DARK MATTER IN BSM THEORIES

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invisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME

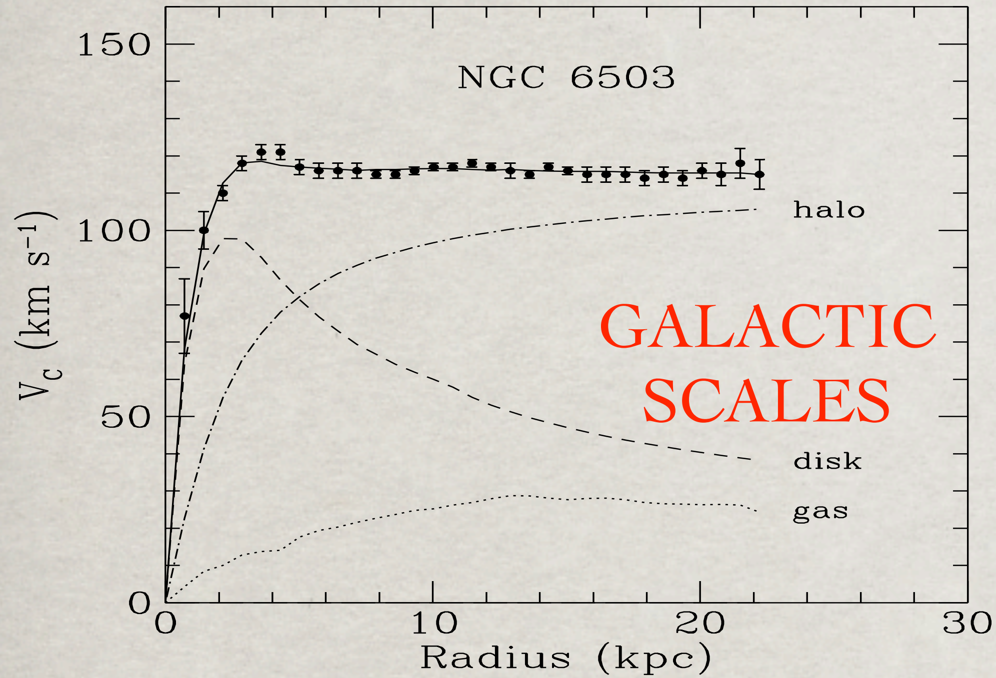
MARIE CURIE ACTIONS

Outline

- Introduction: Dark Matter and SUSY
- Neutralino DM & Higgs mass...
- Unstable Gravitino CDM
- Stable Gravitino CDM
- Gravitino DM @ LHC
- Outlook

Introduction

DARK MATTER EVIDENCE



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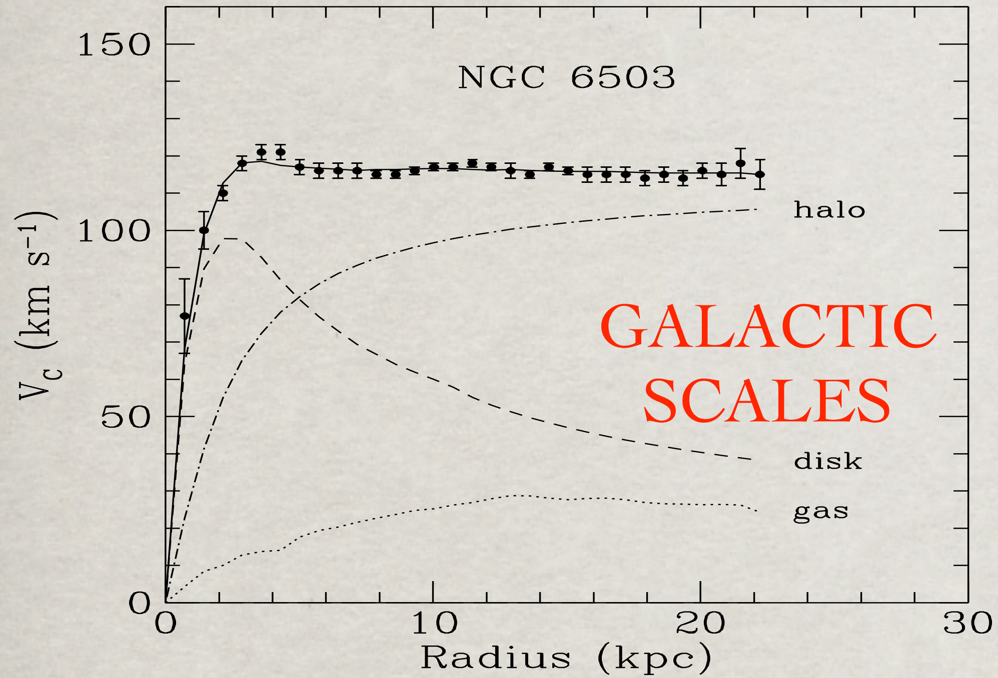

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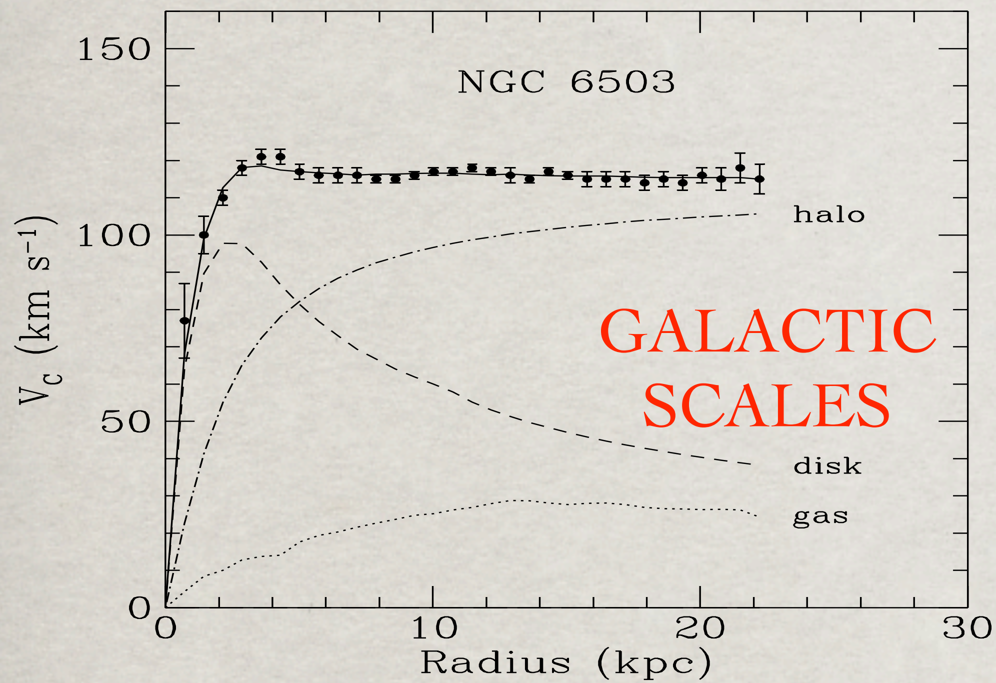

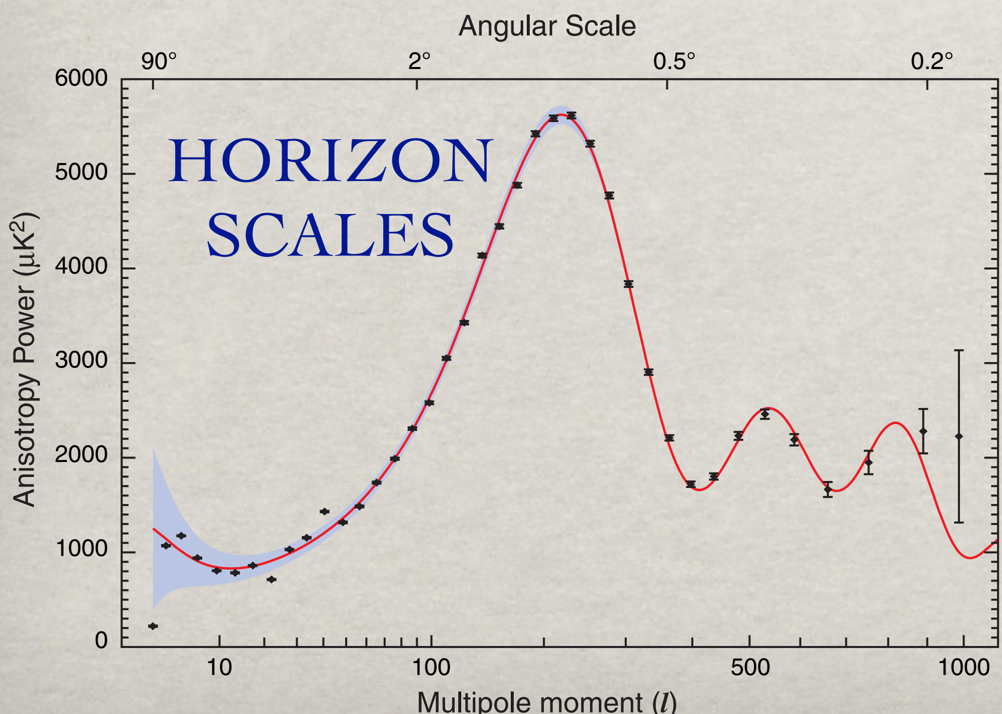

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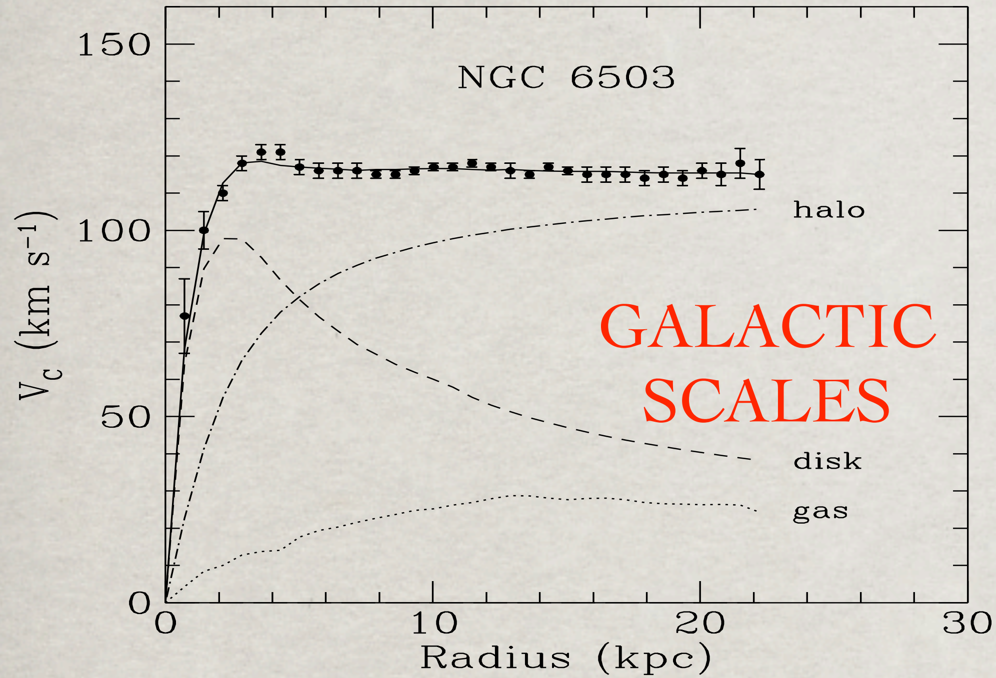
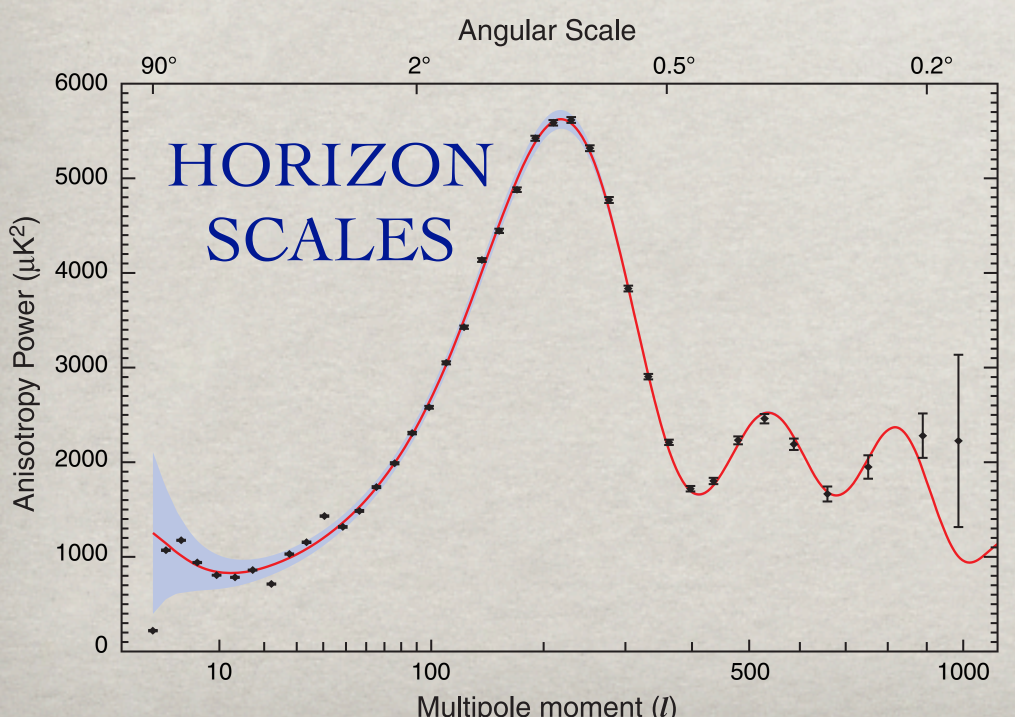




Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	~ 0.1	Cold

All these evidences are just based on the gravitational force: either directly on the attraction of the Dark Matter on the visible matter or on the effect of the Dark Matter energy component on the Universe expansion or on the evolution of the density perturbation...

So there is no doubt:

DARK MATTER
IS GRAVITATING !

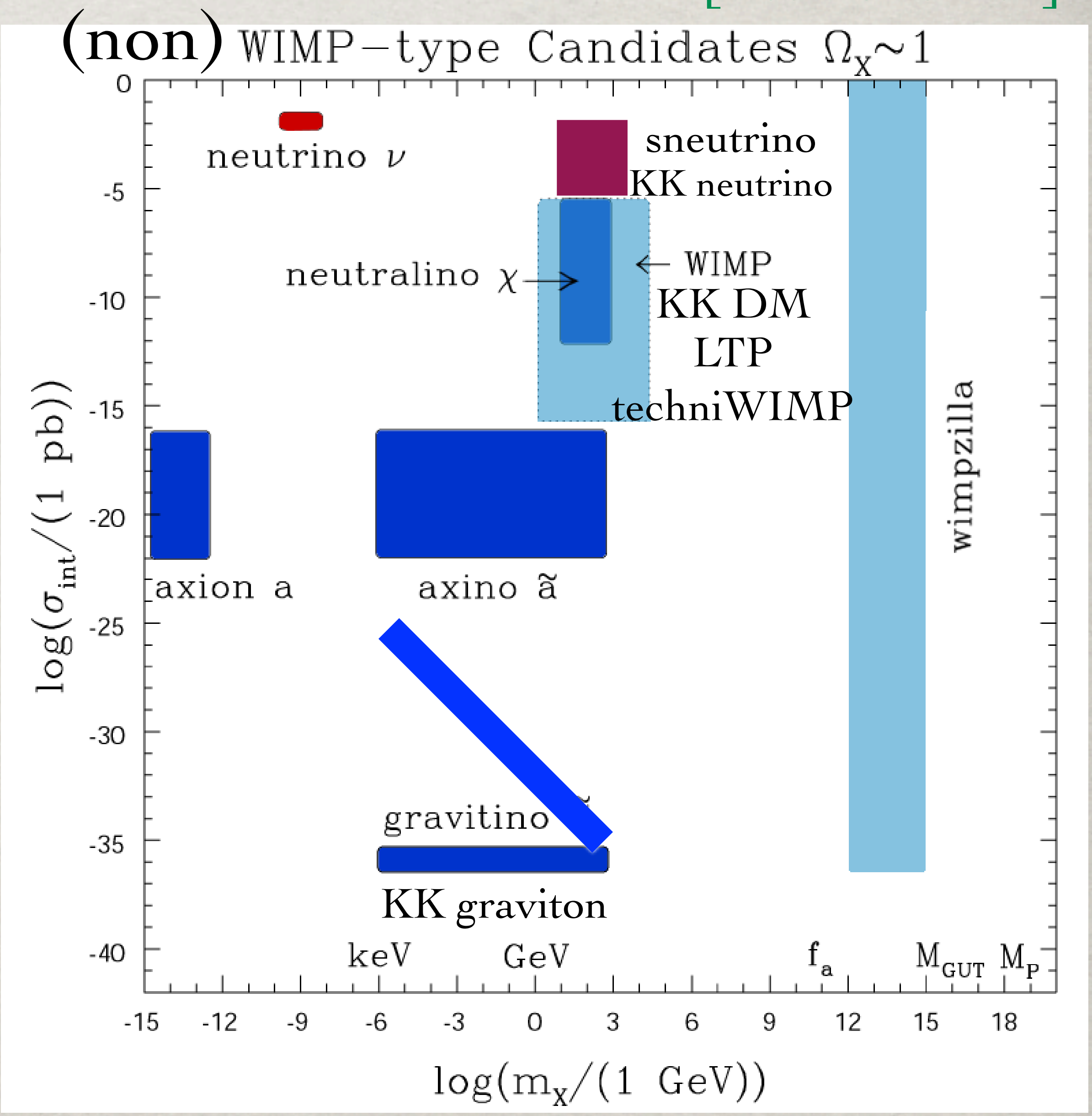
But what about other interactions ???

Only upper bounds from Bullet cluster or the shape of halos, at the order σ/m ~ 1-0.04 barn/GeV, but no lower bound down to gravity !

DM could be a WIMP, but may also be much more weakly interacting, like the candidates I will discuss...

DARK MATTER CANDIDATES

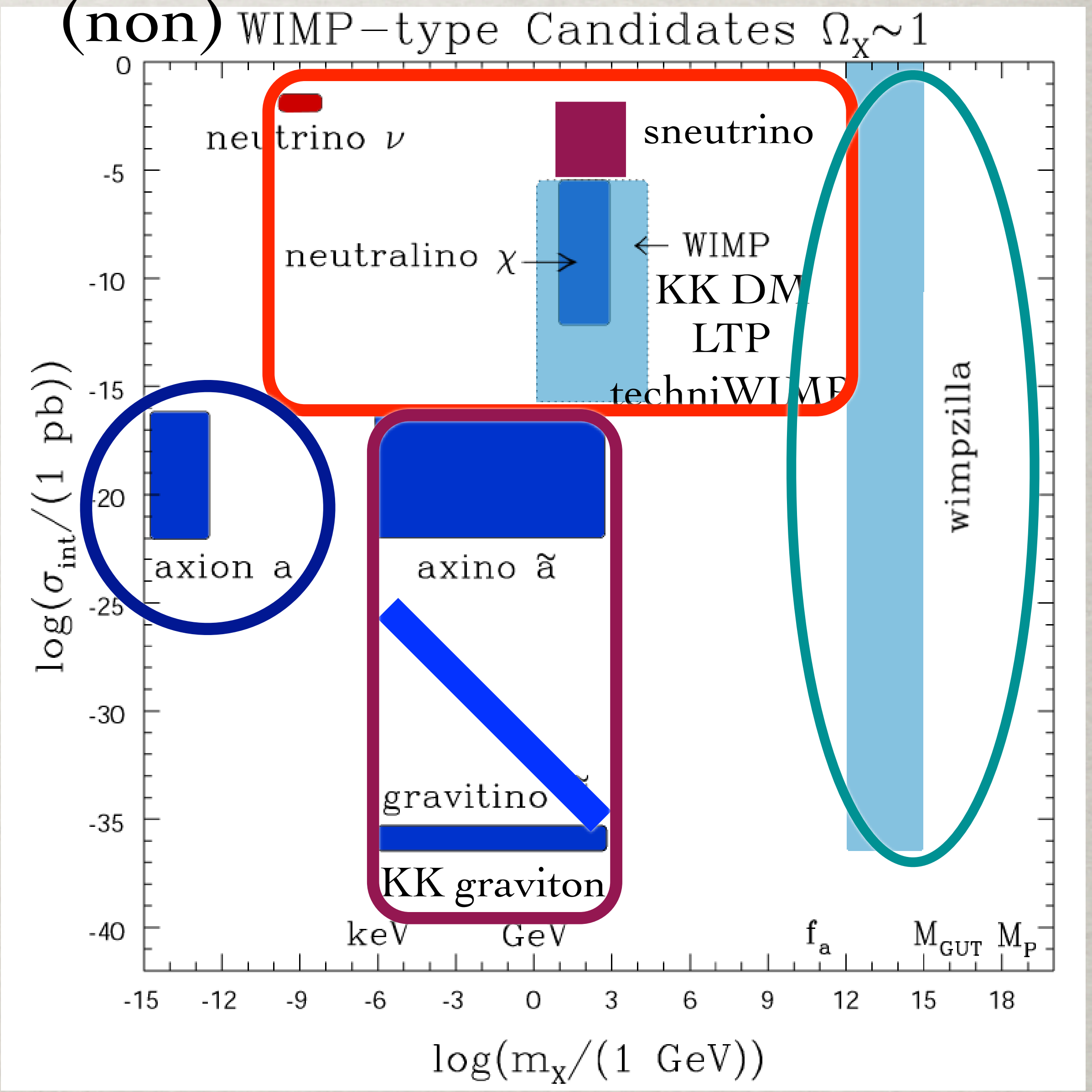
[Roszkowski 04]



DARK MATTER CANDIDATES

- Thermal relics: WIMPs
- "SuperWIMPs"
- Condensate
- Produced gravitationally

[Roszkowski 04]



What is supersymmetry?

Its generators are fermionic operators, building a graded Lie algebra together with the generators of the Poincare` group:

SUPERSYMMETRY: boson <-> fermion

Standard Model			
Matter			Forces
e	μ	τ	γ
ν_e	ν_μ	ν_τ	$W^\pm, Z$
u	c	t	g
d	s	b	G

SUSY SM			
SMatter			SForces
$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$	$\tilde{\gamma}$
$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{W}^\pm, \tilde{Z}$
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SUSY is broken: MASSIVE !

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Lots of massive new particles... any good one for DM ?

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$\tilde{\chi}$

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$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{g}$	
$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	$\tilde{G}$	$\psi_{3/2}$

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Who is the LSP ?

Depending on the SUSY breaking mediation mechanism, different SUSY particles can be the LSP:

Gauge mediation: gravitino is lighter than the rest as long as the messenger mass is smaller than Planck...

Gravity mediation: for universal boundary conditions on can have either neutralino, RH stau or gravitino as LSP; for non-universal boundary conditions also LH sleptons can be the lightest or Higgsinos

Anomaly mediation: in pure anomaly mediation the leptons are tachyonic, usually a mixed mediation is needed. Then of the neutralinos the Wino is the lightest, while the gravitino is always the heaviest state...

Different LSP and DM in different scenarios !

GRAVITINO properties: completely fixed by SUGRA !

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

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

~~SUSY~~

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:

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

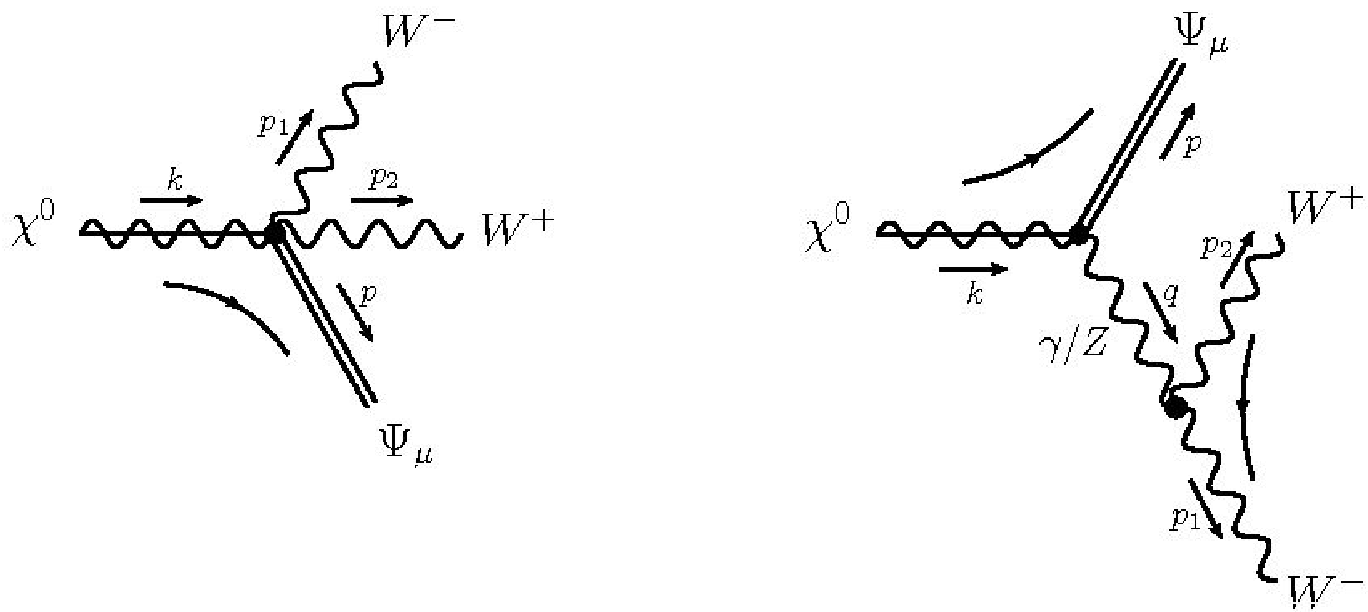
$$\Rightarrow \quad \frac{-m_\lambda}{4\sqrt{6}M_P m_{\tilde{G}}}\bar{\psi}\sigma^{\nu\rho}\lambda^a F^a_{\nu\rho} + \frac{i(m^2_\phi - m^2_\chi)}{\sqrt{3}M_P m_{\tilde{G}}}\bar{\psi}\chi_R \phi^* + h.c.$$

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

The gravitino gives us direct information on SUSY breaking

Unitarity in WW scattering

[LC, Ferrantelli, Hasenkamp ??]



Funny interplay between the SUSY/EW symmetry breaking: in [A. Ferrantelli 07] terms diverging as $1/M_W^2, 1/m_{3/2}^2$ were obtained. [Luo, Olive & Peloso 10] showed numerically that those terms cancel and gave arguments why based on the supercurrent. We are doing a fully analytical computation: we found full cancellation of $1/M_W^2$, but we are still working on $1/m_{3/2}^2$.

Gravitino & Cosmology

Gravitinos can interact very weakly with other particles and therefore cause trouble in cosmology, either because they decay too late, if they are not LSP, or, if they are the LSP, because the NLSP decays too late...

If gravitinos are in thermal equilibrium in the Early Universe, they decouple when relativistic with number density given by

$$\Omega_{3/2} h^2 \simeq 0.1 \left(\frac{m_{3/2}}{0.1 \mathrm{keV}} \right) \left(\frac{g_*}{106.75} \right)^{-1}$$

Warm DM !

[Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

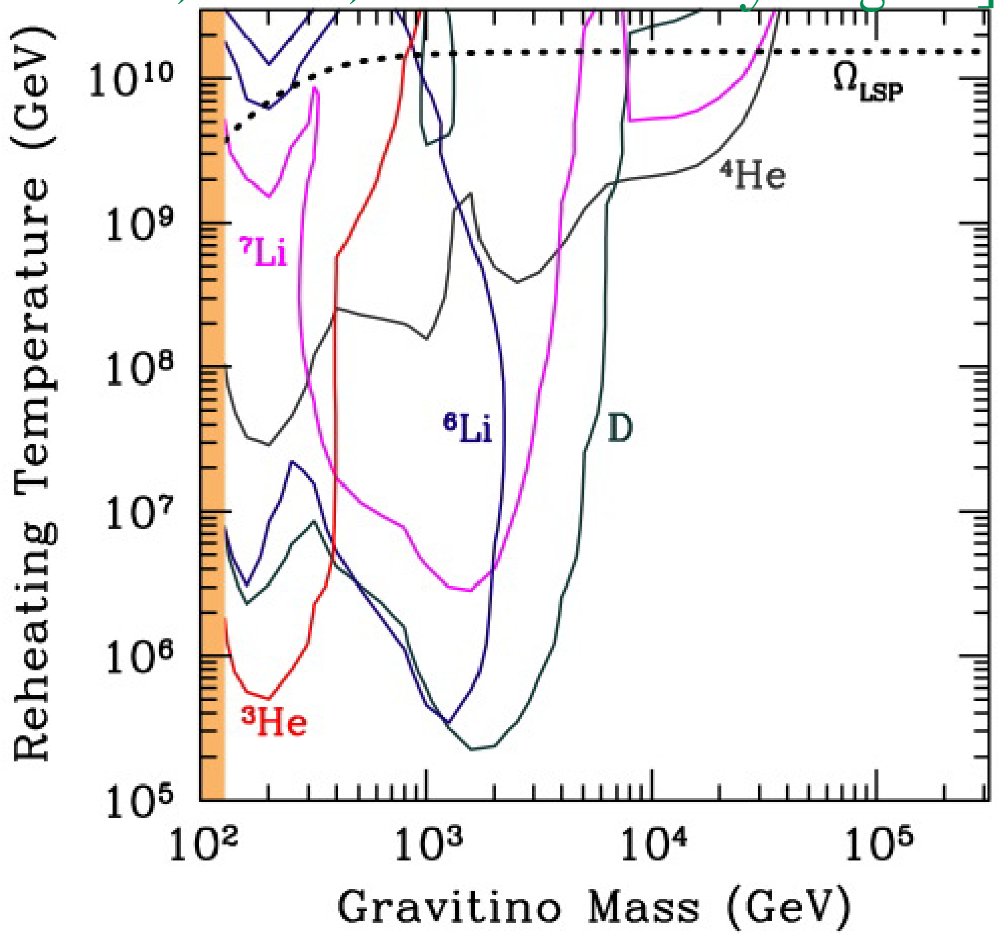
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1 \mathrm{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10}\ \mathrm{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}} \right)^2$$

[Bolz,Brandenburg & Buchmuller 01],
[Pradler & Steffen 06, Rychkov & Strumia 07]

THE GRAVITINO PROBLEM

The gravitino, the spin 3/2 superpartner of the graviton, interacts only "gravitationally" and therefore decays or "is decayed into" very late on cosmological scales.

[Kawasaki, Kohri, Moroi & Yotsuyanagi 08]

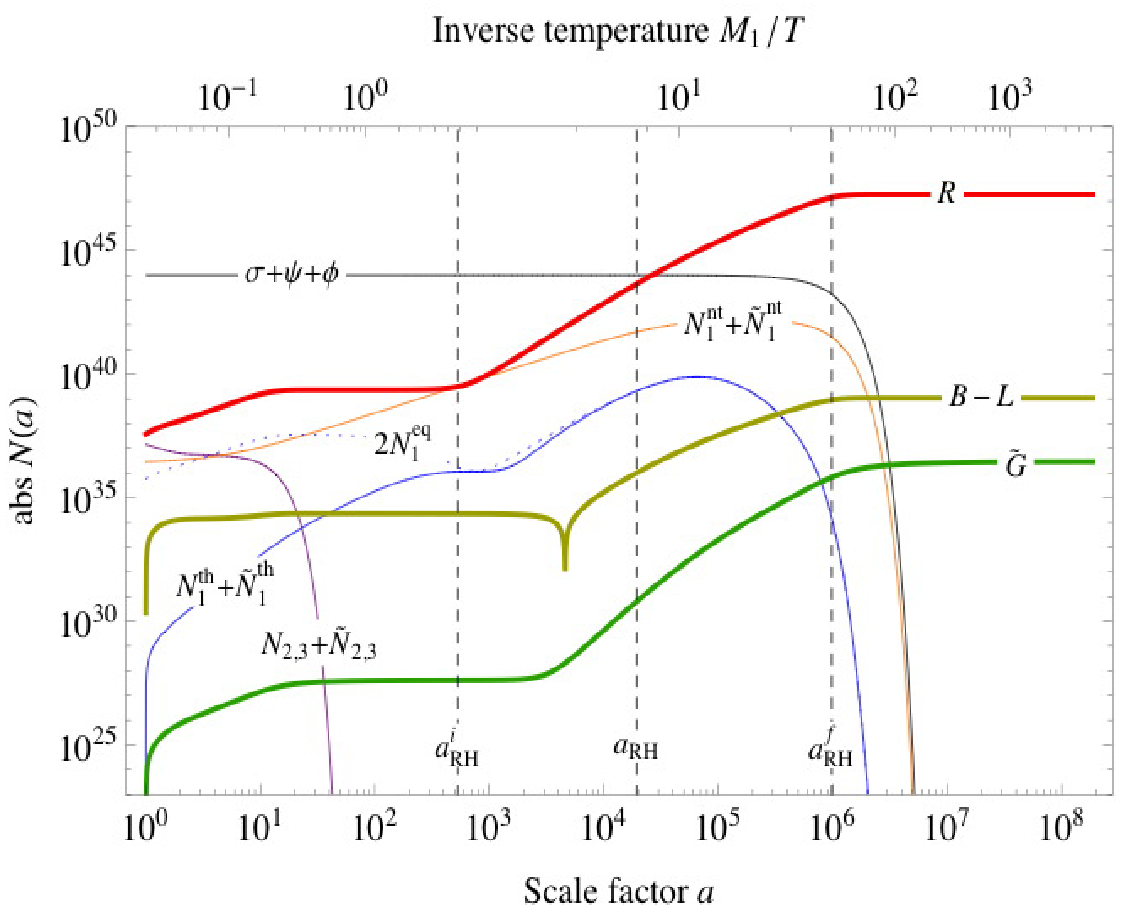


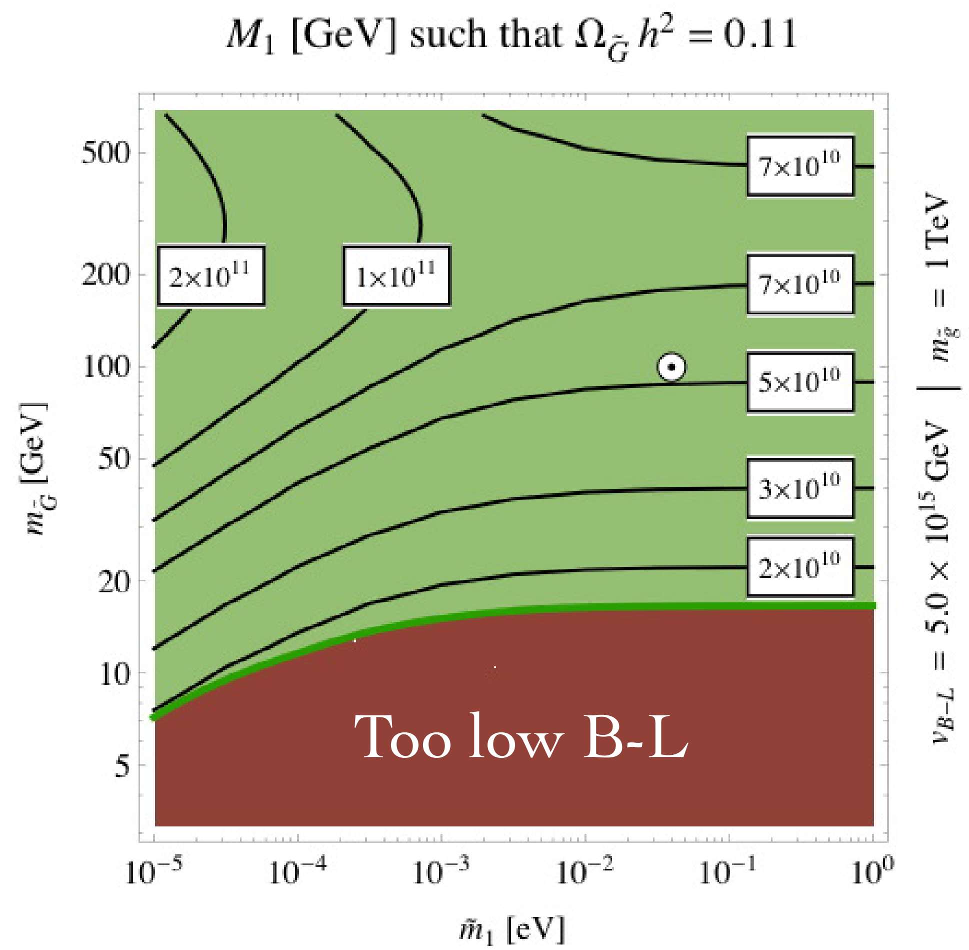
$$\tau_{3/2} = 6 \times 10^7 \mathrm{s} \left(\frac{m_{3/2}}{100 \mathrm{GeV}} \right)^{-3}$$

BBN is safe only if the gravitino mass is larger than 40 TeV, i.e. the lifetime is shorter than ~ 1 s, or if the reheating temperature is much smaller than that required for leptogenesis !

Gravitinos from reheating

[W. Buchmuller, V. Domcke, K. Schmitz 12]





Gravitino DM and B-L may be produced both from heavy RH neutrino decay during reheating: then there is a relation with the neutrino sector parameters and a lower bound on $m_{\tilde{G}}$

Neutralino DM & the Higgs

Neutralino as a WIMP

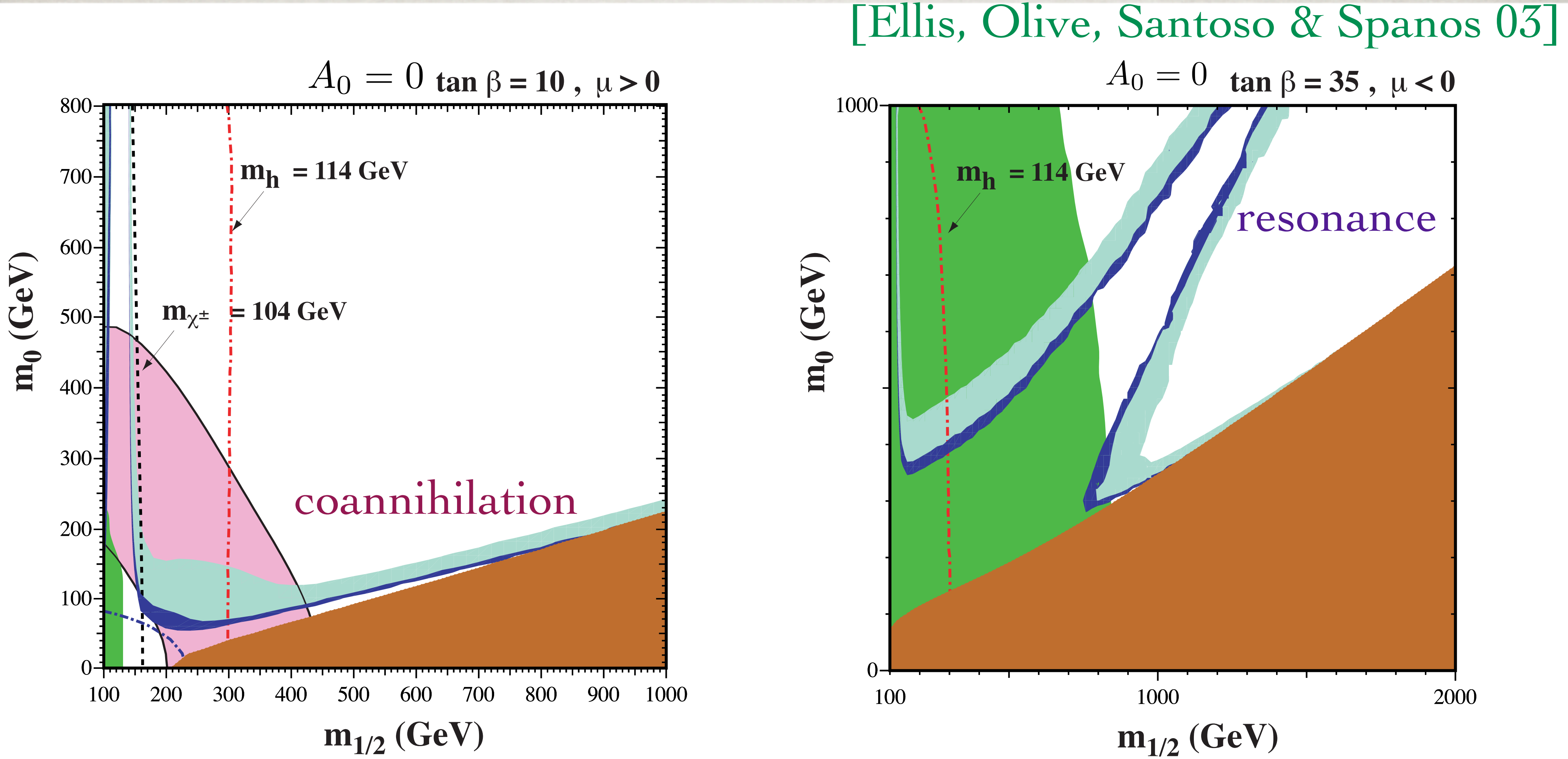
The neutralino is a natural WIMP, but its mass and couplings change strongly depending on the SUSY breaking parameters: its density can span 5-6 orders of magnitude.

In general the Bino neutralino has a too large density for 100 GeV mass, while the Higgsino and the Wino too low... Due to the limits obtained at LEP on the sparticles masses, the natural "bulk" region of parameters (CMSSM) is excluded. An enhancement is needed for the annihilation cross-section:

- Coannihilation with another SUSY particle;
- Resonance in the annihilation;
- Large coupling with W (large higgsino component).

Perhaps not so natural, but how does it fare with recent data ?

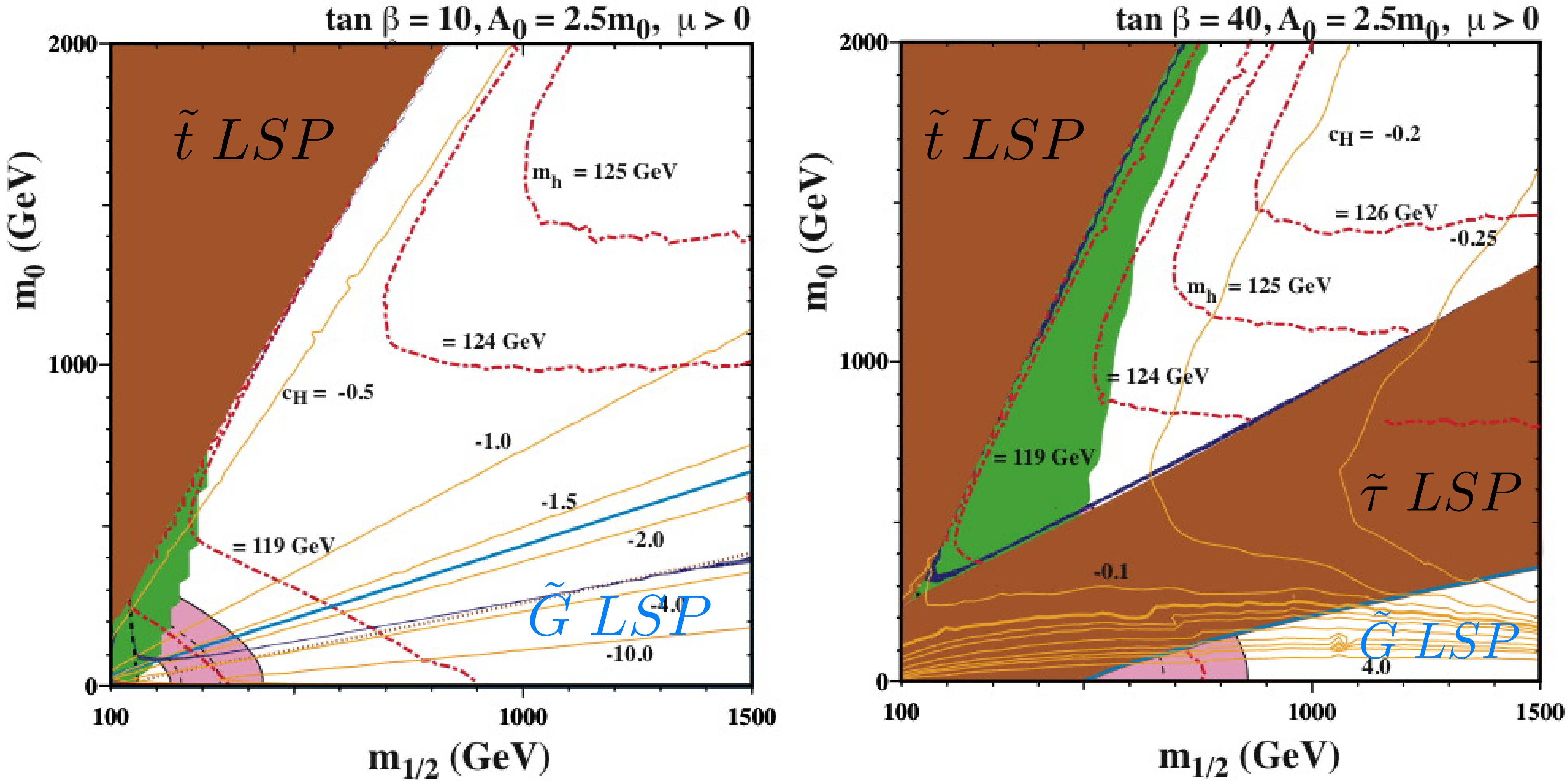
Neutralino DM in the Constrained MSSM



Tiny strips in the parameter space are allowed...,
but the Higgs mass is small.
Switch on a large A_0 to increase the Higgs mass !

Neutralino DM in the Constrained MSSM

[Dudas, Mambrini, Mustafayev, Olive 2012]



Even in the large A-term regions, no coannihilation region for large Higgs mass at small $\tan\beta$ ...

At large $\tan\beta$ the funnel/focus point plane appears

Unstable gravitino Dark Matter

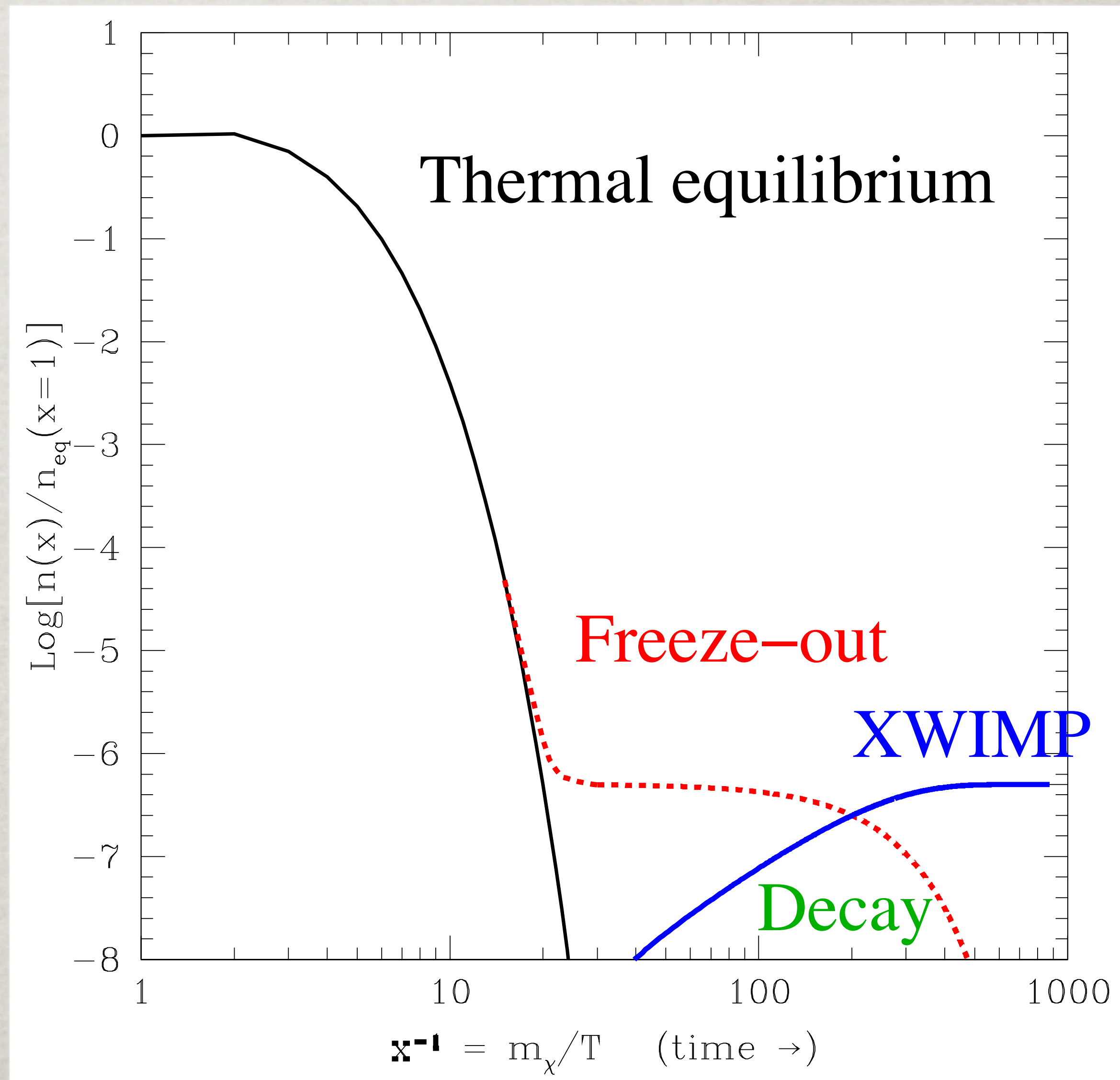
NLSP DECAY

[JE Kim, Masiero, Nanopoulos ‘84]
[LC, JE Kim, Roszkowski ‘99], [Feng et al ‘04]

- If R-parity is conserved and for GeV gravitino masses, the NLSP decays after freeze-out

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

- The LSP is not thermal
- Other energetic particles are produced in the decay: beware of BBN...



R-parity or not R-parity

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

Actually there is a simple way to avoid BBN constraints: break R-parity a little... ! Then the NLSP decays quickly to SM particles before BBN and the cosmology returns standard.

$$W_{R\!\!\!/p} = \mu_i L_i H_u + \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c$$

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Open window:

$$10^{-12-14} < |\frac{\mu_i}{\mu}|, |\lambda|, |\lambda'| < 10^{-6-7}$$

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For the NLSP to decay before BBN

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For the NLSP to decay before BBN

To avoid wash-out of lepton number

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To avoid wash-out of lepton number

Explicit bilinear R-parity breaking model which ties R-parity breaking to B-L breaking and explains the small coupling.

A SIMPLE MODEL with (suppressed) BROKEN R-PARITY

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

R-parity is usually not a fundamental symmetry of the MSSM completion. Our idea is to 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 $\mu_i L_i H_u$:

$$W_{B-L} = X(NN^c - \Phi^2) + \frac{NNN_i^c N_j^c}{M_P} \quad \Rightarrow \quad \langle N \rangle = \langle N^c \rangle = \langle \Phi \rangle = v_{B-L}$$

$$\delta K_1 = \left[\frac{(a_i Z + a_i' Z^\dagger)\Phi^\dagger N^c}{M_P^3} + \frac{(c_i Z + c_i' Z^\dagger)\Phi N^\dagger}{M_P^3} \right] H_u L_i \quad \Rightarrow \quad \delta W_1 = \mu_i H_u L_i$$

Then we have

$$M_3 = \frac{v_{B-L}^2}{M_P} \qquad\qquad \mu_i \propto m_{3/2} \frac{v_{B-L}^2}{M_P^2} \sim \mu \, \frac{M_3}{M_P}$$

The charge of Φ is such that 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.

	$\mathbf{16}_i$	H_u	H_d	N	N^c	Φ	X	Z
R	1	0	0	0	-2	-1	4	0

Effectively a model with bilinear R-parity violation, but with a coupling smaller than those usually discussed in the literature...

$$\epsilon_i = \frac{\mu_i}{\mu} \leq 10^{-7}$$

Gravitino LSP decay

[Takayama & Yamaguchi 00, Buchmuller et al 07]

If R-parity is broken, the gravitino can decay into photon and neutrino via neutralino-neutrino mixing or via a one-loop diagram or into 3 SM fermions via the trilinear couplings.

$$\tilde{G} \to \gamma\nu, Z\nu, W^{\pm}\ell^{\mp} \qquad \tilde{G} \to \ell_L \bar{\ell}_L e_R \quad \tilde{G} \to \ell_L \bar{q}_L d_R$$

For bilinear R-parity breaking the 2-body channel dominates:

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

[Lola, Osland & Raklev 07] computed also the 2-body one-loop decay and found it also important for most parameter space. For heavy gravitino the decays prefers to go into EW gauge boson final states. [Ibarra & Tran 07]

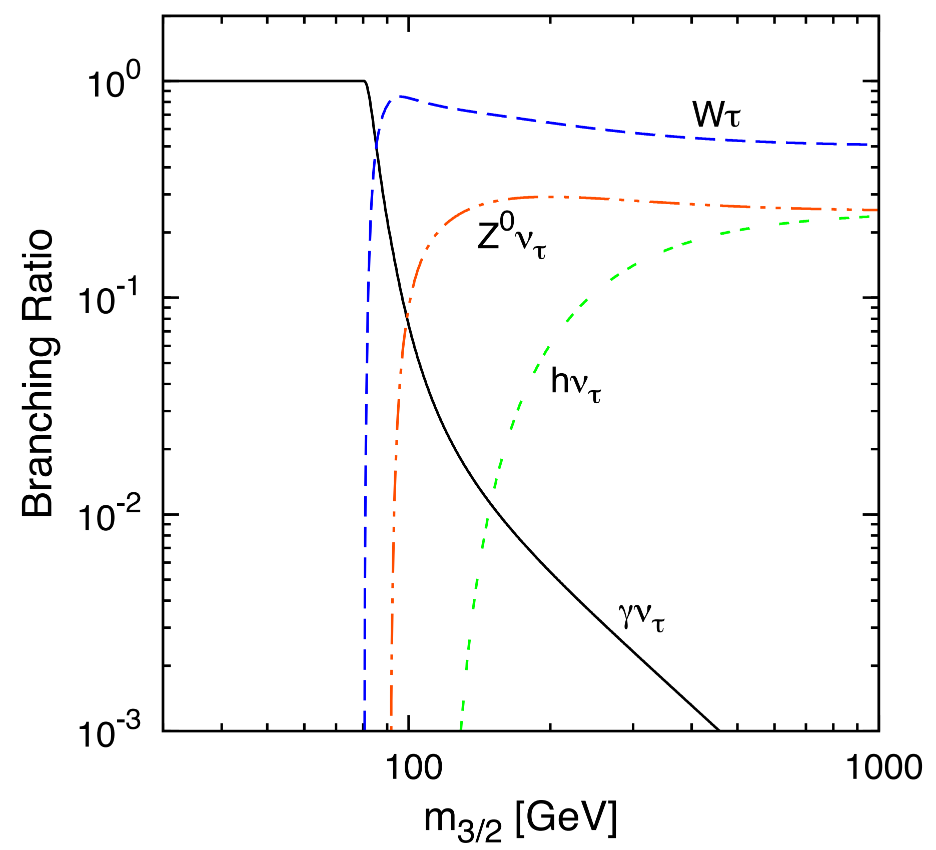
Gravitino decay modes

For bilinear R-parity violation, the gravitino decays into neutrino and (gauge) boson: photon, W, Z or Higgs
or via trilinear couplings into neutrino and 2 leptons

The lifetime is very long, suppressed by M_P and the small mixing between neutrinos and gauginos:

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

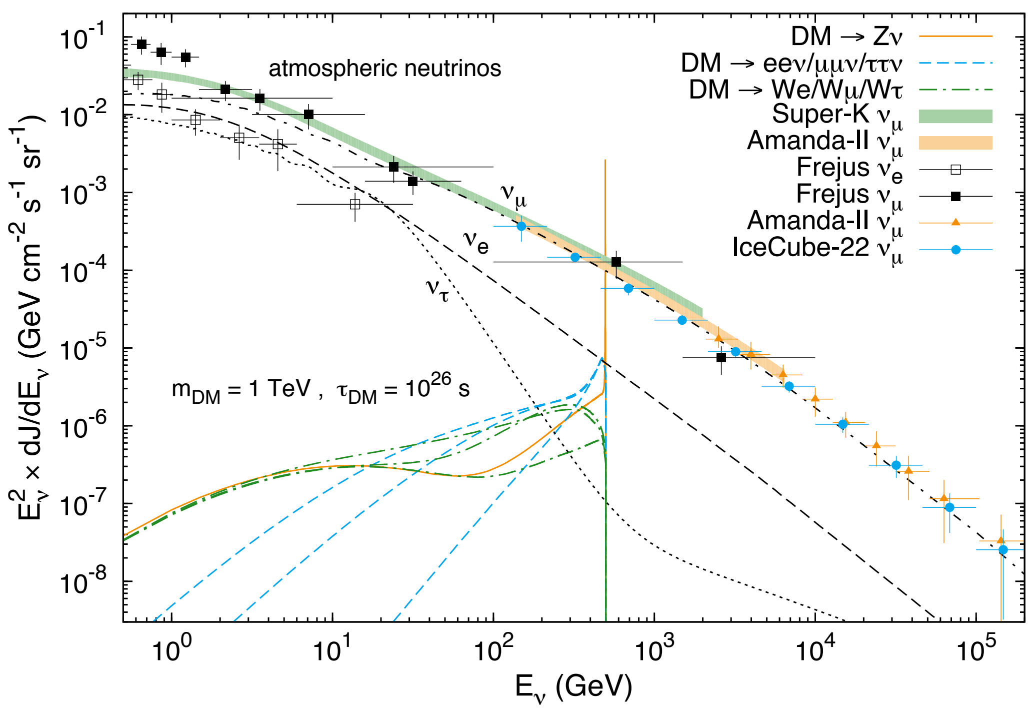
[LC, Grefe, Ibarra & Tran 08]

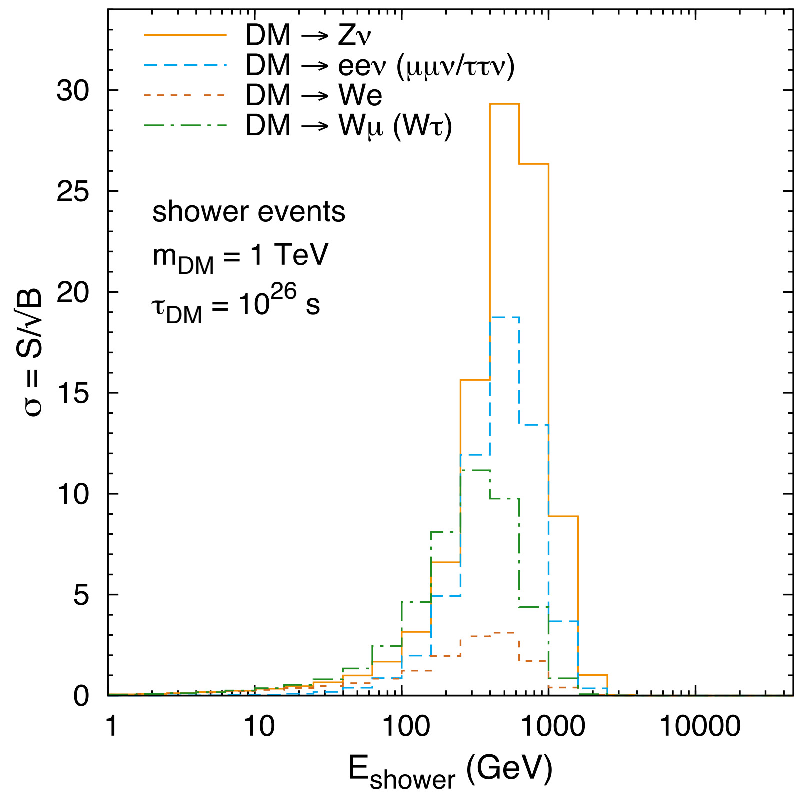


Heavy decaying DM

For heavy decaying DM, the atmospheric neutrino background is large, but still the signal is detectable at km3 detectors like IceCube, esp. if showers may be measured:

[LC, Grefe, Ibarra & Tran 09]

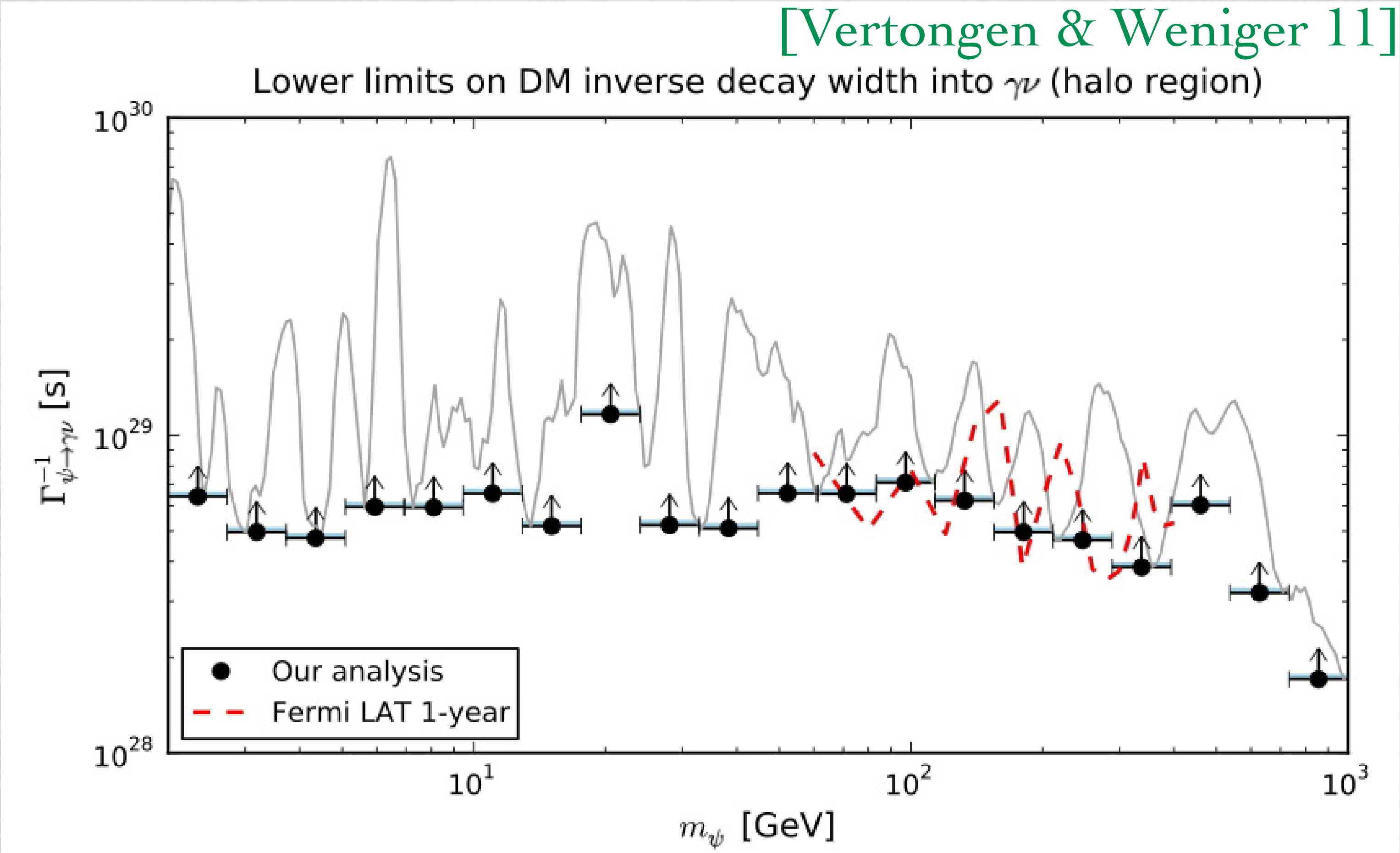




Best significance for cascade/shower events

Possible to detect in IceCube ?

FERMI LINE CONSTRAINTS

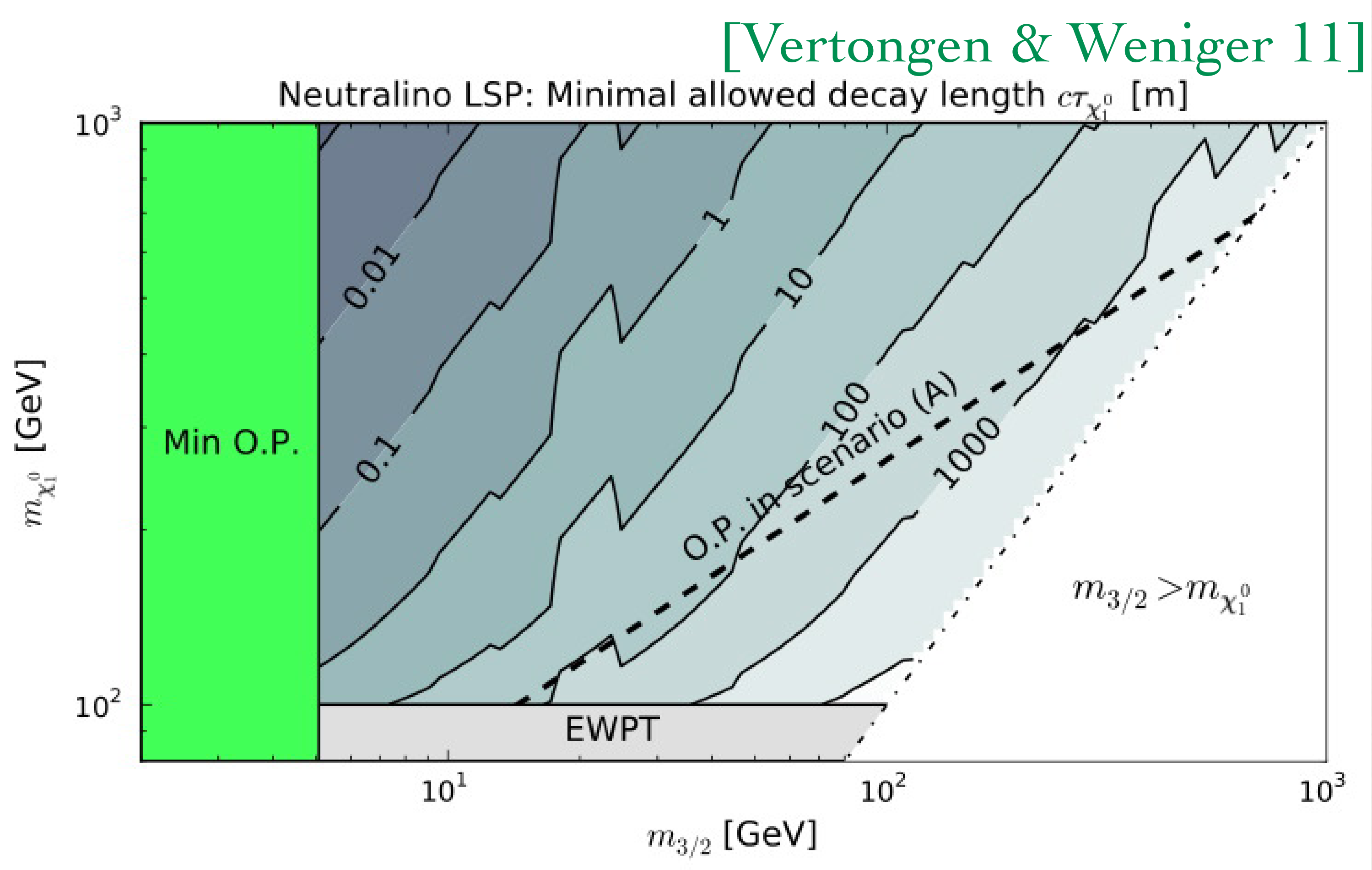


A recent analysis extends the FERMI line search in a wider mass region, for energies to 500 GeV, i.e. masses between 1-1000 GeV

From the FERMI gamma-line search: $\tau \geq 6\ 10^{28}$ s @ 95% CL

LHC:NLSP DECAY LENGTH

Broken Rp: The limits from the search for gamma-lines require a relatively large decay length for the neutralino NLSP:

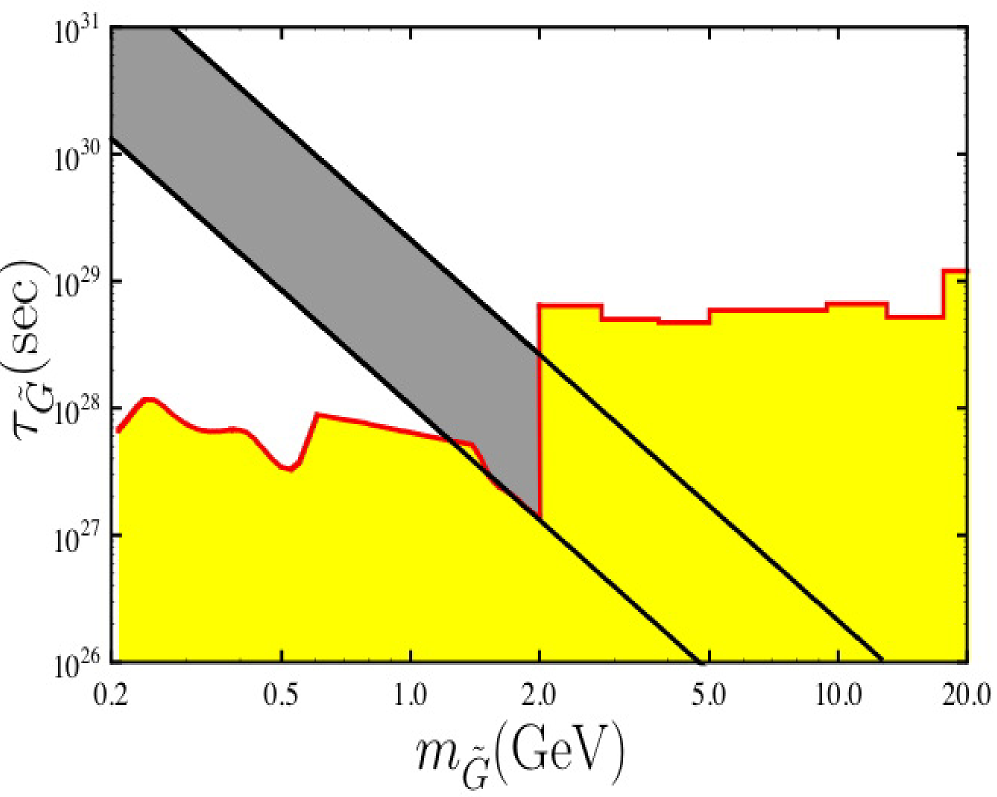


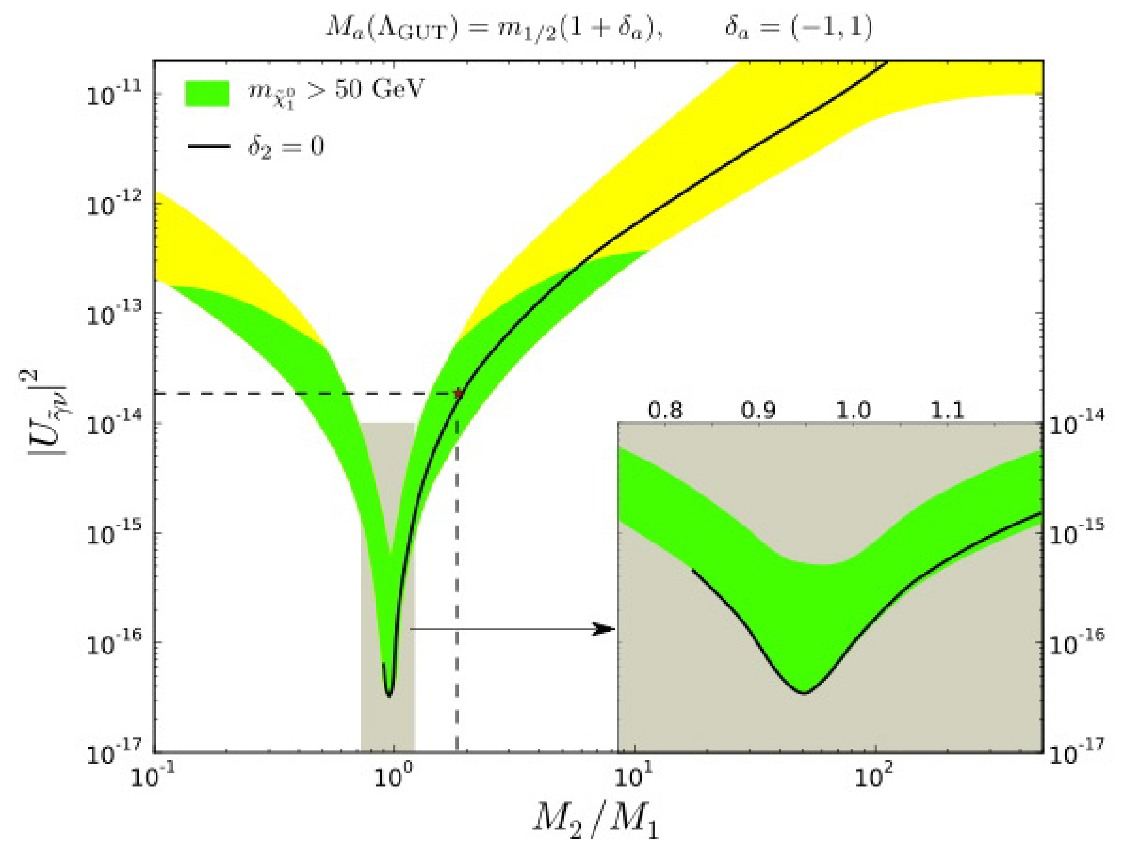
But no definite prediction on decay length for stau NLSP...

[Bobrovskyi, Buchmuller, Hajer & Schmidt 10]

R_p and neutrino masses

For smaller gravitino masses the gamma constraints become weaker and allows for R_p breaking in the range explaining the observed neutrino masses [Restrepo, Taoso, Valle & Zapata.12]



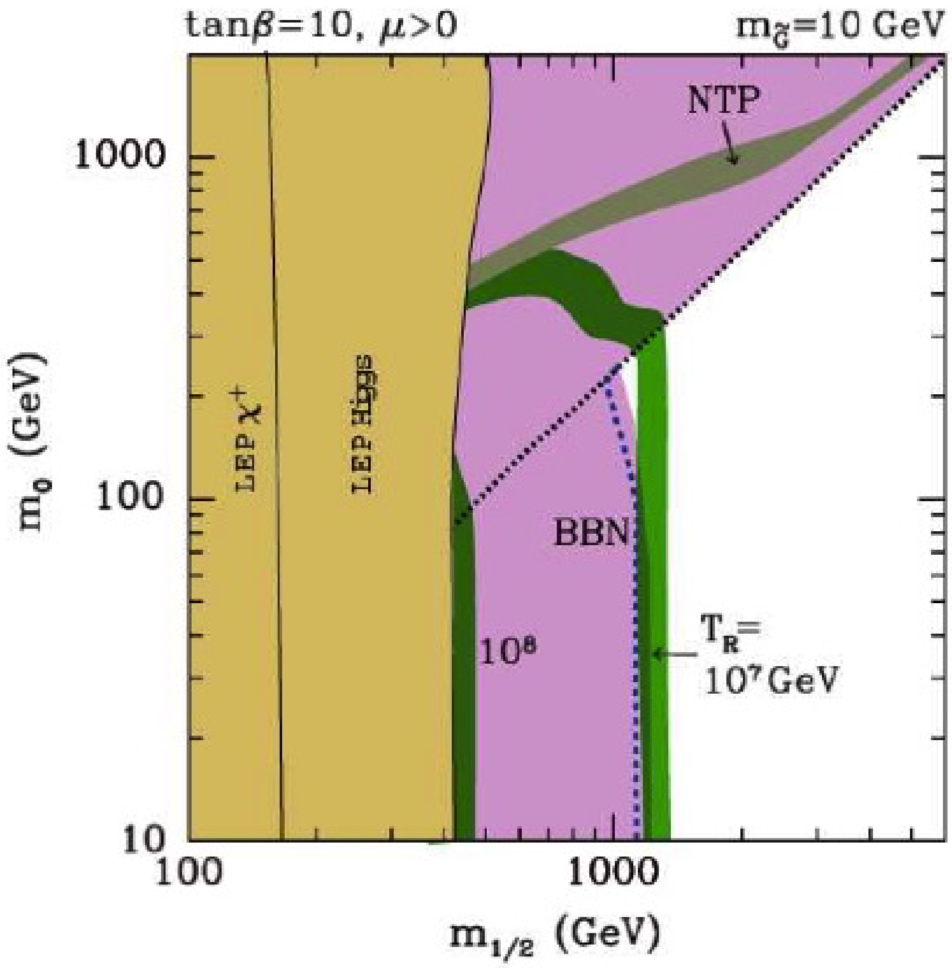


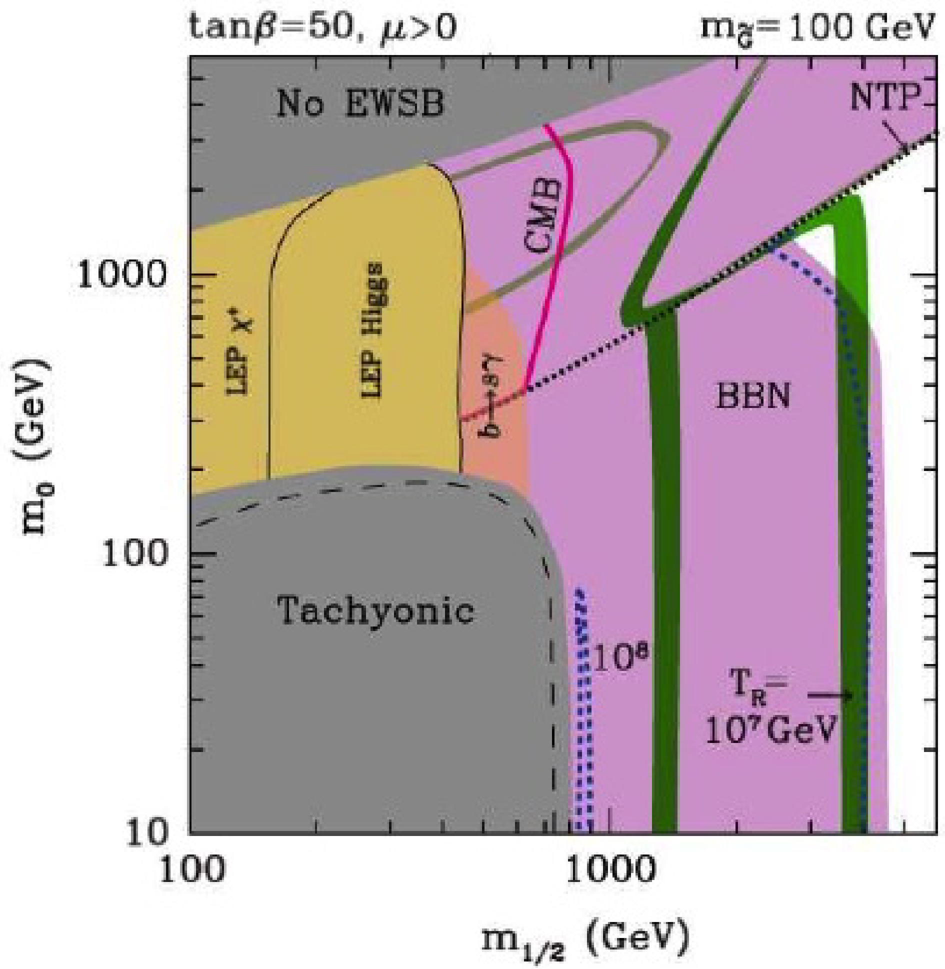
Moreover, for non-universal gaugino also a mass suppression for the gamma decay channel is possible

stable
Gravitino CDM

BBN bounds on CMSSM

[Bally, Choi, Jedamzik, Roszkowski 09]



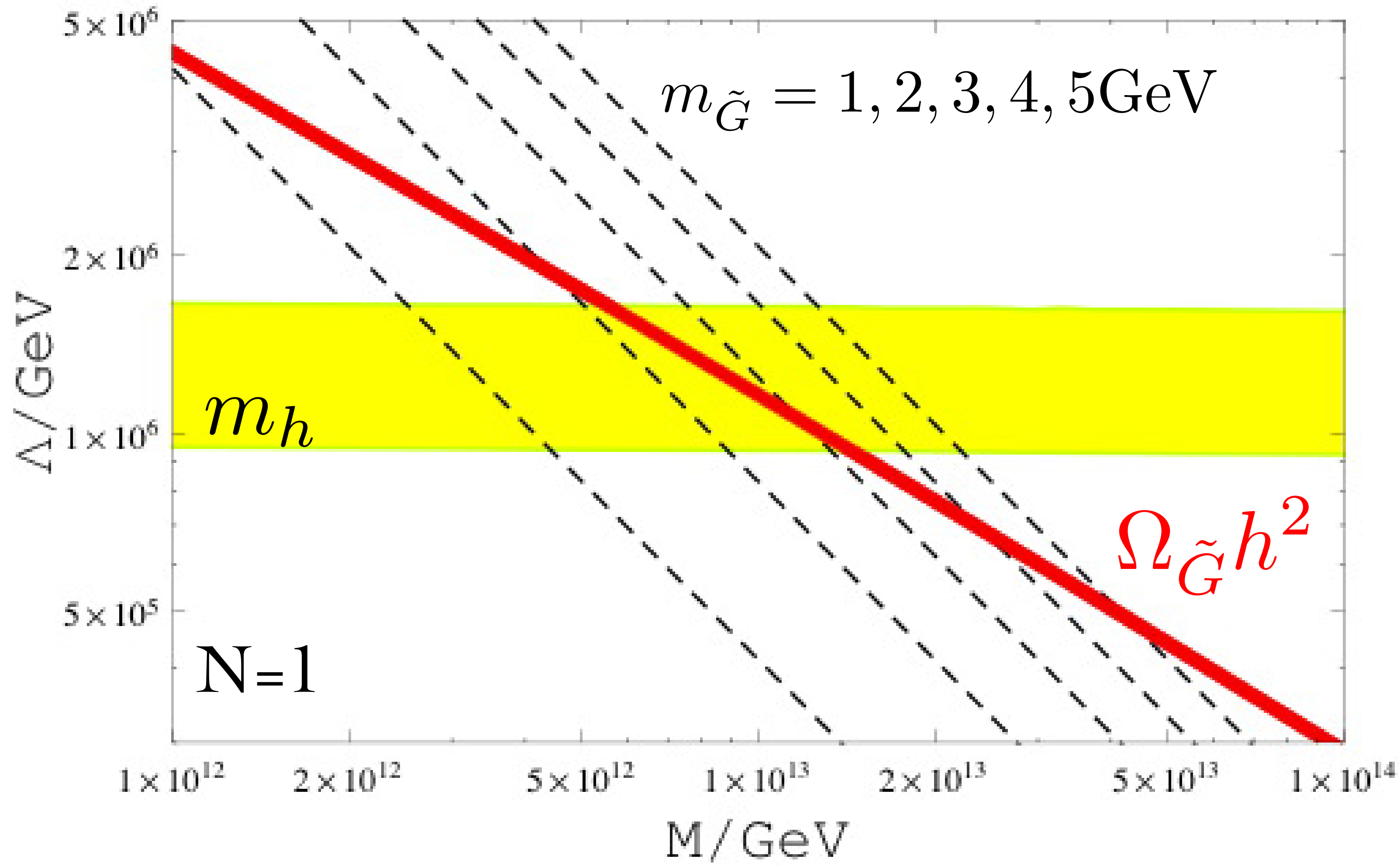


The magenta region is excluded by BBN: only heavy stau region and low T_R below 10^7 remaining

Big problem for gravitino LSP with 10-100 GeV mass...

SuperWIMPs in GMSB

[Okada 12]



Possible to satisfy both Higgs mass and gravitino DM via neutralino decay constraints, but the remaining spectrum is very heavy: $m_{\tilde{G}} \sim 2 - 7$ GeV $\quad m_{\tilde{\chi}} \geq 1, 4$ TeV .

MAXIMAL T_R

Look again at the thermal production yield:

$$\Omega_{3/2}h^2 \simeq 0.3 \left(\frac{1\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{T_R}{10^{10}\ \mathrm{GeV}}\right)\sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}}\right)^2$$

Best case scenario, all gaugino masses M_i equal and as light as possible..., while $m_{3/2}$ as large as possible.

→ light degenerate gaugino spectrum
as it is possible in general gauge mediation

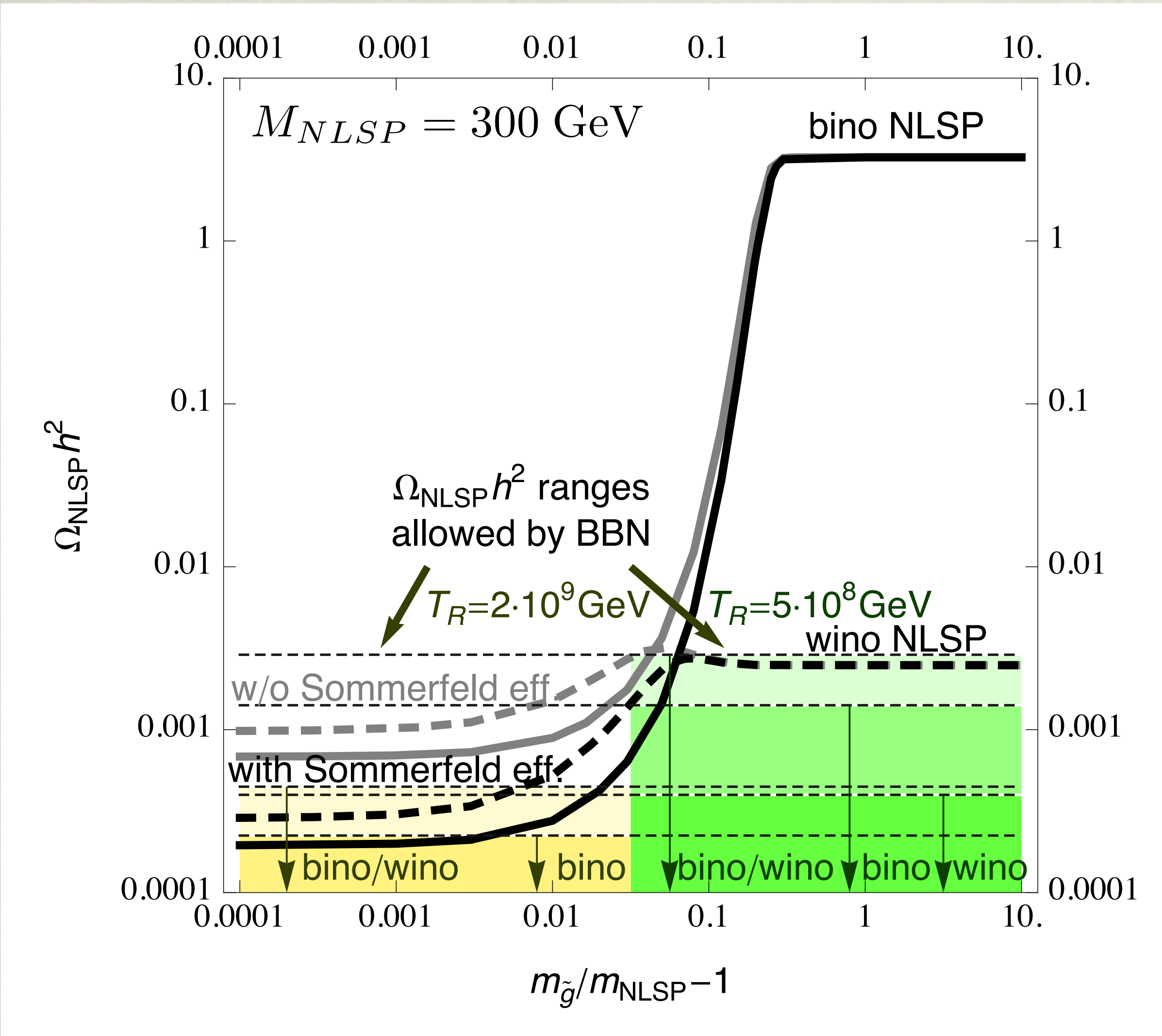
[Olechowski, Pokorski, Turzynski,Wells 09]

Light and degenerate gaugino or "compressed susy" also ameliorates the fine-tuning problem, while heavy scalar superpartners help with the flavour problem...

Other advantage of degenerate masses at the low scale: coannihilation helps reducing the NLSP density !

Degenerate gauginos NLSP

[LC, Olechowski, Pokorski, Turzynski,Wells 10]



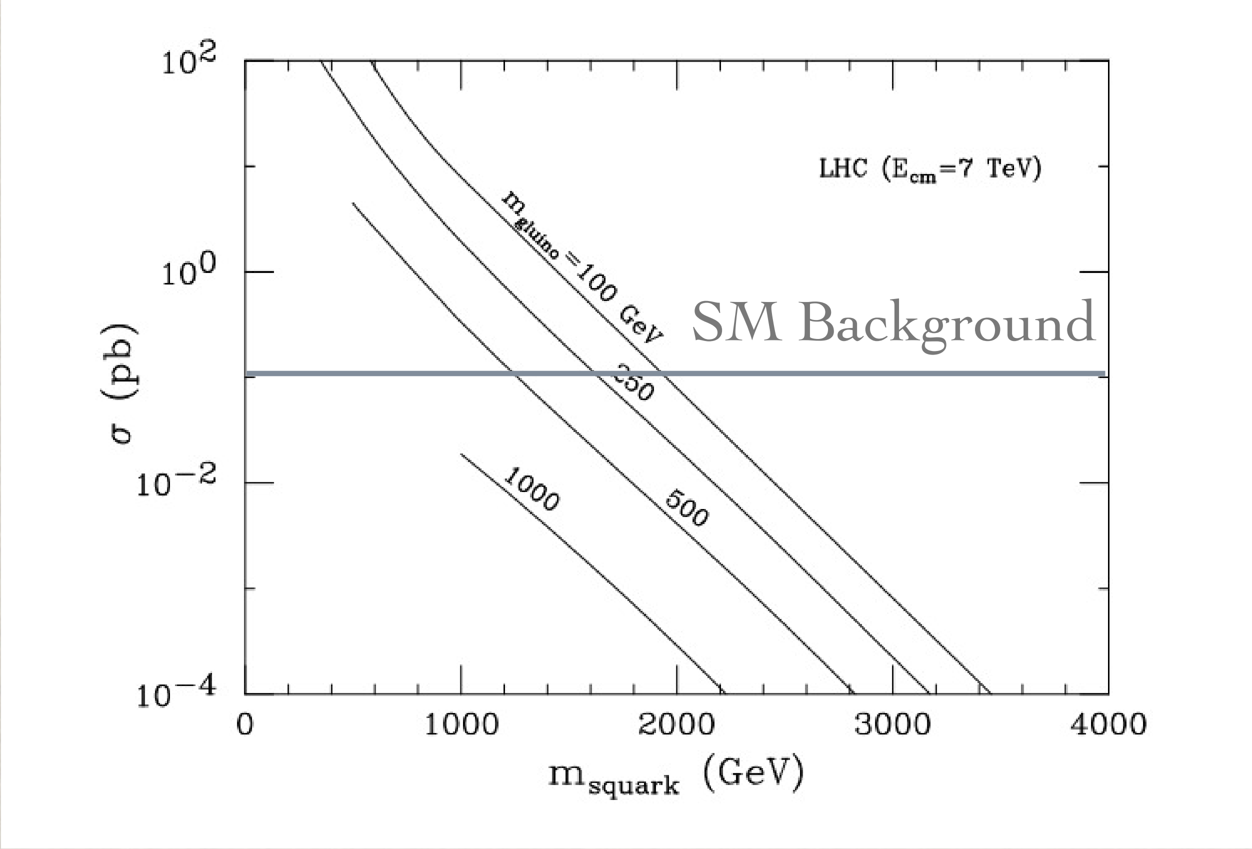
Gluinos annihilate most efficiently, but are a bad NLSP due to BBN bound state effects...

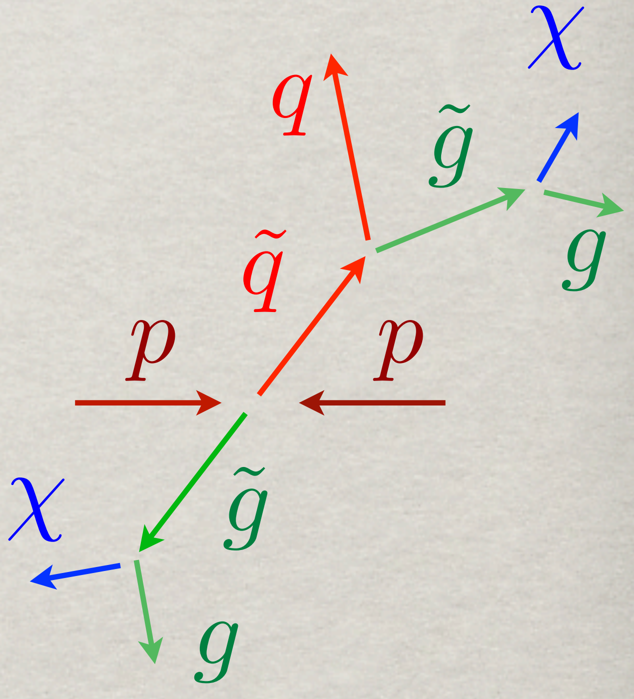
On the other hand they can help the other neutralinos NLSP.

The coannihilation with gluinos has a very strong effect on the Bino, even for just 10% degeneracy. Weaker effect for the Wino.

LHC: Mono-jet signature

More promising perhaps the squark-gluino channel, where the squark decays into quark and gluino (= missing Energy !). Since the other gluino also decays invisibly, the signal is a mono-jet and large missing transverse momentum.





Detectable at LHC probably up to 1.8 TeV squark mass !

Gravitino DM @ the LHC

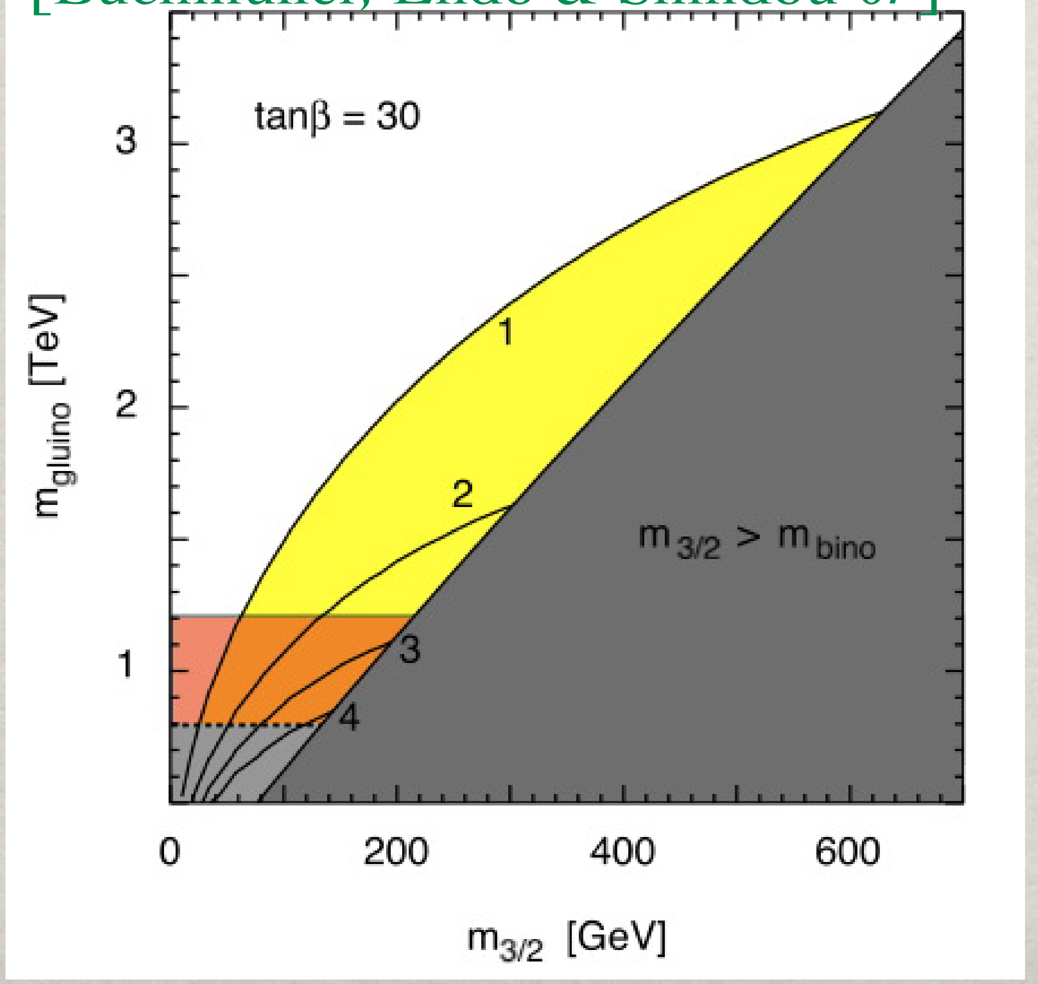
LHC: MASS SPECTRUM?

Requiring large T_R still points to relatively light gluinos

[Fujii, Ibe & Yanagida 04, Buchmuller, Endo & Shindou 07]

They should be produced at LHC, whatever the NLSP

[Buchmuller, Endo & Shindou 07]



Yellow:
Allowed region for neutralino NLSP, with gaugino mass unification and

$$T_R \geq 10^9 \mathrm{GeV}$$

(N)LSP decay at colliders

Same signals as in classical gauge mediation/R-parity breaking scenarios, the main decay channels for neutralino or stau are

R-parity conserved

$$\chi^0 \to \psi_{3/2}\,\gamma$$
$$\tilde{\tau} \to \psi_{3/2}\,\tau$$

R-parity violated

$$\chi^0 \to \tau W, \nu Z, b\bar{b}\nu$$
$$\tilde{\tau} \to \tau\nu_\mu, \mu\nu_\tau, \bar{b}bW$$

but with longer lifetimes than expected if gravitino is DM...

$$m_{3/2} > 4\ \mathrm{keV}$$

$$\tau_{3/2} > 6 \times 10^{28}\ \mathrm{s}$$

$$\tau_{NLSP} > 10^{-13}\ \mathrm{s}\left(\frac{m_{NLSP}}{2\mathrm{TeV}}\right)^{-5}$$

$$\tau_{NLSP} > 10^{-8}\ \mathrm{s}$$

DISPLACED VERTICES... perhaps even too much !

LHC: Displaced vertices or charged tracks ?

Conserved Rp Gravitino: The decays happen surely within the detector for gravitino masses of 10 keV. Nevertheless thank to the sizable fraction of boosted NLSP it may be possible to reach even 0.1-1 MeV. [Ishiwata, Ito & Moroi 08]

[Chang & Luty 09, Meade, Reed & Shih 10]

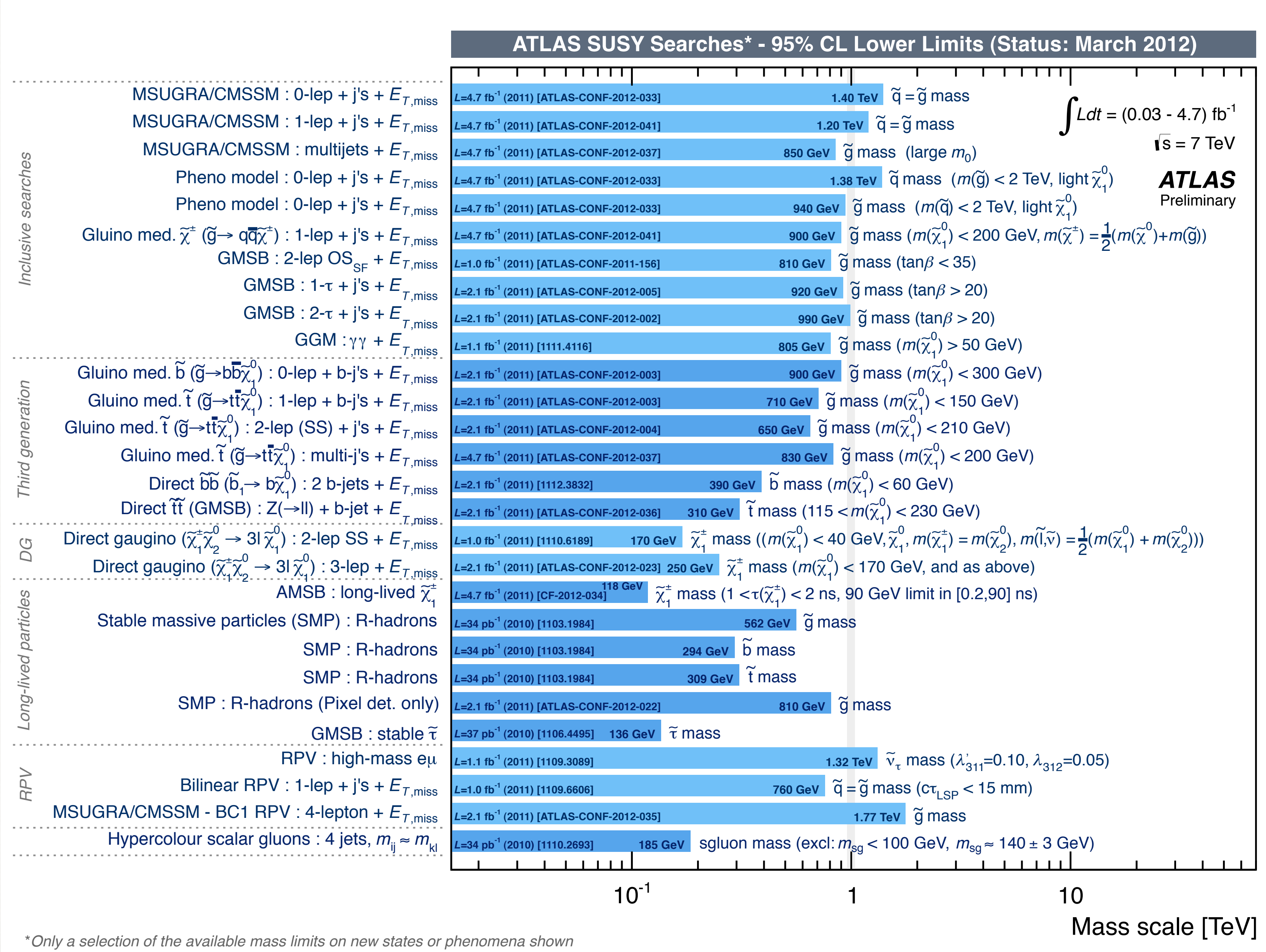
Broken Rp Gravitino: The decays may also happen within the detector with a sufficient number of events. Possible discovery or exclusion down to couplings $\epsilon \sim 10^{-9} - 10^{-10}$ if the colored states are accessible at LHC.

[Bobrovskyi, Buchmuller, Hajer & Schmidt 11]

Easier to see displaced vertices in case the R-parity is large enough to explain neutrino masses [Porod et al 2001]

LHC news: SUSY search

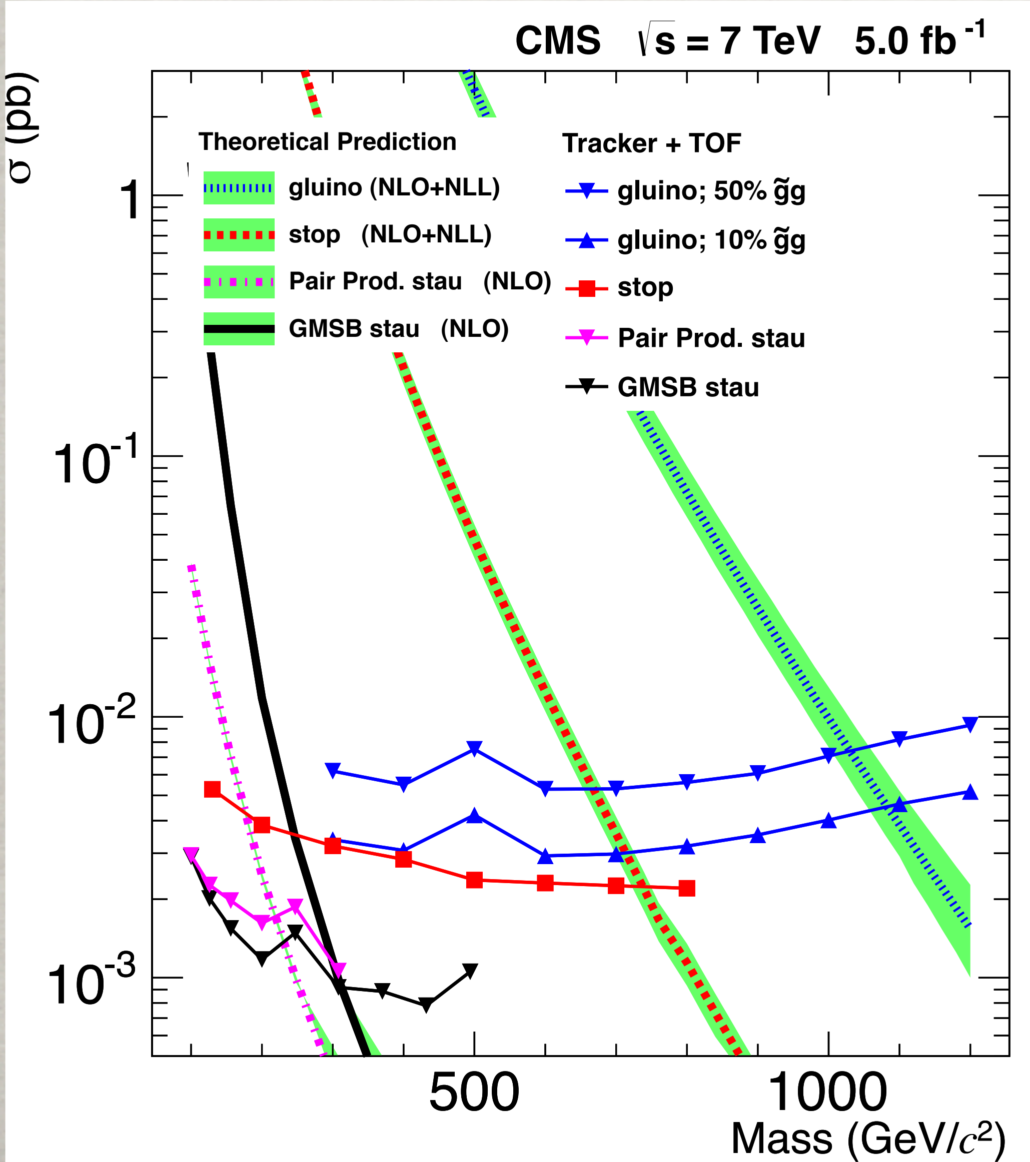
At the moment no significant excess found....



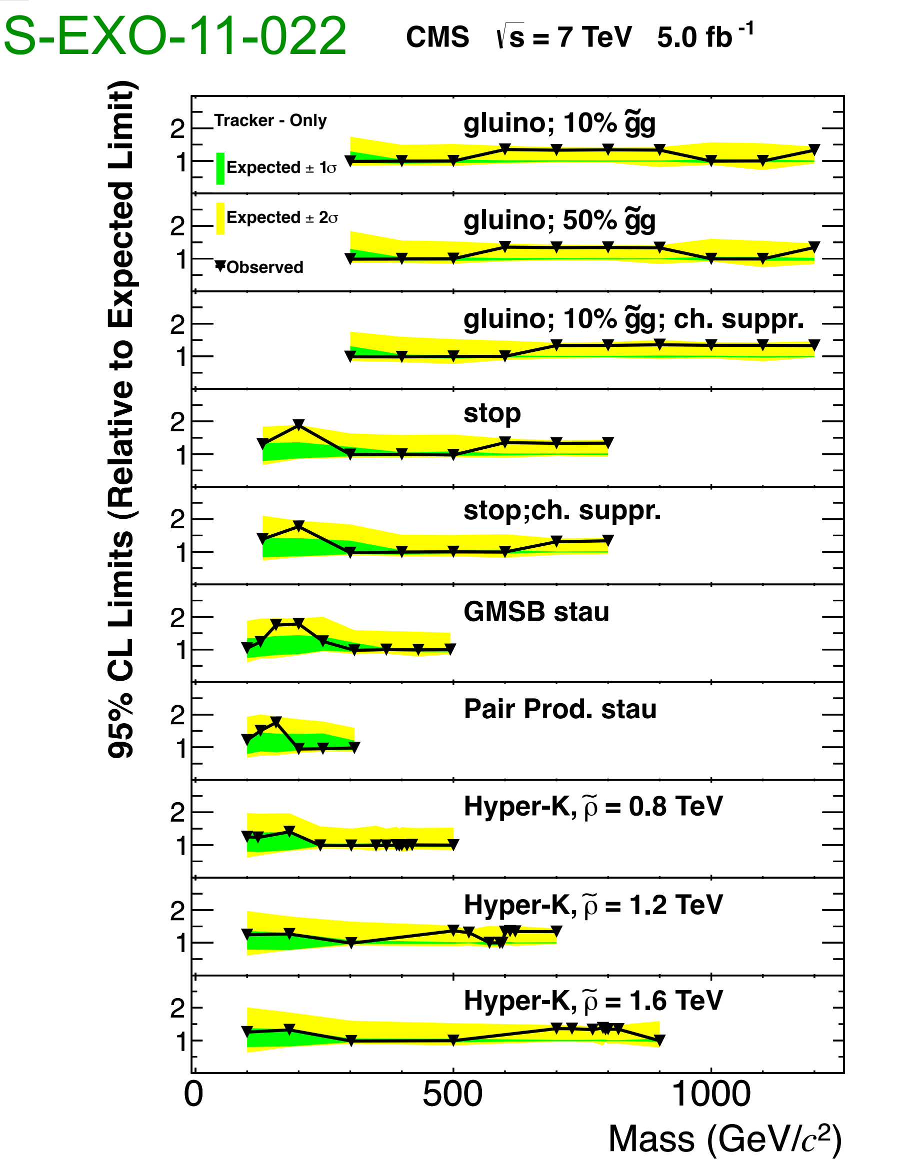
LHC: METASTABLE PARTICLES

Recent results from CMS for metastable SUSY particles:

at the moment no significant excess found....

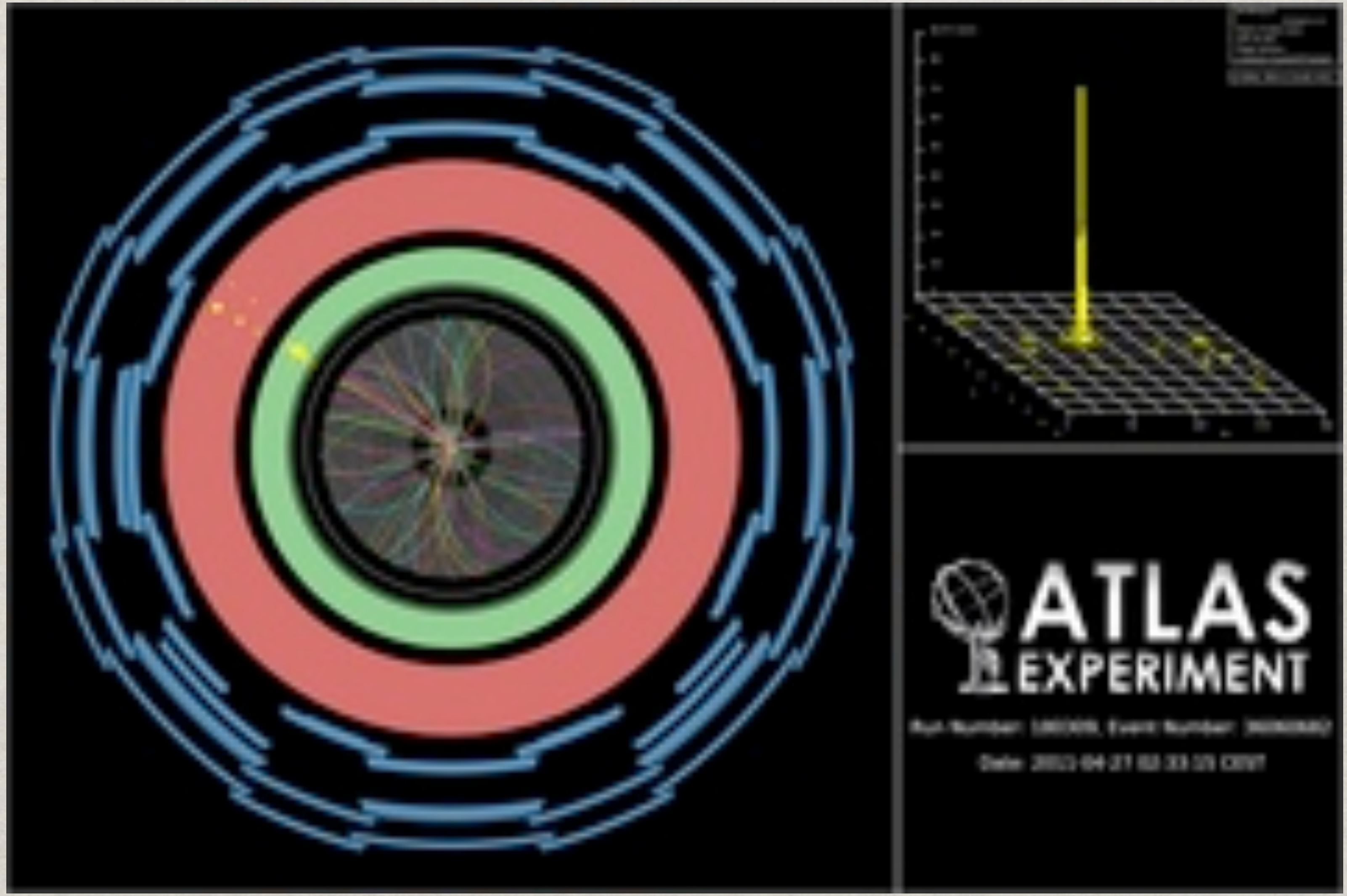


CMS-EXO-11-022



LHC: Monojets ?

For larger gravitino masses the compressed light neutralino spectrum is already being tested at LHC...

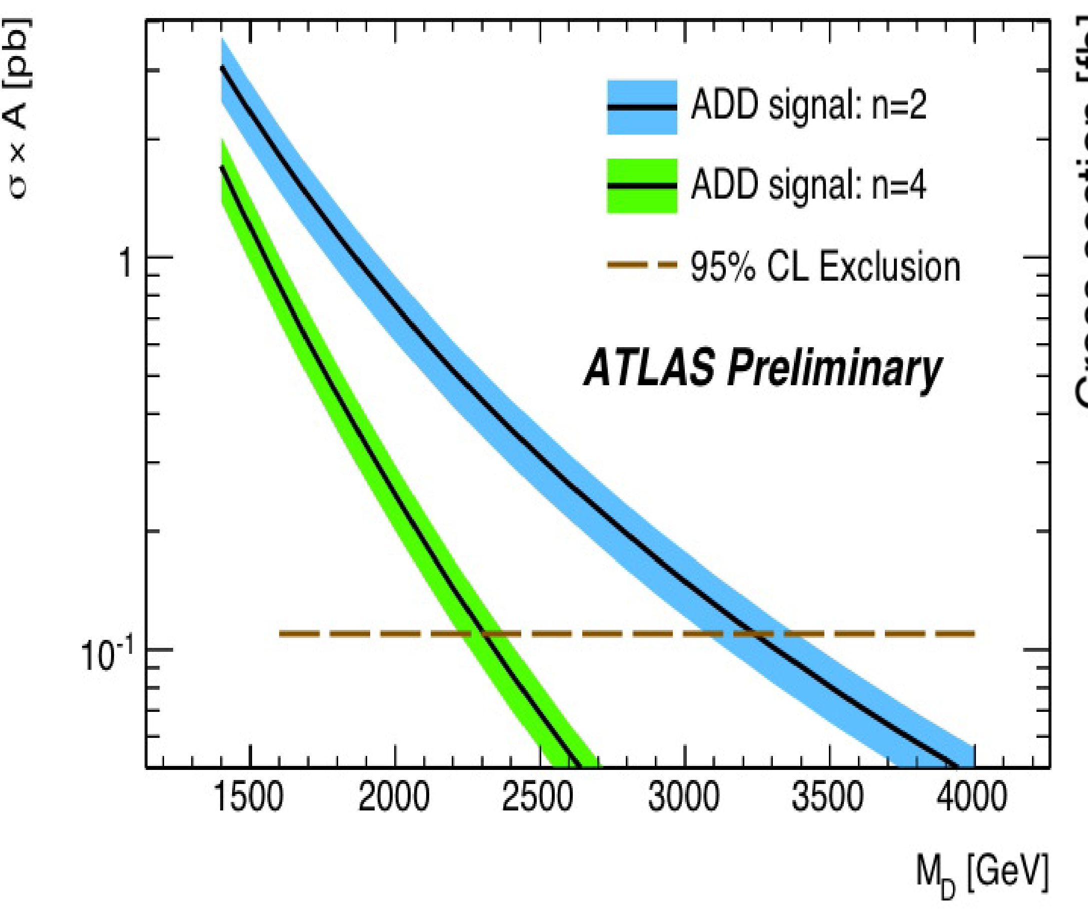


Monojet candidate event !

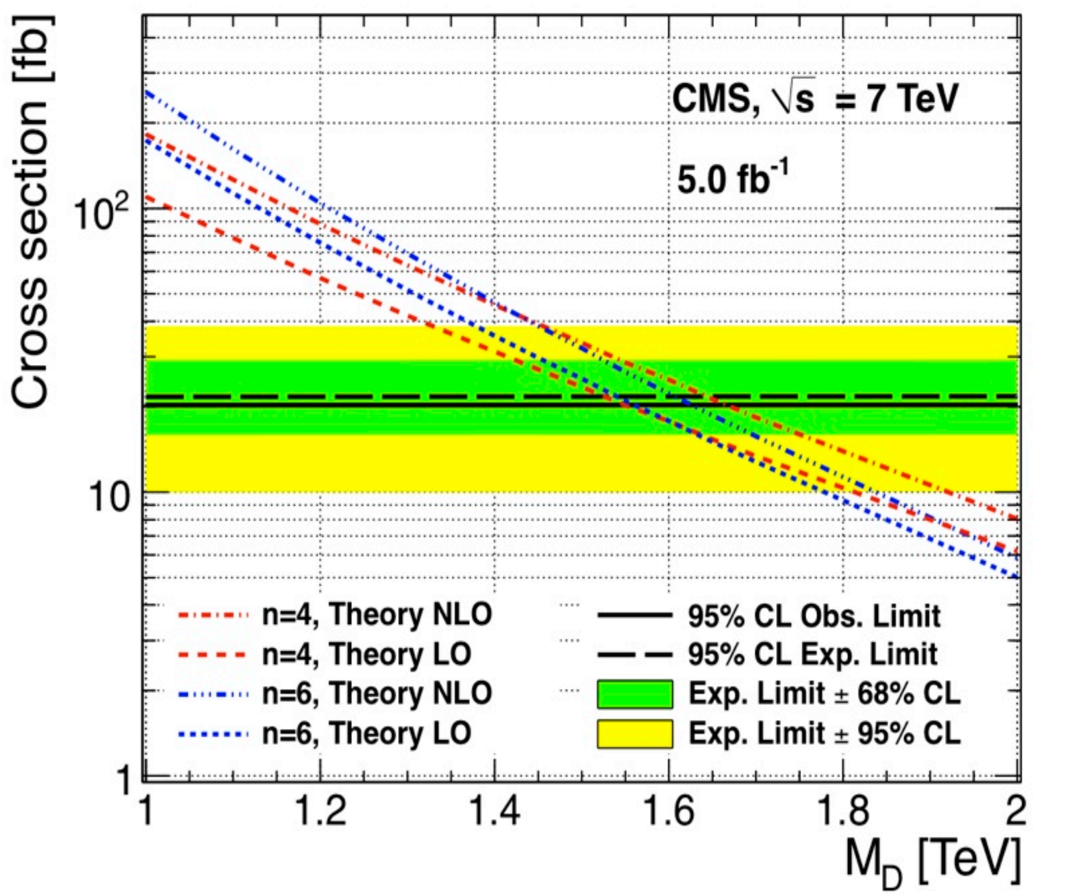
LHC: Monojets ?

For larger gravitino masses the compressed light neutralino spectrum is already being tested at LHC...

ATLAS-CONF-2011-096



CMS-EXO-11-096



Not clear if excluded yet...

Outlook

Outlook

- The supersymmetry offers good CDM candidates with different properties: in general there are bounds on the reheat temperature (somewhat relaxed for gravitino CDM)

- Gravitinos can survive as DM also for broken R-parity, but the breaking has to be suppressed (ν masses ?). Indirect DM searches set limits on these parameters. Otherwise BBN can constrain the lifetime and density of the NLSP or point to heavy SUSY !

- Different signals are possible at the LHC: displaced vertices, missing energy or metastable charged particles:

  Let us hope for a signal soon !