WIMP identification through a simultaneous measurement of its axial and scalar couplings

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Contents

- Dark matter is a necessary ingredient in present models for the Universe…
… but we have not identified it yet.

It can be a Weakly Interacting Massive Particle (WIMP)

- Lightest SUSY particle (LSP), e.g., the NEUTRALINO
- Lightest Kaluza-Klein particle (LKP)

Direct detection experiments will continue providing data in the near future.

- Identifying the WIMP

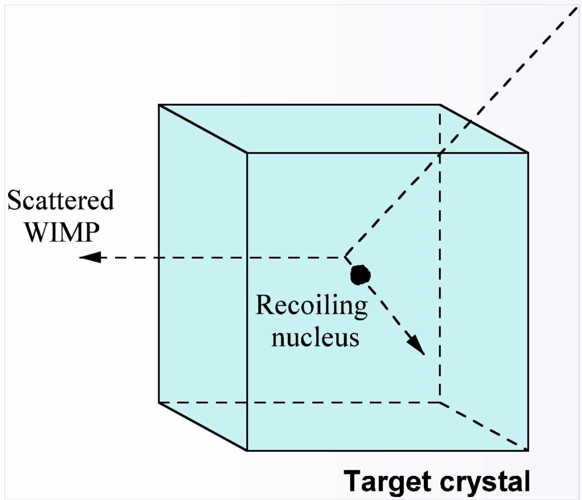
Detectors sensitive to the spin-dependent WIMP cross section: COUPP

Prospects for LSP and LKP detection

Who's the WIMP? Discriminating between LSP and LKP

WIMP direct detection

• The direct detection of WIMPS can take place through their elastic scattering with nuclei inside a detector



The recoiling energy is measured via different techniques

• Ionization on solids (**IGEX**)

• Ionization in scintillators (measured by the emmited photons) (**NAIAD, DAMA, ZEPLIN I**)

• Temperature increase (measured by the released phonons) (**CRESST I**)

Modern and projected detectors use a combination of these techniques

Ionization + phonons: **CDMS, EDELWEISS**

Ionization + scintillation: **ZEPLIN II, III, XENON**

Scintilation + phonons: **CRESST II, ROSEBUD**

WIMP-nucleus interaction

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

$$\boxed{\sigma_{\chi-N}}$$

Axial-Vector

$$\mathcal{L}_A \sim \bar{\chi}\gamma^{\mu}\gamma_5\chi\ \bar{q}\gamma^{\mu}\gamma_5 q \qquad \frac{(J+1)}{J}$$

- Adds incoherently

SPIN-DEPENDENT (Nucl. Angular mom)

Scalar

$$\mathcal{L}_S \sim \bar{\chi}\chi\ \bar{q}q \qquad A^2$$

SPIN-INDEPENDENT (Nucleon #)

Vector

$$\mathcal{L}_V \sim \bar{\chi}\gamma^{\mu}\chi\ \bar{q}\gamma^{\mu}q \qquad A^2$$

- Adds coherently
- Only for non-Majorana WIMPs

SPIN-INDEPENDENT

Spin-independent cross section

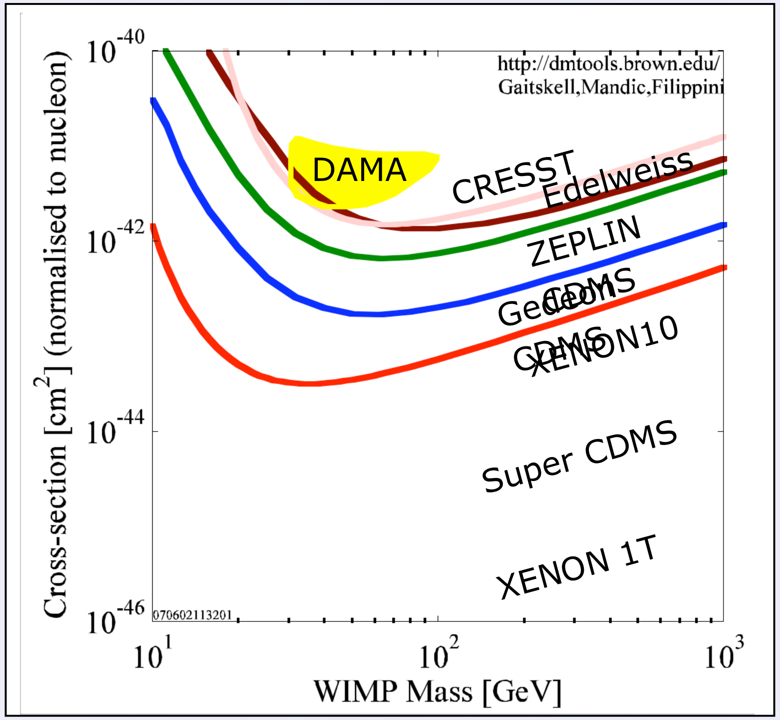
- Most of the experiments nowadays are mostly sensitive to the scalar (spin-independent) part of the WIMP-nucleon cross section (using, e.g., with Iodine or Germanium).

(Dominant for nuclei with A ≥ 20)

Many experiments around the world are currently looking for this signal with increasing sensitivities

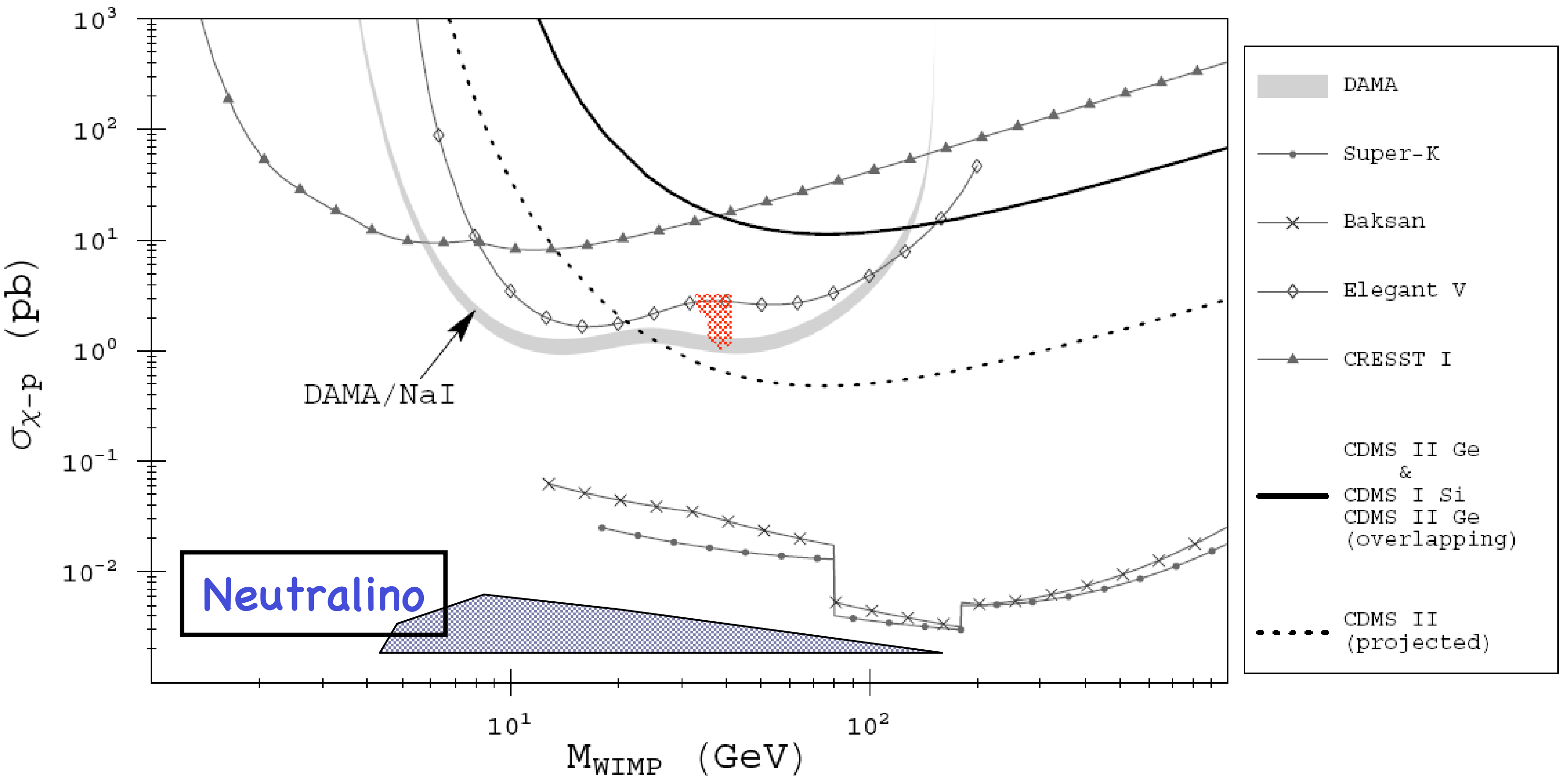
How large can the WIMP detection cross section be?

Which dark matter candidates could account for a hypothetical WIMP detection?



Spin-dependent cross section

- On the other hand, the sensitivity to the spin-dependent part of the WIMP-nucleus cross section is not that big



Savage, Gondolo, Freese ´06

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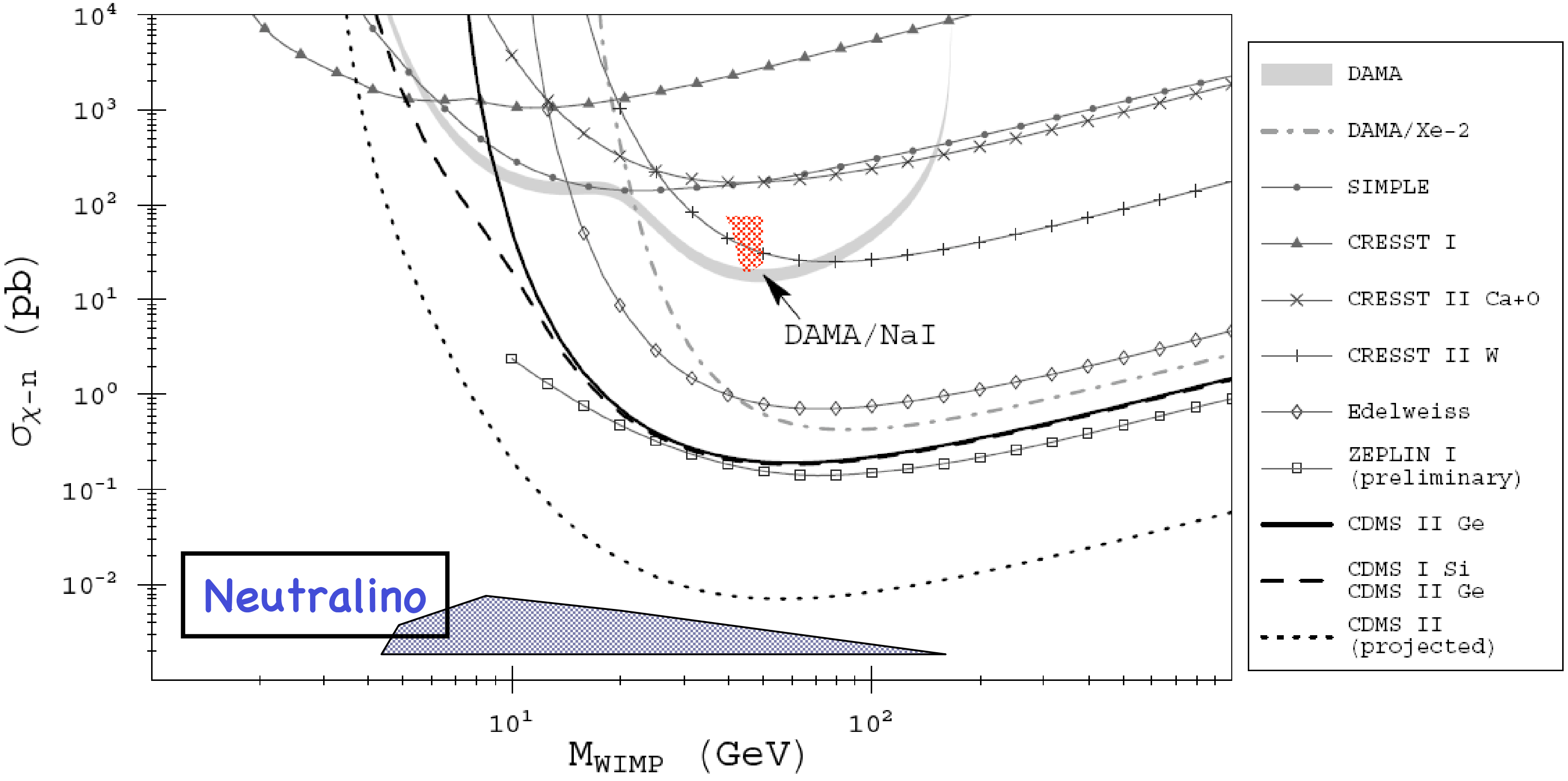
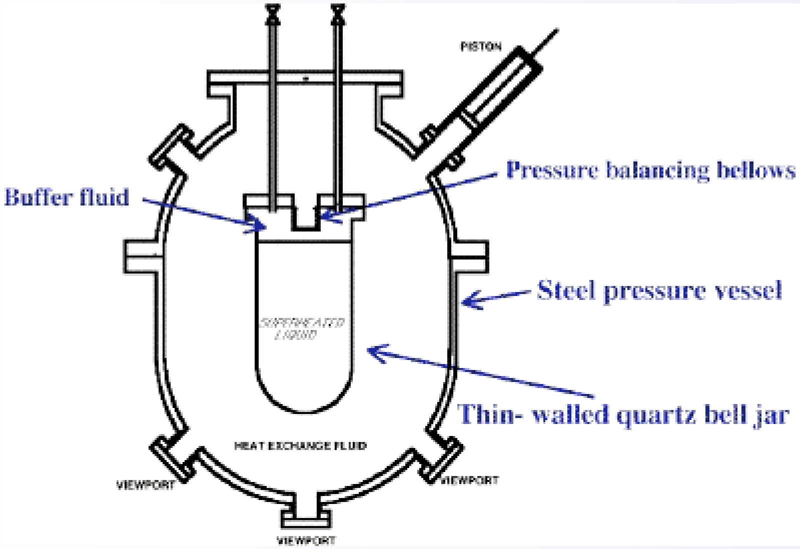


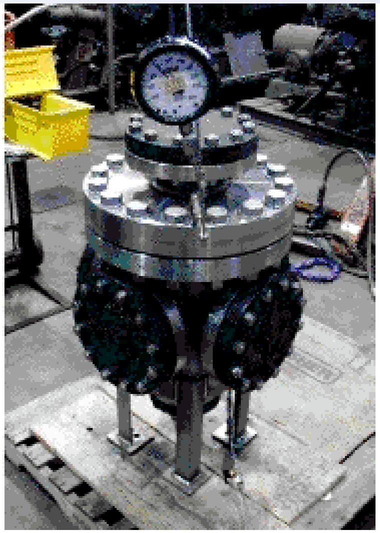
Savage, Gondolo, Freese ´06

COUPP (Chicagoland Observatory for Underground Particle Physics)

- A bubble chamber sensitive to Weakly Interacting Massive Particles (WIMPs)

A vessel containing CF_3I, that can be superheated to respond to very low energy nuclear recoils like those expected from WIMPs while being totally insensitive to minimum ionizing particles

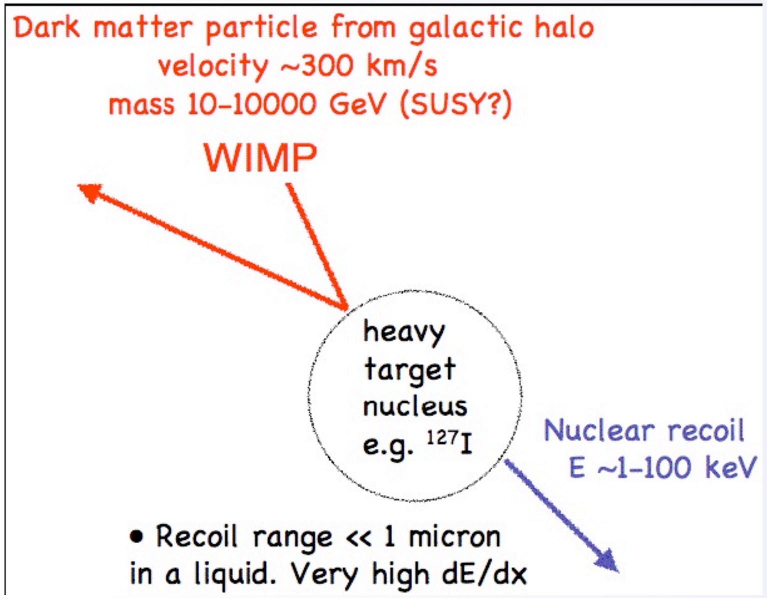


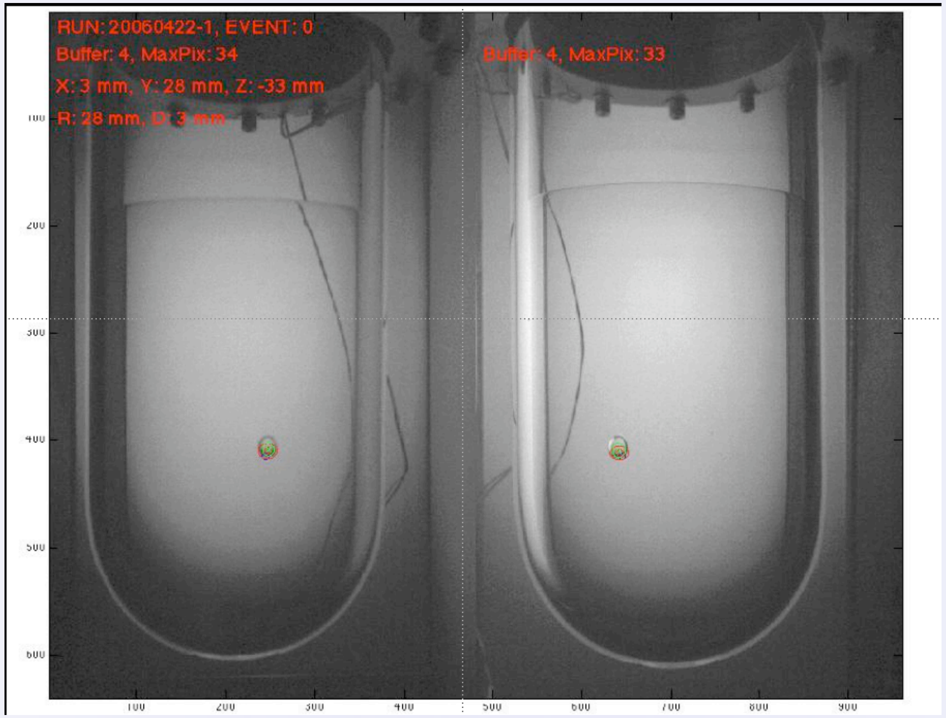


http://collargroup.uchicago.edu/news/coupp.html

COUPP

• Detection of single bubbles in a superheated liquid, induced by high dE/dx nuclear recoils in heavy liquid bubble chambers





Stereo view of a typical event in 2 kg chamber

• Choice of three triggers: pressure, acoustic, motion

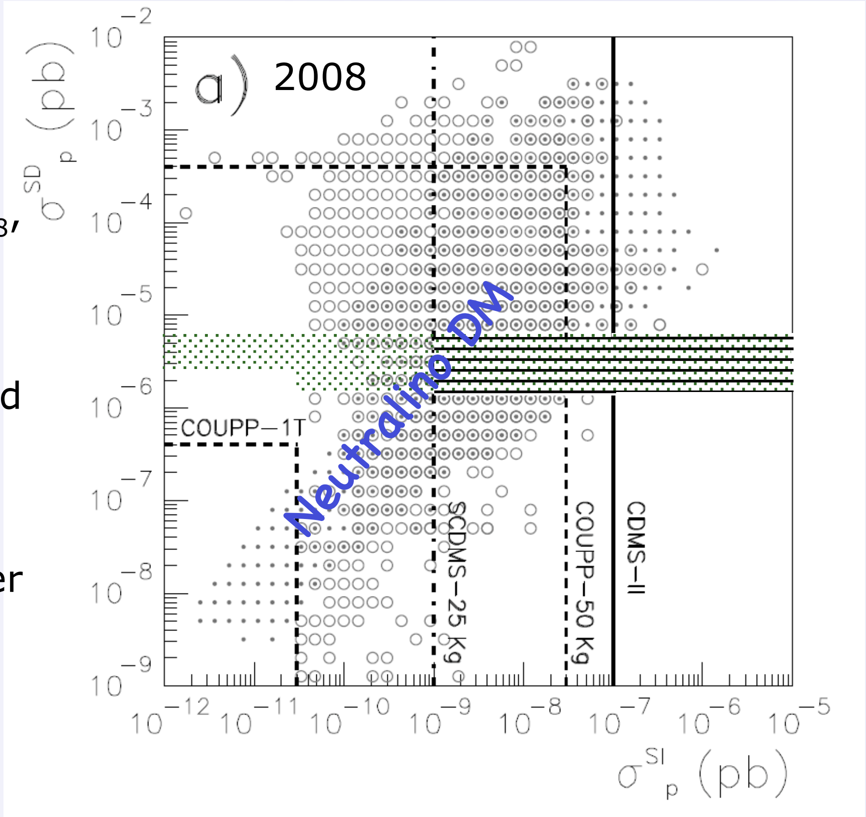
Spin-dependent cross section

- It offers an excellent sensitivity to both Spin-dependent and Spin-independent WIMP-nucleon cross section.

Target fluid can be replaced (e.g., C_3F_8, C_4F_{10}, CF_3Br).

Useful for separation between n- and WIMP-recoils and

Pinpointing WIMP in SUSY parameter space.



Theoretical predictions for WIMP detection

- **Lightest neutralino (SUSY theories)**
- **Lightest KK particle (extra dimensions)**

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

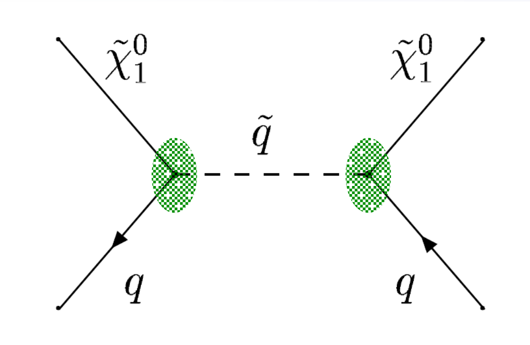
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 \end{pmatrix}$$

The detection properties of the lightest neutralino depend on its composition

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

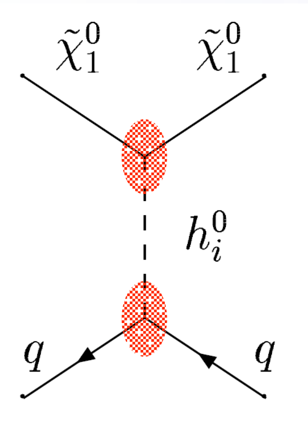
Spin-independent cross section

- 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

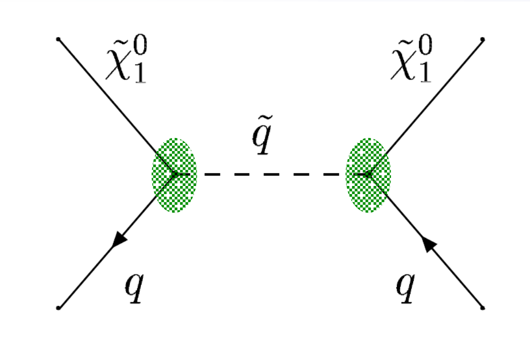
It is the leading contribution, and increases when

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

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

Spin-dependent cross section

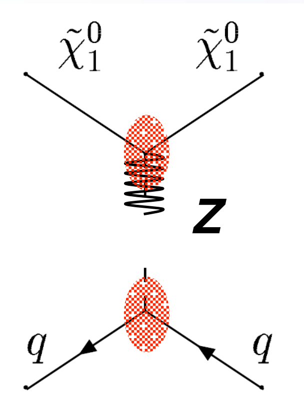
- Contributions from **squark-** and **Z-**exchanging diagrams:



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: $\mu \downarrow$

Effective MSSM

- In the effMSSM all the parameters are defined at low-energy:

$$M_1\,,\quad m,\quad \tan\beta\,,\quad m_A\,,\quad A\,,\quad \mu$$

Scalar masses (squarks, sfermions) are usually considered universal

- Experimental constraints are imposed

Masses of supersymmetric particles

Supersymmetric contribution to the muon anomalous magnetic moment

Rare B decays ($B \to s\gamma$, $B \to \mu^+ \mu^-$)

- Constraint on the neutralino relic density

$$0.094 < \Omega_{CDM}\, h^2 < 0.13 \ (2\sigma \text{ c.l.})$$

Supergravity scenarios

- The same analysis can be done from the point of view of a more fundamental Supergravity theory at high energy

1) The Soft supersymmetry-breaking terms are taken as inputs at the GUT scale and RGE are used to evaluate the SUSY spectrum

$$M_i \quad m_i \quad A_{ijk}$$

2) Experimental constraints are applied on the parameter space

masses of superpartners

Low energy observables ($(g-2)_\mu$, $b \to s\gamma$, $B_S \to \mu^+\mu^-$, ...)

3) Constraint on relic density

$$0.094 \lesssim \Omega_{\tilde{\chi}_1^0} h^2 \lesssim 0.129$$

Non-universal soft terms

• In a more general SUGRA, non-universal scalar (and gaugino) masses allow more flexibility in the neutralino sector

- Non-universal Higgses provide the most important variations

$$m_{H_d}^2 = m_0^2(1+\delta_1), \qquad m_{H_u}^2 = m_0^2(1+\delta_2)$$

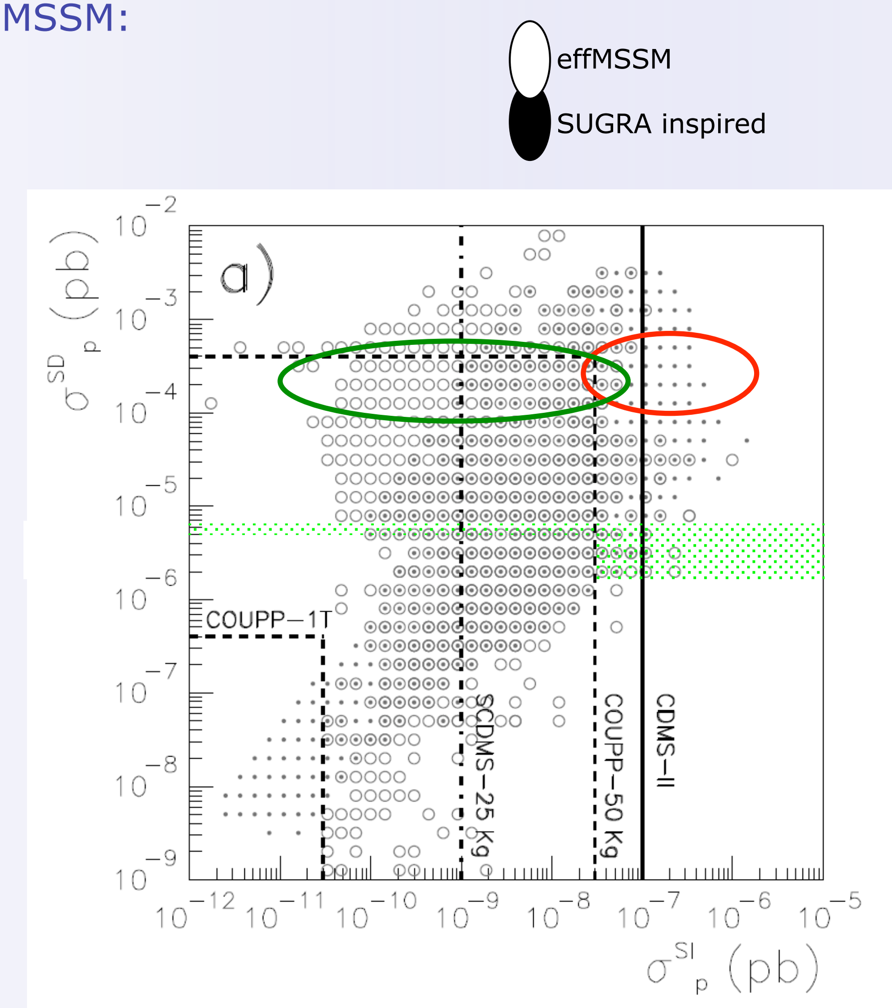
- Non-universal gauginos can change the mass and composition of the lightest neutralino

$$\begin{aligned} M_1 &= M \\ M_2 &= M(1+\delta'_2) \\ M_3 &= M(1+\delta'_3) \end{aligned}$$

Appropriate non-universal schemes can lead to a large increase in the neutralino detection cross section.

Effective MSSM

- Overall theoretical predictions in the MSSM:



Enhancement of Z-exchange

Through a decrease in the μ parameter

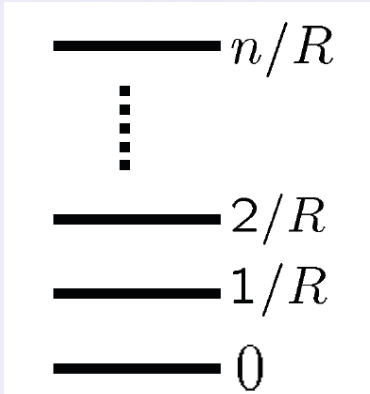
Enhancement of $\tilde{q}$-exchange

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

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.

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



• Extra dimensional moment conservation implies KK number conservation

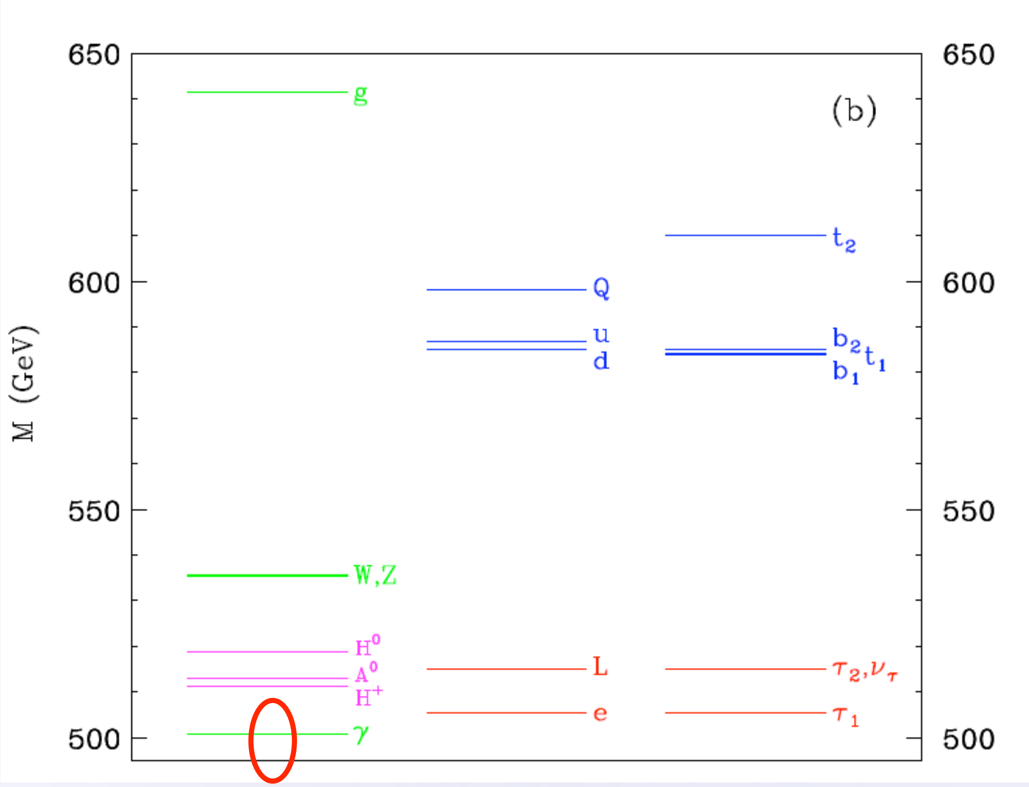
• In order to obtain Chiral fermions the extra dimension has to be orbifolded, leading to conservation of KK-Parity

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

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



$$R^{-1} = 500 \text{ GeV}$$

Cheng, Matchev, Schmaltz ´02

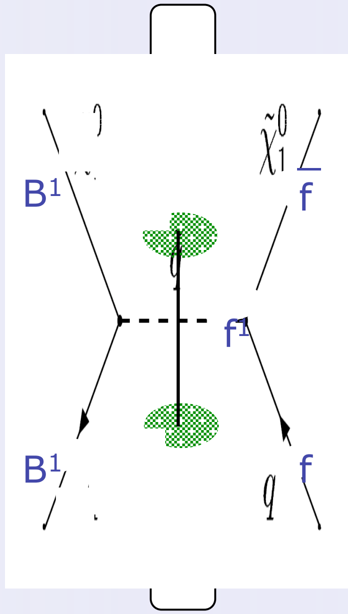
KK dark matter

• 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.



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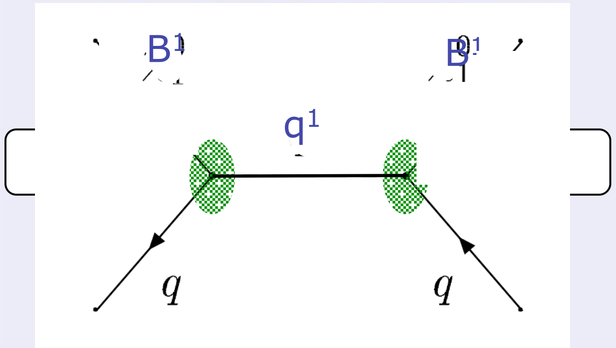


• B(1) interaction with quarks also dominated by s-channel with KK-quark exchange

KK dark matter

• The resulting spin-dependent cross section is then a function of the mass-difference between B(1) and q(1).

$$\sigma_{\mathrm{spin}}^{p,n} = \frac{1}{6\pi}\frac{m_N^2}{(m_{B^{(1)}}+m_N)^2}J_N(J_N+1)\left[\sum_{u,d,s}\alpha_q\Delta_q^{p,n}\right]^2$$

$$\alpha_q = \frac{2e^2}{\cos^2\theta_W}\left[\frac{Y_{q_L}^2 m_{B^{(1)}}}{m_{q_L^1}^2 - m_{B^{(1)}}^2} + (L \rightarrow R)\right]$$

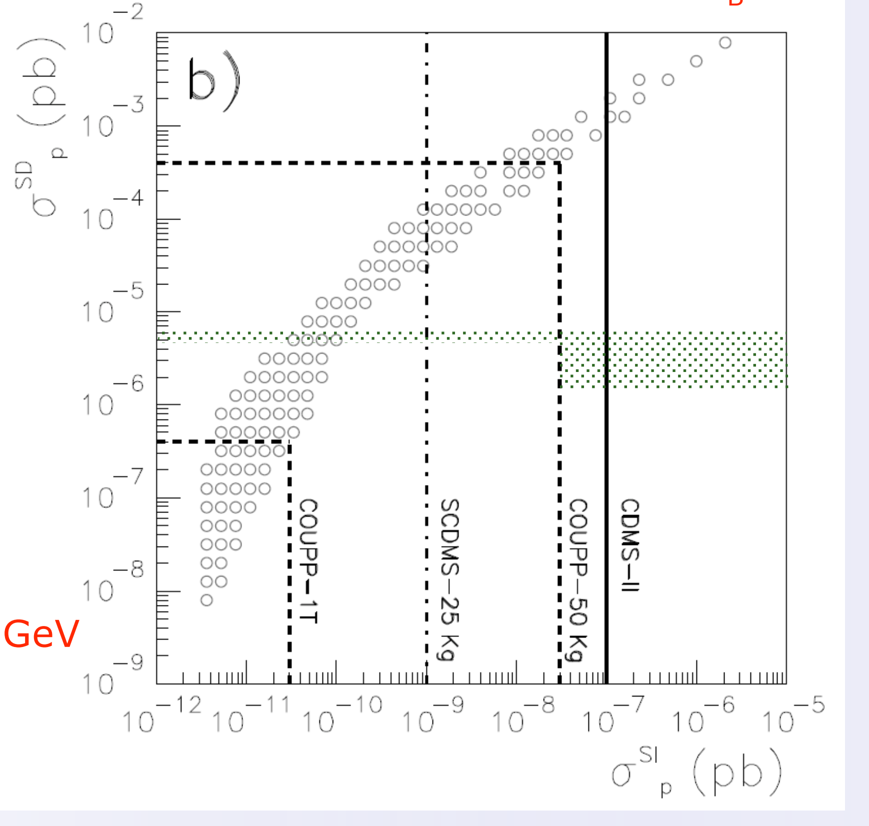
Spin-dependent cross section

• The resulting spin-dependent cross section is then a function of the mass-difference between B(1) and q(1).

It can be sizable when both are very close to each other. Unlike SUSY models, degeneracy is immediate in UED models at tree level.

$$r \equiv (m_{q^{(1)}}) - m_{B^{(1)}})/m_{B^{(1)}}$$

r=0.01
m_B=300 GeV



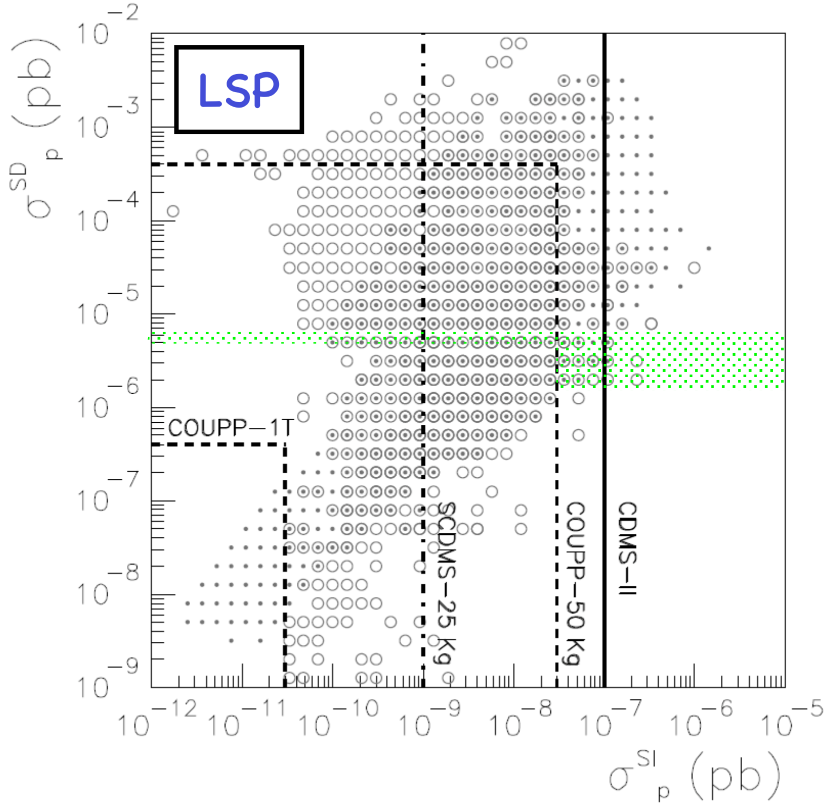
r=0.5
m_B=1000 GeV

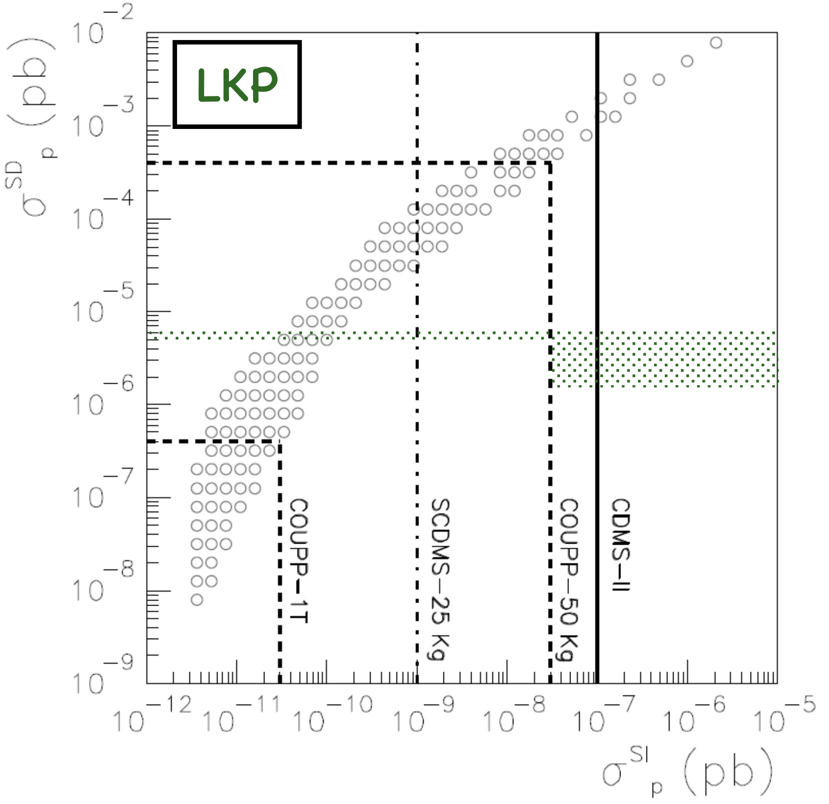
Who’s the WIMP?

- **Discriminating between LSP and LKP**

Discriminating Neutralino vs LKP

- The predictions from neutralino dark matter and KK dark matter can be within the reach of COUPP detector in some regions of the parameter space





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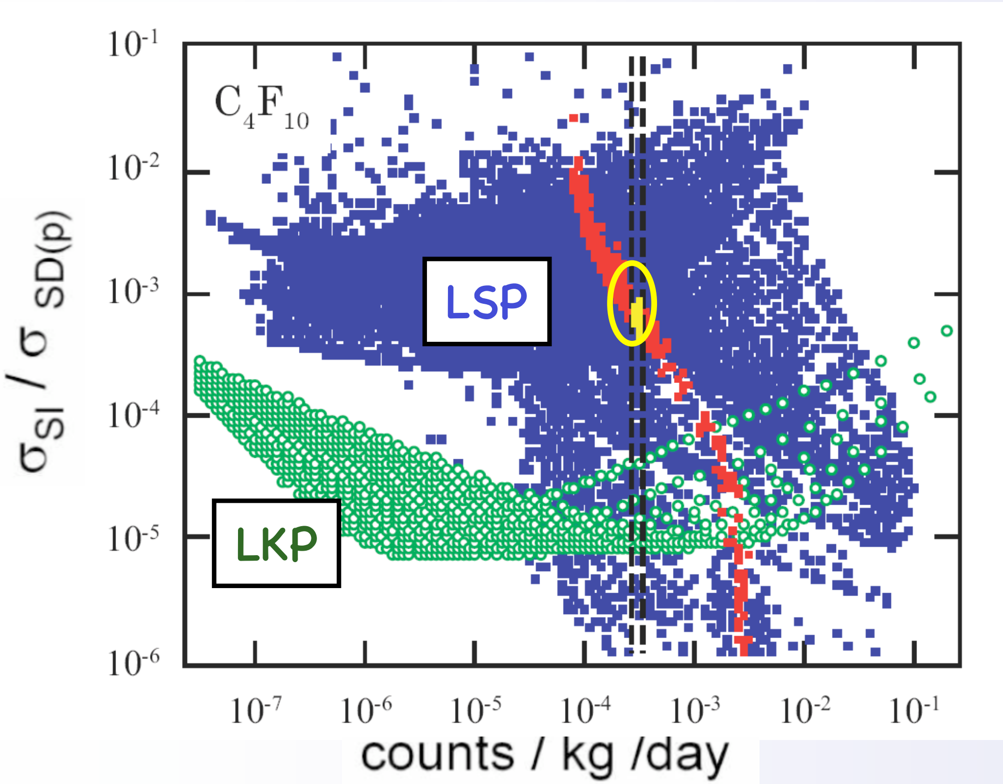

The hypothetical detection of a DM signal with a CF_3I detector loosely constrains DM candidates.

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

This can potentially be used to distinguish between LSP and LKP WIMPs.

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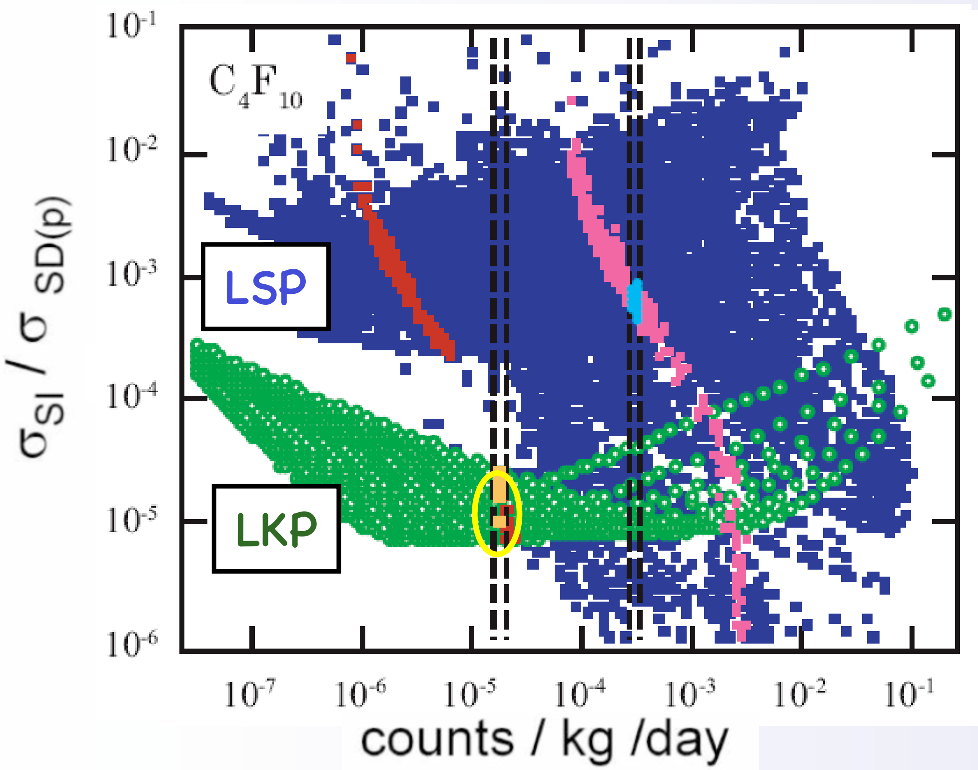

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Conclusions

• For certain classes of WIMPs a detector exclusively sensitive to one detection mode (spin-indepedent) may lack sensitivity to a large fraction of the parameter space

Complementary information is needed from experiments which are sensitive to the spin-dependent part of the WIMP-nucleon cross section:

- The lightest neutralino can have a large spin-dependent detection cross section (Higgsino-like neutralinos or when squark masses are very close to the neutralino mass)

- The LKP in UED models can also have sizable axial couplings (due to q(1)-exhange diagrams)

• The simultaneous direct measurement of axial and scalar couplings can help discriminating between WIMP candidates: e.g, Neutralino LSP and LKP in UED

The possibility of operating experiments such as COUPP with a range of detection fluids allows a better determination of these couplings.