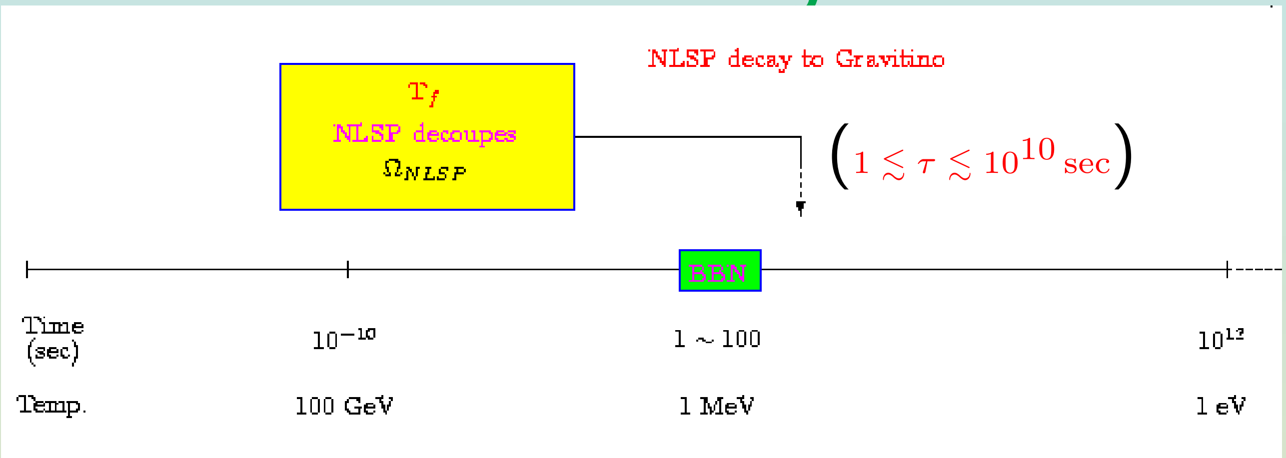
NLSP decay



- NLSP decay produces photons and hadrons with high energy

χ NLSP

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

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

$\Rightarrow$ had showers

$\tilde{\tau}$ NLSP

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

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

$\Rightarrow$ had showers

- Late time decay due to gravitational interaction: $1 \sim 10^{10}\,\mathrm{sec}$

- 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

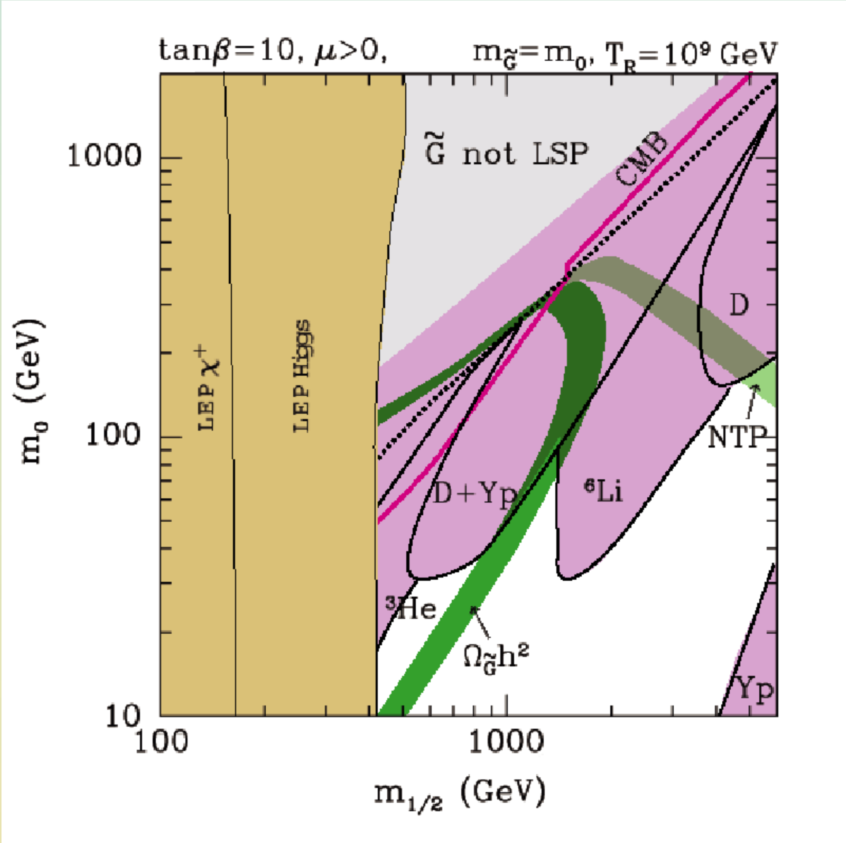
BBN constraints
conservative observational limit

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

CMB constraints
dimensionless chemical potential μ

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

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

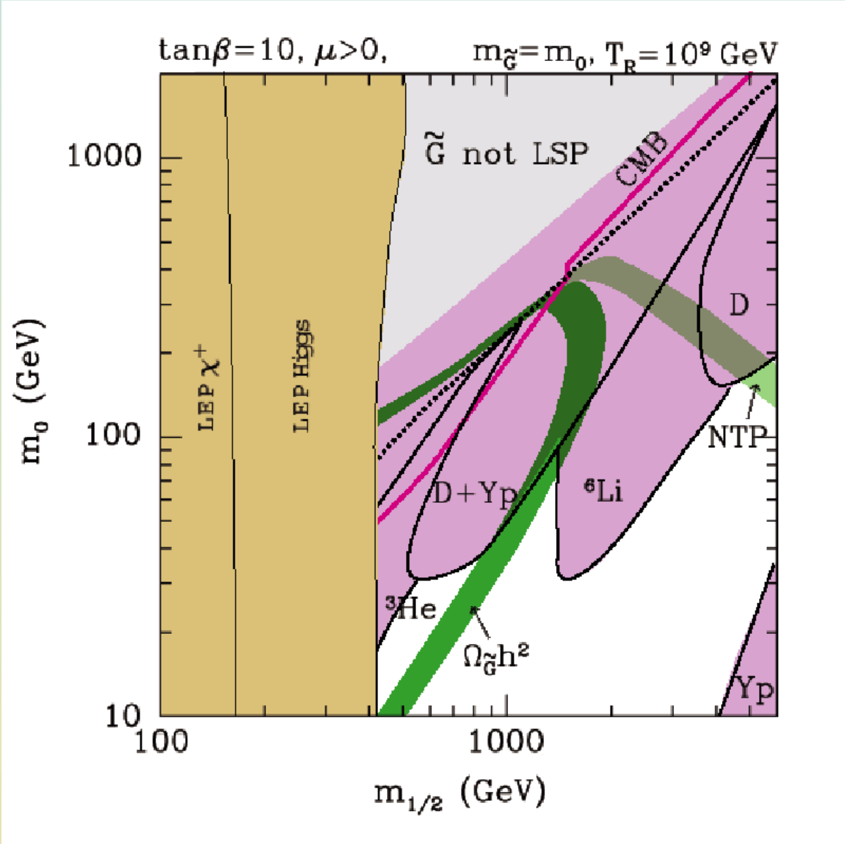


D/H+Y_p+^{7}Li/H+^{3}He/D+^{6}Li/^{7}Li

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
- 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

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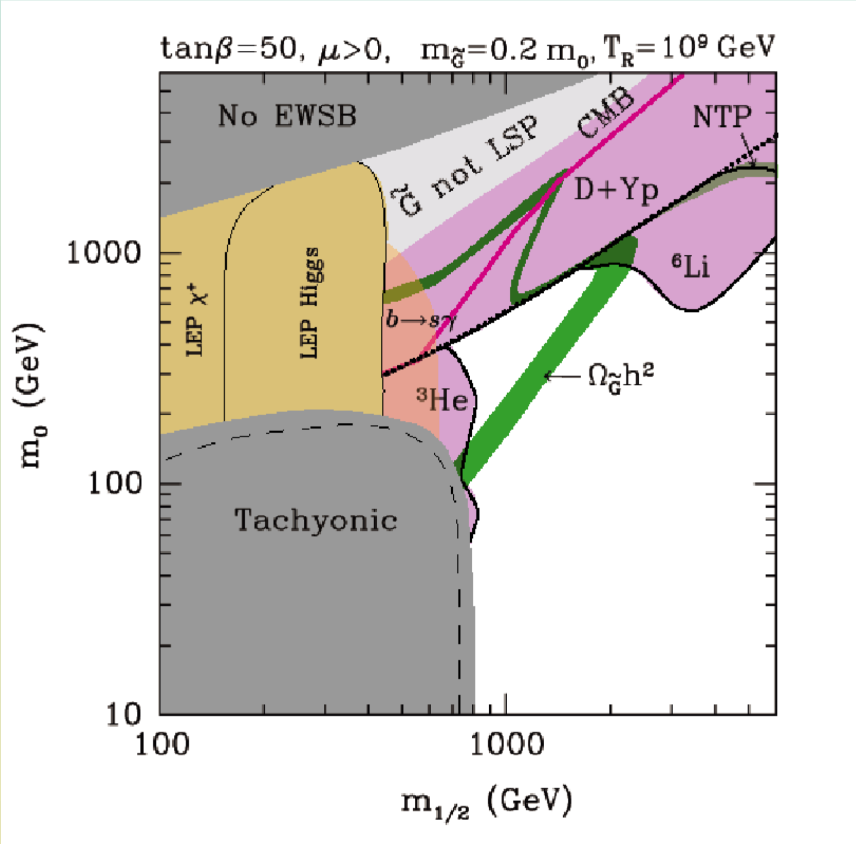
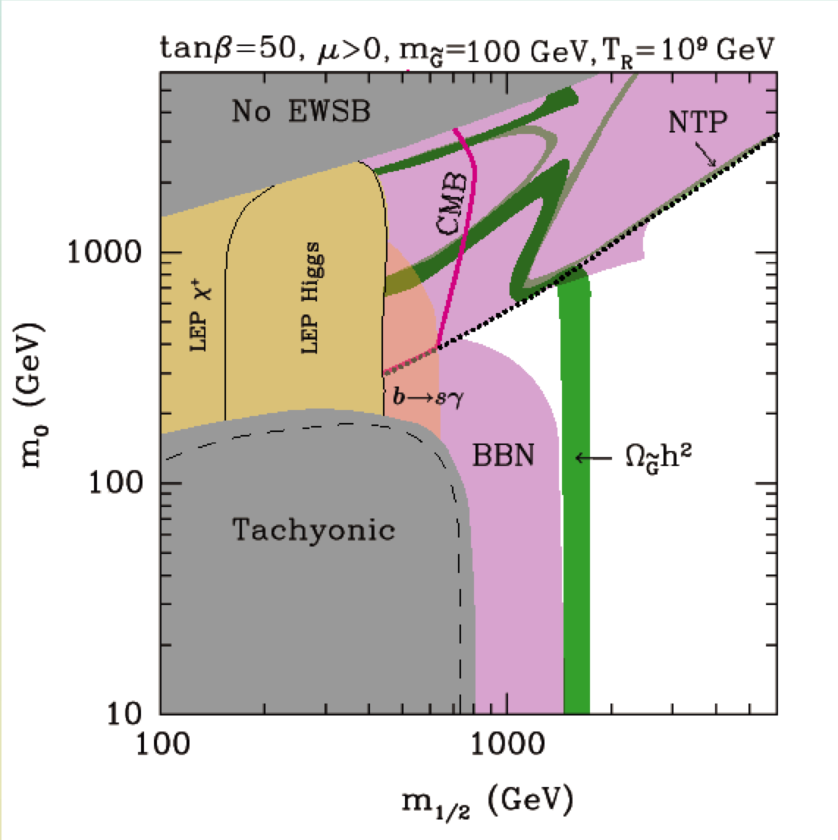
BBN constraints

$m_{\tilde{G}} = 0.2m_0,\ T_R = 10^9$ GeV



$m_{\tilde{G}} = 100\ GeV,\ T_R = 10^9$ GeV



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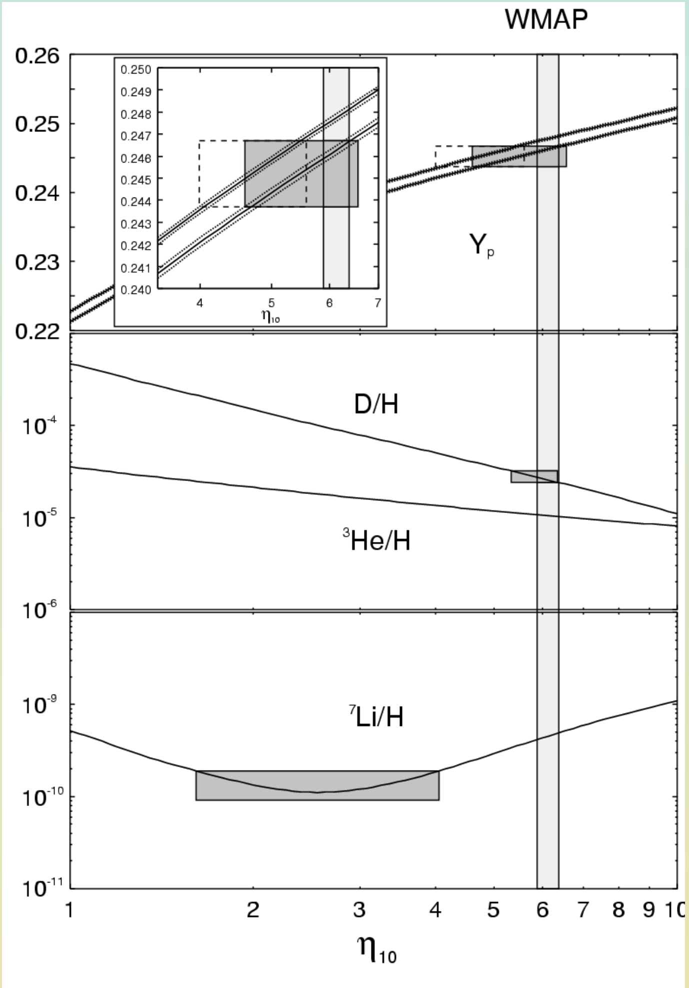
Cosmic Lithium Problems



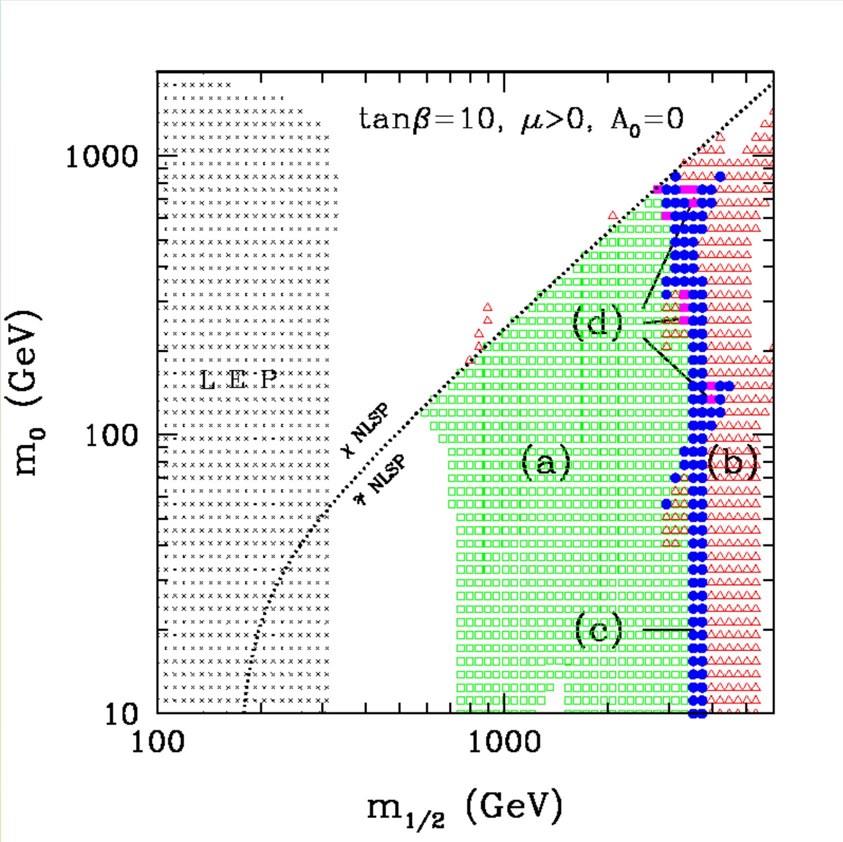
Mathews et al., PRD (2005)

$$\eta_{10} = n_B/n_\gamma \times 10^{10}$$

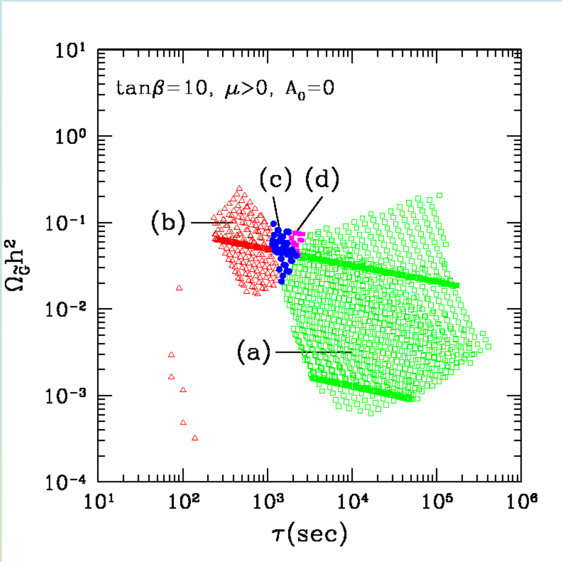
- Standard BBN predicts factor 2-3 more ^{7}Li than observed at low [Z]
- Standard BBN synthesize ^{6}Li around ^{6}Li/H $\sim 10^{-14} - 10^{-13}$
  1-2 orders below than observed

Cosmic Lithium Problems and Gravitino

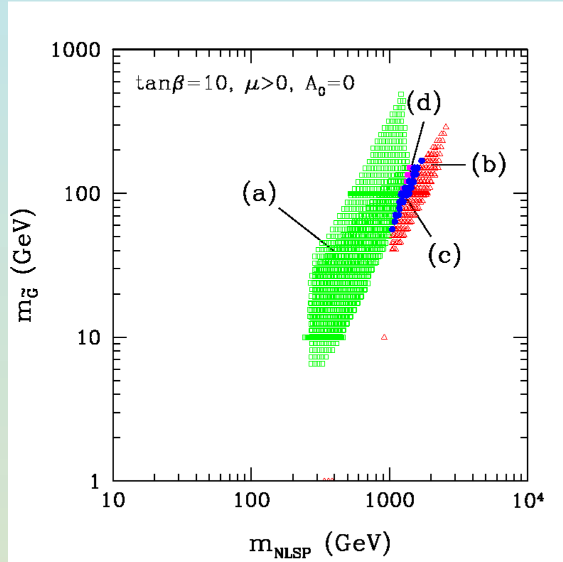
- Relic particle decay destruct ^{7}Li and produce ^{6}Li
- ^{7}Li overproduced, ^{6}Li solved
- ^{7}Li solved, ^{6}Li underproduced
- ^{7}Li solved, ^{6}Li solved



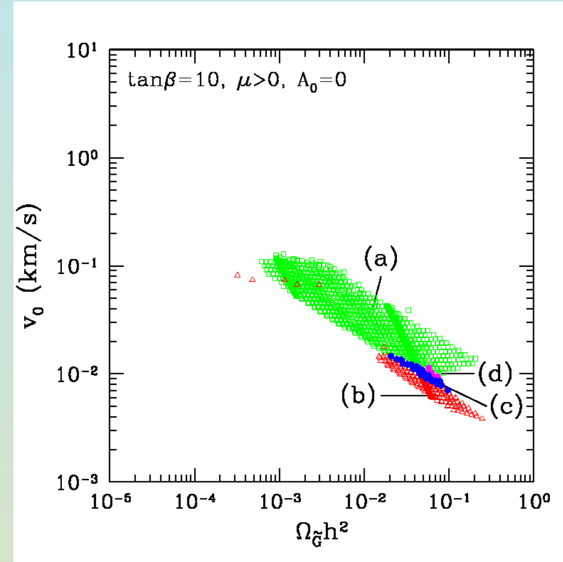
K.Jedamzik, K-Y Choi, L.Roszkowski, R.Ruiz de Austri, (2005)



$\Omega_{\tilde{G}}h^2 - \tau_{NLSP}$



$m_{\tilde{G}} - m_{NLSP}$



$v_0 - \Omega_{\tilde{G}}h^2$

K.Jedamzik, K-Y Choi, L.Roszkowski, R.Ruiz de Austri, (2005)

$\Omega_{\tilde{G}}h^2 \sim 0.01 - 0.1$, $\tau_{NLSP} \sim 10^3$ sec

$m_{NLSP} \sim 1$ TeV, $m_{\tilde{G}} \sim 100$ GeV

$v_0 \sim 10^{-2}$ km/sec

free streaming velocity at present $\lesssim 0.1$ from matter power spectrum Jedamzik et al., (2005)

Vacuum structure of the Universe

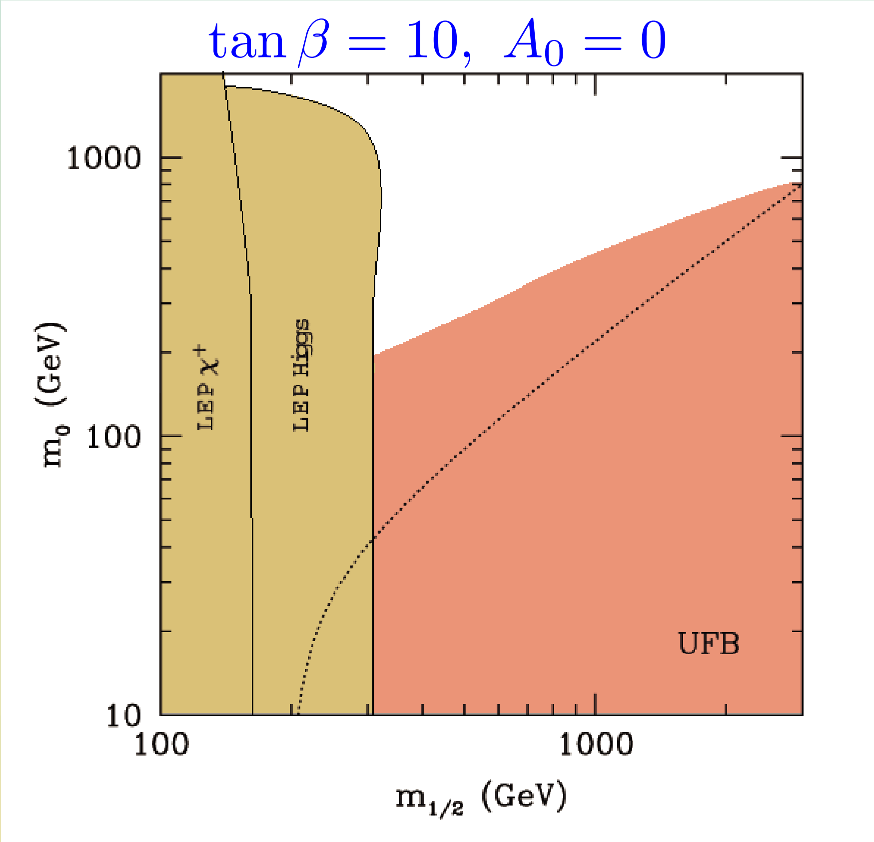
- charge and/or color breaking (CCB) minima

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

- We live in a meta-stable state!



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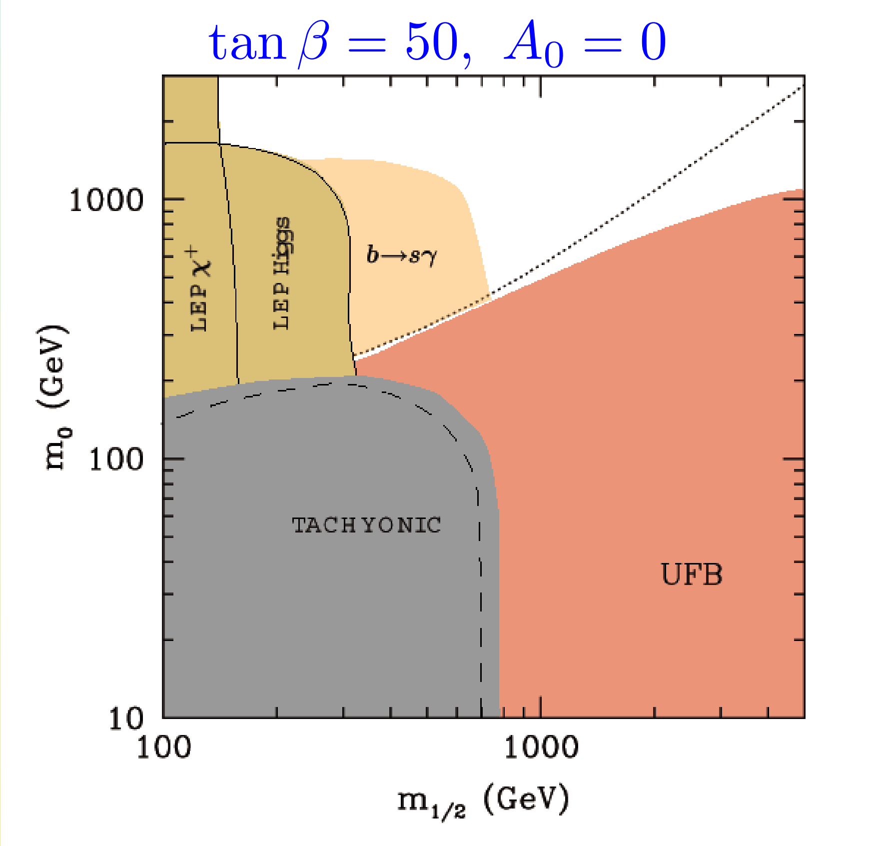

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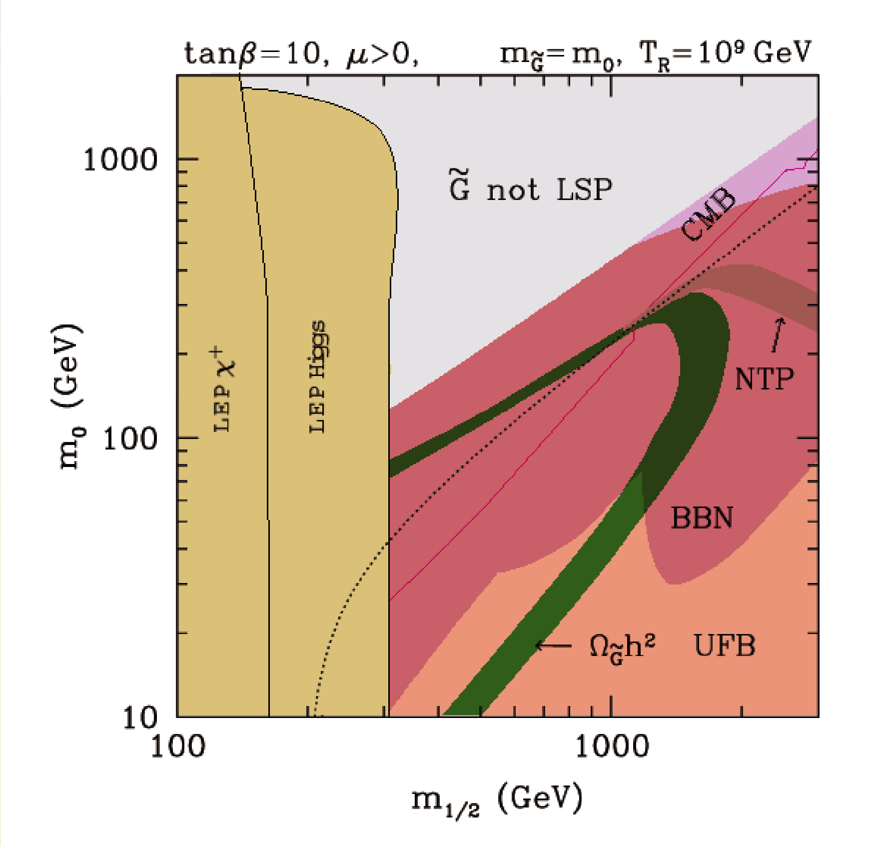


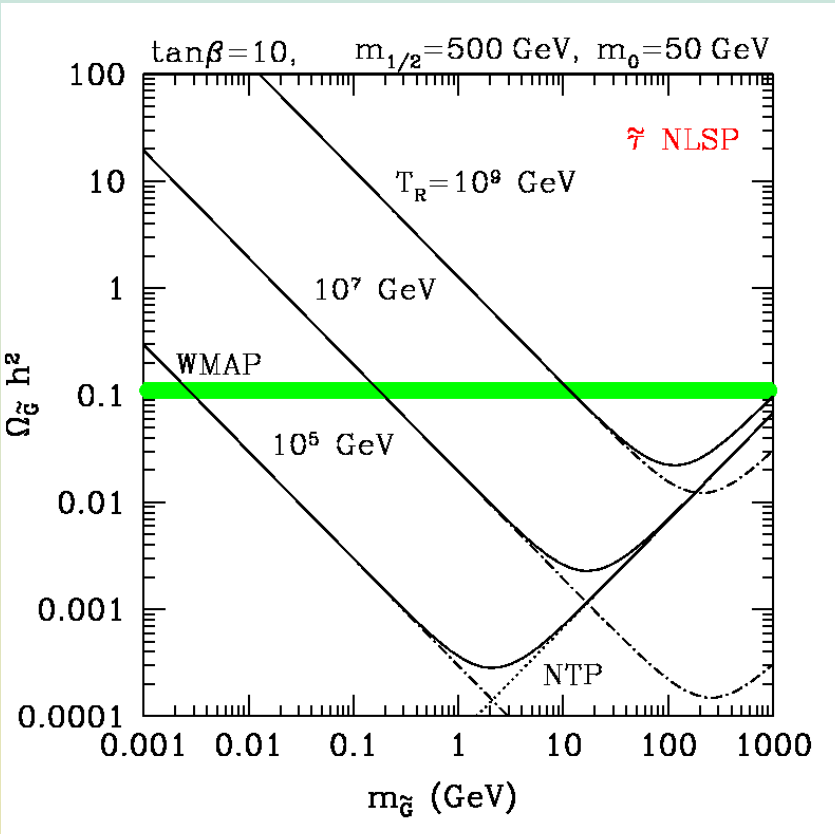
D.Cerdeño, K.Jedamzik, K-Y Choi, L.Roszkowski, R.Ruiz de Austri, (2005)

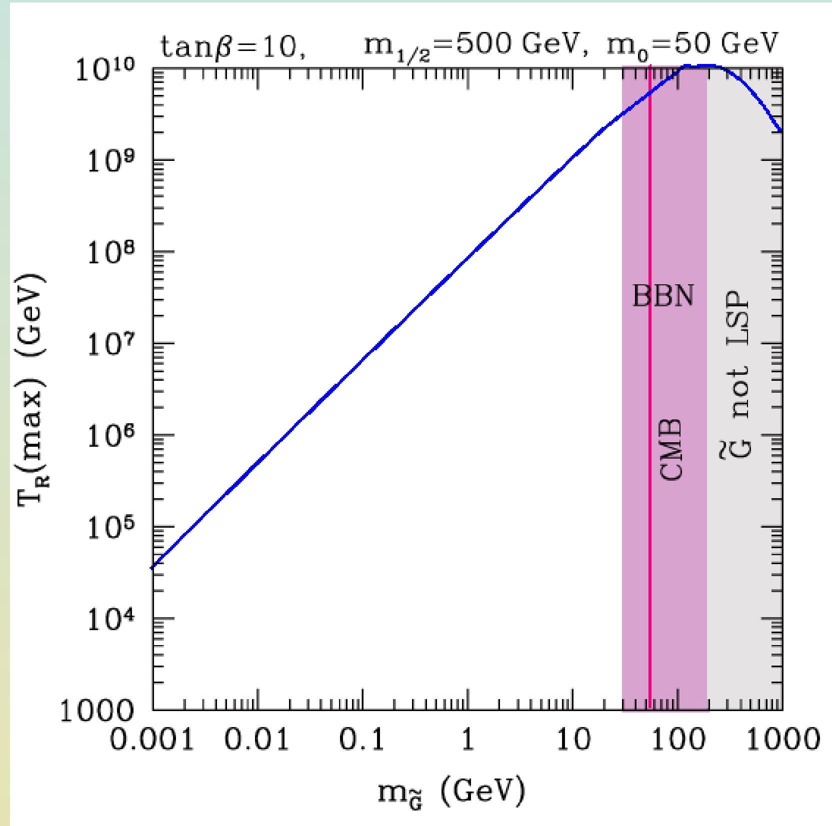
Summary

- Gravitino can be a good candidate for Dark Matter
- Neutralino NLSP and O(100)GeV Gravitino LSP is disfavored by BBN
- Stau NLSP and Gravitino LSP is a possible combination in CMSSM
- Both Lithium problems can be solved simultaneously by the decay of a stau relic 1000 sec after the Big Bang
- Stau NLSP indicate a hint about the vacuum structure of our Universe

Constraint on Reheating Temperature

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





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

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

D.Cerdeño, K.Jedamzik, K-Y Choi, L.Roszkowski, R.Ruiz de Austri, (2005)

Contents of present Unverse

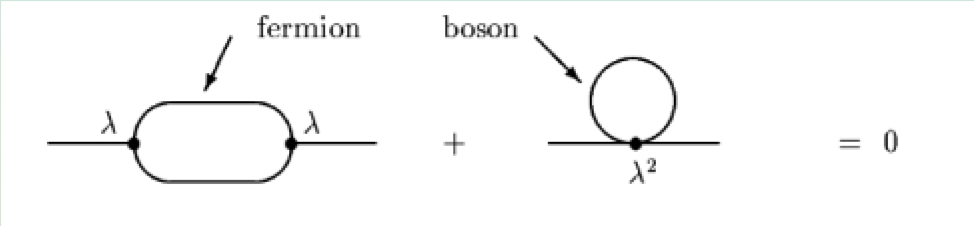
WMAP data with other CMB experiments (ACBAR and CBI), 2dFGRAS measurements, and Lyα forest data determines the best-fit cosmological parameters[Spergel et.al, (2003)]:

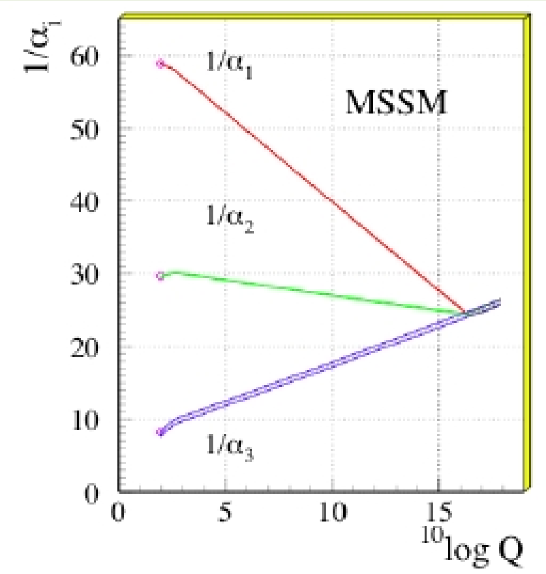
$$\Omega_{tot} = \Omega_\Lambda + \Omega_m + \cdots = 1.02 \pm 0.02 \text{ (Flat Universe)}$$

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

Supersymmetry

- Extends SM with superpartners
- Solves hierarchy problem
- Gauge coupling unification
- Radiative EW symmetry breaki
- Possible new source for CP and flavor
- Lightest Supersymmetric Particle: non-baryonic dark matter candida-te
- Neutralino





Gravitino Problem

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

$\Omega_{\tilde{G}} \equiv \frac{\rho_{\tilde{G}}}{\rho_c}$

- 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

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

T_R : Reheating temperature

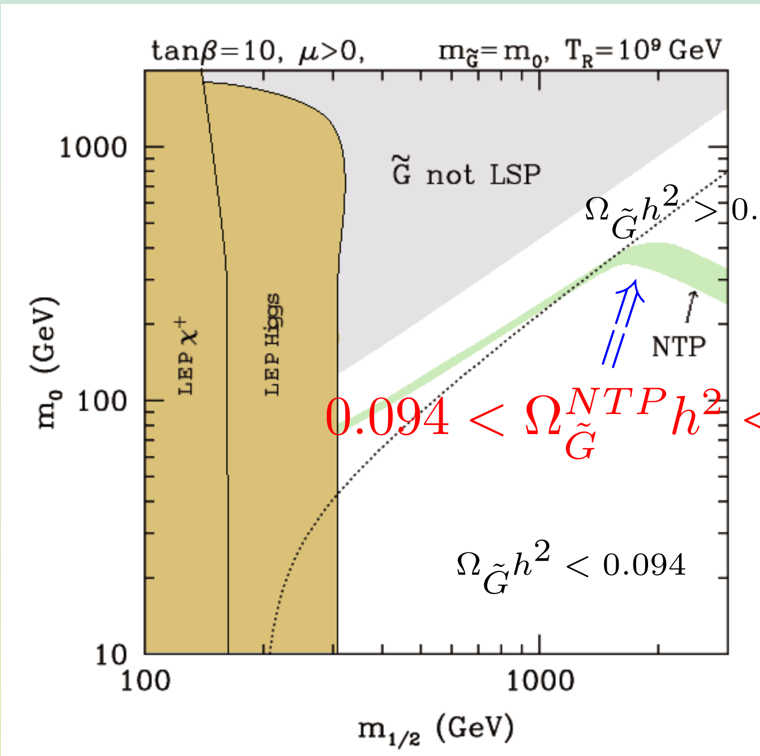
[Bolz,Brandenburg,Buchmüller, (2001)]

- 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 $\Omega_{tot} < 1$ $\Omega h^2 = 3.63 \times 10^9 \frac{m}{100\ \mathrm{GeV}} Y$

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

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

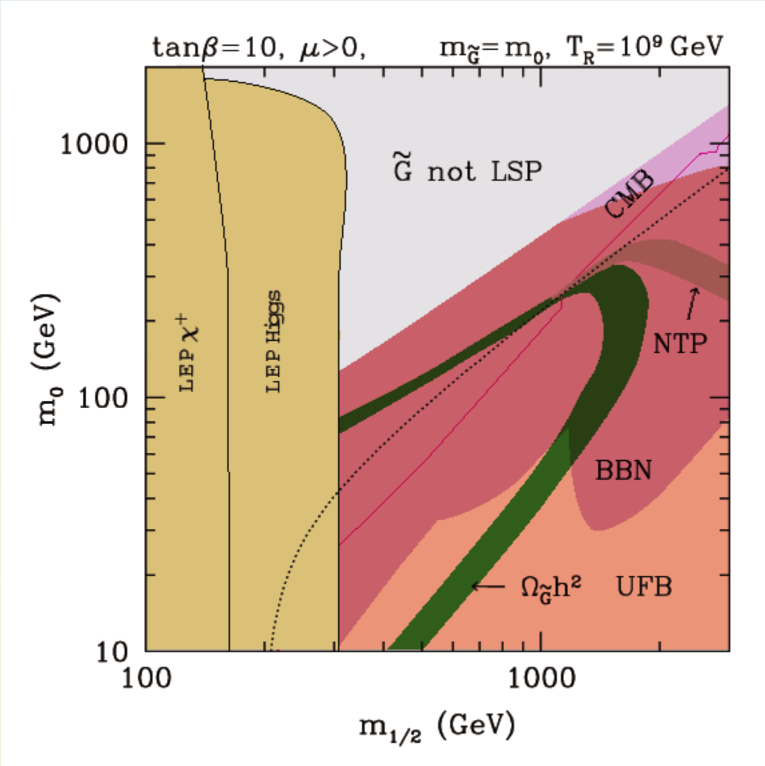
$\tilde{\tau} \longrightarrow \tilde{G}\tau Z, \tilde{G}\nu_\tau Ws, \tilde{G}\tau(\gamma^*/Z^*)q\bar{q}$

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

Combining UFB and BBN

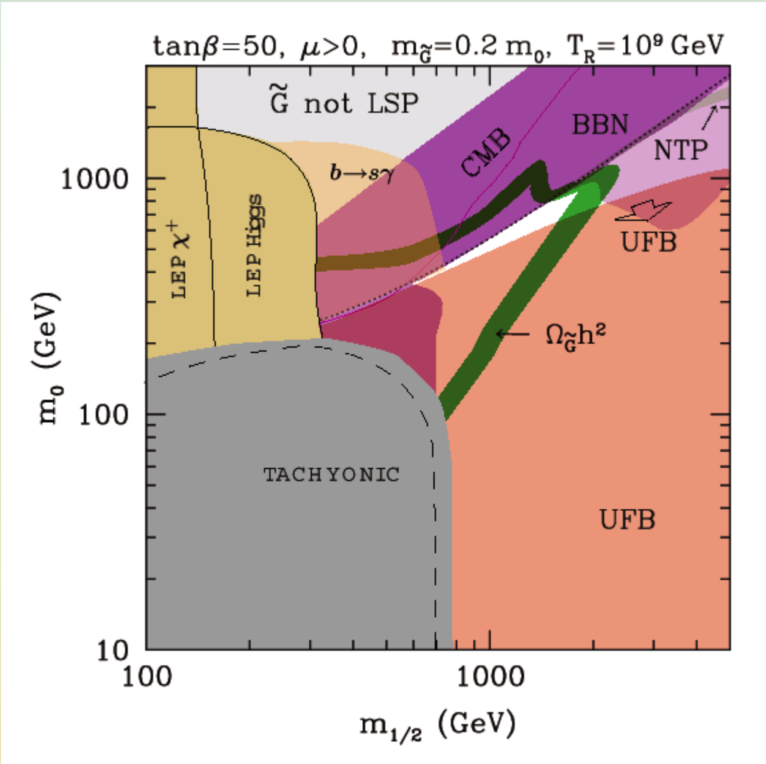
For $\mathrm{T_R} = 10^9$ GeV,

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



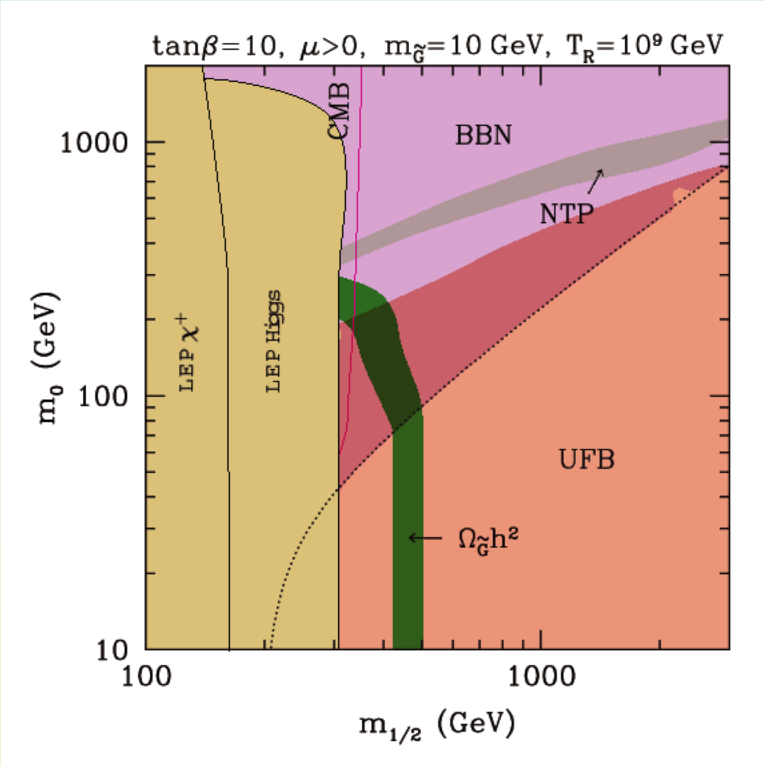
all excluded

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



small regions left allowed

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



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