Title: Gravitino Dark Matter and Cosmological Constraints with a stau NLSP

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Abstract:

Outline

- Thermal Gravitino Production
- Upper Bound on $T_{\rm R}$ from Thermal Production
- Gravitino Production from Decays
- Constraints from Big Bang Nucleosynthesis
- Constraints from Catalyzed Big Bang Nucleosynthesis
- Late-time Entropy Production
- Conclusion

From SUSY to SUGRA

QED:

$$S_0 = \int d^4x\, \overline{\psi}(x)\, i\gamma^\mu \partial_\mu\, \psi(x)$$

local gauge transformation:

$$\psi(x) \;\longrightarrow\; e^{i\alpha(x)}\psi(x)$$

action not invariant:

$$\delta S_0 \sim \int d^4x\, J^\mu(x)\partial_\mu \alpha(x)$$

with $J^\mu = \overline{\psi}(x)\gamma^\mu\psi(x)$.

photon $A_\mu(x)$: $\delta A_\mu(x) \sim \partial_\mu \alpha(x)$

$$S = S_0 + \int d^4x\, J^\mu(x) A_\mu(x)$$

invariant under *local* U(1) transf.!

SUGRA:

$S_0 =$ invariant under global SUSY

local SUSY transformation:

$$\Phi(y,\theta,\overline{\theta}) \;\longrightarrow\; e^{i(\overline{\varepsilon}(x)Q+\overline{Q}\varepsilon(x))}\Phi(y,\theta,\overline{\theta})e^{-i(\dots)}$$

action not invariant:

$$\delta S_0 \sim \int d^4x\, \overline{J}^\mu_r(x)\partial_\mu \varepsilon_r(x)$$

where J^μ_r is the supercurrent.

gravitino $\psi^\mu_r(x)$: $\delta\psi^\mu_r(x) \sim M_\mathrm{P}\partial_\mu\varepsilon_r(x)$

$$S = S_0 + \frac{1}{2M_\mathrm{P}}\int d^4x\, \overline{J}^\mu(x)\psi_\mu(x) + \dots$$

invariant under *local* SUSY transf.!

Properties of the Gravitino $\widetilde{G}$

→ $\widetilde{G}$ is the gauge field of *local* SUSY (=SUGRA) transformations

→ superpartner of graviton, spin $3/2$ Majorana field

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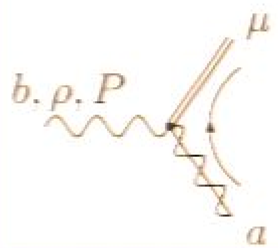
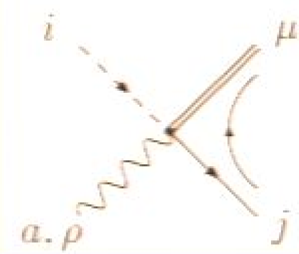
→ couplings fixed by the symmetry, e.g.

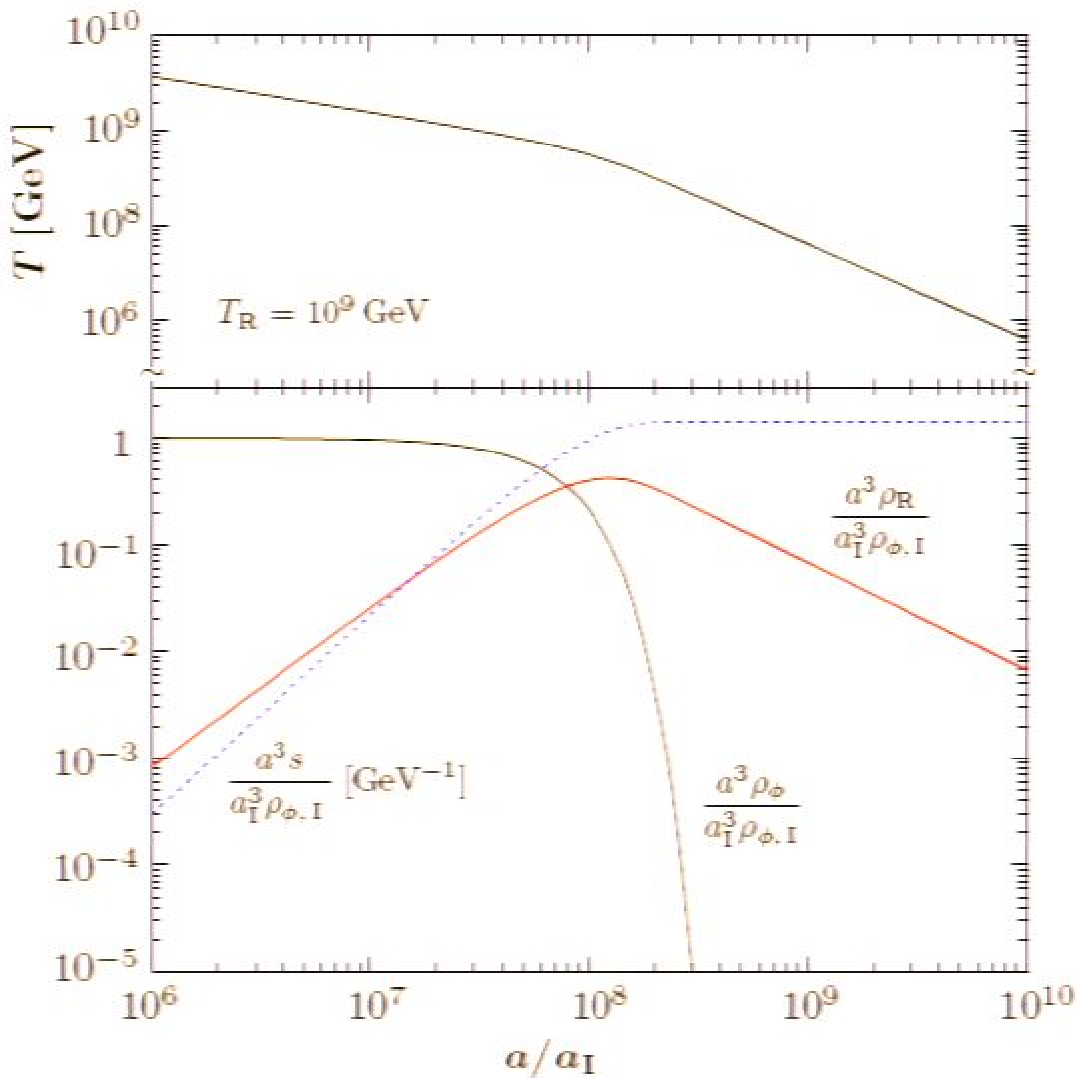


$-\frac{i}{4M_P}\delta_{ab}\left[\not{P},\gamma^{\rho}\right]\gamma^{\mu}$



$-\frac{ig_{\alpha}}{\sqrt{2}M_P}T^{(\alpha)}_{a,ji}P_R\gamma^{\rho}\gamma^{\mu}$

Reheating



- Inflaton decays

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

- Universe enters radiation dominated epoch

$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = \Gamma_\phi \rho_\phi$$

Thermal Gravitino Production - Framework

- End of Inflation

- Reheating
$T_{\rm R} \sim \mathcal{O}(10^6 - 10^{10})$ GeV
$\rightarrow$ thermal $\widetilde{G}$ production

~ 1 MeV BBN

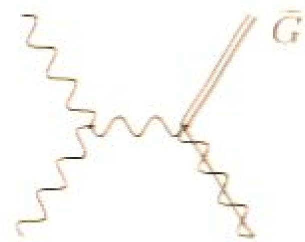
~ 0.3 eV CMB

- today

- time evolution of $\widetilde{G}$-density governed by the Boltzmann equation

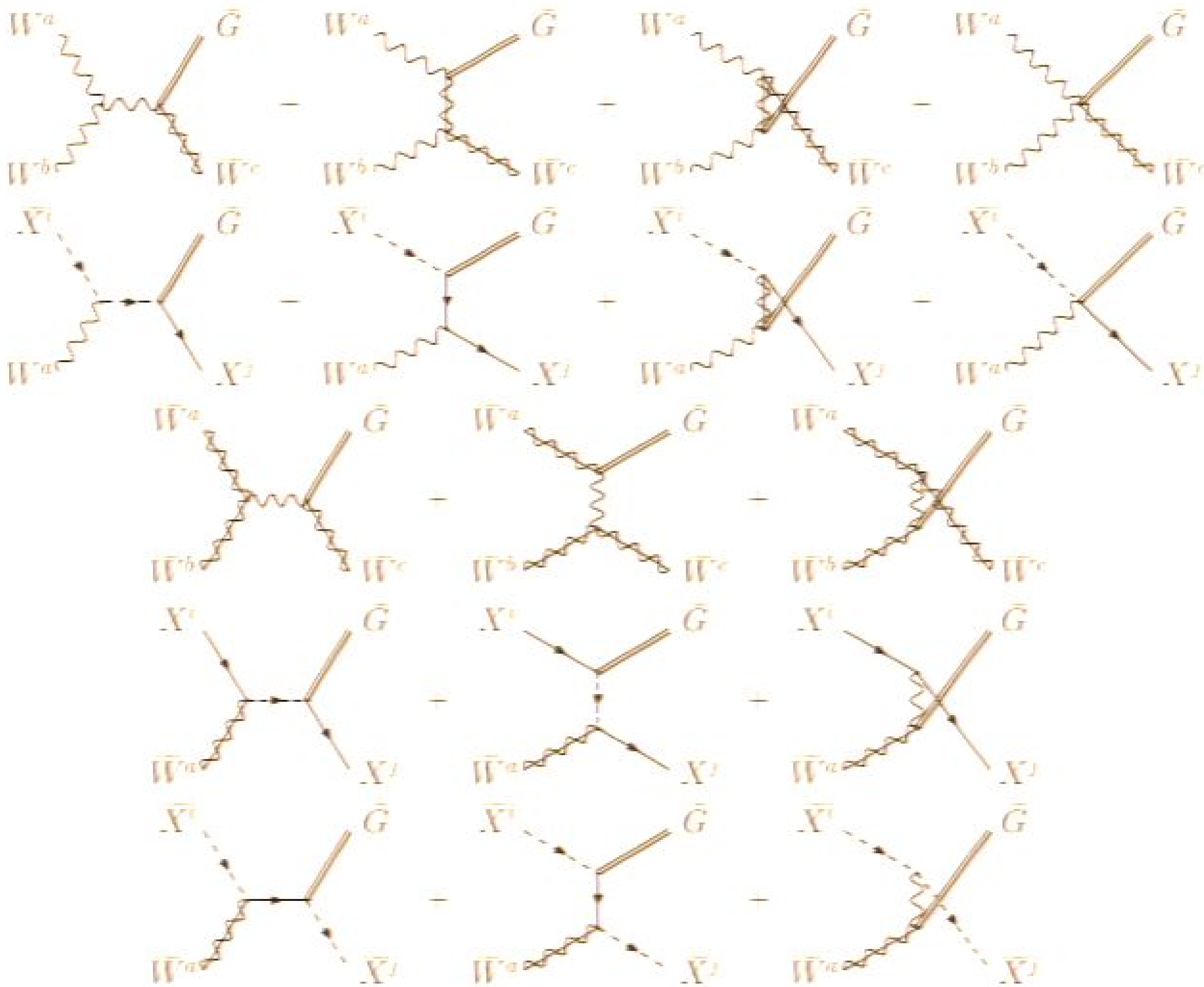
$$\frac{dn_{\widetilde{G}}}{dt} + 3Hn_{\widetilde{G}} = C_{\widetilde{G}}$$

- $C_{\widetilde{G}}$: $2 \rightarrow 2$ scatterings + finite T approach



$SU(2)_L$ Contributions

$$|\mathcal{M}_i|^2 = \frac{g_2^2}{M_P^2}\left(1+\frac{M_2^2}{3m_{\widetilde{G}}^2}\right)[\dots]$$



A: $\left[\left(4s+8t+8\frac{t^2}{s}\right)|\varepsilon^{abc}|^2\right]$

C: $\left[\frac{1}{2}s|\sigma_{(a)ij}|^2\right]$

F: $\left[-8\frac{(s^2+st+t^2)^2}{st(s+t)}|\varepsilon^{abc}|^2\right]$

G: $\left[\left(-s-\frac{s^2}{t}\right)|\sigma_{(a)ij}|^2\right]$

H: $\left[\left(-s-\frac{t}{2}-\frac{s^2}{t}\right)|\sigma_{(a)ij}|^2\right]$

+ crossings — in total 10 processes

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A:

C:

logarithmic singularity

→ regularized screening effects of the plasma

→ Hard Thermal Loop (HTL) resummed propagator

[Braaten, Pisarski, 1990]

F: $\left[-8\frac{(s^2+st+t^2)^2}{s\,t\,(s+t)}|\varepsilon^{abc}|^2\right]$

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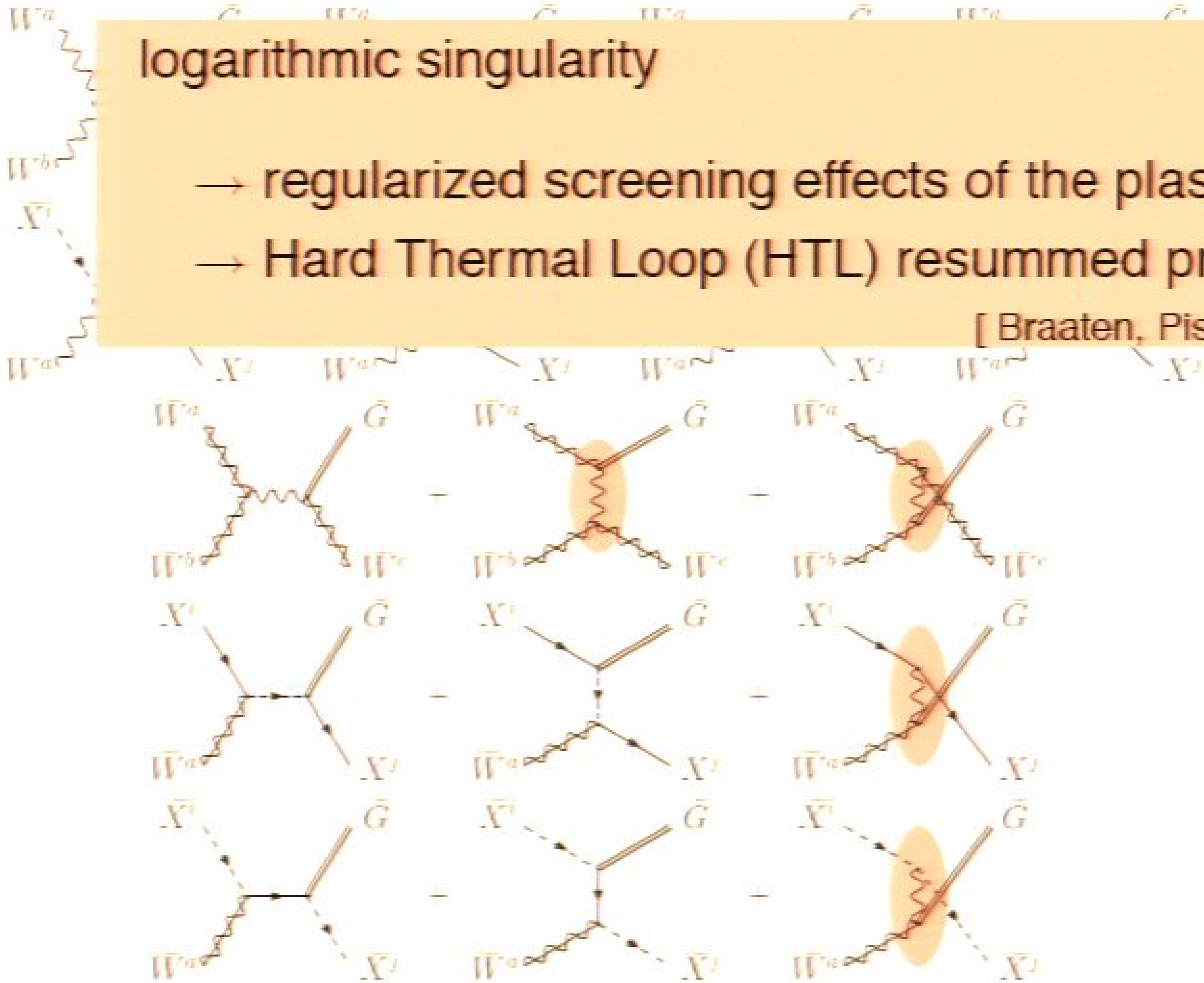

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Thermal Production Rate

[Braaten, Yuan, 1991]

seperate scales

$$\text{soft} \leftarrow gT \ll q^* \ll T \rightarrow \text{hard}$$

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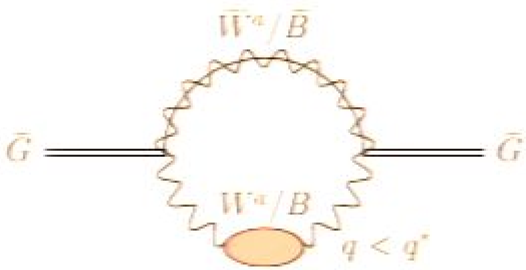
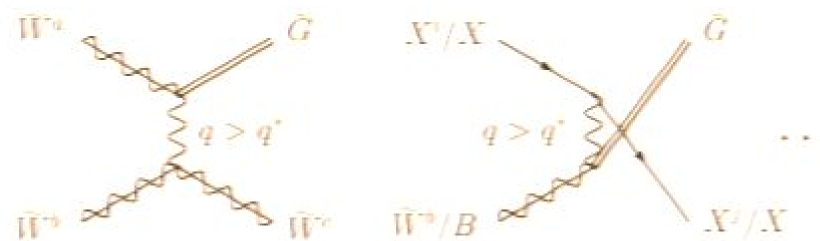
- Soft Part:



$$\Gamma_{\tilde{G}}^{\text{soft}}(E) = -\left.\frac{\text{Im}\Sigma_{\tilde{G}}(E + i\varepsilon, \boldsymbol{p})}{E}\right|_{|\boldsymbol{p}_1 - \boldsymbol{p}_3| < q^*}$$

$$= A_{\text{soft}} + B \ln\left(\frac{q^*}{m_{W/B}^{\text{therm}}}\right)$$

- Hard Part:



$$\Gamma_{\tilde{G}}^{\text{hard}}(E) = \int \ldots |\mathcal{M}|^2 \theta(|\boldsymbol{p}_1 - \boldsymbol{p}_3| - q^*)$$

$$= A_{\text{hard}} + B \ln\left(\frac{T}{q^*}\right)$$

Thermal Production Rate

[Braaten, Yuan, 1991]

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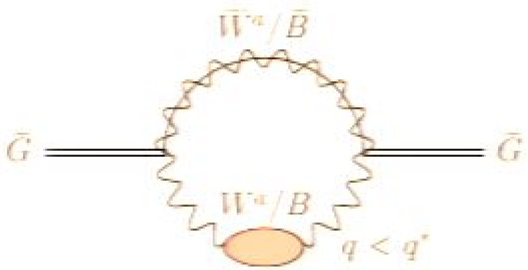

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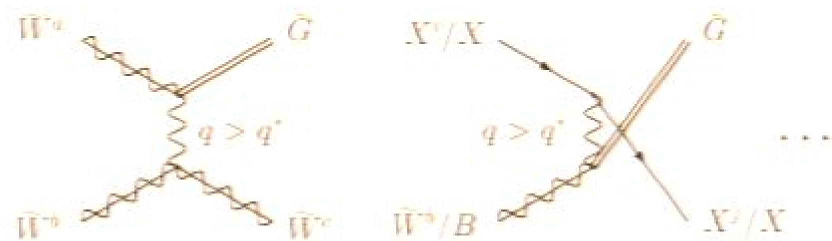

$$C_{\tilde{G}}(T) = \int \frac{d^3\mathbf{p}}{(2\pi)^3} f_F(E) \left[\Gamma^{\text{soft}}_{\tilde{G}}(E) + \Gamma^{\text{hard}}_{\tilde{G}}(E) \right]$$

$$= \int \frac{d^3\mathbf{p}}{(2\pi)^3} f_F(E) \left[A_{\text{soft}} + A_{\text{hard}} + B \ln\left(\frac{1}{g}\right) \right]$$

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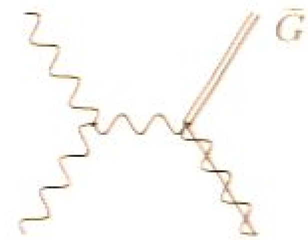

$$C_{\widetilde{G}} = \sum_{i=1}^{3} \frac{3\zeta(3)T^6}{16\pi^3 M_\mathrm{P}^2} \left(1 + \frac{M_i^2}{3m_{\widetilde{G}}^2}\right) c_i\, g_i^2 \ln\left(\frac{k_i}{g_i}\right)$$

[Bolz, Brandenburg, Buchmüller, 2001]

[JP, Steffen, 2006]

(see also [Rychkov, Strumia, 2007])

→ solve Boltzmann equation in terms of the Yield: $Y_{\widetilde{G}}^{\rm TP} \equiv \frac{n_{\widetilde{G}}}{s}$

$$Y_{\widetilde{G}}^{\rm TP} = \sum_{i=1}^{3} y_i\, g_i^2(T_{\rm R}) \left(1 + \frac{M_i^2(T_{\rm R})}{3 m_{\widetilde{G}}^2}\right) \ln\left(\frac{k_i}{g_i(T_{\rm R})}\right) \left(\frac{T_{\rm R}}{10^{10}\,\mathrm{GeV}}\right)$$

Gravitino Dark Matter

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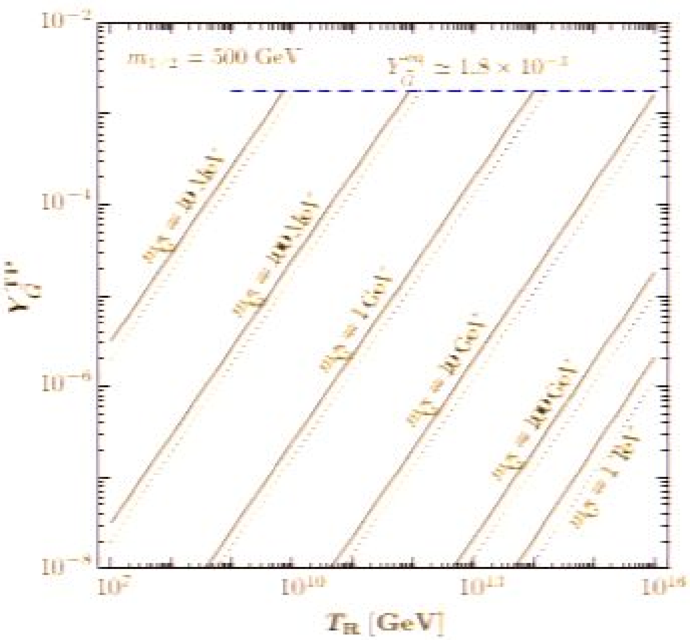

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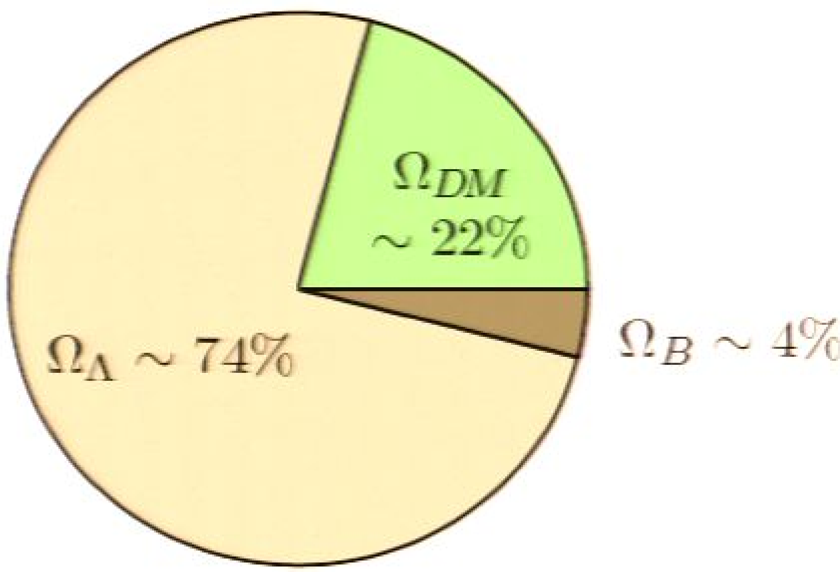
Assume

- $\widetilde{G}$ lightest SUSY particle (LSP)
- R-Parity conservation

$\longrightarrow$ $\widetilde{G}$ stable and can be dark matter



Upper Limit on T_{R} from Thermal Production

relic $\widetilde{G}$ density:

$$\Omega_{\widetilde{G}}^{\mathrm{TP}} = m_{\widetilde{G}} \, Y_{\widetilde{G}}^{\mathrm{TP}} \, s \big/ \rho_c$$

observed DM abundance:

$$\Omega_{\mathrm{dm}}^{3\sigma} h^2 = 0.105^{+0.021}_{-0.030}$$

$\rightarrow$ upper limit on T_{R}:

$$\Omega_{\widetilde{G}}^{\mathrm{TP}} h^2 \leq 0.126$$

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$T_{\mathrm{R}} \ldots$ reheating temperature $\quad m_{\widetilde{G}} \ldots$ gravitino mass

$M_i \ldots$ gaugino masses $\quad y_i \ldots \mathcal{O}(10^{-12}) \quad i = 3, 2, 1 \ldots \mathrm{SU}(3)_{\mathrm{c}}, \mathrm{SU}(2)_{\mathrm{L}}, \mathrm{U}(1)_{\mathrm{Y}}$

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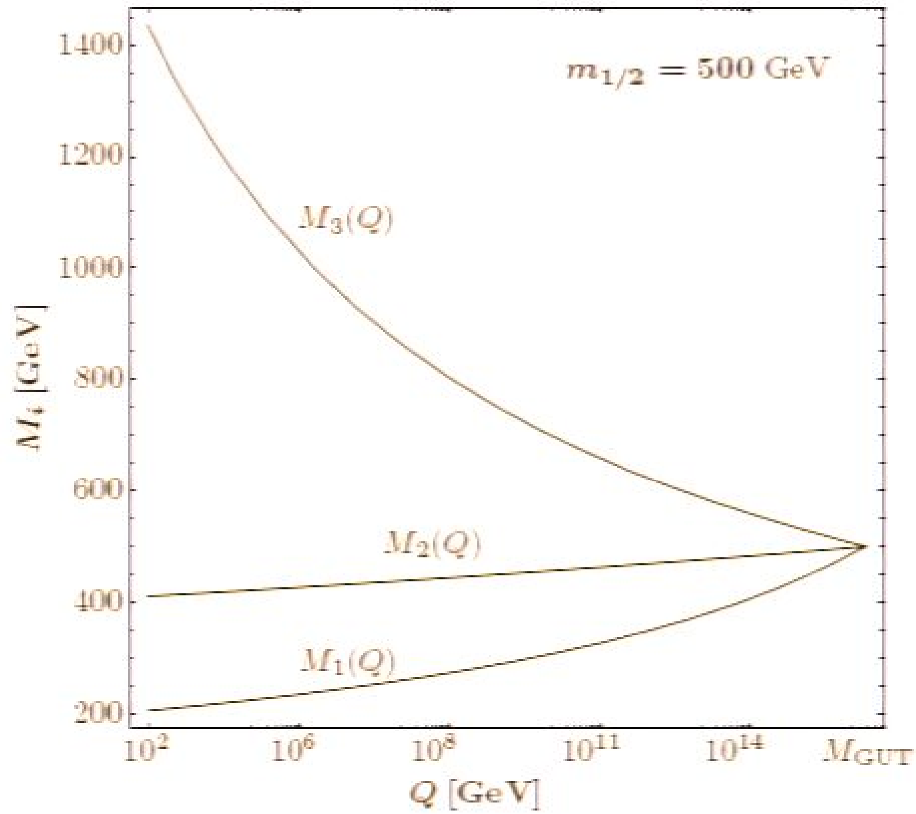

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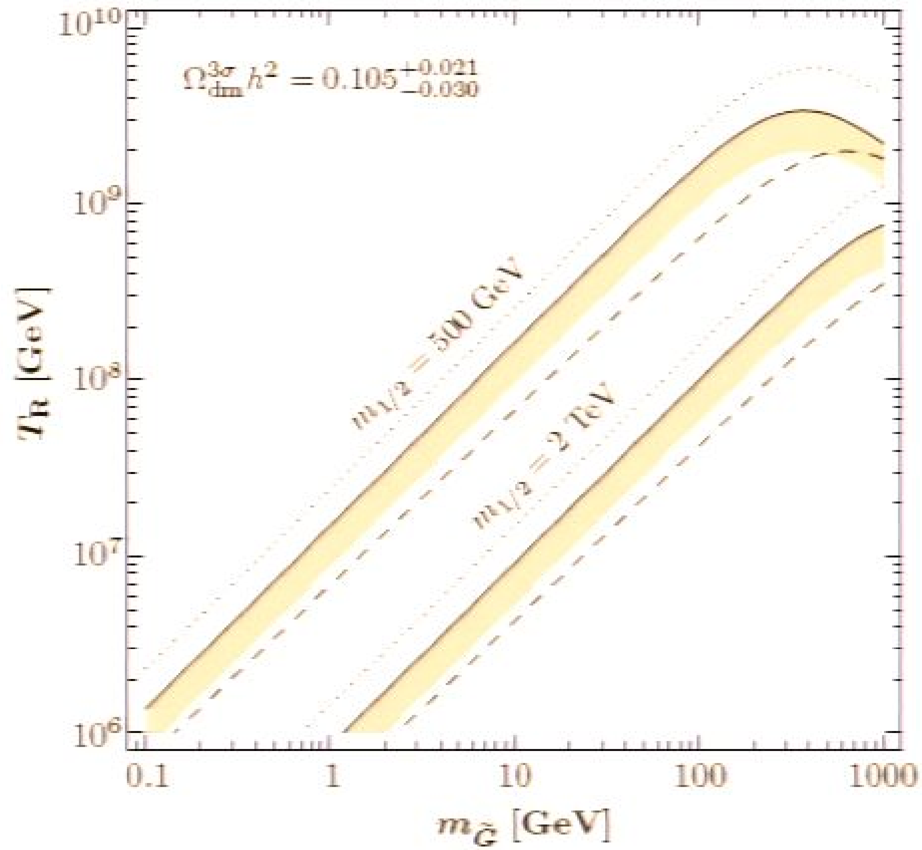

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Gravitino Production from Decays: NLSP $\rightarrow \widetilde{G} +$ SM

- $\widetilde{G}$ LSP $\rightarrow$ lightest MSSM particle (NLSP) unstable

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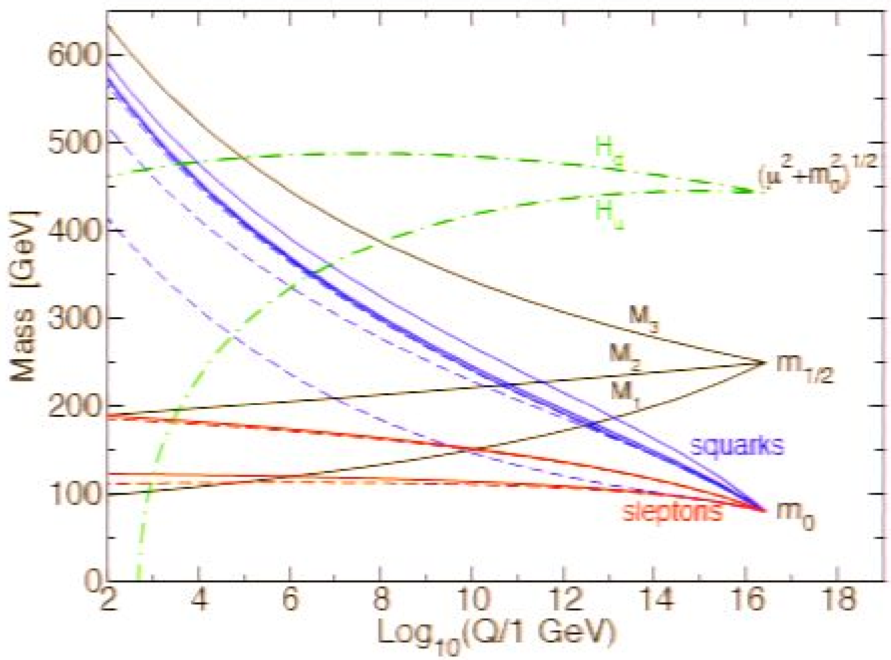

systematic study of Ω_{NLSP}

$\rightarrow$ Constrained-MSSM

- $m_{1/2}$ ... universal gaugino mass
- m_0 ... universal scalar mass
- A_0 ... universal trilinear scalar interaction
- $\tan\beta$ ... ratio of the Higgs vev's
- $\mathrm{sgn}\,\mu$ ... sign of the higgsino parameter

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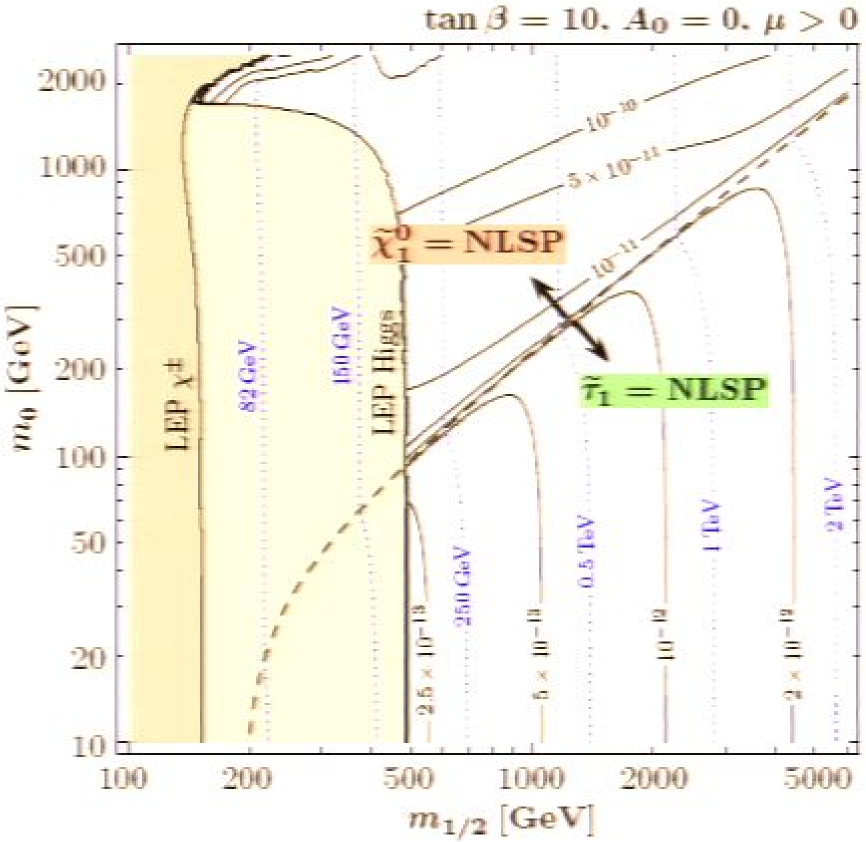

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Constraints on T_{R} in the CMSSM

$$0.075 \leq (\Omega_{\tilde{G}}^{\mathrm{TP}} + \Omega_{\tilde{G}}^{\mathrm{NTP}})h^2 \leq 0.126$$

→ 2 more parameters: $m_{\tilde{G}}$ & T_{R}

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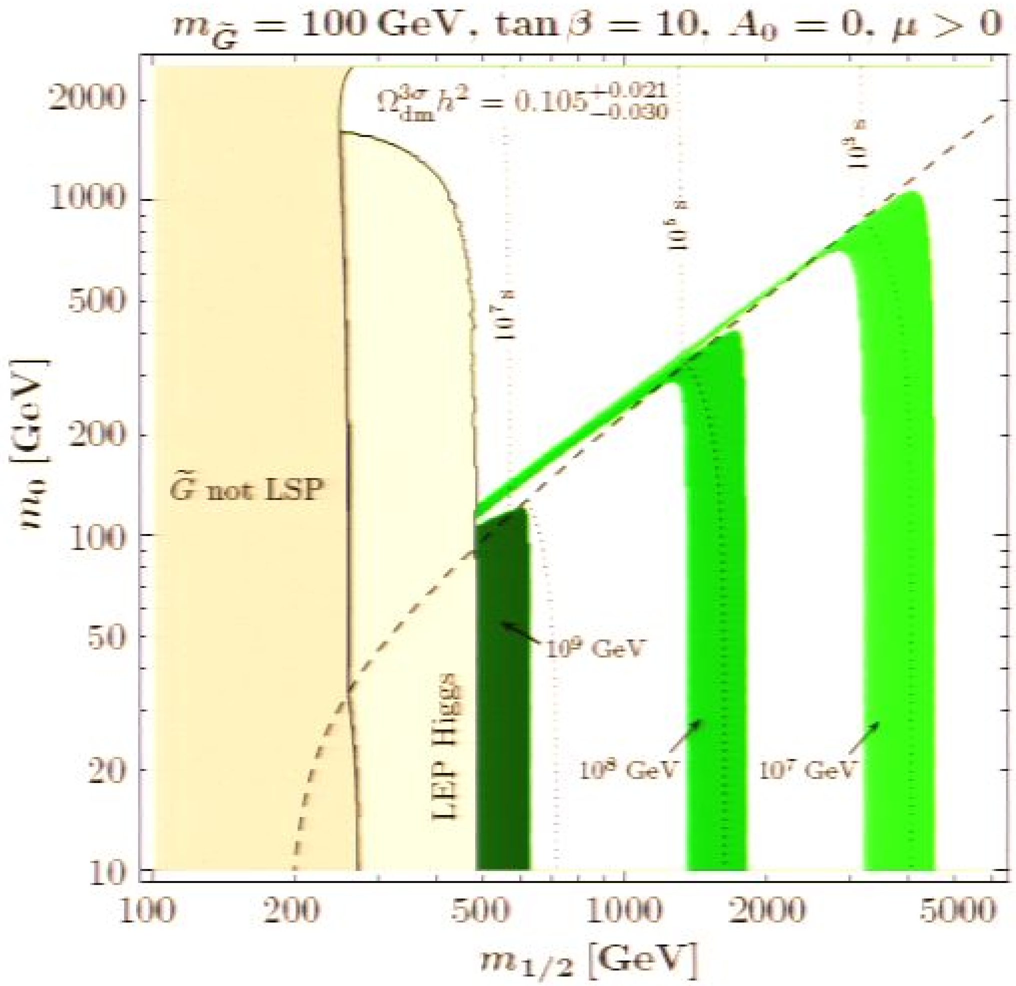
$m_{\tilde{G}} = 100$ GeV



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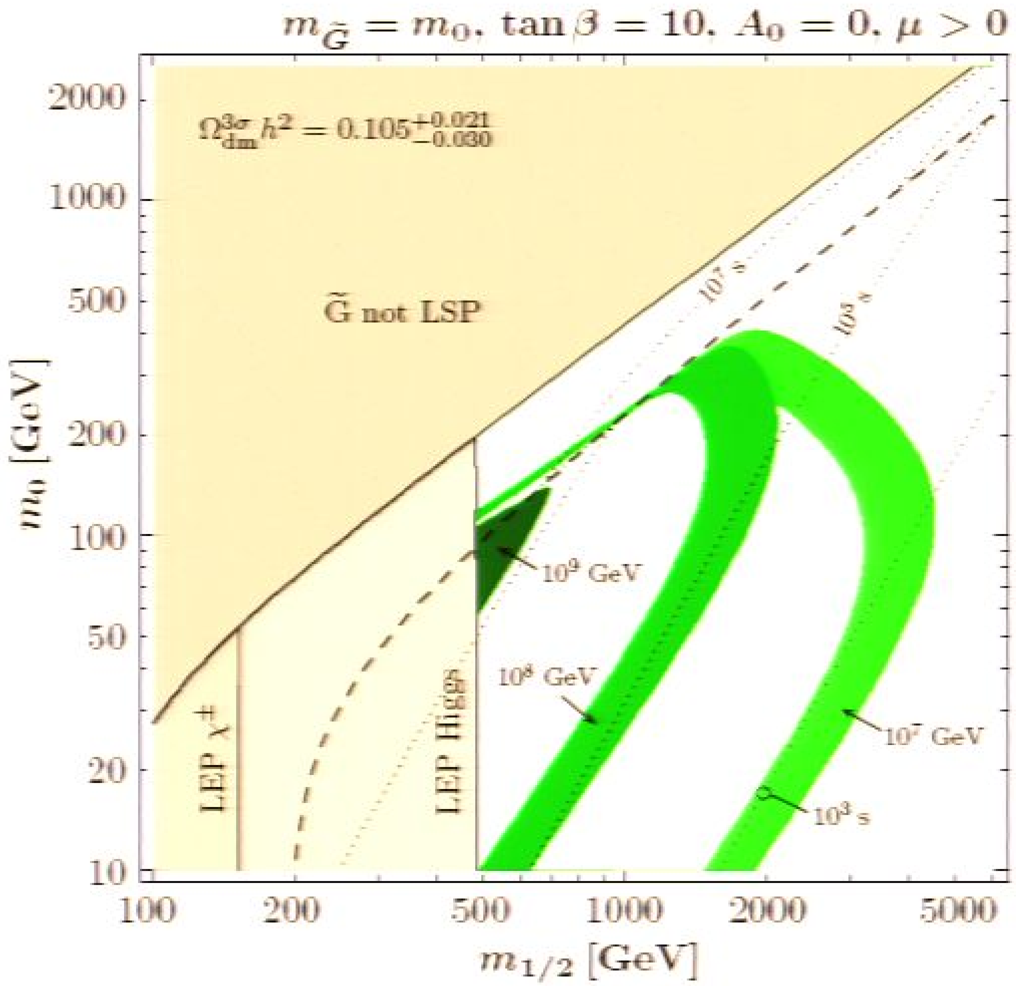
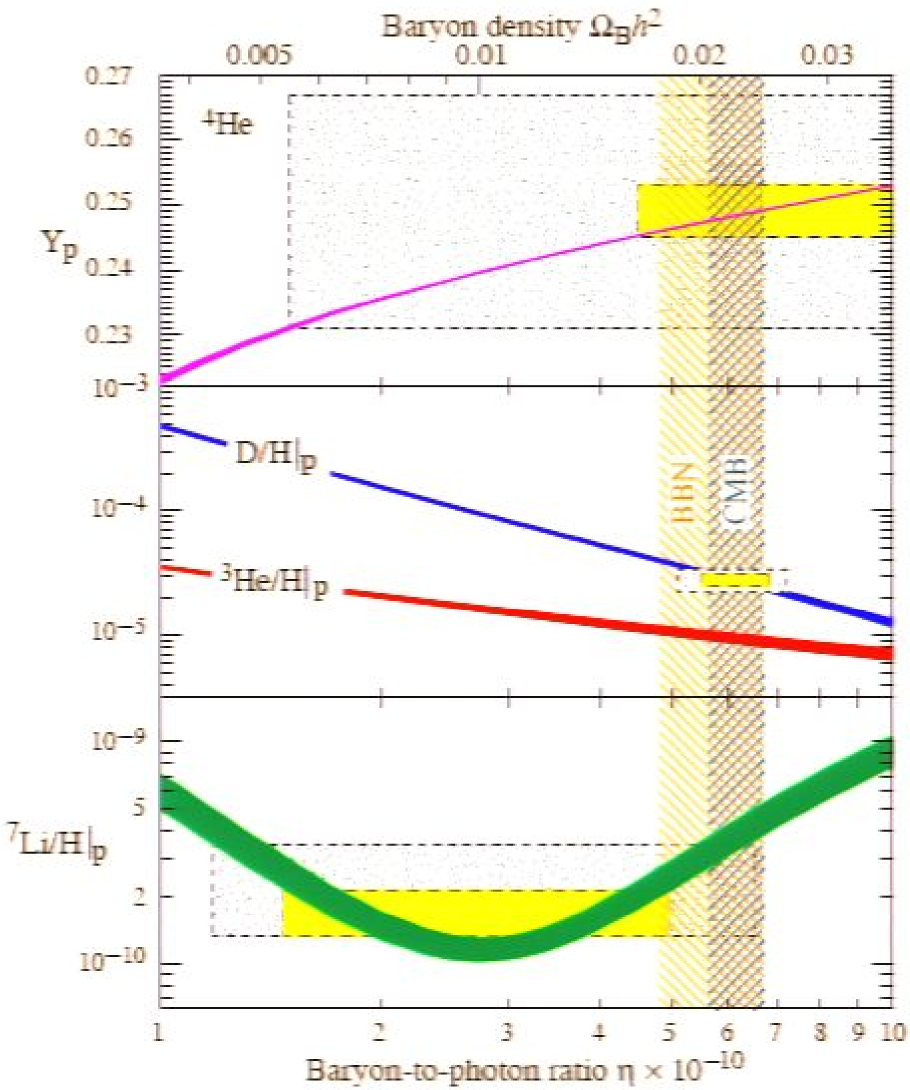
$$m_{\tilde{G}} = m_0$$



Big Bang Nucleosynthesis (BBN)



[Fields, Sarkar, PDG2006]

Beyond the Standard Model:

Timing "extra neutrino species"

Non-thermal nuclear reactions

NLSP decay during BBN

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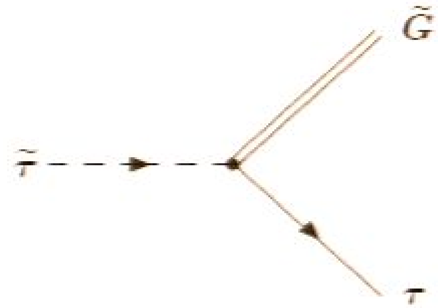
$\to$ contraints on $m_{\tilde{G}}$, m_{NLSP} and Y_{NLSP}

- $\tilde{\chi}_1^0$ NLSP disfavoured in CMSSM
  $\tilde{\tau}_1$ region: BBN bounds important but much less severe
  e.g. [Ellis et al., 2004; Feng et al., 2004; Jedamzik et al., 2006; Steffen, 2006; Cyburt et al., 2006]
- $\to$ in the following $\tilde{\tau}_1$ = NLSP

NLSP decay during BBN

- $\tilde{\tau}_1$ can decay during/after BBN, leading to ...
- electromagnetic energy release



$$\tau_{\tilde{\tau}_1} \simeq \Gamma^{-1}(\tilde{\tau}_1 \to \tilde{G}\tau) = \frac{48\pi m_{\tilde{G}}^2 M_{\mathrm{P}}^2}{m_{\tilde{\tau}_1}^5}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}_1}^2}\right)^{-4}$$

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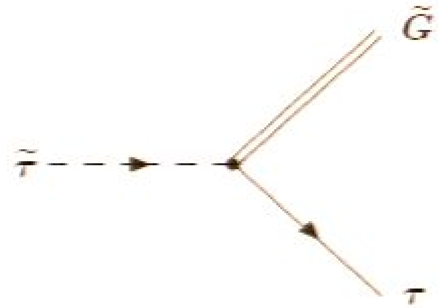

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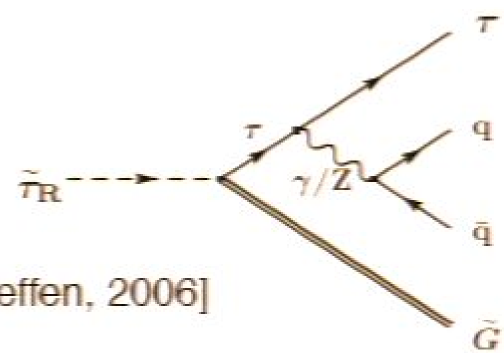
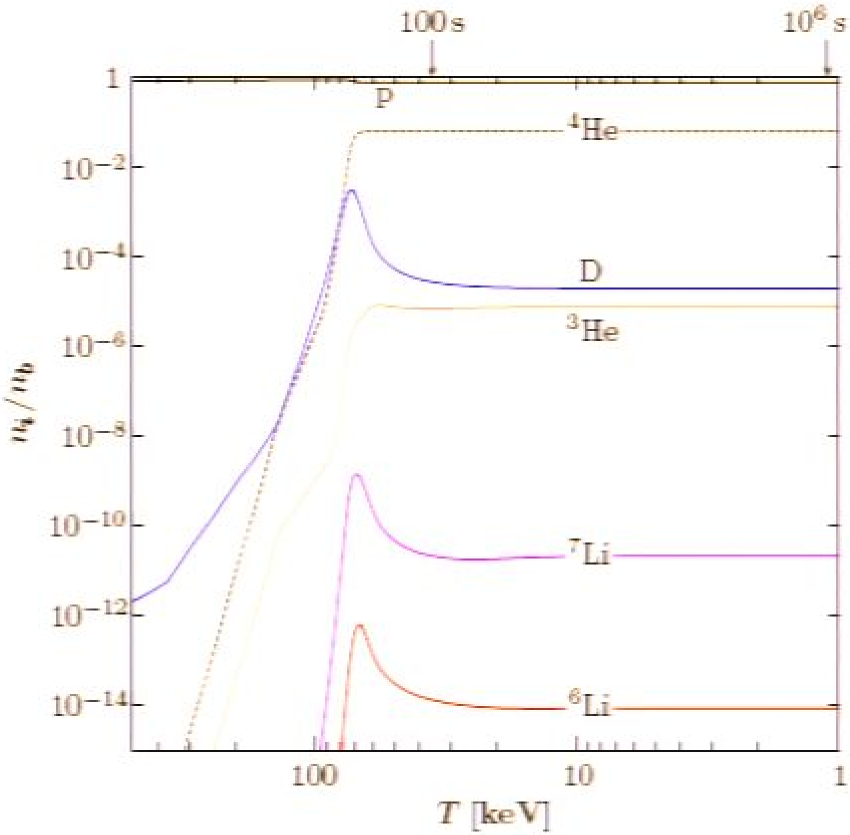


$B_{\mathrm{h}} \lesssim 3 \times 10^{-3}\ (m_{\tilde{\tau}_1} < 2\ \mathrm{TeV})$ [Steffen, 2006]

BBN Constraints from em./had. energy injection



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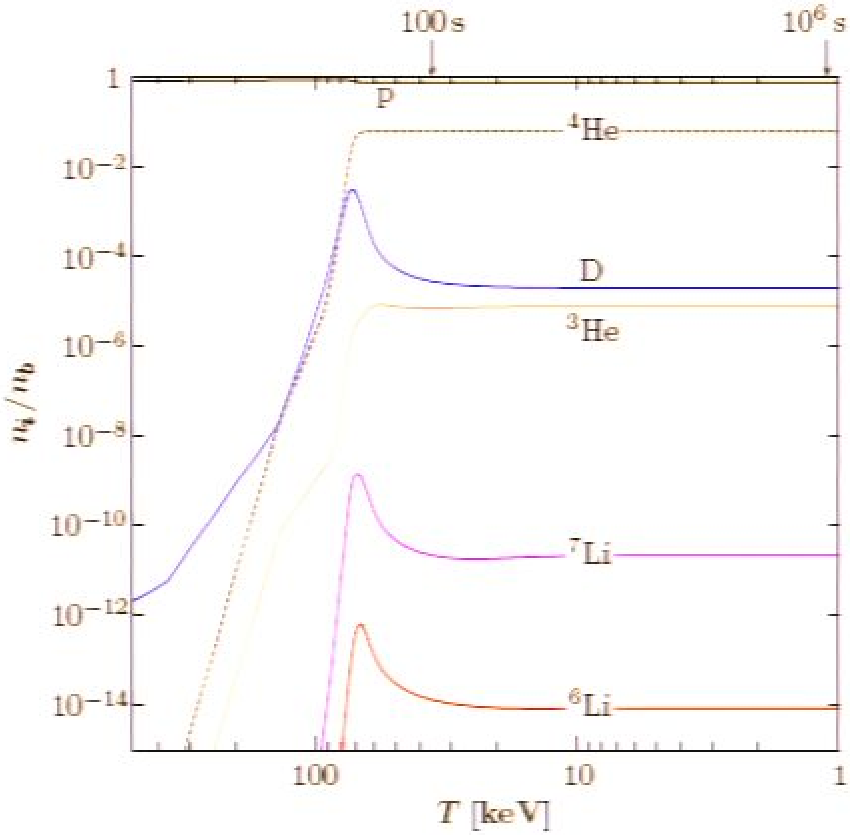
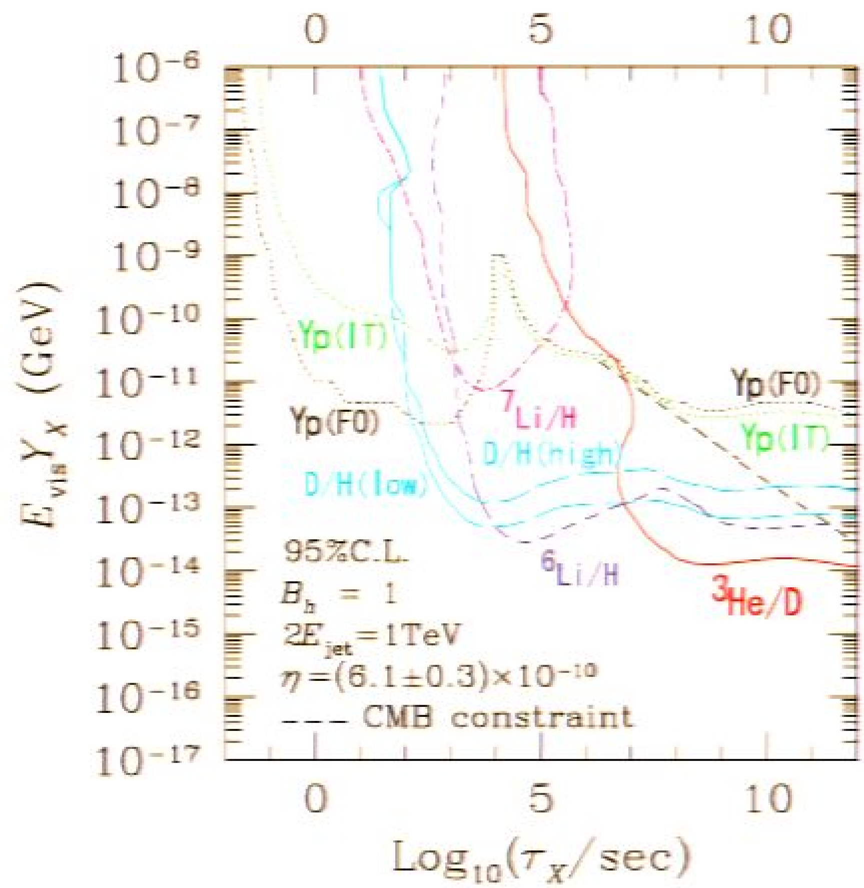
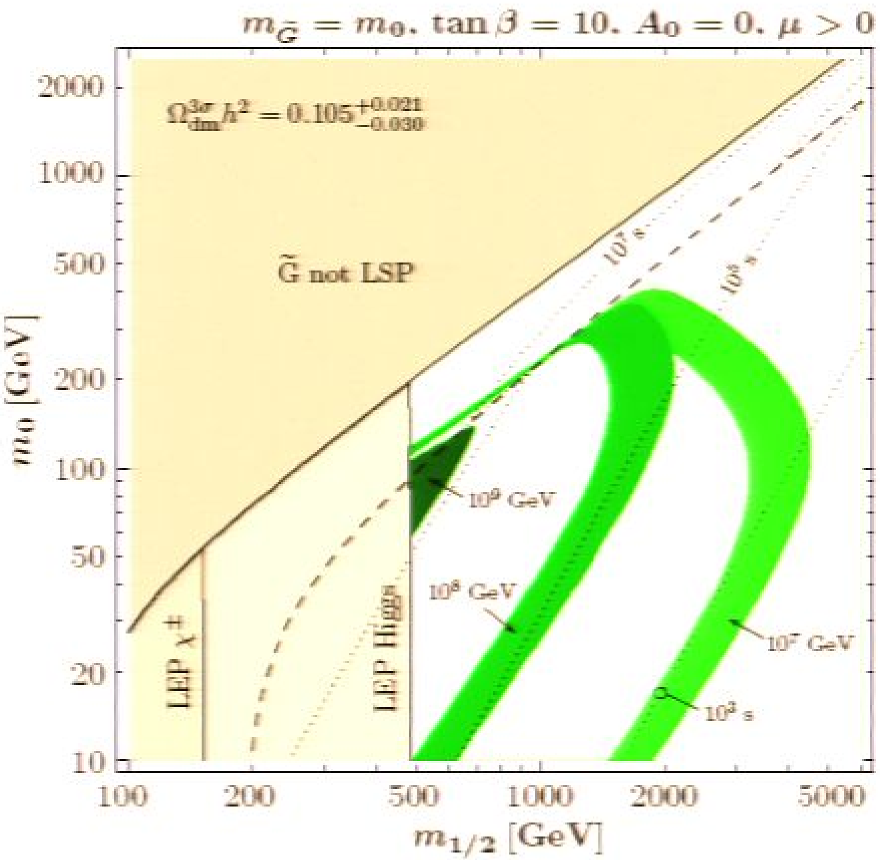




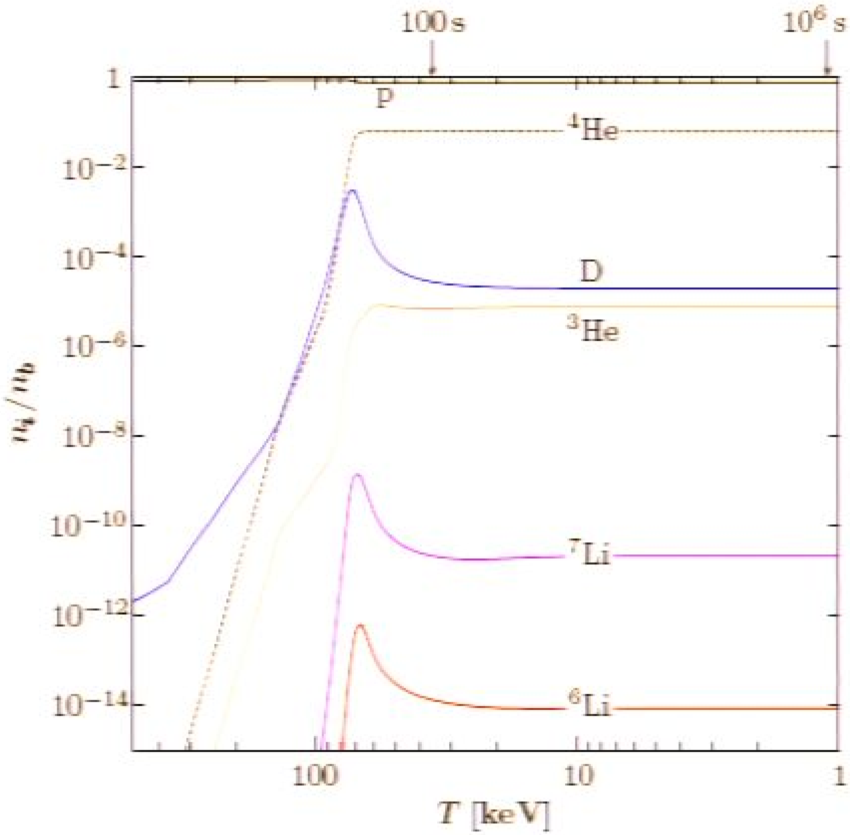
$m_X = 1$ TeV

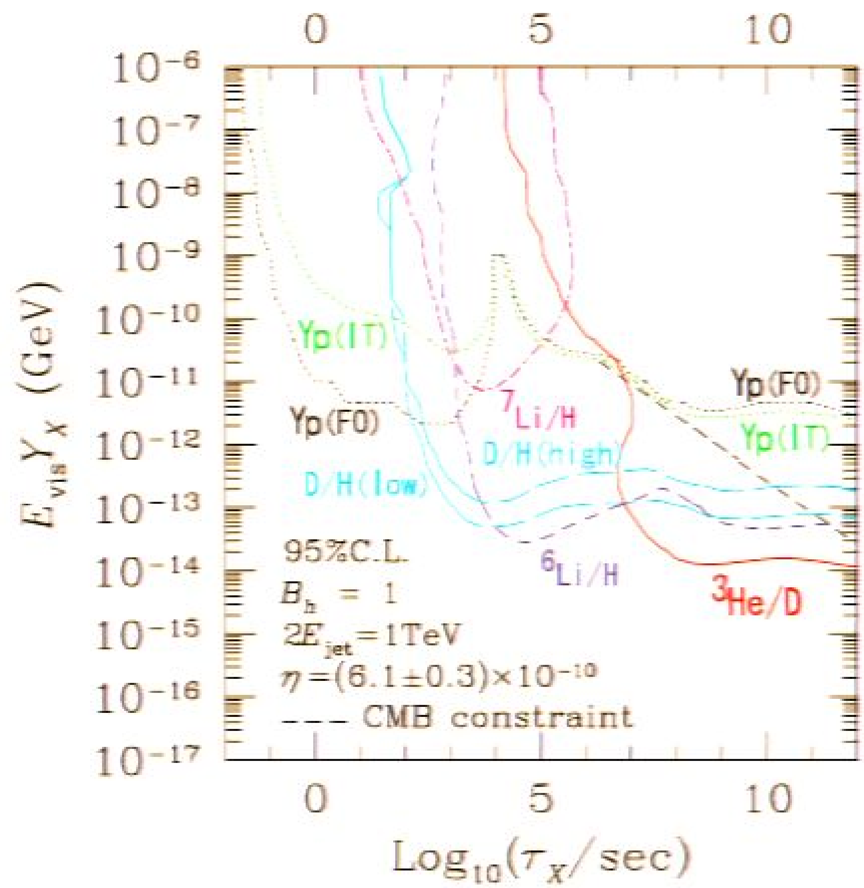
[Kawasaki, Kohri, Moroi, 2005]

Constraints on T_R from catalyzed BBN



BBN Constraints from em./had. energy injection





$m_X = 1$ TeV

[Kawasaki, Kohri, Moroi, 2005]

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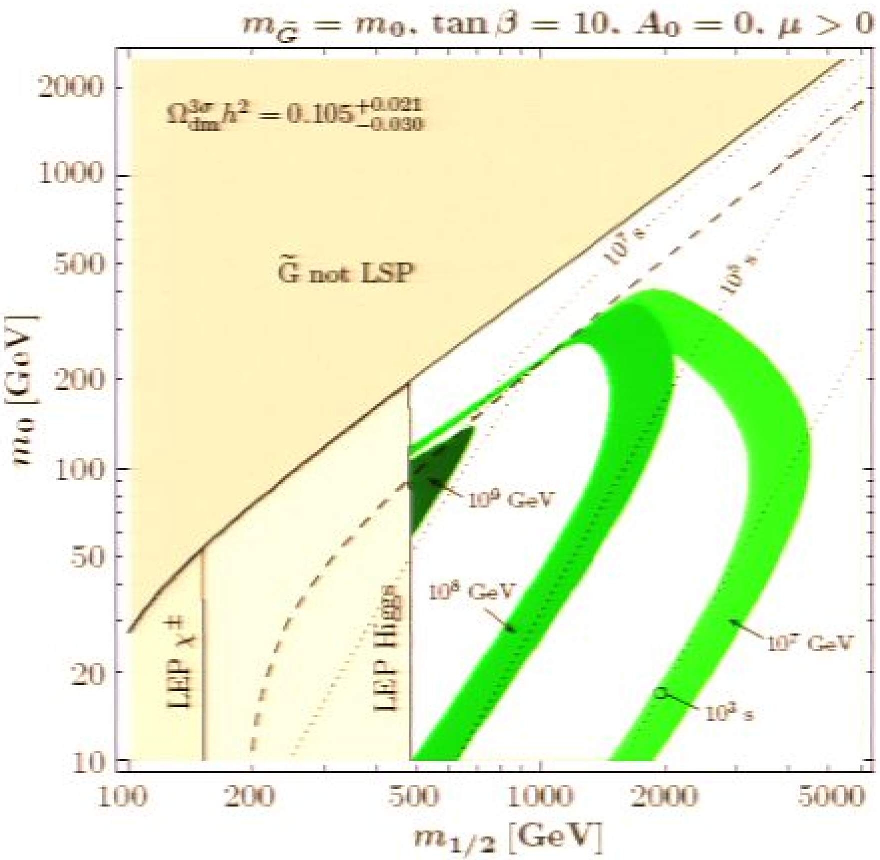

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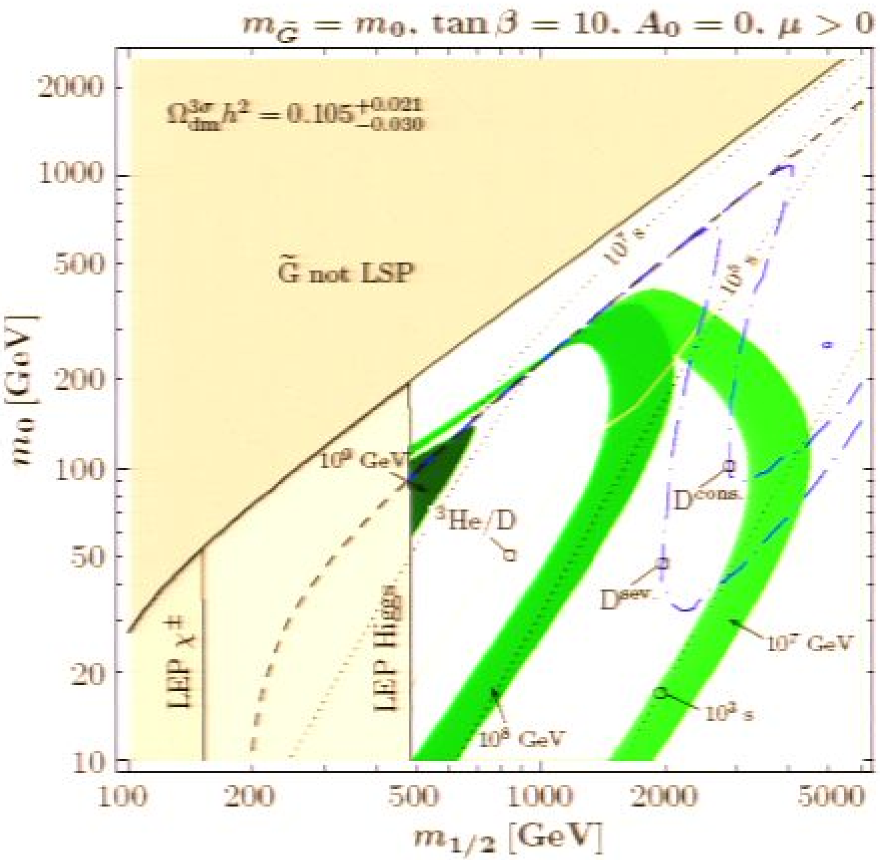

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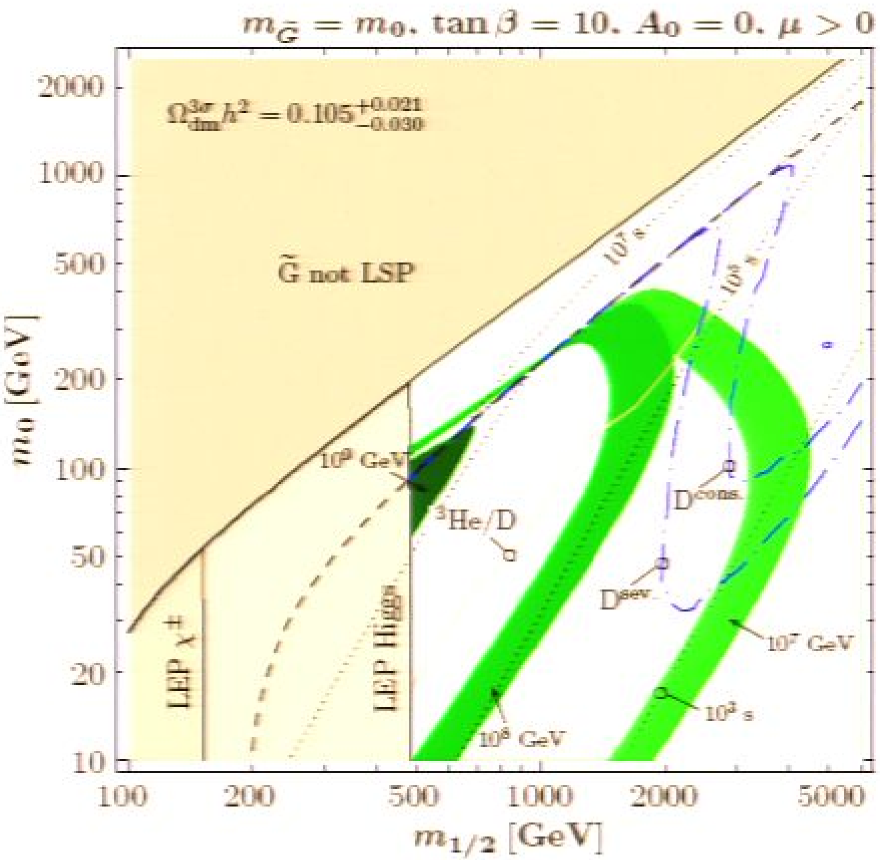
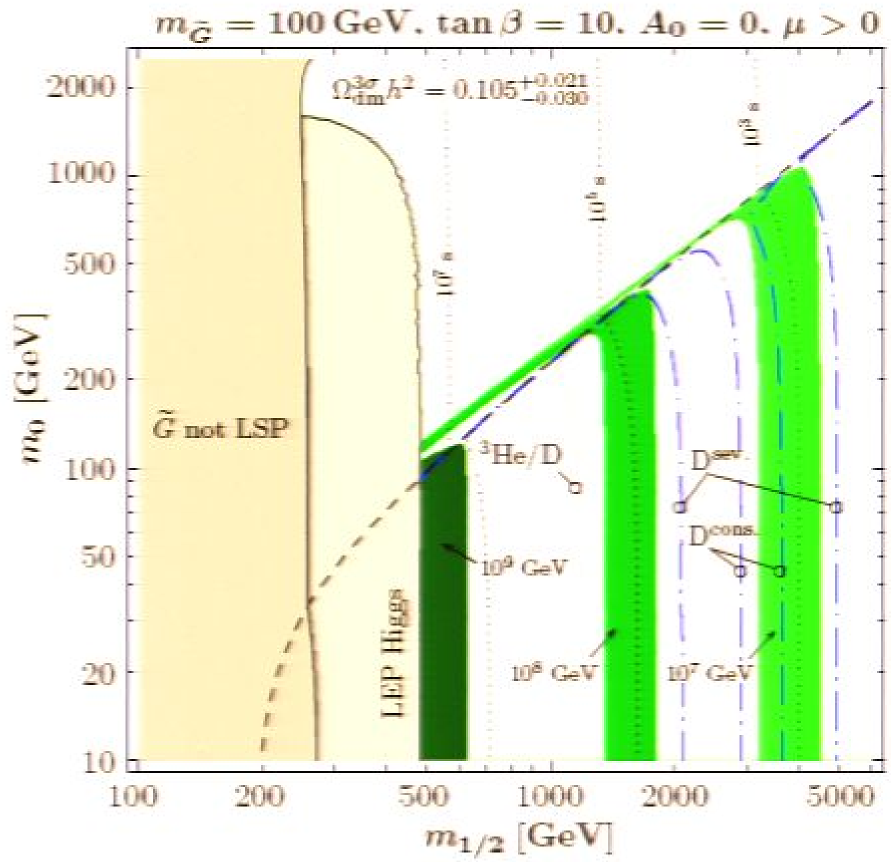
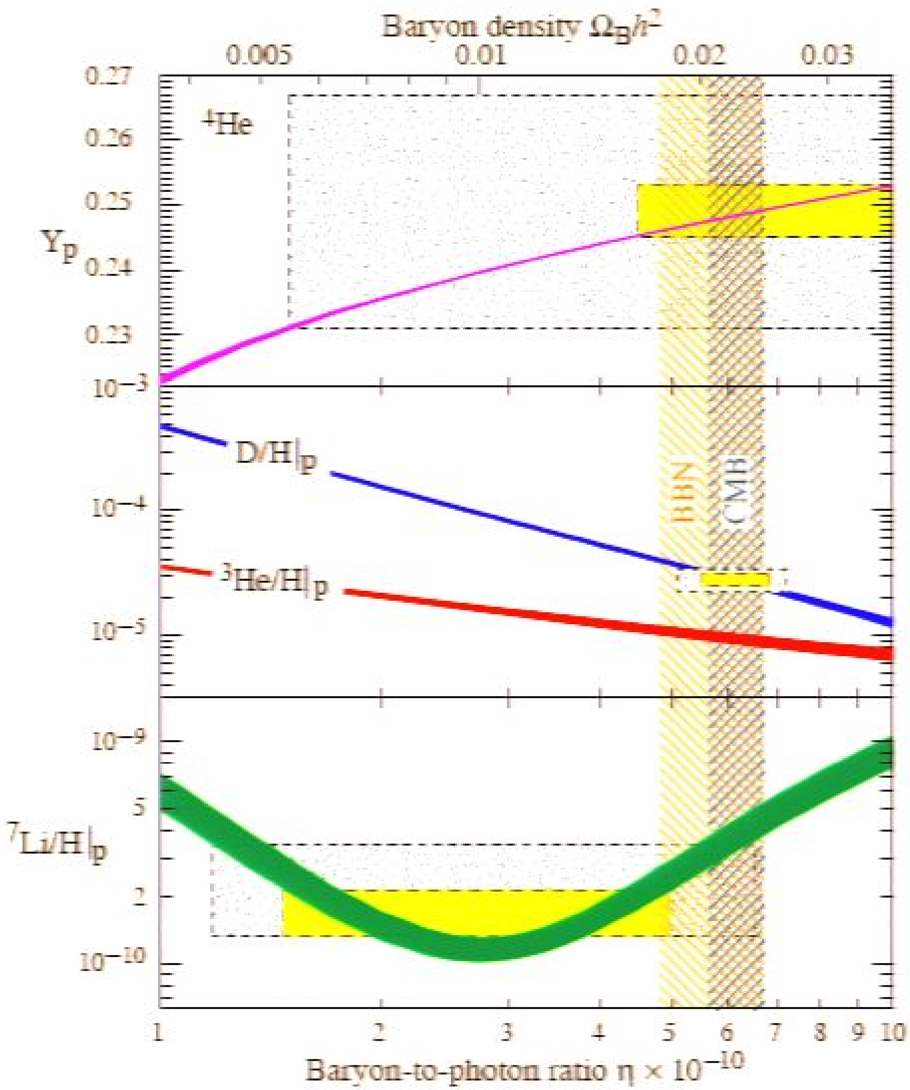




Big Bang Nucleosynthesis (BBN)



[Fields, Sarkar, PDG2006]

Beyond the Standard Model:

Timing "extra neutrino species"

Non-thermal nuclear reactions

"catalyzed BBN"

Catalyzed BBN

- bound-state formation of X^- with light elements opens up new reaction channels

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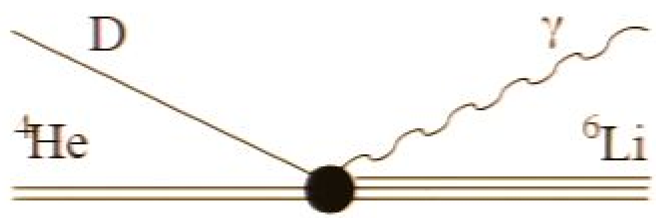
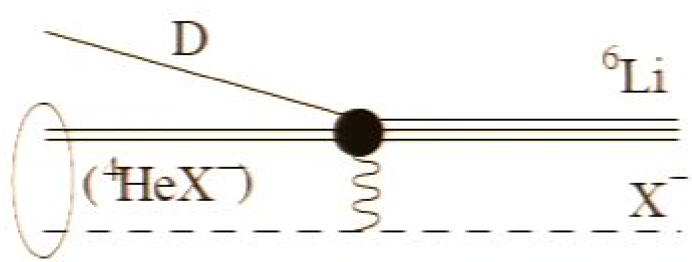
- bound-state formation of X^- with light elements opens up new reaction channels

- most significant for production of $^6\mathrm{Li}$ [Pospelov, 2006]

standard BBN:
$\rightarrow \langle \sigma_S v \rangle$



catalyzed BBN:
$\rightarrow \langle \sigma_C v \rangle$



cross-section enhanced by 7 orders of magnitude

Numerical Study of CBBN

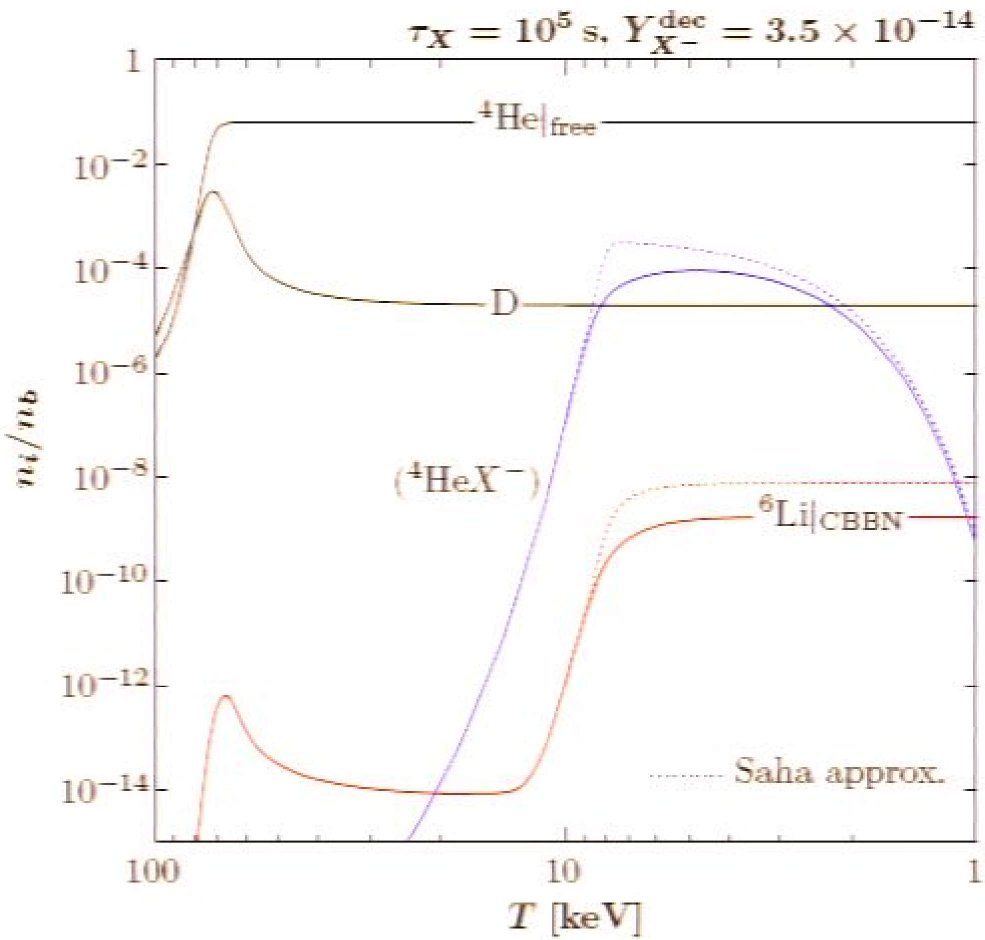
- Bound state (BS) formation becomes efficient at $T \sim 10\,\mathrm{keV}$ after Standard BBN

$$\frac{dY_{^6\mathrm{Li}}}{dt} = \langle\sigma_C v\rangle s Y_{\mathrm{BS}} Y_{\mathrm{D}}$$

$$\frac{dY_{\mathrm{BS}}}{dt} = \langle\sigma_{\mathrm{r}} v\rangle s Y_{\delta} - \Gamma_{X^-} Y_{\mathrm{BS}} - \langle\sigma_C v\rangle s Y_{\mathrm{BS}} Y_{\mathrm{D}}$$

etc...

- $\langle\sigma_{\mathrm{r}} v\rangle Y_{\delta}$ parameterizes competition between photodissociation and recombination of $(^4\mathrm{He}X^-)$
- $\langle\sigma_C v\rangle$ ... [Kamimura et al., 2007]



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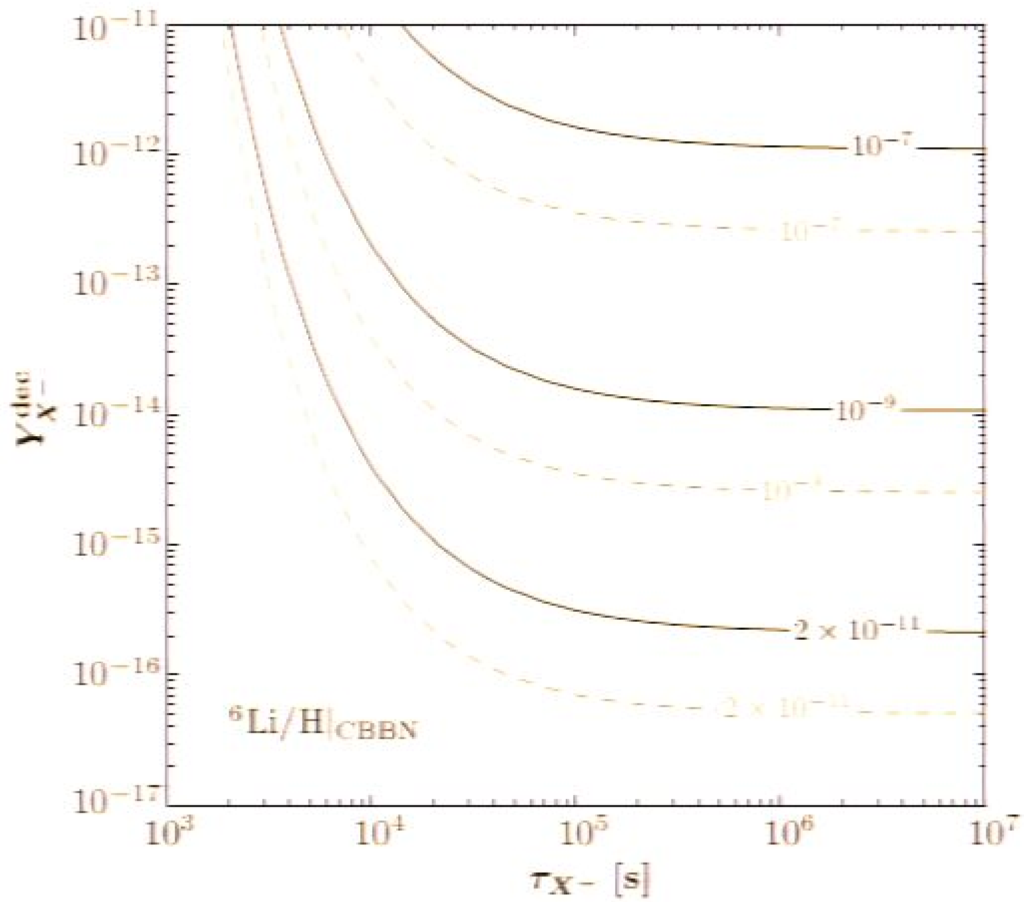


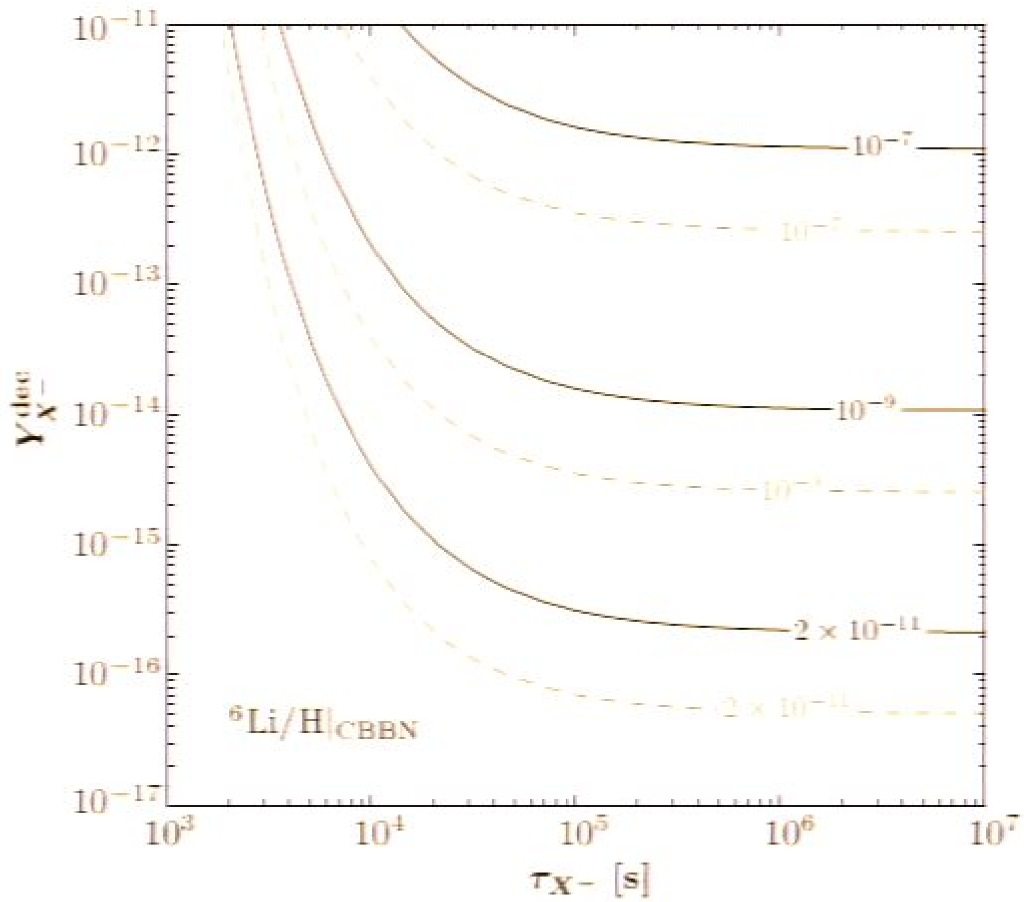
Numerical Study of CBBN

- observationally inferred primordial abundance:

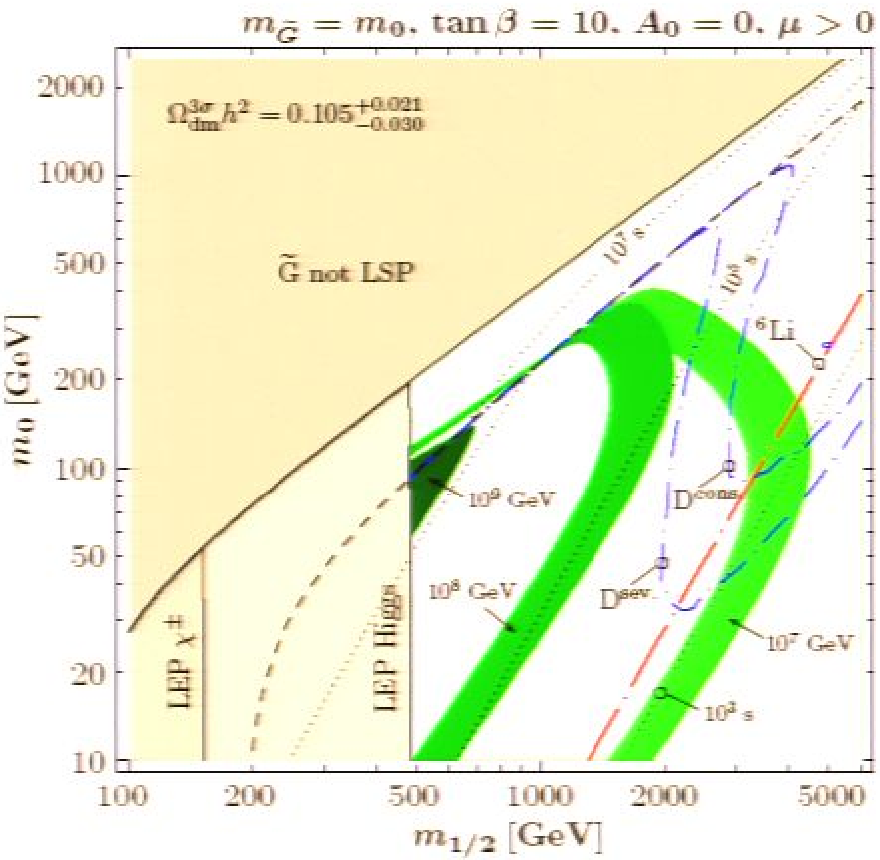
  [Cyburt et al., 2002]

  $$(^6\mathrm{Li/H})_\mathrm{p} \lesssim 2 \times 10^{-11}$$

  → upper bound on $Y_{X^-} = Y_{\tilde{\tau}_1}/2$



Constraints on T_R from catalyzed BBN



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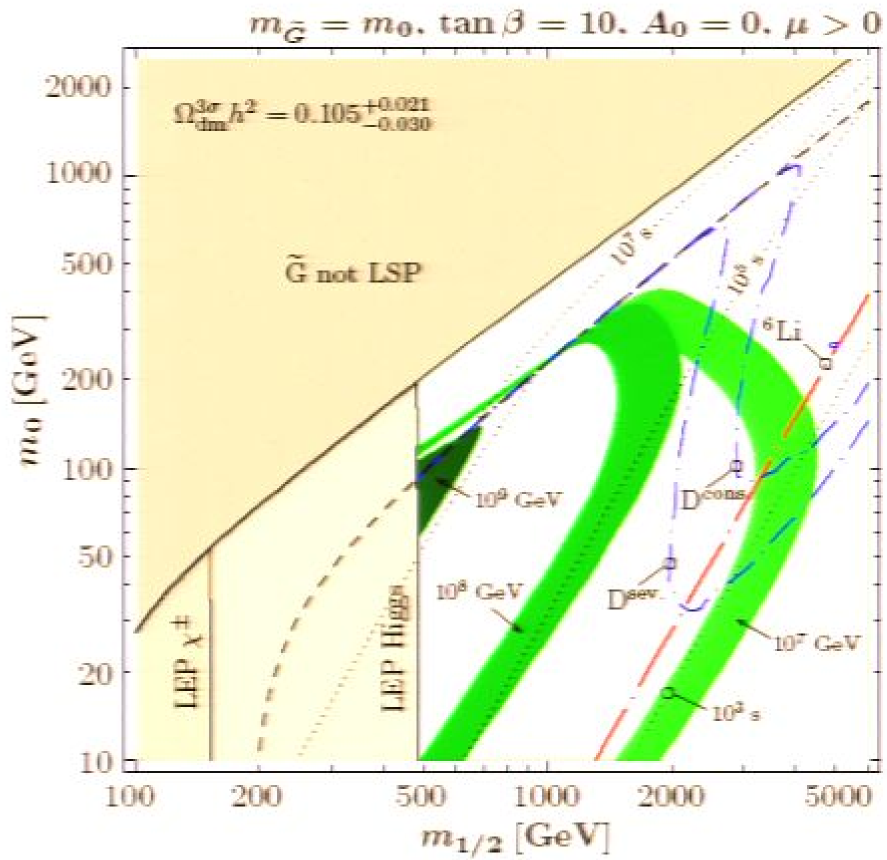

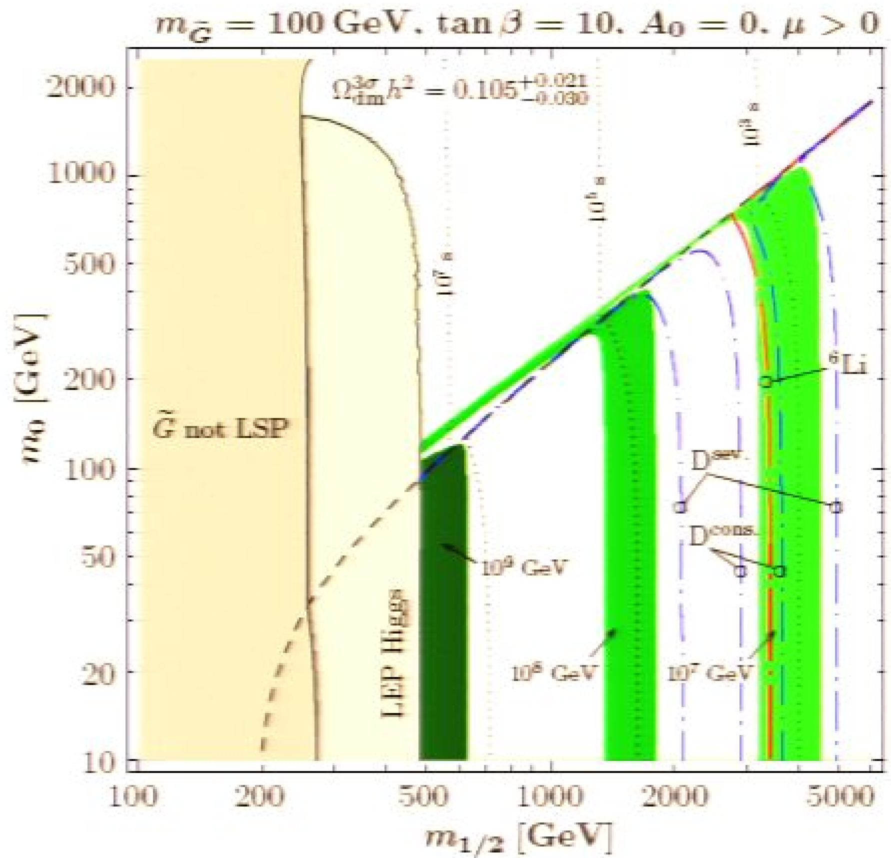

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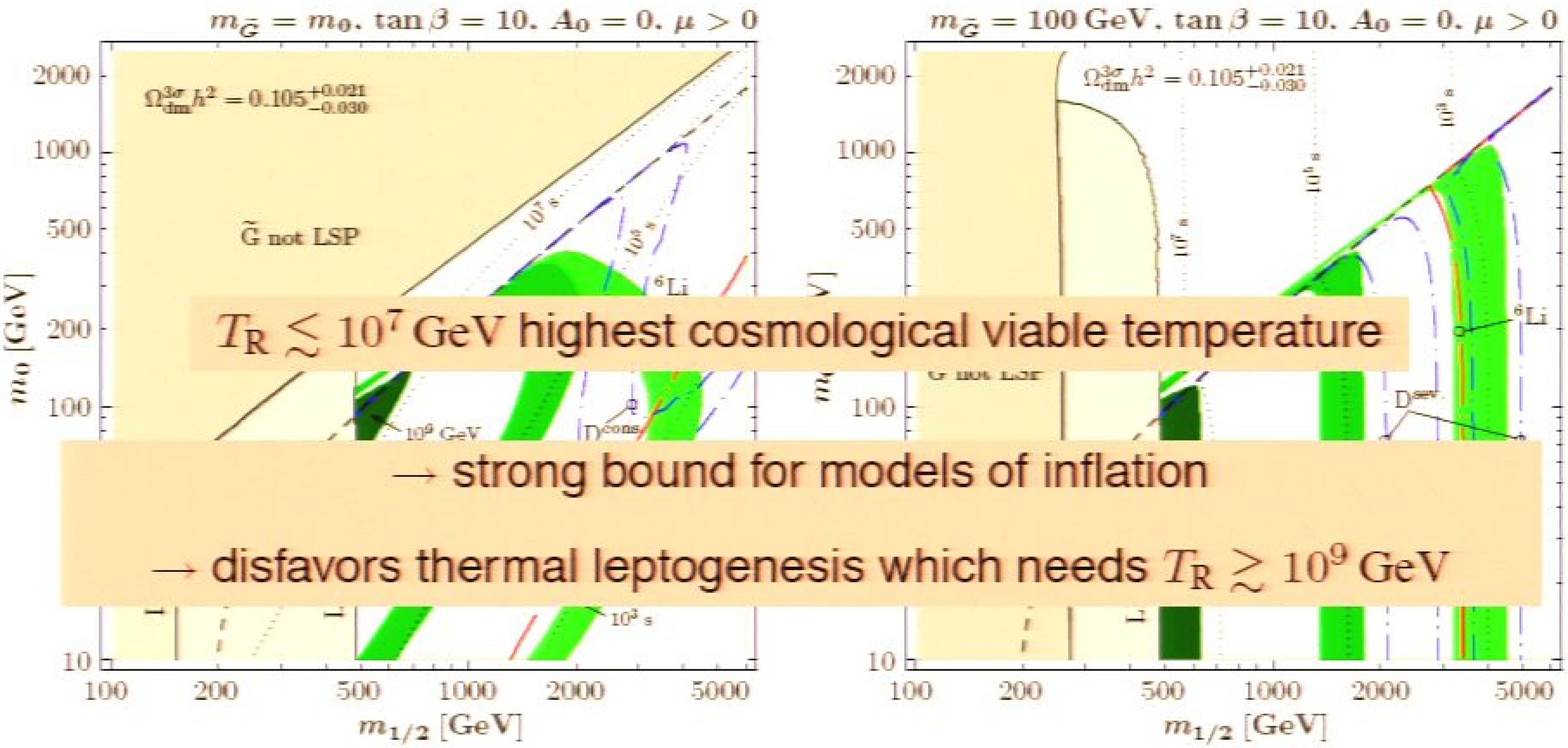

$T_R \lesssim 10^7$ GeV highest cosmological viable temperature

→ strong bound for models of inflation

→ disfavors thermal leptogenesis which needs $T_R \gtrsim 10^9$ GeV

Constraints on T_{R} from catalyzed BBN

- For typical $Y_{\mathrm{NLSP}} \gtrsim 7 \times 10^{-14}$ the stau lifetime is constrained $\tau_{\tilde{\tau}_1} \lesssim 5 \times 10^3\,\mathrm{s}$
- Implies a lower limit on the mass splitting between $m_{\tilde{\tau}_1}$ and $m_{\widetilde{G}}$
- Scan over the CMSSM parameter space ($m_{\tilde{\tau}_1} \leftrightarrow m_{1/2}$):

$$
\begin{aligned}
m_{1/2} &= 0.1 - 6\ \mathrm{TeV}, \\
\tan\beta &= 2 - 60, \\
\mathrm{sgn}\,\mu &= \pm 1, \\
-4m_0 < A_0 &< 4m_0
\end{aligned}
$$

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- SUSY mass spectrum scales with $m_{1/2}$ in the $\tilde{\tau}_1$ NLSP region!

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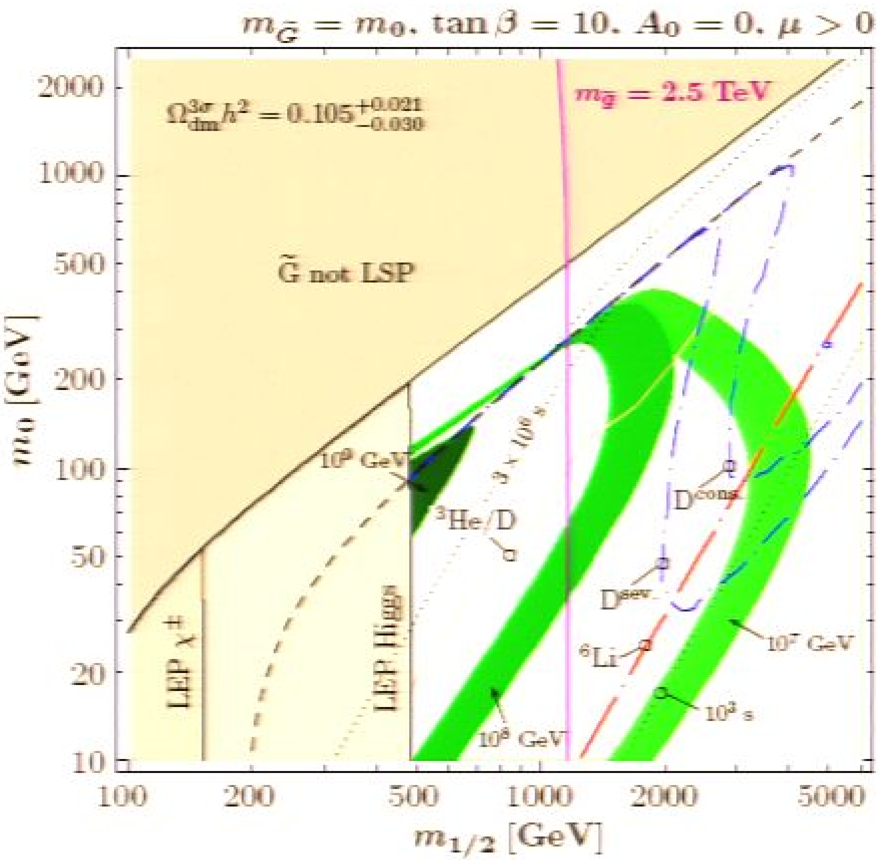

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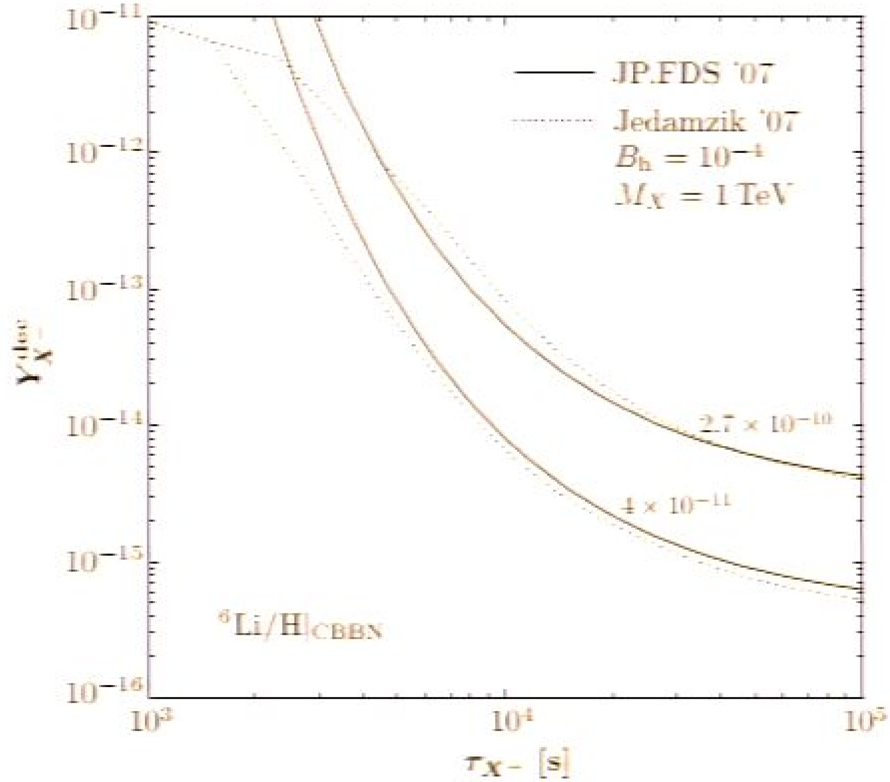
Adopting for

$(^6\mathrm{Li/H})_\mathrm{p} \lesssim 4 \times 10^{-11}\ (2.7 \times 10^{-10})$

[Jedamzik, 2007]

$m_{1/2}:\quad 0.87\ (0.78)$

$T_R:\quad 5.3 \times 10^7\ (6.5 \times 10^7)$

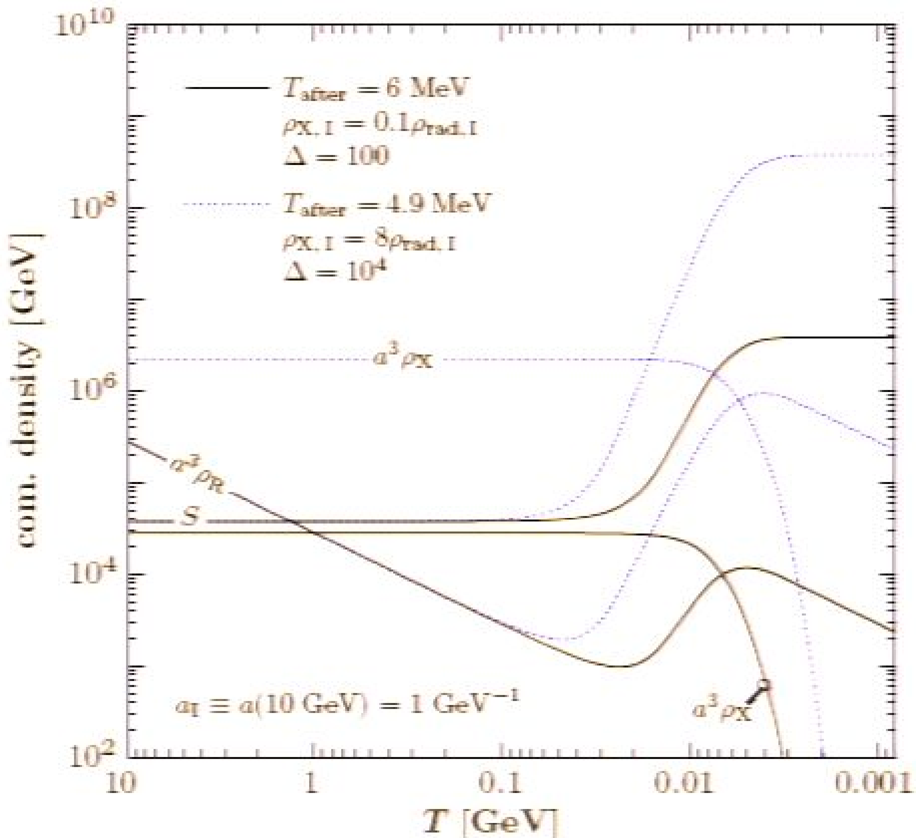


Late-time Entropy Production

out-of-eq. decay of heavy particle X:

$$\frac{dS}{dt} = \frac{dQ}{T} = \frac{\Gamma_{\mathrm{X}} \rho_{\mathrm{X}} a^3}{T}$$

see also [Buchmüller et al., 2006]



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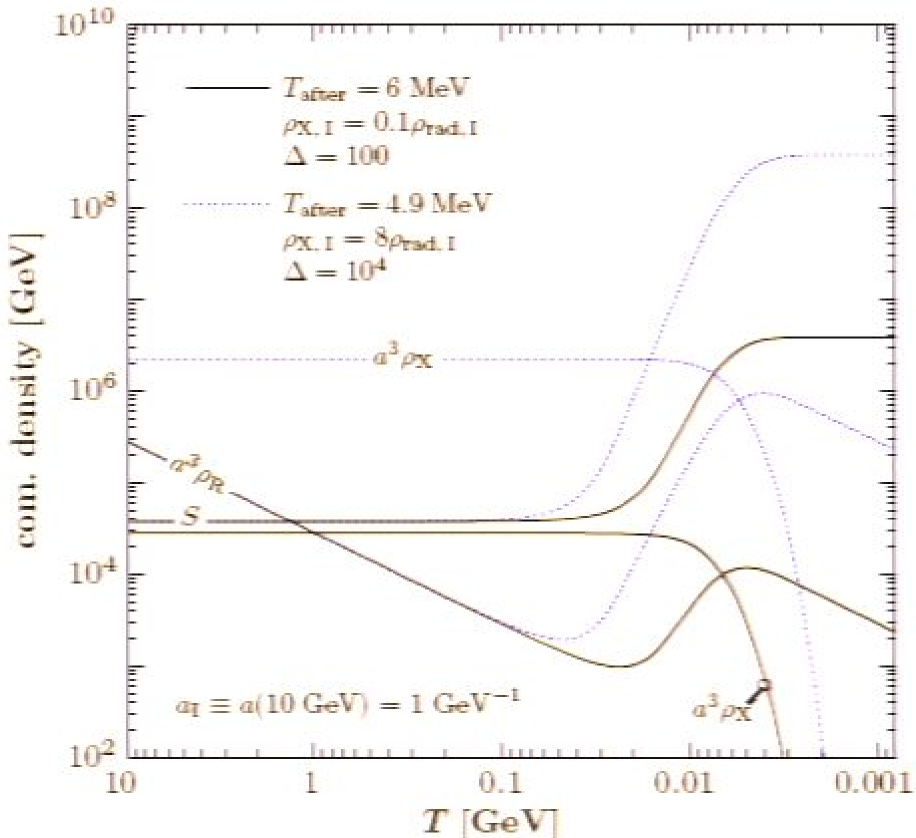

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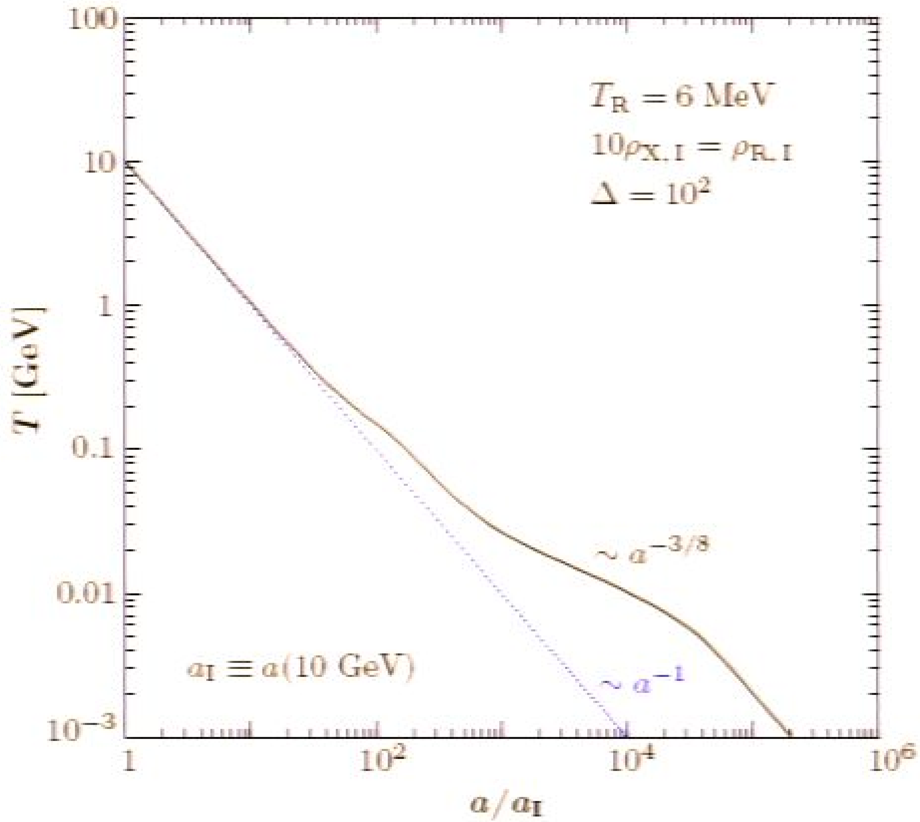

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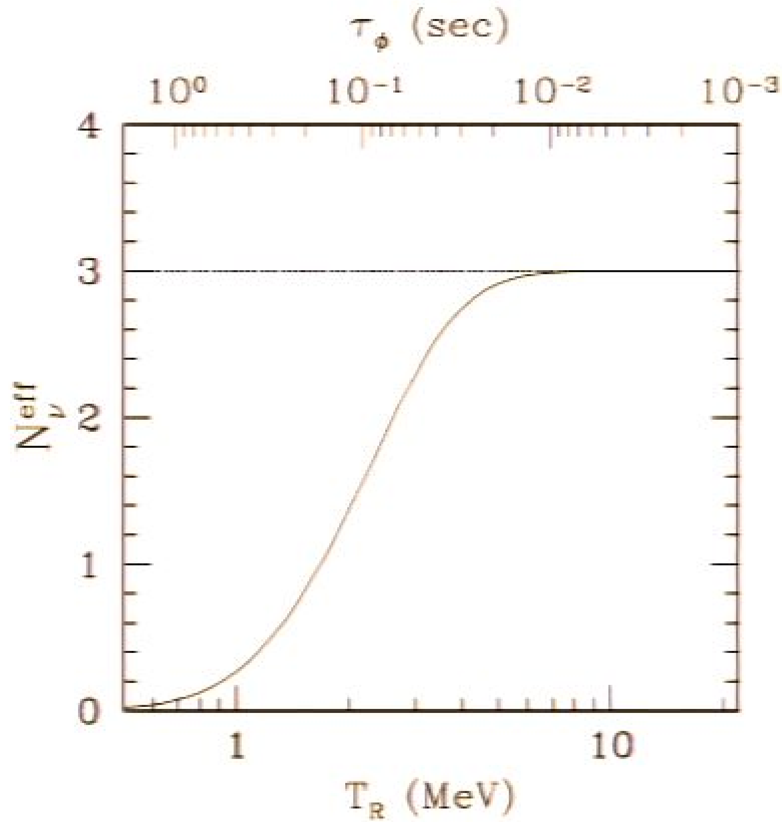

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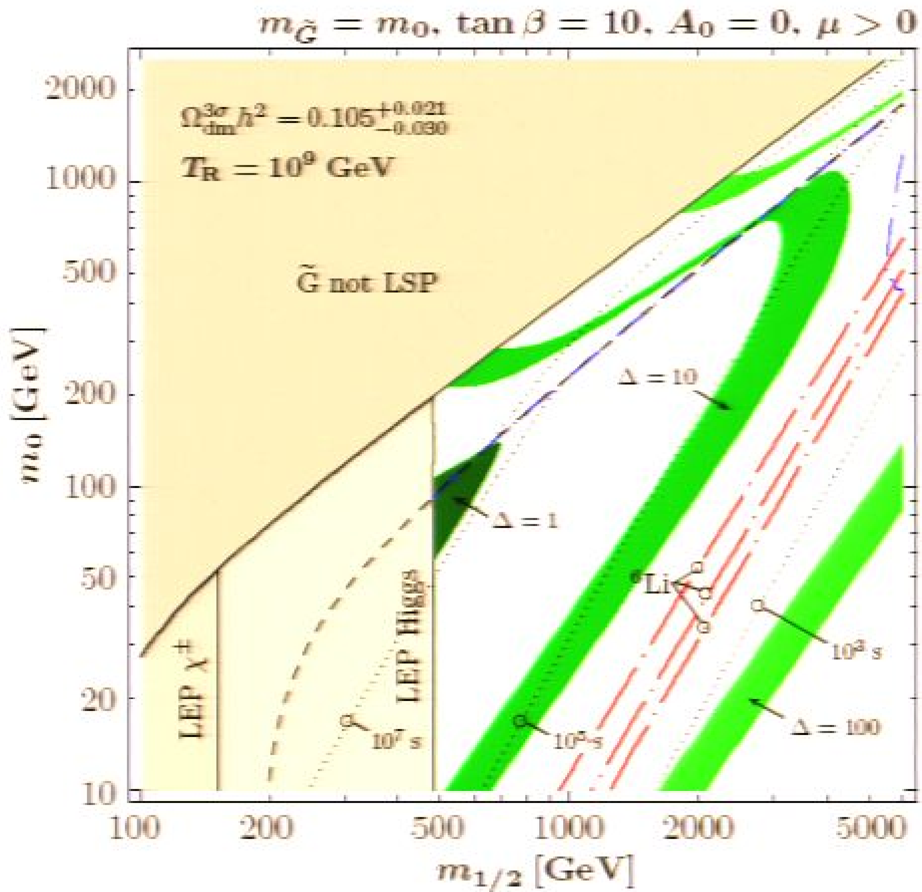

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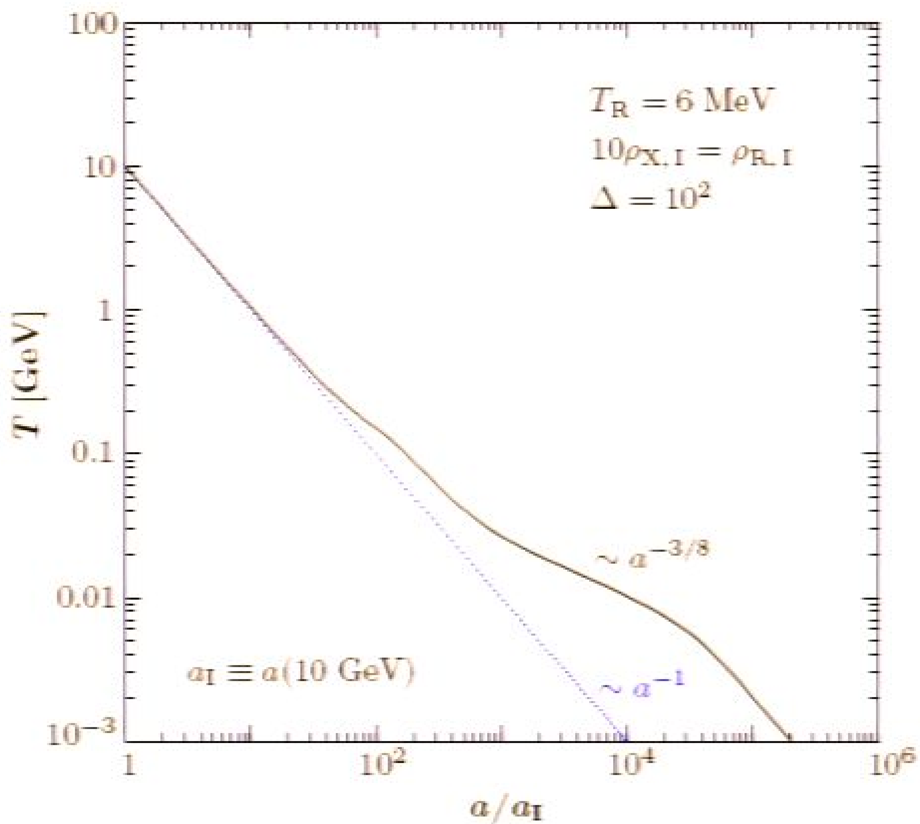

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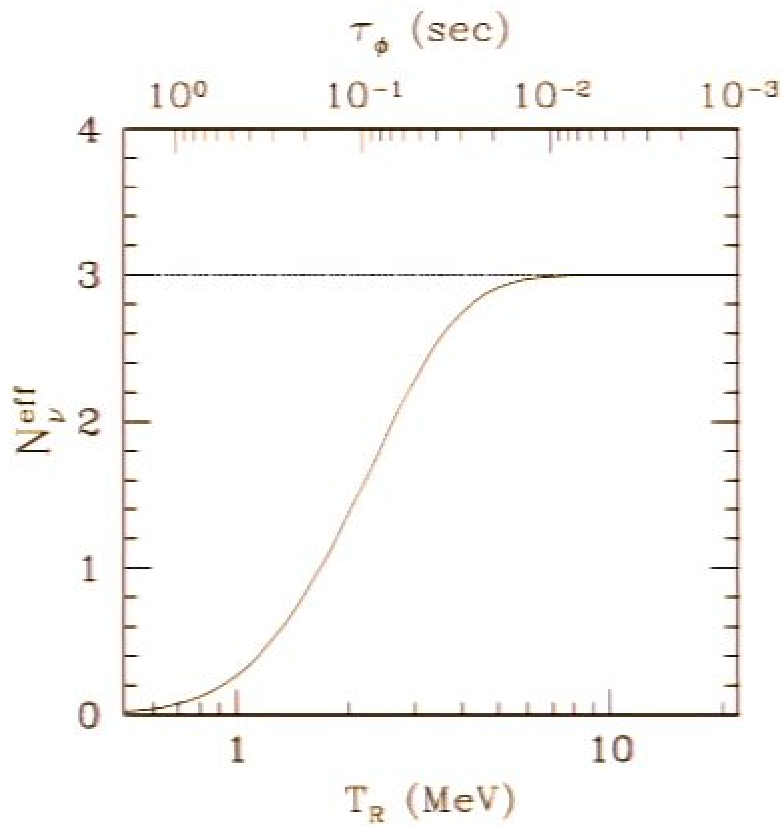

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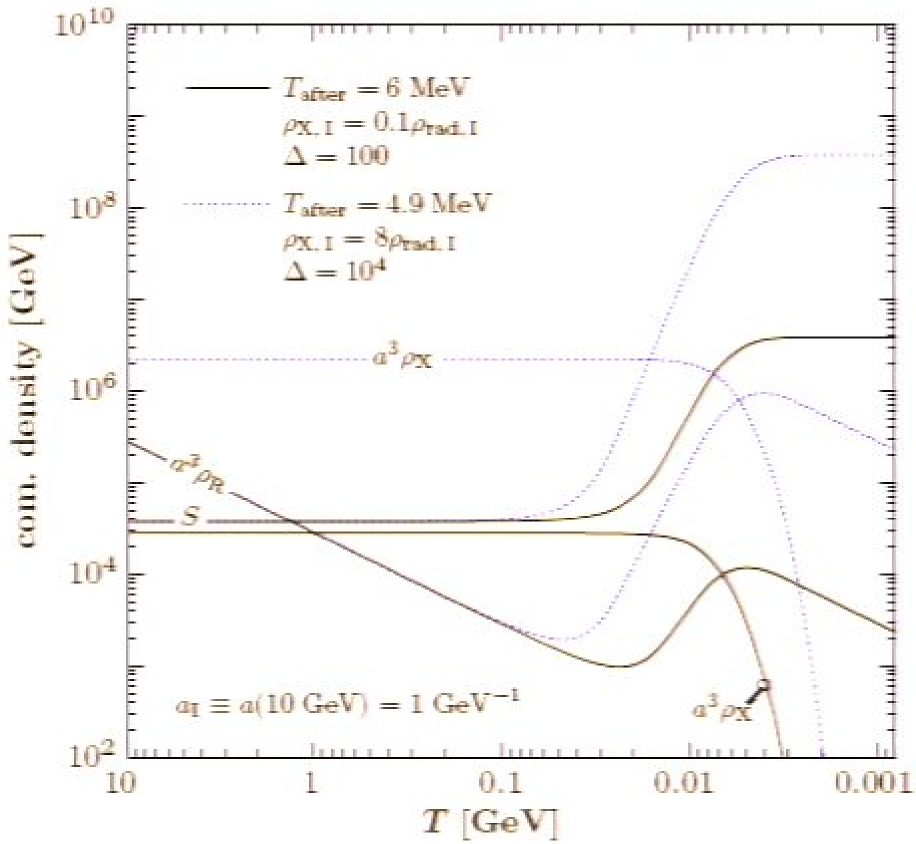

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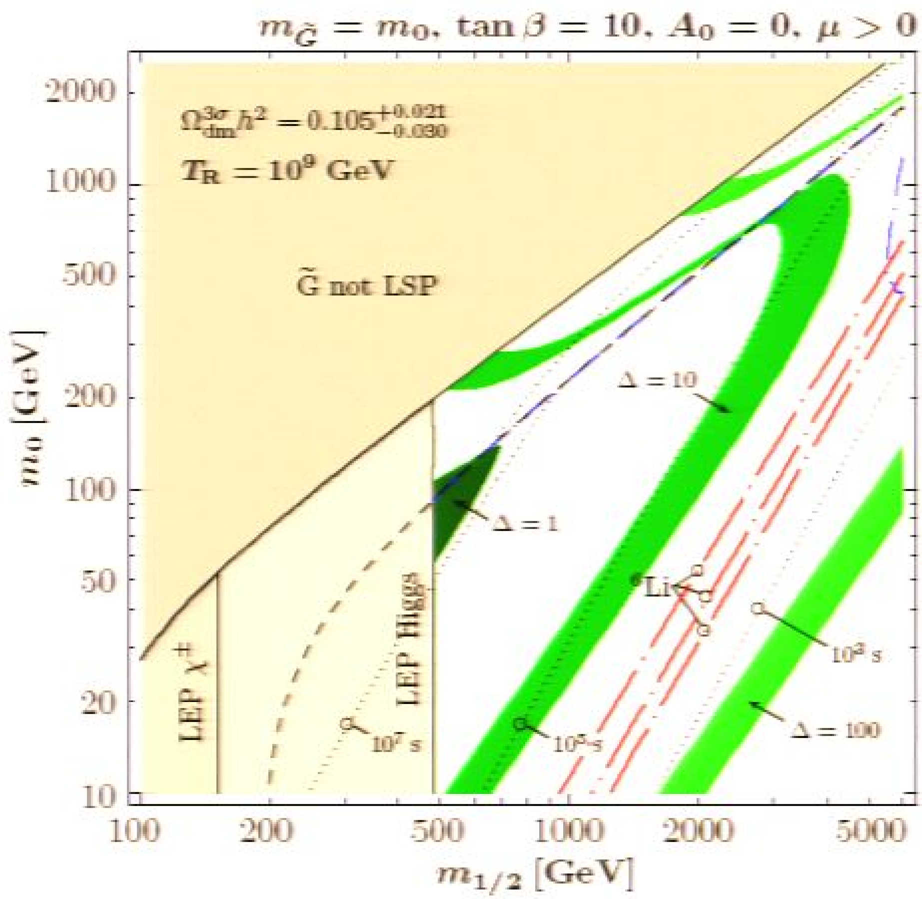

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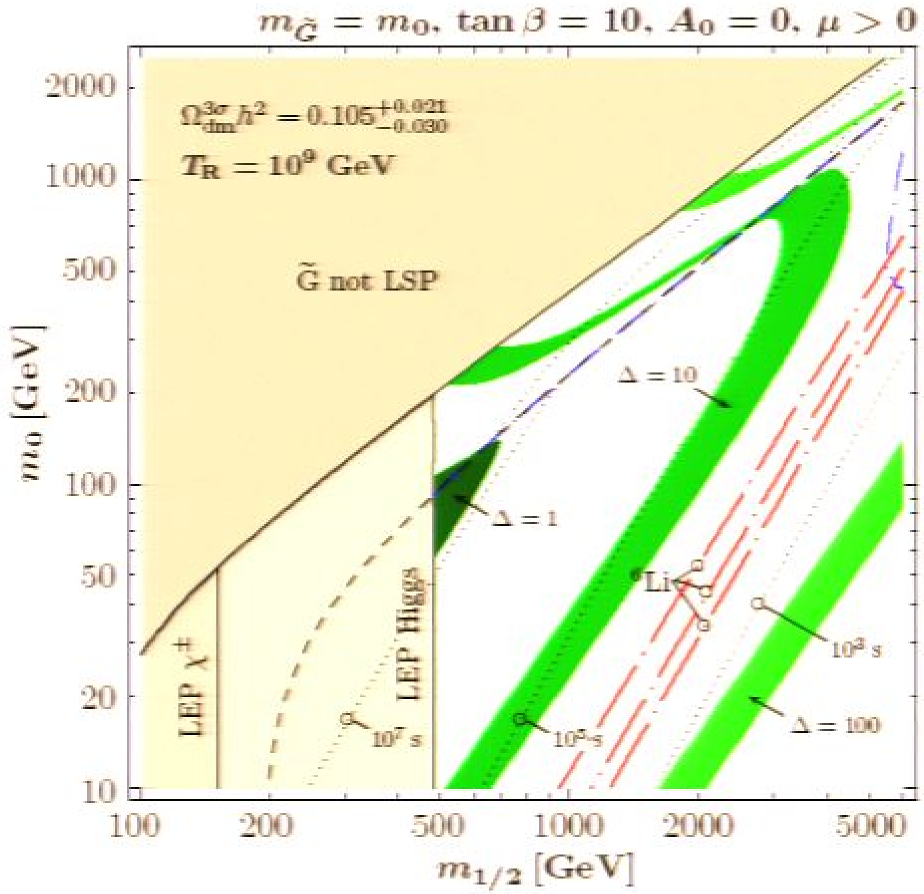

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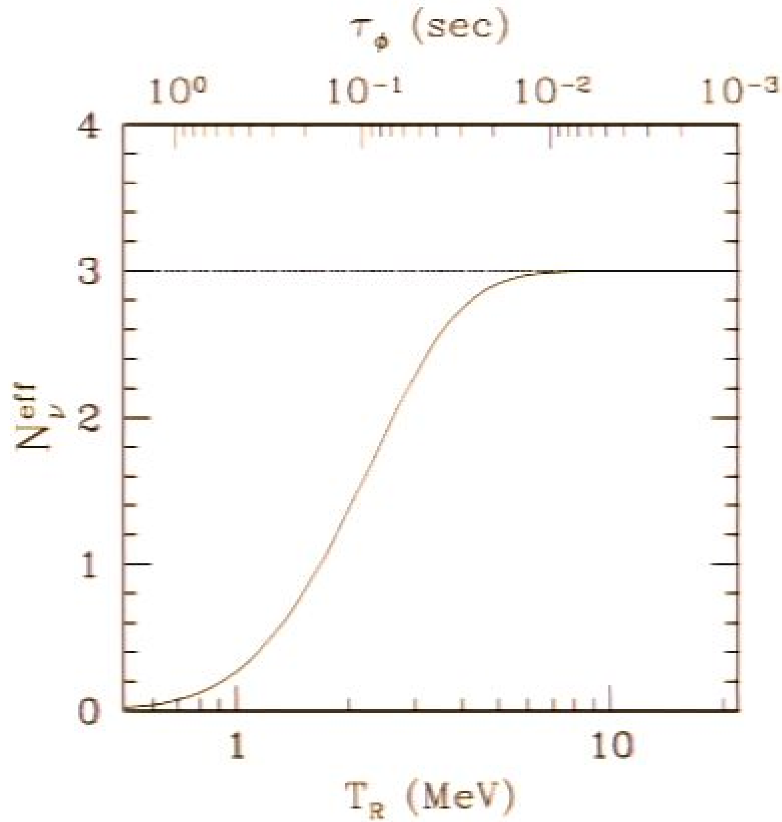

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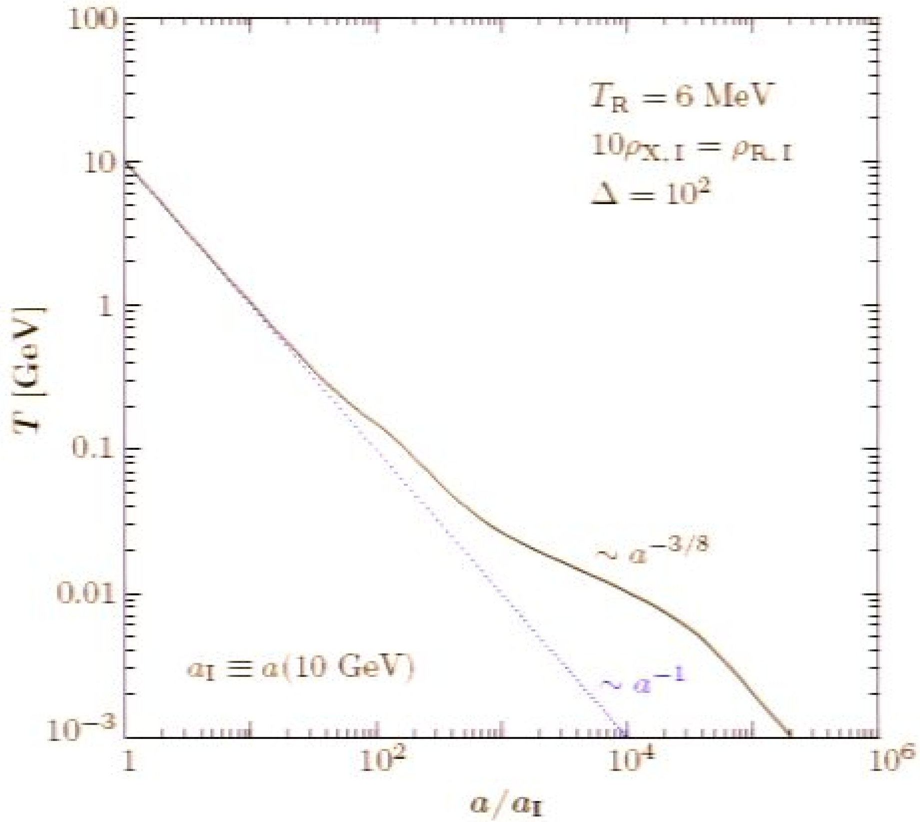

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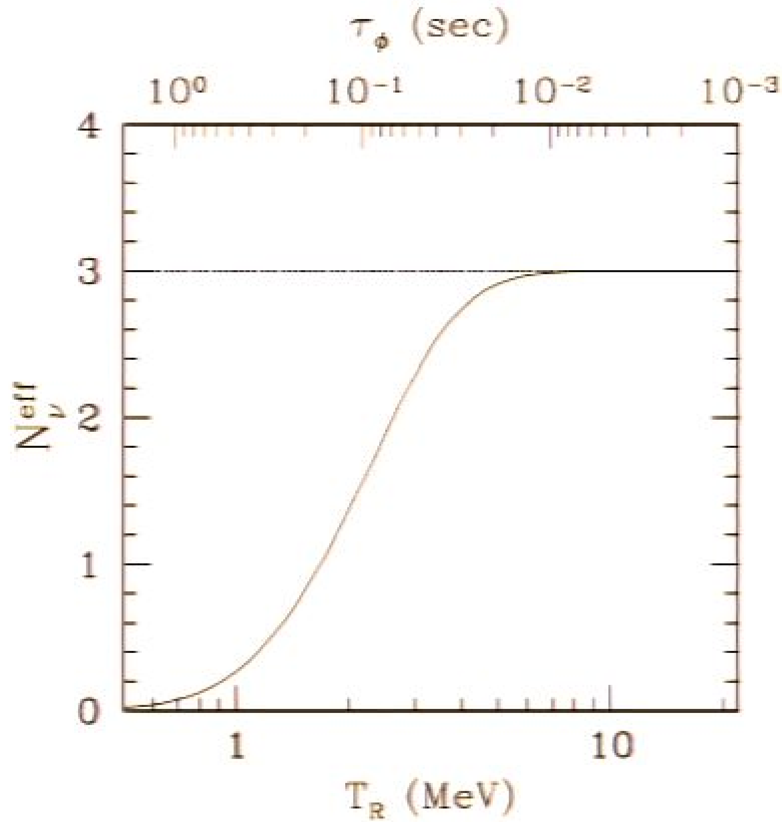

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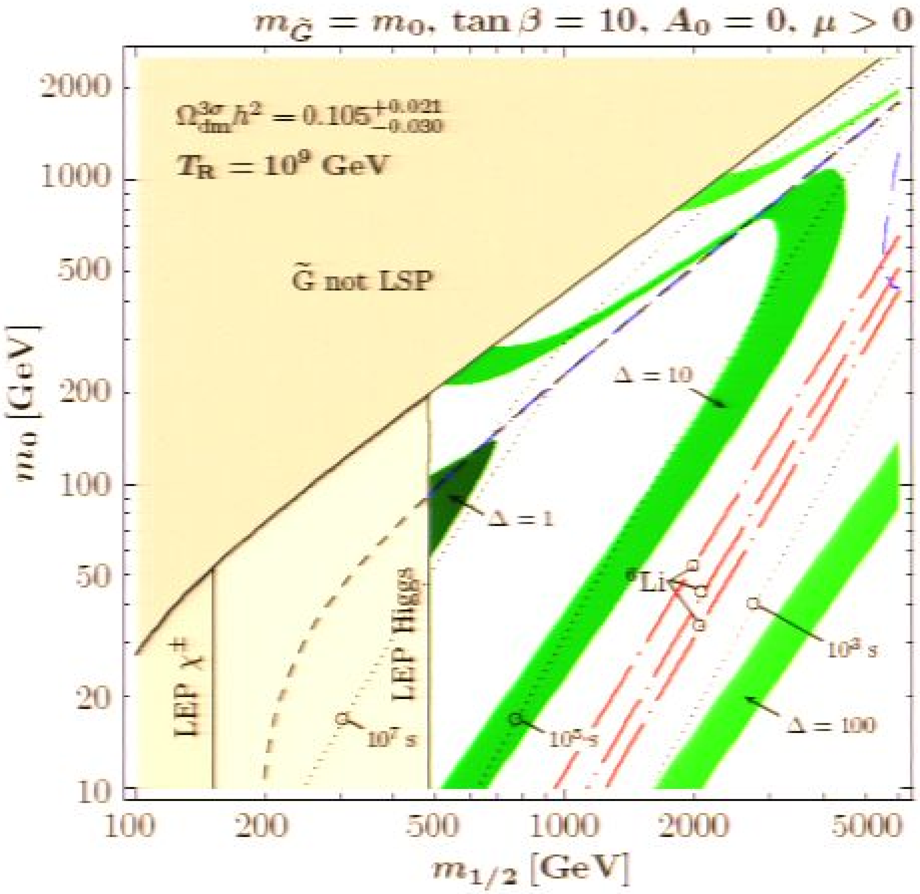
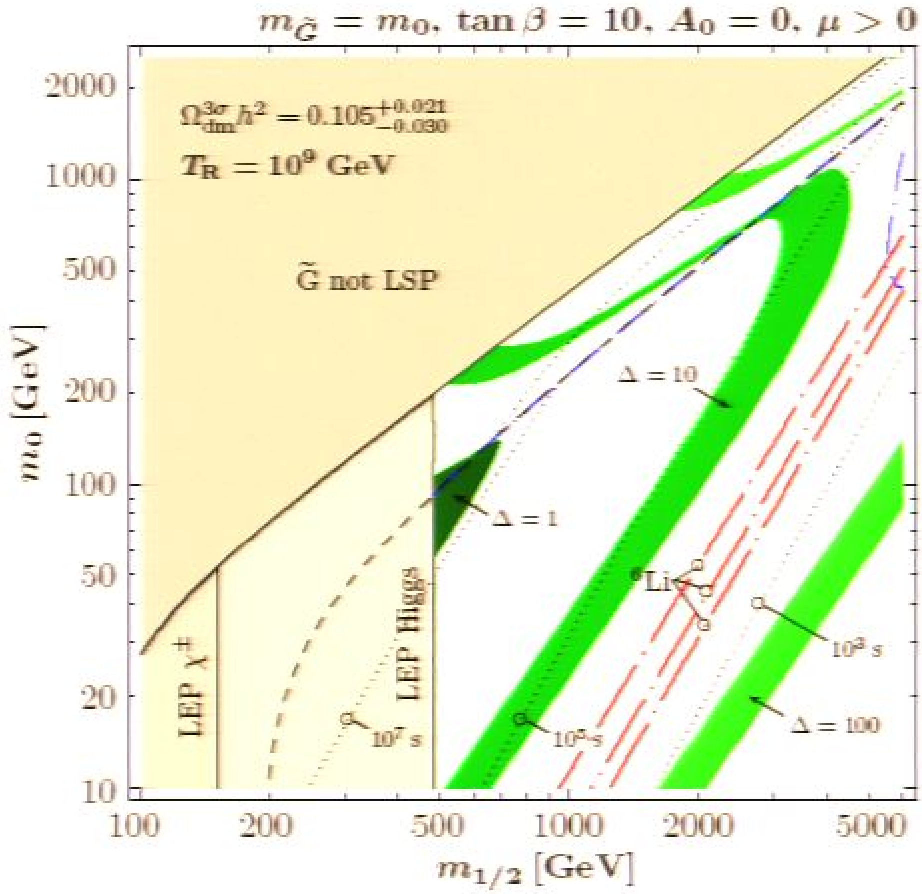


Late-time Entropy Production

$\Delta = 100 \rightarrow T_R \simeq 10^9\text{GeV}$ OK



Late-time Entropy Production

out-of-eq. decay of heavy particle X:

$$\frac{dS}{dt} = \frac{dQ}{T} = \frac{\Gamma_X \rho_X a^3}{T}$$

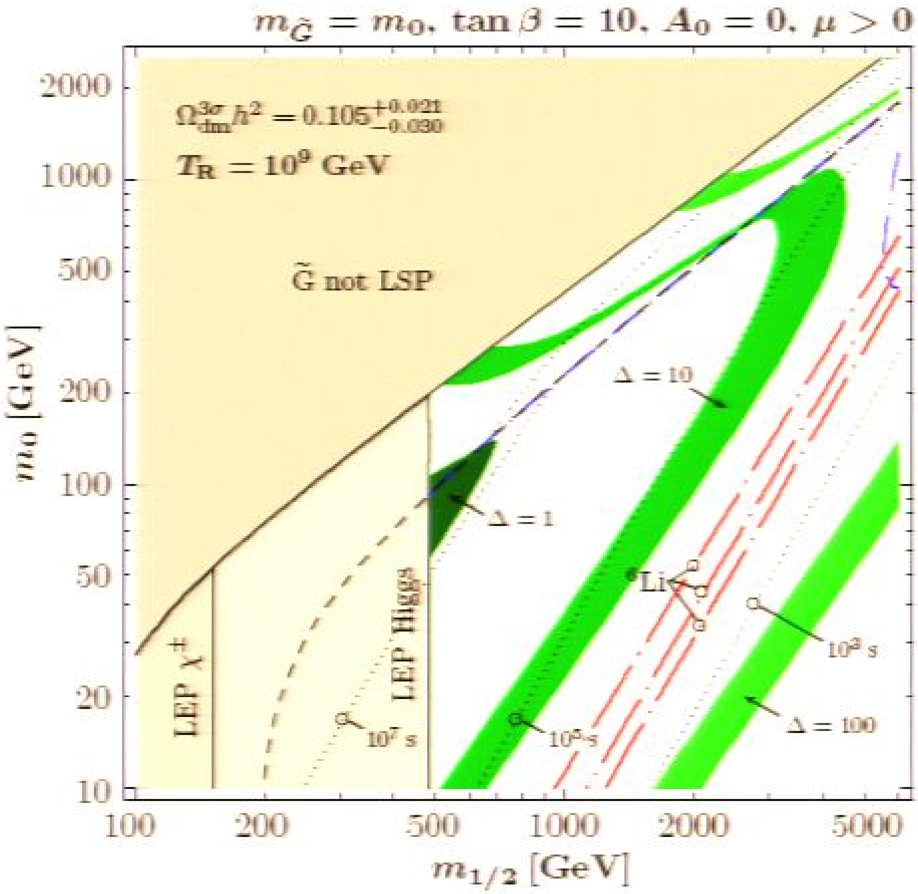
see also [Buchmüller et al., 2006]

decay *after* NLSP-decoupling:

$$Y^{\mathrm{TP}}_{\tilde{G}}(T_{\mathrm{after}}) = \frac{1}{\Delta} Y^{\mathrm{TP}}_{\tilde{G}}(T_{\mathrm{before}})$$

$$Y_{\mathrm{NLSP}}(T_{\mathrm{after}}) = \frac{1}{\Delta} Y_{\mathrm{NLSP}}(T_{\mathrm{before}})$$

$$\Delta = S(T_{\mathrm{after}}) \Big/ S(T_{\mathrm{before}})$$



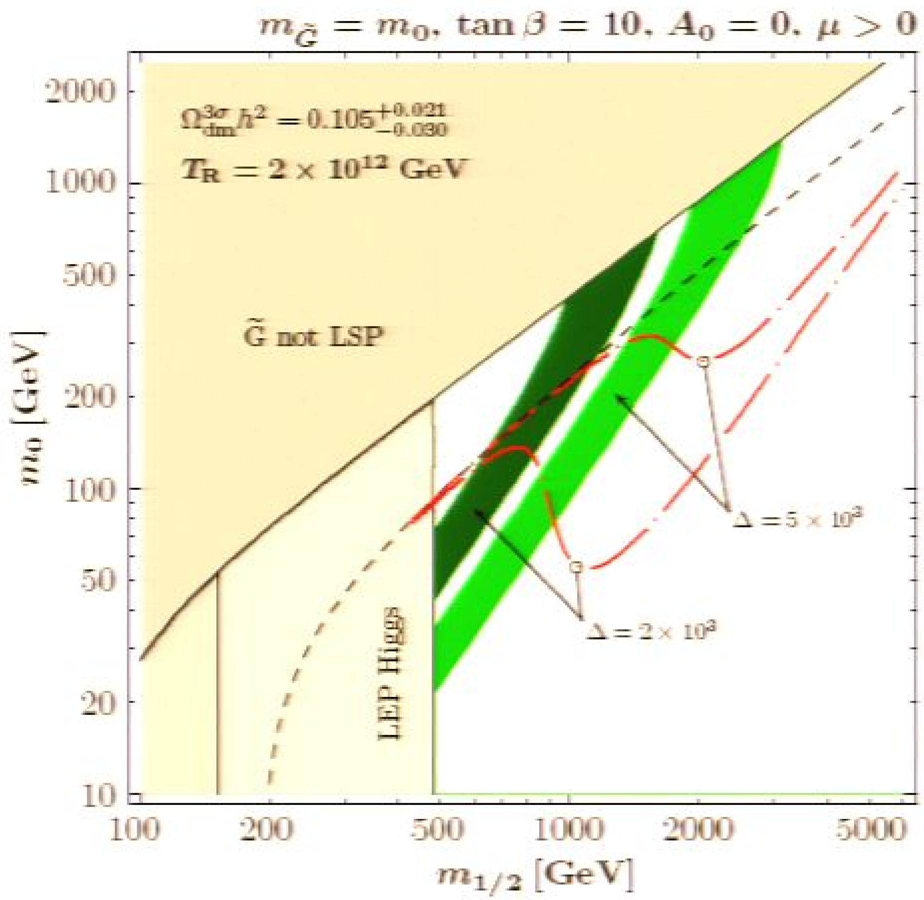
Late-time Entropy Production

$\Delta \sim 10^3, T_R \sim 10^{12}\text{GeV}$

thermal leptogenesis OK

$M_{R1} \sim T_R \sim 10^{12}$ GeV

[Buchmüller, Di Bari, Plümacher, 2002]



Conclusions

- Upper limit on T_{R} from thermal $\widetilde{G}$ production
- Severe Constraint $T_{\mathrm{R}} \lesssim 10^7\,\mathrm{GeV}$ from catalyzed BBN in the $\tilde{\tau}_1$ NLSP region in the framework of the CMSSM

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This talk summarizes

JP and F. D. Steffen, *Implications of Catalyzed BBN in the CMSSM with Gravitino Dark Matter*, arXiv:0710.2213 [hep-ph].

JP and F. D. Steffen, *Constraints on the reheating temperature in gravitino dark matter scenarios*, Phys. Lett. B **648** (2007) 224.

JP and F. D. Steffen, *Thermal gravitino production and collider tests of leptogenesis*, Phys. Rev. D **75** (2007) 023509.

No Signal
VGA-1