Direct detection of WIMPs

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Based on a review with Anne M. Green (arXiv:1002.1912)

Outline

Introduction

Event rate (Spin-dependent + spin-independent cross section)
+ nuclear uncertainties

Astrophysics input

Signals

Particle Physics input (Supersymmetry, Kaluza-Klein DM, Little Higgs, ...)

A note on identification of WIMP DM

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:

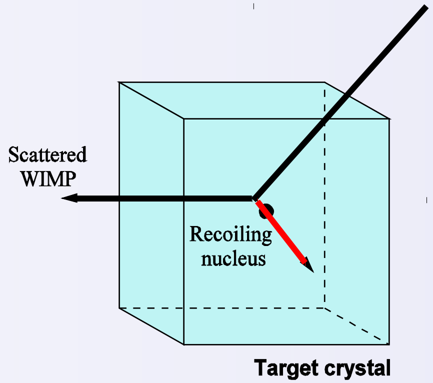
  WIMPs
- SuperWIMPs (gravitino, axino)
- Decaying DM
- SIMPs, CHAMPs, SIDMs, WIMPzillas, Scalar DM, Light DM, ...

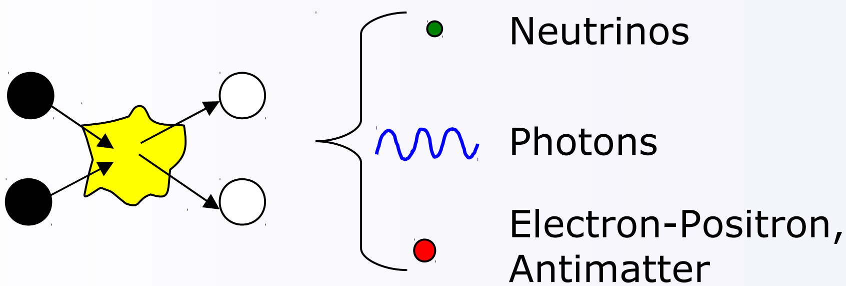
NEW PHYSICS BEYOND THE STANDARD MODEL OF PARTICLE PHYSICS

Detection of Dark Matter

- Direct Detection:

  Look for the elastic scattering of dark matter with nuclei



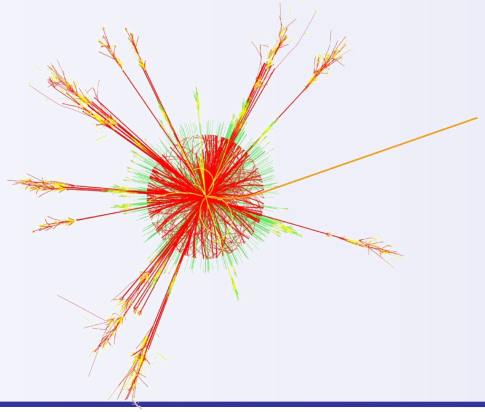


- Indirect Detection:

  Look for the annihilation products

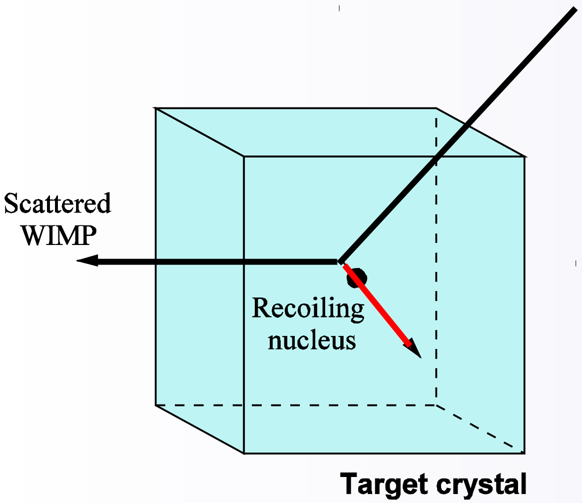
- Accelerator Searches

  Look for signals of new physics



WIMP direct detection

• The direct detection of Dark Matter can take place through their interaction with nuclei inside a detector



The nuclear recoiling energy is measured

• Ionization on solids

• Ionization in scintillators (measured by the emmited photons)

• Temperature increase (measured by the released phonons)

Problems

• Very small interaction rate

• Large backgrounds (experiments must be deep underground)

• Uncertainties in the DM properties in our galaxy

Event rate for WIMP direct detection

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

- Astrophysics input

  Local density of dark matter ρ_0

  Velocity distribution function $f(v)$

Event rate for WIMP direct detection

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- Astrophysics input
  - Local density of dark matter ρ_0
  - Velocity distribution function $f(v)$
- Particle Physics input
  - WIMP-nucleus cross section $\frac{d\sigma_{WN}}{dE_R}$

Event rate for WIMP direct detection

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- Astrophysics input
  - Local density of dark matter ρ_0
  - Velocity distribution function $f(v)$
- Particle Physics input
  - WIMP-nucleus cross section $\frac{d\sigma_{WN}}{dE_R}$
- Detector-dependence
  - Threshold energy E_T
  - Material m_N affects $\frac{d\sigma_{WN}}{dE_R}$

- The interaction of a generic WIMP with nuclei has several contributions

These can be understood at the level of the effective Lagrangian describing the interaction of WIMPs and quarks, e.g., for a fermionic WIMP (as the neutralino)

σ_{WN}

<u>Axial-Vector</u>

$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$$

$$\frac{(J+1)}{J}$$

SPIN-DEPENDENT (Nucl. Angular mom)

<u>Scalar</u>

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q$$

A^2

SPIN-INDEPENDENT (Nucleon #)

<u>Vector</u>

$$\mathcal{L} \supset \alpha_q^V \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

A^2

- Only for non-Majorana WIMPs

SPIN-INDEPENDENT

- The interaction of a generic WIMP with nuclei has several contributions

In general we can write

$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

Generally expressed in terms of the cross section at zero momentum transfer and a Form factor that encodes the dependence of the momentum transfer.

$$\frac{d\sigma_{WN}}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}\left(\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right)$$

These account for coherence loss for heavy WIMPs or nuclei

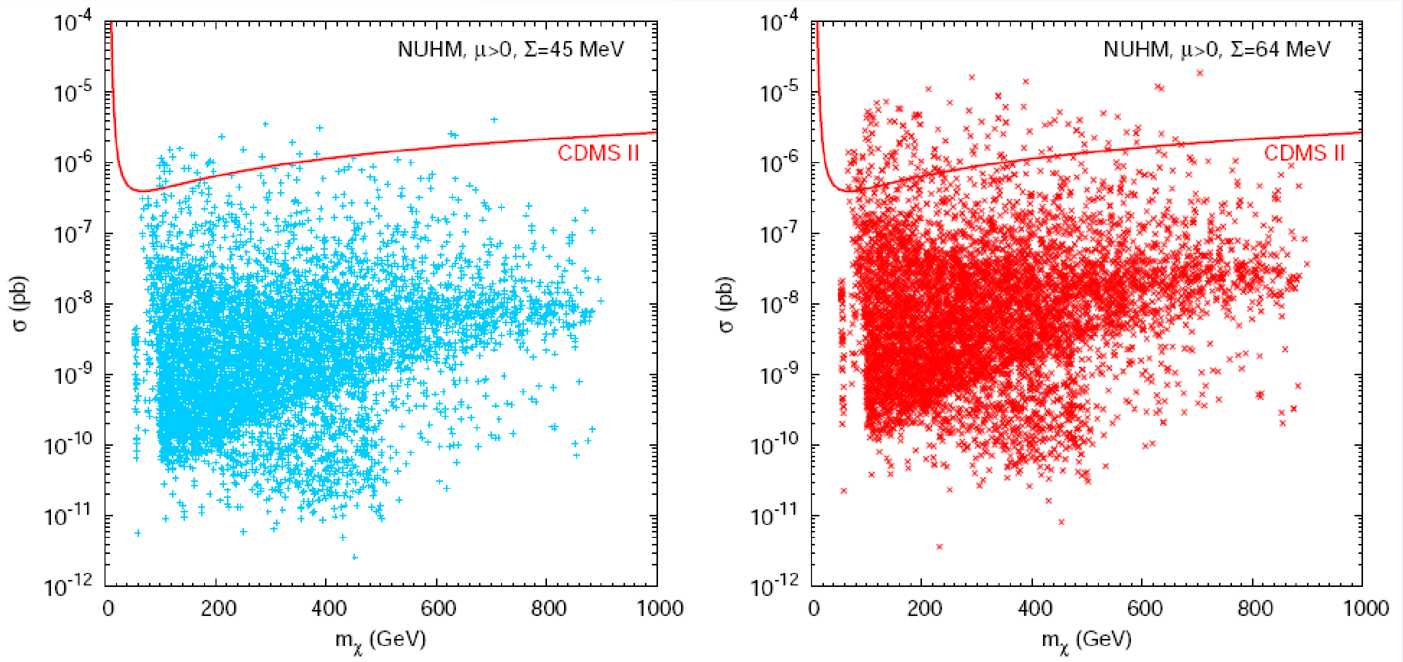
Hadronic matrix elements uncertainties

Uncertainties in the hadronic matrix elements can also be responsible for a large uncertainty in the predicted cross-section. E.g., the π-nucleon sigma term

$$\Sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\langle N|\bar{u}u + \bar{d}d|N\rangle = (64 \pm 8)\,\mathrm{MeV}$$

Leads to an uncertainty of ~ a factor 4 in the s-quark composition in nucleons

Which implies approx 1 order of magnitude in theoretical predictions!



(Ellis, Olive, Santoso, Spanos '05)

Astrophysics Input

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

Local density of dark matter ρ_0

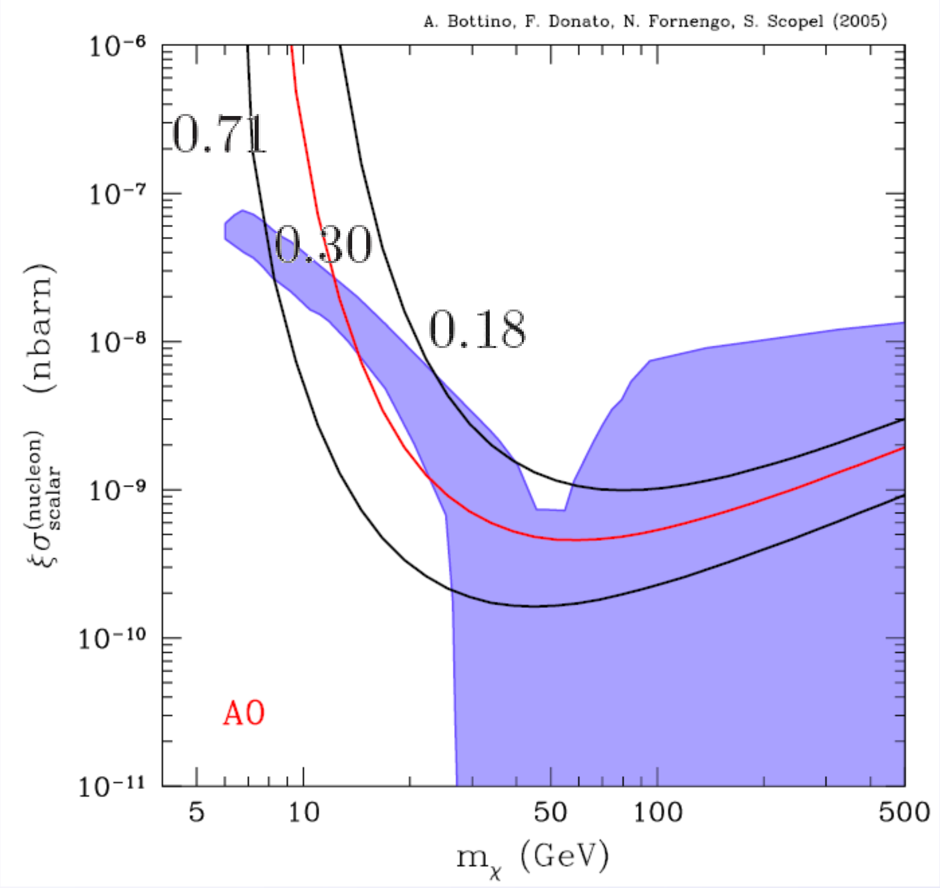
Calculated by applying observational constraints to Milky Way models

E.g., for spherical haloes with a cusp

$$\rho_0 = (0.30 \pm 0.05)\, \mathrm{GeV\ cm}^{-3}$$

(Widrow, Pym, Bubinski ' 08)

Uncertainties can exceed a factor 2



(Bottino, Donato, Fornengo, Scopel '05)

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Velocity distribution function $f(v)$

Standard halo: Maxwellian (isotropic, Gaussian velocity distribution)

$$f(\mathbf{v}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{|\mathbf{v}|^2}{2\sigma^2}\right)$$

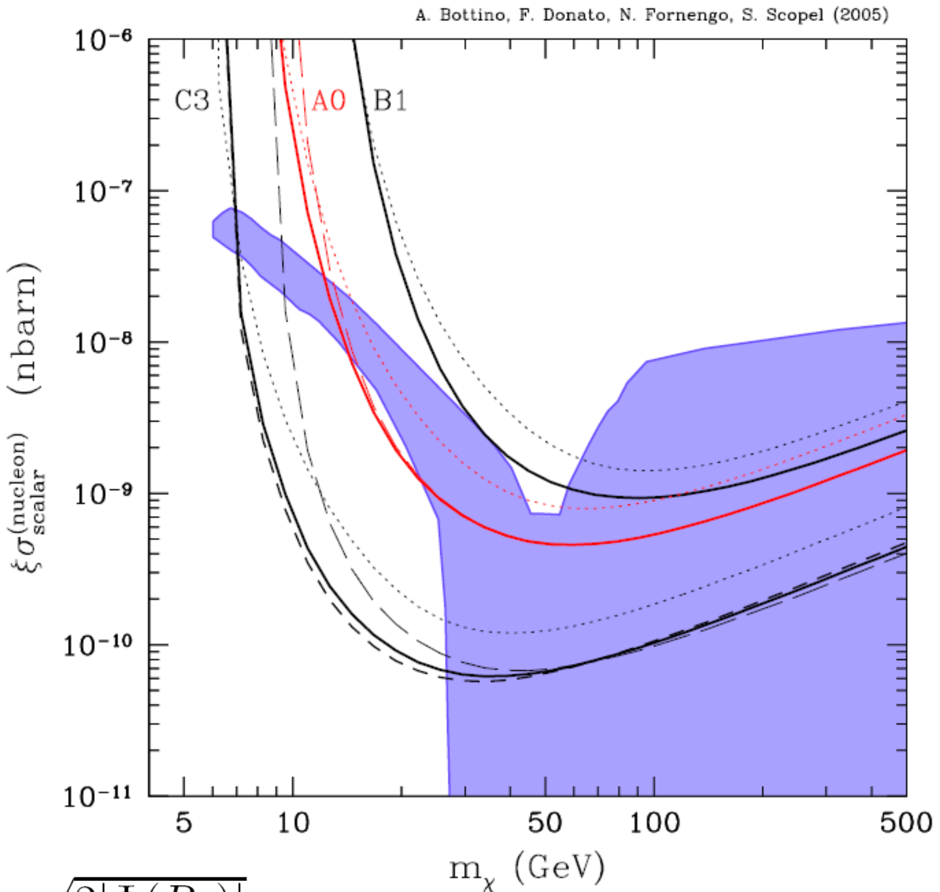
Observations suggest departures from this model (e.g., triaxial and anisotropic density profiles)

Variations in the escape and local velocities have large impact in detection rate

$$170 \text{ km sec}^{-1} \leq v_0 \leq 270 \text{ km sec}^{-1}$$

$$498 \text{km s}^{-1} < v_{esc} < 608 \text{ km s}^{-1}$$

$$v_{esc} = \sqrt{2|\Phi(R_0)|}$$



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Ultra-fine structure

Steady state for phase space distribution: a good assumption?

In CDM cosmologies the relevant dynamical timescales for the Milky Way are not many orders of magnitude smaller than the age of the Universe

Could give rise to non-smooth phase-space distribution at mili-pc scales?

(Moore et al.'01;Stiff, Widrow '03; Fantin, Merrifield, Green '08)

Tidal streams from Saggitarius? Could have implications for directional detection

(Freese, Gondolo, Newberg, Lewis '04, '05)

...or maybe not (not observed in experimental searches).

(Seabroke et al. '07)

Signals

The WIMP recoil rate is...

Energy dependent due to kinematics of elastic scattering and WIMP velocity distribution

Time and **direction** dependent due to the motion of the Earth wrt the Galactic rest frame

Energy-dependence

Energy dependence due to kinematics and WIMP velocity distribution

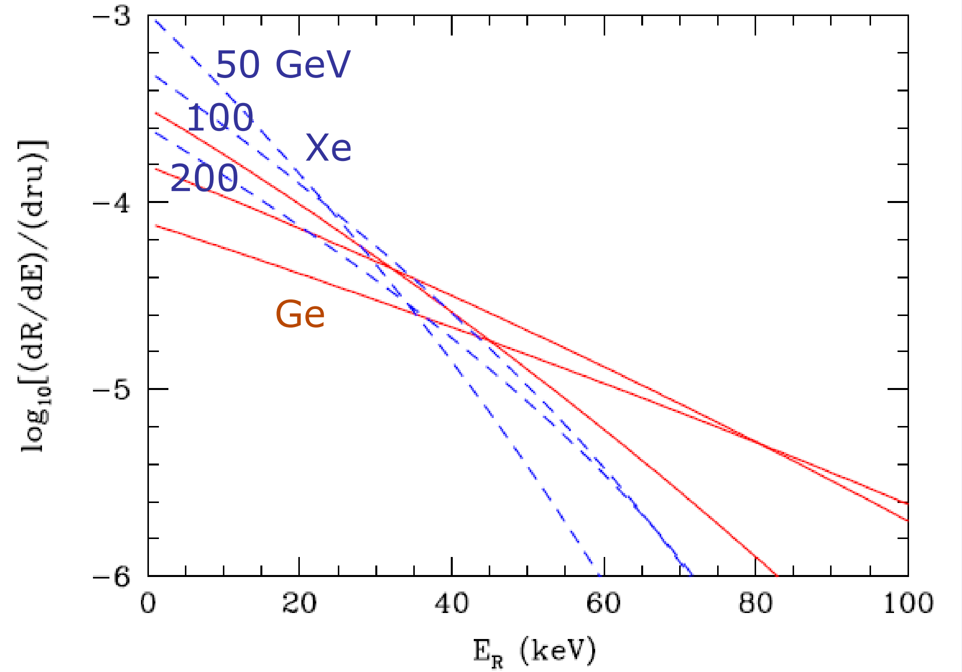
The WIMP recoil rate is s function of the WIMP mass, the target mass and the form factor

A larger target mass is more effective to search for heavy WIMPs

For very light WIMPs a low threshold is required

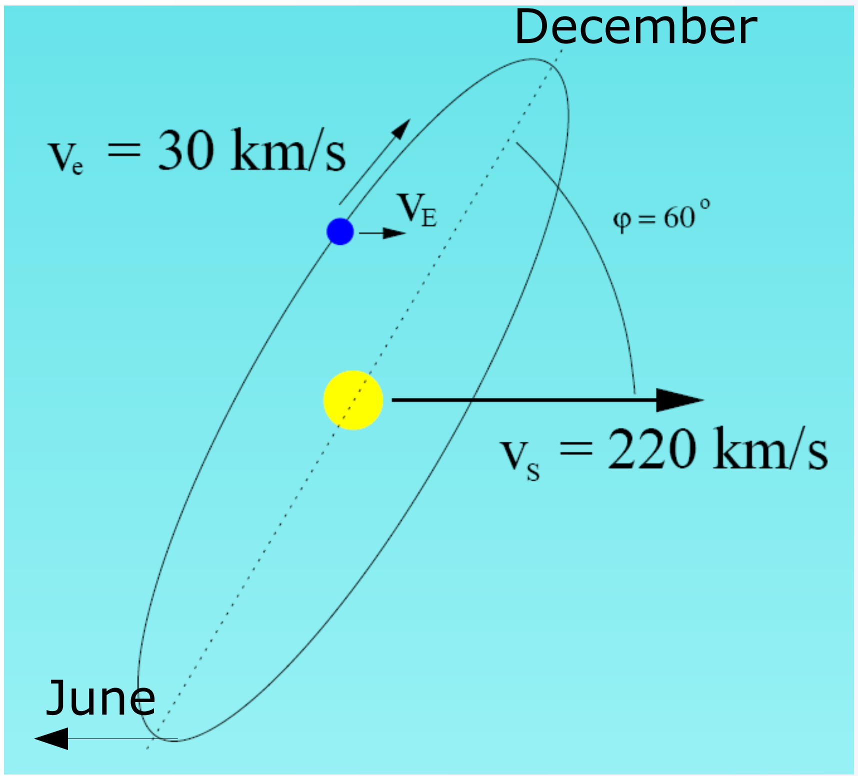
Measurements on various detectors may allow to determine the WIMP mass

(Green '08; Drees, Shan '08)

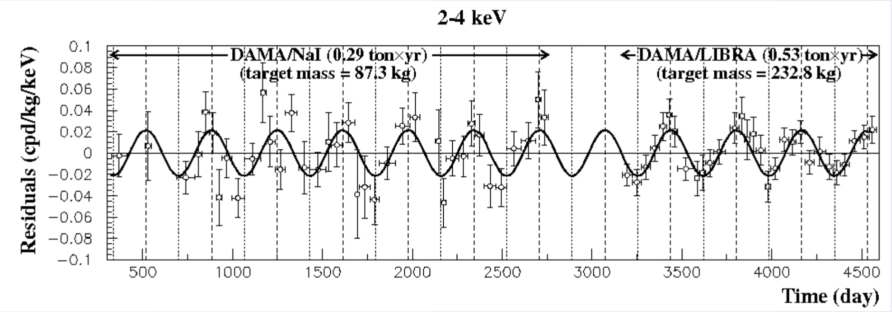


Time-dependence

Time dependence due to the motion of the Earth wrt the Galactic rest frame



$$\frac{\mathrm{d}R}{\mathrm{d}E_R} \approx \left(\frac{\mathrm{d}\bar{R}}{\mathrm{d}E_R}\right)[1 + \Delta(E_R)\cos\alpha(t)]$$



(DAMA/LIBRA Coll.)

Current experimental situation

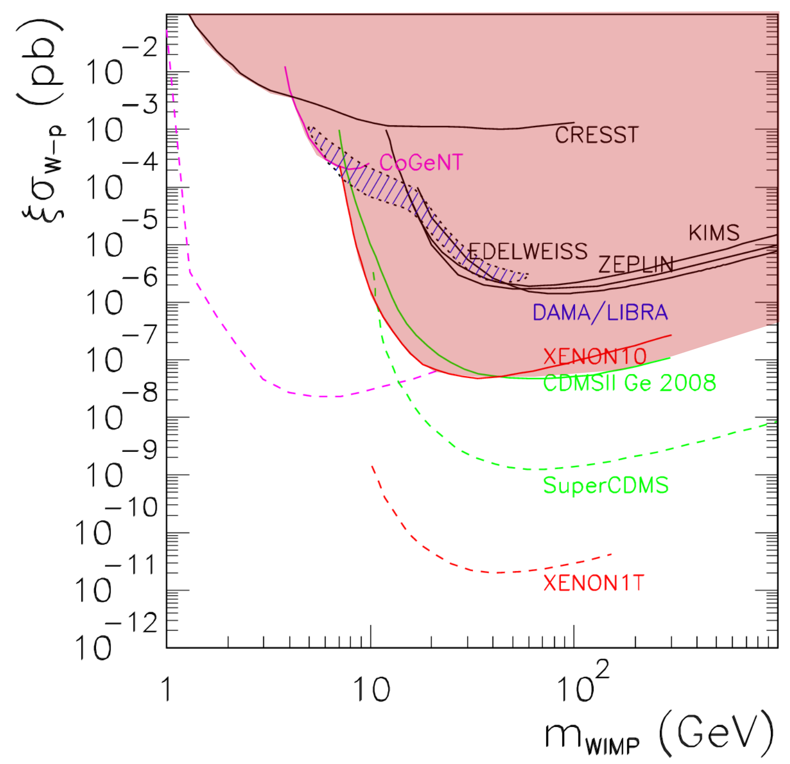
- Most of the experiments nowadays are mostly sensitive to the scalar (spin-independent) part of the WIMP-nucleon cross section

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

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

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

Need to compare with theoretical predictions for WIMP models



Particle Physics Input

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

• 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.

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 $(\tilde{H}_d^0,\ \tilde{H}_u^0)$

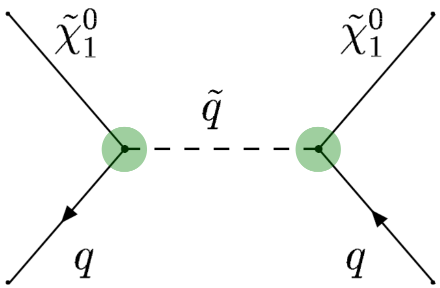
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 \end{pmatrix}$$

The detection properties of the lightest neutralino depend on its composition

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

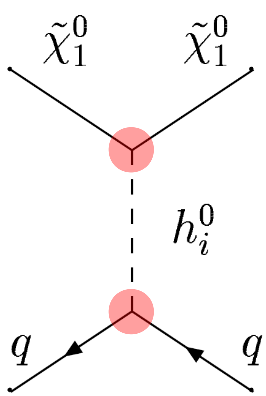
Spin-independent cross section

- 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

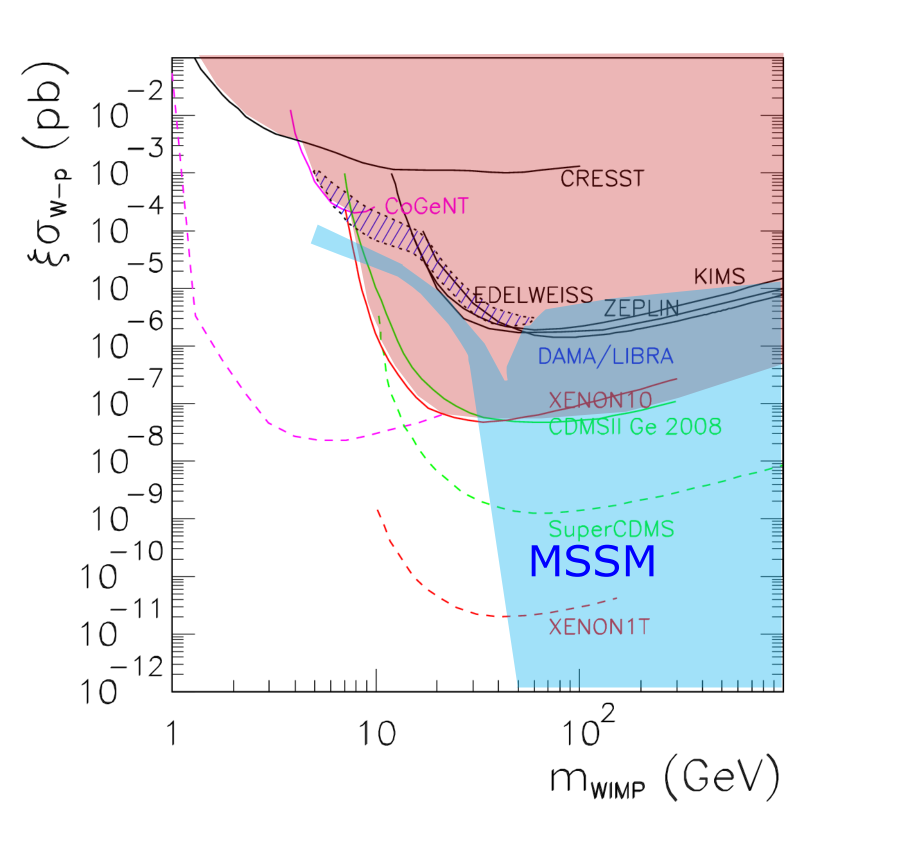
(Bottino, Donato, Fornengo, Scopel '04-'08)

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

(Roszkowski, Ruiz de Austri, Trotta '08)

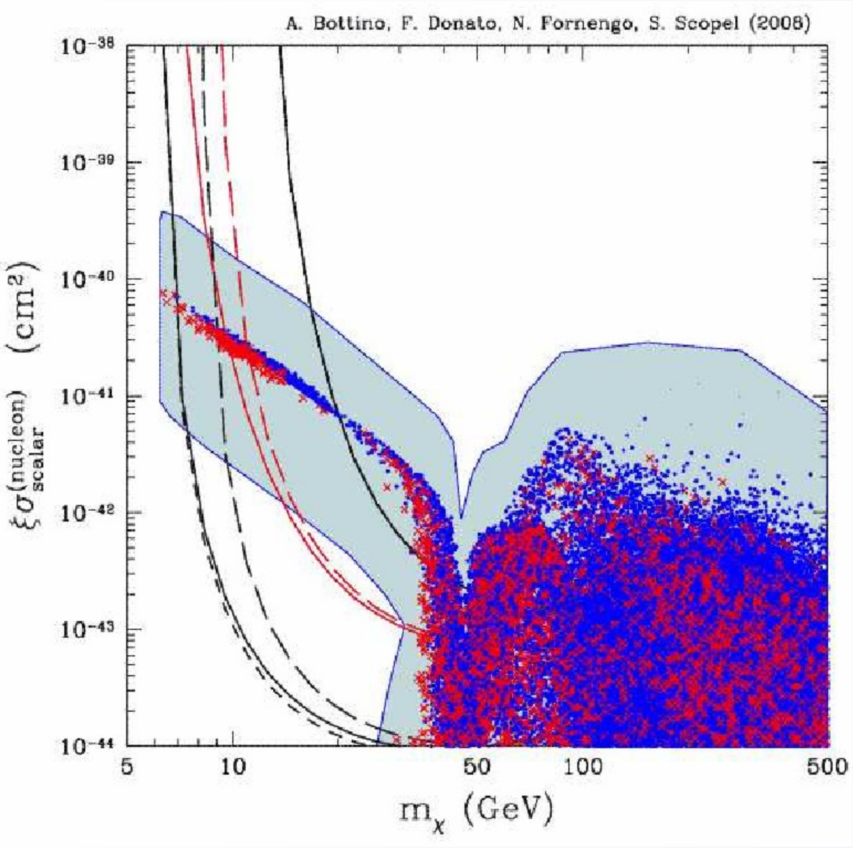
A frequentist approach may favour different regions

(Buchmüller et al. '09)



Recent results for very light WIMPs

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



(Bottino, Donato, Fornengo, Scopel '08)

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

Very light neutralinos (5-12 GeV) could account for the DAMA/LIBRA signal

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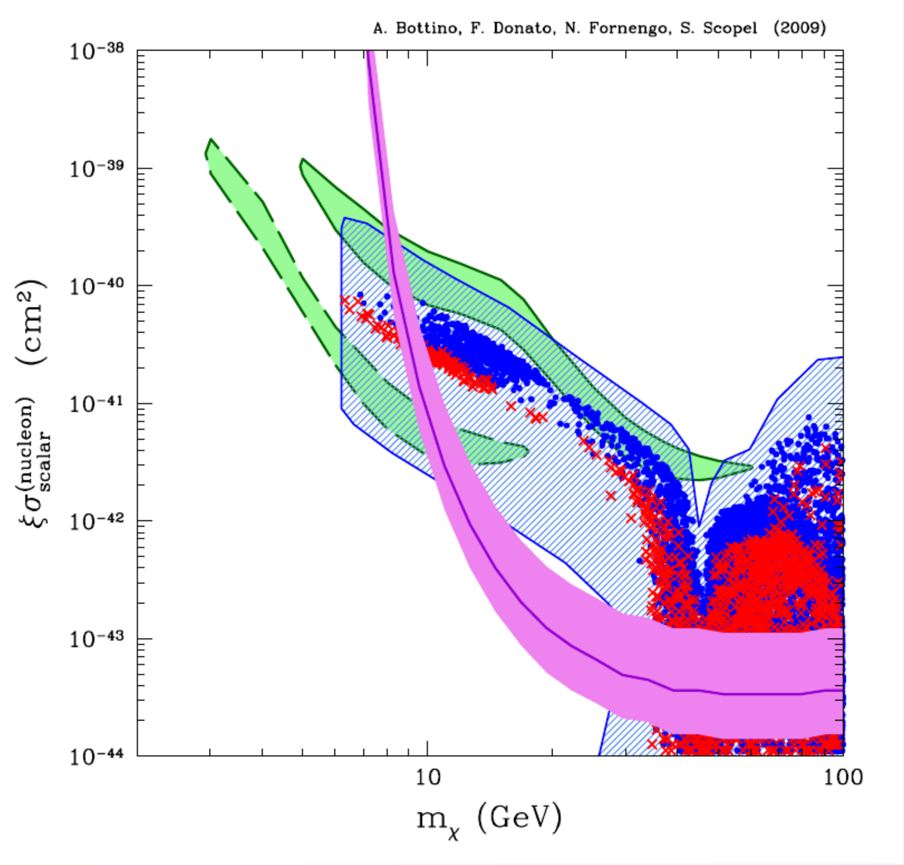

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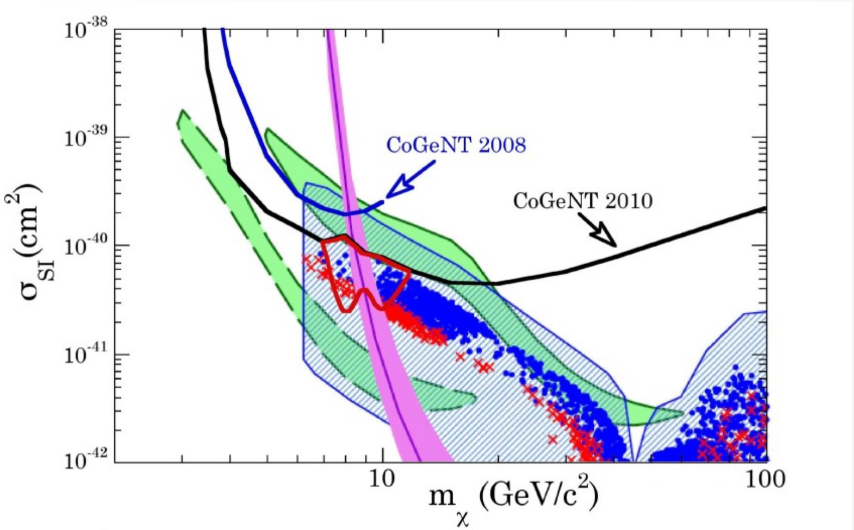
Not necessarily excluded by other experiments (depending on the halo model)

Very light neutralinos (5-12 GeV) could account for the DAMA/LIBRA signal and be compatible with CDMS events

Neutralino in the MSSM

- 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)

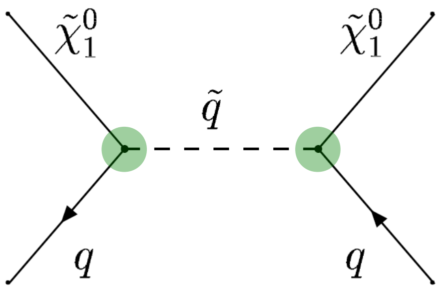
Very light neutralinos (5-12 GeV) could account for the DAMA/LIBRA signal and be compatible with CDMS events and recent results from CoGeNT...

Viable in models with non-universal gaugino masses

Problematic predictions for low-energy observables (excessive contribution to BR($b \to s\gamma$))

Spin-dependent cross section

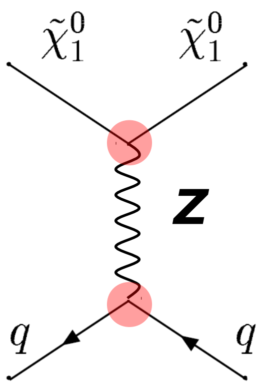
- Contributions from **squark-** and **Z-**exchanging diagrams:



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

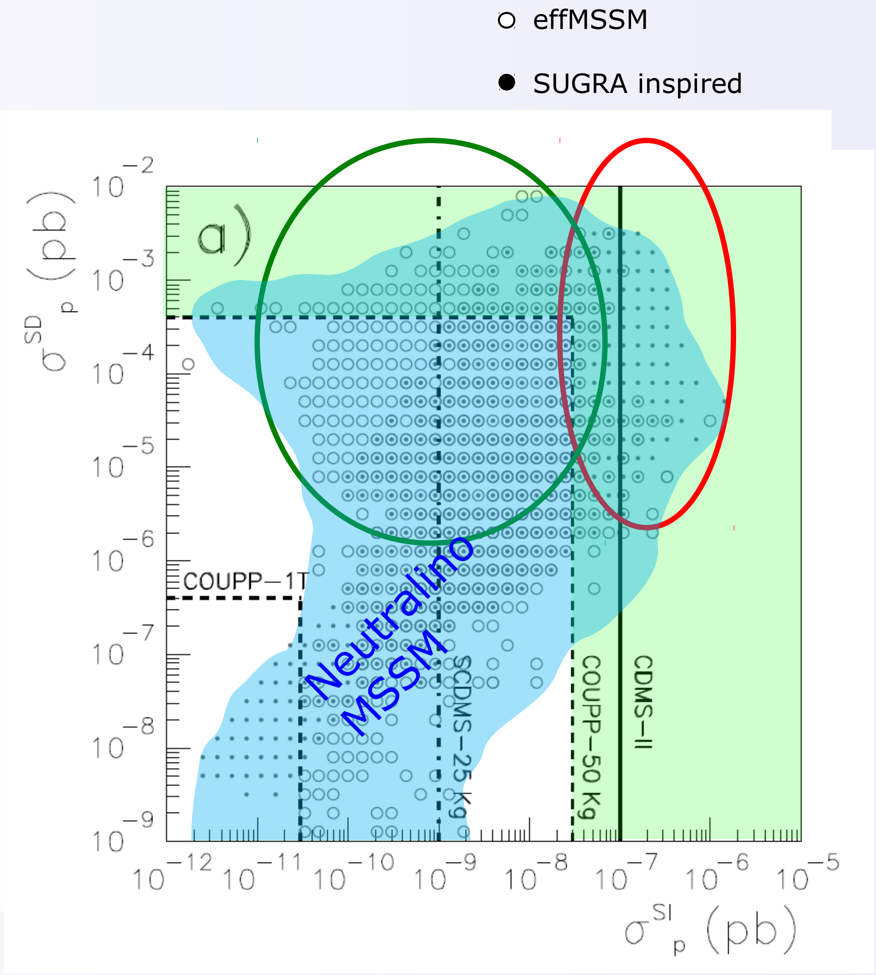
- Overall theoretical predictions in the MSSM:

Enhancement of Z-exchange

Through a decrease in the μ parameter

Enhancement of q̃-exchange

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

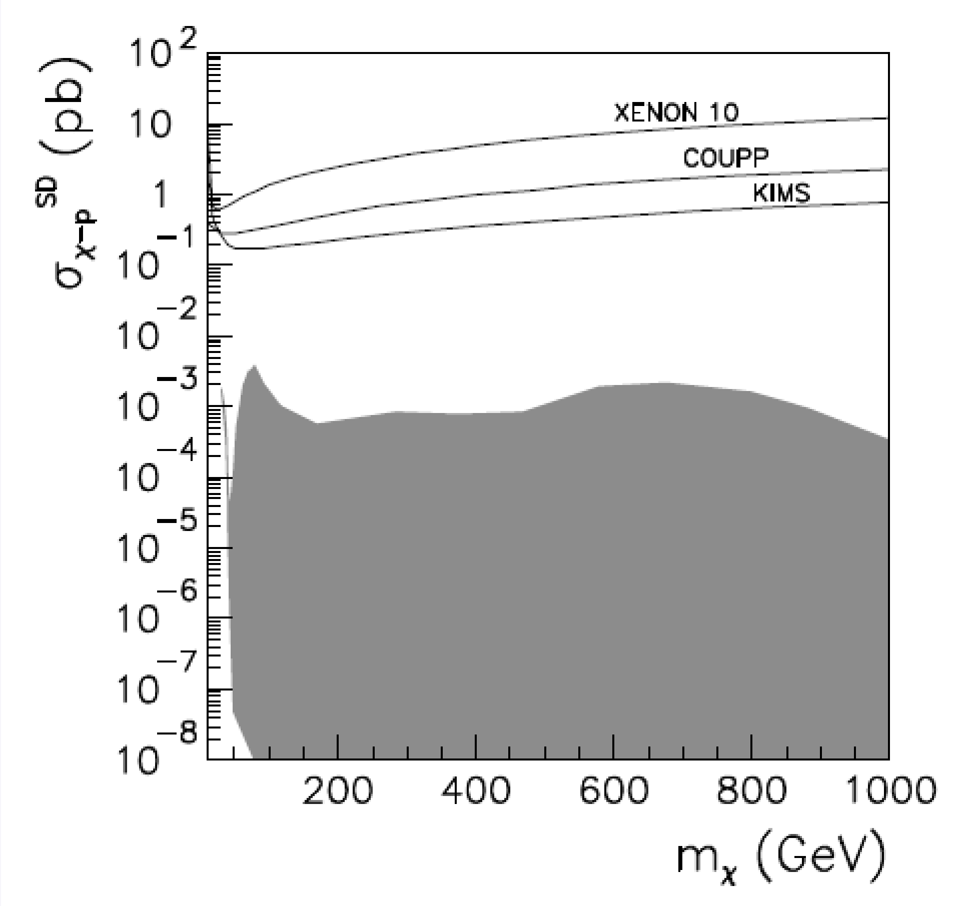


(G.Bertone, D.G.C., J.I.Collar, B.Odom´07)

Spin-dependent searches

- Overall theoretical predictions in the MSSM:

Theoretical predictions are still below present experimental sensitivities



Neutralino in the Next-to-MSSM

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

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

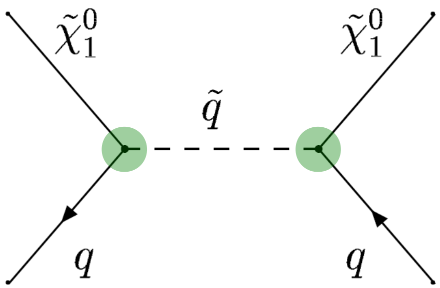
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta & 0 \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta & 0 \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu & -\lambda v_2 \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu &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

The lightest neutralino has now a singlino component

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

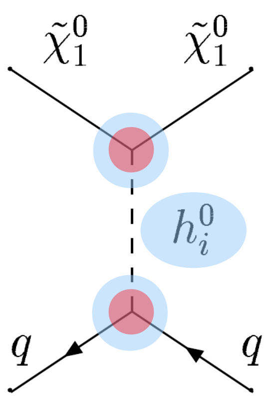
Spin-independent cross section

- 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

- 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)

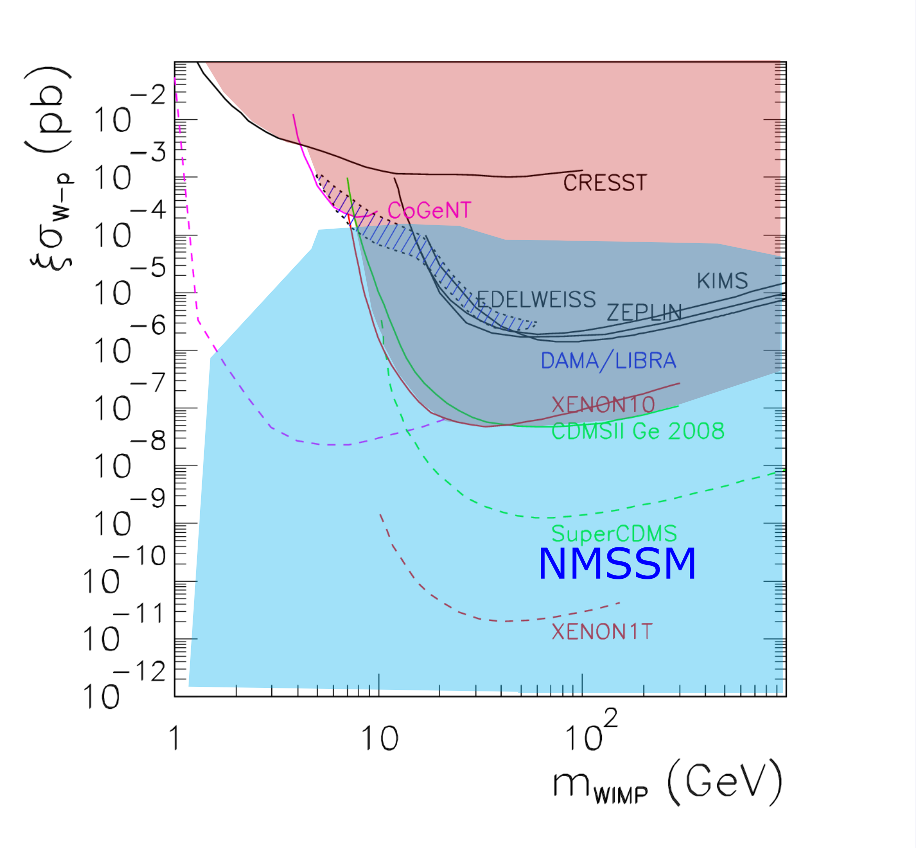
(D.G.C., E. Gabrielli, D.López-Fogliani, A.Teixeira, C.Muñoz ´07)

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

(Gunion, Hooper, McElrath '05)

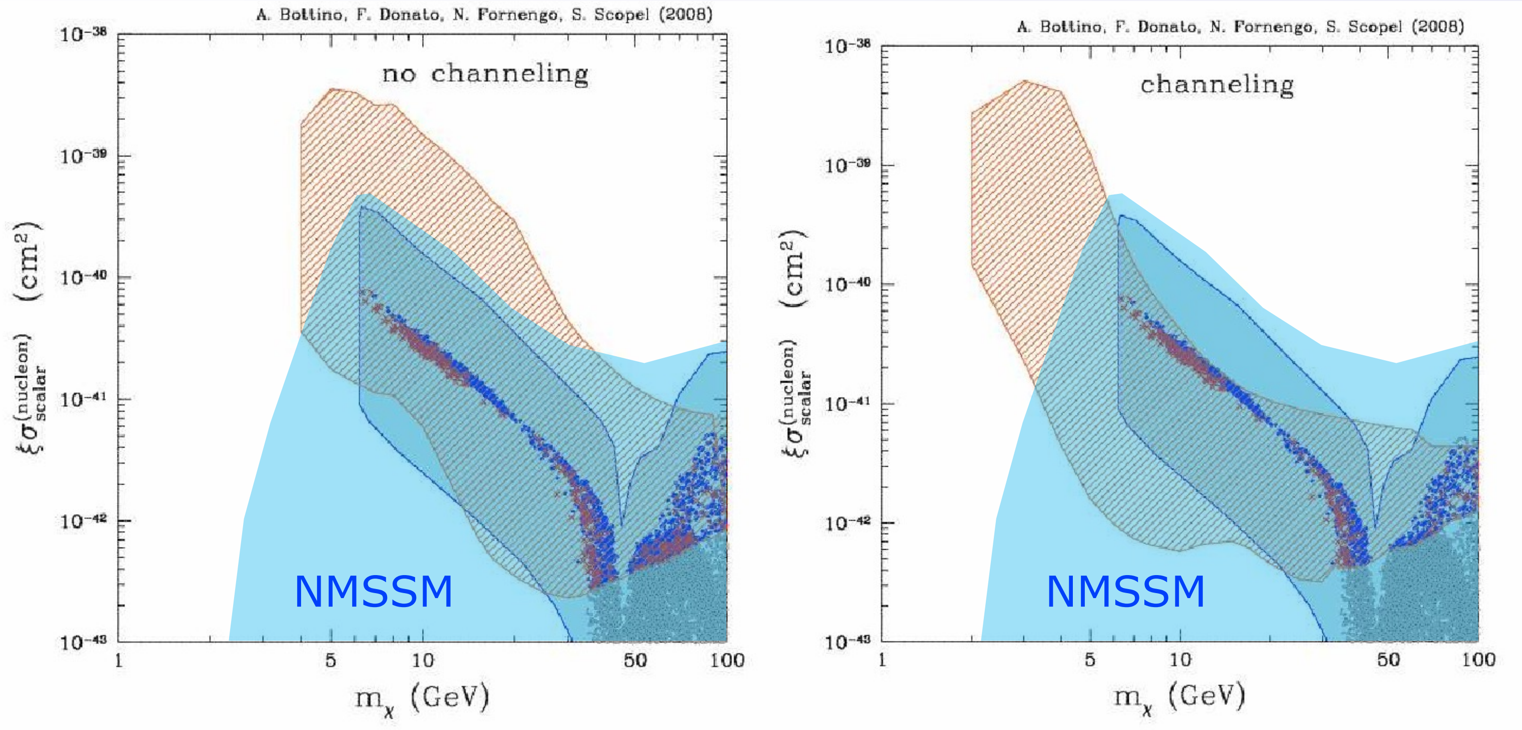
And their detection cross section significantly differs from that in the MSSM

(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

Lightest Supersymmetric Particle

• 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.

In the MSSM, the LSP can be…

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

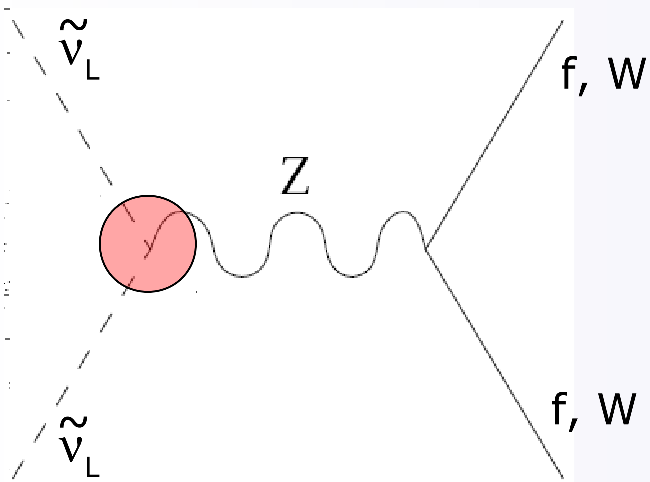
(Ibáñez ’84; Hagelin, Kane, Rabi ’84)

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)

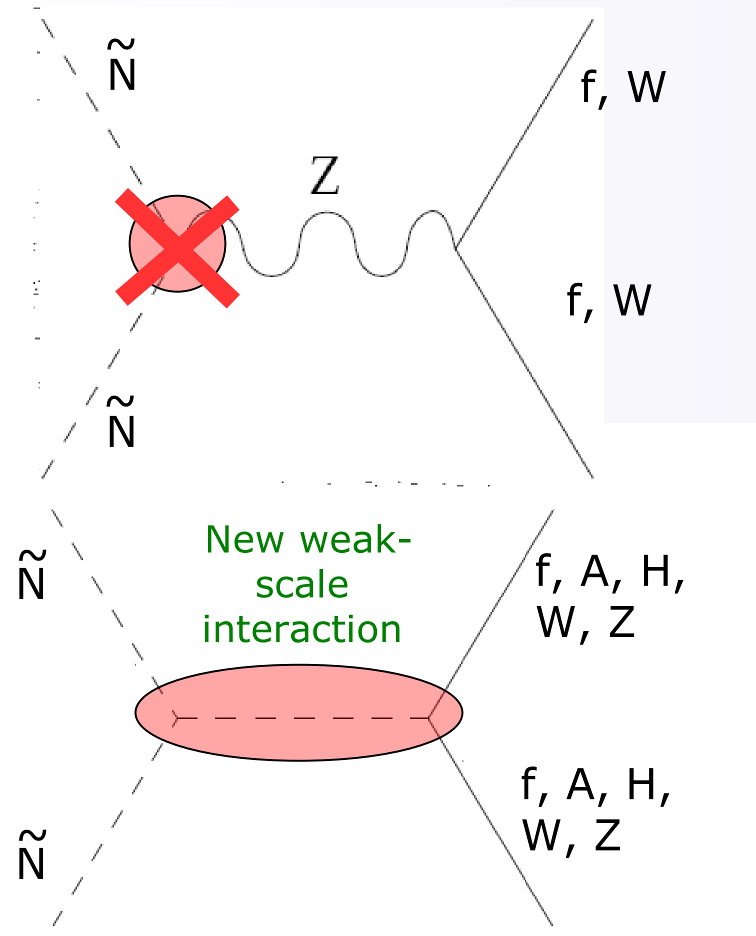
• Too large direct detection cross section (already disfavoured by current experiments)

(Falk, Olive, Srednicki '94)

Sneutrino DM 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

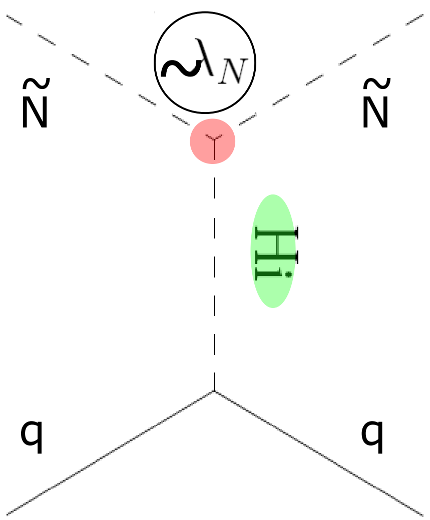
This can be accommodated in a well-motivated extension of the MSSM:

the Next-to-Minimal SUSY SM (NMSSM)

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

Spin-independent cross section

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



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

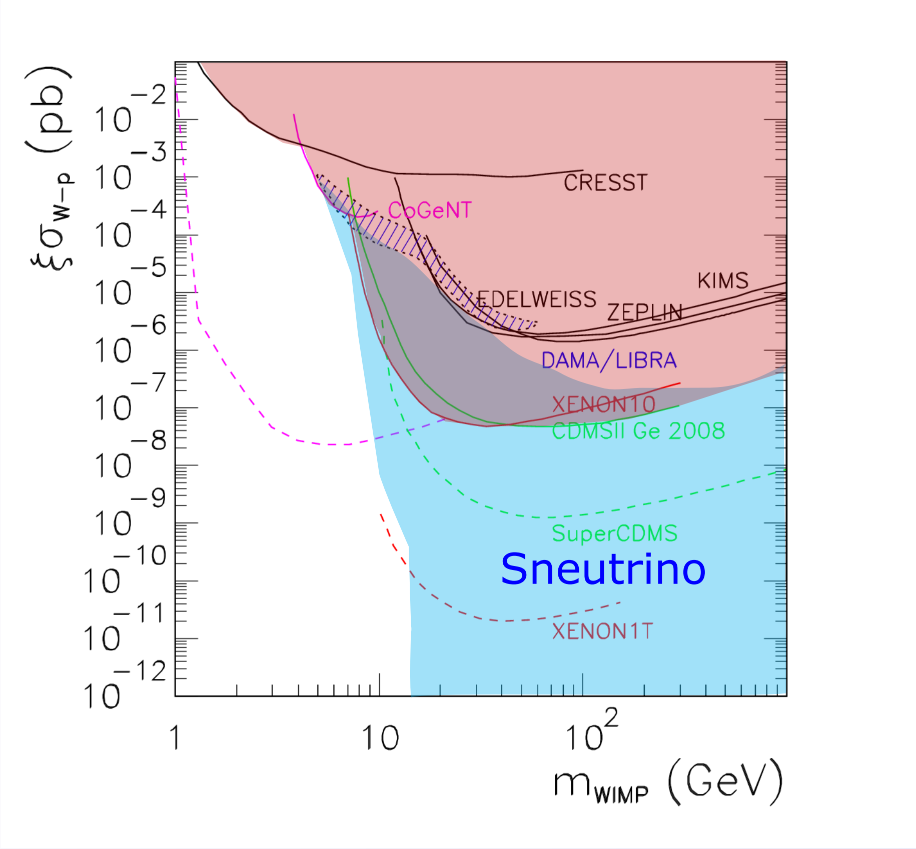
- No spin-dependent contribution: potential discrimination from neutralino

RH-Sneutrino DM overview

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

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

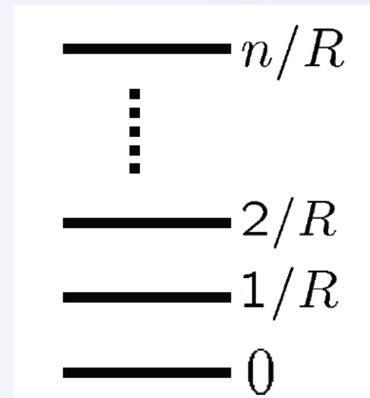
  - Light sneutrinos are viable and distinct from MSSM neutralinos
    (D.G.C., Seto '09)



Kaluza Klein dark matter

• In theories with Universal Extra Dimensions, where all SM particles propagate in the bulk, a Kaluza-Klein tower of states appears for each particle.

$$M \approx R^{-1} \sim TeV$$



• In order to obtain Chiral fermions the extra dimension has to be orbifolded, leading to conservation of KK-Parity

The lightest KK particle (LKP) is stable, and a good dark matter candidate

• B(1) (excited partner of the B boson) is a natural choice For LKP

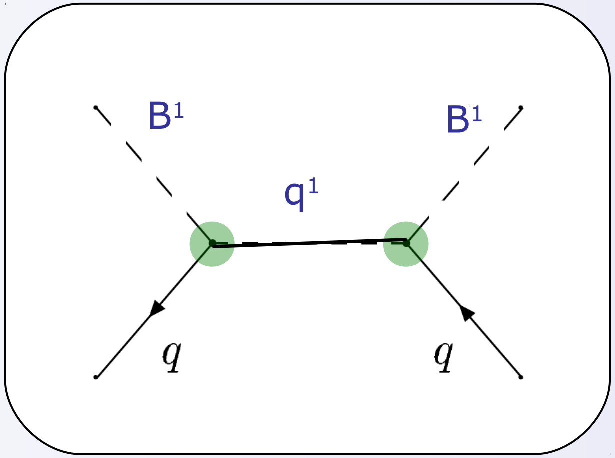
KK dark matter

- The Lightest KK particle (LKP) is a good dark matter candidate in Universal Extra Dimensions models

- B(1) Most Natural Choice For LKP

- t-channel annihilation through KK-fermions is now dominant

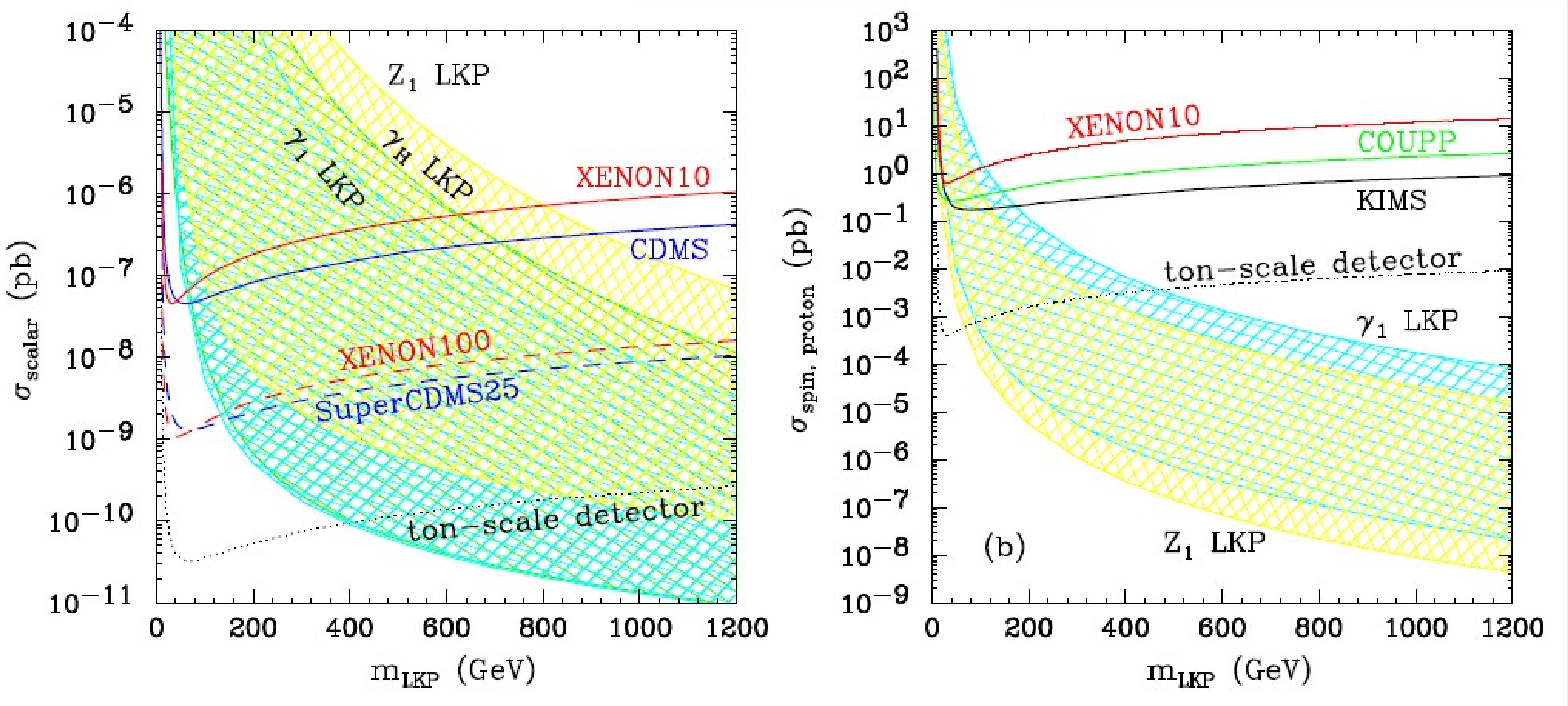
Unlike with neutralinos, their annihilation is not helicity suppressed.



- B(1) interaction with quarks also dominated by s-channel with KK-quark exchange

KK dark matter

• The Lightest KK particle (LKP) is a good dark matter candidate in Universal Extra Dimensions models

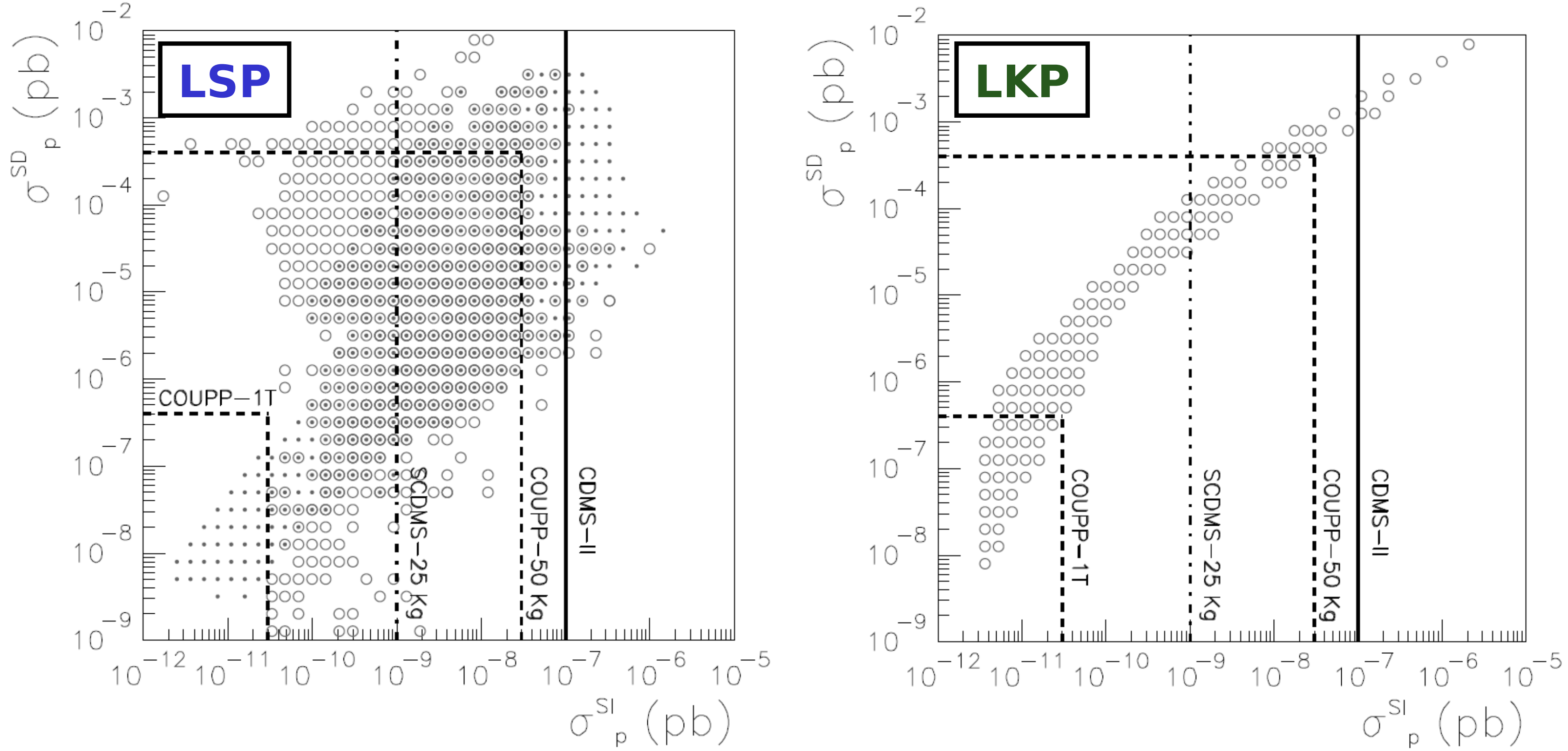


(Arrenberg et al.'08)

A note on WIMP Identification

Discriminating Neutralino vs LKP

- The predictions from neutralino dark matter and KK dark matter have a different distribution in the SI-SD cross-section plane

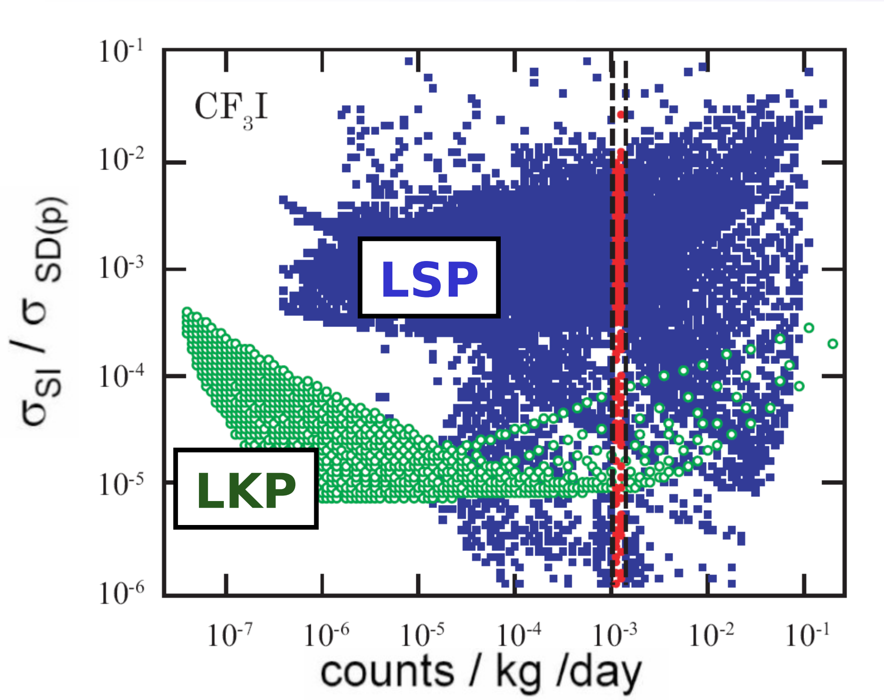


(G.Bertone, D.G.C., J.I.Collar, B.Odom´07)

Complementarity of DM searches

- A simultaneous measurement of the spin-dependent and independent couplings can help discriminating among dark matter experiments (e.g., in COUPP or KIMS)

(Bertone, D.G.C, Collar, Odom ’07)



The hypothetical detection of a DM signal with a CF_3I detector loosely constrains DM candidates.

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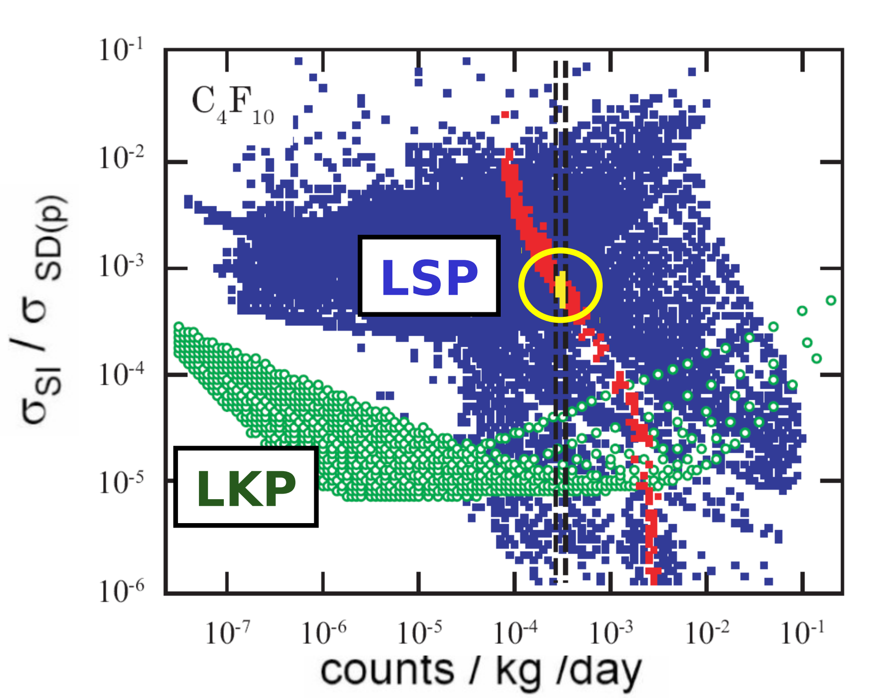

The hypothetical detection of a DM signal with a CF_3I detector loosely constrains DM candidates.

Using then a second detection fluid, C_4F_{10}, with lower sensitivity to spin-independent couplings, reduces the number of allowed models.

The sneutrino (scalar) has no spin-dependent coupling

Un-conclusions (Maybes)

Can we detect WIMP dark matter?

MAYBE: theoretical predictions for WIMP Models can be within experimental sensitivity

HAVE we already detected WIMP dark matter?

MAYBE: signals in DAMA/LIBRA + tempting hints in CDMS and CoGeNT

Can we identify WIMP dark matter?

MAYBE: combination of spin-dependent and independent searches

Can we extract some of the halo parameters upon WIMP detection?

MAYBE: combination with other searches (LHC or indirect DM detection)