Status of mixed sneutrino dark matter

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work in collaboration with
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based on
JCAP09(2012)013 (arXiv:1206.1521)
updated with latest experimental results

HAP DM workshop
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Introduction

Two electrically neutral WIMPs in the MSSM:

- neutralino
- sneutrino

keyword	number of results on INSPIRE-HEP
neutralino dark matter	328
sneutrino dark matter	62

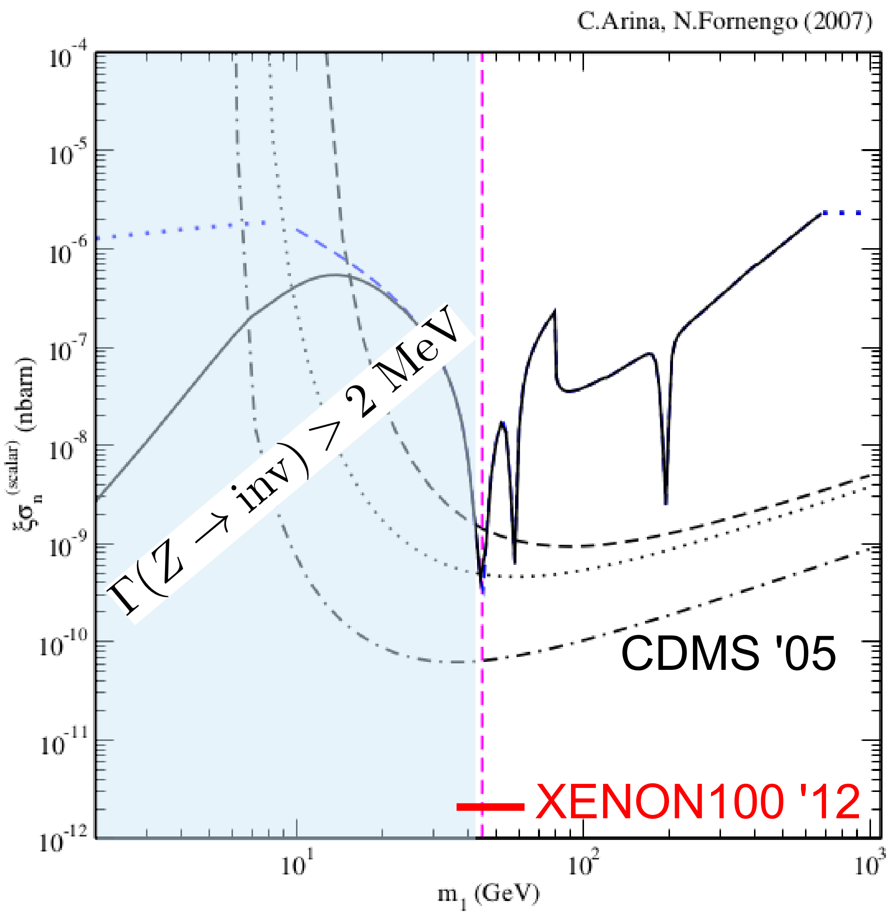
neutralino LSP
is much more popular

Why?

- sneutrino cannot be the LSP in the CMSSM → neutralino historically seen as the “natural” supersymmetric DM candidate

- difficult to evade direct detection limits in the most simple case...

Sneutrino dark matter excluded?



- LH MSSM sneutrino dark matter is excluded
- other options?
  - RH sneutrino (SM singlet)
    - non-thermal DM [Asaka *et al.* '05, Gopalakrishna *et al.* '06, …]
    - extended gauge group [Lee *et al.* '07, Basso, O'Leary, Porod & Staub '11, …]
  - mixed LH/RH sneutrino as thermal dark matter: the case we consider (and many others: [Arkani-Hamed *et al.* '00, Thomas, Tucker-Smith & Weiner '07, ...])

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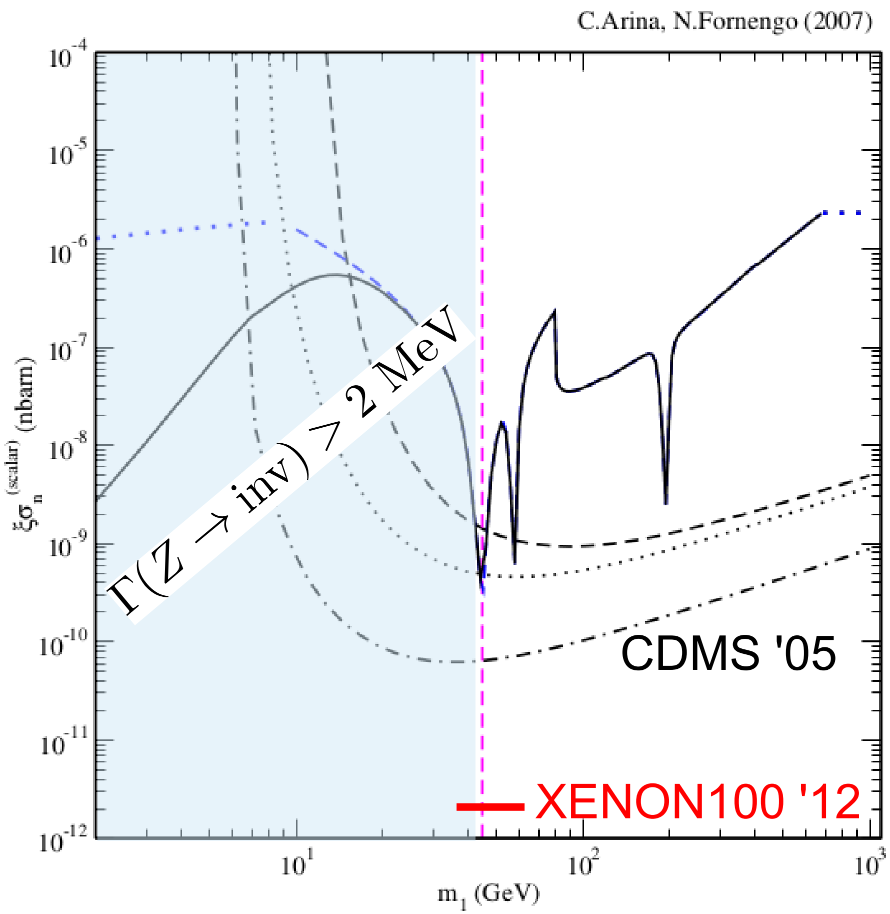

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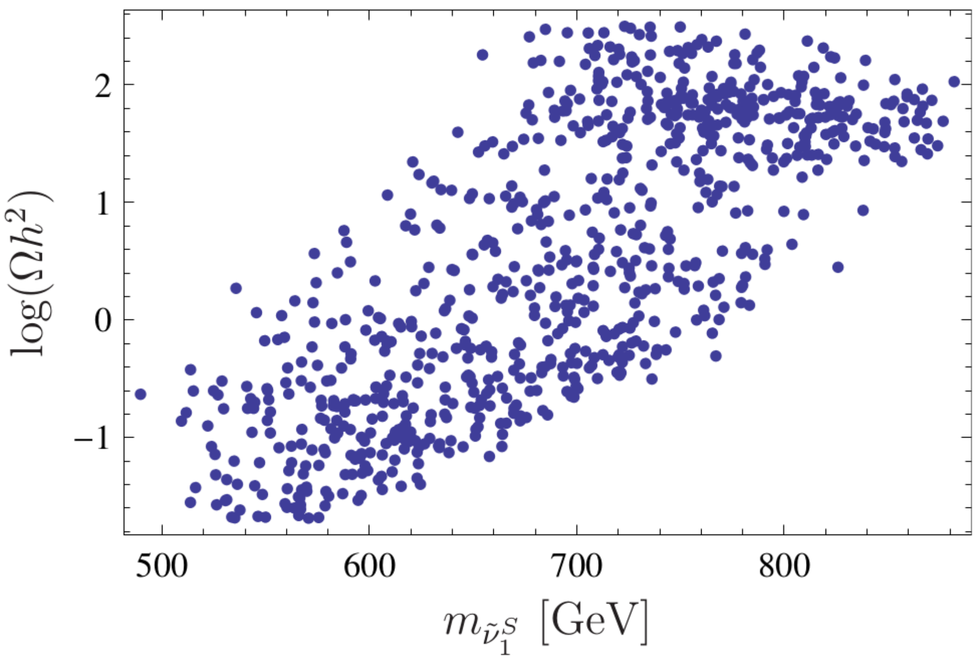
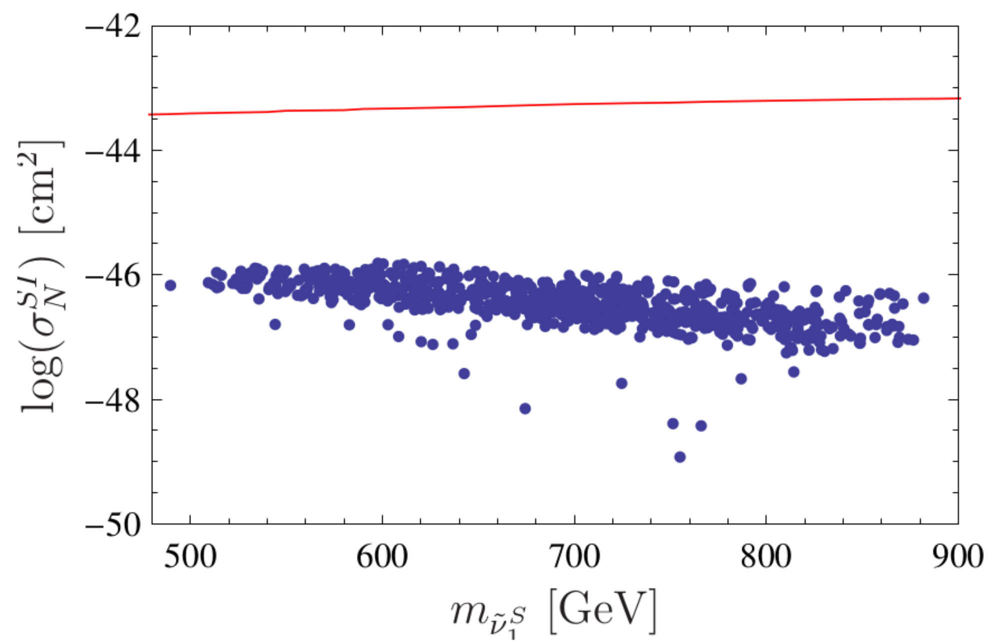
Sneutrino dark matter in the minimal SUSY B-L model

From Basso, O'Leary, Porod & Staub [JHEP09(2012)054 (1207.0507)]:

- extended gauge group: $U(1)_Y \otimes SU(2)_L \otimes SU(3)_C \otimes U(1)_{B-L}$
- leads to CP-even and CP-odd RH neutrinos as possible dark matter candidate – both are viable
- CP-even case:





MSSM with mixed sneutrinos

Framework: MSSM (with Dirac neutrinos)

$$\Delta\mathcal{L}_{\rm soft} = m^2_{\tilde{N}_i}|\tilde{N}_i|^2 + A_{\tilde{\nu}_i}\tilde{L}_i\tilde{N}_i H_u + \text{h.c.}$$

no lepton-number violating bilinear term

$$m^2_{\tilde{\nu}} = \begin{pmatrix} m^2_{\tilde{L}} + \frac{1}{2}m^2_Z\cos 2\beta & \frac{1}{\sqrt{2}}A_{\tilde{\nu}}\, v\sin\beta \\ \frac{1}{\sqrt{2}}A_{\tilde{\nu}}\, v\sin\beta & m^2_{\tilde{N}} \end{pmatrix}$$

with $A_{\tilde{\nu}} \sim \mathcal{O}(100\ \text{GeV})$
instead of $A_{\tilde{\nu}} \propto y_\nu \approx 0$

$\Rightarrow (\tilde{\nu}_1, \tilde{\nu}_2, \sin\theta_{\tilde{\nu}})$

$\tilde{\nu}_1 \longrightarrow$ LSP and (complex scalar) dark matter candidate

$A_{\tilde{\nu}} \sim \mathcal{O}(100\ \text{GeV})$ is theoretically motivated
[Borzumati & Nomura '00, Arkani-Hamed, Hall, Murayama, Smith & Weiner '00]

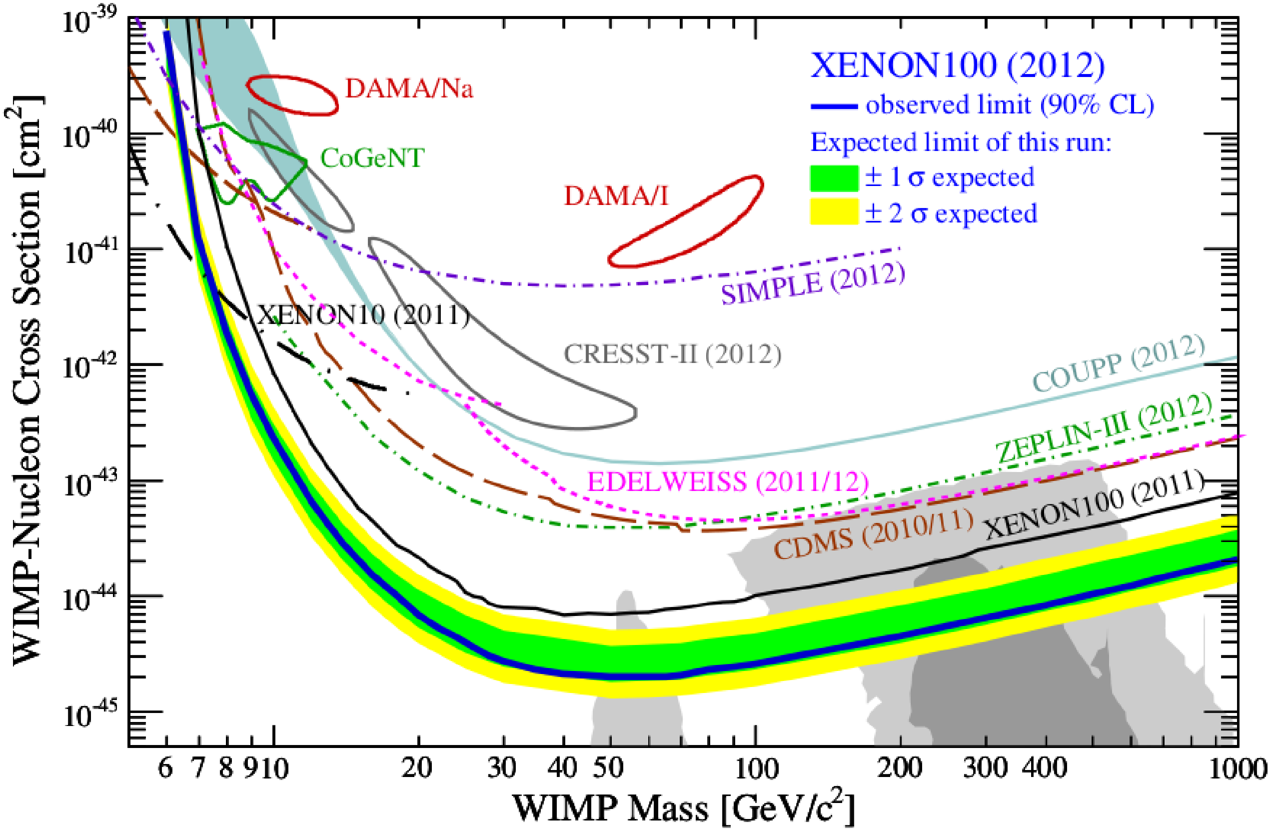
Light and heavy sneutrino dark matter

Two very different cases:

- light sneutrino ($m_{\tilde{\nu}_1} < m_Z/2$)
- heavy sneutrino ($m_{\tilde{\nu}_1} > m_Z/2$)

→ $\Gamma(Z \to \text{invisible})?$

→ $\Gamma(h^0 \to \text{invisible})?$



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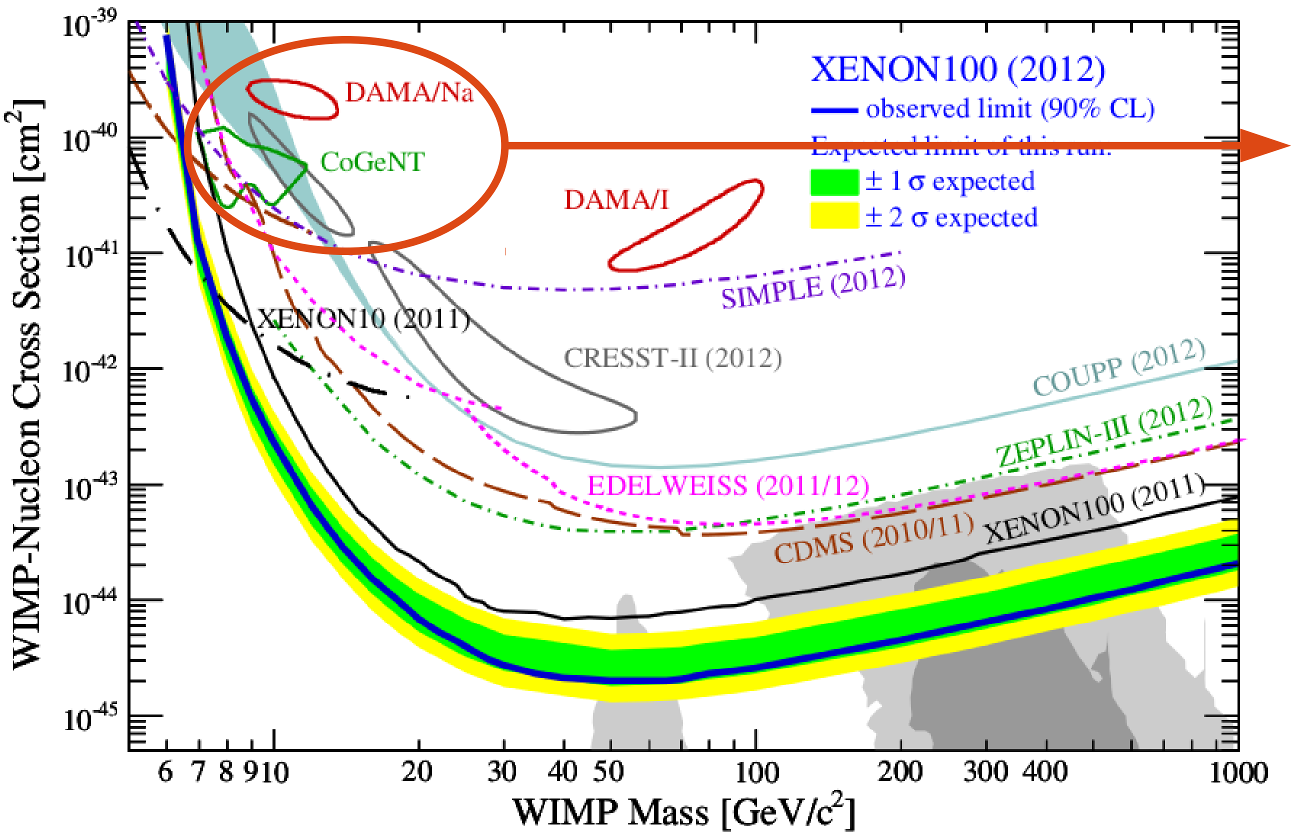
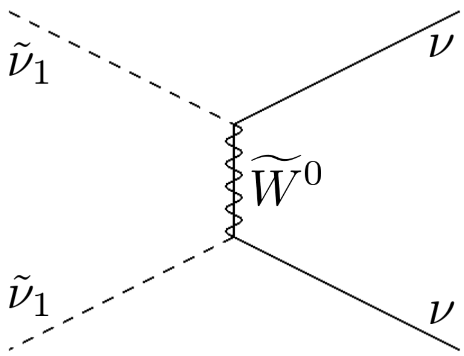


hints of light dark matter?

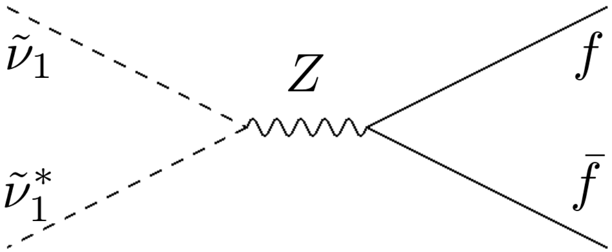
- motivation for light sneutrino dark matter
- however very difficult to reconcile the results [Kopp, Schwetz & Zupan '11, Arina, Hamann & Wong '11, Arina '12, ...]

Main annihilation channels



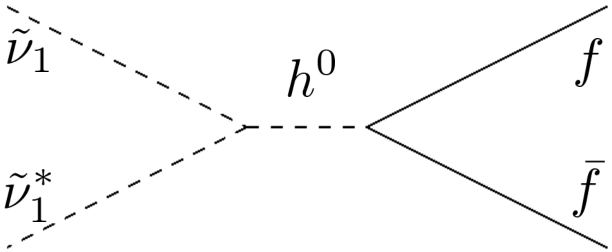
$\propto \sin^4\theta_{\tilde{\nu}}$ (also $\tilde{\nu}_1^*\tilde{\nu}_1^* \xrightarrow{\widetilde{W}^0} \nu^*\nu^*$)

$\tilde{\nu} \neq \tilde{\nu}^*$!
we assume $n_{\tilde{\nu}} = n_{\tilde{\nu}^*}$



$\propto \sin^4\theta_{\tilde{\nu}}$

with heavy sneutrinos: can also have annihilations into a pair of W, Z, h



$\propto (A_{\tilde{\nu}} \sin\theta_{\tilde{\nu}})^2$

Direct detection cross sections

Z exchange

- $\sigma^{\mathrm{SI},\,Z}_{\tilde{\nu}_1 N} = \frac{G_F^2}{2\pi}\mu_\chi^2\left((A-Z)-(1-4\sin^2\theta_W)Z\right)^2\sin^4\theta_{\tilde{\nu}}$

proton cross section much smaller than the neutron one: $f_p/f_n = (1-4\sin^2\theta_W)$

Higgs exchange

- $\sigma^{\mathrm{SI},\,h}_{\tilde{\nu}_1 N} = \frac{\mu_\chi^2}{4\pi}\frac{g^2_{h\tilde{\nu}_1\tilde{\nu}_1}}{m_h^4 m^2_{\tilde{\nu}_1}}\left((A-Z)\sum_q g_{hqq}f_q^n m_n + Z\sum_q g_{hqq}f_q^p m_p\right)^2$

quark coefficients

normalized cross section: $\sigma^{\mathrm{SI}}_{\tilde{\nu}_1 N} = \frac{4\mu_\chi^2}{\pi}\frac{(Zf_p+(A-Z)f_n)^2}{A^2}$

Bayesian inference & MCMC

given:

- parameters ϕ in a model *M*,
- nuisance parameters ψ,

the posterior probability on ϕ given the experimental data is:

$$\underbrace{p(\phi|d,M)}_{\text{marginal posterior on the parameters of interest}} \propto \int \underbrace{L(\phi,\psi)}_{\text{likelihood}}\, \underbrace{p(\phi,\psi|M)}_{\text{prior}}\, d\psi$$

we sample the posterior probability distribution using Markov Chain Monte Carlo (MCMC)

MCMC scan Parameters

i	Parameter ϕ_i	Scan bounds: light sneutrinos	Scan bounds: heavy sneutrinos
1	$m_{\tilde{\nu}_{1\tau}}$	$[1,\ M_Z/2]$	$[M_Z/2,\ 1000]$
2	$m_{\tilde{\nu}_{2\tau}}$	$[m_{\tilde{\nu}_{1\tau}}+1,\ 3000]$	$[m_{\tilde{\nu}_{1\tau}}+1,\ 3000]$
3	$\sin\theta_{\tilde{\nu}_\tau}$	$[0,\ 1]$	$[0,\ 1]$
4	$m_{\tilde{\nu}_{1e}} = m_{\tilde{\nu}_{1\mu}}$	$[m_{\tilde{\nu}_{1\tau}}+1,\ M_Z/2]$	$[m_{\tilde{\nu}_{1\tau}}+1,\ 3000]$
5	$m_{\tilde{\nu}_{2e}} = m_{\tilde{\nu}_{2\mu}}$	$[m_{\tilde{\nu}_{1e}}+1,\ 3000]$	$[m_{\tilde{\nu}_{1e}}+1,\ 3000]$
6	$\sin\theta_{\tilde{\nu}_e} = \sin\theta_{\tilde{\nu}_\mu}$	$[0,\ 1]$	$[0,\ 1]$
7	$\tan\beta$	$[3,\ 65]$	
8	μ	$[-3000,\ 3000]$	
9	$M_2 = 2M_1 = M_3/3$	$[30,\ 1000]$	
10	$m_{\tilde{Q}_3} = m_{\tilde{U}_3} = m_{\tilde{D}_3}$	$[100,\ 3000]$	
11	A_t	$[-8000,\ 8000]$	
12	M_A	$[30,\ 3000]$	

(rows 1–7) also defines the charged slepton sector (assuming $m_{\tilde{R}} = m_{\tilde{L}}$)

other squarks masses set to 2 TeV

(all dimensionful parameters in GeV)

we assume uniform (linear) priors on all the parameters

MCMC scan
Nuisance parameters

i	Nuisance parameter ψ_i	Experimental result Λ_i	Likelihood function $\mathcal{L}_i$	
1	m_u/m_d	0.553 ± 0.043	Gaussian	quark content of the nucleon
2	m_s/m_d	18.9 ± 0.8	Gaussian	
3	$\sigma_{\pi N}$	44 ± 5 MeV	Gaussian	
4	σ_s	21 ± 7 MeV	Gaussian	
5	$\rho_{\rm DM}$	0.34 ± 0.09 GeV/cm^3	Gaussian	dark matter halo
6	v_0	236 ± 8 km/s	Gaussian	
7	$v_{\rm esc}$	550 ± 35 km/s	Gaussian	
8	m_t	173.3 ± 1.1 GeV	Gaussian	SM uncertainties
9	$m_b(m_b)$	$4.19^{+0.18}_{-0.06}$ GeV	Two-sided Gaussian	
10	$\alpha_s(M_Z)$	0.1184 ± 0.0007	Gaussian	

- astrophysical parameters from [McCabe '10]
- lattice QCD values for σ_s and $\sigma_{\pi N}$ from [Thomas, Shanahan & Young '12]

we assume uniform (linear) priors on all the nuisance parameters

MCMC scan
Dark matter constraints

relic density of sneutrinos

- calculated by `micrOMEGAs` (incl. Coannhilations)
  using the implementation of the model in [Belanger, Kakizaki, Park, Kraml & Pukhov '10]
- we take into account the WMAP7 results: $\Omega h^2 = 0.1123 \pm 0.0035$
  (augmented by 10% theory uncertainty)

direct detection

- σ_{SI} calculated by `micrOMEGAs`
- computation of L_{DD} taking into account variations of ρ_{DM}, v_0, v_{esc}
- we consider:
  - XENON10 2011 (low mass)
  - XENON100 ~~2011~~ **2012**
  - CDMS 2011
  - CoGeNT 2011 (we ignore annual modulation)

[Kopp, Schwetz & Zupan '11;
Schwetz & Zupan '11]

MCMC scan
Z, Higgs & SUSY constraints

Z invisible width

- $\text{LEP} : \Delta\Gamma_Z = \sum_{i=1}^{N_f} \Gamma_\nu \frac{\sin^4 \theta_{\tilde{\nu}_i}}{2} \left(1 - \left(\frac{2m_{\tilde{\nu}_i}}{M_Z}\right)^2\right)^{3/2} < 2 \text{ MeV } (95\% \text{ CL})$

  $\Rightarrow \sin\theta_{\tilde{\nu}} \lesssim 0.4 \text{ for } m_{\tilde{\nu}_1} < m_Z/2$

Higgs and SUSY mass limits

- Higgs BRs from `HDECAY`
- Higg(e)s mass limits computed by `HiggsBounds 3.6.1beta`
- **NEW** $m_{h^0} = 125.5 \pm 2 \text{ GeV}$

- limits on chargino and slepton masses from LEP
- a posteriori (not included in MCMC): gluino mass limits

MCMC scan
Low-energy observables

flavour physics

- $\mathcal{B}(b \to s\gamma) = (3.55 \pm 0.34) \times 10^{-4}$ (HFAG average)
- $\mathcal{B}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ (95% CL)
  NEW $\mathcal{B}(B_s \to \mu^+\mu^-) = 3.2^{+1.5}_{-1.2} \times 10^{-9}$ (LHCb)
- calculated by `micrOMEGAs`
- constraints SUSY at large tan β

muon anomalous magnetic moment

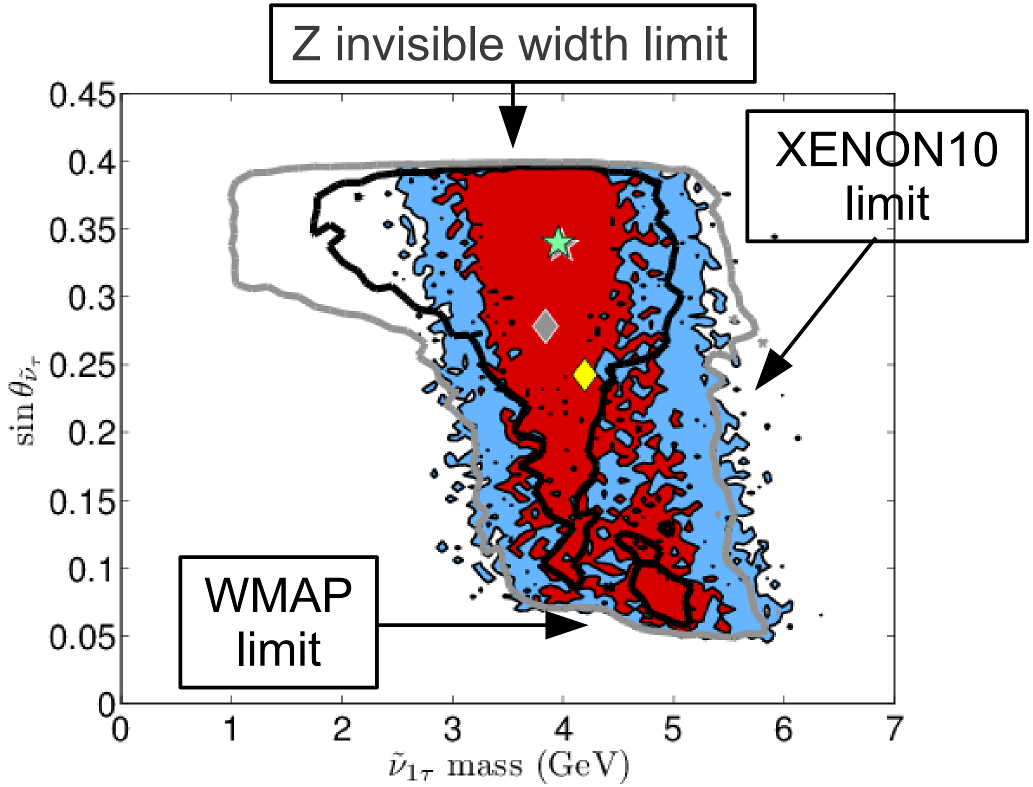
- $\Delta a_\mu = (26.1 \pm 8.0) \times 10^{-10}$ (Hagiwara *et al.* '11)
  (augmented by a theory uncertainty of 10×10^{-10})
- modified 1-loop calculation (due to muon sneutrino mixing)

MCMC scan
Summary of constraints

i	Observable μ_i	Experimental result D_i	Likelihood function $\mathcal{L}_i$
1	Ωh^2	0.1123 ± 0.0035 (augmented by 10% theory uncertainty)	Gaussian
2	σ_N	$(m_{\rm DM}, \sigma_N)$ constraints from XENON10, XENON100, CDMS and CoGeNT	$\mathcal{L}_2 = e^{-\chi^2_{\rm DD}/2}$
3	$\Delta\Gamma_Z$	< 2 MeV (95% CL)	$\mathcal{L}_3 = \mathbf{F}(\mu_3, 2\ \mathrm{MeV})$
4	Higgs mass limits	from `HiggsBounds 3.6.1beta`	$\mathcal{L}_4 = 1$ if allowed $\mathcal{L}_4 = 10^{-9}$ if not
5	h^0 mass	125.5 ± 2 GeV	Gaussian
6	$m_{\tilde{\chi}_1^+}$	> 100 GeV	$\mathcal{L}_6 = 1$ if allowed $\mathcal{L}_6 = 10^{-9}$ if not
7	$m_{\tilde{e}_R} = m_{\tilde{\mu}_R}$	> 100 GeV	$\mathcal{L}_7 = 1$ if allowed $\mathcal{L}_7 = 10^{-9}$ if not
8	$m_{\tilde{\tau}_1}$	> 85 GeV	$\mathcal{L}_8 = 1$ if allowed $\mathcal{L}_8 = 10^{-9}$ if not
9	$m_{\tilde{g}}$	> 750, 1000 GeV or none	not included (a posteriori cut)
10	$\mathcal{B}(b \to s\gamma)$	$(3.55 \pm 0.34) \times 10^{-4}$	Gaussian
11	$\mathcal{B}(B_s \to \mu^+\mu^-)$	$3.2^{+1.5}_{-1.2} \times 10^{-9}$	Two-sided Gaussian
12	Δa_μ	$(26.1 \pm 12.8) \times 10^{-10}$	Gaussian

F: smoothed step function (emulates the 95% CL bounds)

Light sneutrino results



- sneutrino: good DM candidate below 7 GeV
- lower bound on mixing angle
  ⇒ lower bound on σ_{SI}
- bounds on gluinos exclude the very low mass region

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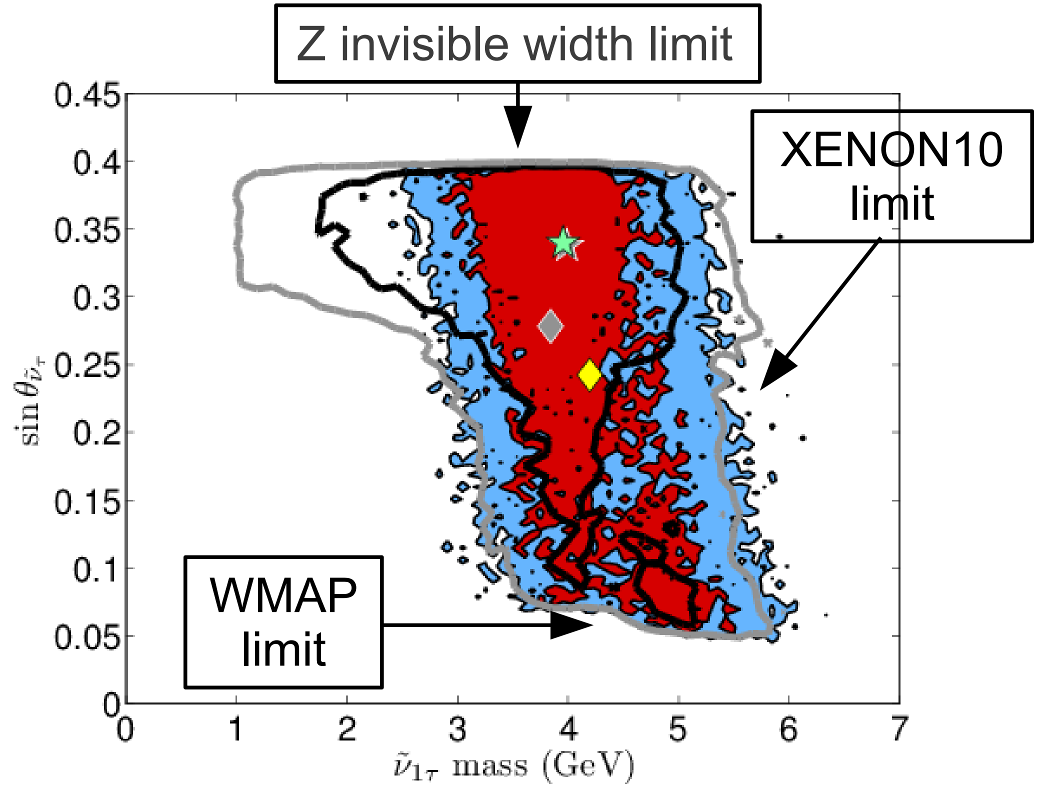
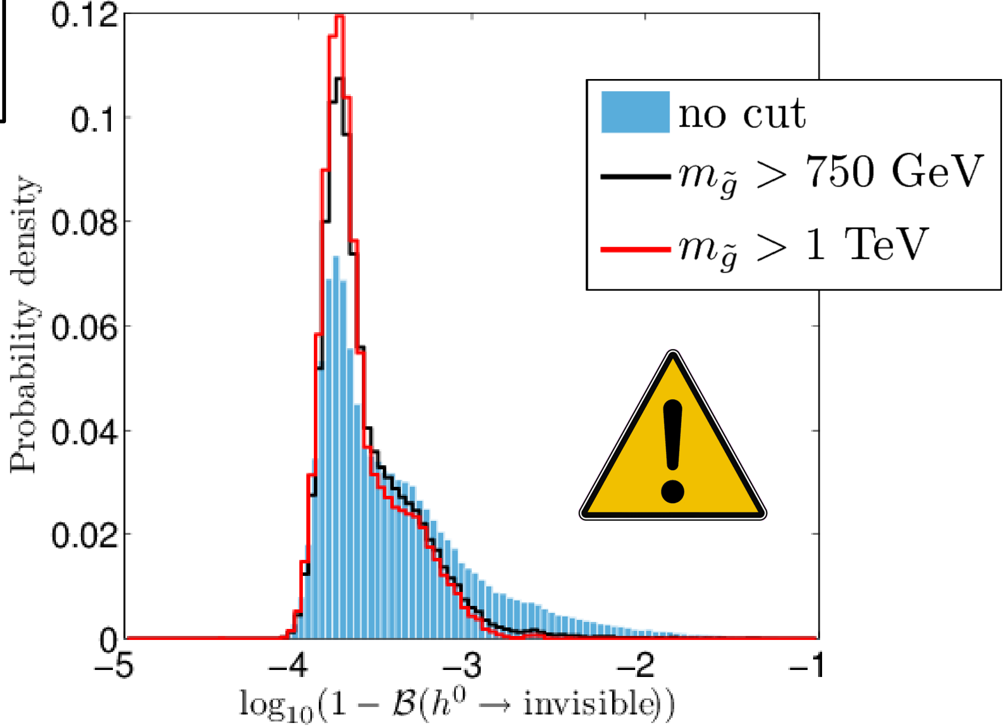


invisible Higgs decays



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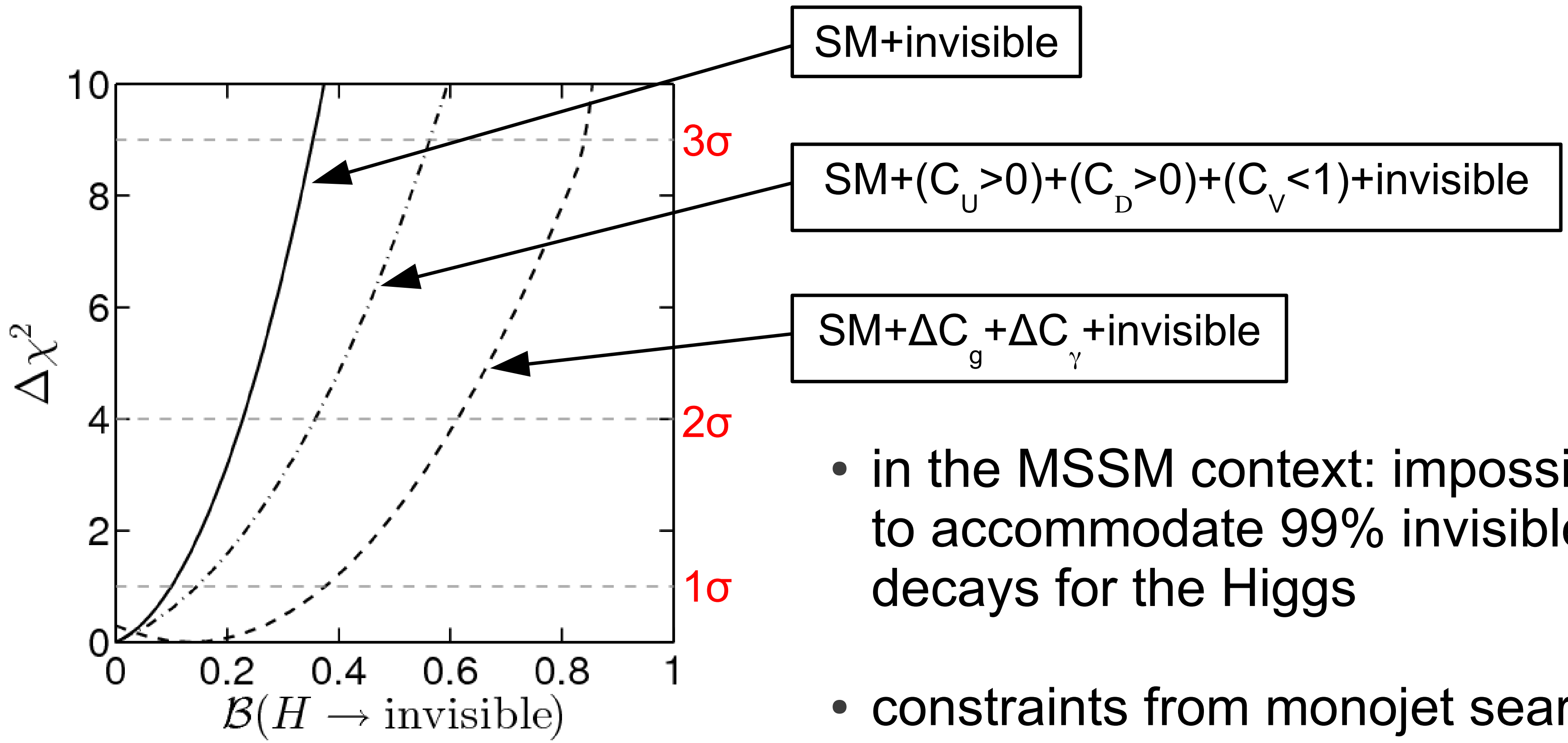
the Higgs decays dominantly (> 99%) into sneutrinos

how much invisible is actually allowed?

Status of invisible Higgs decays

Performing a fit to all available Higgs results from ATLAS, CMS and Tevatron:



[Bélanger, BD, Ellwanger, Gunion, Kraml, in preparation]

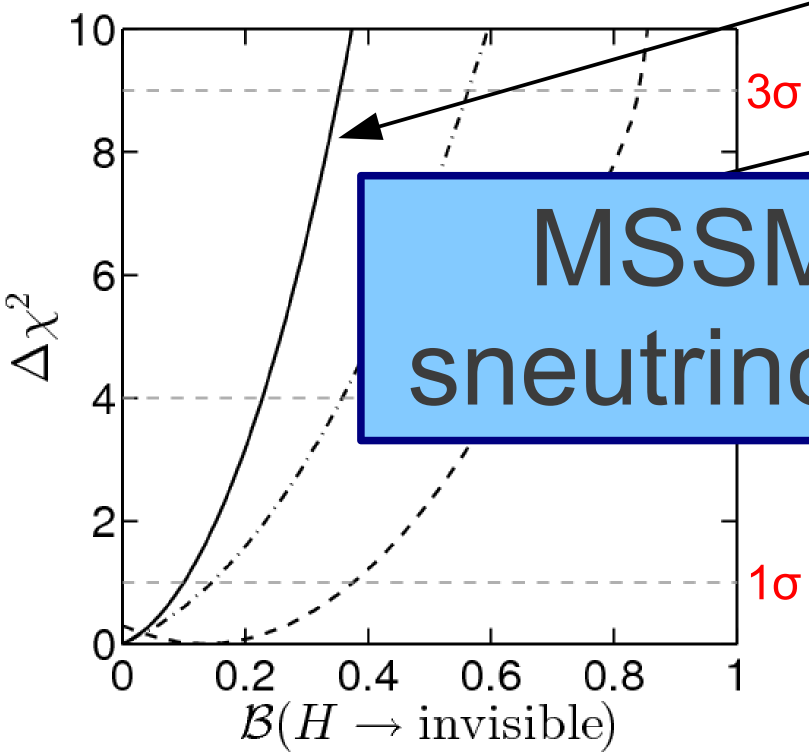
- in the MSSM context: impossible to accommodate 99% invisible decays for the Higgs
- constraints from monojet searches [Djouadi *et al.* '12] also rule out this possibility

Status of invisible Higgs decays

Performing a fit to all available Higgs results from ATLAS, CMS and Tevatron:

SM+invisible

SM+(C_U>0)+(C_D>0)+(C_V<1)+invisible



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MSSM light mixed sneutrinos are excluded

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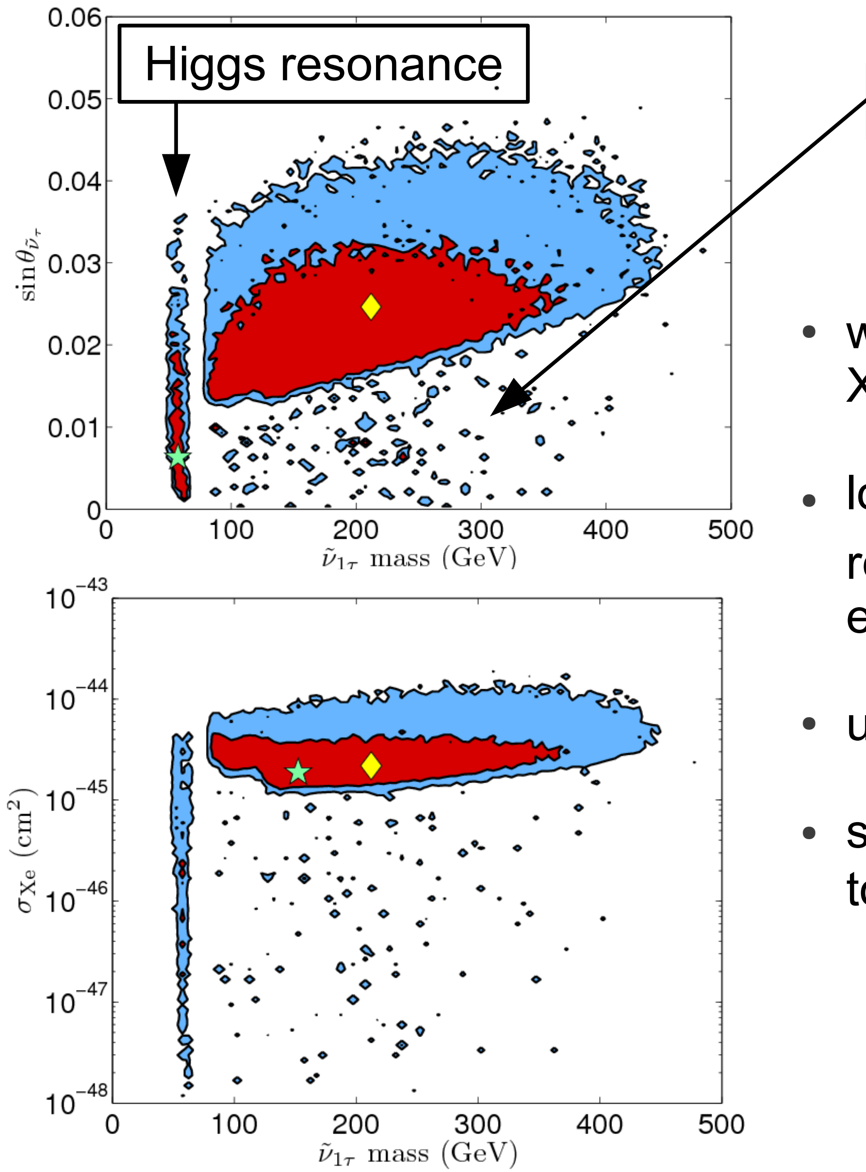
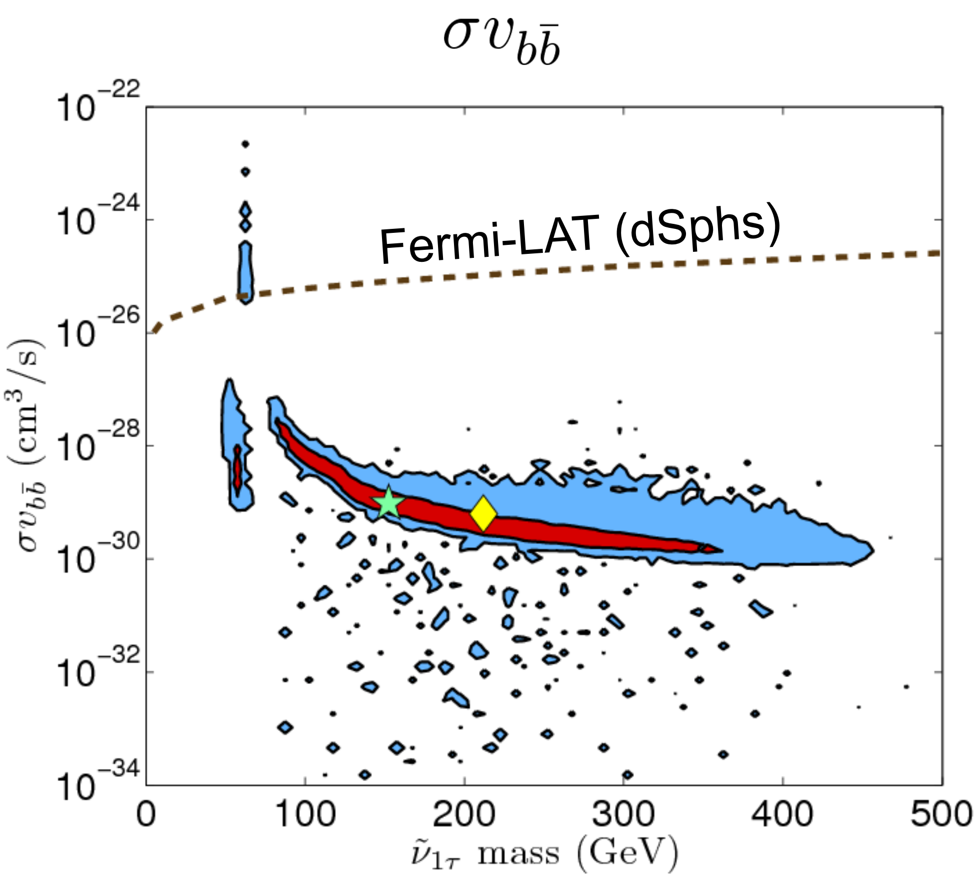
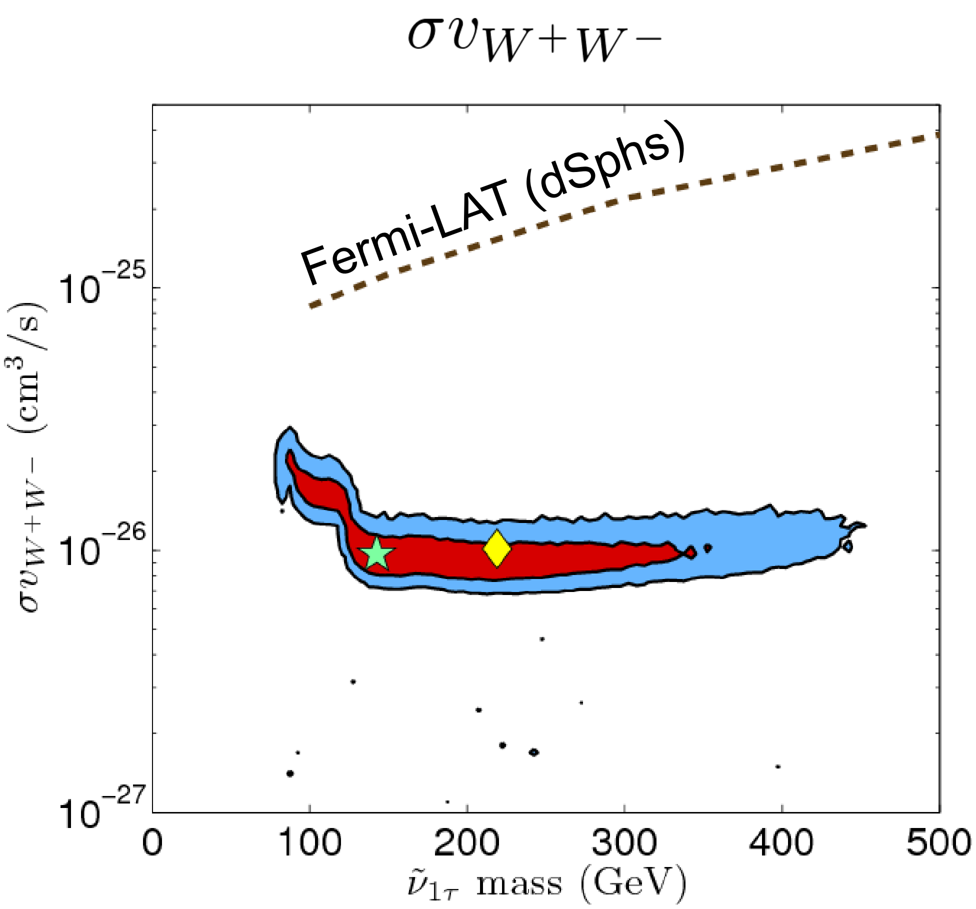
Heavy sneutrino results



- we need a very low mixing angle to pass the XENON100 limit
- lower bound on σ_{SI} except for coannihilation and resonance cases: the main region could soon be excluded by direct detection
- upper limit on the LSP sneutrino mass
- similar results if the e, μ and τ sneutrinos are required to be close in mass (“democratic” case)

Heavy sneutrino results
indirect detection – Fermi-LAT limits on γ-rays





- usually two orders of magnitude below the limit
- special region with Breit-Wigner enhancement

- one order of magnitude improvement from Fermi-LAT would constrain the model

LHC phenomenology

- having a sneutrino LSP significantly changes the expected SUSY signal:
  - lepton+MET from chargino decay: $\tilde{\chi}_1^\pm \to \ell^\pm \tilde{\nu}_1$
  - invisible neutralino 1 & 2 decays: $\tilde{\chi}_{1,2}^0 \to \tilde{\nu}_1^* \tilde{\nu}_1$
    $\to$ up to 3 invisible sparticles in the decay chain!

the flavour of the light sneutrino(s) matters!

	heavy	heavy democratic
$\mathcal{B}(\tilde{\chi}_1^0 \to \text{inv}) > 0.9$	96%	98%
$\mathcal{B}(\tilde{\chi}_2^0 \to \text{inv}) > 0.9$	29%	42%
$\mathcal{B}(\tilde{\chi}_1^\pm \to \ell^\pm \, \tilde{\nu}_{1\ell}) > 0.5$	9%	48%
$\mathcal{B}(\tilde{\chi}_1^\pm \to \tau^\pm \, \tilde{\nu}_{1\tau}) > 0.5$	46%	10%

not up-to-date numbers

- previous studies: [Thomas, Tucker-Smith & Weiner '07, Belanger, Kraml & Lessa '11]

- work in progress...

Conclusion

- the discovery of a SM-like Higgs boson at the LHC rules out the possibility for light (< 10 GeV) mixed sneutrino dark matter in the MSSM
- heavy (≈ 60–500 GeV) mixed sneutrinos are viable dark matter candidates
- (in)direct detection could soon probe the main allowed region for sneutrino dark matter
- indirect detection: possible neutrino signal?
- interesting LHC phenomenology to be explored!

Backup

Annihilation into neutrino pairs