Axinos as CDM

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DESY

based on work in collaboration with

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OUTLINE

1. Introduction
2. Axino's production in the Early Universe: $\nearrow$ thermal $\searrow$ non-thermal
3. BBN bounds and coloured NLSP
4. Collider signatures for a $\tilde{\tau}$ NLSP
5. Conclusions and Outlook

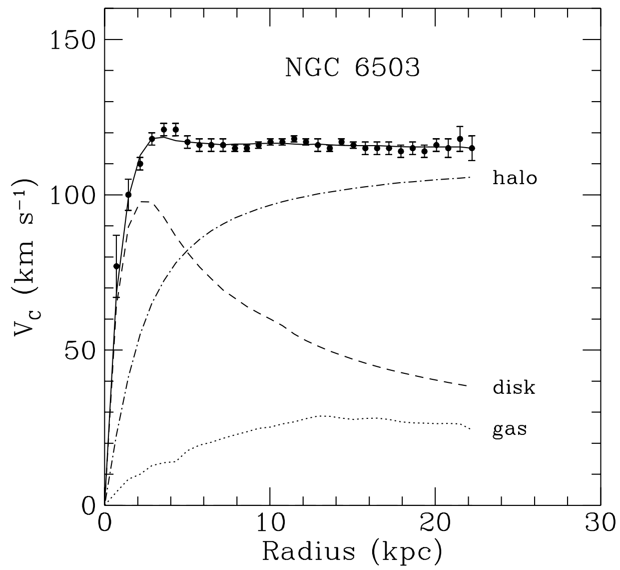
THE MATTER CONTENT

The clumpy energy density/matter divides into

Particles	$\Omega_i(t_{\text{now}})h^2$ (WMAP)	Type
Baryons	0.0224	Cold
Massive ν	$6.5 \times 10^{-4} - 0.01$	Hot
???	$\sim 0.1 - 0.13$	COLD

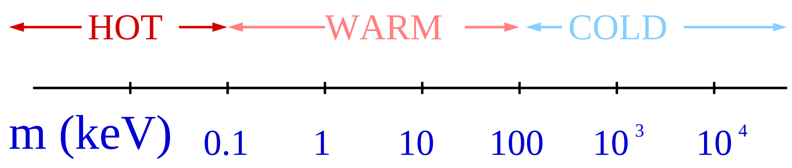
DARK matter !

[Begeman, Broeils & Sanders '91]



Note that DM was first discovered in local systems from the galaxies rotational curves...

Structure formation requires COLD Dark Matter, otherwise the structure formation on scales smaller than its free-streaming length at t_{eq} is suppressed.



NEED to produce after inflation a large number of particles sufficiently massive, stable and neutral !

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 (SM) 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.

$\longrightarrow$ SUSY

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 $\longrightarrow$ WIMP scenario

Primordial abundance of stable massive species

[see e.g. Kolb & Turner '90]

The number density of a stable particle X in an expanding Universe is given by the Bolzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle\sigma(X + X \to \text{anything})v\rangle \left(n_{eq}^2 - n_X^2\right)$$

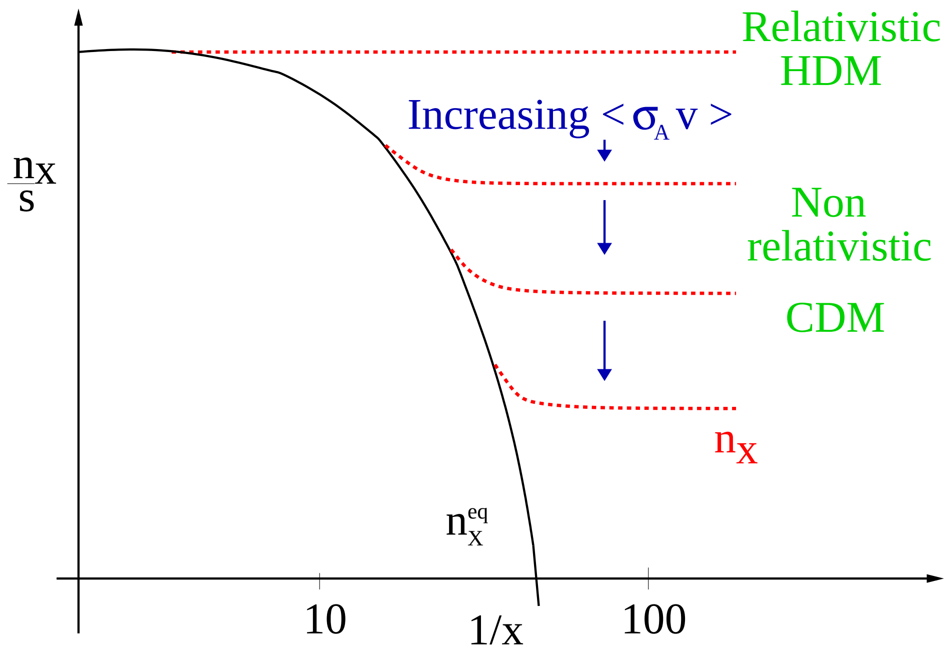
Hubble expansion   Collision integral

The particles stay in thermal equilibrium as long as the interactions are fast enough, then they freeze-out when

$$n_{eq}\langle\sigma_A v\rangle = H \qquad \Rightarrow \qquad \Omega \propto \frac{1}{\langle\sigma_A v\rangle}$$

If a particle X decouples when it is still relativistic, it survives with high number density, $n_X(T_D) = n_\gamma(T_D)$ and so

$$m_X \leq 10^{-3}\text{keV}\;\; g_\star(T_D)\left(\frac{\Omega_X h^2}{0.15}\right)$$



VERY LIGHT $\longrightarrow$ HOT/WARM Dark Matter !

Since we need COLD DM either they are not DM or they never were in thermal equilibrium !

AXION:

STRONG CP problem $\Rightarrow$ PQ symmetry [Peccei & Quinn 1977]

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

Introduce a global $U(1)_{PG}$ symmetry broken at f_a, then θ becomes the dynamical field a,

a pseudogoldstone boson with interaction:

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

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

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

[Nilles & Raby '82]

[Frére & Gerard '83]

The AXINO is the fermionic superpartner of the axion with same mass & couplings *if supersymmetry is unbroken*.

AXION and AXINO MODELS

KSVZ

[Kim '79], [Shifman, Vainstein & Zakharov '80]

$W = h_H \Phi_a \bar{Q} Q$ $\quad \bar{Q}, Q$ heavy quarks

SM fields are not charged under $U(1)_{PQ}$

$m_Q = h_H f_a$

$h_H \simeq \mathcal{O}(1)$

DFSZ

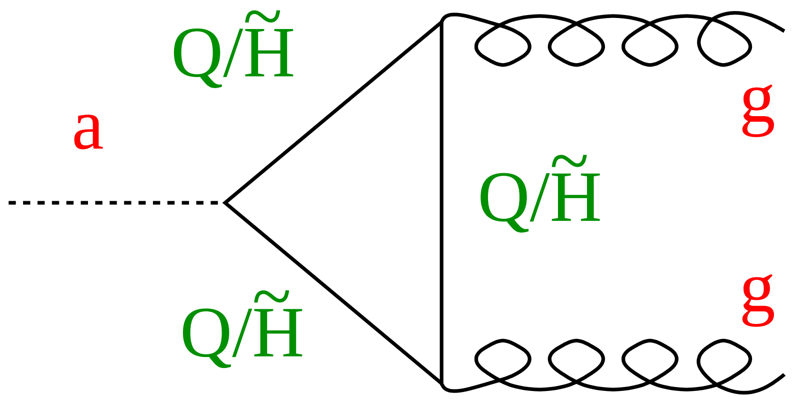
[Dine, Fischler & Srednicki '81], [Zhitnitskii '80]

$W = h\, \Phi_a H_u H_d$ $\quad H_u, H_d$ Higgs multiplets

SM fields are charged under $U(1)_{PQ}$

$h f_a = \mu$ $\quad \mu$-term

$\rightarrow h \ll 1$



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 $\longrightarrow$ 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 $\Phi_a = \frac{1}{\sqrt{2}}(S_1 - S_2)$

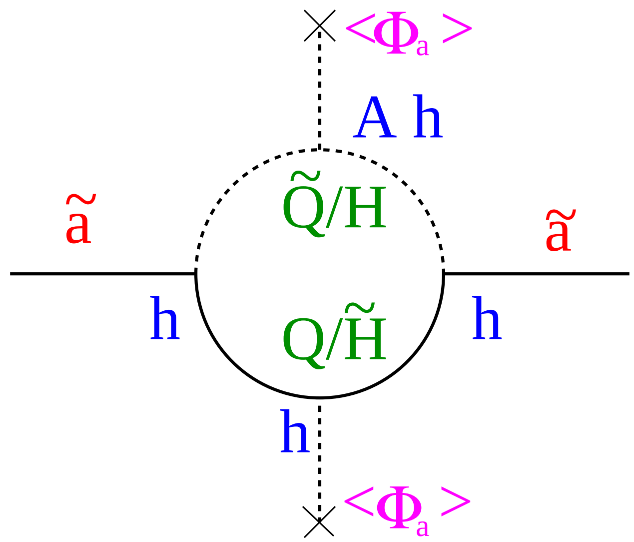
$$W = fZ(S_1 S_2 - f_a^2)$$

$$\Rightarrow \; m_{\tilde{a}} = f\langle Z\rangle \sim |A_1 - A_2| \lesssim m_{3/2}$$

$$W = fZ(S_1 S_2 - X^2) + \frac{1}{3} f'(X - f_a)^3$$

$$\Rightarrow \; m_{\tilde{a}} \sim \frac{m_{3/2}^2}{f_a}$$

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



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

$\Longrightarrow$ the axino could be the LSP !!!

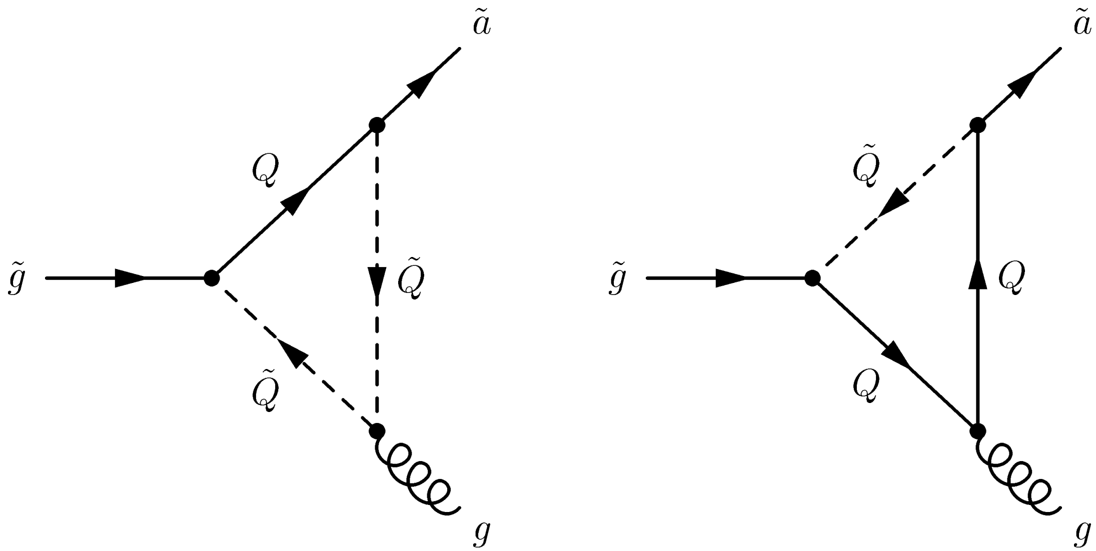
In our analysis we will take the axino mass as free parameter.

AXINO COUPLINGS

$\star$ "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 !



Similarly for the $U(1)$ factor, depending on the heavy quark charges:

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

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

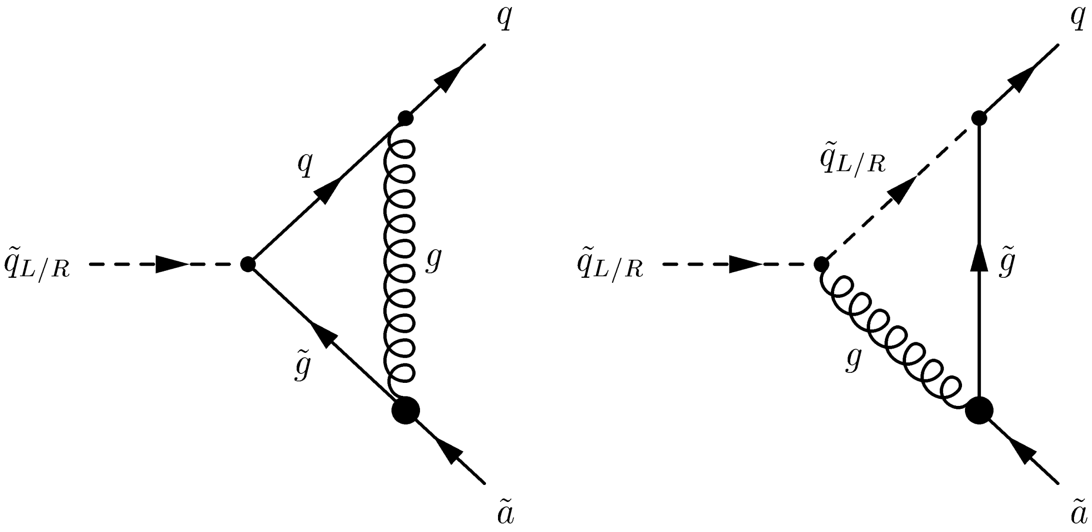
$\star$ Couplings with matter: $\mathcal{L}_{\tilde{a}f\tilde{f}} = g^{L/R}_{eff} \tilde{f}^{L/R}_j \bar{f}_j P_{R/L} \gamma_5 \tilde{a}$ for quarks and leptons !

How to estimate $g^{L/R}_{eff}$? For the KVSZ case, use as an effective theory the MSSM + anomalous coupling above

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

Compute the effective vertex: but 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



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

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

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

But the coupling can be substancial 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 and axinos can be at most a Warm DM candidates with $m_{\tilde{a}} < 2\,(0.36)$ 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

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

[LC, L Roszkowski & M Small '02]

Solve the Bolzmann equation for the axinos:

$$\frac{dn_{\tilde{a}}}{dt} + 3Hn_{\tilde{a}} = \sum_{ij} \langle \sigma(i + j \to \tilde{a} + ...) v_{rel} \rangle n_i n_j + \sum_i \langle \Gamma(i \to \tilde{a} + ...) \rangle n_i$$

scatterings　　　　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 !

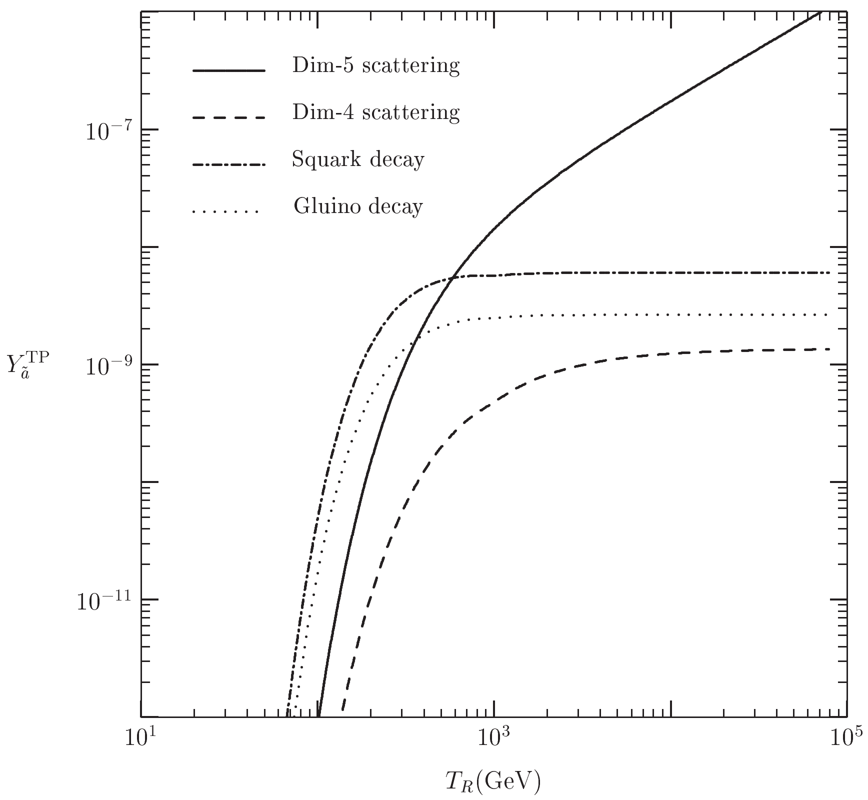
NB: some channels are logarithmic IR divergent $\Rightarrow$ IR cut-off: gluon thermal mass $\mu_g = gT$

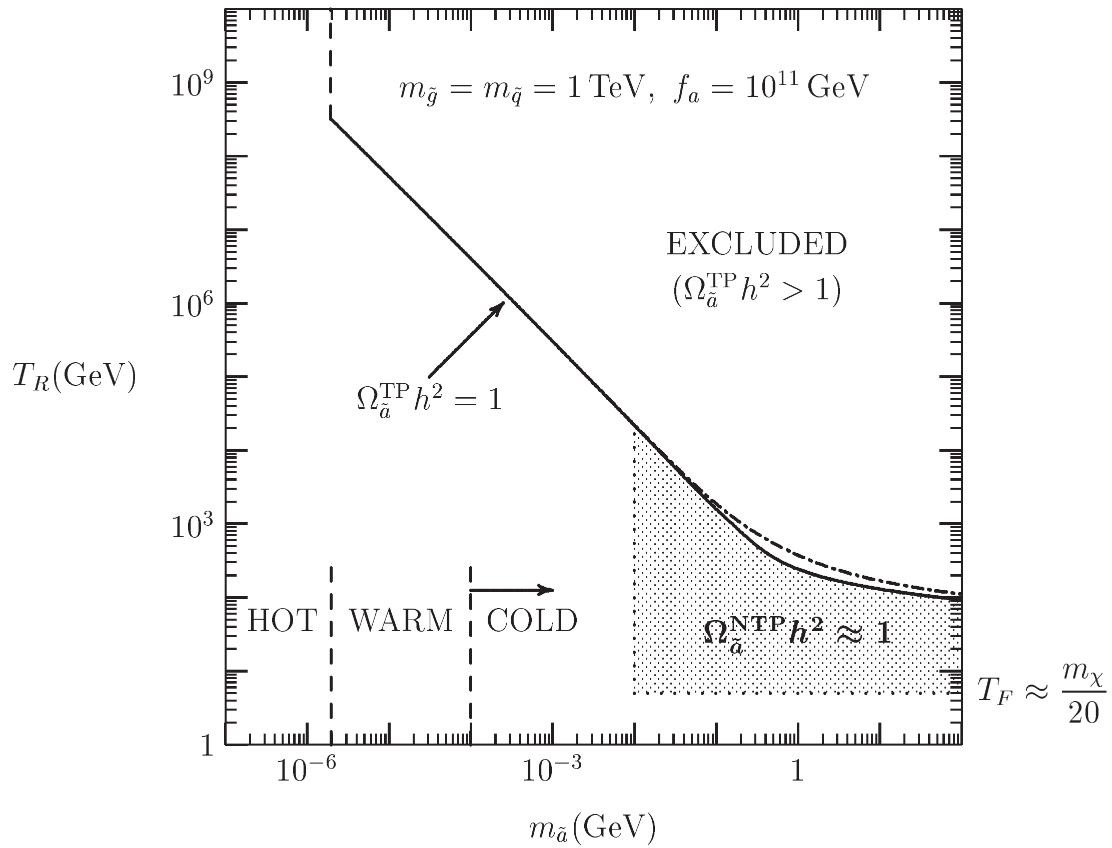
More appropriate procedure is to perform a full resummation of the Hard Thermal Loops as has been done also for the gravitinos　　[A Brandenburg & FD Steffen '04]

Note that at temperatures of the order of the sparticle masses, the decay terms start to dominate !

Contributions to the axino yield and bound on T_R using

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





PRETTY LOW REHEAT TEMPERATURE NEEDED !

OUT OF EQUILIBRIUM DECAY

[JE Kim, A Masiero & DV Nanopoulos '84], [LC, JE Kim & L Roszkowski '99]

An axino (or any LSP !) population is also generated by NLSP decay after freeze-out: e.g. for neutralino we have usually $\chi \longrightarrow \tilde{a}\gamma$ or for scalar taus $\tilde{\tau} \longrightarrow \tilde{a}\tau$.

The important parameter is the lifetime:

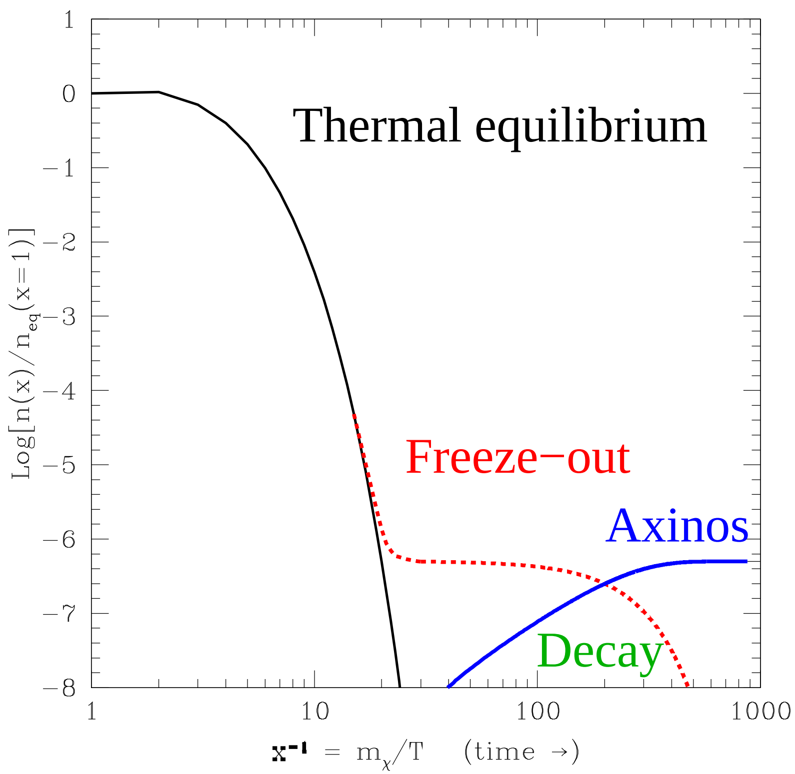
$\tau \gg 1/H(x_f)$

$\Rightarrow$ the NLSP freeze-out is not modified:

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

Still a connection to weak physics via Ω_{NLSP}!

$\tau \leq 1$ sec $\Rightarrow$ weak BBN constraints !

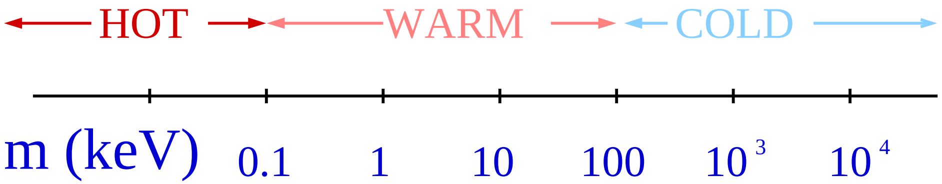


Constraints on the decay scenario: the trouble of long-lived particles...

- Big Bang Nucleosynthesis: strong limits on the injection of energetic particles for $\tau > 1$ sec. At early times the stronger bounds are given by hadronic showers, later also electromagnetic showers become important. In general the bounds are much weaker
- Distortion of the CMB at late times, only important for lifetimes above 10^4 sec.
- Are these particles cold enough to be CDM ? They are produced as relativistic and with a

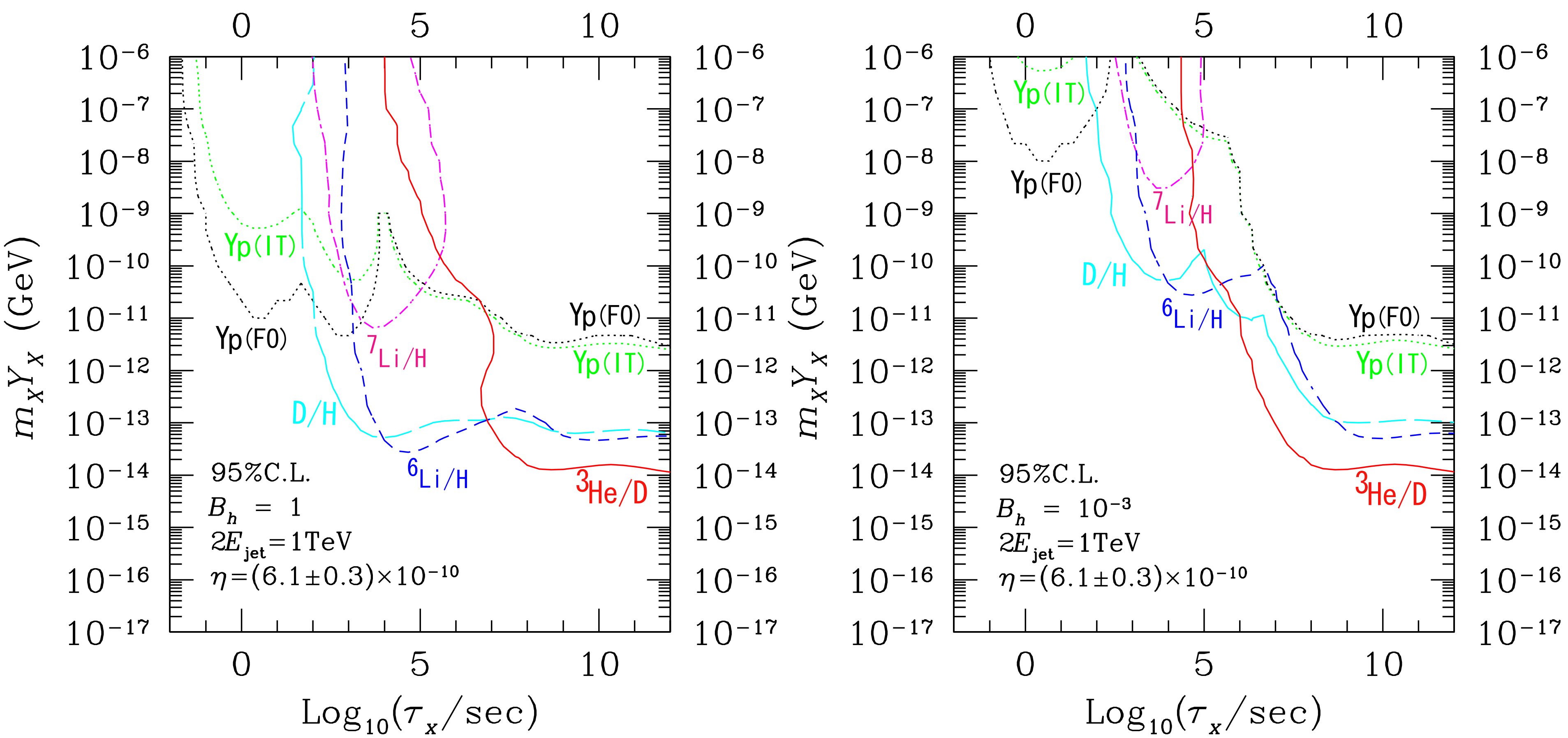
non-thermal spectrum: $$p(T) \simeq \frac{m_{NLSP}}{2} \left(\frac{g_*(T)}{g_*(T_{dec})} \right)^{1/3} \frac{T}{T_{dec}}$$

For a thermal relic one has



but "X"WIMPS generated by NLSP decay can be still warm at larger masses...

BBN bounds from [Kohri, Kawasaki & Moroi '04]



Strong bounds for the gravitino scenario, very weak for the axino case, due to the shorter lifetime.

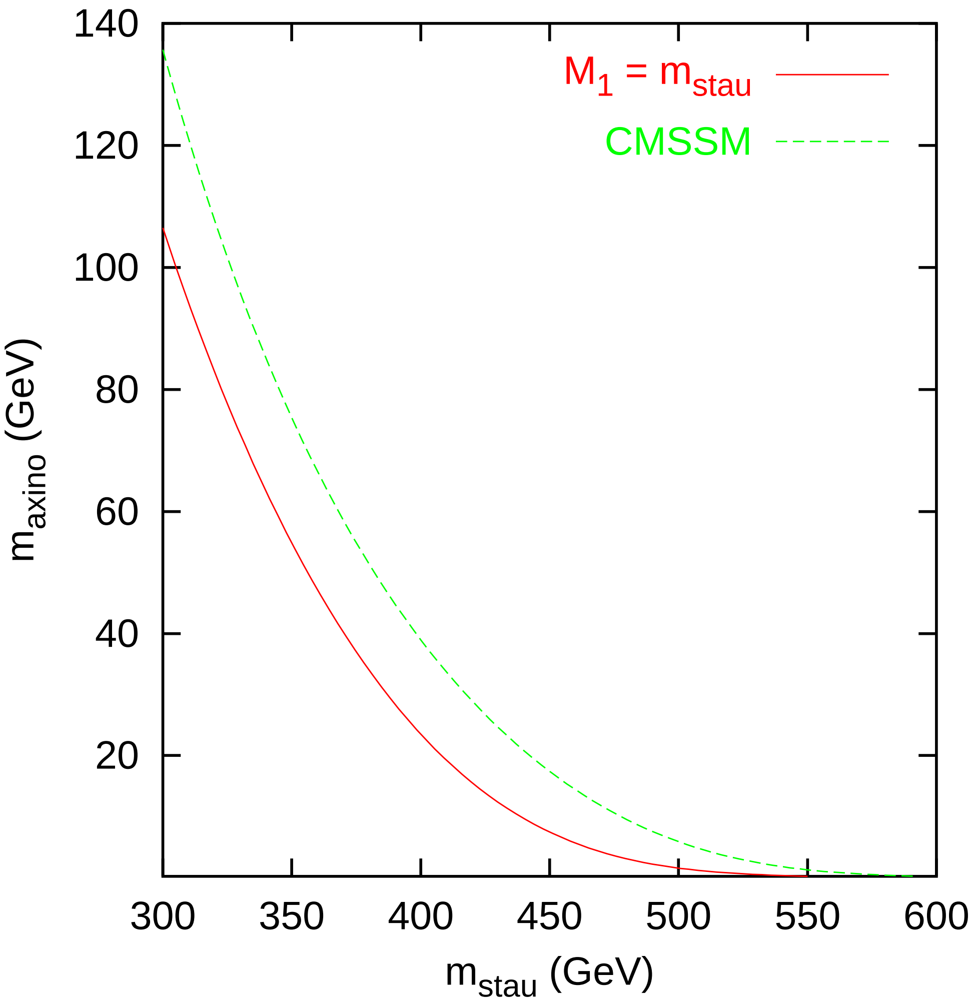
BBN bound for axinos

We obtain a bound on $Y_{\tilde{\tau}_1} = Y_{\tilde{a}}^{NTP}$ depending on the $\tilde{\tau}_1$ lifetime, which we can recast in the plane $m_{\tilde{a}}$ vs $m_{\tilde{\tau}}$ using the fact that to give enough CDM, one must have

$$m_{\tilde{a}} Y_{\tilde{a}}^{NTP} > 0.34 \text{ eV}$$

$\Rightarrow$ WORST CASE SCENARIO !

Here on the right we are reporting the maximal bound of [Kohri '01]

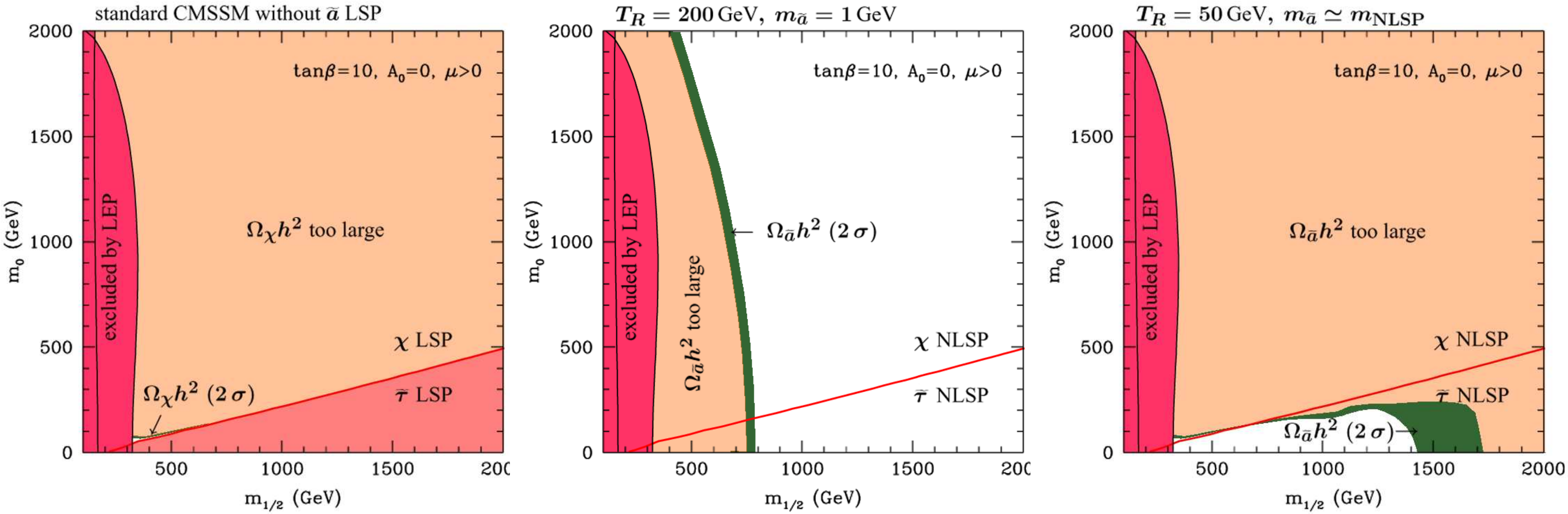


NOTE: much weaker bounds, in the MeV's range of $m_{\tilde{a}}$ and for $m_\chi \leq 150$ GeV for the neutralino !!!

What are the consequences of axino CDM for SUSY & CMSSM-like models?

different/more parameter space allowed, especially the $\tilde{\tau}$ NLSP region, but strong dependence on T_R...

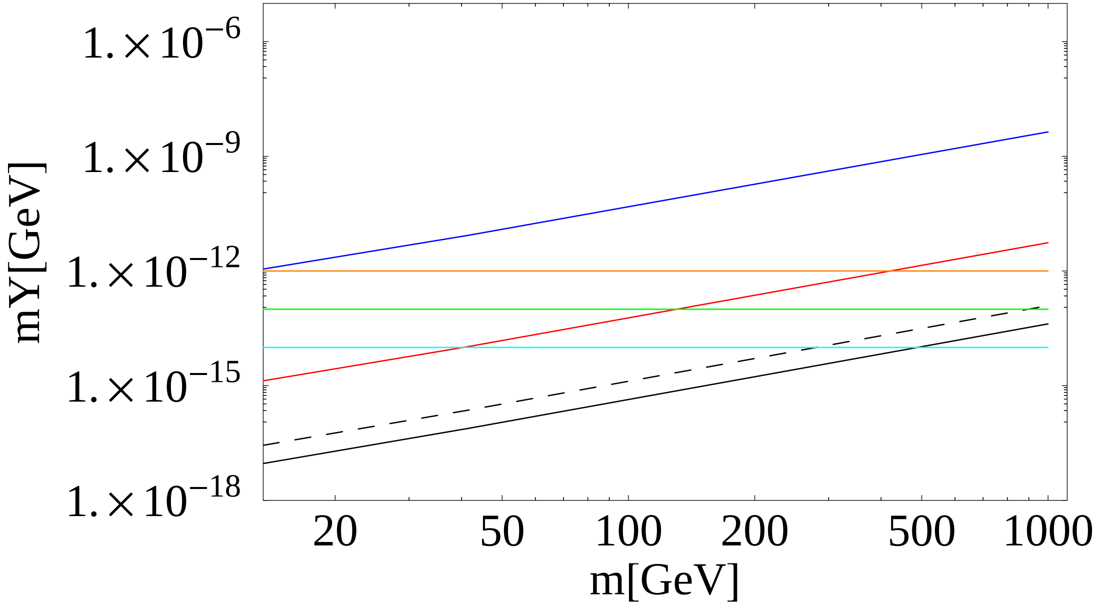
[LC, Roszkowski, Ruiz de Austri & Small '04]



Question: is it possible to evade BBN bounds completely ???

work in progress with Federica Palorini

Consider a charged relic and compare its density:



e.m. charged ($\sim \frac{1}{2}\tilde{\tau}$)

strongly charged ($\sim \tilde{t}$)

unitarity bound

BBN: ^{4}He, Li/D, ^{3}He/D

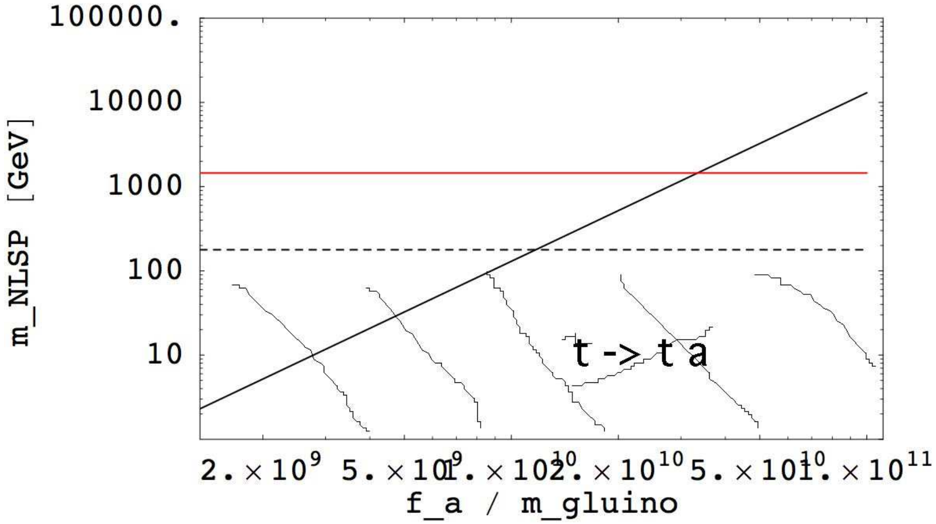
No coannihilation nor resonances at the moment... they are probably necessary to avoid all bounds.

Coloured NLSP case: the STOP

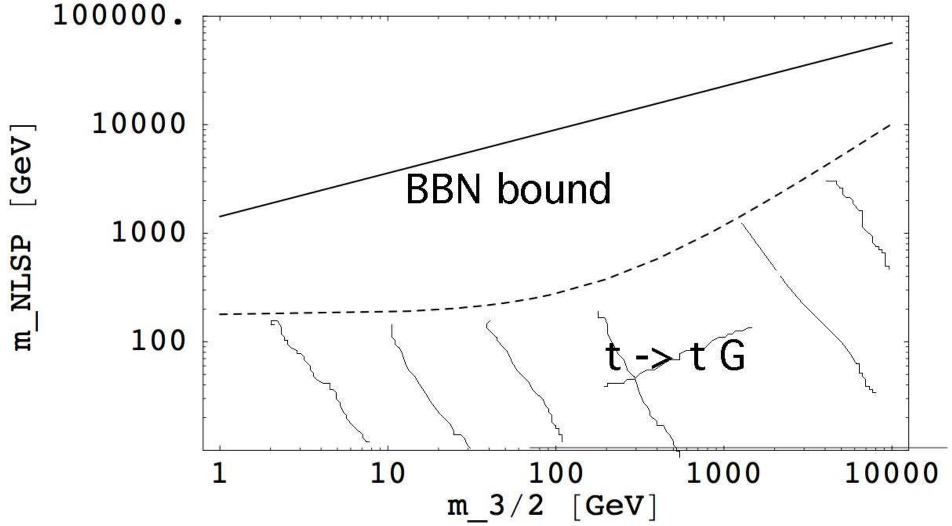
In the CMSSM one of the stops is light if A_t is large, but it usually cannot be the NLSP due to the limit on the Higgs mass $\longrightarrow$ need to go beyond CMSSM

Even if the number density is lower, the stop decays mainly into top and therefore produces hadronic showers, so some BBN constraints appear depeding on the lifetime.

Stop NLSP with axino LSP



Stop NLSP with gravitino LSP



HOW TO DISTINGUISH AXINO FROM GRAVITINO LSP ???

Possible if the NLSP is charged and can be stopped and stored to observe its decays...

see e.g. [Hamaguchi, Kuno, Nakaya & Nojiri '04] and [Feng & Smith '04] for proposals about stopping long-lived $\tilde{\tau}$ around the LHC/ILC.

The dominant decay mode is in both cases $\tilde{\tau}_R \to \tau \;\; \tilde{a}/\tilde{G}$ and the lifetime can vary considerably:

- $\tilde{a}$: the lifetime is independent of the axino mass for $m_{\tilde{a}} \ll m_{\tilde{\tau}}$ and can range from 0.01 sec to 10 h depending on $f_a, m_{\tilde{\tau}}$:

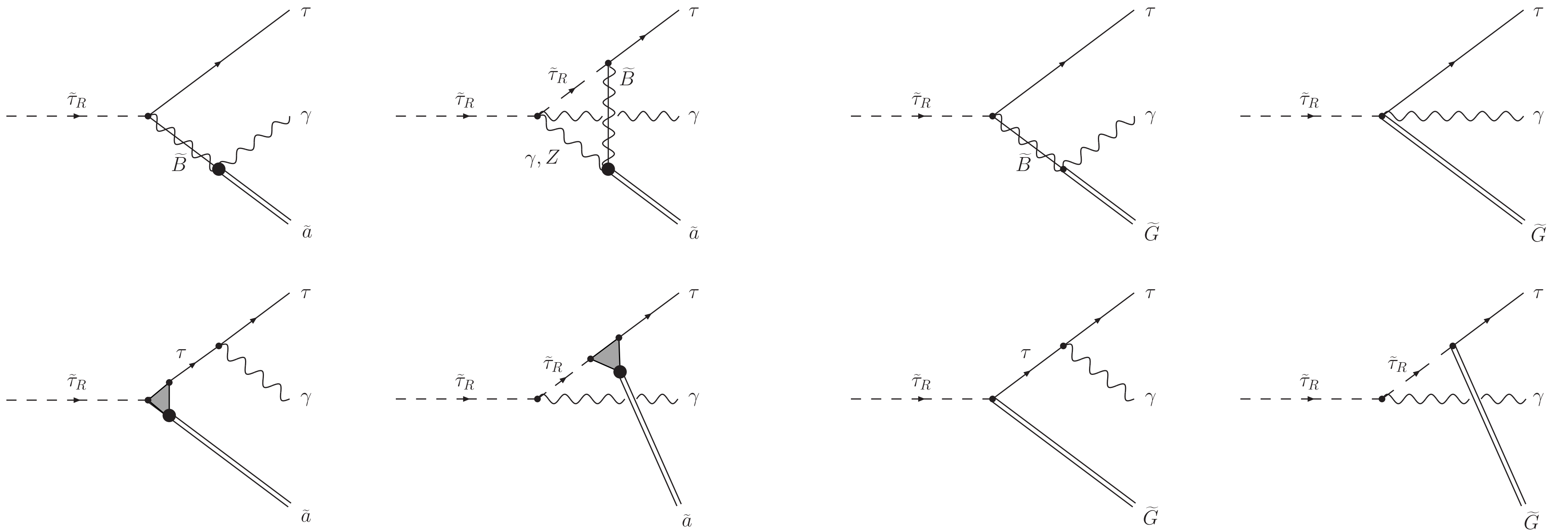
$$\Gamma \sim (25 \text{ sec})^{-1} \left(\frac{m_{\tilde{\tau}_R}}{100 \text{ GeV}}\right) \left(\frac{m_{\tilde{B}}}{100 \text{ GeV}}\right)^2 \left(\frac{10^{11} \text{ GeV}}{f_a}\right) \left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{\tau}_R}^2}\right);$$

- $\tilde{G}$: the lifetime is strongly dependent on the gravitino mass and can range within 10^{-7} sec to 15 yrs depending on $m_{\tilde{G}}, m_{\tilde{\tau}}$:

$$\Gamma \sim (6 \text{ sec})^{-1} \left(\frac{m_{\tilde{\tau}_R}}{100 \text{ GeV}}\right)^5 \left(\frac{10 \text{ MeV}}{m_{\tilde{G}}}\right)^2 \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}_R}^2}\right)^4.$$

$\Rightarrow$ difficult to distinguish in the overlapping region. Need to see the STAU DECAY MODES !

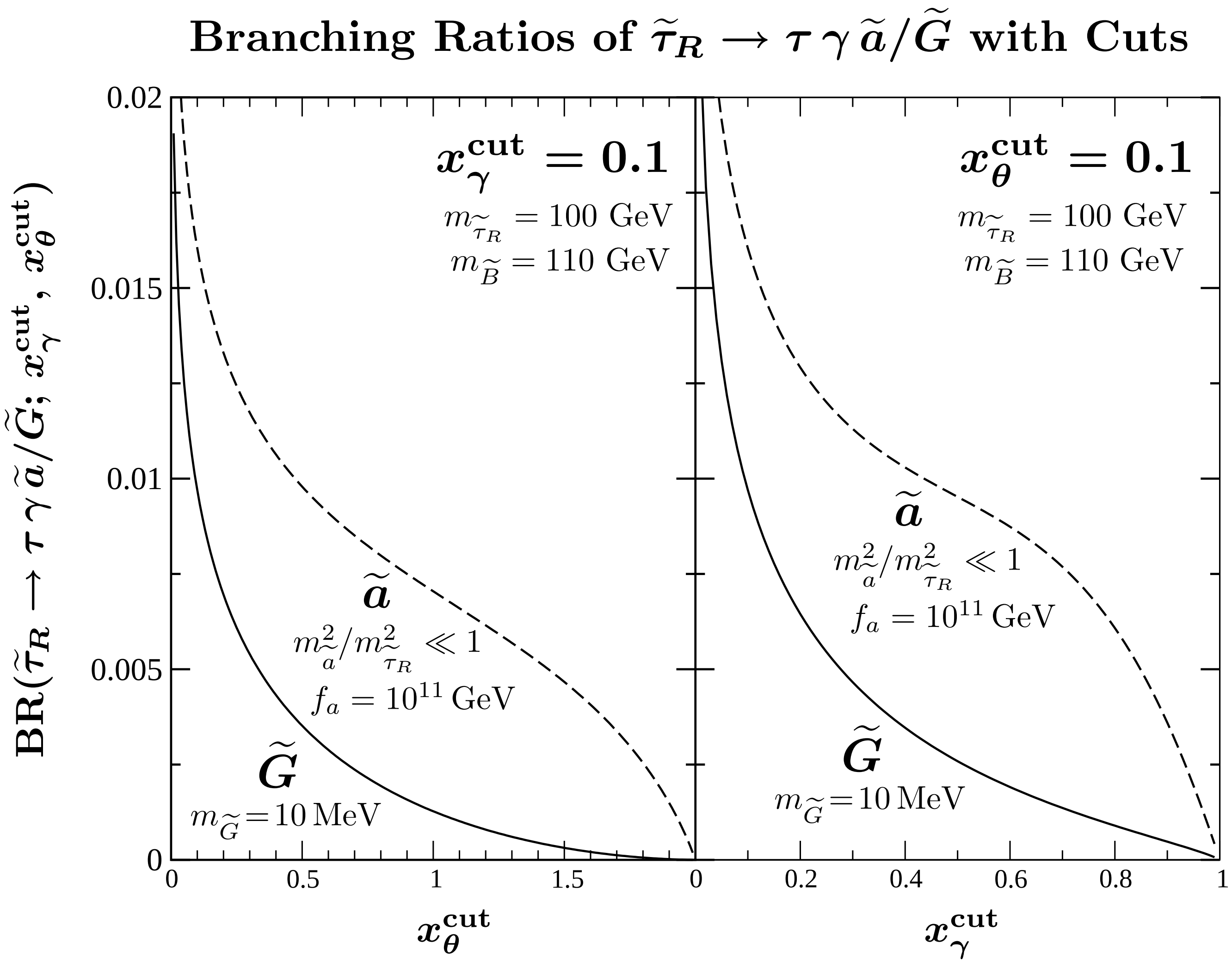
KEY measurement: STAU THREE-BODY DECAY !



$\Rightarrow$ Similar diagrams but different vertex structure !

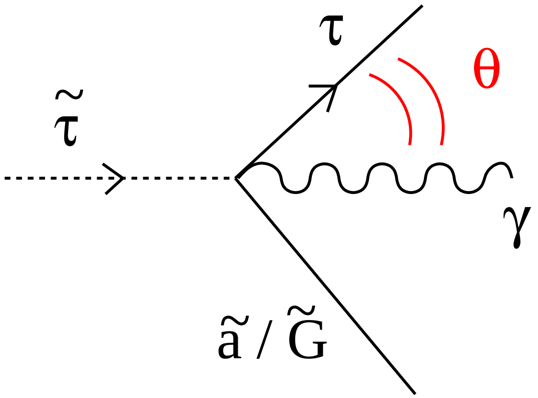
The branching ratios in two or three body are different

[A Brandenburg, LC, K Hamaguchi, L Roszkowski & F Steffen '05]



The clearest signal is probably the angular dependence

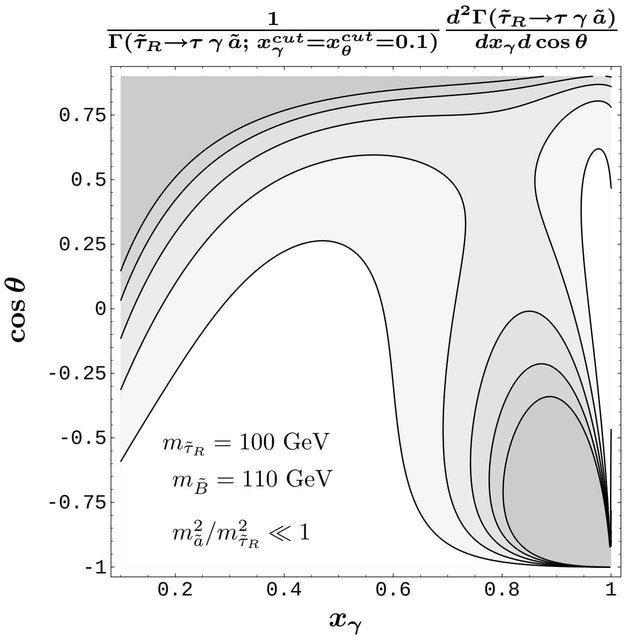
[A Brandenburg, LC, K Hamaguchi, L Roszkowski & F Steffen '05]



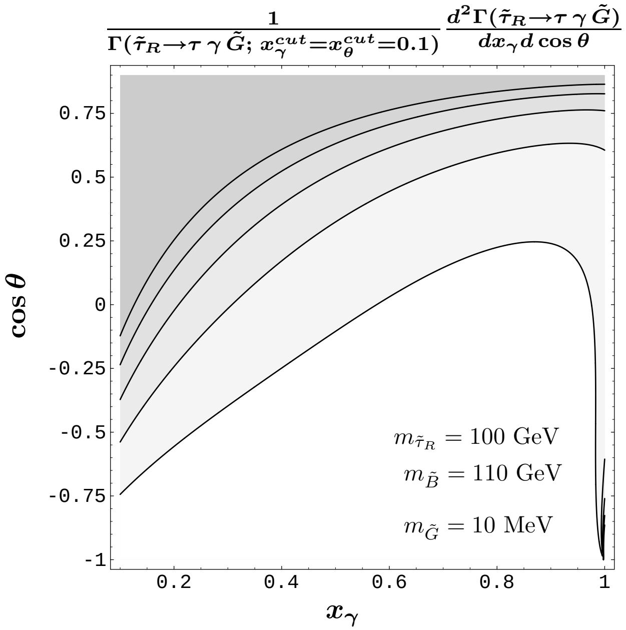
$$x_\gamma = \frac{E_\gamma}{2m_{\tilde\tau}}$$

$\longrightarrow$ angular distribution in $\tilde\tau \to \gamma\,\tau\,\tilde a/\tilde G$:

Axino LSP Scenario



Gravitino LSP Scenario



The axino distribution has two peaks for $\cos\theta = \pm 1$, while the gravitino peaks only at $\cos\theta = 1$!

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 usually evade BBN bounds, since the NLSP lifetime is usually shorter than 10^2 sec.
  For gravitinos even a coloured NLSP with low number density is a problem.

- 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

  $\longrightarrow$ heavier sparticles are allowed !

- An axino (gravitino) LSP opens up the possibility of a charged NLSP, which looks stable in colliders
  $\longrightarrow$ striking scenario LHC or LC possibility of storing $\tilde{\tau}$???

- Studying the $\tilde{\tau}$ NLSP decay could allow to distinguish between axino and gravitino LSP.
  For $\tilde{t}$ NLSP probably only the axino scenario survives BBN constraints...