Gravitino, dark matter candidate and BBN

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LAPTH, Annecy

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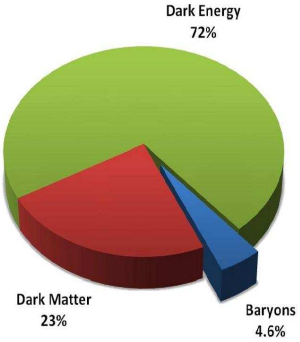
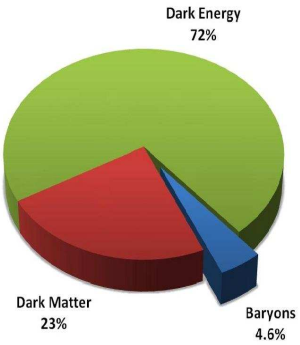
SB, K. Jedamzik, G. Moultaka, Phys.Rev.D80:063509,2009.
SB, K.Y. Choi, K. Jedamzik, L. Roszkowski, JHEP 0905:103,2009.
SB, JCAP 1103:022,2011.



A few questions

- What is Dark Energy ?
- What is Dark Matter ?
  - SUSY particles
- How is matter produced in the Early Universe ?
  - Big Bang Nucleosynthesis
  - Lithium problems
- Where is the antimatter ?
  - Baryogenesis, leptogenesis



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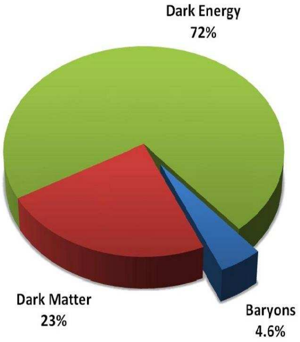

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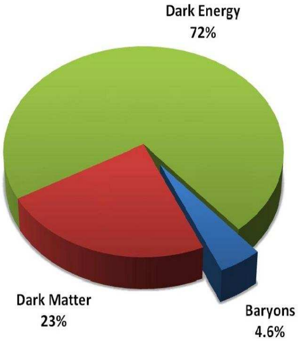

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A simple framework

- Extension of the Standard Model: Supersymmetry
- Constrained Minimal Supersymmetric Standard Model (CMSSM)
- Lightest Supersymmetric Particle (LSP): gravitino
- Conservation of R-parity

In this scenario

- The gravitino is a good candidate for dark matter
- The decay of the Next-to-LSP to the LSP during BBN can solve the lithium problem

However

- The constraints require low reheating temperature and heavy mass spectrum
- Non-standard cosmology with a modified Hubble parameter

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Symmetry between bosons and fermions

$$Q\,|\text{fermion}\rangle = |\text{boson}\rangle \qquad Q\,|\text{boson}\rangle = |\text{fermion}\rangle$$

New particles with same mass as SM partners

Broken symmetry

- No observation of superpartners
- SUSY breaking mechanism is unknown
- Explicit breaking terms included in effective SUSY lagrangian

CMSSM: $m_{1/2}, \quad m_0, \quad A_0, \quad \tan\beta, \quad \text{sgn}\,\mu$

R-parity conservation

$$P_R = (-1)^{3B+L+2S}$$

The lightest SUSY particle is stable

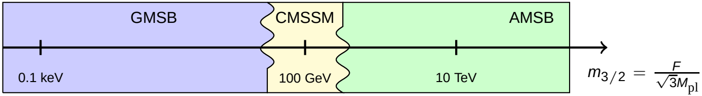
Gravitino

Supergravity

- If supersymmetry is a broken local symmetry: supergravity
- Graviton and its superpartner, the gravitino $\tilde{G}$ ($3/2$-spin particle)
- Super-Higgs mechanism: $\tilde{G}$ becomes massive

$$m_{3/2} = \frac{F}{\sqrt{3}M_{\mathrm{Pl}}}$$

where $\sqrt{F}$ is the SUSY breaking scale



But here we will take the gravitino mass as a free parameter.

Gravitino interactions

$$\text{Gravitational interactions} \propto \frac{m^2_{\mathrm{soft}}}{F} \propto \frac{m^2_{\mathrm{soft}}}{m_{3/2} M_{\mathrm{Pl}}}$$

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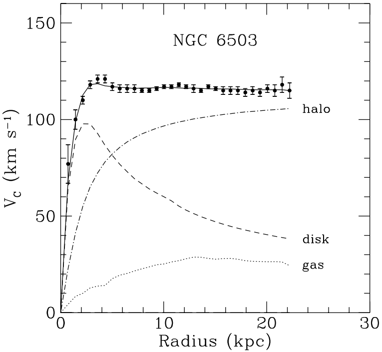
Evidence for dark matter

- First observations: F. Zwicky (1933)
- Study of galactic rotation curves: V. Rubin (1970's)



Other observations

- Large scale structure formation
- Gravitational lensing
- CMB
- Bullet Cluster
- ...

WMAP five-year data giving at 3σ Komatsu et al. (2008)

$$\Omega_{\rm DM} h^2 = 0.1099 \pm 0.0124$$

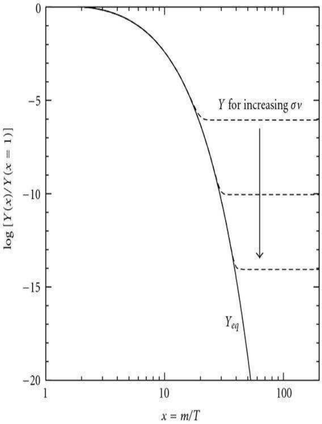
The Boltzmann equation

$$\dot{n}_X + 3Hn_X = -\langle\sigma v\rangle\left(n_X^2 - {n_X^{eq}}^2\right)$$

In a radiation dominated universe

$$\frac{dY}{dx} = -\sqrt{\frac{\pi}{45G}}\frac{g_*^{1/2}m_X}{x^2} < \sigma v > \left(Y^2 - {Y_{eq}}^2\right)$$

with $x = m_X/T$ and $Y = n_X/s$



The relic density reads:

$$\Omega_X h^2 = 2.742 \times 10^8 \left(\frac{m_X}{1\ \text{GeV}}\right) Y(T_0)$$

Gravitino dark matter candidate and non-thermal production

Good candidate

- No charges
- Super Weakly Interacting Massive Particle
- SUSY LSP with R-parity conservation: stable

Gravitino production

- Non-thermal production
- Thermal production

Non-thermal production from NLSP decay

- All SUSY particles decay to NLSP
- NLSP freeze-out
- NLSP decays to LSP

$$\Omega_{3/2}^{\rm NTP} h^2 = \frac{m_{3/2}}{m_{\rm NLSP}} \Omega_{\rm NLSP} h^2$$

During reheating, gravitinos can be produced in scattering processes

Bolz et al. (2001), Pradler & Steffen (2007)

$$\begin{aligned} g+g &\rightarrow \tilde{g}+\tilde{G} \\ q+g &\rightarrow \tilde{q}+\tilde{G} \\ q+q &\rightarrow \tilde{g}+\tilde{G} \\ &\ldots \end{aligned}$$

$$Y_{\mathrm{PS}}(T_{\mathrm{BBN}}) = \sum_{\alpha=1}^{3}\left(1+\frac{M_\alpha^2}{3m_{3/2}^2}\right) y_\alpha g_\alpha^2 \ln\left(\frac{k_\alpha}{g_\alpha}\right)\left(\frac{T_R}{10^{10}\ \mathrm{GeV}}\right)$$

Thermal contribution to relic density

$$\Omega_{3/2}^{\mathrm{TP}} h^2 \simeq 0.32\left(\frac{10\ \mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{1/2}}{1\ \mathrm{TeV}}\right)^2\left(\frac{T_R}{10^8\ \mathrm{GeV}}\right)$$

Gravitino relic density

$$\Omega_{3/2} h^2 = \Omega_{3/2}^{\mathrm{TP}} h^2 + \Omega_{3/2}^{\mathrm{NTP}} h^2$$

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- Before 1 s : weak interactions

$$n + e^{+} \rightarrow p + \bar{\nu}_e$$

- Weak interaction freeze-out
$n/p = e^{-Q/T_f} \sim 1/6 \rightarrow 1/7$

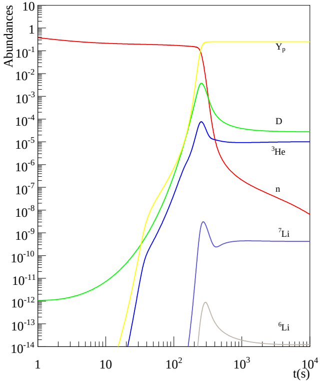
- Deuterium bottleneck

$$\begin{aligned} p + n &\rightarrow \gamma + \mathrm{D} \\ \gamma + \mathrm{D} &\rightarrow p + n \end{aligned}$$

- Deuterium production starts at 200 s
- $\mathrm{D} + p \rightarrow {}^3\mathrm{He} + \gamma$, $\mathrm{D} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + p$

- ^{4}He: most stable element, absorbs all neutrons

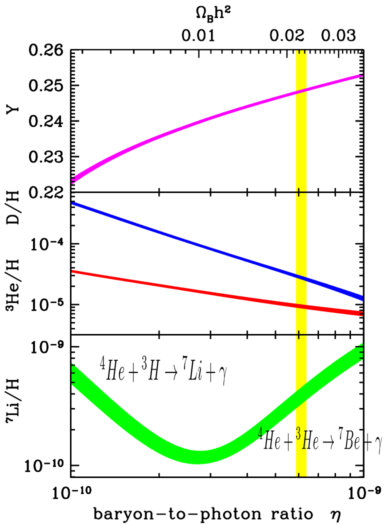
$$Y_p = \frac{2n}{p+n} \simeq 0.25$$



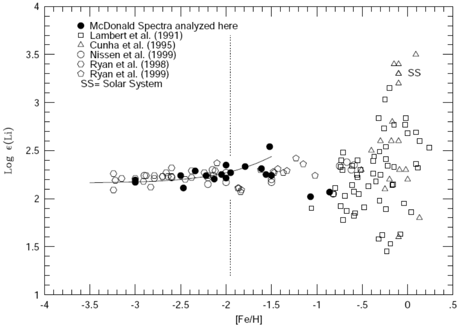
- No stable element at $A = 5$ and $A = 8$
- Small abundances of ^{6}Li, ^{7}Li

- SBBN has only one free parameter
- Measurement by WMAP

$$\eta = \frac{n_b}{n_\gamma} = (6.225 \pm 0.170) \times 10^{-10}$$



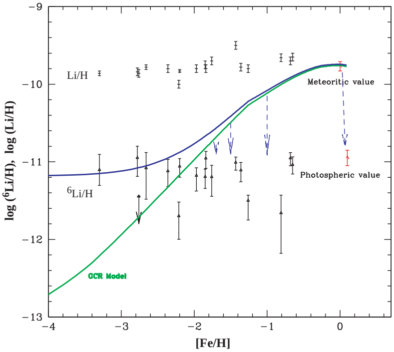
Element	SBBN	Observations
$\left(\frac{D}{H}\right)$	$(2.60 \pm 0.16) \times 10^{-5}$	$(2.68^{+0.27}_{-0.25}) \times 10^{-5}$
$\left(\frac{^3He}{H}\right)$	$(1.05 \pm 0.04) \times 10^{-5}$	$(1.1 \pm 0.2) \times 10^{-5}$
Y_p	0.2487 ± 0.0006	0.242 ± 0.002
$\left(\frac{^6Li}{H}\right)$	$10^{-14} - 10^{-15}$	$(3 - 5) \times 10^{-12}$
$\left(\frac{^7Li}{H}\right)$	$(4.26^{+0.91}_{-0.86}) \times 10^{-10}$	$(1.2 - 1.9) \times 10^{-10}$



Spite plateau points to a primordial abundance which disagrees with SBBN

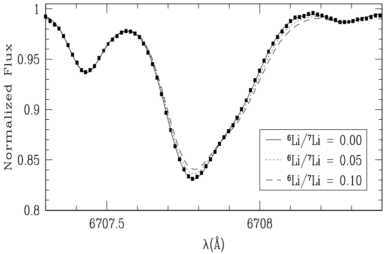
Possible origin of discrepancy

- Nuclear rates (re-examined and restricted by solar neutrino flux Coc et al. (2003), Cyburt et al. (2003))
- Stellar depletion Richard et al. (2004), Korn et al. (2006)
- Star temperature scale Melendez & Ramirez (2004)
- Particle decay during BBN Moroi et al. (1993), Feng et al. (2003), Cerdeno et al. (2005)



Rollinde et al. (2006)

Debate on the existence of plateau ?



Origin

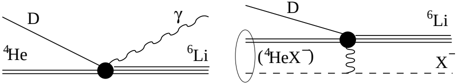
- Cosmic rays in the galactic formation Suzuki & Inoue (2002)
- Cosmic rays from Pop III stars Rollinde et al. (2006)
- Particle decay during BBN

Decay of relic particles

- Massive unstable particle X with lifetime $\tau_X \sim 10^2 - 10^6$ s
- Decay to Standard Model particles
- Injection of photons and nucleons: photodisintegration, ^{4}He spallation...

- ^{6}Li production: $n(^4\text{He}, pn)^3\text{H}(\alpha, n)^6\text{Li}$
- ^{7}Li destruction: $^7\text{Be}(n, p)^7\text{Li}(p, \alpha)^4\text{He}$
- Abundance change is constrained by observations

- Negatively charged X particles: bound state formation
- Reactions catalyzed Pospelov (2006)



- $\sigma_{\rm CBBN} \simeq 10^8 \times \sigma_{\rm SBBN}$
- Important production of lithium-6 for $\tau \gtrsim 3000$ s

The BBN code developed by K. Jedamzik (2006) takes all CBBN effects into account (CBBN reaction rates Kamimura et al. (2008))

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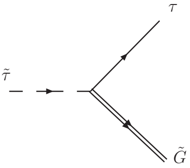
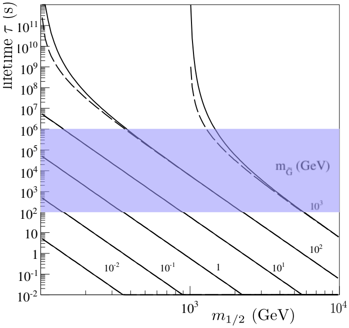
The two-body decay dominates

$$\Gamma(\tilde{\tau} \to \tau \tilde{G}) = \frac{1}{48\pi} \frac{m_{\tilde{\tau}}^5}{M_{\rm Pl}^2 m_{3/2}^2} \left(1 - \frac{m_{3/2}^2}{m_{\tilde{\tau}}^2}\right)^4$$





The lepton τ decay processes:

- mesons : $\tau \to \pi^- \nu_\tau$, $\tau \to \pi^- \pi^0 \nu_\tau$
- leptons : $\tau \to e^- \bar{\nu}_e \nu_\tau$, $\tau \to \mu^- \bar{\nu}_\mu \nu_\tau$

For stau lifetimes $<$ 100 s, the mesons interact hadronically inducing charge exchange reactions $n \leftrightarrow p$ with an increasing ratio n/p. The impact on BBN is an increased ^{4}He abundance strongly constrained by observations.

For stau lifetimes $>$ 100 s, the mesons decay electromagnetically. In a good approximation, the two body decay of the stau induces dominantly an electromagnetic cascade.

$$B_{\rm em} = 1 - B_{\rm had} \simeq 1 \qquad \text{and} \qquad E_{\rm em} = \alpha \left(\frac{m^2_{\rm NLSP} - m^2_{3/2}}{2 m_{\rm NLSP}} \right) \qquad \alpha \simeq \frac{1}{2}$$

Hadronic cascade: four-body decay (1/3)

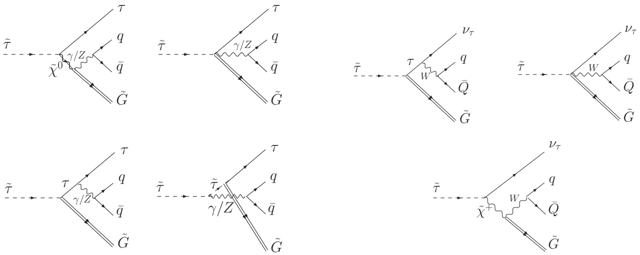
First approach : $B_{\rm had}(\tilde{\tau} \to \tau \tilde{G} q \bar{q}) = B_{\rm had}(\tilde{\tau} \to \tau \tilde{G} Z) B(Z \to q\bar{q})$ Feng (2003)

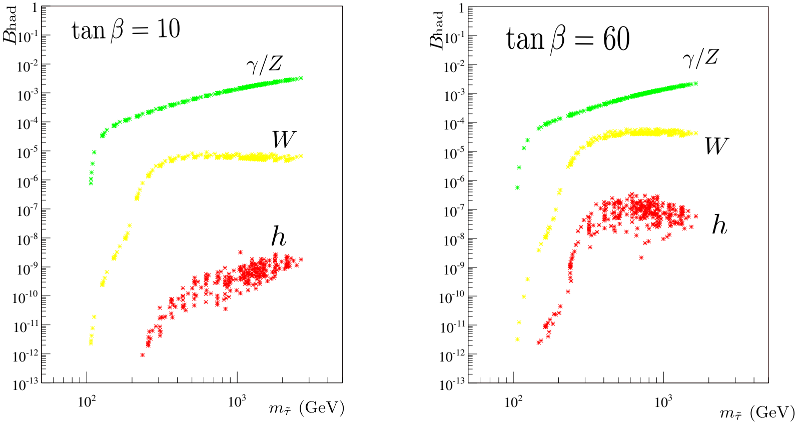
A more general calculation Steffen (2006)

$$B_{\rm had}(\tilde{\tau} \to \tau \tilde{G} q \bar{q}; m_{q\bar{q}}^{\rm cut}) = \frac{\Gamma(\tilde{\tau} \to \tau \tilde{G} q \bar{q})}{\Gamma_{\rm tot}}$$

with the 4-body decay width

$$\Gamma(\tilde{\tau} \to \tau \tilde{G} q \bar{q}; m_{q\bar{q}}) = \int_{m_{q\bar{q}}}^{m_{\tilde{\tau}} - m_{3/2} - m_\tau} dm_{q\bar{q}} \frac{d\Gamma(\tilde{\tau} \to \tau \tilde{G} q \bar{q})}{dm_{q\bar{q}}}$$



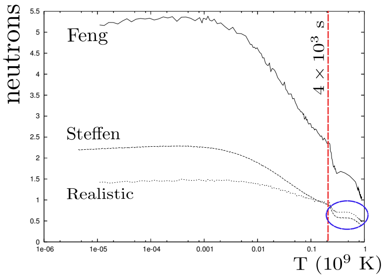

B_{had}
$\tan\beta = 10$
γ/Z
W
h
$m_{\tilde\tau}$ (GeV)
B_{had}
$\tan\beta = 60$
γ/Z
W
h
$m_{\tilde\tau}$ (GeV)

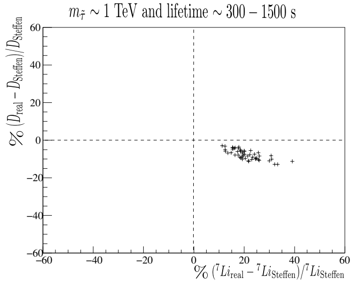
Hadronic energy Steffen (2006)

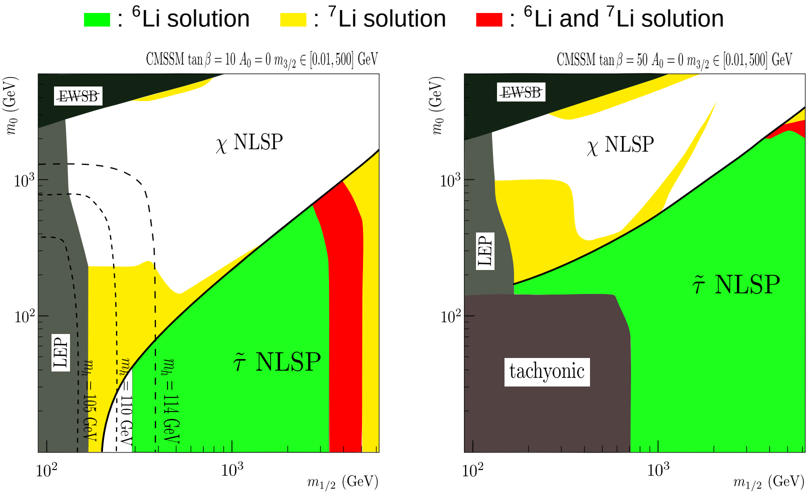
$$E_{\text{had}} = \frac{1}{\Gamma(\tilde{\tau} \to \tau \tilde{G} q \bar{q})} \int_{m_{q\bar{q}}}^{m_{\tilde{\tau}} - m_{3/2} - m_{\tau}} dm_{q\bar{q}}\, m_{q\bar{q}} \frac{d\Gamma(\tilde{\tau} \to \tau \tilde{G} q \bar{q})}{dm_{q\bar{q}}}$$

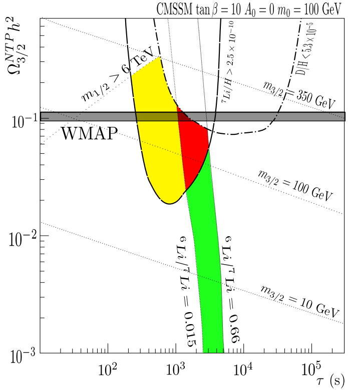
Realistic calculation

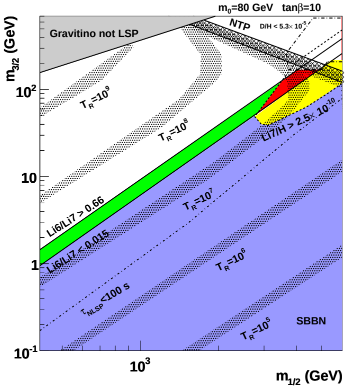
Use of CalcHEP (event generation) + PYTHIA (realistic neutron distribution)






: ^{6}Li solution
: ^{7}Li solution
: ^{6}Li and ^{7}Li solution
CMSSM $\tan\beta = 10$ $A_0 = 0$ $m_{3/2} \in [0.01, 500]$ GeV
EWSB
χ NLSP
$\tilde{\tau}$ NLSP
LEP
$m_h = 105$ GeV
$m_h = 110$ GeV
$m_h = 114$ GeV
m_0 (GeV)
$m_{1/2}$ (GeV)
10^2
10^3
CMSSM $\tan\beta = 50$ $A_0 = 0$ $m_{3/2} \in [0.01, 500]$ GeV
EWSB
χ NLSP
$\tilde{\tau}$ NLSP
LEP
tachyonic
m_0 (GeV)
$m_{1/2}$ (GeV)
10^2
10^3





The red region solves both problems simultaneously for $m_{1/2} = [3 - 5]$ TeV corresponding to stau masses $m_{\tilde{\tau}} = [1 - 1.8]$ TeV and gravitino masses $m_{3/2} = 60 - 120$ GeV

Matter-antimatter asymmetry

To explain

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.225 \pm 0.170) \times 10^{-10}$$

A possible scenario is the thermal leptogenesis

A requirement for this model is $T_R > 2 \times 10^9$ GeV

Our scenario:

- requires lower reheating temperature $T_R \lesssim 10^7$ GeV
- has quite heavy masses (above LHC range)

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Addition of a dark component in the early Universe Arbey & Mahmoudi (2008)

$$\rho_D(T) = \rho_D(T_{\rm BBN}) \left(\frac{T}{T_{\rm BBN}} \right)^{n_D}$$

with $T_{\rm BBN} = 10$ MeV

As we require a radiation dominated era for BBN, we introduce the parameter

$$\kappa_D = \frac{\rho_D(T_{\rm BBN})}{\rho_{\rm rad}(T_{\rm BBN})} \ll 1$$

where the radiation density $\rho_{\rm rad}(T) = g_{\rm eff}(T)\frac{\pi^2}{30}T^4$

Modified Hubble parameter

$$H^2 = \frac{8\pi G}{3} \left(\rho_m + \rho_{\rm rad} + \rho_D \right)$$

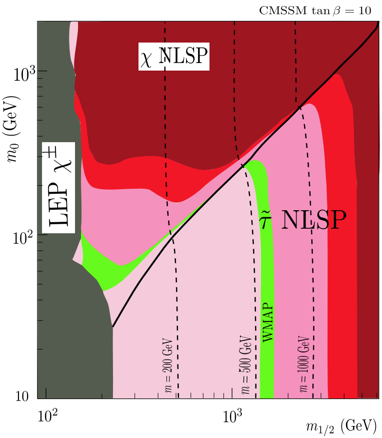
Since the Hubble parameter is larger as in the standard scenario, the NLSP freeze-out occurs earlier

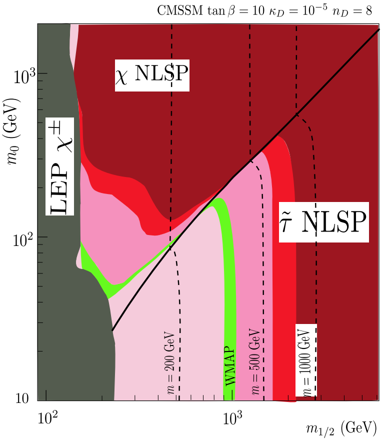
Boltzmann equation

$$\frac{dY}{dx} = -\sqrt{\frac{\pi}{45}}\frac{g_*^{1/2} m_{\rm NLSP}}{x^2}\left(1 + \frac{\rho_D(T)}{\rho_{\rm rad}\frac{\pi^2}{30}T^4}\right)^{-1/2}\langle\sigma_{\rm eff} v\rangle\left(Y^2 - Y_{\rm eq}^2\right)$$

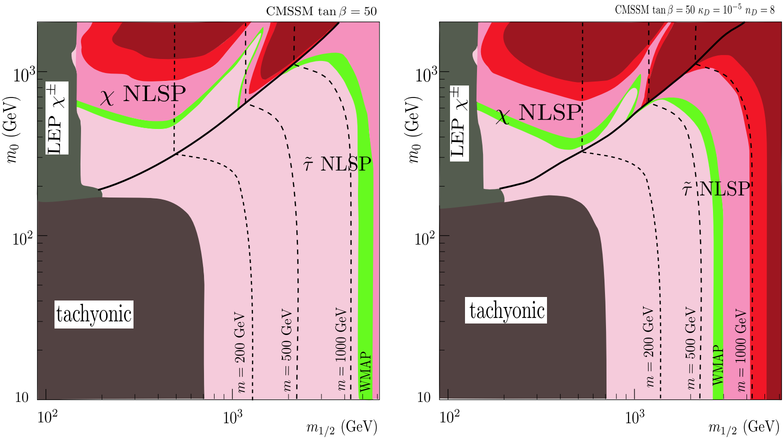
The NLSP abundance is higher, same for the gravitino relic density

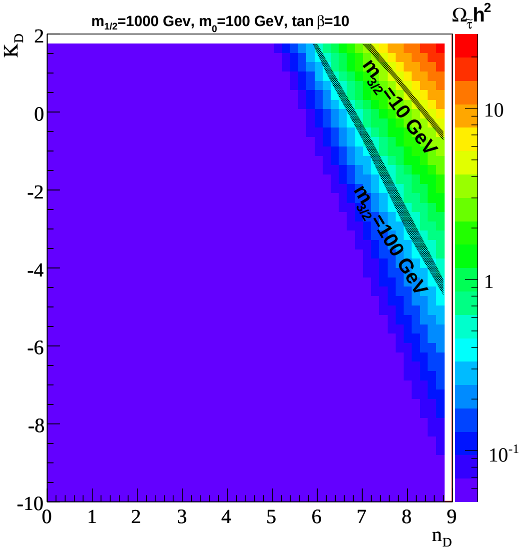
$$\Omega_{3/2}^{\rm NTP} h^2 = \frac{m_{3/2}}{m_{\rm NLSP}}\Omega_{\rm NLSP} h^2$$


CMSSM tan β = 10
χ NLSP
LEP χ±
τ̃ NLSP
WMAP
m = 200 GeV
m = 500 GeV
m = 1000 GeV
m_0 (GeV)
$m_{1/2}$ (GeV)
10
10^2
10^3


CMSSM tan β = 10 $\kappa_D = 10^{-5}$ $n_D = 8$
χ NLSP
LEP χ±
τ̃ NLSP
WMAP
m = 200 GeV
m = 500 GeV
m = 1000 GeV
m_0 (GeV)
$m_{1/2}$ (GeV)
10
10^2
10^3

Non-thermal production (3/4)





$m_{1/2}$=1000 Gev, m_0=100 GeV, tan β=10
$\Omega_{\tilde{\tau}}h^2$
K_D
2
0
-2
-4
-6
-8
-10
0 1 2 3 4 5 6 7 8 9
n_D
$m_{3/2}$=10 GeV
$m_{3/2}$=100 GeV
10
1
10^{-1}

$$Y_{3/2}(T_{\rm BBN}) = \sum_{\alpha=1}^{3}\left(1+\frac{M_\alpha^2}{3m_{3/2}^2}\right) y_\alpha^{'} g_\alpha^2 \ln\left(\frac{k_\alpha}{g_\alpha}\right)\int_{T\rm BBN}^{T_R}\frac{dT}{\left[1+\kappa_D\left(\frac{T}{T_{\rm BBN}}\right)^{n_D-4}\right]^{1/2}}$$

For κ_D, we recover the standard value Y_{PS}

- $n_D = 4$

$$Y_{3/2}(T_{\rm BBN}) = \frac{1}{1+\kappa_D} Y_{\rm PS}(T_{\rm BBN})$$

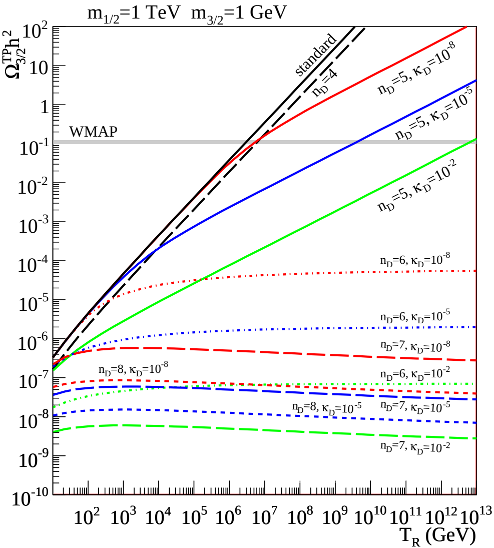
- $n_D > 4$

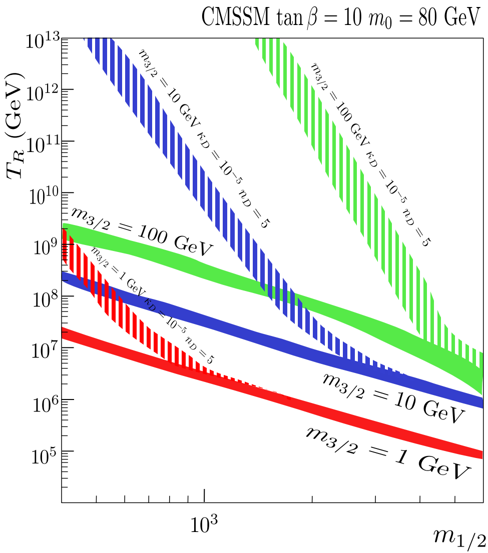
$$Y_{3/2}(T_{\rm BBN}) = Y_{\rm PS}(T_{\rm BBN}) \times {}_2F_1\left(1/N, 1/2; 1+1/N; -\kappa_D\left(\frac{T_R}{T_{\rm BBN}}\right)^N\right)$$

Relic density

$$\Omega_{3/2}^{\rm TP} h^2 = 2.742\times 10^8 \left(\frac{m_{3/2}}{1\ \rm GeV}\right) Y_{3/2}(T_{\rm BBN})$$

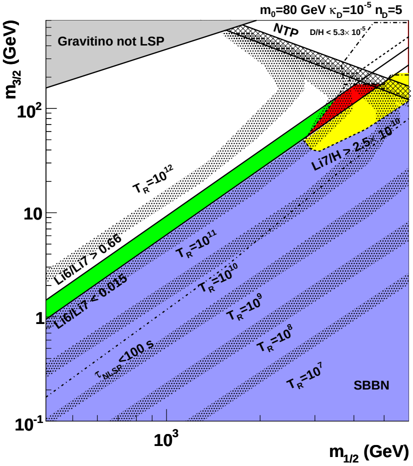
The thermal contribution is suppressed compared to the standard scenario

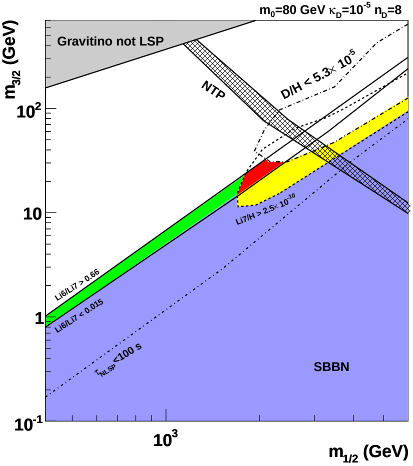

m1/2=1 TeV m3/2=1 GeV
Ω3/2TP h2
TR (GeV)
WMAP
standard
nD=4
nD=5, κD=10-8
nD=5, κD=10-5
nD=5, κD=10-2
nD=6, κD=10-8
nD=6, κD=10-5
nD=7, κD=10-8
nD=8, κD=10-8
nD=6, κD=10-2
nD=8, κD=10-5
nD=7, κD=10-5
nD=7, κD=10-2


CMSSM tan β = 10 m_0 = 80 GeV
T_R (GeV)
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{3}
$m_{1/2}$
$m_{3/2} = 10$ GeV $\kappa_D = 10^{-5}$ $n_D = 5$
$m_{3/2} = 100$ GeV $\kappa_D = 10^{-5}$ $n_D = 5$
$m_{3/2} = 100$ GeV
$m_{3/2} = 1$ GeV $\kappa_D = 10^{-5}$ $n_D = 5$
$m_{3/2} = 10$ GeV
$m_{3/2} = 1$ GeV

Results

For a given mass, more NLSP particles decay during BBN





Conclusion

Dark matter

- Gravitino good cadidate
- Non-thermal production and thermal production

Lithium problems

- Scenario to solve the lithium problems
- SBBN puts constraints on the model

Modified Hubble parameter

- Solution for the reheating temperature
- Lighter mass spectrum
- Constraints on the pre-BBN era