GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

IFIC - INSTITUTO DE FÍSICA CORPUSCULAR

I was at BNL as a Fulbright fellow from September 1984 to August 1986. I am not sure; I think it was in the second half of my stay that Goran appeared from time to time. I remember great ping-pong matches with him at Brookhaven centre.

Fortunately, we gathered a few times at Chong-Sa Lim office to talk about physics. There I learned why "The joy of making physics" is the perfect title for GoranFest.

It has been impossible for me to attend this meeting but I am very pleased to contribute a few words, to desire all the best to Goran and why not, to congratulate specially the organizers from Croatia.

My best regards to Goran and to all my BNL friends.

Francisco Botella
Director of IFIC
University of Valencia and CSIC
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The degenerate gravitino scenario

Lotfi Boubekeur
University of Valencia & IFIC

GoranFest

LB, K-Y Choi, R. R. de Austri & O. Vives, arXiv:1002.0340, JCAP 1004:005,2010.

The gravitino

Spin 3/2 particle $\psi_\mu \longleftrightarrow g_{\mu\nu}$

Cosmological problems due to 1/M_{Pl} couplings

- Too much gravitinos (Weinberg '82)
- Even with inflation, re-created at reheating. (Ellis etal, ...)
- Number prop. to T_{RH} .
- Bound on reheating temperature in leptogenesis. $T_{\rm RH} \lesssim 10^9~{\rm GeV}$

Is it possible to relax these constraints?

The gravitino

Thermal production of $N_1 \Rightarrow T_{RH} > M_{N_1} \simeq 10^9$ GeV

On the other hand, gravitino abundance after reheating

$$\Omega_{3/2}\, h^2 \quad = 0.21 \left(\frac{T_{\rm RH}}{10^{10}\ {\rm GeV}} \right) \left(\frac{100\ {\rm GeV}}{m_{3/2}} \right) \left(\frac{m_{\tilde{g}}}{1\ {\rm TeV}} \right)^2$$

No overproduction of gravitinos $T_{RH} < 10^9$ GeV

Possible solutions

- Heavy gravitino (e.g. Anomaly mediation)
- Gravitino is dark matter -- what about the Neutralino (LOSP)?
- Non-thermal production of RHN (preheating, inflaton decay, ...) -- model-dependent.
- Low reheat temperature + low scale RHN.
- ....

LB, hep-ph/0208003.
LB, T. Hambye & G. Senjanović, PRL '04.

Low scale Leptogenesis

Thermal production $T_{RH} > 10^9$ GeV $\not\leftrightarrow$ Gravitinos $T_{RH} < 10^9$ GeV

<u>Proposal</u>: The RH neutrinos have smaller masses.

$\Downarrow$

Dirac Yukawas will be smaller

$\Downarrow$

NOT ENOUGH $\cancel{CP}$

Additional sources of $\cancel{L}$ and $\cancel{CP}$ are needed. $\Rightarrow$ Soft SUSY at ~ TeV

LB, hep-ph/0208003.
LB, T. Hambye & G. Senjanović, PRL '04.

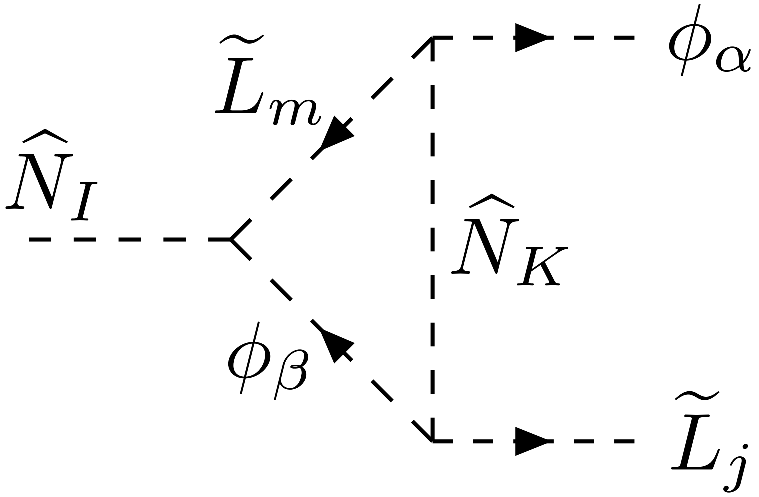
➡ Additional contributions to light neutrino masses.

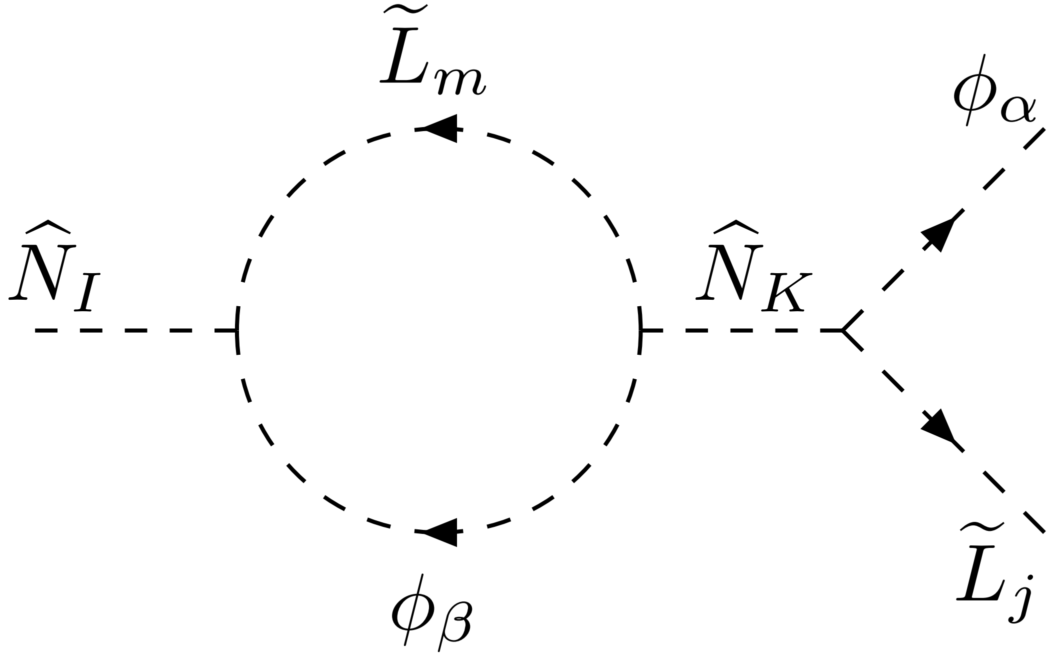
Low scale Leptogenesis

LB, hep-ph/0208003
LB, T. Hambye & G. Senjanović, PRL '04.

The soft SUSY breaking terms respecting R-parity.

$$\mathcal{L}_{\widetilde{N}} = (m^2_{\widetilde{N}})_{ij} \widetilde{N}^*_i \widetilde{N}_j + B_{ij} \widetilde{N}_i \widetilde{N}_j + A^U_{ij} \widetilde{L}_i H_U \widetilde{N}_j$$
$$+ A'^U_{ij} \widetilde{L}_i H_U \widetilde{N}^*_j + A^D_{ij} \widetilde{L}_i H^*_D \widetilde{N}_j + A'^D_{ij} \widetilde{L}_i H^*_D \widetilde{N}^*_j + \text{h.c.}$$





Going to the diagonal basis

$$\mathcal{L}_{\widetilde{N}} = M^2_{\widehat{N}_I} \widehat{N}_I^2 + \mu^{\alpha}_{Ij} \widehat{N}_I \widetilde{L}_j \phi_\alpha + \mu^{\alpha *}_{Ij} \widehat{N}_I \widetilde{L}^*_j \phi^*_\alpha \,,$$

The CP asymmetry reads

$$\varepsilon^V_I = \frac{-1}{8\pi M^2_{\widehat{N}_I}} \frac{1}{|\mu^\alpha_{Ij}|^2} \sum_{K\neq I} \mathrm{Im}\big[\mu^\beta_{Im}\mu^{\beta *}_{Kj}\mu^{\alpha *}_{Km}\mu^\alpha_{Ij}\big]\, F_V(x_K),$$

$$\varepsilon^S_I = \frac{-1}{4\pi M^2_{\widehat{N}_I}} \frac{1}{|\mu^\alpha_{Ij}|^2} \sum_{K\neq I} \mathrm{Im}\big[\mu^\beta_{Im}\mu^{\beta *}_{Km}\mu^{\alpha *}_{Kj}\mu^\alpha_{Ij}\big]\, F_S(x_K),$$

With $x_K = M^2_{\widehat{N}_I}/M^2_{\widehat{N}_K}$ and $F_V(x) = \ln(1+x)$, $F_S(x) = x/(1-x)$.

Numerical example:

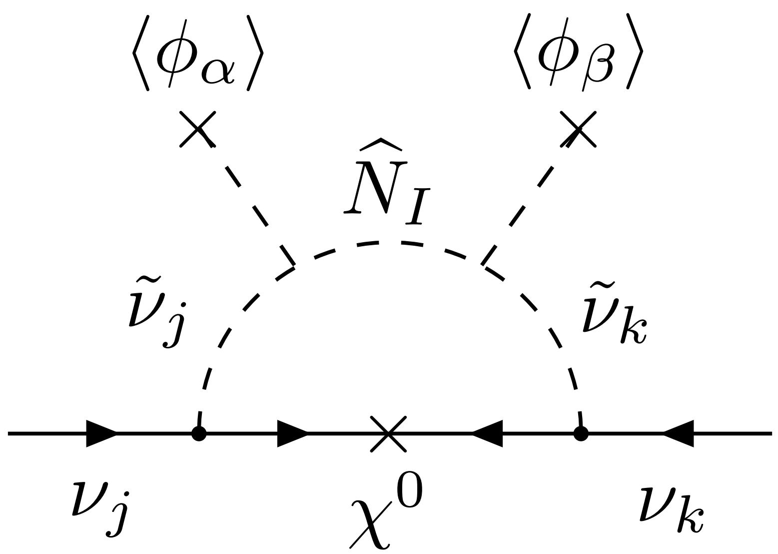
$$M_{\widehat{N}_1} \sim 2\,\mathrm{TeV},\ M_{\widehat{N}_2} \sim 6\mathrm{TeV}$$

$$(\mu^\alpha_{1j})^{\max} \sim 5\cdot 10^{-8}\, M_{\widehat{N}_1},\ (\mu^\alpha_{2j})^{\max} \sim 10^{-3}\, M_{\widehat{N}_2}$$

gives $\varepsilon_1 \sim 10^{-7}$ and $n_B/n_\gamma \sim 6\cdot 10^{-10}$

Neutrino masses

➡New contributions to light neutrino masses



$$(m_\nu^{\rm rad})_{jk} \simeq \frac{\alpha}{4\pi}\frac{\mu^\alpha_{Ij}\,\mu^\beta_{Ik}}{M^2_{\widehat{N}_I}}\frac{m_\chi}{m^2_{\tilde{\nu}_j}-m^2_{\tilde{\nu}_k}}\langle\phi_\alpha\rangle\langle\phi_\beta\rangle \times\left[\frac{m^2_{\tilde{\nu}_j}}{m^2_{\tilde{\nu}_j}-m^2_\chi}\ln\frac{{m_{\tilde{\nu}_j}}^2}{m^2_\chi} - j\to k\right].$$

For our numerical example with $m_{\tilde{\nu}_i}\approx 500$ GeV and $m_\chi \approx 100$ GeV gives

$$m_\nu^{\rm rad}\approx 1~{\rm eV}!$$

$$\Downarrow$$

Degenerate spectrum for light neutrinos

RHN at LHC

RH (s)neutrinos have very small Yukawa couplings to normal matter

Difficult to observe even-though their masses are relatively low-TeV.

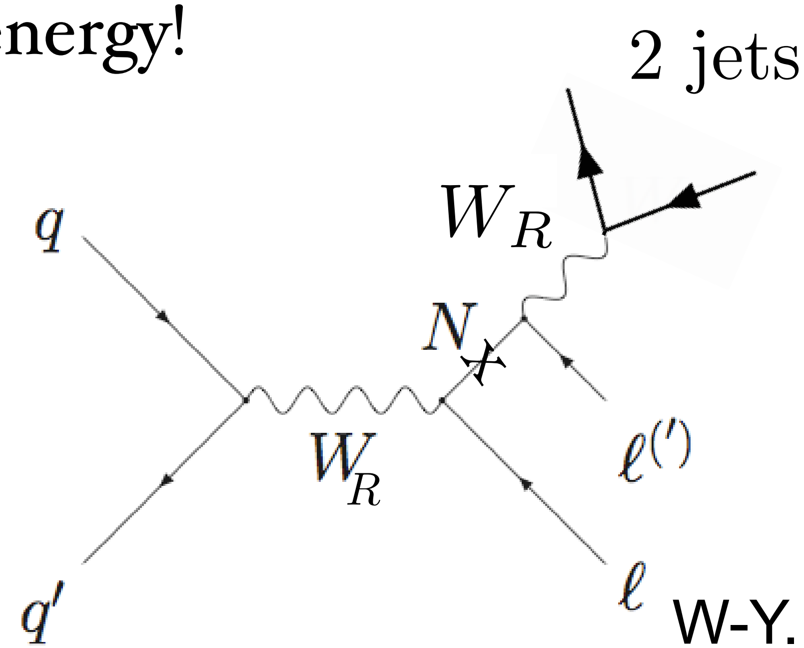
<u>Key point:</u> additional interactions were needed to produce RHN thermally through

$$f\bar{f} \to Z' \to NN$$

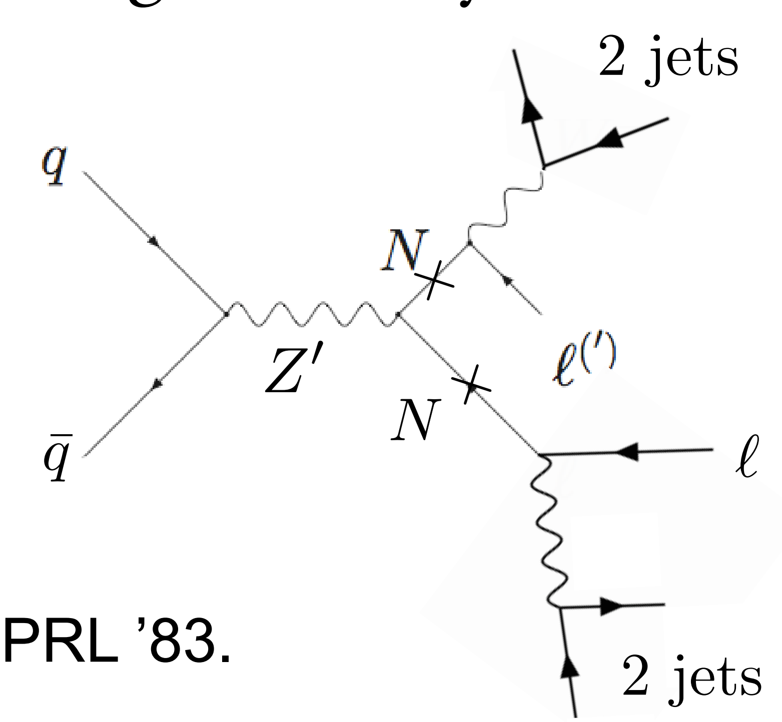
This requirement gave

$$M_{Z'} < \left(\frac{T_{RH}}{10^{10}\ \mathrm{GeV}}\right)^{3/4} 4 \times 10^{11}\ \mathrm{GeV}.$$

Characteristic signature: same sign di-lepton! SM Background very low + no missing energy!



W-Y. Keung & G. Senjanović, PRL '83.



The gravitino

In gravity-mediated, scenario typically co-exists with Neutralino.

Typical decay lifetimes O(10^2-10^6) sec

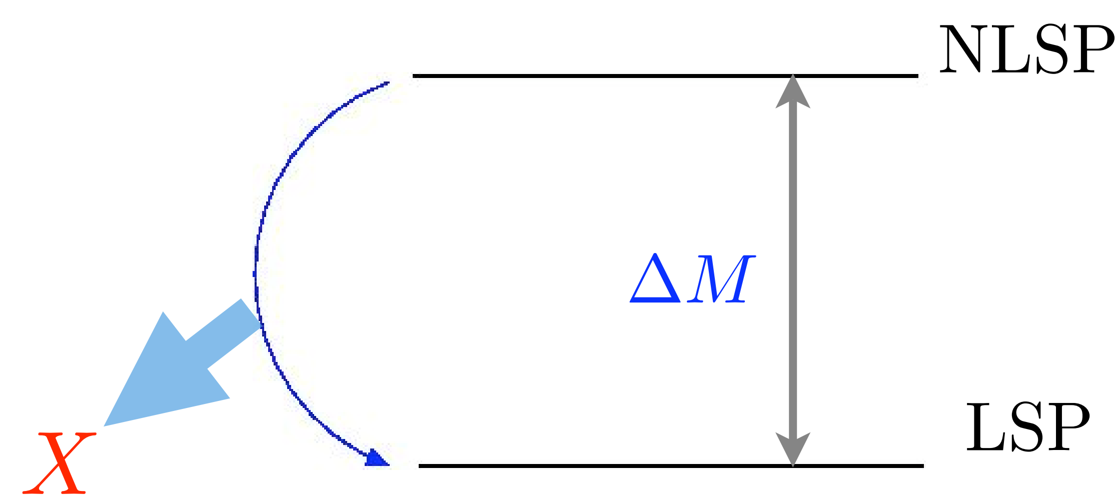
$$\text{NLSP} \to \text{LSP} + X \quad (X = \text{hadrons or } \gamma)$$

puts too much energy in the plasma

$$E_X = m_{\text{NLSP}} - m_{\text{LSP}}$$

BBN (Photodissociation + hadronization)

Hadronization constraints are the most stringent. (Moroi etal.)



To suppress hadronic showers, consider the "**degenerate gravitino scenario**"

$$\Delta M = m_{\text{NLSP}} - m_{\text{LSP}} \equiv \delta \, m_{\text{LSP}} \ll m_{\text{LSP}}$$

Relic Abundance

Total relic density should match observed one

$$\Omega_{\rm CDM}\ h^2 = \Omega_{\rm LSP}^{\rm TP}\ h^2 + \frac{1}{1+\delta}\Omega_{\rm NLSP}^{\rm TP}\ h^2 \simeq 0.11$$

Define the parameter

$$\omega \equiv \frac{Y_{\rm NLSP}}{Y_{\rm CDM}} = 1 - \frac{\Omega_{\rm LSP}^{\rm TP}\ h^2}{\Omega_{\rm WMAP}\ h^2}$$

which quantifies how many LSPs are produced non-thermally through NLSP decay.

The released EM energy is defined

$$\xi_{\rm em} \equiv \delta\ m_{\rm LSP}\, B_{\rm em}\, Y_{\rm NLSP}$$

which can be written as

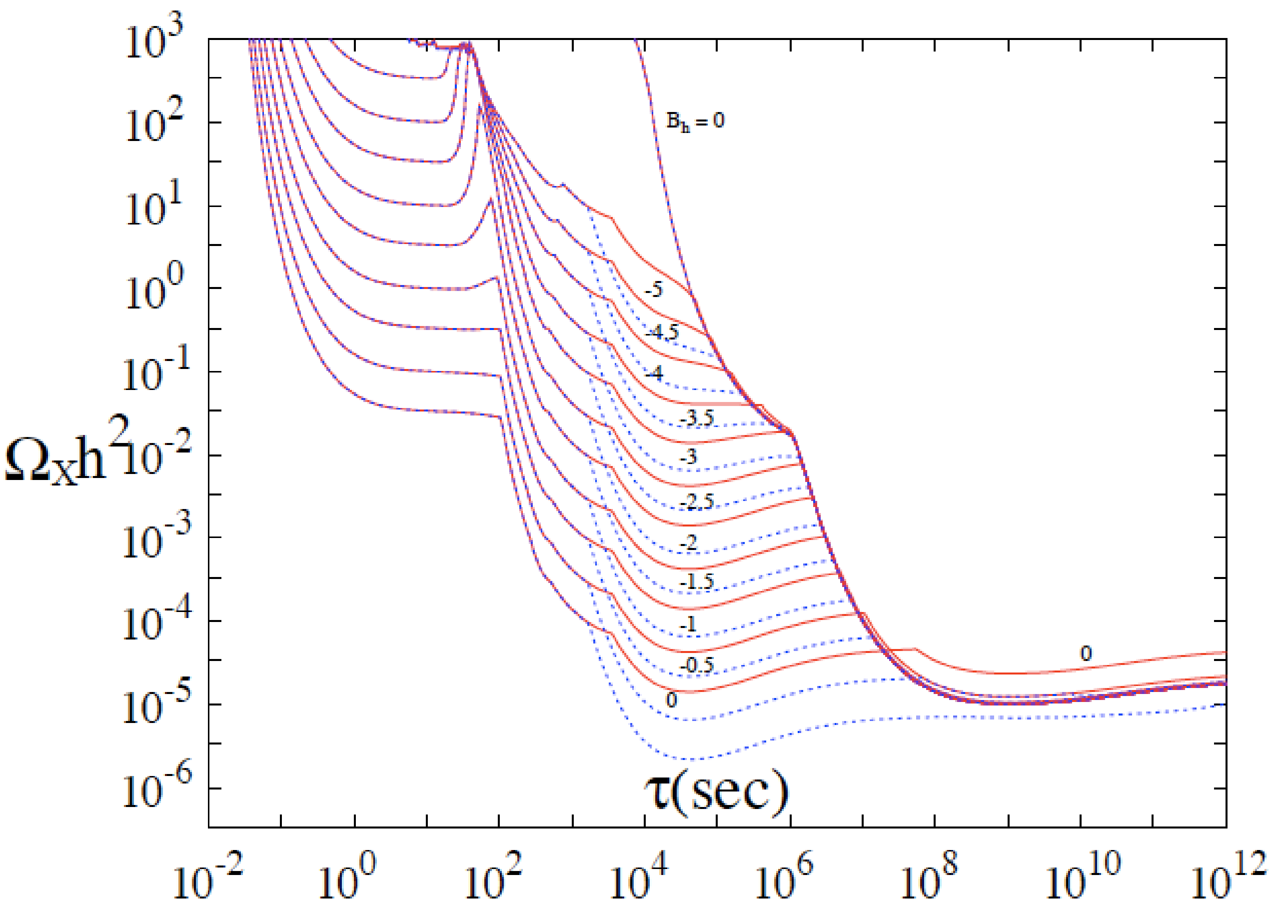
$$\xi_{\rm em} \simeq 4.1\times 10^{-10}{\rm GeV}\left(\frac{\Omega_{\rm WMAP}h^2}{0.11}\right)\omega\, B_{\rm em}\,\delta$$

BBN

Since the mass difference is small $\Delta M < m_Z$ to suppress hadronic decays

- we can take $B_{\text{had}} \simeq 0$.
- we consider only 2-body decays.

We can use the results of Jedamzik, arXiv:hep-ph/0604251.



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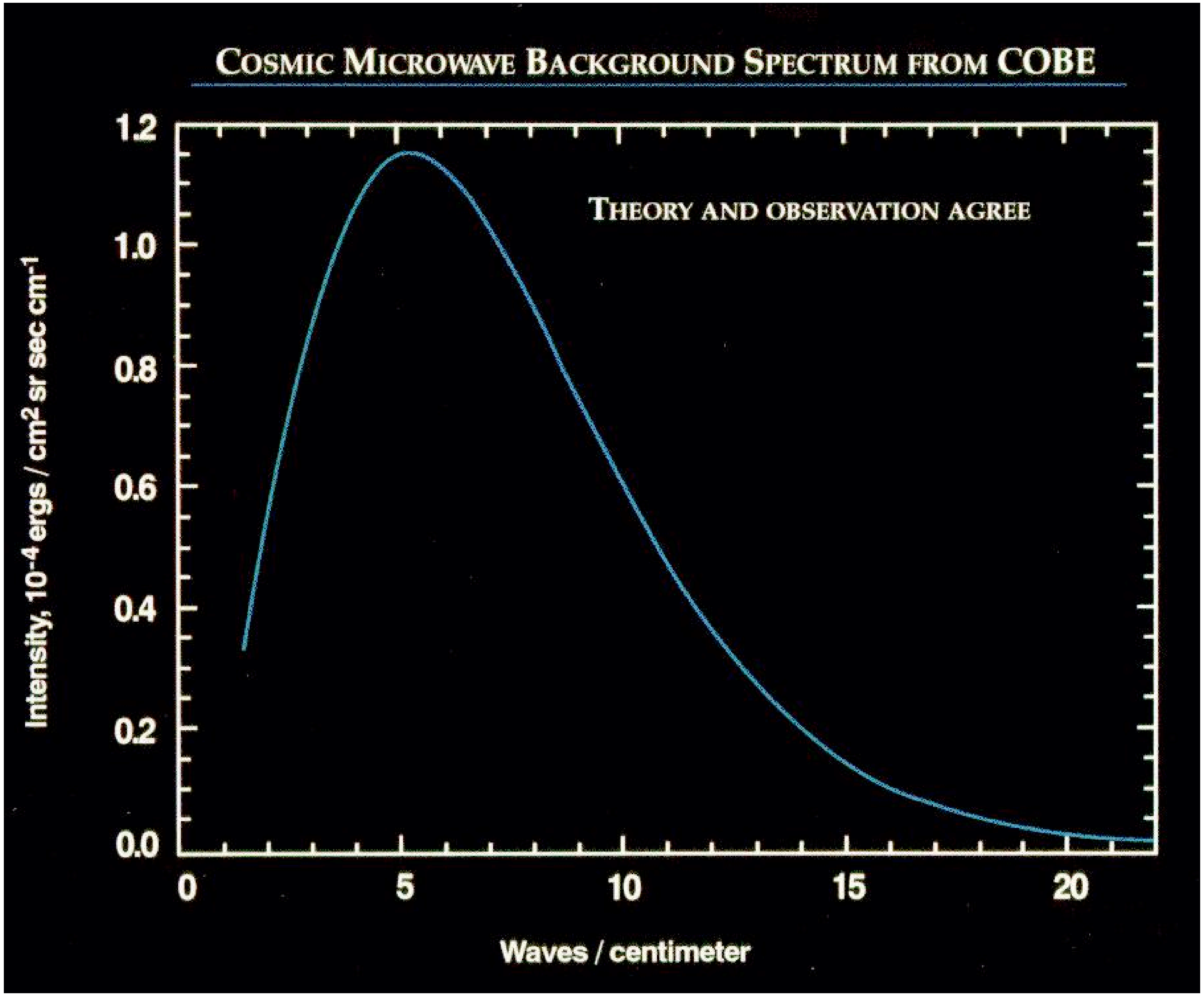
Furthermore the lifetime increases as ΔM^{-3}, we need to consider additional constraints

- CMB: for $\tau_{\rm NLSP} \gtrsim 10^7\,\text{sec} \Longrightarrow 1\,\text{GeV} \lesssim \Delta M \lesssim 10\,\text{GeV}$
- Diffuse gamma rays background: for much longer lifetimes.

CMB



COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
Intensity, 10^-4 ergs / cm^2 sr sec cm^-1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter

CMB

Spectrum very well described by a Bose-Einstein distribution

$$f_\gamma(E) = \frac{1}{e^{E/(kT)+\mu} - 1},$$

where $|\mu| < 9 \times 10^{-5}$ from FIRAS.

For $\tau_{\rm NLSP} \lesssim 8.8\ 10^9$ sec

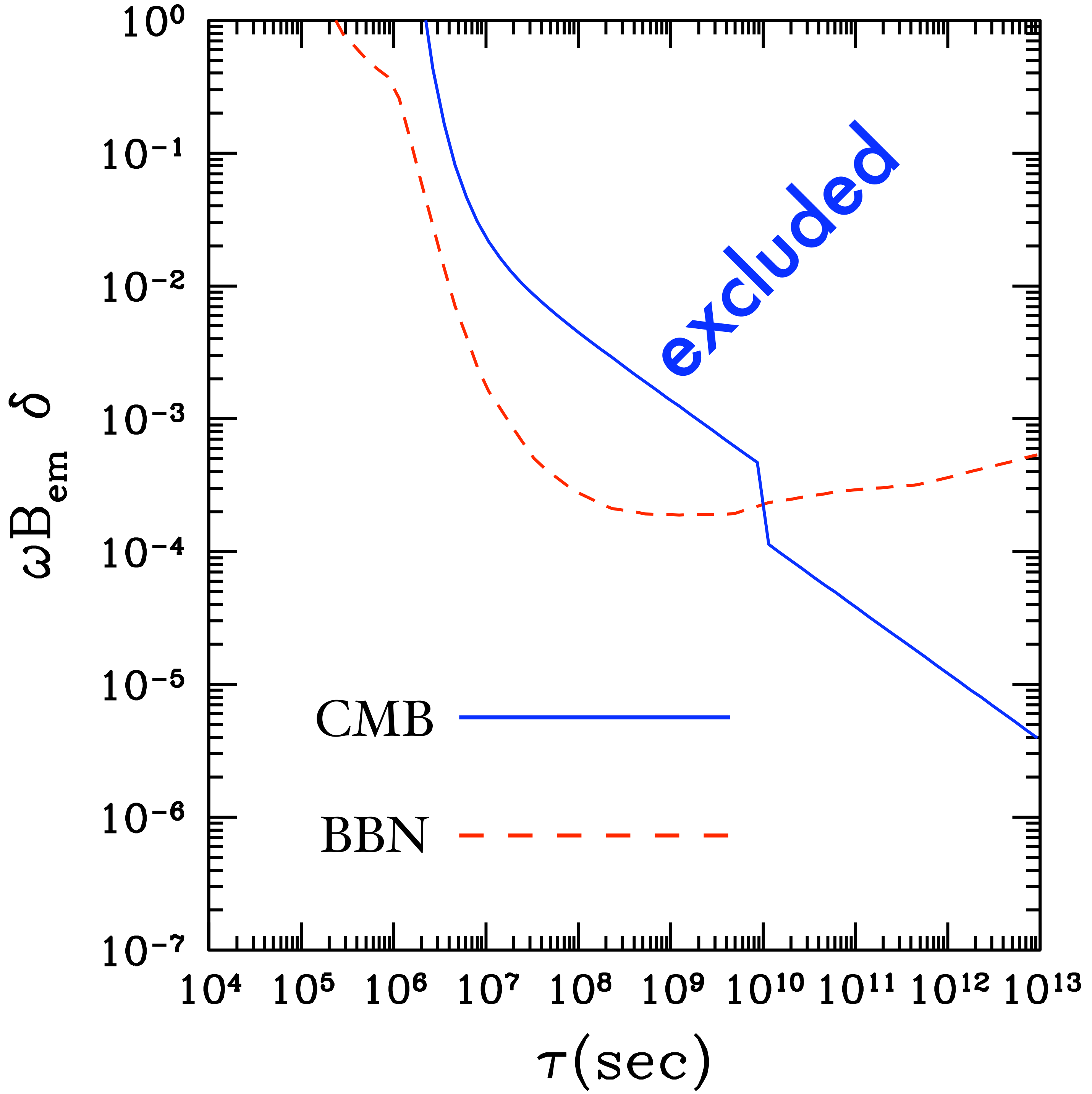
$$\xi_{\rm em} < 1.59 \times 10^{-8}\, e^{(\tau_{dC}/\tau_{\rm NLSP})^{5/4}} \left(\frac{1 \rm sec}{\tau_{\rm NLSP}}\right)^{1/2} \rm GeV$$

where $\tau_{dC} \simeq 6.085 \times 10^6$ sec

For $\tau_{\rm NLSP} \gtrsim 8.8\ 10^9$ sec

$$\xi_{\rm em} \lesssim 4.42 \times 10^{-9} \rm GeV \sqrt{\frac{1\ sec}{\tau_{\rm NLSP}}}.$$

BBN + CMB



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\omega B_{em}\ \delta$
excluded
CMB
BBN
10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13}
τ(sec)

Diffuse Gamma Rays

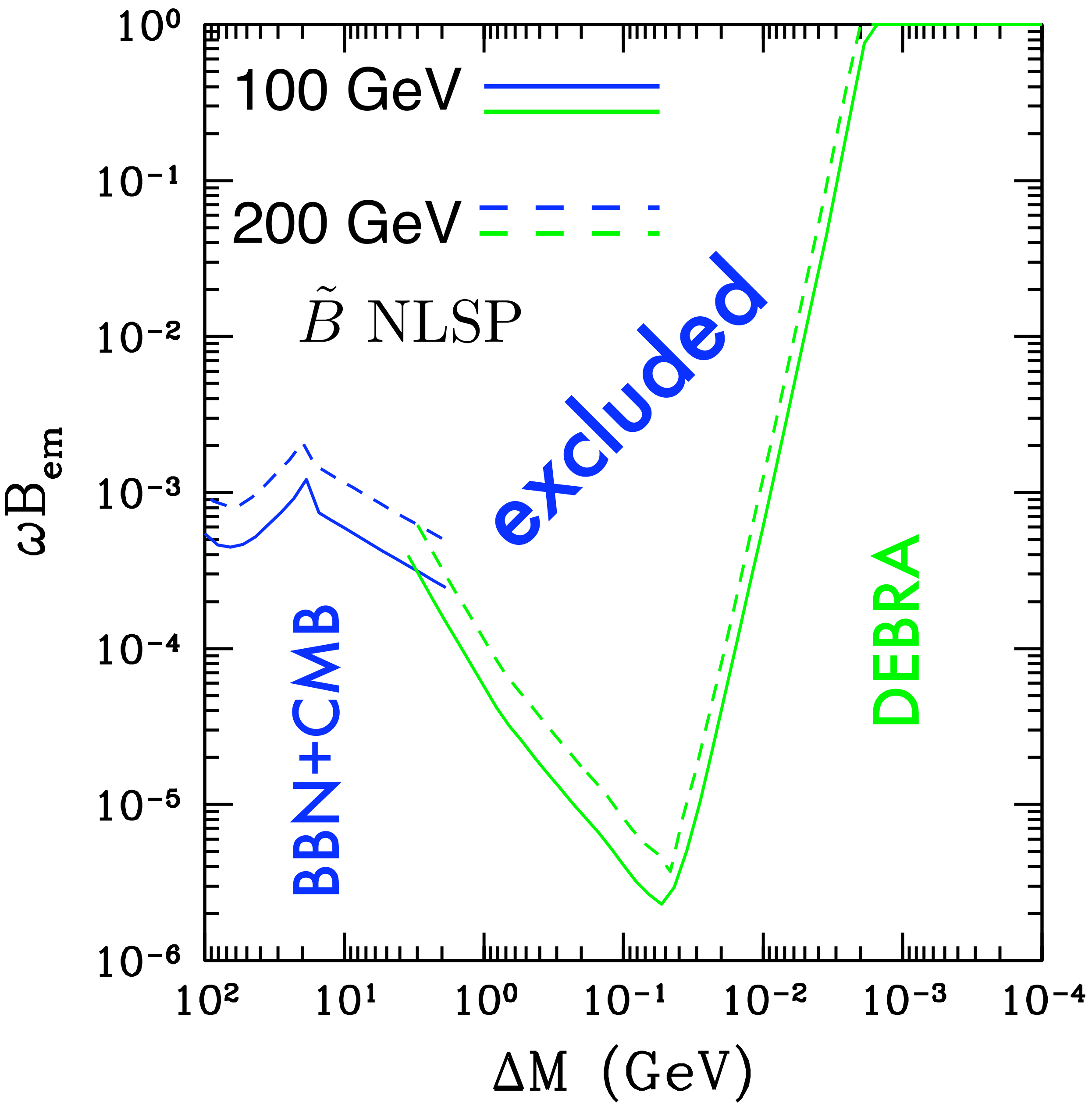
$$\frac{d\Phi}{dE_\gamma} = \frac{c}{4\pi}\int_{t_i}^{t_0} \frac{dt}{\tau_{\rm NLSP}} \frac{\rho_c\, \Omega_{\rm WMAP}\, \omega\, B_{\rm em}}{m_{\rm NSLP}}\, e^{-t/\tau_{\rm NLSP}}\, \delta(E_\gamma - aE_{\rm em}),$$

Compare expected diffuse extragalactic gamma rays flux with data from

1. SPI
2. COMPTEL
3. EGRET

Yuksel & Kistler '07

NB: Galactic center gamma rays bounds are of the same order.



The reheating temperature

Combining these bounds, get limits on T_{RH}

Gravitino LSP

$$\boxed{T_{\mathrm{RH}} = 4.1 \times 10^9\,\mathrm{GeV}\left(\frac{m_{3/2}}{100\,\mathrm{GeV}}\right)\left(\frac{1\,\mathrm{TeV}}{M_3}\right)^2 (1-\omega)\,.}$$

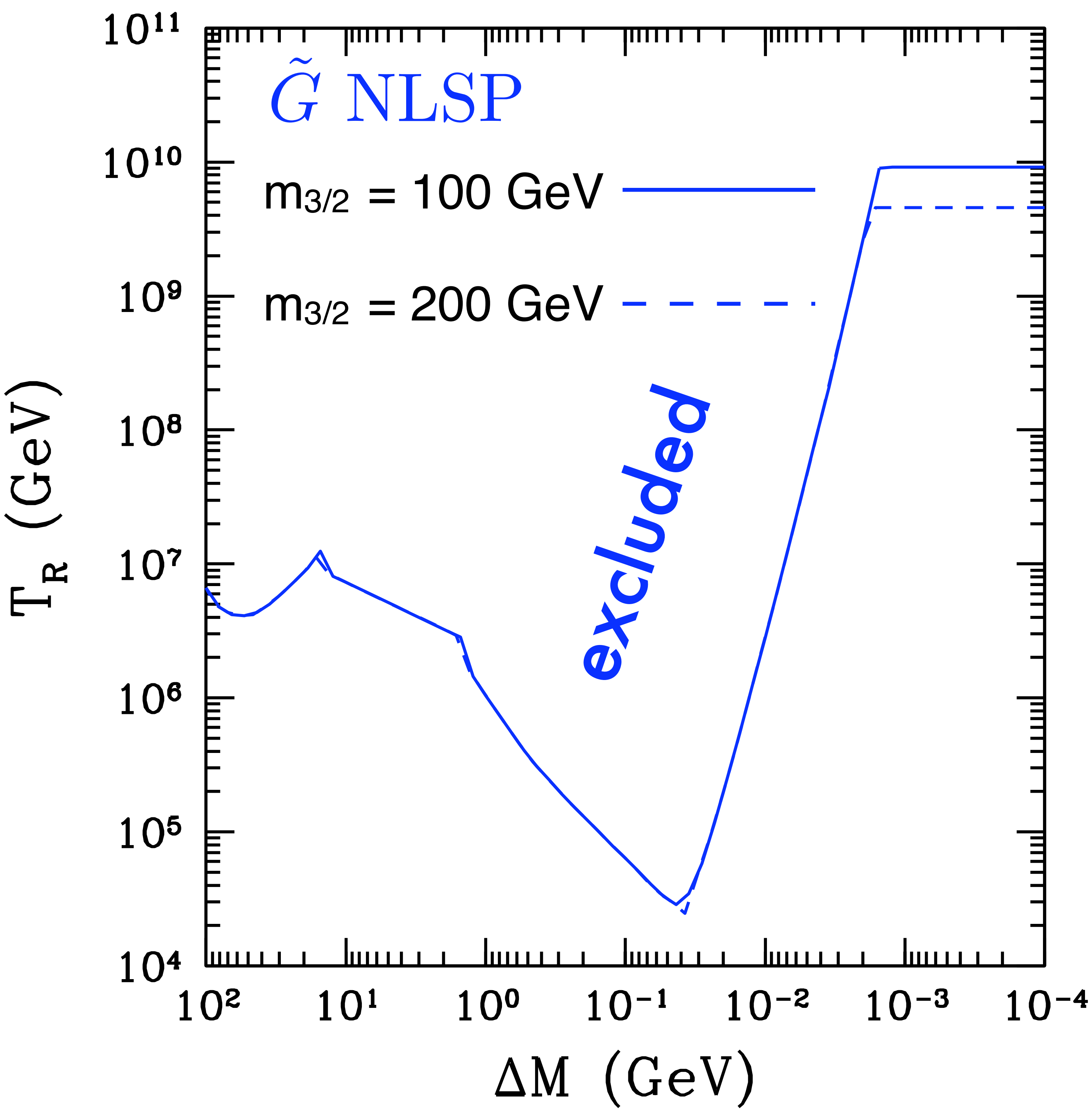
T_{RH} is always $O(10^9)$ GeV provided $\omega < 1$ and the sum of relic densities LSP + NLSP = total CDM.

Gravitino NLSP

$$\boxed{T_{\mathrm{RH}} \simeq 4.1 \times 10^9\,\mathrm{GeV}\left(\frac{m_{3/2}}{100\,\mathrm{GeV}}\right)\left(\frac{1\,\mathrm{TeV}}{M_3}\right)^2 \omega\left(\frac{1}{1+\delta}\right)\,.}$$

T_{RH} is $O(10^9)$ GeV, provided $\omega \simeq 1$ and $\delta \ll 1$ and the sum of relic densities LSP + NLSP = total CDM.

The reheating temperature



Gravitino-stau degeneracy

Long-lived negatively charged particle X^-

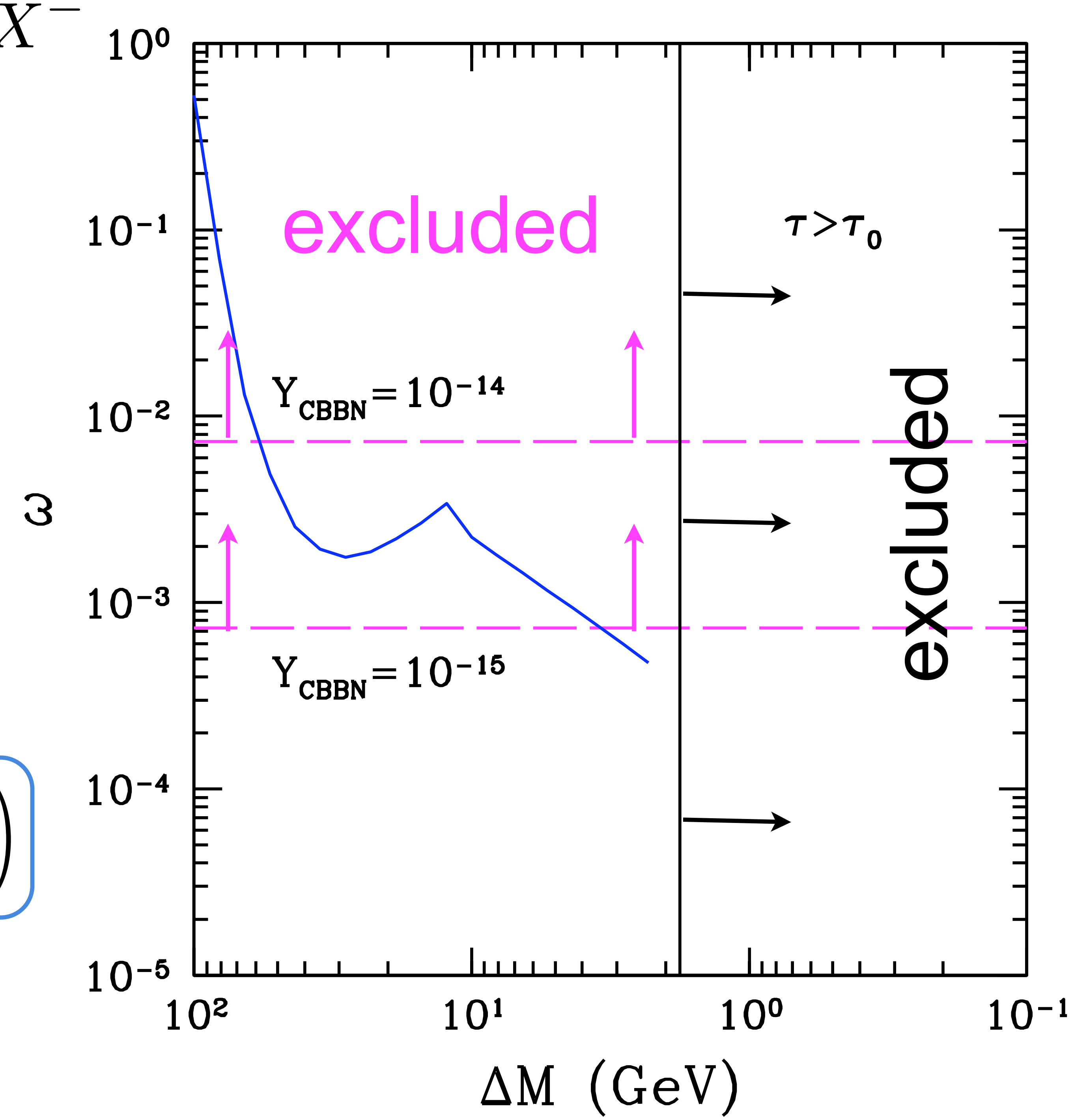
modifies BBN → Catalyzed BBN

Can solve the Li^7 problem.

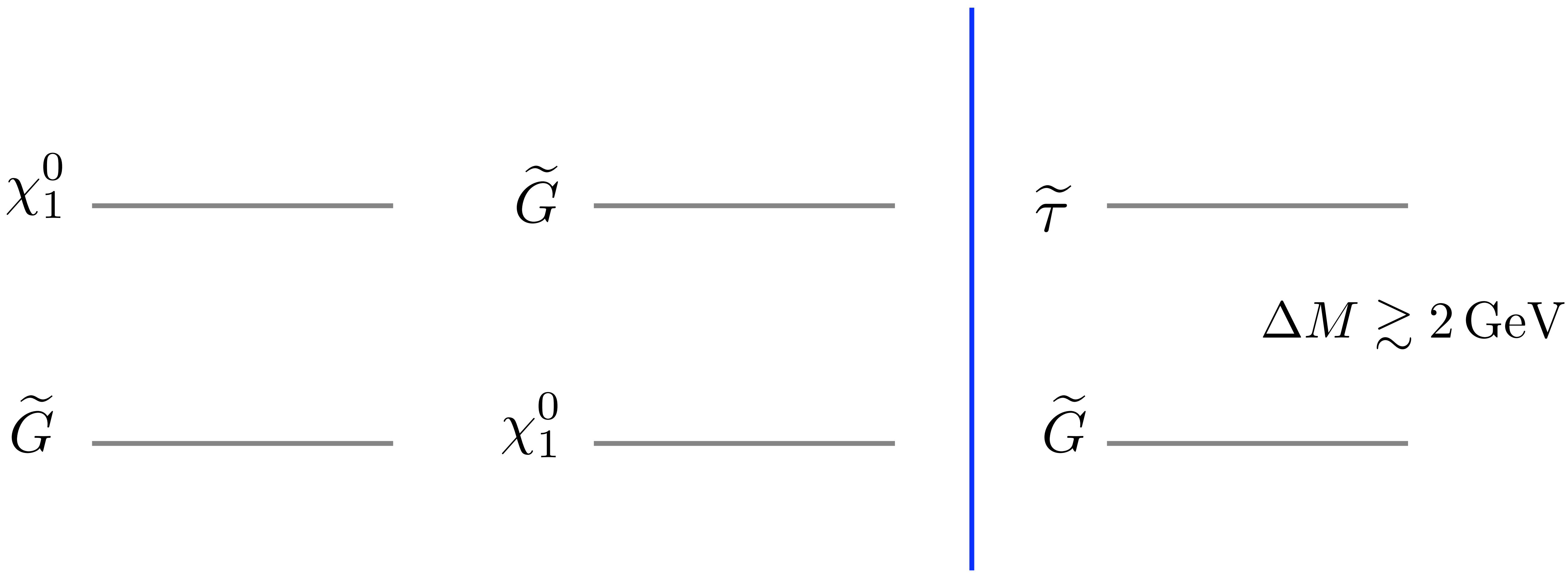
Conservative bound:

$$Y_{X^-} < 10^{-14} - 10^{-15}$$

$$\boxed{\omega \lesssim 2.44 \times 10^{-3} \left(\frac{m_{\rm LSP}}{100\,\mathrm{GeV}}\right)\left(\frac{Y_{\rm CBBN}}{10^{-14}}\right)}$$



....in the CMSSM

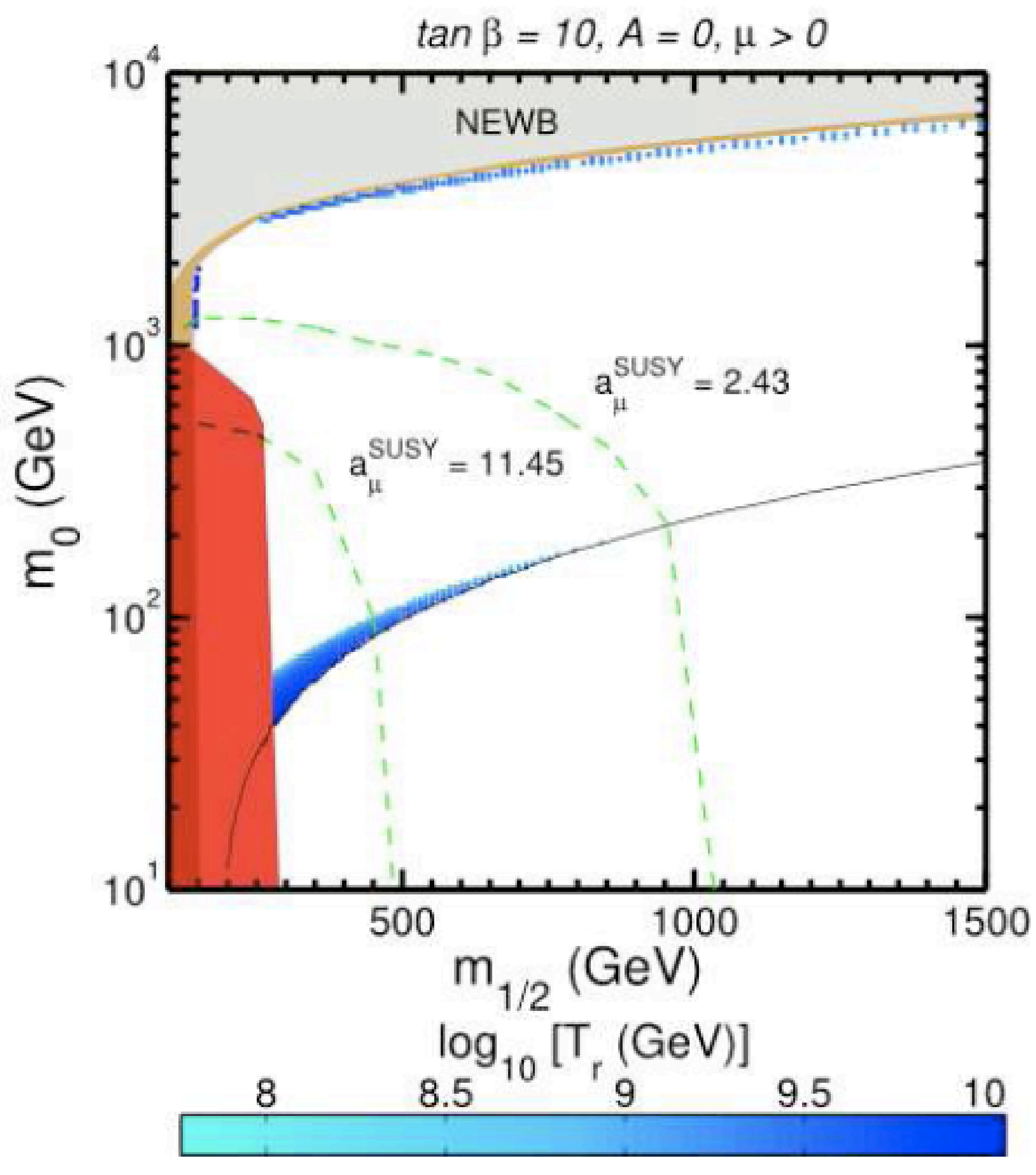


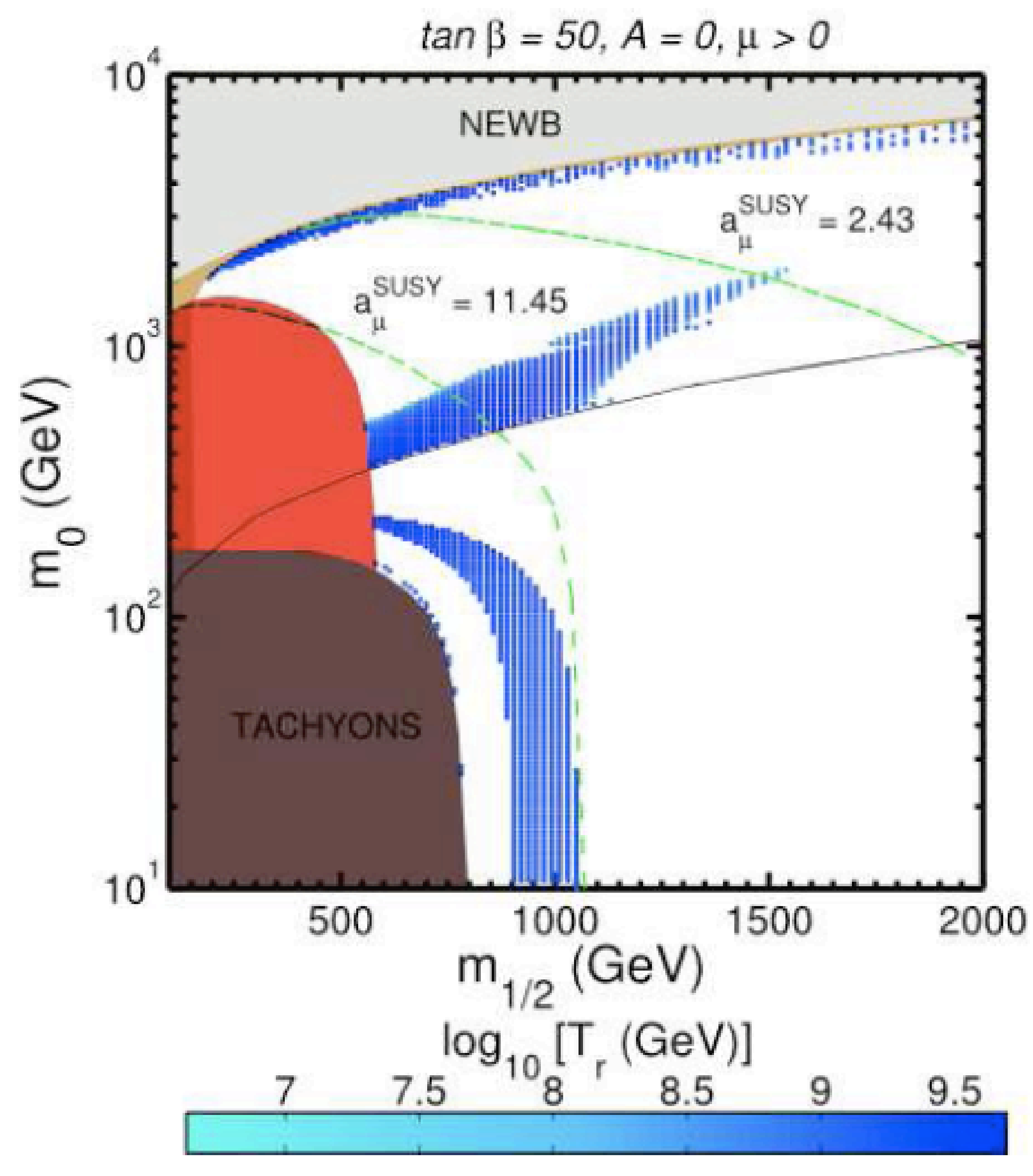
NB: stau abundance today is strongly constrained through "heavy water data"

$$\omega \leq 2.2 \times 10^{-27}\,(m_{\widetilde{\tau}}/100\,\mathrm{GeV})$$

....in the CMSSM

Scan over usual CMSSM parameters $\{m_0,\ m_{1/2},\ A_0,\ \mathrm{sgn}(\mu),\ \tan\beta\}$
plus the gravitino mass $m_{3/2}$





Conclusions

Yes, it is possible to relax constraints on gravitinos.

The price to pay:

1. degeneracy between the gravitino and the LOSP.

- Coannihilation.
- Inelastic DM.

2. Suppressed LOSP abundance $\omega \ll 1$.

➡ A possible way-out to the gravitino impasse in thermal leptogenesis scenarios.

Experiments:

$\widetilde{G} - \chi_1^0$ CDM relic density inferred from direct detection $\neq$ relic density from colliders.

$\widetilde{G} - \widetilde{\tau}$ Charged slow tracks + null results in direct detection.

Thanks Goran!

For all these years of good Physics!

For being enthusiastic about good Physics!

And communicating the “JOY OF MAKING PHYSICS”!

We wish you many more years doing Physics!