Constraints on the Reheating Temperature in Gravitino Dark Matter Scenarios

Josef Pradler

in Collaboration with Frank D. Steffen

Susy 07

Max-Planck-Institut
für Physik
(Werner-Heisenberg-Institut)

Properties of the Gravitino $\widetilde{G}$

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

$\rightarrow$ superpartner of graviton, spin $3/2$ Majorana field

Properties of the Gravitino $\widetilde{G}$

- $\rightarrow$ $\widetilde{G}$ is the gauge field of *local* SUSY (=SUGRA) transformations
- $\rightarrow$ superpartner of graviton, spin $3/2$ Majorana field
- $\rightarrow$ spontaneous SUSY breaking:
  - $\rightarrow$ super-Higgs mechanism:
    goldstino becomes helicity $\pm 1/2$ components of $\widetilde{G}$
    depending on breaking: $10\ \mathrm{eV} \lesssim m_{\widetilde{G}} \lesssim 100\ \mathrm{TeV}$
  - $\rightarrow$ softly broken global SUSY (e.g. MSSM) + $\widetilde{G}$ interactions

Properties of the Gravitino $\widetilde{G}$

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

$\rightarrow$ superpartner of graviton, spin $3/2$ Majorana field

$\rightarrow$ spontaneous SUSY breaking:

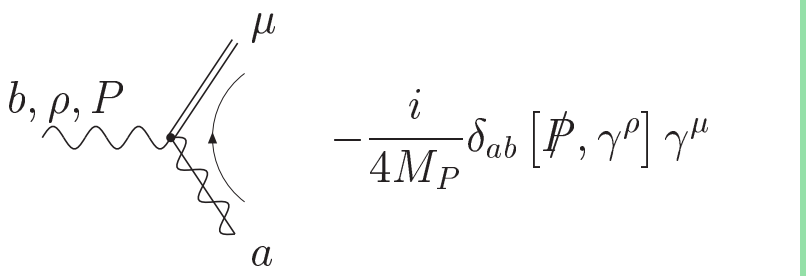
$\rightarrow$ super-Higgs mechanism:

goldstino becomes helicity $\pm 1/2$ components of $\widetilde{G}$

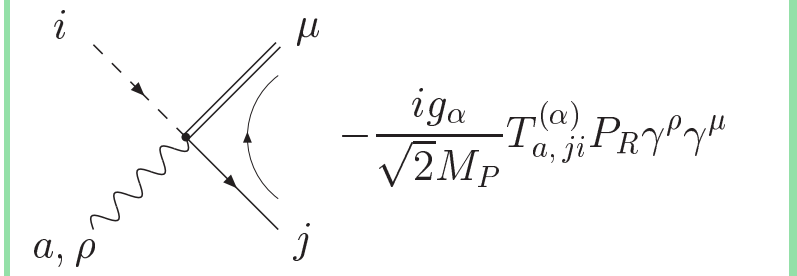
depending on breaking: $10\ \mathrm{eV} \lesssim m_{\widetilde{G}} \lesssim 100\ \mathrm{TeV}$

$\rightarrow$ softly broken global SUSY (e.g. MSSM) + $\widetilde{G}$ interactions

$\rightarrow$ couplings fixed by the symmetry, e.g.

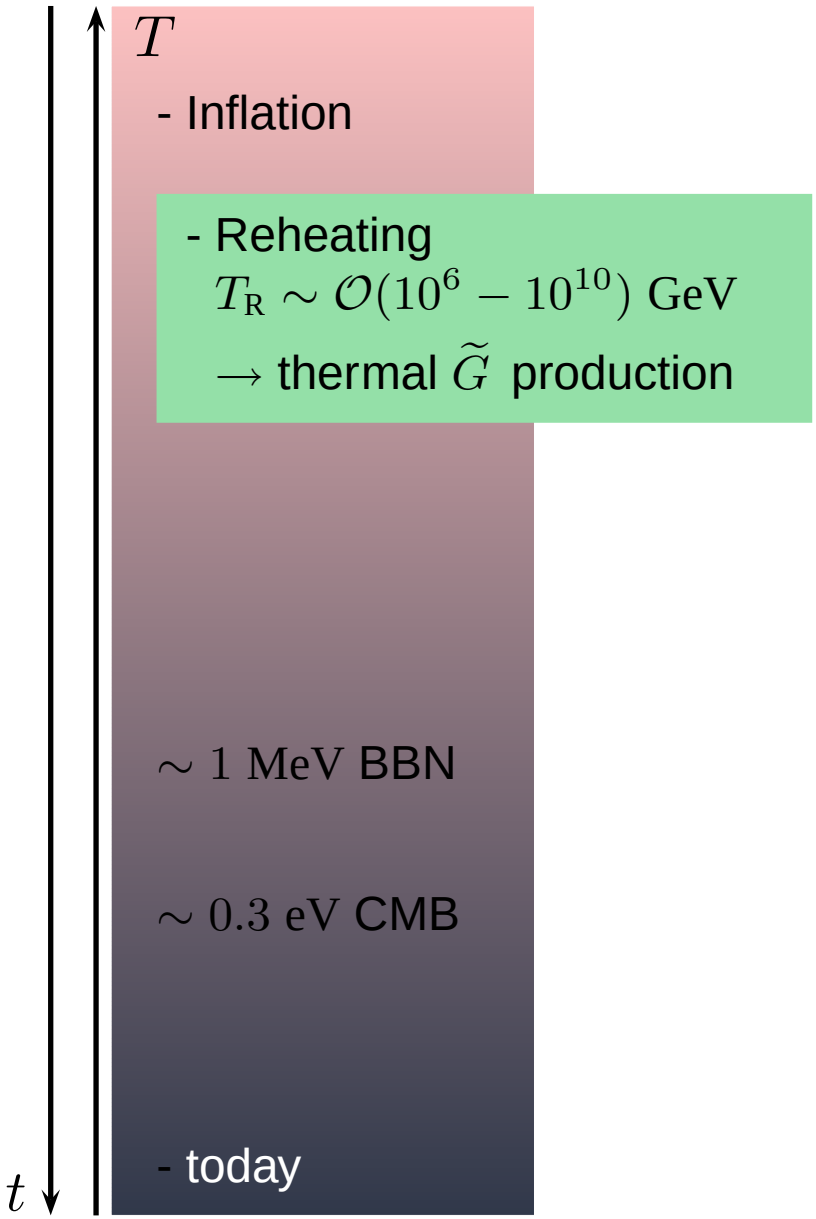


$$-\frac{i}{4M_P}\delta_{ab}\left[\not{P}, \gamma^\rho\right]\gamma^\mu$$

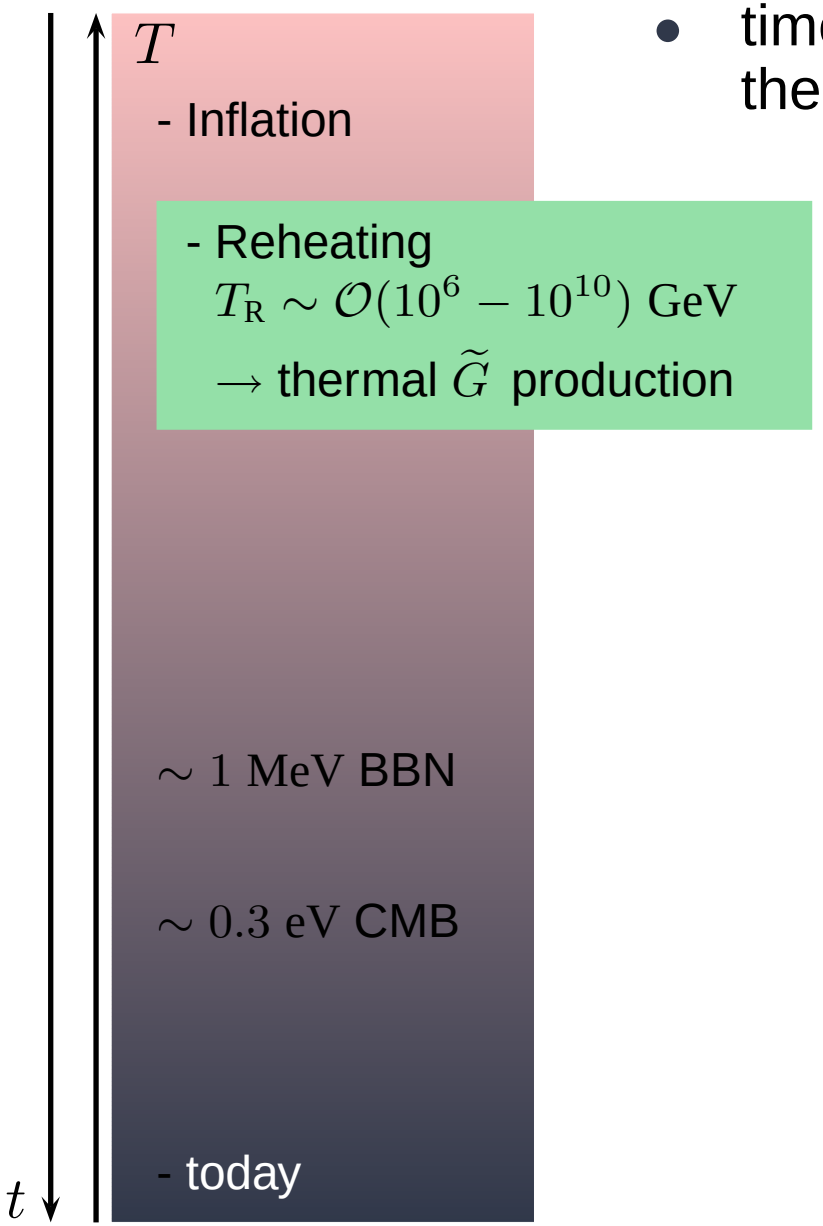


$$-\frac{ig_\alpha}{\sqrt{2}M_P}T^{(\alpha)}_{a,ji}P_R\gamma^\rho\gamma^\mu$$

Thermal Gravitino Production - Framework



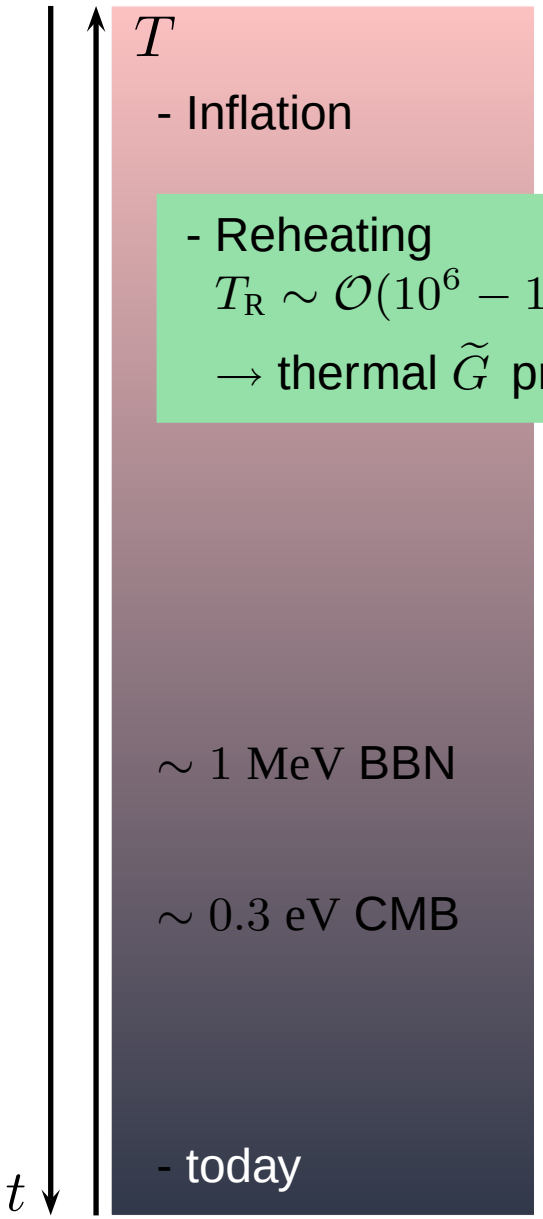
Thermal Gravitino Production - Framework



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

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

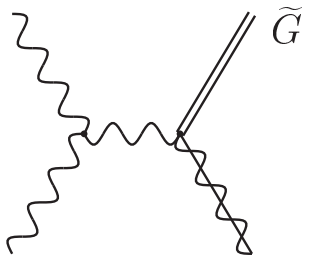
Thermal Gravitino Production - Framework



- 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, e.g.



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

[Bolz, Brandenburg, Buchmüller, 2001]

[JP, Steffen, 2006]

(see also [Rychkov, Strumia, 2007])

Gravitino Dark Matter

$\rightarrow$ solve Boltzmann equation in terms of the Yield: $Y_{\widetilde{G}}^{\mathrm{TP}} \equiv \dfrac{n_{\widetilde{G}}}{s}$

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

Gravitino Dark Matter

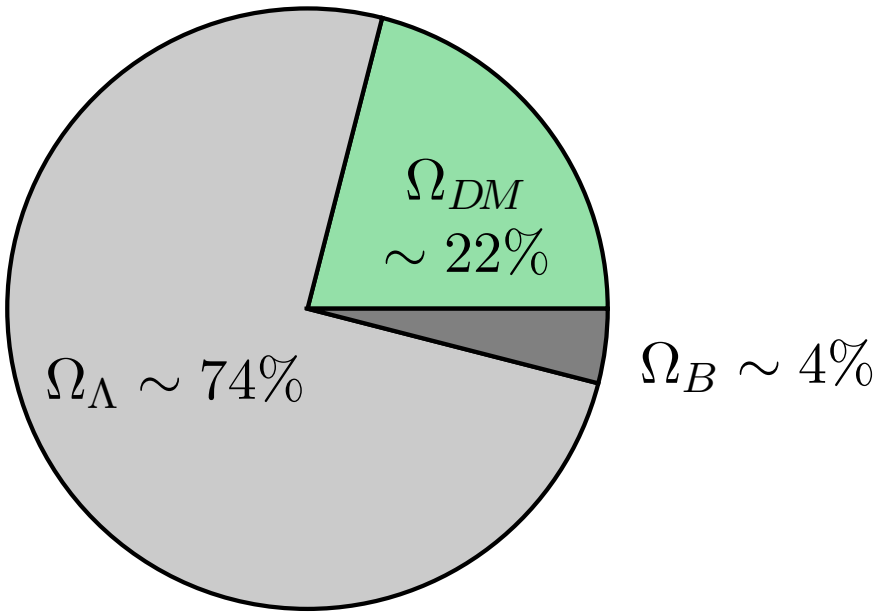
$\rightarrow$ solve Boltzmann equation in terms of the Yield: $Y_{\widetilde{G}}^{\mathrm{TP}} \equiv \frac{n_{\widetilde{G}}}{s}$

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

Assume

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

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



Upper Limit on $T_{\rm R}$ from Thermal Production

relic $\widetilde{G}$ density:

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

observed DM abundance:

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

→ upper limit on $T_{\rm R}$:

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

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

$T_{\rm R}$ ... reheating temperature $m_{\widetilde{G}}$ ... gravitino mass
M_i ... gaugino masses $y_i \ldots \mathcal{O}(10^{-12})$ $i = 3, 2, 1 \ldots \mathsf{SU(3)_C}, \mathsf{SU(2)_L}, \mathsf{U(1)_Y}$

Upper Limit on $T_{\rm R}$ from Thermal Production

relic $\widetilde{G}$ density:

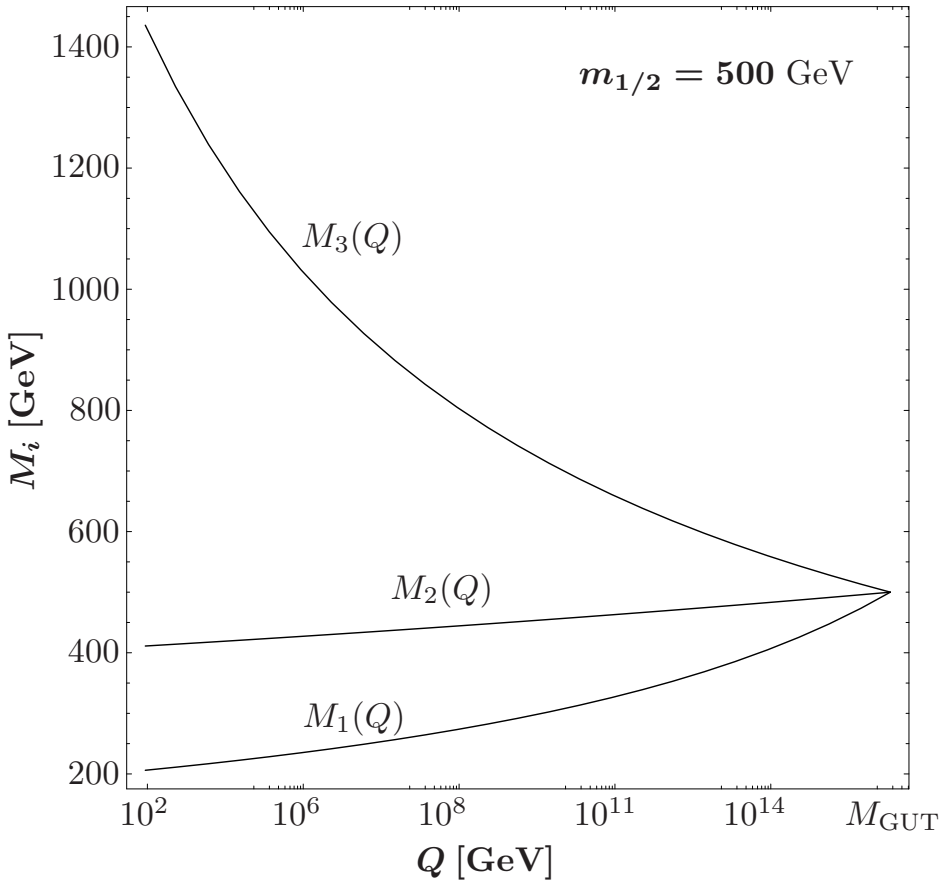
$$\Omega_{\widetilde{G}}^{\rm TP} = m_{\widetilde{G}}\, Y_{\widetilde{G}}^{\rm TP}\, s \Big/ \rho_c$$

observed DM abundance:

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

→ upper limit on $T_{\rm R}$:

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



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

$T_{\rm R}$ ... reheating temperature $m_{\widetilde{G}}$ ... gravitino mass
M_i ... gaugino masses $y_i \ldots \mathcal{O}(10^{-12})$ $i = 3, 2, 1 \ldots {\rm SU(3)_C},\ {\rm SU(2)_L},\ {\rm U(1)_Y}$

Upper Limit on $T_{\rm R}$ from Thermal Production

relic $\widetilde{G}$ density:

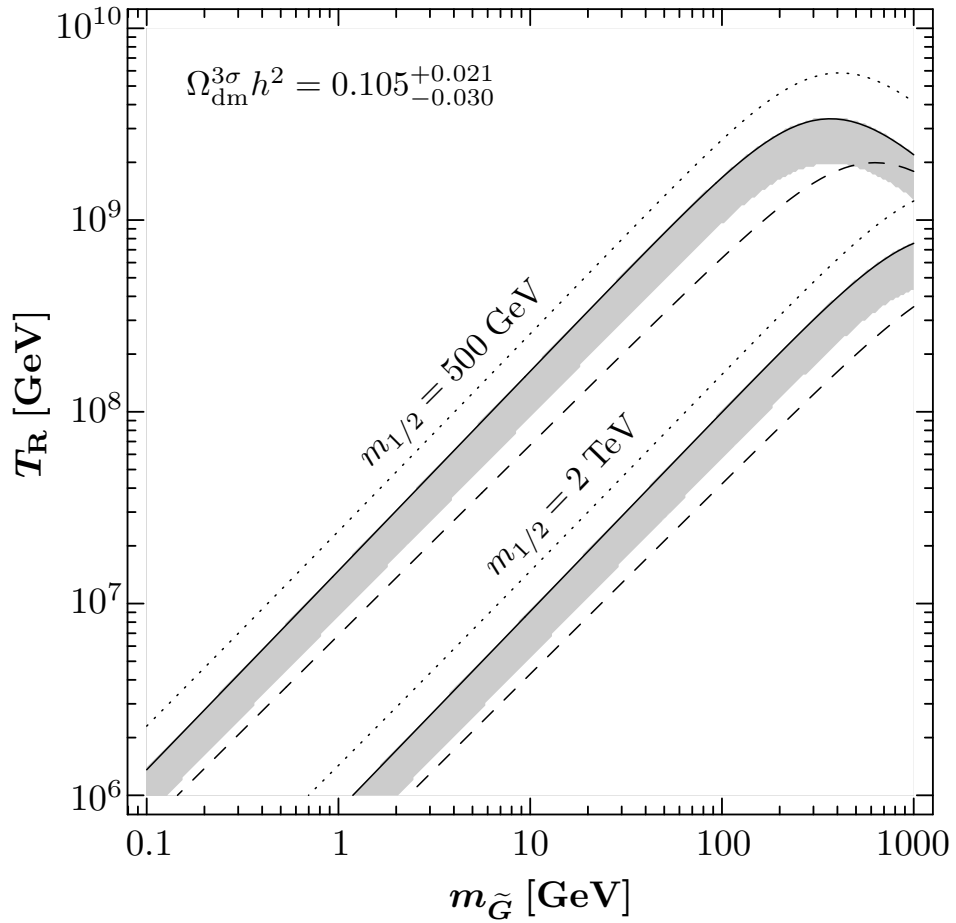
$$\Omega_{\widetilde{G}}^{\rm TP} = m_{\widetilde{G}}\, Y_{\widetilde{G}}^{\rm TP}\, s \Big/ \rho_c$$

observed DM abundance:

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

→ upper limit on $T_{\rm R}$:

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



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

$T_{\rm R}$ ... reheating temperature
M_i ... gaugino masses
$m_{\widetilde{G}}$ ... gravitino mass
$y_i \ldots \mathcal{O}(10^{-12})$
$i = 3, 2, 1 \ldots {\rm SU(3)_C},\ {\rm SU(2)_L},\ {\rm U(1)_Y}$

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

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

$$\Omega_{\widetilde{G}}^{\rm NTP} = m_{\widetilde{G}}\, Y_{\rm NLSP}\, s \Big/ \rho_c = \frac{m_{\widetilde{G}}}{m_{\rm NLSP}}\, \Omega_{\rm NLSP}$$

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

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

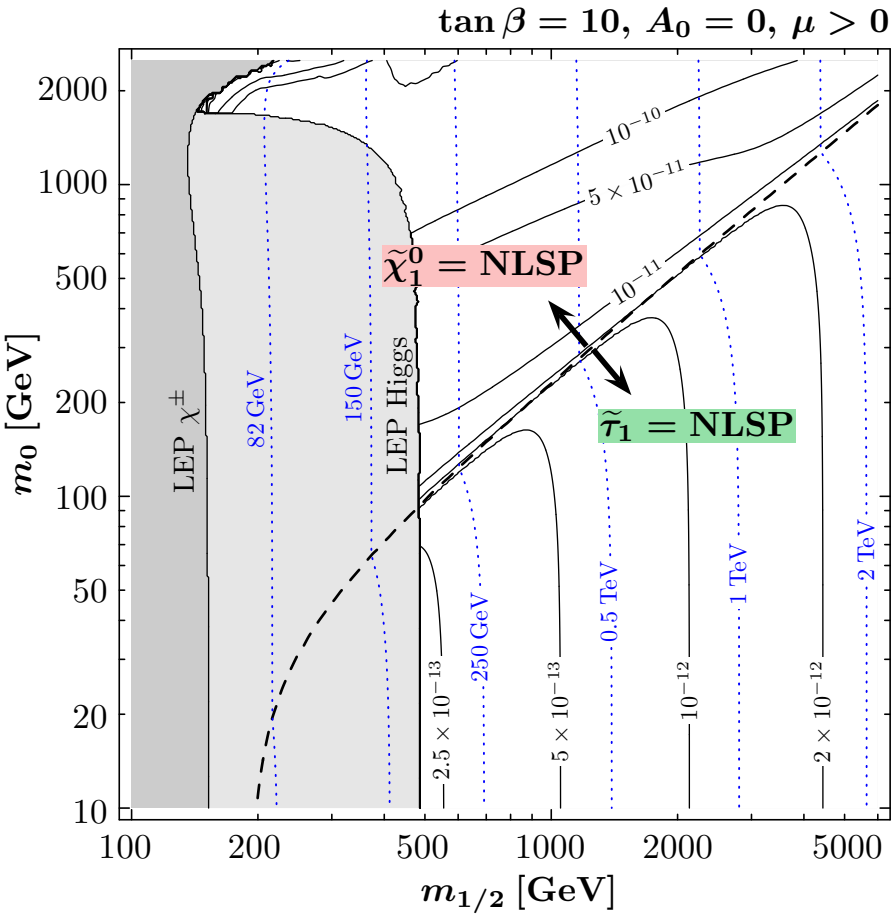
$$\Omega_{\widetilde{G}}^{\rm NTP} = m_{\widetilde{G}}\, Y_{\rm NLSP}\, s \Big/ \rho_c = \frac{m_{\widetilde{G}}}{m_{\rm NLSP}}\, \Omega_{\rm NLSP}$$

- $\widetilde{G}\,'s$ from $\phi\,'s \to$ e.g. talks by Fuminobu Takahashi and Motoi Endo

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

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

$$\Omega_{\widetilde{G}}^{\mathrm{NTP}} = m_{\widetilde{G}}\, Y_{\mathrm{NLSP}}\, s \Big/ \rho_c = \frac{m_{\widetilde{G}}}{m_{\mathrm{NLSP}}}\, \Omega_{\mathrm{NLSP}}$$



systematic study of Ω_{NLSP}

$\to$ Constrained-MSSM

- $m_{1/2}$ ... universal gaugino mass
- m_0 ... universal scalar mass
- A_0 ... universal trilinear scalar interaction
- $\tan\beta$ ... mixing angle in the Higgs sector
- sgn μ ... sign of the higgsino parameter

Constraints on $T_{\rm R}$ in the CMSSM

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

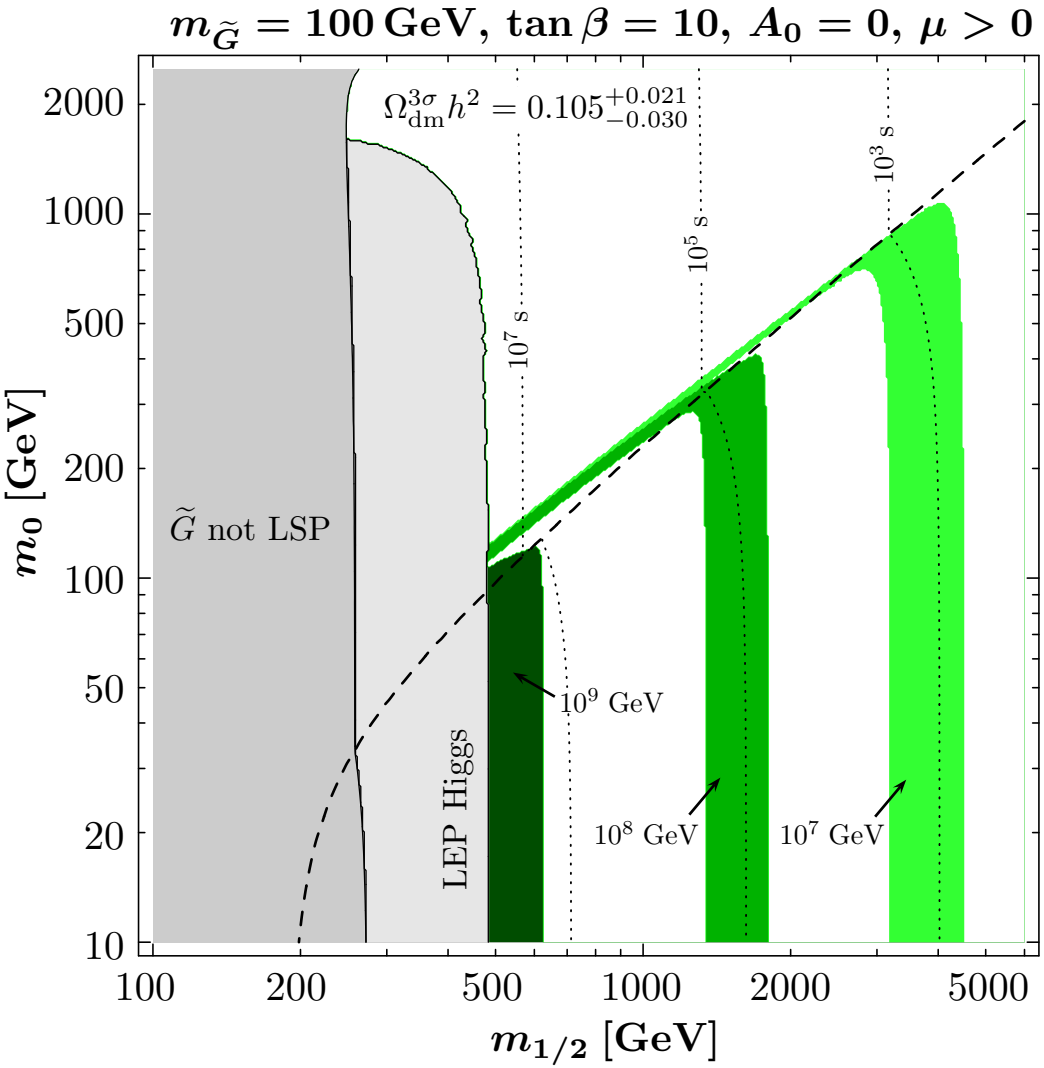
$\rightarrow$ 2 more parameters: $m_{\widetilde{G}}$ & $T_{\rm R}$

Constraints on $T_{\rm R}$ in the CMSSM

$$0.075 \leq (\Omega^{\rm TP}_{\widetilde{G}} + \Omega^{\rm NTP}_{\widetilde{G}})h^2 \leq 0.126$$

$\rightarrow$ 2 more parameters: $m_{\widetilde{G}}$ & $T_{\rm R}$

$$m_{\widetilde{G}} = 100 \text{ GeV}$$

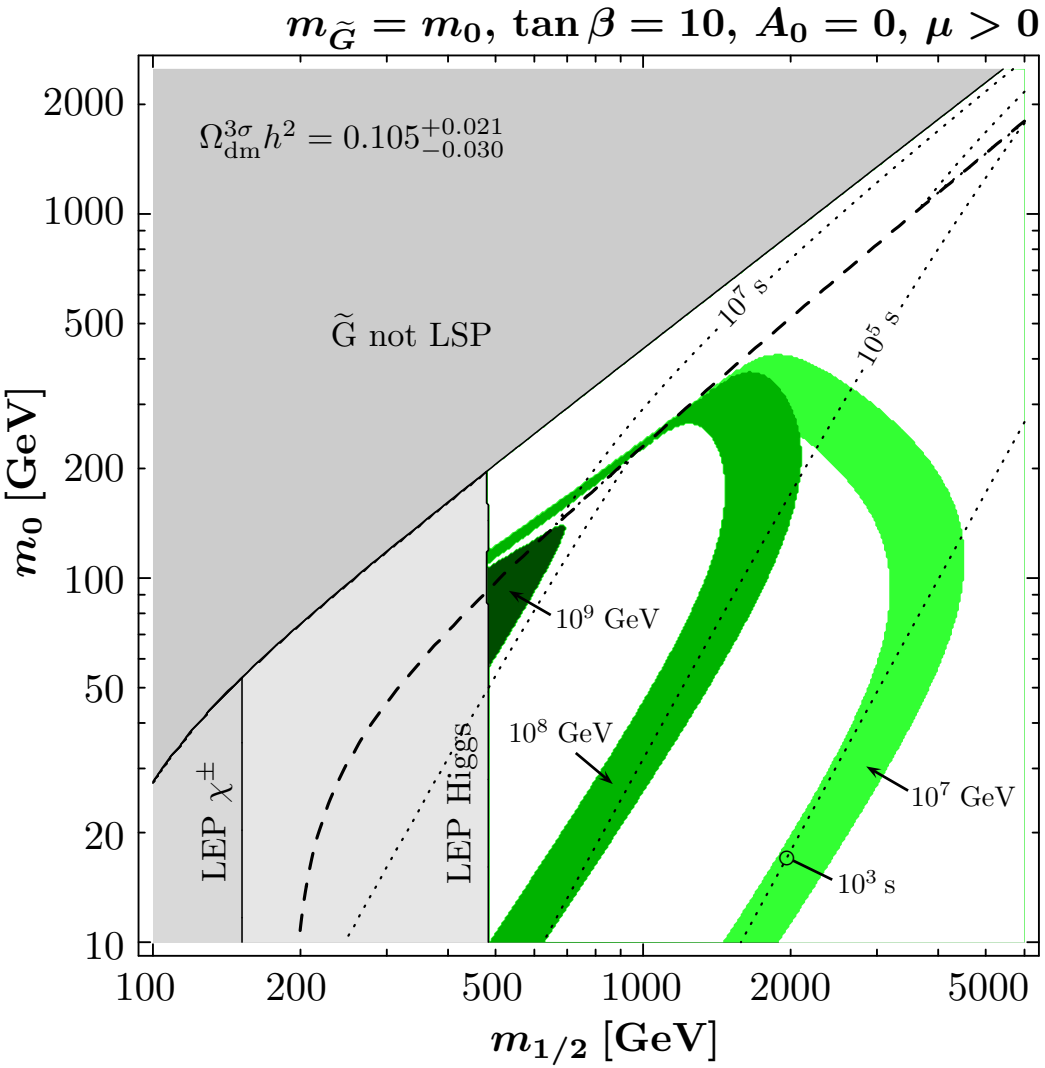


Constraints on $T_{\rm R}$ in the CMSSM

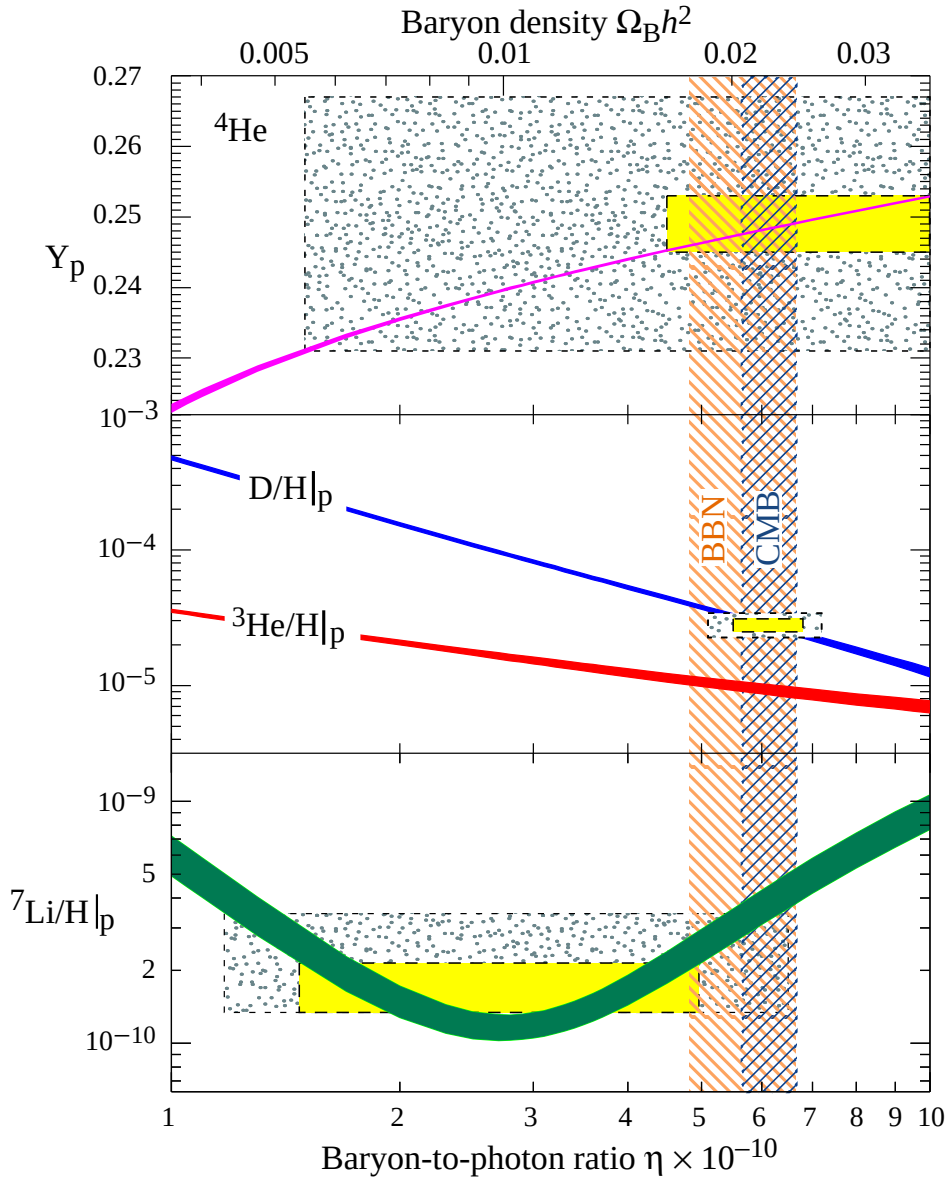
$$0.075 \leq (\Omega^{\rm TP}_{\widetilde{G}} + \Omega^{\rm NTP}_{\widetilde{G}})h^2 \leq 0.126$$

$\rightarrow$ 2 more parameters: $m_{\widetilde{G}}$ & $T_{\rm R}$

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



Big Bang Nucleosynthesis (BBN)



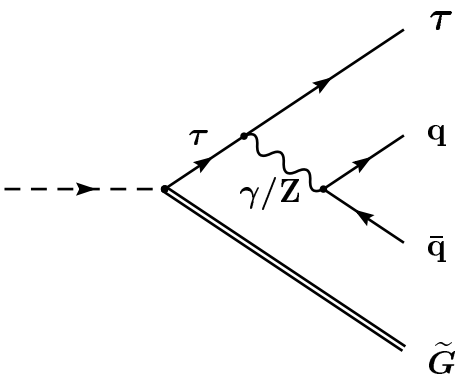
[Fields, Sarkar, PDG2006]

Beyond the Standard Model:

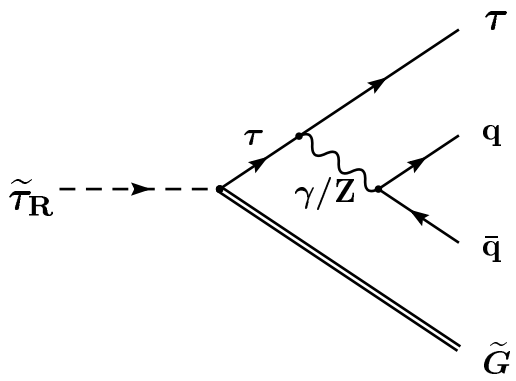
Timing “extra neutrino species”

Non-thermal nuclear reactions

Bounds from BBN

- NLSP can decay during/after BBN, e.g. $\widetilde{\tau}_{\mathrm{R}}$ 

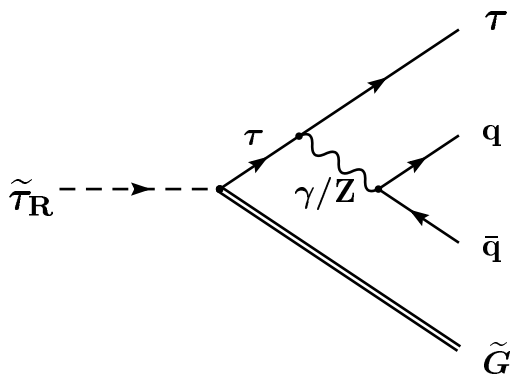
Bounds from BBN

- NLSP can decay during/after BBN, e.g. 

- electromagnetic and hadronic energy release by decay products affect abundances of light elements, i.e., D, He, and Li

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

Bounds from BBN

- NLSP can decay during/after BBN, e.g. 

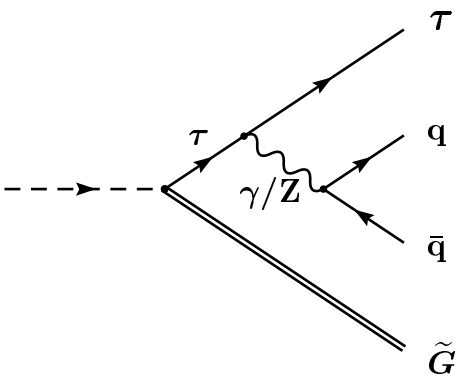
- electromagnetic and hadronic energy release by decay products affect abundances of light elements, i.e., D, He, and Li

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

- $\tilde{\chi}_1^0$ NLSP completely disfavoured in CMSSM
  $\tilde{\tau}_1$ region: BBN bounds important but much less severe

  e.g. [Ellis et al., 2004; Feng et al., 2004; Cerdeño et al., 2006; Steffen, 2006; Cyburt et al., 2006]

Bounds from BBN

- NLSP can decay during/after BBN, e.g. $\tilde{\tau}_{\mathrm{R}}$ 

- electromagnetic and hadronic energy release by decay products affect abundances of light elements, i.e., D, He, and Li

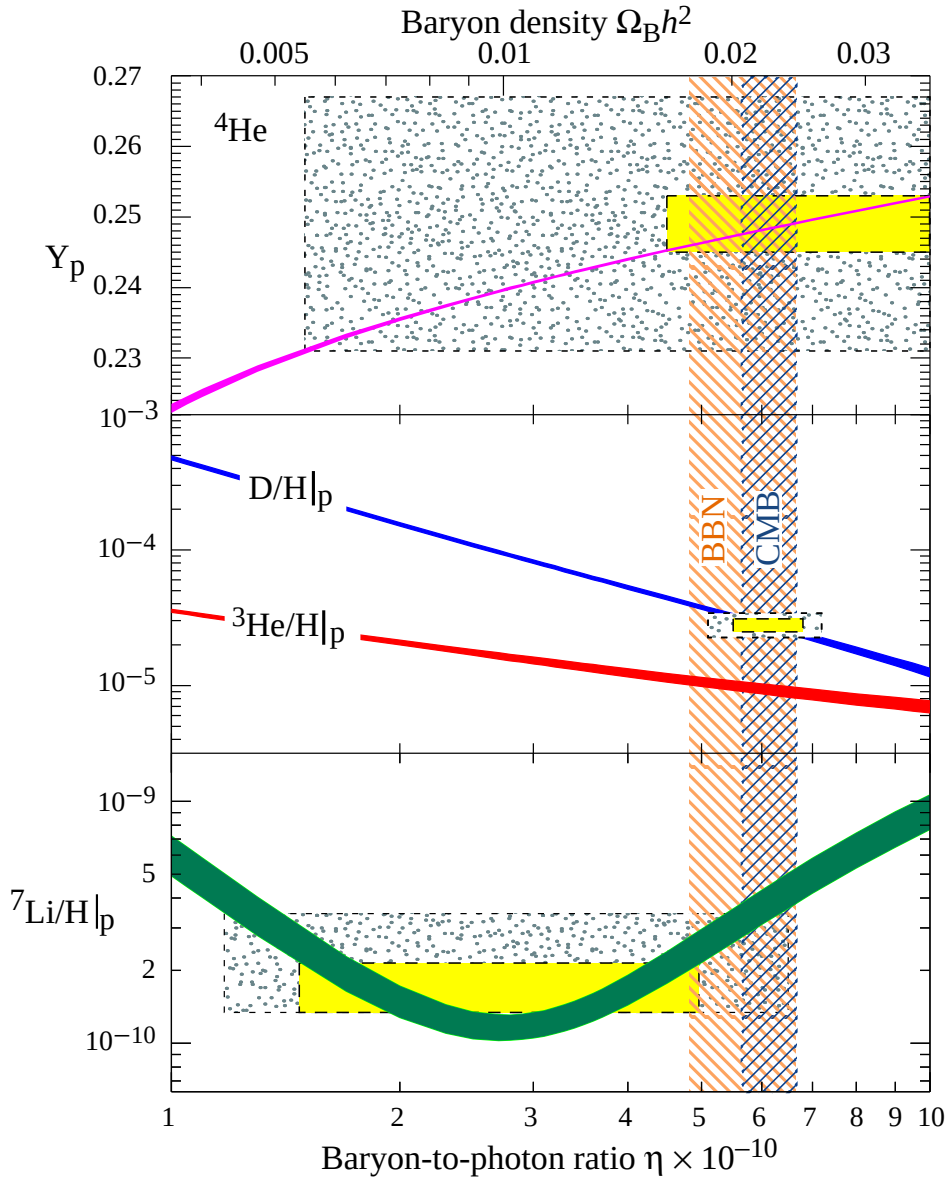
$\rightarrow$ contraints on $m_{\tilde{G}}$, m_{NLSP} and Y_{NLSP}

- $\tilde{\chi}_1^0$ NLSP completely disfavoured in CMSSM
  $\tilde{\tau}_1$ region: BBN bounds important but much less severe

  e.g. [Ellis et al., 2004; Feng et al., 2004; Cerdeño et al., 2006; Steffen, 2006; Cyburt et al., 2006]

$\rightarrow$ picture changed!

Big Bang Nucleosynthesis (BBN)



[Fields, Sarkar, PDG2006]

Beyond the Standard Model:

Timing “extra neutrino species”

Non-thermal nuclear reactions

“catalyzed BBN”

Catalyzed BBN

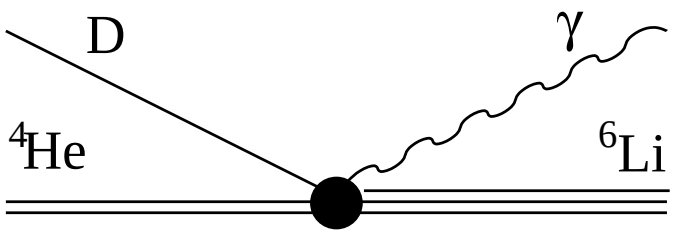
- bound-state formation of X^- with light elements opens up new reaction channels

Catalyzed BBN

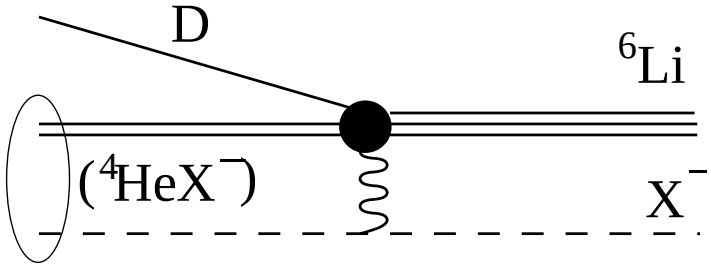
- bound-state formation of X^- with light elements opens up new reaction channels

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

standard BBN:
$\rightarrow \langle \sigma_\mathrm{S} v \rangle$



catalyzed BBN:
$\rightarrow \langle \sigma_\mathrm{C} v \rangle$



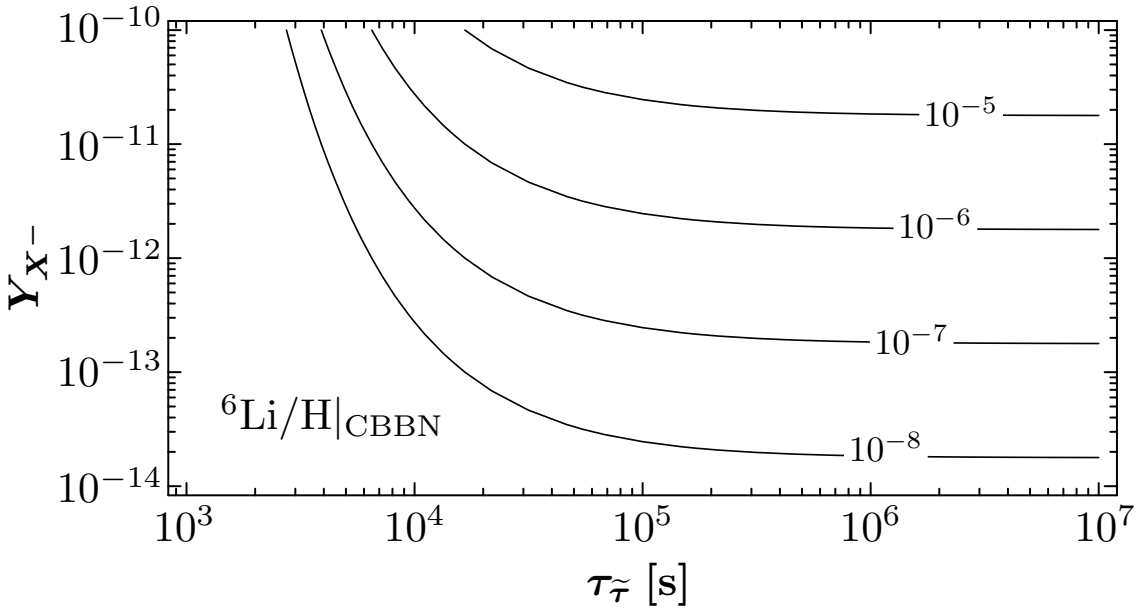
cross-section enhanced by 7 orders of magnitude

Catalyzed BBN

- bound-state formation of X^- with light elements opens up new reaction channels
- most significant for production of $^6\mathrm{Li}$ [Pospelov, 2006]
- recent result for $^6\mathrm{Li}$ production cross section $\langle \sigma_{\mathrm{C}} v \rangle$ [Hamaguchi et al., 2007]

Catalyzed BBN

- bound-state formation of X^- with light elements opens up new reaction channels
- most significant for production of $^6\mathrm{Li}$ [Pospelov, 2006]
- recent result for $^6\mathrm{Li}$ production cross section $\langle \sigma_\mathrm{C} v \rangle$ [Hamaguchi et al., 2007]



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

[Cyburt et al., 2002]

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

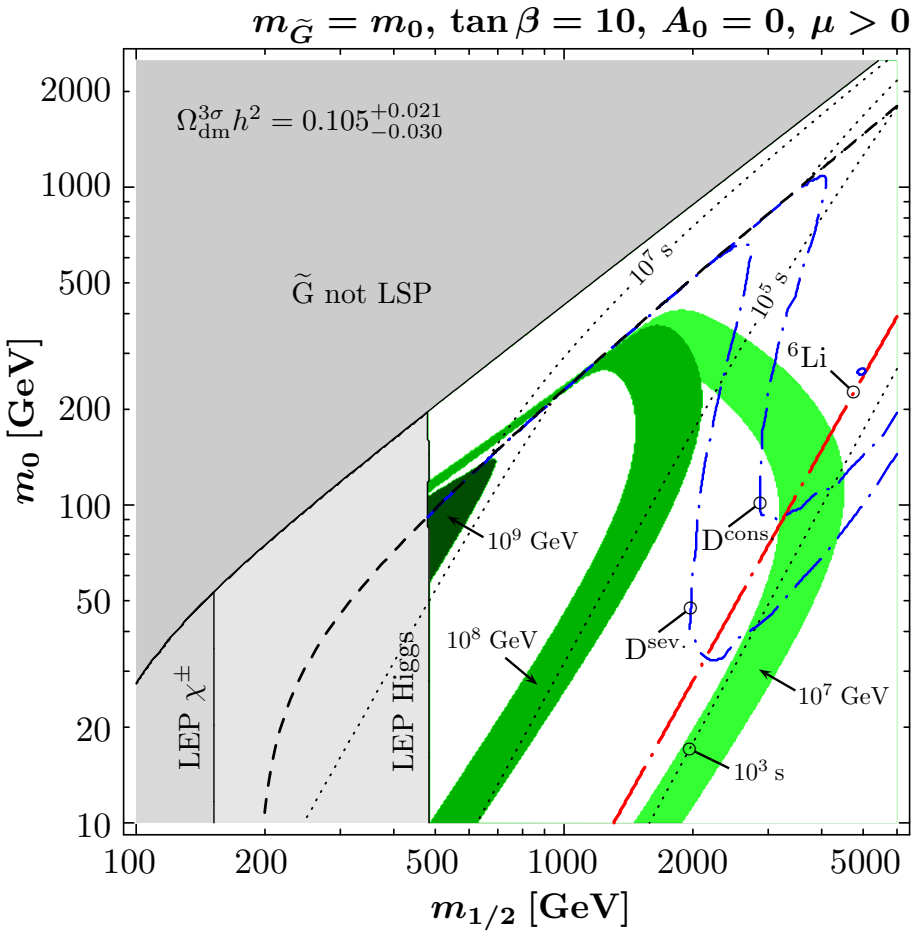
Catalyzed BBN

- bound-state formation of X^- with light elements opens up new reaction channels
- most significant for production of $^6\mathrm{Li}$ [Pospelov, 2006]
- recent result for $^6\mathrm{Li}$ production cross section $\langle \sigma_\mathrm{C} v \rangle$ [Hamaguchi et al., 2007]
- For additional constraints on $^4\mathrm{He}$, $^3\mathrm{He}/\mathrm{D}$, D, $^7\mathrm{Li}$ and $^6\mathrm{Li}/^7\mathrm{Li}$ see e.g. [Sigl et al., 1995, Jedamzik, 2000, 2004, 2006; Kawasaki et al. 2005; Cyburt et al., 2006; Kawasaki et al., 2007]
  $\longrightarrow$ talk by Vassilis Spanos

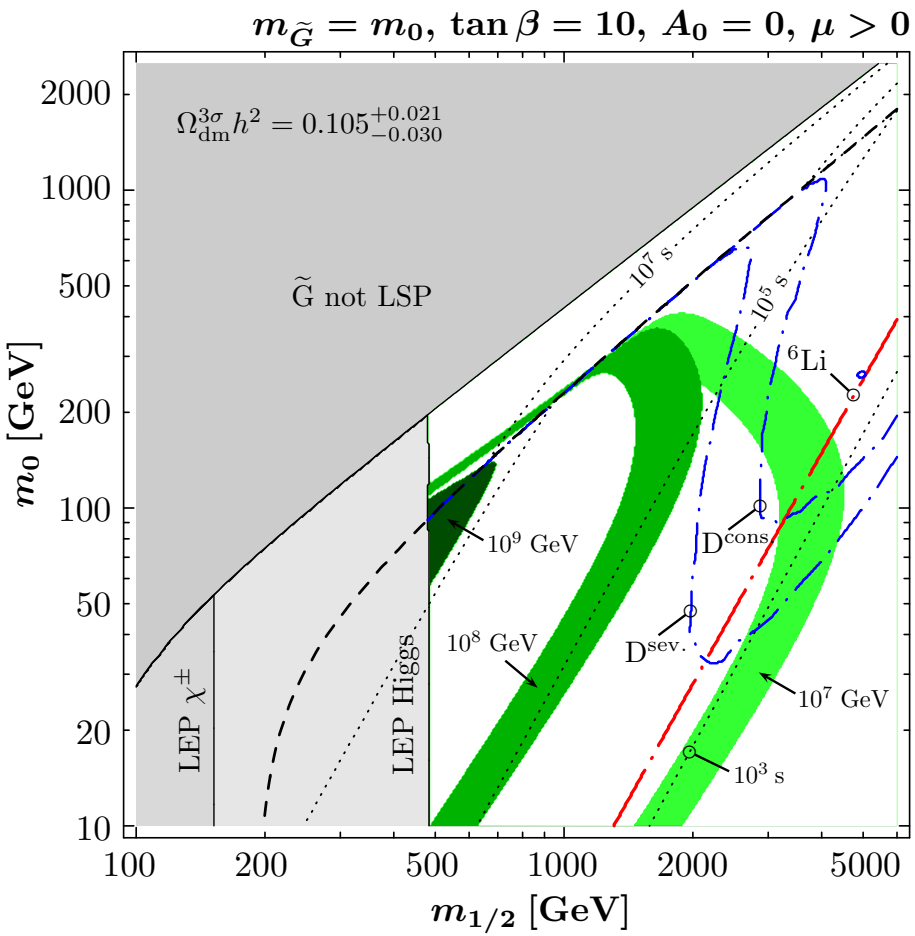
Catalyzed BBN

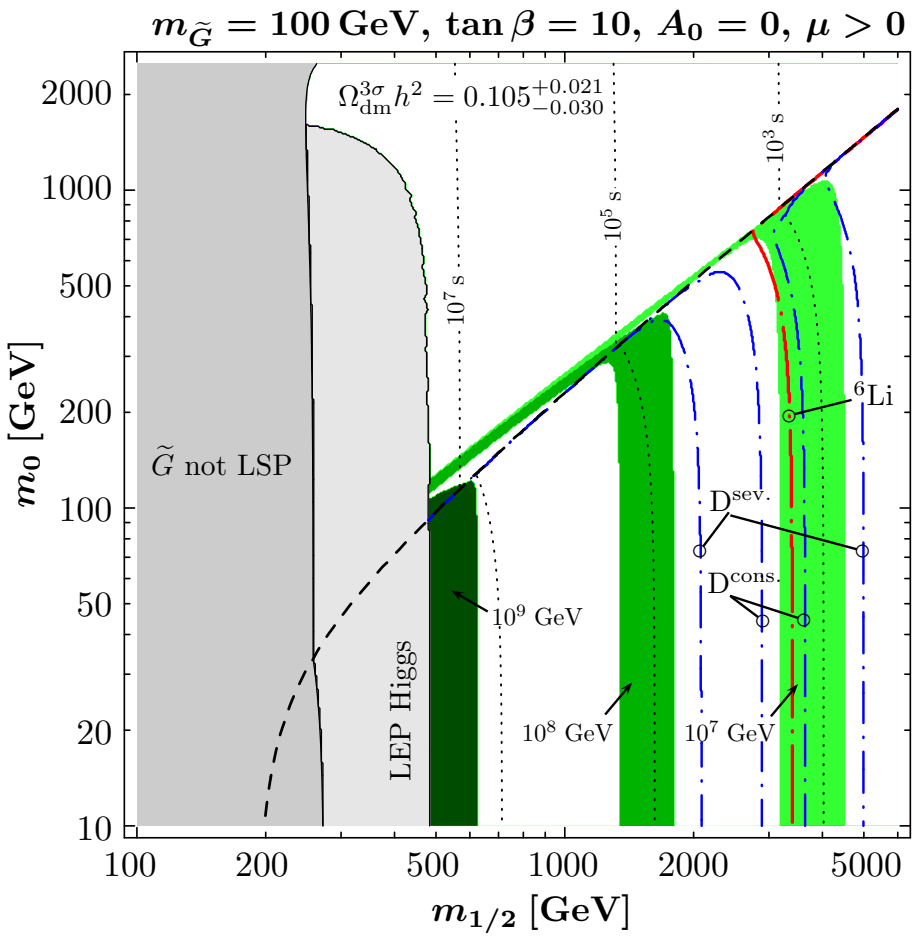
- bound-state formation of X^- with light elements opens up new reaction channels
- most significant for production of $^6\mathrm{Li}$ [Pospelov, 2006]
- recent result for $^6\mathrm{Li}$ production cross section $\langle \sigma_\mathrm{C} v \rangle$ [Hamaguchi et al., 2007]
- For additional constraints on $^4\mathrm{He}$, $^3\mathrm{He}/\mathrm{D}$, D, $^7\mathrm{Li}$ and $^6\mathrm{Li}/^7\mathrm{Li}$ see e.g. [Sigl et al., 1995, Jedamzik, 2000, 2004, 2006; Kawasaki et al. 2005; Cyburt et al., 2006; Kawasaki et al., 2007]
  $\rightarrow$ talk by Vassilis Spanos
- $\rightarrow$ only D bound can be more severe than $^6\mathrm{Li}|_\mathrm{CBBN}$ bound
- $^6\mathrm{Li}|_\mathrm{CBBN}$ bound might vanish for $\tau_{\widetilde{\tau}} \gtrsim 10^7 \ \mathrm{s}$ [Jedamzik, 2007]

Constraints on $T_{\rm R}$ from catalyzed BBN

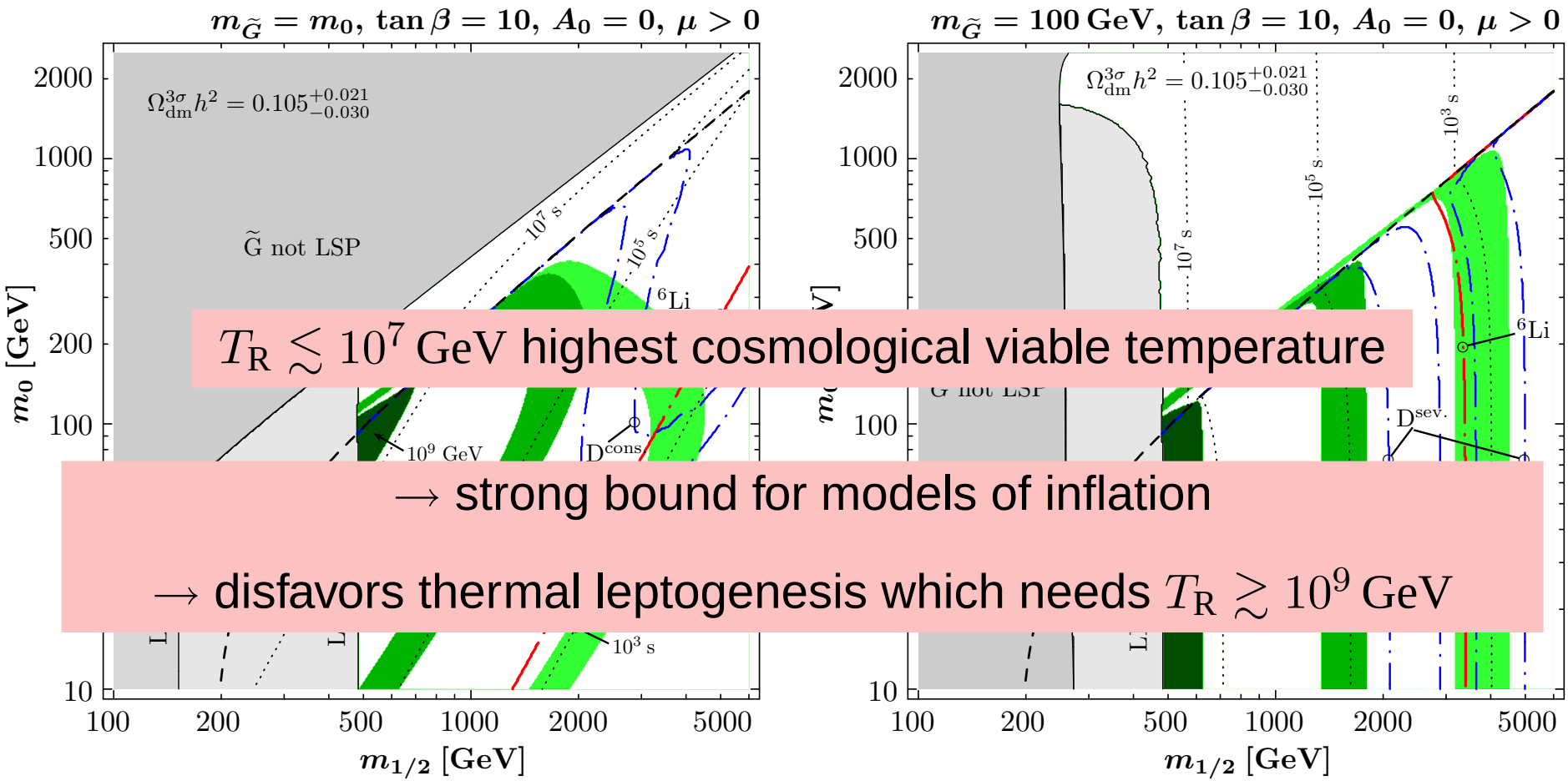


Constraints on $T_{\rm R}$ from catalyzed BBN





Constraints on $T_{\rm R}$ from catalyzed BBN



$T_{\rm R} \lesssim 10^7\,{\rm GeV}$ highest cosmological viable temperature

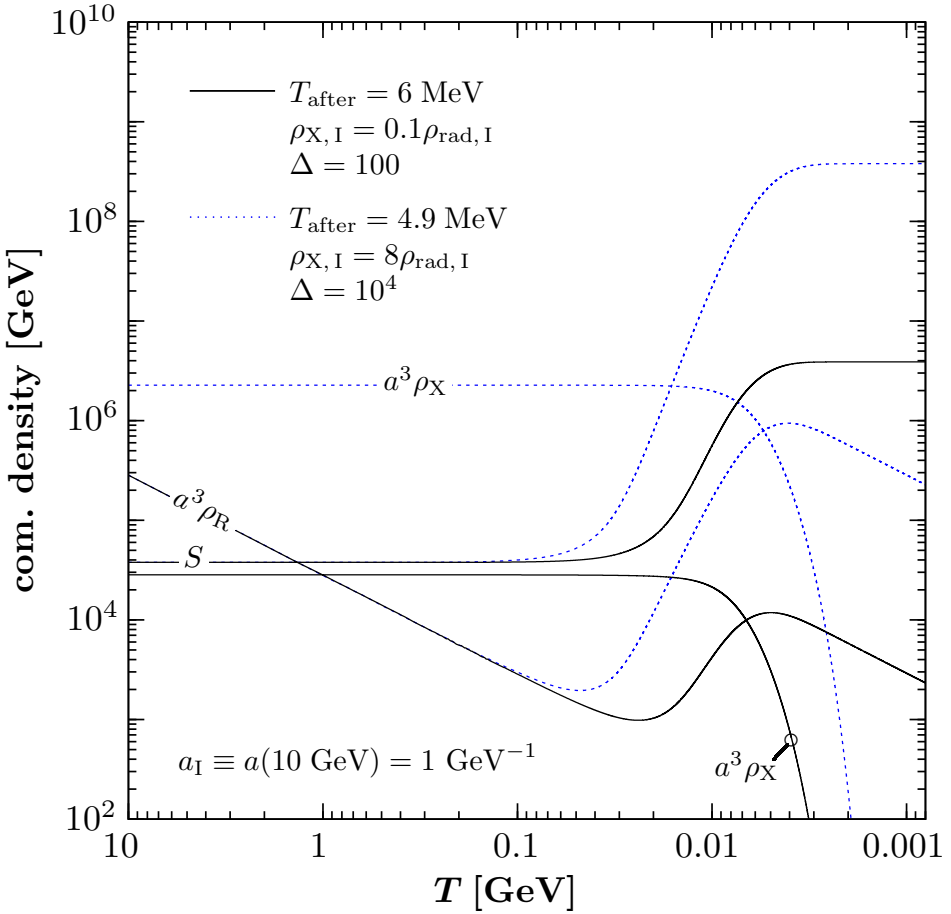
$\rightarrow$ strong bound for models of inflation

$\rightarrow$ disfavors thermal leptogenesis which needs $T_{\rm R} \gtrsim 10^9\,{\rm GeV}$

Late-time Entropy Production

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

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



Late-time Entropy Production

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

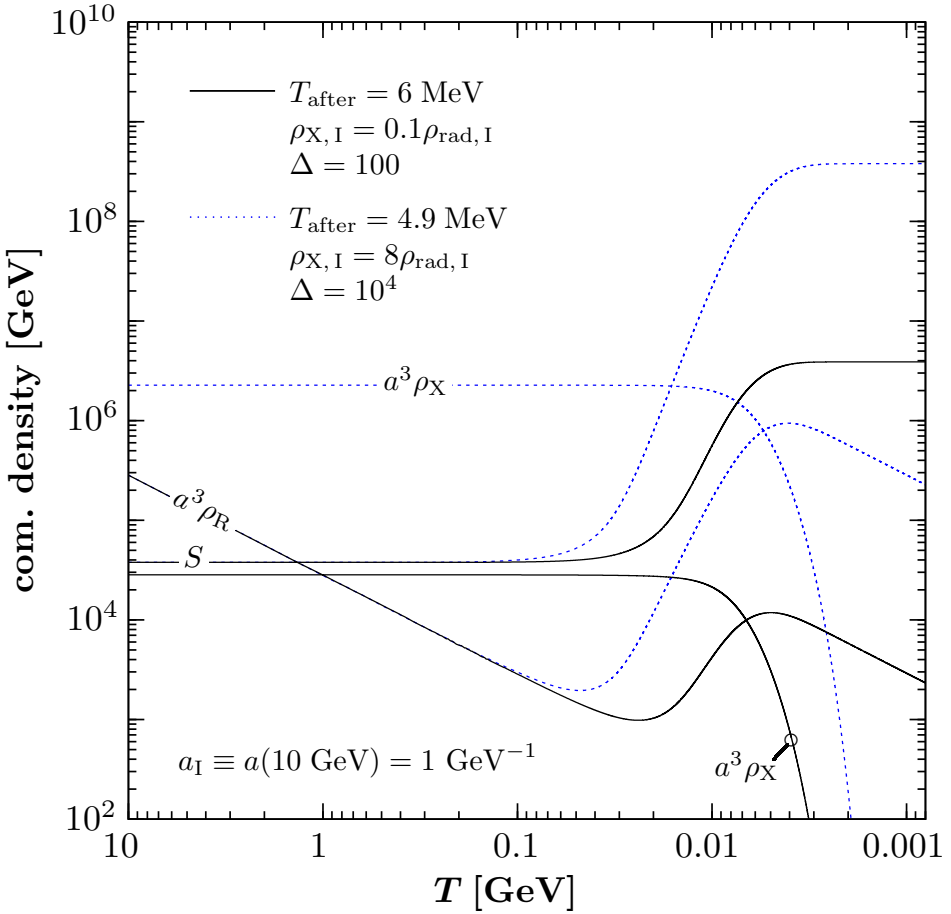
$$\frac{dS}{dt} = \frac{dQ}{T} = \frac{\Gamma_{\rm X}\rho_{\rm X}a^3}{T}$$

decay *after* NLSP-decoupling:

$$Y_{\widetilde{G}}^{\rm TP}(T_{\rm after}) = \frac{1}{\Delta}\, Y_{\widetilde{G}}^{\rm TP}(T_{\rm before})$$

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

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



Late-time Entropy Production

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

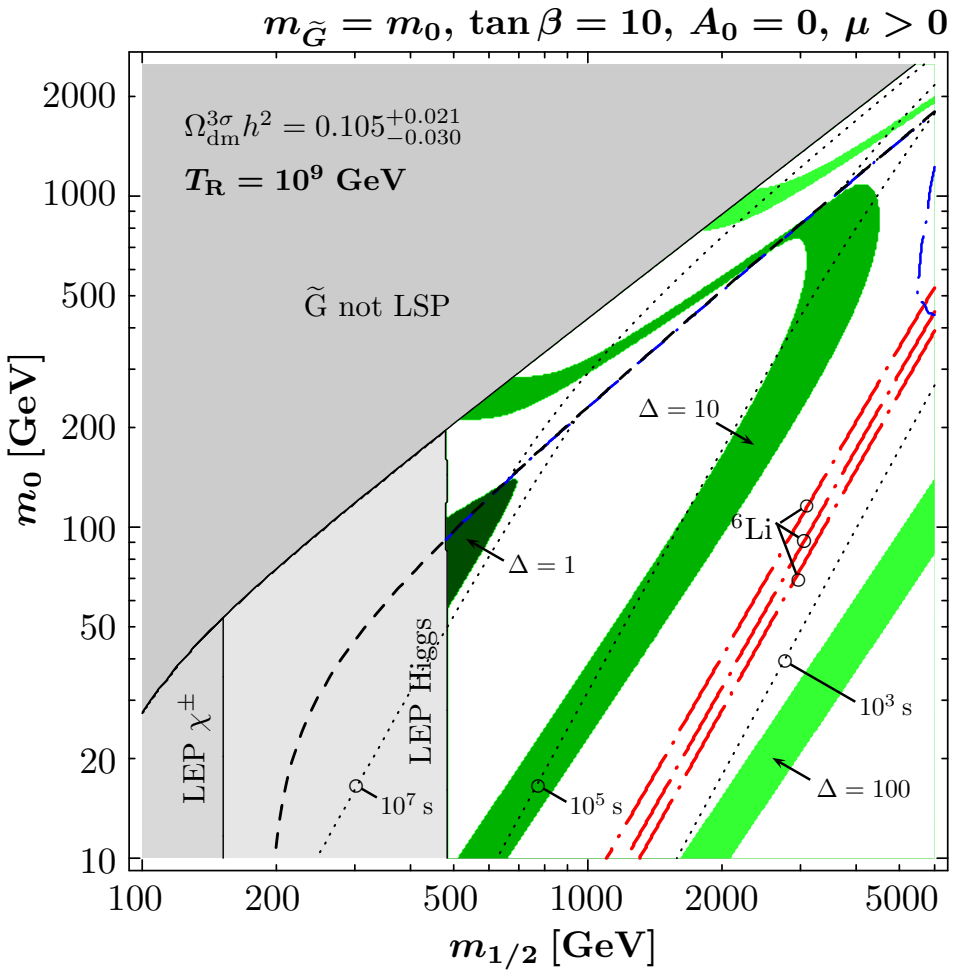
$$\frac{dS}{dt} = \frac{dQ}{T} = \frac{\Gamma_{\rm X}\rho_{\rm X}a^3}{T}$$

decay *after* NLSP-decoupling:

$$Y^{\rm TP}_{\widetilde{G}}(T_{\rm after}) = \frac{1}{\Delta}\, Y^{\rm TP}_{\widetilde{G}}(T_{\rm before})$$

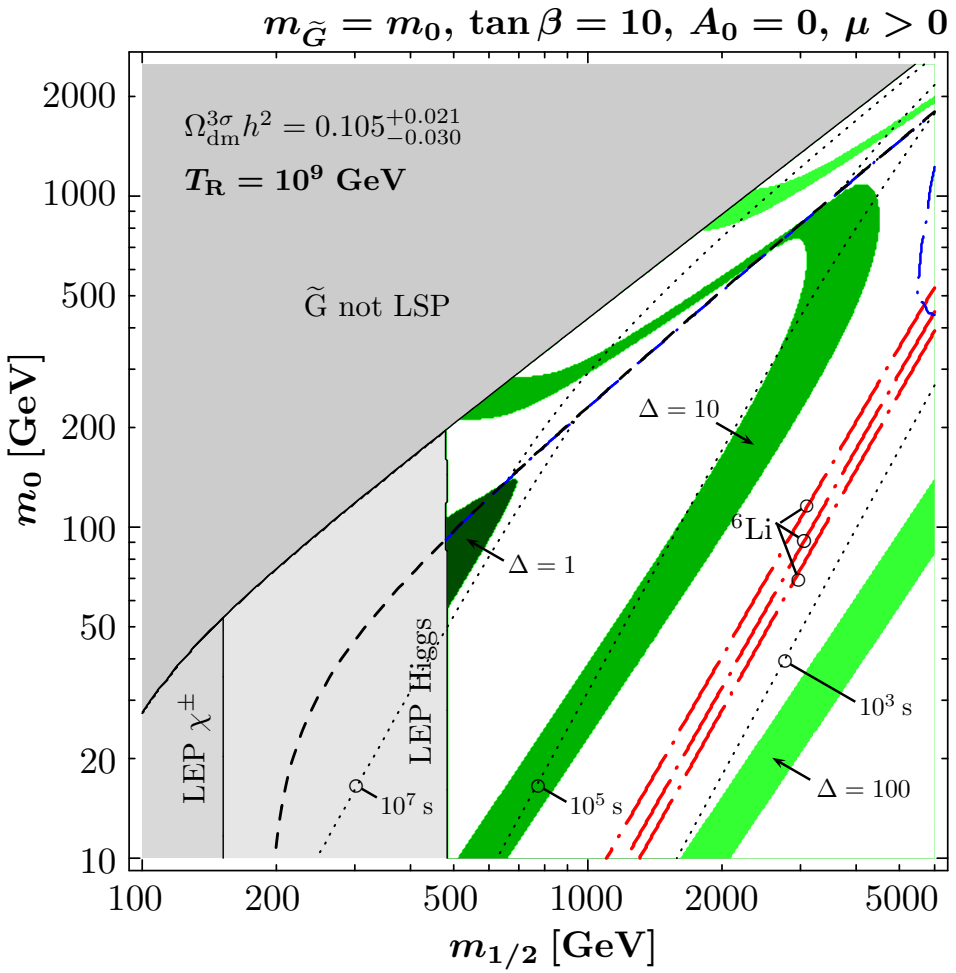
$$Y_{\rm NLSP}(T_{\rm after}) = \frac{1}{\Delta} Y_{\rm NLSP}(T_{\rm before})$$

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



Late-time Entropy Production

$$\Delta = 100 \;\rightarrow\; T_{\rm R} \simeq 10^9 {\rm GeV} \quad \text{OK}$$

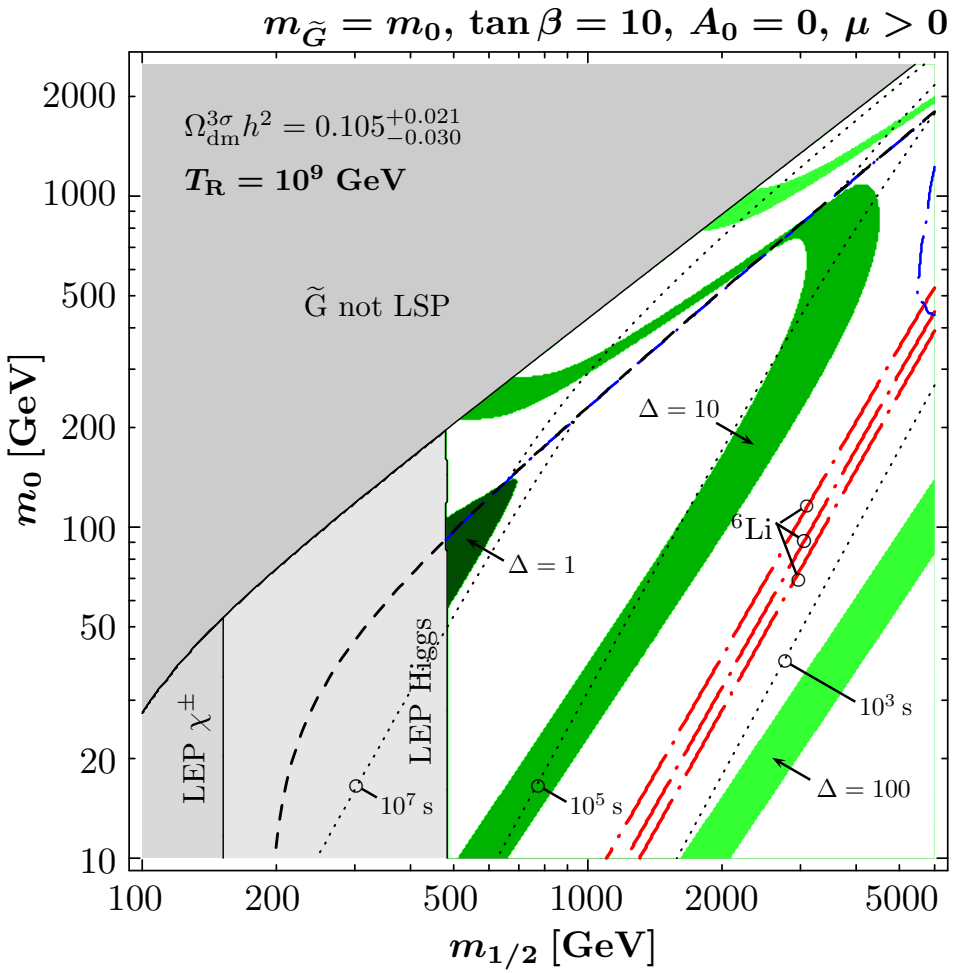


Late-time Entropy Production

$$\Delta = 100 \;\rightarrow\; T_{\rm R} \simeq 10^9 {\rm GeV} \quad \text{OK}$$

but baryon asymmetry gets diluted

$$\eta(T_{\rm after}) = \frac{1}{\Delta}\,\eta(T_{\rm before})$$



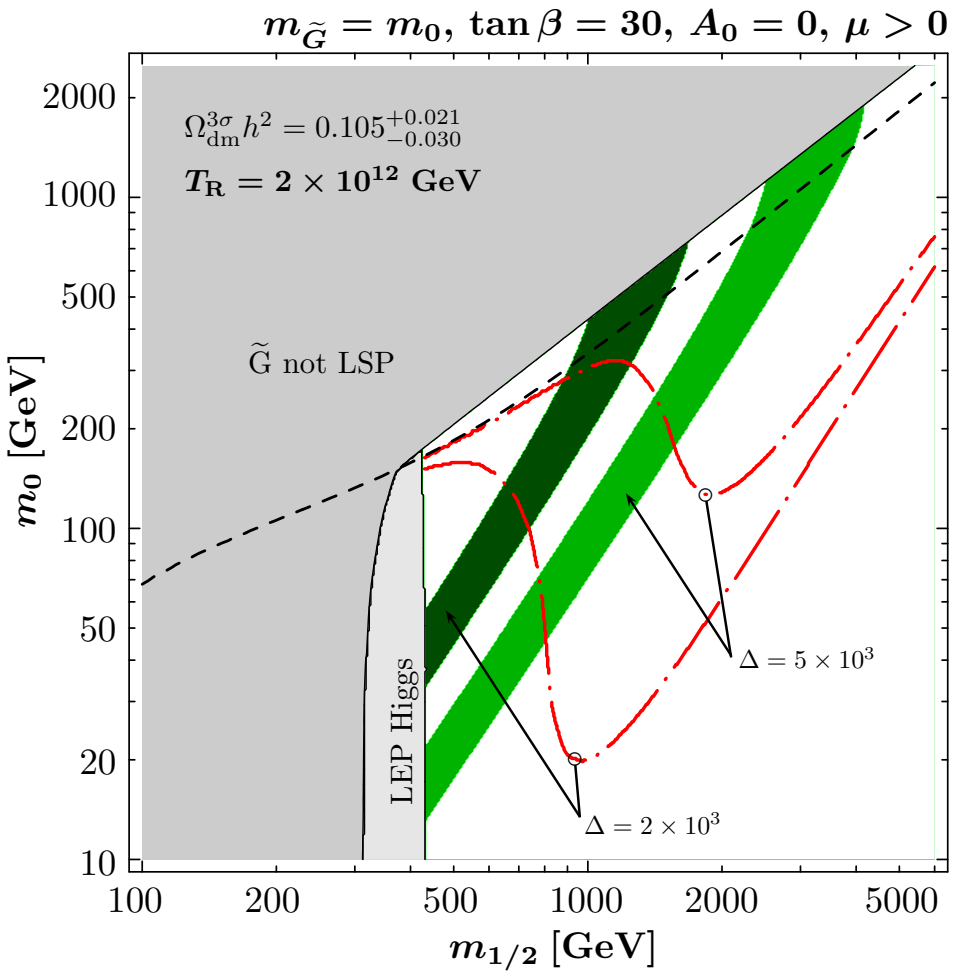
Late-time Entropy Production

$\Delta \sim 10^3$, $T_{\rm R} \sim 10^{12}$GeV

thermal leptogenesis OK

$M_{\rm R1} \sim T_{\rm R} \sim 10^{12}$ GeV

[Buchmüller, Di Bari, Plümacher, 2002]



Conclusions

[hep-ph/0612291, Phys. Lett. B 648 (2007) 224]

- Upper limit on $T_{\rm R}$ from thermal $\widetilde{G}$ production
- Constraint on $T_{\rm R}$ from catalyzed BBN in the $\tilde{\tau}_1$ NLSP region

$$T_{\rm R} \lesssim 10^7\,{\rm GeV}$$

Conclusions

[hep-ph/0612291, Phys. Lett. B 648 (2007) 224]

- Upper limit on $T_{\rm R}$ from thermal $\widetilde{G}$ production
- Constraint on $T_{\rm R}$ from catalyzed BBN in the $\tilde{\tau}_1$ NLSP region

$$T_{\rm R} \lesssim 10^7\,{\rm GeV}$$

- ways-out: - Late-time entropy production
  - R-parity violation [Buchmüller et al., 2007]
  - $\rightarrow$ talk by Alejandro Ibarra

Conclusions

[hep-ph/0612291, Phys. Lett. B 648 (2007) 224]

- Upper limit on $T_{\rm R}$ from thermal $\widetilde{G}$ production
- Constraint on $T_{\rm R}$ from catalyzed BBN in the $\tilde{\tau}_1$ NLSP region

$$T_{\rm R} \lesssim 10^7\,{\rm GeV}$$

- ways-out: - Late-time entropy production
  - R-parity violation [Buchmüller et al., 2007]
  - $\rightarrow$ talk by Alejandro Ibarra
- more on bound state effects: $\rightarrow$ talk by Vassilis Spanos
  $\rightarrow$ talk by Fumihiro Takayama