Axino CDM and Consequences for SUSY Searches

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in collaboration with

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see also

LC, L. Roszkowski and M. Small JHEP 0207 (2002) 023

LC, H.B. Kim, J.E. Kim and L. Roszkowski
JHEP 0105 (2001) 033

LC, J.E. Kim and L. Roszkowski PRL 82 (1999) 4180

OUTLINE

1. Introduction:

- motivation
- axino models and interactions

2. Axino's production in the early universe:

- thermal
- non-thermal

3. Axinos vs CMSSM and consequences for SUSY searches

4. Conclusions and Outlook

Motivation:

we need COLD Dark Matter with

$$0.095 < \Omega_{CDM} h^2 < 0.130$$

[WMAP '03]

What are the possible candidates ???
The Standard Model does not offer any suitable particle, the neutrinos are at most Hot DM, so we are obliged to look beyond...
If low energy supersymmetry is realized and R parity is conserved, a natural candidate emerges:

the Lightest Supersymmetric Particle.

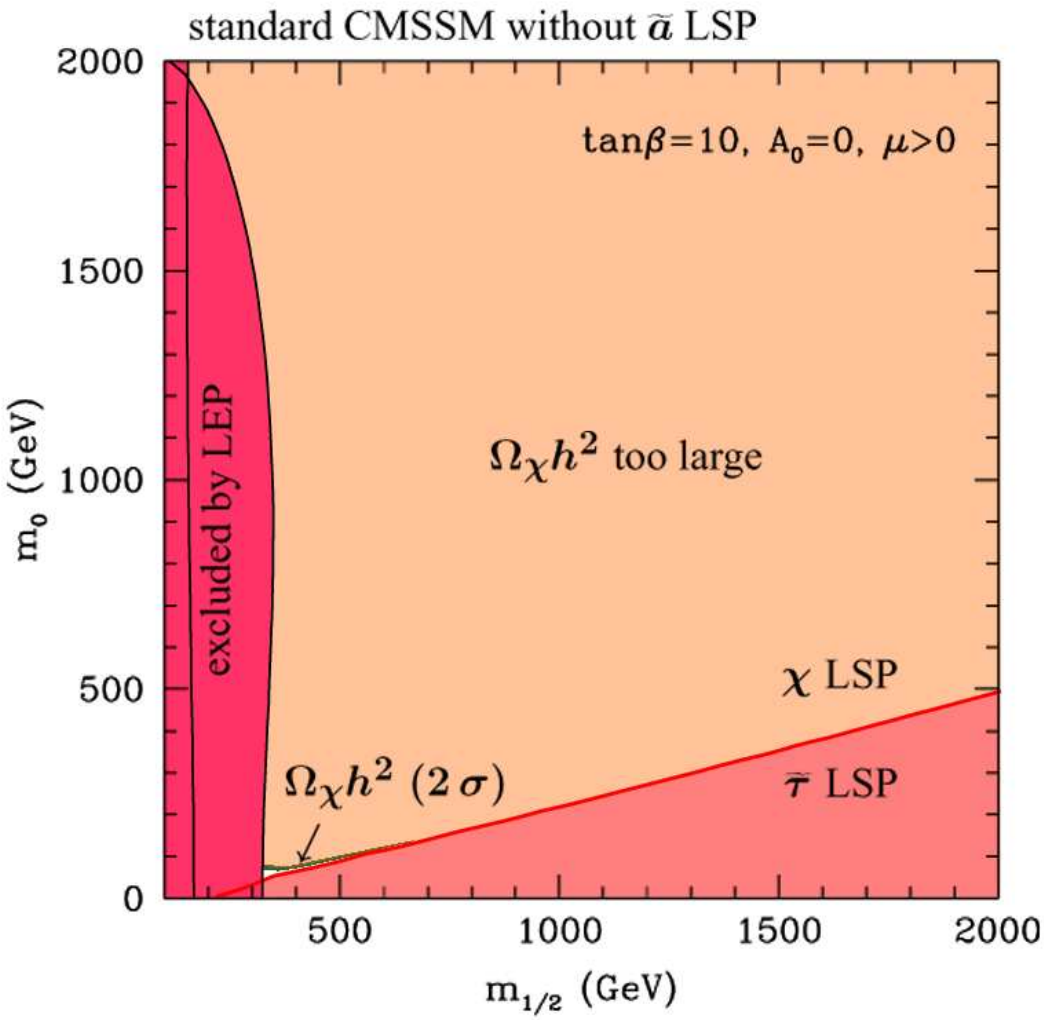
Such particle is massive and stable and to be a good DM candidate it has also to be neutral.

In the (C)MSSM the LSP is pretty naturally a neutralino with weak couplings and so its thermal abundance falls relatively often in the right ballpark

→ WIMP scenario

But for low $\tan\beta$ the "bulk region" is already excluded by LEP and not much parameter space is left. → fine–tuning ?

CMSSM



Only the coannihilation strip is still allowed...

In this talk let us look beyond the CMSSM and consider another candidate, the axino: very weakly interacting, as the gravitino... NO WIMP !

STRONG CP problem $\Rightarrow$ PQ symmetry

[Peccei & Quinn '77]

$\theta_{QCD} < 10^{-9}$ axion a

$$\mathcal{L}_{PQ} = \frac{g^2}{32\pi^2} a \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

introduce a dynamical field, a, the pseudogoldstone boson of the global $U(1)_{PG}$ symmetry, broken at f_a.

A small axion mass is generated at the QCD phase transition by instanton's effects

$$m_a = 6.2 \times 10^{-5} \text{eV} \left(\frac{10^{11} \text{ GeV}}{f_a} \right)$$

Axion physics constrains

$$5 \times 10^9 \text{ GeV} \leq f_a \leq 10^{12} \text{ GeV}$$

SN cooling $\Omega_a h^2 \leq 1$ [Raffelt '98]

ADD SUPERSYMMETRY: [Nilles & Raby '82]

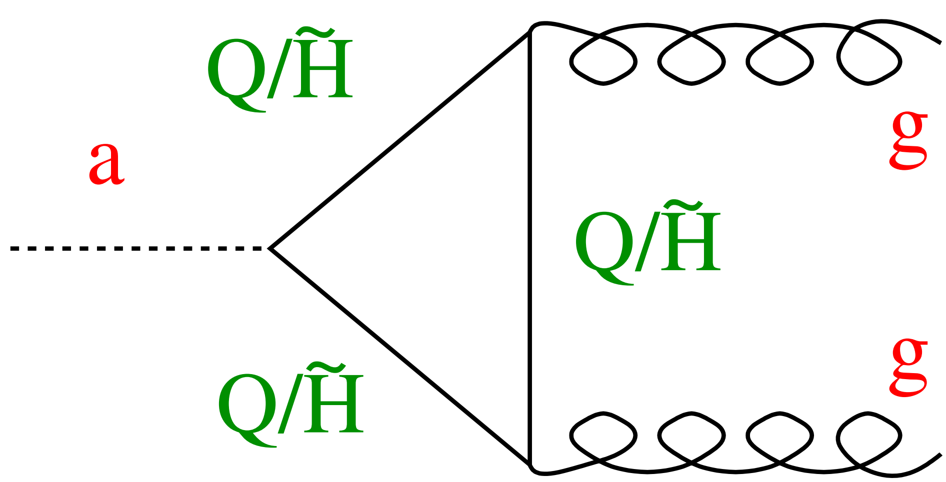
$a \Rightarrow \Phi_a \equiv (s + ia, \tilde{a})$ with

$$W_{PQ} = \frac{g^2}{16\sqrt{2}\pi^2 f_a} \Phi_a W^\alpha W_\alpha$$

The axino is the fermionic superpartner of the axion: it has similar mass/couplings if SUSY is unbroken.

AXION/AXINO MODELS

KSVZ	DFSZ
[Kim '79]	[Dine, Fischler & Srednicki '81]
[Shifman, Vainstein & Zakharov '80]	[Zhitnitskii '80]
$W = h_H \Phi_a \bar{Q} Q$	$W = h\, \Phi_a H_u H_d$
$\bar{Q}, Q$ heavy quarks	H_u, H_d Higgs multiplets
SM fields are not charged under $U(1)_{PQ}$	SM fields are charged under $U(1)_{PQ}$
$< \Phi_a >= f_a$	$< \Phi_a >= f_a$
$m_Q = h_H f_A$	$h f_A = \mu$ μ-term
$h_H \simeq \mathcal{O}(1)$	$\rightarrow h \ll 1$



AXINO MASS

[EJ Chun, JE Kim & HP Nilles '92]
[EJ Chun & A Lukas '95]

In the supersymmetric limit, the whole axion multiplet is mass degenerate → complex $U(1)_{PQ}$

When SUSY is broken, the saxion obtains a mass similarly to the other scalars, while for the axino one must study case by case the tree contribution:

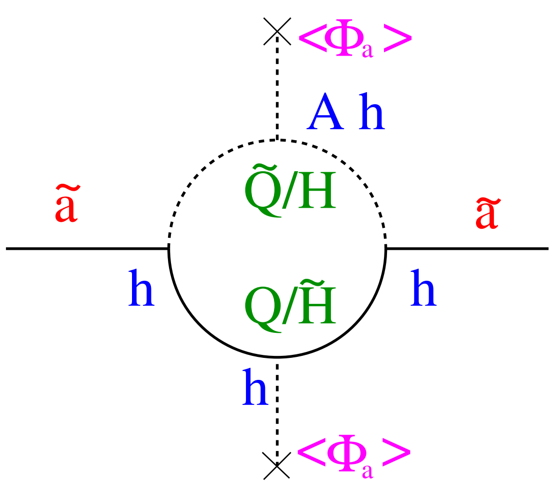
highly model-dependent !

e.g. for $\Phi_a = \frac{1}{\sqrt{2}}(S_1 - S_2)$

$$W = fZ(S_1 S_2 - f_a^2) \quad \rightarrow m_{\tilde{a}} = f\langle Z\rangle \sim |A_1 - A_2| \lesssim m_{3/2}$$

$$W = fZ(S_1 S_2 - X^2) + \frac{1}{3} f'(X - f_a)^3 \quad \rightarrow m_{\tilde{a}} \sim \frac{m_{3/2}^2}{f_a}$$

At one loop a mass term is in general generated by an A-term insertion [P Moxhay & K Yamamoto '85]

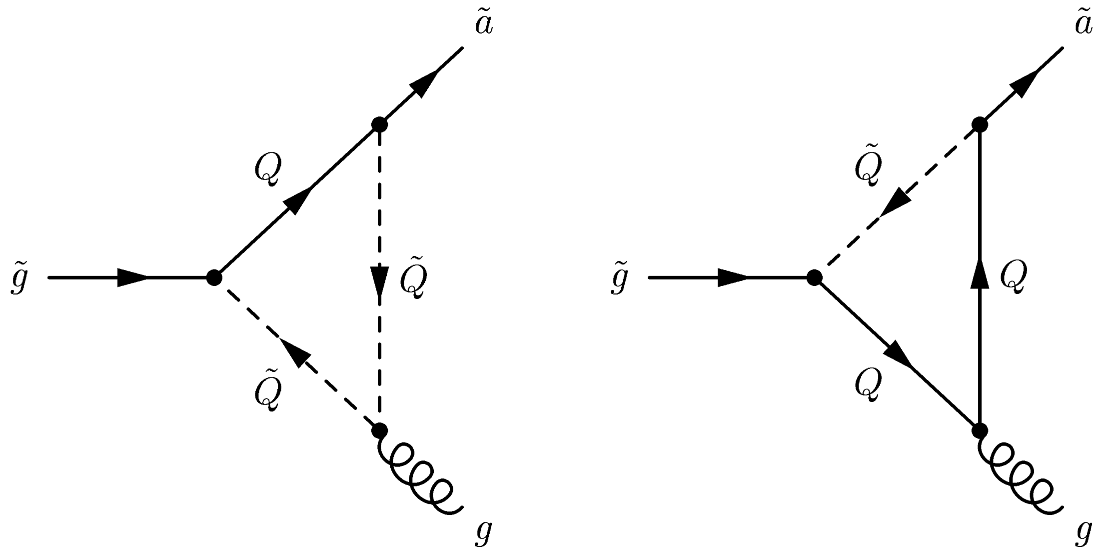


$$m_{\tilde{a}} \sim \frac{h^2}{16\pi^2} A < m_{3/2}$$

⟹ the axino could be the LSP !!!

In our analysis: the axino mass as free parameter !

AXINO COUPLINGS



⋆ "Anomalous" couplings:

$$\mathcal{L}_{\tilde{a}g\tilde{g}} = \frac{\alpha_s}{8\pi f_a} \bar{\tilde{a}} \gamma_5 \sigma^{\mu\nu} \tilde{g}^b G^b_{\mu\nu}$$

model independent !

$$\mathcal{L}_{\tilde{a}B\tilde{B}} = \frac{\alpha_Y C_{aYY}}{8\pi f_a} \bar{\tilde{a}} \gamma_5 \sigma^{\mu\nu} \tilde{B} B_{\mu\nu}$$

$C_{aYY} \sim \mathcal{O}(1)$ model dependent

⋆ Couplings with matter:

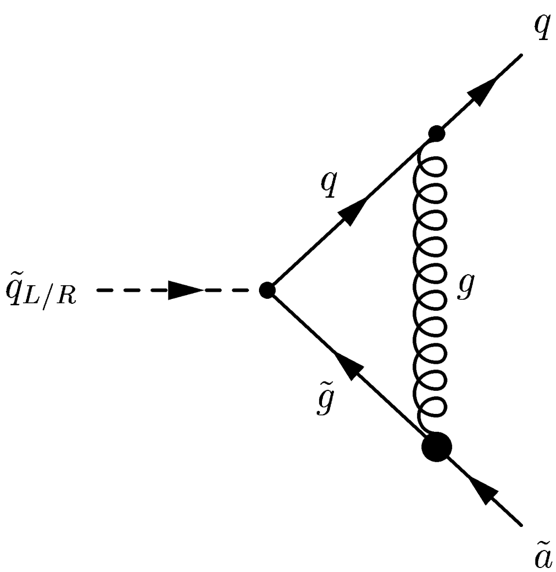
$$\mathcal{L}_{\tilde{a}f\tilde{f}} = g^{L/R}_{eff} \tilde{f}^{L/R}_j \bar{f}_j P_{R/L} \gamma_5 \tilde{a}$$

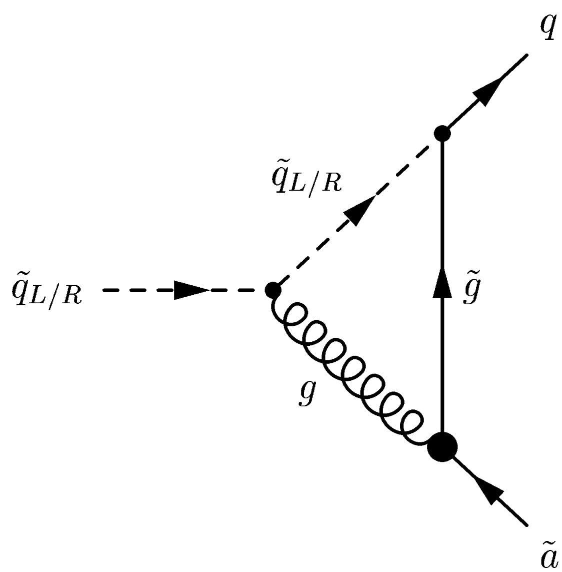
for quarks and leptons !

How to estimate $g^{L/R}_{eff}$?

For the KVSZ case, use as an effective theory the MSSM + anomalous coupling above

⇒ Effective (QCD/EW) one loop generates $g^{L/R}_{eff}$!





The one loop diagrams for the fermionic couplings are logarithmically divergent and depend on the UV completion of the theory $\Rightarrow$ use f_a as a cutoff

$$g_{eff}^{L/R} \simeq \mp \frac{\alpha_s}{\sqrt{2}\pi} \frac{m_{\tilde{g}}}{f_a} \left[\log\left(\frac{f_a}{m_{\tilde{g}}}\right) + \mathcal{O}(1) \right] + \mathcal{O}\left(\frac{m_q}{f_a}\right)$$

& similarly for the leptons

Due to the chiral structure, the loop is proportional to the internal fermionic masses

$\rightarrow$ SUSY limit $m_{\tilde{g}} = 0$: $g_{eff} \sim \frac{m_q}{f_a}$ as axion !

But the coupling can be substantial for heavy gluino/neutralino and it cannot be neglected !!!

For the DFSZ axino the effective coupling above could be enhanced due to the axino mixing with the neutralinos, but not much since the mixing $\propto \frac{v_{EW}}{f_a}$.

Axino production in the early universe

All the axino couplings are suppressed by the PQ scale f_a, so it decouples early at the temperature

$$T_D \simeq 10^9 \text{ GeV} \left(\frac{f_a}{10^{11} \text{ GeV}}\right)^2 \left(\frac{\alpha_s}{0.1}\right)^{-3}$$

[Rajagopal, Turner & Wilczek '91]

If the reheat temperature is larger than T_D, then the axino number density at decoupling is large $n_{\tilde{a}}(T_D) \simeq n_\gamma(T_D)$ and it can be at most a Warm DM candidate with $m_{\tilde{a}} < 2\,(0.36)\,\text{keV}$ (for $\Omega_{\tilde{a}} h^2 = 0.2$).

But assume the reheat temperature is lower and the axinos were NOT in thermal equilibrium (similar to the gravitino case).

One has two different ways of production through:

THERMAL PROCESSES	OUT OF EQUILIBRIUM DECAYS
↓	↓
"Thermal production"	"Non-thermal production"

THERMAL PRODUCTION

[LC, HB Kim, JE Kim & L Roszkowski '01]

[LC, L Roszkowski & M Small '02]

Solve the Boltzmann equation for the axinos:

$$\frac{dn_{\tilde{a}}}{dt} + 3Hn_{\tilde{a}} = \sum_{ij} < \sigma(i + j \rightarrow \tilde{a} + ...)v_{rel} > n_i n_j$$

scatterings

$$\sum_{i} < \Gamma(i \rightarrow \tilde{a} + ...) > n_i$$

decays

Since axinos are not in thermal equilibrium and $n_{\tilde{a}} \ll n_i$ we can neglect back-reactions !

At high temperatures the dominant contribution comes from QCD scatterings: many diagrams involving quarks, gluons, gluinos, squarks...

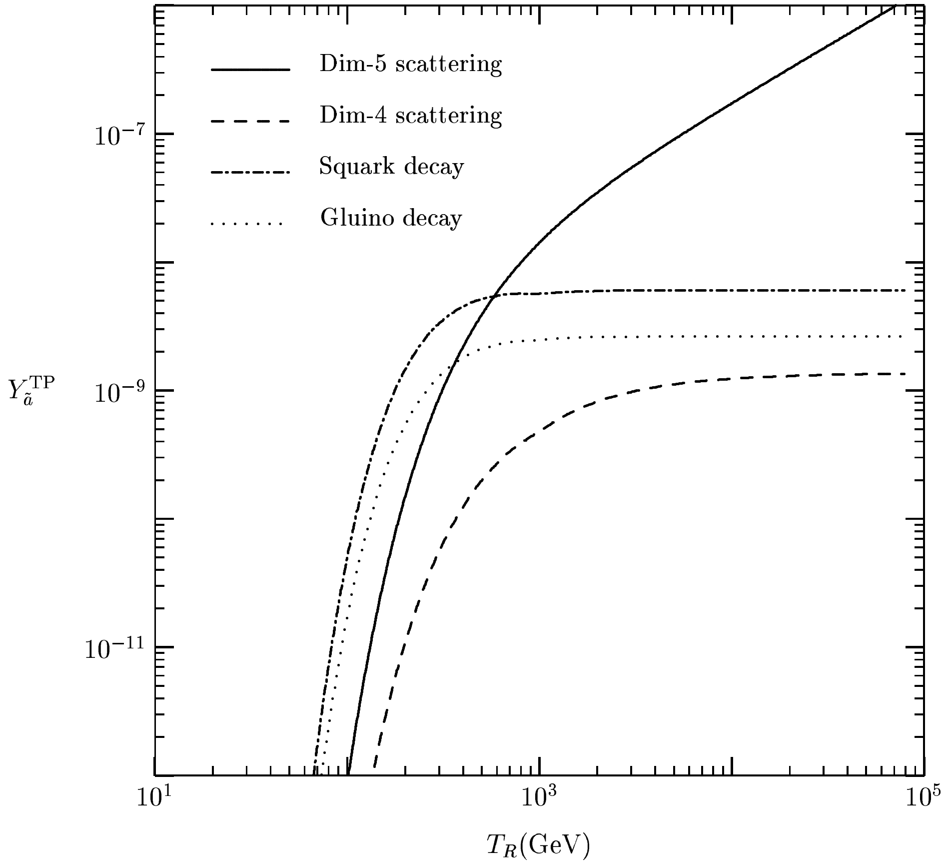
analogous to the gravitino's case !

NB: some channels are logarithmic IR divergent $\Rightarrow$ IR cut-off: gluon thermal mass $\mu_g = gT$

More appropriate procedure is to perform a full resummation of the Hard Thermal Loops $\rightarrow$ about factor of 10 reduction [A Brandenburg & FD Steffen '04]

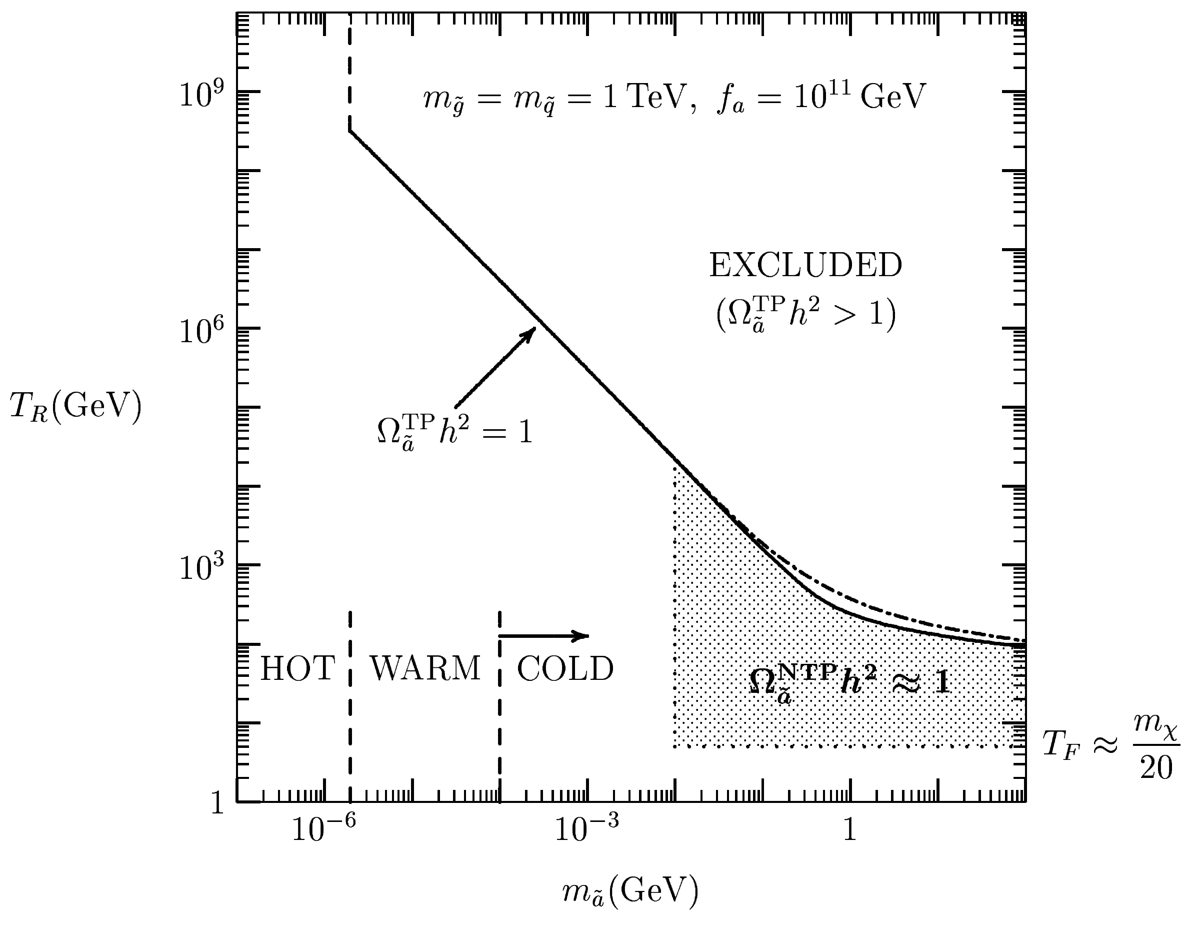
At temperatures of the order of the sparticle masses, the decay terms start to dominate !

From the Boltzmann equation we obtain



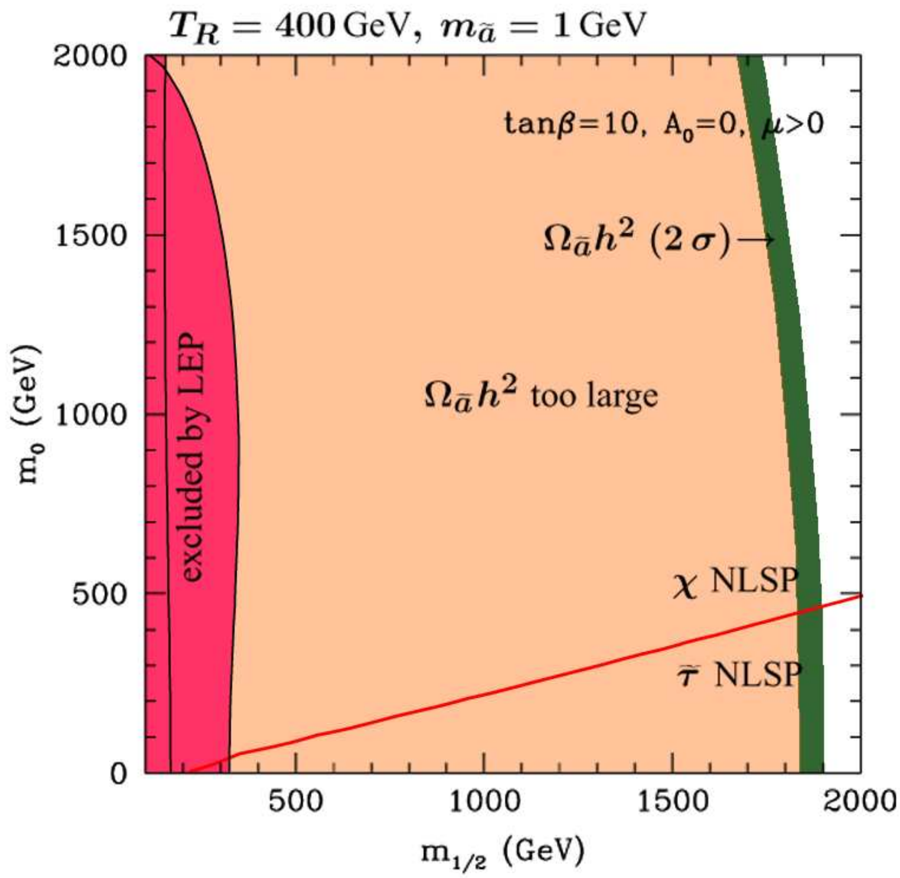
Transform this plot into a bound on T_R using

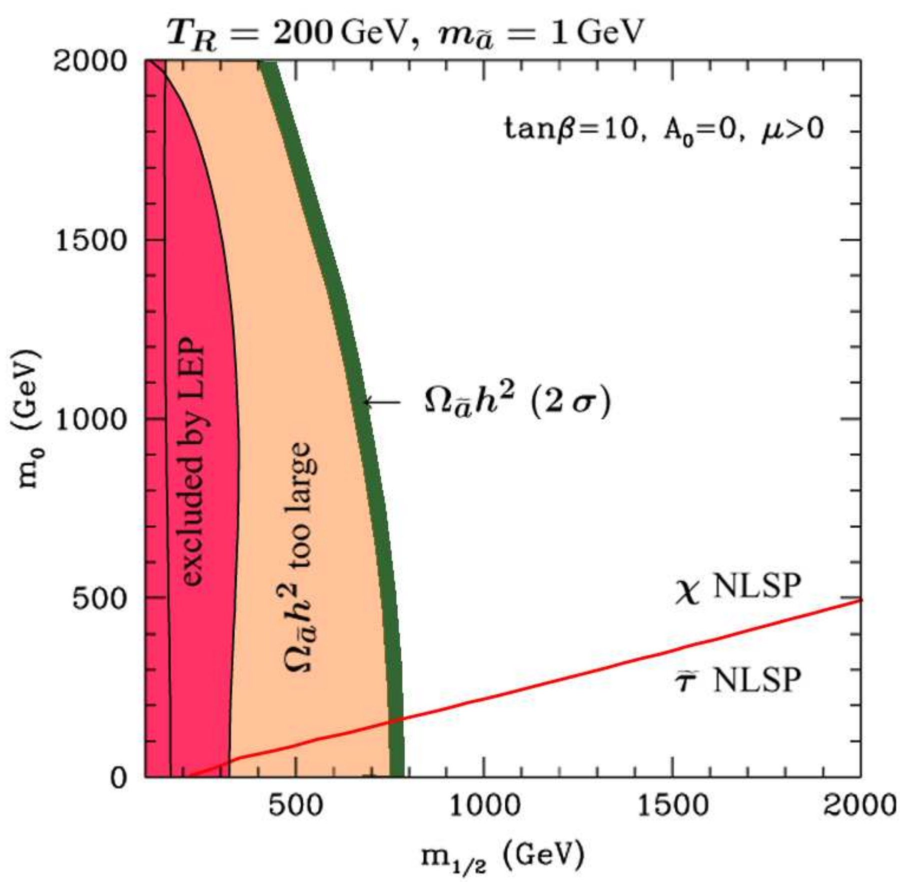
$$m_{\tilde{a}} Y_{\tilde{a}} = 0.72\,\mathrm{eV}\left(\Omega_{\tilde{a}} h^2/0.2\right)$$



Light axino

→ thermal production





NON THERMAL PRODUCTION

[JE Kim, A Masiero & DV Nanopoulos '84]

[LC, JE Kim & L Roszkowski '99]

An axino LSP population is also regenerated by NLSP decay after freeze-out: e.g. for neutralino $\chi \to \tilde{a}\gamma$ we have

$$\tau_\chi = \frac{128\pi^3}{\alpha_{em}^2 C_{aYY}^2} \frac{f_a^2}{m_\chi^3}$$
$$= \frac{0.33 \text{ sec}}{Z_{11}^2 C_{aYY}^2} \left(\frac{f_a}{10^{11} \text{ GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_\chi}\right)^3$$

where Z_{11} is the $\tilde{B}$ fraction of the neutralino.

Note:

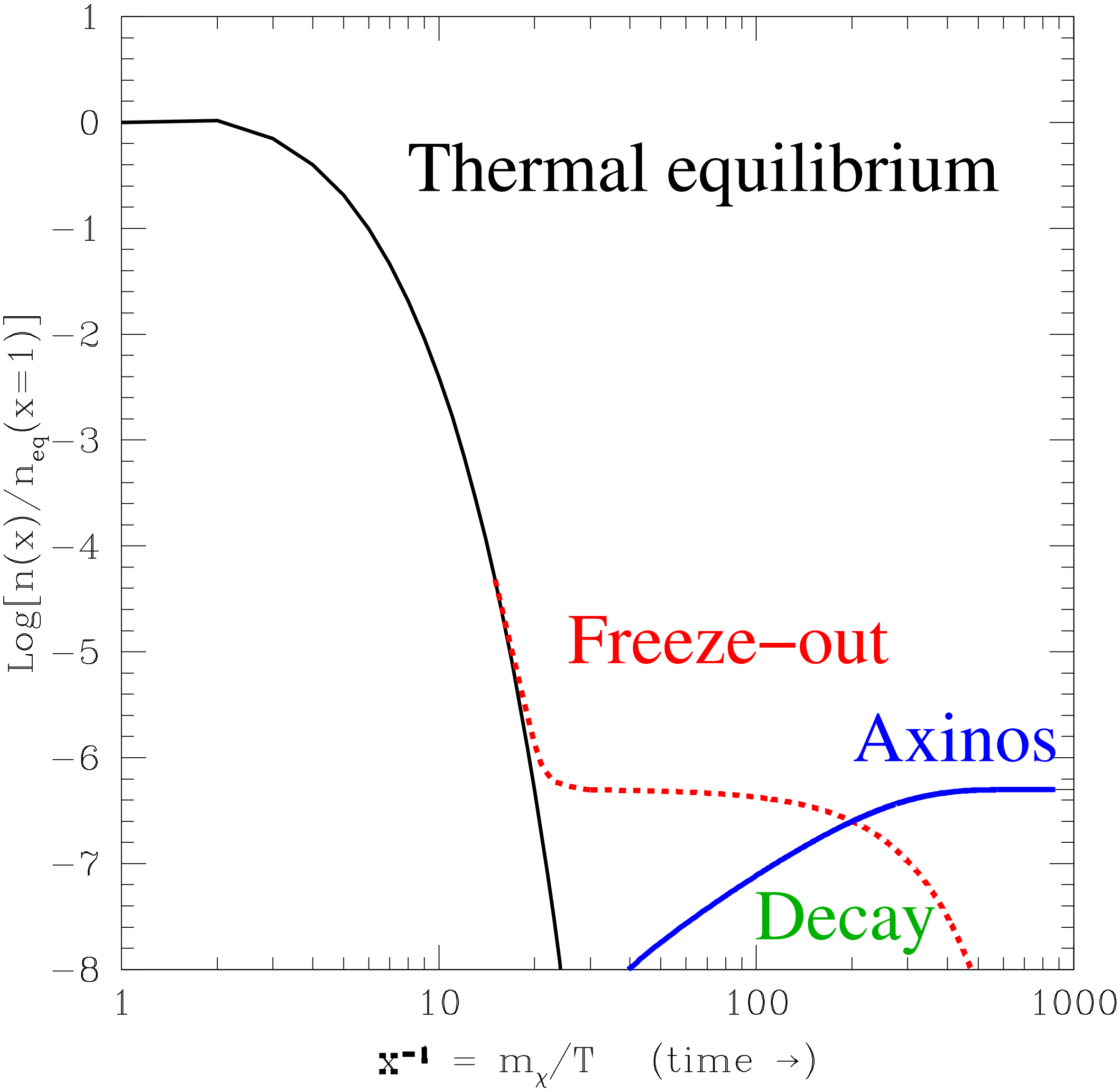
$\tau \gg 1/H(x_f)$ $\to$ the neutralino freeze-out is not modified:

$$\Omega_{\tilde{a}} = \frac{m_{\tilde{a}}}{m_\chi} \Omega_\chi$$

$\tau \lesssim 1$ sec $\to$ weak BBN constraints compared to the gravitino case with $\tau \geq 10^4$ sec !

Similar picture also for stau NLSP, but WITH SLIGHTLY LARGER LIFETIME !

NON THERMAL PRODUCTION



The final axino abundance is just given by:

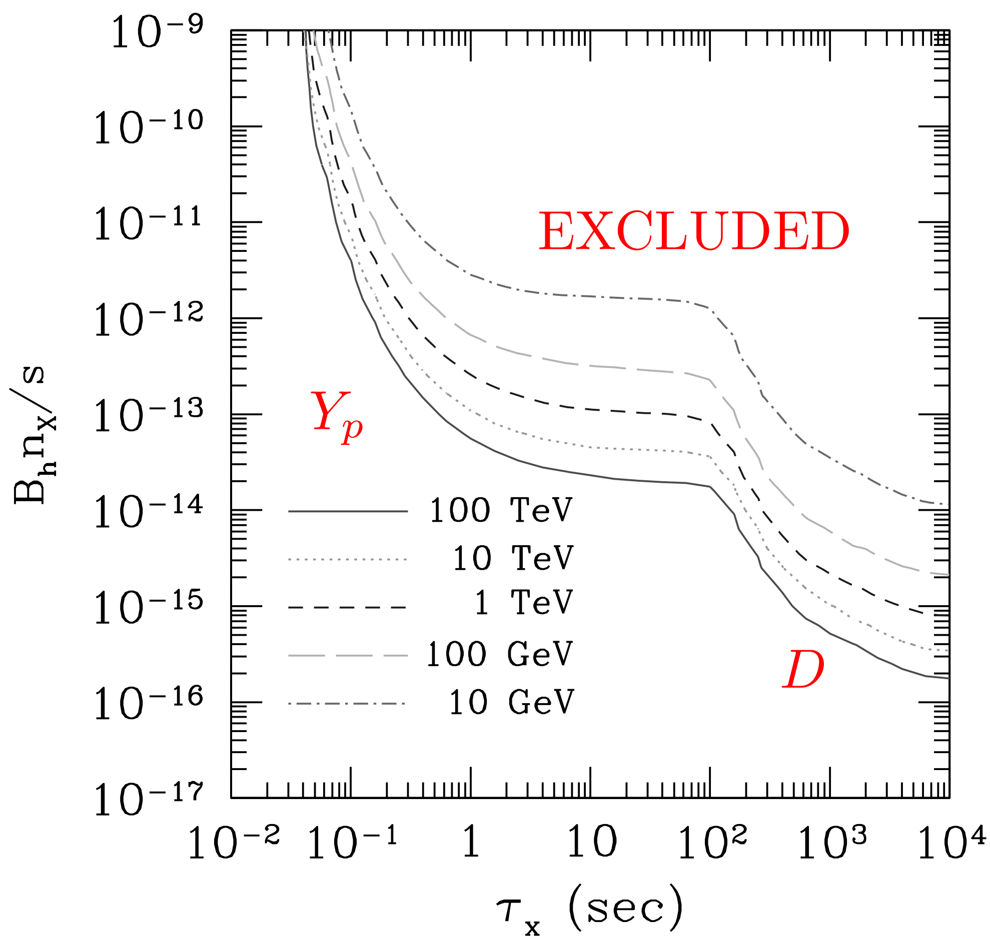
$$\Omega_{\tilde{a}}^{NT} = \frac{m_{\tilde{a}}}{m_{\chi}}\,\Omega_{\chi}$$

Which cosmological bounds restrict NT production ?

$\Rightarrow$ Big Bang Nucleosynthesis !

The decay of a heavy particle during or after BBN can alter the predictions for the light elements abundances. For $\tau \leq 10^2$ sec as in our case the stronger bounds arise from considering hadronic decays, since at this temperatures the photons usually thermalize fast with the CMB tail.

[Kohri '01]



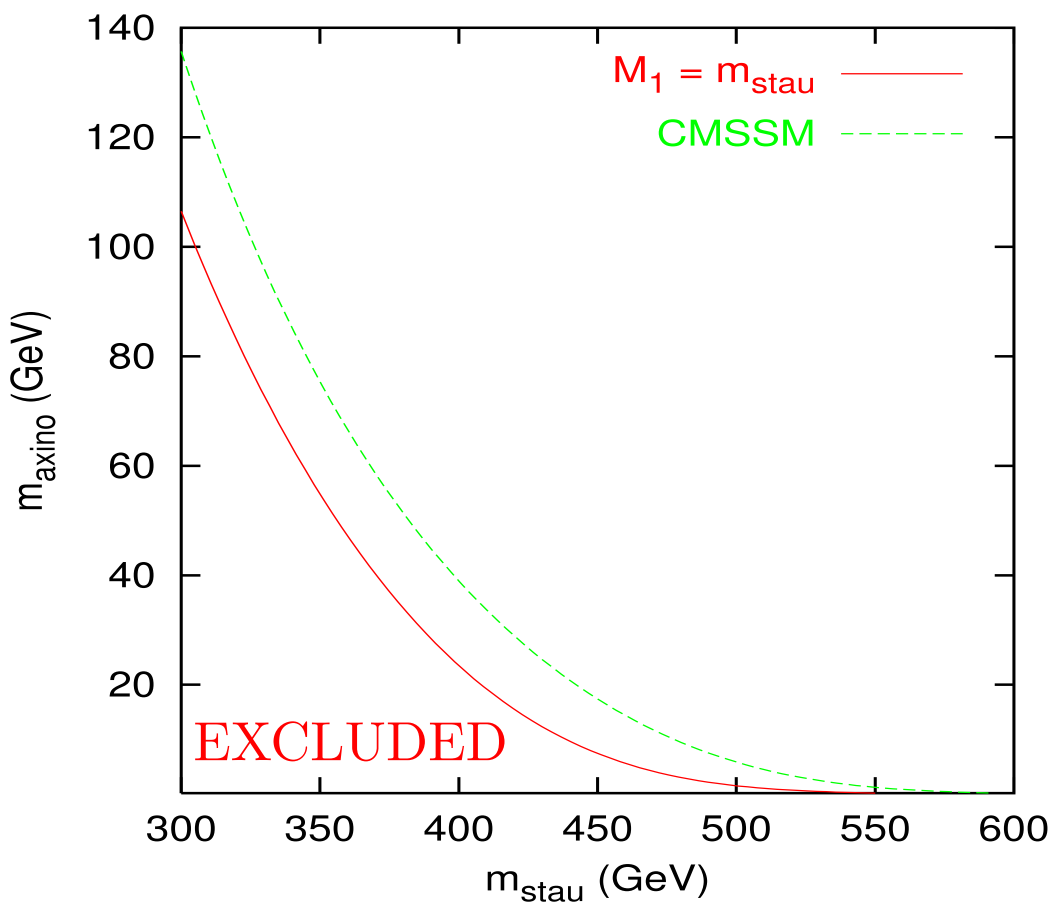
B_h is the hadronic branching ratio and the different curves refer to different decaying particle mass.

BBN bound

The constraint is stronger for a stau NLSP, due to the longer lifetime and greater B_h: in fact mostly $\tilde{\tau}_1 \rightarrow \tilde{a} + \tau \rightarrow \tilde{a} + hadrons$.

The upper bound on $Y_{\tilde{\tau}_1} \equiv Y_{\tilde{a}}^{NTP}$ depends on the $\tilde{\tau}_1$ lifetime, and can be recast in the plane $m_{\tilde{a}}$ vs $m_{\tilde{\tau}}$ assuming that all CDM comes from NTP, i.e. $m_{\tilde{a}} Y_{\tilde{a}}^{NTP} > 0.34$ eV

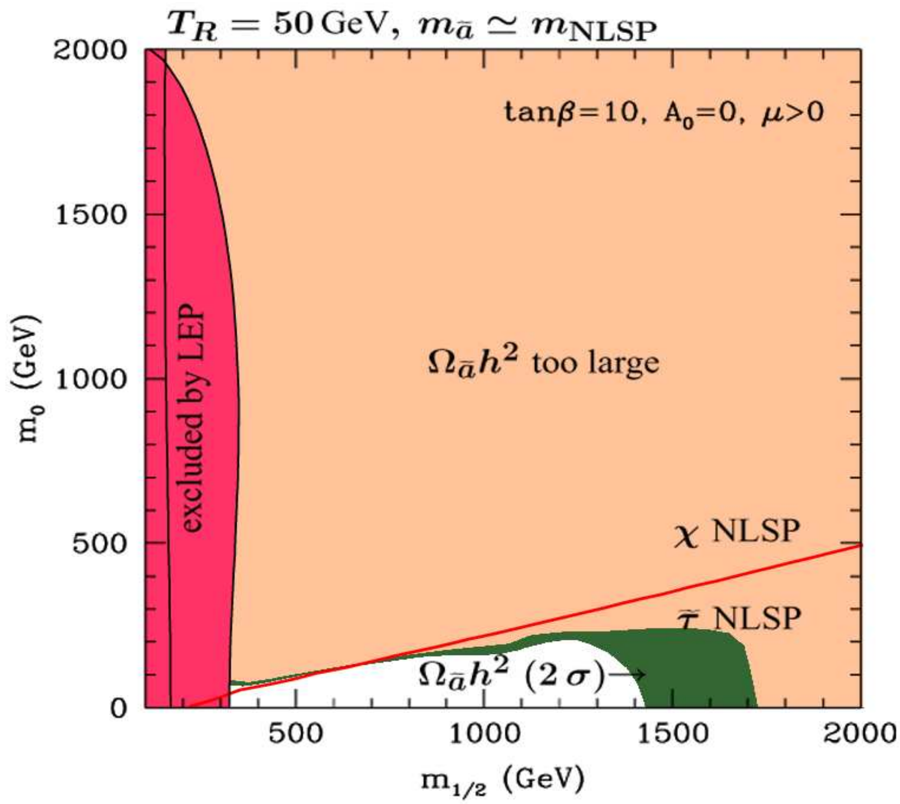
$\Rightarrow$ WORST CASE SCENARIO !



NOTE: much weaker bounds, in the MeV's range of $m_{\tilde{a}}$ and below $m_\chi = 150$ GeV for the neutralino !!!

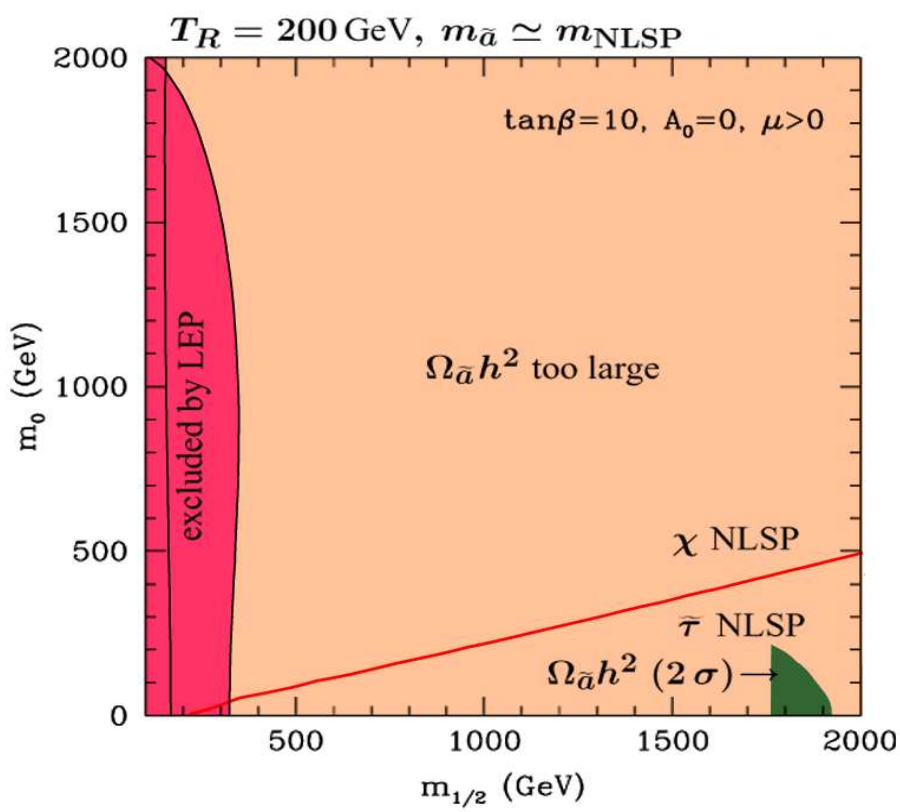
Axino mass proportional to LSP mass

- low reheat temperature $\longrightarrow$ non–thermal production



- higher reheat temperature

$\longrightarrow$ thermal + non–thermal



CONSEQUENCES FOR SUSY SEARCHES

- NLSP practically stable within the detector since

$$\tau \gtrsim 1 \ \text{sec}$$

  For the DFSZ case, the decay could be faster and perhaps seen in the detector,

  see e.g. [S. Martin '00]

- for neutralino "stable" NLSP: need to reconstruct the SUSY parameters and the neutralino number density to check if the Universe appears "overclosed"

- for charged NLSP, probably a $\tilde{\tau}$:
  $\rightarrow$ striking signature of an escaping track !

- a study of the NLSP decay is necessary to discover the nature of the LSP, and possibly the observation of more than one decay channel; e.g. the radiative decay of a charged NLSP can probe the LSP spin, as proposed by [W Buchmüller, K Hamaguchi, M Ratz & T Yanagida '04] for the gravitino case; the axino is work in progress...

Conclusions and Outlook

- Axinos with masses in the MeV-GeV are good CDM candidates for low reheat temperature: they can be produced either from thermal processes or from NLSP decay.
- Axinos are less constrained than gravitinos and usually evade BBN bounds, since the NLSP lifetime is shorter than 10^2 sec.
- An axino (gravitino) LSP opens up the chance of a charged NLSP, which looks stable in colliders $\rightarrow$ striking scenario at LHC or LC:

  need to store NLSPs and study their decay
- In the case of axino CDM, different regions of the CMSSM parameter space become allowed and preferred compared to the usual CMSSM with neutralino CDM

  $\rightarrow$ heavier sparticles are allowed