GRAVITINO DARK MATTER CONFRONTS LHC

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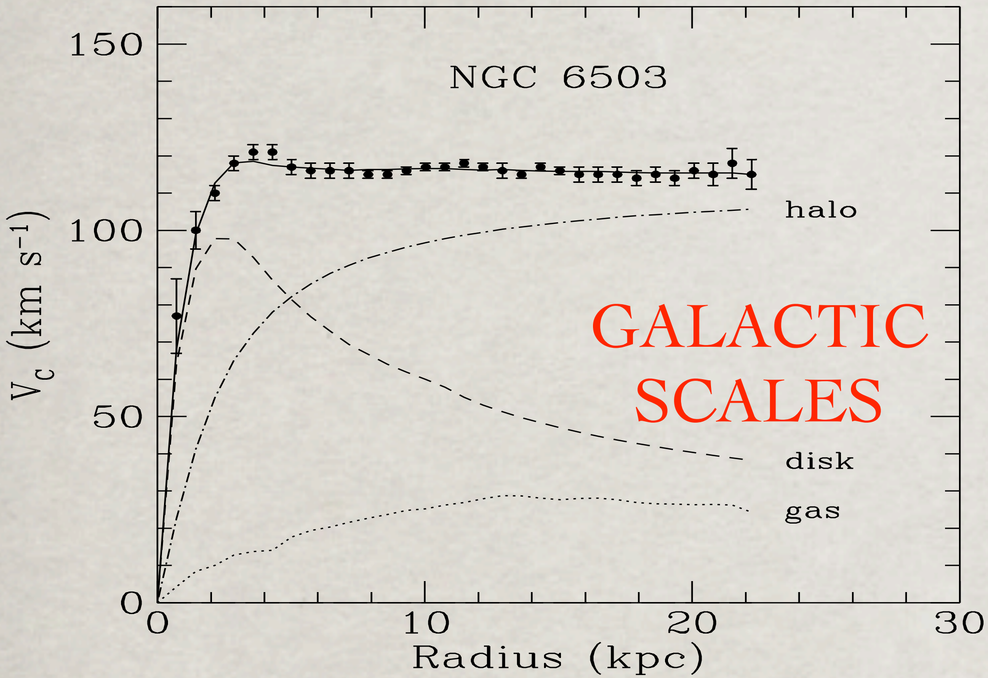
$[q,p]=i\hbar$

Outline

- Introduction:
  Gravitino cosmology
- Stable Gravitino Cold Dark Matter
- Unstable Gravitino CDM
- Supersymmetry @ LHC
- Outlook

Introduction

DARK MATTER EVIDENCE



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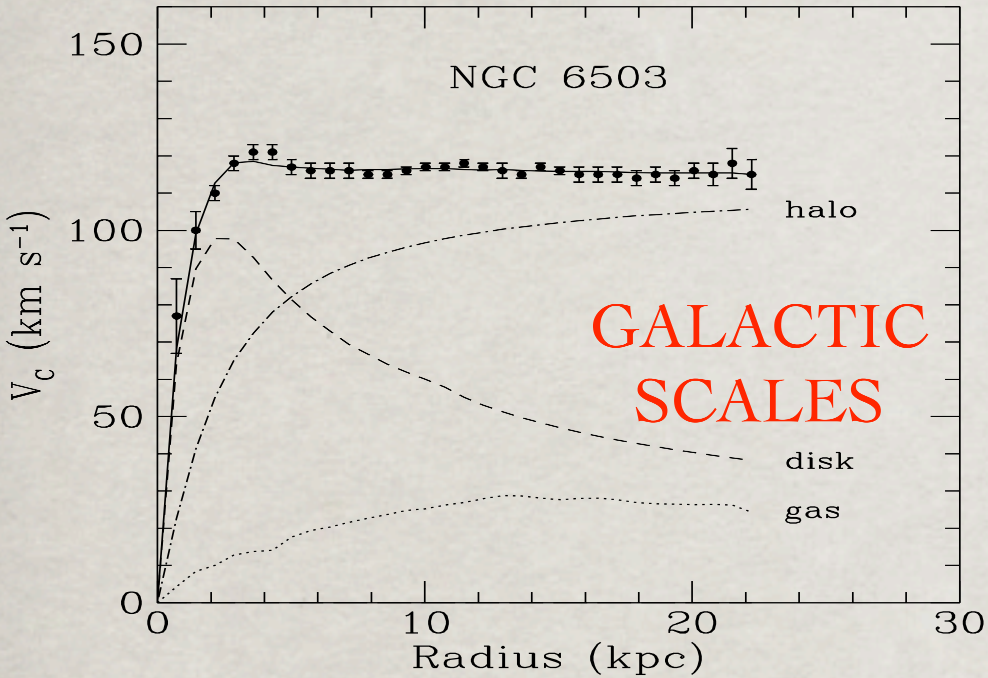

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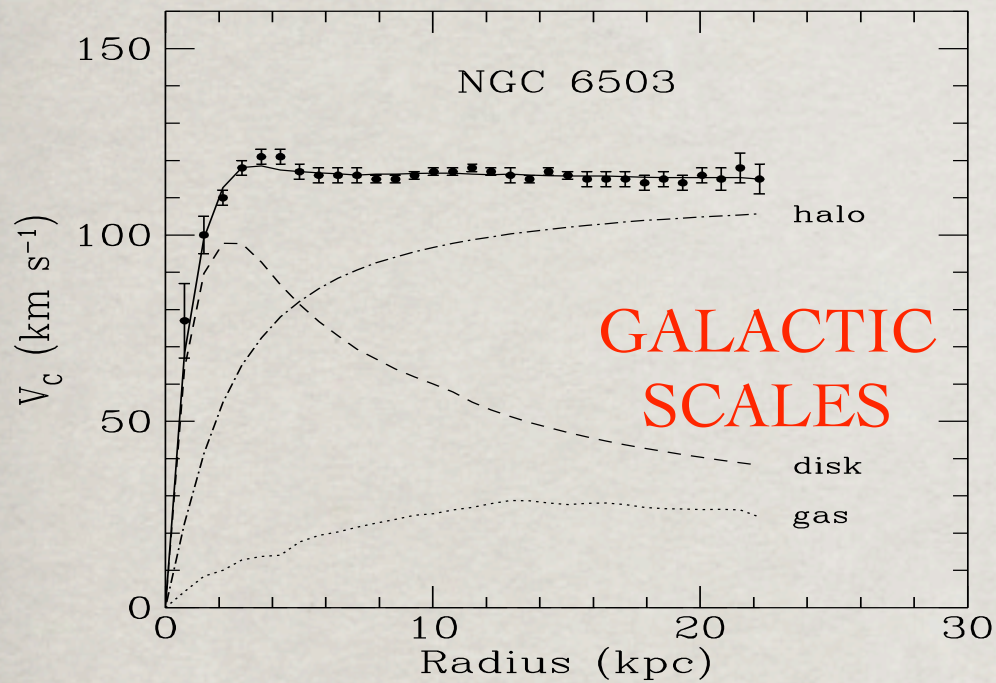

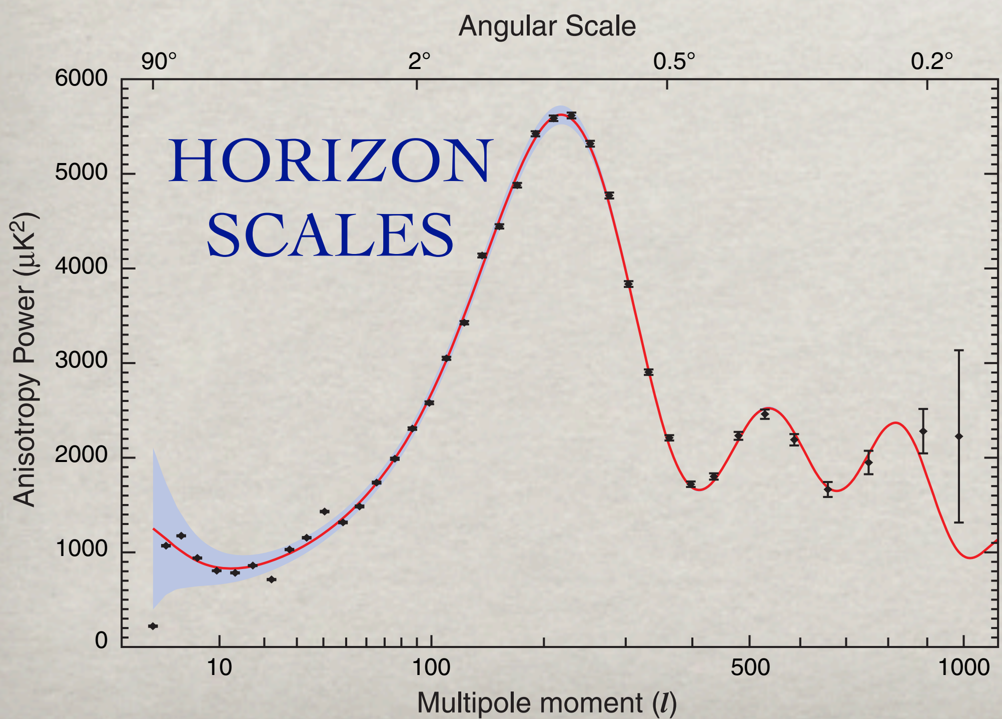

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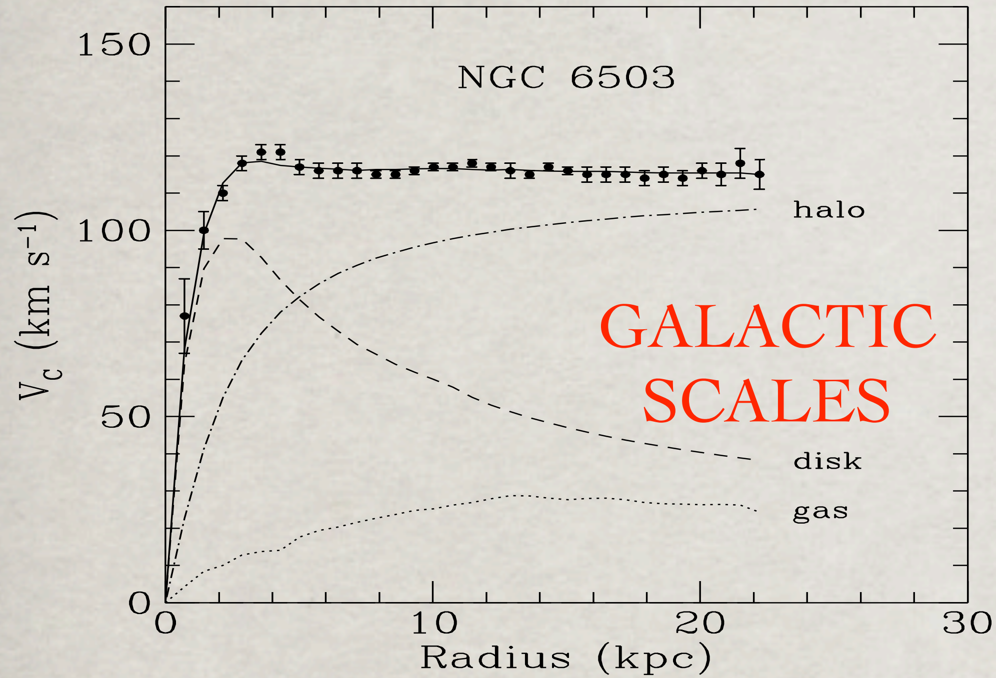
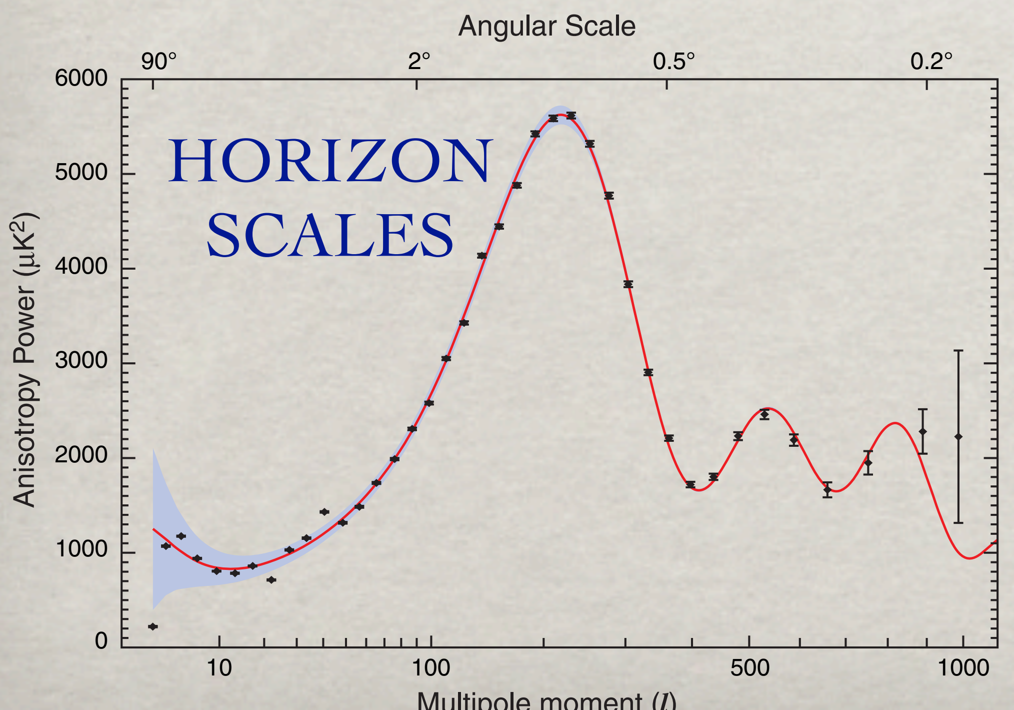


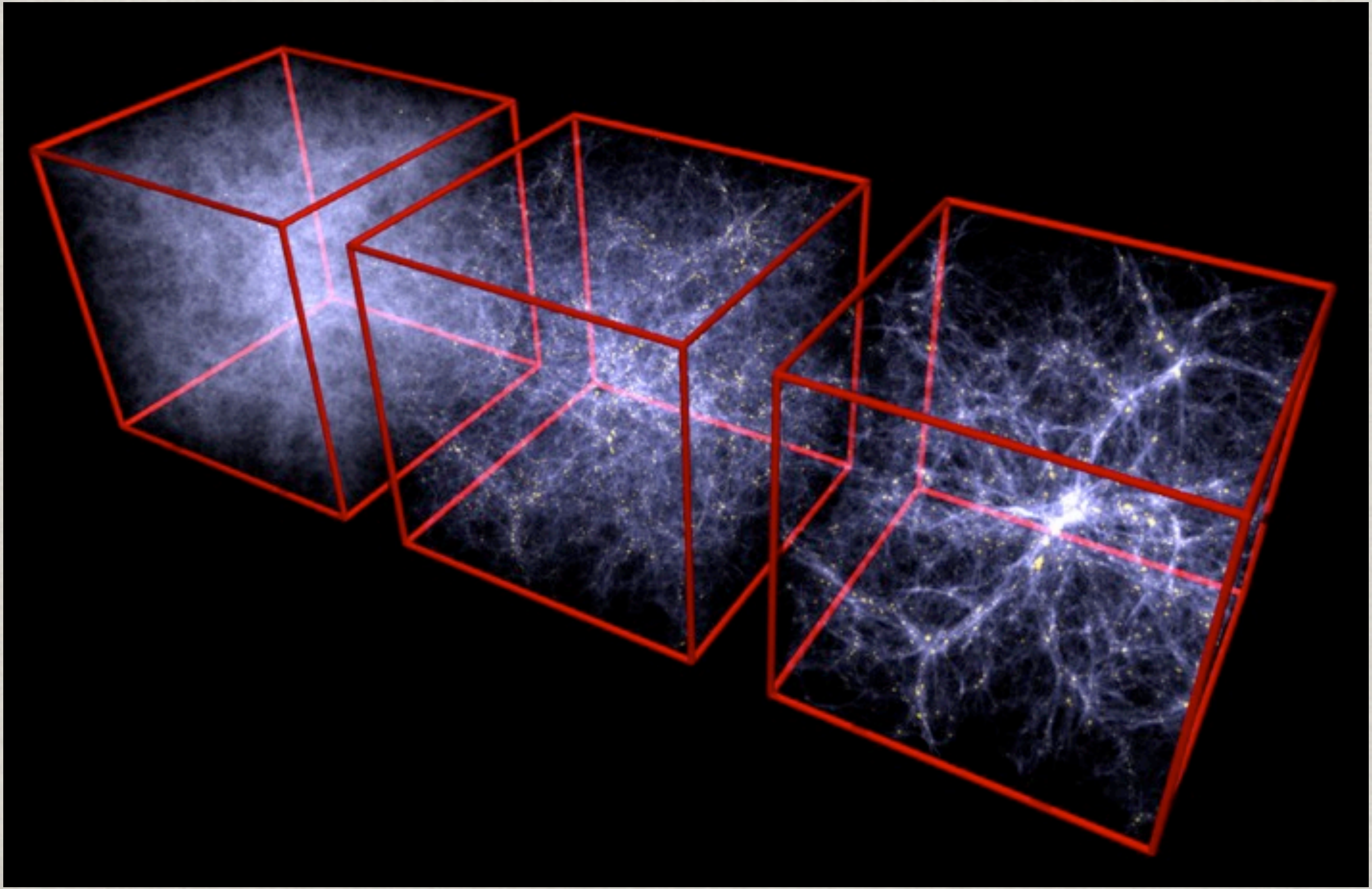


Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	~ 0.1	Cold

Structure Formation

V. Springel @MPA Munich

Yoshida et al 03



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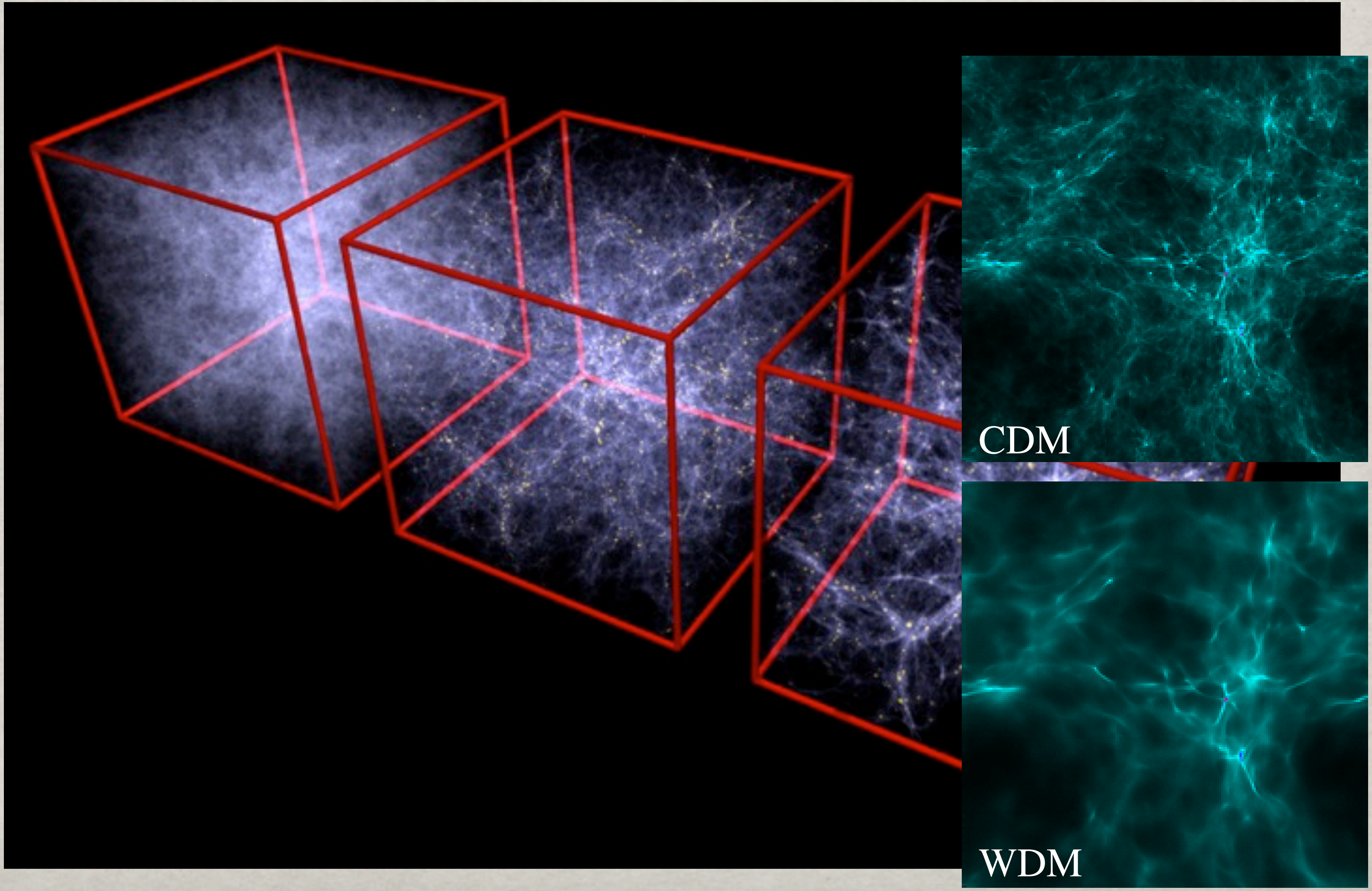

All these evidences are just based on the gravitational force: either directly on the attraction of the Dark Matter on the visible matter or on the effect of the Dark Matter energy component on the Universe expansion or on the evolution of the density perturbation...

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...

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

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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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$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	$\tilde{G}$	$\psi_{3/2}$

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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:

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

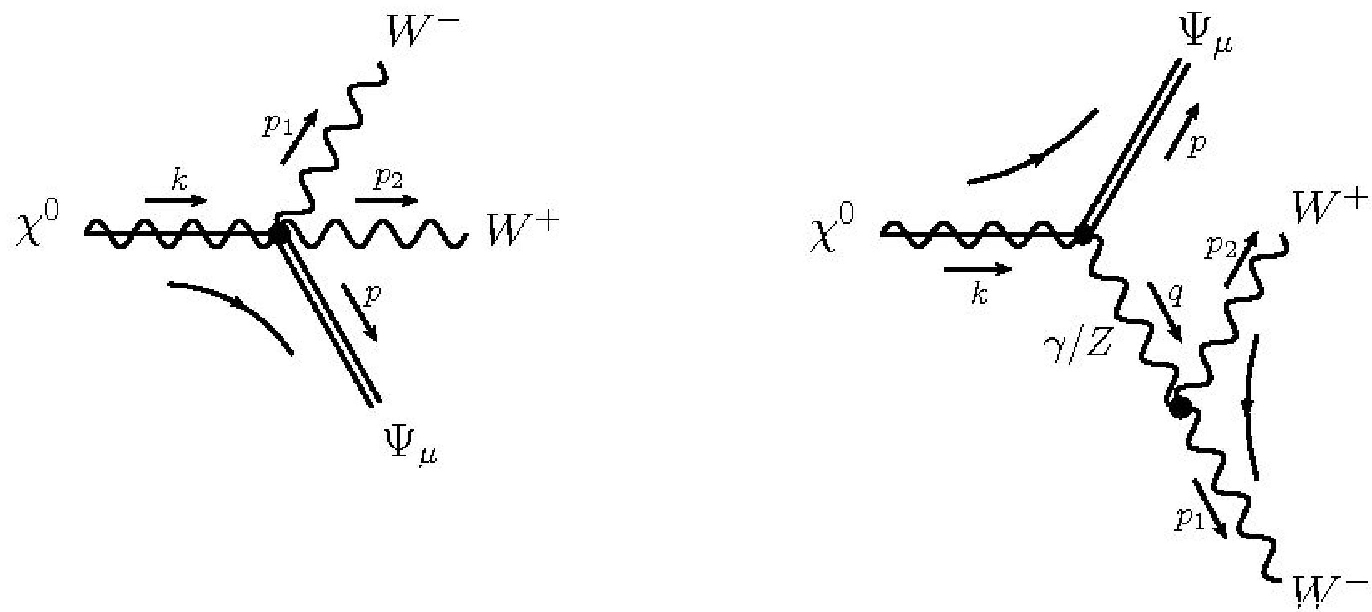
$$\Rightarrow \quad \frac{-m_\lambda}{4\sqrt{6}M_P m_{\tilde{G}}}\bar{\psi}\sigma^{\nu\rho}\lambda^a F^a_{\nu\rho} + \frac{i(m_\phi^2 - m_\chi^2)}{\sqrt{3}M_P m_{\tilde{G}}}\bar{\psi}\chi_R \phi^* + h.c.$$

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

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

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

Warm DM !

[Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

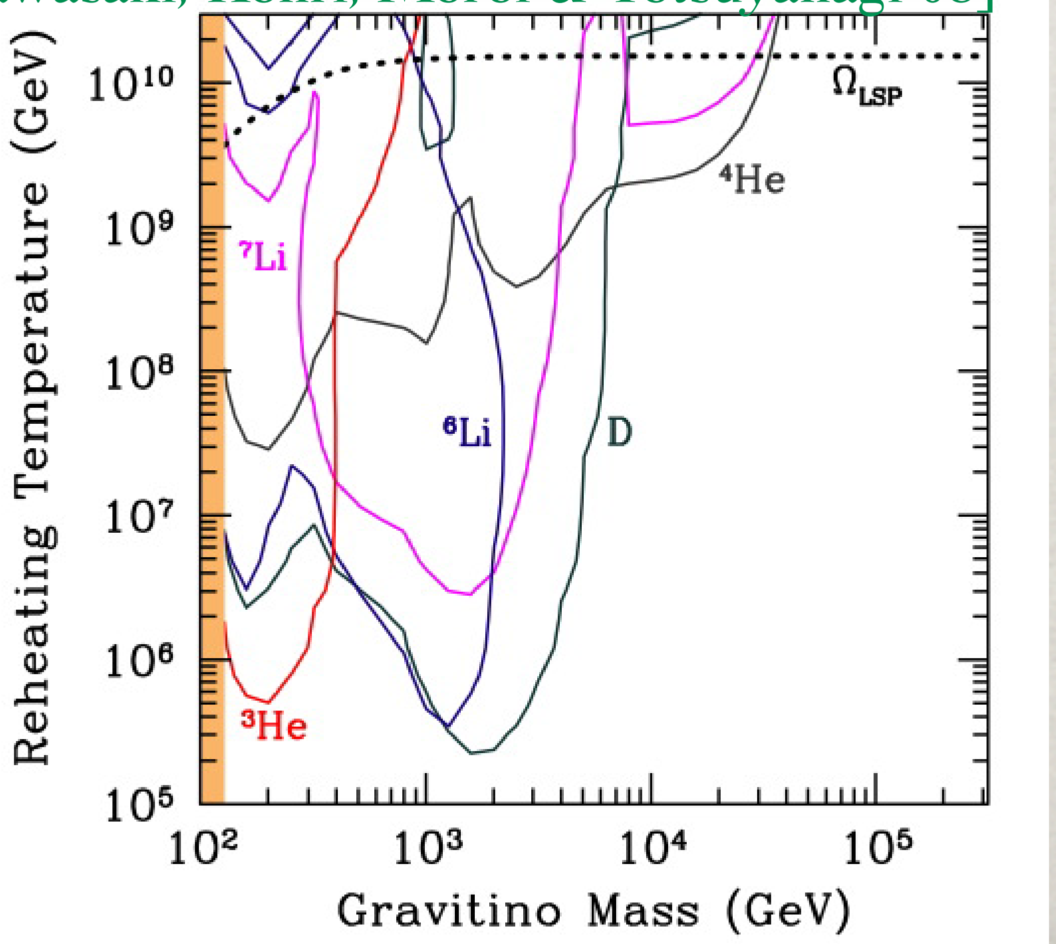
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1\text{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10}\ \text{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100\ \text{GeV}} \right)^2$$

[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.

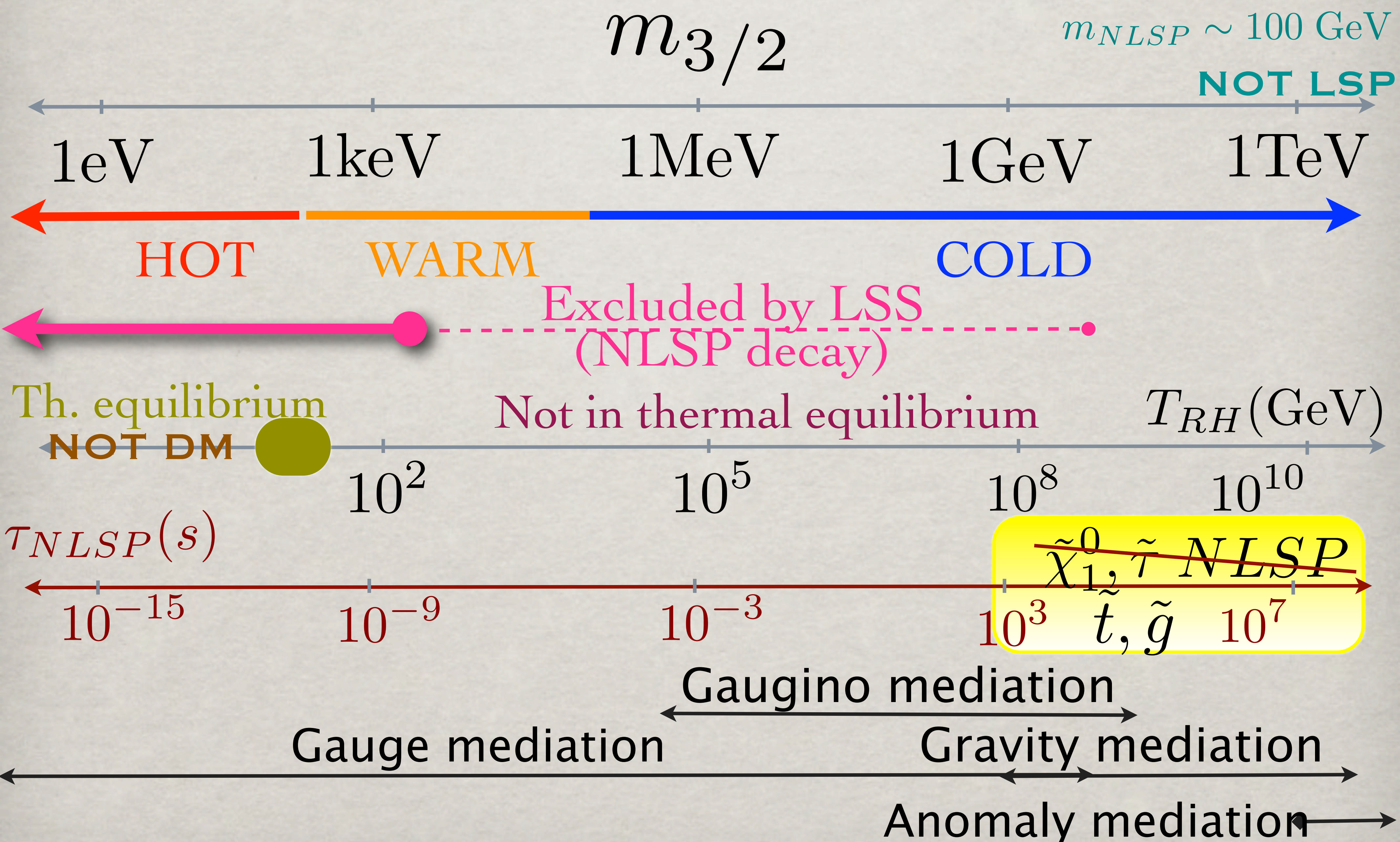
[Kawasaki, Kohri, Moroi & Yotsuyanagi 08]



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

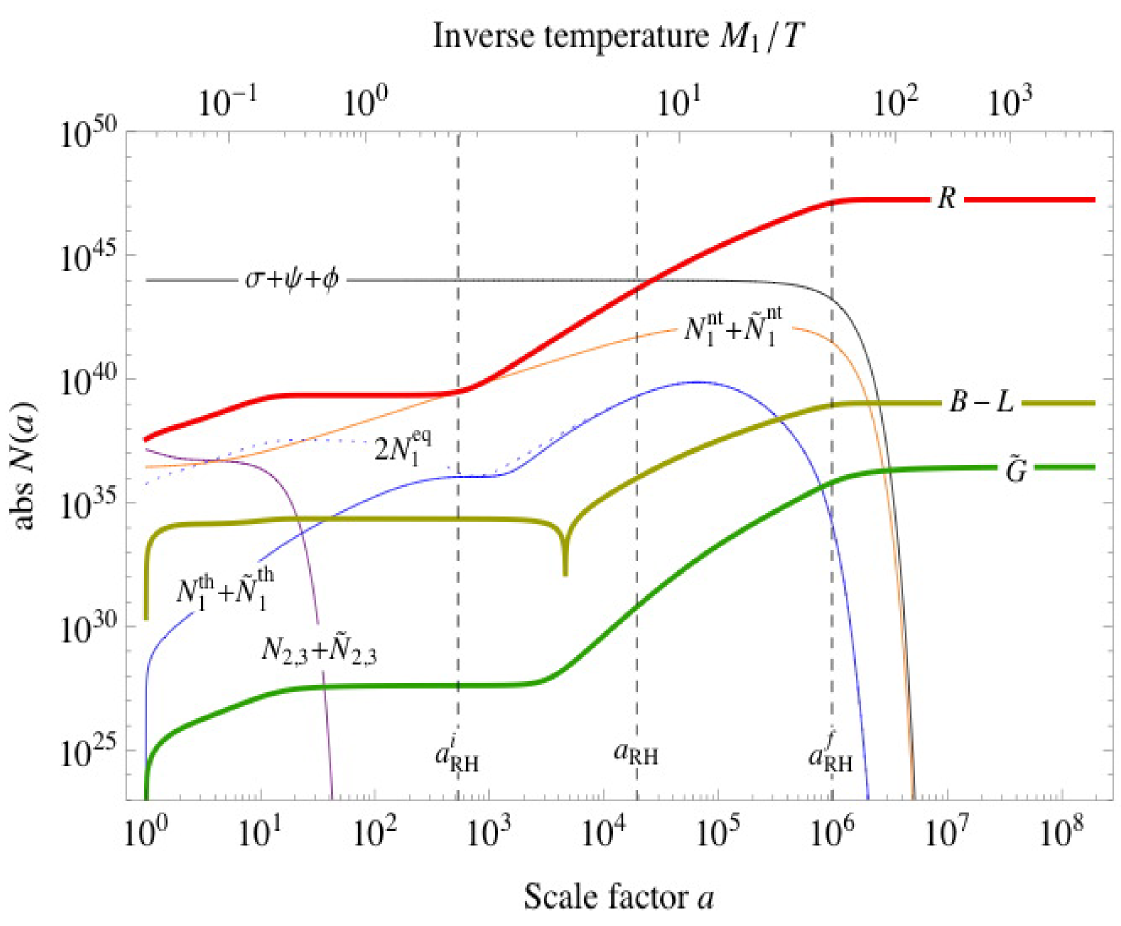
BBN is safe only if the gravitino mass is larger than 40 TeV, i.e. the lifetime is shorter than ~ 1 s, or if the reheating temperature is much smaller than that required for leptogenesis !

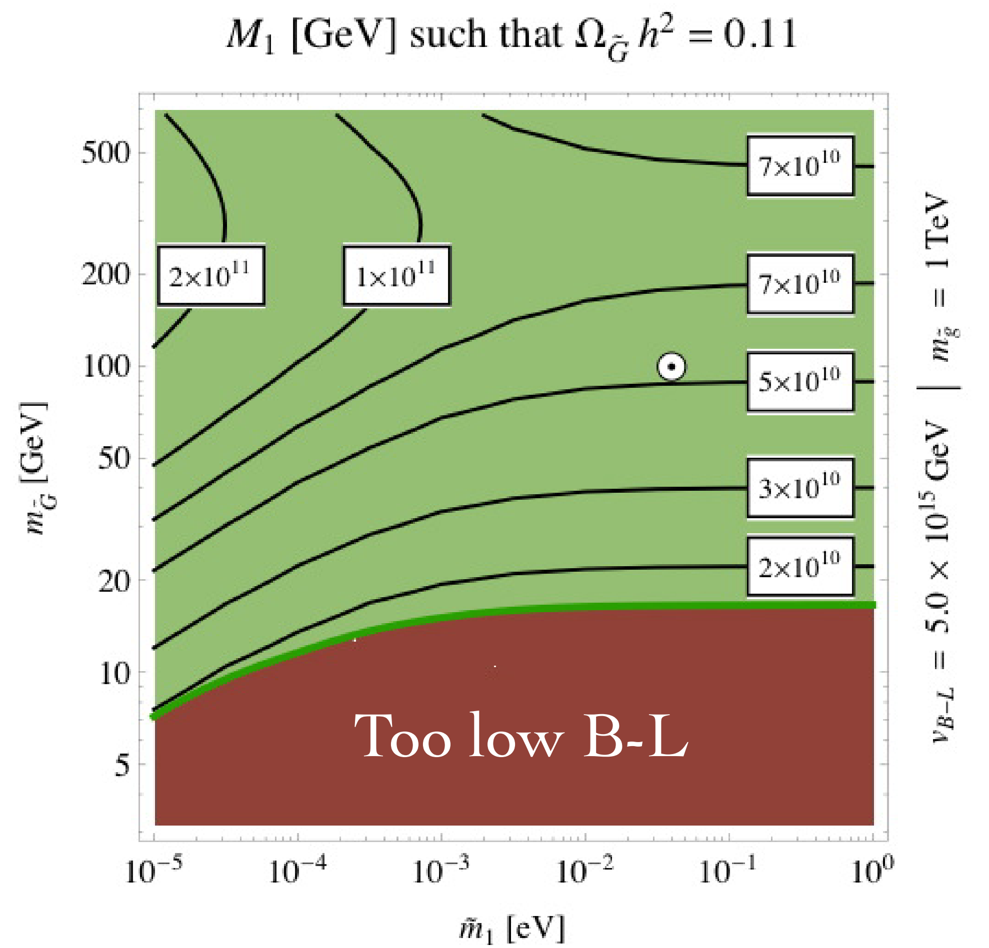
Gravitino DM summary



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 $m_{\tilde{G}}$

Stable gravitino Dark Matter

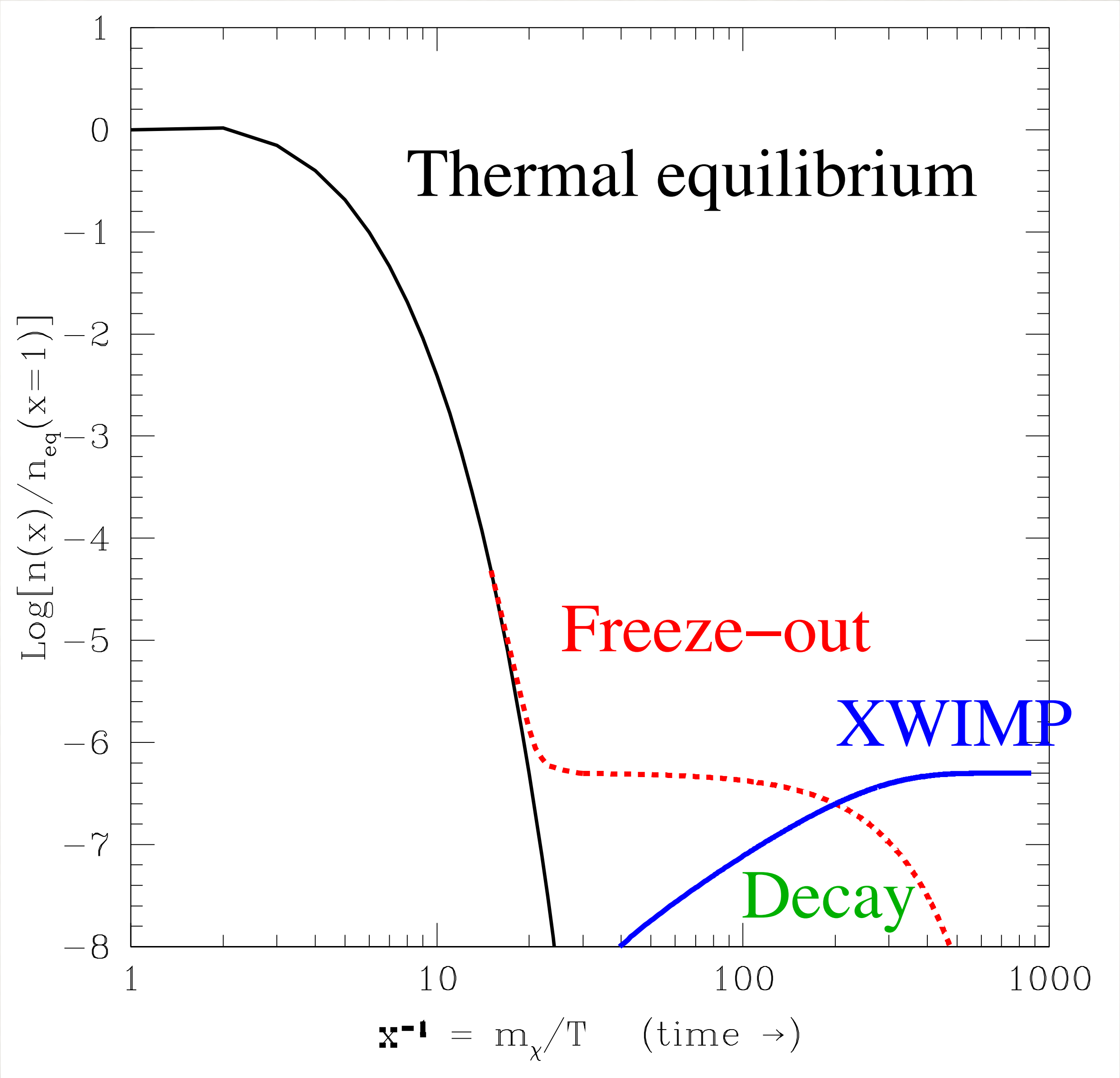
NLSP DECAY

[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

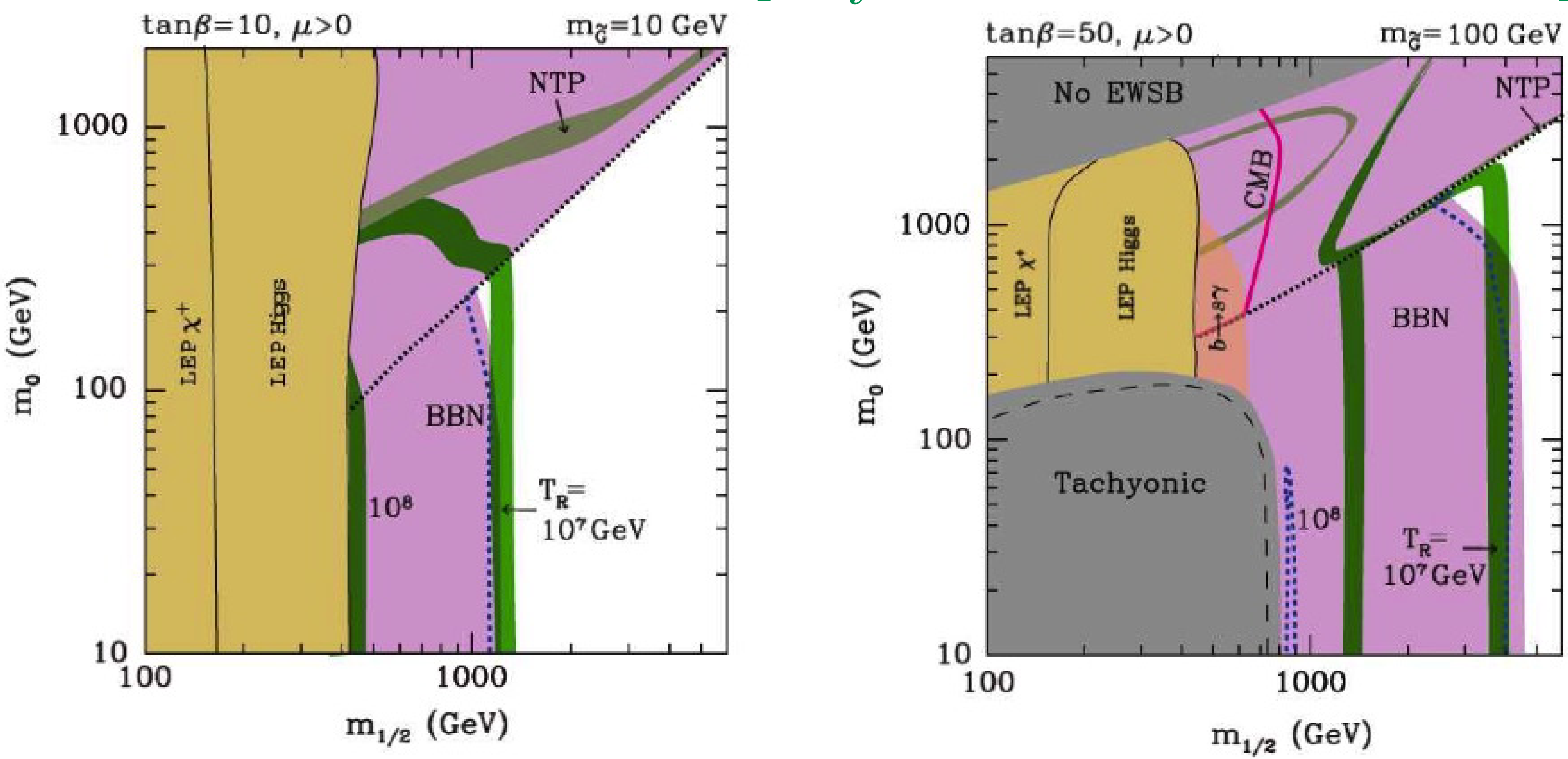
$$\Omega_X^{NT} = \frac{m_X}{m_{NLSP}} \Omega_{NLSP}$$

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



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...

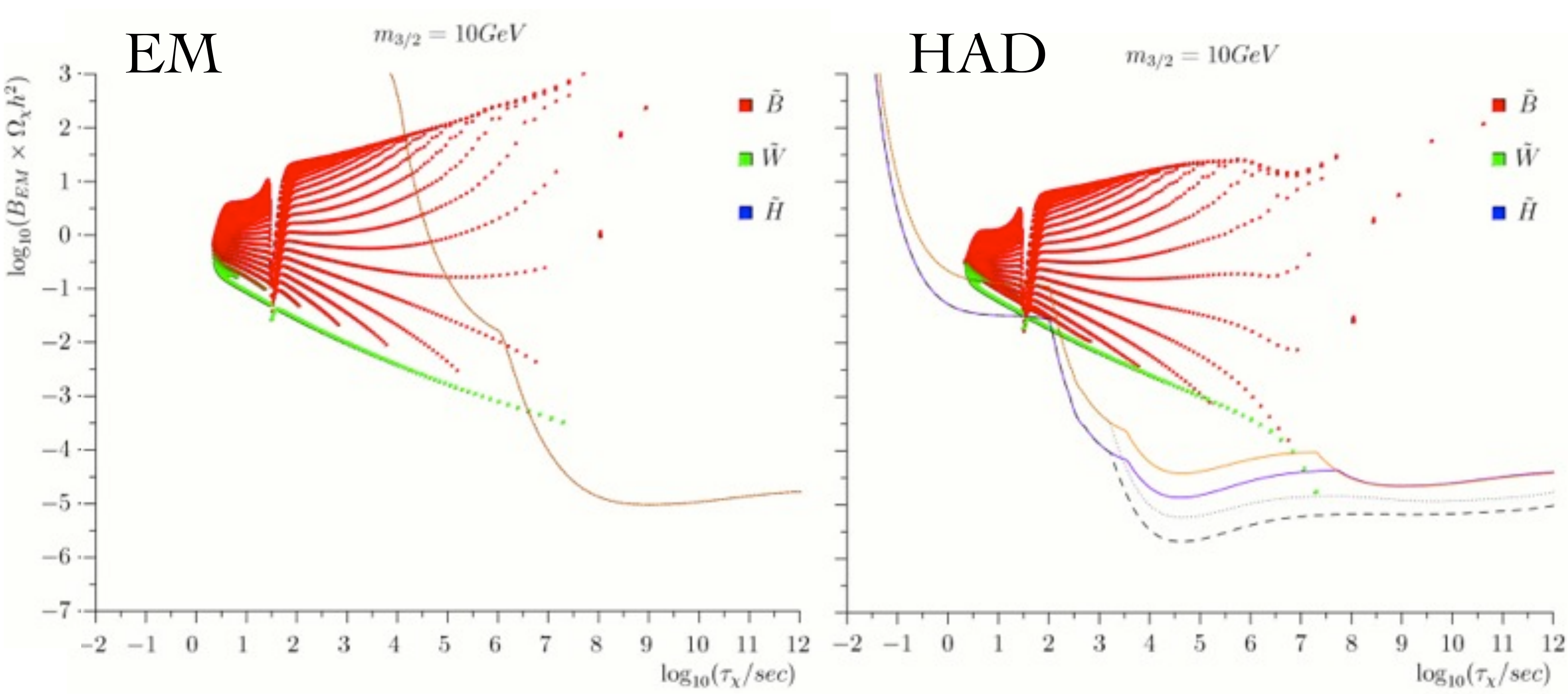
General neutralino NLSP

[LC, Hasenkamp, Roberts & Pokorski 09]

- In the CMSSM the neutralino NLSP is strongly constrained and requires a gravitino mass < 1 GeV. Check which regions are still open in the general case and how light the gravitino has to be...
- Important parameter is the neutralino branching ratio into hadrons e.g. via 3 body decay.
- The other important parameter for BBN constraints is the number density: We compute it with Micromegas 2.0 by [Belanger et al. 06] in the general mixed case.
- We compare our results with the BBN bounds for neutral relics given for the pure electromagnetic decays and also for different values of the hadronic branching ratios by [K. Jedamzik 06]

Bino-Wino neutralino

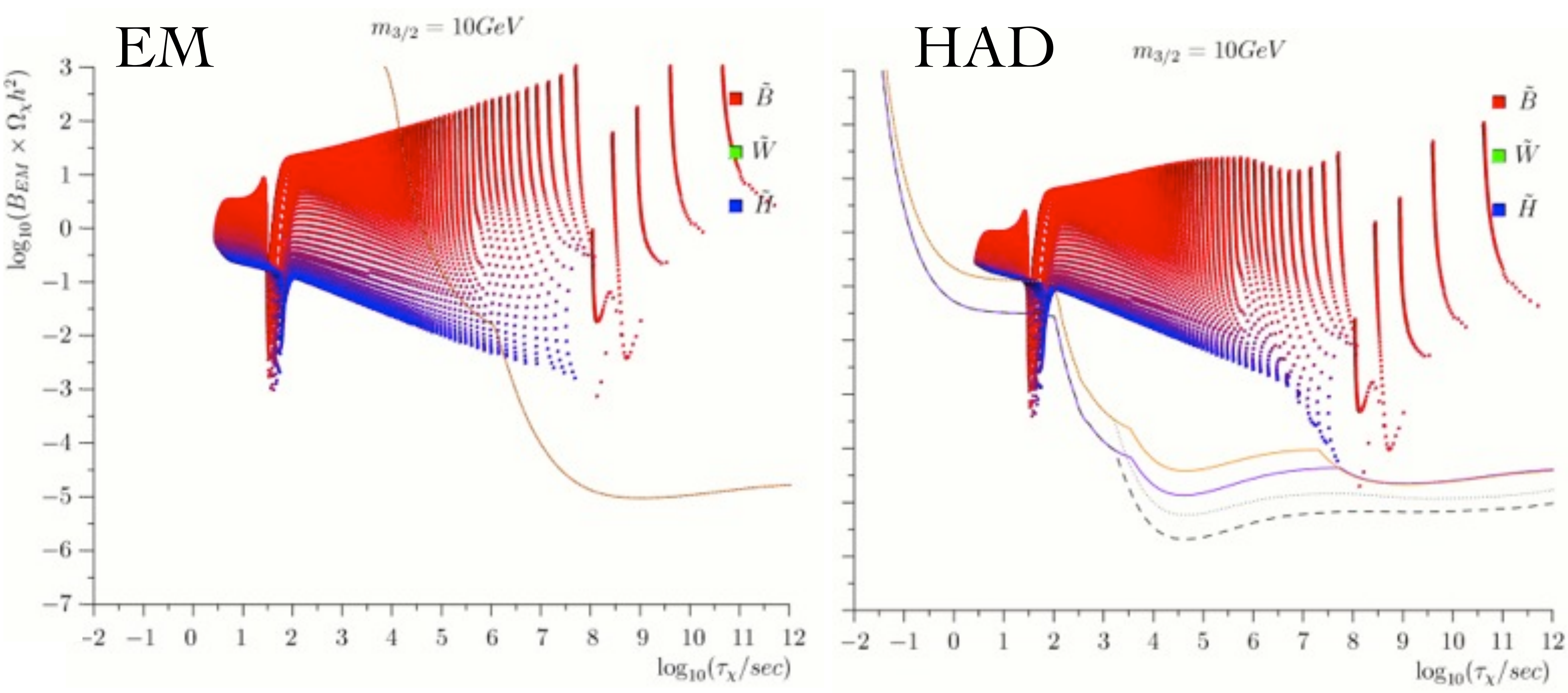
[LC, Hasenkamp, Roberts & Pokorski 09]



Not much room for Bino-Wino neutralino, even when the branching ratio is reduced by interference...
Still for low Wino masses the EM constraints are stronger !

Bino-Higgsino

[LC, Hasenkamp, Roberts & Pokorski 09]



The resonant annihilation into heavy Higgses becomes much more effective & reduces the density by 4 orders of magnitude !

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

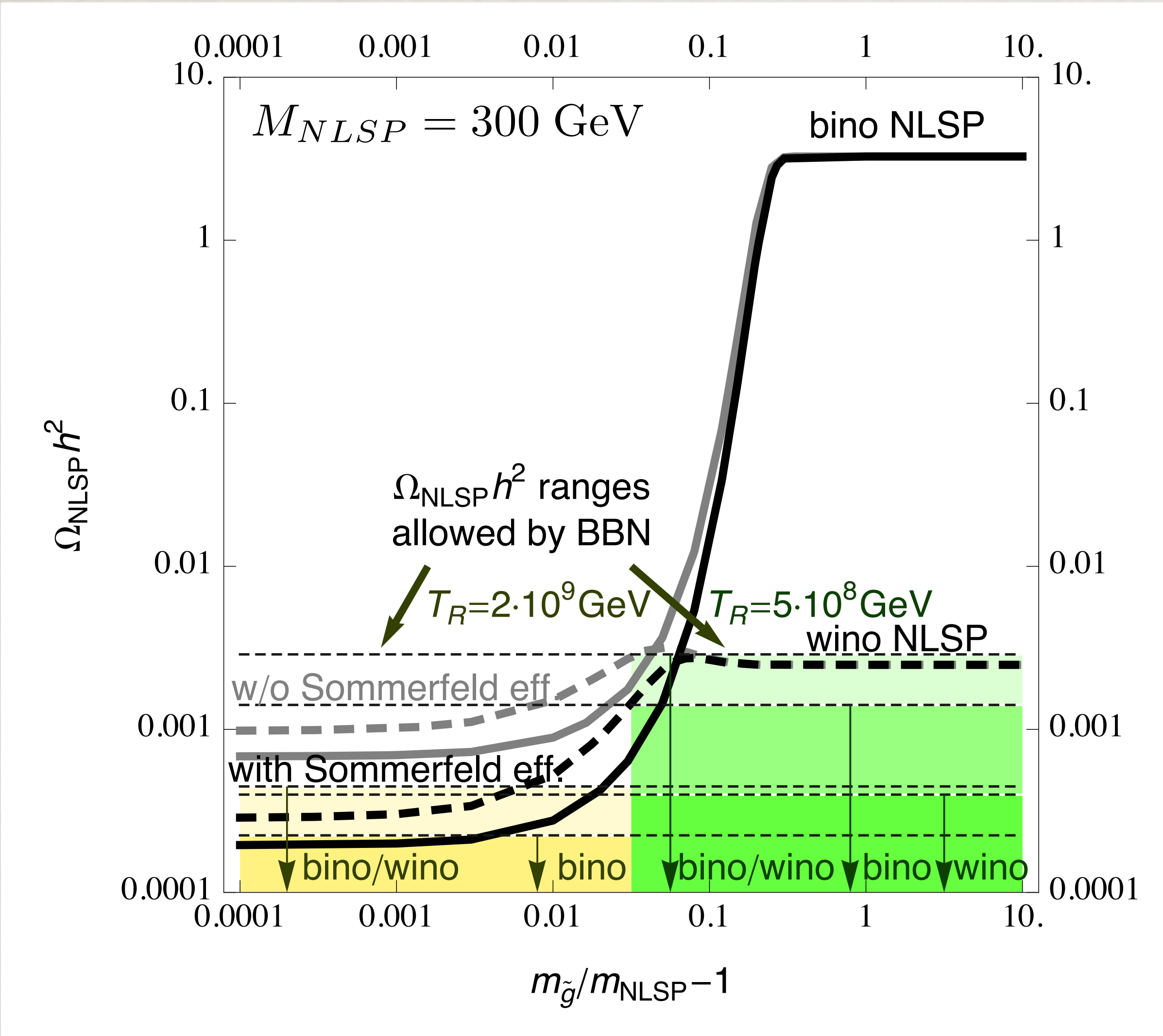
[Olechowski, Pokorski, Turzynski,Wells 09]

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.

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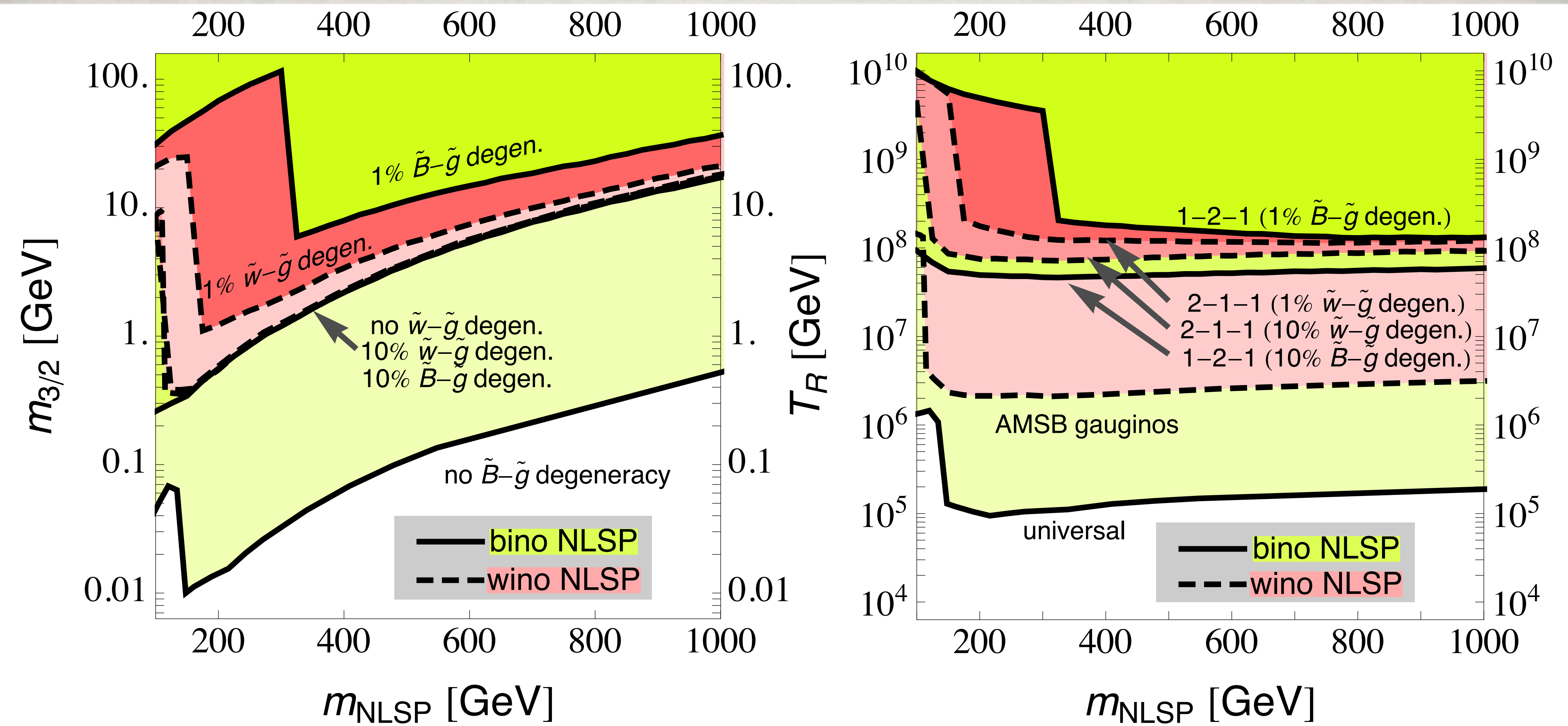


The coannihilation with gluinos allows to reach large T_R, but with very strong degeneracy and light masses...

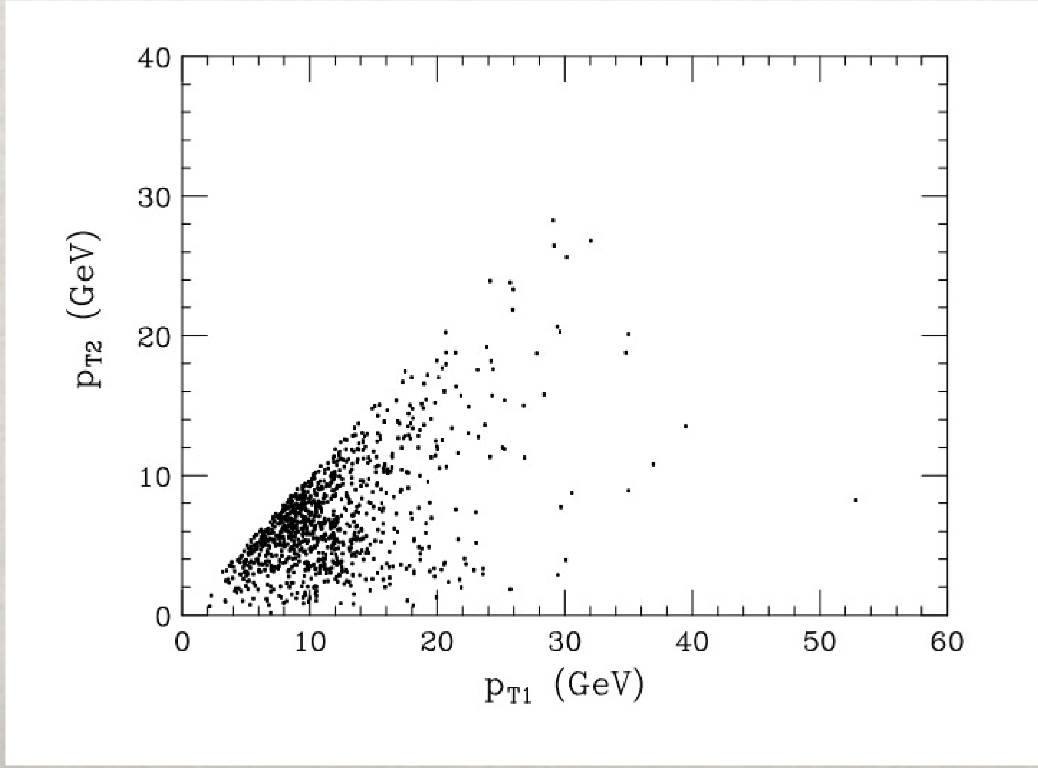
LHC: DEGENERATE GAUGINOS?

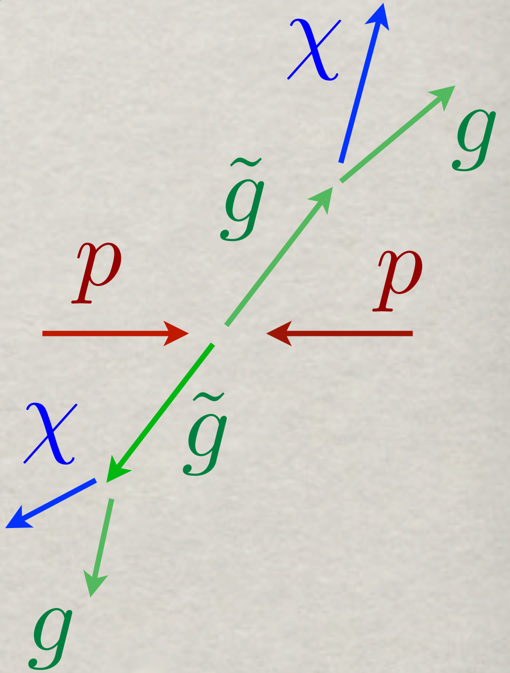
In this scenario of maximal T_R and stable gravitino DM we expect light gauginos with 1-10% degeneracy between NLSP and gluino NNLSP.

The largest cross-section at LHC is gluino pair production, but if they decay dominantly into gluon and neutralino, the arising jets are possibly too soft to trigger on...

$$m_{\tilde{g}} = 309$$
$$m_{\tilde{B}} = 300$$

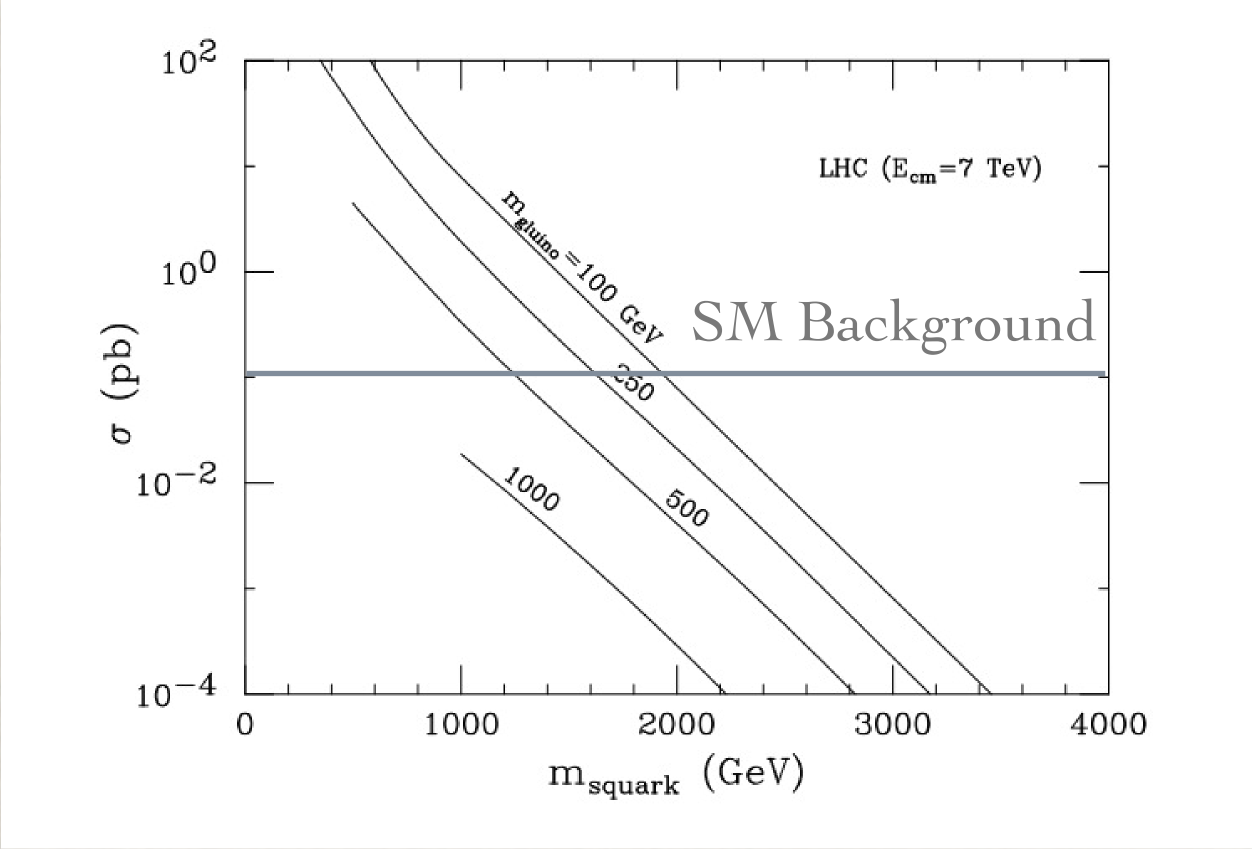
to low p_T !

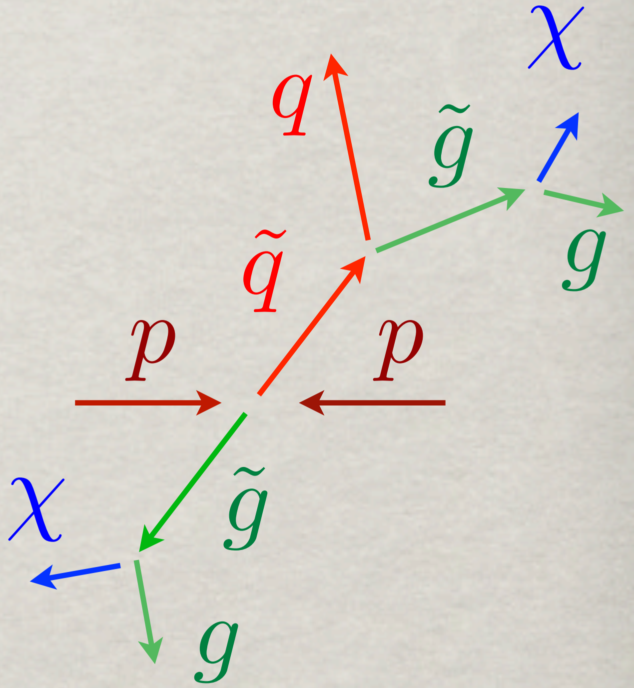




LHC: Mono-jet signature

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.



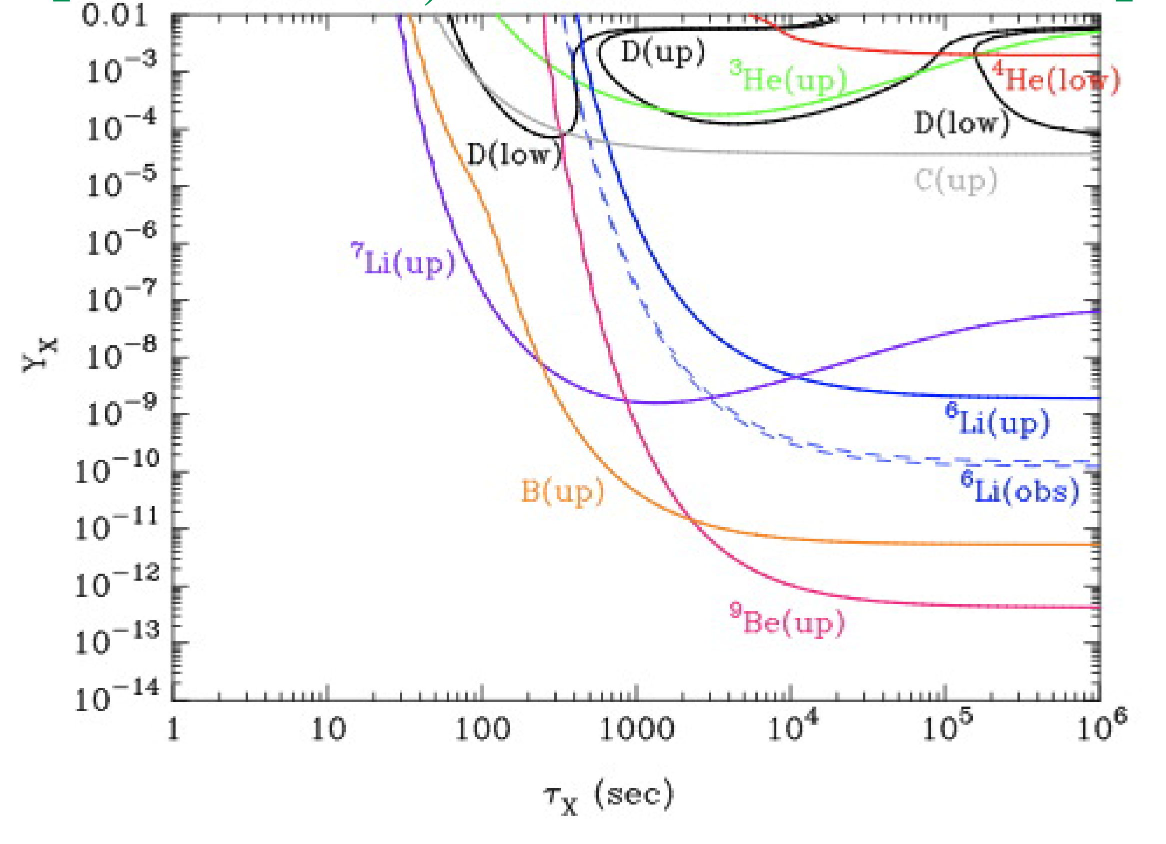


Detectable at LHC probably up to 1.8 TeV squark mass !

BBN bounds: colored relics

Colored relics: even stronger BBN bound state effects...

[Kusakabe,Kajino,Yoshida, Mathews 09]



BBN bounds: colored relics

Colored relics: even stronger BBN bound state effects...

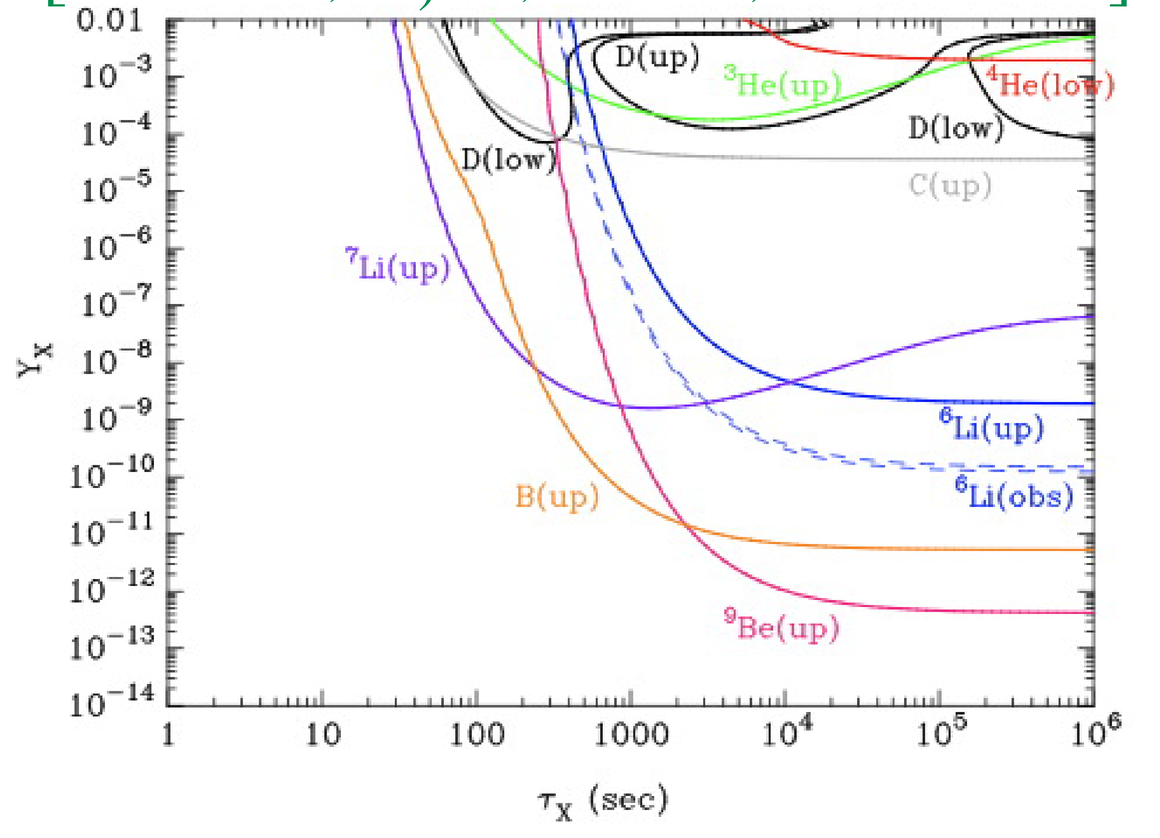
Beware:

$$Y_X^{BBN} = \frac{n_X}{n_b} \sim 10^{-9}\, Y_X$$

$$\rightarrow 0.02\, \frac{m_X}{GeV} \text{ in } \Omega h^2$$

Bounds so strong that even strong interaction is not strong enough...

[Kusakabe,Kajino,Yoshida, Mathews 09]



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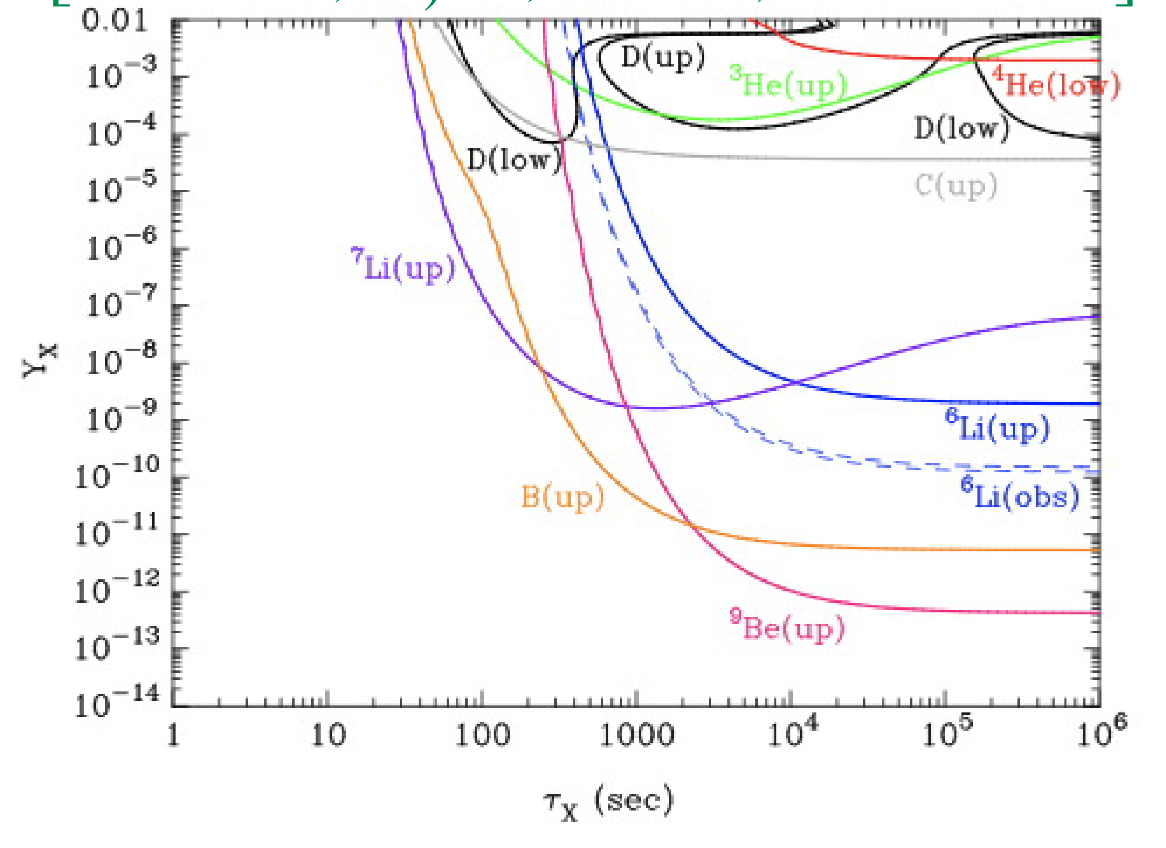
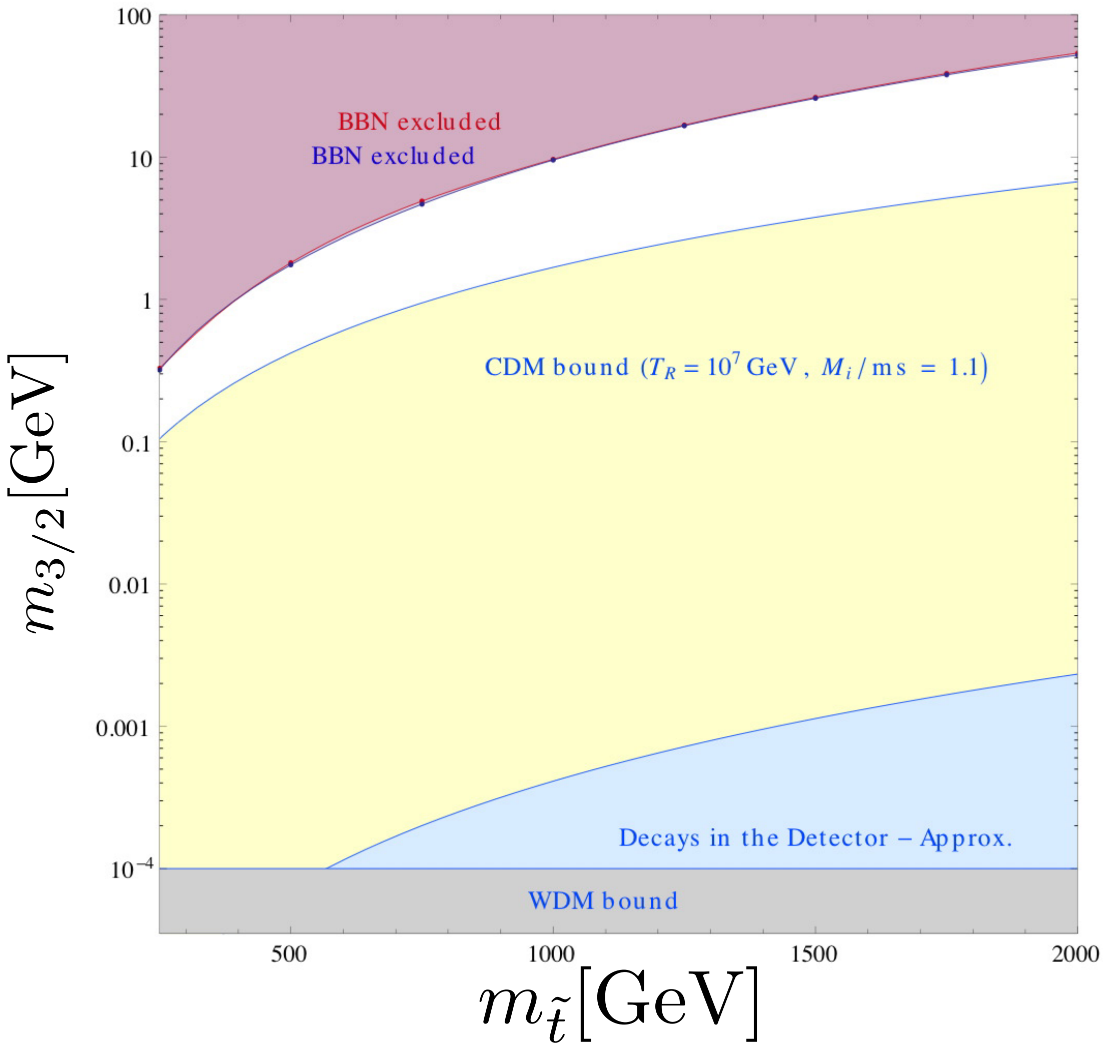


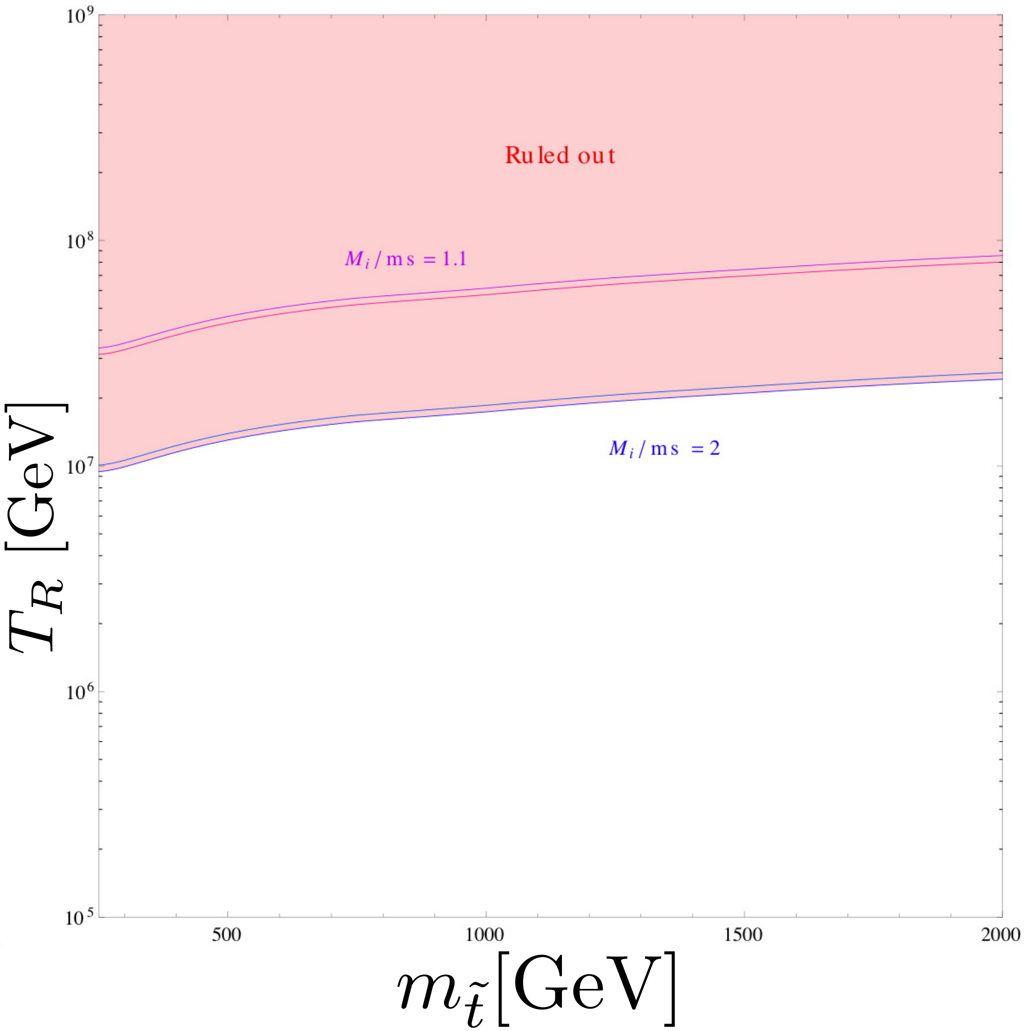
Only short lifetime for colored NLSP allowed:

$$\tau_{\tilde{g},\tilde{t}} < 200 \text{ s} \quad \longrightarrow \quad m_{\tilde{g},\tilde{t}} > 800 \text{ GeV} \left(\frac{m_{3/2}}{10 \text{ GeV}}\right)^{2/5}$$

COLORED NLSPs

[LC & Dradi xx]





The BBN constraints allow only for T_R about few 10^7GeV

Unstable gravitino Dark Matter

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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no p decay

Open window:

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

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$$W_{R\!\!\!/p} = \mu_i L_i H_u + \lambda LLE^c + \lambda' LQD^c + \cancel{\lambda'' U^c D^c D^c}$$

no p decay

Open window:

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

For the NLSP to decay before BBN

R-parity or not R-parity

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For the NLSP to decay before BBN

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.

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.

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

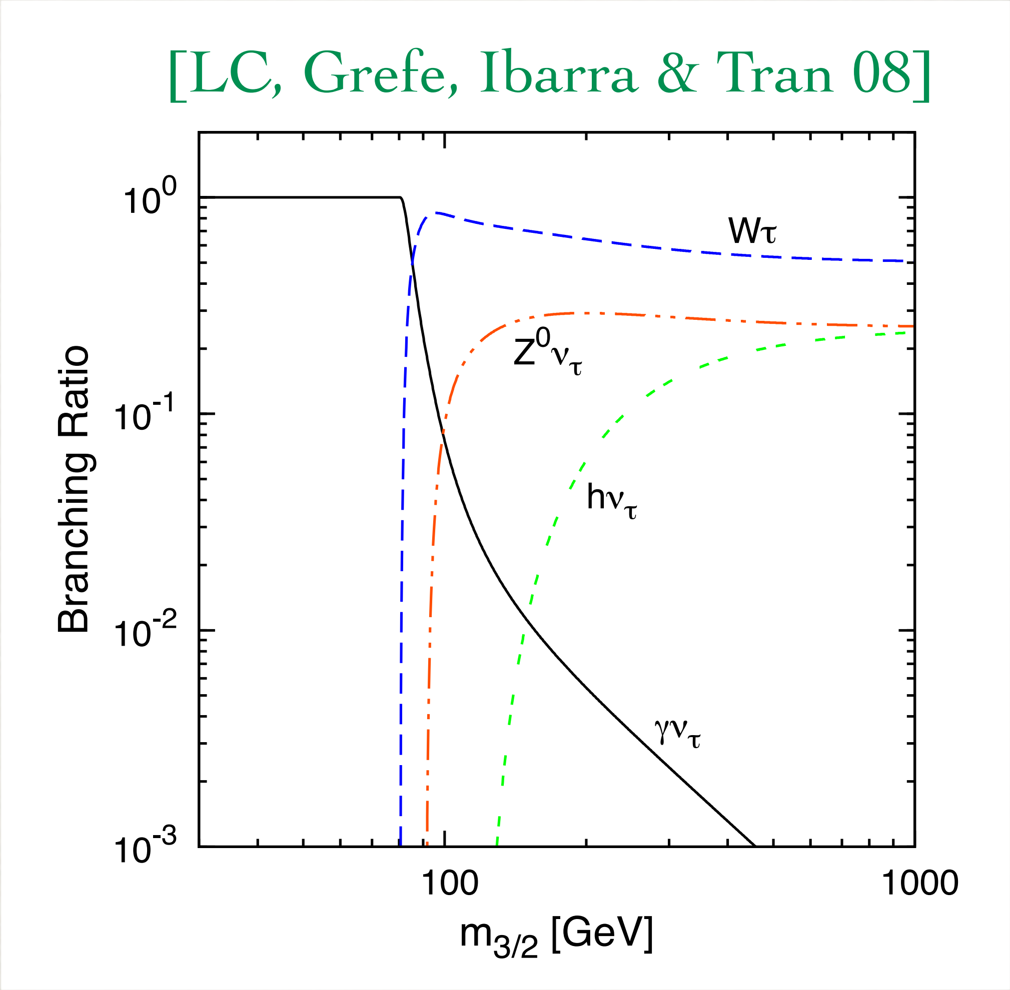
For bilinear R-parity breaking the 2-body channel dominates:

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

[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

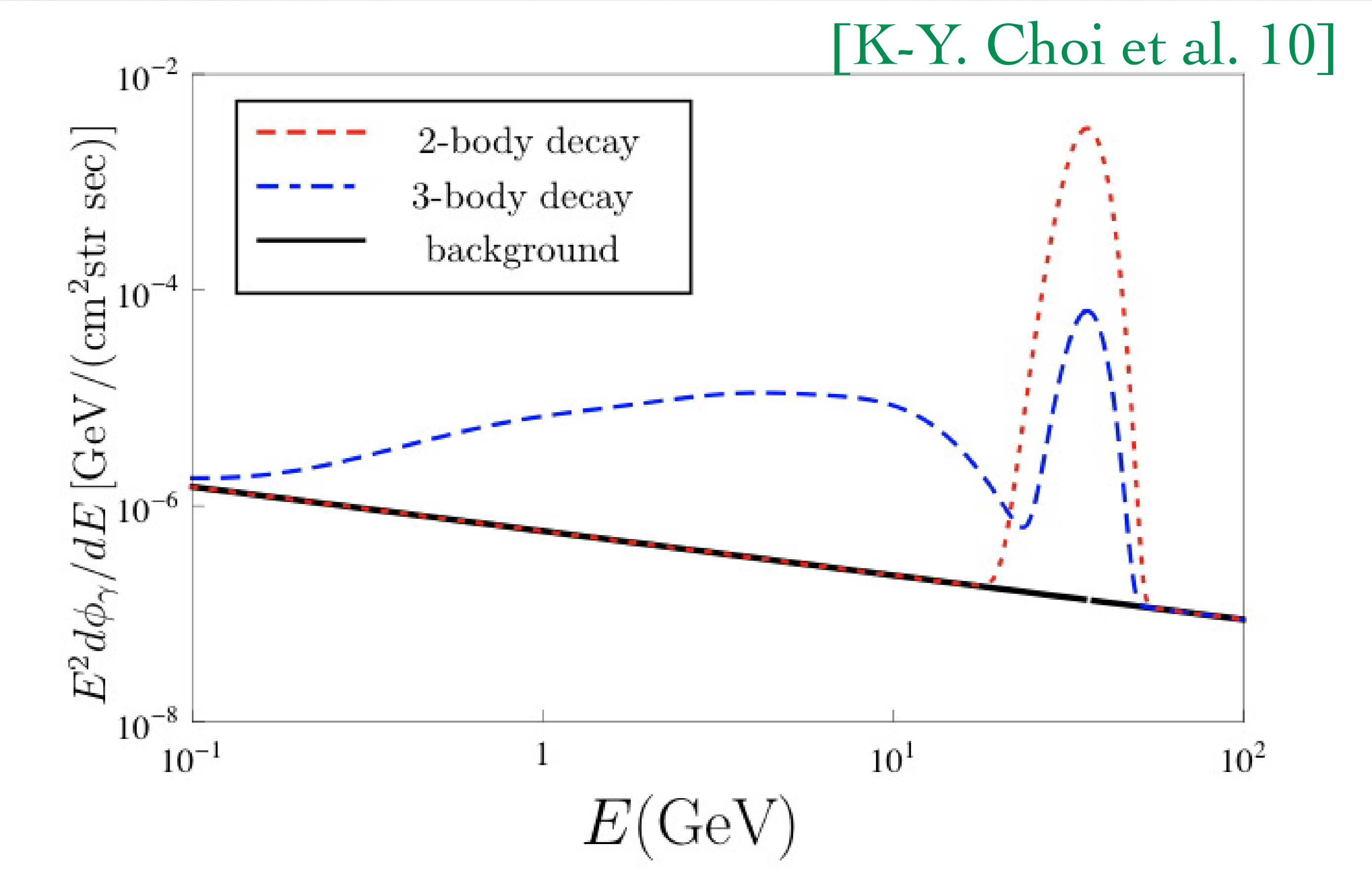
For bilinear R-parity violation, the gravitino decays into neutrino and (gauge) boson: photon, W, Z or Higgs
or via trilinear couplings into neutrino and 2 leptons



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

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

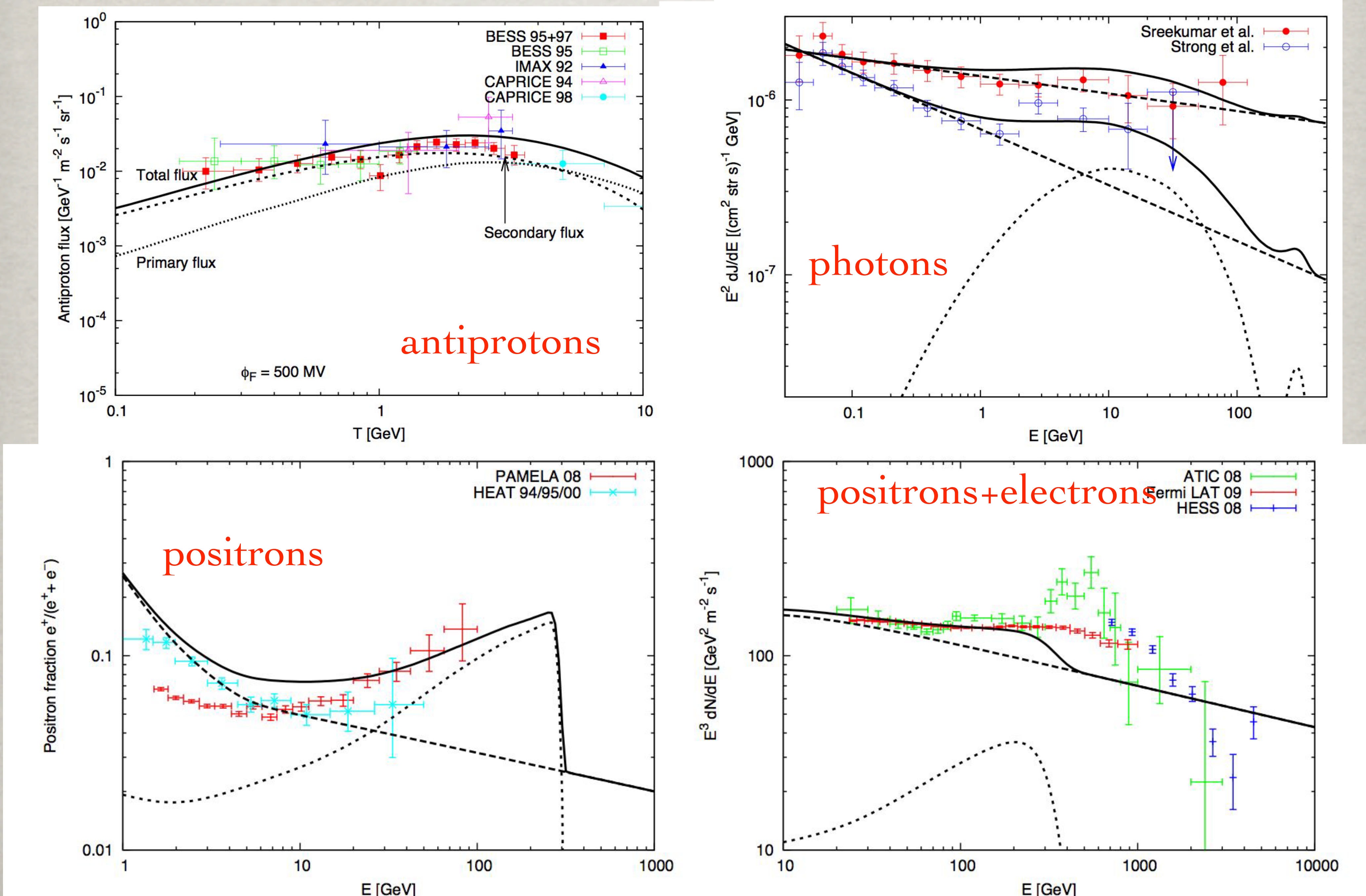
Below M_W also 3-body



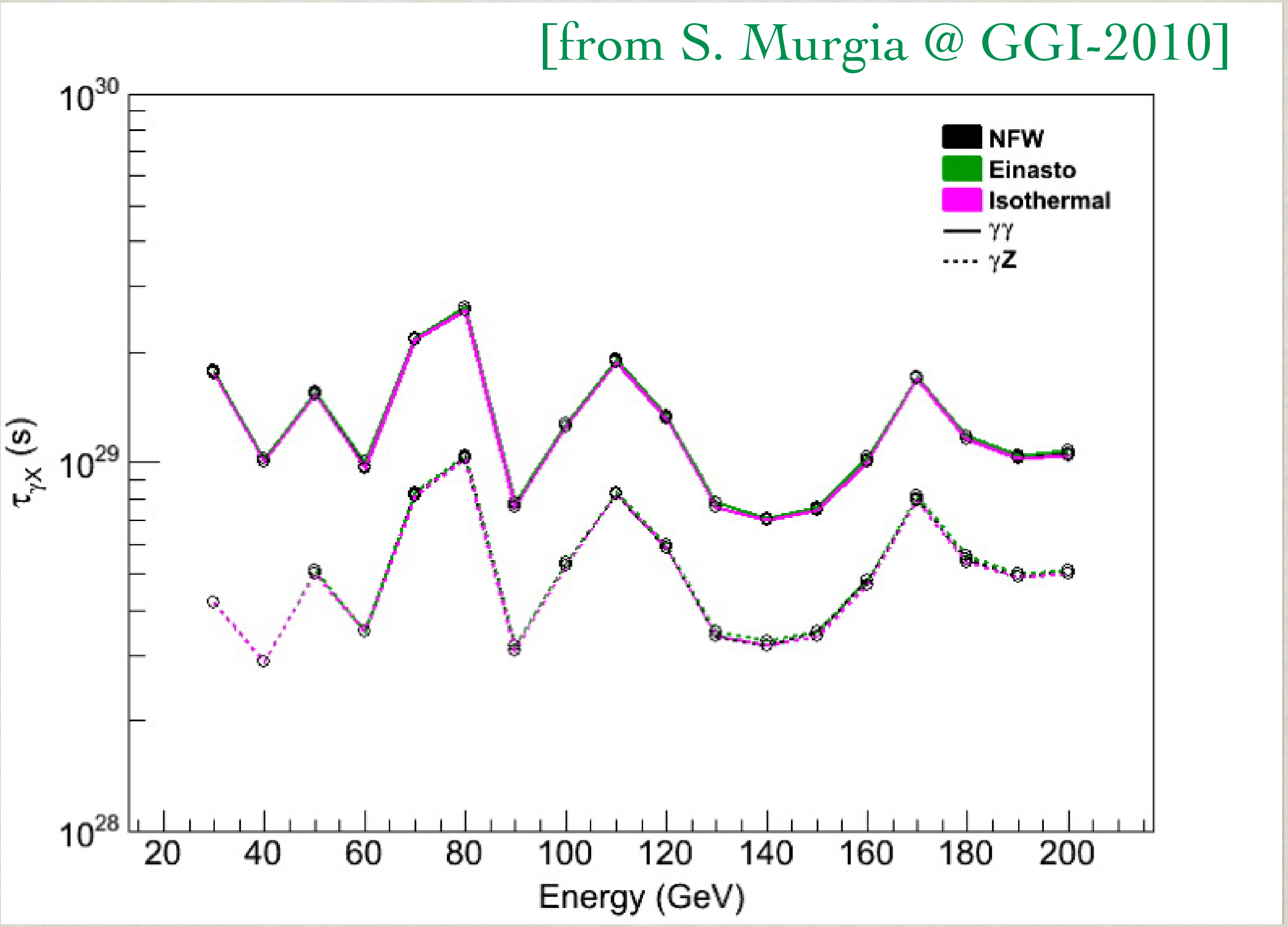
For bilinear R-parity breaking, the gravitino decays mostly into lepton and gauge boson... Below the W/Z threshold though, also the 3-body decay via virtual W/Z are important because the photon channel can be suppressed... [K-Y. Choi & Yaguna 10]

Gravitino DM without R_p

[Buchmuller, Ibarra, Shindou, Takayama, Tran 09] ([Ishiwata, Matsumoto & Moroi 08])



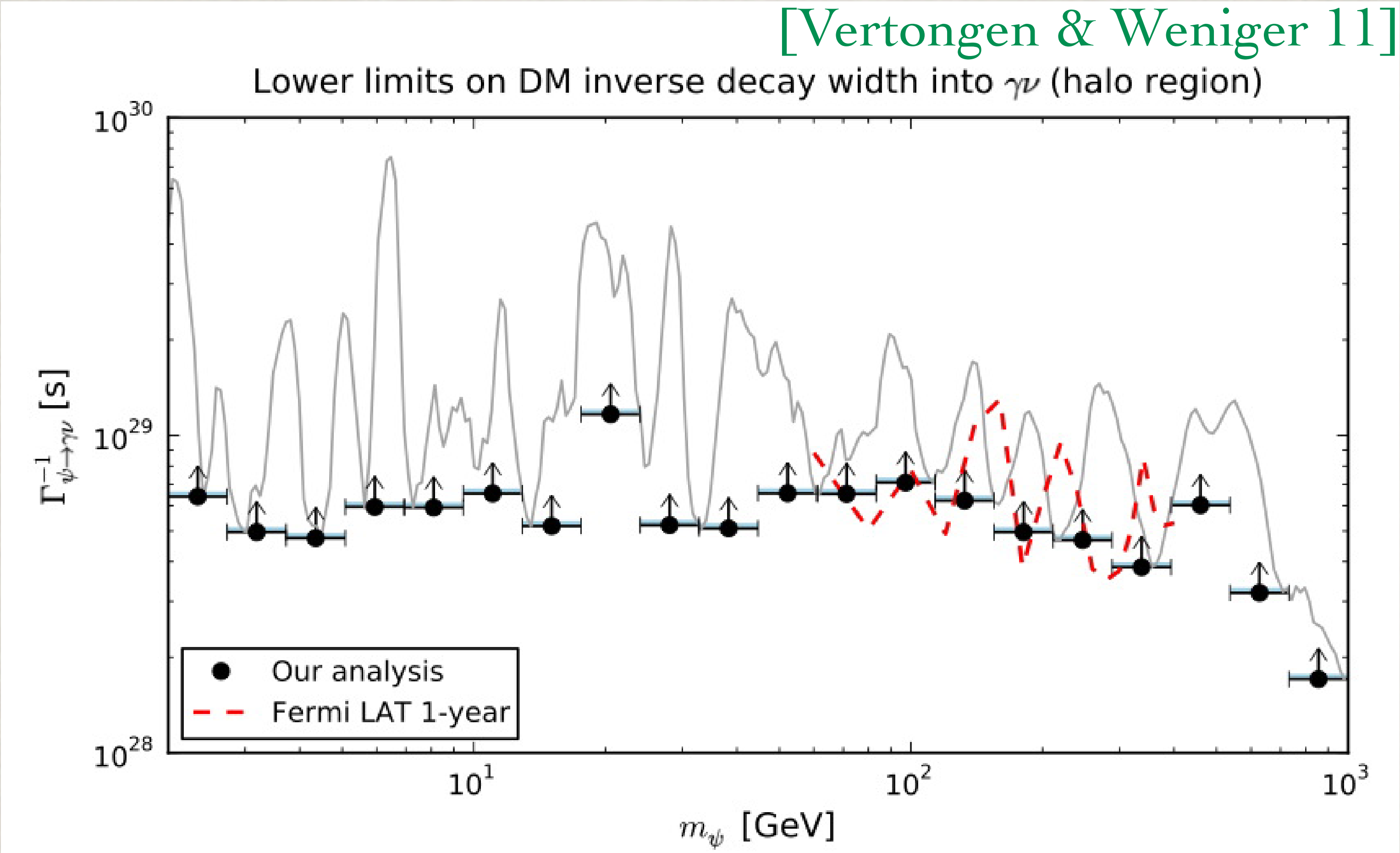
FERMI LINE CONSTRAINTS



The FERMI space telescope looks for lines in the galactic emissions in the energy range 30-200 GeV and gives the stronger constraint for gravitinos below 400 GeV:

From the FERMI gamma-line search: $\tau \geq 5\ 10^{28}$s @ 95% CL

FERMI LINE CONSTRAINTS



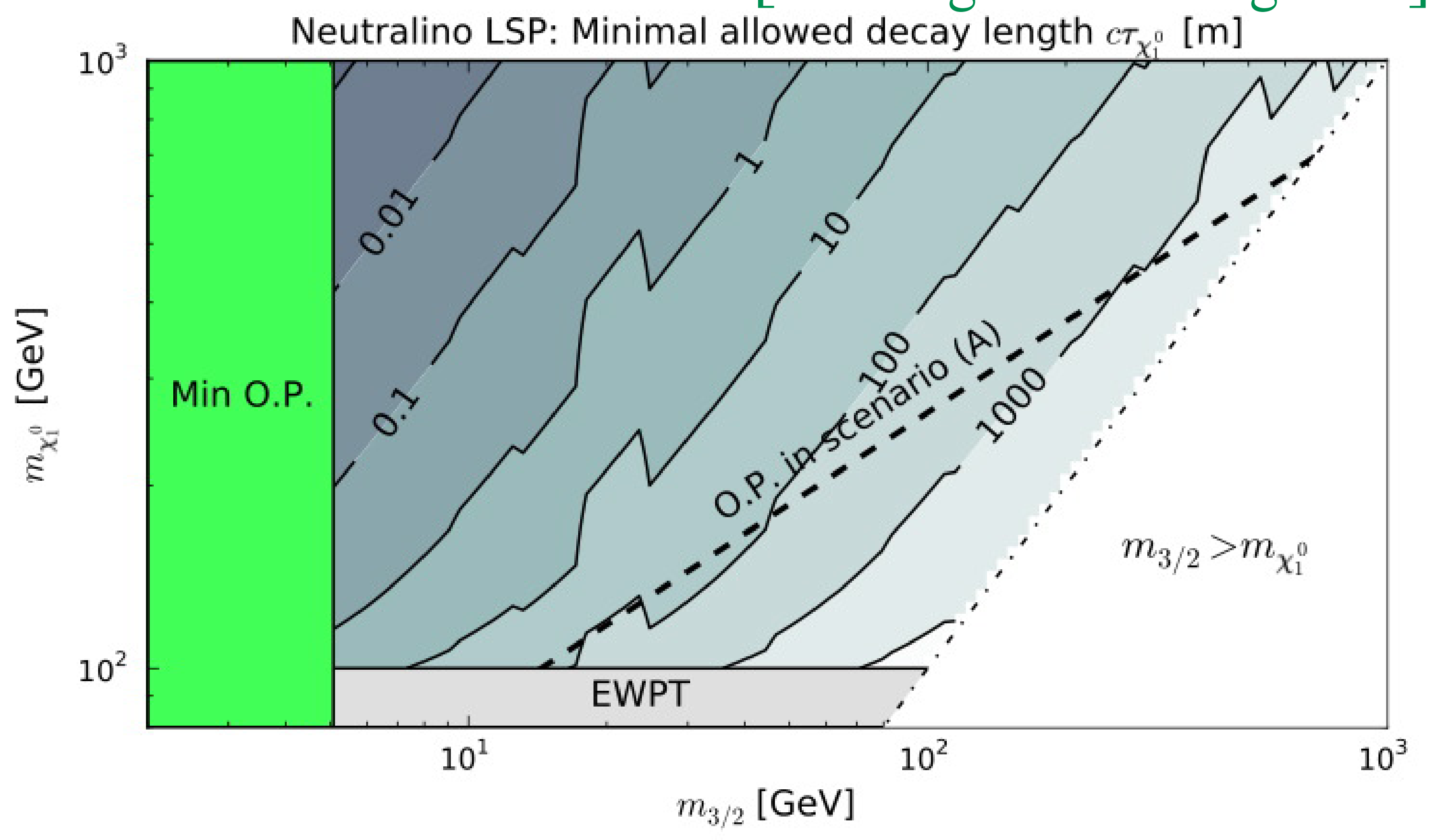
A recent analysis extends the FERMI line search in a wider mass region, for energies to 500 GeV, i.e. masses between 1-1000 GeV

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:

[Vertongen & Weniger 11]

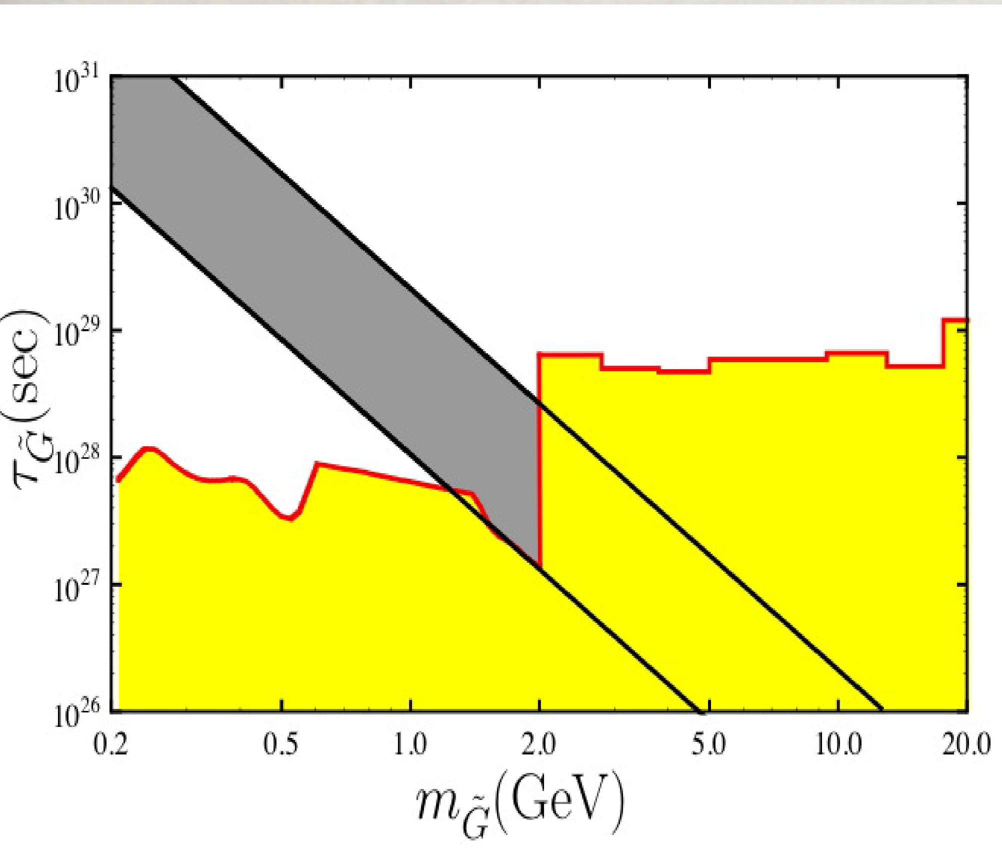


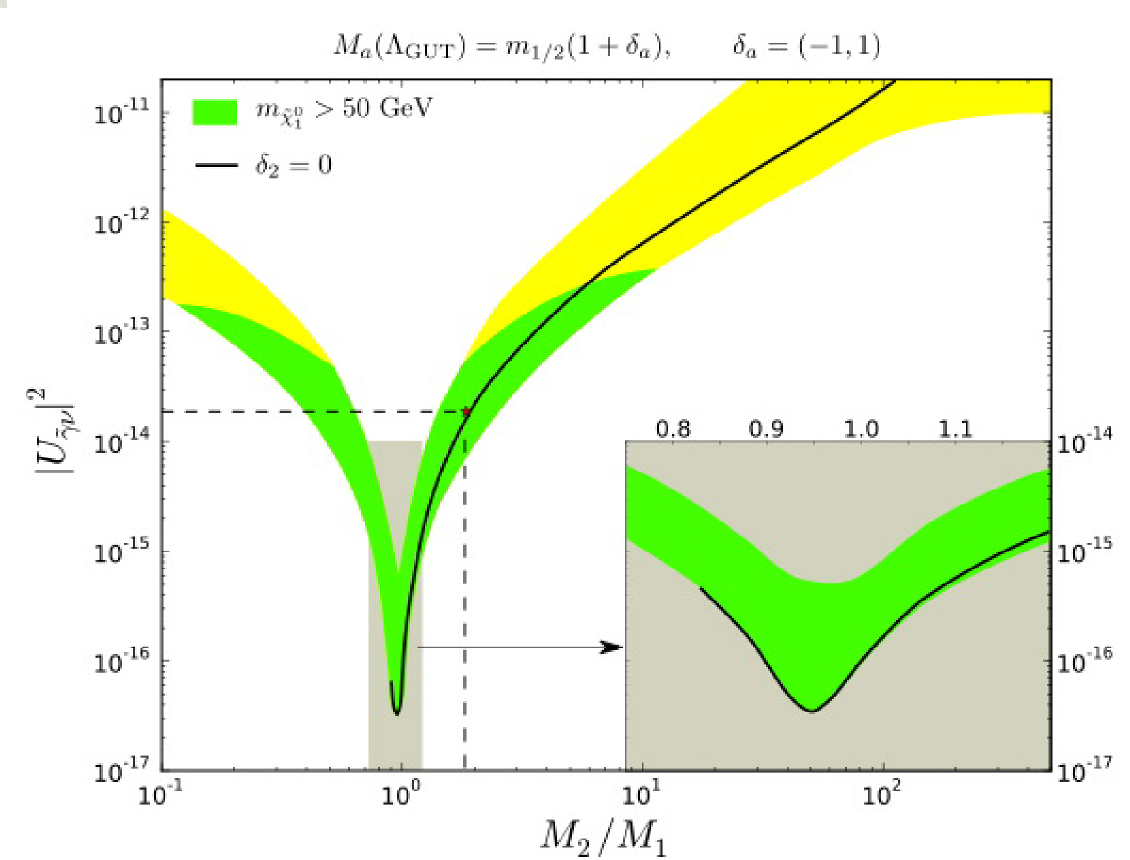
But no definite prediction on decay length for stau NLSP...

[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

Supersymmetry @ the LHC

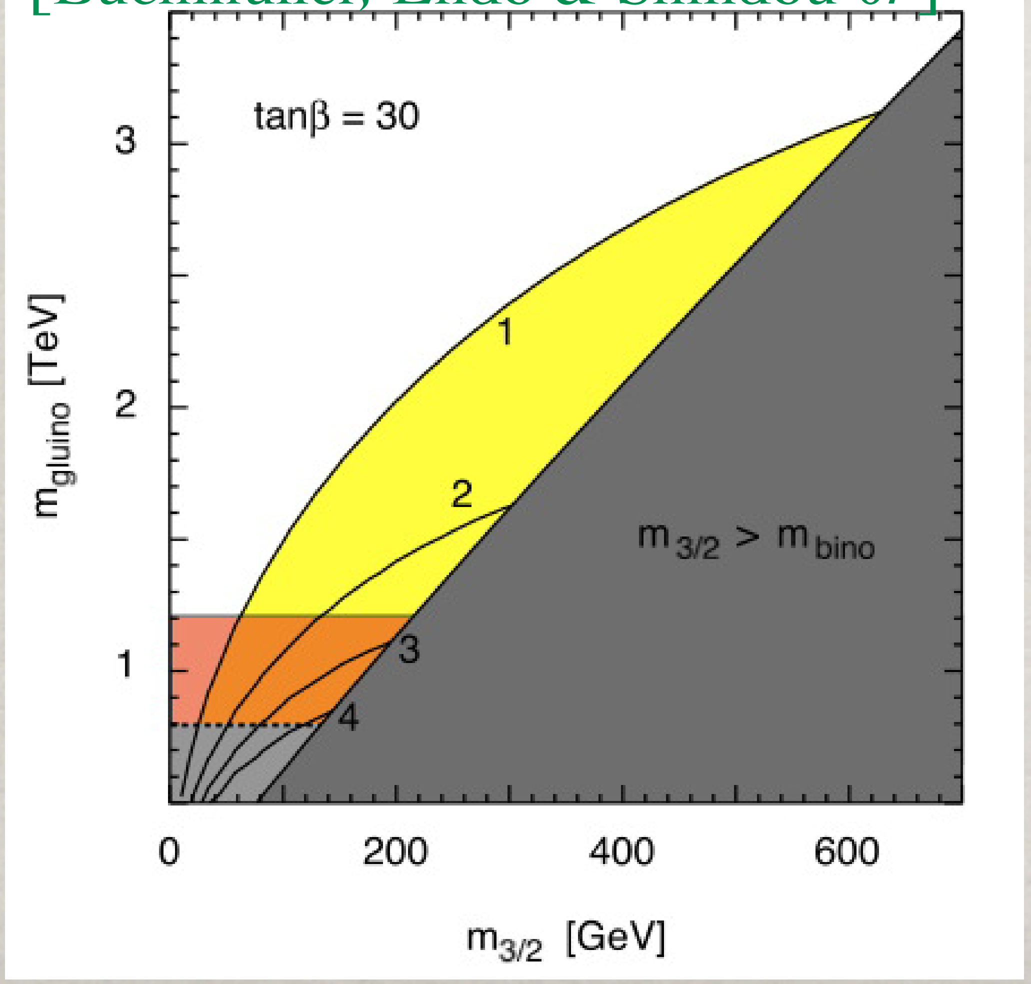
LHC: MASS SPECTRUM?

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...

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

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

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

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

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]

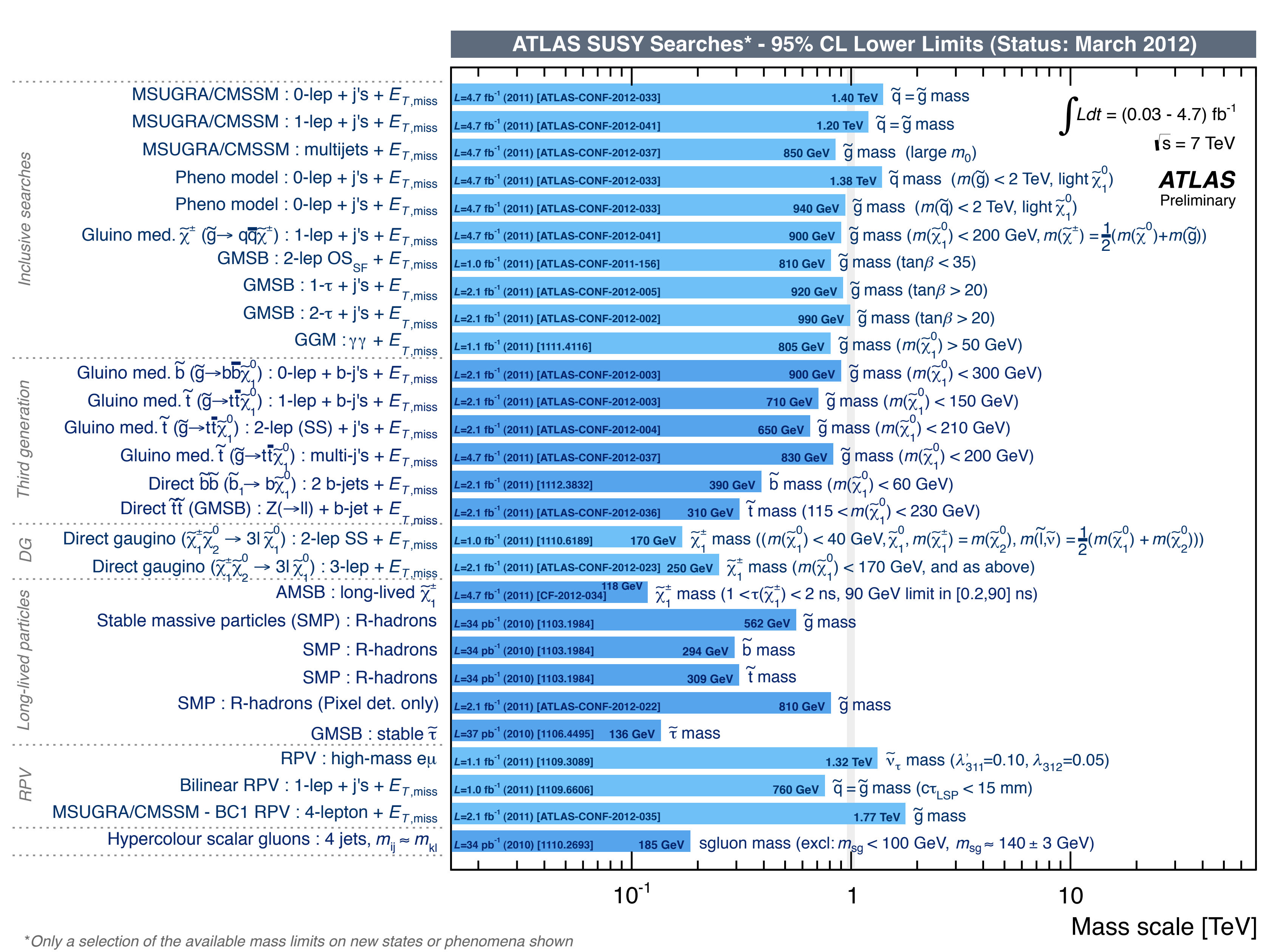
Broken Rp Gravitino: The decays may also happen within the detector with a sufficient number of events. Possible discovery or exclusion down to couplings $\epsilon \sim 10^{-9} - 10^{-10}$ if the colored states are accessible at LHC.

[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

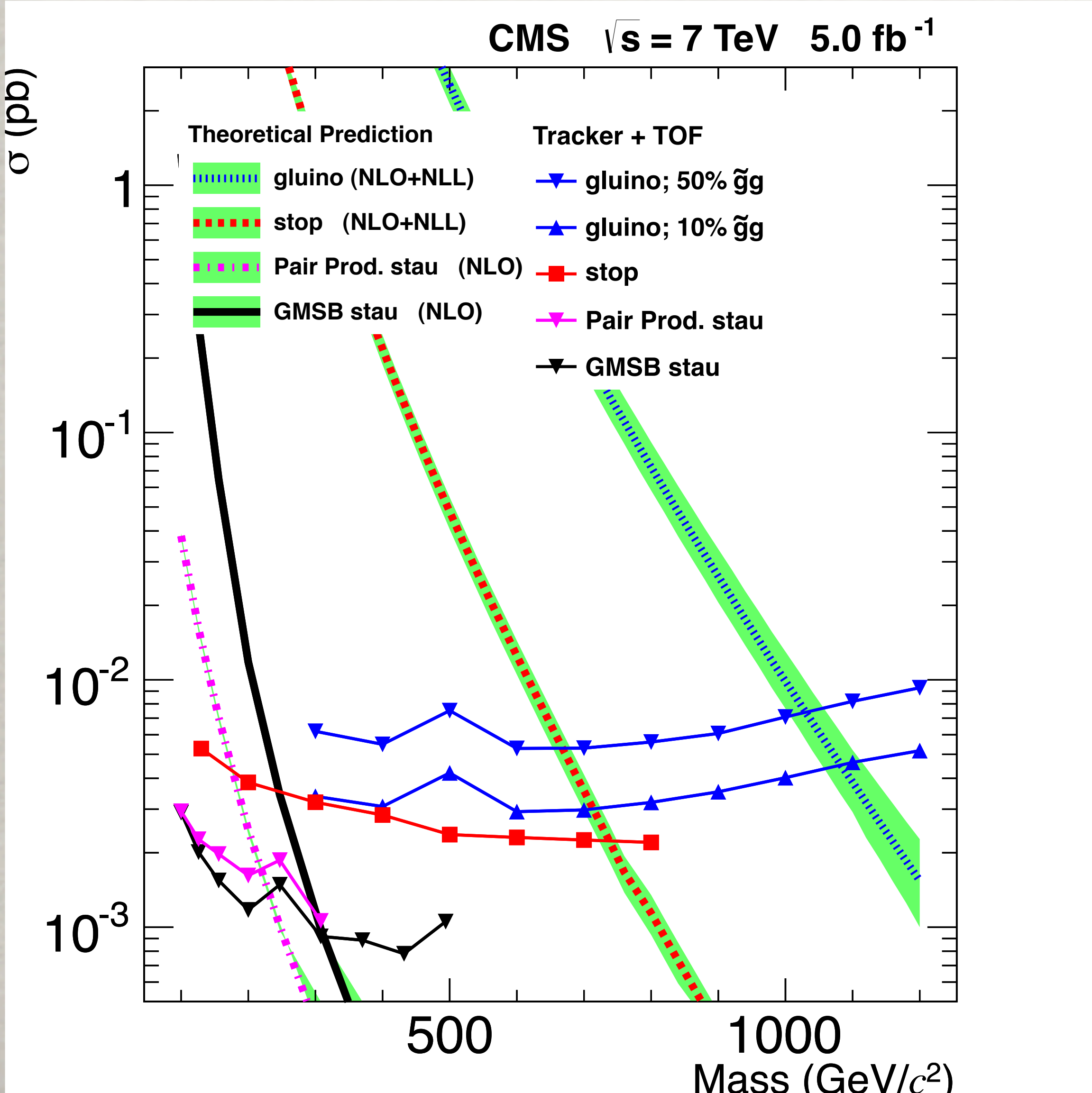
At the moment no significant excess found....

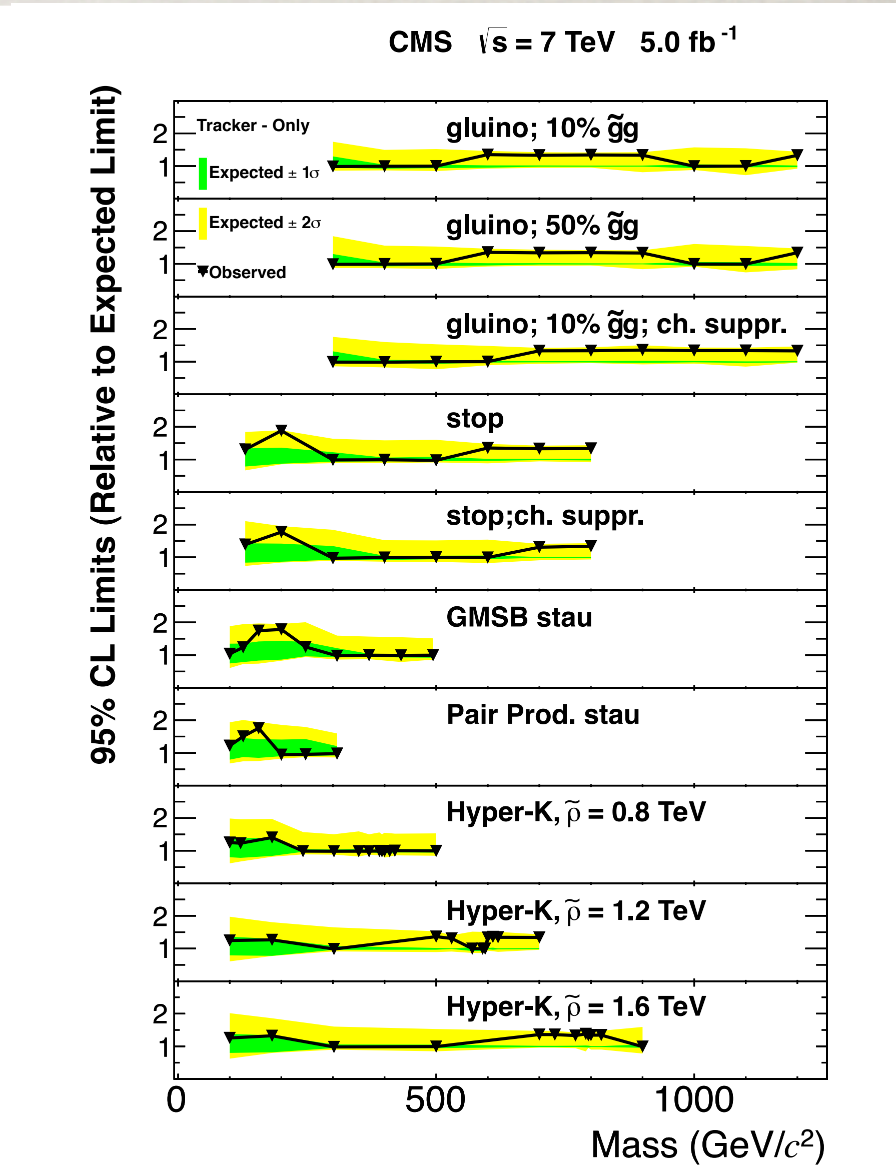


LHC: METASTABLE PARTICLES

Recent results from CMS for metastable SUSY particles:

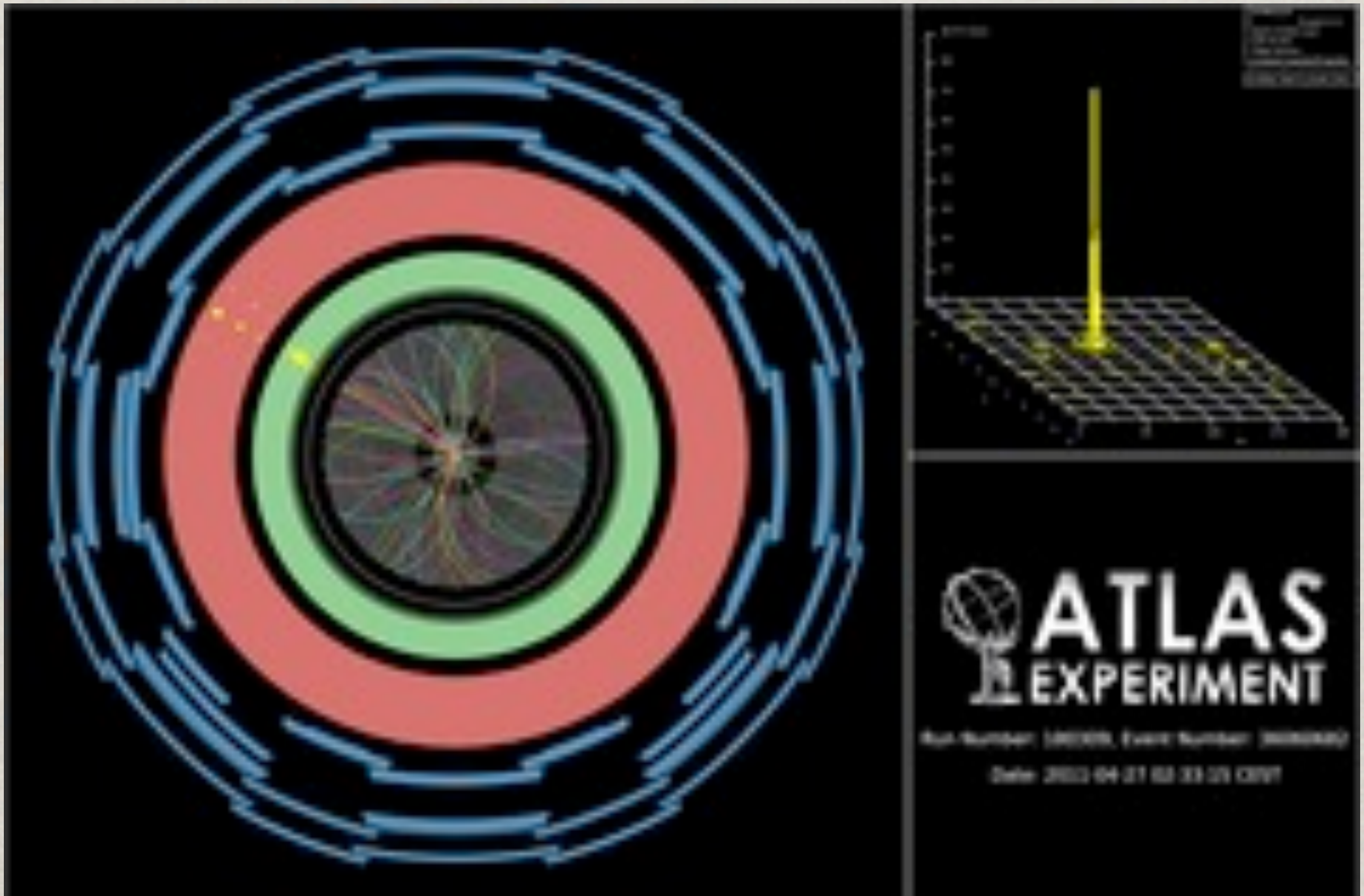
at the moment no significant excess found....





LHC: Monojets ?

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



Monojet candidate event !

LHC: Monojets ?

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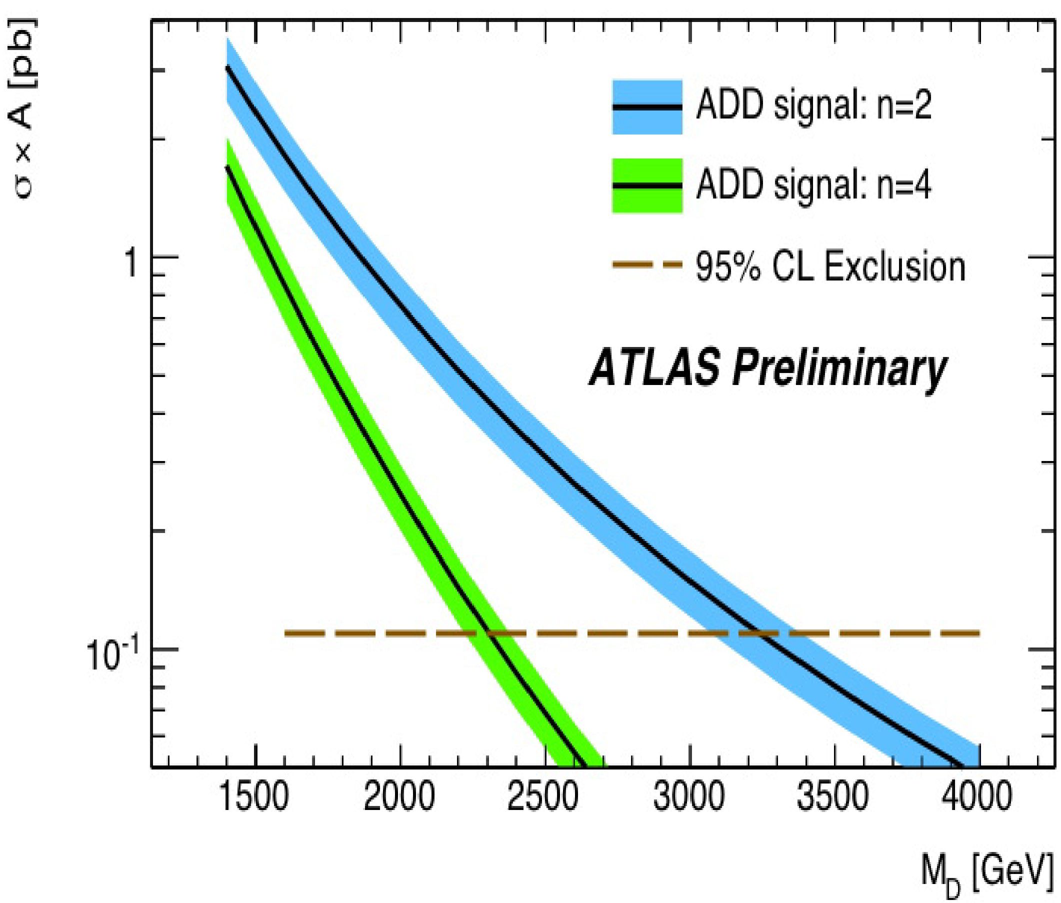
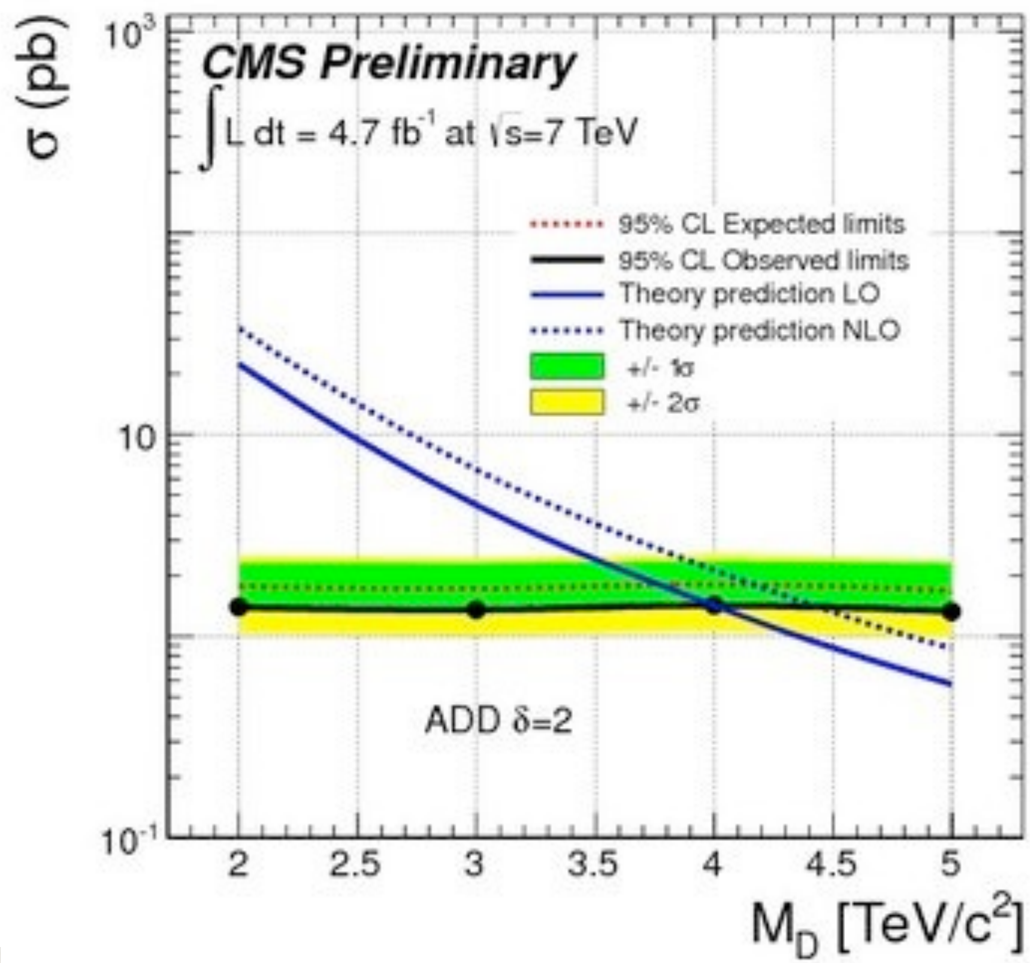




Not clear if excluded yet...

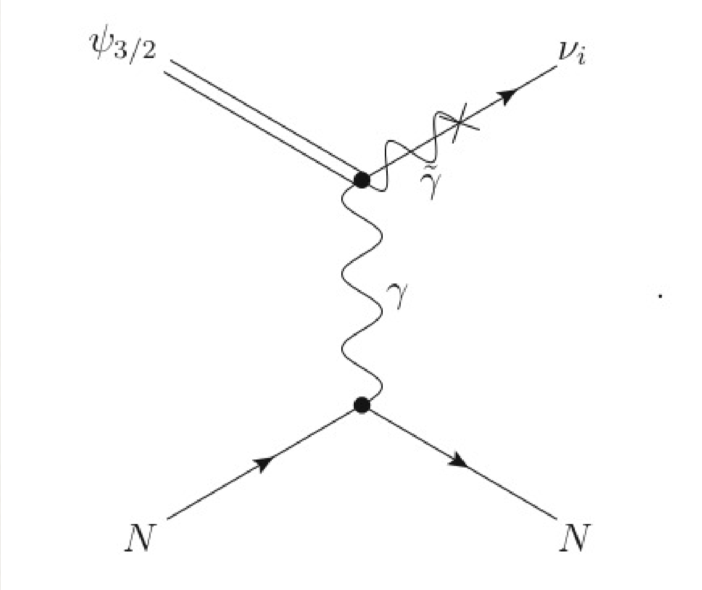
Gravitino
Direct detection
?

Gravitino Direct Detection

[Grefe PhD thesis 11], [LC, Grefe 12]

For R-parity breaking a new channel for inelastic scattering opens up for the gravitino/axino: photon exchange !

Need gravitino mass in the 1-100 MeV range to have recoil energies in the 1-100 keV



Similar to Exothermic DM

Simple coupling to the charge of the nucleus !

Unfortunately the rate is way too small for detection...

$$\sigma_p \sim 3.4 \times 10^{-43} pb \left(\frac{\xi_i}{10^{-7}} \right)^2$$

Outlook

Outlook

- The gravitino is a good CDM candidate which can reconcile high reheat temperatures with supersymmetry.
- BBN can constrain the lifetime and density of the NLSP. For neutralino NLSP the constraints can be relaxed for a degenerate gaugino spectrum with special signatures at the LHC !
- Gravitinos can survive as DM also for broken R-parity, but the breaking has to be suppressed. Indirect DM searches already set limits on these parameters.
- Different signals are possible at the LHC: displaced vertices, missing energy or metastable charged particles:

  Let us hope for a signal soon !