EISA
European Institute for Sciences and Their Applications
Corfu Summer Institute
12th Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece 2012

DARK MATTER CANDIDATES

Laura Covi

Institute for Theoretical Physics
Georg-August-University Göttingen

$[q,p]=i\hbar$

invisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME

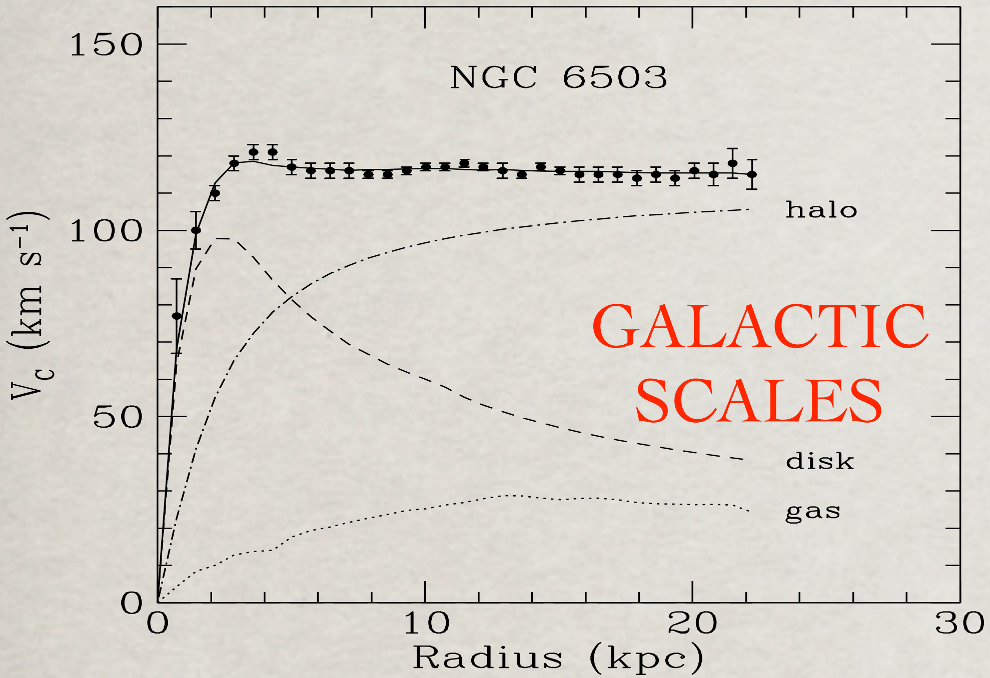
MARIE CURIE ACTIONS

Outline

- Introduction: Dark Matter and SUSY
- Neutralino DM & Higgs mass...
  - CMSSM & less constrained scenarios
  - How light can neutralino DM be ?
- Gravitino CDM
- DM candidates & the FERMI line(s)
- Outlook

Introduction

DARK MATTER EVIDENCE



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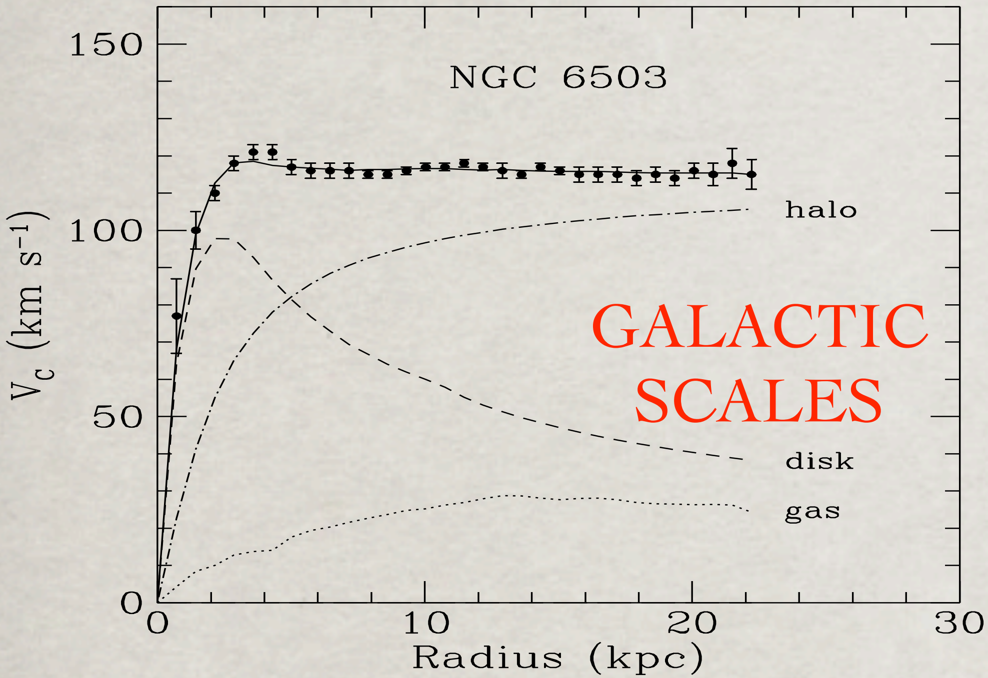

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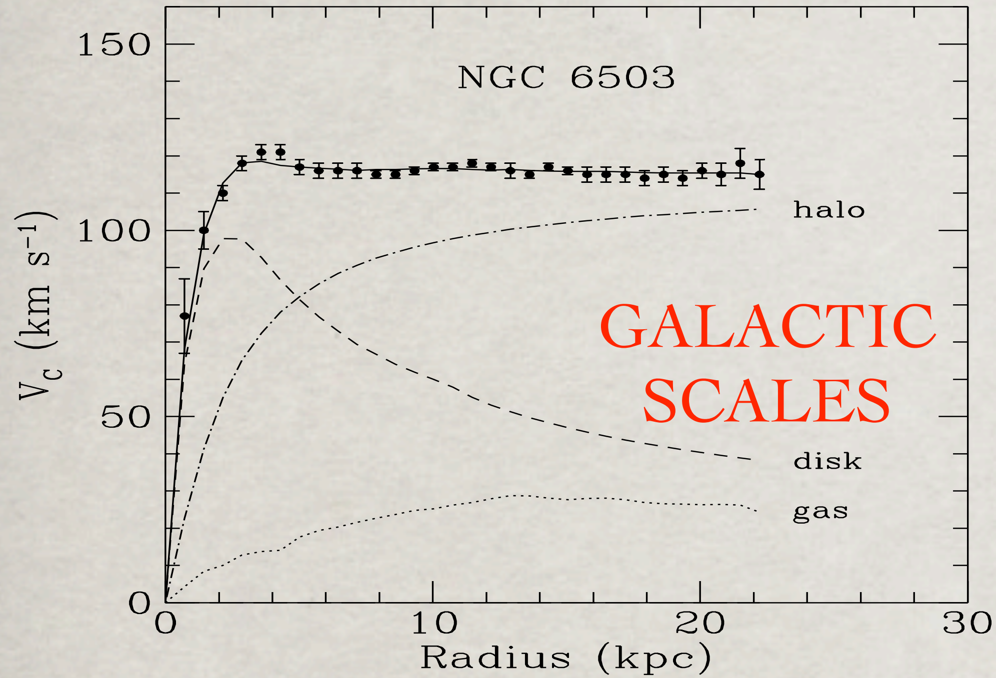

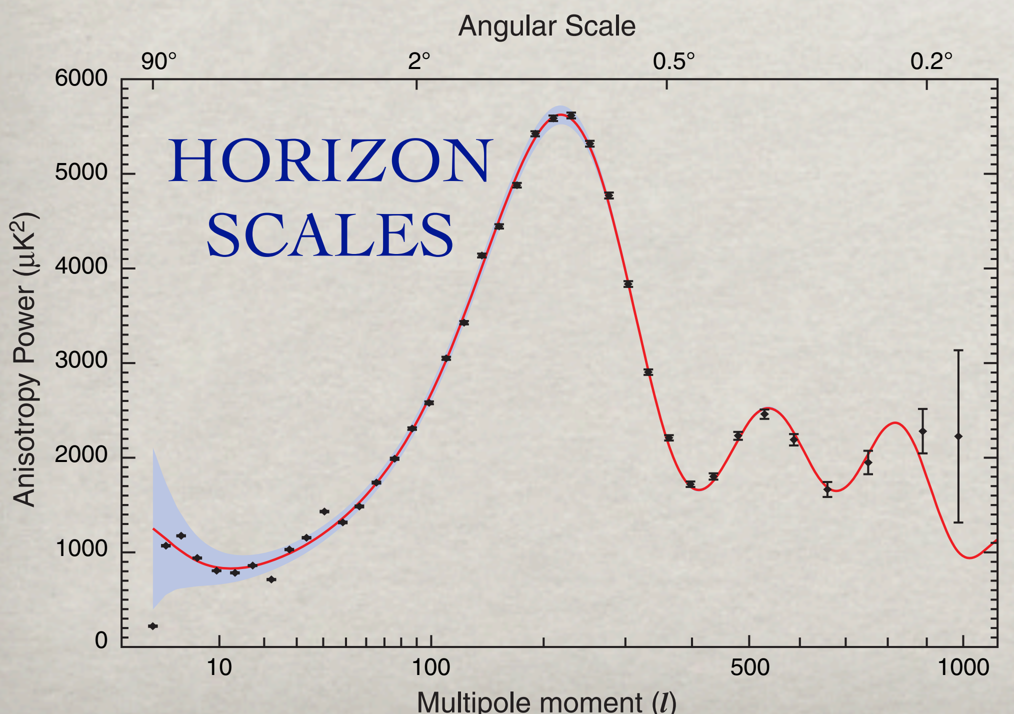

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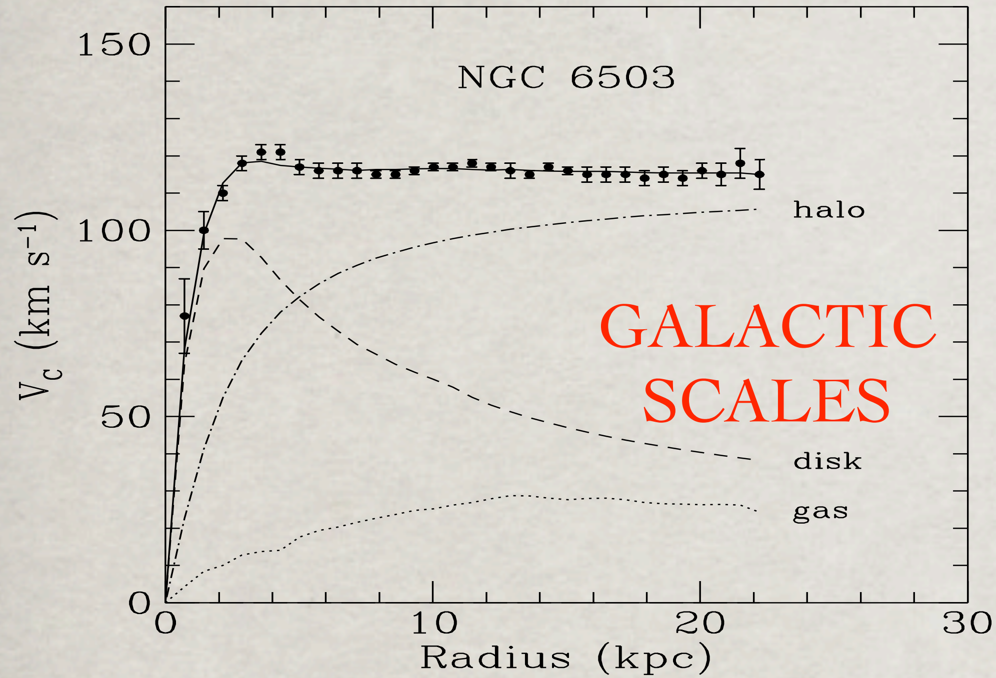
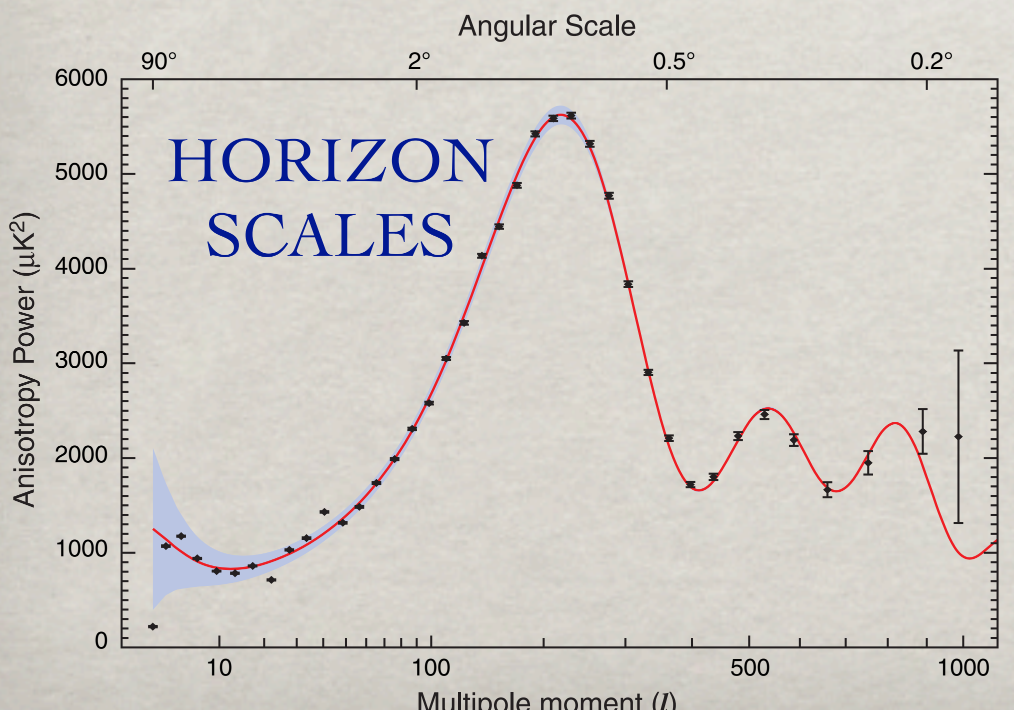




Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	~ 0.1	Cold

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 ???

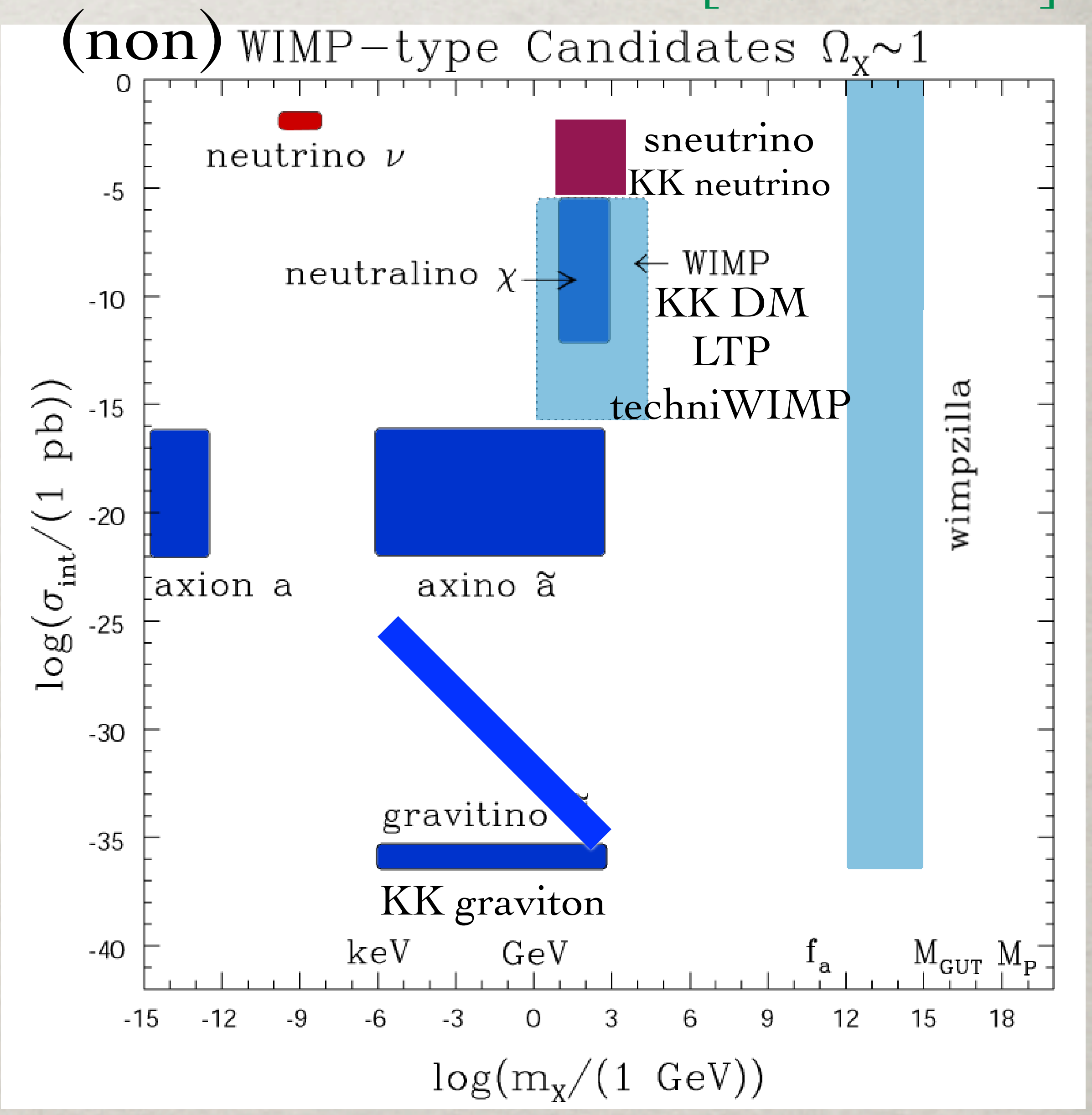
Only upper bounds from Bullet cluster or the shape of halos, at the order σ/m ~ 1-0.04 barn/GeV, but

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

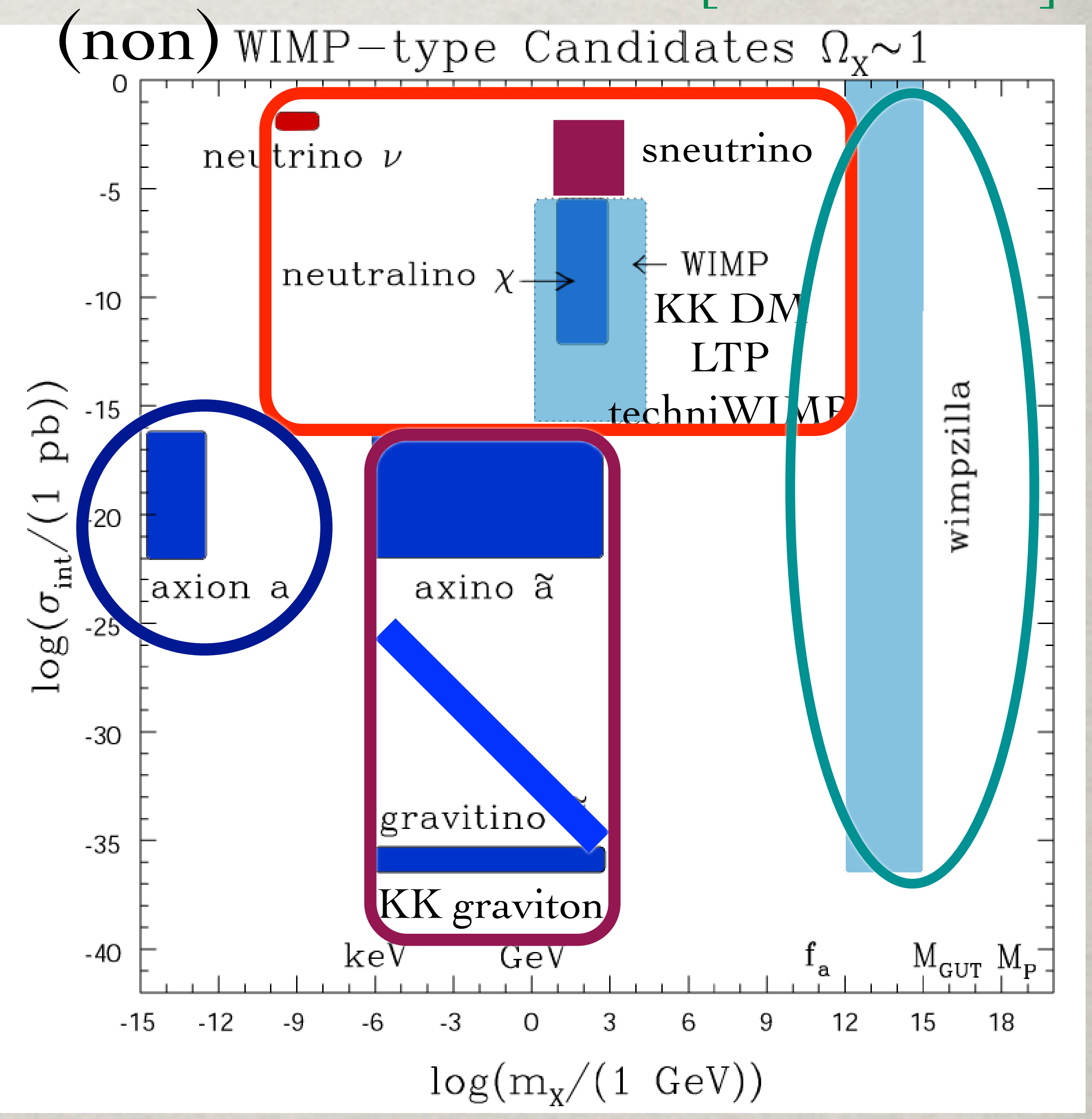
[Roszkowski 04]



DARK MATTER CANDIDATES

[Roszkowski 04]

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



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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$\tilde{\chi}$

$\psi_{3/2}$

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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:

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

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

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

The gravitino gives us direct information on SUSY breaking

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

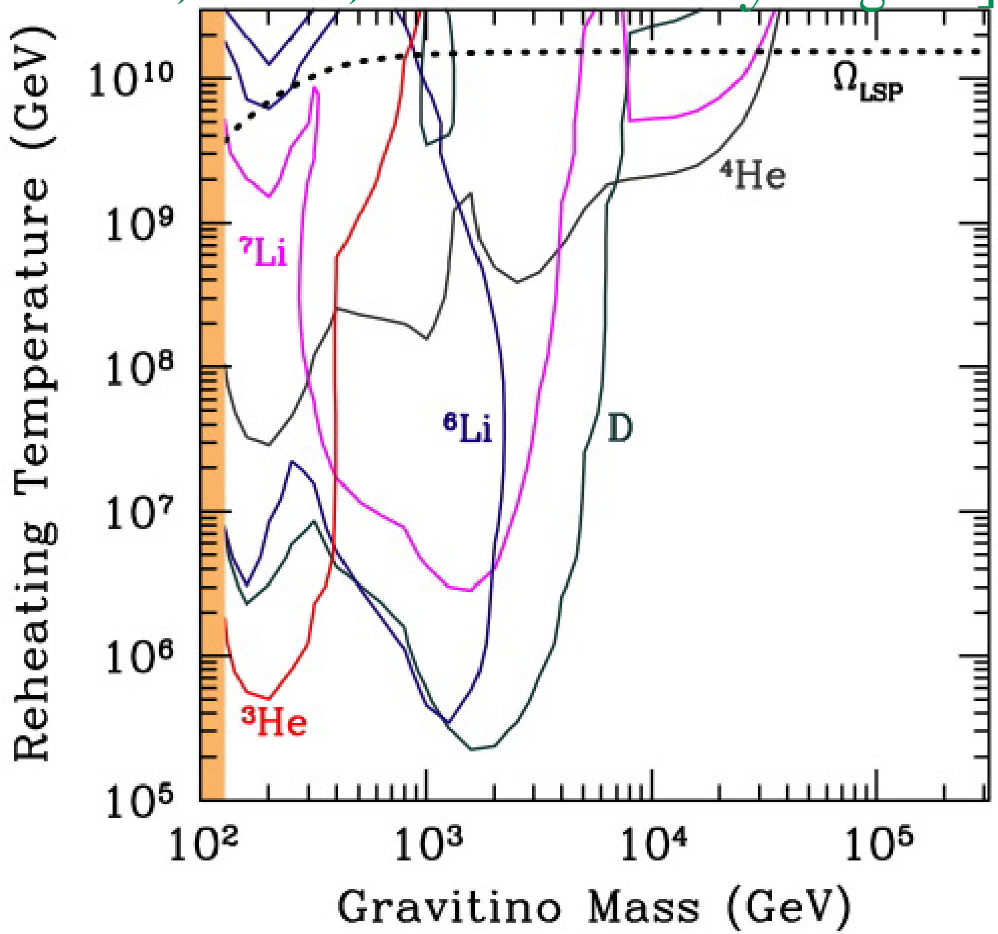
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1 \mathrm{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10}\ \mathrm{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}} \right)^2$$

[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]

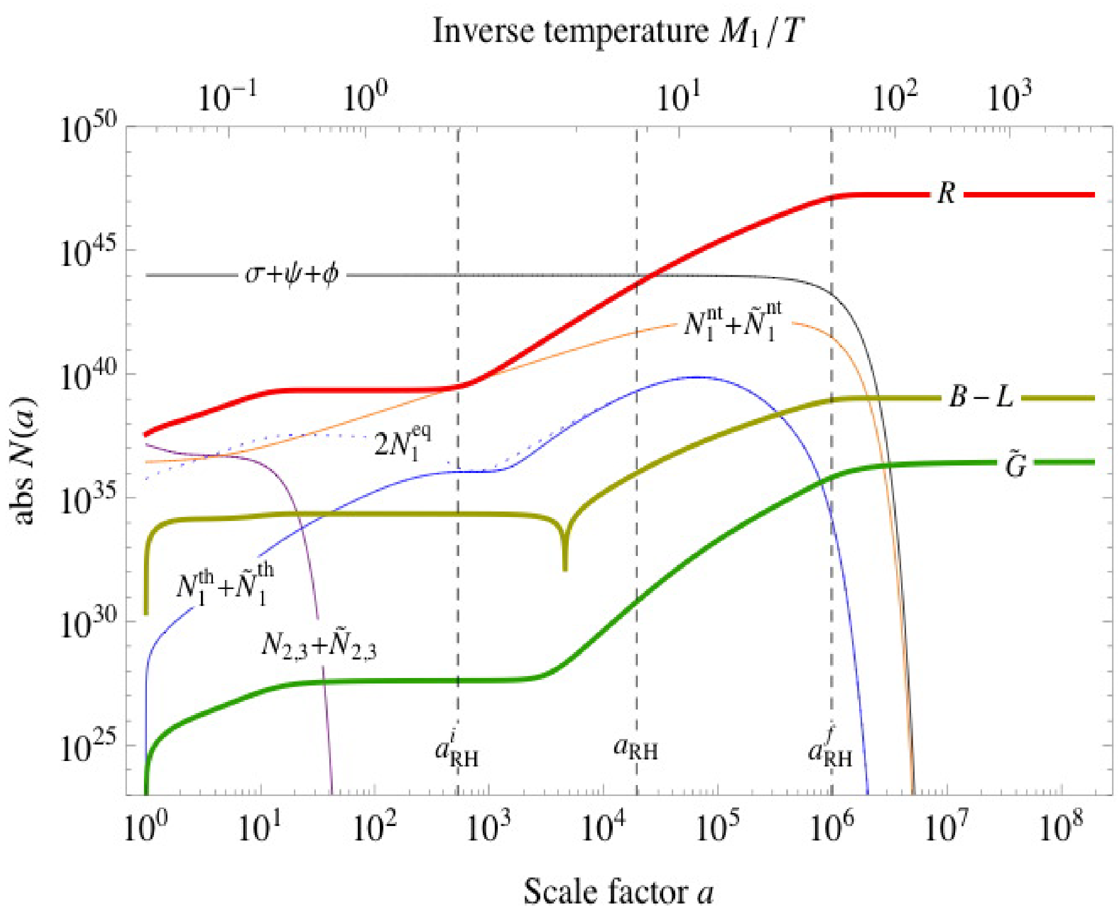


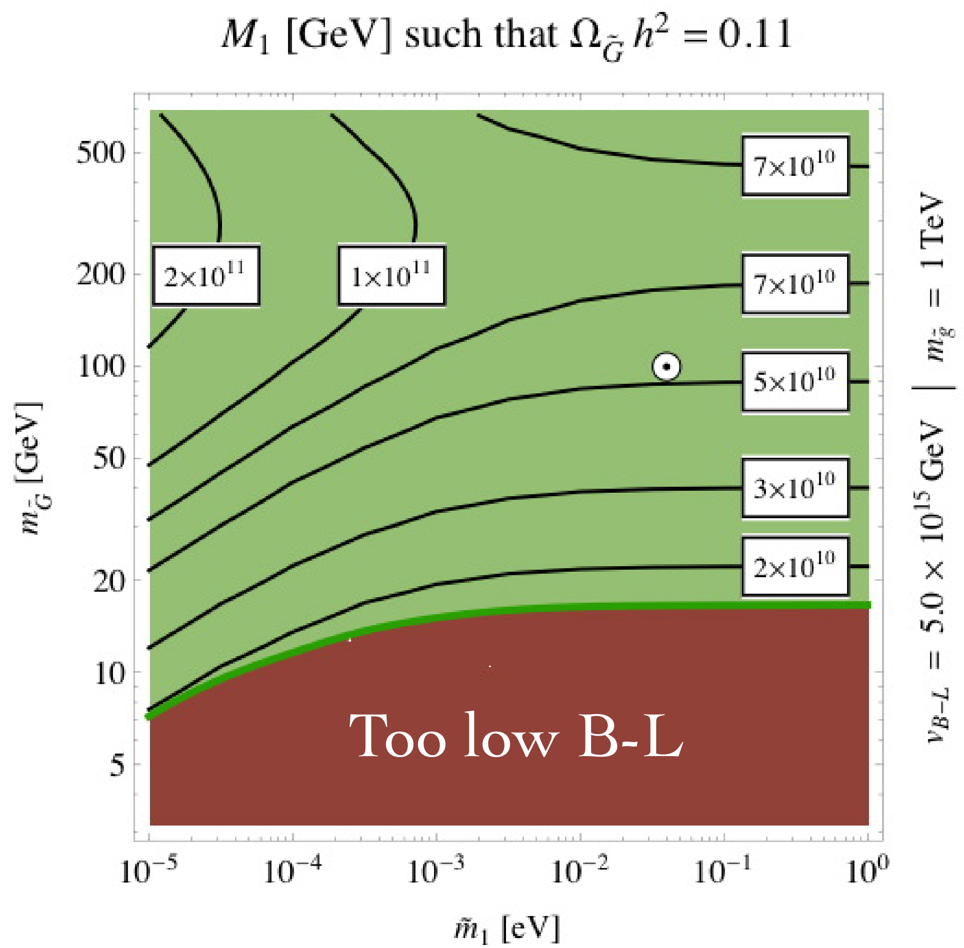
$$\tau_{3/2} = 6 \times 10^7 \mathrm{s} \left(\frac{m_{3/2}}{100\mathrm{GeV}} \right)^{-3}$$

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 or obtained by high scale inflation!

Gravitinos from reheating

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



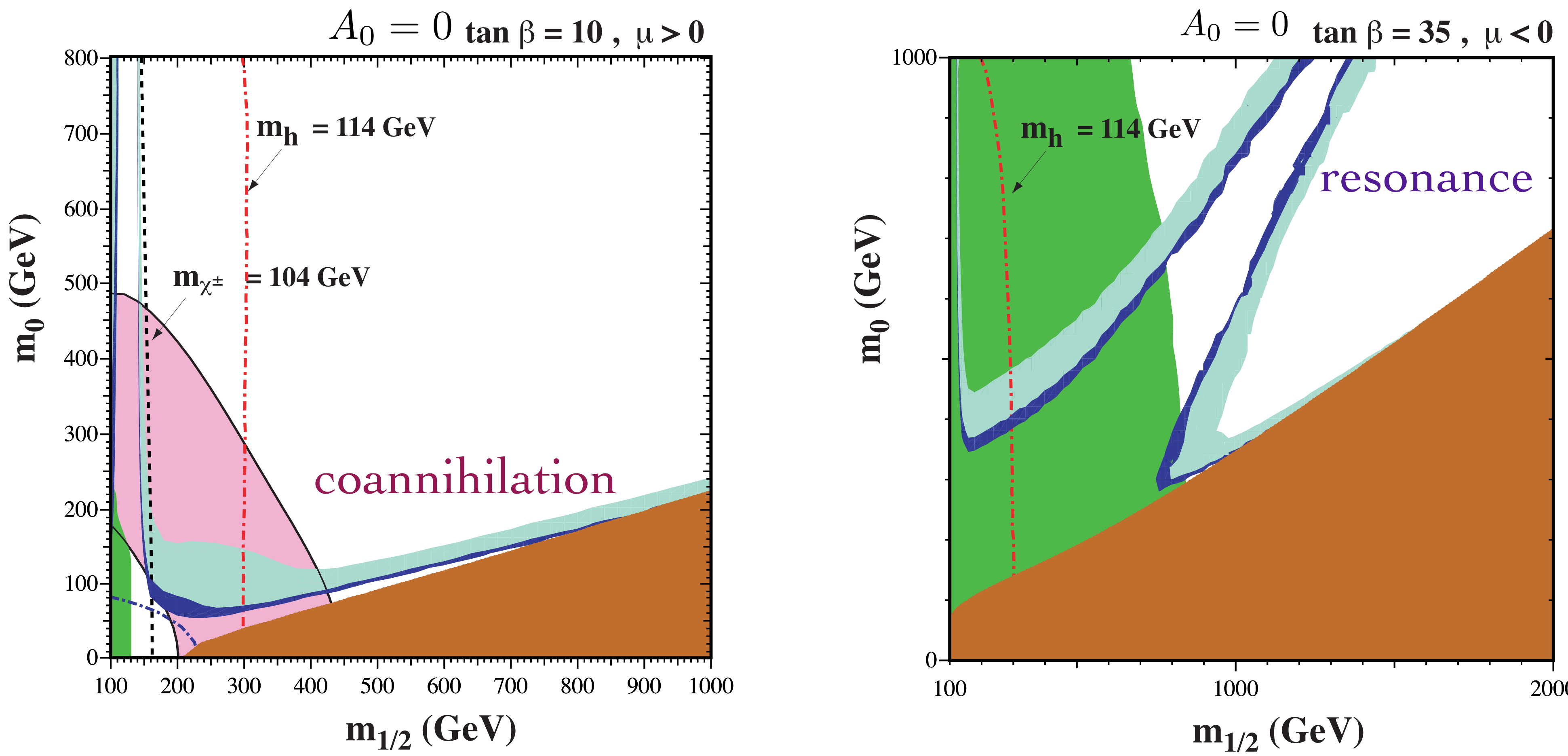


Gravitino DM and B-L may be produced both from heavy RH neutrino decay during reheating: then there is a relation with the neutrino sector parameters and a lower bound on $m_{\tilde{G}}$

Neutralino DM & the Higgs

Neutralino DM in the Constrained MSSM

[Ellis, Olive, Santoso & Spanos 03]



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 !

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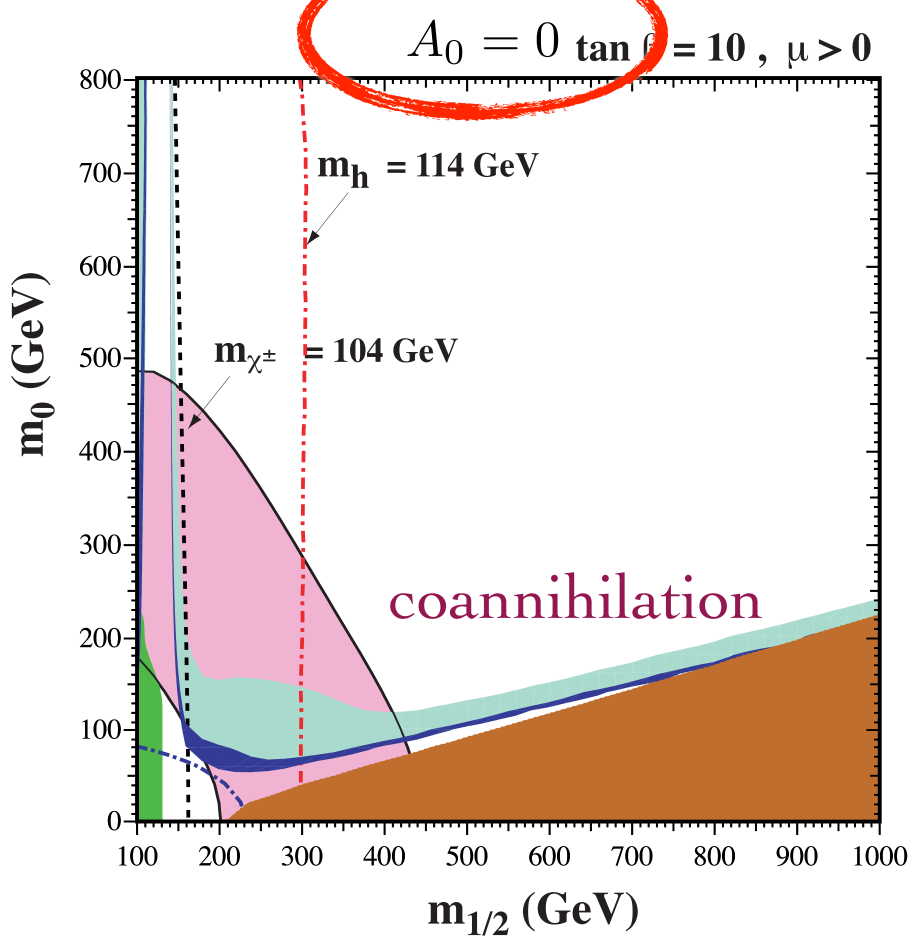

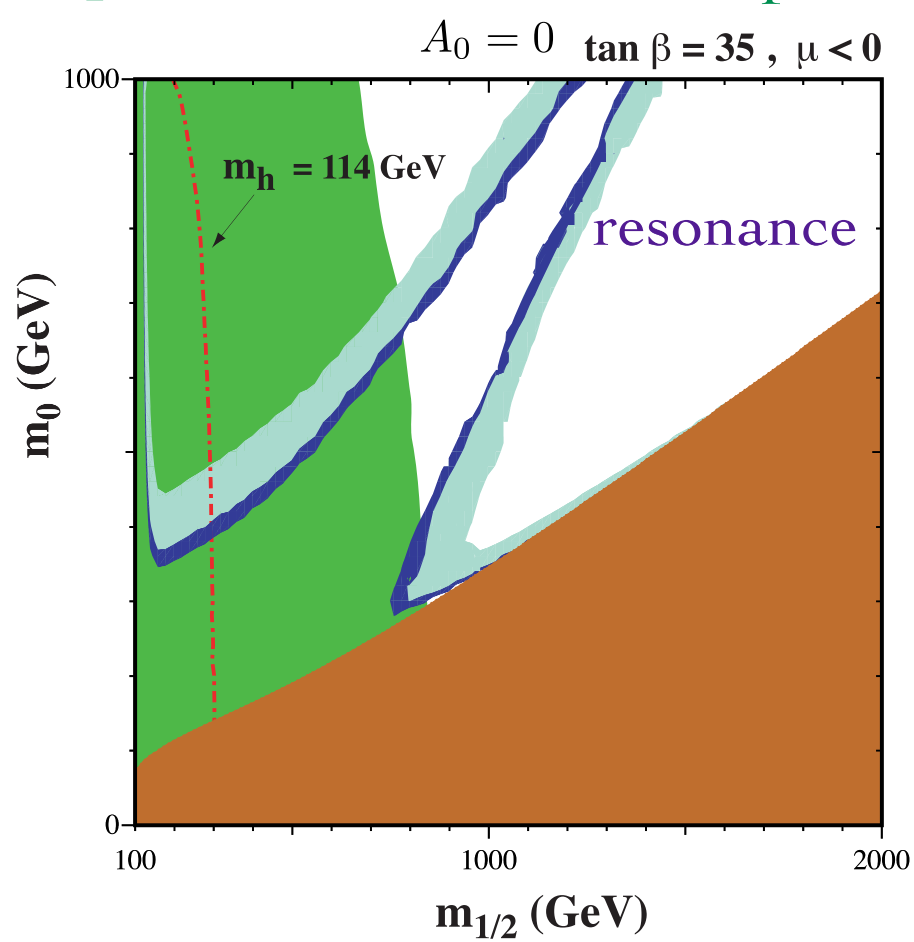

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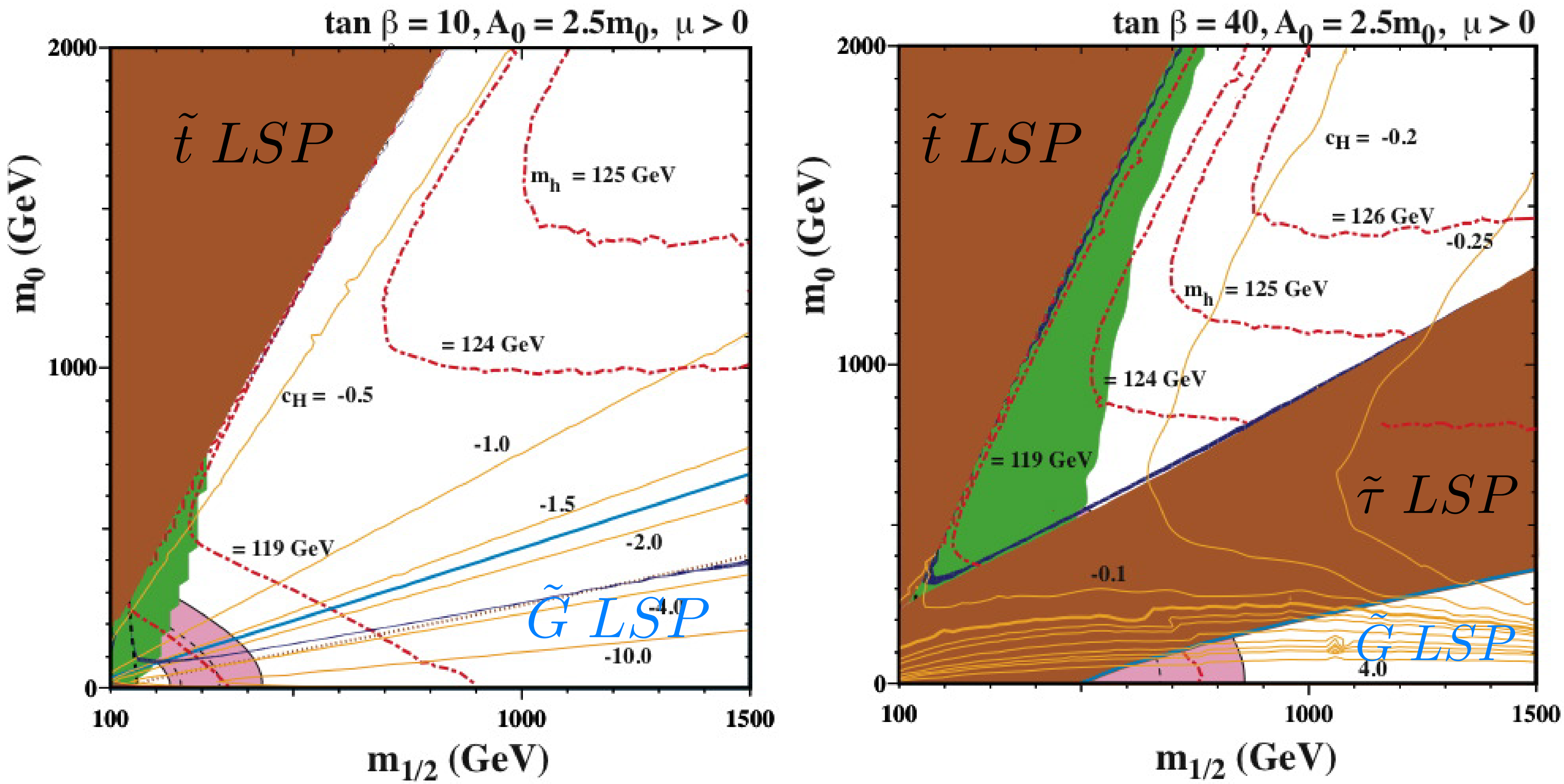

Even in the large A-term regions, no coannihilation region for large Higgs mass at small $\tan\beta$ ...

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

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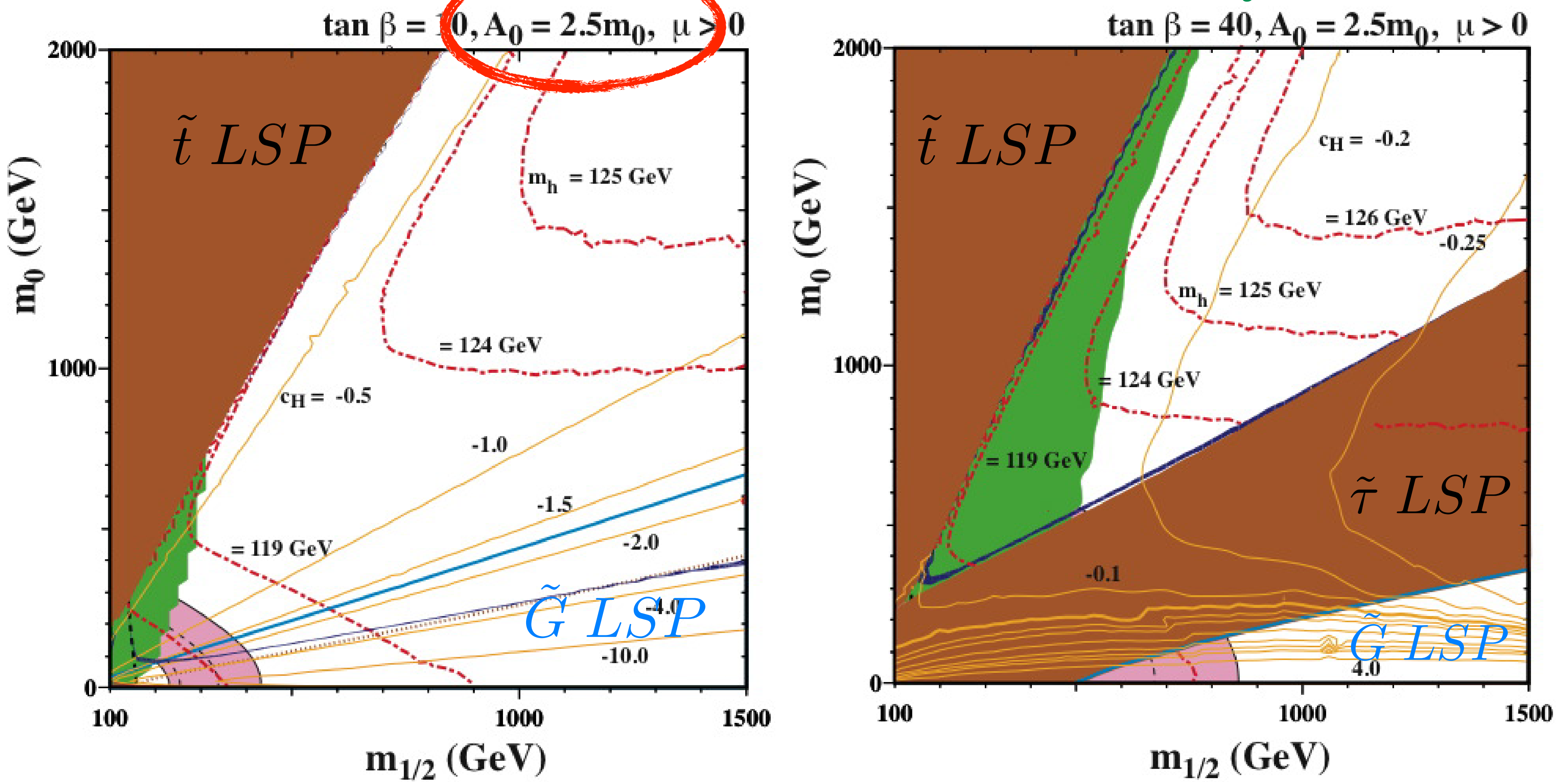

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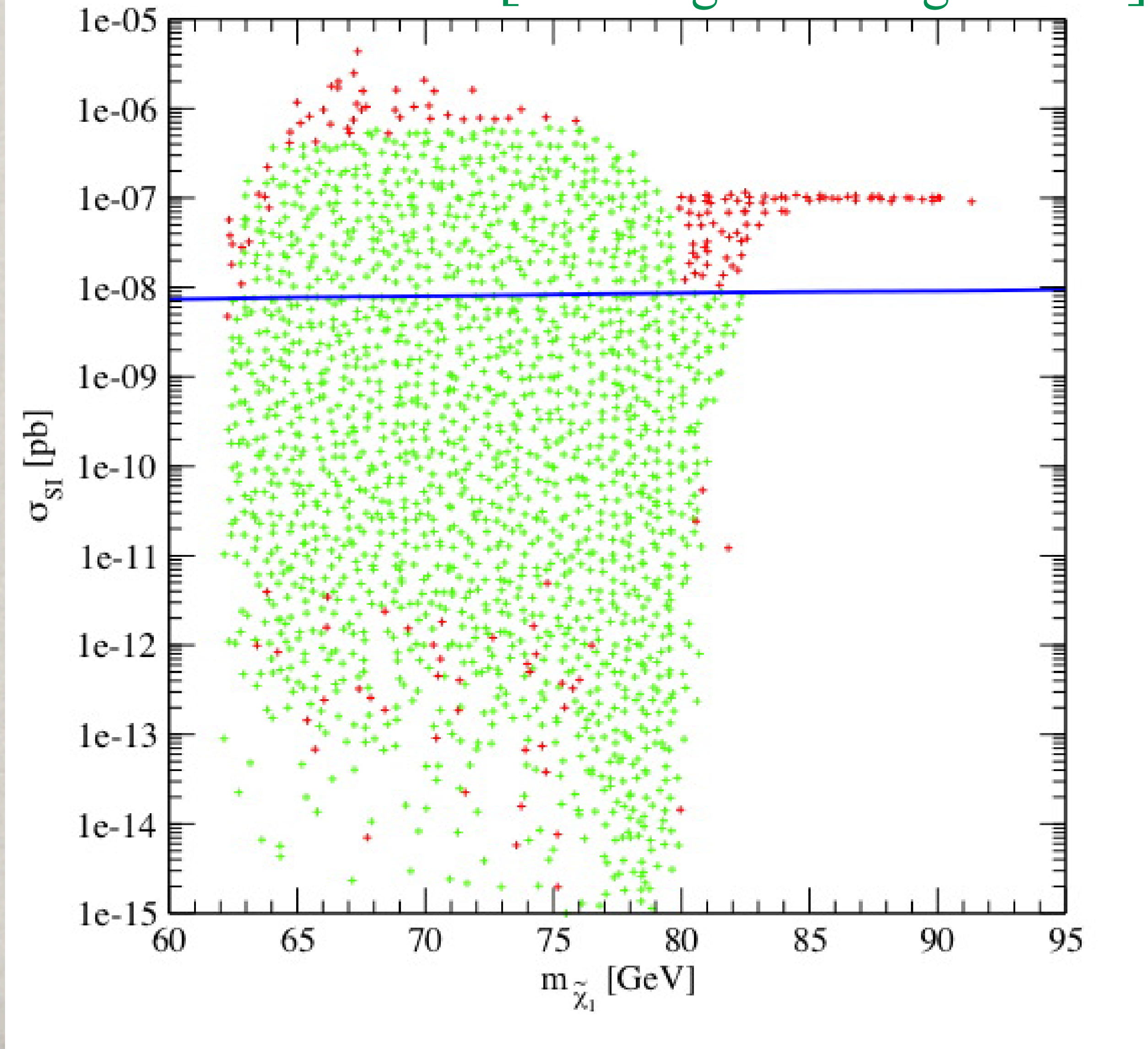
The NMSSM can help, but without C...

Allow for non-universal Higgs masses and one can find regions with the right Higgs mass and neutralino DM density

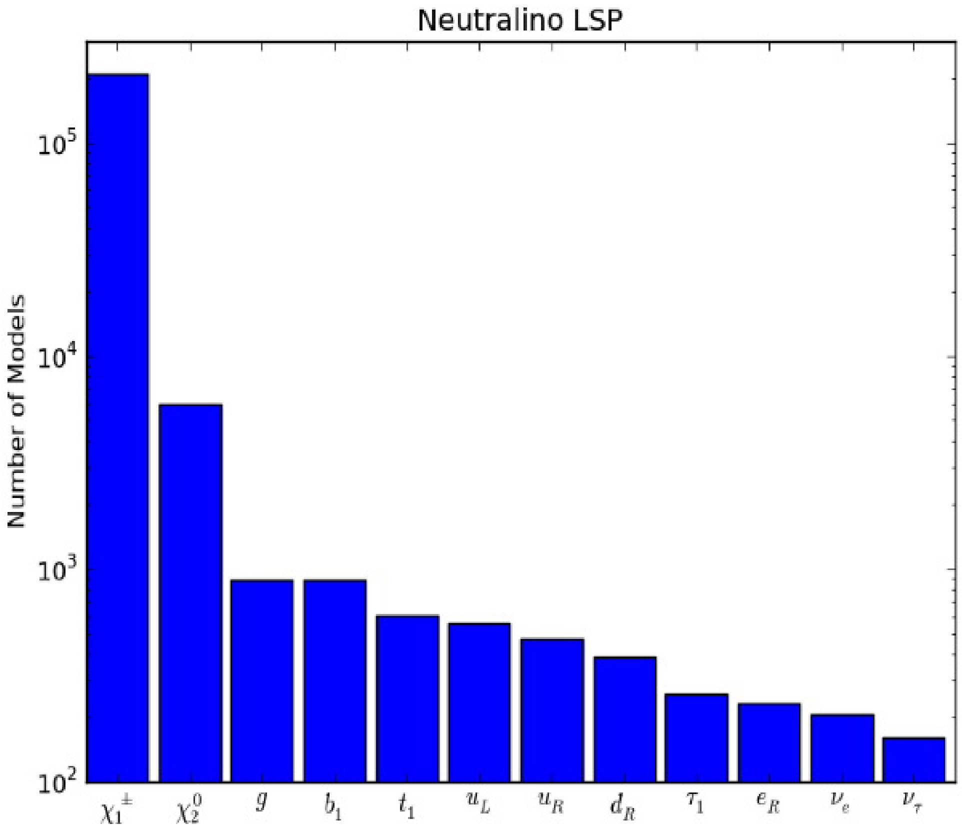
[Ellwanger & Hugonie 12]

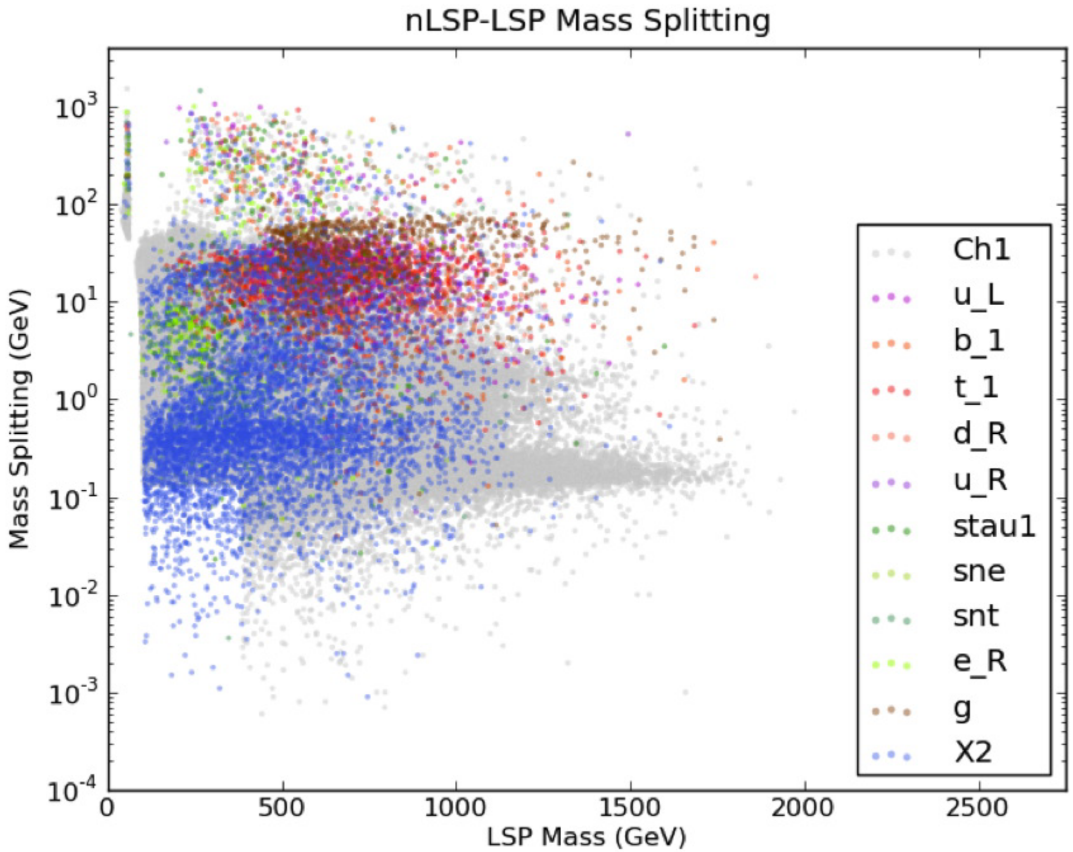


Many orders of magnitude spanned due to the neutralino singlet component

New pMSSM scan with LHC Higgs mass bound

[Cahill-Rawley et al 12]

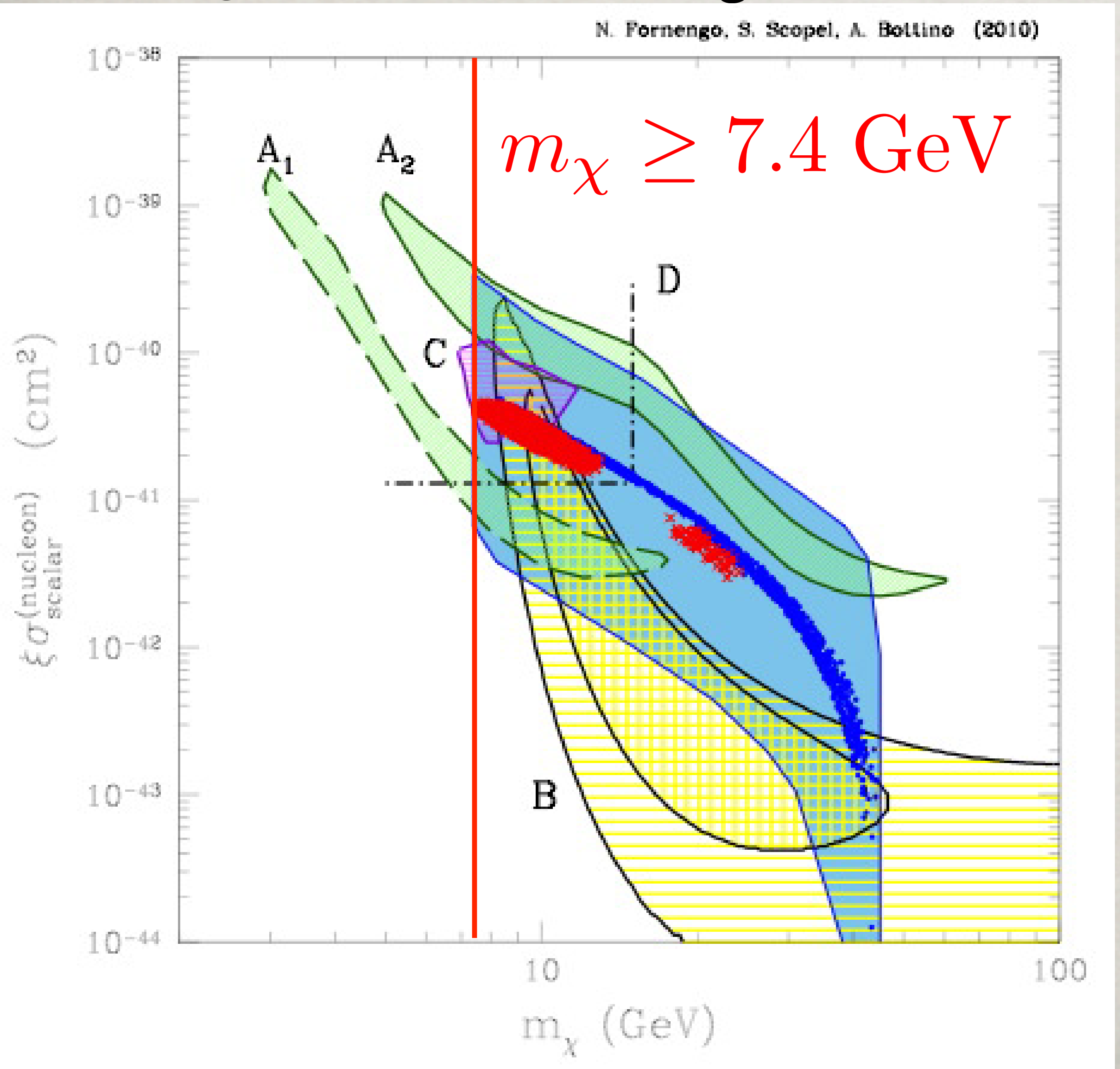




LIGHT NEUTRALINO ?

Recently several experiments hint to a low mass WIMP (CoGeNT, CRESST, CDMS) as does the DAMA/LIBRA signal...

Question: can a light neutralino explain this ? YES !



[Fornengo et al '10, Calibbi et al '11]

A1/2 DAMA/LIBRA

B CDMS

C CoGeNT

D CRESST

$\Omega_\chi h^2 = \Omega_{CDM} h^2$

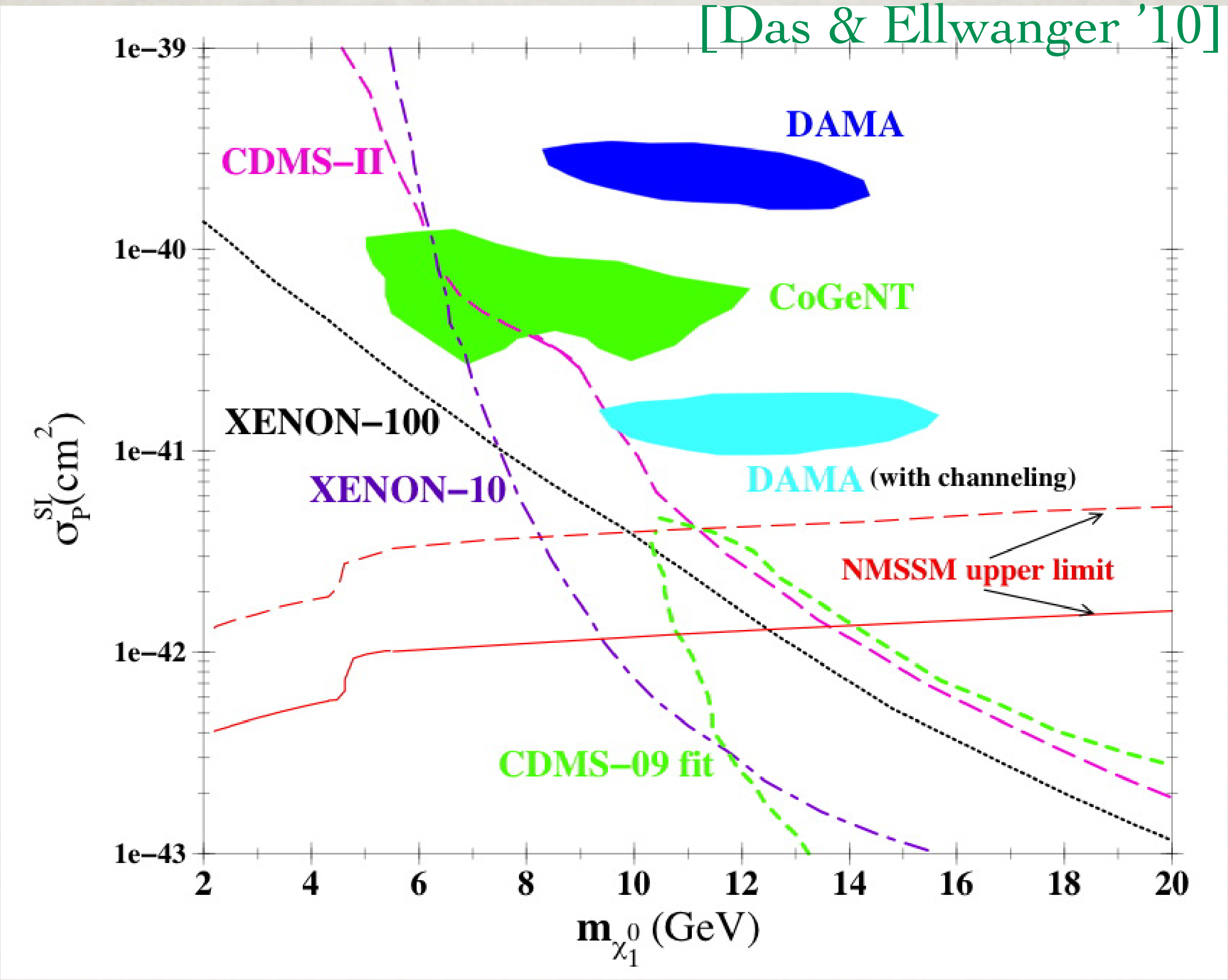
$\Omega_\chi h^2 < \Omega_{CDM} h^2$

But excluded by XENON-100

Light neutralino in NMSSN?

Not possible to obtain such large cross-section in the NMSSM, even if there it is easier to have a light neutralino.

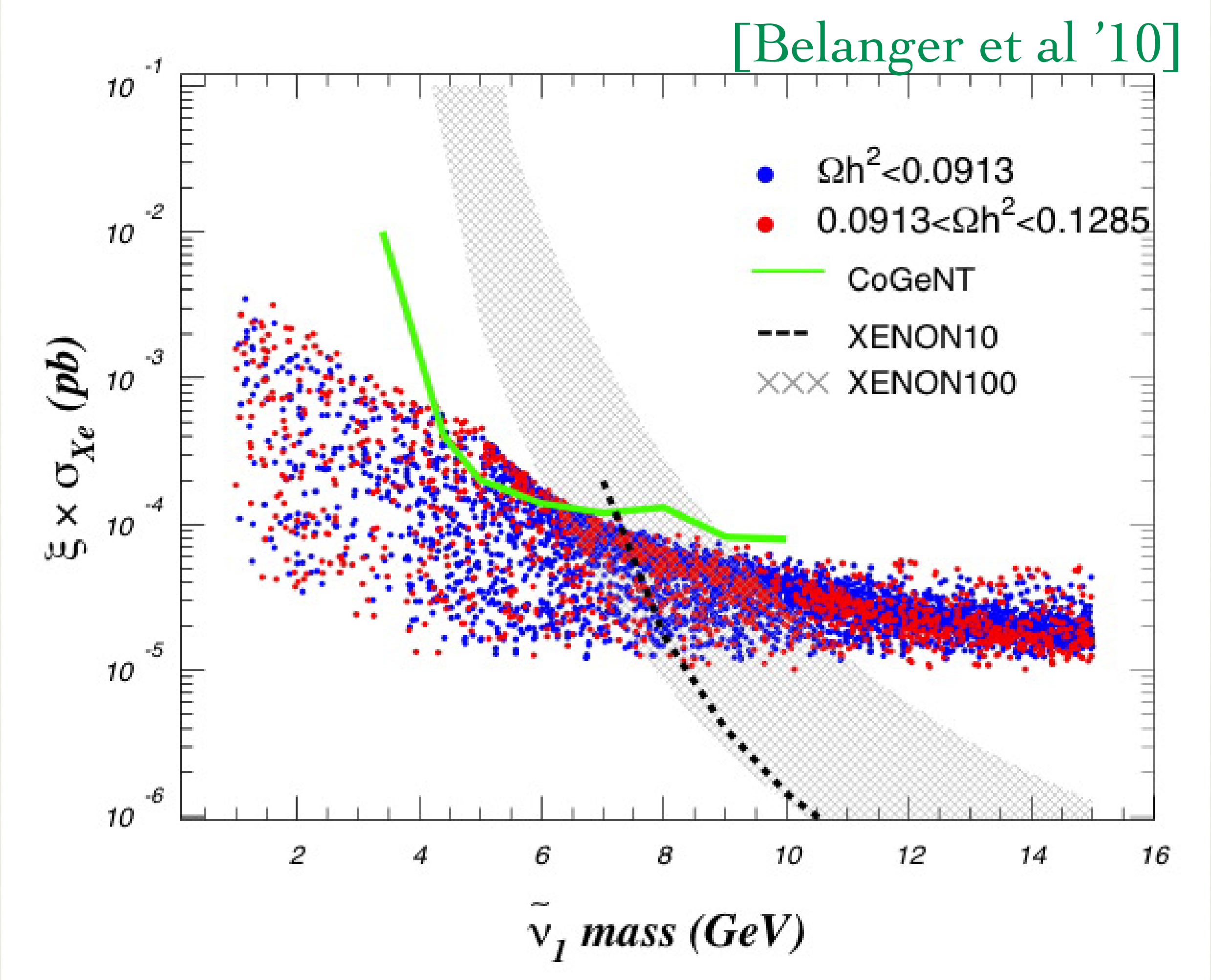
[Das & Ellwanger '10]



But possible in other singlet extensions [Kappl, Ratz & Winkler '10]

Mixed sneutrino DM

A mixed sneutrino can be also very light and still have the right thermal density... But also regions at large mass are open.



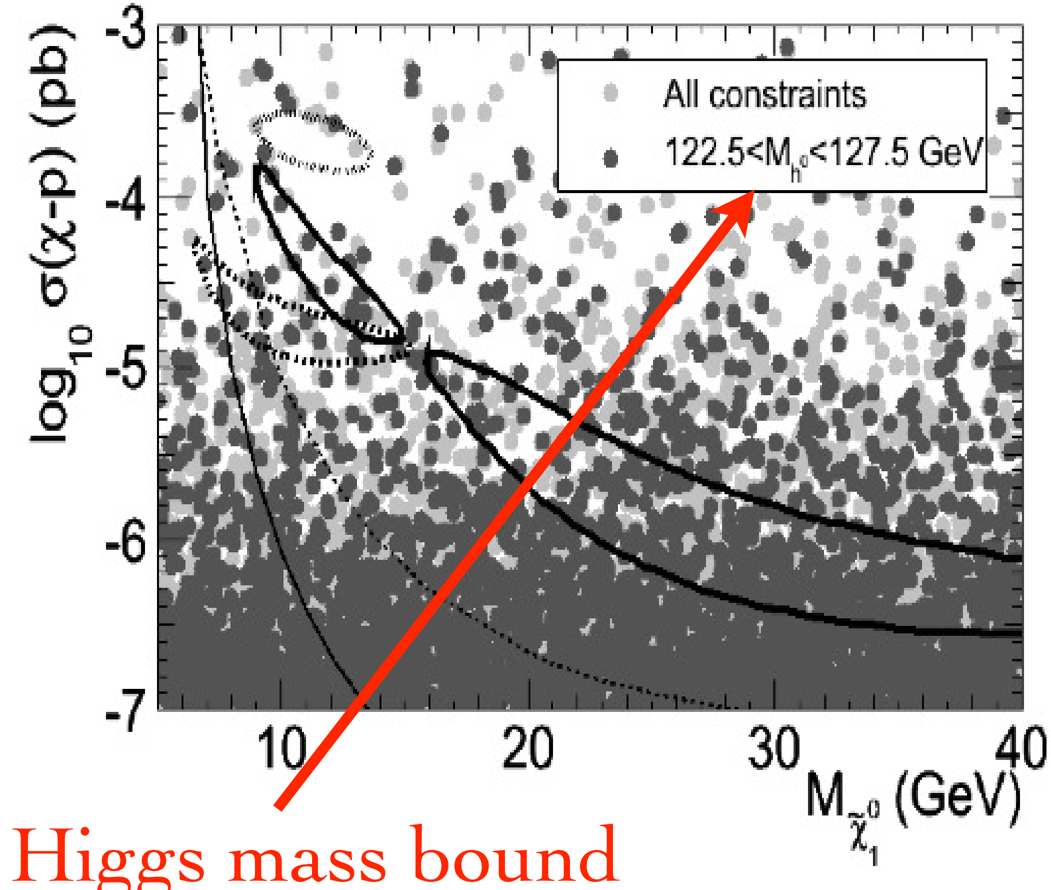
Similar region and more also for mixed sneutrino in NMSSM

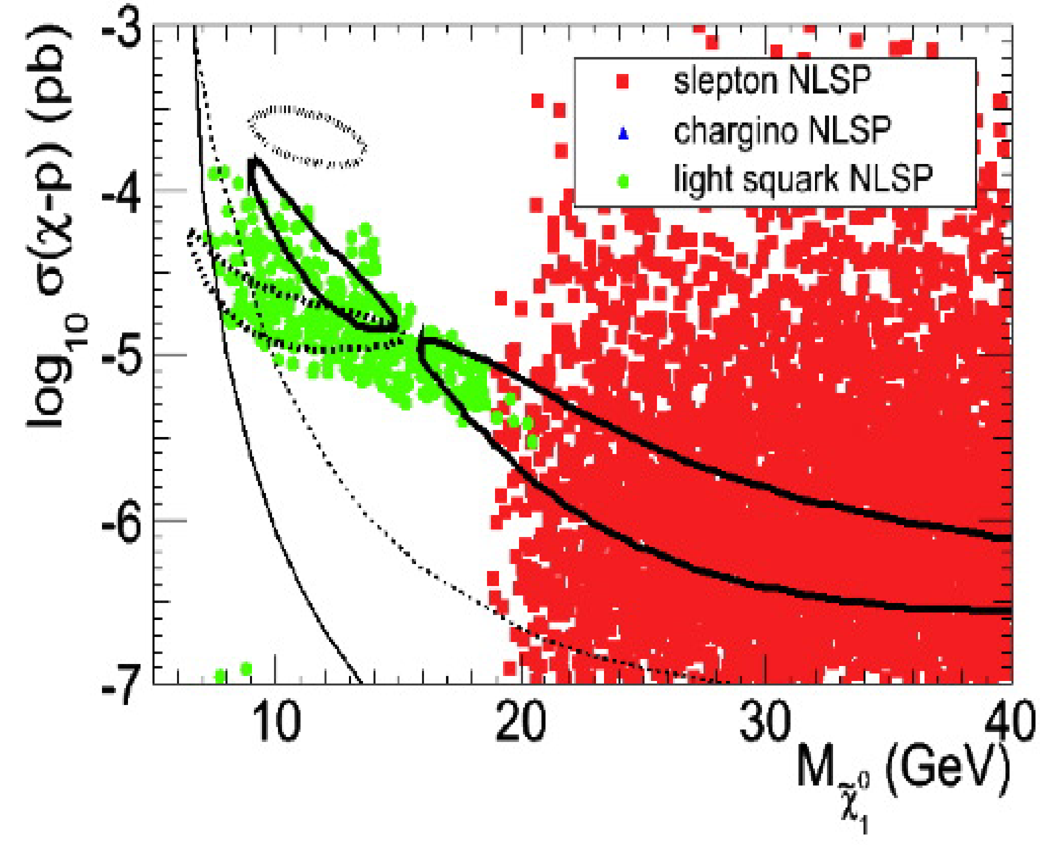
[Cerdeno et al '09]

Light neutralino DM in the pMSSM...

Light neutralinos compatible with right thermal density and compatible with the light DM signal are possible in the 19 parameters phenomenological MSSM (pMSSM)

[Arbey, Battaglia & Mahmoudi 12]





DM density points to squarks NLSP, degenerate with LSP...

gravitino Cold Dark Matter

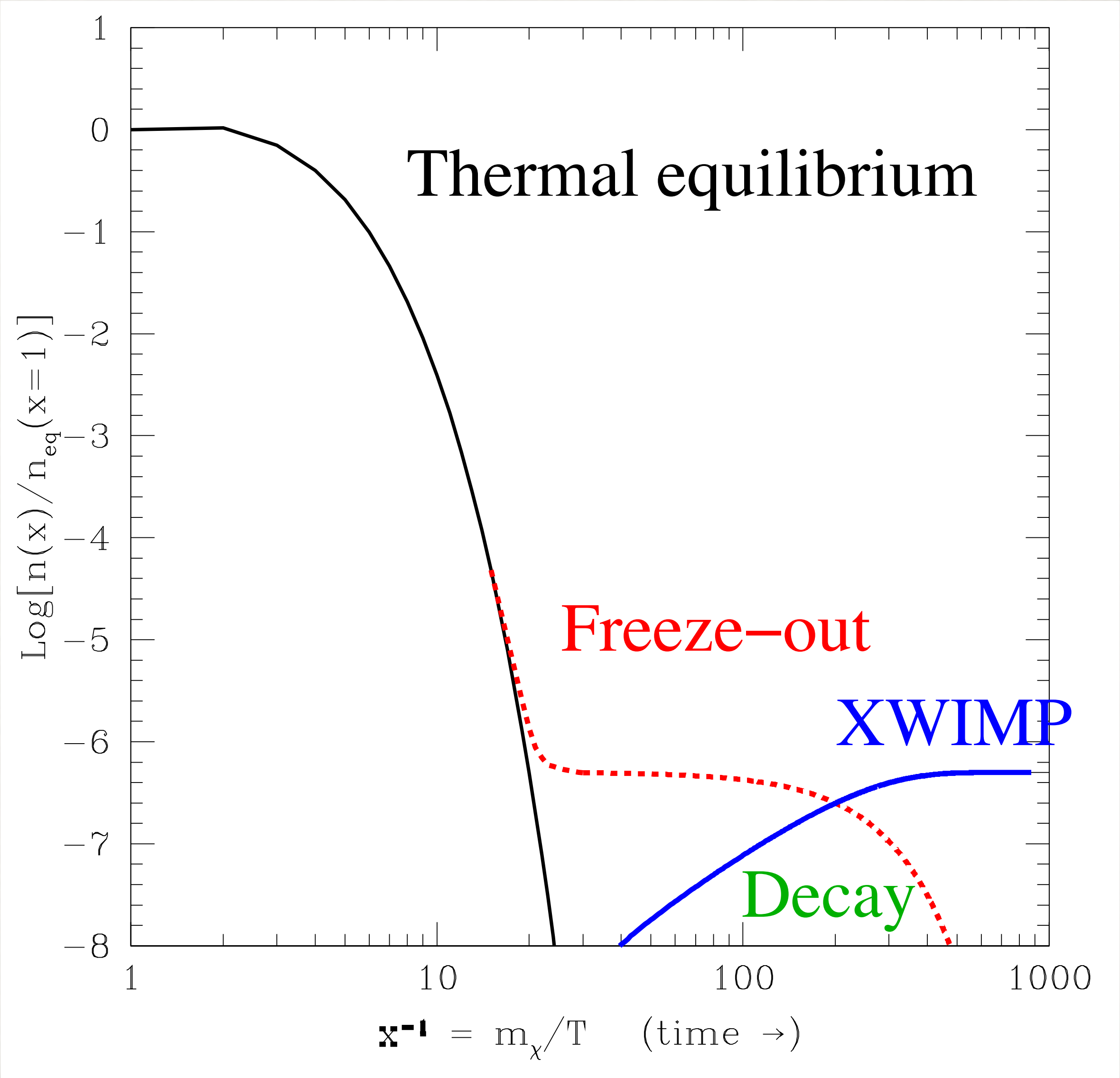
NLSP DECAY

[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...



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

To avoid wash-out of lepton number

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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.

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

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

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

[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]

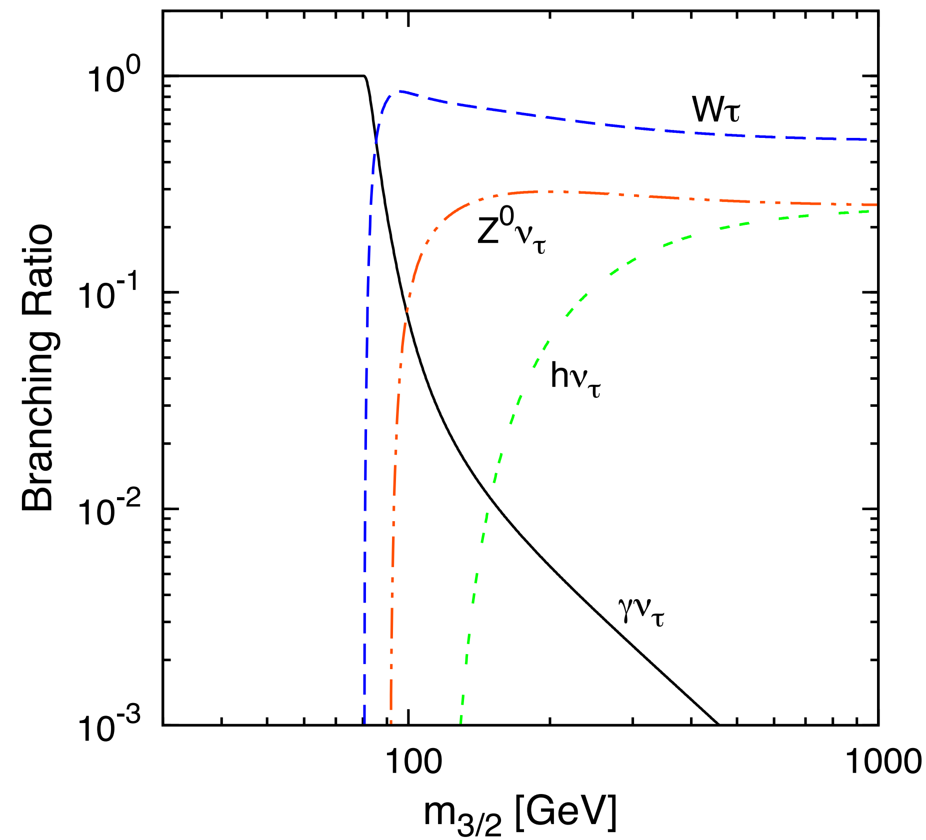
Gravitino decay modes

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

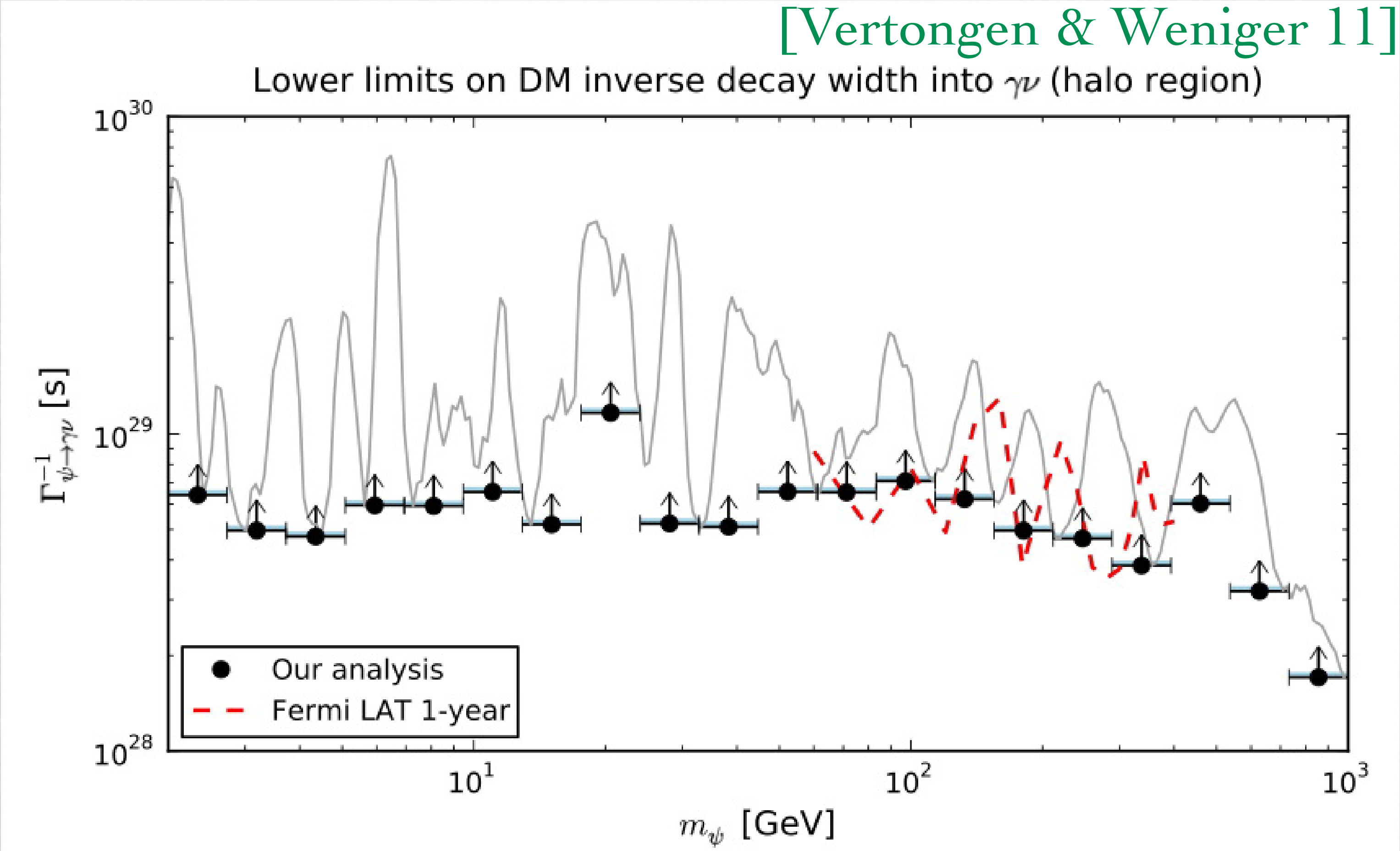
The lifetime is very long, suppressed by M_P and the small mixing between neutrinos and gauginos:

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

[LC, Grefe, Ibarra & Tran 08]



FERMI line constraints



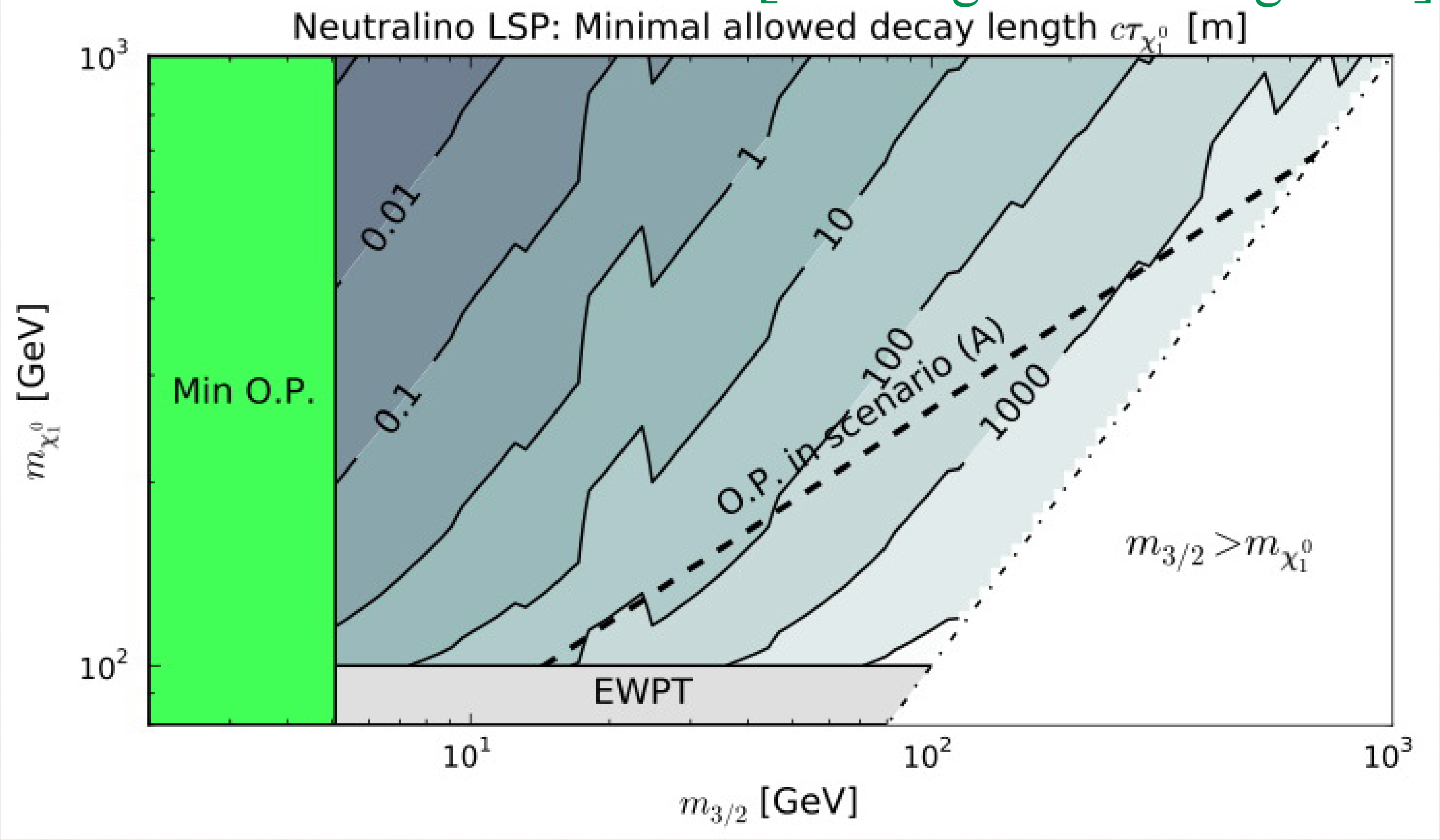
A recent analysis extends the FERMI line search in a wider mass region, for energies to 500 GeV, i.e. masses between 1-1000 GeV

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]

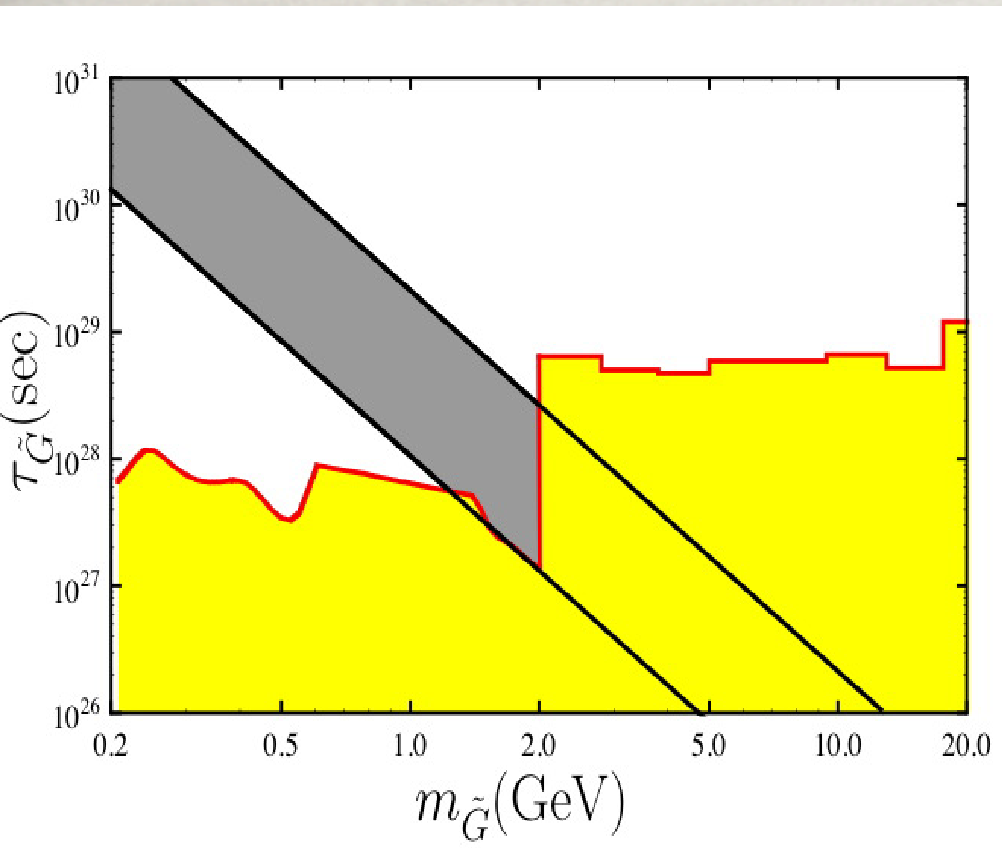


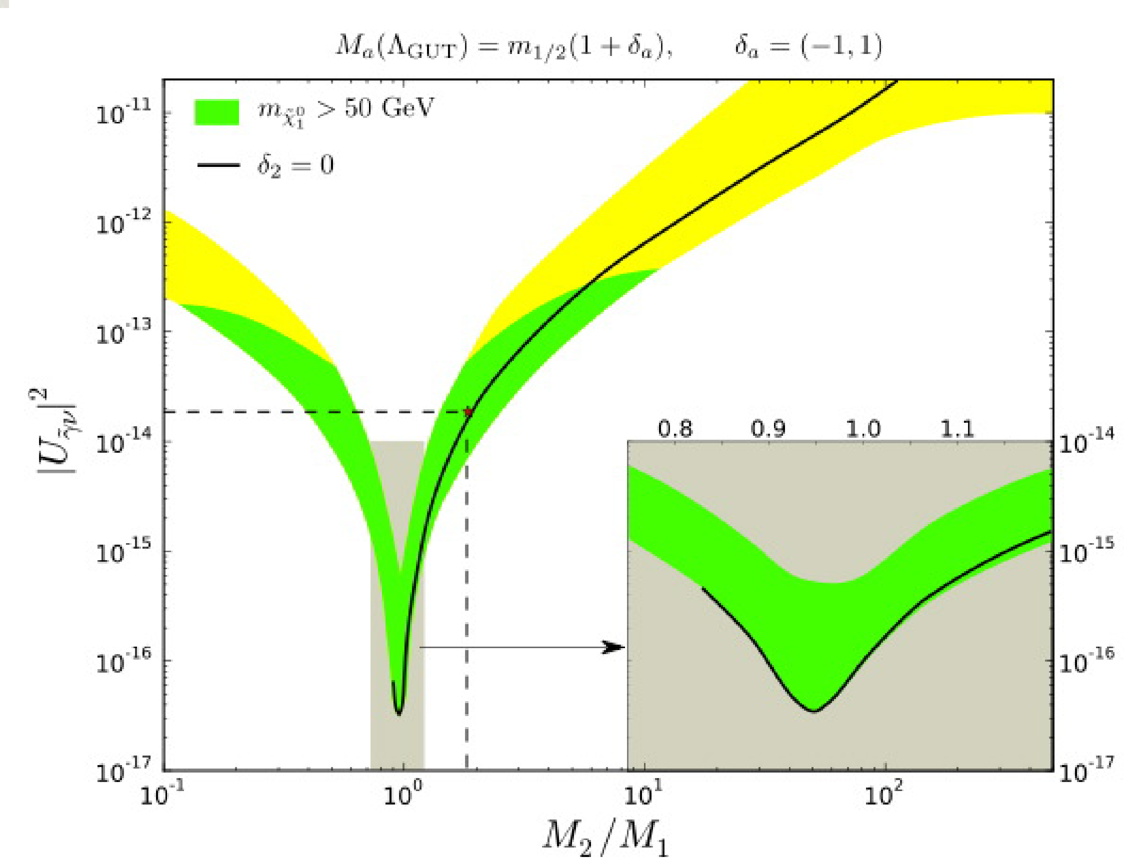
But no definite prediction on decay length for stau NLSP...

[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]

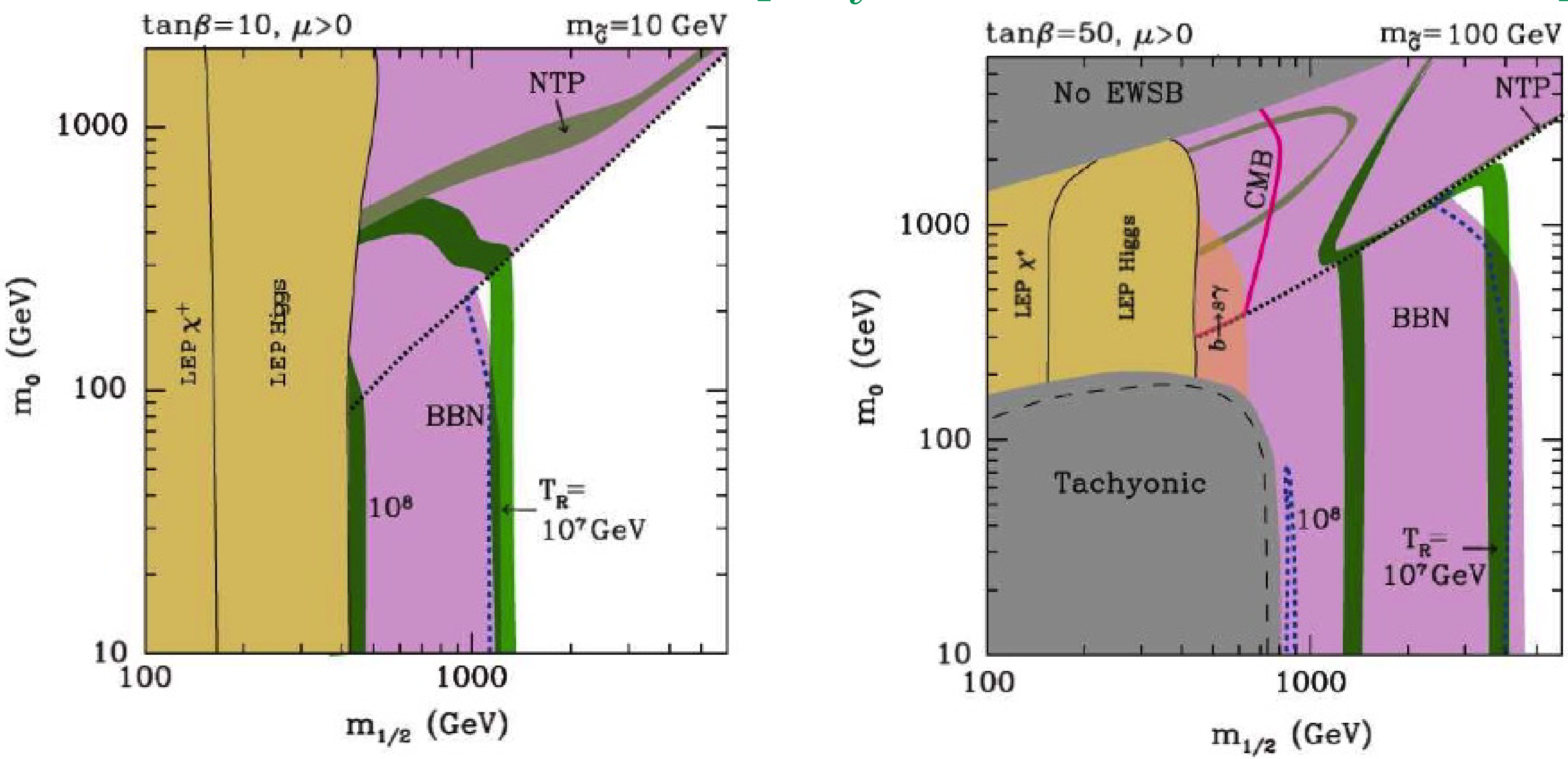




Moreover, for non-universal gaugino also a mass suppression for the gamma decay channel is possible

BBN bounds on CMSSM

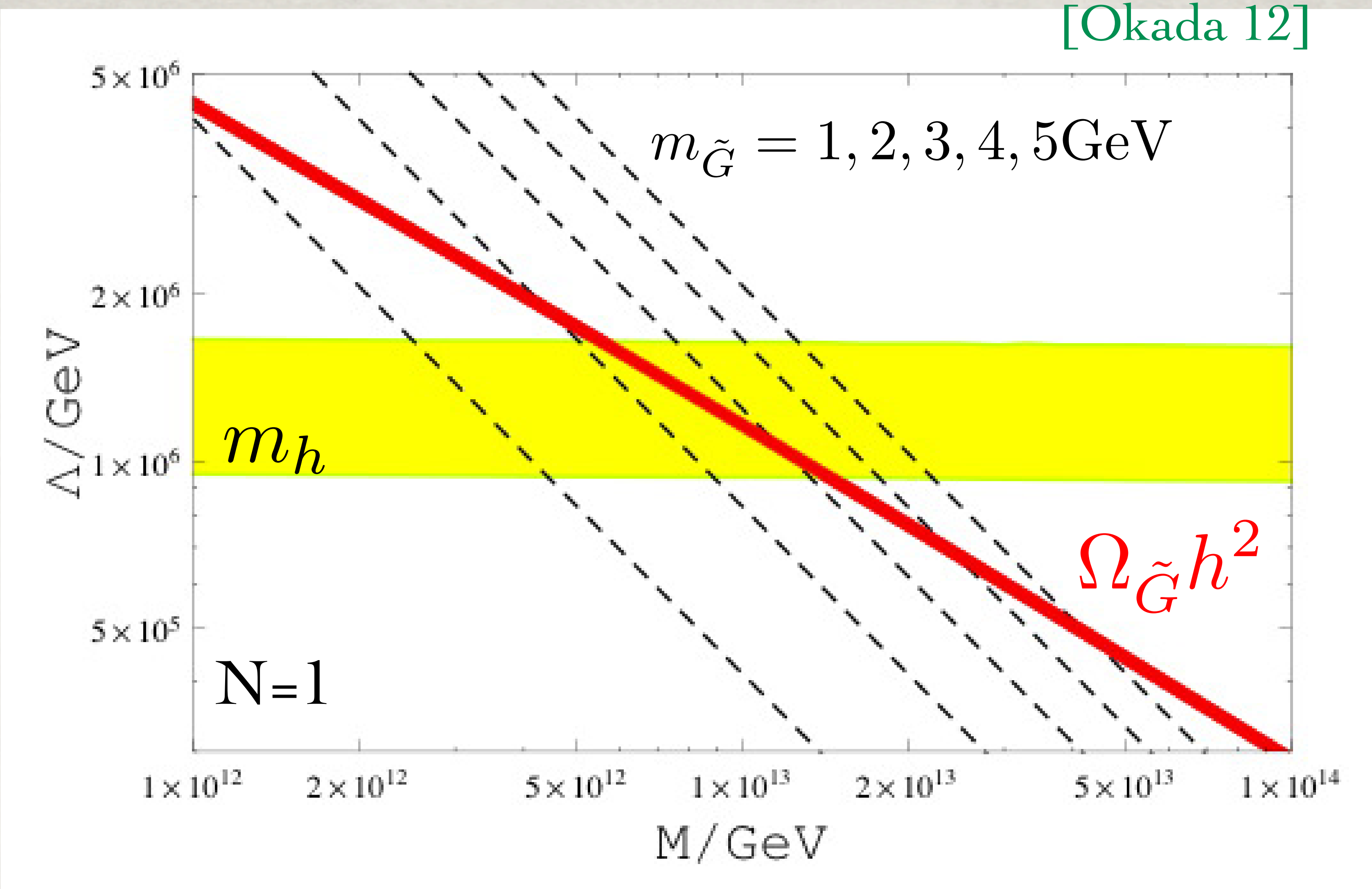
[Bally, Choi, Jedamzik, Roszkowski 09]



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



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 .

Evading BBN with high T

Look again at the thermal production yield:

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

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

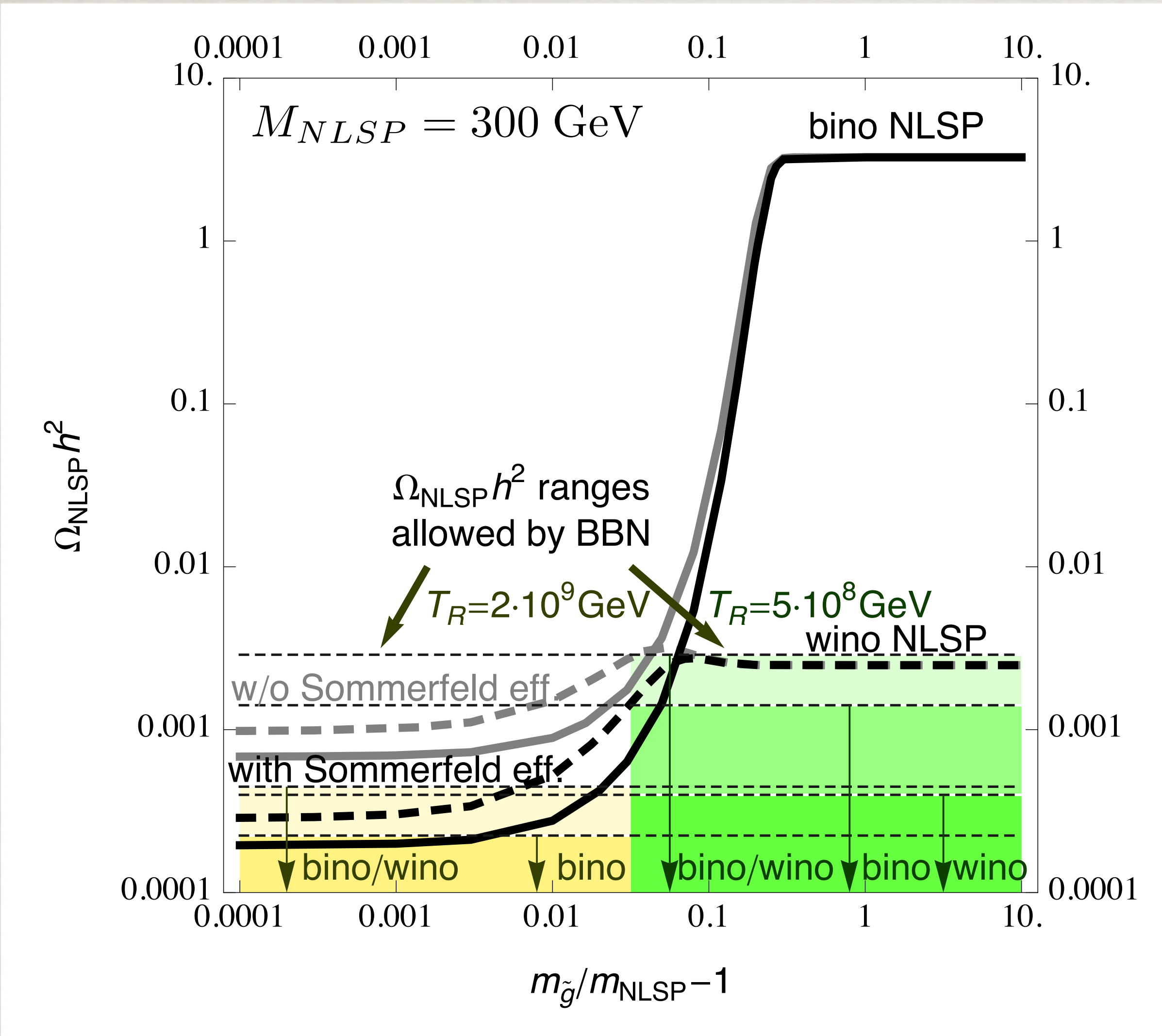
[Olechowski, Pokorski, Turzynski,Wells 09]

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]



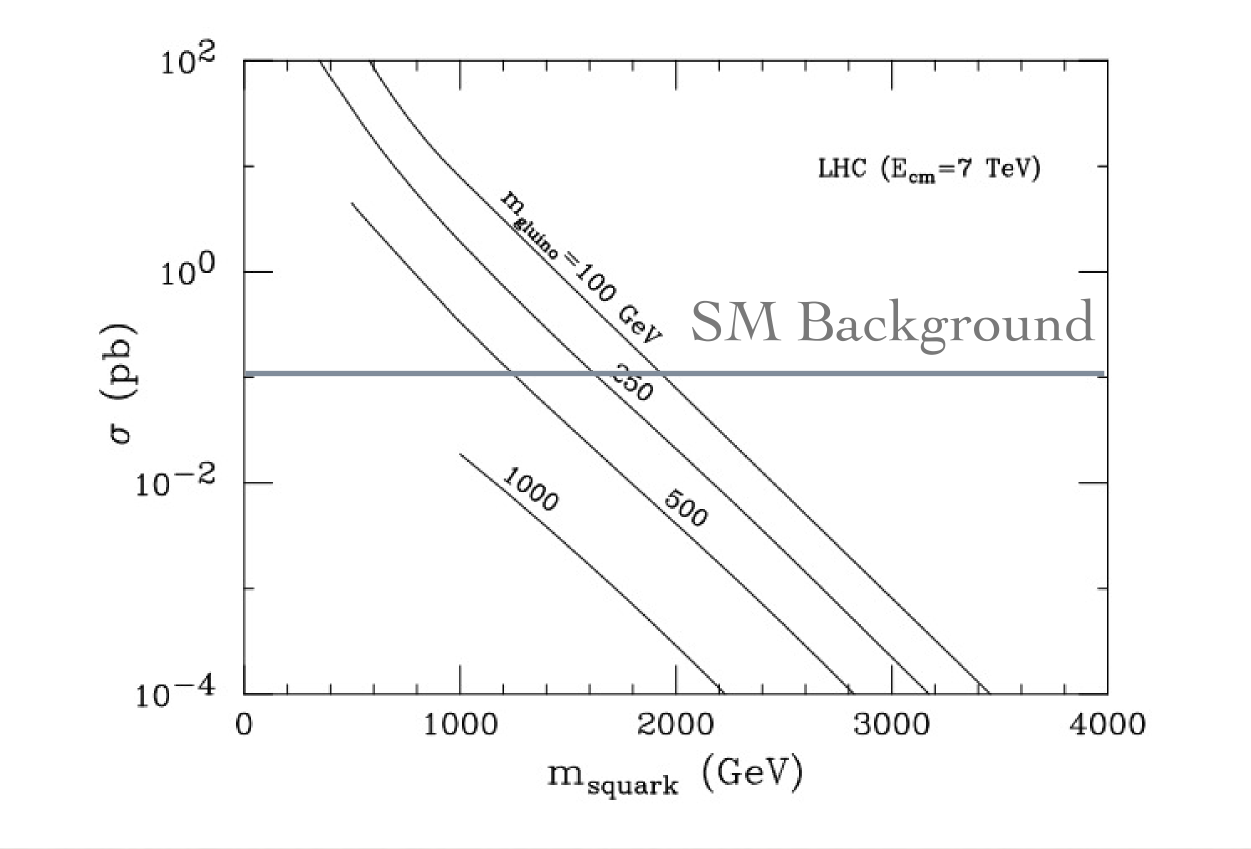
Gluinos annihilate most efficiently, but are a bad NLSP due to BBN bound state effects...

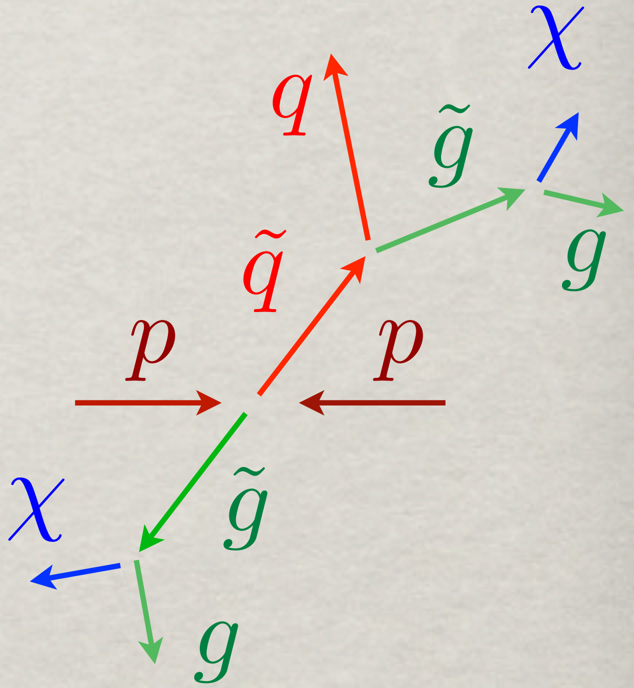
On the other hand they can help the other neutralinos NLSP.

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 !

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]

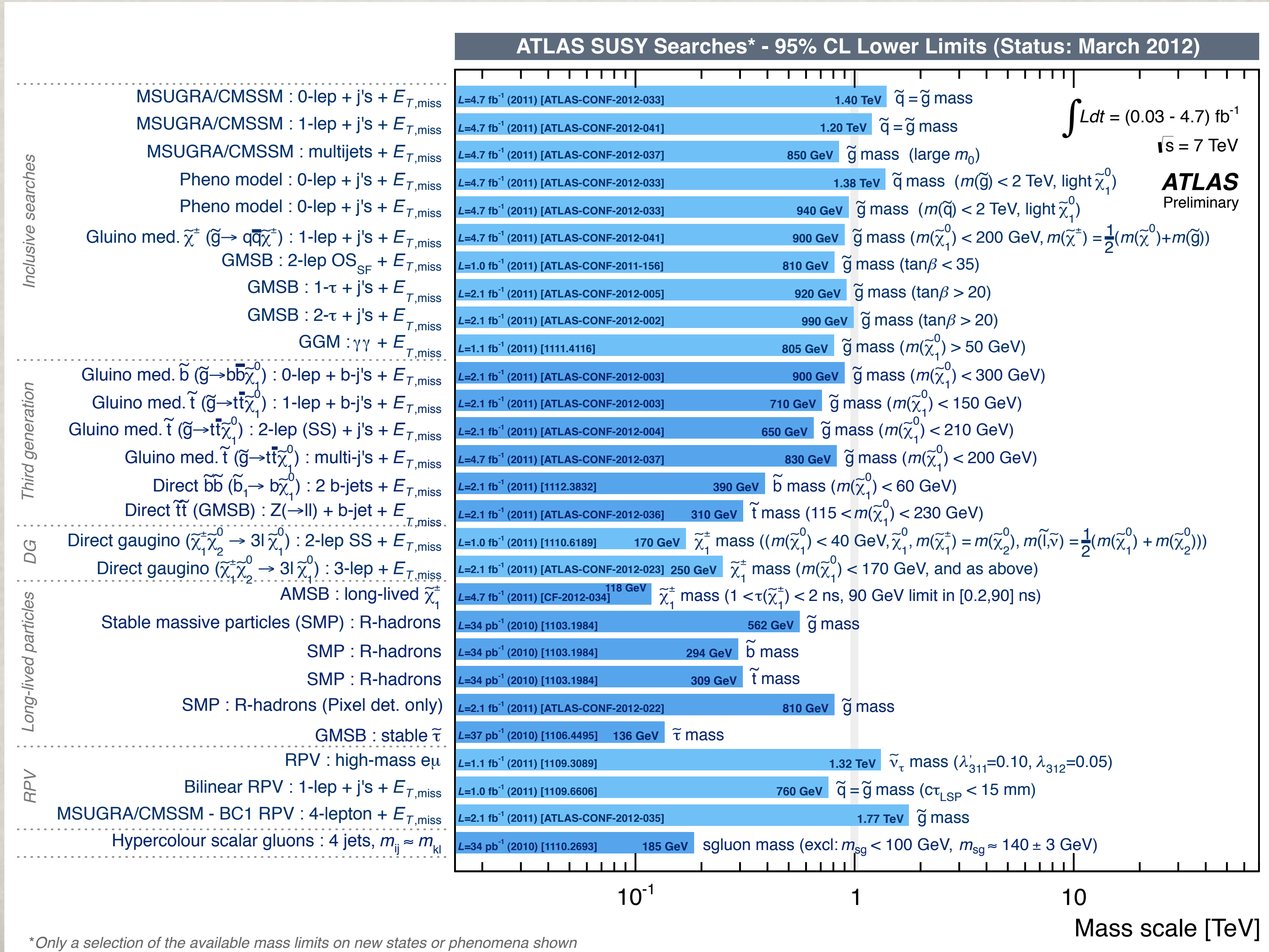
Broken Rp Gravitino: The decays may also happen within the detector with a sufficient number of events. Possible discovery or exclusion down to couplings $\epsilon \sim 10^{-9} - 10^{-10}$ if the colored states are accessible at LHC.

[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

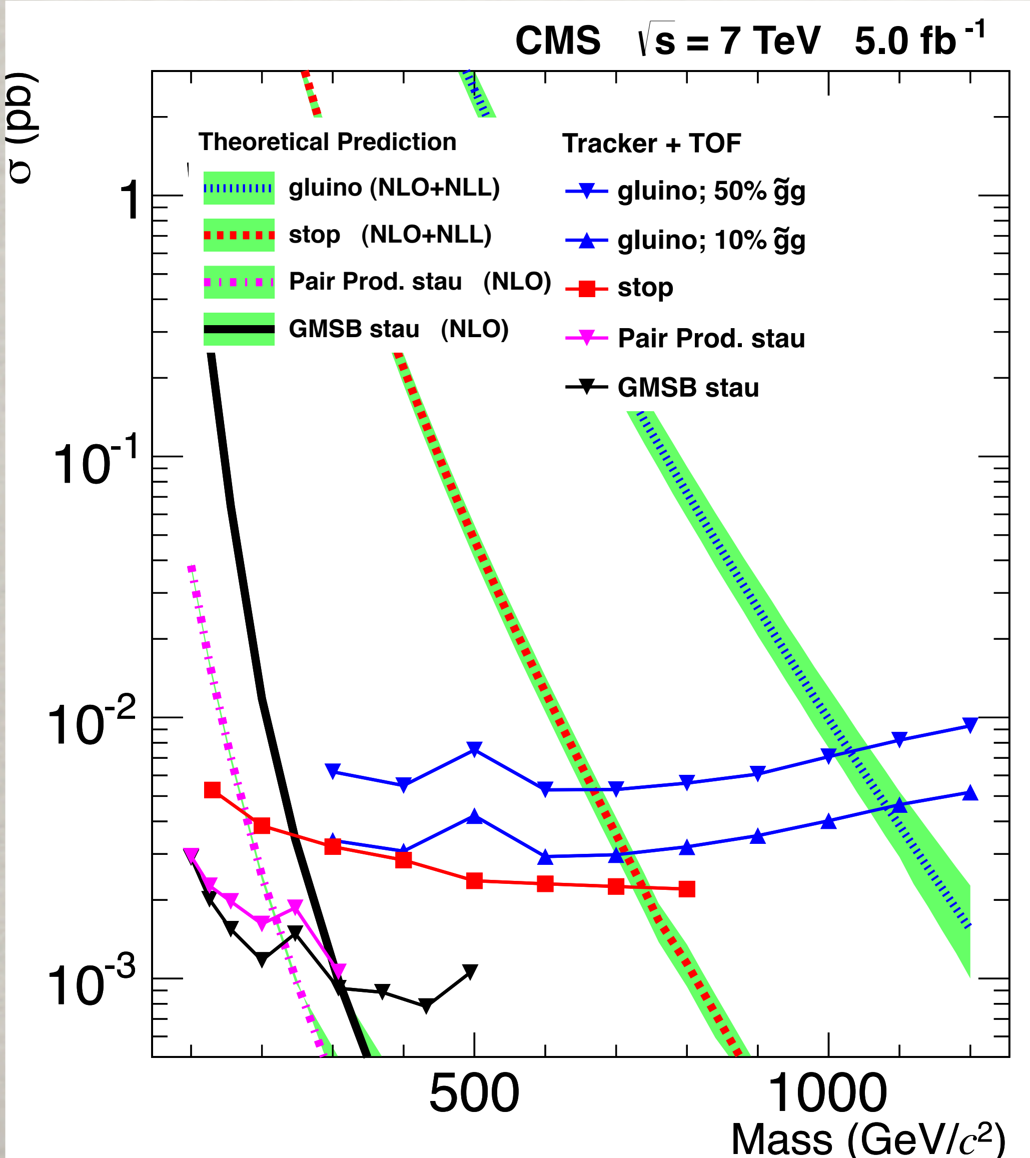
At the moment no significant excess found....



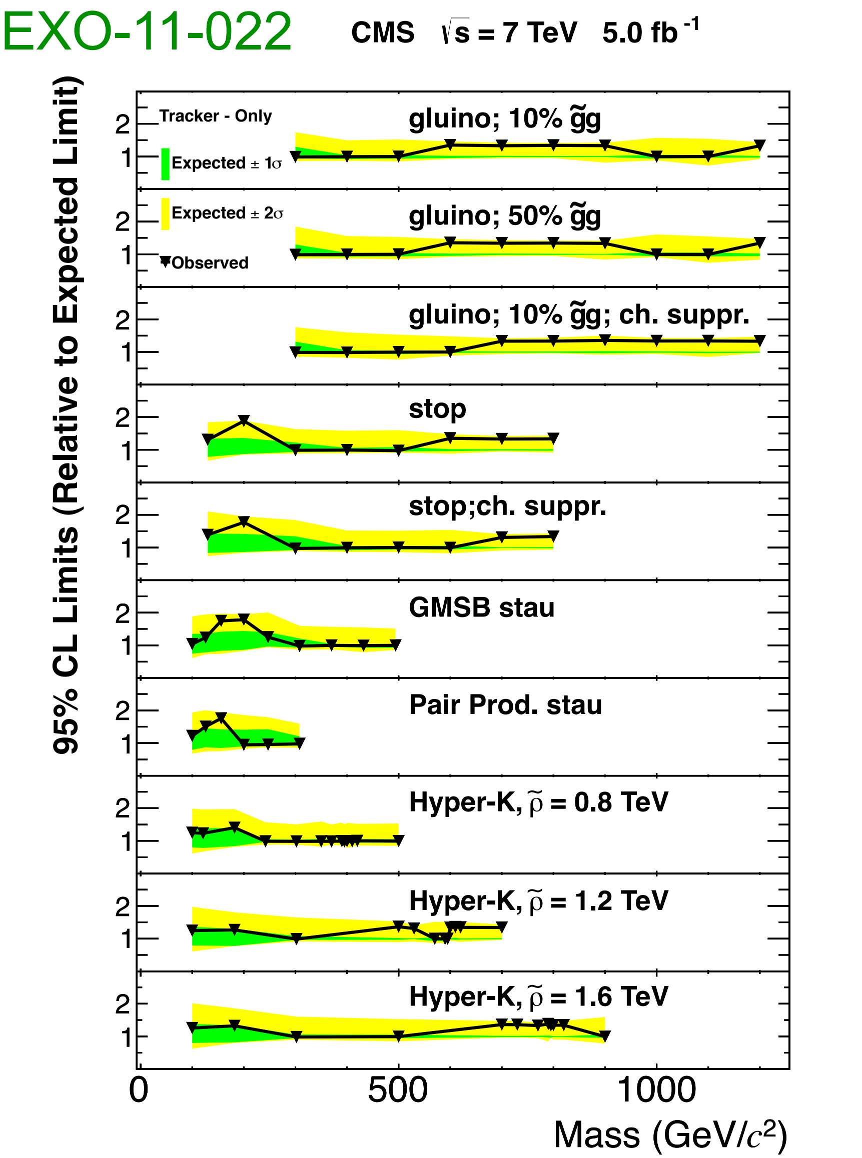
LHC: METASTABLE PARTICLES

Recent results from CMS for metastable SUSY particles:

at the moment no significant excess found….



CMS-EXO-11-022

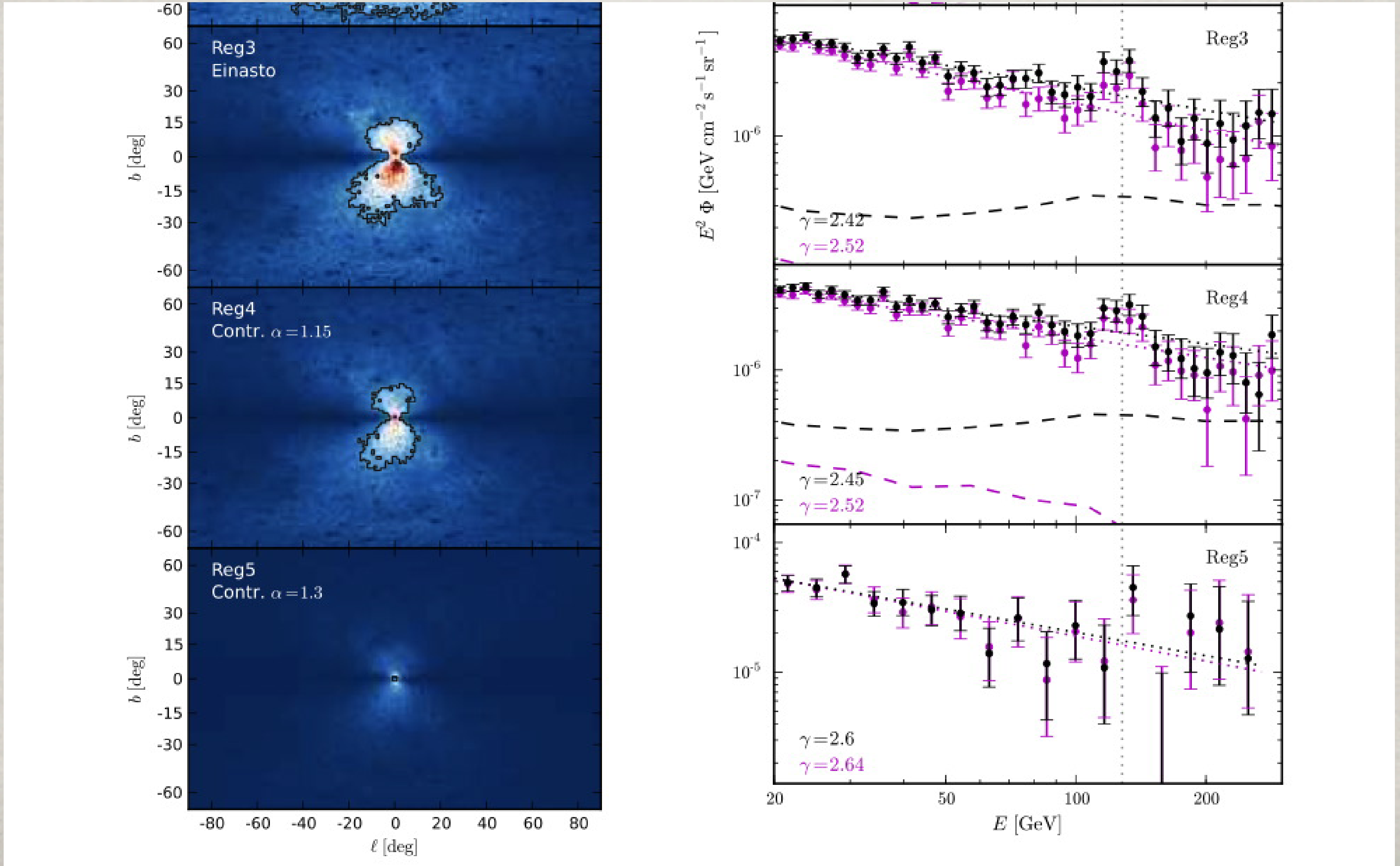


DM candidates
&
the FERMI line(s)

News from the sky

But possibly the FERMI collaboration missed a line signal ?

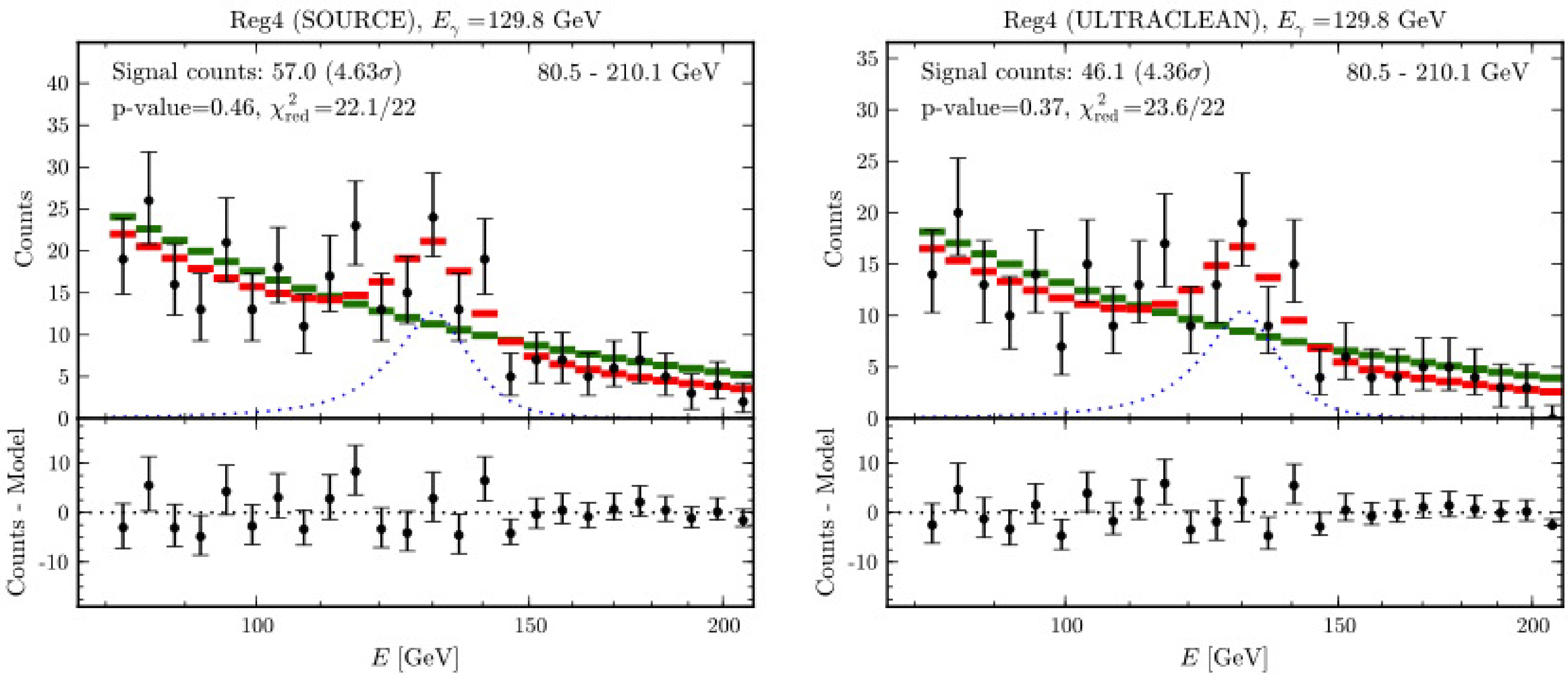
Choose optimized regions in the sky: [Ch. Weniger, 1204.2797]



News from the sky

In regions 3-4 the best significance in both FERMI data sets

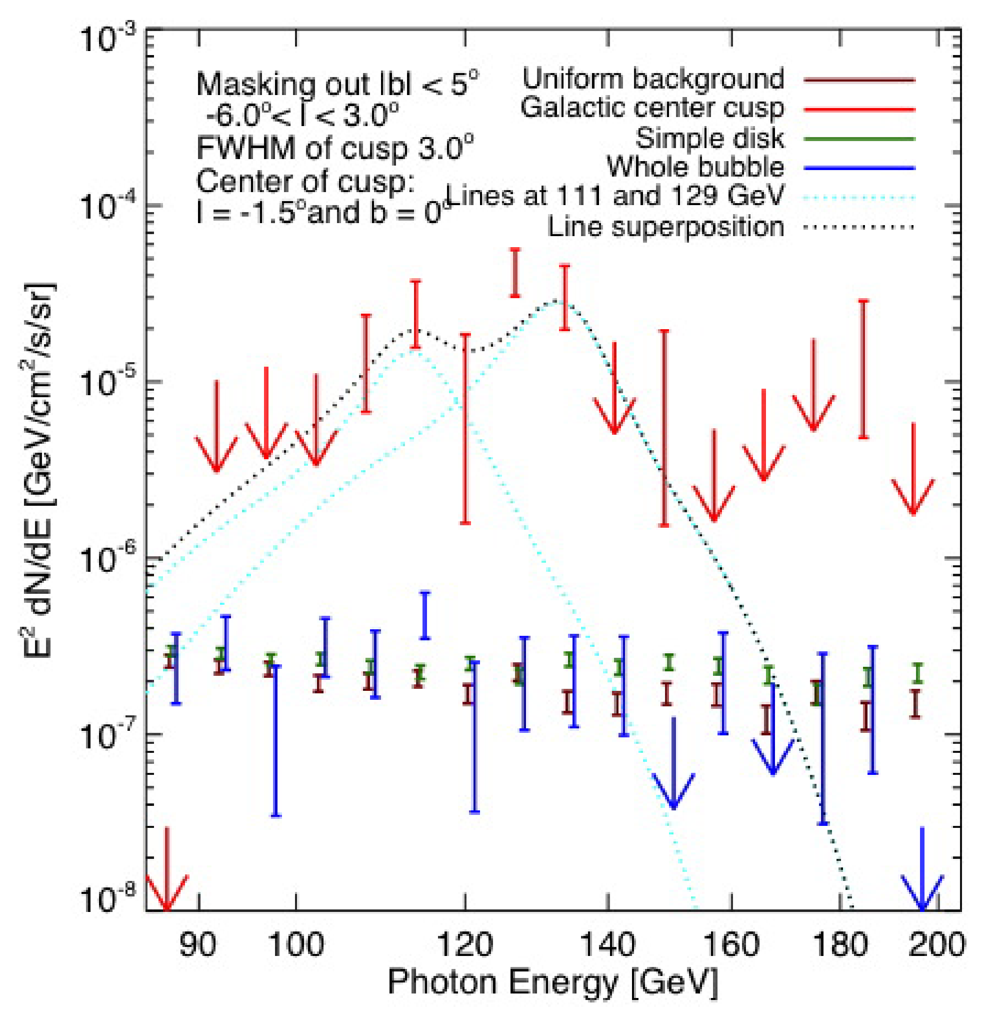
[Ch. Weniger, 1204.2797]



Local significance more than 4 sigma, taking into account the look elsewhere effect it gives 3.2 sigma

News from the sky

Actually the data are compatible also with two line, but...



[Finkbeiner & Su, 1206.1616]

News from the sky

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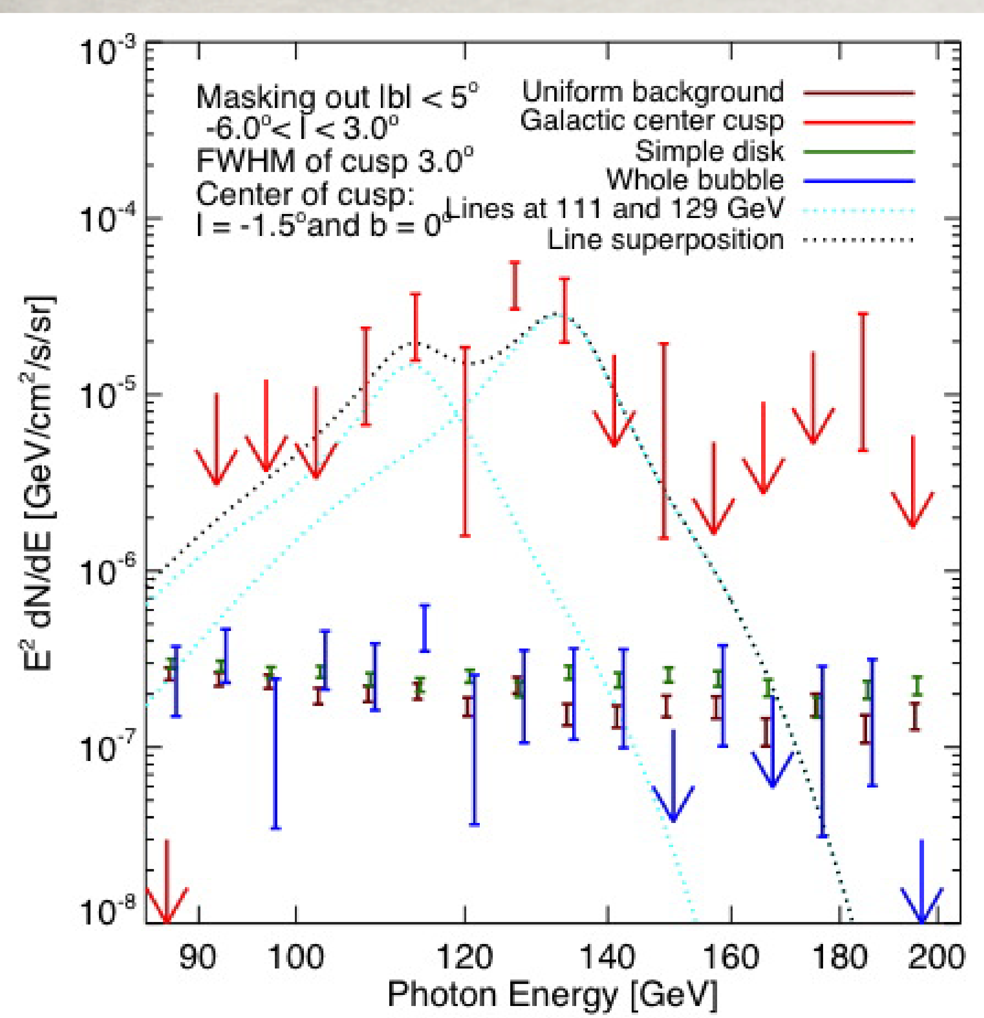
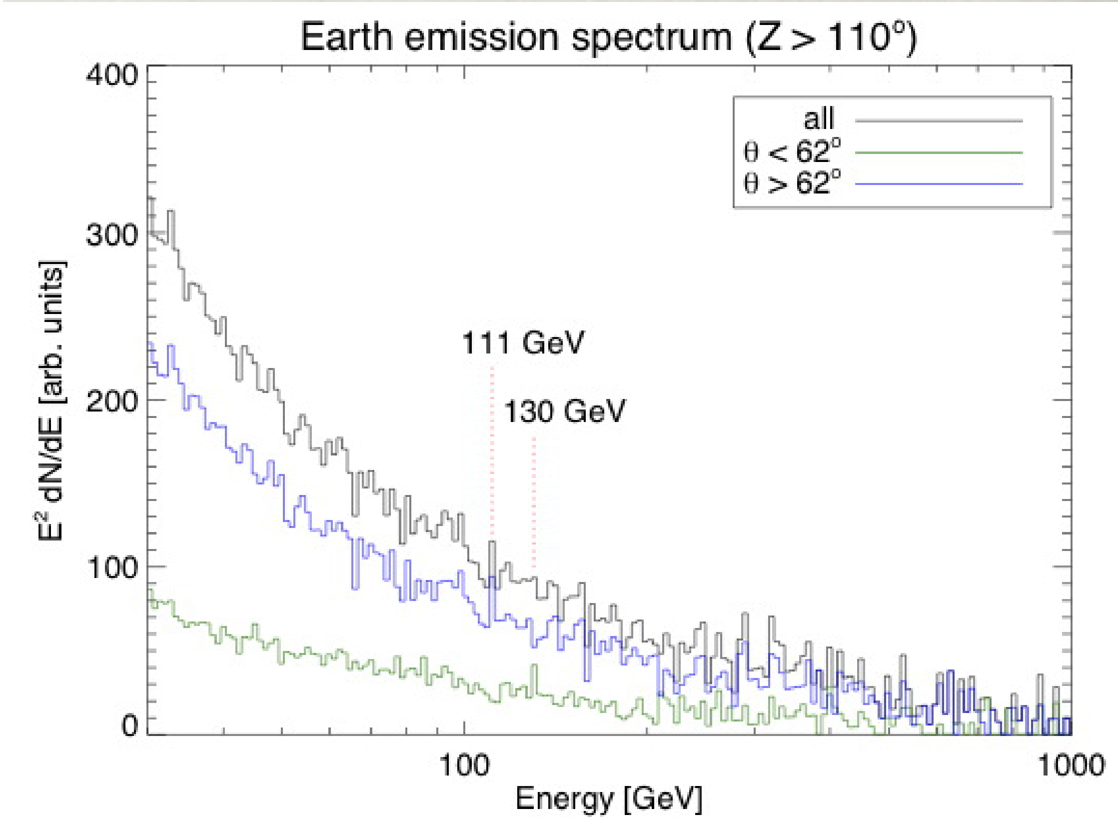
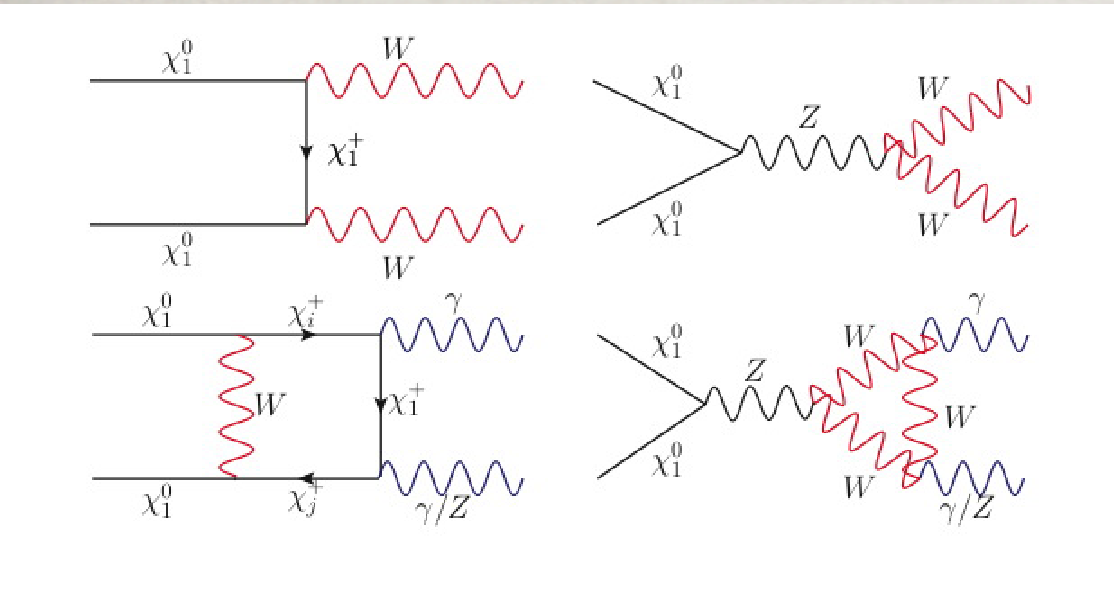


[Finkbeiner & Su, 1206.1616]



...the same lines appear also in the earth emission spectrum...
Possibly a systematics ?

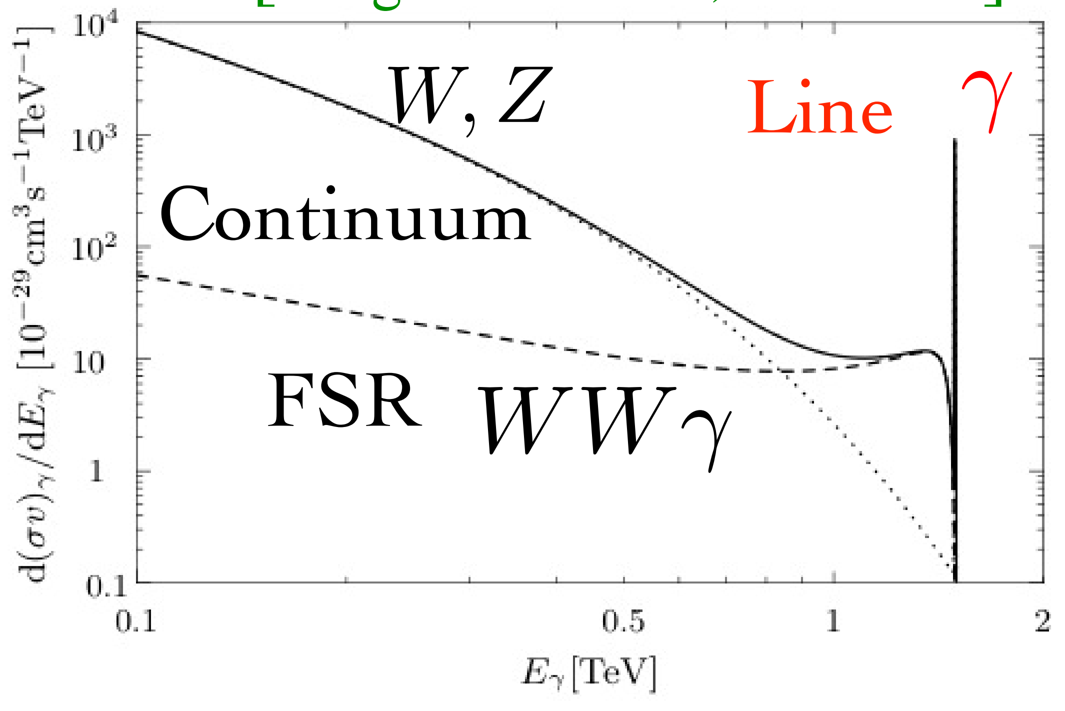
Indirect detection lore



Annihilation into two photons appears only at one loop, while the channel into EW gauge boson is at tree-level

The line signal is therefore suppressed compared to the continuum from EW gauge bosons.
It may be enhanced by Final State Radiation, but that also gives a continuum

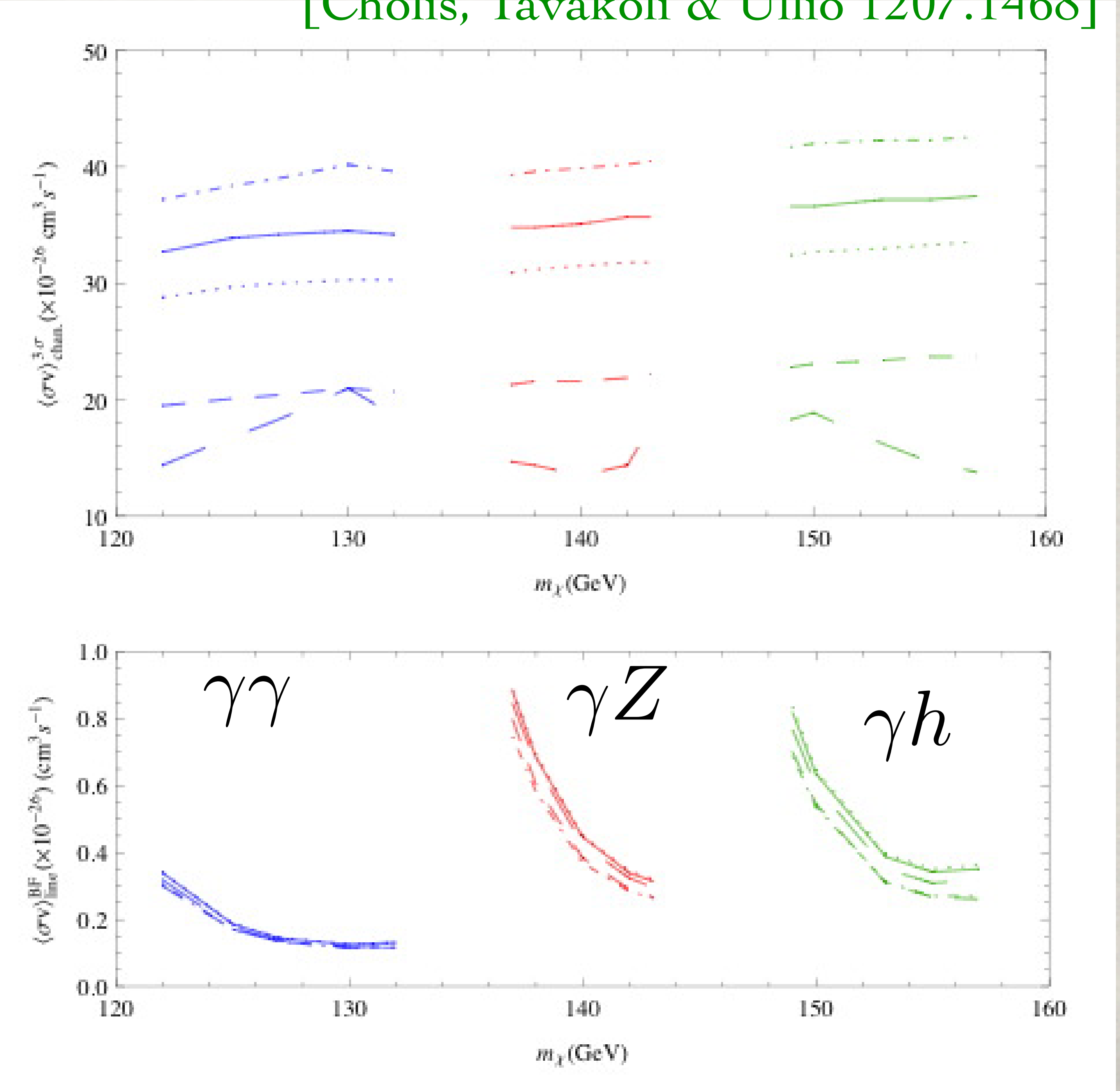
[Bergstroem et al, 0609.510]



GAMMA CONTINUUM ???

[Cholis, Tavakoli & Ullio 1207.1468]

Limit on the continuum



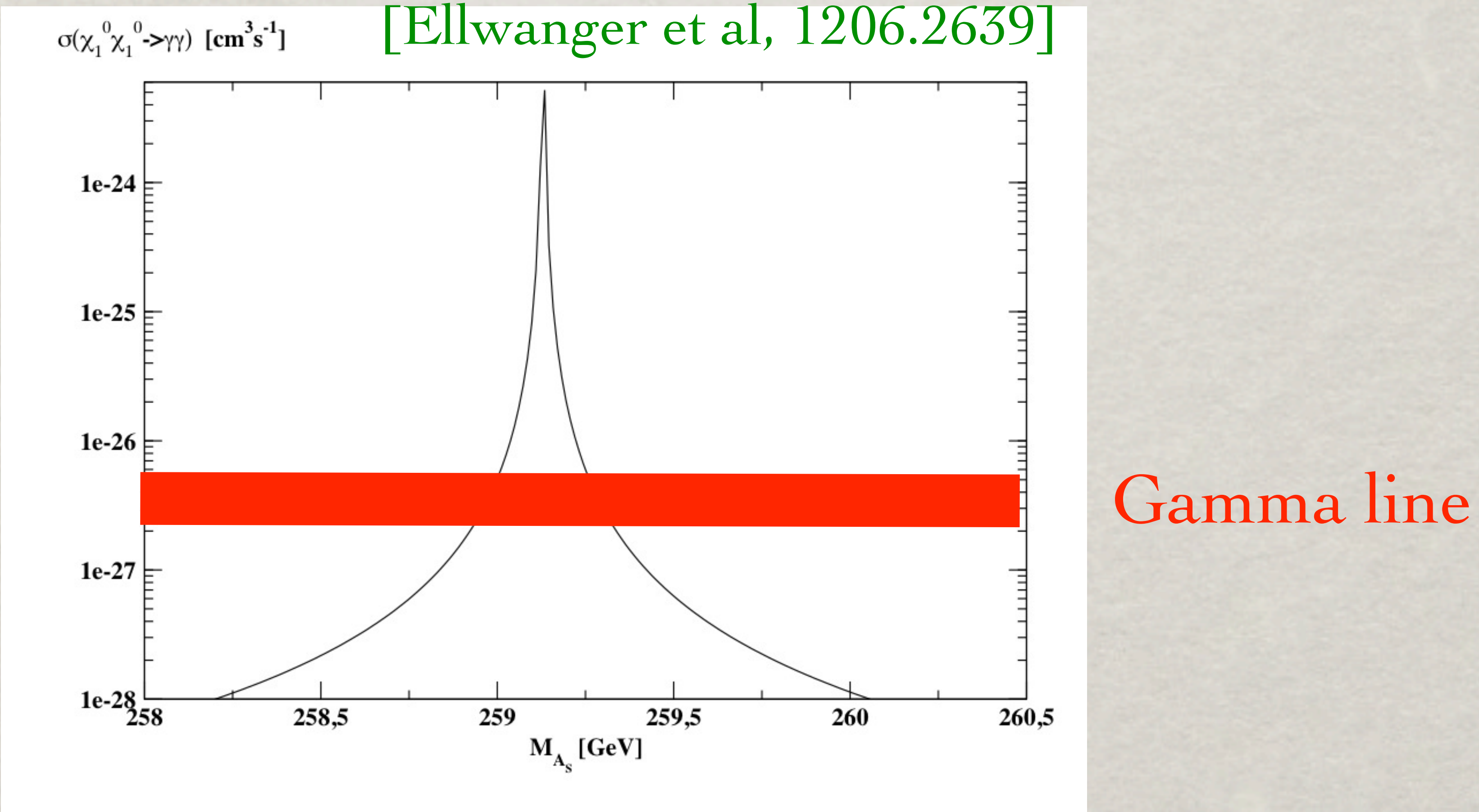
Fit line

$\mu^+\mu^-$
W^+W^-
$b\bar{b}$
$\tau^+\tau^-$
e^+e^-

Neutralino & gamma line

Possible to enhance strongly the gamma line in the NMSSM via resonant neutralino annihilation via singlet A- boson and at the same time have the right Higgs mass !

[Ellwanger et al, 1206.2639]



Direct detection rates can be near to the experimental bounds

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)
- Neutralino DM, also light, can be accomodated in SUSY models consistent with the LHC exclusion region and the Higgs mass in non-minimal models. (Fine-tuning ?)
- Gravitinos can survive as DM also for broken R-parity, but then indirect DM searches set limits on the parameters. Otherwise BBN can constrain the lifetime and density of the NLSP or point to heavy SUSY !
- The tantalizing line-signal in the FERMI data can be also explained in SUSY, but not very natural.

Let us hope for a better/clearer signal soon !