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Gravitino Dark Matter with a sneutrino NLSP

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DESY

based on work in collaboration with

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OUTLINE

1. Introduction
2. Gravitino DM
3. Gaugino mediation
4. $\tilde{\nu}$ NLSP at colliders
5. Conclusions and Outlook

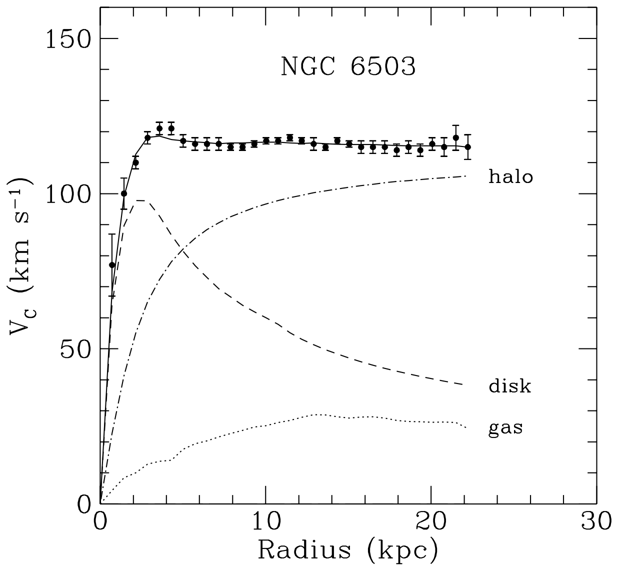
THE MATTER CONTENT

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

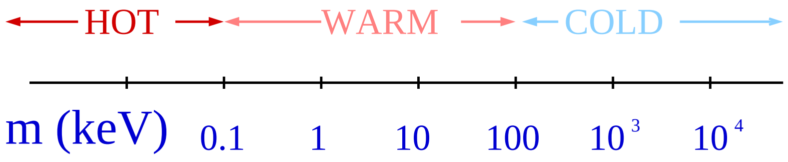
DARK matter !

[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 !

Which are the suitable SUSY DM candidates if R parity is conserved ?

Classic candidates within the MSSM:

- neutralinos: still very promising, even if a bit fine-tuned...
- sneutrinos: excluded by LEP/direct WIMP searches

Some more elusive SUSY candidates, but still particle physics motivated:

- very weakly interacting particles (Super WIMPs) like gravitinos, axinos, RH sneutrinos, singlinos, etc...
- SUSY condensates: Q-balls

Recall also well-motivated NON-SUSY candidates:

- axions with mass $m_a \sim 0.01 - 5$ meV
- very heavy particles produced gravitationally or in preheating (Wimpzillas, ...)
- KK dark matter, etc...

GRAVITINO properties: completely fixed by SUGRA !

Gravitino mass: set by the condition of ”vanishing” cosmological constant

$$m_{\tilde{G}} = \langle W e^{K/2} \rangle = \frac{\langle F_X \rangle}{M_P}$$

It is proportional to the SUSY breaking scale and varies depending on the mediation mechanism, e.g. gauge mediation can accomodate very small $\langle F_X \rangle$ giving $m_{\tilde{G}} \sim$ keV, while in anomaly mediation we can even have $m_{\tilde{G}} \sim$ TeV (but then it is not the LSP...).

Gravitino couplings: determined by masses, especially for a light gravitino since the dominant piece becomes the Goldstino spin 1/2 component: $\psi_\mu \simeq i\sqrt{\frac{2}{3}} \frac{\partial_\mu \psi}{m_{\tilde{G}}}$. Then we have:

$$-\frac{1}{4M_P} \bar{\psi}_\mu \sigma^{\nu\rho} \gamma^\mu \lambda^a F^a_{\nu\rho} - \frac{1}{\sqrt{2} M_P} \mathcal{D}_\nu \phi^* \bar{\psi}_\mu \gamma^\nu \gamma^\mu \chi_R - \frac{1}{\sqrt{2} M_P} \mathcal{D}_\nu \phi \bar{\chi}_L \gamma^\mu \gamma^\nu \psi_\mu + h.c.$$

$$\Rightarrow \quad \frac{-m_\lambda}{4\sqrt{6} M_P m_{\tilde{G}}} \bar{\psi} \sigma^{\nu\rho} \gamma^\mu \partial_\mu \lambda^a F^a_{\nu\rho} + \frac{i(m_\phi^2 - m_\chi^2)}{\sqrt{3} M_P m_{\tilde{G}}} \bar{\psi} \chi_R \phi^* + h.c.$$

Couplings proportional to SUSY breaking masses and inversely proportional to $m_{\tilde{G}}$.

SUSY breaking mechanism determines which particle is the LSP and the gravitino couplings !

Gravitino DM

Primordial abundance of a thermal relic

[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 until the interactions are fast enough, then they freeze-out at $x_f = T_f/m_X$

defined by $n_{eq} \langle \sigma_A v \rangle_{x_F} = H(x_f)$ and that gives

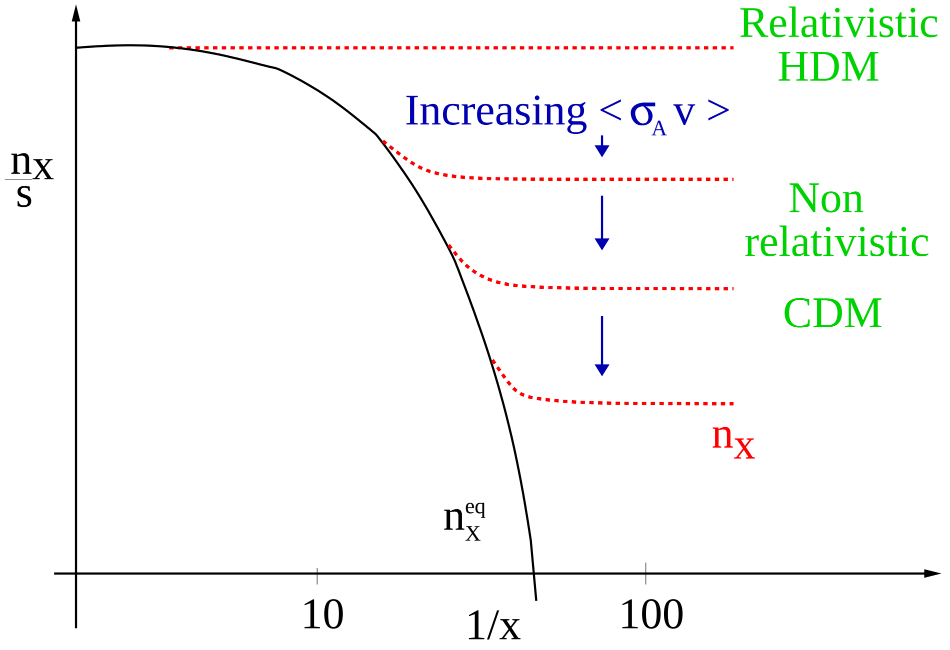
$$\Omega_X = m_X n_X(t_{now}) \propto \frac{1}{\langle \sigma_A v \rangle_{x_F}}$$

Abundance ⇔ Particle properties

For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle (WIMP)

For weaker interactions the number density is larger and one needs smaller masses HOT DM !



But can CDM be more weakly interacting than a WIMP ? ⇒ "X"WIMPs !

We have seen that very weakly interacting particles freeze-out with a large number density, therefore they must be light to give the same energy density since $\rho = mn$... → HOT/WARM DM !

But another possibility is that the temperature of the Universe was always too low for such particles to reach equilibrium $T_{RH} < T_D$. Then their present density is given (at least) by two mechanisms:

– thermal scattering and decays in the plasma (Boltzmann equation without backreactions)

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

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

[Bolz, Brandenburg & Buchmüller '01]

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

[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.

For contributions from other gauge groups, top Yukawa and thermal corrections see the recent papers [Pradler & Steffen 06, Rychov & Strumia 07].

Non thermal production via inflaton decay neglected here... $\longrightarrow$ F. Takahashi

In general UPPER BOUND on the REHEAT TEMPERATURE !

Special T_{RH} needed to have the observed DM density.

OUT OF EQUILIBRIUM DECAY

[JE Kim, A Masiero & DV Nanopoulos 84]

[LC, JE Kim & L Roszkowski 99], [Feng *et al.* 04]

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

The important parameter is the lifetime:

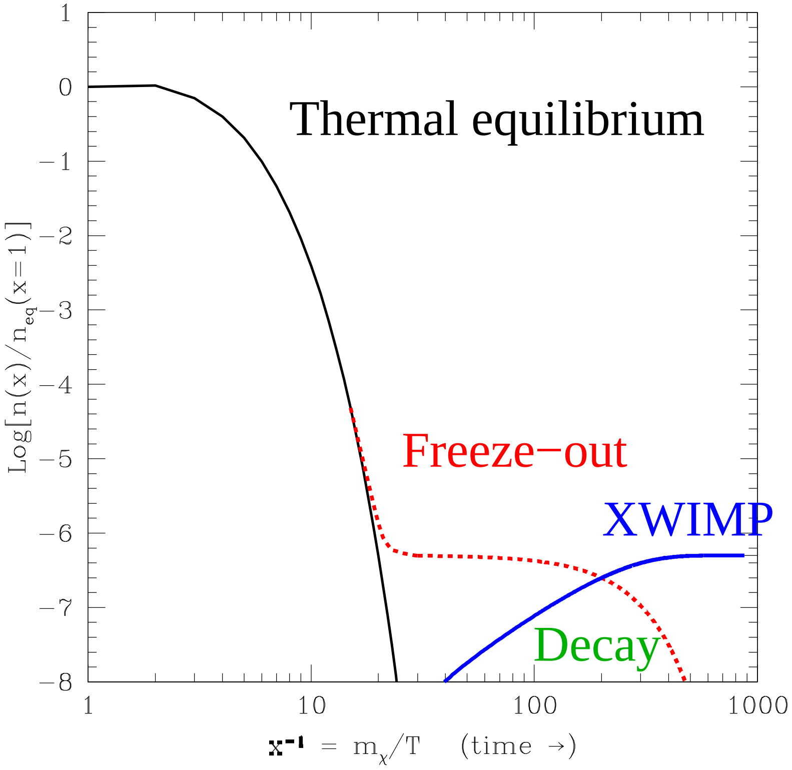
$\tau \gg 1/H(x_f)$

$\Rightarrow$ 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}!

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

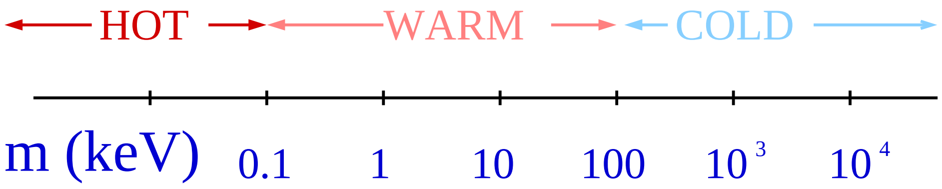


Constraints on the decay scenario: the trouble of long-lived particles...

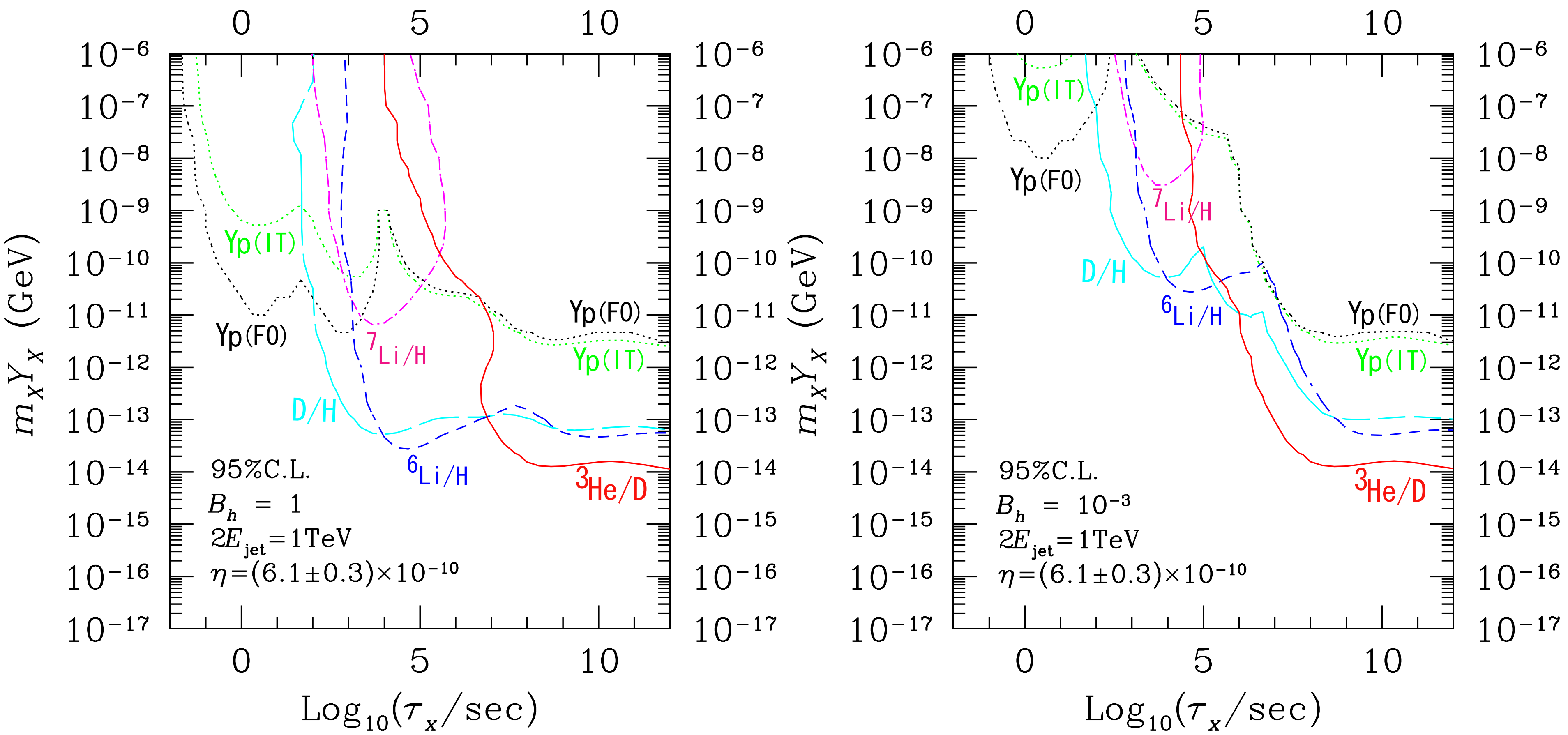
- Moduli problem *if* they dominate the energy density before decay. Not our case...
- Big Bang Nucleosynthesis: strong limits on the injection of energetic particles for $\tau > 1$ sec. At early times the stronger bounds are given by hadronic showers, later also electromagnetic showers become important and effects of bound states for charged particles.
- 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]



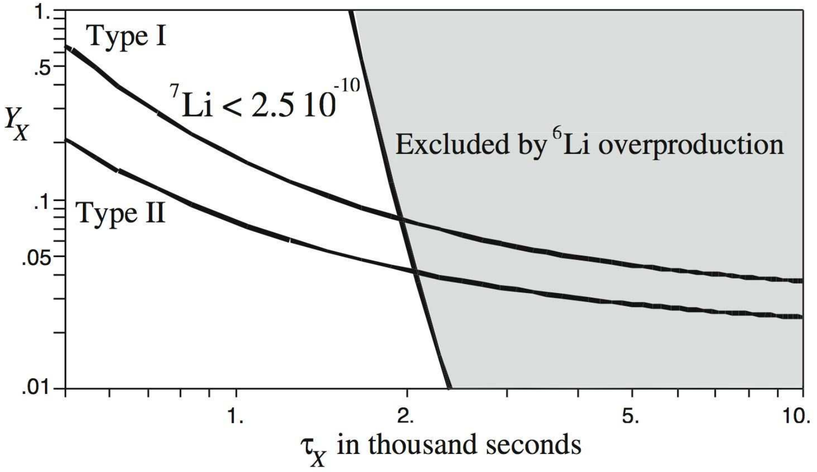
Strong bounds for the gravitino scenario, very weak for the axino case, due to the shorter lifetime.

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

BBN & bound states

[Pospelov 05; Kohri & Takayama 06, Cyburt *et al.* 06]

If the NLSP is electrically negatively charged and lives longer than 10^2 s, it bounds to light nuclei and causes the nuclear reactions to proceed faster by lowering the Coulomb barrier. This enhances some reaction rates even of a factor of 10^5 and mostly affects the Lithium abundance. Strong bound $\tau_{\tilde{\tau}} \leq 10^3$s !



However standard BBN does not agree very well with the observed Lithium abundance...: It predicts too much ^7Li and too few ^6Li. With a $\tilde{\tau}$ NLSP decaying at about 10^3 sec it is possible to improve the agreement with observations for a specific choices of parameters, but usually for very large $\tilde{\tau}$ masses.

Note most of the gravitino DM region with stau NLSP is excluded in the CMSSM apart if the stau density was diluted by a factor 100 after freeze-out ! $\Rightarrow$ Non standard cosmology below 5-10 GeV

Recent claim by K. Jedamzik: could be fine if NLSP decay gives sufficient destruction...

Note: a stop NLSP can be safe thanks to sbaryon and mesino annihilation at the quark-hadron transition well before BBN starts. [Khang, Luty & Nasri 06, Diaz-Cruz, Ellis, Olive & Santoso 07]

HOW TO EVADE THE BBN BOUNDS ?

- make the lifetime shorter:

  light(er) gravitino or heavi(er) NLSP: $\tau_{NLSP} \simeq 10^5\text{s} \left(\frac{m_{NLSP}}{200\text{GeV}}\right)^{-5} \left(\frac{m_{3/2}}{10\text{GeV}}\right)^{2}$

  → TeV scale for the NLSP ?

  R-parity violation: the NLSP decays quickly, while the gravitino can still live enough to be DM...

  → W. Buchmüller's seminar

  change LSP... : e.g. axino has much shorter lifetime since $F_a < M_P$!

- harmless NLSP:

  decaying mainly in harmless particle as the sneutrino $\tilde{\nu} \rightarrow \nu\psi$;

  with efficient annihilation and so suppressed abundance like the stop;

  with abundance, lifetime and BR$_\gamma$ such to destroy ^7Li/produce ^6Li [K. Jedamzik '07].

- dilute NLSP abundance by entropy production: a factor if about 100 is sufficient to satisfy the bounds... [Buchmüller, Hamaguchi, Ibe, Yanagida '05, ...] → non-standard cosmology !

NB: the trouble with BBN persist also for unstable gravitino, but it can be solved by taking very low T_{RH}.

Gaugino mediation

GAUGINO MEDIATION

In extra dimensional models, SUSY breaking can take place away from the observable brane and be transmitted to the observable sector by the gauginos in the bulk or other bulk fields.

[Kaplan, Kribs & Schmaltz 99, Chacko, Luty, Nelson & Ponton 99]

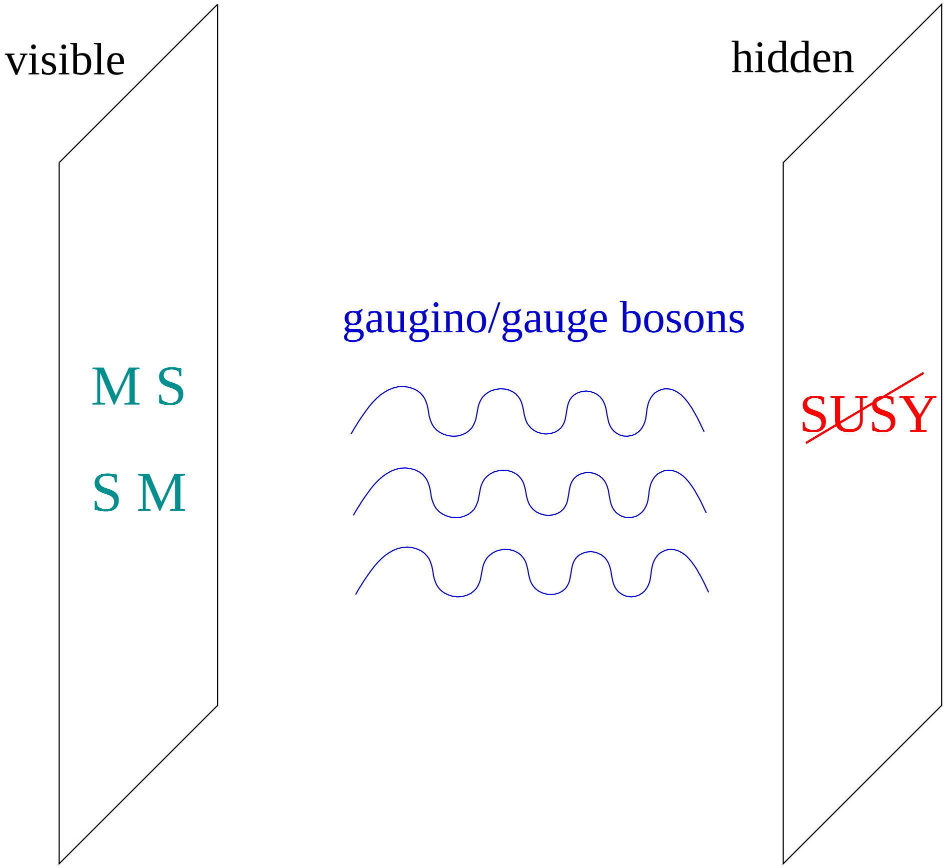
The gaugino and gravitino mass are given by the same SUSY breaking scale, but arise from different non-renormalizable operators

$$m_{1/2} = \frac{g_4^2 h F_S}{\Lambda} \qquad m_{3/2} = \frac{F_S}{\sqrt{3} M_P}$$

where $\Lambda < M_P$ is the cut-off of the extra-dimensional theory...

If the gaugino mass is not suppressed by the coupling, the gravitino can be naturally the lightest particle.

[Buchmüller, Hamaguchi & Kersten 05]



Gaugino mediation in 6D

Consider in this case an explicit 6D model where only bulk fields feel directly SUSY breaking, in this case gauginos, Higgs fields and some 4th generation split multiplet...

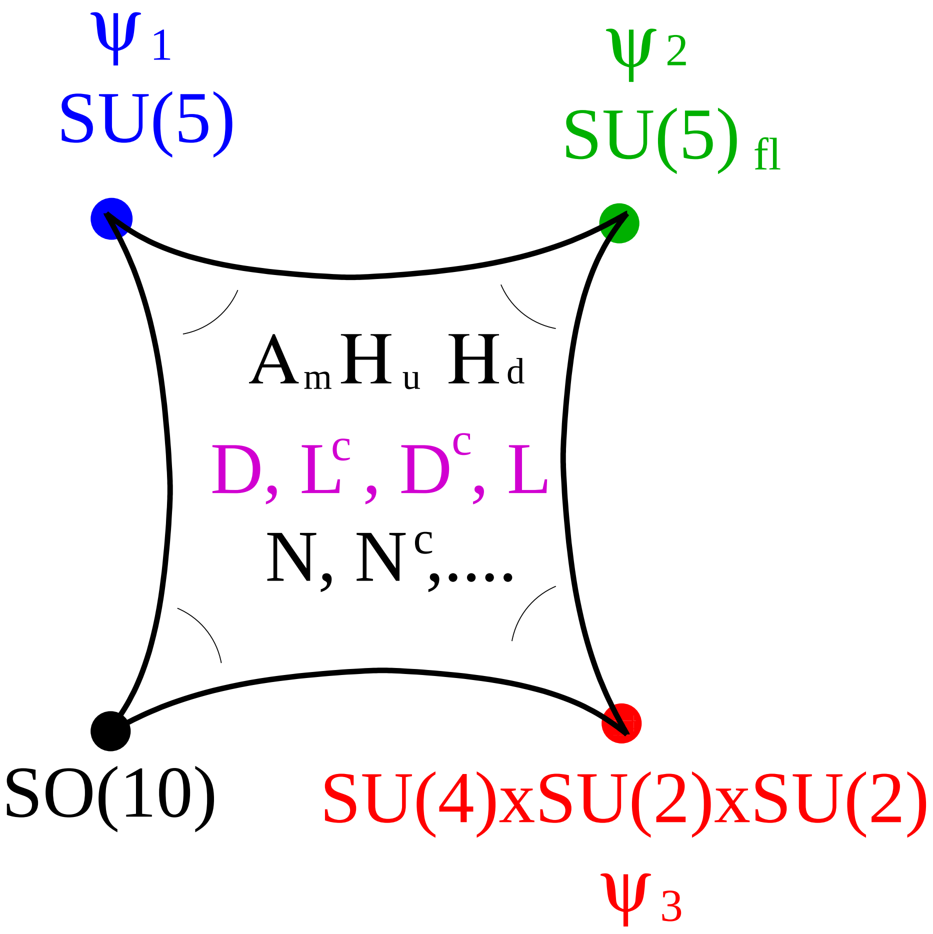
FCNCs strongly constraint the 4th generation soft masses: $m_{4L/R} \to 0$!

Then the boundary conditions at the GUT scale are a special case of the Non-Universal Higgs Masses models (NUHM):

$$m_0 = A_0 = 0 \quad \text{while}$$

$$m_{1/2}, \mu, B\mu, m_{H_{1,2}} \neq 0$$

[Buchmüller, Kersten & Schimidt-Hoberg 05]



[Asaka, Buchmüller & LC 01]

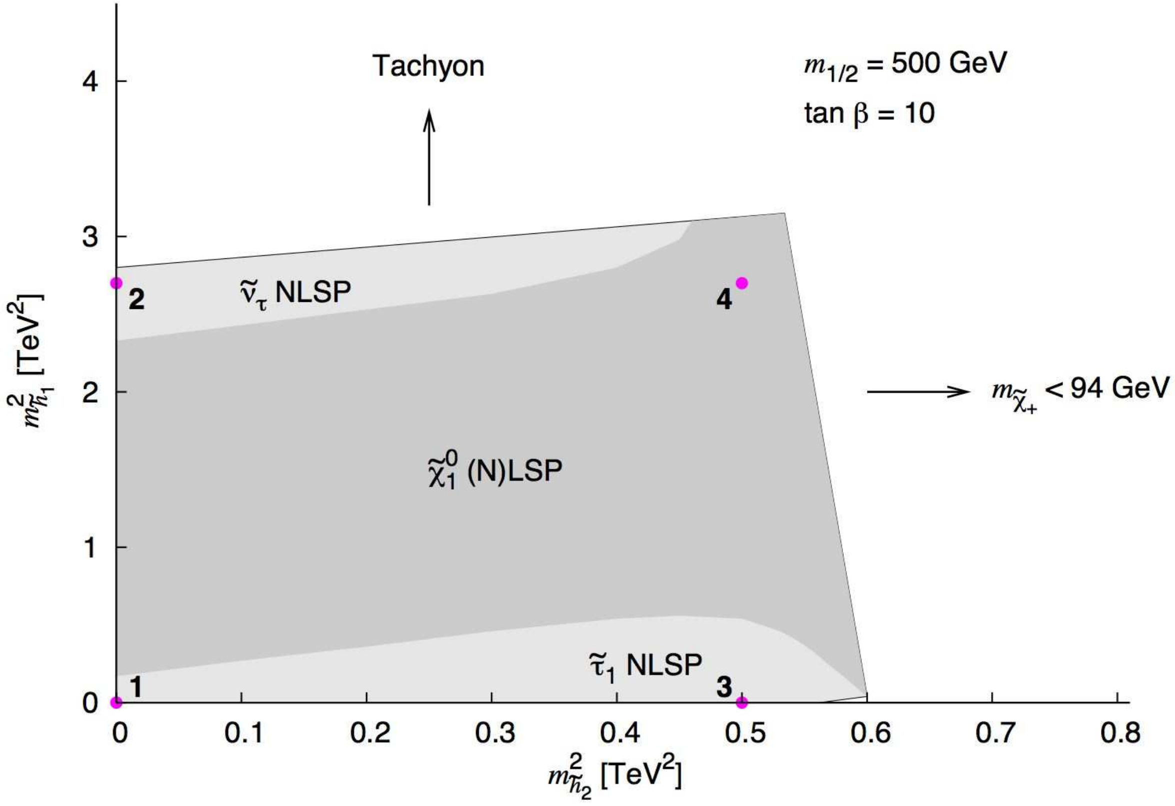
Explore the parameter space...: $m_{1/2}, m_{H_{1,2}}, \tan\beta, sign(\mu)$

[Buchmüller, Kersten & Schimidt-Hoberg 05]

In general very different spectrum compared to CMSSM: Much stronger degeneracy in the masses and light sleptons !

The Higgs mass difference drives the LH sleptons masses lower than the RH ones and so the sneutrino and charged sleptons are nearly degenerate.

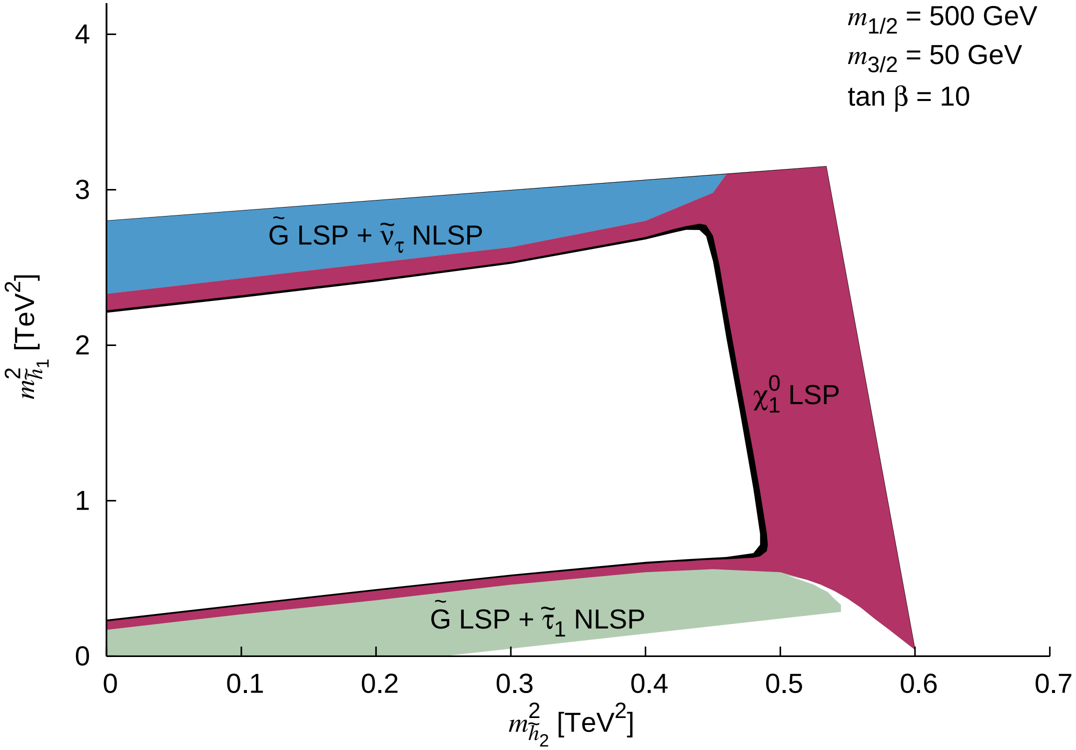
The gravitino can be the LSP.



GAUGINO MEDIATION & DARK MATTER

[Buchmüller, LC, Kersten & Schimidt-Hoberg 06]

Most of the neutralino parameter space is excluded since either the density is too large if the neutralino is the LSP or by BBN constraints if it is the NLSP.



The stau region is also reduced by bounds coming from electromagnetic showers during BBN and is actually excluded by the bound state constraints if the gravitino mass is around 10 GeV or larger...

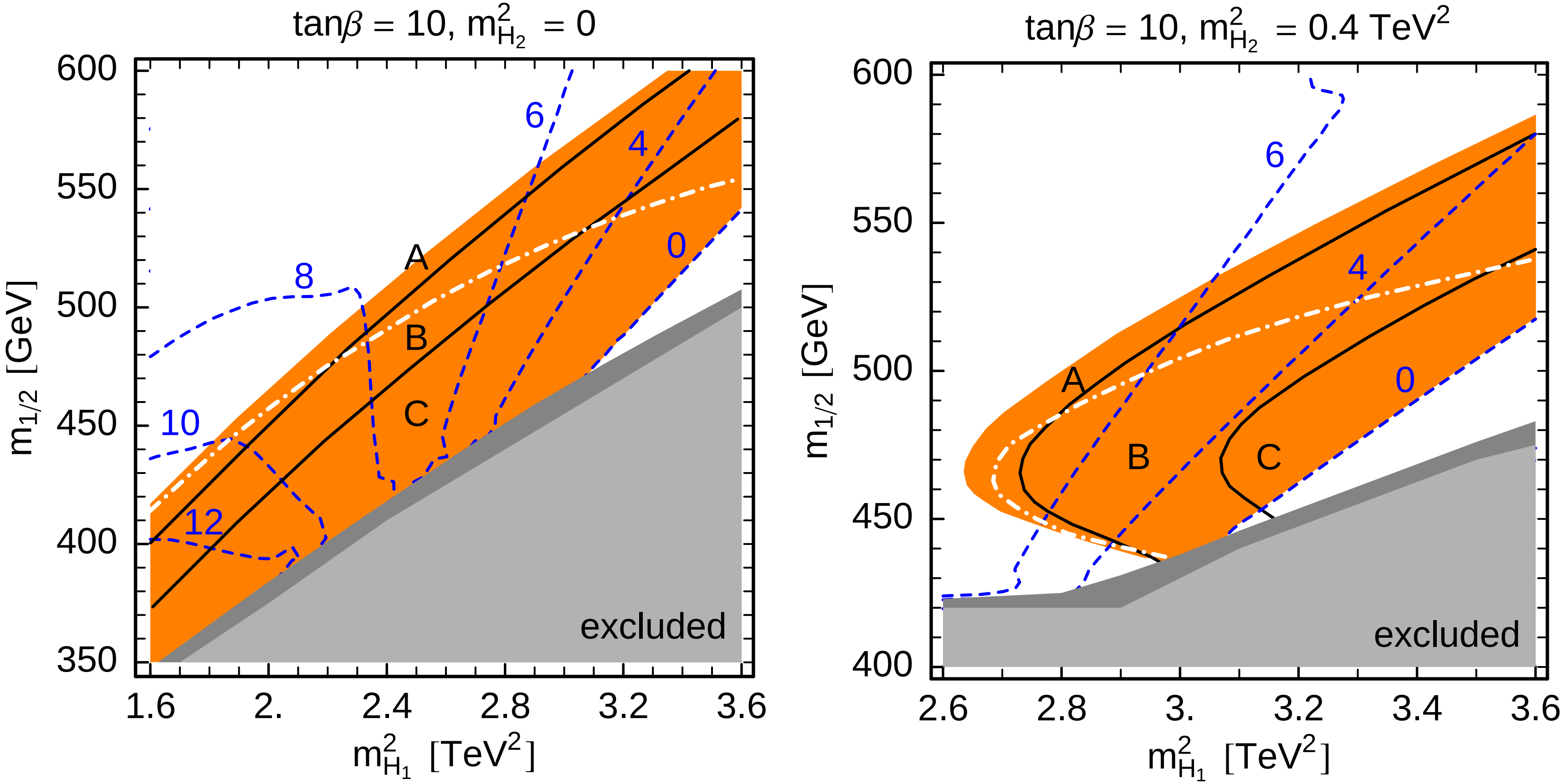
$$\tau_{\tilde{\tau}} = 1.8 \times 10^5 \mathrm{s} \left(\frac{m_{\tilde{\tau}}}{200\mathrm{GeV}} \right)^{-5} \left(\frac{m_{3/2}}{10\mathrm{GeV}} \right)^2$$

In this case not even photodissociation invoked by K. Jedamzik helps...

ONLY the sneutrino NLSP region survives all the BBN bounds for standard cosmology.

$\tilde{\nu}$ NLSP

Let us have a look at the sneutrino NLSP region in more detail: [LC & Kraml 07]



Very close spacing between $\chi^0_1, \tilde{\tau}_1, \tilde{e}(\tilde{\mu})$: the mass ordering can be $\tilde{e} > \tilde{\tau}_1 > \chi^0_1 > \tilde{\nu}_\tau$ (A), $\tilde{e} > \chi^0_1 > \tilde{\tau}_1 > \tilde{\nu}_\tau$ (B) or even $\chi^0_1 > \tilde{e} > \tilde{\tau}_1 > \tilde{\nu}_\tau$ (C) !

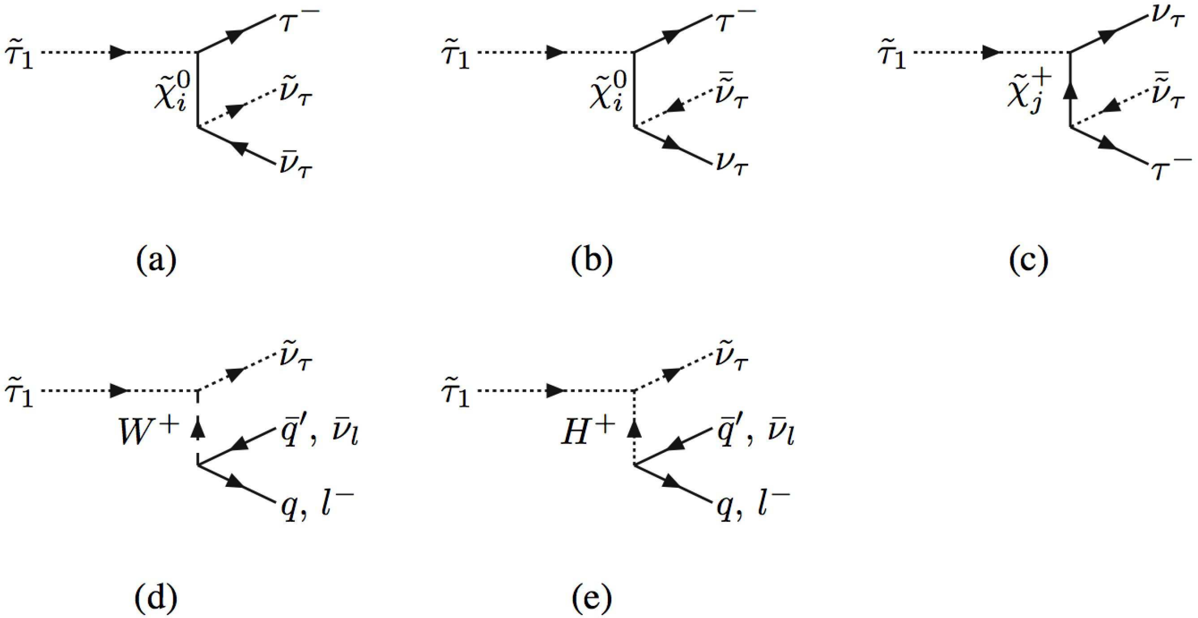
In any case the mass differences are very small ⟶ coannihilation is important and the sneutrino number density is usually small $\Omega_{\tilde{\nu}} h^2 < 0.01$ giving weak BBN bounds (white line shows the bound from [Kanzaki,Kawasaki, Kohri & Moroi 06] for a hadronic branching ratio of 10^{-3}).

Sneutrino NLSP at colliders

[LC & Kraml 07]

In general it is very difficult to identify if the missing neutral particle is a neutralino or a sneutrino...,

but for gaugino mediation there is also another smoking gun: the sleptons are nearly degenerate and if the neutralino is heavier than the stau, the last decay of the chain is a three-body decay with (mostly) an off-shell W and produces soft leptons.



(a) (b) (c)

(d) (e)

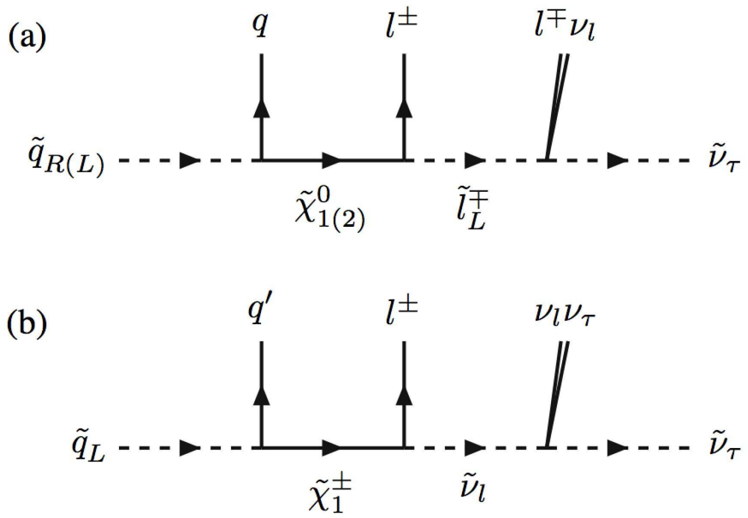
Unfortunately the decay time is too short to give a displaced vertex...: $\Gamma_{\tilde\tau}^{-1} \sim 10^{-17}$s

Which signals can we expect at LHC ?

LHC: Most of the decay chains are modified and end with a three-body decay !

If the mass difference between the two lightest states is large enough some of the soft leptons can pass the p_T cuts and/or one can see that there are different missing energies, then it will perhaps be possible to recognize the scenario.

$\longrightarrow$ lower p_T cuts ?



Lepton number can appear to be violated because the NLSP carries it away..., but it is not clear if the the stau can be easily identified !

Another distinctive signal is the excess of leptons as in the case of the NUHM with neutralino LSP.

[Evans, Morrissey & Wells 06]

Hopefully possible to distinguish the scenario from $\tilde{\tau}$ NLSP and gravitino LSP and R-parity violation.

What about ILC instead ?

ILC offers a much cleaner environment and will allow much more detailed studies of the neutralino, chargino and stau decays and determine the mass differences. Possible to use similar techniques as for chargino decay into sneutrino in the CMSSM where the sneutrinos are lighter than charginos and decay invisibly. [Freitas, Porod & Zerwas 05]

Studying the angular distributions in chargino or stau decay could perhaps determine that a scalar particle is escaping.

Also very promising the possibility to study Initial State Radiation in $e^+e^- \longrightarrow \tilde{\nu}\tilde{\nu}\gamma$!
In fact the cross section for sneutrino production is larger than for neutralino due to the unsuppressed couplings with Z.

Question: possible to distinguish the sneutrino from the neutralino in general ?

Conclusions and Outlook

- The identity of Dark Matter is still an open question in cosmology:

  Supersymmetry gives some good candidates, but with very different characteristics.

- More elusive candidates as the gravitinos with masses in the MeV-GeV are also good CDM candidates and in that case the allowed supersymmetric parameter space changes.

  $\longrightarrow$ heavier sparticles, sneutrinos NLSPs, small R-parity violation are allowed !

- If the (N)LSP decays is charged or decays in the detector, it will give a clear signal that the neutralino is not DM. $\longrightarrow$ other LSP/non-standard cosmology ?

- If the (N)LSP is neutral and appears stable at colliders, then disentangling the true LSP becomes more complex, but not impossible... Sneutrino NLSP could be identified at LHC if it is possible to detect the soft decay products of the $\tilde{\tau}$; more precise signals are possible at the ILC...