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Quasi stable $\tilde{\tau}$s at the LHC

Laura Covi
DESY

OUTLINE

1. Introduction: very weakly interacting particles as Dark Matter

2. Production mechanisms and parameters

3. CMSSM: long-lived $\tilde{\tau}$ and colliders

4. Away from the CMSSM: other charged NLSP...

MOTIVATION: I will argue that the neutralino is not the only DM candidate, even in simple supersymmetric models...

In this talk I will assume that SUPERSYMMETRY is the right extension of the Standard Model, but that the LSP is not the superpartner of a SM particle, so that it is interacting much more weakly than electroweak. I will call such particle

"X"WIMPs (a.k.a. SuperWIMPs, E-WIMPs, etc...).

Typical examples are the gravitino or the axino LSP whose interactions scale respectively as $\frac{1}{M_{Pl}}$ or $\frac{1}{f_a}$ ($f_a \sim 10^{10-12}$ GeV)...

But any other elusive particle could do, e.g. a singlino, KK graviton, modulino or a stable modulus, etc.., as long as the couplings to matter are known and very weak.

I will try to show you that such a particle is a well-motivated Dark Matter candidate even if it is not a classical thermal relic.

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

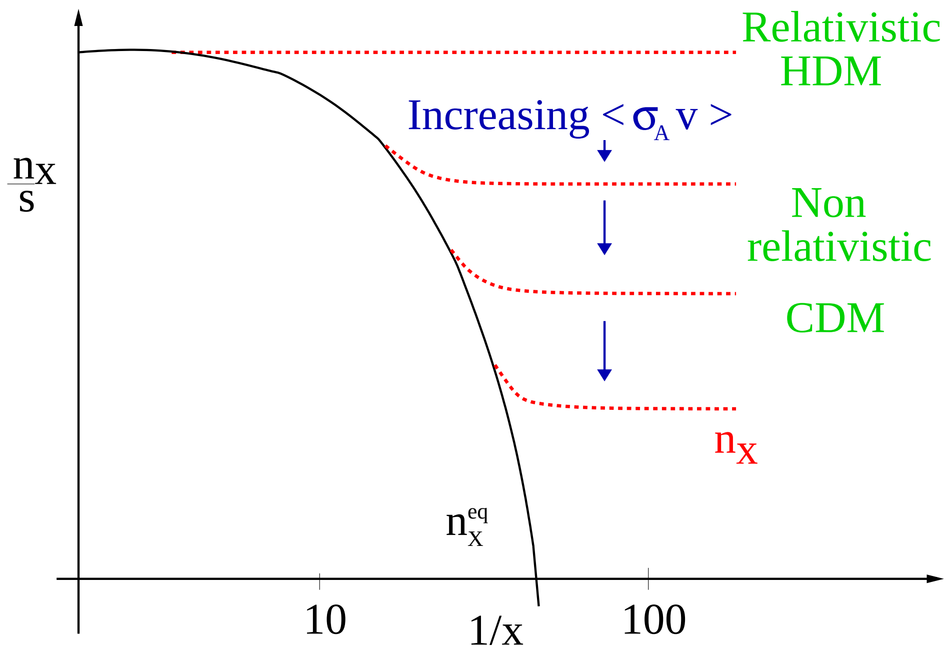
$$n_{eq}\langle\sigma_A v\rangle = H \qquad \Rightarrow \qquad \Omega \propto \frac{1}{\langle\sigma_A v\rangle}$$

So "X"WIMPs decouple when they are still relativistic and so with high number density; from $n_X(T_D) = n_\gamma(T_D)$

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

Very light particles are required $\longrightarrow$ HOT/WARM Dark Matter

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



How to produce unthermalized ”X”WIMPs ?

Assume low reheat temperature $T_{RH} < T_D$ and no initial population (difficult to produce such very weakly interacting particles via non-perturbative mechanisms like preheating, etc...).

Then their yield is given (at least) by two mechanisms:

– thermal scattering and decays in the plasma

$$\frac{d}{dT}\frac{n_X}{s} = \frac{-1}{HTs(T)} \left[\sum_{ij} \langle \sigma(i+j \to X+ ...) v_{rel} \rangle n_i n_j + \sum_i \langle \Gamma(i \to X + ...) \rangle n_i \right]$$

scatterings decays

strongly dependent on T_{RH} !

– decay *out of equilibrium* of the NLSP:

$$\Omega_X^{NT} = \frac{m_X}{m_{\text{NLSP}}}\, \Omega_{\text{NLSP}}$$

BEWARE of the decay products (γs or hadrons) not spoiling Nucleosynthesis or distort the CMB !

THERMAL PRODUCTION: At high temperatures, the dominant contribution to the production come from 2-body scatterings with colored states, mediated by non-renormalizable operators:

- gravitino case: $$\Omega_{\tilde{G}}^{TH} h^2 \simeq 0.2 \left(\frac{100\text{GeV}}{m_{\tilde{G}}}\right) \left(\frac{m_{\tilde{g}}}{1\text{TeV}}\right)^2 \left(\frac{T_R}{10^{10}\text{GeV}}\right)$$

[Bolz, Brandenburg & Buchmüller '01]

- axino case: $$\Omega_{\tilde{a}}^{TH} h^2 \simeq 0.6 \left(\frac{m_{\tilde{a}}}{0.1\text{GeV}}\right) \left(\frac{10^{11}\text{GeV}}{f_a}\right)^2 \left(\frac{T_R}{10^4\text{GeV}}\right)$$

[LC, HB KIm, JE Kim & Roszkowski '01, Brandenburg & Steffen '04]

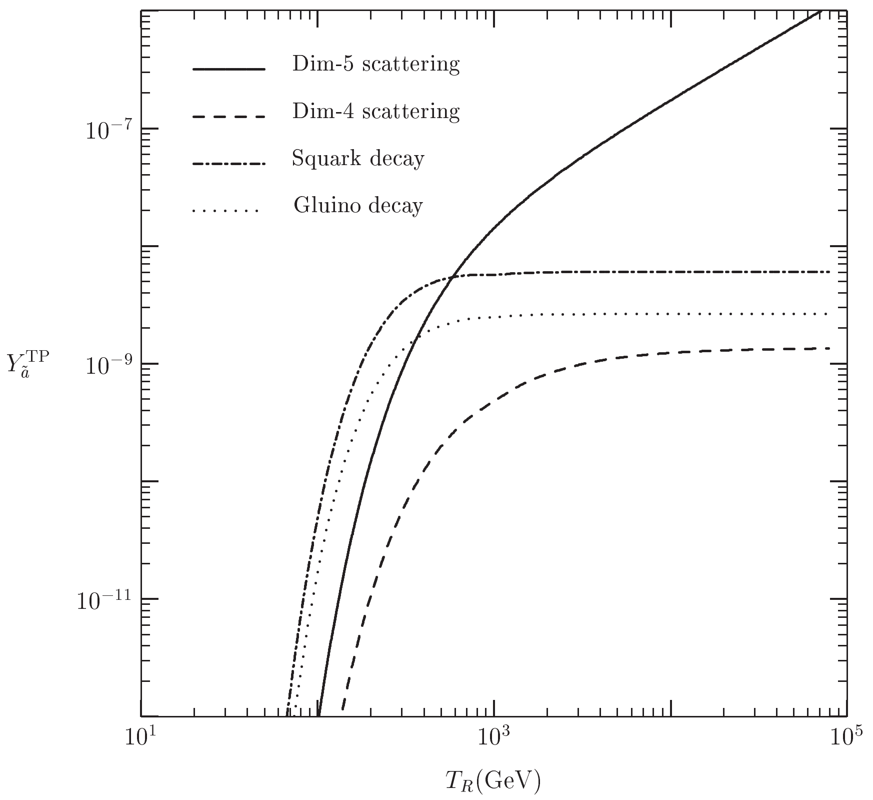
NOTE the completely different dependence on the "X"WIMP mass !!! It is due to the fact that the gravitino is produced via its Goldstino component, whose couplings are enhanced by the ratio $\frac{m_{\tilde{g}}}{m_{\tilde{G}}}$!

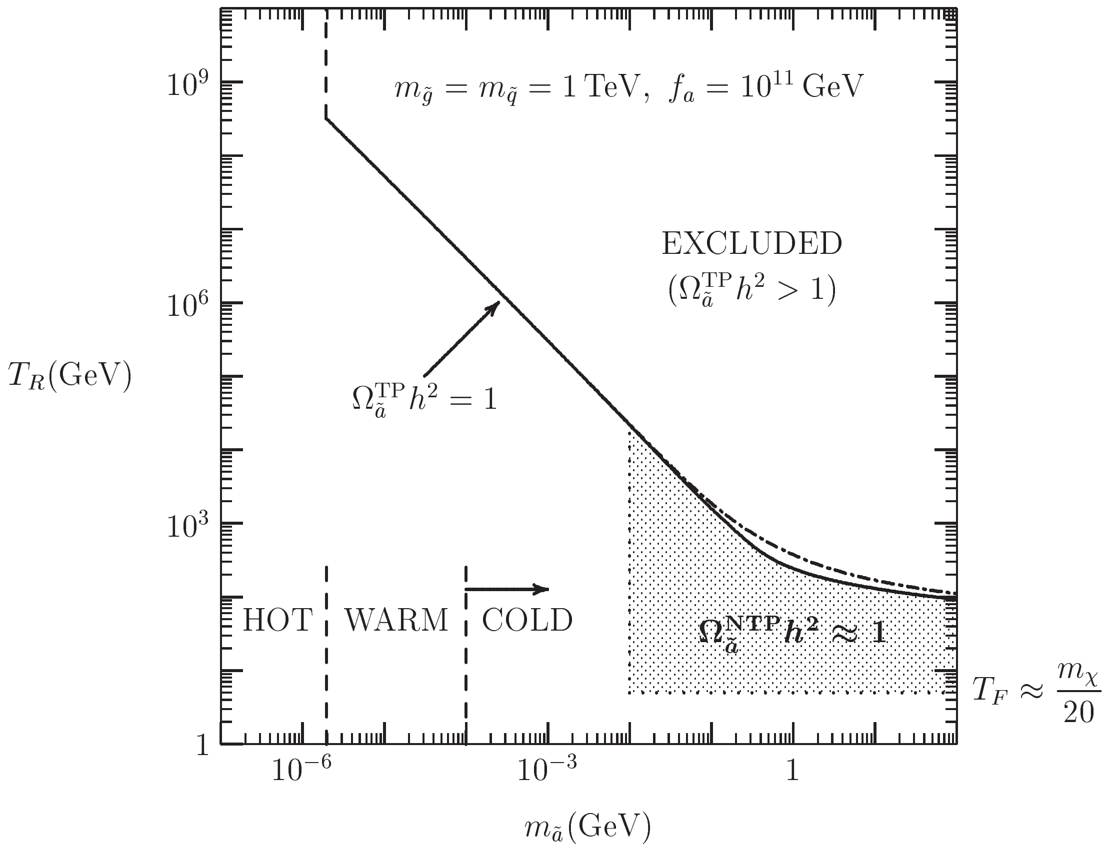
Technical point: Hard Thermal loop resummation needed to regularize the gluon IR divergences.

At temperatures of the order of the superpartner masses also the effect of the sparticle decays become important, so there is a stronger dependence on the parameters of supersymmetry breaking.

Axinos: their interactions are suppressed by the Peccei-Quinn scale $f_a \simeq 10^{10-12}$ GeV.

Find the bound on T_R:





PRETTY LOW REHEAT TEMPERATURE NEEDED !

OUT OF EQUILIBRIUM DECAY

An "X"WIMP population is also generated by NLSP decay after freeze-out: e.g. for neutralino we have usually $\chi \longrightarrow X\gamma$ or for staus $\tilde{\tau} \longrightarrow X\tau$.

The important parameter is the lifetime:

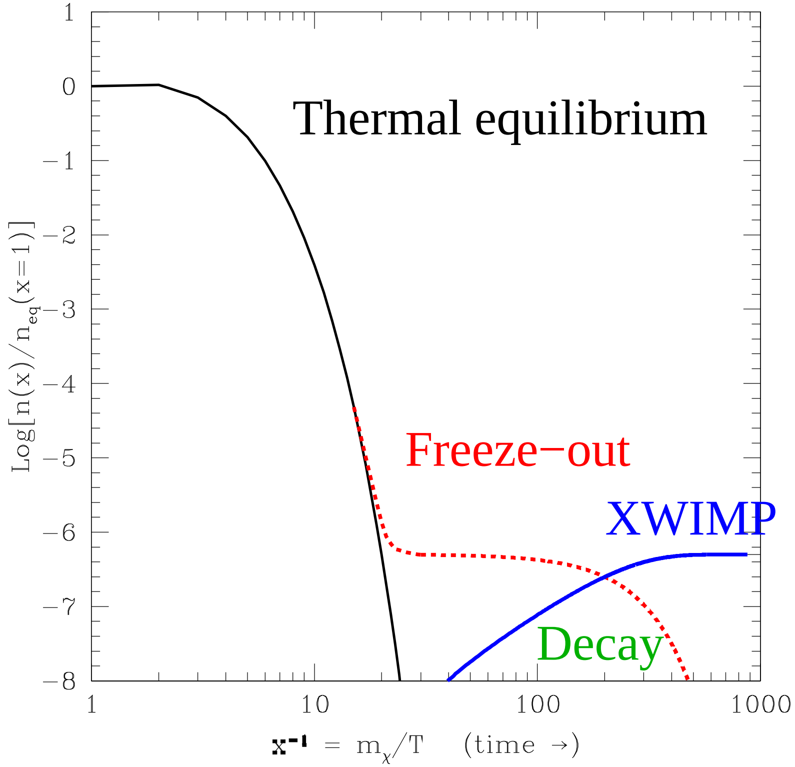
$\tau \gg 1/H(x_f)$

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

$$\Omega_X^{NT} = \frac{m_X}{m_{NLSP}} \Omega_{NLSP}$$

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

$\tau > 1$ sec $\Rightarrow$ strong BBN constraints !

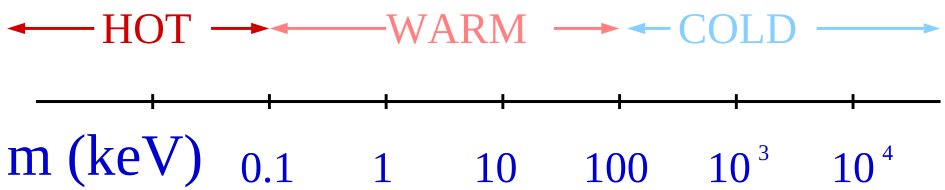


Constraints on the decay scenario: the trouble of long-lived particles...

- Moduli problem *if* they dominate the energy density before decay. Not our case...
- 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

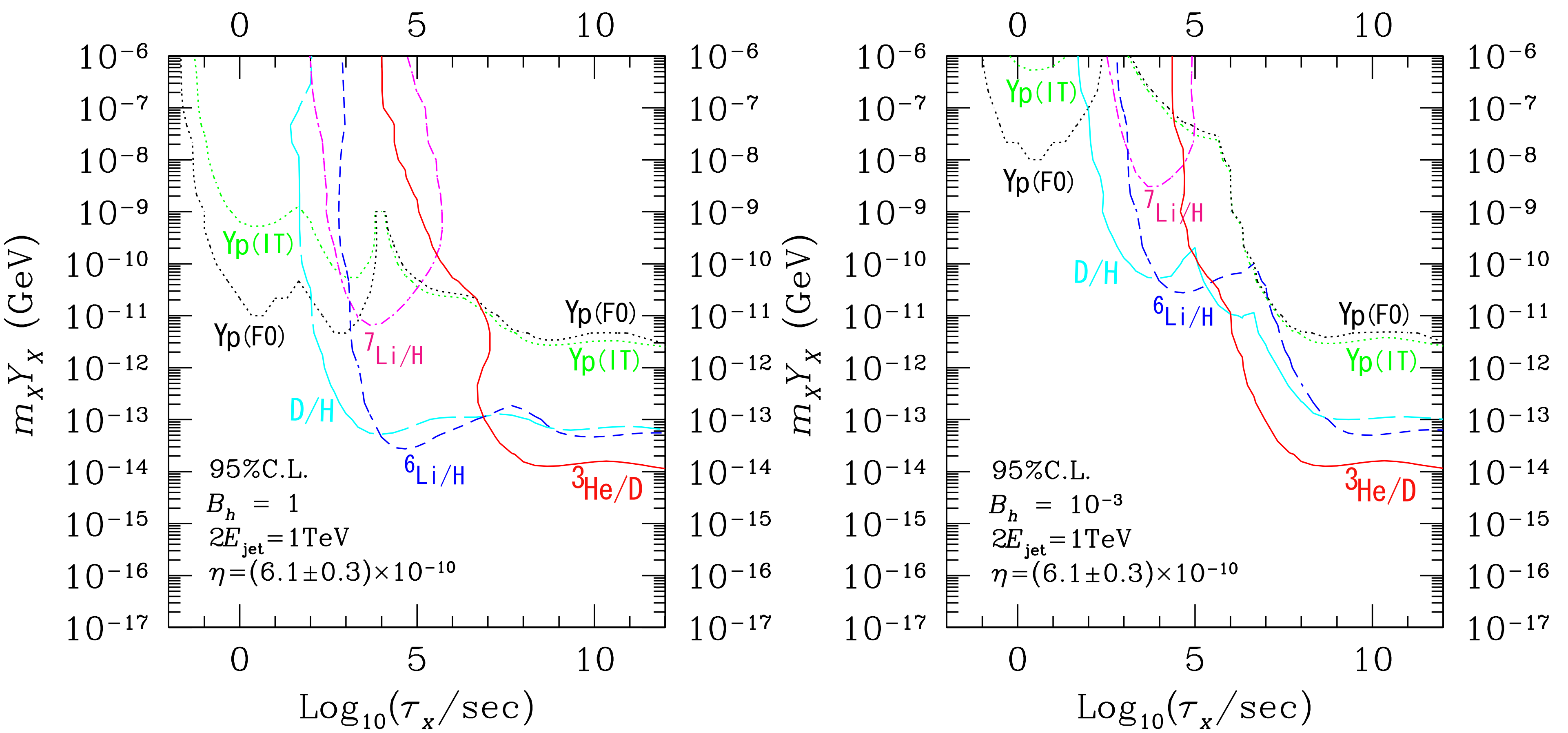
  non-thermal spectrum: $$p(T) \simeq \frac{m_{NLSP}}{2} \left(\frac{g_*(T)}{g_*(T_{dec})} \right)^{1/3} \frac{T}{T_{dec}}$$

  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.

NOTE: in general the weaker the particle interacts, the longer is the lifetime and the stronger the constraints !!!

Thermal or non-thermal production ???

Depending from the parameters, either mechanism can dominate and in general both could give the right amount of DM.

The thermal production is ALWAYS present and therefore either T_{RH} is bounded or the ”X”WIMP is so light it must be a subdominant (warm) DM component (mixed DM picture Cold + Warm as in the old days...). Note that this would be the case for the GMSB type of models where the gravitino is very light...

axion CDM ???

Out of equilibrium decay must satisfy more constraints, as we have seen, and in general prefers a charged NLSP, with lower number density, at least for long lifetimes.

A charged NLSP is also preferred from the experimental point of view !

There is no hope to produce such a weakly interacting particle as a XWIMP directly at colliders or to detect it in Dark Matter searches... But a striking signal could be the detection of an *apparently stable* charged particle at LHC or another collider.

In fact a thermal charged relic is excluded by direct searches on the earth up to masses of about 10 TeV. So the observation of such a new charged massive particle would require

- a modification of the thermal history of the Early Universe so to suppress the particle relic density to acceptable values, e.g. either by some mechanism reducing the production cross-section or by dilution after freeze-out;
- the conclusion that such particle cannot be stable and must have decayed so to not disrupt Nucleosynthesis and other cosmological observations.

Assume that the presence of a XWIMP LSP does not change the spectrum in the supersymmetric observable sector and for simplicity consider universal scalar and gaugino masses and unification at the GUT scale (CMSSM or MSUGRA): we have only 5 universal parameters:

$$\tan\beta, \mu, m_0, m_{1/2} \& A_0$$

$|\mu|$ can be fixed by radiative breaking of EW symmetry !

The LIGHTEST state between gauginos, squarks and sleptons due to the running is either a neutralino, a slepton or a squark; in particular favoured are the scalars corresponding to the heaviest fermions since they present larger LH-RH mixing ($\propto m_f, \tan\beta \& A_0$)

$$m^2_{\tilde{\tau}} = \begin{pmatrix} m^2_{LL} & m^2_{LR} \\ m^2_{RL} & m^2_{RR} \end{pmatrix} \quad \Rightarrow m^2_{1/2} = \frac{m^2_{LL} + m^2_{RR}}{2} \pm \sqrt{\left(\frac{m^2_{LL} - m^2_{RR}}{2}\right)^2 + m^2_{LR} m^2_{RL}}$$

Since the present bound on the Higgs mass usually requires the stops to be relatively heavy, usually the stop has to be heavier than the others: $\Rightarrow$ the possible NLSPs in the CMSSM are the neutralino or the stau !

”X”WIMPs and the CMSSM

This scenario allows to relax many of the cosmological bounds on the supersymmetric parameters, but not completely...

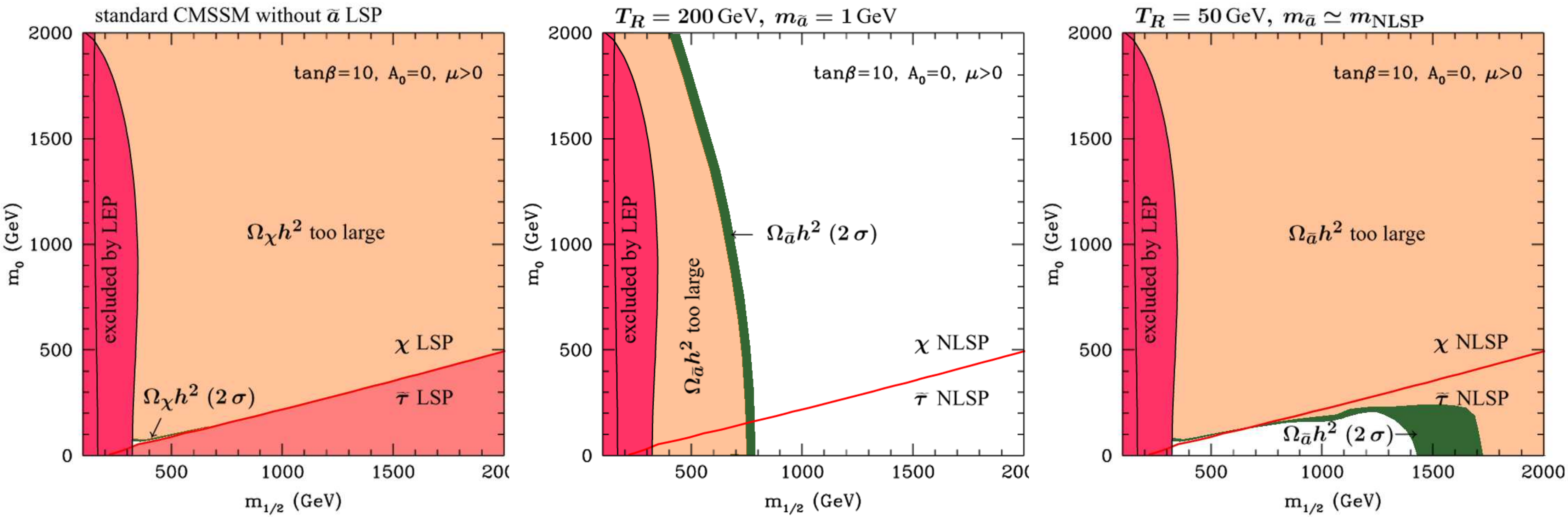
In the high temperature range, the main parameter fixing the relic density are T_{RH} and the ”X”WIMP mass, so the DM density is completely independent of the other SUSY parameters, apart in the case of the gravitino...

At lower temperature some additional dependence on the other superpartner’s masses remains... In particular for $T_{RH} \simeq m_{\tilde{g}}, m_{\tilde{q}}$, the decay part of the Bolzmann equation becomes important, even before the NLSP decay.

Let us consider two different cases: axino LSP, with the axino mass as completely free parameter and the gravitino LSP, where the SUSY breaking is connected to the gravitino mass.

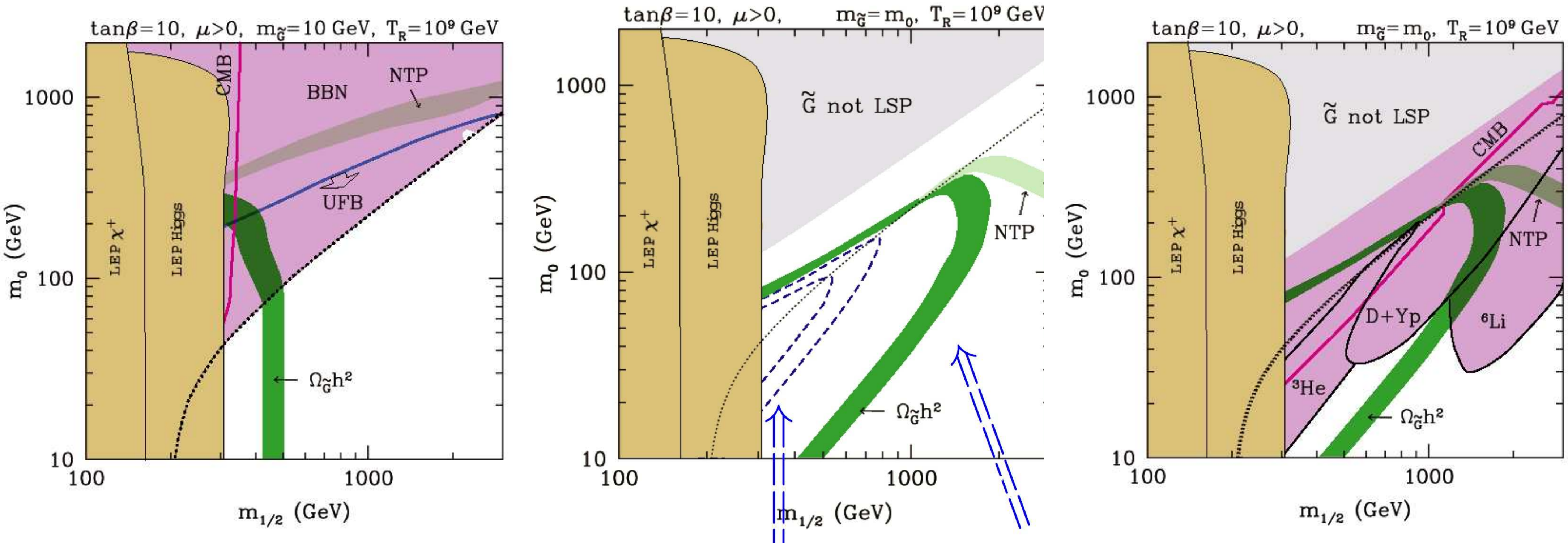
Axino+CMSSM models: more parameter space allowed, especially the $\tilde{\tau}$ NLSP region.

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



Gravitino+CMSSM models: more constraints from BBN, allowed only the $\tilde{\tau}$ NLSP region.

[Cerdeno, Choi, Jedamzik, Roszkowski, Ruiz de Austri '06]



$T_R = 5 \times 10^9$GeV $\quad$ $T_R = 10^9$GeV

CAN WE IDENTIFY THE "X"WIMP ???

Not so easy if the NLSP decays outside the detector: but if the NLSP is charged it could 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 $f_a, m_{\tilde{\tau}}$:

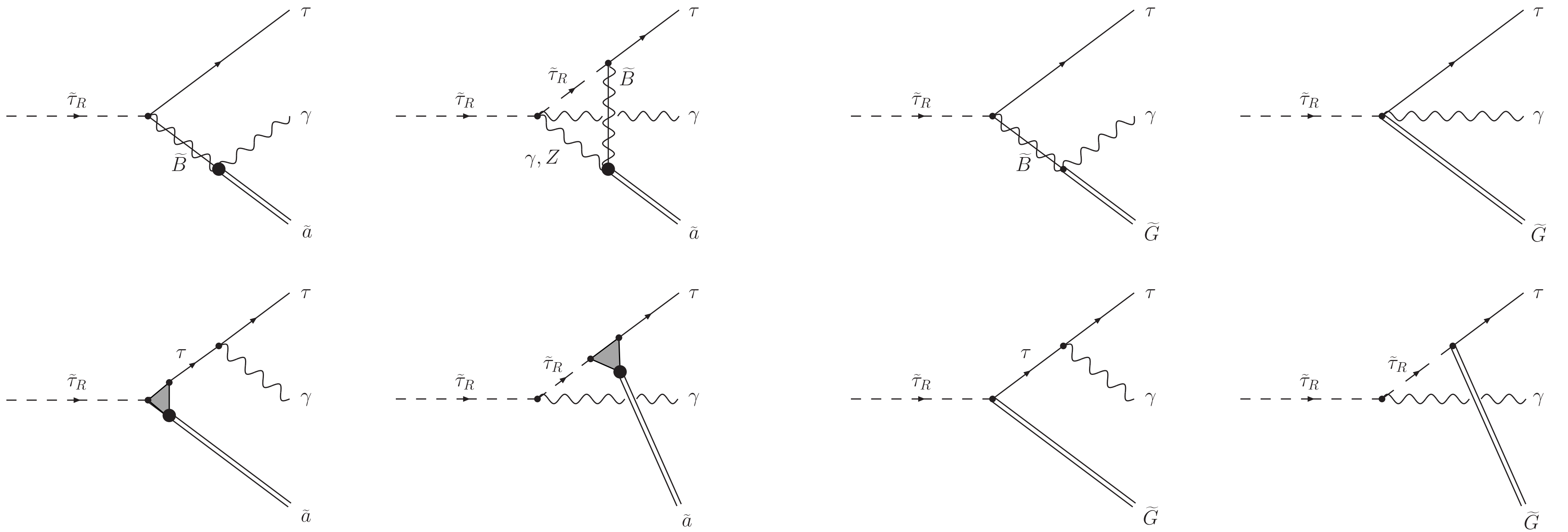
$$\Gamma \sim (25\text{sec})^{-1} \left(\frac{m_{\tilde{\tau}_R}}{100\text{GeV}} \right) \left(\frac{m_{\tilde{B}}}{100\text{GeV}} \right)^2 \left(\frac{10^{11}\text{GeV}}{f_a} \right) \left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{\tau}_R}^2} \right);$$

- $\tilde{G}$: 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 !

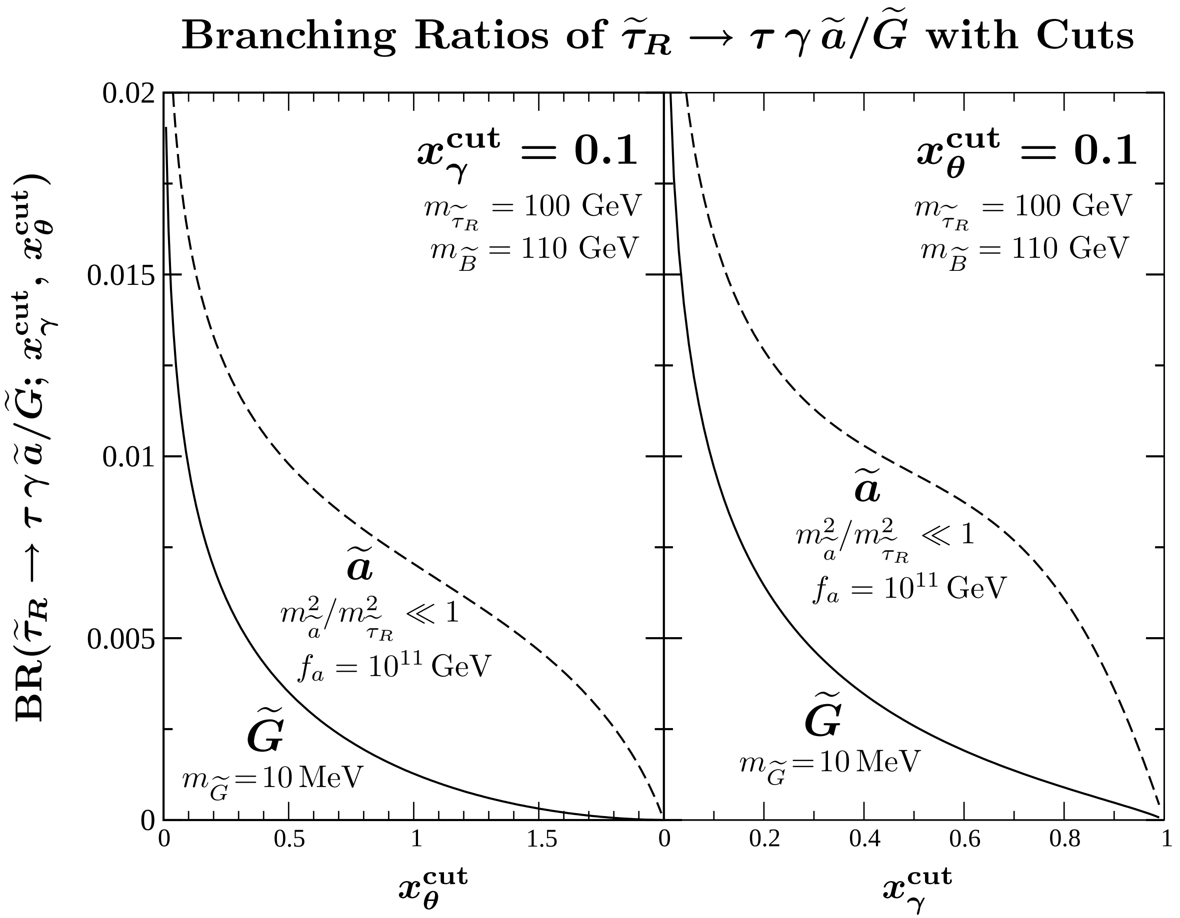
KEY measurement: STAU THREE-BODY DECAY !



$\Rightarrow$ Similar diagrams but different vertex structure !

The branching ratios in two or three body are different

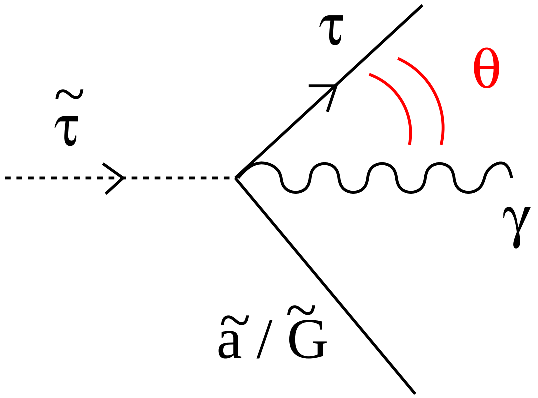
[Brandenburg, LC, Hamaguchi, Roszkowski & Steffen '05]



Both decays suffer from IR divergencies and we need to have a cut in the photon energy and in the cosine of the opening angle.

The clearest signal perhaps is the angular dependence

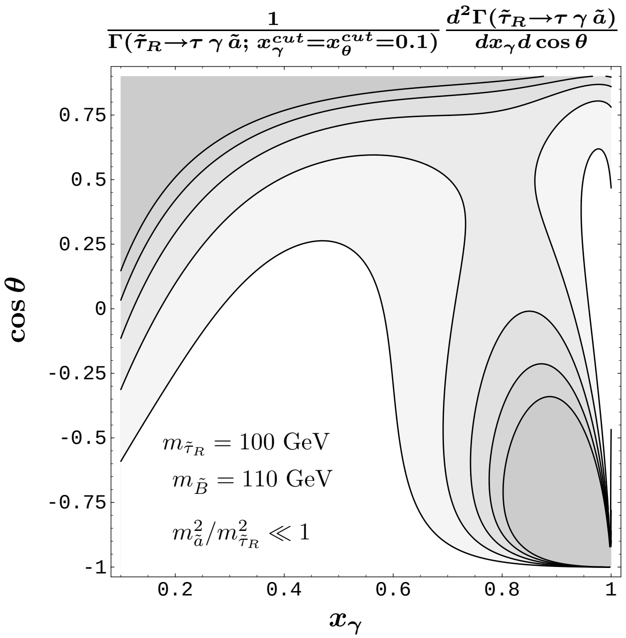
[Buchmüller, Hamaguchi, Ratz & Yanagida ’04], [Brandenburg, LC, Hamaguchi, Roszkowski & Steffen ’05]



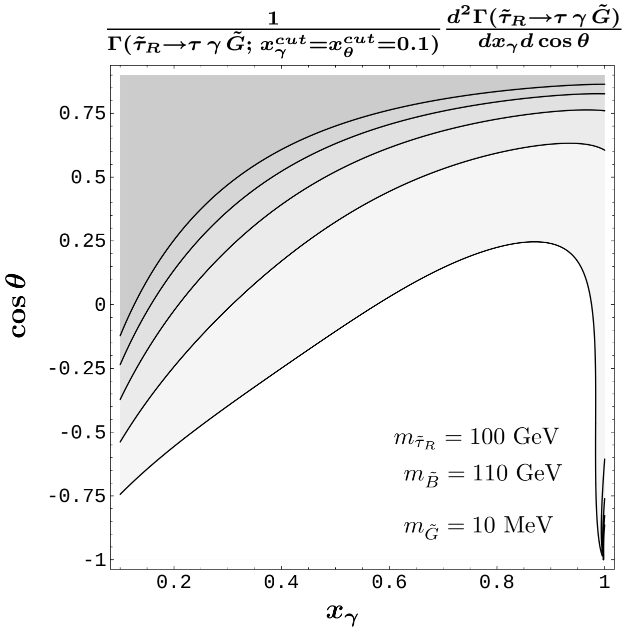
$x_\gamma = \frac{E_\gamma}{2m_{\tilde{\tau}}}$

$\rightarrow$ angular distribution in $\tilde{\tau} \rightarrow \gamma\,\tau\,\tilde{a}/\tilde{G}$:

Axino LSP Scenario



Gravitino LSP Scenario



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

Beyond the CMSSM other NLSPs are possible...
and could perhaps also give a characteristic signature:

- sneutrino: typical e.g. in gaugino mediation and excluded as stable candidate by direct DM searches... It is unfortunately neutral and invisible, but perhaps it could be individuated by the presence of more leptons in the supersymmetric decay chains ? Possible to distinguish if the apparent LSP is a neutralino or a sneutrino ???
- stop: requires non-universal masses and is very strongly constrained by BBN due to the hadronic showers in its decay; it would probably hadronize into R-hadrons like the gluino...
- chargino: similar signal as the stau, but again different decay chains and spin...

Outlook

- ”X”WIMPs with masses in the MeV-GeV are good CDM candidates for low T_{RH}: they can be produced either from thermal processes or from NLSP decay.
- Axinos usually evade BBN bounds, since the NLSP lifetime is shorter than 10^2 sec, for gravitinos those bounds are stronger and exclude part of the parameter space.
- In the case of ”X”WIMP 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 ”X”WIMP as LSP opens up the possibility of a charged NLSP, which looks stable in colliders $\Rightarrow$ striking scenario LHC but difficult to see the decay...

  possibility of storing $\tilde{\tau}$???
- Studying the $\tilde{\tau}$ NLSP decay could allow to distinguish between axino and gravitino LSP