WIMP dark matter

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(Supersymmetric)

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(... very light)

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RH-Sneutrinos

Containing work done (and in progress) in collaboration with C. Muñoz, O. Seto, M. Peiró

Outline

Motivation: Direct DM Detection (hints of very light WIMPs?)

Neutralino DM in the MSSM and extensions

Right-Handed Sneutrino as WIMP dark matter

Predictions for direct detection

Very light sneutrinos

Conclusions

WHAT is the Dark Matter?

… WHAT DO WE KNOW…

- Good dark matter candidates must fulfil a number of requirements

- Neutral
- Stable on cosmological scales
- Reproduce the correct relic abundance
- Not excluded by direct or indirect searches
- No conflicts with BBN or stellar evolution

- Many candidates in Particle Physics

- Axions
- Weakly-Interacting massive particles:

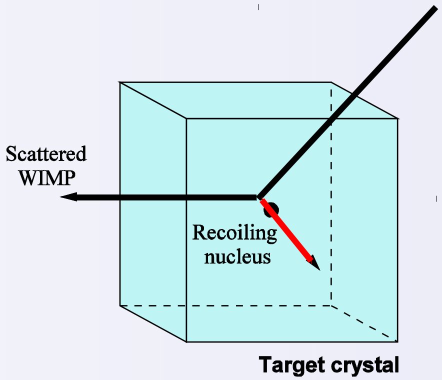
  WIMPs
- SuperWIMPs (gravitino, axino)
- SIMPs, CHAMPs, SIDMs, WIMPzillas, Scalar DM, Light DM, ...

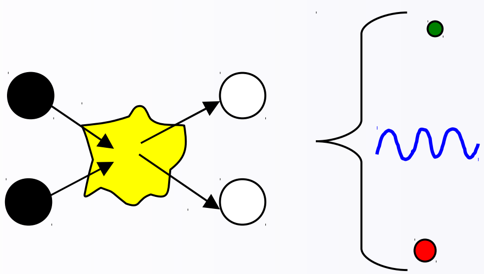
NEW PHYSICS BEYOND THE STANDARD MODEL OF PARTICLE PHYSICS

Detection of Dark Matter

- Direct Detection:

  Look for the elastic scattering of dark matter with nuclei





Neutrinos

Photons

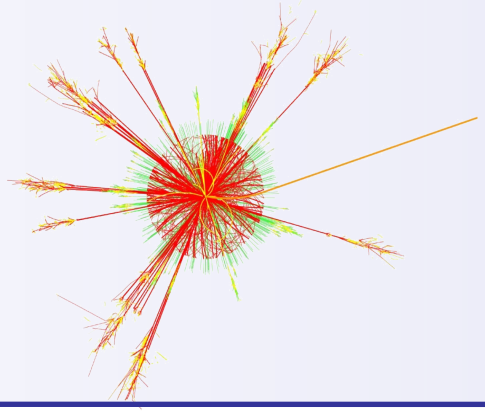
Electron-Positron, Antimatter

- Indirect Detection:

  Look for the annihilation products

- Accelerator Searches

  Look for signals of new physics



Direct detection of DM

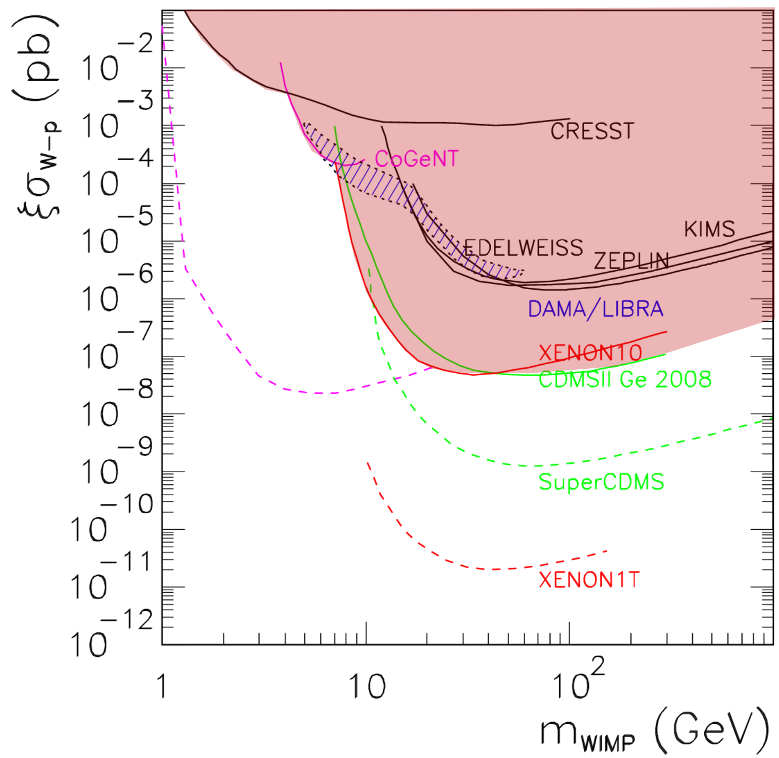
- Most of the experiments nowadays are mostly sensitive to the scalar (spin-independent) part of the WIMP-nucleon cross section

DAMA/LIBRA (based on NaI) claims a potential dark matter signal

Other experiments (XENON10-100, CDMS and CoGeNT) have not yet confirmed any WIMP in the DAMA region (maybe very light WIMPs?)

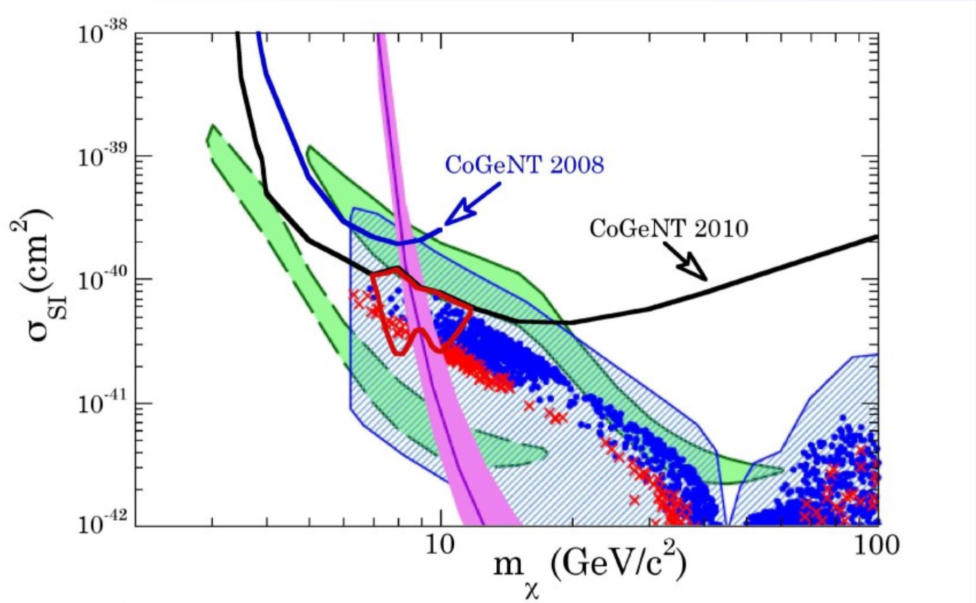
The current sensitivity and future predictions will allow to explore models for particle dark matter.

Need to compare with theoretical predictions for WIMP models



Recent results for light WIMPs

• Light WIMPs might be motivated by experimental results from direct detection



(CoGeNT Coll. 2010)

Not necessarily excluded by other experiments (depending on the halo model)

Very light WIMPs (5-12 GeV) could account for the DAMA/LIBRA signal and be compatible with CDMS events and recent results from CoGeNT...

Compatible with XENON10-100?

(Subtleties in the treatment of L_{eff})

(Aprile et al (XENON Coll) 2010)
(Savage et al. 2010)
(Collar, McKinsey 2010)

Are there theoretical models for these WIMPs?

Supersymmetric Dark Matter

• The Lightest SUSY Particle is stable in theories with R-parity. Thus, it will exist as a remnant from the early universe and may account for the observed Dark Matter.

In the MSSM, the LSP can be…

Squarks	$\tilde{u}_{R,L}$, $\tilde{d}_{R,L}$ $\tilde{c}_{R,L}$, $\tilde{s}_{R,L}$ $\tilde{t}_{R,L}$, $\tilde{b}_{R,L}$
Sleptons	$\tilde{e}_{R,L}$, $\tilde{\nu}_e$ $\tilde{\mu}_{R,L}$, $\tilde{\nu}_\mu$ $\tilde{\tau}_{R,L}$, $\tilde{\nu}_\tau$
Neutralinos	$\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_{1,2}$
Charginos	$\tilde{W}^\pm$, $\tilde{H}^\pm_{1,2}$
Gluino	$\tilde{g}$

Lightest sneutrino: They annihilate very quickly and the regions where the correct relic density is obtained are already experimentally excluded

(Ibáñez ’84; Hagelin, Kane, Rabi ’84)

Lightest neutralino: WIMP

(Goldberg ‘83; Ellis, Hagelin, Nanopoulos, Olive, Srednicki ‘83; Krauss ‘83)

The neutralino in the MSSM

- Neutralinos in the MSSM are physical superpositions of the bino and wino $(\tilde{B}^0,\ \tilde{W}_3^0)$ and Higgsinos $(\tilde{H}_d^0,\ \tilde{H}_u^0)$

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 \end{pmatrix}$$

The detection properties of the lightest neutralino depend on its composition

$$\tilde{\chi}_1^0 = \underbrace{N_{11}\,\tilde{B}^0 + N_{12}\,\tilde{W}_3^0}_{\texttt{Gaugino content}} + \underbrace{N_{13}\,\tilde{H}_d^0 + N_{14}\,\tilde{H}_u^0}_{\texttt{Higgsino content}}$$

Neutralino in the MSSM

- The neutralino can be within the reach of present and projected direct DM detectors

Large cross section for a wide range of masses

Very light **Bino-like** neutralinos with masses ~10 GeV

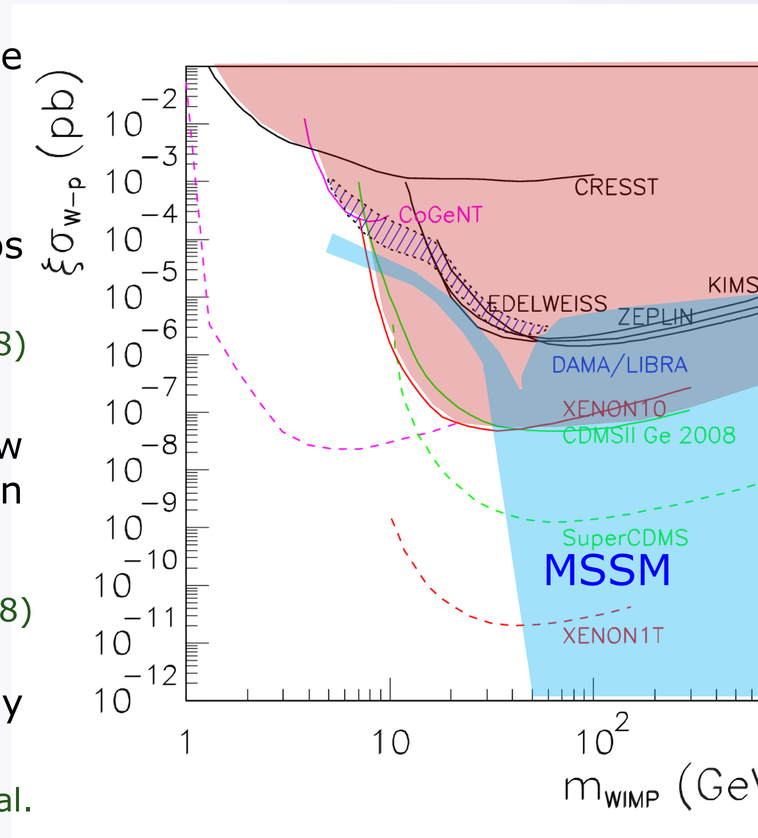
(Bottino, Donato, Fornengo, Scopel '04-'08)

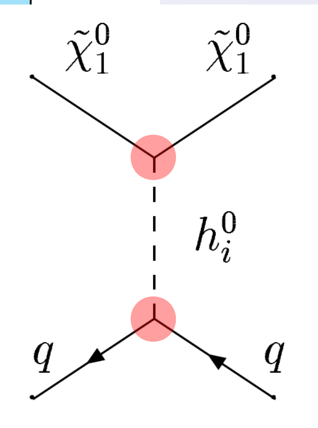
Bayesian analyses show preference for regions within the reach of CDMS and Xenon

(Roszkowski, Ruiz de Austri, Trotta '08)

A frequentist approach may favour different regions

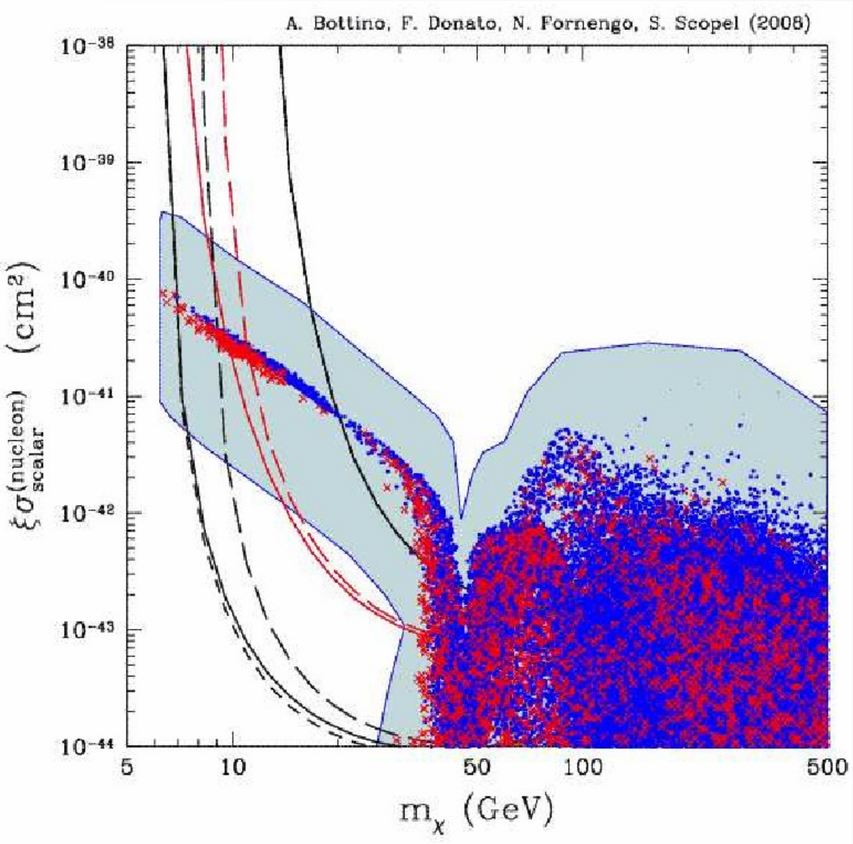
(K. Olive et al.





Very light neutralinos in the MSSM

- Light neutralinos in the MSSM are possible (though fine-tuned)



(Bottino, Donato, Fornengo, Scopel '08)

These neutralinos are Bino-like

$$M_1 \ll M_{2,} M_3$$

Correct relic density due to increase of annihilation through pseudoscalar Higgses

$$m_A \leq 200\, GeV$$
$$\tan\beta \geq 40$$

Very problematic for low-energy observables, e.g., BR(Bs → μ+μ−)

Very light neutralinos in the MSSM

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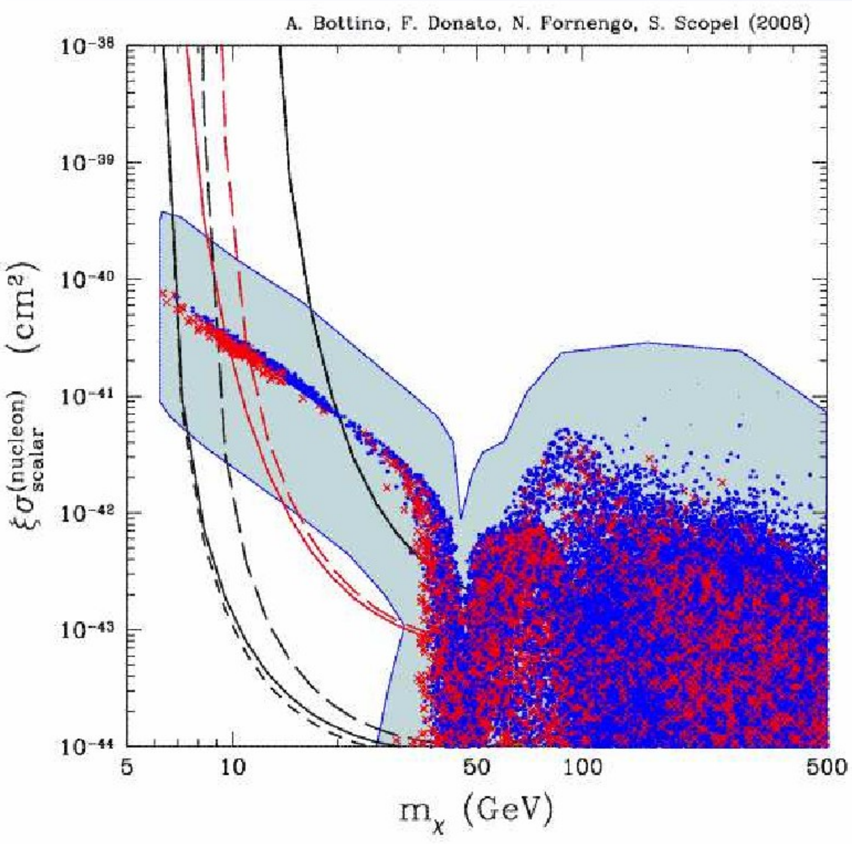

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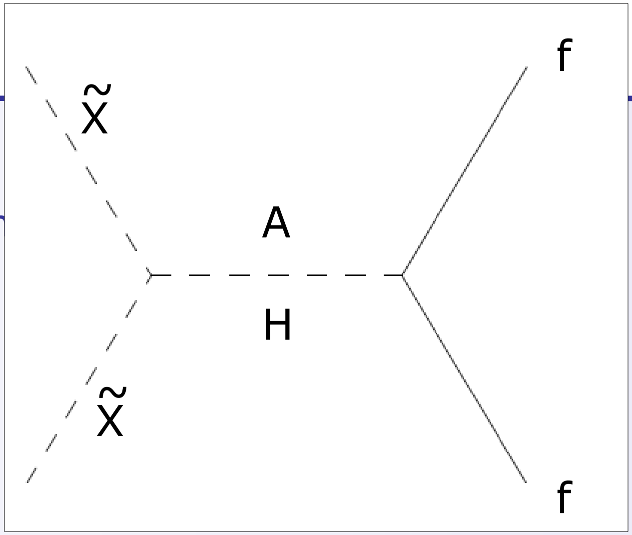
These



Correct relic density due to increase of annihilation through pseudoscalar Higgses

$$m_A \leq 200\,GeV$$

$$\tan\beta \geq 40$$

Very problematic for low-energy observables, e.g., BR(Bs → μ+μ−)

Neutralino in the Next-to-MSSM

$$\text{NMSSM} = \text{MSSM} + \hat{S} \begin{cases} 2 \text{ extra Higgs } (\text{CP}-\text{even},\ \text{CP}-\text{odd}) \\ 1 \text{ additional Neutralino} \end{cases}$$

- In the Next-to-MSSM there is a fifth neutralino due to the mixing with the singlino

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta & 0 \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta & 0 \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu & -\lambda v_2 \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2\kappa \frac{\mu}{\lambda} \end{pmatrix}$$

The lightest neutralino has now a singlino component

$$\tilde{\chi}_1^0 = \underbrace{N_{11}\,\tilde{B}^0 + N_{12}\,\tilde{W}_3^0}_{\text{Gaugino content}} + \underbrace{N_{13}\,\tilde{H}_d^0 + N_{14}\,\tilde{H}_u^0}_{\text{Higgsino content}} + \underbrace{N_{15}\,\tilde{S}}_{\text{Singlino content}}$$

Neutralino in the NMSSM

- Different predictions from the MSSM (extensions with extra U(1) are also possible)

The detection cross section can be larger (through the exchange of light Higgses)

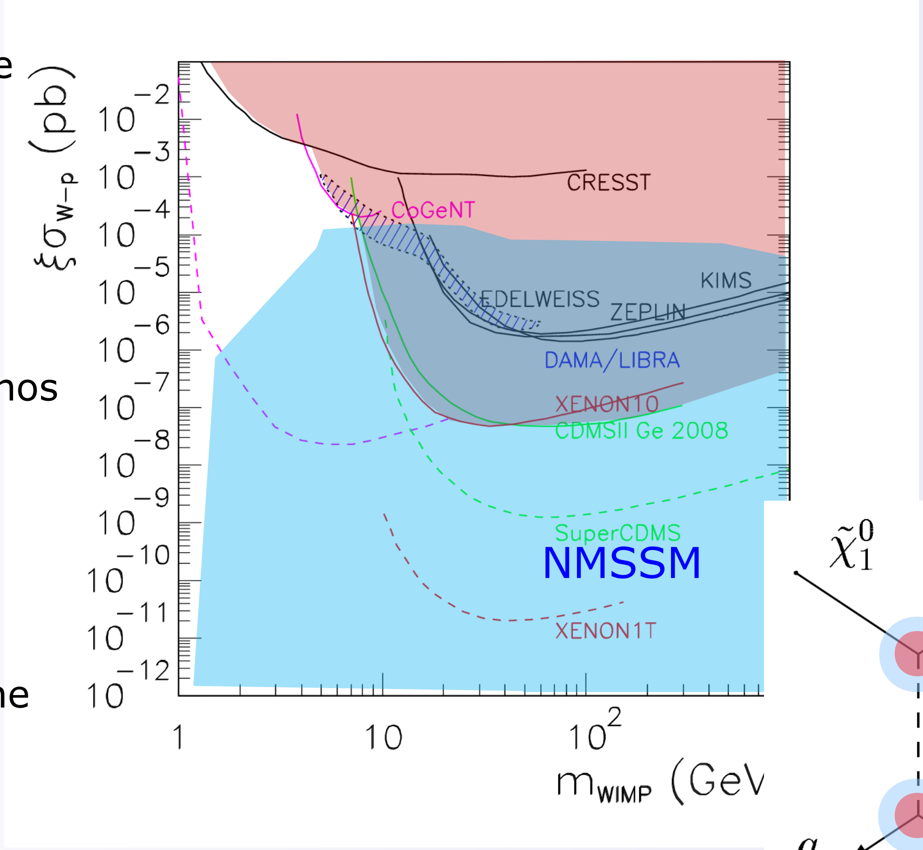
(D.G.C., E. Gabrielli, D.López-Fogliani, A.Teixeira, C.Muñoz ´07)

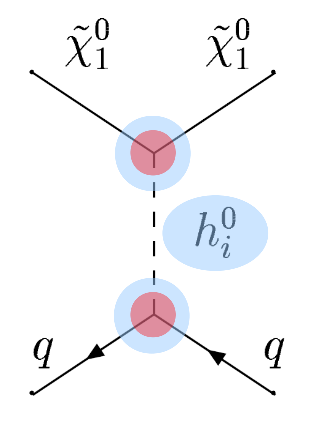
Very light **Bino-singlino** neutralinos are possible

(Gunion, Hooper, McElrath '05)

And their detection cross section significantly differs from that in the MSSM

(CoGeNT '08)





Neutralino in the NMSSM

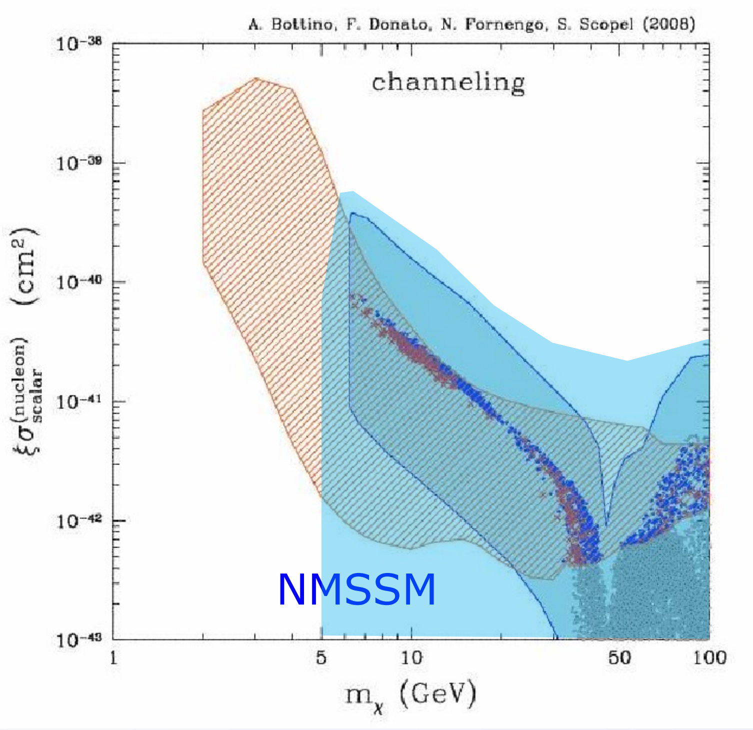
- Very light neutralinos (~5-7 GeV) can be in agreement with DAMA observation

- Better fit of low-energy observables (e.g., smaller contribution to BR(b→sγ))

Higgses can be singlet-like

- Wider regions of the parameter space

Pseudoscalar can be much lighter without the need of large tan β

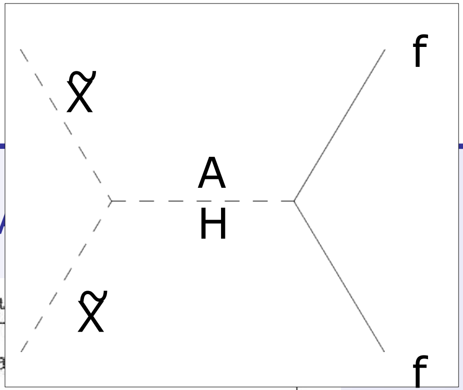


(CoGeNT '08)

- Less constrained if there is no observation of light WIMPs

Neutralino in the NMSSM

- Very light neutralinos (~5-7 GeV) can be in agreement with D



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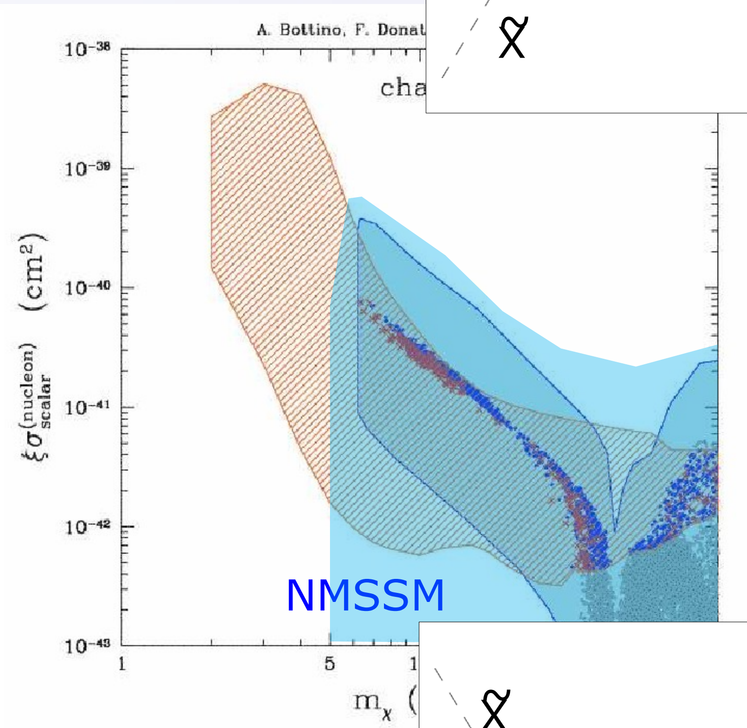

- Wider regions of the parameter space

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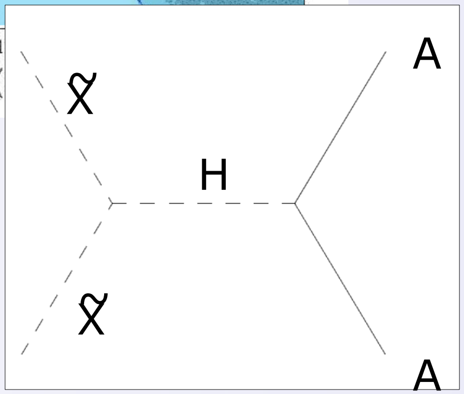


(CoGeNT '08)

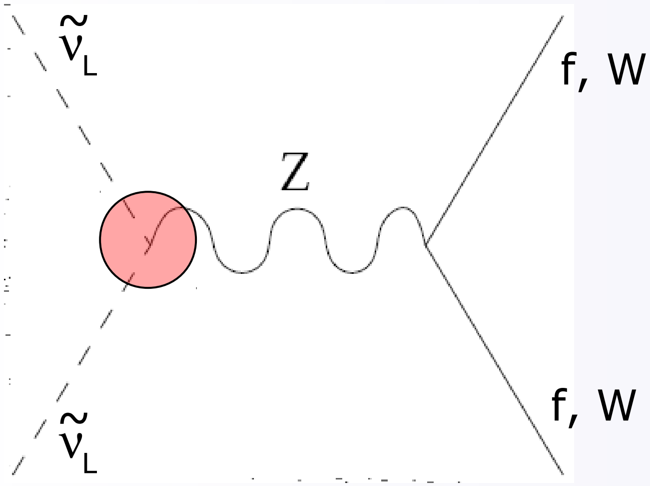
- Less constrained if there is no observation of light WIMPs

Other SUSY WIMPs?

- Sneutrino dark matter in the NMSSM

Sneutrino DM in the MSSM

- On the Standard MSSM: Pure left-handed sneutrino, faces some problems



Sizable coupling with Z boson, leading to

- Too large annihilation cross section (implying too small relic density)

(Ibáñez '84; Hagelin, Kane, Rabi '84; Goodmann, Witten'85; Freese '86)

- Too large direct detection cross section (already disfavoured by current experiments)

(Falk, Olive, Srednicki '94)

Attempts to solve this including (unnaturally large) mixing with sterile (RH sneutrino)

(Arkani-Hamed et al. '91; Hooper et al. '05)

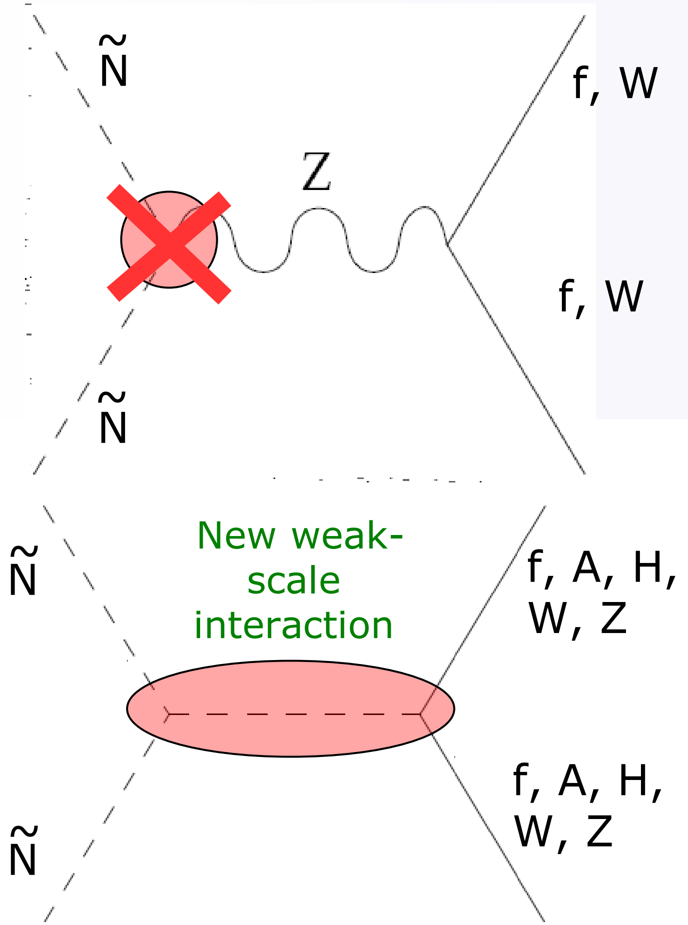
Or considering a (NON-WIMP) pure RH-sneutrino

(Asaka et al. '06; Gopalakrishna et al. '06; McDonald '07)

Sneutrino DM beyond the MSSM

• Solution? Coupling the RH sneutrino to the observable sector WEAKLY (e.g., extending gauge or Higgs sectors)

(Lee et al. ‘07; Garbrecht et al. '06)



$$\tilde{\nu} = \tilde{N}$$

WIMP

This can be accommodated in a well-motivated extension of the MSSM:

the Next-to-Minimal SUSY SM (NMSSM)

(D.G.C., Muñoz, Seto ‘08; D.G.C. Seto '09)

The NMSSM with right-handed neutrinos

- Addition of TWO new superfields, ***S***, ***N***, singlets under the SM gauge group

$$\mathrm{NMSSM} \quad = \quad \mathrm{MSSM} + \hat{S} \left\{ \begin{array}{l} 2 \text{ extra Higgs } (\mathrm{CP-even},\ \mathrm{CP-odd}) \\ 1 \text{ additional Neutralino} \end{array} \right.$$

$$+ N \left\{ \begin{array}{l} 1 \text{ additional (right-handed) Neutrino} \\ \text{and sneutrino} \end{array} \right.$$

S cures the μ problem

N provides right-handed neutrinos (see-saw)

The NMSSM with right-handed neutrinos

- Addition of TWO new superfields, ***S***, ***N***, singlets under the SM gauge group

$$\mathrm{NMSSM} = \mathrm{MSSM} + \hat{S} \begin{cases} 2 \text{ extra Higgs (CP} - \text{even, CP} - \text{odd)} \\ 1 \text{ additional Neutralino} \end{cases}$$

$$+ N \begin{cases} 1 \text{ additional (right-handed) Neutrino} \\ \text{and sneutrino} \end{cases}$$

- New terms in the superpotential

$$W = Y_u\, H_2\, Q\, u + Y_d\, H_1\, Q\, d + Y_e\, H_1\, L\, e - \lambda\, S\, H_1 H_2 + \frac{1}{3}\kappa S^3$$

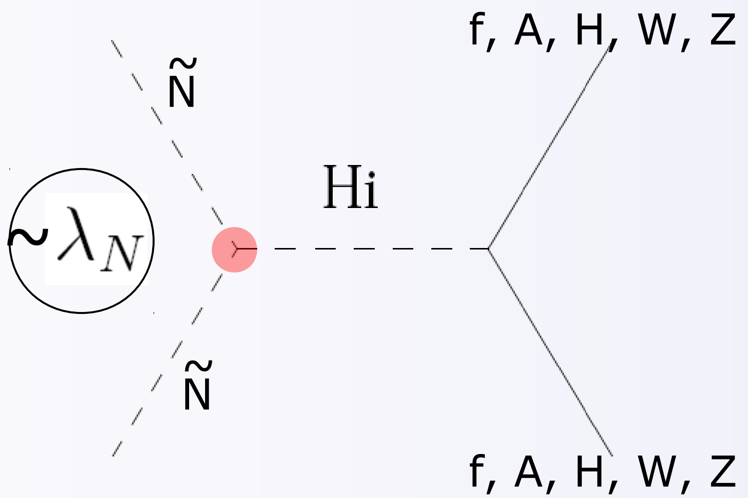
$$W = W_{\mathrm{NMSSM}} + \lambda_N S N N + y_N L\, H_2 N$$

- After Radiative Electroweak Symmetry-Breaking

$$\langle H_1^0 \rangle = v_1 \quad ; \quad \langle H_2^0 \rangle = v_2 \quad ; \quad \langle S \rangle = s \qquad \begin{cases} \mu\, H_1\, H_2 \\ m_N\, N\, N \end{cases}$$

Sneutrino Interactions

$\tilde{\nu} = \tilde{N}$ PURE RH-SNEUTRINO (LR mixing proportional to very small Yukawa)



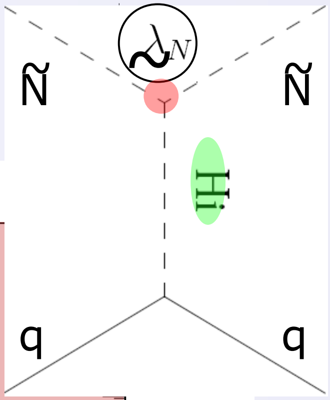
BUT COUPLED TO THE HIGGS (and therefore to SM particles)

WIMP

RH-Sneutrino DM overview

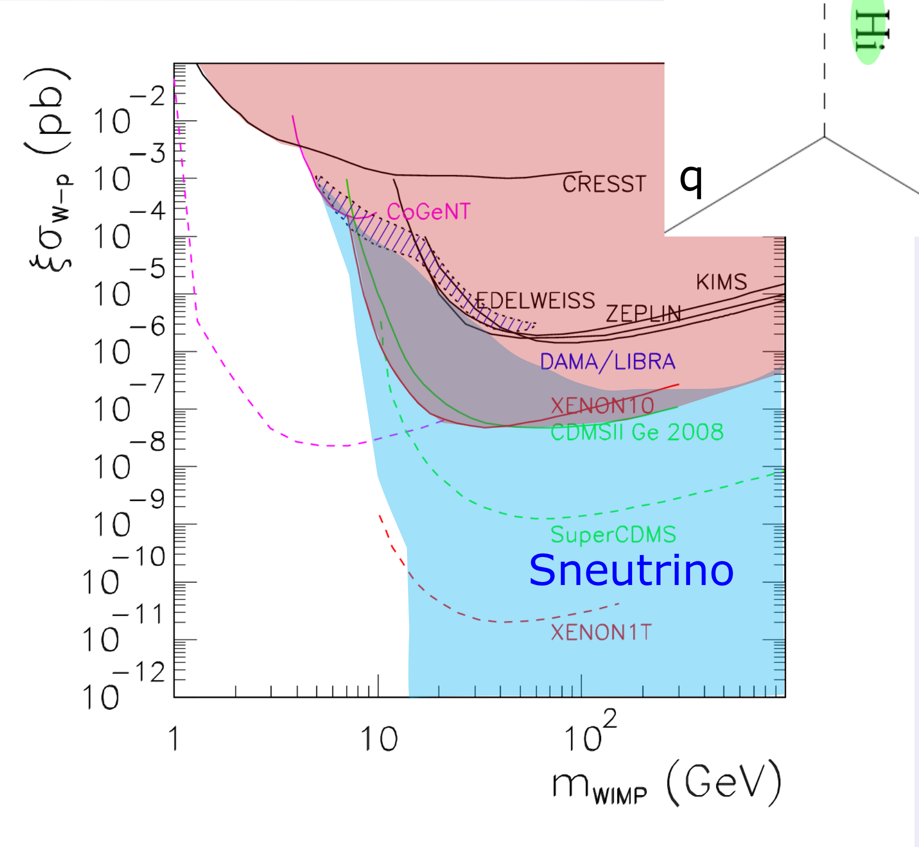
- (Right-handed) sneutrinos in the NMSSM: Predictions for direct detection

Main contribution from **Higgs-**exchanging diagrams
dependent on the new coupling and Higgs mass



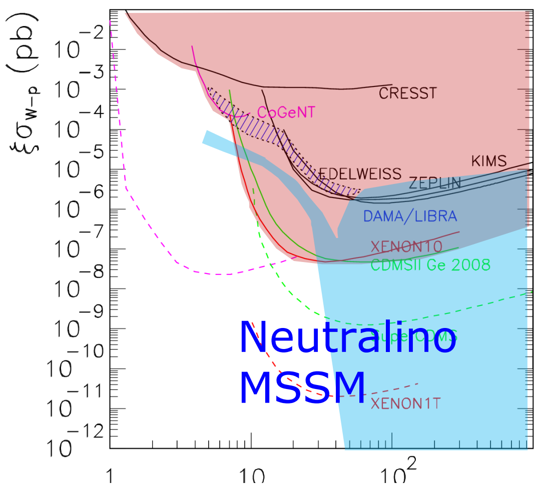
- ○ Viable, accessible and not yet excluded
  (D.G.C., Muñoz, Seto '08)

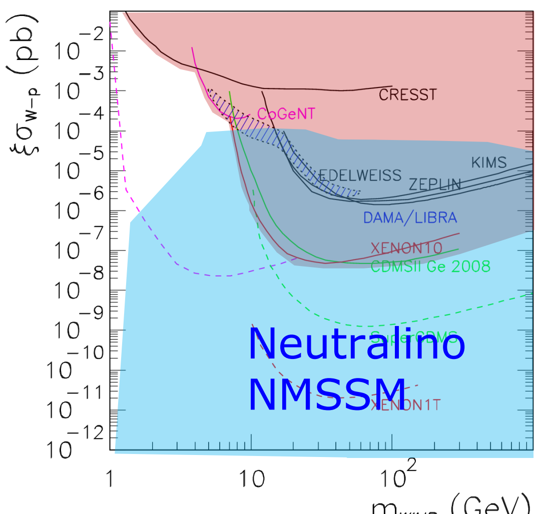
- ○ Light sneutrinos are viable and distinct from MSSM neutralinos
  (D.G.C., Seto '09)

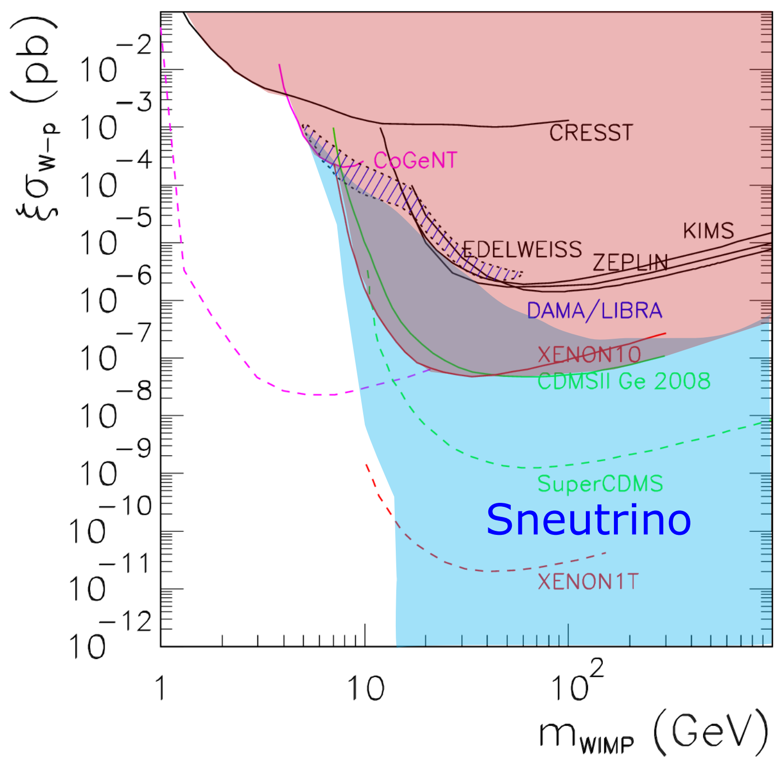


Comparison with other SUSY WIMPs (neutralinos)

- These predictions differ from those of the neutralino







Very light RH-Sneutrinos

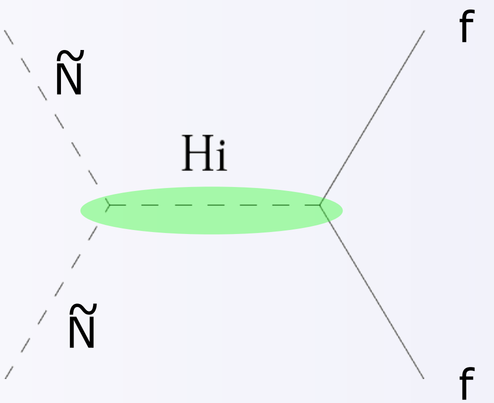
• Very light RH-sneutrinos can occur (with the correct relic abundance) in two ways:

• Annihilation $\tilde{N}\tilde{N} \rightarrow ff$

Large coupling to fermions

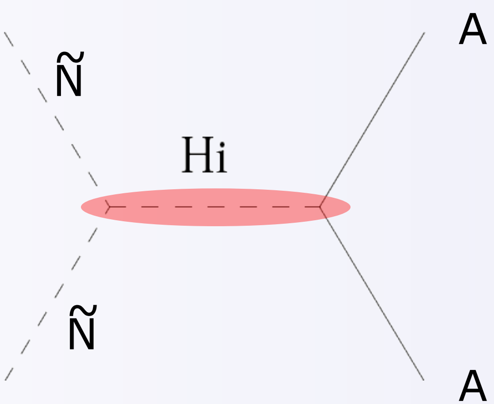
Easier than MSSM due to freedom with new coupling and small Higgs masses

Better low-energy phenomenology



• Annihilation $\tilde{N}\tilde{N} \rightarrow AA$

Requires very light pseudoscalars (singlet-like)



Very light RH-Sneutrinos

- The properties under Direct Detection are very different

- Annihilation $\tilde{N}\tilde{N} \to ff$

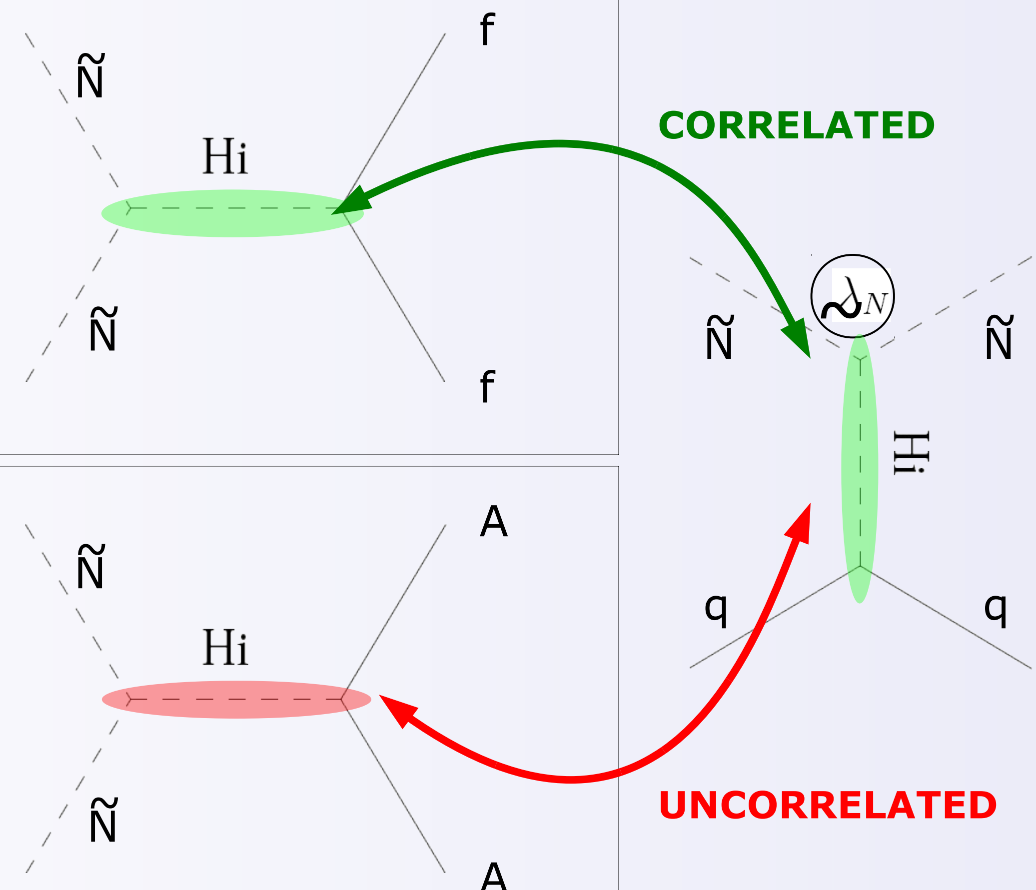
Large coupling to fermions

Easier than MSSM due to freedom with new coupling and small Higgs masses

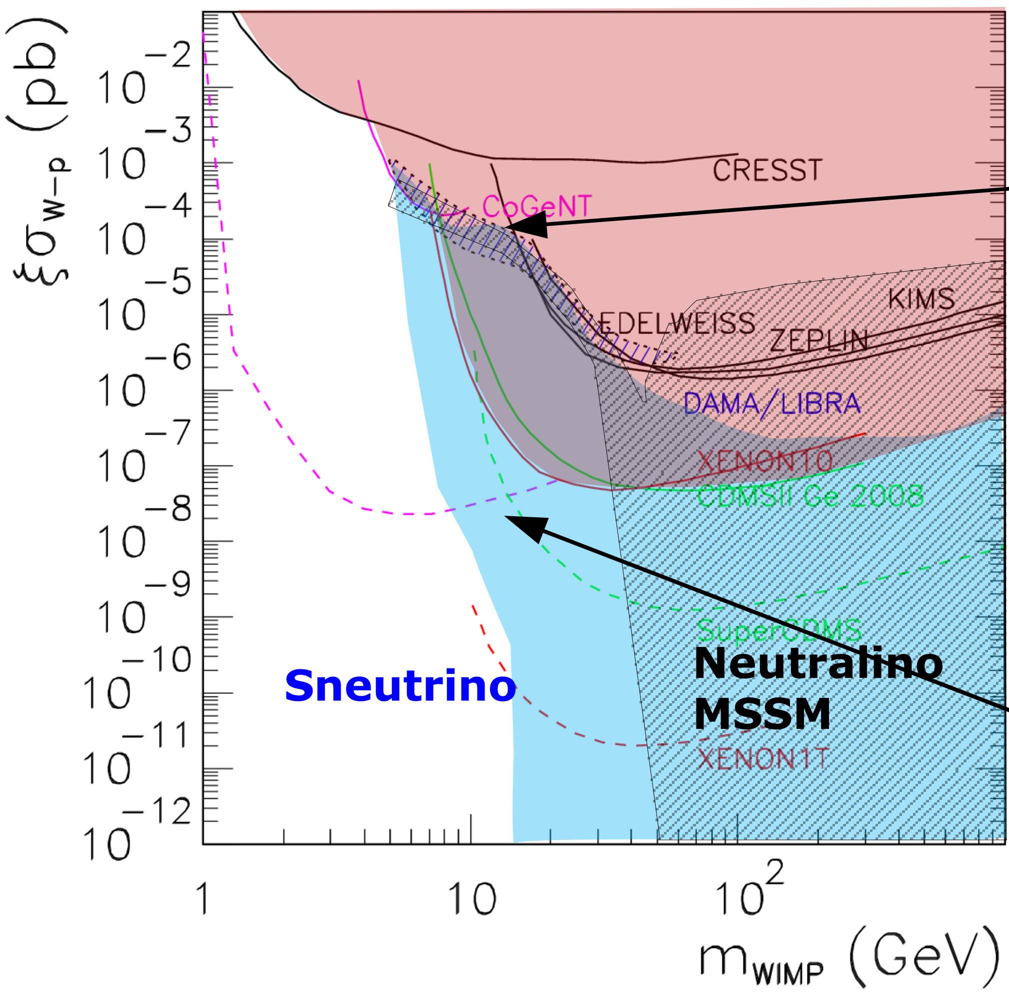
Better low-energy phenomenology

- Annihilation $\tilde{N}\tilde{N} \to AA$

Requires very light pseudoscalars (singlet-like)



Very light RH-Sneutrinos



$\tilde{N}\tilde{N} \to ff$

Similar to Neutralino in MSSM

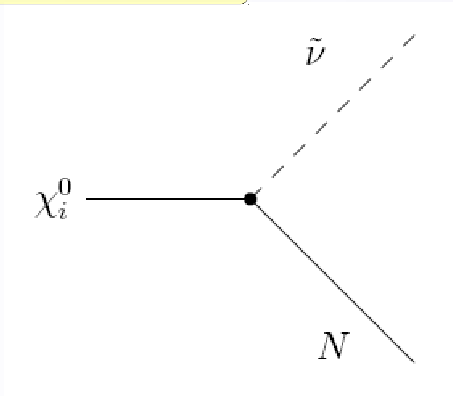
$\tilde{N}\tilde{N} \to AA$

Can be similar to Neutralino in NMSSM

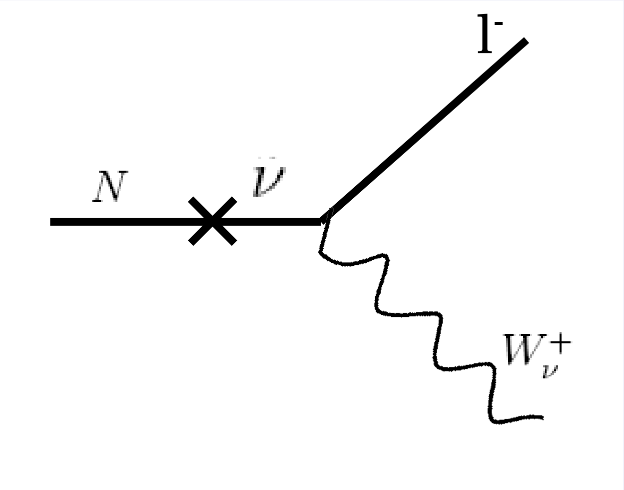
Collider signals

- (Right-handed) sneutrinos in the NMSSM: Signals at colliders?

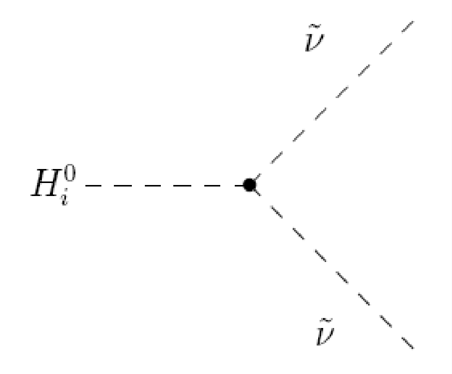
  - Missing energy

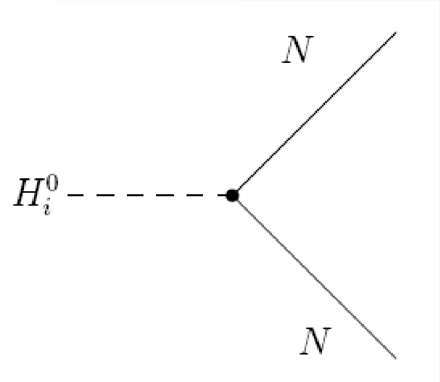


  - Displaced vertices of RH-neutrino decay



  - Invisible Higgs decays





with M.Peiró and O. Seto

Conclusions

Light SUSY WIMPs:

Neutralino (MSSM and NMSSM) and **RH-Sneutrino** (in the NMSSM)

Right-Handed Sneutrino can be a **viable WIMP DM candidate**

Very light RH-Sneutrinos are possible

- Annihilation $\tilde{N}\tilde{N} \rightarrow ff$ (similar to neutralino in the MSSM)
- Annihilation $\tilde{N}\tilde{N} \rightarrow AA$ (can be confused with neutralinos in the NMSSM)

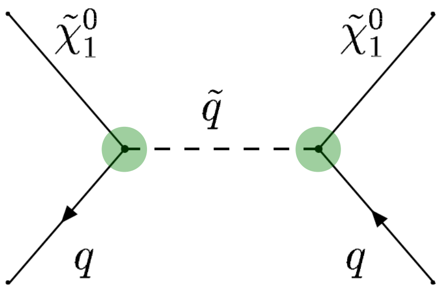
Distinguishable with combined DD experiments or with LHC signals

Complementary material

Neutralino

Spin-dependent cross section

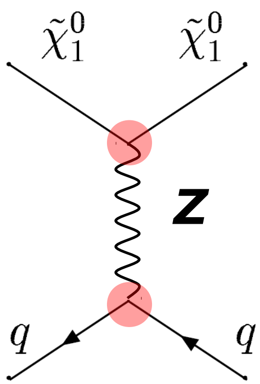
- Contributions from **squark-** and **Z-**exchanging diagrams:



Squark-exchange

$$\alpha_{2i}^{\tilde{q}} = \frac{1}{4(m_{1i}^2 - m_\chi^2)}\left[|Y_i|^2 + |X_i|^2\right] + \frac{1}{4(m_{2i}^2 - m_\chi^2)}\left[|V_i|^2 + |W_i|^2\right]$$

- Typically very small unless $m_q \sim m_\chi$



Z-exchange

$$\alpha_{2i}^{Z} = -\frac{g^2}{4m_Z^2\cos^2\theta_W}\left[|N_{13}|^2 - |N_{14}|^2\right]\frac{T_{3i}}{2}$$

Leading contribution but has an upper bound: $\sigma \leq 6.2\times 10^{-2}$ pb

- It also increases with the neutralino Higgsino components: $\mu \downarrow$

Spin-dependent searches

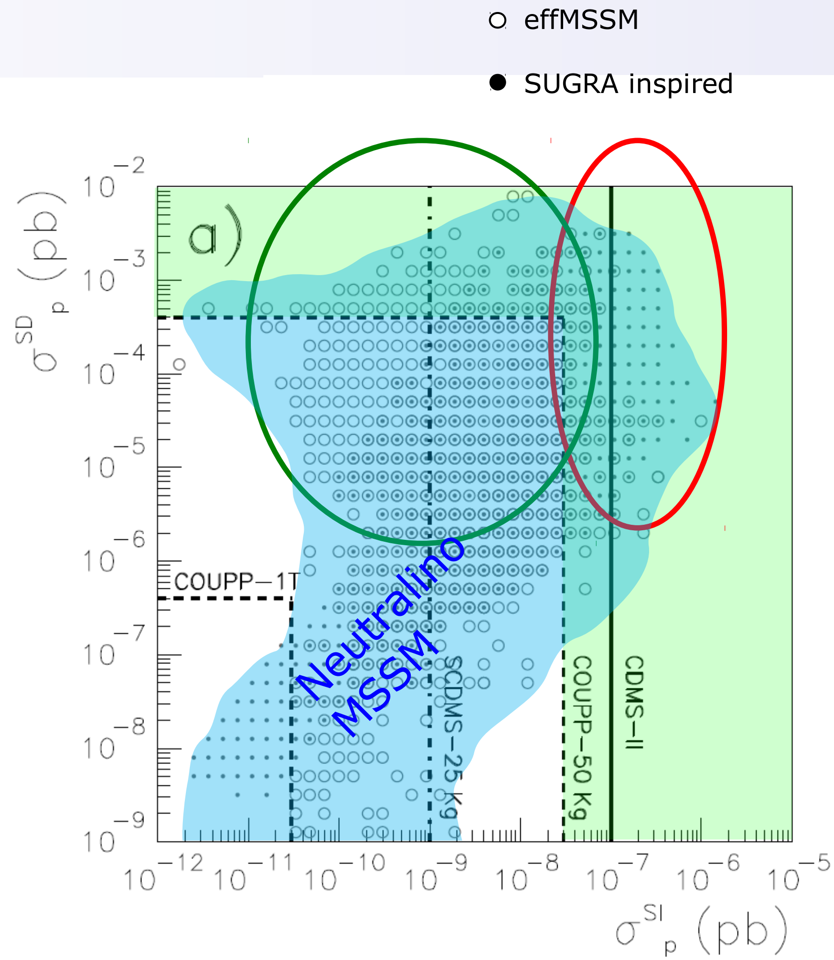
- Overall theoretical predictions in the MSSM:

Enhancement of Z-exchange

Through a decrease in the μ parameter

Enhancement of q̃-exchange

$$(m_{\tilde{u},\tilde{d},\tilde{s}} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0} \lesssim 0.1$$



(G.Bertone, D.G.C., J.I.Collar, B.Odom´07)

The neutralino in the NMSSM

- In the Next-to-MSSM there is a fifth neutralino due to the mixing with the singlino

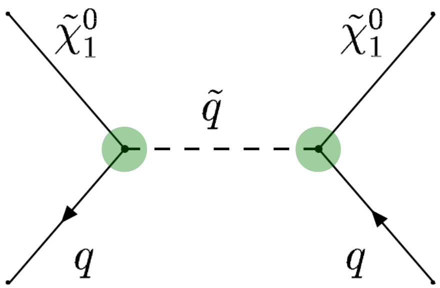
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta & 0 \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta & 0 \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu & -\lambda v_2 \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2\kappa\frac{\mu}{\lambda} \end{pmatrix}$$

The lightest neutralino has now a singlino component

$$\tilde{\chi}_1^0 = \underbrace{N_{11}\,\tilde{B}^0 + N_{12}\,\tilde{W}_3^0}_{\text{Gaugino content}} + \underbrace{N_{13}\,\tilde{H}_d^0 + N_{14}\,\tilde{H}_u^0}_{\text{Higgsino content}} + \underbrace{N_{15}\,\tilde{S}}_{\text{Singlino content}}$$

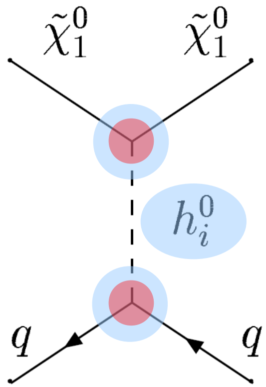
Spin-independent cross section

- Contributions from **squark-** and **Higgs-**exchanging diagrams:



Squark-exchange

$$\sigma_{\tilde{\chi}_1^0 - p} \propto \frac{m_r^2}{4\pi} \left(\frac{g'^2 \sin\theta}{m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2} \right)^2 |N_{11}|^4$$



Higgs-exchange

It is the leading contribution, and increases when

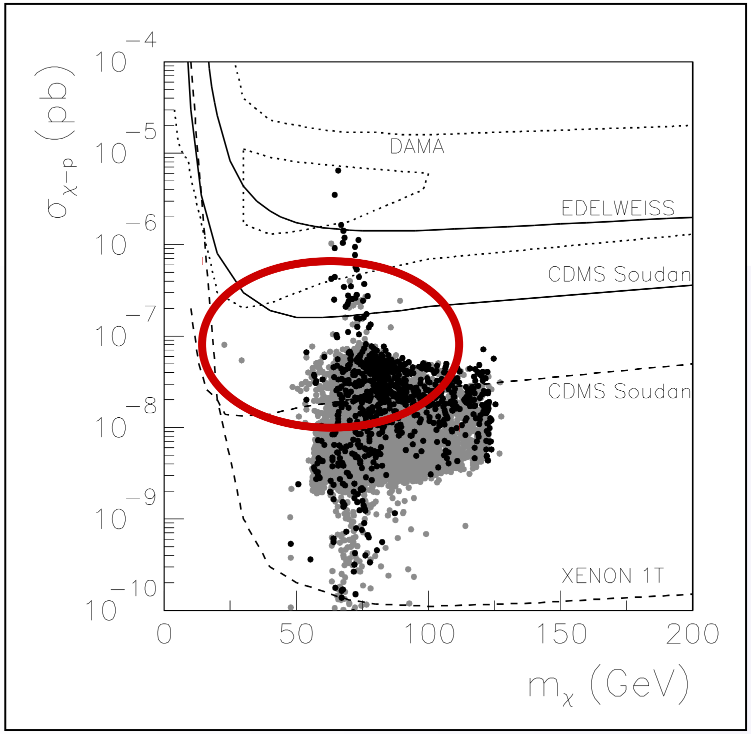
In the NMSSM very light Higgses ($m_h \geq$ 20 GeV) can be obtained in the NMSSM. These have a large singlet component and avoid experimental constraints.

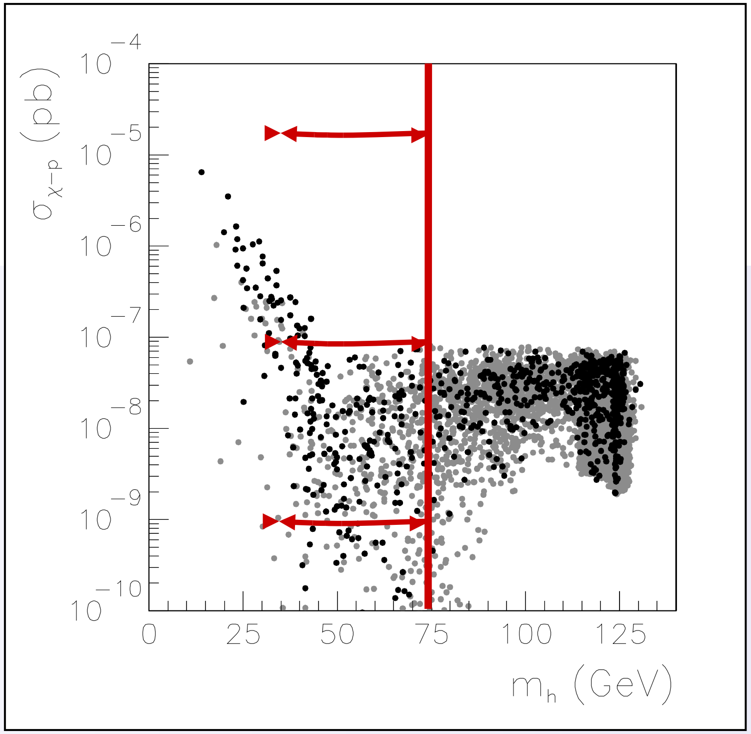
- The Higgs masses decrease $m_h, m_{H^0}\, m_{A^0} \downarrow$

Neutralino in the NMSSM

- Very large detection cross sections can be obtained for singlino-line neutralinos

Higgses lighter than 70 GeV and mostly singlet-like





(D.G.C., C.Hugonie, D.López-Fogliani, A.Teixeira, C.Muñoz ´04)
(D.G.C., E. Gabrielli, D.López-Fogliani, A.Teixeira, C.Muñoz ´07)

Neutralino in the NMSSM

- Different predictions from the MSSM (extensions with extra U(1) are also possible)

○ The detection cross section can be larger (due to light Higgses)

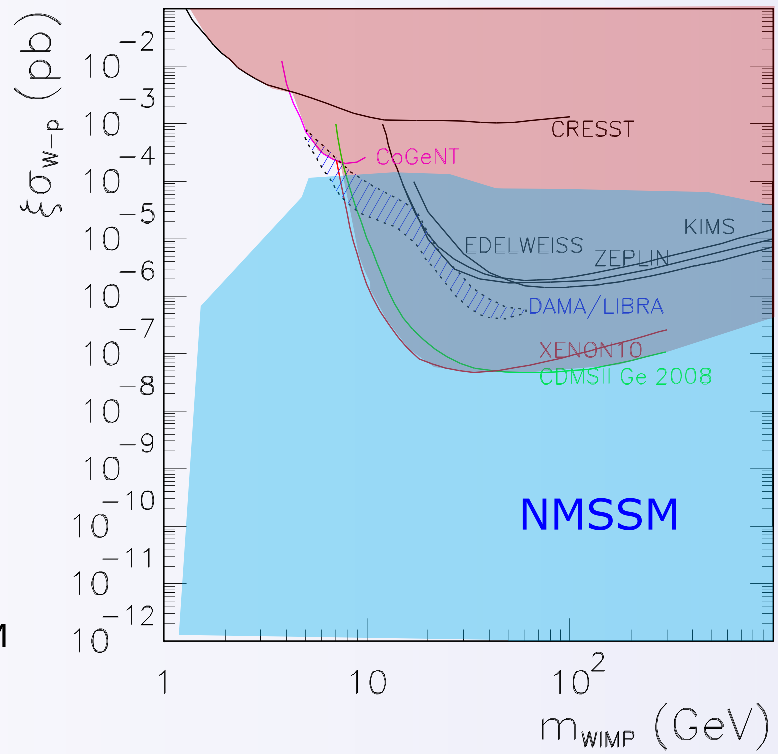
(D.G.C., E. Gabrielli, D.López-Fogliani, A.Teixeira, C.Muñoz ´07)

○ Very light **Bino-singlino** neutralinos are possible

(Gunion, Hooper, McElrath '05)

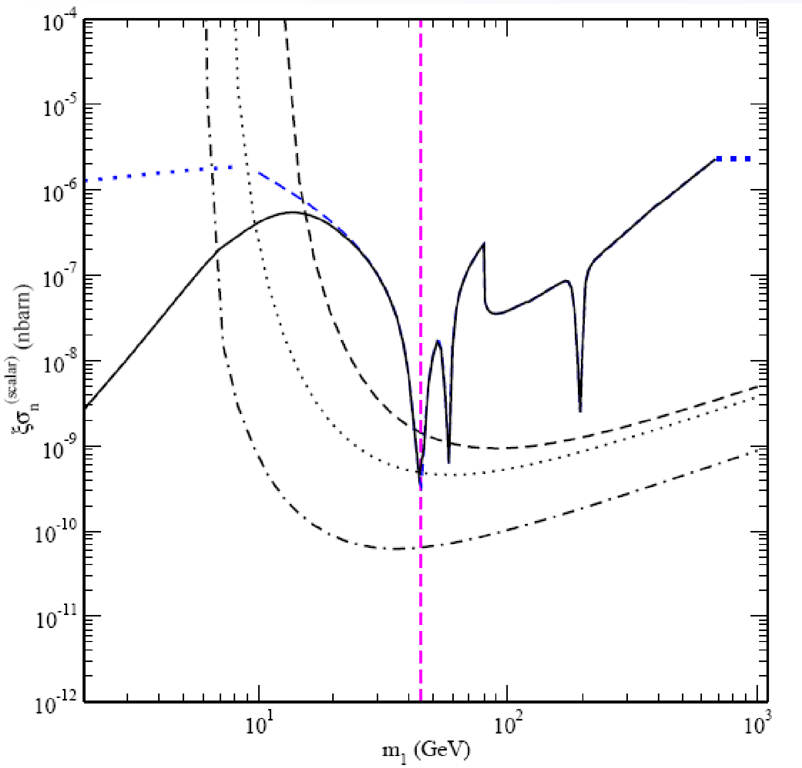
○ And their detection cross section significantly differs from that in the MSSM

(CoGeNT '08)



Sneutrino DM in the MSSM

- On the Standard MSSM: Pure left-handed sneutrino, faces some problems



(C. Arina, N. Fornengo ´07)

Sizable coupling with Z boson, leading to

- Too large annihilation cross section (implying too small relic density)

(Ibáñez ’84; Hagelin, Kane, Rabi ’84; Goodmann, Witten’85; Freese ‘86)

- Too large direct detection cross section (already disfavoured by current experiments)

(Falk, Olive, Srednicki ‘94)

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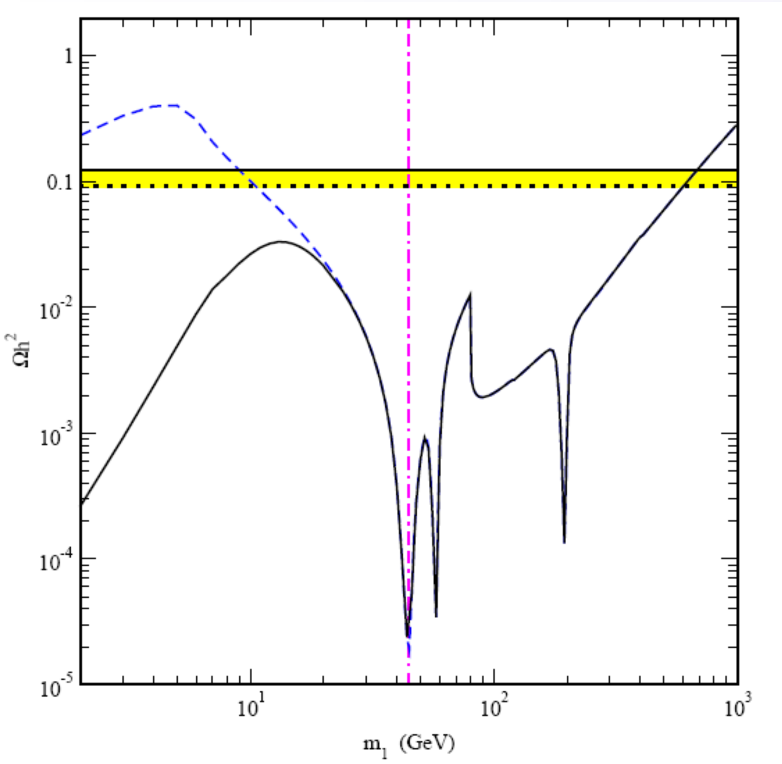

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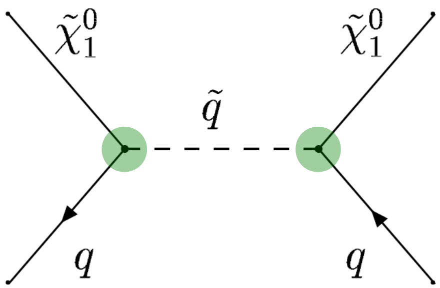
- Contributions from **squark-** and **Higgs-**exchanging diagrams:



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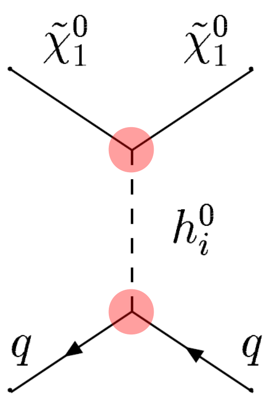
$$\sigma_{\tilde{\chi}_1^0 - p} \propto \frac{m_r^2}{4\pi}\left(\frac{g'^2 \sin\theta}{m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2}\right)^2 |N_{11}|^4$$



Higgs-exchange

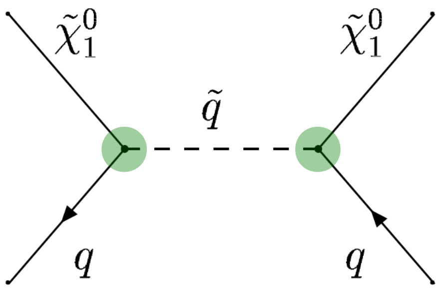
It is the leading contribution, and increases when

$$\sigma_{\tilde{\chi}_1^0 - p} \propto \frac{m_r^2}{4\pi}\frac{\lambda_q^2}{m_h^4}|N_{13,\,14}\,(g' N_{11} - g N_{12})\,|^2$$

- The Higgsino components of the neutralino increase $\mu \downarrow$
- The Higgs masses decrease $m_h,\ m_{H^0}\ m_{A^0} \downarrow$

Spin-independent cross section

- Contributions from **squark-** and **Higgs-**exchanging diagrams:



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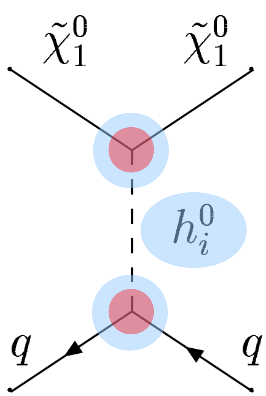
$$\sigma_{\tilde{\chi}_1^0-p} \propto \frac{m_r^2}{4\pi}\left(\frac{g'^2\sin\theta}{m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2}\right)^2 |N_{11}|^4$$



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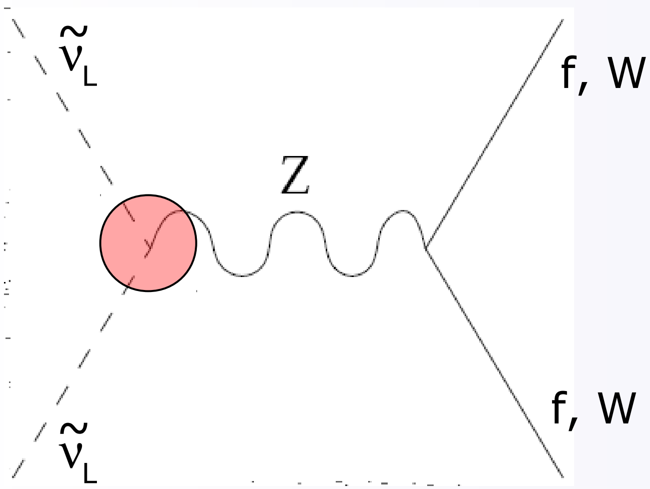
- The Higgs masses decrease $m_h,\ m_{H^0}\ m_{A^0} \downarrow$

Sneutrino DM in the MSSM

- These problems alleviated by reducing the Zνν coupling

Including a “sterile” (e.g., right-handed) component → mixed left-right mass eigenstates

(Arkani-Hamed et al. '91; Hooper et al. '05)



$$\tilde{\nu}_i = N^{\tilde{\nu}}_{i\tilde{\nu}_L}\tilde{\nu}_L + N^{\tilde{\nu}}_{i\tilde{N}}\tilde{N}$$

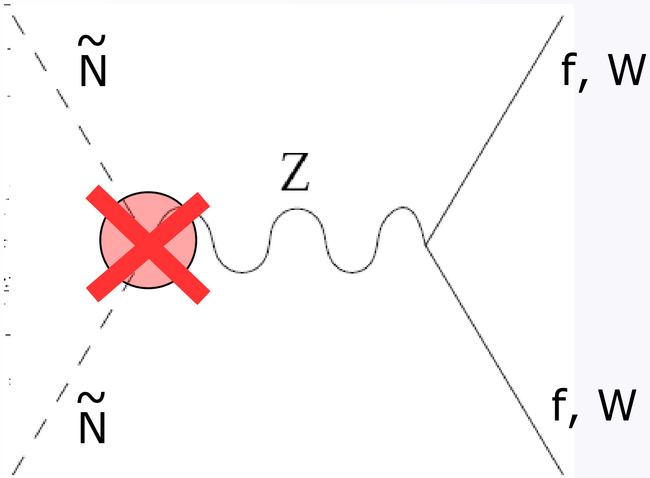
- Smaller annihilation cross section
- Smaller detection cross section

BUT: sneutrino mixing proportional to neutrino Yukawa → a large mixing is difficult to reconcile with see-saw generation of neutrino masses

Sneutrino DM in the MSSM

- Alternatively, a pure right-handed neutrino → no coupling with Z boson

(Asaka et al. '06; Gopalakrishna et al. '06; McDonald '07)



$$\tilde{\nu} = \tilde{N}$$

- Non-thermally produced

NOT WIMPS

BUT: very small detection cross section (would not account for a WIMP observation)

- Neutrino masses (low-scale see-saw)

$$M_N = 2\lambda_N v_s$$ (EW scale)

$$m_{\nu_L} = \frac{y_N^2 v_2^2}{M_N}$$

y_N constrained to be ~O(10^-6)

- Sneutrino masses:

$$\tilde{\nu}_L \equiv \frac{1}{\sqrt{2}}(\tilde{\nu}_{L1} + i\tilde{\nu}_{L2}) \qquad \tilde{N} \equiv \frac{1}{\sqrt{2}}(\tilde{N}_1 + i\tilde{N}_2)$$

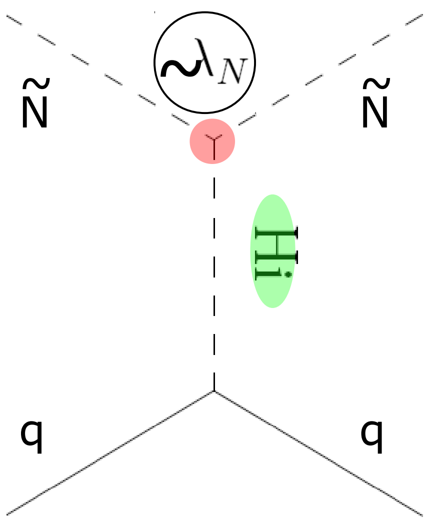
$$\frac{1}{2}(\tilde{\nu}_{L1}, \tilde{N}_1)\begin{pmatrix} m_{L\bar{L}}^2 & m_{LR}^2 + m_{L\bar{R}}^2 \\ m_{LR}^2 + m_{L\bar{R}}^2 & m_{R\bar{R}}^2 + 2m_{RR}^2 \end{pmatrix}\begin{pmatrix} \tilde{\nu}_{L1} \\ \tilde{N}_1 \end{pmatrix}$$
$$+\frac{1}{2}(\tilde{\nu}_{L2}, \tilde{N}_2)\begin{pmatrix} m_{L\bar{L}}^2 & -m_{LR}^2 + m_{L\bar{R}}^2 \\ -m_{LR}^2 + m_{L\bar{R}}^2 & m_{R\bar{R}}^2 - 2m_{RR}^2 \end{pmatrix}\begin{pmatrix} \tilde{\nu}_{L2} \\ \tilde{N}_2 \end{pmatrix}$$

Proportional to y_N ➡ NEGLIGIBLE MIXING

$$\tilde{\nu}_i = N_{i\tilde{\nu}_L}^{\tilde{\nu}}\tilde{\nu}_L + N_{i\tilde{N}}^{\tilde{\nu}}\tilde{N}$$ ➡ $$\tilde{\nu} = \tilde{N}$$ PURE RH-SNEUTRINO

Spin-independent cross section

- Contributions from **Higgs-**exchanging diagrams:



$$\sigma \sim \frac{m_p^2 C_{H_i \nu\nu}^2}{(m_p + m_N)^2 m_{H_i}^4}$$

- No spin-dependent contribution: potential discrimination from neutralino