Gravitino Dark Matter with $\tilde{\nu}$ NLSP or R-parity violation

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DESY

based on work in collaboration with

G. Bertone, W. Buchmüller, A. Ibarra,	work in progress
S. Kraml	hep-ph/0703130
W. Buchmüller, K. Hamaguchi, A. Ibarra, T. Yanagida	JHEP 0703 (2007) 037
W. Buchmüller, J. Kersten & K. Schmidt-Hoberg	JCAP 0611 (2006) 007
A. Brandenburg, K. Hamaguchi, L. Roszkowski & F.D. Steffen	PLB 617 (2005) 99

OUTLINE
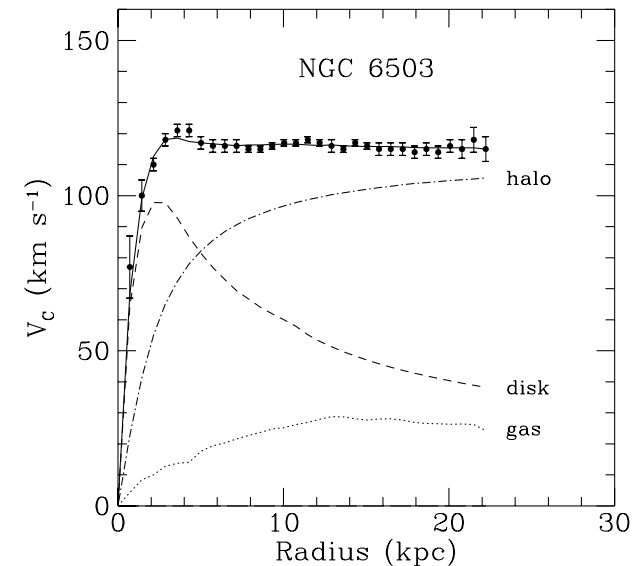
THE MATTER CONTENT

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

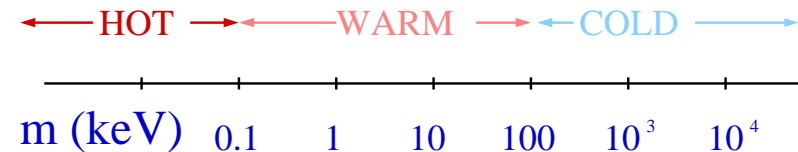**DARK matter !**

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

$\longleftarrow$ HOT $\longrightarrow$ $\longleftarrow$ WARM $\longrightarrow$ $\longleftarrow$ COLD $\longrightarrow$

than its free-streaming length at t_{eq} is suppressed.   m (keV) 0.1   1   10   100 10^3 10^4

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 !

Supersymmetry and the Constrained MSSM

Supersymmetry: boson $\Leftrightarrow$ fermion

● protects the scalar masses and the hierarchy

● predicts for every SM particle a super-partner with the same quantum numbers and couplings, but different spin

SM Particles	Superpartners
q_L, u_R, d_R, l_L, e_R	$\tilde{q}_L, \tilde{u}_R, \tilde{d}_R, \tilde{l}_L, \tilde{e}_R$
$g, \gamma, Z, W^\pm$	$\tilde{g}, \tilde{\gamma}, \tilde{Z}, \tilde{W}^\pm$
$H_u, H_d \to h, H, A, H^\pm$	$\tilde{H}_u, \tilde{H}_d$

SUPERSYMMETRY is not observed, softly broken

$\to$ massive superpartners, 105 parameters !

Assuming universality at the GUT scale, we can restrict them to 5:

$$\text{SUSY parameters:} \quad \tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}, \quad \mu, m_0, m_{1/2}, A_0$$

EW symmetry is broken radiatively: $|\mu|$ is fixed ! $\Rightarrow$ Constrained Minimal Supersymmetric SM

That is not the only choice though ! Much more is freedom possible depending on the mediation mechanism !

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]

Consider in this case an explicit 6D model where gauginos and Higgs fields live in the bulk and feel directly SUSY breaking while the other fields acquire non-zero masses only via loop effects. Then the boundary conditions at the GUT scale are a special case of the Non-Universal Higgs Masses models (NUHM):
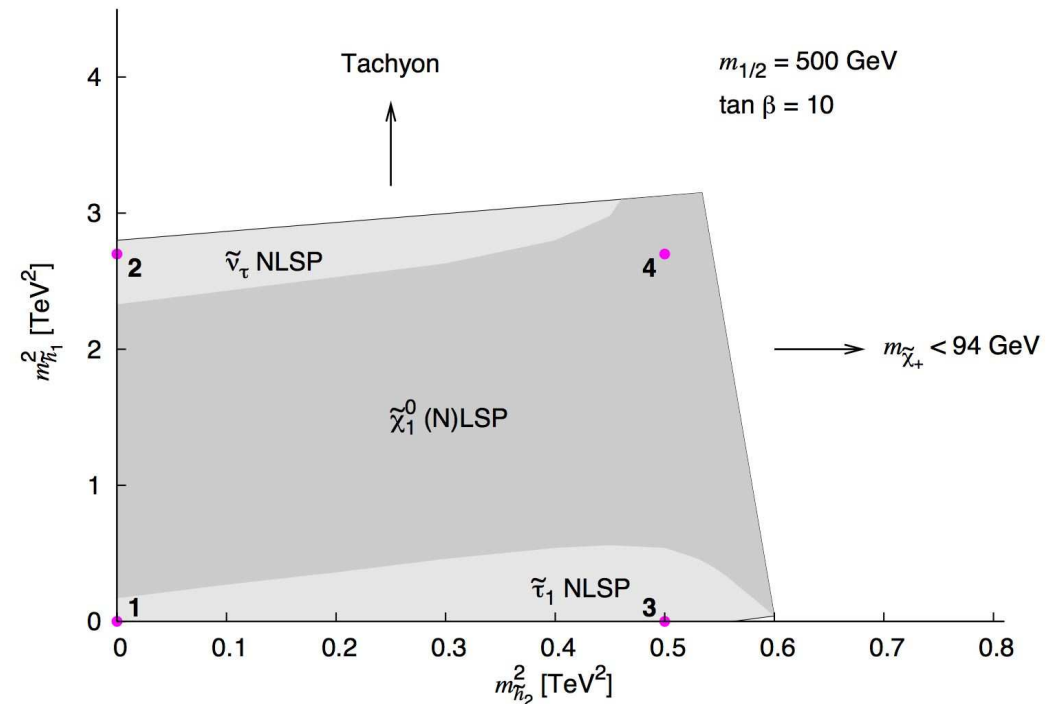
$$m_0 = A_0 = 0 \quad \text{while}$$

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

and the gravitino can be the LSP.

[Buchmüller, Kersten & Schimidt-Hoberg 05]

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

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

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

Hubble expansion   Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = T_f/m_X$

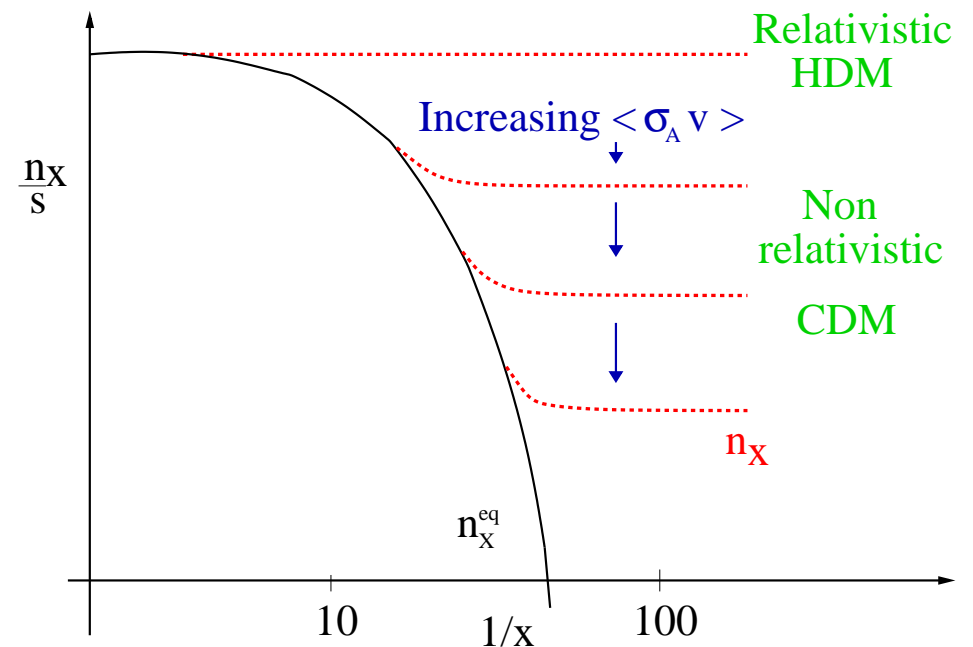defined by $n_{eq}\langle\sigma_A v\rangle_{x_F} = H(x_f)$ and that gives

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

Abundance $\Leftrightarrow$ 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 !

Relativistic
HDM

Increasing $<\sigma_A v>$

Non relativistic
CDM

$\frac{n_X}{s}$

n_X

n_X^{eq}

10    $1/x$ 100

But can CDM be more weakly interacting than a WIMP ? $\Rightarrow$ "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 $\rho = mn$... $\rightarrow$ 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)

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

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.

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

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 $\tilde{\tau} \to X\tau$.

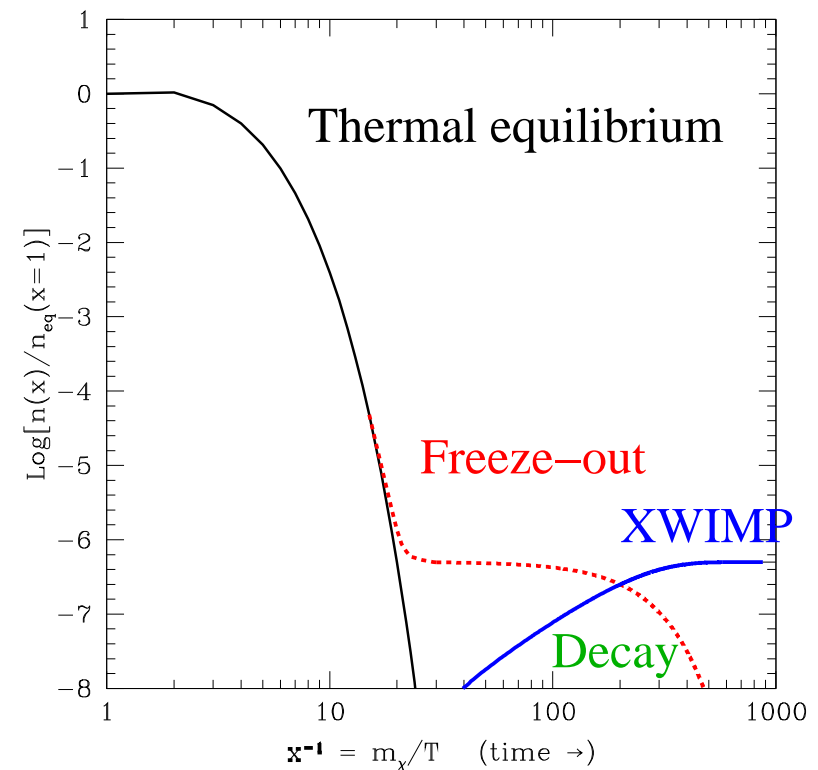The important parameter is the lifetime:

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

$\Rightarrow$ 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:
$$p(T) \simeq \frac{m_{NLSP}}{2} \left(\frac{g_*(T)}{g_*(T_{dec})} \right)^{1/3} \frac{T}{T_{dec}}$$
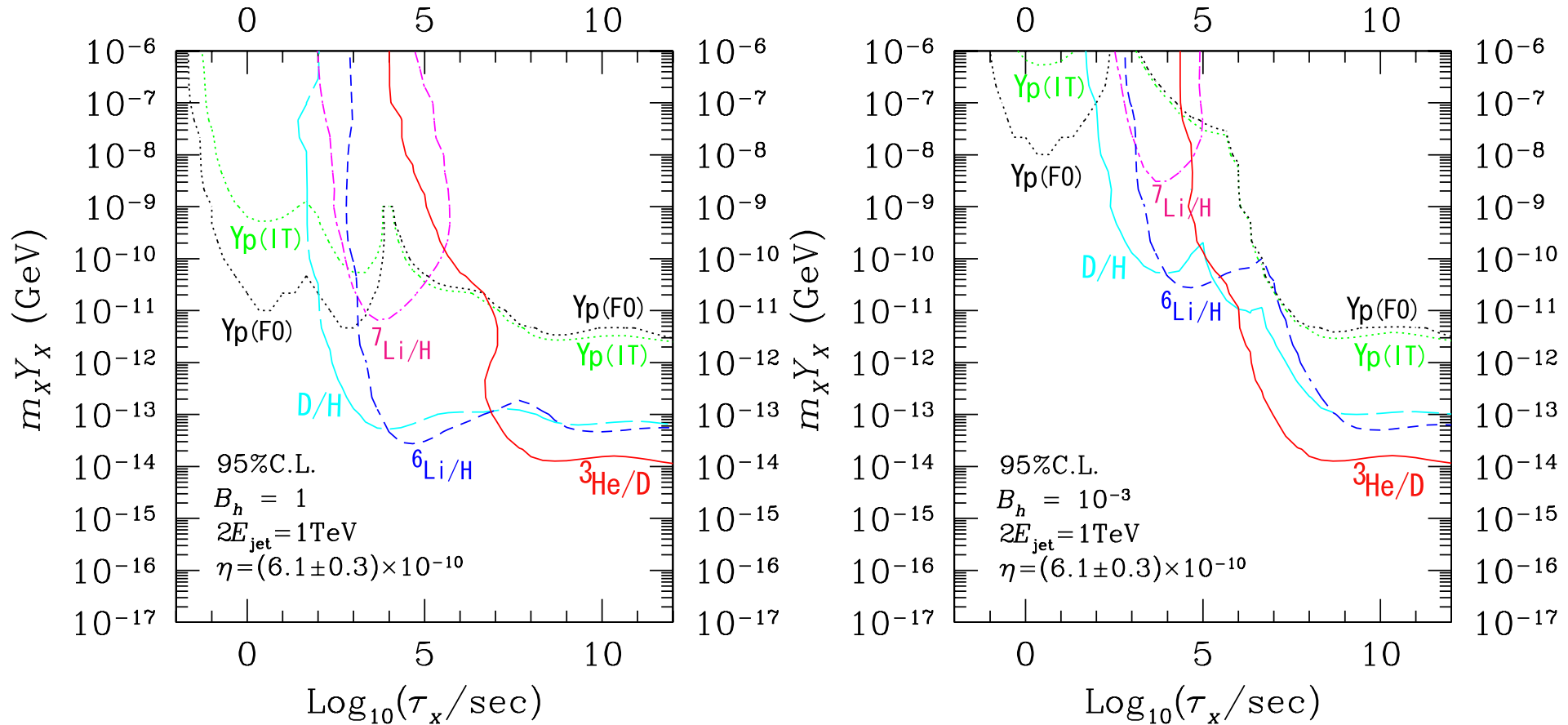
For a thermal relic one has

$\longleftarrow$ HOT $\longrightarrow$ $\longleftarrow$ WARM $\longrightarrow$ $\longleftarrow$ COLD $\longrightarrow$

but "X"WIMPS

m (keV)   0.1   1   10   100 10^3 10^4

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 !
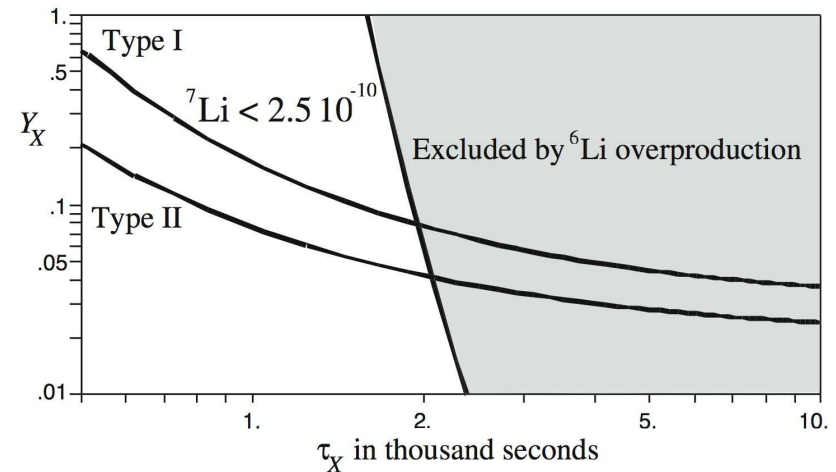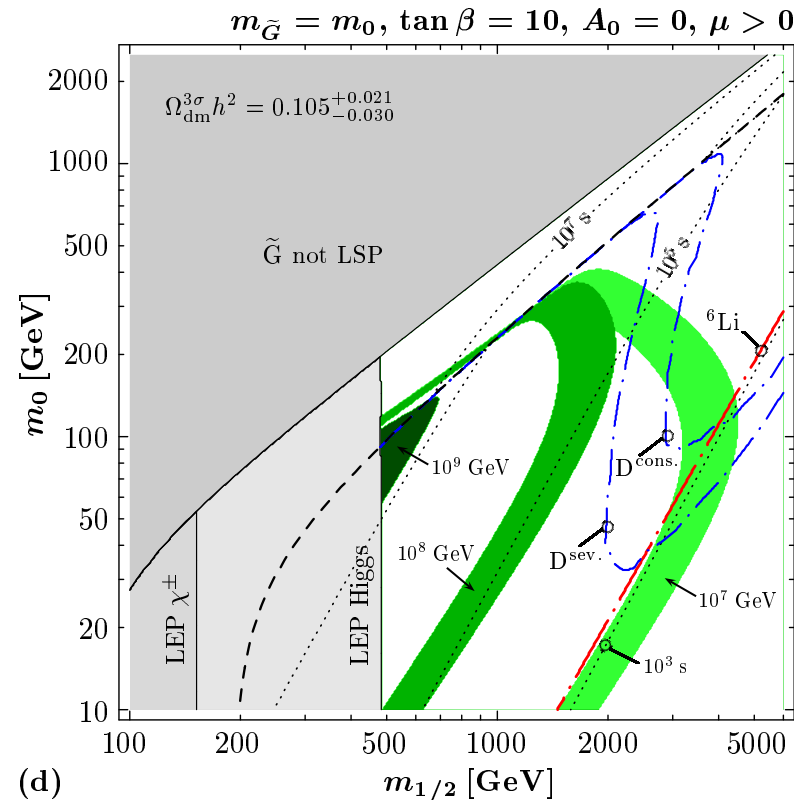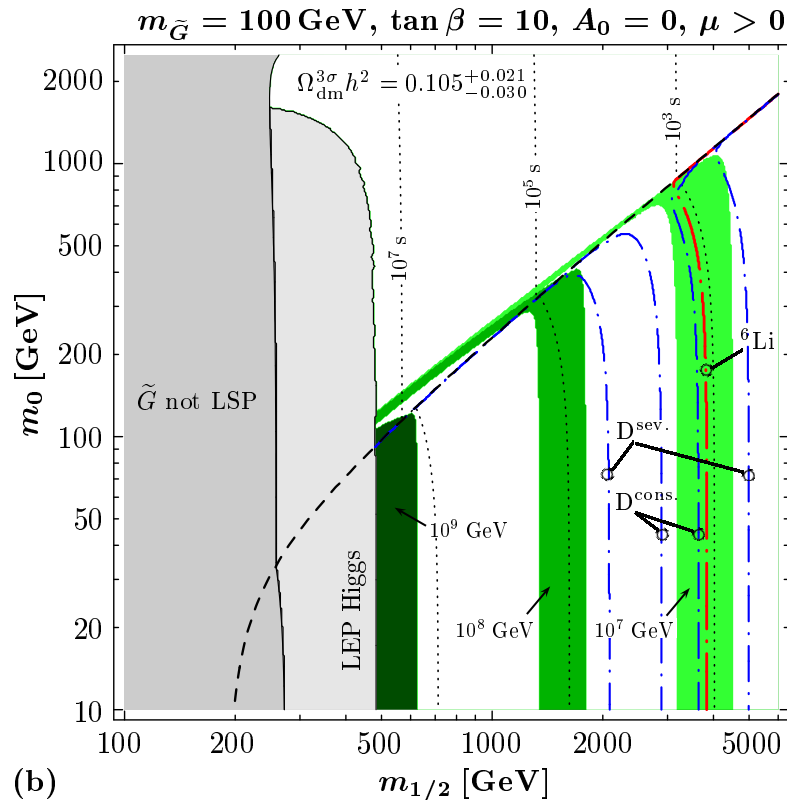

However standard BBN does not agree very well with the observed Lithium abundance...: It predicts too much ^7Li and too few ^6Li. With a $\tilde{\tau}$ NLSP decaying at about 10^3 sec it is possible to improve the agreement with observations for a specific choices of parameters, but usually for very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

A stop NLSP can be safe thanks to sbaryon and mesino annihilation at the quark-hadron transition well before BBN starts.

[Diaz-Cruz, Ellis, Olive & Santoso 07]

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

[Pradler & Steffen 06]

(b) — $m_{\widetilde{G}} = 100\,\text{GeV},\ \tan\beta = 10,\ A_0 = 0,\ \mu > 0$

(d) — $m_{\widetilde{G}} = m_0,\ \tan\beta = 10,\ A_0 = 0,\ \mu > 0$

Region on the rhs of the red line excluded by bound state effects. Region between blue curves in the stau wedge and the neutralino region is excluded by hadronic energy release during BBN.

But [Cyburt *et al.* 06] found a region in the $\tilde{\tau}$ wedge where the agreement with BBN is better than the standard case; unfortunately there the mass of the NLSP is very large since $m_{1/2} = 3 - 4$ TeV...

$\tilde{\nu}$ NLSP
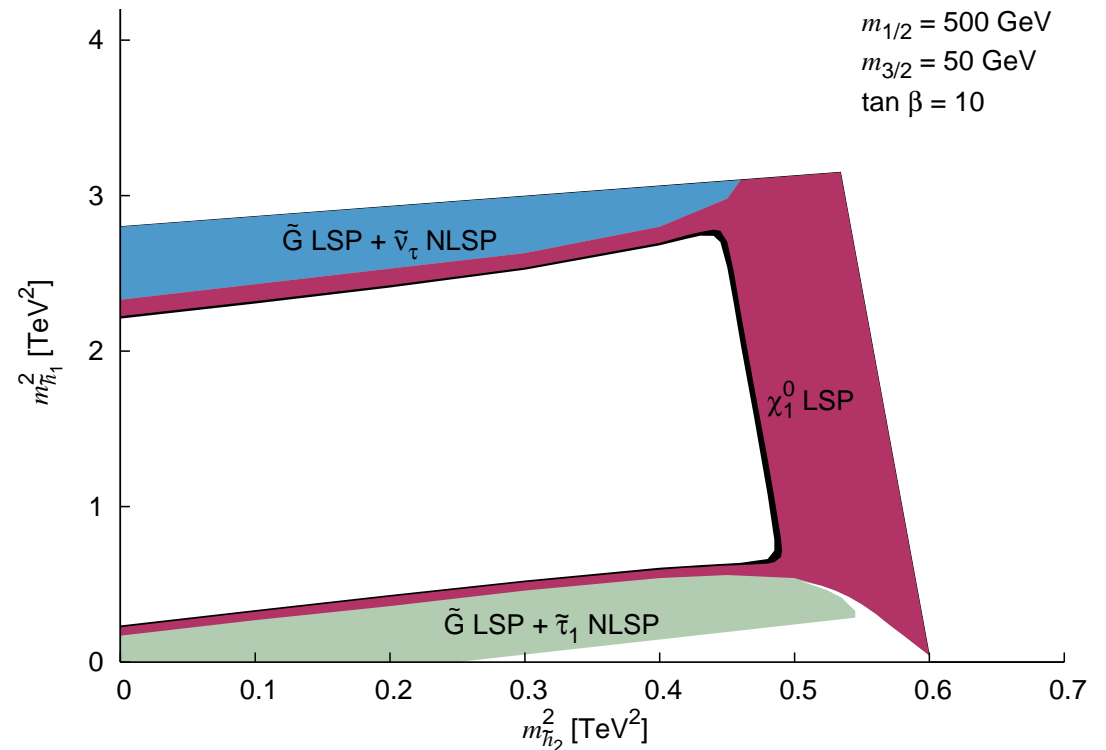
GAUGINO MEDIATION & DARK MATTER

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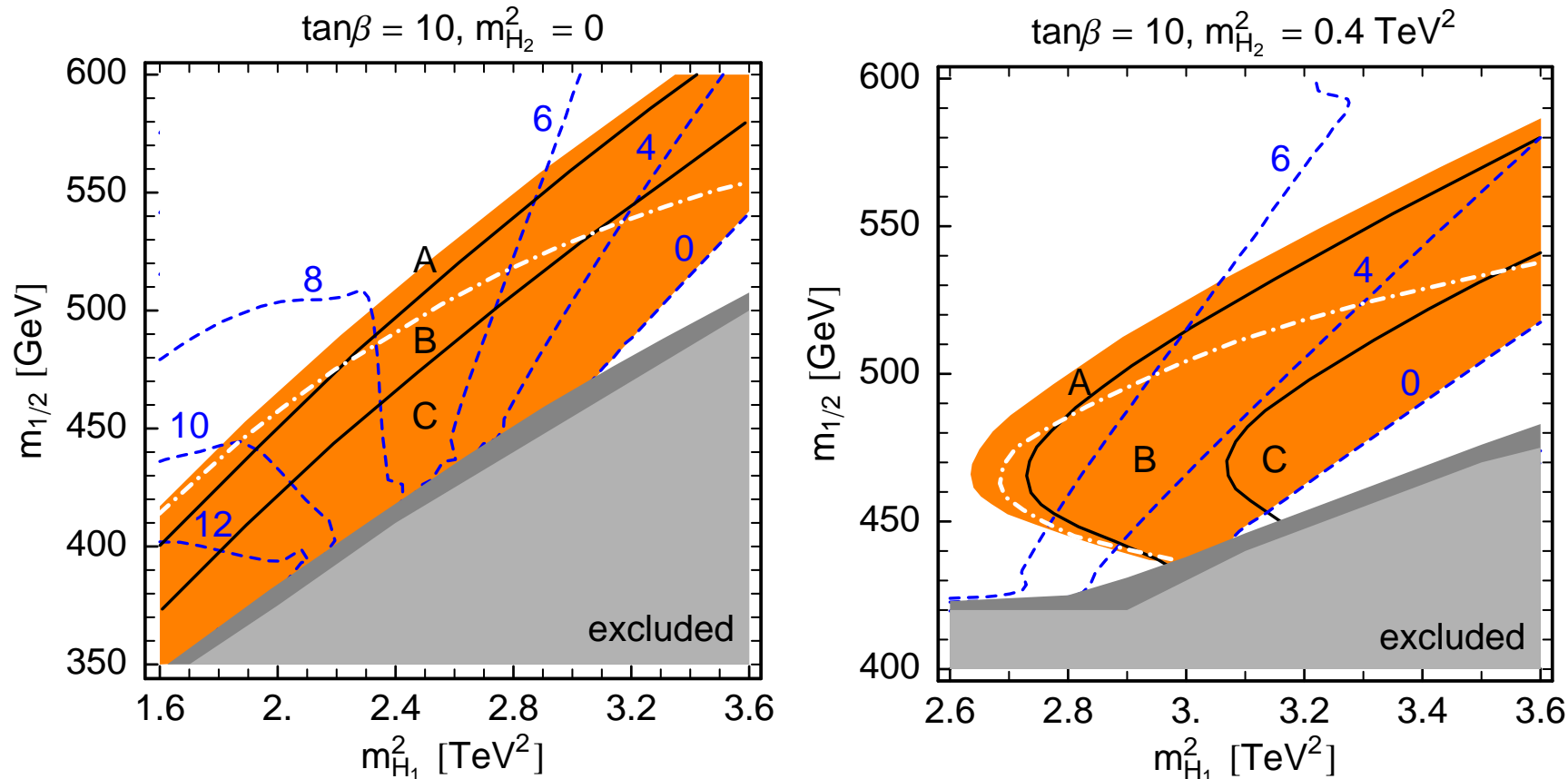
$$\tau_{\tilde{\tau}} = 1.8 \times 10^5 \text{s} \left(\frac{m_{\tilde{\tau}}}{200 \text{GeV}} \right)^{-5} \left(\frac{m_{3/2}}{10 \text{GeV}} \right)^2$$

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

$m_{1/2}$ = 500 GeV
$m_{3/2}$ = 50 GeV
tan β = 10

$\tilde{G}$ LSP + $\tilde{\nu}_\tau$ NLSP

χ_1^0 LSP

$\tilde{G}$ LSP + $\tilde{\tau}_1$ NLSP

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

Very close spacing between $\chi_1^0, \tilde{\tau}_1, \tilde{e}(\tilde{\mu})$: the mass ordering can be $\tilde{e} > \tilde{\tau}_1 > \chi_1^0 > \tilde{\nu}_\tau$ (A),

$\tilde{e} > \chi_1^0 > \tilde{\tau}_1 > \tilde{\nu}_\tau$ (B) or even $\chi_1^0 > \tilde{e} > \tilde{\tau}_1 > \tilde{\nu}_\tau$ (C) !

In any case the mass differences are very small $\rightarrow$ 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]).

Sneutrino NLSP at colliders

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)
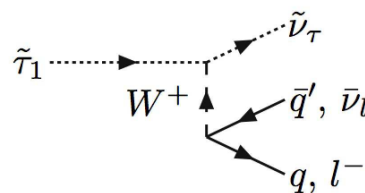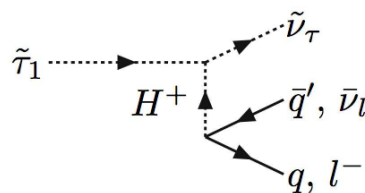an off-shell W and produces soft leptons.
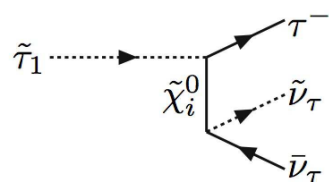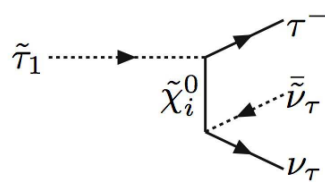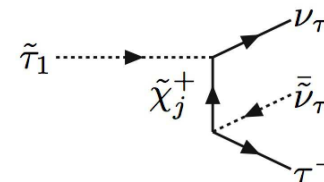
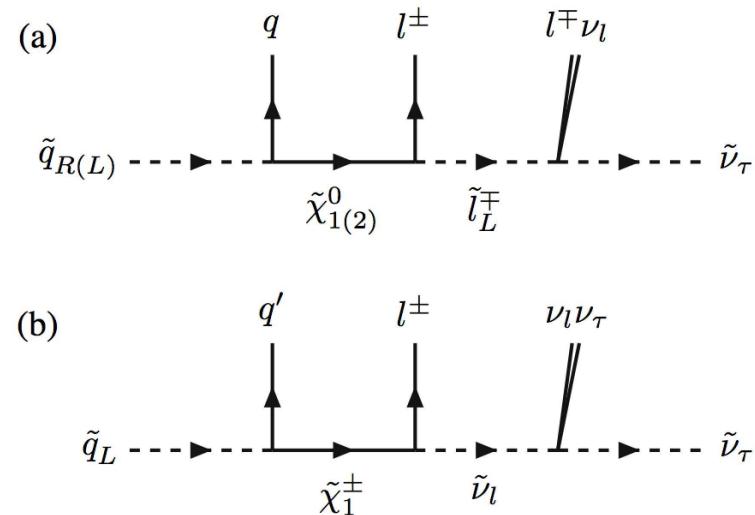$$(a) \qquad\qquad (b) \qquad\qquad (c)$$

$$(d) \qquad\qquad (e)$$

Unfortunately the decay time is too short to give a displaced vertex...

Which signals can we expect at LHC/ILC ?

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.

(a) q $\quad l^{\pm}$ $\quad l^{\mp}\nu_l$

$\tilde{q}_{R(L)} \dashrightarrow \tilde{\chi}^0_{1(2)} \quad \tilde{l}^{\mp}_L \quad \tilde{\nu}_\tau$

(b) q' $\quad l^{\pm}$ $\quad \nu_l\nu_\tau$

$\tilde{q}_L \dashrightarrow \tilde{\chi}^{\pm}_1 \quad \tilde{\nu}_l \quad \tilde{\nu}_\tau$

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

[Evans, Morrissey & Wells 06]

ILC offers a much cleaner environment and will allow much more detailed studies of the neutralino and stau decay and also the possibility to study $\tilde{\nu}\tilde{\nu}\gamma$!

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

R parity breaking

R-parity or not R-parity ?

R-parity is imposed by hand in the MSSM in order to avoid
fast proton decay due to renormalizable couplings explicitly
violating B and L:

$$W = \lambda LLE^c + \lambda' LQD^c + \lambda'' U^c D^c D^c + \mu_i L_i H_2$$

$\Rightarrow$ Dimension 4 proton decay operators $\propto \frac{\lambda' \lambda''}{m_{\tilde{q}}^2}$

R-parity = $(-1)^{3B+L+2s}$ forbids these terms $\Rightarrow$ No dimension 4 proton decay (and LSP is stable)!

Proton decay can be avoided also if only B violating couplings λ'' are forbidden. So do we really need
R-parity to have gravitino DM ? NO: the decay rate of the gravitino is doubly suppressed by M_P and

the R-parity breaking couplings: $\tau_{3/2} \simeq 10^{26} s \left(\frac{\lambda^{(')}}{10^{-7}} \right)^2 \left(\frac{m_{3/2}}{10 \text{GeV}} \right)^3$

It is sufficient to have $\lambda, \lambda' < 10^{-7}$ for the gravitinos to live long enough. Such small value also gives
sufficient suppression to L violating wash out processes and allows for leptogenesis. On the other
hand, requiring the NLSP to decay before BBN just gives $\lambda, \lambda' > 10^{-14}$.

ANY NLSP is allowed if R-parity is broken and still we can have supersymmetric DM !
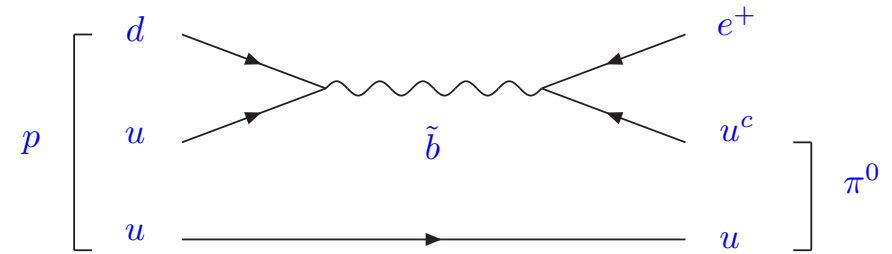
A SIMPLE MODEL with (suppressed) BROKEN R-PARITY

[Buchmüller, LC, Hamaguchi, Ibarra & Yanagida 07]

Tie the R-parity breaking to the $B - L$ breaking: the v.e.v. of a single field Φ generates both the Majorana mass for RH neutrinos and bilinear R-parity breaking $\mu_i L_i H_u$:

$$M_3 = \frac{v_{B-L}^2}{M_P} \qquad \mu_i \propto \frac{v_{B-L}^2}{M_P^2}$$

Choose charge of Φ such that these are the dominant terms, while the other R-parity breaking terms are generated only with higher powers of $\left(\frac{v_{B-L}}{M_P}\right)^{4+n}$ and are harmless.

Effectively a model with bilinear R-parity violation, but with a coupling smaller than those usually discussed in the literature... We require $\epsilon_i = \frac{\mu_i}{\mu} \leq 10^{-7}$.

Rotating away the bilinear, generates couplings $\lambda, \lambda' \simeq \epsilon_i Y_{\ell,d}$ at the required level to avoid BBN/leptogenesis bounds, while the contribution to the neutrino masses from the mixing with the neutralinos remains small:

$$m_\nu \simeq 10^{-4}\text{eV} \left(\frac{\epsilon_3}{10^{-7}}\right)\left(\frac{\tilde{m}}{200 GeV}\right)$$

The largest neutrino mass comes still from the seesaw mechanism.

Gravitino decay

[Takayama & Yamaguchi 00, Buchmüller *et al.* 07]

In this scenario the gravitino is not stable and can decay into a neutrino photon via the photino-neutrino mixing or into 3 leptons via the λ coupling. If the mixing between photino-neutrino is not suppressed, the two body channel dominates with lifetime:

$$\tau_{3/2} = 4 \cdot 10^{27} \text{s} \left(\frac{U_{\tilde{\gamma}\nu}}{10^{-8}} \right)^{-2} \left(\frac{m_{3/2}}{10\text{GeV}} \right)^{-3}$$

this is much longer than the age of the Universe, but nevertheless some of the gravitinos have already decayed or are decaying now $\rightarrow$ (redshifted) photon and neutrino line at $\frac{m_{3/2}}{2}$ with flux

$$\Phi \propto \frac{\rho_{CDM}}{8\pi\tau_{3/2}H_0}$$

The neutrino flux is unfortunately below the atmospheric neutrino one, but the photon flux is of the same order than the observed EGRET extragalactic flux: has the gravitino decay already been observed ??? Or will it be soon ??? still unclear ...   work in progress

R-parity breaking at COLLIDERS

see e.g. [Allanach *et al.* 04, Barbier *et al.* 05]

As long as the parameters ϵ_i are not too small, the phenomenology is the typical one for R-parity breaking, i.e. the (N)LSP decays into SM particles within the detector. To have

$$c\tau \leq 50 \text{ m}, \quad \text{we need} \quad \epsilon_i \gtrsim 10^{-8}...$$

For smaller values, the NLSP will look stable ! The main decays for the stau and neutralino are

$$\tilde{\tau}_R \rightarrow \tau\nu_\mu, \mu\nu_\tau \qquad \tilde{\tau}_L \rightarrow \bar{b}t$$

$$\chi^0 \rightarrow \tau W \qquad \chi^0 \rightarrow b\bar{b}\nu$$

with decay lenghts given by $0.2 - 0.3 (1.6 - 600) \text{ m} \left(\frac{\epsilon_i}{10^{-7}}\right)^2$ for the leptonic (quark) channel.

displaced vertices at LHC !

So if the R-parity breaking is "maximal", we will have a striking signal !

Clearer signal at colliders for $\epsilon < 10^{-8}$: metastable charged NLSP !

The typical signal is a (meta)stable charged particle that escapes the detector leaving a highly ionized track (a heavier μ...).

Very difficult to miss and it would immediately tell us that the neutralino is NOT the LSP and NOT DM.

Unfortunately if the stau does not decay in the detector, it is not possible to identify which is the LSP and if it is stable. We need to measure the decay in order to check if R parity is conserved or not and which is the LSP. There are infact also more "X"WIMP candidates...

$$\tilde{\tau} \to \tau\psi_{3/2}, \tau\tilde{a}, ... \qquad \text{R-parity conserved}$$

$$\tilde{\tau} \to \tau\nu_\mu, \mu\nu_\tau, 2 \text{ jets + lepton}, 4 \text{ jets} \qquad \text{R-parity broken}$$

See e.g. [Hamaguchi, Kuno, Nakaya & Nojiri 04] , [Feng & Smith 04] ,[Hamaguchi, Nojiri & de Roeck 06] for proposals about stopping long-lived $\tilde{\tau}$ around the LHC/ILC and U. Martyn talk about metastable staus at ILC in the SUSY session yesterday.
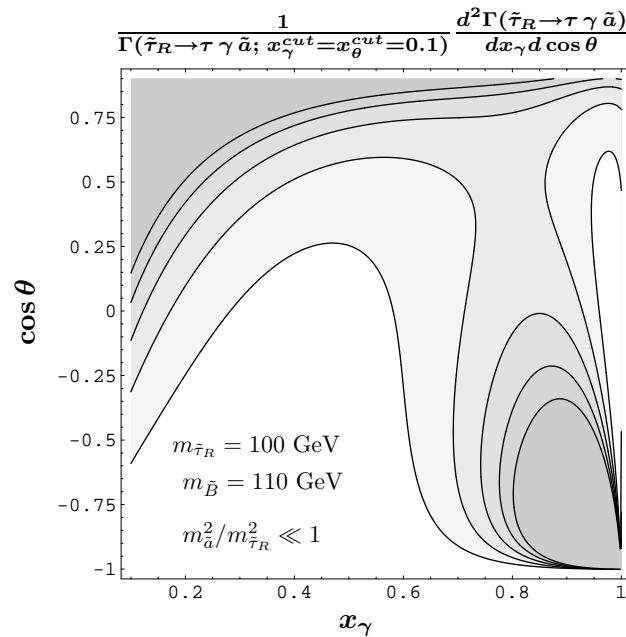
$\psi_{3/2}$ vs $\tilde{a}$: angular dependence in radiative decays

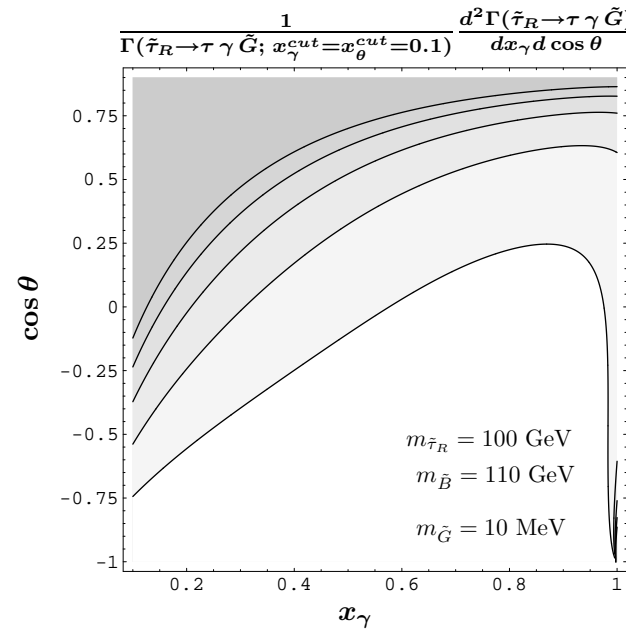[Buchmüller, Hamaguchi, Ratz & Yanagida '04], [Brandenburg, LC, Hamaguchi, Roszkowski & Steffen '05]

$$x_\gamma = \frac{E_\gamma}{2m_{\tilde{\tau}}}$$
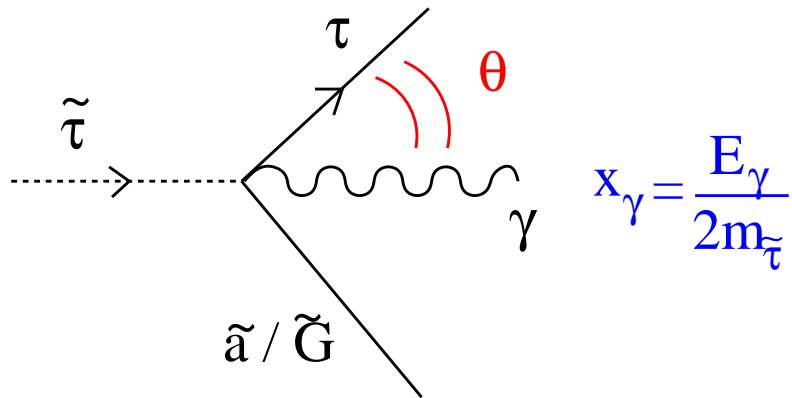
$\rightarrow$ angular distribution in $\tilde{\tau} \rightarrow \gamma\,\tau\,\tilde{a}/\tilde{G}$:

Axino LSP Scenario

$$\frac{1}{\Gamma(\tilde{\tau}_R \rightarrow \tau\,\gamma\,\tilde{a};\, x_\gamma^{cut}=x_\theta^{cut}=0.1)} \frac{d^2\Gamma(\tilde{\tau}_R \rightarrow \tau\,\gamma\,\tilde{a})}{dx_\gamma\,d\cos\theta}$$

$m_{\tilde{\tau}_R} = 100$ GeV

$m_{\tilde{B}} = 110$ GeV

$m_{\tilde{a}}^2/m_{\tilde{\tau}_R}^2 \ll 1$

Gravitino LSP Scenario

$$\frac{1}{\Gamma(\tilde{\tau}_R \rightarrow \tau\,\gamma\,\tilde{G};\, x_\gamma^{cut}=x_\theta^{cut}=0.1)} \frac{d^2\Gamma(\tilde{\tau}_R \rightarrow \tau\,\gamma\,\tilde{G})}{dx_\gamma\,d\cos\theta}$$

$m_{\tilde{\tau}_R} = 100$ GeV

$m_{\tilde{B}} = 110$ GeV

$m_{\tilde{G}} = 10$ MeV

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

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.

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

- A window for R-parity breaking with $10^{-14} \leq \epsilon \leq 10^{-7}$ is open where the gravitino can still be

  DM and not spoil leptogenesis; if the parameters are near to the upper bound, a signal could be

  seen both at LHC and in gamma rays, e. g. by GLAST.

  This would give the possibility to detect gravitino DM !

- If the (N)LSP decays in the detector or is charged, it will give a clear signal that the neutralino is not

  DM. If the (N)LSP is neutral and appears stable at colliders, then disentangling the true LSP

  becomes more complex, but not impossible...