SUSY WIMPs
Neutralinos & Sneutrinos

David G. Cerdeño

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:

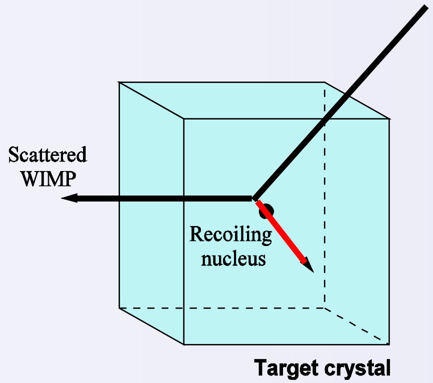
  WIMPs
- SuperWIMPs (gravitino, axino)
- Decaying DM
- SIMPs, CHAMPs, SIDMs, WIMPzillas, Scalar DM, Light DM, ...

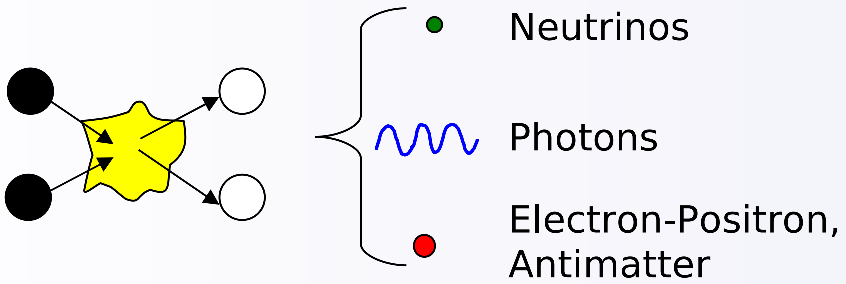
NEW PHYSICS BEYOND THE STANDARD MODEL OF PARTICLE PHYSICS

Detection of Dark Matter

- Direct Detection:

  Look for the elastic scattering of dark matter with nuclei



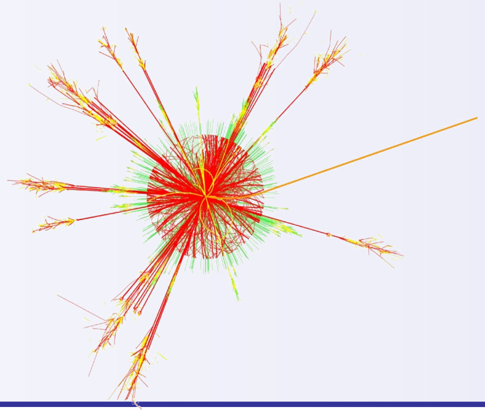


- Indirect Detection:

  Look for the annihilation products

- Accelerator Searches

  Look for signals of new physics



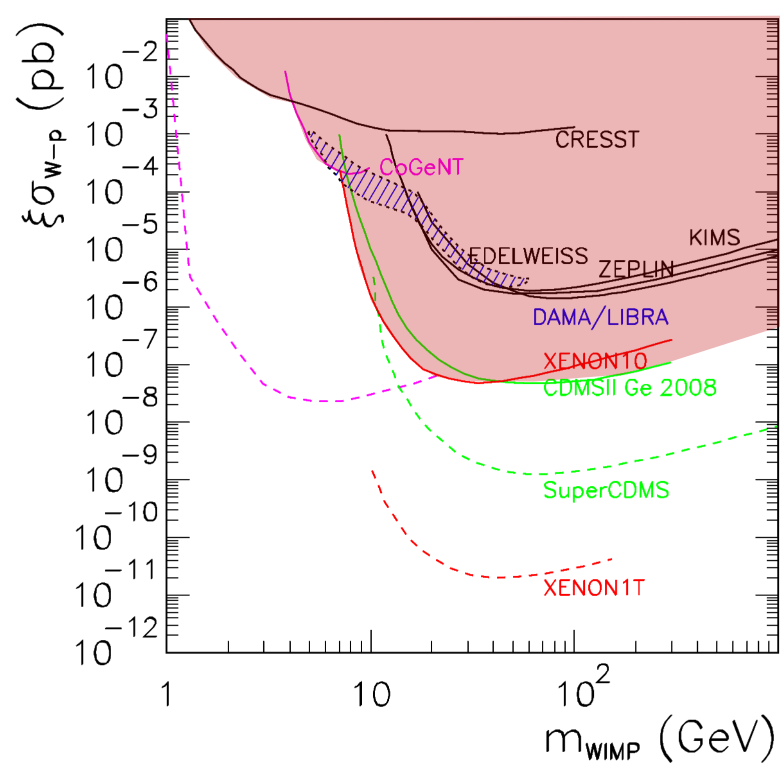
Direct Detection of WIMPs

- 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

All other experiments (XENON10, CDMS and CoGeNT) have not found any WIMP in the DAMA region, however...

- Very light WIMPs
- Inelastic DM
- Channelling
- Electron recoils from light DM



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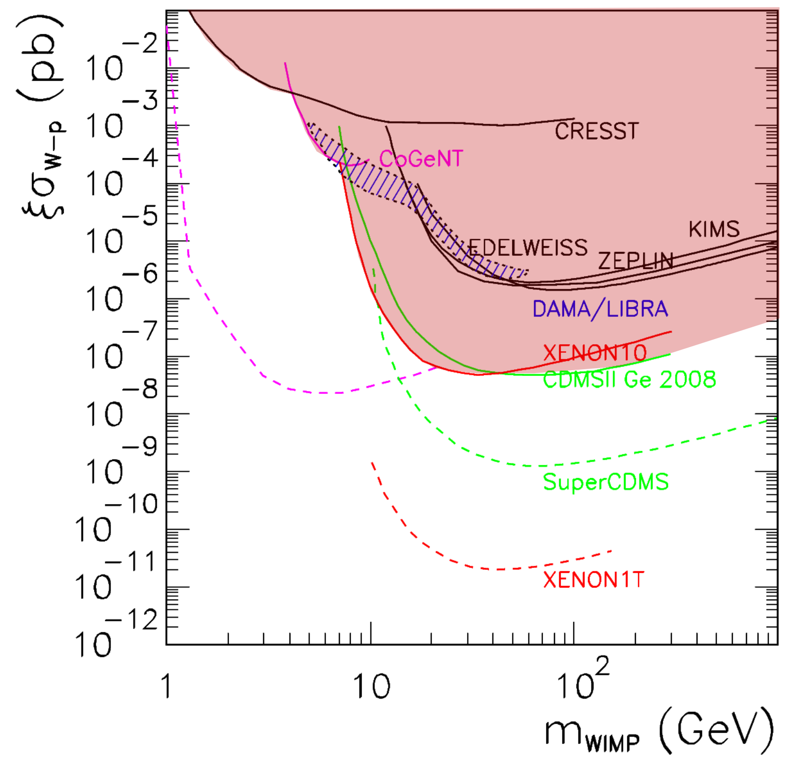
The current sensitivity and future predictions will allow to explore models for particle dark matter.

Need to compare with theoretical predictions for WIMP models



Indirect searches

- PAMELA's results on antimatter searches

Excess in positron flux (no excess in antiproton flux)

A large boost factor is necessary

Inhomogeneities

Sommerfeld enhancement

Non thermal candidate

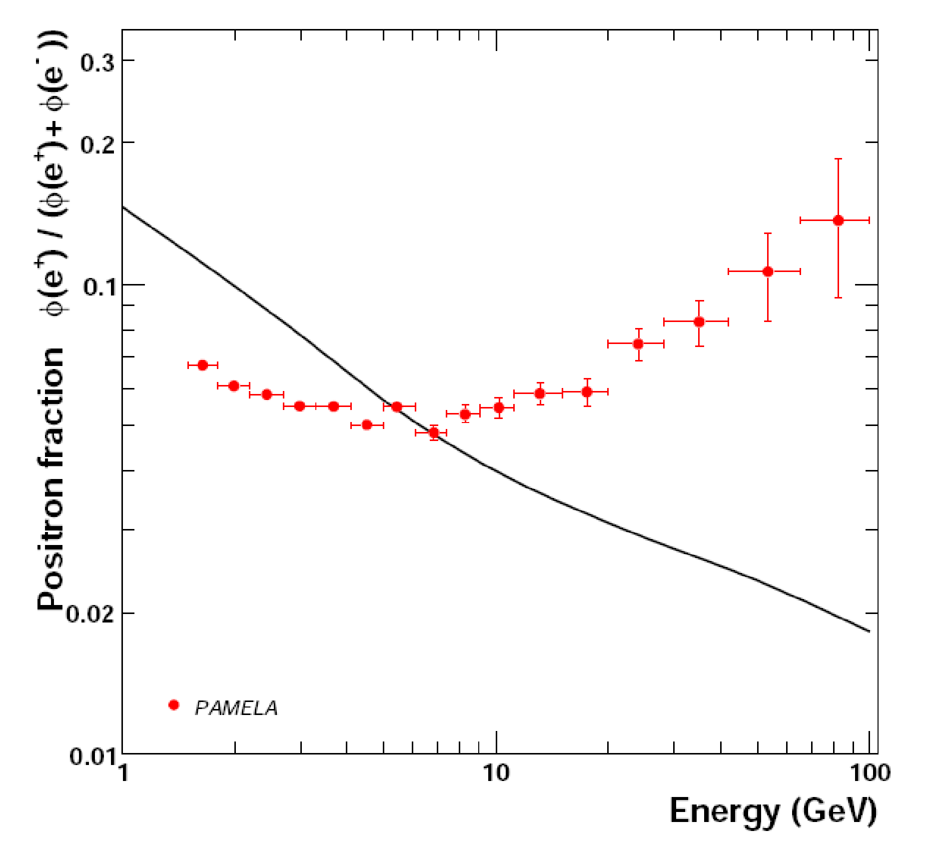
In principle, favours some candidates:

✗ (Majorana): Neutralino

✓ (Dirac or Spin 1): Kaluza-Klein

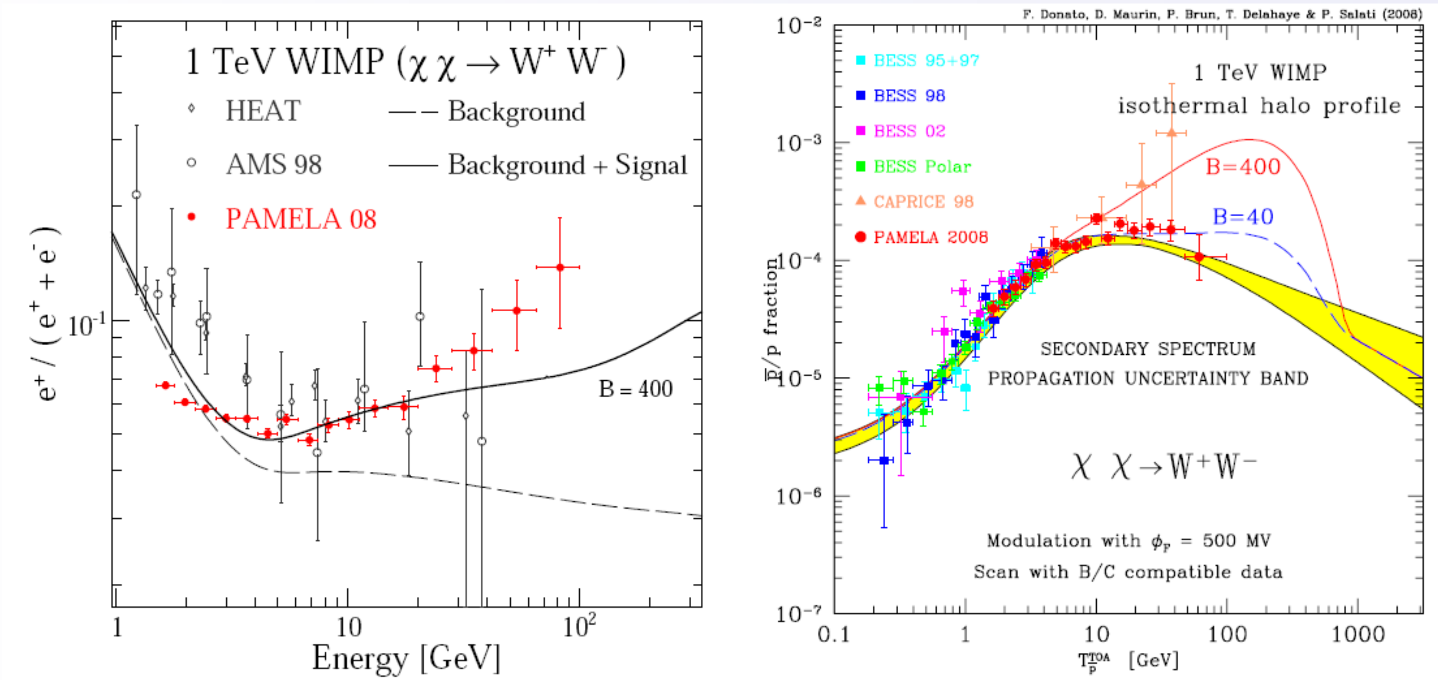
Decaying DM

Multicomponent DM...



(PAMELA Coll. '08)

Indirect searches



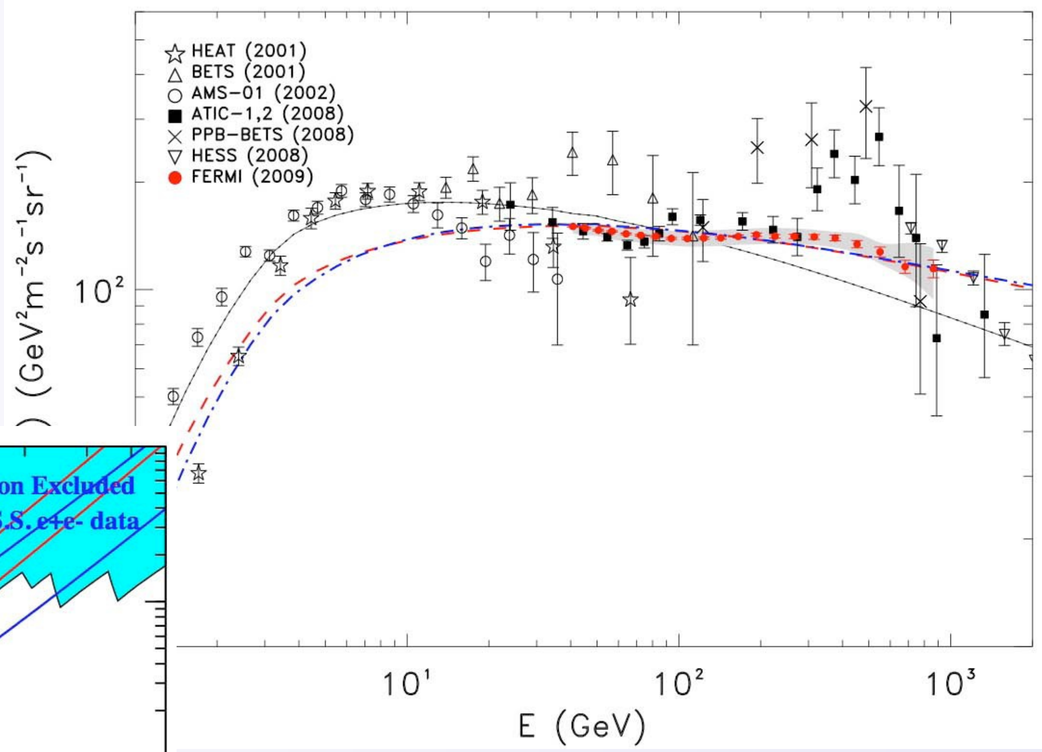
(Donato, Maurin, Brun, Delahaye, Salati ’08)

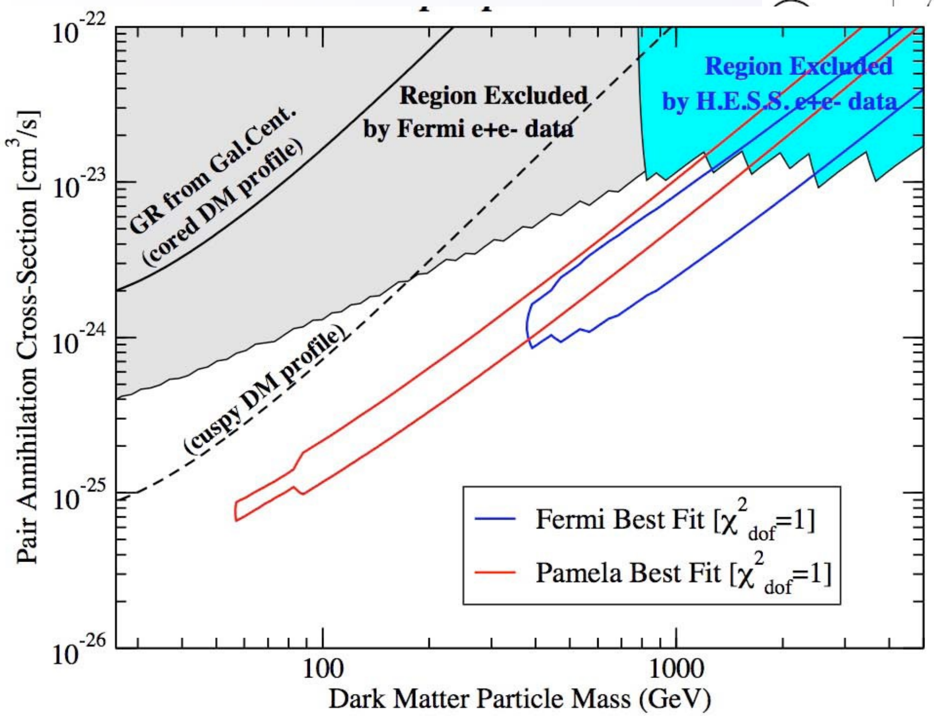
The non-observation of antiproton excess sets stringent constraints on WIMP models

Is Dark Matter “leptophilic”? (Is there a natural scenario for this?)

Indirect searches

- Can Fermi spectrum be explained with WIMP dark matter?





E.g., leptophilic and quite heavy

And a huge annihilation cross section

WIMP candidates

- Heavy (Dirac or Majorana) 4th generation neutrino

(Lee, Weinberg ’77)

Arising from well-motivated theories

- Lightest Supersymmetric Particle (SUSY theories)
- Lightest Kaluza-Klein Particle (Models with extra dimensions)
- LTP (Little Higgs Models)

And some “phenomenologically motivated” models

- Singlet scalar Dark Matter (McDonald ’94)
- Secluded WIMP dark matter (Pospelov, Ritz, Voloshin ‘07)
- Inert doublet model (Lopez-Honorez, Nezri, Oliver, Tytgat ‘07)
- …

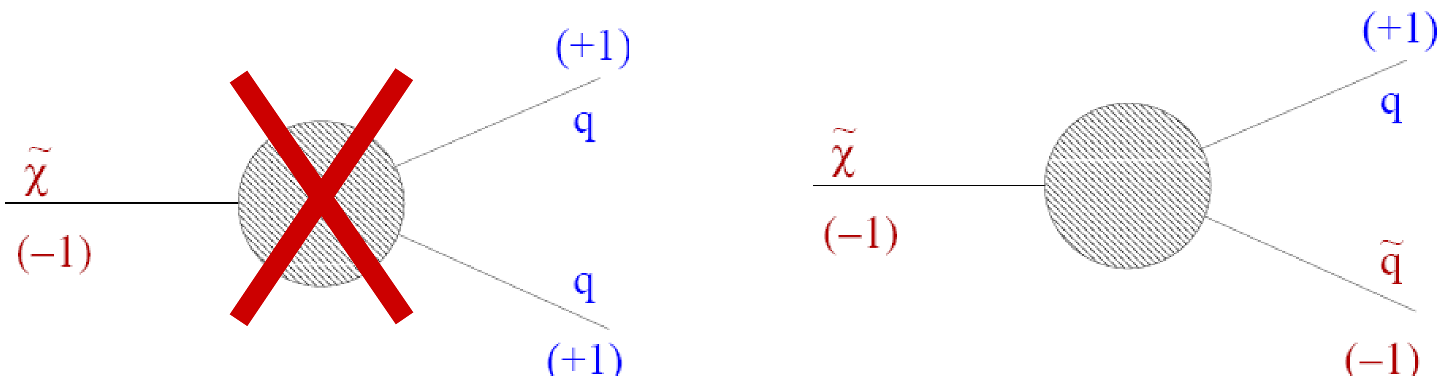
Lightest Supersymmetric Particle

- R-parity is usually invoked in Supersymmetric theories in order to forbid new baryon and lepton number violating interactions at the weak scale

$$R = (-1)^{(3B+L+2S)}$$

Particles $R = +1$

Sparticles $R = -1$



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

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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	$\tilde{B}^0$, $\tilde{W}^0$, $\tilde{H}^0_{1,2}$
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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 $(\tilde{H}_d^0,\ \tilde{H}_u^0)$

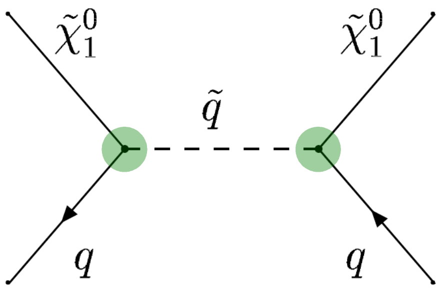
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 \end{pmatrix}$$

The detection properties of the lightest neutralino depend on its composition

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

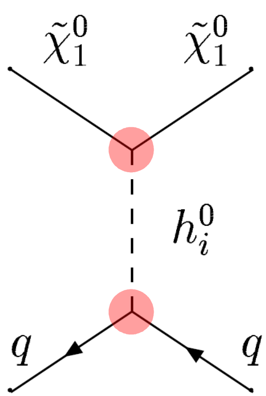
Spin-independent cross section

- 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

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

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

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

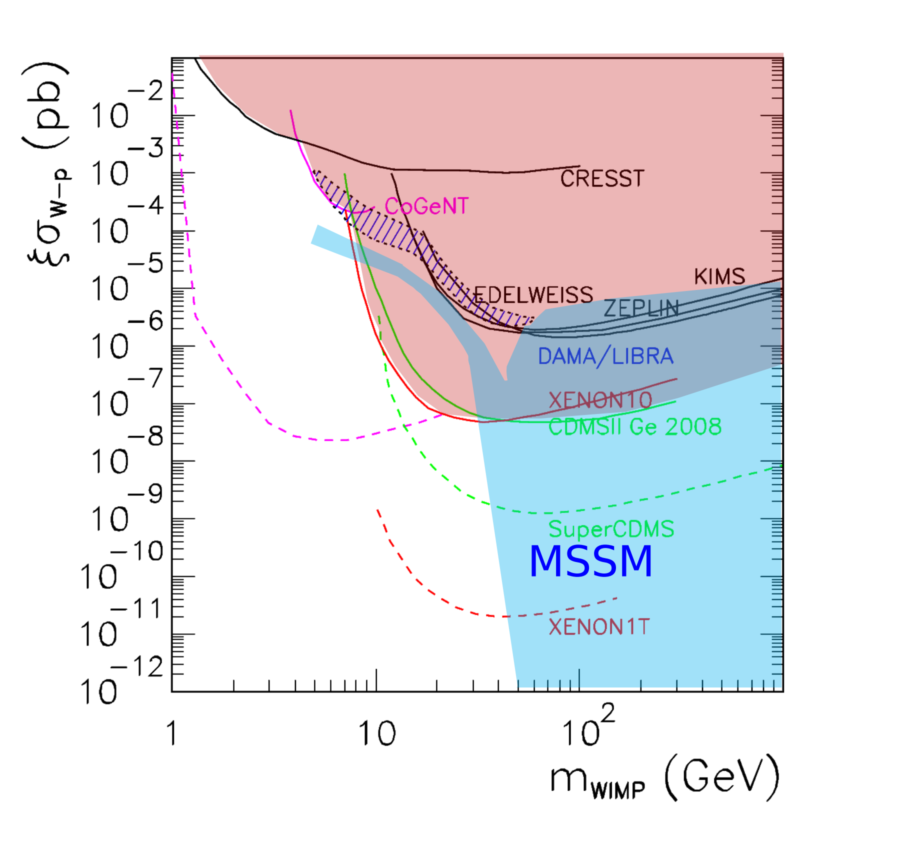
(Bottino, Donato, Fornengo, Scopel ‘04-'08)

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

(Roszkowski, Ruiz de Austri, Trotta ‘08)

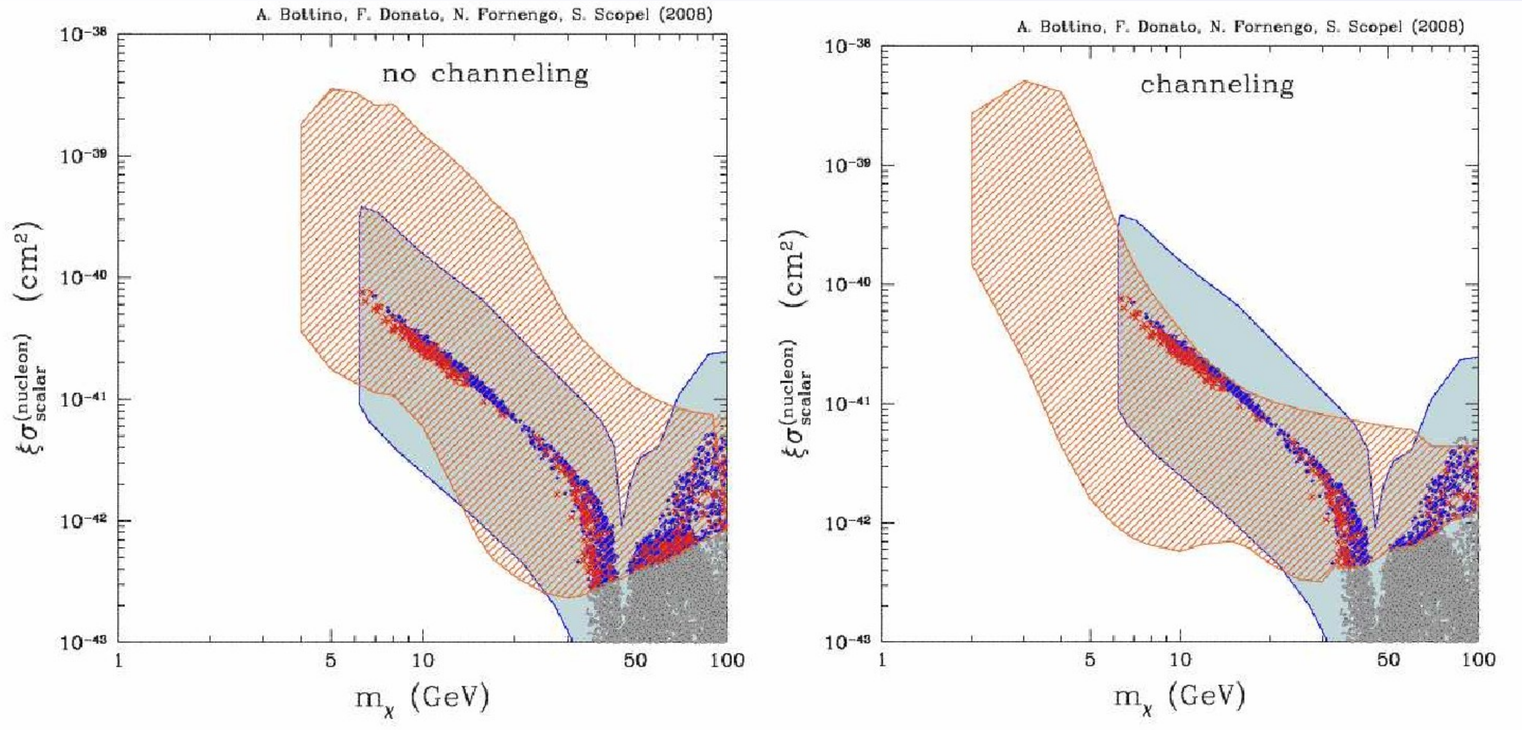
A frequentist approach may favour different regions

(Buchmüller et al. '09)



Neutralino in the MSSM

- Very light neutralinos (~7-10 GeV) can be in agreement with DAMA observation



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Problematic predictions for low-energy observables (excessive contribution to BR(b→sγ))

Constrained by the non-observation in the CoGeNT experiment

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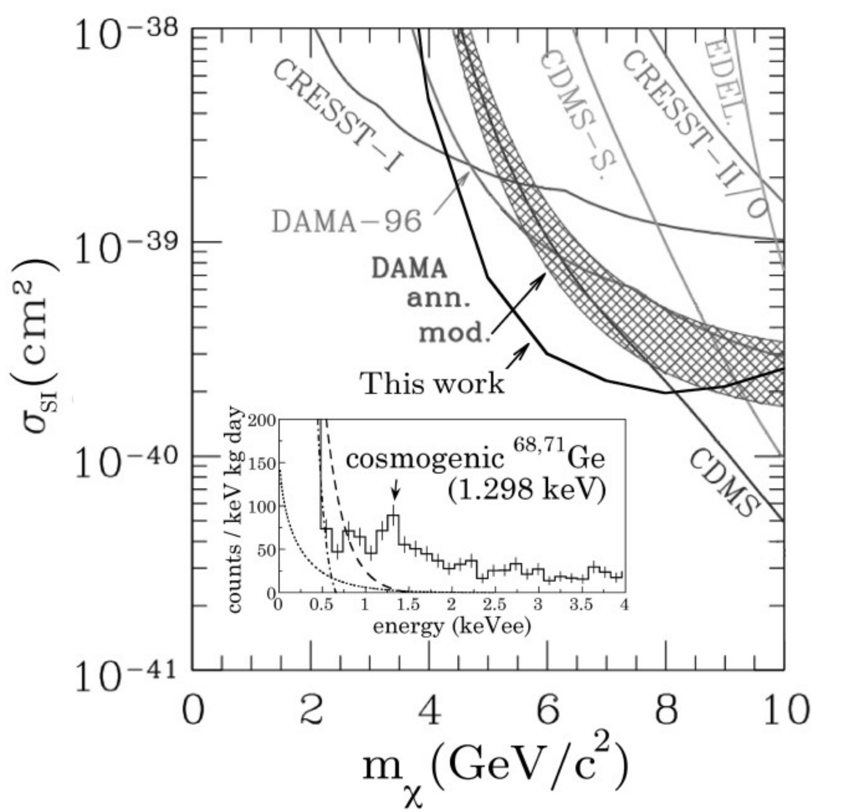

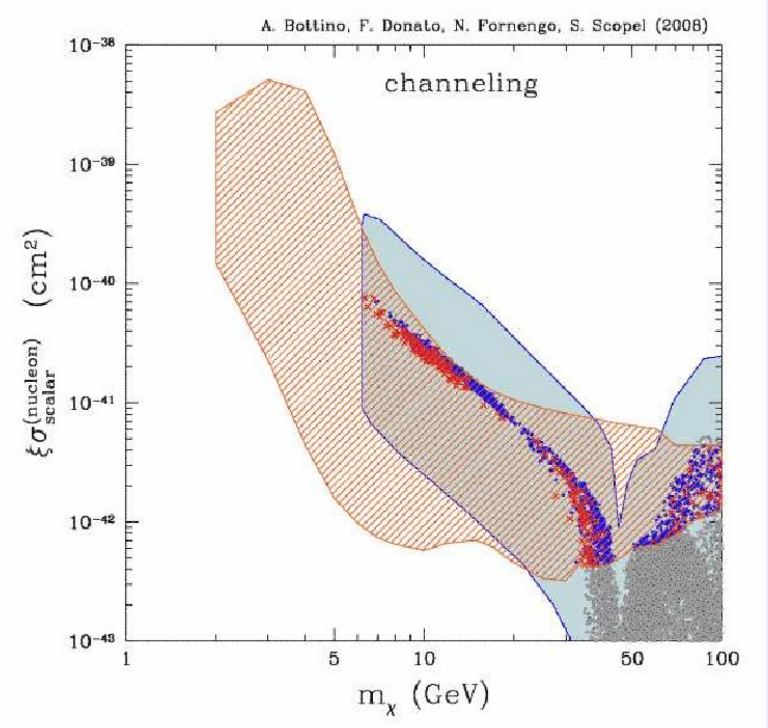

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Neutralino in the Next-to-MSSM

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

- 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

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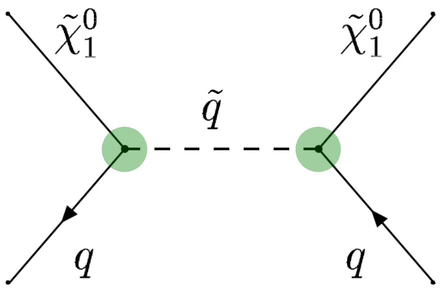

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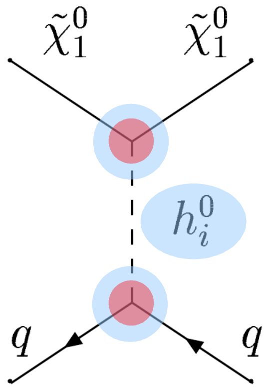


Higgs-exchange

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

- 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)

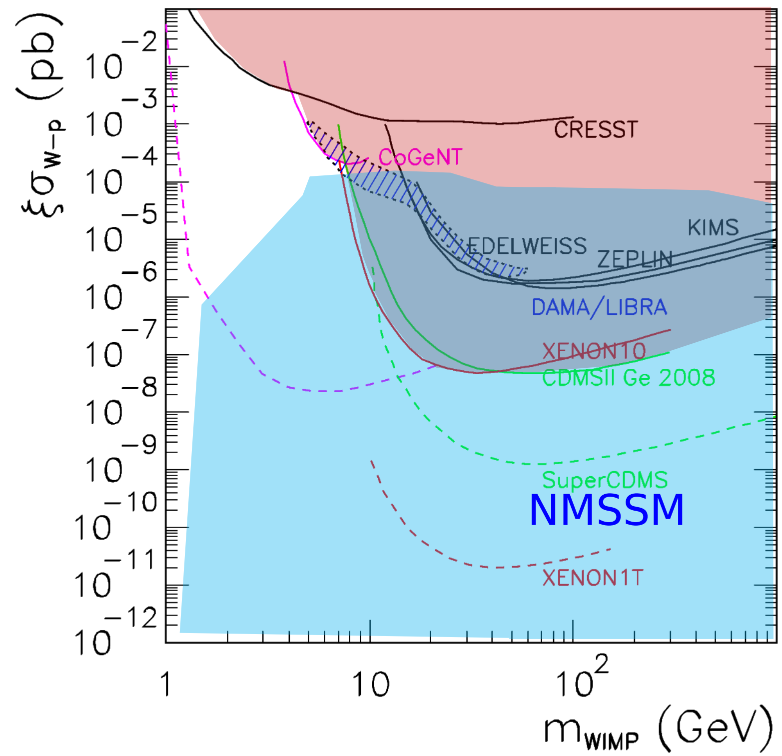
(D.G.C., E. Gabrielli, D.López-Fogliani, A.Teixeira, C.Muñoz ´07)

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

(Gunion, Hooper, McElrath '05)

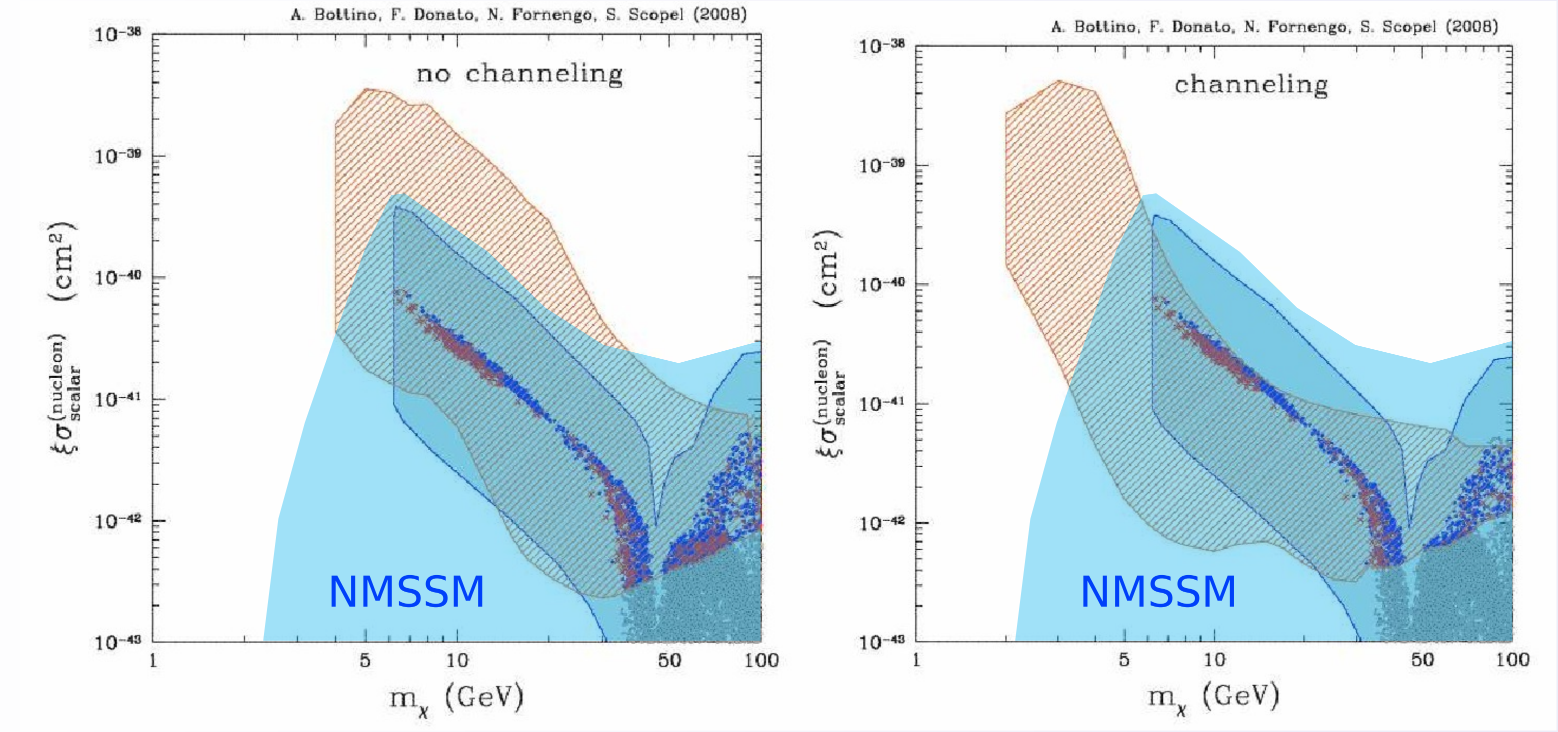
And their detection cross section significantly differs from that in the MSSM

(CoGeNT '08)



Neutralino in the NMSSM

- Very light neutralinos (~4-20 GeV) can be in agreement with DAMA observation



(CoGeNT '08)

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

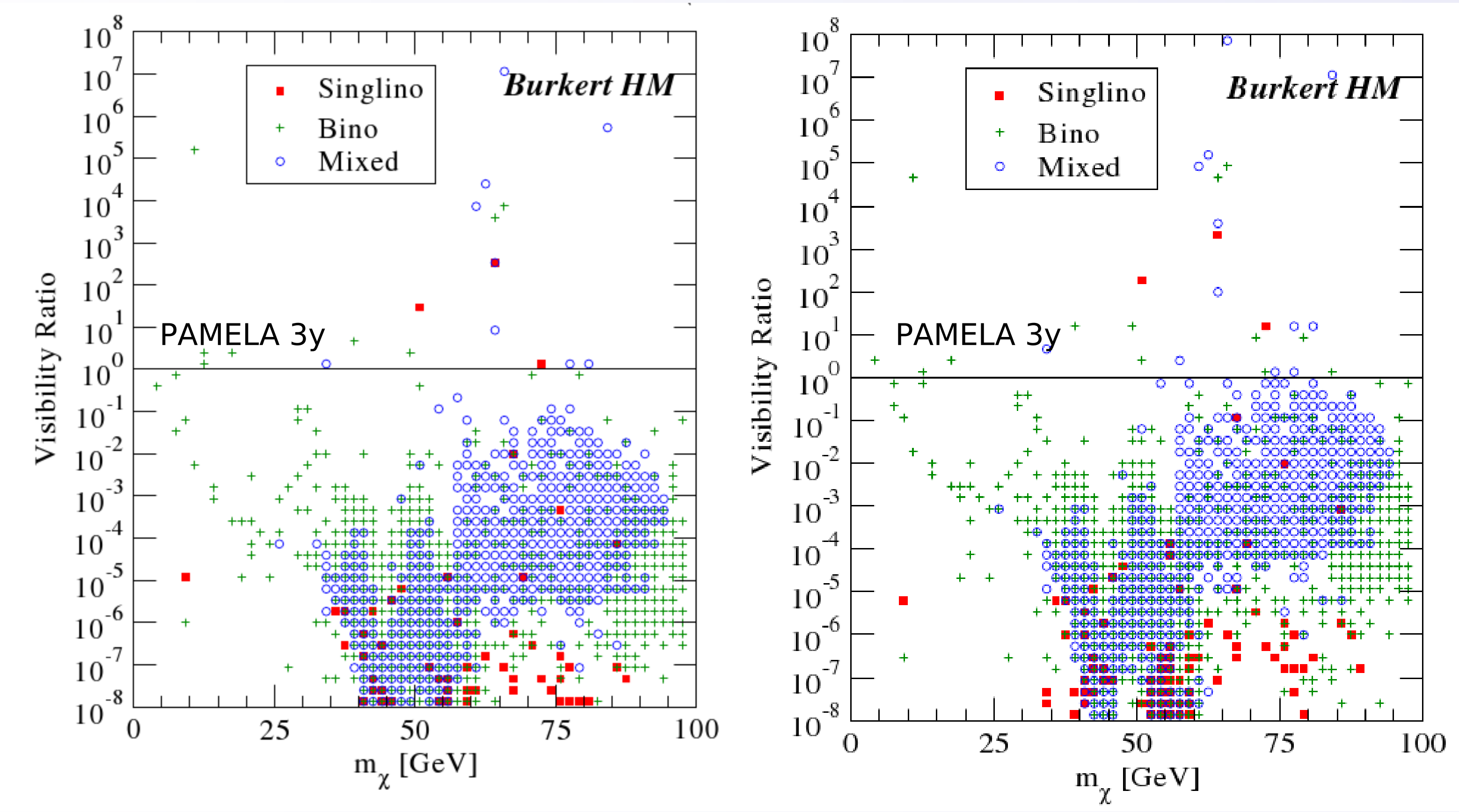
Less fine-tuned (wider regions of the parameter space)

Less constrained by the non-observation in the CoGeNT experiment

Indirect detection of light neutralinos in the NMSSM

Better prospects for detection at neutrino telescopes than in MSSM

Prediction for positron and antiproton flux similar as in MSSM (can be larger)



(Ferrer, Krauss, Profumo '06)

The neutralino is not the only SUSY WIMP

- The SUSY partner of the neutrino, the **sneutrino**, is also neutral and weakly-interacting

Lightest Supersymmetric Particle

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

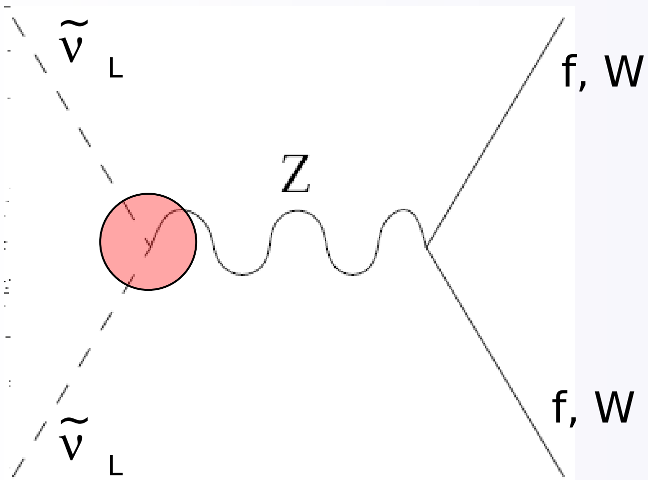
(Ibáñez ’84; Hagelin, Kane, Rabi ’84)

Lightest neutralino: WIMP

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

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)

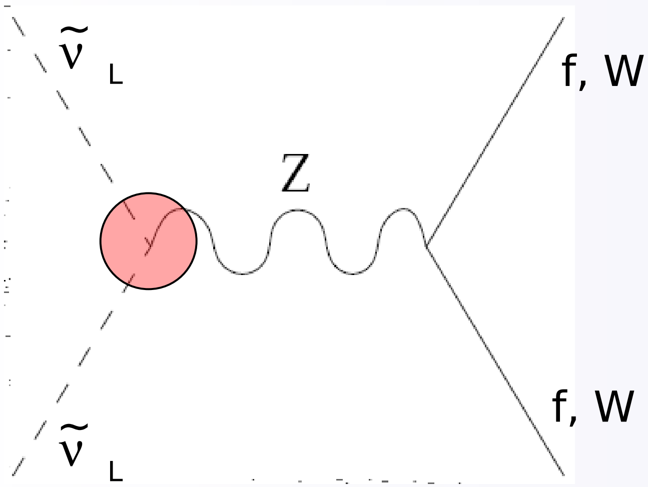
(Falk, Olive, Srednicki ‘94)

Sneutrino DM in the MSSM

- These problems alleviated by reducing the $Z\nu\nu$ coupling

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

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



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

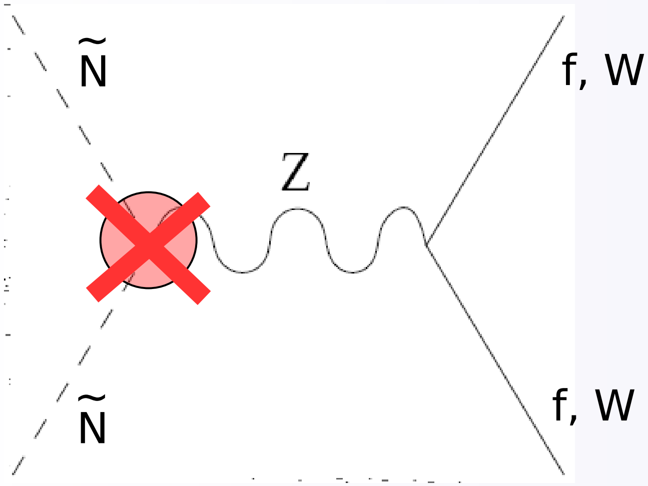
- Smaller annihilation cross section
- Smaller detection cross section

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

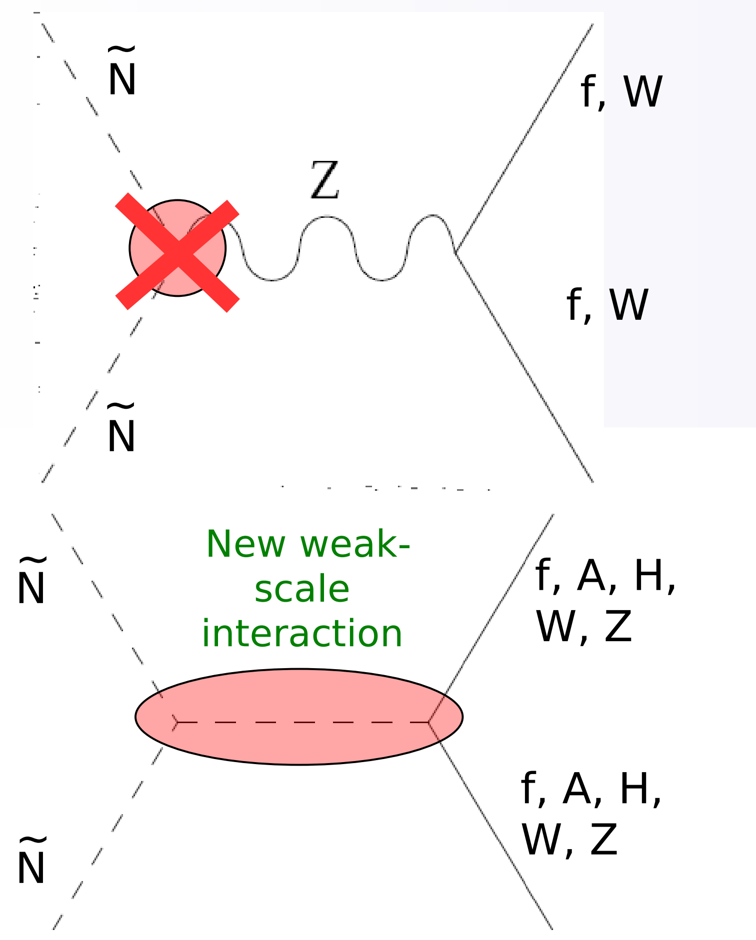
NOT WIMPS

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

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)



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WIMP

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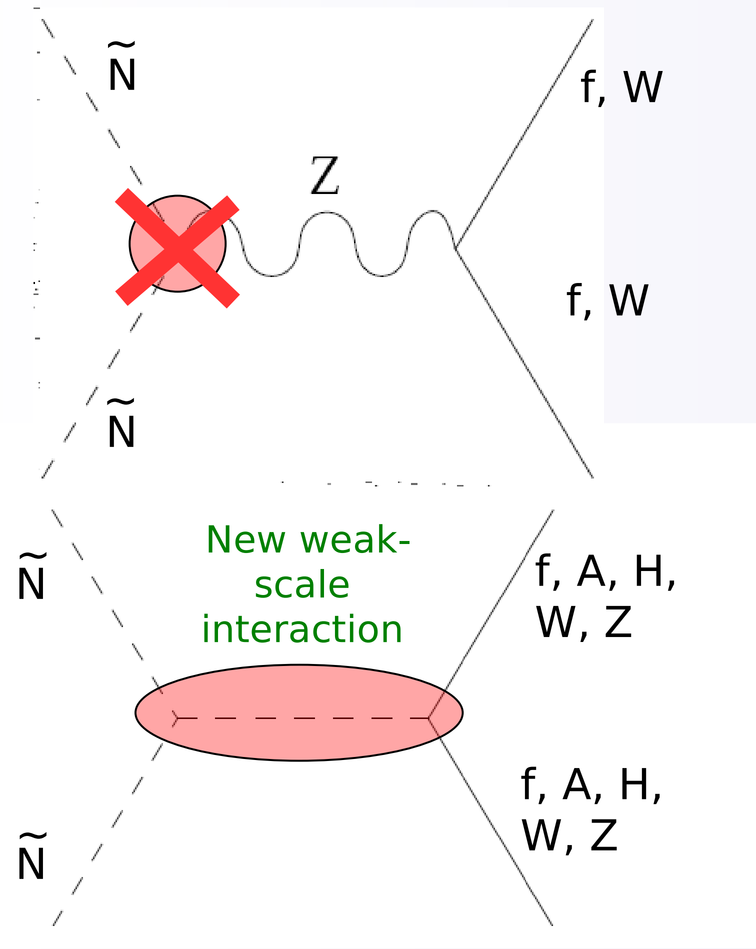


$$\tilde{\nu} = \tilde{N}$$

WIMP

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

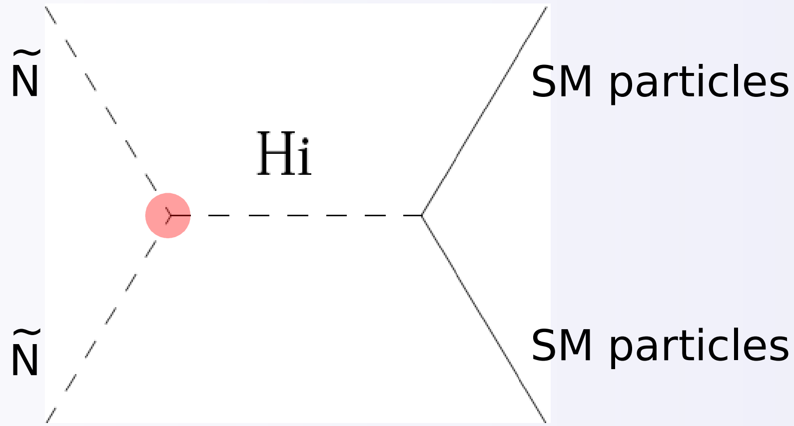
the Next-to-Minimal SUSY SM (NMSSM)

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

RH-Sneutrino in the NMSSM

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

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

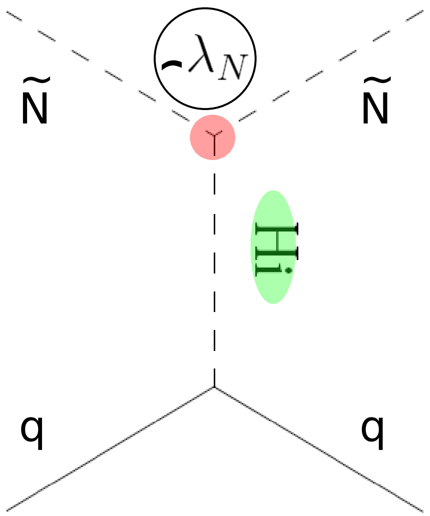


COUPLED TO THE HIGGS (and therefore to SM particles)

WIMP

Spin-independent cross section

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



$$\sigma \sim \frac{m_p^2 C^2_{H_i \nu \nu}}{(m_p + m_N)^2 m^4_{H_i}}$$

- No spin-dependent contribution: potential discrimination from neutralino

RH-Sneutrino DM overview

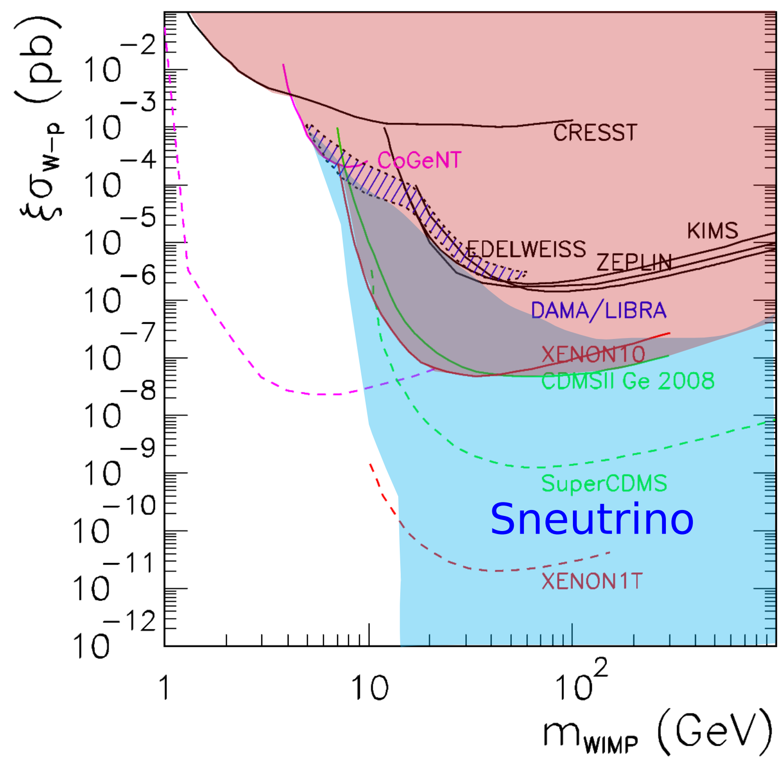
- (Right-handed) sneutrinos in the NMSSM: Predictions for direct detection

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

o Light sneutrinos are viable and distinct from MSSM neutralinos

(D.G.C., Seto '09)

o No spin-dependent coupling. Experiments sensitive to this component could discriminate between neutralinos and sneutrinos.
(Bertone, D.G.C, Collar, Odom '07)



Overview

- **The MSSM is not the only (well motivated) SUSY scenario**

  Extended models (**Next-to-MSSM**) are equally viable

  Neutralino detection properties differ (e.g., larger direct detection rates, light neutralinos)

- **The neutralino is not the only SUSY WIMP**

  The **sneutrino** in extended SUSY models is a viable WIMP

  Similar direct detection as neutralino (but no spin-dependent couplings)

  Different indirect signals (possible “leptophilic” DM)